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03HQGR0033

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP
Review of Utah Paleoseismic-Trenching Data and Determination of Consensus Recurrence-Interval and Vertical Slip-Rate Estimates

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ABSTRACT

The Utah Quaternary Fault Parameters Working Group has completed a comprehensive evaluation of paleoseismic-trenching data available for Utah's Quaternary faults, and where the data permit have assigned consensus preferred recurrence-interval (RI) and vertical slip-rate (VSR) estimates for the faults/fault sections under review. Trenching data are available for 33 (16%) of Utah's 212 Quaternary faults/fault sections and related structures. The available paleoseismic-trenching data are most abundant and best constrained on the six central, active segments of the Wasatch fault zone coincident with the populous Wasatch Front, and are much less abundant and typically less well constrained for faults elsewhere in Utah.

The general paucity of paleoseismic-trenching data, combined with large uncertainties associated with some of the data, prevented using rigorous statistical techniques to determine RI and VSR values. Consequently, the Working Group relied on the broad experience and best professional judgment of its members to assign preferred RI and VSR estimates to the faults/fault sections under review. For some faults/fault sections, the trenching data were insufficient for the Working Group to make RI and VSR estimates. The Working Group also determined "best estimate" confidence limits for the RI and VSR estimates that reflect both epistemic and aleatory uncertainties associated with each fault/fault section. Until superseded by information from new paleoseismic investigations, the Working Group's preferred RI and VSR estimates and associated confidence limits represent the best available information regarding surface-faulting activity for the faults/fault sections reviewed, and can be considered as approximating average RI and VSR values and two-sigma variability about those mean values.

The Working Group recommends additional paleoseismic study of 20 faults/fault sections to characterize Utah's earthquake hazard to a minimally acceptable level. The

Working Group considered NEHRP minimum slip-rate criteria and specific fault priorities for urban areas in Utah when evaluating which faults to recommend for additional study. However, the Working Group selected some faults precisely because so little is known about their recurrence or slip history. Others, while not located adjacent to urban areas, are near major transportation, utility, and pipeline corridors critical to Utah’s citizens and economy.

Consensus RI and VSR estimates are necessary to (1) update the National Seismic-Hazard Maps, (2) characterize seismic sources, (3) perform probabilistic seismic-hazard analyses, and (4) provide data for research into other earthquake topics. The Working Group’s consensus RI and VSR estimates are currently the best available data to meet those needs.

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UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP
Review of Utah Paleoseismic-Trenching Data and Determination of Consensus Preferred Recurrence-Interval and Vertical Slip-Rate Estimates

William R. Lund
Utah Geological Survey
Principal Investigator/Working Group Coordinator

INTRODUCTION

This report presents the results of the Utah Quaternary Fault Parameters Working Group, hereafter referred to as the Working Group, review and evaluation of Utah's Quaternary fault paleoseismic-trenching data. The purpose of the review was to (1) critically evaluate the accuracy and completeness of the paleoseismic-trenching data, particularly regarding earthquake timing and displacement, (2) where the data permit, assign consensus, preferred recurrence-interval (RI) and vertical slip-rate (VSR) estimates with appropriate confidence limits to the faults/fault sections under review, and (3) identify critical gaps in the paleoseismic data and recommend where and what kinds of additional paleoseismic studies should be performed to ensure that Utah's earthquake hazard is adequately documented and understood. It is important to note that the Working Group's review was limited to faults/fault sections having paleoseismic-trenching data. Most Quaternary faults/fault sections in Utah have not been trenched, but many have RI and VSR estimates based on tectonic geomorphology or other non-trench-derived studies. Black and others (2003) compiled the RI and VSR data for Utah's Quaternary faults, both those with and without trenches.

Although used extensively by researchers and geologic and engineering practitioners, prior to this review, Utah's Quaternary fault paleoseismic-trenching data had not been critically evaluated to establish consensus fault parameter values and confidence limits. Consequently, users unfamiliar with the database and unaware of important caveats often did not recognize variations in the quality and completeness of the data.

Consensus RI and VSR estimates are a critical component in four areas directly related to reducing losses from earthquakes in Utah: (1) updating the National Seismic Hazard Maps, (2) characterizing seismic sources, (3) performing probabilistic seismic hazard analyses, and (4) providing consensus paleoseismic data for research into other earthquake topics. With a widely distributed consensus dataset, all users can have access to expert-reviewed paleoseismic-trenching data that are qualified with appropriate caveats, and from which they can make informed judgments regarding their own research and projects.

Table 1 presents a summary of the Working Group's results. An expanded table in appendix A contains additional critical background information regarding the paleoseismic data considered in the Working Group review. Appendix B summarizes the paleoseismic data available for each fault/fault section, and lists the paleoseismic source documents consulted for this review.

Table 1. Summary of Working Group consensus values for timing of most recent surface faulting and preferred recurrence-interval and vertical slip-rate estimates.

Fault Fault Section/Segment[1]	Timing of Most Recent Earthquake	Preferred Recurrence Interval (kyr)[2]	Preferred Vertical Slip Rate (mm/yr)[2]
Wasatch fault zone			
Brigham City segment	2100±800 cal yr B.P.	0.5-**1.3**-2.8	0.6-**1.4**-4.5
Weber segment	0.5±0.3 ka/950±450 cal yr B.P.[3]	0.5-**1.4**-2.5	0.6-**1.2**-4.3
Salt Lake City segment	1300±650 cal yr B.P.	0.5-**1.3**-2.4	0.6-**1.2**-4.0
Provo segment	600±350 cal yr B.P.	1.2-**2.4**-3.2	0.6-**1.2**-3.0
Nephi segment	≤1.0±0.4 ka[4]	1.2-**2.5**-4.8	0.5-**1.1**-3.0
Levan segment	≤1000±150 cal yr B.P.	>3, <12[5]	0.1-0.6[5]
Joes Valley fault zone[6]	Not constrained	5-**10**-50	No estimate
West Valley fault zone	1.3-1.7 ka	No estimate	0.1-**0.4**-0.6
West Cache fault zone Clarkston fault	3600-4000 cal yr B.P.	5-20[5]	0.1-**0.4**-0.7
Junction Hills fault	8250-8650 cal yr B.P.	10-25[5]	0.05-**0.1**-0.2
Wellsville fault	4400-4800 cal yr B.P.	10-25[5]	0.05-**0.1**-0.2
East Cache fault zone central section	4.3-4.6 ka	4-**10**-15	0.04-**0.2**-0.4
Hurricane fault zone Anderson Junction section	5-10 ka	5-50[5]	0.05-**0.2**-0.4
Great Salt Lake fault zone[7] Fremont Island section	3150+235/-211 cal yr B.P.	1.8-**4.2**-6.6	0.3-**0.6**-1.6
Antelope Island section	586+201/-241 cal yr B.P.	1.8-**4.2**-6.6	0.3-**0.6**-1.6
Oquirrh fault zone	4.8-7.9 ka	5-**20**-50	0.05-**0.2**-0.4
Southern Oquirrh Mountain fault zone Mercur fault	Shortly after 4.6±0.2 ka	5-**20**-50	0.05-**0.2**-0.4
Eastern Bear Lake fault southern section	>0.6±0.08 ka, <2.1±0.2 ka	3-**8**-15	0.2-**0.6**-1.6
Bear River fault zone	2370±1050 yr B.P.[8]	1-100[5]	0.05-**1.5**-2.5
Morgan fault zone central section	<8320 ^{14}C yr B.P.	25-100[5]	0.01-**0.02**-0.04
James Peak fault	>30-70 ka	10-**50**-100	0.01-**0.03**-0.07
Towanta Flat graben[6]	>130-150 ka	25-**50**-200	No estimate
Bald Mountain fault	>130 ka	No estimate	No estimate
Strawberry fault	≥1.5 ka	5-**15**-25	0.03-**0.1**-0.3
Hansel Valley fault	C.E. 1934[9]	15-**25**-50	0.06-**0.12**-0.24
Hogsback fault southern section	Not constrained	No estimate	No estimate
North Promontory fault	Latest Pleistocene/Holocene	No estimate	0.1-**0.2**-0.5
Sugarville area faults	Not constrained	No estimate	No estimate
Washington fault zone northern section	Not constrained	No estimate	No estimate
Fish Springs fault	<2280±70 ^{14}C yr B.P	No estimate	No estimate

[1] "Section" refers to a portion of a fault defined on the basis of static geologic criteria (geomorphic or structural), but for which no evidence presently exists to show that its history of surface faulting is different from adjacent parts of the fault. "Segment" refers to a portion of a fault, typically also identifiable on the basis of geomorphic or structural criteria, but for which historical surface ruptures or paleoseismic data show that the history of surface faulting is different from adjacent portions of the fault, and therefore that the seismogenic behavior of the segment is independent from that of the remainder of the fault.

[2]Consensus preferred recurrence-interval and vertical slip-rate estimates (**bold**) with approximate two-sigma confidence limits; see section on Consensus Process for a discussion of the process used to determine these values.
[3]Two most recent earthquakes are reported for Weber segment, no consensus among investigators regarding the 0.5 ka event.
[4]Most recent surface-faulting earthquake may be as young as 0.4 ka.
[5]Due to limited data, parameter is reported as a range rather than as a central value with approximate two-sigma confidence limits.
[6]Seismogenic origin of structure is uncertain.
[7]Information for the GSLFZ is derived from high-resolution geophysics and drilling information, there are no trench data.
[8]Calendar calibrated but no mean residence correction applied.
[9]Historical surface-faulting earthquake; C.E. = Current Era.

PREVIOUS WORK

Hecker (1993) made a comprehensive compilation of information regarding Quaternary ($\leq$1.6 million years) tectonic features in Utah, particularly information relevant to earthquake hazards. That compilation built upon Anderson and Miller's (1979) *Quaternary Fault Map of Utah*, and was subsequently updated by Black and others (2003), who incorporated the results of paleoseismic and Quaternary mapping studies from the succeeding 10 years.

The Black and others' (2003) *Quaternary Fault and Fold Database and Map of Utah* includes all presently recognized Quaternary tectonic features in Utah. It is unlikely that any large Quaternary faults or folds remain unidentified, although smaller features may be discovered as the Utah Geological Survey (UGS) and others continue systematic 1:24,000-scale geologic mapping of Utah. The Black and others (2003) compilation summarizes the paleoseismic-trenching data for Utah's Quaternary faults. Those data are presented as reported in the paleoseismic source documents from which the database was compiled, and have not been evaluated for accuracy, completeness, or associated uncertainty.

McCalpin and Nishenko (1996) reviewed the numerical-age data (chiefly radiocarbon [^{14}C] and thermoluminescence [TL]) then available for the five central segments of the Wasatch fault zone (WFZ) having evidence for recurrent Holocene surface faulting. They identified 89 ages as closely limiting the timing of past surface faulting on those segments. The McCalpin and Nishenko (1996) study is discussed in detail below.

Youngs and others (2000) and Wong and others (2002) performed probabilistic analyses of the Wasatch Front region and Salt Lake City metropolitan areas, respectively. Both studies include estimates of activity rates for faults within their study areas.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP

Various seismic-hazard-evaluation initiatives in California (Working Group on California Earthquake Probabilities, 1988, 1990, 1999) have successfully employed the concept of working groups composed of technical experts in a field of interest to critically evaluate various datasets and arrive at consensus decisions regarding data values and reliability. The UGS employed a similar strategy and convened the Utah Quaternary Fault Parameters Working Group composed of experts in the fields of paleoseismology and seismology. The paleoseismologists on the Working Group collectively represent many decades of experience in conducting paleoseismic investigations in Utah as well as throughout the United States and around the world. Likewise, the seismologists on the Working Group are familiar with Utah tectonics, and have worked directly with Utah's paleoseismic data.

The Working Group includes two categories of experts, all serving in a volunteer capacity. The first category consists of paleoseismologists having direct knowledge of Utah's Quaternary fault dataset. These individuals have investigated one or more of Utah's Quaternary faults, and are responsible for much of the paleoseismic-trenching data reviewed by the Working Group. The second category consists of knowledgeable experts capable of providing critical analysis of the paleoseismic data, but who have not conducted paleoseismic studies in Utah and therefore have no vested interest in the Utah data; this group includes both paleoseismologists and seismologists. Table 2 lists the members of the Utah Quaternary Fault Parameters Working Group and their affiliations.

Table 2. Members of the Utah Quaternary Fault Parameters Working Group.

Category 1: Paleoseismologists who have conducted paleoseismic investigations in Utah.

Suzanne Hecker – U.S. Geological Survey; Menlo Park, California
Michael Hylland – Utah Geological Survey; Salt Lake City, Utah
William Lund – Utah Geological Survey; Cedar City, Utah
Michael Machette – U.S. Geological Survey; Denver, Colorado
James McCalpin – GEO-HAZ Consulting; Crestone, Colorado
Alan Nelson – U.S. Geological Survey; Denver, Colorado
Susan Olig – URS Corporation; Oakland, California
Dean Ostenaa – U.S. Bureau of Reclamation; Denver, Colorado
Stephen Personius – U.S. Geological Survey; Denver, Colorado
David Schwartz – U.S. Geological Survey; Menlo Park, California

Category 2: Subject matter experts who have not conducted paleoseismic investigations in Utah.

Craig dePolo – Nevada Bureau of Mines and Geology; Reno, Nevada
Kathleen Haller – U.S. Geological Survey; Denver, Colorado
Philip Pearthree – Arizona Geological Survey; Tucson, Arizona
James Pechmann – University of Utah Seismograph Stations; Salt Lake City, Utah
Mark Petersen – U.S. Geological Survey; Denver, Colorado
Robert Smith – University of Utah Dept. of Geology and Geophysics; Salt Lake City, Utah
Ivan Wong – URS Corporation; Oakland, California

In addition to being a member of the Working Group, William Lund, UGS, served as principal investigator for the National Earthquake Hazards Reduction Program (NEHRP)-funded *Utah Quaternary Fault Parameters Working Group* project, and as the Working Group Coordinator. As Coordinator, Mr. Lund was responsible for Working

Group logistics, made an initial review of all relevant paleoseismology source documents, summarized the paleoseismic-trenching information in those documents for the Working Group's consideration, moderated and recorded Working Group meetings, and authored this Final Technical Report.

PALEOSEISMIC-TRENCHING DATABASE

Utah Quaternary Faults

There are 212 Quaternary faults, fault sections, and fault-related folds in Utah (Hecker, 1993; Black and others, 2003). They are chiefly normal-slip faults or are related to normal-slip deformation. Utah includes parts of three physiographic provinces: the Basin and Range, Colorado Plateau, and Middle Rocky Mountains. Quaternary faults are present in all three provinces; however, the greatest number of faults is in the Basin and Range Province, which comprises roughly the western half of Utah. Over the past approximately 30 years, a time span encompassing the entire history of paleoseismic investigations on normal-slip faults worldwide, investigators have conducted paleoseismic-trenching studies on 33 (16%) of Utah's Quaternary faults or fault sections. Much of that effort was directed at the six central segments of the Wasatch fault zone (WFZ; see appendix E for a list of fault abbreviations used in this report) that have evidence of Holocene surface faulting. However, 27 other Quaternary faults have had paleoseismic-trenching investigations performed on them. Table 3 lists the Quaternary faults in Utah that have paleoseismic-trenching information and figure 1 shows their locations.

Table 3. Utah Quaternary faults/fault sections that have paleoseismic-trenching data.

Wasatch fault zone	Great Salt Lake fault zone*
Brigham City segment	Fremont Island section
Weber segment	Antelope Island section
Salt Lake City segment	Oquirrh fault zone
Provo segment	Southern Oquirrh Mountains fault zone
Nephi segment	Mercur fault
Levan segment	Eastern Bear Lake fault
Joes Valley fault zone	southern section
East Joes Valley fault	Bear River fault zone
West Joes Valley fault	Morgan fault zone
Intragraben faults	James Peak fault
West Valley fault zone	Towanta Flat graben
Taylorsville fault	Bald Mountain fault
Granger fault	Strawberry fault
West Cache fault zone	Hansel Valley fault
Clarkston fault	Hogsback fault
Junction Hills fault	southern section
Wellsville fault	North Promontory fault
East Cache fault zone	Sugarville area faults
central section	Washington fault zone
Hurricane fault zone	northern section
Anderson Junction section	Fish Springs fault

** Paleoearthquake information is from detailed seismic reflection surveys and drilling*

Paleoseismic-Trenching Investigations

Paleoseismic-trenching investigations in Utah fall into one of five categories: (1) U.S. Geological Survey (USGS)-funded studies performed by Woodward-Clyde Consultants (WCC), (2) studies performed during the "Wasatch Front Regional Earthquake Hazards Assessment," cosponsored by the USGS and the UGS (3) other USGS-funded studies under NEHRP, (4) U.S. Bureau of Reclamation (USBR) studies related to water impoundment or conveyance structures, and (5) other studies performed chiefly by universities and geotechnical consultants. Black and others (2003) show the location of all paleoseismic-trenching studies conducted on Utah's Quaternary faults.

Woodward-Clyde Consultants

Beginning in the 1970s and extending to the mid-1980s with funding from the USGS, WCC pioneered the paleoseismic study of normal-slip faults by first mapping and then trenching young scarps on the WFZ. The WCC investigations (Swan and others, 1980, 1981a, 1981b; Hanson and others, 1981, 1982; Schwartz and others, 1983; Schwartz and Coppersmith, 1984) were the first performed on normal-slip faults anywhere, and much of what is now known regarding the study of normal faults in trenches was first developed on the WFZ by WCC. Conducted early in the history of normal-fault paleoseismology, the WCC studies predate more recent advancements in paleoseismology and geochronology.

Wasatch Front Regional Earthquake Hazards Assessment

Beginning in 1983 and continuing until 1989, the USGS targeted the Wasatch Front region for intense study under the auspices of the Regional Earthquake Hazards Assessment element of NEHRP. The "Wasatch Front Regional Earthquake Hazard Assessment" conducted in cooperation with the UGS resulted in the first detailed (1:50,000-scale) geologic maps of the Brigham City (BCS), Weber (WS), Salt Lake City (SLCS), and Provo segments (PS) of the WFZ (Personius, 1990; Personius and Scott, 1992; Machette, 1992; Nelson and Personius, 1993), as well as the East Cache fault zone (ECFZ; McCalpin, 1989). Additionally, both USGS and other investigators performed paleoseismic-trenching studies, chiefly on the WFZ and other faults in northern Utah (McCalpin, 1985; Keaton and others, 1987; Machette and Lund, 1987; Nelson and others, 1987; Schwartz and Lund, 1988; Keaton and Currey, 1989; Forman and others, 1991; McCalpin, 1990, 1994, 2003; Jackson, 1991; Lund and others, 1991; McCalpin and Forman, 1991; Personius, 1991; Machette and others, 1992; McCalpin and others, 1992).

USGS National Earthquake Hazards Reduction Program

Following the end of the five-year Wasatch Front Regional Earthquake Hazard Assessment in 1989, the USGS funded additional paleoseismic-trenching studies in Utah through the External Research Program of NEHRP. While performed chiefly

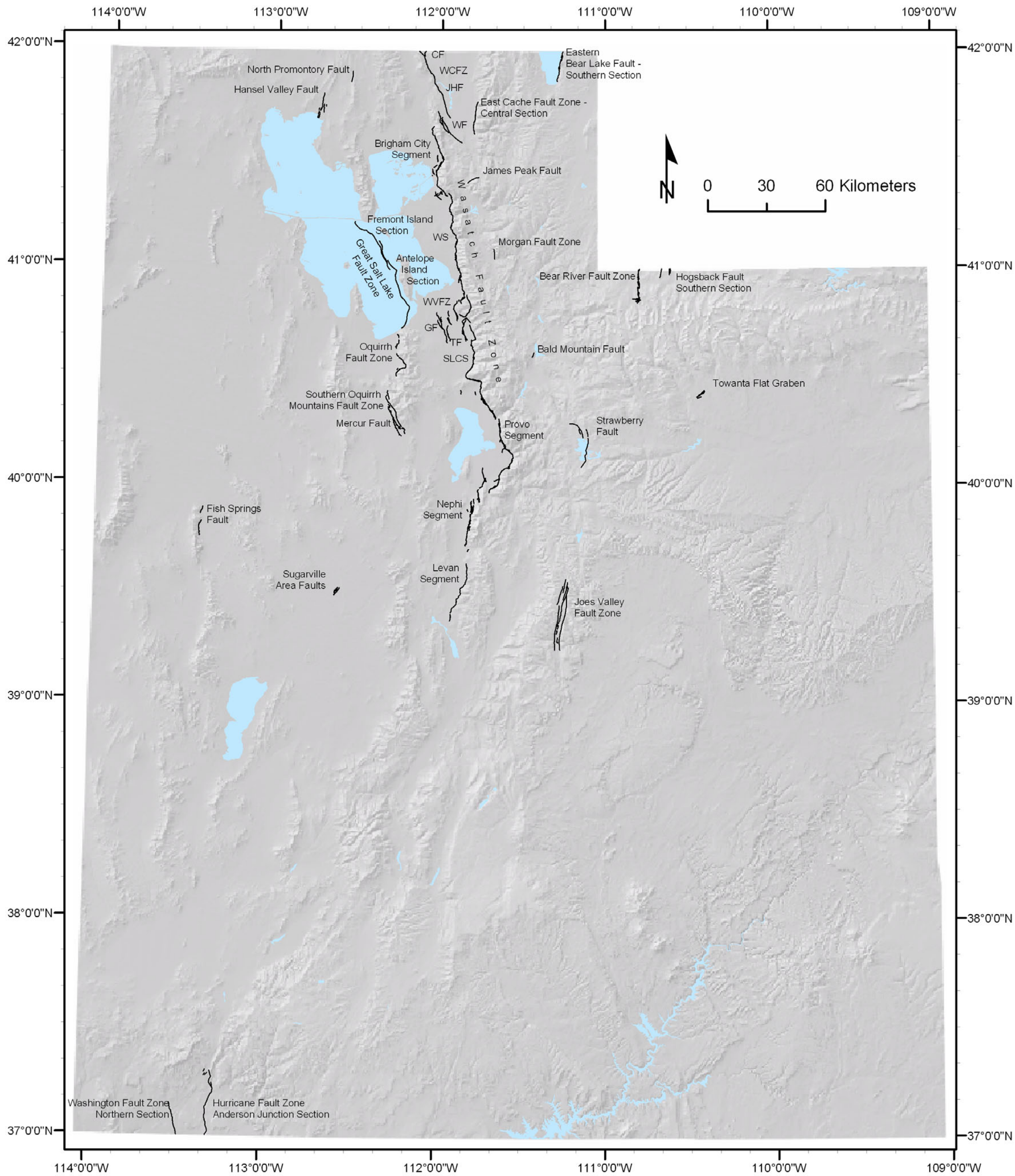

Figure 1. Locations of Quaternary faults/fault sections for which paleoseismic-trenching data are available: WVFZ = West Valley fault zone, GF= Granger fault, TF = Taylorsville fault, WCFZ = West Cache fault zone, CF = Clarkston fault, JHF = Junction Hills fault, WF = Wellsville fault, WS = Weber segment of the Wasatch fault zone, SLCS = Salt Lake City segment of the Wasatch fault zone.

on the WFZ and other nearby faults (McCalpin and Forman, 1993, 2002; McCalpin and others, 1994; Black and others, 1996; Lund and Black, 1998; McCalpin and Nelson, 2000; McCalpin, 2002; Olig and others, 2004), NEHRP-funded trenching studies expanded to other areas of Utah as well (Olig and others, 1996; Stenner and others, 1999; Black and others, 2000; Lund and others, 2001; Olig and others, 2001). NEHRP also funded the detailed mapping (1:50,000 scale) of the Nephi segment (NS) of the WFZ (Harty and others, 1997), the West Cache fault zone (WCFZ; Solomon, 1999), and the Levan segment of the WFZ (LS; Hylland and Machette, 2004). NEHRP is presently supporting mapping of the Fayette segment (FS) of the WFZ by the UGS, trenching on the PS of the WFZ (Olig and others, 2004), and a geophysical and drilling investigation of the Great Salt Lake fault zone (GSLFZ) beneath Great Salt Lake (Dinter and Pechmann, 2004a, 2004b).

U.S. Bureau of Reclamation

Between 1982 and 1992, the USBR conducted both regional and project-specific paleoseismic-trenching investigations in support of construction and operation of USBR dams, reservoirs, and water-conveyance structures in Utah (Nelson and Martin, 1982; Martin and others, 1985; Nelson and Weisser, 1985; Foley and others, 1986; Nelson and VanArsdale, 1986; Sullivan and others, 1988a, 1988b; Ostenaa, 1990; Nelson and Sullivan, 1992; Sullivan and Nelson, 1992). These studies constitute the bulk of the paleoseismic-trenching investigations performed in the Middle Rocky Mountains and Colorado Plateau in Utah.

Other Studies

Universities and geotechnical consulting firms have also conducted fault-trenching studies in Utah. West (1994) trenched the Bear River fault zone (BRFZ) and Hogsback fault (HF) as part of his Ph.D. studies at the Colorado School of Mines (project originally initiated as a USBR investigation). As recognition of earthquake hazards in Utah has increased, some local jurisdictions have adopted ordinances requiring earthquake-hazard evaluations for critical facilities. This is particularly true in Salt Lake County, where geotechnical consultants have trenched the SLCS of the WFZ (Robison and Burr, 1991; Korbay and McCormick, 1999; Simon and Shlemon, 1999). Other faults investigated by geotechnical firms include the Washington fault zone (WaFZ) and Hurricane fault zone (HFZ; Earth Sciences Associates, 1982) in southwestern Utah and the Sugarville area faults (SAFs; Dames and Moore, 1978) in Utah’s Sevier Desert.

WORKING GROUP REVIEW PROCESS

Although the Utah paleoseismic-trenching database is small compared to California’s, where similar evaluations of paleoseismic data have been conducted, it was neither reasonable nor practical to expect Working Group members serving in a volunteer capacity to review each of the more than 60 paleoseismic source documents available for Utah's Quaternary faults. To expedite the process, the Working Group Coordinator summarized the available paleoseismic-trenching data and forwarded the summary information to Working Group members for their review. The Working Group convened three times to evaluate the data, and to come to consensus decisions regarding preferred RI and VSR estimates for the faults under review. The Working Group Coordinator then summarized the paleoseismic data and the results of the Working Group's deliberations on a "Consensus Recurrence-Interval and Vertical Slip-Rate Estimate" form for each fault/fault section (appendix B). The consensus forms represent the principal result of the Working Group review, and should be consulted for details of each fault/fault section and of the review process.

Results of the Working Group review have been presented at local, regional, and national professional society meetings (2004 Utah Earthquake Conference, 2/26/04; Seismological Society of America 2004 Annual Meeting, 4/17/04; Western States Seismic Policy Council Basin and Range Province Seismic Hazards Summit II, 5/17/04). To make the Working Group results widely available, the UGS will publish this Final Technical Report, in slightly modified format, in the UGS *Paleoseismology of Utah* publication series. The UGS also will use the Working Group's results to revise the *Quaternary Fault and Fold Database and Map of Utah* (Black and others, 2003).

Review Process Tasks

The Working Group review consisted of the following principal tasks:

1. Preliminary Working Group meeting to establish review parameters and process. Due to delays in approval of the Federal FY 2003 budget, this initial meeting was replaced by e-mail and telephone contacts to facilitate project start-up.
2. Detailed review by the Working Group Coordinator of published and unpublished paleoseismic-trenching data available for the six central segments (BCS, WS, SLCS, PS, NS, LS) of the WFZ; preparation of summary data forms for each paleoseismology source document, and of a synthesis form for each segment as a whole (see appendix C for example forms).
3. Distribution of completed summary and synthesis forms to the Working Group for their review.
4. First Working Group meeting in Salt Lake City, Utah, on June 4 and 5, 2003, to evaluate the paleoseismic-trenching data for the six central WFZ segments.
6. Detailed review of published and unpublished paleoseismic-trenching data pertaining to the remaining Quaternary faults/fault sections in Utah that have paleoseismic-trenching data; preparation of data forms summarizing the information in each paleoseismology source document, and of a synthesis form for each Quaternary fault/fault section.
7. Distribution of completed data and synthesis forms to the Working Group for their review.

8. Second Working Group meeting in Salt Lake City, Utah, on September 4 and 5, 2003, to evaluate the paleoseismic-trenching data available for Quaternary faults/fault sections, exclusive of the WFZ.
9. Incorporation of the Working Group's recommendations regarding earthquake timing, RI, and VSR into Consensus Recurrence-Interval and Vertical Slip-Rate Estimate forms for the WFZ segments and other Quaternary faults/fault sections (appendix B).
10. Distribution of the draft consensus forms to Working Group members for review and comment.
11. Third Working Group meeting in Salt Lake City, Utah, on February 27, 2004, to finalize RI and VSR estimates.
12. Presentation of the Working Group's results and recommendations at professional society meetings, and to geological and engineering groups in Utah.
13. Preparation of a USGS Final Technical Report presenting the Working Group's results and recommendations (this report).
14. Future release of the Final Technical Report as a UGS publication to make the results of the Working Group review widely available to the interested user community.
15. Planned update of the *Quaternary Fault and Fold Database and Map of Utah* (Black and others, 2003) with new consensus RI and VSR values.

Consensus Process

The Working Group review showed that the paleoseismic-trenching data for Utah's Quaternary faults are generally not adequate to permit rigorous statistical analysis of the data, or to constrain RI and VSR values within rigidly quantifiable bounds. Therefore, the Working Group relied on the expertise and collective judgment of its members to assign preferred RI and VSR estimates to the faults/fault sections under review. The preferred values represent the Working Group's best collective judgment regarding a "mean" RI and VSR for the fault/fault section, based on paleoseismic-trenching data available at the time of the review.

The Working Group also assigned confidence limits to the RI and VSR estimates. Although much of the trenching data are not amenable to statistical analysis, the Working Group kept in mind the concept of two-sigma variability (5^{th} and 95^{th} percentiles) about the preferred RI and VSR estimates as they assigned upper and lower bounds to their confidence limits (table 1, appendices A and B). The goal was to capture both the uncertainty associated with incomplete knowledge of the fault/fault section (epistemic uncertainty – for example, data available from only a single trench site along a many kilometer-long fault) and natural variation in the seismogenic process through time (aleatory uncertainty – for example, variations in the length of interevent intervals). The confidence-limit distribution around the preferred RI and VSR estimates is sometimes skewed to capture apparent variability in fault/fault section behavior.

Establishing preferred RI and VSR estimates and associated confidence limits often generated spirited discussion among Working Group members, and in several instances considerably stretched their comfort levels. Although individual members of the Working Group may retain reservations regarding some RI and VSR estimates or associated confidence limits, the reported values represent the final consensus of the Working Group. Therefore, until superseded by information from new paleoseismic investigations, the Working Group's preferred RI and VSR estimates and confidence limits represent the best available fault activity information for those faults/fault sections, and can be considered as approximating mean RI and VSR values and two-sigma variability about those mean values.

ISSUES RELEVANT TO THE WORKING GROUP REVIEW

Sources of Uncertainty

Epistemic Uncertainty

A key component of the Working Group review was identification of "sources of uncertainty" within Utah's paleoseismic-trenching data. Hecker and others (1998) compiled possible sources of uncertainty in fault-activity studies for the Long Beach, California 30'x60' quadrangle fault map and database. A modified form of that list (appendix D) was used to evaluate epistemic uncertainty resulting from incomplete or imperfect knowledge regarding Utah's paleoseismic-trenching data.

Principal sources of uncertainty for the six central, active segments of the WFZ include:

- Investigators identified two different most recent surface-faulting earthquakes (MRE) at the two trench sites on the BCS, even though the two sites are within a few kilometers of each other.
- Timing of older earthquakes on the BCS have ± uncertainties that equal or exceed the interevent intervals between the earthquakes.
- Multiple investigators differ in their interpretation of the timing of the MRE on the WS, raising the possibility of partial segment rupture or rupture overlap from adjacent segments.
- Latest Pleistocene and early Holocene surface-faulting earthquakes on the SLCS are identified on the basis of a retrodeformation analysis of a trench exposure; the earthquakes lack direct stratigraphic and structural evidence of their occurrence.
- Differences in the number and timing of surface-faulting earthquakes near the southern end of the PS (Water Canyon), when compared to the timing of earthquakes farther north on the segment, indicate either partial segment rupture of the PS, or rupture overlap from surface faulting on the NS to the south. Conversely, recent scarp mapping and diffusion modeling on the NS indicates that surface rupture may propagate from the PS to the NS during some large earthquakes.

- Both paleoseismic-trenching investigations performed on the NS produced conflicting sets of numerical ages on samples from the same geologic units resulting in significant uncertainty regarding paleoearthquake timing; as a result, the surface-faulting chronology for the NS can vary depending on which ages are selected to constrain earthquake timing.
- Over 300 numerical age determinations, chiefly ^{14}C and TL accumulated over 30-plus years, constrain the timing of surface faulting on the WFZ; the ^{14}C ages represent a wide variety of sampling, dating, and calibration techniques, thus injecting variability into the absolute-age dataset.
- The Working Group considers many of the confidence limits originally reported with the timing of surface-faulting earthquakes as too narrow, and as not fully accounting for the geologic (aleatory) uncertainty associated with earthquake timing.

For Utah's other Quaternary faults, typical uncertainties encountered include:

- Seismogenic capability of fault uncertain.
- Zone of deformation wider than the zone of study – not all scarps trenched.
- Time period too long or too short to represent contemporary conditions.
- Studies limited to a single strand or section of a complex fault zone.
- Number of surface-faulting earthquakes uncertain.
- Surface-faulting earthquake timing only broadly constrained (thousands to tens of thousands of years) or unknown.
- Vertical displacement per earthquake and/or cumulative vertical displacement poorly constrained or unknown.
- Interevent intervals open at one or both ends.
- Number of interevent intervals may be too few to yield representative mean recurrence.
- Earthquake recognition based on indirect stratigraphic or structural evidence.
- Selected paleoseismic parameter conflicts with other data at the site.
- Uncertain correlation of earthquakes between fault strands.

Aleatory Uncertainty

Uncertainty due to inherent variability of the seismogenic process is largely unknown for the faults/fault sections reviewed by the Working Group. All of the fault/fault sections lack the definitively complete and sufficiently long paleoseismic records required to illustrate the full range of variability in the seismogenic process. This is true even for the five central segments of the WFZ (BCS, WS, SLCS, PS, NS), which are the most studied faults in Utah, but where McCalpin and Nishenko (1996) note that "The small number of observed recurrence intervals from individual fault segments (1 to 3) during the past 5.6 kyr [thousand years] precludes the unequivocal demonstration of a particular type of recurrence behavior (i.e., random versus periodic)." The coefficient of variation (COV; ratio of the standard deviation to the mean) provides a measure of the periodicity of earthquake recurrence intervals (Norman Abrahamson, Pacific Gas and Electric Company, written communication to Susan Olig, Working

Group member, 2000). The smaller the COV (<0.3) the more periodic is earthquake recurrence, while a large COV (>1) indicates earthquakes are not periodic. The limited long-term recurrence information available for Utah faults/fault sections (BCS, SLCS, West Valley fault zone [WVFZ], Southern Oquirrh Mountain fault zone [SOMFZ], Hansel Valley fault [HVF]; appendices A and B) indicate that large variations in earthquake repeat times and size are possible, likely representing large COV values.

The Working Group recognized the potential affect of aleatory uncertainty on their RI and VSR estimates, and attempted to incorporate the effects of that variability when assigning confidence limits to their preferred RI and VSR values. However, the Working Group acknowledges that due to a lack of data, they may have underestimated the effects of process variability for some faults/fault sections.

Data Adequacy

Closely associated with data uncertainty is the issue of data adequacy – are the available paleoseismic-trenching data sufficiently abundant to make reliable RI and VSR estimates for the faults or fault sections under review? Utah's paleoseismic-trenching data divide naturally into two groups: (1) data for the WFZ Utah's largest, most active, and most studied fault, and (2) data available for Utah's other Quaternary faults that have been studied in trenches or natural exposures.

Wasatch Fault Zone

The WFZ, by virtue of its collocation with the populous Wasatch Front and abundant geomorphic evidence of geologically recent surface faulting, is the most studied and best understood Quaternary fault in Utah. Investigators have performed multiple paleoseismic investigations on the six active central segments of the WFZ, and although significant questions remain unanswered (see above) the surface-faulting histories of most segments are generally well understood to at least the middle Holocene. Two segments, BCS and SLCS, also have information on surface faulting extending to the latest Pleistocene; however, the timing of the older earthquakes is not as well constrained, and in some instances direct physical evidence of surface faulting (colluvial wedges, fault terminations, fissures and fissure-fill deposits) is lacking. A NEHRP-funded paleoseismic-trenching investigation conducted cooperatively between URS Corporation and the UGS in 2003 (Olig and others, 2004) is designed to extend the surface-faulting record on the PS to the latest Pleistocene; however, final results of that investigation are not yet available.

Other Quaternary Faults

Paleoseismic-trenching data for Utah's other Quaternary faults are more limited than for the WFZ. Reasons for the limited data are related to four principal causes: (1) reduced fault activity, (2) remote fault locations away from large population centers, (3) typically shorter fault lengths, and (4) difficulty identifying older earthquakes. Less active faults produce fewer earthquakes over a given time period; consequently, unless the deposits being trenched are old, a typical three- or four-meter-deep paleoseismic trench exposes evidence for fewer earthquakes. The remote location of many faults equates to lower earthquake risk and consequently to less intensive study. Off the Wasatch Front, most faults have only a single trenching investigation, even on faults with evidence of possible segmentation or other complexities. Short faults typically produce smaller earthquakes with smaller displacements, which can make recognizing the geologic record of their occurrence more difficult. Finally, where trenches expose evidence for early to middle Quaternary surface faulting, recognition of individual surface-faulting earthquakes has proven difficult; investigators typically report evidence of surface faulting, but are unsure of the exact number of earthquakes. This problem becomes more acute for older earthquakes that were also small.

Constraining Age Estimates

Numerical Ages

Radiocarbon ages: Paleoseismic-trenching studies in Utah have resulted in more than 300 numerical ages. The majority are ^{14}C ages, which are of two principal types: (1) ages from charcoal obtained by standard gas proportional counting techniques, or ages obtained using an accelerator mass spectrometer for samples too small for conventional counting methods, and (2) apparent mean residence time (AMRT) ages on bulk organic samples, usually collected from buried soils, tectonic crack-fill material, or colluvial-wedge deposits. Bulk organic samples contain carbon of different ages, and the ^{14}C ages obtained from them must be corrected to account for this “carbon-reservoir” effect. Machette and others (1992) and McCalpin and Nishenko (1996) include discussions of AMRT ages and their proper correction for carbon age spans and carbon mean residence time.

Production of ^{14}C in the upper atmosphere has varied through time due to fluxes in the Earth’s magnetic field, and more recently due to open-air nuclear weapons testing. The variable rate of production means that ^{14}C has been incorporated into living organisms (plant and animal) in different proportions to ^{12}C at different times in the past. Therefore, ^{14}C ages (^{14}C yr B.P.) must be calibrated to adjust for the different production rates. Correction of ^{14}C years to calendar years (cal yr B.P.) relies chiefly on the radiometric dating of tree rings and marine corals of otherwise known age, and comparing the ages of those materials to the resulting ^{14}C ages. Calibrating ^{14}C ages beyond about 20,000 years ago (kilo-annum, ka; appendix E) remains difficult. Once a properly corrected and calibrated calendar age is obtained, it remains for the paleoseismic investigator to interpret the age within the sample’s geologic context and determine how closely the age constrains the timing of surface faulting.

Since the inception of paleoseismic-trenching studies in Utah, significant advances have been made in methodologies for calendar-calibrating ^{14}C ages, and in our understanding of how to properly sample for, correct, and interpret AMRT ages on bulk organic samples. The science of paleoseismology also has advanced over that same time period, and our understanding of how to conduct paleoseismic-trenching investigations and interpret their results has also improved. The result is a dataset of ^{14}C ages that are calibrated to a variety of standards, if at all; sampled by a variety of techniques; analyzed by different laboratories; and interpreted by investigators with varying levels of experience and expertise.

Luminescence ages: Investigators have employed a variety of luminescence dating techniques in paleoseismic-trenching investigations in Utah. Thermoluminescence dating is the most common. Most TL ages were obtained during the 1980s on the central segments of the WFZ. There is no recognized need or procedure to calibrate TL or other luminescence ages and they are assumed to be calendar ages.

Relative Ages

Lake Bonneville chronology: Much of the WFZ and many other Quaternary faults in northern and western Utah lie below the highstand of Lake Bonneville, a late Pleistocene pluvial lake (Gilbert, 1890) that occupied the Bonneville basin from about 32.5 to 13.9 ka (Donald Currey, University of Utah Geography Department, written communication to the UGS, 1996; verbal communication to Working Group, 2004). At its highest elevation (Bonneville shoreline, 1551 m [5090 ft]), Lake Bonneville had a surface area in excess of 50,000 km^2 (20,000 mi^2), and was more than 305 m (1000 ft) deep. Lake Bonneville lacustrine deposits and post-Bonneville alluvium and colluvium dominate the Quaternary geology of the Bonneville basin.

Four prominent shorelines, two transgressive (Stansbury and Bonneville), one regressive (Provo), and one related to the post-Bonneville highstand of Great Salt Lake (Gilbert), provide well-documented time lines against which the timing of surface faulting can be compared. However, Lake Bonneville deposits also bury older Quaternary deposits in the basin, making it difficult to decipher the history of older surface faulting. The details of Lake Bonneville chronology continue to evolve through time (Oviatt and Thompson, 2002; Donald Currey, University of Utah Geography Department, verbal communication to Working Group, 2004), and many early paleoseismic studies relied on age estimates of Bonneville deposits and shorelines that were subsequently revised. Additionally, early paleoseismic-trenching investigations used Lake Bonneville age estimates reported in ^{14}C years. Currey (University of Utah Geography Department, written communication to UGS, 1996; verbal communication to Working Group, 2004) calendar calibrated key Lake Bonneville ages, and showed that Lake Bonneville events and features are as much as 4.5 kyr older than indicated by ^{14}C ages. Table 4 presents Currey's Lake Bonneville chronology.

Table 4. Timing of events related to the transgression and regression of Lake Bonneville (modified from Donald Currey, University of Utah, written communication to the UGS, 1996; verbal communication to Working Group, 2004).

Lake Stage	Radiocarbon Years (^{14}C yr B.P.)	Calendar Years (cal yr B.P.)
Start of Lake Bonneville	28,000	~32,500
Stansbury shoreline	21,000 – 20,000	24,400 – 23,200
Bonneville shoreline	15,500 – 14,500	18,000 – 16,800

Start Bonneville flood End Bonneville flood	14,500 14,500	16,800 16,800
Provo shoreline	14,500 – 14,000	16,800 – 16,200
Gilbert shoreline	11,000 – 10,000	12,800 – 11,600

When possible, the Working Group used the calendar-calibrated ages in table 4 to revise RI and VSR estimates for paleoseismic-trenching investigations that relied on ^{14}C years for the ages of Lake Bonneville features and events.

Soil-profile development: Relative age estimates based on soil-profile development play an important part in many paleoseismic-trenching investigations in Utah, particularly reconnaissance investigations off the Wasatch Front. Information presented in paleoseismic source documents seldom permits an independent evaluation of relative soil age. Therefore, unless there was a compelling reason to do otherwise, the Working Group accepted relative age estimates based on soil development as reported by original investigators, while recognizing that uncertainties associated with soil-profile age estimates may be thousands to tens of thousands of years.

Net Vertical-Displacement Data

Net vertical-displacement data for Utah's Quaternary faults come from two principal sources: (1) topographic profiles measured across scarps, with or without an accompanying trench, and (2) measurements made in trenches. Uncertainties in net vertical-displacement data are of three principal types: (1) measurement uncertainty, (2) sparse data, and (3) incomplete documentation.

Measurement Uncertainty

Scarp profiles: Scarp profiles are commonly used to determine scarp height and net vertical displacement across fault scarps. Profiling techniques range from highly accurate, computer-assisted surveying, to sequential measurements of slope angle along a profile line using a meter stick lying on the ground and an Abney level resting on the stick to measure slope angles. Both methods, and others, produce accurate profiles; uncertainty with the resulting net displacement data relates chiefly to issues of erosion and deposition on and adjacent to the scarp, effects of near-field deformation (for example – graben formation, back-tilting, and warping), failure to profile all scarps at a site, and difficult site conditions. Where unmodified pre-faulting surfaces on both sides of a scarp can be accurately projected to the fault, topographic profiles provide a reliable measurement of cumulative net vertical displacement. However, where complicating factors are present, uncertainty enters into the measurements, and considerable experience is required to interpret profile results and arrive at reliable net vertical-displacement estimates.

Measurements in trenches: Correlative stratigraphy displaced across a fault zone and exposed in a trench can provide a direct measure of fault displacement. However, many trenches lack correlative stratigraphy, and net vertical-displacement measurements from trenches are often estimates based on secondary stratigraphic and structural relations, thickness of colluvial-wedge deposits, retrodeformation reconstructions, and trench depth. As with scarp profiles, in the absence of a best-case scenario, experience is required to obtain reliable net vertical-displacement estimates from trench exposures.

Sparse Data

Net vertical-displacement measurements are point values made at individual locations along a fault. Slip-distribution during a surface-faulting earthquake varies along strike, rising to a maximum at one or more points and decreasing to zero at the ends of the rupture (Crone and others, 1985). Characterizing slip distribution along a fault requires careful geologic mapping and the making of numerous displacement measurements along the fault trace. With the possible exception of the WS of the WFZ, no Quaternary faults/fault sections in Utah have sufficient displacement data to fully characterize their slip distribution.

Net vertical-displacement information is most abundant for the BCS, WS, SLCS, and PS of the WFZ. These data represent a combination of measurements made during paleoseismic-trenching investigations from both scarps and trenches, and scarp-profile measurements made as the USGS mapped these segments. With few exceptions, the net vertical-displacement data are sparsely distributed along the segments, and their interpretation is complicated by complex rupture patterns, poorly constrained deposit ages, and the presence of non-correlative geologic units on either side of many scarps. The exception is the WS, where the USGS measured 375 scarp profiles (77 in the field and 298 using a photogrammetric plotter and aerial photographs); however, only about 30 of those measurements are included on the geologic map of the WS (Nelson and Personius, 1993).

Off the WFZ, net vertical-displacement information is commonly limited to one or two points along a fault, and represents “best available” data for the fault/fault section. Where the measurements lie within the slip distribution curve for the faults is almost always unknown.

Incomplete Documentation

Incomplete documentation of net vertical-displacement measurements is common in many paleoseismic source documents. As discussed above, measurements of net vertical displacement, whether from scarp profiles or trenches, frequently include important caveats that require explanation. The net vertical-displacement data reviewed by the Working Group ranged from detailed explanations of how displacement was measured and associated uncertainty evaluated, to cursory statements of displacement values, commonly reported to the nearest meter, with no accompanying explanatory information. The Working Group review showed that for some investigations not all scarps were trenched or profiled, so reported net vertical-displacement values are minima, while at other sites antithetic scarps, even when recognized, were not included in the net displacement budget, and the resulting net vertical-displacement measurements are too large. Consequently, where explanatory details are lacking, the accuracy of the net vertical-displacement information for Utah's Quaternary faults is often questionable.

PALEOSEISMIC PARAMETERS

Earthquake Timing

The timing of surface-faulting earthquakes reported in paleoseismic-source documents typically is constrained by either numerical or relative ages and in several instances by a combination of both. Depending on the number of ages available and their geologic context, surface faulting can be constrained in the best cases to within a few hundred years. More often, resolution of earthquake timing is less precise, in some instances tens of thousands of years or more. Because the WFZ is Utah's most intensely studied Quaternary fault, and therefore has the greatest number of numerical ages, the timing of surface-faulting earthquakes on the six active central segments of the WFZ is better constrained, at least to the middle Holocene, than are earthquakes on other faults in Utah. Because earthquake timing is critical to determining RI and VSR, the Working Group made a careful review of information relevant to earthquake timing on Utah's Quaternary faults (appendices A and B).

Wasatch Fault Zone

McCalpin and Nishenko (1996): Recognizing the variability inherent in the WFZ numerical-age dataset, McCalpin and Nishenko (1996) re-evaluated the 276 ^{14}C and TL ages then available for the five central segments of the WFZ having evidence for multiple Holocene surface-faulting earthquakes (BCS, WS, SLCS, PS, NS). Based on stratigraphic criteria, they identified 89 limiting ages (76 maximum and 13 minimum) as closely constraining the timing of surface faulting on those segments (see McCalpin and Nishenko [1996] table 1). They recalibrated the ^{14}C ages, using a single calibration dataset (CALIB v. 3.0; Stuiver and Reimer, 1993) while applying a consistent methodology for assigning carbon age span, carbon mean residence time, and other calibration parameters. The result was a set of consistently calibrated, closely limiting ^{14}C ages and associated TL ages for surface-faulting earthquakes on the central WFZ current for investigations done up to about 1995. McCalpin and Nishenko (1996) used the revised absolute ages to calculate weighted means for the timing of surface-faulting earthquakes on the five WFZ segments. The $\pm$ confidence limits reported for the weighted means (see McCalpin and Nishenko [1996] table 1) reflect cumulative laboratory uncertainty associated with the calibrated ages used to calculate the weighted means, but do not incorporate geologic uncertainty associated with earthquake timing (James McCalpin, GEO-HAZ Consulting, verbal communication to Working Group, 2003).

With the exceptions noted below, McCalpin and Nishenko's (1996) revised ^{14}C and associated TL ages remain the best available numerical-age data for the WS and

PS. On those segments, the Working Group re-determined surface-faulting timing by calculating the simple mean of the McCalpin and Nishenko (1996) closely limiting absolute ages for each earthquake (appendices A and B). The means were then rounded to the nearest half-century. In nearly every instance, the results were within 100 years of the corresponding McCalpin and Nishenko (1996) weighted means. To better accommodate geologic uncertainty associated with earthquake timing, the Working Group revised the ± confidence limits assigned to each earthquake. The Working Group determined revised confidence limits by dividing the range between the youngest and oldest bounding age limits resulting from calibration of the closely limiting ages for each earthquake by 2, and rounding the result to the nearest half-century (table 5). The Working Group confidence limits are significantly broader than those of McCalpin and Nishenko (1996), and are thought to better incorporate both the aleatory and epistemic uncertainty associated with earthquake timing.

Table 5. Example of determining earthquake timing and approximate two-sigma confidence limits using earthquakes Y and Z, Brigham City segment, Wasatch fault zone.

Limiting ^{14}C or TL age[1]	Earthquake	McCalpin and Nishenko (1996) Calibrated Ages[2]	McCalpin and Nishenko (1996) Weighted-mean Earthquake Timing[3]	Working Group Mean Earthquake Timing
1720±90	Z	1691(1412)1142	2125±104 cal yr B.P.	2100[3]±800[4] cal yr B.P.
1.7 ±0.2, 2.1 ±0.3 (TL)	Z	1900±300		
2320±70	Z	2251(2020)1801		
2580±60	Z	2680(2513)2200		
2630±90	Z	2767(2571)2187		
3320±80	Y	3615(3344)3085	3434±142 cal yr B.P.	3450±300 cal yr B.P.
3430±70	Y	3687(3462)3166		
3430±60	Y	3700(3476)3261		

[1,2,3]McCalpin and Nishenko (1996) table 1; [3](1412+1900+2020+2513+2571)/5 = 2083, rounded = 2100; [4](2767-1142/2) = 813, rounded = 800; approximates 2 sigma variability and includes analytical and sample context uncertainties.

New paleoseismic trenching information: Trenching information on the timing of surface-faulting earthquakes obtained subsequent to McCalpin and Nishenko (1996) is available for the BCS and SLCS. McCalpin and Forman (2002) present an updated interpretation of their trenching investigation on the BCS originally performed in 1992-93, and first reported in McCalpin and Forman (1993). Table 4 in McCalpin and Forman (2002) revises the ^{14}C and TL ages both as reported in the original investigation and in McCalpin and Nishenko (1996). Differences in ages between McCalpin and Nishenko (1996) and McCalpin and Forman (2002) are related chiefly to older earthquakes (T, U, V). The timing of earthquakes U and V remains the same, but the ± confidence limits are broader in McCalpin and Forman (2002). Event T is constrained by a single ^{14}C age, which McCalpin and Nishenko (1996) report in radiocarbon years, but which McCalpin and Forman (2002) calendar calibrate and then report as a range (>14,800±1200 cal yr B.P., <17,100 [16.8 ka; see table 4]) using the time of the Bonneville flood as the upper bound for the timing of event T. The Working Group broadened the ± confidence limits for event U by using the new limiting ages reported in McCalpin and Forman (2002) and employing the same methodology described above (table 5) for the McCalpin and Nishenko (1996) ages.

Trenching by Black and others (1996) constrained the timing of the four youngest earthquakes (W, X, Y, Z) on the SLCS, and McCalpin (2002) identified three older earthquakes (T, U, V) on the basis of a retrodeformation analysis of his "Megatrench" exposure at Little Cottonwood Canyon. The Working Group judged the results of these two new investigations credible, and combined the results of the two studies to create a composite surface-faulting chronology for the SLCS. The Working Group re-evaluated the Black and others (1996) earthquake ± confidence limits as described above. The Working Group believes that the revised limits account for both the laboratory and geologic uncertainty associated with younger surface faulting on the SLCS, but timing of the three older earthquakes can be constrained only to broad time intervals.

Existing information: In two instances, the Working Group chose to adopt earthquake timing on the WS and PS as reported by the original investigators prior to the McCalpin and Nishenko (1996) re-evaluation. They include: (1) the third-oldest (antepenultimate) earthquake on the PS as originally reported by Machette and others (1992), and (2) the MRE on the WS as reported by Swan and others (1981b) and Machette and others (1992); McCalpin and Nishenko (1996) discounted a late Holocene surface-faulting earthquake at about 0.5 ka on the WS. Additionally, the Working Group chose to include the LS in their deliberations and accepts the timing of the MRE as reported by Jackson (1991) and later confirmed by the UGS (Hylland and Machette, 2004; table 1, appendices A and B).

Nephi segment: The NS exhibits evidence of multiple Holocene surface-faulting earthquakes, but earthquake timing on the NS is the least well understood of any of the central WFZ segments. Two paleoseismic-trenching investigations (Hanson and others, 1981; Jackson, 1991) produced conflicting sets of numerical ages for horizons critical to determining the surface-faulting history of the NS. McCalpin and Nishenko (1996) re-evaluated the ages used by the original investigators to define their surface-faulting chronologies, but did not consider the alternative ages, or comment regarding the suitability of the alternate ages to constrain surface faulting. Additionally, McCalpin and Nishenko (1996) used five previously unpublished ^{14}C ages from the southern part of the PS to help constrain the timing of the MRE and second oldest (penultimate) event (PE) on the NS. The Working Group believes that in the absence of supporting paleoseismic information from the northernmost trace of the NS, it is premature to use ^{14}C ages from the PS to determine the timing of surface faulting on the NS. Lacking new paleoseismic-trenching information to better define earthquake timing, the Working Group used the preferred surface-faulting chronologies of the original investigators to establish a composite chronology for the NS, but acknowledges a high level of uncertainty regarding earthquake timing.

Other Quaternary Faults

The timing of surface faulting generally is not as well constrained for Utah's other Quaternary faults. Reasons include: (1) fewer earthquake-limiting absolute ages, (2) many investigations were reconnaissance in nature and either lack numerical ages entirely, or the available ages only confine surface faulting to broad time intervals, and (3) the primary purpose of the study was not to determine earthquake timing.

A comprehensive reinterpretation and recalibration of numerical ages similar to that performed by McCalpin and Nishenko (1996) for the central WFZ segments has not been made for Utah's other Quaternary faults. The principal reasons for not doing so include: (1) many studies lack information about the material dated; the manner in which samples were collected, processed, and analyzed; and the geologic context of the sample, and (2) where available ages are only sufficient to constrain earthquake timing to broad time intervals, variations of a few tens to hundreds of years resulting from recalibration are inconsequential. Those studies that contain sufficient information to permit a re-evaluation of their absolute ages were carefully scrutinized during the Working Group review process.

Recurrence Intervals

Active faults generate repeated surface-faulting earthquakes through time. Recurrence interval refers to the time span between those earthquakes. Recurrence intervals are a fundamental descriptor of fault activity (McCalpin, 1996), and defining earthquake recurrence is a major goal of most paleoseismic-trenching investigations. Recurrence intervals are typically reported in one of two ways: (1) as the interval between two individual paleoearthquakes, or (2) as an average RI encompassing several paleoearthquakes. Considerable variation is possible between individual interevent intervals on some faults (see above). Average RI smooth out individual interevent variations, resulting in a mean value that is useful for earthquake-hazard analyses. However, average recurrence, especially determined over a long time period, can mask large variations in individual RIs, some of which may represent fundamental changes or large irregularity in fault behavior. For example, the average RI for the SOMFZ determined for five to seven earthquakes over a nearly 100-kyr period is 12 to 25 kyr (Olig and others, 2001). However, information on earthquake timing for the SOMFZ indicates individual interevent intervals may be as long as 46 kyr or as short as a few kyr. Similarly large variations in interevent intervals over long time periods are seen on some other Utah Quaternary faults, and are of particular concern on the WFZ, where evidence suggests that post-Bonneville (late Pleistocene/Holocene) and particularly mid- to late-Holocene RIs are significantly shorter and more regular than recurrence prior to or during Lake Bonneville time (Machette and others, 1992; McCalpin and Forman, 2002; McCalpin, 2002).

Wasatch Fault Zone

Surface-faulting chronologies for the five central segments of the WFZ that have multiple Holocene surface-faulting earthquakes are relatively well constrained through the middle Holocene (appendices A and B), and permit calculation of interevent intervals between paleoearthquake pairs (table 6, appendix B). Additionally, longer surface-faulting chronologies on the BCS and SLCS define less well-constrained interevent intervals to the latest Pleistocene (Lake Bonneville and immediate post-Bonneville time).

Table 6. Example of determining mean recurrence intervals and two-sigma confidence limits for the Brigham City segment of the Wasatch fault zone.

<table>
<tr><th>Earthquake</th><th>Timing</th><th>Interevent Recurrence Interval</th><th>Mean Recurrence Interval</th></tr>
<tr><td>Z</td><td>2100±800</td><td rowspan="6">Y-Z = 1350±900[1]
X-Y = 1200±600
W-X = 1300±600
V-W = 1500±1000
U-V = 1000±1800</td><td rowspan="4">W-Z = 1300[2] ±200[3]</td></tr>
<tr><td>Y</td><td>3450±300</td></tr>
<tr><td>X</td><td>4650±500</td></tr>
<tr><td>W</td><td>5950±250</td></tr>
<tr><td>V</td><td>7500±1000</td><td rowspan="2">U-Z = 1300[2] ±400[3]</td></tr>
<tr><td>U</td><td>8500±1500</td></tr>
</table>

[1]±confidence limits equal the square root of the sum of the squares of the individual ± confidence limits for each bracketing earthquake; [2]weighted mean rounded to the nearest 100 years; [3]two-sigma standard deviation rounded to the nearest 100 years.

The Working Group determined mean RI for the five central WFZ segments by calculating the weighted mean of the individual interevent intervals (rounded to the nearest 100 years) and then calculating two-sigma confidence limits for the interevent interval distribution. This method was not applicable to the LS, where scarp-profile evidence (Hylland and Machette, 2004) indicates the possibility of two surface-faulting earthquakes on the southern part of the LS in latest Pleistocene/Holocene time, although only one earthquake has been positively identified and its timing constrained on that segment.

After a careful review of the available information regarding earthquake timing, interevent interval lengths, and data variability for each segment, the Working Group assigned preferred Holocene RI estimates for each segment along with “approximate” two-sigma (5th and 95th percentile) confidence limits (table 1, appendices A and B). However, limited data restricted the Working Group’s preferred RI estimate for the LS to a broadly defined range.

Other Quaternary Faults

Few of the other Quaternary faults/fault sections considered by the Working Group have sufficient information on earthquake timing to permit calculation of even a single, well-constrained interevent interval. Typically, the timing of bracketing earthquakes is poorly constrained, and resulting interevent intervals are broad.

The Working Group evaluated the information on earthquake timing available for each fault/fault section, and again employing a consensus process, assigned a preferred RI with “approximate” two-sigma confidence limits to each fault/fault section where the data permitted (table 1, appendices A and B). However, because the data are limited, most RI confidence limits are broad to reflect high uncertainty. Additionally, the Working Group review showed that existing paleoseismic information for several faults/fault sections is insufficient to make even a broadly constrained RI estimate (table 1, appendices A and B).

Vertical Slip Rates

Vertical slip (displacement) represents the vertical component of total dip slip on a fault. Vertical slip is always smaller than dip slip unless the fault is vertical, in which case vertical slip and dip slip are the same. Accurately calculating dip slip requires knowing the fault dip, which is generally poorly constrained for most Utah faults. Vertical slip is calculated by normalizing net vertical displacement at a point on a fault over time (net vertical displacement/time), and is a second fundamental descriptor of fault activity (McCalpin, 1996). In a manner similar to RIs, VSRs typically are reported in one of two ways: (1) as the slip rate between two individual paleoearthquakes, or (2) as the slip rate over a longer time period that encompasses slip from several to possibly hundreds of paleoearthquakes. In the first instance, the net vertical displacement from the more recent of the two earthquakes is divided by the time interval between the earthquakes. In the second, cumulative net vertical displacement and time are required parameters, but knowing the number of earthquakes that produced the displacement is not necessary.

For a VSR to be well constrained, both the net vertical displacement and the time interval must be bracketed (closed) by surface-faulting earthquakes (Wong and Olig, 1998). A common source of uncertainty in paleoseismic-source documents reviewed by the Working Group was the use of open time intervals when calculating slip rates. Intervals open to the present include time that is not represented by corresponding displacement, and thus produce slip rates that are too small (too much time and not enough displacement). Intervals open to the past typically include displacement that is not fully represented by time, and thus result in slip rates that are too large (too much displacement and not enough time). Intervals open at both ends can produce slip rates that are either too small or too large depending on the ratio of time not accounted for in the past compared to extra time included since the most recent surface faulting. However, the greater the interval length and the more earthquakes it represents, generally the smaller is the effect of open-ended intervals.

Because net vertical displacement is an essential component of slip-rate calculations, and because net vertical displacement produced by a surface-faulting earthquake varies along strike of a fault (see above), so does the VSR. Like the net vertical-displacement measurements from which they are derived, VSRs are point values that reflect the rate of vertical displacement at a particular location on a fault. Whether a slip rate is a maximum or some lesser amount depends on the nature of the corresponding net vertical-displacement measurement.

Well-constrained net vertical-displacement measurements are limited on the faults/fault sections considered by the Working Group; therefore, well-constrained VSRs are similarly limited. This is particularly true for faults/fault sections off the Wasatch Front where net vertical-displacement and slip-rate data may come from as few as one or two locations on a fault/fault section that is tens of kilometers long.

The Working Group evaluated available information on earthquake timing and net vertical displacement for each fault/fault section under their review, and employed a consensus process to assign a preferred VSR with “approximate” two-sigma confidence limits to each fault/fault section where the data permitted (table 1, appendices A and B). However, because the data are limited, many of the Working Group’s confidence limits are broad to reflect high uncertainty. Additionally, the Working Group review showed that existing paleoseismic information for several faults/fault sections is insufficient to make even broadly constrained VSR estimates. Special cases in that regard are the Joes Valley and Towanta Flat grabens, which have no measurable net vertical displacement across them and therefore may not be seismogenic structures.

PALEOSEISMIC DATA GAPS

Recommended Paleoseismic Investigations

Effective earthquake-hazard characterization relies on information regarding the paleoseismic parameters of seismic sources. To date, only 16 percent of Utah’s Quaternary faults/fault sections have paleoseismic-trenching data available for them. A small number of other Quaternary faults/fault sections (less than an additional 5%) have well-constrained VSR obtained from geomorphic studies. The Working Group is charged with identifying critical gaps in Utah’s paleoseismic database and recommending future paleoseismic investigations to fill those gaps.

Table 7 lists the faults/fault sections by region within Utah, which the Working Group considers of highest priority for additional paleoseismic investigation to ensure that Utah’s earthquake hazard is adequately characterized to a minimally acceptable level. These faults/fault sections are shown on figure 2. The Working Group considered NEHRP criteria for the National/Intermountain West region regarding minimum slip rates (0.1 mm/yr near urban areas and 0.2 mm/yr in other areas) and the specific fault priorities for urban areas in Utah listed on the USGS External Research Web site (http://erp-web.er.usgs.gov/) when compiling table 7. The faults/fault sections recommended for additional study in each region of the state are listed in order of decreasing priority.

Table 7 represents the faults/fault sections that the Working Group believes require additional study considering the current status of Utah development and a reasonable projection of future growth. It is important to note, however, that we continually learn more about what we do not know, and as our knowledge base regarding Quaternary faults in Utah increases, other important issues and data gaps may present themselves that either are not yet identified or currently not recognized as important. More than 150 Quaternary faults remain for which the Working Group makes

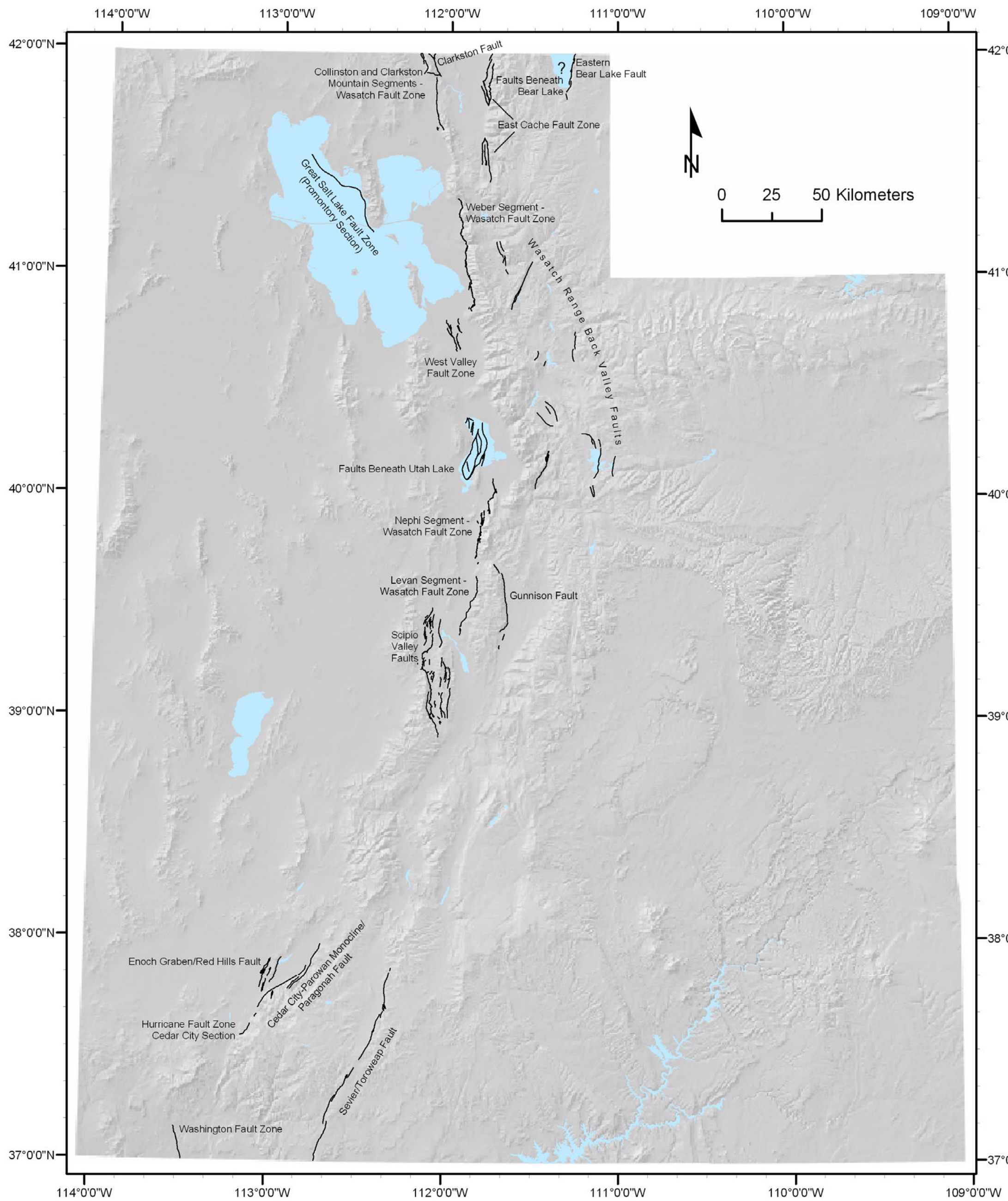

Figure 2. Locations of high-priority Quaternary faults/fault sections recommended for future paleoseismic investigations.

no recommendation at this time. Paleoseismic information regarding those faults may become critical in the future as Utah's population continues to grow and development encroaches on ever more remote areas of the state. Likewise, a major project for which paleoseismic information is a necessary siting criterion (for example, waste-disposal or power-generating facilities) may require future study of specific faults or fault sections not listed here.

Table 7. Faults/fault sections by region that require additional study to adequately characterize Utah's earthquake hazard.

Wasatch fault zone

(1) Nephi segment - trench north and south strands to confirm faulting history and segment boundary relations.
(2) Weber segment – trench multiple locations to confirm MRE timing.
(3) Weber segment - megatrench to determine a long-term surface-faulting history.
(4) Collinston and Clarkston Mountain segments – detailed field reconnaissance and geologic mapping, to determine the timing of the MRE.
(5) Levan segment - trench to extend faulting history.

Wasatch Front/Northern Utah (exclusive of WFZ)

(1) West Valley fault zone – trench to better constrain faulting history and compare with WFZ earthquake history.
(2) Utah Lake faults – geophysical surveys and possibly drilling to determine relation to WFZ; another WVFZ?
(3) Great Salt Lake fault zone – drilling to obtain samples to determine earthquake timing on the Promontory segment.
(4) East Cache fault zone – trench to determine faulting history on northern and southern sections.
(5) Clarkston fault – trench to determine multiple earthquake record (megatrench?).
(6) Wasatch Range back-valley fault – trench one back-valley fault to constrain earthquake timing and use as a model for similar back-valley faults.
(7) Faults beneath Bear Lake – geophysical surveys and possible drilling to determine relation to Eastern Bear Lake fault.
(8) Eastern Bear Lake fault – trench to determine faulting history on northern fault sections.

Central/Southern Utah

(1) Sevier/Toroweap fault - determine number and timing of surface-faulting earthquakes, segmented?
(2) Washington fault zone - trench to determine faulting history in a rapidly urbanizing area.
(3) Cedar City-Parowan monocline/Paragonah fault – geomorphic studies to investigate possible Holocene deformation.
(4) Enoch graben– geomorphic studies and possibly trenching to determine faulting history in this rapidly urbanizing area, determine relation to nearby HFZ.
(5) Hurricane fault zone - trench to confirm faulting history on Cedar City section
(6) Gunnison fault - investigate possibly very young activity and large displacements in Sevier Valley
(7) Scipio Valley faults – geomorphic studies and possibly trenching to investigate possible very young activity and determine seismic hazard to nearby major transportation corridors

Table 8 ranks the recommended paleoseismic investigations in table 7 on a statewide-priority basis. The Working Group considers these investigations to be of highest priority and recommends them for future NEHRP funding.

Table 8. Paleoseismic investigations required to adequately characterize Utah's earthquake hazard in order of decreasing statewide priority.

(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

Investigation Summaries

The faults/fault sections listed in table 7 are those that the Working Group believes require additional investigation to ensure that Utah's earthquake hazard is characterized to a minimally acceptable level. However, details of the recommended investigations such as site selection, land ownership, and investigation methods remain to be determined. Therefore, the following discussion summarizes only the need for the investigations, and not details of how or where the investigations should be performed.

Wasatch Fault Zone

Nephi segment: The NS is the southernmost of the five central segments of the WFZ with documented evidence of recurrent Holocene surface faulting. The NS consists of two distinct fault strands: the northern Santaquin strand and the southern Nephi strand, separated by a 4-5 kilometer right step in the segment trace (DuRoss and Bruhn, 2003). Existing paleoseismic data from two previous trench studies on the Nephi strand are not well constrained; both investigations produced conflicting sets of numerical ages on samples from the same geologic units resulting in significant uncertainty regarding paleoearthquake timing. No paleoseismic-trench data are available for the rapidly urbanizing Santaquin strand. New scarp-modeling information indicates that the paleoearthquake histories on the Nephi and Santaquin strands may be different (DuRoss and Bruhn, 2003), and yet present seismic-hazard analyses assume that the two strands form a single segment, and therefore rely entirely on the poorly constrained record of Nephi strand earthquakes. Understanding the individual rupture histories of the two strands is critical, as asynchronous ruptures would result in more frequent moderate to large magnitude earthquakes, whereas synchronous rupturing of the strands would generate less frequent but larger earthquakes. A minimum of two trench sites on the NS are required to: (1) clarify the history of paleoearthquakes on the Nephi strand, (2) determine the timing of paleoearthquakes on the Santaquin strand, (3) accurately characterize the seismic-source potential of the NS, and (4) compare the NS paleoearthquake parameters with the adjacent PS and LS to evaluate the possibility of rupture overlap between the segments.

Weber segment MRE: Different paleoseismic-trenching investigations have identified different MREs on the WS (table 1, appendicies A and B), raising the possibility of (1) partial segment rupture during some earthquakes, or (2) rupture overlap from adjoining segments, on one of Utah's most densely urbanized faults/fault sections. Trenching at multiple locations along the WS is recommended to document MRE timing and resolve these possible rupture scenarios.

Weber segment megatrench: The current surface-faulting chronology for the WS extends to the middle Holocene. Long-term earthquake histories are important when performing PSHAs, especially along the heavily urbanized Wasatch Font. A "megatrench" similar to those excavated on the SLCS and PS, or a series of smaller trenches similar to those excavated on the BCS, are required to determine the long-term (latest Pleistocene) earthquake history of the densely urbanized WS.

Collinston and Clarkston Mountain segments: The Collinston and Clarkston Mountain segments are the two northernmost WFZ segments in Utah. They are the only WFZ segments in Utah that lack geologic strip maps. Relatively modern 1:24,000-scale geologic maps are available along the segment, but detailed paleoseismic studies of scarps and geologic relations along the segment have not been performed. The Working Group recommends that such studies be performed, and if evidence of Holocene or latest Pleistocene surface faulting is discovered, the segments be trenched to determine earthquake timing, RIs, and VSRs.

Levan segment: Previously only one Holocene surface-faulting earthquake was recognized on the LS (appendix B). Additional scarp-profile analysis (Hylland and Machette, 2004) indicates that there may have been a second earlier earthquake near the southern end of the segment in early Holocene or latest Pleistocene time. The Working Group recommends trenching near the southern end of the segment to determine a long-term surface-faulting chronology for the LS.

Wasatch Front/Northern Utah Exclusive of the WFZ

West Valley fault zone: The WVFZ lies entirely within the densely urbanized Salt Lake Valley. As many as six or seven surface-faulting/flexuring earthquakes are proposed for the WVFZ (appendices A and B). Earthquake timing is poorly constrained, and the WVFZ may or may not have ruptured coseismicly with some or all of the surface-faulting earthquakes on the nearby SLCS of the WFZ. The Working Group recommends trenching the various strands of the WVFZ to better constrain surface-faulting timing and to determine the relation between surface faulting on the WVFZ and the SLCS.

Utah Lake faults: Several poorly understood, questionable Holocene faults and folds beneath Utah Lake in the densely urbanized Utah Valley have been identified from widely spaced seismic-reflection data (Brimhall and Merritt, 1981). Displacements of <2 to 5 m in the past 16.8-18 kyr (period of the Bonneville highstand) indicate slip rates from <0.1 to about 0.4 mm/year. Little is known regarding these sub-lacustrine structures; they may represent east-dipping faults antithetic to the PS of the WFZ, and therefore be analogous to the WVFZ in Salt Lake Valley. The Working Group recommends additional geophysical investigations and if warranted drilling to assess the seismic potential of these faults.

Great Salt Lake fault zone: A NEHRP-funded seismic-reflection study of the Promontory section of the Great Salt Lake fault zone (GSLFZ) is scheduled for summer 2004 (Pechmann and Dinter, University of Utah, verbal communication to Working Group, 2004). If the survey identifies evidence of paleoearthquakes in the sediments beneath Great Salt Lake, the Working Group recommends drilling and sampling lake-bottom sediments at critical locations to provide carbon samples necessary to constrain earthquake timing.

East Cache fault zone: The East Cache fault zone (ECFZ) consists of three sections (northern, central, and southern) based on fault zone complexity, tectonic geomorphology, and expression of fault scarps (appendix B). Paleoseismic-trenching data are available only for the central section, which shows evidence of Holocene surface faulting. Geomorphic evidence for Holocene faulting is not evident on the northern and southern sections, but the east-dipping West Cache fault zone (WCFZ) on the opposite (west) side of Cache Valley is segmented, and all three segments have experienced Holocene surface faulting (table 1, appendices A and B). The ECFZ trends along the base of the precipitous Bear River Range, where numerous well-developed faceted spurs indicate a high rate of tectonic activity. Cache Valley is rapidly urbanizing, and the Working Group recommends that both the northern and southern ECFZ sections receive additional paleoseismic evaluation to assess their seismic potential.

Clarkston fault: The Clarkston fault (CF) is the northernmost and longest of the three segments comprising the WCFZ (appendices A and B). Black and others (2000) trenched the CF and identified Holocene surface faulting. The trench was not sufficiently deep to expose evidence for older earthquakes, so little is known about the long-term behavior of the CF; however, geomorphic relations indicate a minimum of two surface-faulting earthquakes since the Bonneville highstand (past 18 kyr). Prominent scarps along the CF, particularly where the fault trends northward into southern Idaho, indicate recurrent late Quaternary surface faulting. The Working Group recommends that the long-term history of surface faulting on the CF be investigated by excavating additional, deeper trenches across multiple-earthquake scarps, possibly in Idaho if a suitable site is not available in Utah.

Wasatch Range back-valley fault: The USBR investigated several Wasatch Range back-valley faults as part of seismic-hazard evaluations for USBR dams and water conveyance structures (appendices A and B). These studies were chiefly reconnaissance in nature and lack sufficient numerical ages to narrowly constrain the time of surface faulting. Consequently, present RI and VSR estimates for back-valley faults have high uncertainties (appendices A and B). Considering their location in or close to rapidly urbanizing areas of the Wasatch Front, and their potential inclusion in future PSHAs, the Working Group recommends that one back-valley fault be selected for detailed paleoseismic study to serve as a model for all such faults until detailed study of other structures becomes warranted.

Faults beneath Bear Lake: Several normal faults appear on seismic profiles across Bear Lake (Skeen, 1976; Coleman, 2001). These sub-lacustrine faults are downthrown both to the east and west, and some on the eastern side of the lake displace the lake bottom, indicating possible Holocene movement (McCalpin, 2003). The relation of these faults to the Eastern Bear Lake fault (EBLF) and to faults on the west side of Bear Lake is unknown. The Working Group recommends additional geophysical investigation and, if warranted, drilling to assess the seismic potential and hazard these faults present to nearby communities on both sides of the Utah/Idaho border.

Eastern Bear Lake fault: The EBLF can be subdivided into northern, central, and southern sections on the basis of fault-rupture patterns, youthfulness of fault scarps, and subsurface geophysical data (appendix B). Only a portion of the southern section is in Utah, and only that part of the fault has been trenched. Multiple-earthquake scarps in geologically recent unconsolidated deposits along the central section of the EBLF in Idaho indicate recurrent late Quaternary movement. Ground shaking related to a large earthquake on the central section of the EBLF would affect nearby communities in Utah. The Working Group recommends that the central section of the EBLF be trenched to assess the fault's seismic potential and the hazard it presents to nearby communities on both sides of the Utah/Idaho border.

Central/Southern Utah

Sevier/Toroweap fault: The Sevier/Toroweap fault trends in a north-south direction for more than 167 kilometers in northern Arizona and southern Utah. The fault is designated the Sevier fault (SF) in Utah and the Toroweap fault (TF) in Arizona (Black and others, 2003). Pearthree (1998) subdivides the TF into three subsections; the SF has not received similar paleoseismic study and therefore is not subdivided. However, the fault's long length in Utah (88 km end to end) indicates the likelihood of more than one seismogenic section. A displaced basalt flow (200 m net vertical displacement) at Red Canyon provides a late Quaternary VSR estimate for the SF of 0.36 mm/yr (Black and others, 2003). The UGS plans a reconnaissance investigation of the SF in the second half of 2004 to look for evidence of fault segmentation, and sites where additional RI and VSR information can be obtained. If potential sites are found, detailed mapping and geomorphic studies should be performed to assess their potential for paleoseismic trenching, and if found suitable, trenching should be performed.

Washington fault zone: The Washington fault zone (WaFZ) trends in a north-south direction for more than 40 kilometers (end to end) from northern Arizona into the St.

George basin of southern Utah (appendix B). Earth Sciences Associates (1982) trenched the WaFZ near four flood control dikes in Utah. The trenching produced net vertical-displacement estimates, but no information on the number or timing of paleoearthquakes. The Working Group recommends that additional paleoseismic investigations be performed on the WaFZ to assess its seismic potential and the earthquake hazard it presents to the rapidly urbanizing St. George basin.

Cedar City-Parowan monocline/Paragonah fault: The Cedar City-Parowan monocline (CC-PM) is a complex zone of deformation that may form a structural bridge between the Paragonah fault (PF) to the north and the Hurricane fault zone (HFZ) to the south (Threet, 1963). Hecker (1993) indicates the possibility that a blind, plateau-bounding, normal fault with significant seismic potential underlies the main mountain-front monocline. Both normal and strike-slip faults deform the monocline and form numerous closed range-front basins only partially filled with sediment. Stream downcutting exposes faults in late Holocene deposits and a geodetic network (Anderson and Bucknam, 1979) indicates significant horizontal and vertical changes in directions opposite to the topographic gradient, suggesting tectonic deformation consistent with right-lateral fault slip. Modern deformation has not been accompanied by seismicity above a threshold of about M_L 3.0, suggesting ongoing, aseismic deformation. The Working Group recommends additional geodetic monitoring and detailed geologic mapping of the CC-PM and PF to determine if rapid tectonic deformation is continuing and if so, what hazard the CC-PM and PF represent to nearby communities in the Cedar City area.

Enoch graben: The Enoch graben (EG) is a poorly understood late Pleistocene to Holocene structure that bounds the southern end of the Red Hills, and extends into the valley north of Cedar City. Scarps in the town of Enoch on unconsolidated alluvium are 5-7m high and have been trenched in numerous places by local residents to stimulate spring flow. Anderson (1980) reports a soil layer (paleosol) in one such exposure that separates faulted coarse alluvium below from well-bedded sandy clay above. The relation of faulting to the soil, which yielded an age of 9,500 ^{14}C yr B.P., is uncertain, although subjacent strata are faulted (Hecker, 1993). Five kilometers north of Enoch, faults with up to 50 meters or more of throw displace Quaternary basalt flows. Some of these bedrock faults likely have moved recently as indicated by the Enoch alluvial scarp (Hecker, 1993). The Working Group recommends detailed geologic mapping and geomorphic investigations be performed on the EG to better constrain the rate of slip and time of most recent surface faulting on this structure. If warranted by the reconnaissance investigations, the Working Group recommends trenching one or more bounding faults to obtain detailed paleoseismic information for earthquake-hazard analysis.

Hurricane fault zone: The HFZ is the longest and likely the most active fault in southwestern Utah and northwestern Arizona (appendix B). Previous attempts to trench the HFZ in Utah have proven unsuccessful due to a limited number of suitable trench sites, landowner constraints, and scarps formed on deposits containing boulders too large to excavate with locally available trackhoes (Lund and others, 2001). Single- and multiple-earthquake scarps identified at Coyote Gulch on the Ash Creek section of the HFZ (Lund and others, 2001) remain the best potential site for determining the surface faulting history of the northern HFZ. That site is currently unavailable due to landowner restrictions; however, should that situation change in the future, the Working Group recommends that the Coyote Gulch scarps be trenched.

A large scarp ($\geq$10 m net slip) on the Cedar City section of the HFZ at Shurtz Creek is formed on very coarse bouldery alluvium. An attempt to trench the Shurtz Creek scarp was unsuccessful due to boulders in the trench too large to excavate with available trackhoes (Lund and others, 2001). The displaced alluvial surface at Shurtz Creek is covered with numerous large basalt boulders. Preliminary cosmogenic isotope dating (^{36}Cl, ^{3}He) of the boulders resulted in an age for the Shurtz Creek surface of between 30 and 60 kyr. The Working Group recommends additional efforts to determine the age of the Shurtz Creek surface to better constrain the late Quaternary VSR for the northern part of the HFZ.

Gunnison fault: The Gunnison fault (GF) is marked by northwest- to southwest-trending scarps in alluvium in western Sanpete Valley along the east side of the Gunnison Plateau. The MRE may be as young as late Holocene and likely produced less than a meter of displacement (Black and others, 2003). Progressively older alluvial surfaces have greater displacements, and old Quaternary (Tertiary?) surfaces have tens of meters of displacement across steep, high scarps. At Birch Canyon, 2-4 ka fluvial and debris-flow deposits underlie a 10- to 15-m-high scarp (Elliott Lips, verbal communication to Suzanne Hecker, 1989). The sequence of deposits appears to be monoclinally folded, with an apparent dip that is parallel to the face of the scarp and fairly uniform throughout the section. These relations suggest locally intense, recent deformation along this portion of the range front (Hecker, 1987). The Working Group recommends that geologic mapping and a geomorphic investigation be conducted of the GF to better constrain its VSR and to investigate the unusual geologic relations reported at Birch Creek.

Scipio Valley faults: The Scipio Valley faults (SVF) are northeast-trending normal faults along the west side of northern Scipio Valley (Black and others, 2003). The faults show a total displacement greater than 11.1 meters in alluvium, and evidence for two periods of fault movement (pre-Holocene and Holocene). Alluvium is displaced 2.7 meters by the younger earthquake (Hecker, 1993). The morphology and degree of dissection of the young scarps are similar to the Fish Springs fault scarps, which formed 2-3 ka; scarp-profile data are insufficient to constrain the age of the pre-Holocene scarps. The SVF are adjacent to major transportation, utility, and pipeline corridors. The Working Group recommends that geologic mapping and a geomorphic investigation be conducted of the SVF to better constrain their slip rates and the timing of the MRE.

SUMMARY

The Utah Geological Survey convened the Utah Quaternary Fault Parameters Working Group, a panel of experts in paleoseismology and seismology, to critically review Utah's Quaternary fault paleoseismic-trenching data, and to establish consensus preferred RI and VSR estimates and confidence limits for those faults/fault sections where the data permit. The *Quaternary Fault and Fold Database and Map of Utah* (Black and others, 2003) indicates that 33 of Utah's 212 Quaternary faults or fault-related structures have paleoseismic-trenching data available for them. The six active, central segments of the WFZ, collocated with the most populous part of Utah's Wasatch Front, account for the greatest number of investigations and best quality paleoseismic data. However, even for those segments, well-constrained information on surface faulting generally extends only to the middle Holocene, with less reliable information to the latest Pleistocene for two segments, and new long-term information pending for a third segment. Paleoseismic-trenching data for Utah's other Quaternary faults are generally less abundant and not as well constrained. Those data are typically limited to a single location along a fault/fault section, including many suspected segmented faults or faults/fault sections exhibiting other tectonic complexities. Numerical ages available to constrain the timing of paleoearthquakes on faults/fault sections off the Wasatch Front are commonly much less abundant, and several trenching investigations resulted in no numerical ages at all. Consequently, significant questions remain to be answered, including questions pertaining to some comparatively well-studied WFZ segments, to ensure that Utah's earthquake hazard is characterized to the minimum level necessary for accurate hazard evaluation.

Issues related to data uncertainty and adequacy weighed heavily upon the Working Group's deliberations. The combined result of limited data and data uncertainties for many faults prevented rigorous statistical analysis of most paleoseismic-trenching data or constraint of RI and VSR estimates within rigidly quantifiable bounds. Consequently, the Working Group relied on its collective experience and best professional judgment to determine consensus preferred RI and VSR estimates and confidence limits for the faults under review. For several faults, the data were too sparse or too uncertain to make meaningful estimates.

The preferred RI and VSR estimates presented in this report are typically bracketed by upper and lower bounds that represent the Working Group's best estimate of two-sigma confidence limits for the estimated values. The confidence limits are approximations, and were not derived in a statistically rigorous manner. Instead, they again represent the Working Group's best collective judgment regarding the range over which recurrence and slip is expected to vary for a particular fault. They are intended to incorporate both epistemic and aleatory uncertainty, and to approximate two-sigma (5^{th} and 95^{th} percentile) confidence limits. In a few instances, the available data were not sufficient to determine individual preferred RI or VSR values. In those cases, the Working Group's consensus estimates are reported as a range of values rather than as a central value with associated confidence limits. In other instances, the trenching data were insufficient to allow the Working Group to make fault parameter estimates at all.

The Working Group recommends additional paleoseismic study of 20 faults/fault sections to characterize Utah's earthquake hazard to a minimally acceptable level. The faults/fault sections include segments of the WFZ that have already received considerable study, but for which significant questions remain regarding earthquake timing and/or fault segmentation; other previously investigated faults for which questions remain regarding their seismic behavior; and faults that have not yet received detailed study. The Working Group considered NEHRP minimum slip-rate criteria and specific fault priorities for urban areas in Utah when evaluating which faults to recommend for additional study. However, the Working Group selected some faults/fault sections specifically because so little is known about their recurrence or slip history, and others, while not located adjacent to urban areas, are near major transportation, utility, and pipeline corridors critical to Utah's economic well being. The faults/fault sections recommended for study reflect the current status of Utah development and a reasonable projection of future growth. However, with future population increases and expansion into previously undeveloped areas, additional faults/fault sections will undoubtedly become critical to future earthquake-hazard reduction and will require study and characterization at that time.

CONCLUSIONS

The Utah Quaternary Fault Parameters Working Group has completed a comprehensive evaluation of the paleoseismic-trenching data available for Utah's Quaternary faults, and where data permitted determined preferred RI and VSR estimates with approximate two-sigma confidence limits. Although not based on rigorous statistical analysis, the consensus values and confidence limits represent the best professional judgment of a panel of experts thoroughly familiar with Utah's paleoseismic data, and until superseded by information from new paleoseismic investigations, the Working Group's preferred RI and VSR estimates and associated confidence limits represent the best available information regarding surface-faulting activity for the faults/fault sections reviewed, and can be considered as approximating average RI and VSR values and two-sigma variability about those mean values.

With paleoseismic-trenching performed on only 16 percent of Utah's Quaternary faults, clearly much remains to be done to characterize Utah's earthquake hazard. Future paleoseismic investigations will undoubtedly result in new data that will refine some Working Group estimates, answer outstanding questions, and fill data gaps. The Working Group looks forward to the completion of those studies and the clarity they will bring to earthquake-hazard evaluation in Utah.

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Utah Quaternary Fault Parameters Working Group: Critical Review of Trenching Paleoseismic Data and Consensus Recurrence-Interval and Slip-Rate Estimates for Utah's Quaternary Faults

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The Utah Geological Survey convened a Utah Quaternary Fault Parameters Working Group comprised of experts in paleoseismology, seismology, and other fields, to critically review Utah's Quaternary fault paleoseismic trenching data, and to determine

consensus mean recurrence and slip-rate estimates for faults when the data permitted. Utah has 212 potentially active Quaternary faults or fault sections; paleoseismic trenching data are available for 33 (16%) of them. Available data come from approximately 60 sources representing the work of more that 40 researchers over the past ~25 years. Although used extensively by researchers and geologic and engineering practitioners, Utah's paleoseismic trenching data have not been critically reviewed to establish consensus fault parameter values and appropriate uncertainty limits. Consensus paleoseismic data are critical in four areas directly related to reducing earthquake loses in Utah: (1) updating the National Seismic Hazard Maps, (2) providing consensus paleoseismic data and appropriate uncertainty limits for use by other researchers, (3) characterizing seismic sources, and (4) preparing PSHAs.

The Working Group review showed considerable variation in the quality and completeness of Utah's paleoseismic data. Only the six active central segments of the Wasatch fault zone and a few other faults either close to the Wasatch Front or near critical facilities have received detailed study, and even for those faults, reliable paleoseismic data seldom extend beyond the middle Holocene. Information for the remaining faults typically is relegated to a single study, often of a reconnaissance nature, and often on only one section of a suspected multi-section fault. Consequently, critical surface-faulting parameters are only broadly constrained and recurrence and slip-rate estimates have high associated uncertainty.

APPENDIX A

WORKING GROUP CONSENSUS
EARTHQUAKE TIMING
AND
PREFERRED RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES
WITH SUPPORTING INFORMATION

Fault/Fault Section[1]	Length[2] (km) Straight Line	Length[2] (km) Surface Trace	Earthquake Timing[3]	Consensus Preferred Recurrence Interval[4]	Consensus Preferred Vertical Slip Rate[5]
Wasatch fault zone Brigham City segment	35.5	40	Z 2100±800 cal yr B.P. Y 3450±300 cal yr B.P. X 4650±500 cal yr B.P. W 5950±250 cal yr B.P. V 7500±1000 cal yr B.P. U 8500±1500 cal yr B.P. T >14,800±1200, <17,000 cal yr B.P.	Three most recent (W to Z) interevent interval average recurrence: 1300[6]±200[7] cal yr Five most recent (U to Z) interevent interval average recurrence: 1300[6]±400[7] cal yr Working Group Preferred Recurrence Interval 500-**1300**-2800 yr	Personius BC Slip Rates X-Y 0.6 –0.8-1.4 mm/yr, W-X 1.4-1.9-3.1 mm/yr V-W 1.0-1.6-4.5 mm/yr Longer term slip rates in Provo-age deposits range from 0.24 mm/yr near the north segment boundary to 1.36 mm/yr near Willard. Bonneville-age deposits at Willard Canyon record a single slip-rate of 1.5-1.6 mm/yr. Working Group Preferred Vertical Slip Rate 0.6-**1.4**-4.5 mm/yr
Weber segment	56	61	Za 0.5±0.3 ka[8] (partial segment rupture?) Zb 950±450 cal yr B.P.[8] Y 3000±700 cal yr B.P. X 4500±700 cal yr B.P. W 6100±700 cal yr B.P.	Three most recent (W to Zb) interevent interval average recurrence: 1600[6]±600[7] cal yr Four most recent (W to Za) interevent interval average recurrence: 1000[6]±1400[7] cal yr Working Group Preferred Recurrence Interval 500-**1400**-2400 yr	Y-Zb 0.6-0.9-1.4 mm/yr, X-Y 1.0-1.9-4.3 mm/yr, W-X 0.6-0.9-1.6 mm/yr, Using an updated Lake Bonneville chronology and net-slip values from Nelson and Personius (1993) shows long-term slip rates as high as 2.0 mm/yr in Bonneville-cycle deposits, and up to 1.3 mm/yr in Provo-cycle deposits. Working Group Preferred Vertical Slip Rate 0.6-**1.2**-4.3 mm/yr
Salt Lake City segment	39	46	Z 1300±650 cal yr B.P. Y 2450±550 cal yr B.P. X 3950±550 cal yr B.P.	Three most recent (W to Z) interevent interval average recurrence: 1300[6]±400[7] cal yr	Swan and others (1981) reported 14.5+10/-3 meters of net slip across the WFZ on the crest of the Bells Canyon glacial moraine south of Little

			W 5300±750 cal yr B.P. V ~7.5 ka (after 8.8-9.1 ka but before 5.1-5.3 ka) U ~9 ka (shortly after 9.5-9.9 ka) T ~17 ka S (?) 17–20 ka	V-W and U-V intervals are each roughly 2 kyr; the T-U mean interevent interval is ~8 kyr, indicating surface-faulting quiescence during earliest Holocene and latest Pleistocene time (McCalpin, 2002). Working Group Preferred Recurrence Interval 500-**1300**-2400 yr	Cottonwood Canyon. Scott (1989) reports the age of the moraine as 18-26 ka, resulting in a late Pleistocene slip rate of: 0.4-0.7-1.4 mm/yr Working Group Preferred Vertical Slip Rate 0.6-**1.2**-4.0 mm/yr
Provo segment	59	69.5	Z 600±350 cal yr B.P. Y 2850±650 cal yr B.P. X 5300±300 cal yr B.P.	Two most recent (X to Z) interevent interval average recurrence: 2400[6]±300[7] cal yr Working Group Preferred Recurrence Interval 1200-**2400**-3200 yr	Hobble Creek Post Provo time 0.68-0.76-0.83 mm/yr Post Bonneville time 2.2-2.4-2.7 mm/yr American Fork Canyon Post Bonneville time 0.8-1.1-1.4 mm/yr Spanish Fork Canyon Post Provo time 0.18-0.19 mm/yr East of Provo between Slate and Slide Canyons: Post Bonneville time ≤ 1.1-1.2 mm/yr Working Group Preferred Vertical Slip Rate 0.6-**1.2**-3.0 mm/yr
Nephi segment	37.5	42.5	Z ≤1.0±0.4 ka Y ~3.9±0.5 ka X >3.9±0.5 ka, <5.3±0.7 ka	Two most recent (X to Z) interevent interval average recurrence: ~2500[6]±2100[7] cal yr Working Group Preferred Recurrence Interval 1200-**2500**-4800 yr	North Creek (Schwartz and Coppersmith, 1984), Middle Holocene 1.27-1.36±0.1 mm/yr Harty and others (1997) middle Holocene slip-rate estimates North Creek 0.8-1.2 mm/yr Willow Creek 0.7-1.0 mm/yr Gardner Creek 0.5-0.7 mm/yr Red Canyon 0.6-1.0 mm/yr

Levan segment	25.5	30	Z ≤1000±150 cal yr B.P. Y unknown but likely earliest Holocene to latest Pleistocene; partial segment rupture possible along southern portion of segment (Hylland and Machette, 2004).	Working Group Preferred Recurrence Interval **>3 and <12** kyr[9]	Working Group Preferred Vertical Slip Rate 0.5-**1.1**-3.0 mm/yr Working Group Preferred Vertical Slip Rate **0.1-0.6** mm/yr[9] Slip rate is based on the likelihood that an event Y (Hylland and Machette, 2004) occurred during early Holocene or latest Pleistocene time on the LS.
Joes Valley fault zone[10] East Joes Valley fault West Joes Valley fault Middle Mountain fault Bald Mountain faults (intragraben)	 57 57 34	 61 81 39	The JVFZ forms a long, narrow graben (JVG) on the Wasatch Plateau. The EJVF experienced a minimum of 4 earthquakes in 250 kyr; the WJVF and intragraben faults have each experienced a minimum of 2 earthquakes in the past ~30 kyr. Individual earthquake timing is not constrained.	Foley and others (1986) report broad recurrence interval estimates of: <u>Individual Fault Recurrence</u> EJVF <60 kyr (~250 ka record) WJVF 10-20 kyr (~30 ka record) MMF 10-15 kyr (~30 ka record) Earthquake timing is constrained only within broad time intervals. Consequently, the Working Group's recurrence-interval estimate is intentionally broad to reflect high uncertainty. Working Group Consensus Preferred Recurrence Interval 5-**10**-50 kyr	Foley and others (1986) report no net vertical slip across the JVG, and question the seismogenic capability of the JVFZ. Therefore, despite the presence of scarps on Quaternary deposits along the northern JVFZ, a fundamental question remains regarding the nature of the JVG, and the seismogenic capability of the JVFZ. Lacking net vertical slip across the JVFZ, the Working Group recommends: (1) that the JVFZ be considered a single integrated structure, and (2) that a consensus vertical slip rate not be reported for the JVFZ at this time. **No estimate**
West Valley fault zone Taylorsville fault	16 15	44 19	The WVFZ includes the subparallel Taylorsville fault (TF) and Granger fault (GF) and a zone of short, less well-defined	Keaton and others (1987) report a mean recurrence of 1.8-2.2 kyr for the southern WVFZ. Keaton and Currey	Keaton and others (1987) report the following vertical slip rates for the WVFZ: Taylorsville fault <12 ka

Granger fault	16	25	faults to the north. Based chiefly on geomorphic and drill-hole evidence, Keaton and others (1987) and Keaton and Currey (1989) report a minimum of 2 surface-faulting earthquakes in ~12 kyr on the TF and 5 earthquakes on the GF in the past 13 kyr, for a total of 6-7 earthquakes for the WVFZ as a whole; however, individual earthquake timing is not constrained. Solomon (1998) and unpublished UGS data show that the TF and GF MREs occurred shortly after 2.0-2.4 ka and 1.3-1.7 ka, respectively, which is similar to the timing of the two most recent surface-faulting earthquakes on the nearby SLCS of the WFZ. The similarity in timing between the earthquakes on the WVFZ and the SLCS raises questions regarding whether the WVFZ ruptures coseismicly with the WFZ. However, until demonstrated otherwise, the Working Group considers the WVFZ independently seismogenic.	(1989) report a mean recurrence on the less well-defined northern part of the WVFZ of 6 to 11 kyr. Based on their review, the Working Group considers the available paleoseismic data insufficient to make a recurrence-interval estimate for the WVFZ. **Insufficient data – no estimate possible.**	0.1-0.2 mm/yr Granger fault 13 ka 0.4-0.5 mm/yr WVFZ (entire) 13 ka 0.5-0.6 mm/yr Granger fault 47±20 ka 0.1-0.3 mm/yr Granger fault 60±20 ka 0.02-0.04 mm/yr Granger fault 80±30 ka 0.03-0.1 mm/yr Granger fault 140±10 ka 0.01 mm/yr Slip-rate information for the WVFZ comes chiefly from geomorphic and drill-hole information and is broadly constrained. Therefore, the confidence limits for the WVFZ as a whole are intentionally broad to reflect high uncertainty: Working Group Preferred Vertical Slip Rate 0.1-**0.4**-0.6 mm/yr
West Cache fault zone	51	70[11]	The WCFZ consists of three east-dipping normal faults: the Clarkston (CF), Junction Hills (JHF), and Wellsville faults (WF). Each fault is a seismogenic segment of the WCFZ, and each has experienced Holocene surface faulting.	The timing of older earthquakes either could not be determined or could only be constrained within broad time intervals. Therefore, the Working Group's preferred recurrence-interval estimates for the CF, JHF, and WF are reported as ranges and are intentionally broad to reflect high uncertainty. Working Group Preferred Recurrence Intervals	The timing and displacement of older earthquakes either could not be determined or could only be constrained within broad time intervals. Therefore, confidence limits for the Working Group's slip-rate estimates for the CF, JHF, and WF are intentionally broad to reflect high uncertainty. Working Group Preferred Vertical Slip Rates
Clarkston fault	?	35[11]	Z 3600-4000 cal yr B.P. No trench evidence of older earthquakes,	**5-20** kyr[9]	0.1-**0.4**-0.7 mm/yr

			but geomorphic relations indicate a minimum of two earthquakes in post-Bonneville time.		
Junction Hills fault	25	25	Z 8250-8650 cal yr B.P. Y > 22 ka	**10-25** ky[9]	0.05-**0.1**-0.2 mm/yr
Wellsville fault	20	31	Z 4000-4800 cal yr B.P. Y 15 to 25 ka	**10-25** kyr[9]	0.05-**0.1**-0.2 mm/yr
East Cache fault zone central section	16	16	McCalpin (1989, 1994) subdivided the ECFZ into northern, central, and southern sections. The central section is the only section with geomorphic evidence of Holocene surface faulting, and is the only section for which paleoseismic trenching data are available. Z 4.3-4.6 ka Y between 16.2 and 18 ka	Single interevent interval (Y-Z): minimum 11.6 kyr, maximum 13.7 kyr, average 12.7 kyr. Evidence for a third earthquake (X) during the Bonneville transgression is equivocal. If a third earthquake did occur, the interval between events X and Y is likely ~4 kyr, which implies large variations in interevent interval length. Therefore, the confidence limits assigned to the Working Group's recurrence-interval estimate are intentionally broad to reflect high uncertainty: Working Group Preferred Recurrence Interval 4-**10**-15 kyr	The minimum, maximum, and average Y-Z recurrence intervals, and an event Z displacement of 0.5-1.2 m (McCalpin, 1994), produce a slip-rate range of: 0.04-0.07-0.10 mm/yr Possible large differences in interevent interval length would produce corresponding large variations in slip rate through time. Therefore, the confidence limits assigned to the Working Group's slip-rate estimate are intentionally broad to reflect high uncertainty: Working Group Preferred Vertical Slip Rate 0.04-**0.2**-0.4 mm/yr
Hurricane fault zone Anderson Junction section	42	54	The Anderson Junction section (AJS) straddles the Utah/Arizona border and is one of 6 identified HFZ sections. Two trench sites, both in Arizona, provide evidence for 3 surface-faulting earthquakes; however, earthquake timing is only constrained to broad time intervals: Z 5-10 ka Y >5-10 ka and <25-50 ka	Earthquake timing is poorly constrained on the AJS. The Working Group's recurrence-interval estimate is based largely on slip-rate information, and therefore, the confidence limits are intentionally broad to reflect high uncertainty: Working Group Preferred Recurrence Interval	Scarp profiles (Stenner and others, 1999) indicate slip rates of 0.1-0.3 mm/yr in deposits ~70-125 ka, and 0.1-0.4 mm/yr in ~25-50 ka deposits. Slip rates from displaced basalt flows (Lund and others, 2001) indicate middle Quaternary slip rates ≥ 0.45 mm/yr, slowing to ≤0.2 mm/yr sometime before 350 ka. Because information on earthquake

			X >25-50 ka?	**5-50** kyr[9]	timing and displacement is limited, the Working Group's slip-rate estimate is based chiefly on information from scarp profiles and displaced basalt flows, confidence limits are intentionally broad to reflect high uncertainty: Working Group Consensus Preferred Vertical Slip Rate 0.05-**0.2**-0.4 mm/yr
Great Salt Lake fault zone[12] Fremont Island segment	30		Z 3150+235/-211 cal yr B.P. Y 6412+209/-211 cal yr B.P. X <11,247 +605/-499 cal yr B.P.	Y-Z 3262+151/-184 yr X-Y <5015+587/-424 yr Working Group Preferred Recurrence Interval 2.8-**4.2**-5.6 kyr	Working Group Preferred Vertical Slip Rate 0.3-**0.6**-1.1 mm/yr
Antelope Island segment	35		Z 586+201/-241 cal yr B.P. Y 6170+236/-234 cal yr B.P. X 9898+247/-302 cal yr B.P.	Y-Z 5584+219/-172 yr X-Y 3728+204/-351 yr Working Group Preferred Recurrence Interval 2.8-**4.2**-5.6 kyr	Working Group Preferred Vertical Slip Rate 0.3-**0.6**-1.1 mm/yr
Oquirrh fault zone	21	22	Olig and others (1996) excavated trenches at two sites on the northern portion of the OFZ and found evidence for three surface-faulting earthquakes: Z between 4.8 and 7.9 cal kyr B.P Y between 20.3 and 26.4 ^{14}C kyr B.P. X > 26.4 ^{14}C kyr B.P. Olig and others (2001) believe that the OFZ ruptures coseismicly with the	Single interevent interval (Y-Z): minimum 12.4 kyr, maximum 21.6 kyr, average 17.0 kyr. Recurrence information is restricted to one poorly constrained interevent interval. Therefore, confidence limits for the Working Group's recurrence-interval estimate are intentionally broad to reflect high uncertainty:	The minimum, maximum, and average Y-Z recurrence intervals, and an event Z displacement of 2.0-2.7 m (Olig and others, 1996) produce a slip-rate range of 0.09-0.14-0.22 mm/yr. Because information on recurrence and vertical net slip for the OFZ is restricted to a single, poorly constrained interevent interval, the confidence limits for the Working Group's slip-rate estimate are

			Southern Oquirrh Mountain fault zone to the south.	Working Group Preferred Recurrence Interval 5-**20**-50 kyr	intentionally broad to reflect high uncertainty: Working Group Preferred Vertical Slip Rate 0.05-**0.2**-0.4 mm/yr
Southern Oquirrh Mountains fault zone (Mercur fault)	24	56	Olig and others (1999) include the Mercur, West Eagle Hill, Soldier Canyon, and Lakes of Kilarney faults in the SOMFZ. Three trenches (east, central, and west) excavated across strands of the Mercur fault (MF) exposed evidence for 5 to 7 surface-faulting earthquakes since ~92±14 ka Z shortly after 4.6±0.2 ka and well before 1.4±0.1 ka Y between 20 and 50 ka X shortly after 42±8 ka – may or may not correlate with earthquakes V_C (central trench) or W_E (east trench), W shortly after 75±10 ka – may or may not correlate with earthquakes V_C and W_E, although event V_C is probably older V around (shortly after?) 92±14 ka Olig and others (2001) consider these 5 earthquakes well established but poorly constrained. Uncertainty regarding the total number of earthquakes comes from difficulty correlating some earthquakes between trenches.	Olig and others (2001) report a mean recurrence of 12 to 25 kyr based on 5 to 7 surface-faulting earthquakes between 92±14 and 4.6±0.2 ka. However recurrence intervals between individual earthquakes could be as much as 46 kyr, or as short as a few kyr, suggesting order of magnitude variations in interevent intervals. Olig and others (2001) believe that the SOMFZ likely ruptures coseismicly with the OFZ to the north, and the Working Group's recurrence-interval and slip-rate estimates are the same for both faults to reflect that possibility. Working Group Preferred Recurrence Interval 5-**20**-50 kyr	Based on the past 4 to 6 interevent intervals over ~90 kyr, Olig and others (2001) report average slip rates ranging from 0.09 to 0.14 mm/yr. The Working Group's slip-rate estimate reflects the Olig and others (2001) long-term average above; however, confidence limits have been increased to accommodate uncertainty resulting from possible large variations in slip through time: Working Group Preferred Vertical Slip Rate 0.05-**0.2**-0.4 mm/yr
Eastern Bear Lake fault southern section	23	27	McCalpin (2003) divided the EBLF into northern, central, and southern sections. He excavated two trenches on the southern section and determined the following composite earthquake timing:	McCalpin (2003) reports a long-term mean recurrence (5 interevent intervals) of 7.6 kyr. However, individual interevent intervals are highly variable, ranging from ~2.9 kyr between earthquakes Y and Z to ≥ 10.2 kyr	McCalpin (2003) reports ≥22.1 m of net vertical displacement over the past 5 interevent intervals, producing an average vertical slip rate of ≥0.58 mm/yr. However, this slip rate may be affected by undetected antithetic faulting beneath

			Z <2.1+0.2 ka, but >0.6±0.08 ka Y >5.0±0.5 ka, but likely not much greater X <31±6 ka, but much >15.2±0.8 ka W >31±6 ka, but <39±3 ka V >31±6 ka, but <39±3 ka U >39±3 ka, but likely not much greater The southern section is the only section for which paleoseismic trenching data are available.	between earthquakes X and Y. The confidence limits assigned to the Working Group's recurrence-interval estimate are intentionally broad to reflect uncertainty due to possible large variations in interevent interval length through time: Working Group Preferred Recurrence Interval 3-**8**-15 kyr	Bear Lake or by unmeasured tectonic back tilting. Additionally, slip rates for individual interevent intervals are highly variable, reflecting both variability in the length of time between earthquakes and in the net vertical slip per earthquake. The confidence limits assigned to the Working Group's slip-rate estimate are intentionally broad to reflect uncertainty associated with possible large variations in slip through time: Working Group Preferred Vertical Slip Rate 0.2-**0.6**-1.6 mm/yr
Bear River fault zone	35	93	West (1994) excavated seven trenches, logged an irrigation ditch exposure, and measured 11 scarp profiles on the BRFZ. Results indicate a minimum of two surface-faulting earthquakes on the BRFZ, although a third earthquake is possible on some scarps. West concludes that the BRFZ is a young (new) normal fault resulting from geologically recent normal-slip reactivation on an underlying thrust fault Z 2370 ±1050 yr B.P.[13] Y 4620±690 yr B.P. [10] (These ages are on bulk organics and are calendar calibrated, but are not corrected for carbon mean residence time)	The Y-Z interevent interval is 2250 (+690/-1050) yrs. Event Z timing is 2370±1050 yr B.P., indicating that the elapsed time since the MRE exceeds the Y-Z interevent interval. The Working Group recognizes the likelihood of a young age for the BRFZ, but notes the possibility of an alternative fault-behavior model for the BRFZ, one of an old fault that produces large, infrequent earthquakes or earthquake clusters. Therefore, the Working Group's recurrence-interval estimate reflects both possibilities, and is reported as a broad range rather than as an preferred value with ~2-sigma confidence limits. Working Group Preferred Recurrence Interval **1-100** kyr[9]	Vertical slip-rate estimates for the Y-Z interevent interval range from 0.5-2.3 mm/yr depending on the scarp investigated and assumptions made about surface-faulting recurrence. The Working Group's slip-rate estimate reflects the possibility of two potential fault-behavior models, and therefore, the assigned confidence limits are appropriately broad. Working Group Preferred Vertical Slip Rate 0.05-**1.5**-2.5 mm/yr

Morgan fault zone central section	17 5	23 7	Sullivan and others (1988) divide the MFZ into 3 sections. No fault scarps are formed on unconsolidated deposits along the MFZ. Five trenches exposed evidence for the MRE and an unknown number of older, smaller earthquakes. Two ^{14}C ages provide a maximum limit for MRE timing, when the older earthquakes occurred is unknown, but they may extend from the middle Pleistocene. Z <8320±100 ^{14}C yr B.P. (~9.3 cal ka) Y-? middle through late Pleistocene, individual earthquake timing unknown The central section is the only section of the MFZ for which paleoseismic-trenching data are available.	Sullivan and Nelson (1992) measured 4 m of net slip and state that the slip represents eight earthquakes if the average displacement is 0.5 m and four earthquakes if it is 1 m. However, available data are insufficient to determine the actual number of earthquakes. Based on soil-profile development, the displacement occurred over the past 200 to 400 ka, resulting in middle to late Quaternary mean recurrence for eight earthquakes of 25-50 kyr, and for four earthquakes of 50-100 kyr. Because the timing of individual surface-faulting earthquakes is poorly constrained, the Working Group's recurrence-interval estimate is reported as a broad range rather than as a preferred value with ~2-sigma confidence limits. Working Group Preferred Recurrence Interval **25-100** kyr[9]	Sullivan and Nelson (1992) report a minimum average slip rate of 0.01 to 0.02 mm/yr based on 4 m of displacement in 200 to 400 kyr. Because the age of the displaced deposits is poorly constrained (±200 kyr), confidence limits assigned to the Working Group's slip-rate estimate are intentionally broad to reflect the uncertainty associated with possible variations in slip through time. Working Group Preferred Vertical Slip Rate 0.01-**0.02**-0.04 mm/yr
James Peak fault	6	6	Sullivan and others (1988) excavated a trench across a 7-m-high scarp formed on a Bull Lake (~140 ka) glacial outwash fan. Their results indicate two surface-faulting earthquakes rather than a one large earthquake. Based on soil-profile development, the two earthquakes occurred after 110-70 ka but before 30-70 ka.	Soil development provides maximum/minimum constraints for earthquake timing, limiting the two earthquakes to an 80-kyr interval. As much as 40 kyr could separate the earthquakes; however, absence of a soil on the older colluvial wedge argues for a short interevent interval between the two earthquakes. Because individual earthquake timing is unknown, confidence limits for the Working Group's recurrence-interval estimate are intentionally broad to	Based on an estimated 4.2 m of net vertical displacement in ~140 ka, Nelson and Sullivan (1992) report a mean late Quaternary slip rate for the JPF of 0.03 mm/yr. Nelson (verbal communication to UQFPWG, 2003) now considers the JPF a likely southern extension of the East Cache fault zone to the north. The Working Group concurs with that assessment and recommends the following slip-rate estimate for the JPF:

				reflect uncertainty associated with possible large variations in recurrence through time. Working Group Preferred Recurrence Interval 10-**50**-100 kyr	Working Group Preferred Vertical Slip Rate 0.01-**0.03**-0.07 mm/yr
Towanta Flat graben[10]	5	16	Nine short fault scarps on Towanta Flat bound a narrow, 5-km-long graben. Martin and others (1985) excavated three trenches and found evidence for at least three surface-faulting earthquakes. Based on soil-profile development on colluvial wedges, the earthquakes occurred within the past 250-500 ka, with no earthquakes younger than 130-150 ka. Z, Y, X >130 ka, <250-500 ka	Martin and others (1985) report a mean recurrence for surface faulting between 250-500 ka and 130-150 ka of 25 to 90 kyr, with no surface faulting since 130-150 ka. Because the timing of individual surface-faulting earthquakes is unknown, confidence limits assigned to the Working Group's recurrence-interval estimate are intentionally broad to reflect uncertainty associated with possible large variations in recurrence through time. Working Group Preferred Recurrence Interval 25-**50**-200 kyr	Martin and others (1985) estimate maximum slip rates across individual TFG scarps ranging from 0.02 to 0.04 mm/yr, and Piety and Vetter (1999) state the maximum slip rate for the TFG faults is $\leq$0.09 mm/yr. However, Nelson and Weisser (1985) found no net vertical displacement across the graben as a whole, and question the seismogenic capability of the TFG. In the absence of any net vertical displacement across the graben, the Working Group is unable to make a slip-rate estimate for the TFG. **Insufficient data – no estimate possible**
Bald Mountain Fault	2	2	MRE >130 ka based on soil-profile development on an unfaulted colluvial wedge and associated basin-fill deposits. No scarps on unconsolidated deposits.	**Insufficient data – no estimate possible.**	**Insufficient data – no estimate possible.**
Strawberry fault	32	43	Quaternary deposits are not displaced along the main SF. Two trenches across a subsidiary fault (1 of 4) on an alluvial fan 1.3 km west of the main SF indicate 2 to 3 surface-faulting earthquakes in the past 15-30 kyr, with the youngest earthquake occurring in the early to mid-Holocene	Nelson and VanArsdale (1986) report a mean recurrence of 5 to 15 kyr based on two or three earthquakes since 15 to 30 ka. Because paleoseismic data are poorly constrained and limited to a subsidiary	Nelson and VanArsdale (1986) report a slip rate for the trenched scarp of 0.04-0.17 mm/yr based on 1 to 2 m of displacement per earthquake. However, they assume the displacement recorded by the alluvial scarps represents only part of the total slip during the earthquakes

			(minimum 1.5 ka). Estimates of earthquake timing are based on soil-profile development and older earthquakes are only constrained as >MRE and <15-30 ka.	fault, the confidence limits assigned to the Working Group's recurrence-interval estimate are intentionally broad to reflect high uncertainty. Working Group Preferred Recurrence Interval 5-**15**-25 kyr	that formed them. Because paleoseismic data are poorly constrained and limited to a subsidiary fault, the confidence limits assigned to the Working Group's slip-rate estimate are intentionally broad to reflect the possibility of unrecognized slip on the main trace of the SF. Working Group Preferred Vertical Slip Rate 0.03-**0.1**-0.3 mm/yr
Hansel Valley fault	13	22	Utah's only historical surface-faulting earthquake – 1934 M_L 6.6 Hansel Valley earthquake occurred on this fault. McCalpin and others (1992) logged a gully exposure and interpreted surface faulting based on pluvial lake cycles. They argue for multiple earthquakes between 140 and 72 ka, no earthquakes between 72 to 58 ka, at least one earthquake between 58 and 26 ka, an earthquake around 14 to 15 ka, and possibly an earthquake at 13 ka. The actual timing and displacement of individual earthquakes is unknown.	McCalpin and others (1992) report wide variation in interevent intervals on the HVF. Time between earthquakes ranges from ≥32 kyr to possibly as little as 1-2 kyr, although the data supporting such a short recurrence interval are equivocal. Based on the limited information available, the confidence limits assigned to the Working Group's recurrence-interval estimate are intentionally broad to reflect uncertainty associated with possible large variations in recurrence through time. Working Group Preferred Recurrence Interval 15-**25**-50 kyr	McCalpin (verbal communication to Working Group, 2003) reevaluated his paleoseismic data for the HVF based on an estimated 1 to 4 m of displacement since ~17 ka. The Working Group adopts McCalpin's late Pleistocene/Holocene slip rate as their preferred slip-rate estimate for the HVF: Working Group Preferred Vertical Slip Rate 0.06-**0.12**-0.24 mm/yr
Hogsback fault southern section	39	103	West (1994) excavated a trench across a 2.5-m-high, uphill-facing scarp on the southern section of the HF in Utah. The trench did not expose evidence of faulting and no datable material was recovered.	**Insufficient data – no estimate possible.**	**Insufficient data – no estimate possible.**
North Promontory fault	26	27	No trench data are available. McCalpin	McCalpin and others (1992) propose a	McCalpin (verbal communication to

			and others (1992) believe that two large scarps along the main NPF represent multiple surface-faulting earthquakes, but evidence of recurrent movement is lacking. They believe faulting is latest Pleistocene or early Holocene (?) based on estimated ages of the displaced deposits and slope-angle versus scarp-height relations. A subsidiary fault in a road cut near the north end of the main fault shows evidence for a single, young (<15 ka) surface-faulting earthquake in the past ~100 kyr. This fault's relation to the main NPF is unknown.	variety of possible mean recurrence values for the NPF based on assumed numbers of earthquakes with average displacements. However, both the number and timing of individual surface-faulting earthquakes remain unknown, and the Working Group is unable to make a meaningful recurrence-interval estimate for the NPF. **Insufficient data – no estimate possible.**	Working Group, 2003) reevaluated his paleoseismic data for the NPF based on an estimated 8 m of displacement since ~17 ka. The Working Group adopts McCalpin's late Pleistocene/Holocene slip rate as their preferred slip-rate estimate for the NPF: Working Group Preferred Vertical Slip Rate 0.1-**0.2**-0.5 mm/yr
Sugarville area faults	4	13	Eight trenches exposed liquefaction features and faults, but no evidence of individual surface-faulting earthquakes. Broad correlations with Lake Bonneville stratigraphy established fault timing. A short fault trace and $\geq$ 3.8 m of cumulative slip on one fault trace, caused Dames and Moore (1978) to conclude that the displacement represents multiple small earthquakes.	**Insufficient data – no estimate possible.**	**Insufficient data – no estimate possible**.
Washington fault zone northern section	36	43	Individual earthquakes could not be identified, trenches excavated by Earth Sciences Associates (1982) documented displacement only.	**Insufficient data – no estimate possible.**	**Insufficient data – no estimate possible.**
Fish Springs fault	30	20	Single-event fault scarp Z ~2ka (maximum limiting age 2280$\pm$70^{14}C yr B.P.)	**Insufficient data – no estimate possible.**	**Insufficient data – no estimate possible.**

[1]"Section" refers to a portion of a fault defined on the basis of static geologic criteria (geomorphic or structural), but for which no evidence presently exists to show that its history of surface faulting is different from other adjacent parts of the fault. "Segment" refers to a portion of a fault, typically also identifiable on the basis of geomorphic or structural criteria, but

for which historic surface ruptures or paleoseismic data show that the history of surface faulting is different from other adjacent portions of the fault, and that the segment therefore behaves in an independently seismogenic manner from the remainder of the fault.

[2]Straight line and surface trace lengths as determined from best available geologic mapping, surface trace length may or may not reflect total rupture length during the most recent surface-faulting earthquake.

[3]Earthquake timing for the WFZ rounded to the nearest 50 years, timing for remaining faults reported as published in paleoseismic source documents.

[4]Working Group consensus preferred recurrence-interval estimate (**bold**) and approximate two-sigma confidence limits; see Consensus Process section in report text for a discussion of the methodology used to determine these values.

[5] Working Group consensus preferred vertical slip-rate estimate (**bold**) and approximate two-sigma confidence limits; see section on Consensus Process in report text for a discussion of the process used to determine these values.

[6]Weighted mean rounded to the nearest 100 years.

[7]Two-sigma confidence limits rounded to the nearest 100 years.

[8] Earthquake timing reported in calendar corrected years (cal yr B.P.) where the data from the original study permit, and as kilo-annum – 10^3 years before present (ka) where the available data do not permit calendar calibration; note that for both cal yr B.P. and ka, “present” refers to A.D. 1950 (North American Commission on Stratigraphic Nomenclature, 1983).

[9]Due to limited data, reported as a range rather than as an average with approximate 2 sigma confidence limits.

[10]Suspected fault, seismogenic origin uncertain

[11] Length of WCFZ in Utah only, the CF extends northward into Idaho for several additional km.

[12] Information for the GSLFZ is derived from high-resolution geophysics and drilling information, there are no trench data.

[13]Calendar calibrated but no mean residence correction applied

APPENDIX B

SUMMARY DATA FORMS
FOR
CONSENSUS RECURRENCE-INTERVAL
AND
VERTICAL SLIP-RATE ESTIMATES

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
Brigham City segment (BCS), Wasatch fault zone (WFZ), Box Elder County, Utah

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

Personius, S.F., 1991, Paleoseismology of Utah, volume 2-Paleoseismic analysis of the Wasatch fault zone at the Brigham City trench site, Brigham City, Utah, and Pole Patch trench site, Pleasant View, Utah: Utah Geological and Mineral Survey Special Studies 76, 39 p.

McCalpin, J.P., and Forman, S.L., 1993, Assessing the paleoseismic activity of the Brigham City segment, Wasatch fault zone, Utah - Site of the next major earthquake on the Wasatch Front?, *in* Jacobson, M.L., compiler, Summaries of Technical Reports, v. XXXIV: U.S. Geological Survey Open-File Report 93-195, p. 485-489.

McCalpin, J.P., and Forman, S.L., 2002, Post-Provo paleoearthquake chronology of the Brigham City segment, Wasatch fault zone, Utah: Utah Geological Survey Miscellaneous Publication 02-9, 46 p.

Age of Youngest Faulting:
Holocene

Discussion:
The BCS is 35.5 km long end-to-end, has a cumulative (trace) length of 40 km (Machette and others, 1992), and is the northernmost segment of the WFZ that exhibits clear evidence of recurrent Holocene faulting along its entire length (Machette and others, 1992). West-facing scarps along the western base of the Wellsville Mountains and Wasatch Range characterize the BCS along most of its length. Scarps on the valley floor between Willard and Brigham City may be associated with incipient lateral spreads, but have orientations and relief consistent with a faulting origin. In the southern part of the segment, 15- to 20-m-high scarps formed on a Provo-level delta suggest as many as 6-10 surface-faulting earthquakes may have occurred since about 16 ka (assuming an average displacement per event of 2+ m). Only a few short, discontinuous scarps are in upper Holocene deposits near the southern segment boundary, which is in contrast to the abundance of Holocene scarps on the Weber segment (WS) to the south. The northern boundary of the BCS with the Collinston segment (CS) is defined by a change in fault trend, differences in displacement of similar aged pre-Bonneville deposits, and a lack of geomorphic evidence for Holocene faulting on most of the CS (Machette and others, 1992).

Earthquake Timing
Earthquake timing for the BCS is based on the results from two paleoseismic-trenching studies, Personius (1991) and McCalpin and Forman (1993, 2002). The two trench sites are only a few kilometers apart on the central part of the segment, but both studies identified a surface-faulting earthquake that was not recognized at the other site. Event Z was only identified by McCalpin and Forman (1993, 2002), and event X was only identified by Personius

(1991). Both paleoearthquakes are well documented at their respective trench sites and therefore were included in the composite surface-faulting chronology for the BCS prepared by McCalpin and Nishenko (1996) and reported in McCalpin and Forman (2002). Additionally, although the interevent interval between them is comparatively short and their associated confidence limits are large and overlap, McCalpin and Forman (2002) conclude that events V and U are separate, discernable paleoearthquakes.

The Working Group determined earthquake timing on the BCS by calculating a simple mean for each earthquake using the earthquake-limiting, calendar-calibrated radiocarbon (^{14}C) ages and thermoluminescence (TL) ages presented in McCalpin and Nishenko (1996, table 1) and rounding the results to the nearest half-century. The ± confidence limits have been increased beyond those reported in McCalpin and Nishenko (1996, table 3) to accommodate the full range of limiting ^{14}C and TL ages used to constrain earthquake timing as described in the section on Earthquake Timing in the accompanying report. The Working Group believes that the resulting ± confidence limits account for both epistemic and aleatory uncertainty associated with the timing of each earthquake.

Z	2100±800 cal yr B.P.
Y	3450±300 cal yr B.P.
X	4650±500 cal yr B.P.
W	5950±250 cal yr B.P.
V	7500±1000 cal yr B.P.
U	8500±1500 cal yr B.P.
T	>14,800±1200, <17,000 cal yr B.P.

Surface-Faulting Recurrence:

Interevent recurrence intervals with associated confidence limits are:

Elapsed time since event Z	2100±800 cal yr
Y-Z interval	1350±900[1] cal yr
X-Y interval	1200±600 cal yr
W-X interval	1300±600 cal yr
V-W interval	1550±1000 cal yr
U-V interval	1000±1800 cal yr
T-U interval	~3.6-10 kyr

The weighted mean recurrence for the three most recent interevent intervals (X-Z) rounded to the nearest century is:

1300[2]±200[3] cal yr

The weighted mean recurrence for the five most recent interevent intervals (V-Z) rounded to the nearest century is:

1300[2]±400[3] cal yr

[1]±confidence limits equal the square root of the sum of the squares of the individual ± confidence limits for each bracketing earthquake rounded to nearest 100 years.
[2]weighted mean rounded to nearest 100 years.
[3]two-sigma confidence limits rounded to nearest 100 years.

The elapsed time since event Z exceeds the length of both mean-recurrence intervals. Additionally, a possible 3.6 to 10-kyr gap between events T and U indicates an extended period of seismic quiescence on the BCS in latest Pleistocene and early Holocene time. However, McCalpin and Forman (2002) indicate that an unknown number of unrecognized sublacustrine earthquakes may have occurred in the interval between events U and T.

Based on currently available information on earthquake timing and variability in the length of individual interevent intervals, the Working Group's preferred recurrence-interval estimate and confidence limits for the BCS are:

500-**1300**-2800 yr

Vertical Slip Rate:

Slip-rate information for the BCS is sparsely distributed along the segment. Combining the length of the interevent intervals above with per-event displacements from Personius (1991) results in the following vertical slip rates at the Personius (1991) trench site.

X-Y (1 m/1200±500 yr) = 0.6-0.8-1.4 mm/yr
W-X (2.5 m/1300±500 yr) = 1.4-1.9-3.1 mm/yr
V-W (2.5 m/1550±1000 yr) = 1.0-1.6- 4.5 mm/yr

Long-term vertical slip rates for the BCS from scarp-profile measurements (Personius, 1990) vary depending on the deposit age and profile location along the segment trace. Slip rates recorded in Provo-age deposits range from a low of 0.24 mm/yr near the north segment boundary south of Two Jump Canyon to 1.36 mm/yr south of Pearsons Canyon near Willard. Bonneville-cycle delta deposits at the mouth of Willard Canyon record a vertical slip rate of 1.5-1.6 mm/yr.

Based on currently available information on earthquake timing and displacement, the Working Group's preferred vertical slip-rate estimate and confidence limits for the BCS are:

0.6-**1.4**-4.5 mm/yr

Summary:

For the past five interevent intervals (six surface-faulting earthquakes) on the BCS, surface faulting mean recurrence has been approximately 1300±400 years and 1300±200 years for the three most recent, and better constrained, interevent intervals. The elapsed time since event Z exceeds both recurrence intervals. The BCS experienced a possible long period (~3.6-10 kyr) of seismic quiescence during the latest Pleistocene and early Holocene, although McCalpin, (2002) states that as yet unrecognized sublacustrine earthquakes may fill part of the gap. These two possible extended periods with no surface faulting indicate that the long-term record of paleoearthquake recurrence on the BCS is likely irregular.

Additional References:

Machette, M.N., Personius, S.F., and Nelson, A.R., 1992, Paleoseismology of the Wasatch fault zone - A summary of recent investigations, interpretations, and conclusions, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-A, 71 p.

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

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP
CONSENSUS
RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Weber segment (WS), Wasatch fault zone (WFZ), Weber and Davis Counties, Utah

Paleoseismic Data Source Documents:

Swan, F.H., III, Schwartz, D.P., and Cluff, L.S., 1980, Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch fault zone, Utah: Bulletin of the Seismological Society of America, v. 70, no. 5, p. 1431-1462.

Swan, F.H., III, Schwartz, D.P., Hanson, K.L., Knuepfer, P.L., and Cluff, L.S., 1981b, Study of earthquake recurrence intervals on the Wasatch fault at the Kaysville site, Utah: U.S. Geological Survey Open-File Report 81-228, 30 p.

Nelson, A.R., Klauk, R.H., Lowe, M., and Garr, J.D., 1987, Holocene history of displacement on the Weber segment of the Wasatch fault zone at Ogden, northern Utah [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 5, p. 322.

Nelson, A.R., 1988, The northern part of the Weber segment of the Wasatch fault zone near Ogden, Utah, *in* Machette, M.N., editor, In the footsteps of G.K. Gilbert - Lake Bonneville and neotectonics of the eastern Basin and Range Province, Guidebook for Field Trip Twelve: Utah Geological and Mineral Survey Miscellaneous Publication 88-1, p. 33-37.

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

Machette, M.N., Personius, S.F., and Nelson, A.R., 1992, Paleoseismology of the Wasatch fault zone - A summary of recent investigations, interpretations, and conclusions, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-A, 71 p.

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

McCalpin, J.P., Forman, S.L., and Lowe, M., 1994, Reevaluation of Holocene faulting at the Kaysville site, Weber segment of the Wasatch fault zone, Utah: Tectonics, v. 13, no. 1, p. 1-16.

Age of Youngest Faulting:

Holocene

Discussion:

West-facing scarps along the western base of the Wasatch Range characterize the WS, the second longest segment (56 km end-to-end; 61 km cumulative trace) of the WFZ (Machette and others, 1992). The southern segment boundary is a prominent bedrock salient (Salt Lake salient) where the WFZ makes a 2 km right step to the Warm Springs fault at the north end of the Salt Lake City segment (SLCS), but fault scarps in that area are easily confused with nontectonic features and scarp identification and distribution is less certain (Machette and others, 1992). The northern segment boundary is at another bedrock salient (Pleasant View salient). Scarp heights along the northern part of the WS suggest a high rate of late Holocene surface faulting (Machette and others, 1992).

Earthquake Timing:

Information about surface-faulting recurrence on the WS comes from three trench sites: Garner Canyon (Nelson and others, 1987; Nelson, 1988; Machette and others, 1992), East Ogden (Nelson and others, 1987; Nelson, 1988; Forman and others, 1991; Machette and others, 1992), and Kaysville, where investigators performed two independent trenching studies more than a decade apart (Swan and others, 1980, 1981b; McCalpin and others, 1994). Study results from East Ogden and the first investigation at Kaysville both identified two surface-faulting earthquakes post ~1.5 ka. The second investigation at Kaysville identified the most recent surface-faulting earthquake (MRE) at 0.6-0.8 ka and the second oldest event (penultimate event [PE]) at 2.8±0.7 ka, and discounted the occurrence of a second earthquake younger than 1.5 ka at either Kaysville or East Ogden.

McCalpin and Nishenko (1996) report four surface-faulting earthquakes for the WS since mid-Holocene time (past ~6 kyr) based on their reevaluation of earthquake-limiting ^{14}C and TL ages from the Garner Canyon, East Ogden, and Kaysville trench sites. As part of their reevaluation, they also discounted the very young (~0.5 ka) paleoearthquakes previously identified at East Ogden and Kaysville. However, the investigators at East Ogden and for the first Kaysville study remain confident in their results, and believe the WS, or portions of it, have experienced two earthquakes within the past ≤1.5 kyr. Following their review of the available paleoseismic information for the East Ogden and Kaysville sites, the Working Group concluded that the possibility of a fifth (youngest) earthquake on the WS at about 0.5±0.3 ka does exist.

Evidence for a fifth earthquake is limited and indicates that it was small (≤0.6 m displacement) and therefore possibly did not rupture the entire 81-km-long WS. This raises questions regarding whether the young earthquakes at East Ogden and Kaysville are the same or different, and therefore the possibility of partial segment rupture on the WS. Nelson and Personius (1993) and McCalpin and others (1994) both discuss the possibility of partial segment rupture either from small, non-characteristic earthquakes on the WS, or from overlap of surface rupture from a large earthquake on an adjoining segment.

Based upon currently available paleoseismic information for the WS, the Working Group's consensus surface-faulting chronology for the WS is:

Za	0.5±0.3 ka (partial segment rupture?)
Zb	950±450 cal yr B.P.
Y	3000±700 cal yr B.P.
X	4500±700 cal yr B.P.
W	6100±700 cal yr B.P.

The Working Group determined the timing of earthquakes W, X, Y, and Zb from the earthquake-limiting, calendar-calibrated ^{14}C ages and TL ages presented in McCalpin and Nishenko (1996, table 1), by calculating a simple mean for each earthquake and rounding the results to the nearest half-century. The ± confidence limits have been increased beyond those reported in McCalpin and Nishenko (1996, table 3) to accommodate the full range of limiting ^{14}C and TL ages used to constrain earthquake timing as described in the section on Earthquake Timing in the accompanying report. The Working Group believes the resulting ± confidence limits account for both epistemic and aleatory uncertainty associated with the timing of each earthquake. The timing and associated confidence limits for event Za are from Machette and others (1992).

Surface-Faulting Recurrence:

The two presently proposed models for surface-faulting recurrence on the WS allow for either three or four interevent intervals since the middle Holocene. The McCalpin and Nishenko (1996) four-earthquake model permits three interevent intervals:

Y-Zb interval	2050±800[1] cal yr
X-Y interval	1500±1000 cal yr
W-X interval	1600±1000 cal yr

The weighted mean recurrence for the three most recent interevent intervals (X-Zb) rounded to the nearest century is:

1600[2]±600[3] cal yr

The five-earthquake model proposed by Swan and others (1980, 1981b) and Machette and others (1992), creates a fourth interevent interval of about 450 years.

Zb-Za	450±500[1] cal yr
Y-Zb interval	2050±800 cal yr
X-Y interval	1500±1000 cal yr
W-X interval	1600±1000 cal yr

The weighted mean recurrence for the four most recent interevent intervals (X-Za) rounded to the nearest century is:

1000[2]±1400[3] cal yr

[1]±confidence limits equal the square root of the sum of the squares of the individual ± confidence limits for each bracketing earthquake rounded to nearest 100 years.
[2]weighted mean rounded to nearest 100 years.
[3]two-sigma confidence limits rounded to nearest 100 years.

Based on currently available information on earthquake timing and variability in the length of individual interevent intervals, the Working Group's preferred recurrence-interval estimate and confidence limits for the WS are:

500-**1400**-2400 yr

Vertical Slip Rate:

Net vertical-slip data per earthquake from trench sites on the WS are generally poorly constrained (not all scarps trenched) or are estimates based on stratigraphic and structural relations in trenches (no direct measurement of displaced strata across the fault). Swan and others (1981b) estimated minima of 1.7 and 1.8 m of displacement for events Y and Za, respectively, at Kaysville. McCalpin and others (1994) reported 1.7-1.9 m for event Zb, 2.3-3.4 m for event Y, and 1.4 m for event X.

Using the interevent intervals above, and the net vertical-slip measurements of McCalpin and others (1994), results in the following interevent slip rates at Kaysville:

Y-Zb (1.7-1.9 m/2050±700 yr) = 0.6-0.9-1.4 mm/yr
X-Y (2.3-3.4 m/1500±700 yr) = 1.0-1.9-4.3 mm/yr
W-X (1.4 m/1600±700 yr) = 0.6-0.9-1.6 mm/yr

Net vertical displacement across the main scarp at Kaysville is 11.5 m in middle Holocene to uppermost Pleistocene "Fan alluvium 2" (Nelson and Personius, 1993). Swan and others (1981b) estimate the fan age at 6±2 kyr; McCalpin and others (1994) estimate the age as post-Provo (≤16.2 ka). If the fan is ~ 6 kyr old, the mid-Holocene to present slip rate at the Kaysville site would be 1.9+1.0/-0.5 mm/yr. If the slip occurred in post-Provo time (≤16.2 ka), the late Pleistocene to present slip rate would be ≥0.7 mm/yr, depending on the actual fan age.

Nelson (U.S. Geological Survey, written communication to Working Group, 2003) reports a minimum vertical displacement of Bonneville-Provo-cycle deposits at the East Ogden trench site of 23.7 m. Assuming a maximum age for the Bonneville-cycle deposits of 18 ka results in a long-term, minimum slip rate at East Ogden of 1.3 mm/yr.

Nelson and Personius (1993) measured 375 scarp profiles (77 measured in the field and 298 measured from air photos using a photogrammetric plotter) along the WS. They estimate that approximately 15% of the 375 profiles gave surface-displacement values that were within ±10-30% of the total net vertical displacement across the fault zone. However, uncertainties in estimating the age of the deposits, particularly Holocene deposits, in which many profiles were measured, could be ±50-100%. Additionally, the Lake Bonneville chronology used to constrain the age of lacustrine deposits for the slip-rate calculations is dated. Presently reported calendar-calibrated ages for the Bonneville and Provo shorelines (Currey, University of Utah, written communication to the UGS, 1996; verbal communication to Working Group, 2004) are ≤4.5 kyr older than those used by Nelson and Personius (1993).

Despite the limitations of the scarp-profile data, the slip rates reported by Nelson and Personius (1993) clearly demonstrate that latest Pleistocene and Holocene slip is greatest along the central WS and decreases toward the segment ends.

Using an updated Lake Bonneville chronology and net-vertical-displacement values from Nelson and Personius (1993) measured in Lake Bonneville lacustrine deposits or alluvial-fan units graded to Lake Bonneville shorelines, provides scattered point data along the segment that indicates that slip rates recorded in Bonneville-cycle deposits are as high as 2.0 mm/yr, and up to 1.3 mm/yr in Provo-cycle deposits.

Based on currently available information on earthquake timing and displacement, the Working Group's preferred vertical slip-rate estimate and confidence limits for the WS are:

0.6-**1.2**-4.3 mm/yr

Summary:

Although one of the most intensively studied of the six central, active segments of the WFZ, significant questions remain regarding the paleoseismic history of the WS. These questions limit the Working Group's ability to establish closely constrained recurrence-interval and slip-rate values for the WS. Chief among the questions are:

1. Has the MRE on the WS been accurately identified – is event Za real?

2. Is the MRE different on different parts of the WS; is the WS subject to partial segment rupture, and if so, on which parts of the segment and how often?

3. What is the long-term (past ~18 ka) history of surface faulting on the WS? Present information on surface-faulting recurrence only extends to the middle Holocene; the number and timing of earlier surface-faulting earthquakes is unknown, as is any corresponding variability in long-term recurrence and slip similar to that reported for the adjacent BCS and SLCS.

Additional References:

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

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Salt Lake City segment (SLCS), Wasatch fault zone (WFZ), Salt Lake County, Utah

Paleoseismic Data Source Documents:

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

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Korbay, S.R., and McCormick, W.V., 1999, Faults, lateral spreading, and liquefaction features, Salt Palace Convention Center, Salt Lake City [abs.]: Association of Engineering Geologists, 42nd Annual Meeting Program with Abstracts, p. 73.

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Age of Youngest Faulting:
Holocene

Discussion:
From north to south the SLCS is divided into three enechelon subsections: the Warm Springs fault, East Bench fault, and Cottonwood subsection (Personius and Scott, 1992). The Warm Springs fault forms a prominent escarpment for about 7 km along the western flank of the Salt Lake salient and then trends south into basin fill and dies out beneath downtown Salt Lake City. At the south end of the Warm Springs fault, the SLCS steps 2 km to the east to the East Bench fault. The East Bench fault forms prominent northwest- to southwest-facing intrabasin fault scarps that generally parallel 1100 East Street and Highland Drive from Salt Lake City south to Big Cottonwood Creek. The Cottonwood subsection forms a prominent (often wide and complex) zone of faulting along the range front from just north of Big Cottonwood Canyon to the Traverse Mountains. At the mouth of Little Cottonwood Canyon, the fault zone forms a complex 50-m-wide graben with main scarps as high as 25 m and antithetic scarps as high as 20 m. Farther south at South Fork Dry Creek, the graben is 400 m wide, and six enechelon scarps comprise the main fault zone.

Earthquake Timing:
All surface-faulting recurrence and slip-rate information for the SLCS comes from the Little Cottonwood and South Fork Dry Creek/Dry Gulch trench sites near the south end of the Cottonwood subsection in the southeastern part of Salt Lake Valley.

Following a review of the paleoseismic information available from those two sites, the Working Group's consensus for the timing of surface faulting on the SLCS is:

Z	1300±650 cal yr B.P.
Y	2450±550 cal yr B.P.
X	3950±550 cal yr B.P.
W	5300±750 cal yr B.P.
V	~7.5 ka (after 8.8-9.1 ka but before 5.1-5.3 ka)
U	~9 ka (shortly after 9.5-9.9 ka)
T	~17 ka
S(?)	17-20 ka

Timing for earthquakes W, X, Y, and Z is from Black and others (1996). The ± confidence limits have been increased for each earthquake to accommodate the full range of limiting ^{14}C ages used to constrain the timing of the earthquakes as described in the section on Earthquake Timing in the accompanying report. The Working Group believes that the resulting ± confidence limits account for both the epistemic and aleatory uncertainty associated with the timing of each earthquake.

McCalpin (2002) identified earthquakes V, U, and T based on a retrodeformation analysis of stratigraphic and structural relations exposed in a trench at Little Cottonwood Canyon. No direct evidence (colluvial wedges, tectonic crack fills, fault terminations, etc.) was found to document these earthquakes, and consequently their timing can only be broadly constrained.

Surface-Faulting Recurrence:

Interevent recurrence intervals with associated confidence limits for the SLCS are:

Elapsed time since event Z	1300±650 cal yr
Y-Z interval	1150±900[1] cal yr
X-Y interval	1500±800 cal yr
W-X interval	1350±900 cal yr

The weighted mean recurrence for the three most recent interevent intervals (W-Z) rounded to the nearest century is:

1300[2]±400[3] cal yr

[1]±confidence limits equal the square root of the sum of the squares of the individual ± confidence limits for each bracketing earthquake rounded to nearest 100 years.
[2]weighted mean rounded to nearest 100 years.
[3]two-sigma confidence limits rounded to nearest 100 years.

The ages of events U and V on the SLCS are broadly constrained. McCalpin (2002) reports the U-V and V-W interevent intervals are both about 2 kyr, resulting in a similarly broadly constrained mean recurrence for surface faulting of 2 kyr for mid- to early Holocene time.

The timing of event T is likewise broadly constrained. McCalpin (2002) reports a range in the interevent interval between events T and U of 7.1 to 9.6 kyr, with a mean of 8.4 kyr, indicating a long period of surface-faulting quiescence during earliest Holocene and latest Pleistocene time on the SLCS, similar to that noted on the Brigham City segment to the north (McCalpin and Forman, 2002). However, McCalpin (2002) notes, but considers the possibility unlikely, that the physical evidence of additional earthquakes in the gap has been removed by alluvial-fan erosion in the interval 9-10 ka and is lost from the stratigraphic record.

Based on currently available information on earthquake timing and variability in the length of individual interevent intervals, the Working Group's preferred recurrence-interval estimate and confidence limits for the SLCS are:

500-**1300**-2400 yr

Vertical Slip Rate:

Trenching investigations at Little Cottonwood Canyon and at South Fork Dry Creek/Dry Gulch did not provide well-constrained net vertical-slip data for the SLCS. Swan and others (1981a) reported 14.5 (+10/-3) m of net vertical displacement across the WFZ determined from a scarp profile measured along the crest of the Bells Canyon glacial moraine a few hundred meters south of the Little Cottonwood Canyon site. Scott (1989) reports the age of the moraine as 18-26 ka. The resulting slip rate is:

(14.5 (+10/-3) m /18-26 kyr): 0.4-0.7-1.4 mm/yr

Complex rupture patterns, poorly constrained ages of faulted mixed lacustrine units, and difficulties associated with measuring topographic scarp profiles in a densely urbanized environment prevented using the net vertical-slip information reported by Personius and Scott (1992) to calculate additional late Pleistocene/early Holocene slip rates along the SLCS.

The slip rate reported for Bells Canyon (Little Cottonwood Canyon site) is a long-term rate extending from the latest Pleistocene. Well-constrained Holocene vertical slip-rate data are lacking for the SLCS. Therefore, the Working Group considered the slip data on the Weber segment to the north and the Provo segment to the south when arriving at a consensus Holocene slip-rate estimate for the SLCS. Because the Bells Canyon long-term slip-rate estimate includes a possible period of seismic quiescence on the SLSC in the late Pleistocene, the Working Group's estimate for the Holocene is higher than the longer term rate at Bells Canyon.

Based on currently available information on earthquake timing and displacement, the Working Group's preferred vertical slip-rate estimate and confidence limits for the SLCS are:

0.6-**1.2**-4.0 mm/yr

Summary:

Reliable paleoseismic-trenching data for the SLCS are limited to the Cottonwood subsection. Sites of opportunity along the more heavily urbanized Warm Springs and East Bench subsections have not produced reliable recurrence, net vertical-displacement, or vertical slip-rate information.

Investigators have identified four surface-faulting earthquakes on the SLCS since mid-Holocene time (~5.3 ka) on the basis of colluvial-wedge stratigraphy, tectonic crack fills, and fault terminations. The timing of these earthquakes is based on ^{14}C ages on both charcoal and bulk organic samples (primarily paleosol A horizons and tectonic crack-fill deposits). The Working Group considers both the number of earthquakes and their timing well constrained, as is the resulting mid-Holocene mean recurrence between surface-faulting earthquakes of 1300±400 years.

Three older earthquakes (T, U, V) identified based on a retrodeformation analysis lack direct stratigraphic or structural evidence (colluvial wedges, crack-fill deposits, fault terminations) of their occurrence. The Working Group considers the evidence for these earthquakes compelling; however, event timing is only broadly constrained. Available data indicate two recurrence intervals of about 2 kyr in mid- to early Holocene time, preceded by a >7 kyr period of surface-faulting quiescence.

The elapsed time since the MRE (event Z) on the SLCS is equal to or greater than the Working Group's preferred recurrence-interval estimate (500-**1300**-2400 yr) for the segment.

Despite being one of the most intensely studied of the six central segments of the WFZ, well-constrained vertical slip-rate information for the SLCS is limited to a single latest Pleistocene slip rate at the mouth of Bells Canyon on the Cottonwood subsection.

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UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Provo segment (PS), Wasatch fault zone (WFZ), Utah County, Utah

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Age of Youngest Faulting:

Holocene

Discussion:

Machette and others (1992) tentatively subdivided the PS (as originally proposed by Schwartz and Coppersmith, 1984) into three subsections based on fault geometry and apparent recency of movement as indicated by scarp morphology: from north to south, they are the American Fork, Provo "restricted sense," and Spanish Fork subsections. The American Fork subsection has a 22.5 km-long trace length and ends on the south at a 2-km left step in the fault at the Provo River. The Provo "restricted sense" subsection extends from Provo Canyon south to Springville, Utah, a trace length of 18.5 km and includes the Springville fault, which continues into Utah Valley after the main WFZ makes a large southeast bend. The Spanish Fork subsection forms a major concave-to-the-west bend in the WFZ and extends 31.5 km along trace from Springville to Payson Canyon in the southeastern corner of Utah Valley. However, despite the distinctive geometry of the fault trace in Utah Valley, paleoseismic studies (Machette, 1988; Lund and others, 1991; Machette and others, 1992; Lund and Black, 1998) show that the entire length of the PS ruptured during at least the two most recent surface-faulting earthquakes.

Earthquake Timing:

Five trenching studies (from north to south: American Fork Canyon, Rock Canyon, Hobble Creek, Mapleton, and Water Canyon) provide paleoseismic-trenching information for the PS. A sixth, cooperative study between URS Corporation and the Utah Geological Survey reoccupied the Mapleton North trench site in 2003 to extend the record of surface faulting on the PS beyond the three most recent earthquakes. The "megatrench" at Mapleton exposed evidence of older surface-faulting earthquakes (Olig and others, 2004); however, final results of that study are not yet available.

At American Fork Canyon, Machette and others (1992) identified three surface-faulting earthquakes at 500±200, 2650±250, and 5300±300 cal yr B.P. At Rock Canyon, Lund and Black (1998) identified the timing of the MRE at 650+50/-100 cal yr B.P. In an early study at Hobble Creek, Swan and others (1980) identified 6 to 7 surface-faulting earthquakes based on a combination of strath terraces inset along streams on the upthrown side of the fault and colluvial wedges in trenches. However, no numerical ages were obtained as part of this study, so earthquakes are only constrained to broad time intervals. Lund and others (1991) determined the timing of the two most recent earthquakes at Mapleton as 600±80 and 2820+150/-130 cal yr B.P., respectively. Within the bounds of geologic uncertainty, the MRE (event Z) appears to have occurred at the same time at the American Fork Canyon, Rock Canyon, and Mapleton sites, as does the PE (event Y) at the American Fork Canyon and Mapleton sites. The trench and stream cut exposure investigated at Rock Canyon were not deep enough to uncover evidence of the PE.

At Water Canyon near the boundary between the PS and Nephi segments (NS), Ostenaa (1990) identified 3 or more Holocene surface-faulting earthquakes. The timing of some Water Canyon earthquakes does not correlate well with earthquakes identified farther north on the PS. Ostenaa (1990) attributed this discrepancy to Water Canyon's location close to the southern segment boundary, and the possibility that the Water Canyon site records surface faulting from both the PS and adjacent NS.

McCalpin and Nishenko (1996) reported preferred times for the three most recent surface-faulting earthquakes on the PS (rounded to the nearest half-century) of 600, 2850, and 5500 cal yr B.P. Their reevaluation of earthquake-limiting ^{14}C and TL ages for the PS included five Water Canyon ^{14}C ages, three of which they assigned to event Z and one of which they assigned to event X. They assigned the remaining Water Canyon dates to surface-faulting earthquakes on the NS.

Following their review of available paleoseismic information, the Working Group's consensus for surface-faulting timing on the PS is:

Z	600±350 cal yr B.P.
Y	2850±650 cal yr B.P.
X	5300±300 cal yr B.P.

The Working Group determined the timing of events Y and Z by calculating a simple mean for each earthquake using the earthquake-limiting ^{14}C ages and TL ages presented in McCalpin and Nishenko (1996, table 1) and rounding the results to the nearest half-century. The ± confidence limits have been increased beyond those reported in McCalpin and Nishenko (1996, table 3) to accommodate the full range of limiting ^{14}C and TL ages used to constrain earthquake timing as described in the section on Earthquake Timing in the accompanying report. The Working Group believes that the resulting ± confidence limits account for both epistemic and aleatory uncertainty associated with the timing of each earthquake.

Event X was obtained from Machette and others (1992), who present a comprehensive analysis of uncertainty affecting the timing of that earthquake.

Surface-Faulting Recurrence:

Interevent recurrence intervals with associated confidence limits are:

Elapsed time since event Z	600±350 cal yr
Y-Z interval	2250±700[1] cal yr
X-Y interval	2450±700 cal yr

The weighted mean recurrence for the two most recent interevent intervals (X-Z) rounded to the nearest century is:

2400[2]±300[3] cal yr

[1]±confidence limits equal the square root of the sum of the squares of the individual ± confidence limits for each bracketing earthquake rounded to nearest 100 years.
[2]weighted mean rounded to nearest 100 years.
[3]two-sigma confidence limits rounded to nearest 100 years.

Based on currently available information on earthquake timing and variability in the length of individual interevent intervals, the Working Group's preferred recurrence-interval estimate and confidence limits for the PS are:

1200-**2400**-3200 kyr

However, preliminary results from new trenching at Mapleton indicate that the interval from the middle Holocene to latest Pleistocene may include several surface-faulting earthquakes (Olig and others, 2004). If so, the Working Group's preferred recurrence-interval estimate for the PS will likely require future modification.

Vertical Slip-Rate:

Vertical slip-rate information for the PS is widely scattered along the segment trace, and is summarized below using the revised Lake Bonneville chronology of Currey (University of Utah Geography Department, written communication to the UGS, 1996; verbal communication to Working Group, 2004).

Hobble Creek[1]

Post Provo time: 11.5-13.5 m/16.2-16.8 kyr = 0.68-0.76-0.83 mm/yr.
Post Bonneville time: 40-45 m/16.8-18.0 kyr = 2.2-2.4-2.7 mm/yr.

American Fork Canyon[2]
Post Bonneville time: 15-23 m/16.8-18.0 kyr = 0.8-1.1-1.4 mm/yr.

[1]Net-vertical-slip data are from Swan and others (1980), net displacement in Bonneville shoreline deposits revised by Machette and others (1992).
[2] Net-vertical-slip data are from Machette (1988).

Slip-rate data are not available for the Mapleton, Rock Canyon, and Water Canyon sites.

Machette (1992) reported net displacements across scarps at several locations along the PS. Two locations provide displacement data that are sufficiently well age-constrained to calculate long-term vertical slip rates.

Mouth of Spanish Fork Canyon
Stream alluvium related to the Provo phase of Lake Bonneville: 3 m/16.2-16.8 kyr = 0.18-0.19 mm/yr

East of Provo between Slate and Slide Canyons:
Gravel related to the Bonneville phase of Lake Bonneville: >20 m/16.8-18.0 kyr = minimum 1.1-1.2 mm/yr

Based on currently available information on earthquake timing and displacement, the Working Group's preferred vertical slip-rate estimate and confidence limits for the PS are:

0.6-**1.2**-3.0 mm/yr

Summary:

Timing of the three most recent surface-faulting earthquakes (X, Y, Z) on the PS is well constrained and provides recurrence information for the segment since the mid-Holocene. Little is known about the timing of older earthquakes; however, a recent cooperative trenching project between URS Corporation and the Utah Geological Survey (Olig and others, 2004) at the Mapleton North site of Lund and others (1991) will provide additional information about the timing of earlier earthquakes. Results of that study are not yet available.

Vertical slip-rate information for the PS consists of widely distributed data, which generally shows that slip rates on the segment since Provo time have been as high as 1.0-1.4 mm/yr, but likely average closer to 0.8-1.2 mm/yr along the central part of the segment. A slip rate of 2.2-2.7 mm/yr resulting from an anomalously high displacement measured in sediments of the Bonneville and Provo cycles of Lake Bonneville, as documented by both Swan and others (1980) and Machette and others (1992) at Hobble Creek, remains unexplained. Reliable information regarding the long-tem rate of slip at the segment ends is not available.

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Olig, S., McDonald, G., Black, B., DuRoss, C., and Lund, B., 2004, The Mapleton "Megatrench" – Deciphering 11,000 years of earthquake history on the Wasatch fault near Provo: Utah Geological Survey, Survey Notes, v. 36, no. 2, p. 4-6.

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

UAH QUATERNARY FAULT PARAMETERS WORKING GROUP
CONSENSUS
RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
Nephi segment (NS), Wasatch fault zone (WFZ), Juab County, Utah

Paleoseismic Data Source Documents:

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Jackson, M.E., 1991, Paleoseismology of Utah, Volume 3 - The number and timing of Holocene paleoseismic events on the Nephi and Levan segments, Wasatch fault zone, Utah: Utah Geological Survey Special Studies 78, 23 p.

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Age of Youngest Faulting:
Holocene

Discussion:
The NS consists of two subsections identified by Machette and others (1992) as the main western (southernmost) strand and an eastern (northernmost) strand. The western strand bounds the Wasatch Range along the east side of Juab Valley and the eastern strand bounds the west side of Dry Mountain. Heavy vegetation and landslides in Mancos Shale bedrock obscure a suspected connecting fault between the two strands. The northern end of the eastern strand overlaps the Provo segment (PS) at the Payson salient. The Benjamin fault forms the west side of the salient and extends northward into Utah Valley where it dies out (Machette, 1992; Harty and others, 1997). Sediments of the Provo phase of Lake Bonneville are displaced

up to 2 m along this fault (Machette, 1992). No paleoseismic-trenching investigations have been conducted on the eastern (northern) strand of the NS.

Scarps on the western strand exhibit very young scarp morphology, prompting Hanson and others (1981) and Schwartz and Coppersmith (1984) to suspect a very young age (latest Holocene) for the MRE on this part of the NS. Faults associated with young scarps on the western strand north of the town of Nephi are probably continuous with near-surface faults in town identified from seismic-reflection data (Crone and Harding, 1984). The southern boundary of the NS is at a 5-15-km gap in Holocene and latest Pleistocene surface faulting that separates the NS from the Levan segment to the south (Machette and others, 1992; Harty and others, 1997; Hylland and Machette, 2004).

Earthquake Timing:

Hanson and others (1981) and Jackson (1991) identified three surface-faulting earthquakes on the western strand of the NS at the North Creek and Red Canyon trench sites, respectively. Two stacked colluvial wedges and a stream terrace inset into the upthrown block of the fault at North Creek, and three stacked colluvial wedges at Red Canyon provide evidence for repeated Holocene surface faulting on the NS. However, while the number of earthquakes is well constrained, earthquake timing remains uncertain.

North Creek

At North Creek Hanson and others (1981) interpreted the three earthquakes as occurring after 4580$\pm$250 ^{14}C yr B.P. (5890 [5307] 4532 cal yr B.P.; calibrated as per table 1 in McCalpin and Nishenko, 1996) based on a ^{14}C age on charcoal from a burn layer in North Creek alluvium (Bucknam, 1978); the alluvium is displaced by all three earthquakes. Evidence for the two youngest earthquakes consists of scarp-derived colluvial-wedge deposits exposed in trenches, while the third (oldest) earthquake is represented by a tectonic strath terrace inset into the North Creek alluvial fan on the upthrown side of the fault. Event Z displaces an alluvial deposit and a soil; both containing charcoal dated at 1350+70 ^{14}C yr B.P. (1262 [1086] 828 cal yr B.P.; as per McCalpin and Nishenko, 1996), and 1110$\pm$60 ^{14}C yr B.P. (1165 [983] 924 cal yr B.P.; as per McCalpin and Nishenko, 1996), respectively. Based on the steep scarp angles at North Creek and the presence of a nickpoint in a stream channel just above the scarp, Hanson and others (1981) and Schwartz and Coppersmith (1984) prefer a timing for event Z of about 0.4$\pm$0.1 ka.

Event Y is constrained by ^{14}C ages on both charcoal and soil organics from a soil formed on top of the event Y colluvial wedge. Conventional ^{14}C ages on the soil organics and charcoal yielded ages of 3640$\pm$75 ^{14}C yr B.P. (4427 [4144] 3874 cal yr B.P.; as per McCalpin and Nishenko, 1996) and 1650$\pm$50 ^{14}C yr B.P. (not calibrated by McCalpin and Nishenko, 1996), respectively. A second set of ages obtained using an accelerator mass spectrometer resulted in similar divergent ages. Given the choice of two sets of ages for the soil, Hanson and others (1981) concluded that the younger ages represent younger material incorporated into the soil prior to burial, and therefore consider the older ages as providing minimum-limiting constraints on the timing of event Y, making it older than 3640$\pm$75 ^{14}C yr B.P., but younger than 4580 ^{14}C yr B.P. Event X, represented by the tectonic strath terrace must also have occurred within that interval, indicating that two surface-faulting earthquakes occurred in an approximately 2 kyr (3874 – 5890 cal yr B.P.).

Red Canyon

Jackson (1991) estimated the timing of the three surface-faulting earthquakes at Red Canyon using a combination of ^{14}C and TL ages on soils buried by colluvial wedges. The soil buried by the event Z wedge yielded TL ages of 1300±500 and 1400±400 yr B. P., and a conventional ^{14}C age of 2900±90 ^{14}C yr B.P. Jackson reports the soil as having a low carbon content, and therefore preferred the two closely corresponding TL ages and determined the timing of event Z to be ~1400 yr B.P.

Jackson (1991) obtained two ^{14}C and two TL ages from the soil buried by the event Y colluvial wedge and formed on top of the event X wedge. One ^{14}C age (1380±120 ^{14}C yr B.P.) and one TL age (1700±200 yrs B.P.) gave results that Jackson considered too young and subsequently disregarded. The second ^{14}C sample yielded a ^{14}C age of 3690±170 ^{14}C yr B.P. (4423 [3900) 3429 cal yr B.P., as per McCalpin and Nishenko, 1996), and the second TL age estimate was 7000±800 yrs B.P. Jackson considered the TL age too old, likely due to incomplete bleaching prior to sediment deposition, and selected the ^{14}C age as the preferred maximum time for event Y. Event X was consigned to be older than 3690±170 ^{14}C yr B.P., but younger than the alluvial-fan sediments it displaces. Machette (personal communication in Jackson, 1991) estimated the age of the faulted alluvial-fan surface as latest Pleistocene. However, based on the Bucknam (1978) ^{14}C age of 4580±250 ^{14}C yr B.P. for the alluvial-fan deposits at North Creek, Jackson assigned a time to event X of between 4 and 4.5 ka.

McCalpin and Nishenko Earthquake-Limiting Ages

McCalpin and Nishenko (1996) accepted the Hanson and others (1981) and Jackson (1991) choices of earthquake-limiting ^{14}C and TL ages for earthquakes Y and Z. Additionally, they included five previously unpublished ^{14}C ages from the Water Canyon site (Ostenaa, 1990) on the PS in their analysis of surface-faulting timing for the NS. Three Water Canyon ages were used to help constrain the timing of event Z, and the other two were used to help to constrain the timing of event Y. By including the Water Canyon ages in their analysis of the NS, McCalpin and Nishenko (1996) implicitly accept the partial segment rupture model for the Nephi and Provo segments originally proposed by Ostenaa (1990). Rounded to the nearest half-century, the McCalpin and Nishenko (1996) estimates for the timing of events Y and Z on the NS are 3850 and 1150 cal yr B.P., respectively.

Working Group Evaluation

Following review of the available paleoseismic data for the NS, the Working Group concludes that the NS has experienced a minimum of three surface-faulting earthquakes since ~5300 cal yr B.P. The Working Group's consensus for the timing of surface-faulting earthquakes on the NS is:

Z	≤1.0±0.4 ka, possibly as young as 0.4±0.1 ka
Y	~3.9±0.5 ka
X	>3.9±0.5 ka, <5.3±0.7 ka

The Working Group agrees with the McCalpin and Nishenko (1996) observation that for the WFZ as a whole, "*Until more precise dating is available to evaluate this possibility [partial segment rupture], the "megaquake" hypothesis needs to be considered as a valid end member scenario for planning purposes along the Wasatch Front*." However, in the absence of corroborating data regarding surface-faulting timing from the eastern strand of the NS, which is the strand closest to the PS and the Water Canyon trench site, the Working Group believes that it is premature to use information on earthquake timing from the PS to constrain the timing of surface faulting on the western (southernmost) strand of the NS.

Surface-Faulting Recurrence:

Because the timing of surface faulting on the NS is not tightly constrained, interevent intervals are broad. Interevent recurrence intervals with associated confidence limits for the BCS are:

Elapsed time since event Z	$\leq$1000$\pm$400 cal yr
Y-Z interval	$\leq$2900$\pm$600[1] cal yr
X-Y interval	$\leq$1400$\pm$900 cal yr

The approximate weighted mean recurrence for the two most recent interevent intervals rounded to the nearest century is:

~2500[2]$\pm$2100[3] cal yr

[1]$\pm$confidence limits equal the square root of the sum of the squares of the individual $\pm$ confidence limits for each bracketing earthquake rounded to nearest 100 years.
[2]weighted mean rounded to nearest 100 years.
[3]two-sigma confidence limits rounded to nearest 100 years.

Based on the poorly constrained information available on earthquake timing and variability in the length of individual interevent intervals, the Working Group's preferred recurrence-interval estimate and confidence limits for the NS are:

1200-**2500**-4800 kyr

Vertical Slip Rate:

The western strand of the NS lies entirely above the highstand of Lake Bonneville, so lacustrine geomorphic features and stratigraphy do not help constrain the age of deposits along that portion of the NS. Hanson and others report 7.0$\pm$0.5 m of net vertical displacement at North Creek and report a late Holocene vertical slip rate of 1.3$\pm$0.1 mm/yr. Schwartz and Coppersmith (1984) report a vertical slip rate for the same site of 1.27-1.36$\pm$0.1 mm/yr.

Harty and others (1997) calculated middle to late Holocene vertical slip rate ranges at four locations (North Creek, Willow Creek, Gardner Creek, and Red Canyon) on the western strand of the NS. At North Creek and Red Canyon the slip rates are based on net vertical-displacement estimates made from scarp profiles and the thickness of colluvial-wedge deposits exposed in trenches. They used earthquake timing and the net vertical-displacement values reported by Hanson and others (1981) and Jackson (1991). At Willow Creek and Gardner Creek, alluvial-fan ages were assumed to be the same as at North Creek based on the Bucknam (1978) ^{14}C age of ~5300 cal yr B.P.

North Creek	0.8-1.2 mm/yr
Willow Creek	0.7-1.0 mm/yr
Gardner Creek	0.5-0.7 mm/yr
Red Canyon	0.6-1.0 mm/yr

Machette (1984) described a soil just north of Gardner Creek on faulted upper Pleistocene alluvial-fan deposits. The fan deposits are displaced a minimum of 26-28 m, and based on soil-profile development the fan age is about 250 ka. The resulting vertical slip rate is 0.12 mm/yr, which is approximately 20 percent of the slip rate at Gardner Creek in more recent geologic time.

Based on currently available information on earthquake timing and displacement, the Working Group's preferred vertical slip-rate estimate and confidence limits for the NS are:

0.5-**1.1**-3.0 mm/yr

Summary:

Investigators have conducted two paleoseismic-trenching investigations on the western (southernmost) strand of the NS. The investigations revealed evidence for at least three surface-faulting earthquakes since middle Holocene time. Both investigations produced conflicting sets of numerical ages on samples from geologic units critical to determining the timing of surface faulting. Consequently, the existing paleoseismic data for the NS are considered poorly constrained, and multiple surface-faulting chronologies are possible depending on which ages are accepted and which are discarded. Paleoseismic-trenching data are lacking from the eastern (northernmost) strand.

Because surface-faulting timing on the NS is the least well constrained of the five central WFZ segments with multiple Holocene surface faulting earthquakes, and because paleoseismic-trenching information is lacking from the northern (easternmost) strand of the NS, the Working Group recommends that additional investigations be conducted on both the eastern and western strands of the NS to better constrain earthquake timing, and that vertical slip-rate data along the segment be reevaluated in light of that new earthquake information. Information about earthquake timing on the eastern subsection of the NS would help resolve questions regarding possible rupture overlap between the NS and the PS.

Additional References:

Crone, A.J., and Harding, S.T., 1984, Near-surface faulting associated with Holocene fault scarps, Wasatch fault zone, Utah-A preliminary report, *in* Hays, W.W., and Gori, P.L., editors, A workshop on "Evaluation of regional and urban earthquake hazards and risk in Utah": U.S. Geological Survey Open-File Report 84-763, p. 241-268.

Hylland, M.D., and Machette, M.N., 2004, Part III – Interim surficial geologic map of the Levan segment of the Wasatch fault zone, Juab and Sanpete Counties, *in* Christenson, G.E., Ashland, F.X., Hylland, M.D., McDonald, G.N., and Case, Bill, Database compilation, coordination of earthquake-hazards mapping and study of the Wasatch fault and earthquake induced landslides, Wasatch Front, Utah: Utah Geological Survey Final Contract Report to the U.S. Geological Survey, contract no. 03HGAG0008, 30 p.

Machette, M.N., 1984, Preliminary investigation of late Quaternary slip rates along the southern part of the Wasatch fault zone, central Utah, *in* Hays W.W. and Gori, P. L., editors, Proceedings of Conference XXVI, A workshop on "Evaluation of regional and urban earthquake hazards and risk in Utah": U.S. Geological Survey Open-File Report 84-763, p. 391-406.

Machette, M.N., 1992, Surficial geologic map of the Wasatch fault zone, eastern Utah Valley, Utah County and parts of Salt Lake and Juab Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-2095, scale 1:50,000.

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

Ostenaa, Dean, 1990, Late Holocene displacement history, Water Canyon site, Wasatch fault zone [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 6, p. 42.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
Levan segment (LS), Wasatch fault zone (WFZ), Juab and Sanpete Counties, Utah

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

Jackson, M.E., 1991, Paleoseismology of Utah, Volume 3 - The number and timing of Holocene paleoseismic events on the Nephi and Levan segments, Wasatch fault zone, Utah: Utah Geological Survey Special Studies 78, 23 p.

Machette, M.N., Personius, S.F., and Nelson, A.R., 1992, Paleoseismology of the Wasatch fault zone - A summary of recent investigations, interpretations, and conclusions, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-A, 71 p.

Hylland, M.D., and Machette, M.N., 2004, Part III – Interim surficial geologic map of the Levan segment of the Wasatch fault zone, Juab and Sanpete Counties, *in* Christenson, G.E., Ashland, F.X., Hylland, M.D., McDonald, G.N., and Case, Bill, Database compilation, coordination of earthquake-hazards mapping and study of the Wasatch fault and earthquake induced landslides, Wasatch Front, Utah: Utah Geological Survey Final Contract Report to the U.S. Geological Survey, contract no. 03HGAG0008, 30 p.

Age of Youngest Faulting:
Holocene

Discussion:
A 5-15-km-long gap in Holocene and latest Pleistocene faulting marks the boundary between the LS and the Nephi segment (NS; Machette and others, 1992; Harty and others, 1997; Hylland and Machette, 2004) of the WFZ. Landslide deposits occupy much of this gap, and likely obscure any Holocene scarps (Michael Hylland, Utah Geological Survey, verbal communication to Working Group, 2004). South of the gap, most fault scarps on Holocene deposits are less than 3 m high, while scarps on upper to middle Pleistocene alluvium are 5 to 10 m high or higher, suggesting recurrent late Quaternary surface faulting (Machette and others, 1992). Holocene ruptures on the LS extend from about 4 km north to 18 km south of the town of Levan, where the fault steps left about 0.5 km and enters bedrock. Clear evidence of faulting extends for another 3 km to the south. The geomorphic appearance of the scarps and new (2004) scarp-profile data (Michael Hylland, Utah Geological Survey, verbal communication to Working Group, 2004) indicate that Holocene faulting continues further south.

Although the gap between the NS and LS lacks evidence of Holocene and latest Pleistocene surface faulting, it does contain older fault scarps formed on middle Pleistocene alluvial fans extending along the front of the San Pitch Mountains south of Nephi (Machette and others, 1992; Harty and others, 1997). The older fault scarps may indicate that the boundary between the two segments is nonpersistant, at least in earlier Quaternary time. To the south, the boundary between the LS and Fayette segment (FS) of the WFZ is marked by a 3.5-km step to the east and 5-km step to the south in late Quaternary faulting. Fault scarp morphology on the FS indicates that the most recent surface faulting is older than on the LS, and probably is no younger than earliest Holocene (Michael Hylland, Utah Geological Survey, verbal communication to Working Group, 2004).

Earthquake Timing:

Based on scarp morphology at Deep Creek and Pigeon Creek, Schwartz and Coppersmith (1984) concluded that the LS has experienced a single surface-faulting earthquake in Holocene time. At Pigeon Creek they obtained a ^{14}C age on charcoal from faulted alluvial-fan sediments of 1750±350 ^{14}C yr B.P., which provides a maximum limiting age for the MRE. At Deep Creek a charcoal sample collected from the fault footwall yielded a ^{14}C age of 7300±1000 ^{14}C yr B.P. They interpret the scarp at Deep Creek as the product of a single surface-faulting earthquake and concluded that the MRE on the LS postdates 1750±350 ^{14}C yr B.P., and that the PE is older than 7300±1000 ^{14}C yr B.P.

Jackson (1991) collected a TL sample from the upper few centimeters of a soil buried beneath the MRE colluvial wedge exposed in a stream cut at Deep Creek. The soil yielded an age of 1000±100 yr B.P., which provides a closely limiting maximum time for the earthquake. Hylland and Machette (2004) revisited Deep Creek in 2003 and sampled the upper 5 cm of the same buried soil for ^{14}C dating. The soil yielded an age of 1200±80 ^{14}C yr B.P., which calendar calibrated and rounded to the nearest half-century results in an AMRT age of 1000±150 cal yr B.P. Therefore, based on both TL and ^{14}C ages from the Deep Creek stream exposure, the MRE on the LS likely occurred shortly after 1000± 150 cal yr B.P.

Jackson (1991) excavated a trench across a 3-m high scarp at Skinner Peaks south of Deep Creek and found colluvial-wedge evidence for a single surface-faulting earthquake in the late Holocene (between 1000 and 1500 yr B.P.). Evidence for a second surface-faulting earthquake was equivocal and was based on secondary stratigraphic relations exposed in the fault's hanging wall. All that Jackson could say with confidence regarding the timing of the PE at Skinner Peaks is that it predates 3.1-3.9 ka.

Hylland and Machette (2004) report that scarp-profile data south of Chriss Canyon indicate the possibility of two surface-faulting earthquakes on the southern approximately 15 km of the LS. Scarp data alone are not sufficient to constrain PE timing. The PE may have ruptured only the southern part of the LS, or conversely, evidence for a northern continuation of the rupture is not expressed in the scarp morphology (Michael Hylland, Utah Geological Survey, verbal communication to Working Group, 2004).

The Working Group's consensus for the timing of surface-faulting earthquakes on the LS is:

Z	shortly after 1000±150 cal yr B.P.
Y	unknown but likely early Holocene to latest Pleistocene (possible partial segment rupture)

Surface-Faulting Recurrence:

Because information on timing of surface faulting is limited for the LS, but recognizing the possibility of two Holocene earthquakes near the southern end of the segment, the Working Group's preferred Holocene recurrence-interval estimate for the LS is reported as a range and not as a central value with approximate two-sigma confidence limits.

>3 and < 12 kyr

Vertical Slip Rate:

Hylland and Machette (2004) state that determining an accurate late Quaternary slip rate for the LS is presently not possible because the timing of only one surface-faulting earthquake is known. However, they estimated the age of older fan alluvium based on the degree of secondary $CaCO_3$ development in soils formed on the fan surfaces, and used the height of scarps formed on those surfaces to calculate “order of magnitude” long-term vertical slip rates for the LS. Their estimated long-term average vertical slip rate for the LS is 0.05-0.15 mm/yr. Hylland and Machette (2004) used the mean diffusion age of scarps south of the Skinner Peaks trench site to calculate a vertical slip rate since the latest Pleistocene/earliest Holocene of 0.33-0.53 mm/yr for the southern part of the LS.

Because the paleoseismic information available for the LS is limited, the Working Group’s consensus Holocene preferred vertical slip-rate estimate for the LS is reported as a range and not as a central value with approximate two-sigma confidence limits.

0.1-0.6 mm/yr

Summary:

Geomorphic evidence and a natural stream-cut exposure indicate that a minimum of one surface-faulting earthquake since the early to middle Holocene on the LS. However, scarp-profile analysis indicates a possible second earthquake in the early Holocene or latest Pleistocene near the south end of the LS. The Working Group recommends additional paleoseismic investigation (additional scarp profiles and trenching) to resolve this earthquake timing issue and to better resolve both surface-faulting recurrence and vertical slip rates on the LS.

Additional References:

Harty, K.M., Mulvey, W.E., and Machette, M.N., 1997, Surficial geologic map of the Nephi segment of the Wasatch fault zone, eastern Juab County, Utah: Utah Geological Survey Map 170, scale 1:50,000, 14 p. booklet.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Joes Valley fault zone (JVFZ), Sanpete County, Utah

Paleoseismic Data Source Documents:

Foley, L.L., Martin, R.A., Jr., and Sullivan, J.T., 1986, Seismotectonic study for Joes Valley, Scofield, and Huntington North Dams, Emery County and Scofield Projects, Utah: Denver, U.S. Bureau of Reclamation Seismotectonic Report No. 86-7, 132 p., scale 1:60,000 and 1:155,000.

Age of Youngest Faulting:

Holocene

Discussion:

The JVFZ consists of parallel, en echelon, and locally overlapping, north- to northeast-trending faults which extend for 120 km on the east side of the Wasatch Plateau (Foley and others, 1986). The fault system contains two major structures, a southern and a northern graben, each of which have distinct geomorphic characteristics that may reflect differences in total displacement and recency of movement on bounding faults. The northern part of the fault zone is characterized by greater total stratigraphic throw within the graben; more continuous and linear bedrock escarpments that mark graben-bounding faults, and Quaternary scarps, which are generally absent to the south (Foley and others, 1986).

The northern part of the JVFZ extends for a distance of about 50 km and is bounded by the East and West Joes Valley faults (EJVF & WJVF) and contains several intragraben faults, the most prominent being the Middle Mountain fault (MMF) and the Bald Mountain faults. Distinct scarps mark both graben-bounding faults and intragraben structures on unconsolidated Quaternary deposits (Foley and others, 1986).

Despite the presence of scarps formed on Quaternary deposits along the northern JVFZ, a fundamental question remains regarding the nature of the Joes Valley graben (JVG), and the seismogenic capability of the associated JVFZ. Foley and others (1986) report no significant net displacement across the JVG, and the graben's close association with the active Wasatch Plateau monocline suggests that JVG may be a keystone graben formed along or near the monocline crest (Suzanne Hecker, U.S. Geological Survey, verbal communication to Working Group, 2003). Foley and others (1986) propose three additional possible origins for the JVG, only one of which involves faulting that extends to seismogenic depths, and conclude, "*the origin of the long linear grabens on the Wasatch Plateau* [JVG] *cannot be resolved with presently available geologic and seismologic data.*" They further state:

> *The main issue regarding the scarps in Joes Valley involves whether or not these faults formed in response to recurrent large-magnitude earthquakes. The available data on subsurface geometry of the Wasatch Plateau faults is equivocal; therefore, the possibility that the Joes Valley faults and other similar faults extend to seismogenic depths cannot be precluded.*

Due to uncertainty regarding the seismogenic nature of the JVFZ, the Utah Geological Survey intends to reclassify the Joes Valley faults (EJVF, WJVF, and intragraben faults) as "Suspected Faults" in the next revision of the *Quaternary Fault and Fold Database and Map of Utah* (Mike Hylland, Utah Geological Survey, verbal communication to Working Group, 2003).

Earthquake Timing:

Foley and others (1986) excavated six trenches across three faults in the north JVG: the EJVF, WJVF, and the MMF to investigate the timing and displacement of surface-faulting earthquakes. Trenching results showed that the EJVF has experienced a minimum of four surface-faulting earthquakes over the past ~250 ka, while the WJVF and MMF have each experienced a minimum of two surface-faulting earthquakes since ~30 ka. The ability to resolve the timing of individual earthquakes in the trenches was limited, and Foley and others (1986) state that the measured displacement of 1 to 5 m may record cumulative displacement from several earthquakes rather than from one or two larger earthquakes.

Surface-Faulting Recurrence:

Due to the ambiguity of the paleoseismic data, Foley and others (1986) were able to provide only broadly constrained recurrence-interval estimates for the faults comprising the JVFZ.

Fault	Recurrence
EJVF[1]	<60 kyr
WJVF[2]	10-20 kyr
MMF[2]	10-15 kyr

[1] *~250 kyr period of record*
[2] *~30 kyr period of record*

Vertical Slip Rate:

Foley and others (1986) report no net vertical displacement across the JVG. Based on that observation, the Working Group recommends that the JVFZ be considered a single integrated structure. Lacking net displacement, the JVFZ as a whole has no vertical slip rate, again raising questions about the seismogenic capability of the fault zone. Foley and others (1986) do not report vertical slip rates for individual faults comprising the JVFZ. However, Black and others (2003) do report vertical slip rates for the EJVF, WJVF and MMF, which they determined by dividing the maximum displacement recorded in Quaternary deposits along those faults by the estimated age of the displaced deposits. In some instances the Black and others (2003) vertical slip rates are as high as 1.1 mm/yr; however, all their slip rates have open seismic cycles at both ends, and the maximum displacements were reported by Foley and others (1986) as "scarp heights," not as net displacement. Because Foley and others (1986) distinguish between scarp height and net displacement on the EJVF where they measured scarp profiles, their "scarp height" values presumably do not represent net displacement.

Summary:

Due to ambiguities regarding both the seismogenic capability of the JVFZ and the number and timing of surface-faulting earthquakes on individual faults, the Working Group recommends that the JVFZ be treated as a single integrated structure rather than as several independently seismogenic faults and that the combined fault zone be assigned a single consensus preferred recurrence interval. The Working Group's preferred recurrence-interval estimate and confidence limits for the JVFZ are:

5-**10**-50 kyr

In the absence of measurable net displacement across the JVG, no vertical slip-rate estimate is possible for the JVFZ.

Additional References:

Black, B.D., Hecker, S., 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 1:50,000, compact disk.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

West Valley fault zone (WVFZ), Salt Lake County, Utah

Paleoseismic Data Source Documents:

Keaton, J.R., Currey, D.R., and Olig, S.J., 1987, Paleoseismicity and earthquake hazards evaluation of the West Valley fault zone, Salt Lake City urban area, Utah: Salt Lake City, Dames and Moore, Final Technical Report for U.S. Geological Survey, Contract No. 14-08-0001-22048, 55 p.; published as Utah Geological Survey Contract Report 93-8, 1993.

Keaton, J.R., and Currey, D.R., 1989, Earthquake hazard evaluation of the West Valley fault zone in the Salt Lake City urban area, Utah: Salt Lake City, Dames and Moore, Final Technical Report for U.S. Geological Survey, Contract No. 14-08-001-G1397, 69 p.; published as Utah Geological Survey Contract Report 93-7, 1993.

Solomon, B.J., 1998, New evidence for the age of faulting on the West Valley fault zone: Utah Geological Survey, Survey Notes, v. 30, no. 3, p. 8 and 13.

Age of Youngest Faulting:

Holocene

Discussion:

The WVFZ is a north- to northwest-trending fault zone about 15 km long and 7 km wide that consists of generally east-dipping faults that form the western boundary of a fault-bounded basin in the center of Salt Lake Valley. The Salt Lake City segment (SLCS) of the Wasatch fault zone (WFZ; Machette and others, 1992) traverses the eastern side of the valley at the base of the Wasatch Range and forms the eastern side of the basin. The WVFZ is at about the midpoint of the valley and exhibits scarps up to 6.1 m high formed on late Pleistocene Lake Bonneville lacustrine deposits. Whether the WVFZ is independently seismogenic or an antithetic fault that ruptures coseismicly with the SLCS is unclear based on currently available information.

The southern portion of the WVFZ consists of two subparallel east-dipping faults, the Taylorsville fault (TF) to the east, and Granger fault (GF) to the west, whereas the northern portion is broader and characterized by many smaller, east- and west-dipping faults that form a broad, indistinct graben. Seismic-reflection data from an area on-trend with the fault zone at the south end of Great Salt Lake (north of the fault zone) indicate a buried, east-dipping fault that cuts the inferred base of the Quaternary section (Wilson and others, 1986).

The WVFZ shows evidence for Holocene surface faulting, but exposures are poor and often lack clear evidence of faulting, earthquake timing, and datable material.

Earthquake Timing:

<u>Taylorsville fault</u>

Keaton and others (1987) and Keaton and Currey (1989) excavated several trenches across the central of the three strands that comprise the TF, but were unable to identify discrete fault zones, evidence for individual surface-faulting earthquakes, or to determine earthquake timing. Displacement on the TF is chiefly monoclinal flexuring, which occurred at or close to the threshold for surface fault rupture. Keaton and others (1987) interpret a minimum of two surface-faulting earthquakes in post-Gilbert shoreline time (~12 ka) based on the presence of a 1.2-1.5 m-high scarp they believe formed during the PE which was then followed by the MRE that truncated the PE scarp.

Solomon (1998) described an exposure of the TF in a consultant's trench near the north end of the fault trace, and identified the MRE based on the presence of a tectonic crack filled with organic-rich sediment. He obtained two ^{14}C ages on organic bulk samples, one from the crack-fill material and the other from pre-faulting sag-pond sediments. The ^{14}C ages indicate the MRE occurred shortly after 2.0-2.4 ka, which corresponds in a general way with the timing of the PE (2.45 ka) on the SLCS.

Granger fault

Scarps up to 6.1 m high in Lake Bonneville lacustrine deposits mark the trace of the GF. Keaton and others (1987) excavated two trenches and drilled eight boreholes on the GF. The fault formed a prominent, discrete, planar trace in both trenches, but neither the number nor the timing of individual earthquakes could be determined from trench exposures. Keaton and Currey (1989) drilled 24 boreholes at three additional sites along the fault. They identified two earthquakes on the GF based on the presence in the boreholes of displaced Lake Bonneville deposits and calcareous playa deposits buried by scarp colluvium. Their interpretation is that the PE created the depression in which the playa formed and that the MRE scarp generated the colluvium. They also identified evidence for three additional surface-faulting earthquakes based on morphostratigraphic scarp relations, for a total of 5 earthquakes on the GF in 13 ka.

A ^{14}C age on a bulk sample of organic fault-zone colluvium, obtained by the UGS from a consultant's trench across the GF, indicates the MRE occurred slightly after 1.3-1.7 ka (UGS unpublished data), which is similar to the timing of the MRE (1.3 ka) on the SLCS.

Entire WVFZ

Keaton and Currey (1987) report 6-7 surface-faulting/flexure earthquakes in the past 13 kyr for the WVFZ as a whole, the MRE being younger than ~ 12 ka, but were unable to determine the timing of individual surface-faulting earthquakes. Later work by Solomon (1998) and the UGS (unpublished data) shows that the MREs on the TF and GF are similar in age to the PE and MRE, respectively, on the SLCS.

Surface-Faulting Recurrence:

Taylorsville fault

Keaton and others (1987) report a mean recurrence of 6 kyr for the TF based on two earthquakes in ~12 kyr. However, the timing of the two earthquakes is unknown, and therefore so is the length of the interval between them.

Granger fault

Keaton and others (1987) report a mean recurrence of 2.6 kyr for the GF based on five earthquakes in 13 kyr. However, earthquake timing is unknown, and therefore so is the length of the intervals between them.

Entire WVFZ

For the WVFZ as a whole, Keaton and others (1987) report a total of 6-7 surface-rupture/flexure earthquakes in the past 13 kyr producing a latest Pleistocene/Holocene mean recurrence of 1.8-2.2 kyr. Keaton and Currey (1989) focused their attention on the less well-defined scarps at the north end of the WVFZ and report a mean recurrence of surface faulting or folding on that part of the WVFZ of 6 to 11 kyr. They acknowledge the shorter recurrence intervals reported by Keaton and others (1987) for the southern part of the WVFZ, and state that the more prominent fault traces to the south are likely indicative of shorter recurrence intervals.

Solomon (1998) and the UGS (unpublished data) documented the MREs on the TF and GF at 2.0-2.4 ka and 1.3-1.7 ka, respectively. These data indicate that a minimum of two surface-faulting earthquakes have occurred on the WVFZ in the past ~2.4 kyr, with an interval of 0.3-1.1 kyr between them. These two earthquakes may have been coseismic with the two most recent surface-faulting earthquakes on the SLCS. The timing of older surface-faulting/flexuring earthquakes on the TF and GF remains unknown and therefore the Working Group was unable to make a recurrence-interval estimate for the WVFZ.

Vertical Slip Rate:

Vertical slip-rate estimates reported by Keaton and others (1987) for the WVFZ are based on a combination of displacements estimated from trench exposures and boreholes. The trend is for the rate of slip to increase in more recent geologic time.

	Time Interval	Vertical Slip Rate
Taylorsville fault	<12 kyr	0.1-0.2 mm/yr
Granger fault	13 kyr	0.4-0.5 mm/yr
WVFZ - entire	13 kyr	0.5-0.6 mm/yr
Granger fault	47±20 kyr	0.1-0.3 mm/yr
Granger fault	60±20 kyr	0.02-0.04 mm/yr
Granger fault	80±30 kyr	0.03-0.1 mm/yr
Granger fault	140±10 kyr	0.01 mm/yr

Available vertical slip-rate data for the WVFZ come chiefly from geomorphic fault-scarp studies and from drill-hole data. Those data indicate that slip on the WVFZ has increased in more recent geologic time (see table above).

Based on available information, the Working Group's preferred vertical slip-rate estimate and confidence limits for the WVFZ, as a whole, are:

0.1-**0.4** -0.6 mm/yr

Summary:

The Working Group believes that current paleoseismic data are insufficient to make a recurrence-interval estimate for the WVFZ. Exposures in consultant's trenches allowed the UGS (Solomon, 1998; UGS unpublished data) to determine the timing of the MREs on the TF and GF. The timing of those earthquakes are in general agreement with the timing of the PE and MRE on the SLCS, respectively; indicating that for at least some surface-faulting earthquakes on the WFZ, all or part of the WVFZ may rupture coseismicly. However, the relation between the WVFZ and the SLCS remains unclear, and additional paleoseismic investigations are required to determine if the WVFZ is persistently coseismic with the WFZ, or if it is independently seismogenic. Until such investigations are performed, the Working Group considers the WVFZ an independently seismogenic fault.

Additional References:

Machette, M.N., Personius, S.F., and Nelson, A.R., 1992, Paleoseismology of the Wasatch fault zone - A summary of recent investigations, interpretations, and conclusions, *in* Gori, P.L.,

and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-A, 71 p.
Wilson, E.A., Saugy, Luc, and Zimmermann, M.A., 1986, Cenozoic tectonics and sedimentation of the eastern Great Salt Lake area, Utah: Bulletin de Société Géologicque Francaise, v. 2, no. 5, p. 777-782.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
West Cache fault zone (WCFZ), Cache County, Utah

Paleoseismic Data Source Documents:
Black, B.D., Giraud, R.E., and Mayes, B.H., 2000, Paleoseismic investigation of the Clarkston, Junction Hills, and Wellsville faults, West Cache fault zone, Cache County, Utah: Utah Geological Survey Special Study 98, 23 p.

Age of Youngest Faulting:
Holocene

Discussion:
Cache Valley is a large north-south structural basin formed by repeated movement on the east-dipping WCFZ and the west-dipping East Cache fault zone. The valley was occupied by Pleistocene Lake Bonneville until sometime after 16.2 ka, when Lake Bonneville began to recede from the Provo shoreline. The WCFZ trends along the west side of the Cache Valley in northern Utah and southern Idaho.

The WCFZ consists of three related east-dipping normal faults, which from north to south are the Clarkston (CF), Junction Hills (JHF), and Wellsville (WF) faults. The three faults are subparallel and extend for 70 km along the west side of the Cache Valley at the base of the Malad Range, Junction Hills, and Wellsville Mountains, respectively. All three faults show evidence for recurrent late Quaternary activity. The age of each fault's MRE is different, as are their estimated vertical slip rates; therefore, Solomon (1999) and Black and others (2000) consider each fault an independent seismogenic segment of the WCFZ.

Earthquake Timing:
<u>Clarkston fault</u>

Black and others (2000) excavated a trench across a 4-m-high scarp that exposed a single fault trace and evidence for one surface-faulting earthquake. Radiocarbon age estimates on carbon from the upper few centimeters of a paleosol beneath the MRE colluvial wedge, from organic-rich wedge matrix near the middle of the wedge, and from organic-rich wedge matrix from the wedge heel immediately adjacent to the scarp result in an estimate of MRE timing of 3600 to 4000 cal yr B.P. The trench did not contain evidence of older events.

<u>Junction Hills fault</u>

A stream-cut exposure provides the only conclusive evidence of late Quaternary faulting on the JHF (Solomon, 1999). Black and others (2000) logged the exposure and found evidence for two surface-faulting earthquakes. A ^{14}C age obtained from slightly organic material from the bottom of the MRE colluvial wedge and the top of an underlying paleosol resulted in an estimate of MRE timing of 8250 to 8650 cal yr B.P. The timing of the PE could not be constrained other than older than overlying Lake Bonneville transgressive deposits that Black and others (2000) believe were deposited about 22.5 ka.

Wellsville fault

Black and others (2000) excavated a trench across a 7-m-high scarp of the western strand of the WF and exposed evidence for two surface-faulting earthquakes. Radiocarbon ages from bulk-soil samples collected from the MRE colluvial wedge and an underlying paleosol resulted in an estimate of MRE timing of 4400 to 4800 cal yr B.P. A ^{14}C age from small pieces of degraded detrital charcoal in alluvial-fan sediments that predate the PE provides a maximum limiting constraint on the timing of that earthquake of about 25 kyr. A post-earthquake loess deposit overlies the PE colluvial wedge. Black and others (2000) interpreted the loess as deposited about 15 ka following the desiccation of many pluvial lakes in the region and the retreat of glaciers in the mountains. Therefore, timing of the PE on the WF is constrained between broadly limiting ages of 15 and 25 kyr.

Surface-Faulting Recurrence:

Clarkston fault

Lack of evidence for a PE prevented Black and others (2000) from directly determining the interevent interval between the PE and MRE on the CF. However, based on a minimum age for the Bonneville shoreline of 16.8 ka, they report an estimated recurrence interval of 13.2 kyr (shoreline age minus MRE age) if there have been two post-Bonneville shoreline earthquakes and 6.6 kyr if there have been three earthquakes in that interval. Both recurrence-interval estimates assume that the oldest earthquake occurred shortly after abandonment of the Bonneville shoreline, a supposition for which no direct evidence exists, nor can the number of surface-faulting earthquakes on the CF in post-Bonneville time be constrained. Therefore, current recurrence-interval estimates for the CF have high uncertainty.

Junction Hills fault

Black and others (2000) estimate a minimum elapsed time of ~13.8 kyr between the MRE (8.7 ka) and PE ($\geq$ 22.5 ka) on the JHF. However, timing of the PE has high uncertainty, and consequently there is high uncertainty regarding the length of the interevent interval, which could be much longer than 13.8 kyr.

Wellsville fault

Black and others (2000) estimate the PE/MRE interevent interval on the WF as 10.2 to 20.6 kyr. However, PE timing is poorly constrained, so the actual length of the interevent interval is uncertain.

Vertical Slip Rate:

Clarkston fault

Black and others (2000) used the 9 m displacement of the Bonneville shoreline between the CF and JHF to make a vertical slip-rate estimate for the CF. Using the approximately 13 kyr interval between the minimum age of the Bonneville shoreline (16.8 ka) and the MRE (3.8 ka), and the 9 m of displacement that occurred in that interval results in a late Pleistocene/Holocene vertical slip rate for the CF of 0.7 mm/yr. Black and others (2000) consider this value to be a high estimate and believe that the true vertical slip rate is likely lower, possibly in the range of 0.25–0.5 mm/yr; however, if the interval between events Y and Z is less than 13 kyr, the slip rate would be higher, not lower than 0.7 mm/yr.

Junction Hills fault

Black and others (2000) report a vertical slip rate for the PE/MRE interevent interval on the JHF of 0.21 mm/yr based on 2.9 m of net vertical displacement during the MRE and a minimum elapsed time of ~13.8 kyr between the two earthquakes. However, PE timing is poorly constrained, and the 2.9 m of vertical net displacement may or may not represent the maximum MRE displacement on the JHF. Given the uncertainties in timing and net vertical displacement of the PE, 0.21 mm/yr is likely a near maximum value for the JHF.

Wellsville fault

Black and others (2000) report a vertical slip rate of approximately 0.1-0.2 mm/yr for the PE/MRE interevent interval based on 1.9 m of MRE net vertical displacement and an interevent interval of 10.2-20.6 kyr.

Summary:

Each of the three faults comprising the WCFZ has experienced a different Holocene surface-faulting earthquake, confirming that each fault is an independent seismogenic segment of the WCFZ. Penultimate earthquake timing on the segments either could not be determined or could be constrained only within broad time intervals with large uncertainties. As a result, preferred recurrence-interval and vertical slip-rate estimates for the segments also have high uncertainties. No information is available for earthquakes older than the PE on any of the segments, so the Working Group's preferred recurrence-interval and vertical slip-rate estimates are based on a single, poorly constrained interevent interval between the PE and MRE and have high uncertainty. Note that due to the lack of well-constrained information on earthquake timing, the Working Group's preferred recurrence-interval estimates represent a range of values and not a central value with approximate two-sigma confidence limits.

Segment	Recurrence Interval	Vertical Slip Rate
Clarkston fault	5-20 kyr	0.1-0.4-0.7 mm/yr
Junction Hills fault	10-25 kyr	0.05-0.1-0.2 mm/yr
Wellsville fault	10-25 kyr	0.05-0.1-0.2 mm/yr

Continued rapid growth is quickly converting Cache Valley from a rural farming region into an urban/industrial center. Despite the recent paleoseismic investigation by Black and others (2000), with the exception of the timing and displacement of the MRE on each of its three segments, the WCFZ remains poorly understood as a source of large, damaging earthquakes in Cache Valley and in northern Utah and southern Idaho in general. The Working Group recommends that additional paleoseismic investigations be performed on the WCFZ to better understand the slip distribution along the three fault segments, and that based on those investigations, additional trenching be performed to better constrain the timing of the PE and earlier earthquakes, particularly on the CF before urbanization makes such studies more difficult or impossible.

Additional References:

Solomon, B.J., 1999, Surficial geologic map of the West Cache fault zone and nearby faults, Box Elder and Cache Counties, Utah: Utah Geological Survey Map 172, scale 1:50,000, 21 p. pamphlet.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

East Cache fault zone, central section (ECFZ), Cache County, Utah

Paleoseismic Data Source Documents:

McCalpin, J.P., and Forman, S.L., 1991, Late Quaternary faulting and thermoluminescence dating of the East Cache fault zone, north-central Utah: Bulletin of the Seismological Society of America, v. 81, no. 1, p. 139-161.

McCalpin, J.P., 1994, Neotectonic deformation along the East Cache fault zone, Cache County, Utah: Utah Geological Survey Special Study 83, 37 p.

Age of Youngest Faulting:

Holocene

Discussion:

The ECFZ is a roughly 80-km-long, generally north-trending range-front normal fault along the western base of the Bear River Range in eastern Cache Valley. McCalpin (1989, 1994) subdivided the ECFZ into three sections (northern, central, and southern) based on fault zone complexity, tectonic geomorphology, and expression of fault scarps. The central section is the only one that shows evidence of Holocene activity, and is the only section on which detailed paleoseismic-trenching studies have been performed.

The 16-km-long central section is typified by a single, straight fault trace. Fault scarps displace Bonneville-lake-cycle or younger deposits along the northern half (8 km) of the section, where scarps may diverge as much as 400 m from the range front. On the southern half of the section post-Bonneville faulting may have occurred, but no scarps are preserved, possibly due to mass movements at the base of faceted spurs (McCalpin, 1994).

McCalpin and Forman (1991) excavated two trenches on the central section of the ECFZ. The “Bonneville trench” on a Lake Bonneville-highstand delta exposed evidence for two surface-faulting earthquakes. Soil-profile development, TL ages, and a ^{14}C age on a gastropod shell provide limits on event Y timing and broadly constrain the timing of event Z. The “Provo trench” was about 1 km north of the Bonneville trench on a Provo-age delta surface. This trench exposed stratigraphic evidence for event Z, and organic-rich bulk samples of crack-fill material, debris-facies colluvium, and a paleosol beneath the event Z colluvial wedge provided ^{14}C age estimates to constrain the timing of this earthquake (McCalpin, 1994).

Earthquake Timing:

Radiocarbon ages from three locations constrain the timing of event Z in the Provo trench. Organic matrix from the basal part of material filling a crack created by event Z yielded an age of 3100$\pm$80 ^{14}C yr B.P. Organic basal debris-facies colluvium from the event Z colluvial wedge yielded an age of 4240$\pm$80 ^{14}C yr B.P., and a soil buried by the colluvial wedge gave an age of 4040$\pm$60 ^{14}C yr B.P. McCalpin (1994) interprets the crack-fill ^{14}C age as erroneously young. He considers the small age difference between the earliest debris-facies colluvial-wedge material and the top of the underlying buried soil to constrain the time of event Z to about 4.0-4.2 ka. However, calibration of those two ^{14}C ages, assuming a carbon age span and a carbon mean residence time each of 200 years for both samples, results in a revised estimate for the timing of event Z of 4.3-4.6 kyr.

Stratigraphic relations and numerical ages from the Bonneville trench bracket event Y between a TL age of 8.7±1.0 ka and the ^{14}C age on the gastropod shell of 15,540±130 ^{14}C yr B.P. The scarp height at the Bonneville trench is roughly twice the height of the scarp at the Provo trench implying that event Y predates formation of the Provo delta surface. McCalpin (1994) concludes that event Y occurred between about 13 ka (age of Provo delta) and 15.5 ka.

However, Currey's revised Lake Bonneville chronology (Currey, University of Utah Department of Geography, written communication to the UGS, 1996; verbal communication to Working Group, 2004) places the age of the Provo delta between 16.8 and 16.2 ka. Calibration of the ^{14}C age on the gastropod shell (not previously done) results in a calibrated age of 18.6+0.7/-0.6 cal yr B.P. (two sigma). Following McCalpin's (1994) original reasoning, those revised ages place event Y between about 18 (maximum age of the Bonneville delta) and 16.2 ka (minimum age of the Provo delta).

Based upon currently available paleoseismic information, the Working Group's consensus surface-faulting chronology for the central section of the ECFZ is:

Z 4.3-4.6 ka
Y between 16.2 and 18 ka

Surface-Faulting Recurrence:

Y/Z interevent interval (using the revised ages above): minimum 11.6 kyr, maximum 13.7 kyr, mean 12.7 kyr.

Evidence for an earlier surface-faulting earthquake (event X) during the Bonneville transgression is equivocal. However, McCalpin (1994) speculates that if a third earthquake did occur, the interval between events X and Y is likely only about 4 kyr, much shorter than the elapsed time between events Y and Z.

Because limited information regarding event X indicates possible large variations in the length of the intervals between events X and Y and Y and Z, the Working Group's preferred recurrence-interval estimate for the ECFZ is intentionally broad to reflect possible large variations in time between surface-faulting earthquakes. Based on available information, the Working Group's preferred recurrence-interval estimate and confidence limits for the central section of the ECFZ are:

4-**10**-15 kyr

Vertical Slip Rate:

McCalpin (1994) reports a long-term vertical slip rate for the central section of the ECFZ based on 8.5 m of displacement in pre-Bonneville alluvium of as high as 0.06 mm/yr, depending on the age assigned to the alluvium – but the actual alluvium age, and therefore the slip rate, is unknown.

The minimum (11.6 kyr), maximum (13.7 kyr), and mean (12.7 kyr) length of the Y-Z interevent interval, and a reported displacement for event Z of 0.5-1.2 m in the Provo trench (McCalpin, 1994), results in a range of vertical slip rates for the most recent interevent interval of 0.04-0.10 mm/yr with an mean slip rate of 0.07 mm/yr.

Because limited information regarding event X indicates a possible large variation in the length of the interevent intervals between events X and Y and Y and Z, the confidence limits for the Working Group's preferred vertical slip-rate estimate for the ECFZ are intentionally broad to reflect possible large variations in time between surface-faulting earthquakes. Based on available information, the Working Group's preferred vertical slip-rate estimate and confidence limits for the central section of the ECFZ are:

0.04-**0.2**-0.4 mm/yr

Summary:

The ECFZ forms the eastern bounding fault of the Cache Valley graben. It consists of three sections in a manner similar to the West Cache fault zone (WCFZ), which forms the west side of the graben (Black and others, 2000). However, unlike the WCFZ, only the central section of the ECFZ has been the subject of a paleoseismic-trenching investigation. Trenching studies conducted by Black and others (2000) documented Holocene surface faulting on all three segments of the WCFZ. In contrast, based on geologic mapping and geomorphic relations, McCalpin (1994) reports no evidence of Holocene surface faulting on the northern and southern sections of the ECFZ. McCalpin (GEO-HAZ Consulting, verbal communication, 2004) states that the range front geomorphology (faceted spurs) of the Bear River Range indicates a higher slip rate than has been documented on the ECFZ.

The earthquake hazard represented by the ECFZ to the rapidly urbanizing Cache Valley remains poorly understood. The occurrence of three different Holocene surface-faulting earthquakes, one on each of the three segments of the WCFZ on the west side of the Cache Valley, raises questions regarding the timing of surface faulting on the three proposed sections of the ECFZ. The Working Group recommends additional paleoseismic investigations on the ECFZ to extend the surface-faulting chronology on the central section and to investigate the history of surface faulting on the northern and southern sections of the fault as well.

Additional References:

Black, B.D., Giraud, R.E., and Mayes, B.H., 2000, Paleoseismic investigation of the Clarkston, Junction Hills, and Wellsville faults, West Cache fault zone, Cache County, Utah: Utah Geological Survey Special Study 98, 23 p.

McCalpin, J.P., 1989, Surficial geologic map of the East Cache fault zone, Cache County, Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-2107, scale 1:50,000.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
Hurricane fault zone (HFZ), Anderson Junction section (AJS), Washington County, Utah and Mohave County, Arizona

Paleoseismic Data Source Documents:
Stenner, H.D., Lund, W.R., Pearthree, P.A., and Everitt, B.L., 1999, Paleoseismic investigation of the Hurricane fault, northwestern Arizona and southwestern Utah: Arizona Geological Survey Open-File Report 99-8, 137 p.

Lund, W.R., Hozik, M.J., and Hatfield, S.C., in press, Paleoseismic investigation of earthquake hazard and long-term movement history of the Hurricane fault in southwestern Utah: Utah Geological Survey Bulletin.

Stenner, H.D., Crosby, C.J., Dawson, T.E., Amoroso, L., Pearthree, P.A., and Lund, W.R., 2003, Evidence for variable slip from the last three surface-rupturing earthquakes along the central Hurricane fault zone [abs.]: Seismological Research Letters, v. 74, no. 2, p. 238.

Age of Youngest Faulting:
Holocene

Discussion:
The HFZ is a long (250 km), generally north-trending fault near the western margin of the Colorado Plateau in southwestern Utah and northwestern Arizona. From the Utah-Arizona border, the HFZ trends generally north along the steep Hurricane Cliffs, forming a narrow zone of sub-parallel, en-echelon, west-dipping normal faults. Stewart and Taylor (1996) document 450 m of stratigraphic separation in Quaternary basalt and a total separation of 2520 m across the HFZ near Anderson Junction in Utah. Displacement decreases southward; Pearthree (1998) indicates Cenozoic displacement of only 200-400 m along most of the HFZ in Arizona. Several swarms of historical seismicity have occurred adjacent to, but cannot be correlated directly with, the north end of the HFZ (Arabasz and Smith, 1979; Pechmann and others, 1995).

The AJS is one of six sections identified along the HFZ (Black and others, 2003). The AJS is near the center of the HFZ, extending approximately 45 km from north of Toquerville in Utah to south of Cottonwood Canyon in Arizona. The fault trace generally follows a high, north-trending, west-facing escarpment in Paleozoic bedrock. Scarps up to 30 m high with slopes up to 35^{o} on late Pleistocene colluvium and alluvium mark the fault along the base of the escarpment.

Earthquake Timing:
Stenner and others (1999) excavated two trenches on the AJS at Cottonwood Canyon in Arizona. One trench crossed a low fault scarp less than 1 m high formed on a stream terrace; the second trench crossed a 5-m-high scarp formed on an intermediate-age alluvial fan a few tens of meters to the south. Additionally, Stenner and others (2003) excavated a trench across a single fault scarp formed on an alluvial fan at Rock Canyon, approximately 4 km south of Cottonwood Canyon.

At Cottonwood Canyon, Stenner and others (1999) identified two surface-faulting earthquakes on the basis of stratigraphic displacement, shear fabric, and fault drag. Soil development on the faulted stream terrace implies a surface age of 8-15 ka. Based on stratigraphic relations in the trench across the low scarp on the terrace, Stenner and others (1999) estimate an age of 5-10 ka for the MRE (event Z). No carbon or other material suitable for dating was recovered from the first trench. Similarly, soil-profile development on the older alluvial-fan surface indicates an age of 25-50 ka. Charcoal from slope colluvium above fissure-fill material in the second trench yielded a ^{14}C age of 870 years, which was interpreted as too young to be representative of the age of the colluvium and likely the result of bioturbation. Based on stratigraphic relations in the second trench, Stenner and others (1999) believe the timing of event Z is the same as in the first trench. The timing of event Y could not be determined in the second trench other than >5-10 ka and $\leq$25-50 ka (the age of the fan).

The trench at Rock Canyon revealed evidence for three surface-faulting earthquakes of variable displacement based on stratigraphic displacement, shear fabric, fault drag, fissuring, and minor graben formation. Laboratory results from bulk samples collected from the trench for ^{14}C analyses are not yet available, so the timing of the three earthquakes is unknown.

The timing of surface-faulting earthquakes on the HFZ is poorly constrained; consequently, the Working Group's consensus surface-faulting chronology for the Anderson Junction section of the HFZ, is limited to broad time intervals.

Z 5-10 ka
Y >5-10 ka and <25-50 ka
X >25-50 ka?

Surface-Faulting Recurrence:

Stenner and others (1999, 2003) do not report recurrence intervals at either Cottonwood Canyon or Rock Canyon. However, the surface-age estimates at Cottonwood Canyon imply one surface-faulting earthquake in the past 8-15 kyr and likely within the past 5-10 kyr, and two earthquakes in 25-50 kyr. Neither age estimates for the surface of the alluvial fan, nor the three surface-faulting earthquakes at Rock Canyon are presently available. However, if events Y and Z at Rock Canyon are the same as at Cottonwood Canyon, then event X at Rock Canyon must be >25-50 kyr, since it was not recognized in the second trench at Cottonwood Canyon.

Because information on the timing of surface faulting on the AJS of the HFZ is poorly constrained, the Working Group's preferred recurrence-interval estimate is reported as a range rather than as a central value with approximate two-sigma confidence limits to reflect the large uncertainty associated with the data. Based on available information, the Working Group's preferred recurrence-interval estimate for the AJS is:

5-50 kyr

Vertical Slip-Rate:

Based on scarp profiles measured at Cottonwood Canyon, Stenner and others (1999) calculate vertical slip rates of 0.1-0.3 mm/yr in deposits ~70-125 ka, and 0.1-0.4 mm/yr in ~25-50 ka deposits. Lund and others (in press) geochemically correlated and radiometrically dated ($^{40}Ar/^{39}Ar$) displaced basalt flows across the HFZ at the Ash Creek Section/AJS boundary, and at South Black Ridge, Pah Tempe Hot Springs, and Grass Valley, all on the AJS. These flows indicate a vertical slip rate since the middle Quaternary of $\geq$0.45 mm/yr, slowing to about $\leq$0.2 mm/yr since about 350 ka.

Based on available information, the Working Group's preferred vertical slip-rate estimate and confidence limits for the AJS are:

0.05-**0.2**-0.4 mm/yr

Summary:

Three of the six fault sections identified along the HFZ lie entirely or partially in southwestern Utah. The AJS is the southernmost of the three sections and straddles the Utah/Arizona border. The AJS is the only Utah section of the HFZ that has been successfully trenched, and both trench sites are on the Arizona portion of the section. The trenches provide evidence for three surface-faulting earthquakes; however, earthquake timing can only be constrained to broad time intervals.

Vertical slip-rate estimates for the AJS come from profiles measured across scarps formed on unconsolidated late Quaternary deposits and from displaced basalt flows. These data show a decreasing rate of slip from middle Quaternary time to the present.

Additional References:

Arabasz, W.J., and Smith, R.B., 1979, The November 1971 earthquake swarm near Cedar City, Utah, *in* Arabasz, W.J., Smith, R.B., and Richins, W.D., editors, Earthquake studies in Utah, 1850 to 1978: Salt Lake City, University of Utah Seismograph Stations Special Publication, p. 423-432.

Black, B.D., Hecker, S., 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 1:50,000, compact disk.

Pearthree, P.A., 1998, Quaternary fault data and map for Arizona: Arizona Geological Survey Open-File Report 98-24, scale 1:750,000, 122 p.

Pechmann, J.C., Arabasz, W.J., and Nava, S.J., 1995, Seismology, *in* Christenson, G.E., editor, The September 2, 1992 M_L 5.8 St. George earthquake, Washington County, Utah: Utah Geological Survey Circular 88, p.1.

Stewart, M.E., and Taylor, W.J., 1996, Structural analysis and fault segment boundary identification along the Hurricane fault in southwestern Utah: Journal of Structural Geology, v. 18, p. 1017-1029.

UTAH QUATERNARY FAULT PARAMETER WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Great Salt Lake fault zone (GSLFZ), Davis, Weber, and Box Elder Counties, Utah

Paleoseismic Data Source Documents:

Dinter, D.A., and Pechmann, J.C., 2000, Paleoseismology of the East Great Salt Lake fault: U.S. Geological Survey, National Earthquake Hazards Reduction Program Final Technical Report, Award Number 98HQGR1013, 6 p.

Coleman, S. M., Kelts, K. R., and Dinter, D. A., 2002, Depositional history and neotectonics in Great Salt Lake, Utah, from high-resolution seismic stratigraphy: Sedimentary Geology, v. 148, p. 61-78.

Dinter, D.A., and Pechmann, J.C., 2004a, Segmentation and Holocene displacement history of the East Great Salt Lake fault: Salt Lake City, PowerPoint presentation to the 2004 Utah Earthquake Conference, 26 February, 2004.

Dinter, D.A., and Pechmann, J.C., 2004b, Holocene segmentation and displacement history of the East Great Salt Lake fault, Utah [ext. abs.]: submitted to Proceedings of the Basin and Range Province Seismic Hazards Summit II, Reno, Nevada, May 16-19, 2004, 5 p.

Age of Youngest Faulting:

Holocene

Discussion:

The GSLFZ is a major active system of normal faults, which lies submerged beneath Great Salt Lake along the west side of Antelope and Fremont Islands and the Promontory Mountains peninsula (Coleman and others, 2002). The GSLFZ is north of and generally on trend with the Oquirrh fault zone (OFZ; Olig and others, 1996), which bounds the east side of Tooele Valley at the base of the Oquirrh Mountains. Dinter and Pechmann (2000, 2004a, 2004b) subdivide the GSLFZ into three segments on the basis of high-resolution seismic-reflection data. From south to north the three segments are: the Antelope Island segment (AIS), Fremont Island segment (FIS), and Promontory segment (PS). The boundary between the AIS and FIS is a 1-2 km left step in the fault west of White Rock Bay on Antelope Island. The AIS is 35 km long, is marked by a lakebed scarp up to 3.6 m high, and bends sharply to the southwest at its southern end where it appears to merge with the OFZ. The FIS is 30 km long and has no fault scarps along most of its length. No high-resolution seismic-reflection data are presently available for the PS.

The high-resolution seismic-reflection data collected for the AIS and FIS both show evidence for three lake-sediment-displacing earthquakes in post Lake Bonneville time. Subsequent drilling and sampling at critical locations along the two fault segments resulted in the recovery of carbon suitable for ^{14}C dating.

Earthquake Timing:

Dinter and Pechmann (2004a, 2004b) report the following earthquake timing for the AIS and FIS of the GSLFZ.

Event	^{14}C yr B.P.[1]	cal yr B.P.[2]	Residence-corrected cal yr B.P.[3]	Residence-corrected cal yr before 2004
Antelope Island segment				
EH-A3	>804±38 <1027±44	>706 +81/-40 <944 +106/-147	586 +201/-241[5]	640 +201/-241[5]
EH-A2	5711±50	6491 +163/-135	6170 +236/-234	6224 +236/-234
EH-A1	9068±66	10,219 +178/-234	9898 +247/-302	9952 +247/-302
Fremont Island segment				
EH-F3	3269±47	3471 +161/-90	3150 +235/-211	3204+235/-211
EH-F2	5924±44	6733 +121/-90	6412 +209/-211	6466 +209/-211
EH-F1	<10,155±72	<11,748 +580/-406	<11,427 +605/-449	<11,481 +605/-449

[1]Before 1950, one-sigma error bars.
[2]Before 1950, two-sigma error bars, Stuiver and others (1998), terrestrial calibration (CALIB v. 4.3).
[3]Before 1950, two-sigma error bars, correction for carbon residence time in provenance area prior to deposition = 321 +191/-171 cal yr—the difference between the terrestrially calibrated ^{14}C date of Mazama ash interval in the Antelope Island segment core (7994 +170/-128 cal yr BP) and terrestrial calibration (7673 +133/-86 cal yr BP) of published Mazama ^{14}C age (6845 ± 50 ^{14}C yr B.P., Bacon, 1983).
[4]Two-sigma error bars.
[5]age of event horizon interpolated from dates of material collected above and below it.

Surface-Faulting Recurrence:

Dinter and Pechmann (2004a, 2004b) report the following earthquake recurrence intervals for the AIS and FIS of the GSLFZ. Their average single-segment recurrence interval of 4200±1400 yrs represents the mean, with its two-sigma error bars, for the three closed recurrence intervals.

Earthquake Pairs	Timing (terrestrially calibrated[1], residence corrected[2], calendar year B.P.[3])[4]	Recurrence Interval (yr) [4]
Antelope Island segment (Mw[max] = 6.9±0.3)[5]		
EH-A3 EH-A2	586 +201/-241 6170 +236/-234	5584 +219/-172
EH-A2 EH-A1	6170 +236/-234 9898 +247/-302	3728 +223/-285
Fremont Island segment (Mw[max] = 6.8±0.3)[5]		
EH-F3 EH-F2	3150+235/-211 6412 +209/-211	3262 +151/-184
EH-F2 EH-F1	6412 +209/-211 <11,427 +605/-449	<5015 +587/-424
Average single-segment recurrence interval = 2800-4200-5600 years		

[1]Raw ^{14}C years were converted to calendar years using Stuiver and others (1998) terrestrial calibration (CALIB v.4.3; Stuiver and Reimer, 1993)
[2] Correction for carbon residence time in provenance area prior to deposition = 321+191/-171 cal yr, the difference between the terrestrially calibrated ^{14}C date of Mazama ash interval at Site GSL00-3 (=7994+170/-128 cal yr B.P.) and terrestrial calibration (=7673+113/-86 cal yr B.P.) of published Mazama ^{14}C age (6845±50 ^{14}C yr B.P.; Bacon [1983]).
[3] Calendar years before 1950
[4] Errors shown are two-sigma
[5]Calculated from surface rupture length using an empirical relation for normal faults from Wells and Coppersmith (1994). Uncertainty limits are one-sigma.

Vertical Slip Rate:

Pechmann and Dinter (University of Utah, written communication to Working Group, 2004) report a slip rate applicable to both the AIS and FIS of 0.55+0.5/-0.25 mm/yr. This slip rate is based upon net vertical tectonic displacements (NVTD) determined at 17 locations across the sublacustrine AIS scarp from high-resolution seismic profiles. Integration of the 17 NVTD measurements versus distance along the fault and dividing by the length of the AIS fault trace resulted in an average NVTD of 2.3±0.6 m. Pechmann and Dinter interpret the average NVTD along the AIS to be the average during the last surface-faulting earthquake on the segment, which was 586 +201/-241 cal yr B.P. Their basis for this interpretation is (1) the observation that there is a prominent fault scarp along the AIS, but not along most of the FIS, which has not had a surface-faulting earthquake since 3150 +235/-211 cal yr B.P., and (2) that their seismic-reflection data shows no significant difference in the amount of sediment accumulation between the two sides of the fault since the last earthquake. The slip rate comes from dividing the average AIS NVTD of 2.3±0.6 m by the average recurrence interval of 4200±1400 yrs. They assume that the slip rate for the AIS is also applicable to the FIS given the similarities in sediment thickness along both segments (Viveiros, 1986).

Summary:

Information on surface-faulting timing and NVTD for the GSLFZ comes from high-resolution seismic-reflection profiles and drilling information. Because the GSLF lies entirely submerged beneath Great Salt Lake no trench data are available for this fault.

Based on the available data, the Working Group adopts the values reported by Dinter and Pechmann (2004a, 2004b, written communication 2004) as their consensus average recurrence-interval and vertical slip-rate estimates for both the Fremont Island and Antelope Island segments of the GSLFZ. However, for consistency with the Working Group consensus parameters for other faults, the uncertainty limits on the average recurrence interval have been changed from two standard deviations of the mean to two standard deviations of the distribution (2400 yrs). The uncertainty limits on the slip rate were correspondingly adjusted.

Recurrence interval	1800-4200-6600 years
Vertical slip rate	0.55+1.06/-0.30 mm/yr

References:

Bacon, C. R., 1983, Eruptive history of Mount Mazama and Crater Lake Caldera, Cascade Range, USA: Journal of Volcanology and Geothermal Research, v. 18, p. 57-115.

Olig, S.S., Lund, W.R., Black, B.D., and Mayes, B.H., 1996, Paleoseismic investigation of the Oquirrh fault zone, Tooele County, Utah, *in* Lund, W.R., editor, Paleoseismology of Utah, Volume 6, The Oquirrh fault zone, Tooele County, Utah -Surficial geology and paleoseismicity: Utah Geological Survey Special Study 88, p. 22-64.

Stuiver, M., and Reimer, P., 1993, University of Washington Quaternary Isotope Lab Radiocarbon Calibration Program Rev. 4.3: Radiocarbon, v. 35, p. 215-230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., and Braziunas, T.F., 1998, Revised calibration dataset: Radiocarbon, v. 40, p. 1127-1151.

Viveiros, J. J., 1986, Cenozoic tectonics of the Great Salt Lake from seismic reflection data: M.S. Thesis, University of Utah, Salt Lake City, Utah, 99 p.

Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, p. 974-1002.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Oquirrh fault zone (OFZ), Tooele County, Utah

Paleoseismic Data Source Documents:

Olig, S.S., Lund, W.R., Black, B.D., and Mayes, B.H., 1996, Paleoseismic investigation of the Oquirrh fault zone, Tooele County, Utah, *in* Lund, W.R., editor, Paleoseismology of Utah, Volume 6, The Oquirrh fault zone, Tooele County, Utah - Surficial geology and paleoseismicity: Utah Geological Survey Special Study 88, p. 22-64.

Age of Youngest Faulting:

Holocene

Discussion:

The OFZ is a north-trending, range-front normal fault bounding the east side of Tooele Valley at the western base of the Oquirrh Mountains. Scarps formed on alluvium and lake deposits range from 12 to 18 m high, have maximum slope angles of 24 to 32^{o} and surface displacements of 4.0 to 6.8 m. Everitt and Kaliser (1980) and Barnhard and Dodge (1988) divide the OFZ into two sections: a northern section expressed by Quaternary fault scarps formed on basin-fill sediments, and a southern section expressed as a prominent break in slope at the base of the range front. Large displacements documented on the northern section imply a rupture length greater than 12 km (the length of the northern trace), suggesting both sections of the fault probably form a single rupture segment extending from the town of Stockton to Great Salt Lake (Solomon, 1996).

Olig and others (2001) excavated trenches at two sites where the OFZ crosses Lake Bonneville deposits overlain by late Holocene alluvium/colluvium. Three trenches at the Big Canyon site were about 0.3 km west of the mouth of Big Canyon. Radiocarbon ages on bulk samples from debris-flow deposits directly overlain by colluvial-wedge material, and from unfaulted fluvial deposits that bury the fault scarp, constrain the timing of the MRE. The Big Canyon trenches did not expose evidence for older earthquakes.

A single trench at the Pole Canyon site 1.7 km northwest of the mouth of Pole Canyon, lacked diagnostic stratigraphy and datable organic material necessary to resolve the timing of event Z beyond a post-Bonneville age. Radiocarbon ages from charcoal in a Bonneville transgressive marsh deposit and an older fluvial deposit constrain the timing of the PE. A ^{14}C age from charcoal in fluvial sediments that bury the eroded free face of the antepenultimate earthquake (event X) provides a broadly limiting minimum age for that earthquake.

Earthquake Timing:

Olig and others (1996) identified the three most recent surface-faulting earthquakes on the OFZ. Evidence for events Y and Z consists of scarp-derived colluvial-wedge deposits. A buried scarp free face provides indirect evidence for event X; the trench was not deep enough to expose the event X colluvial wedge.

<u>Event Z</u>

At Big Canyon, bulk samples from the youngest faulted deposit, an organic-rich debris flow, yielded ^{14}C ages of 6840±100 and 7650±90 ^{14}C yr B.P. Because the ^{14}C age from the debris flow came from a mix of detrital material entrained in the debris flow when it was active, Olig and others (1996) considered the younger date to represent a better maximum limit for the timing of event Z. Calendar calibrated and rounded to the nearest century, the younger age is 7600+300/-100 cal yr B.P. A bulk sample of an unfaulted, organic-rich, debris-flow deposit 0.5 m above the event Z colluvial wedge yielded a calendar-calibrated age of 4900±100 cal yr B.P., which provides a minimum limit on event Z timing. Therefore, at Big Canyon event Z is constrained within a 3100 yr interval between 4800 and 7900 cal yr B.P. Where within that time period the earthquake occurred is not known; however, Olig and others (1996) report event Z timing as 6350±1550 cal yr B.P., which is the middle of the interval.

The Pole Canyon trench provided neither stratigraphic relations nor datable organic material that allowed event Z to be constrained more closely than at Big Canyon.

Event Y

At Pole Canyon, three ^{14}C ages help constrain the timing of event Y. Two ages came from a faulted, charcoal-rich, channel-fill deposit. A single, large charcoal fragment yielded an age of 33,950±1160 ^{14}C yr B.P., and several small detrital charcoal fragments combined for dating yielded an average age of 26,200±200 ^{14}C yr B.P. Both ^{14}C ages were too old to calendar calibrate (Stuiver and Reimer, 1993), and Olig and others (1996) considered the younger age the best limiting age for the deposit, and a maximum limit on event Y timing, which must be younger than the deposits it displaces.

The third ^{14}C age came from detrital charcoal recovered from a lake-marginal marsh deposit at the base of the Lake Bonneville transgressive sequence directly overlying the event Y colluvial wedge. The charcoal yielded a ^{14}C age of 20,370±120 ^{14}C yr B.P., which is also too old to calendar calibrate.

Therefore, event Y occurred within an approximate 6100 ^{14}C yr interval between 26,400 and 20,300 ^{14}C yr B.P. Where within that time period the earthquake occurred is not known; however, Olig and others (1996) report event Y timing as 23,350±3100 ^{14}C yr B.P., which is the middle of the interval.

Event X

The Pole Canyon trench provides indirect evidence to partially constrain the age of the antepenultimate earthquake. The charcoal-rich, stream-channel deposit (see above) exposed in the trench unconformably overlies a stratigraphic package, which includes post-event X slope colluvium that mantles the event X free face. The event X colluvial wedge remained buried beneath the trench floor. The sedimentary units comprising the older stratigraphic package did not contain organics and could not be directly dated. However, the event X free face lies beneath the stream-channel deposit and therefore the earthquake is older than 26,400 ^{14}C yr B.P (see above). How much older is unknown; however, a paleosol formed on the colluvial unit overlying the event X free face includes strong Bt and Bk (stage III) horizons, implying a long period of soil formation. Therefore, event X could be several thousand to several tens of thousands of years older than event Y.

Based upon currently available paleoseismic information, the Working Group's consensus surface-faulting chronology for the OFZ is:

Z between 4800 and 7900 cal yr B.P

Y between 20,300 and 26,400 ^{14}C yr B.P.
X > 26,400 ^{14}C yr B.P.

Surface-Faulting Recurrence:

Data on surface-faulting recurrence for the OFZ are restricted to a single, poorly constrained interevent interval. Age estimates for earthquakes Y and Z constrain the most recent interevent interval on the OFZ as follows: minimum = 12.4 kyr, maximum = 21.6 kyr, mean = 17 kyr.

Because information on surface-faulting recurrence for the OFZ is poorly constrained, the confidence limits for the Working Group's preferred recurrence-interval estimate are intentionally broad to reflect high uncertainty.

5-**20**-50 kyr

Vertical Slip Rate:

Using the above maximum, minimum, and mean estimates for the length of the Y-Z interevent interval, and a net vertical displacement for event Z of 2.0-2.7 m as reported by Olig and others (1996) from the Big Canyon and Pole Canyon trench sites, results in a vertical slip rate for the most recent interevent interval of 0.09-0.14-0.22 mm/yr.

Because information on surface-faulting recurrence and net vertical displacement for the OFZ are poorly constrained, the confidence limits for the Working Group's preferred vertical slip-rate estimate for the OFZ are intentionally broad to reflect high uncertainty.

0.05-**0.2**-0.4 mm/yr

Summary:

Paleoseismic information available for the OFZ is limited. The two most recent earthquakes (Y and Z) are constrained to broad time intervals, each thousands of years long. Indirect evidence for a penultimate earthquake (X) indicates that event occurred several thousand to tens of thousands of years prior to event Y, but the actual age of event X remains unknown. Likewise vertical slip-rate estimates are based on net vertical-displacement measurements for event Z from just two locations along the fault trace. How representative those displacements are of the long-term slip distribution along the fault is unknown. Net vertical-displacement measurements for longer time intervals from scarp profiles are not possible because the OFZ scarps lie below the high stand of Lake Bonneville and were heavily modified as the lake transgressed and regressed across them.

Results of the Olig and others (1996) investigation show that the OFZ is a low slip rate fault typical of much of the Basin and Range Province. Comparison of earthquake timing on the OFZ with that on the Salt Lake City segment (SLCS) of the Wasatch fault zone (WFZ) approximately 45 km to the east, shows little or no correlation between surface-faulting earthquakes. The SLCS has had as many as six surface-faulting earthquakes in the Holocene; the OFZ has had one. Because event Z on the OFZ is only broadly constrained, it is not possible to correlate it with a particular Holocene earthquake on the WFZ.

The OFZ lies on tend with the Great Salt Lake fault zone to the north and the Southern Oquirrh Mountains fault zone (SOMFZ) to the south. All three faults exhibit Holocene surface faulting, and Olig and others (1996) and Olig and others (2001) speculate that the three faults may be part of a single, more than 200-km-long fault zone that parallels the Weber, Salt Lake City, and Provo segments of the WFZ to the east. Additionally, Olig and others (2001) believe that the OFZ and the SOMFZ have ruptured coseismicly, at least since the late Pleistocene.

Additional References:

Barnhard, T.P., and Dodge, R.L., 1988, Map of fault scarps formed on unconsolidated sediments, Tooele 1^{o} x 2^{o} quadrangle, northwestern Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1990, scale 1:250,000.

Everitt, B.L, and Kaliser, B.N., 1980, Geology for assessment of seismic risk in Tooele and Rush Valleys, Tooele County, Utah: Utah Geological and Mineral Survey Special Studies 51, 33 p.

Olig, S.S., Gorton, A.E., Black, B.D., and Forman, S.L., 2001, Paleoseismology of the Mercur fault and segmentation of the Oquirrh - East Great Salt Lake fault zone, Utah: Oakland, California, URS Corporation, unpublished technical report for U.S. Geological Survey, Award No. 98HQGR1036, variously paginated.

Solomon, B.J., 1996, Surficial geology of the Oquirrh fault zone, Tooele County, Utah, *in* Lund, W.R., editor, Paleoseismology of Utah, Volume 6, The Oquirrh fault zone, Tooele County, Utah - Surficial geology and paleoseismicity: Utah Geological Survey Special Study 88, p. 1-17.

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C database and revised CALIB 3.0 ^{14}C calibration program: Radiocarbon, v. 35, no. 1, p. 215-230.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Southern Oquirrh Mountains fault zone (SOMFZ), Tooele County, Utah

Paleoseismic Data Source Documents:

Everitt, B.L., and Kaliser, B.N., 1980, Geology for assessment of seismic risk in the Tooele and Rush Valleys, Tooele County, Utah: Utah Geological and Mineral Survey Special Studies 51, 33 p.

Barnhard, T.P., and Dodge, R.L., 1988, Map of fault scarps formed on unconsolidated sediments, Tooele 1^{o} x 2^{o} quadrangle, northwestern Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1990, scale 1:250,000.

Olig, S.S., Gorton, A.E., and Chadwell, L., 1999, Mapping and Quaternary fault scarp analysis of the Mercur and West Eagle Hill faults, Wasatch Front, Utah: Oakland, California, URS Greiner Woodward Clyde, National Earthquake Hazards Reduction Program Final Technical Report, Award No. 1434-HQ-97-GR-03154, variously paginated, scale 1:48,000.

Olig, S.S., Gorton, A.E., Black, B.D., and Forman, S.L., 2000, Evidence for young, large earthquakes on the Mercur fault - implications for segmentation and evolution of the Oquirrh-East Great Salt Lake fault zone, Wasatch Front, Utah [abs.]: Geological Society of America Abstracts with Programs, 2000 Annual Meeting, v. 32, no. 7.

—2001, Paleoseismology of the Mercur fault and segmentation of the Oquirrh - East Great Salt Lake fault zone, Utah: Oakland, California, URS Corporation, unpublished technical report for U.S. Geological Survey, Award No. 98HQGR1036, variously paginated.

Age of Youngest Faulting:

Holocene

Discussion:

The SOMFZ consists of enechelon, down-to-the-west normal faults bounding the western flank of the southern Oquirrh Mountains. Olig and others (1999) define the SOMFZ as including the previously recognized Mercur (MF), West Eagle Hill (WEHF), Soldier Canyon (SCF), and Lakes of Kilarney (LKF) faults. The MF and WEHF comprise 17 km of the total SOMFZ along-strike length of 25 km, and show evidence for repeated Quaternary displacement in late Pleistocene alluvial fans and terraces. The SCF and LKF comprise the remaining 8 km and are chiefly expressed in bedrock or as bedrock-alluvial contacts. Barnhard and Dodge (1988) report that MF scarps show displacements of 1.8 to 5.6 m. Faulted alluvium exposed in a mine shaft, and an uplifted bedrock pediment, suggest a minimum of 60 m of Quaternary displacement on the MF (Everitt and Kaliser, 1980). Olig and others (1999) report that net vertical displacements of intermediate-age surfaces average 5.3 to 6.3 m, and are 1.0 to 2.0 m on the MF and WEHF, respectively. Maximum displacements on older surfaces are 21.7 and 2.8 m, respectively. Displacement patterns indicate faulting has shifted basinward and most Quaternary displacement was partitioned on the MF, although coseismic rupture on both faults remains a possibility.

Everitt and Kaliser (1980) excavated a trench near the southern end of the MF, about 4.5 km west of Fivemile Pass and just south of where the scarp intersects the Bonneville shoreline. Trench stratigraphy revealed evidence for repeated surface faulting during the late Pleistocene, and a 0.6-m-high scarp was interpreted as indicating post-Bonneville displacement.

Barnhard and Dodge (1988) reinterpreted Everitt and Kaliser's trench data, analyzed fault-scarp morphology from 11 scarp profiles, and excavated a shallow trench just south of the Everitt and Kaliser (1980) trench; they found no evidence of post-Bonneville surface faulting. Neither study included numerical age dating. Olig and others (2001) trenched three traces of the MF where it crosses alluvial-fan deposits about 30 km south of Tooele, near the intersection of Utah Highway 73 and Mercur Canyon Road. The trenching revealed evidence for five to seven surface-faulting earthquakes since about 92±14 ka and as recently as about 4.6±0.2 ka.

Earthquake Timing:

Olig and others (2001) identified evidence for five to seven surface-faulting earthquakes in three trenches (c-center, e-east, and w-west) across the MF. The evidence included stacked colluvial-wedge stratigraphy and differential displacement and crosscutting relations. Earthquake timing is summarized below:

Z	shortly after 4.6±0.2 ka and well before 1.4±0.1 ka
Y	between 20 and 50 ka
X	shortly after 42±8 ka – may or may not correlate with earthquakes V_C or W_E
W	shortly after 75±10 ka – may or may not correlate with earthquakes V_C and W_E, although event V_C is probably older
V	around (shortly after?) 92±14 ka

Olig and others (2001) consider the timing of the above five earthquakes, although broadly constrained, to be well established. Uncertainty regarding the total number of earthquakes comes from difficulty in correlating earthquakes between trenches. Specifically earthquakes V_C and W_E may correlate with one or more earthquakes in the west trench, or they may represent separate earthquakes, resulting in the possibility of five to as many as seven surface-faulting earthquakes on the SOMFZ. The above earthquake chronology is constrained by two ^{14}C ages and six infrared spin luminescence ages from buried vesicular A horizon soils.

Based on available data, the Working Group adopts the Olig and others (2001) surface-faulting chronology presented above as their consensus chronology for the SOMFZ.

Surface-Faulting Recurrence:

Olig and others (2001) calculated average recurrence intervals for the SOMFZ based on 5 to 7 earthquakes between 92±14 and 4.6±0.2 ka, resulting in average recurrence intervals of 12 to 25 kyr. However, they state that due to uncertainty in earthquake timing, intervals between earthquakes could be as great as 46 kyr. Additionally, they note that the lack of soil development between earthquakes X_W and Y_W in contrast to the strong soil development between earthquakes X_W and Z_W, suggests an order of magnitude or more difference in the length of individual interevent intervals.

Because available paleoseismic information indicates that interevent intervals on the SOMFZ may vary by an order of magnitude, the confidence limits for the Working Group's recurrence-interval estimate for the OFZ are intentionally broad to reflect high uncertainty. Additionally, Olig and others (2001) believe that the SOMFZ likely ruptures coseismicly with the OFZ to the north and their recurrence-interval estimate also reflects that possibility. Based upon available paleoseismic information, the Working Group's preferred recurrence-interval estimate and confidence limits for the SOMFZ are:

5-**20**-50 kyr

Vertical Slip Rate:

Based on data for the past four to six interevent intervals on the SOMFZ, Olig and others (2001) report an average slip rate of 0.09-0.14 mm/yr for the past approximately 90 kyr.

The Working Group’s preferred vertical slip-rate estimate for the SOMFZ reflects the Olig and others (2001) long-term average above; however, the confidence limits have been increased to accommodate uncertainty resulting from possible large variations in slip through time. Additionally, Olig and others (2001) believe that the SOMFZ likely ruptures coseismicly with the OFZ to the north, and consequently the fault’s vertical slip-rate estimates also reflect that possibility. Based upon available paleoseismic information, the Working Group’s preferred vertical slip-rate estimate and confidence limits for the SOMFZ are:

0.05-**0.2**-0.4 mm/yr

Summary:

The Olig and others (2001) study demonstrates that the SOMFZ is a low slip rate, long recurrence interval normal fault typical of the Basin and Range Province. The timing of the surface-faulting earthquakes identified by trenching could only be broadly constrained even after careful paleoseismic study. The SOMFZ and the OFZ to the north lie on trend with each other along the western base of the Oquirrh Mountains. Based on range-front geomorphology and similarities in the timing of events X, Y, and Z on both the SOMFZ and OFZ, Olig and others (2001) believe that the two faults have ruptured coseismicly, at least since the late Pleistocene.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Eastern Bear Lake fault (EBLF) southern section, Rich County, Utah and Bear Lake County, Idaho

Paleoseismic Data Source Documents:

McCalpin, J.P., 1990, Latest Quaternary faulting in the northern Wasatch to Teton corridor (NWTC): Final Technical Report for U.S. Geological Survey, Contract No. 14-08-001-G1395, 42 p.

——1993, Neotectonics of the northeastern Basin and Range margin, western USA, *in* Stewart, I., Vita-Finzi, C., and Owen, L., editors, Neotectonics and active faulting: Zeitschrift fur Geomorphologie, Supplement Bd., p. 137-157.

——2003, Neotectonics of Bear Lake Valley, Utah and Idaho; A preliminary assessment: Utah Geological Survey Miscellaneous Publication 03-4, 43 p.

Age of Youngest Faulting:

Holocene

Discussion:

The EBLF is a 78-km-long, west-dipping normal fault bounding the east side of the Bear Lake Valley half graben in Utah and Idaho (McCalpin, 1990, 1993, 2003). Seismic-reflection data show that the lake floor and reflectors within the underlying Neogene sediments dip eastward into the EBLF (Skeen, 1975). Total throw of the top of the Eocene Wasatch Formation across the fault is about 1.5 km at the north end of Bear Lake (McCalpin, 1990). McCalpin (2003) divides the EBLF into northern, central, and southern sections on the basis of fault-rupture patterns, morphology of fault scarps, and subsurface geophysical data. Only a portion of the southern section is in Utah. Whether these geomorphic sections define earthquake rupture segments cannot be determined from currently completed paleoseismic studies because paleoseismic data are only available for the southern section of the fault (McCalpin, 2003).

The southern section of the EBLF extends for 32 km from Laketown, Utah in the south to Bear Lake Hot Springs at the northeastern corner of Bear Lake in Idaho. Along its length, the southern section is marked by discontinuous fault scarps up to 13 m high in Quaternary deposits at the base of a steep escarpment of Mesozoic rocks on the east side of Bear Lake. Scarps are best developed where the fault crosses the mouths of major drainages such as at North Eden Creek, where McCalpin (1990, 1993, 2003) excavated two trenches.

Earthquake Timing:

At North Eden Creek, McCalpin (2003) constrained the timing of surface faulting on the southern section of the EBLF as follows:

East Trench

Y >5.0±0.5 ka, but likely not much greater

X <31±6 ka but much >15.2±0.8 ka

W >31±6 ka but <39±3 ka
V >31±6 ka but <39±3 ka
U >39±3 ka, but likely not much greater

West Trench

Z <2.1±0.2 ka but >0.6±0.08 ka
Y ~5 ka (2.5 ka TL age estimate considered erroneously young)

Despite a young TL age (2.5 ka) in the west trench indicating that the two earthquakes recorded there occurred within the past 2.5 kyr, McCalpin (2003) questions how both surface-faulting earthquakes can be younger than 2.5 ka, and why neither earthquake was recognized in the eastern trench only a few tens of meters away. He hypothesizes that event Y in the western trench may be older than 2.5 ka, and that the soil sample from the western trench that gave the 2.5±0.5 ka TL age may have been inadvertently collected from younger material, possibly in an animal burrow. In that case, event Y in the western trench may correlate with event Y in the eastern trench (hence the same letter designation in the chronology above) and there would only be one earthquake younger than about 5 ka.

Based on available data, the Working Group adopts the McCalpin (2003) surface-faulting chronology presented above as their consensus chronology for the southern section of the EBLF.

Surface-Faulting Recurrence:

McCalpin (2003) reports a mean recurrence for the southern section of the EBLF over the past five interevent intervals (events U to Z) of 7.6 kyr. However, although earthquake timing is generally poorly constrained on the EBLF, the elapsed time between individual surface-faulting earthquakes appears highly variable, ranging from about 2.9 kyr between earthquakes Y and Z to a minimum of 10.2 kyr between earthquakes X and Y.

Because available paleoseismic information indicates that interevent intervals on the southern section of the EBLF may be highly variable, the confidence limits for the Working Group's preferred recurrence-interval estimate are intentionally broad to reflect high uncertainty. Based upon available paleoseismic information, the Working Group's preferred recurrence-interval estimate and confidence limits for the southern section of the EBLF are:

3-**8**-15 kyr

Vertical Slip Rate:

McCalpin (2003) reports that all but 1.2 m of the net ≥23.3 m of vertical displacement measured at the North Eden site occurred since 39 ka. Therefore, over the past 5 interevent intervals, ≥22.1 m of net vertical displacement has been released in about 38 kyr for an average vertical slip rate of ≥0.58 mm/yr. However, this slip rate may be affected (made smaller) by undetected antithetic faulting beneath Bear Lake or by unmeasured tectonic back-tilting; both of which would decrease stratigraphic displacement, and if not accounted for result in net vertical-displacement values that are too large.

Paleoseismic data show that vertical slip rates for individual interevent intervals on the central section of the EBLF are highly variable, reflecting variability in the length of time between individual earthquakes and in the net vertical displacement per earthquake. Therefore, the confidence limits for the Working Group's preferred recurrence-interval estimate are intentionally broad to reflect high uncertainty. Based upon available paleoseismic information, the Working

Group's preferred recurrence-interval estimate and confidence limits for the southern section of the EBLF are:

0.2-**0.6**-1.6 mm/yr

Summary:

The EBLF consists of three geometric sections that may or may not be independent seismogenic segments. Paleoseismic data are only available for a single location on the southern section. Those data indicate that there have been six surface-faulting earthquakes on the southern part of the EBLF in the past ~40 kyr. Only the timing of the youngest earthquake is well constrained, and available net-vertical-displacement measurements are mostly minimum estimates.

Additional References:

Skeen, R.C., 1975, A reflection seismic study of the subsurface structure and sediments of Bear Lake, Utah-Idaho: Salt Lake City, University of Utah, senior thesis, 25 p.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Bear River fault zone (BRFZ), Summit County, Utah and Uinta County, Wyoming

Paleoseismic Data Source Documents:

West, M.W., 1994, Paleoseismology of Utah, Volume 4 - Seismotectonics of north central Utah and southwestern Wyoming: Utah Geological Survey Special Study 82, 93 p.

Age of Youngest Faulting:

Holocene

Discussion:

The BRFZ extends for about 40 km from southeast of Evanston, Wyoming to the north flank of the Uinta Mountains in Utah, where it ends at a complex juncture with the Laramide-age North Flank thrust fault. In general, the BRFZ consists of distinct individual scarps each about 3.0 to 3.5 km long arranged in a right-stepping, en echelon pattern. Major scarps trend N. 20° W. to N. 20° E., and show consistent down-to-the-west displacement. Scarps with lesser, down-to-the-east displacements, are interpreted to be antithetic faults and trend N. 15-20° W. Near the south end of the fault zone, scarps show a strong angular discordance (70°) with the main north-northeast pattern of faulting, likely due to the buttressing effect of the Uinta Mountains. Scarp heights and tectonic displacements increase markedly from north to south along the BRFZ. Fault scarps are between 0.5 m and 15 m high on upper Quaternary deposits; sag ponds, beheaded drainages, and antithetic fault scarps are also present. Late Holocene to historic landsliding obscures evidence of faulting through an approximately 9-km-wide gap between the southernmost clearly defined scarps in Wyoming and the northernmost scarps in Utah.

Earthquake Timing:

West (1994) excavated seven trenches, logged an irrigation ditch exposure, and measured 14 scarp profiles on the BRFZ. The irrigation ditch exposure and four of the trenches were on scarps in Wyoming; the other three trenches were in Utah. Results of the trenching showed that there has been a minimum of two surface-faulting earthquakes on the BRFZ based on stacked colluvial-wedge stratigraphy, although additional poorly constrained earthquakes are considered possible on some scarps.

Constraints on earthquake timing were provided by ^{14}C ages and amino acid racemization ratios obtained from land snail shells. West (1994) reported timing for the two most recent surface-faulting earthquakes on the BRFZ as:

Z	2370 ±1050 yr B.P.
Y	4620±690 yr B.P.

The ages for both earthquakes are "best estimate" mean values calculated from the youngest and oldest constraining ages obtained for the two earthquakes, as determined from the trenches excavated across the BRFZ scarps. The "±" confidence limits reflect the greater of the differences between the mean value and the youngest or oldest possible earthquake ages, and are considered by West to incorporate both the analytical uncertainty of the ^{14}C ages and the geologic uncertainty associated with earthquake timing. However, earthquake timing is reported as "yr B.P." because, while all ^{14}C ages on soil organics were calendar calibrated according to de Jong and others (1986), Linick and others (1986), and Pearson and Stuiver (1986), no mean residence corrections (Machette and others, 1992, appendix A) were subtracted from the calibrated ages to account for the age of the carbon in the soil at time of burial. As a result, West (1994) states:

> *"It is likely that the estimated ages [timing] of the surface-faulting events in the project area (4620±690 and 2370±1050 yr B.P.) may be too old by at least several hundred years."*

The estimate of several hundred years too old reflects West's belief that the soils in his study area are significantly better developed and therefore older than the soils studied by Machette and others (1992) along the Wasatch fault zone, where the average soil age was estimated as 200-400 years.

Recognizing that the timing of surface-faulting earthquakes reported by West (1994) may be too old by several hundred years, the Working Group accepts the earthquake timing as published as representing the currently "best available" information for the BRFZ.

Surface-Faulting Recurrence:

The interevent interval between events Y and Z is 2250 (+690/-1050) yrs. The timing for event Z is 2370±1050 yr B.P., indicating that the elapsed time since the MRE exceeds the interevent interval between events Y and Z.

The Working Group recognizes the likelihood of a young age for the BRFZ, but also notes that in many places the BRFZ trends across a stable landscape that likely is hundreds of thousands of years old, thus raising the possibility of an alternative fault-behavior model for the BRFZ; one of large infrequent earthquakes or clusters of earthquakes similar to the Pitaycachi fault in the southern Basin and Range Province, which produced a M>7.2 earthquake in Sonora, Mexico in 1887. The Pitaycachi fault is believed to have a recurrence interval on the order of 100 kyr (Bull and Pearthree, 1988). A long-recurrence interval fault likewise would leave little contemporary geomorphic evidence of its past history.

Unable to resolve which of the two possible fault-behavior models applies to the BRFZ based on available paleoseismic information, the Working Group's preferred recurrence-interval estimate is reported as a broad range, rather than as a central value with approximate two-sigma confidence limits, to better reflect the high level of uncertainty regarding surface-faulting recurrence on the BRFZ.

1-100 kyr

Vertical Slip Rate:

The vertical slip rates reported by West (1994) for BRFZ scarps are open ended because the time intervals used in his calculations extend to the present. Recalculating vertical slip rates for the BRFZ using the interevent interval between events Y and Z and net vertical-displacement values determined from scarps, results in vertical slip rates for the Y-Z interevent interval that range from 0.5 to 1.9 mm/yr. If a single earthquake produced one particularly large scarp, one slip rate is as high as 2.3 mm/yr. However, because the scarp is likely the result of multiple earthquakes the actual slip rate is probably lower.

Unable to determine from presently available paleoseismic data which of the two possible fault behavior models applies to the BRFZ, the confidence limits for the Working Group's preferred vertical slip-rate estimate are intentionally broad to reflect large uncertainty.

0.05-**1.5**-2.5 mm/yr

Summary:

West (1994) believes the BRFZ is a young fault, likely representing normal-slip reactivation over a pre-existing thrust fault. However, the trace of the BRFZ crosses a landscape largely hundreds of thousands of years old, yet the geomorphic expression of the fault zone consists of scarps only a few meters to tens of meters high (no associated mountain range), indicating the possibility of large infrequent earthquakes or clusters of earthquakes separated by long periods of scarp erosion and burial. Trenching reveals good evidence for only two surface-faulting earthquakes, both of which occurred since the middle Holocene. Given the current short paleoseismic record available for the BRFZ, it is not known if the interevent interval between events Y and Z is representative of future surface-faulting recurrence on the BRFZ.

Additional References:

Bull, W.B., and Pearthree, P.A., 1988, Frequency and size of Quaternary surface ruptures of the Pitaycachi fault, northern Sonora, Mexico: Bulletin of the Seismological Society of America. v. 78, p. 965-978.

deJong, A.F.M., Becker, B., and Mook, W.G., 1986, High-precision calibration of the radiocarbon time scale, 3930-3230 BC, *in* Stuiver, M., and Kra, R.S., editors, Radiocarbon calibration issue – Proceedings of the 12th International Radiocarbon Conference, Trondheim, Norway: Radiocarbon, v. 28, no. 2B, p. 939-942.

Linick, T.W., Long, A., Damon, P.E., and Ferguson, C.W., 1986, High-precision radiocarbon dating of bristlecone pine from 6554 to 5350 BC, *in* Stuiver, M., and Kra, R.S., editors, Radiocarbon calibration issue – Proceedings of the 12th International Radiocarbon Conference, Trondheim, Norway: Radiocarbon, v. 28, no. 2B, p. 943-953.

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

Pearson, G.W., and Stuiver, M., 1986, High-precision calibration of the radiocarbon time scale, 500-2500 BC, *in* Stuiver, M., and Kra, R.S., editors, Radiocarbon calibration issue – Proceedings of the 12th International Radiocarbon Conference, Trondheim, Norway: Radiocarbon, v. 28, no. 2B, p. 839-862.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Morgan fault zone (MFZ), central section, Morgan County, Utah

Paleoseismic Data Source Documents:

Sullivan, J.T., Nelson, A.R., LaForge, R.C., Wood, C.K., and Hansen, R.A., 1988b, Central Utah regional seismotectonic study for USBR dams in the Wasatch Mountains: Denver, U.S. Bureau of Reclamation Seismotectonic Report 88-5, 269 p., scale 1:250,000.

Sullivan, J.T., and Nelson, A.R., 1992, Late Quaternary displacement on the Morgan fault, a back valley fault in the Wasatch Range of northeastern Utah, *in* Gori, P.L., and Hays, W.W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front: U.S. Geological Survey Professional Paper 1500-I, 19 p.

Age of Youngest Faulting:

Holocene

Discussion:

The MFZ is a range-front normal fault that extends for 22 km at the base of a bedrock escarpment along the eastern side of Morgan Valley, a back valley of the Wasatch Range. Sullivan and others (1988b) divide the MFZ into three linear sections based on the morphology of the bedrock escarpment in the fault footwall. No fault scarps are recognized on unconsolidated deposits along the three fault sections. The northern section is 13 km long and consists of a main western fault trace and an older eastern fault trace. The central section is 7 km long and consists of a main fault trace and an antithetic fault trace inferred to the west. The southern section consists of a single, short (2-km-long), northwest-trending fault trace. Only the central section has been trenched, so it is unknown if the three sections are independently seismogenic.

Sullivan and Nelson (1992) state that the central section of the fault shows evidence of Holocene movement, whereas the northern and southern sections only show evidence for late Quaternary movement, although scarp morphology is similar for all three sections. The central section of the MFZ consists of a north trending, range-front main fault trace and an inferred northeast-trending antithetic fault trace to the west. Although trenching showed that early Holocene colluvium is faulted, scarps in unconsolidated deposits are not preserved along the fault. Sullivan and Nelson (1992) attributed this to the steepness (20-25^{o}) of escarpment slopes and the inferred small amount of surface displacement (0.5-1.0 m) during earthquakes.

Earthquake Timing:

Sullivan and others (1988b) excavated five trenches at the southern end of the central section of the MFZ. All five trenches were at or near the break in slope at the base of the footwall escarpment and two of the trenches exposed the main trace of the MFZ. Evidence for the MRE consists of an escarpment-derived colluvial wedge. Sullivan and Nelson (1992) report a net vertical displacement of about 1 m for the MRE and cumulative net vertical displacement of approximately 4 m. Stratigraphic relations and ^{14}C ages on pre-MRE peat (8320$\pm$100 ^{14}C yr B.P. [~9300 cal yr B.P.]) and wood (9105$\pm$270 ^{14}C yr B.P. [~10,250 cal yr B.P.]) provide maximum limits on timing of the MRE. It was not possible to establish minimum limits.

Sullivan and Nelson (1992) interpret a massive, moderately indurated sandy silt unit in one of the trenches as a complex, escarpment-derived colluvial deposit that represents an unknown number of small (0.5 to 1 m) surface-faulting earthquakes that occurred in middle through late Pleistocene time; however, the timing of individual earthquakes is unknown.

Based on presently available paleoseismic information, the Working Group's consensus fault chronology for the central section of the MFZ is:

Z	<8320±100 ^{14}C yr B.P. [~9300 cal yr B.P.]
Y-?	middle through late Pleistocene, individual earthquake timing unknown

Surface-Faulting Recurrence:

Sullivan and Nelson (1992) state that if 0.5 m is the average net displacement per earthquake, then 4 m of displacement represents eight earthquakes. If average per earthquake displacement is 1.0 m, then the 4 m represents 4 surface-faulting earthquakes. Assuming that the displacement occurred over the past 200 to 400 ka (based on soil developed on faulted deposits at several locations along the fault), the average middle to late Quaternary vertical slip rate for eight earthquakes would be 25 to 50 kyr, and 50 to 100 kyr for four earthquakes.

Because the timing of individual surface-faulting earthquakes is poorly constrained, the Working Group's recurrence-interval estimate is reported as a broad range rather than as a central value with approximate two-sigma confidence limits to reflect high uncertainty. The Working Group's preferred recurrence-interval estimate for the MFZ is:

25-100 kyr

Vertical Slip Rate:

Sullivan and Nelson (1992) report a minimum average long-term vertical slip rate of 0.01 to 0.02 mm/yr based on 4 m of displacement in deposits that are 200 to 400 kyr old.

Because the age of the displaced deposits is poorly constrained (±200 kyr), the confidence limits for the Working Group's vertical slip-rate estimate are intentionally broad to reflect the uncertainty associated with possible variations in slip through time. The Working Group's preferred vertical slip-rate estimate and confidence limits for the central section of the MFZ are:

0.01-**0.02**-0.04 mm/yr

Summary:

The MFZ is a very low slip rate fault that has experienced a one-meter displacement surface-faulting earthquake during the Holocene. The timing and size of earlier earthquakes are unknown, but are estimated to include 4 to 8 small earthquakes each having 0.5 to 1.0 m of net vertical displacement over the past 200 to 400 kyr. Available paleoseismic data for the MFZ are very poorly constrained and permit only broad characterization of the fault's paleoseismic parameters.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

James Peak fault (JPF), Cache County, Utah

Paleoseismic Data Source Documents:

Sullivan, J.T., Nelson, A.R., LaForge, R.C., Wood, C.K., and Hansen, R.A., 1988b, Central Utah regional seismotectonic study for USBR dams in the Wasatch Mountains: Denver, U.S. Bureau of Reclamation Seismotectonic Report 88-5, 269 p., scale 1:250,000.

Nelson, A.R., and Sullivan, J.T., 1992, Late Quaternary history of the James Peak fault, southernmost Cache Valley, north-central Utah, *in* Gori, P.L., and Hays, W. W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-G, p. J1-J13.

Age of Youngest Faulting:

Late Pleistocene

Discussion:

The JPF is a short (7 km), northeast-trending, range-front normal fault along the northern flank of James Peak at the south end of Cache Valley. Cache Valley is a north-trending intermontane graben (bounded by high-angle normal faults on the east and west) between the Bear River and Wasatch Ranges. Faulting on the JPF displaces Bull Lake outwash deposits (~140 ka). The short fault length suggests that surface faulting may have extended northward, rupturing the southern section of the East Cache fault zone (ECFZ). Faceted spurs at the base of James Peak suggest recurrent Quaternary displacements, though the spurs are smaller, less continuous, and less steep than those along the nearby ECFZ and Wasatch fault zones.

Earthquake Timing:

Sullivan and others (1988b) excavated a trench across a 7-m-high scarp formed on a Bull Lake glacial outwash fan. The trench exposed sandy, quartzite-derived outwash on which was developed a reddish, clayey soil horizon overlain by a bouldery wedge of silty fault colluvium. Silty colluvial units with thick cambic and argillic B-horizons overlie the colluvial wedge. The contrasting lithologies of the outwash, colluvial wedge, and overlying colluvium; cumulative displacement across the scarp (4.2 m); and the short fault length suggest that the scarp was produced by two surface-faulting earthquakes rather than by a single, large earthquake.

All age estimates are based on soil-profile development on Quaternary deposits of different ages. Nelson and Sullivan (1992) estimate that the soil formed on the pre-faulting glacial outwash and the soil formed on the post-earthquake fault colluvium both required 30 to 70 kyr to develop. Therefore, the two postulated surface-faulting earthquakes happened after 110-70 ka (140 ka – 30,000 to 70,000 years) and before 30-70 ka (period of post-earthquake soil formation). Where in that broad time interval the earthquakes actually occurred is unknown, except that no soil was found on the possible older wedge, indicating a relatively short period of time between earthquakes. Additionally, soil development indicates no surface-faulting earthquakes have occurred on the JPF since at least 30 ka and possibly not since 70 ka.

Surface-Faulting Recurrence:

Because the soils developed on the outwash and on the colluvium overlying the fault-derived colluvial wedges provide only broad maximum and minimum constraints on the timing of surface faulting, the true interval of time between surface-faulting earthquakes is unknown. Both the soil formed on the glacial outwash beneath the fault-scarp colluvium and the soil formed on top of the colluvial wedges are estimated to have required 30-70 kyr to form. Thus, the first earthquake could have occurred as early as 110 ka or as late as 70 ka. Considering that the soil on top of the wedges could be as young as 30 ka, a time interval of 80 kyr is available in which the two earthquakes could have occurred. Assuming that 40 kyr separates the two earthquakes, the average recurrence interval is at least 50 kyr (50 kyr + 40 kyr + 50 kyr = 140 kyr). However, the absence of a soil formed on the first colluvial wedge argues for a short interval between the two postulated earthquakes, indicating that surface-faulting recurrence on the JPF is non-uniform.

Because individual earthquake timing is unknown, the confidence limits for the Working Group's recurrence-interval estimate for the JPF are intentionally broad to reflect uncertainty associated with possible large variations in recurrence through time. The Working Group's preferred recurrence-interval estimate and confidence limits for the MFZ are:

10-**50**-100 kyr

Vertical Slip Rate:

Based on an estimated 4.2 m of net vertical displacement in ~140 ka, Nelson and Sullivan (1992) estimate an average late Quaternary slip rate of 0.03 mm/yr for the JPF.

Nelson and Sullivan (1992) speculated that the JPF might be a southern extension of the ECFZ, and Nelson (U.S. Geological Survey, verbal communication to UQFPWG, 2003) now considers the JPF likely a southern extension of the ECFZ to the north. Following a review of available paleoseismic data for the JPF, the Working Group concurs with that assessment and recommends that the JPF be considered part of the ECFZ. Whether it is an extension of the currently defined southern section of the ECFZ (McCalpin, 1994), or is a fourth independent section awaits additional paleoseismic investigation on the southern section of the ECFZ to determine the timing of surface-faulting earthquakes there. Based on geomorphic relations, McCalpin (1994) reports a long-term vertical slip rate for the southern section of the ECFZ as high as 0.07 mm/yr, depending on the ages assumed for displaced deposits. The Working Group recommends using 0.07 mm/yr as the upper bound of possible vertical slip rates for the JPF until further study of the southern section of the ECFZ demonstrates otherwise. The Working Group's preferred vertical slip-rate estimate and confidence limits for the JPF, pending further paleoseismic study of the southern section of the ECFZ are:

0.01-**0.03**-0.07 mm/yr

Summary:

The JPF is a very short, very low slip rate fault located close to the southern end of the ECFZ. Both the number and timing of individual surface-faulting earthquakes are poorly constrained. Based on presently available paleoseismic evidence and its close physical proximity, the Working Group recommends that the JPF be considered part of the ECFZ to the north. Whether the JPF is a part of the southern section of the ECFZ (McCalpin, 1994) or a separate forth section awaits additional paleoseismic investigation.

Additional References:

McCalpin, J.P., 1994, Neotectonic deformation along the East Cache fault zone, Cache County, Utah: Utah Geological Survey Special Study 83, 37 p.

UTAH QUATERNARY FAULT PARAMETER WORKING GROUP
CONSENSUS
RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
Towanta Flat graben (TFG), Duchesne County, Utah

Paleoseismic Data Source Documents:
Martin, R.A., Jr., Nelson, A.R., Weisser, R.R., and Sullivan, J.T., 1985, Seismotectonic study for Taskeech Dam and Reservoir site, Upalco Unit and Upper Stillwater Dam and Reservoir site, Bonneville Unit, Central Utah Project, Utah: Denver, U.S. Bureau of Reclamation Seismotectonic Report 85-2, 95 p.

Nelson, A.R., and Weisser, R.R., 1985, Quaternary faulting on Towanta Flat, northwestern Uinta Basin, Utah, *in* Picard, M.D., editor, Geology and energy resources, Uinta Basin of Utah: Utah Geological Association Publication 12, p. 147-158.

Age of Youngest Faulting:
Middle Quaternary

Discussion:
Nine short, northeast-striking fault scarps are present on Towanta Flat about 6 km south of the Uinta Mountains in the northern part of the Uinta Basin. The scarps bound a 5-km-long graben that varies in width from 170 to 610 m. Scarp heights range from 5-15 m. Nelson and Weisser (1985) found no significant net vertical displacement across the graben, although they determined the average throw across individual scarps to be 2.1-2.6 m per earthquake. The lack of net vertical displacement across the graben, together with an orientation that differs from planes defined by microseismicity, the limited extent of the scarps, and an average recurrence interval that has been exceeded by the elapsed time since the MRE, suggests to Martin and others (1985) that the faults comprising the TFG may not have a seismogenic origin, and may not be capable of significant future surface-faulting earthquakes. Black and others (2003) categorize the TFG as a "Suspected" fault in the *Quaternary Fault and Fold Database and Map of Utah*.

Earthquake Timing:
The U.S. Bureau of Reclamation (Martin and others, 1985; Nelson and Weisser, 1985) excavated three trenches on the TFG. Two trenches crossed aerial-photo lineaments in a glacial meltwater channel in the southeastern part of Towanta Flat. The other trench crossed a 5-m-high scarp bounding the graben on the north near its western end. The trench across the scarp revealed stratigraphic and structural relations that indicate at least three surface-faulting earthquakes. Based on soil-profile development of paleosols formed on colluvial wedges, Nelson and Weisser (1985) believe that the three earthquakes occurred within the past 250-500 kyr, with no scarps mapped in deposits younger than Bull Lake age (130-150 ka), indicating no surface displacement in late Quaternary time. The two trenches in the glacial meltwater channel exposed unfaulted Bull Lake deposits.

Based upon presently available paleoseismic information, the Working Group's consensus surface–faulting chronology for the TFG is:

Z, Y, X   >130 ka, <250-500 ka

Surface-Faulting Recurrence:

Martin and others (1985) report a mean recurrence of 25 to 90 kyr for surface displacement between 250-500 ka and 130-150 ka, with no displacement since 130-150 ka.

Due to uncertainty regarding the seismogenic capability of the TFG, the long elapsed time since the MRE, and the unknown lengths of the intervals between surface-faulting earthquakes, the confidence limits for the Working Group's preferred recurrence-interval estimate for the TFG are intentionally broad to reflect high uncertainty regarding this enigmatic structure. The Working Group's preferred recurrence-interval estimate and confidence limits for the TFG are:

25-**50**-200 kyr

Vertical Slip Rate:

Martin and others (1985) estimate maximum vertical slip rates across individual TFG scarps range from 0.02 to 0.04 mm/yr. Piety and Vetter (1999) indicate the maximum vertical slip rate for the TFG faults is $\leq$0.09 mm/yr. However, Nelson and Weisser (1985) found no net vertical displacement across the graben as a whole, and question the seismogenic capability of the TFG. Because there is no net vertical displacement across the TFG, the Working Group makes no vertical slip-rate estimate for the TFG.

Summary:

The TFG is an enigmatic structure; a short, narrow graben exhibiting no cumulative net vertical displacement and located far from any other active or potentially active faults. The timing of individual surface-faulting earthquakes is unknown, with three earthquakes occurring within a broad time window between about 500 ka and 130 ka, and no earthquakes since 130-150 ka. Martin and others (1985) and Nelson and Weisser (1985) question if this low slip rate fault system is seismogenic. At present, that question remains unanswered; however, the current elapsed time since the MRE exceeds the estimated middle Pleistocene average recurrence interval by tens to several tens of thousands of years, indicating either long-term quiescence of the fault system or cessation of surface-faulting activity.

Additional References:

Black, B.D., Hecker, S., 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 1:50,000, compact disk.

Piety, L.A., and Vetter, U.R., 1999, Seismotectonic report for Flaming Gorge Dam, Colorado River Storage Project, northeastern Utah: Denver, Bureau of Reclamation Seismotectonic Report 98-2, 78 p.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP
CONSENSUS
RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
Bald Mountain fault (BMF), Wasatch County, Utah

Paleoseismic Data Source Documents:
Sullivan, J.T., Martin, R.A., and Foley, L.L., 1988a, Seismotectonic study for Jordanelle Dam, Bonneville Unit, Central Utah Project, Utah: Denver, U.S. Bureau of Reclamation Seismotectonic Report 88-6, 76 p., scale 1:24,000.

Sullivan, J.T., Nelson, A.R., LaForge, R.C., Wood, C.K., and Hansen, R.A., 1988b, Central Utah regional seismotectonic study for USBR dams in the Wasatch Mountains: Denver, U.S. Bureau of Reclamation Seismotectonic Report 88-5, 269 p., scale 1:250,000.

Age of Youngest Faulting:
Middle Quaternary

Discussion:
The BMF is a very short (2 km), northeast-trending normal fault on the east side of Bald Mountain, west of Jordanelle Reservoir and close to Jordanelle Dam. Tertiary volcanic rocks, primarily highly erodible tuff, dominate the geology of the area. The fault escarpment is more eroded, but appears similar to those in other back valleys east of the Wasatch Range. A steep-sided trough (imaged by seismic refraction) beneath the Provo River Valley to the south may be fault bounded, but trenching studies for Jordanelle Dam determined that Quaternary (probably >130 ka) deposits are unfaulted.

Earthquake Timing:
Sullivan and others (1988a) excavated three trenches in surficial deposits across the inferred trace of the BMF, as projected from adjacent bedrock and borehole control (no scarps were recognized on unconsolidated deposits), about 1.5 km northwest of Jordanelle Dam. Late Quaternary faulting was not recognized in the trenches. Sullivan and others (1988a, 1988b) estimate the age of the MRE as >130 ka based on soil-profile development on an unfaulted, escarpment-derived colluvial apron and associated basin-fill deposits, and by the morphology of the base of the escarpment along the fault.

Surface-Faulting Recurrence:
Unknown

Vertical Slip Rate:
Unknown

Summary:
Based on a review of available paleoseismic data, the Working Group is unable to make recurrence-interval or vertical slip-rate estimates for the BMF.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Strawberry fault (SF), Wasatch County, Utah

Paleoseismic Data Source Documents:

Nelson, A.R., and Martin, R.A., Jr., 1982, Seismotectonic study for Soldier Creek Dam, Central Utah Project: Denver, U.S. Bureau of Reclamation Seismotectonic Report 82-1, 115 p., scale 1:250,000.

Nelson, A.R., and VanArsdale, R.B., 1986, Recurrent late Quaternary movement on the Strawberry normal fault, Basin and Range - Colorado Plateau transition zone, Utah: Neotectonics, v. 1, p. 7-37.

Age of Youngest Faulting:

Early to middle Holocene

Discussion:

The SF is an approximately 43-km-long, down-to-the-west normal fault characterized by a zone of north- to northwest-trending faulting along the eastern and northern side of Strawberry Valley near the western edge of the Uinta Basin. Strawberry Valley is the easternmost of several back valleys of the Wasatch Range, a north-south series of discontinuous valleys in the Wasatch Hinterlands east of the Wasatch Range. The SF forms a single bedrock escarpment, 100 to 230 m high, from its southern end northward to Trout Creek. Continuing north from Trout Creek, the SF forms multiple scarps on alluvium and bedrock across a zone 5 km wide. At Co-op Creek, a 200-m-high escarpment juxtaposing Quaternary alluvial-fan sediments against Tertiary bedrock marks the main fault, while subsidiary scarps about 1.3 km to the west formed on the Co-op Creek alluvial fan are up to 3 km long and as much as 7 m high. Due to backtilting and graben formation, stratigraphic displacement on these scarps is much greater than net vertical displacement. Latest Pleistocene or Holocene deformation is also indicated by the asymmetry of stream channels (evidence for tectonic tilting) and the presence of nickpoints in small stream channels above the scarps.

The enechelon pattern of faulting north of Strawberry Reservoir suggests that the main SF is segmented, although similarities in escarpment morphologies suggest a similar movement history along the entire fault.

Earthquake Timing:

Nelson and Martin (1982) excavated two trenches across a 7-m-high fault scarp formed on the Co-op Creek alluvial fan west of the main trace of the SF. The trenched scarp is one of four scarps on the alluvial fan. The two trenches were about 1 km apart, and both exposed faulted alluvial-fan deposits. Investigators did not recognize scarps on unconsolidated deposits along the main fault trace at the base of the bedrock escarpment to the east.

Based on stratigraphic relations in the two trenches, Nelson and VanArsdale (1986) interpret two to three surface-faulting earthquakes on the subsidiary fault strand in the past 15 to 30 kyr. Deposit age estimates are based on soil-profile development and indicate that the MRE occurred during the early to mid-Holocene; with a minimum possible constraint on timing of 1.5 ka based on a ^{14}C age on organic material filling an animal burrow. Older earthquake(s) can only be constrained as older than the MRE and younger than 15 to 30 ka. The relation between surface-faulting earthquakes on the subsidiary fault strand and the main SF is unknown.

Surface-Faulting Recurrence:

Nelson and VanArsdale (1986) report a mean recurrence of 5 to 15 kyr based on the estimated number of earthquakes (2 or 3) on a single alluvial-fan scarp over the past 15 to 30 kyr. The relation between the displacement histories of the fan scarps and the main fault trace are unknown. Because the trenched scarp is only one of four scarps on the fan, the number of surface-faulting earthquakes, displacement per earthquake, and total displacement across the SF as a whole is unknown.

Because paleoseismic-trenching data available for the SF are poorly constrained and restricted to a single alluvial scarp west of the main fault trace, the confidence limits for the Working Group's preferred recurrence-interval estimate for the SF are intentionally broad to reflect large uncertainty. The Working Group's preferred recurrence-interval estimate and confidence limits for the SFG are:

5-**15**-25 kyr

Vertical Slip Rate:

A latest Pleistocene and Holocene vertical slip rate calculated from the estimated net vertical displacement across the 7-m-high subsidiary scarp (1 to 2 m per earthquake) is 0.04-0.17 mm/yr. However, Nelson and VanArsdale (1986) state that while the trenched scarps formed on the Co-op Creek alluvial fan may represent most of the displacement within the fault zone during the earthquakes that produced them, additional displacement probably occurred on the main fault during at least some of these earthquakes. They believe that scarps in unconsolidated deposits at the base of the bedrock escarpment along the main fault are less likely to be preserved than are scarps on the gently sloping alluvial fan 1.3 km west of the escarpment. For this reason, the investigators did not assume that the displacement represented by the alluvial-fan scarps was the total displacement across the fault zone during the earthquakes that produced the scarps. A minimum late Quaternary (~70 - 90 ka) vertical slip rate for the SF of 0.03-0.06 mm/yr is provided by ^{14}C and amino acid dating of samples collected from flood-plain drill cores in the fault footwall near the main escarpment along the southern section of the fault (Nelson and VanArsdale, 1986).

Because paleoseismic-trenching data available for the SF are poorly constrained and restricted to a single alluvial scarp west of the main fault trace, the confidence limits for the Working Group's preferred vertical slip-rate estimate for the SF are intentionally broad to reflect large uncertainty. The Working Group's preferred vertical slip-rate estimate and confidence limits for the SFG are:

0.03-**0.1**-0.3 mm/yr

Summary:

The SF is a low slip rate normal fault, the easternmost of the Wasatch back-valley faults of the Wasatch Range. The main trace of the fault shows no evidence of displaced Quaternary deposits, but four scarps formed on the Co-op Creek alluvial fan about 1.3 km west of the main fault trace provide evidence for latest Pleistocene/Holocene surface faulting. All available paleoseismic trenching data for the SF come from one of those subsidiary fault scarps formed on alluvium, and the relation between slip and surface-faulting recurrence on that fault strand to the main SF is unknown.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Hansel Valley fault (HVF), Box Elder County, Utah

Paleoseismic Data Source Documents:

McCalpin, J.P., 1985, Quaternary fault history and earthquake potential of the Hansel Valley area, north-central Utah: Final Technical Report to the U.S. Geological Survey, Contract No. 14-08-001-21899, 37 p.

McCalpin, J.P., Robison, R.M., and Garr, J.D., 1992, Neotectonics of the Hansel Valley-Pocatello Valley corridor, northern Utah and southern Idaho, *in* Gori, P.L., and Hays, W. W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-G, p. G1–G18.

Age of Youngest Faulting:

Historic

Discussion:

The HVF is a 22-km-long, east-dipping normal fault in southwestern Hansel Valley characterized by northeast-trending scarps several kilometers east of the Hansel Mountains in northwestern Utah. The HVF is the site of the 1934 M_L 6.6 Hansel Valley earthquake, Utah's only historical surface-faulting earthquake. The northern half of the fault is a single continuous trace, whereas the southern half is a wide zone of several short, en-echelon fault traces. The most recent prehistoric earthquake on the fault is estimated to have produced a net vertical displacement of 2.2-2.5 m. The 1934 earthquake only ruptured the southern few kilometers of the HVF and produced a maximum vertical displacement of 0.5 m where the southern portion of the fault intersects the mudflats at the north end of Great Salt Lake (Walter, 1934; dePolo and others, 1989).

Earthquake Timing:

McCalpin (1985) logged a gully exposure near the northern end of the HVF. Stratigraphy, sedimentology, and ostracode assemblages, along with five TL ages and a ^{14}C age on a gastropod shell provide a framework within which McCalpin and others (1992) interpreted surface faulting within a context of pluvial lake cycles. McCalpin and others (1992) argue for multiple earthquakes between about 140 and 72 ka, no earthquakes between 72 to 58 ka, at least one earthquake (but possibly more) between 58 and 26 ka (nearer the latter), an earthquake around 14 to 15 ka, and possibly another earthquake at 13 ka. The exposed portion of the gully wall did not include colluvial wedges or other evidence of individual surface-faulting earthquakes, so it was not possible to determine the timing or displacement of individual surface-faulting earthquakes. Post-Bonneville alluvium truncates all exposed faults in the gully wall, indicating no Holocene surface faulting, including the 1934 earthquake, has occurred on this part of the HVF.

Surface-Faulting Recurrence:

Available paleoseismic data (McCalpin and others, 1992) implies widely varying lengths of interevent intervals between surface-faulting earthquakes on the HVF. Multiple earthquakes of unknown timing between 140 and 72 ka give no clear indication of average recurrence, but no earthquakes between 72 and 58 ka creates a 14-kyr interval. One or more earthquakes from 58 to 26 ka produce a recurrence interval potentially as long as 32 kyr, or possibly several shorter intervals. An earthquake at 14-15 ka possibly followed by another at about 13 ka, would give an interevent interval of only 1-2 kyr; followed by an interval of 13 kyr preceding the 1934 earthquake.

Based on the limited information available, the confidence limits for the Working Group's preferred recurrence-interval estimate for the HVF are intentionally broad to reflect large uncertainty associated with possible large variations in recurrence through time. The Working Group's preferred recurrence-interval estimate and confidence limits for the HVF are:

15-**25**-50 kyr

Vertical Slip Rate:

Neither McCalpin (1985) nor McCalpin and others (1992) report a slip rate for the HVF.

Black and others (2003) estimate a vertical slip rate of 0.14-0.22 mm/yr, based on a 10-16 kyr recurrence and prehistoric displacement of 2.2-2.6 m. The vertical slip rate based on 0.5 m of displacement in the 1934 earthquake and a recurrence of 13 kyr would be much lower. McCalpin (GEO-HAZ Consulting, verbal communication to Working Group, 2003) re-evaluated his paleoseismic data for the HVF based on an estimated 1 to 4 m of displacement since ~17 ka. The Working Group adopts McCalpin's late Pleistocene/Holocene slip rate and confidence limits as their preferred vertical slip-rate estimate for the HVF:

0.06-**0.12**-0.24 mm/yr

Summary:

Both the number and timing of surface-faulting earthquakes on the HVF are unknown. The fault exhibits an irregular pattern of surface faulting with interevent intervals ranging from possibly as little as 1 to 2 kyr to more than 30 kyr; indicating that interevent intervals between surface-faulting earthquakes on the HVF have been highly variable through time. Although there is circumstantial evidence to indicate that the time between some surface-faulting earthquakes may be as short as 1-2 kyr (likely triggered by the Bonneville flood if the earthquake did in fact happen [McCalpin, GEO-HAZ Consulting, verbal communication to Working Group, 2004]), the Working Group believes that much longer interevent intervals are a more likely norm for the HVF.

Additional References:

Black, B.D., Hecker, S., 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 1:50,000, compact disk.

dePolo, C.M., Clark, D.G., Slemmons, D.B., and Aymard, W.H., 1989, Historical Basin and Range Province surface faulting and fault segmentation, *in* Schwartz, D.P., and Sibson, R.H., editors, Fault segmentation and controls of rupture initiation and termination - Proceedings of conference XLV: U.S. Geological Survey Open-File Report 89-315, p. 131-162.

Walter, H.G., 1934, Hansel Valley, Utah, earthquake: The Compass of Sigma Gamma Epsilon, v. 14, no. 4, p. 178-181.

UTAH QUATERNARY FAULT PARAMETER WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Hogsback fault (HF), unnamed south section, Summit County, Utah

Paleoseismic Data Source Documents:

West, M.W., 1994, Paleoseismology of Utah, Volume 4 - Seismotectonics of north central Utah and southwestern Wyoming: Utah Geological Survey Special Study 82, 93 p.

Age of Youngest Faulting:

Late Quaternary?

Discussion:

The HF is expressed as linear drainage alignments, lineaments, and subdued west-facing scarps on Pleistocene terrace and pediment surfaces. The amount of east-directed tilt of terrace surfaces increases with increasing age of the surfaces suggesting recurrent movement. The southern section of the fault (Elizabeth Ridge scarps) lies in Utah and is expressed as southwest-trending scarps, one of which is uphill facing and down to the south; the other two are downhill facing and down to the north. These scarps have apparent displacements of about 1.5-2.5 m and are subparallel to the North Flank thrust fault. The east scarp displaces the Oligocene Bishop Conglomerate on the Gilbert Peak erosion surface. Trenching revealed no direct evidence for faulting; however, West (1994) believes that geomorphic evidence is more in line with a tectonic rather than an erosional origin for the scarps. The subdued expression of the scarps (maximum scarp angles ~5^{o}) suggests that they are substantially older than similar discordant scarps at the south end of the nearby Bear River fault zone (BRFZ).

Earthquake Timing:

West (1994) excavated a trench across a down-to-the-south, uphill-facing, 2.5-m-high scarp about 1 km north of Elizabeth Pass in Utah. No datable material was recovered nor did the trench expose clear evidence of faulting.

Surface-Faulting Recurrence:

The West (1994) investigation resulted in no data concerning the timing, number, or recurrence of surface-faulting earthquakes on the HF. West (1994) suggests that the recurrence interval for the nearby BRFZ, because of analogous tectonic setting, may approximate the recurrence interval for the HF as a whole, and recommends a recurrence interval for the HF of a few thousand years. However, no evidence exists of similar short recurrence intervals during the Holocene for the HF (Black and others, 2003). Based on available paleoseismic data, the Working Group is unable to make a recurrence-interval estimate for the HF.

Vertical Slip Rate:

Poorly constrained vertical slip-rate estimates for the HF to the north range from 0.33-1.5 mm/yr (West, 1994). These vertical slip rates are based on a variety of possible ages for Bigelow Bench (150-600 ka), which is displaced as much as 200 m across the HF in Wyoming. The highest estimate infers a slip rate similar to the BRFZ (West, 1994). The 200-m offset of the Bigelow Bench surface results in a vertical slip rate of 0.33-1.33 mm/yr. Based on scarp-profile data, West (1994) reports a maximum displacement at his trench site of 1.5-2.47 m in the Oligocene Bishop Conglomerate, suggesting a very low slip rate, especially considering that the trench did not expose evidence of faulting.

Black and others (2003) assign the HF to the vertical slip-rate category of 0.2-1.0 mm/yr as a whole based on a belief that the Bigelow Bench surface is substantially older than 150 ka. However, the relation between the large 200-m-high escarpment along the HF in Wyoming and the small approximately 2-m-high scarp in Utah on a possible Oligocene-age surface is unclear, and the Working Group believes assigning such a high vertical slip rate to the Utah portion of the HF is not warranted. Based on available paleoseismic data, the Working Group is unable to make a vertical slip-rate estimate for the HF.

Summary:

No definitive paleoseismic information resulted from trenching the HF in Utah, and no paleoseismic-trenching data are available for the fault in Wyoming. West (1994) believes on the basis of geomorphic relations that the initiation of surface rupture on the HF could be as young as about 150 ka and that slip rates could be as high as 0.33-1.5 mm/yr depending on the age of displaced surfaces farther north along the fault in Wyoming. However, in the absence of substantive paleoseismic data and given the large uncertainty associated with both the age and amount of displacement of critical geomorphic surfaces, the Working Group believes assigning a slip rate to the HF comparable to that of the Wasatch fault zone is highly questionable, and particularly so for the small, subdued scarps along the southern section of the HF in Utah.

The Working Group considers the available paleoseismic data insufficient to make recurrence-interval and vertical slip-rate estimates for the HF in Utah, other than to note that existing evidence supports a very low slip rate for the southern section of the HF.

Additional References:

Black, B.D., Hecker, S., 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 1:50,000, compact disk.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP
CONSENSUS
RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

North Promontory fault (NPF), Box Elder County, Utah

Paleoseismic Data Source Documents:

McCalpin, J.P., 1985, Quaternary fault history and earthquake potential of the Hansel Valley area, north-central Utah: Final Technical Report to the U.S. Geological Survey, Contract No. 14-08-001-21899, 37 p.

McCalpin, J.P., Robison, R.M., and Garr, J.D., 1992, Neotectonics of the Hansel Valley-Pocatello Valley corridor, northern Utah and southern Idaho, *in* Gori, P.L., and Hays, W. W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500-G, p G1 –G18.

Age of Youngest Faulting:

Latest Quaternary

Discussion:

The NPF is a 27-km-long Basin and Range normal fault bounding eastern Hansel Valley in northern Utah. Hansel Valley is in an aggregation of low, north-trending ranges and narrow valleys in northern Utah between Curlew Valley on the west and the Malad River Valley on the east. Scarps appear in only two locations; elsewhere the fault is covered by Holocene talus. At the northern location, a 13-m-high scarp (8 m net vertical displacement?) displaces a delta graded to the Bonneville shoreline. At the southern site, a branch fault diverges southwesterly from the range front and creates a scarp 12.9 m high (9.5 m net vertical displacement) on a pre-Bonneville alluvial fan. Although the fault scarps appear unbeveled, McCalpin and others (1992) believe both scarps resulted from more than one surface-faulting earthquake.

The southern portion of the NPS (expressed as a prominent range front) does not displace upper Pleistocene deposits and likely last moved in the early to middle Pleistocene (Miller and Schneyer, 1990). A subsidiary fault 100 m east of the north end of the NPS is exposed in a road cut along Interstate 84 and shows evidence for a single surface-faulting earthquake.

Earthquake Timing:

Paleoseismic data available for the NPF come chiefly from a geomorphic study of the two fault scarps and from reconnaissance geologic mapping. The road-cut exposure of the subsidiary fault was logged as part of the NPF study.

McCalpin and others (1992) conclude that the two scarps present along the main NPF are probably the result of multiple surface-faulting earthquakes, but because each scarp is limited to a single geomorphic surface and neither displays evidence of multiple crests or bevels, reliable evidence of recurrent movement is lacking. The subsidiary fault exposed in the road cut near the north end of the main fault shows evidence for a single surface-faulting earthquake in the past ~100 ka. McCalpin and others (1992) believe that this earthquake is young (<15 ka), and that it produced 2.6 m of displacement.

Lacking trench data from the main NPF, information on earthquake timing is poorly constrained. McCalpin and others (1992) believe the faulting is latest Pleistocene or early Holocene (?) based on the 13-m-high scarp formed on a delta graded to the Bonneville shoreline. Slope angle versus scarp-height relations suggest that the northern scarp is roughly contemporaneous with the Bonneville shoreline, while the splay scarp to the south is older than the shoreline. Based on stratigraphic relations and soil-profile development, McCalpin and others (1992) believe the surface-faulting earthquake on the subsidiary fault occurred <15 ka, but one earthquake in ~100 kyr does not match the evidence for probable multiple late Pleistocene and early Holocene (?) surface faulting on the main NPF just 100 m to the west.

Surface-Faulting Recurrence:

McCalpin and others (1992) assume that 3 to 4 earthquakes, each exhibiting 2.0-2.5 m of net vertical displacement in the past 15 kyr would be required to construct the northern NPF scarp. On that basis, the recurrence interval for surface-rupturing earthquakes would be 3.75 to 5.0 kyr. However, McCalpin and others (1992) believe that interval is too short in comparison with nearby faults, particularly the much more active appearing Wasatch fault zone.

The southern NPF scarp displaces a pre-Bonneville alluvial fan of otherwise uncertain age. The fan may correlate with either isotope stage 4 (58-72 ka) or stage 6 (140 ka). Depending on the age assumed for the fan, McCalpin and others (1992) report that recurrence intervals of 8.6-10.8 kyr and 25-31.3 kyr are possible.

Given these uncertainties, McCalpin and others (1992) state that all that can be said with confidence is that the NPF has sustained surface rupture at least once since Bonneville time (≤18 ka) and several times since either oxygen isotope stage 4 or 6 time. Given the limited information available on earthquake timing, the Working Group is unable to make a recurrence-interval estimate for the NPF.

Vertical Slip Rate:

None reported by McCalpin (1985) or McCalpin and others (1992).

McCalpin (GEO-HAZ Consulting, verbal communication to Working Group, 2003) re-evaluated his paleoseismic data for the NPF based on an estimated 8 m of displacement since ~17 ka. The Working Group adopts McCalpin's revised late Pleistocene/Holocene vertical slip rate and confidence limits as their preferred vertical slip-rate estimate for the NPF:

0.1-**0.2**-0.5 mm/yr

Summary:

Results of the McCalpin and others (1992) study show that the NPF is a low slip rate fault typical of many similar normal-slip faults in the Basin and Range Province. The fault was not trenched and is not well exposed in stream cuts. Given the lack of information on the number and timing of surface-faulting earthquakes on the NPF, the Working Group is unable to make a recurrence-interval estimate for the NPF.

Additional References:

Miller, D.M., and Schneyer, J.E., 1990, Geologic map of the Sunset Pass quadrangle, Box Elder County, Utah: Utah Geological and Mineral Survey Open-File Report 201, 32 p., scale 1:24,000.

UTAH QUATERNARY FAULT PARAMETER WORKING GROUP
CONSENSUS
RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Sugarville area faults (SAFs), Millard County, Utah.

Paleoseismic Data Source Documents:

Dames and Moore, 1978, Phase II - preliminary geotechnical studies, proposed power plant, lower Sevier River area, Utah: Los Angeles, unpublished consultant's report for Intermountain Power Project, Job nos. 10629-00206 and 10629-003-06, 45 p., scale 1:24,000.

Age of Youngest Faulting:

Holocene (?)

Discussion:

The SAFs comprise a short (<5 km), northeast-trending zone of Quaternary normal faults or fractures in the northern Sevier Desert north and west of Delta, Utah. Lake Bonneville deposits dominate the surficial geology of the area. Lineaments and subtle relief in lake deposits characterize the SAFs. Parallel tonal lineaments 10 km to the north of the zone may be related faults, but are not mapped. Trenching revealed underlying faults, but their relation to deeper structures is unknown. A minimum throw of 3.8 m across one of the faults, combined with the short apparent rupture length, suggests that numerous small-displacement earthquakes occurred along the fault zone (Dames and Moore, 1978).

Earthquake Timing:

Dames and Moore (1978) investigated the SAFs as part of a preliminary geologic-hazards site evaluation for a coal-fired electrical generating plant. They excavated eight trenches and logged five across two suspected fault-related lineaments (the northwestern and southeastern fault zones). Liquefaction features, including injection dikes and distorted bedding, were present in one of the trenches across the southeastern fault. Trenches across the northwestern fault zone revealed stratigraphic evidence for surface faulting as well as complex faulting relations. Dames and Moore (1978) based their interpretation of surface faulting on differential displacement of geologic horizons of different ages - older horizons are displaced more than younger horizons. They established the age of faulting by broad correlation with Lake Bonneville stratigraphy.

Dames and Moore (1978) assumed a minimum of 3.8 m of cumulative vertical displacement on one fault based on maximum trench depth and the lack of correlative stratigraphic units across faults in the trenches – actual net vertical displacement is not known. Given the short length of the fault zone (4.3 km), they concluded that the 3.8 m of displacement must have occurred in multiple earthquakes of likely 30 to 60 cm each. But the trenches did not expose evidence of individual surface-faulting earthquakes.

Surface-Faulting Recurrence:

None reported. Not all faults were trenched and evidence for individual earthquakes was not exposed in the trenches, so neither the number nor timing of surface-faulting earthquakes could be constrained.

Vertical Slip Rate:
None reported; no reliable net vertical-displacement measurements resulted from the SAF investigation.

Summary:
Based upon a review of available paleoseismic information, the Working Group concludes that the data are insufficient to make recurrence-interval or vertical slip-rate estimates for the SAFs. However, the Working Group concurs with Black and others (2003) that the rate of slip on the SAFs is very low and probably <0.02 mm/yr.

Additional References:

Black, B.D., Hecker, S., 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 1:50,000, compact disk.

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:
Washington fault zone, northern section (WaFZ), Washington County, Utah and Mohave County, Arizona

Paleoseismic Data Source Documents:
Earth Sciences Associates, 1982, Phase I report, seismic safety investigation of eight SCS dams in southwestern Utah: Palo Alto, California, unpublished consultant's report for U.S. Soil Conservation Service, 2 volumes, variously paginated.

Age of Youngest Faulting:
Latest Quaternary (<15 ka)

Discussion:
The WaFZ extends for about 43 km (trace length) in a general north-south direction in northwestern Arizona and southwestern Utah. Pearthree (1998) subdivides the WaFZ into three sections: Northern, Mokaac, and Sullivan Draw based on structural and geomorphic relations. Earth Sciences Associates (1982) excavated trenches across lineaments of uncertain origin at three flood-control dams along the Northern section in Utah. Relative ages of Quaternary deposits were estimated from soil development and stratigraphy; no radiometric dating was performed. The trenches at two of the dam sites revealed no evidence of faulting. At the third dam (Gypsum Wash Dam), Earth Sciences Associates (1982) excavated five trenches. Three trenches crossed lineaments about 45 m west of the main fault trace, and revealed a wide zone of high-angle shears that form a series of horsts and grabens with a net down-to-the-west displacement. Younger unfaulted alluvial-fan deposits overlie older faulted alluvium estimated to be 5-10 ka. The other two trenches crossed the main fault trace and revealed bedrock in fault contact with late Pleistocene (?) alluvial-fan deposits, which showed a minimum of 1.2 m of displacement in the past 10-25 kyr. Younger alluvial-fan deposits, estimated no older than 1-1.5 ka, showed 5 cm of vertical displacement. Earth Sciences Associates (1982) state that this displacement could be the result of one of several possible non-tectonic processes, including gypsum dissolution.

Earthquake Timing:
None reported; individual surface-faulting earthquakes could not be identified; the Earth Sciences Associates (1982) study documented displacement only.

Surface-Faulting Recurrence:
None reported; individual surface-faulting earthquakes not recognized or dated.

Vertical Slip Rate:
None reported. However, Earth Sciences Associates (1982) state that up to 5 cm of displacement has occurred in the past 1.5 kyr and a minimum of 1.2 m in the past 10-25 kyr. Those displacements and deposit ages result in slip rates of 0.003 mm/yr for the past 1.5 kyr and a minimum slip rate of 0.05-0.12 mm/yr for the past 10 to 25 kyr.

Several kilometers to the north, a subsidiary strand of the WaFZ displaces the Washington basalt flow approximately 4.5 m. Best and others (1980) determined a K-Ar age of 1.7±0.1 Ma for the Washington flow. Assuming the 4.5-m displacement represents a close approximation of net vertical displacement, the long-term (early Quaternary) slip rate for the subsidiary fault is 0.003 mm/yr.

Summary:

The Earth Sciences Associates (1982) study did not develop information on the number, timing, or displacement of individual surface-faulting earthquakes. Therefore, the Working Group is unable to make recurrence-interval or vertical slip-rate estimates for the Northern section of the WaFZ, other than to state that the long-term rate of slip is low and likely ≤ 0.1 mm/yr.

However, the Northern section of the WaFZ traverses one of Utah's most rapidly urbanizing areas, and this development is taking place in the absence of a clear understanding of the seismic hazard presented by this fault. The Working Group recommends that additional paleoseismic investigation of the WaFZ be conducted prior to significant additional development along its trace to adequately characterize the seismic hazard represented by this potentially active fault.

Additional References:

Best, M.G., McKee, E.H., and Damon, P.E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1035-1050.

Pearthree, P.A., compiler, 1998, Quaternary fault data and map for Arizona: Arizona Geological Survey Open-File Report 98-24, scale 1:750,000, 122 p.

UTAH QUATERNARY FAULT PARAMETER WORKING GROUP CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES

Fault/Fault Section:

Fish Springs fault (FSF), Juab County, Utah

Paleoseismic Data Source Documents:

Bucknam, R.C., Crone, A.J., and Machette, M.N., 1989, Characteristics of active faults, *in* Jacobson, J.L., compiler, National Earthquake Hazards Reduction Program, summaries of technical reports volume XXVIII: U.S. Geological Survey Open-File Report 89-453, p. 117.

U.S. Geological Survey unpublished data.

Age of Youngest Faulting:

Late Holocene

Discussion:

The FSF is a 20-km-long, range-front normal fault along the eastern base of the Fish Springs Range, a north-trending mountain range in the Basin and Range Province in western Utah. Unconsolidated deposits in the valley east of the range are mainly lake deposits and alluvium. Extreme youth for the MRE is suggested by a lack of scarp dissection and by sharply defined nickpoints in small washes within several tens of meters upstream from the scarps, but the scarps lack free faces and thus are likely hundreds to thousands of years old. Scarps related to the MRE are up to 6 m high (Ertec Western, Inc., 1981) and indicate approximately 0.5-3.5 m of net vertical displacement based on scarp profiles measured by Bucknam and Anderson (1979). Hecker (1993) shows a 12.1 km straight-line rupture length and indicates two ages of faulting (a youthful northern half and an older southern half). Oviatt (1991) reports that an exposure of Holocene alluvium overlying older, more steeply dipping alluvium on the east side of Fish Springs Flat, across from the FSF, shows about 6.5^{o} of pre-Holocene westward backtilting.

Earthquake Timing:

The U.S. Geological Survey (USGS) excavated three trenches across the FSF. One trench, near the northern end of the fault, exposed monoclinally folded Lake Bonneville sediments (Provo-aged and younger) but no fault ruptures (Machette, USGS, written communication to UGS, September 2001). The other two trenches, excavated across a prominent fault scarp about 12 km south of the northern trench, both exposed faulted sediment and scarp-derived colluvium indicative of a single surface-faulting earthquake (Machette, USGS, verbal communication to Working Group, 2003).

The northern FSF scarps appear distinctly younger than the nearby Drum Mountains fault scarps, dated at about 9 ka, and have a diffusion-based morphologic age of 3 ka (Hanks and others, 1984). Quantitative morphometric indices used by Sterr (1985) yielded a scarp age of 4.8 ka. Faulted post-Provo alluvial fans provide an upper limit for scarp age. The larger of the two southern trenches contained a soil A horizon buried by scarp-derived colluvium. Radiocarbon dating of bulk carbon from the soil A horizon provided a maximum limit of 2280 ± 70 ^{14}C yr B.P. on surface-faulting timing, from which Bucknam and others (1989) conclude the MRE occurred at about 2 ka.

The number and timing of the surface-faulting earthquakes represented by the older appearing southern fault scarps are unknown.

Surface-Faulting Recurrence:

None reported, trenching evidence for only a single surface-faulting earthquake.

Vertical Slip Rate:

None reported, trenching evidence for only a single surface-faulting earthquake.

Summary:

The FSF is a basin-and-range fault characterized by a young scarp formed over a portion of its length on lacustrine and alluvial deposits. Available paleoseismic information is insufficient for the Working Group to make recurrence-interval or vertical slip-rate estimates for the FSF.

Additional References:

Bucknam, R.C., and Anderson, R.E., 1979, Estimation of fault-scarp ages from a scarp-height-slope-angle relationship: Geology, v. 7, no. 1, p. 11-14.

Ertec Western, Inc., 1981, MX siting investigation, faults and lineaments in the MX siting region, Nevada and Utah: Long Beach, California, unpublished consultant's report no. E-TR-54 for U.S. Air Force, volume I, 77 p.; volume II, variously paginated, scale 1:250,000.

Hanks, T.C., Bucknam, R.C., Lajoie, K.R., and Wallace, R.E., 1984, Modification of wave-cut and faulting-controlled landforms: Journal of Geophysical Research, v. 89, no. B7, p. 5771-5790.

Hecker, S., 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geological Survey Bulletin 127, 157 p., scale 1:500,000.

Oviatt, C.G., 1991, Quaternary geology of the Fish Springs Flat, Juab County, Utah: Utah Geological Survey Special Studies 77, 16 p.

Sterr, H.M., 1985, Rates of change and degradation of hill slopes formed in unconsolidated materials, a morphometric approach to dating Quaternary fault scarps in western Utah, USA: Zeitschrift fur Geomorphologie, v. 29, no. 3, p. 315-333.

APPENDIX C

EXAMPLES
OF
FAULT/FAULT SECTION SYNOPSIS FORM
AND
PALEOSEISMIC STUDY SUMMARY FORM

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP
FAULT/FAULT SECTION SYNOPSIS FORM

Name and Location of Fault/Fault Section:

Paleoseismic Data Source Documents:

Geomorphic Expression:

Evidence for Segmentation:

Age of Youngest Faulting:

Summary of Existing Recurrence Interval Information:

Summary of Existing Slip-Rate Information:

Comments:

References:

Map:

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PALEOSEISMIC STUDY SUMMARY FORM

Site Name: ***Study Synopsis ID*:**

***Fault/Fault Section*:**

Map Reference:

***Study*:**

***Type of Study/Commentary*:**

***Fault Parameter Data*:**

***Number of Surface-Faulting Events/How Identified*:**

***Age of Events/Datum Ages/Dating Techniques*:**

***Event Slip/Cumulative Slip*:**

***Published Recurrence Interval*:**

***Published Slip Rate*:**

***Sources of Uncertainty*:**

***Summary*:**

APPENDIX D
SOURCES OF UNCERTAINTY IN FAULT-ACTIVITY STUDIES

(Modified from Hecker and others, 1998)

UNCERTAINTIES IN EARTHQUAKE RECOGNITION

- Uncertain correlation of earthquakes between fault strands
- Uncertain recognition of discrete earthquakes (for example, no clear event horizon)
- Earthquake recognition based on indirect stratigraphic/structural evidence
- Number of earthquakes based on models or inferences
- Number of earthquakes based on known cumulative net vertical slip divided by an inferred slip per event (for example, use of characteristic earthquake model)

UNCERTAINTIES IN AGES

- Uncertainties inherent with dating technique(s)
- Age is near limits of range of dating technique
- Assumption or model-based age estimates (for example, inferring climate-related deposition)
- Uncertainties in interpolating age of feature from dated material (for example, using average sedimentation rates)
- Uncertainties in correlating age of feature to some dated feature (for example, estimating soil age from a comparison to a dated chronosequence)
- Questionable origin of sample material used in dating (for example, origin/age of detrital charcoal)
- Questionable sampling technique used to collect datable material (for example, channel sampling the entire thickness of a paleosol A horizon)
- Questionable environmental influences on sample material used in dating (for example, secondary contamination, open versus closed system)
- Uncertainties arising from the small number of samples used in dating
- Uncertainties arising from the small amount of material used in dating
- Uncertainties arising from stratigraphic or geomorphic inconsistencies in age estimates (for example, out-of-sequence radiocarbon dates)
- Uncertainties arising from use of relative ages (for example, age estimates based on degree of soil-profile development)
- Uncertainties in a process rate calibrated using an independent dating method (for example, scarp diffusion rates, sedimentation rates)
- Displaced feature may be older than faulting (for example, faulted pediment or basalt flow)
- Upper limits of faulted stratigraphy uncertain (for example, applicable to seismic-reflection studies)

UNCERTAINTIES IN SLIP AMOUNT

- Uncertain pre-faulting geometry of the feature (for example, alluvial-fan slope)
- Uncertain pre-faulting elevation of the feature (for example, stream-terrace elevation)
- Uncertain correlation of features across a fault

- Feature partially buried (for example, buried pre-faulting surface on downthrown side of fault)
- Feature partially eroded
- Vertical slip interpreted from displacement-related deposition (for example, colluvial wedge thickness)
- Uplift as a proxy for vertical component of slip (for example, stream incision rate)
- Vertical separation assumed to approximate net vertical component of slip (for example, unknown effect of antithetic faults)
- Cumulative uncertainties from summing displacements across multiple fault strands
- Uncertain event portioning of cumulative slip (applicable to slip-per-event reporting)
- Uncertain correlation of earthquake-specific displacements between fault strands (applicable to slip-per-event reporting)
- Represents secondary (or unknown) component of total slip (for example, horizontal component of oblique slip faulting)
- Event slip inferred from empirical relation to fault length
- Event-to-event slip assumed to be uniform (use of characteristic earthquake model)
- Number of single-earthquake slip measurements may be too few to yield representative average (applicable to slip-per-event reporting)
- Unclear whether apparent displacement is caused by faulting

UNCERTAINTIES RELATED TO REPORTING

- Results not fully or poorly documented
- Interpretations do not readily follow from data presented
- Slip estimate uncertainties not made explicit
- Basis for age estimates uncertain
- Uncertainties insufficiently quantified (for example, reporting laboratory uncertainty associated with an absolute age, but not constraining the geologic uncertainty associated with the age).

UNCERTAINTIES IN ACCURACY AND APPLICABILITY OF PARAMETER ESTIMATE

- Value reflects local variation in deformation along a fault (for example, localized effects of antithetic faulting)
- Time period too long to represent contemporary conditions (for example, long-term slip rate)
- Number of interevent intervals encompassed by time period may be greater or less than the number of earthquakes recognized (applicable to recurrence-interval determinations)
- Number of interevent intervals may be too few to yield representative average (applicable to slip-per-event reporting)
- Selected value is a compromise between disparate values determined for a site
- Selected value conflicts with other data at a site
- Actual value may be significantly less or greater than the estimate

- Data come from different locations or features along a fault and may not be comparable
- Identification of associated fault is uncertain (for example, uncertain geometry of fault[s] beneath surface fold)
- Uncertain if a fault or fault-related feature (for example, fault inferred from a ground-water barrier) is tectonic in origin
- Seismogenic capability of a fault uncertain (for example, fault inferred to rupture sympathetically; no net vertical slip across a feature)
- Zone of deformation wider than area of study (for example, not all scarps trenched)

OTHER UNCERTAINTIES

- Layers of assumptions from nested models
- Slip-rate uncertainties (applicable to recurrence-interval determinations)
- Slip-per-event uncertainties (applicable to recurrence-interval determinations)

Hecker, Suzanne, Kendrick, K.J., Ponti, D.J., and Hamilton, J.C., 1998, Fault map and database for Southern California: Long Beach 30'x60' quadrangle: U.S. Geological Survey Open-File Report 98-129, 27 p., 3 appendices.

APPENDIX E
GLOSSARY

Term Abbreviations

AMRT	Apparent mean residence time: describes ^{14}C ages obtained on organic concentrates typically from the A horizons of soils, or any organic-rich bulk material such as colluvial-wedge matrix or tectonic crack-fill deposits. Because of the wide range of carbon ages in bulk organic samples, the interpretation and calibration of AMRT ^{14}C ages are geologically complex and their total associated errors are larger than the errors on ages from charcoal (Machette and others, 1992).
^{14}C	Carbon-14: a heavy radioactive isotope of carbon having a mass number of 14 and a half-life of 5730±40 yrs. Carbon-14 is useful in dating materials that are typically less than about 40,000 years old that are involved in the Earth's carbon cycle (Bates and Jackson, 1987) .
^{14}C yr B.P.	Radiocarbon years before present: designates the age of a sample in ^{14}C years prior to calibration to correct for the uneven production of ^{14}C in the atmosphere over time. Present, by convention, is taken as A.D. 1950.
cal yr B.P.	Calendar years before present: designates ^{14}C ages that have been calibrated to calendric years according to one of several available data sets used to correct ^{14}C ages for the uneven production of the ^{14}C in the atmosphere over time. Present, by convention, is taken as A.D. 1950.
ka	Kilo-annum: thousand years before present; restricted by the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983) to designate an age measured from the present. Present, by convention, is taken as A.D. 1950. For example, "The age of the stream-terrace deposits are estimated to be 15-30 ka based on soil-profile development."
kyr	Thousand years: refers to an interval of time without reference to the present. For example, "The interevent interval between the two most recent surface-faulting earthquakes on the fault is 3.6 kyr."
MRE	Most recent surface-faulting earthquake (event): the youngest surface-faulting earthquake in an earthquake chronology.
PE	Penultimate surface-faulting earthquake (event): the second-oldest surface-faulting earthquake in an earthquake chronology.

TL	Thermoluminescence: the property possessed by many crystalline substances of emitting light when heated as energy stored as electron displacements in the crystal lattice is released upon heating. Quantifying the amount of heat released as emitted light to determine the time of burial of silt and other fine-grained materials is widely used as a dating technique in archeological and geologic studies.

Fault/Fault Section Abbreviations

BMF	Bald Mountain fault
BRFZ	Bear River fault zone
ECFZ	East Cache fault zone
PS	Promontory section[1]
FIS	Fremont Island segment[2]
AIS	Antelope island segment
EBLF	Eastern Bear Lake fault
FSF	Fish Springs fault
GSLFZ	Great Salt Lake fault zone
HFZ	Hurricane fault zone
AJS	Anderson Junction section
HVF	Hansel Valley fault
HF	Hogsback fault
JPF	James Peak fault
JVFZ	Joes Valley fault zone
EJVF	East Joes Valley fault
WJVF	West Joes Valley fault
MMF	Middle Mountain fault (intragraben)
BMFs	Bald Mountain faults (intragraben)
MFZ	Morgan fault zone
NPF	North Promontory fault
OFZ	Oquirrh fault zone
SF	Strawberry fault
SOMFZ	Southern Oquirrh Mountains fault zone
LKF	Lakes of Kilarney fault
MF	Mercur fault
SCF	Soldier Canyon fault
WEHF	West Eagle Hill fault
SAFs	Sugarville area faults
TFG	Towanta Flat graben
WFZ	Wasatch fault zone
BCS	Brigham City segment
WS	Weber segment
SLCS	Salt Lake City segment
PS	Provo segment
NS	Nephi segment

LS	Levan segment
WaFZ	Washington fault zone
WCFZ	West Cache fault zone
CF	Clarkston fault
JHF	Junction Hills fault
WF	Wellsville fault
WVFZ	West Valley fault zone
TF	Taylorsville fault
GF	Granger fault

[1]"Section" refers to a portion of a fault defined on the basis of static geologic criteria (geomorphic or structural), but for which no evidence presently exists to show that its history of surface faulting is different from other adjacent parts of the fault. [2]"Segment" refers to a portion of a fault, typically also identifiable on the basis of geomorphic or structural criteria, but for which historic surface ruptures or paleoseismic data show that the history of surface-faulting earthquakes is different from other adjacent portions of the fault, and that the segment therefore behaves in an independently seismogenic manner from the remainder of the fault.