One strand of the complex Drum Mountain fault zone

February 16 & 17, 2011
WELCOME & INTRODUCTIONS
WGUEP Members

Walter Arabasz, UUSS
Tony Crone, USGS
Chris DuRoss, UGS
Nico Luco, USGS
Bill Lund, UGS (Coordinator)
Susan Olig, URS
Jim Pechmann, UUSS
Steve Personius, USGS
Mark Petersen, USGS
David Schwartz, USGS
Bob Smith, UUGG
Ivan Wong, URS (Chair)

With assistance from
Steve Bowman and Mike Hylland, UGS; Patricia Thomas, URS; Christine Puskas, UUGG
<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Speaker(s)</th>
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<tr>
<td>7:30 – 8:00</td>
<td>Continental Breakfast</td>
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<tr>
<td>8:00 – 8:15</td>
<td>Welcome</td>
<td>Bill</td>
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<tr>
<td>8:15 – 8:30</td>
<td>Overview of Agenda</td>
<td>Ivan</td>
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<td>8:30 – 9:15</td>
<td>WGUEP Strawman Logic Tree and Products</td>
<td>Ivan</td>
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<td>9:15 – 10:00</td>
<td>Recurrence Models</td>
<td>Ivan</td>
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<td>10:00 – 10:15</td>
<td>Break</td>
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<td>10:15 – 10:30</td>
<td>Final Wasatch Central Segment Recurrence Rates</td>
<td>Chris</td>
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<td>10:30 – 10:45</td>
<td>Final Recurrence Rates for Wasatch Fault End Segments</td>
<td>Mike</td>
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<td>10:45 – 11:30</td>
<td>Methods for Estimating Mmax</td>
<td>Susan/David</td>
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<td>11:30 – 12:15</td>
<td>Time-Dependent Models</td>
<td>Patricia</td>
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<td>12:15 – 1:15</td>
<td>Lunch</td>
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<td>1:15 – 2:15</td>
<td>Comparison of Paleoseismic, Seismicity, and Geodetic Moment Rates</td>
<td>Christine/Bob</td>
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<td>2:15 – 3:00</td>
<td>Horizontal Strain Rates From Slip Rate and Geodetic Data</td>
<td>Mark</td>
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<td>3:00 – 3:15</td>
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<td>3:15 – 4:00</td>
<td>Moment Balancing the Wasatch Fault</td>
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<td>4:00 – 4:45</td>
<td>Consensus Wasatch Front Earthquake Catalog</td>
<td>Walt/Jim</td>
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<td>4:45 – 5:15</td>
<td>Wrap-up Discussion</td>
<td>All</td>
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<td>5:15</td>
<td>Adjourn</td>
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**WGUEP AGENDA**

**Wednesday, February 16, 2011**
<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Presenter(s)</th>
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<tr>
<td>7:30 – 8:00</td>
<td>Continental Breakfast</td>
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<tr>
<td>8:00 – 8:30</td>
<td>Strawman Rupture Scenarios for the Fault</td>
<td>Jim</td>
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<tr>
<td>8:30 – 10:00</td>
<td>Final Wasatch Front Fault Model</td>
<td>Bill</td>
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<td>10:00 – 10:15</td>
<td>Break</td>
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<td>10:15 – 11:30</td>
<td>Discussion on Calculating Time-Dependent and Time-Independent Rates</td>
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<td>11:30 – 12:30</td>
<td>Lunch</td>
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<td>12:30 – 1:30</td>
<td>Discussion on Final Products and Report</td>
<td>All</td>
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<tr>
<td>1:30 – 2:00</td>
<td>Meeting 5 Schedule</td>
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<td>2:00</td>
<td>Adjourn</td>
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Calculating Time-Dependent Probabilities of Large Earthquakes for the Wasatch Front

Working Group on Utah Earthquake Probabilities

Ivan G. Wong
Seismic Hazards Group
URS Corporation
Oakland, CA 94612

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Salt Lake City, UT 15 February 2011
WGUEP Members

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Bob Smith, UUGG
Ivan Wong, URS (Chair)
With assistance from Patricia Thomas (URS) and Steve Bowman and Mike Hylland (UGS)
Approach

Four models will be implemented in the forecast process:

1. Fault model
2. Deformation model
3. Earthquake rate model
4. Probability model

Epistemic uncertainties in all model input parameters will be explicitly addressed by the WGUEP.
The WGUEP will calculate the probability of a range of moderate to large earthquakes ($M \geq 5.5$) in the Wasatch Front Region for a range of intervals varying from annually to 100 years.

The earthquake probabilities that will be estimated are:

1. Segment-specific for the Wasatch fault
2. Total for the Wasatch fault
3. Fault-specific for other major faults in the area
4. Total for the Wasatch Front region.
The final forecast will undergo a formal internal USGS review, and will be sent to the National Earthquake Prediction Council for review and comment as well.
Accomplishments

- Paleoseismology Subgroup:
  - Comprehensive review of all paleoseismic data for central segments of Wasatch fault zone (WFZ)
  - Development of OxCal earthquake timing models for each paleoseismic site
  - Final earthquake chronologies and recurrence intervals for segments based on integration of OxCal analyses among sites
  - Development of six rupture scenarios for the central WFZ
  - Methodology paper in review
Accomplishments

- Strawman time-independent recurrence intervals/slip rates for end segments of Wasatch fault.

- Strawman time-independent recurrence intervals for Great Salt Lake fault (time-dependent recurrence intervals will be calculated).

- List of other faults and strawman slip rates that will be included in time-independent calculations.
Remaining Issues

1. GPS moment rate versus geologic and seismicity data
2. Moment balancing the Wasatch fault
Next Steps

1. Historical seismicity catalog update and calculation of background earthquake rates.

2. Update West Valley rupture scenarios (including coseismic rupture with Salt Lake City segment).

3. Calculate time-dependent and/or time-dependent rates for all faults.

4. Develop forecast.
Next Steps (cont.)

5. Produce draft report for review.

6. Review and finalize report.

7. Public release and outreach.
Analysis of ANSS Data for Stress Drop, Q(f), and Kappa

Utah Ground Motion Working Group

Ivan Wong
Seismic Hazards Group
URS Corporation
Oakland, CA

Walt Silva and Bob Darragh
Pacific Engineering & Analysis
El Cerrito, CA

Jim Pechmann
Dept. of Geology and Geophysics
University of Utah
Salt Lake City, UT

Tian Yu
Institute of Engineering Mechanics
China Earthquake Administration
Harbin, China

Salt Lake City, UT
14 February 2011
Objective: To evaluate the critical factors that control ground shaking hazard along the Wasatch Front: stress drop, kappa, and crustal attenuation.

Some previous studies have suggested that ground motions in an extensional regime such as the Basin and Range Province may be lower than in California for the same magnitude and distance.

The inference was that this difference may be due to the lower stress drops of extensional earthquakes compared to compressional earthquakes as first suggested by McGarr (1984).
No systematic evaluation of earthquake stress drops has been performed for earthquakes along the Wasatch Front.

No studies have been performed to evaluate the variability in kappa in the central Wasatch Front. Kappa can have a very significant effect on high-frequency ground motions with lower values of kappa resulting in larger high-frequency ground motions.

Only a few studies to estimate Q(f) for the Wasatch Front (Brockman and Bollinger, 1992; Jeon and Herrmann, 2004) have been performed.
To analyze the available strong motion and broadband data from ANSS stations in the central Wasatch Front region for stress drop, kappa, and Q(f).

The approach uses an inversion scheme developed by Walt Silva. In the inversion scheme, earthquake source, path and site parameters are obtained by using a nonlinear least-squares inversion of Fourier amplitude spectra.
Earthquakes to be Analyzed

- Total of 17 events
- Period: May 2001 to November 2007
- Magnitude Range: M 3.0 to 4.2
- Number of stations recording events: 18 to 68
Steps involved in analyses are:

1) Inversions with rock amp factors using rock recordings.

2) Results from Step 1 used to invert soil recordings to obtain an average set of amp factors for soil sites.

3) Rock and soil amp factors are used to invert both rock and soil recordings.

4) Inversions were performed fixing $Q_0$ and $R_0$ fixed to values in Step 3 and rock and soil amp factors to obtain station $K$ and stress drop.
Hard Rock $V_s$ and $V_p$ Profiles
Frequency-Dependent Amplification Factors

WASATCH PROFILE TRANSFER FUNCTION

LEGEND
- ROCK
- SOIL
Spectral Inversion Results for Event #2
Spectral Inversion Results for Event #2
Spectral Inversion Results for Event #4
Spectral Inversion Results for Event #4
Model Bias for Soil Sites
Model Bias for Rock Sites
Model Bias for All Sites (Rock and Soil)
## Final Preliminary Results

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<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Event ID</th>
<th>Magnitude (M)</th>
<th>Latitude (degrees)</th>
<th>Longitude (degrees)</th>
<th>Depth (km)</th>
<th>Δσ (bars)</th>
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# Final Inversion Results

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<td>$Q_0$</td>
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<tr>
<td>$\eta$</td>
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<tr>
<td>$\Delta\sigma$ (bars)</td>
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<td>$\bar{\kappa}$ (sec)</td>
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<td>$\bar{\kappa}$ for rock sites (sec)</td>
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<tr>
<td>$\bar{\kappa}$ for soil sites (sec)</td>
<td>0.036</td>
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<td>$R_0$ (km)</td>
<td>59.88</td>
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## Comparison of Stress Drops

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<th>Source</th>
<th>Region</th>
<th>Magnitude</th>
<th>Stress Drop</th>
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<tr>
<td>Becker and Abrahamson (1997)</td>
<td>Worldwide</td>
<td>5.1 – 6.9</td>
<td>16 – 93 bars, 29 bars (median)</td>
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<td>WCFS et al. (1996)</td>
<td>Basin and Range</td>
<td>2.8 – 6.0</td>
<td>8 – 114 bars, 40 bars (mean)</td>
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<tr>
<td>This study</td>
<td>Wasatch Front</td>
<td>3.0 – 4.2</td>
<td>3 – 147 bars, 20 bars (mean)</td>
</tr>
<tr>
<td>Silva et al. (1997)</td>
<td>California</td>
<td>5.7 – 7.3</td>
<td>59 bars (mean)</td>
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</table>
Strawman Rupture Models for the Central Wasatch Fault

Paleoseismology Subgroup
(Chris DuRoss, Steve Personius, Tony Crone, Susan Olig, and Bill Lund)

Working Group on Utah Earthquake Probabilities, Feb. 2011
Final WFZ Chronology

Revised WFZ chronology post 7 ka – 2-sigma ranges
Revised WFZ chronology post 7 ka – 2-sigma ranges

B4-B1: 1.1 ky

W5-W1: 1.3 ky

S4-S1: 1.4 ky

P4-P1: 1.4 ky

N3-N1: 0.9 ky
Strawman Rupture Models

- **Maximum.** 22 single-segment ruptures. Uncertainties in segment-boundary locations (± 3–8.5 km) allow for leaky-boundary (spill-over) ruptures. Minimum rupture lengths based on paleoseismic sites.

- **Minimum.** 13 earthquakes: 7 multi-segment, 6 single-segment. Fewest possible ruptures generally based on earthquake timing (PDF overlap). Generally considered two-segment ruptures (with exception).

- **Intermediate.** 19-20 earthquakes. Mostly single-segment ruptures, keeping “preferred” multi-segment ruptures B3+W4 and B4+W5 based on earthquake timing data (PDF overlap), large per-event displacements, and segment boundary. Variations:
  - Intermediate A: S2+P3; N3
  - Intermediate B: S2; P3+N3
  - Intermediate C: S2; P3; N3
Maximum Rupture Model

≥ 22 Earthquakes
Minimum Rupture Model

≥ 13 Earthquakes
Intermediate Model A

≥ 19 Earthquakes
Intermediate Model B

≥ 19 Earthquakes
Intermediate Model C

≥ 20 Earthquakes
## Path Forward

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<thead>
<tr>
<th>Rupture Scenario</th>
<th>Weight</th>
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<tr>
<td>Maximum Rupture Model (22 EQs &lt;6.4 ka)</td>
<td>____%</td>
</tr>
<tr>
<td>Minimum Rupture Model (13 EQs &lt;6.4 ka)</td>
<td>____%</td>
</tr>
<tr>
<td>Intermediate Rupture Model A (S2-P3 combined (19 EQs &lt;6.4 ka)</td>
<td>____%</td>
</tr>
<tr>
<td>Intermediate Rupture Model B (P3-N3 combined (19 EQs &lt;6.4 ka)</td>
<td>____%</td>
</tr>
<tr>
<td>Intermediate Rupture Model C (S2/P3/N3 separate (20 EQs &lt;6.4 ka)</td>
<td>____%</td>
</tr>
<tr>
<td>Unsegmented Earthquake Model(?)</td>
<td>____%</td>
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</table>
Path Forward

Rupture Scenario                                      Weight
Maximum Rupture Model (22 EQs <6.4 ka)            60%
  • Long term history of fault; displacement and timing data do support multi-segment ruptures, but not convincing; spill-over ruptures probably more common, which can be addressed by uncertainty in segment-boundary locations
Minimum Rupture Model (13 EQs <6.4 ka)             5%
  • Unlikely scenario(?); 7 of 13 ruptures greater than 70 km long (M_{SRL} 7.2–7.5); conflicts with prominent segment boundaries (unless slip still decreases at segment ends) and along-strike changes in fault-scarp character (size, geomorphology)
Intermediate Rupture Model A (S2-P3 combined (19 EQs <6.4 ka)  10%
Intermediate Rupture Model B (P3-N3 combined (19 EQs <6.4 ka)  5%
Intermediate Rupture Model C (S2/P3/N3 separate (20 EQs <6.4 ka)  20%
  • B4-W5 and B3-B4 have compelling evidence (displacements, similarity in event times, PDF overlap), but given broad timing uncertainties (± 500 –700 yr) still prefer individual-segment ruptures (with spill over). Prefer S2/P3/N3 as separate events (C), over 85-99-km-long ruptures in A and B. Prefer P3-S2 (but maybe not full SLCS rupture?) over P3-N3 considering lack of evidence for P3 on northern Nephi.
Path Forward

Olig

<table>
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<td>Maximum Rupture Model (22 EQs &lt;6.4 ka)</td>
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<td>Minimum Rupture Model (13 EQs &lt;6.4 ka)</td>
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<tr>
<td>Intermediate Rupture Model A (S2-P3 combined (19 EQs &lt;6.4 ka)</td>
<td>5%</td>
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<tr>
<td>Intermediate Rupture Model B (P3-N3 combined (19 EQs &lt;6.4 ka)</td>
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<tr>
<td>Intermediate Rupture Model C (S2/P3/N3 separate (20 EQs &lt;6.4 ka)</td>
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Unsegmented Earthquake Model(?) ___%
Path Forward

Crone

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<td>Intermediate Rupture Model A (S2-P3 combined (19 EQs &lt;6.4 ka)</td>
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<td>Intermediate Rupture Model B (P3-N3 combined (19 EQs &lt;6.4 ka)</td>
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<tr>
<td>Intermediate Rupture Model C (S2/P3/N3 separate (20 EQs &lt;6.4 ka)</td>
<td>25%</td>
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Unsegmented Earthquake Model(?) ___%
## Path Forward

<table>
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<th>Weight</th>
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<tr>
<td>Maximum Rupture Model (22 EQs &lt;6.4 ka)</td>
<td>40-60%</td>
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<tr>
<td>Minimum Rupture Model (13 EQs &lt;6.4 ka)</td>
<td>5-10%</td>
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<tr>
<td>Intermediate Rupture Model A (S2-P3 combined (19 EQs &lt;6.4 ka)</td>
<td>5-10%</td>
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<tr>
<td>Intermediate Rupture Model B (P3-N3 combined (19 EQs &lt;6.4 ka)</td>
<td>5-20%</td>
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<tr>
<td>Intermediate Rupture Model C (S2/P3/N3 separate (20 EQs &lt;6.4 ka)</td>
<td>10-20%</td>
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Unsegmented Earthquake Model(?) ___%
Site PDFs (OxCal)
Per-event Displacements
Along-Strike Displacement
Floating Earthquake Model (test)

≥ 13 Earthquakes

Diagram showing the Floating Earthquake Model with earthquake locations marked along the Wasatch fault zone.
Intermediate Rupture Model

Multi-segment ruptures between BCS and WS:

- Significant overlap in segment PDFs (~70%)
- Large displacements near segment boundary (~2 m); large max displacement (~4 m) for W4
- Relatively simple segment boundary, which also allowed rupture spillover on BCS from ~1.2-ka Weber segment earthquake
Intermediate Rupture Model

Spillover (leaky boundary) rupture from Weber to Brigham City segment:

- Nearly identical earthquake times at Pearsons Canyon (1.2 ± 0.05 ka) and on the Weber segment (1.2 ± 0.1 ka for W2)
- No events younger than ~2 ka on northern BCS
- Large scarp offsets (~1–2 m) across Late(?) Holocene fan surfaces on southernmost Brigham City segment
- Large displacement (~3–4 m) at northern Weber segment
- Northern rupture extent likely south of Willard Canyon, ~8 km north of segment boundary
The Wasatch Fault Zone End Segments
(Malad City, Clarkston Mountain, Collinston, Levan, & Fayette)

Geologic and Paleoseismic Constraints on
Displacement, Slip Rate, and Recurrence

Michael Hylland
Utah Geological Survey

Working Group on Utah Earthquake Probabilities – February 2011
Northern Segments

Malad City Segment

*Paleoseismic data:* none

*Geologic constraints:*
- Bonneville lake-cycle deposits are not faulted
- Fault scarps are present on late Quaternary deposits (“older” alluvium)
- Steep range-front geomorphology
- Steep, linear gravity gradients

*Earthquake timing:*
Geologic data suggest active faulting during the late Pleistocene (pre-Bonneville)

*Slip rate:*
- Database slip rate category: <0.2 mm/yr
- Slip rate estimate:
  \[ \leq 1.5 \text{ m in } >18,000 \text{ yr} = 0.08 \text{ mm/yr (max)} \]

*Recurrence interval:* NA (no individual earthquake timing data)

*Sources:*
Cluff et al. (1974), Machette et al. (1992), Pope et al. (2001)
Northern Segments

Clarkston Mountain Segment

Paleoseismic data:
• Field reconnaissance
• Scarp profiling and empirical analysis
  • Elgrove Canyon
  • Composite scarp (2 or perhaps 3 events)
• MRE & PE surface offset ≈ 2 m

Geologic constraints:
• Bonneville lake-cycle deposits are not faulted
• Fault scarps are present on late Quaternary deposits ("Bonneville and older" alluvium)
• Steep range-front geomorphology
• Steep, linear gravity gradients
Northern Segments

Clarkston Mountain Segment

Earthquake timing:
• MRE—empirical scarp profile analysis indicates early Holocene (likely a minimum age estimate)
• PE timing unknown
• Geologic data suggest active faulting during the late Pleistocene (during or before end of Bonneville lake cycle)
Northern Segments

Clarkston Mountain Segment

Slip rate:
• Database slip rate category: <0.2 mm/yr
• Slip rate estimate:
  2 m in >18,000 yr = 0.1 mm/yr (max)

Recurrence interval: NA (MRE timing poorly constrained, no timing data for the PE)

Sources:
Machette et al. (1992), Biek et al. (2003), Hylland (2007)

Dashed line considers coseismic rupture of Short Divide fault
Northern Segments

Collinston Segment

Paleoseismic data:
• Field reconnaissance
• Scarp profiling and empirical analysis
  • Coldwater Canyon reentrant (S segment boundary)
  • Small single-event to large composite scarps

Geologic constraints:
• Bonneville lake-cycle deposits are faulted, but only in CCR (unfaulted to the N)
• Steep range-front geomorphology S, topographic saddle N (West Cache fault may be a factor; Holocene faulting)
• Steep, linear gravity gradients
Northern Segments

Collinston Segment

Earthquake timing:
• Holocene and latest Pleistocene events, but only in CCR (likely northern end of ruptures on Brigham City segment)
• Geologic data suggest active faulting during the late Pleistocene (pre-Bonneville)
Northern Segments

Collinston Segment

*Slip rate:*
- Database slip rate category: <0.2 mm/yr
- Slip rate estimate:
  \[ \leq 2 \text{ m in } >18,000 \text{ yr} = 0.1 \text{ mm/yr (max)} \]
- Long-term average slip rate:
  \[ <12 \text{ m in } \sim 300,000 \text{ yr} = 0.04 \text{ mm/yr (max)} \]

*Recurrence interval:* NA (no individual earthquake timing data)

*Sources:*
Oviatt (1986a, b), Personius (1990), Machette et al. (1992), Hylland (2007)

Length: 30 km
End point uncertainty: ± 3 km
24–36 km

Dashed line considers coseismic rupture of Short Divide fault
Southern Segments

Levan Segment

Paleoseismic data:
• Scarp profiling and empirical analysis
• Diffusion equation modeling
• Dated charcoal from faulted fan alluvium (Pigeon Creek)
• Natural exposure of fault—displacement and timing data (Deep Creek)
• Fault trench (Skinner Peaks)

Geologic constraints:
Fault scarps are present on late Quaternary deposits
  • Faulted late Holocene alluvium
  • Large (12 m) fault scarps on late to middle Pleistocene alluvium

Earthquake timing:
Pigeon Creek:
  • MRE postdates fan alluvium containing charcoal dated at
    2100 ± 300 yr B.P. (1410–2760 cal yr B.P.) and 1750 ± 350 yr B.P. (950–2490 cal yr B.P.)
Southern Segments

Levan Segment

Earthquake timing (cont.):

Deep Creek:

- MRE closely postdates age of buried soil, dated at:
  - $1200 \pm 80$ yr B.P. ($870–1180$ cal yr B.P.; bulk sample, 100 yr MRT correction)
  - $1000 \pm 100$ yr (TL)
- PE predates(?) fan alluvium containing charcoal dated at $7300 \pm 1000$ yr B.P. ($5980–10,590$ cal yr B.P.)
Southern Segments

Levan Segment

Earthquake timing (cont.):

Skinner Peaks:

• MRE postdates age of “burn layer” on footwall, dated at:
  • 1850 ± 70 yr B.P. (1610–1940 cal yr B.P.; charcoal)
  • 2000 ± 300 yr (TL)
• Jackson (1991) preferred range: 1000–1500 cal yr B.P.
• PE likely predates hanging-wall alluvium containing buried “incipient A horizon” dated at:
  • 3720 ± 90 yr B.P. (3740–4200 cal yr B.P.; charcoal concentrate, 100 yr MRT correction)
  • 3100 ± 300 yr (TL)
Southern Segments

Levan Segment

**Slip rate:**
- Database slip rate category: <0.2 mm/yr
- Slip rate estimate:

<table>
<thead>
<tr>
<th>Site</th>
<th>NVTD (m)</th>
<th>MRE Timing (cal yr B.P.)</th>
<th>PE Timing (cal yr B.P.)</th>
<th>Inter-event Time (yr)</th>
<th>Slip Rate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Creek</td>
<td>1.8</td>
<td>&lt;800-1200</td>
<td>&gt;6000-10,600</td>
<td>&gt;4800-9800</td>
<td>&lt;0.18-0.38</td>
</tr>
<tr>
<td>Skinner Peaks</td>
<td>1.8-3.0</td>
<td>1000-1500</td>
<td>&gt;2800-4300</td>
<td>&gt;1300-3300</td>
<td>&lt;0.55-2.3</td>
</tr>
</tbody>
</table>
Southern Segments

Levan Segment

Slip rate:
• Database slip rate category: <0.2 mm/yr
• Slip rate estimate:

<table>
<thead>
<tr>
<th>Site</th>
<th>NVTD (m)</th>
<th>MRE Timing (cal yr B.P.)</th>
<th>PE Timing (cal yr B.P.)</th>
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<td>&lt;0.55-2.3</td>
</tr>
</tbody>
</table>
Southern Segments

Levan Segment

Slip rate (cont.):
• Database slip rate category: <0.2 mm/yr
• Hylland and Machette (2008) preferred value: 0.3 ± 1 mm/yr (max)
• UQFPWG consensus range: 0.1–0.6 mm/yr
• Long-term average slip rate:
  \[ \frac{4.8 \text{ m}}{100–250 \text{ kyr}} = 0.02–0.05 \text{ mm/yr} \]

Recurrence interval:
• Recurrence interval not calculated because timing of PE is poorly constrained
• UQFPWG consensus range: >3000 and <12,000 yr
  (based on 2 Holocene events and approximate 2σ confidence limits)

Sources:

A - Length: 32 km
  End point uncertainty: ± 3 km
  26–38 km
B - Mapped Holocene rupture: 25 km
  19–31 km
C - Including coseismic rupture of subsidiary faults in step-over: 37 km
  31–43 km

Length range to consider: 19–43 km
Southern Segments

Fayette Segment

Paleoseismic data:
• Scarp profiling and empirical analysis
• Diffusion equation modeling

Geologic constraints:
• Fault scarps are present on late Quaternary deposits
  • Holocene to late Pleistocene alluvium is faulted, but late Holocene alluvium is not
• Scarps on late to middle Pleistocene alluvium typically 4–6 m high
  • Anomalously high scarps (~20 m) at north end of SW strand
Southern Segments

Fayette Segment

Earthquake timing:
- MRE—cross-cutting relations and empirical scarp profile analysis indicates:
  - Early or middle Pleistocene (?) (N strand)
  - Latest Pleistocene (SE strand)
  - Holocene (SW strand)
Southern Segments

Fayette Segment

Slip rate:
- Database slip rate category: <0.2 mm/yr
- Slip rate estimates:
  0.8–1.6 m in <11,500 yr = 0.07–0.1 mm/yr (min) (SW strand)
  0.5–1.3 m in <18,000 yr = 0.03–0.07 mm/yr (min) (SE strand)
  3 m in 100–250 kyr = 0.01–0.03 mm/yr

Recurrence interval: NA (MRE timing poorly constrained, no timing data for the PE)

Sources:
Machette et al. (1992), Hylland (2007), Hylland and Machette (2008)

A - Length: 22 km
   End point uncertainty: ± 3 km
   16–28 km

B - Fayette (N) + Fayette (SW): 18 km
   12–24 km

Length range to consider: 12–28 km
Levan–Fayette combined:

A - Levan (S) + Fayette (SW): 26 km
  20–32 km (similar to Levan Holocene rupture: 19–31 km)

B - Levan + Fayette (original Schwartz & Coppersmith model): 46 km
  40–52 km

So, length range to consider for Levan: **19–52 km**
Southern Segments

Levan–Fayette Segment Boundary
## The Wasatch Fault Zone End Segments
### Summary of Earthquake Parameters

<table>
<thead>
<tr>
<th>Segment</th>
<th>MRE Timing</th>
<th>Displacement/Surface Offset (m)</th>
<th>Time Interval (kyr)</th>
<th>Est. SR (mm/yr)</th>
<th>Recommended SR (mm/yr)</th>
<th>RI (kyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malad City</td>
<td>Late Pleistocene</td>
<td>≤1.5 (est.)</td>
<td>&gt;18</td>
<td>&lt;0.08</td>
<td>0.01–0.1</td>
<td>NA</td>
</tr>
<tr>
<td>Clarkston</td>
<td>Late Pleistocene</td>
<td>2</td>
<td>&gt;18</td>
<td>&lt;0.1</td>
<td>0.01–0.1</td>
<td>NA</td>
</tr>
<tr>
<td>Collinston</td>
<td>Late Pleistocene</td>
<td>≤2 (est.)&lt;12</td>
<td>&gt;18 300</td>
<td>&lt;0.1 &lt;0.04</td>
<td>0.01–0.1</td>
<td>NA</td>
</tr>
<tr>
<td>Levan</td>
<td>≤1000 cal yr B.P. 1000–1500 cal yr B.P.</td>
<td>1.8 1.8–3.0 4.8 100–250</td>
<td>&gt;4.8–9.8 &gt;1.3–3.3 100–250</td>
<td>&lt;0.2–0.4 &lt;0.5–2.3 &lt;0.3±0.1* 0.1–0.6** 0.02–0.05</td>
<td>0.1–0.6 &gt;3 &amp; &lt;12**</td>
<td></td>
</tr>
<tr>
<td>Fayette</td>
<td>Early(?) Holocene (SW strand) Latest Pleistocene (SE strand)</td>
<td>0.8–1.6 0.5–1.3 3 0.8–1.6 0.5–1.3 3</td>
<td>&lt;11.5 &lt;18 100–250</td>
<td>&gt;0.07–0.1 &gt;0.03–0.07 0.01–0.03</td>
<td>0.01–0.1 NA</td>
<td></td>
</tr>
</tbody>
</table>

*Hyland and Machette, 2008  
** UQFPWG (Lund, 2005)
Estimating Maximum Magnitudes for Faults – Take 2

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WGUEP Meeting, Salt Lake City, UT

16 February 2011
Empirical Relations for WGUEP Model

- Wells and Coppersmith (1994) – all fault types
  - Area (A); $M = 4.07 + (0.98 \times \log A)$; $\sigma = 0.24$
  - Surface rupture length (L); $M = 5.08 + (1.16 \times \log L)$; $\sigma = 0.28$
  - Average slip (AD); $M = 6.93 + (0.82 \log AD)$; $\sigma = 0.39$

  - AD (from trench sites) and MVCDS, which is a mode value statistic based on n and the percent of fault length that the n samples cover; $M = 6.93 + 0.82 \log (AD \times MVCDS)$

- Hanks and Kanamori (1979)
  - Seismic moment ($M_0$); $M = (2/3 \times \log M_0) – 10.7$
Strawman Approach

1. Categorize faults according to available data
   A. Well-mapped with 3 or more trench sites
      (segmented with alternative rupture models; have D data)
   B. Well-mapped with 1 or 2 trench sites
      (may or may not be segmented; have minimal D data)
   C. Mapped and no trench sites
      (likely not segmented; no D data)

2. Use different empirical relations (and uncertainties)
   according to available data and rupture models
Strawman Approach (continued)

- For category A faults use:
  - Wells and Coppersmith – A (0.25)
  - Wells and Coppersmith – L (0.25)
  - Hemphill-Haley and Weldon – AD (0.25)
  - Hanks and Kanamori – $M_o$ (0.25)

- For category B faults use (with ± 1 $\sigma$ depending on epistemic uncertainty):
  - Wells and Coppersmith – A (0.3)
  - Wells and Coppersmith – L (0.3)
  - Hanks and Kanamori – $M_o$ (0.2)
  - Wells and Coppersmith – AD (0.2)

- For category C faults use (with ± 1 $\sigma$):
  - Wells and Coppersmith – L (0.5)
  - Wells and Coppersmith – A (0.5)

- Truncate all distributions at M 7.8 maximum. Use aleatory uncertainty of ± 0.12. Review resulting distributions and adjust as needed.
Example Category A Fault: Provo Segment
(Single segment/ Multiple segment)

- W & C – L → M 7.1 [7.3]
- W & C – A → M 7.0 [7.2]
- H-H & W – AD → M 7.3 [7.2]
- H & K – M₀ → M 7.4 [7.4]

- Single segment input: L = 59 km; AD = 3.56 m; A = 1080 km² (dip = 55° and depth = 15 km)
- Use ± 0.12 for aleatory uncertainty
- Multiple segment (Provo + Nephi) input: L = 86 km; AD = 3 m; A = 1574 km² (dip = 55° and depth = 15 km)
Example Category B Fault: Bear River Fault Zone

- H & K – $M_O$ $\rightarrow$ M 7.2 (0.2)
- W & C – L $\rightarrow$ M 6.9 (0.3)
- W & C – A $\rightarrow$ M 6.9 (0.3)
- W & C – AD $\rightarrow$ M 7.3 (0.2)

- Input: AD = 3 m; L = 40 km; (West, 1994)
  $A = 732 \text{ km}^2$ (dip = 55° and depth = 15 km)

- Use $\pm 1 \sigma$ for additional epistemic uncertainty (?)

- Use $\pm 0.12$ for aleatory uncertainty
Example Category C Fault: Carrington Fault

- W & C – L ($\sigma = 0.28$) $\rightarrow$ M 6.8 (L = 28 km) (0.5)
- W & C – A ($\sigma = 0.24$) $\rightarrow$ M 6.7 (A = 512 km) (0.5)

- Use $\pm 0.12$ for aleatory uncertainty
- Above is for dip = 55° and depth = 15 km;
  For dip = 70° and depth of 12 km $\rightarrow$ M 6.5;
  For dip = 30° and depth of 18 km $\rightarrow$ M 7.0.
- Use $\pm 1 \sigma$ for additional epistemic uncertainty?
Time-Dependent Probability Models

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16 February 2011
Components of the Uniform California Earthquake Rupture Forecast 2

**Fault Models**
- Specifies the spatial geometry of larger, more active faults.

**Deformation Models**
- Provides fault slip rates used to calculate seismic moment release.

**Earthquake-Rate Models**
- Gives the long-term rate of all possible damaging earthquakes throughout a region.

**Probability Models**
- Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

**Probability Models**

*How are earthquakes distributed in time?*

*How to incorporate the physics of earthquake cycles and fault interactions?*
Earthquakes are modeled as a renewal process (Cornell and Winterstein, 1988)

- Time between events are independent and identically distributed random variables

- Expected time of next event does not depend on any details of last event except the time it occurred

- A rupture on a segment resets the renewal process to its initial state
Sample of Probability Models

- Poisson – random process, probability does not vary in time
- Empirical – variation of Poisson, long term mean rupture rate is modulated by an extrapolation of the recent regional rate of earthquakes
- Lognormal and BPT
  - Uses time since last event
  - Failure condition of fault is described by a state variable that rises from a ground state to the failure state during the earthquake cycle
  - Movement toward failure is governed by a deterministic parameter (mean recurrence interval) and a stochastic parameter describing variability of recurrence intervals (aperiodicity or COV)
- Time-Predictable
  - Uses time and amount of slip in the most recent event
  - Expected time of next event is equal to time required to restore the fault to the same state when the preceding event occurred
Mathematical Model

Probability Density Function, \( f(t) \), defines the chance that failure will occur in the interval from \( t \) to \( t + \Delta t \), where \( t \) is time since last event

- Survivor function, \( F(T) \)
  \[ h(t) = \frac{f(t)}{F(t)} \]
gives instantaneous rate of failure at time \( t \) conditional on no event occurring up to time \( t \)

Conditional probabilities give probability of an event during an interval of interest, conditional on it not having occurred prior to the start of the interval

\[
P(T \leq t \leq T + \Delta T \mid t > T) = \frac{[F(T) - F(T + \Delta T)]}{F(T)}
\]
Brownian Passage Time (BPT) Model

- **Inputs**
  - mean recurrence interval, $\mu = 1/\lambda$
  - aperiodicity, $\alpha$, or variability of recurrence intervals
    - $\alpha = \sigma / \mu$
- **Probability density function**
  $$f_{BPT}(t) = \sqrt{\frac{\mu}{2\pi \alpha^2 t^3}} e^{-\frac{(t-\mu)^2}{2\mu \alpha^2}}$$
- **Hazard function**

  - Hazard function increases from zero to a maximum and the decreases toward an asymptotic value of $1/(2 \mu \alpha^2)$
  - *When $\alpha = 1 / \sqrt{2}$, the asymptotic failure rate is $1/ \mu$, which is the same as the poisson process with the same $\mu$*
INFLUENCE OF $\alpha$

- **BPT Models**
  - Mean = 1

  - Aperiodicity
    - 0.3
    - 0.5
    - 1/sqrt(2)
    - 0.9
    - Exponential

- **Hazard Functions ($h_{BPT}(t)$)**
  - Mean = 1

- **Survivor Functions**
  - Mean = 1

- **Conditional Probability**
  - for Prediction Interval of 0.3
INFLUENCE OF $\alpha$

- **Smaller $\alpha$ (0.3)**
  - $pdf$ is strongly peaked and remains close to zero longer (more periodic)
  - Larger conditional probabilities in long-term quasi-stationary state

- **Larger $\alpha$ (0.7)**
  - Delay time is shorter, closer to poisson-like behavior
  - Conditional probabilities close to poisson in long-term quasi-stationary state

- **UCERF: 0.3 (0.2), 0.5 (0.5), 0.7 (0.3)**
  - Ellsworth et al. (1999) 37 sequences of events
  - Branches for segment specific and for constant value for all segments.

*WASATCH ?*
LOGNORMAL MODEL

- Shape of pdf very close to BPT model
- However,
  - Hazard function increases from zero initially, but goes to zero as $t \to \infty$

- Long term behavior does not fully satisfy geologic intuition or earthquake renewal process
Time-Predictable Model

• Inputs
  – Slip during most recent event
  – Fault slip rate

• Provides expected time of next event, not the size

• Implemented by WGCEP 2003 for Northern San Andreas
  – BPT model used to describe variation about expected time

• Not implemented in UCERF 2
  – “Slip-predictable methods of computing earthquake probabilities from long-term rates significantly overpredict event rates and moment rates” (Field and Gupta, 2008)
  – Data on average slip from previous events sparse and uncertain
1. Compute slip in most recent event
2. Determine slip rate on each segment
3. Expected return time for segment is slip / slip rate
4. Compute probability of event starting on segment
   - BPT model with $\alpha$
5. Compute probability that an epicenter on a segment will lead to one of the rupture fault sources using slip-predictable model
   - What is the probability for each rupture source that there is enough stored moment since last event?
6. Compute rupture source probabilities
   - Probability of epicenter on each segment * Probability that epicenter will lead to a rupture source
Issues Relating to Multi-segment Rupture Models

Inconsistency with segment rates implied by BPT distribution and actual segment rates produced by the model

\[ P(\text{rup}) = \sum_{\text{seg} \text{ in } \text{rup}} P(\text{seg}) \frac{R(\text{rup})}{R(\text{seg})} \frac{\dot{\mathcal{M}}(\text{seg})}{\sum_{\text{seg} \text{ in } \text{rup}} \dot{\mathcal{M}}(\text{seg})} \]

First, probabilities of segment rupture are computed, then distributed to rupture sources containing that segment.

\[ P(\text{rup}) \approx P_{\text{pos}}(\text{rup}) \frac{\sum_{\text{seg} \text{ in } \text{rup}} P(\text{seg}) \frac{\dot{\mathcal{M}}(\text{seg})}{\sum_{\text{seg} \text{ in } \text{rup}} \dot{\mathcal{M}}(\text{seg})}}{\sum_{\text{seg} \text{ in } \text{rup}} \dot{\mathcal{M}}(\text{seg})} \]
Issues Relating to Multi-segment Rupture Models (continued)

- Final segment probabilities aggregated from the rupture source probabilities are **not** the same as the BPT computed probabilities.
- Probability of segment rupturing and taking its neighbor has nothing to do with when its neighbor ruptured last.
- Problem increases with increasing number of segments (S. SAF worse than N. SAF).

“**WGCEP (2003) methodology remains the best available science**” (Field and Gupta, 2008) and was adopted for UCERF2.
Analysis of Moment Rates from GPS, Historic Earthquakes, and Paleoeearthquakes on the Wasatch Fault

Moment: measure of energy required for deformation

\[ M_o = \mu \dot{u} A \]
2007-2010 Wasatch GPS Velocities

- Basin-Range/Rocky Mountain boundary (stable North America)

1981-2011 Wasatch Earthquakes

- Basin and Range
- Stable North America

- Central Intermountain Seismic Belt
Western U.S. GPS Data

Deformation Models

- Western U.S. rotation in velocity field
- Extensional Basin-Range (including Wasatch Front)
- Locally high deformation rates at Wasatch fault
Deformation Model

- Tectonic stresses drive deformation
- Stress modeling reveals regional tectonics
  - High elevation and high potential energy cause tensional stress (Intermountain West)
  - North America-Pacific-Juan de Fuca plate interaction cause compression and shear (California and Pacific Northwest)
- Inferred stresses account for observed rotation in GPS data

Western U.S. Stress Model
2007-2010 Wasatch GPS Network

- 68 permanent GPS stations
- Operated by University of Utah and Plate Boundary Observatory
- Profiles across Wasatch fault and other faults to measure contemporary deformation
- Monitoring since 1996
• 2007-2010 velocities

• Velocities increase rapidly across the fault zone

• Profiles cross multiple fault systems
  - Wasatch
  - East Cache
  - East Great Salt Lake/Oquirrh
  - Hansel Valley
  - Scipio/Little Valley

Net Slip Rate:
- Brigham City Profile: $2.28 \pm 0.04$ mm/yr
- Salt Lake City Profile: $2.24 \pm 0.04$ mm/yr
- Nephi/Levant Profile: $1.89 \pm 0.04$ mm/yr
• Locked elastic seismogenic layer over creeping lower crustal layer

• Horizontal dislocation to simulate far-field deformation on a detachment

• GPS profiles more closely resemble modeled rates from low-dip (<40°) creeping dislocation
- Interpolate GPS velocities to strain rate grid
- Greatest changes in deformation at Wasatch fault
• Use Kostrov formula to estimate geodetic loading rate

• Moment available for earthquakes depends on:
  - Seismogenic volume (network area x maximum earthquake depth)
  - Strain (deformation rate) for area

• Average surface strain assumed proportional to volume strain

\[ 2 \mu AH_s \dot{\varepsilon} = \frac{1}{T} \sum_{n=1}^{m} M_n \]
• Convert strain rates to moment rates

• Moment rates reflect deformation rates

• Geodetic loading rates are $10^{23}$ to $10^{24}$ dyne cm/yr in 0.2° grid areas

• Greatest loading in south-central Wasatch

• Calculate profile moment rates from single interpolated strain rate in selected area

<table>
<thead>
<tr>
<th>Area</th>
<th>Moment Rate (dyne cm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern GPS profile</td>
<td>6.7E+24</td>
</tr>
<tr>
<td>Central GPS profile</td>
<td>9.1E+24</td>
</tr>
<tr>
<td>Southern GPS profile</td>
<td>1.1E+25</td>
</tr>
</tbody>
</table>
1981-2011 Wasatch Front Earthquakes

- Historic earthquakes
  - Wasatch fault quiescent for M>3
  - Notable N-S zone of seismicity east of Wasatch fault

- Convert magnitude to seismic moment
  - 40,000+ earthquakes for 1981-2011
  - Catalog contains local and coda magnitudes
  - Use empirical relation (Bott et al., 1997)

- Average seismic moment release rate is 8.6E+22 dyne cm/yr - one order of magnitude less than geodetic rates
Wasatch Fault Paleoearthquake History

- Identify Late Quaternary paleo-earthquakes from Wasatch fault trenching
  - Each segment has had 4-5 ruptures

- Data: offset, surface rupture length
  - Moment related to rupture area, slip
  - Surface displacement varies along strike
  - Rupture area depends on fault geometry, rupture length, seismogenic depth

- Use empirical scaling to obtain moment magnitude (Wells and Coppersmith, 1994)
  - Preferred moment magnitudes from surface rupture length relation
    \[ M = 5.08 + 1.16 \cdot \log(SRL) \]
Historic Multi-Segment Earthquakes

Fault Slip Distributions and Segments of Scarp-Forming Basin and Range Earthquakes

- 1954 Rainbow Mountain, Nevada M 6.6
- 1954 Stillwater, Nevada M 6.8
- 1983 Borah Peak, Idaho M 6.8
- 1954 Dixie Valley Nevada M 6.8
- 1954 Fairview Peak Nevada M 7.1
- 1915 Pleasant Valley Nevada M 7.3
- 1959 Hebgen Lake, Montana M 7.4
- 1887 Sonora, Mexico M 7.4
- 1992 Landers California M 7.4

(Parzepane and Dawson, 2010)
Scenario Earthquake Models

- Developed by Working Group on Utah Earthquake Probabilities

- Divide paleoearthquakes into various single and multisegment combinations

- Maximum Rupture Model - single segment ruptures + one leaky-boundary rupture (22 events)

- Intermediate Rupture Model - mostly single-segment with some multisegment scenarios (variations A, B, C) (19-20 events)

- Minimum Rupture Model - multisegment ruptures where possible (13 events)
- Multisegment earthquakes release more moment
- Significant uncertainties in timing and magnitude
- No clear patterns in timing, magnitude
# Comparison of Moment Rates

<table>
<thead>
<tr>
<th>Source</th>
<th>Moment Rate (dyne cm/yr)</th>
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• Paleoearthquake models and GPS disagree by one order of magnitude
  - Problems with M-SLR relation for paleoearthquakes?
  - Overestimate GPS network area?
  - Not all accumulated moment released in earthquake?
  - Some elastic strain recovered during earthquake?
  - Ongoing aseismic deformation?
  - Time-varying loading rate?
  - More/bigger multisegment ruptures?

• Other paleoseismic parameters (average, max offset) not readily available as alternate sources for magnitude
- GPS advantages
  - Measure contemporary deformation
  - Good spatial, time coverage - not just Wasatch fault

- GPS and paleoseismic rates won’t match
  - Uncertainties in moment calculations
  - Loading rates not necessarily uniform
  - Other processes may affect rates
M = 5.08 + 1.16 \cdot \log(SRL)
\log(SRL) = -2.01 + 0.5 \cdot M
\log(SRL) = -3.22 + 0.69 \cdot M
M = 4.86 + 1.32 \cdot \log(SRL)

Default relation
Multiple expressions for M-SLR relation

(Wells and Coppersmith, 1994)
Moment Rate for Utah

Mark Petersen, Stephen Harmsen, Yuehua Zeng, Tony Crone, Kathy Haller
Parameters to calculate moment/moment rate

1. Moment = rigidity*area*displacement

2. Moment rate = rigidity*area*slip rate

3. Slip rate = Moment rate/(rigidity*area)

4. Kostrov’s formula converts strain rate to Moment rate:
   Moment rate~rigidity X length X width X strain rate
   (dependent on fault geometry)

We assume a 3X 10^10 rigidity constant
M_0=10**(1.5*M+9.05)
Lengths (l) are based on segmentation model
Parameters to calculate moment/moment rate

For USGS NSHMs we assume a 15 km vertical depth and a planar fault:
1. 50 degree dip (0.6 wt) → 19.6 km down-dip width
2. 60 degree dip (0.2 wt) → 17.3 km down-dip width
3. 40 degree dip (0.2 wt) → 23.3 km down-dip width

Other models - Wulung Chang and Bob Smith: (approximate numbers shown)
1. listric fault with 10 degree dip between 13-35 km (5 mm/yr)
2. listric fault with 38 degree dip between 7-24 km (8 mm/yr)
3. listric fault with ~40 degree Wasatch 8-20 km (8 mm/yr), Oquirrh 5-20 km (2 mm/yr), and Stansbury 5-20 km (2 mm/yr)
4. listric fault 27 degree dip between 9-20 km (7 mm/yr)
## Wasatch Lengths and Magnitudes

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Puskas and Smith suggest that Wasatch is capable of producing M 7.5 earthquakes. Based on paleoseismic studies of fault slip (McCalpin and Nishenko, 1996 and Chang and Smith, 2002)
WGUEP WASATCH FRONT REGION
(latitude 39.00° - 42.50°, longitude 110.75° - 113.25°)
PROFILE 1:
   a. East Great Salt Lake Fault (dips west) 0.78 mm/yr (downdip), 0.6 mm/yr (vertical), 0.5 (horizontal)
   b. Brigham City Wastatch (dips west) 1.5 mm/yr geologic, M 6.9 at 7.7X10-4/yr, this gives equivalent rate of between 1-3 mm/yr (downdip), 2 mm/yr vert→1.29 horiz
   c. East Casche (dips west) 0.26 mm/yr (downdip), 0.20 mm/yr (vertical), 0.17 (horizontal)
   NET SLIP TO WEST 0.5, 1.3, 0.17

PROFILE 2:
   a. Stansbury (dips west) 0.52 mm/yr (downdip), 0.4 mm/yr (vertical), 0.34 (horizontal)
   b. Oquirrh (dips west) 0.26 mm/yr (downdip), 0.20 mm/yr (vertical), 0.17 mm/yr (horizontal)
   c. West Valley (dips east) 0.52 mm/yr (downdip), 0.4 mm/yr (vertical), 0.34 mm/yr (horizontal)
   d. SLC Wasatch (dips west) 1.5 mm/yr geologic, M 7.0 at 7.7X10-4/yr, this gives equivalent rate of 1-3 mm/yr
   NET SLIP TO WEST 0.34, 0.17, 0.34, 1.3

PROFILE 3:
   a. Joes Valley (dips west) 0.26 mm/yr (downdip), 0.20mm/yr (vertical), 0.17 mm/yr (horizontal)
   NET SLIP TO WEST 0.17 mm/yr
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<td>M7.4: 653 yrs</td>
<td>M7: 164 yrs</td>
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## Comparison (downdip slip rates)

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<th>Segment</th>
<th>Geologic slip rate (mm/yr +/- 15%)</th>
<th>RI based slip rate (mm/yr +/- 15%)</th>
<th>Geodetic slip rate (Zeng)</th>
<th>Geodetic slip rate (Chang and Smith)</th>
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<td>Levan</td>
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<td>0.22</td>
<td>3.3</td>
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</table>
Geodetic data analysis

Mark Petersen and Yuehua Zeng
(data and zones from Puskas and Smith)
Methodology (Zeng)

- Started with GPS data from Puskas and Smith
- Cleaned out the spurious data
- Extrapolated to make strain rate maps
- Modified Puskas and Smith block model (not continuum model, use buried fault model)
- Inverted for slip rate on Wasatch Fault using block model of elastic upper layer and creeping lower layer
GPS velocity field
Processed GPS data
Comparison of GPS and Geology strain rates

GPS strain rate

Geology strain rate

Total Strain Rate (1.0e-9)
Block Model

Red: data, Black predicted
Figure 4.9. A narrow-dislocation model for the Wasatch fault, with the EBAR background extension removed. See Figure 4.6 for detailed descriptions.
Figure 4.15. Inverted dual-dislocation model that best fits the horizontal GPS velocities. (a) The predicted (red arrows) and observed (blue arrows) velocity vectors are plotted with that derived from the single-dislocation model shown in Figure 4.9 (green arrows). $V_N$ and $V_S$ are the loading rates of the northern and southern fault patches, respectively. (b) The west velocity components are plotted with respect to the distances from GPS sites to the Wasatch fault scarp (bold line).
## Comparison of Slip Rates

<table>
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<th>Segment</th>
<th>Geologic slip rate (mm/yr +/- 15%)</th>
<th>RI based slip rate (mm/yr +/- 15%)</th>
<th>Geodetic slip rate (Zeng)</th>
<th>Geodetic slip rate (Chang and Smith)</th>
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<tr>
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<tr>
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<td>Levan</td>
<td>0.39</td>
<td>0.22</td>
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</table>
Comparisons of geodetic and geologic data

<table>
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<tr>
<th>Segment</th>
<th>Geologic slip rate (mm/yr +/- 15%)</th>
<th>RI based slip rate (mm/yr +/- 15%)</th>
<th>Geodetic slip rate (Zeng)</th>
<th>geologic sr/recur</th>
<th>geol sr/geodetic</th>
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<td>1.36</td>
<td>2.6</td>
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<tr>
<td>Salt Lake City</td>
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<td>0.97</td>
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<td>Nephi</td>
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<tr>
<td>Levan</td>
<td>0.39</td>
<td>0.22</td>
<td>3.3</td>
<td>1.8</td>
<td>0.1</td>
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</tbody>
</table>
A Kinematic Fault Network Model of Crustal Deformation for California and Its Application to the Seismic Hazard Analysis

Yuehua Zeng\textsuperscript{1}, Zhengkang Shen\textsuperscript{2}, Steve Harmsen\textsuperscript{1}, and Mark Petersen\textsuperscript{1}

\textsuperscript{1}US Geological Survey, Golden, CO
\textsuperscript{2}Dept of Earth and Space Sciences, UCLA
GPS velocity data for California
UCERF velocity predictions for California
Residuals bw UCERF and GPS
Residuals bw Block model and GPS
GPS rates with geological constraints

geological rates

10 mm/yr
- right-lateral
- left-lateral
Part of the WUS - GPS and geological model comparison

- We do not have the WUS block model completed however we have the Wasatch
- Geologic model based on 2008 slip rates
- Processed GPS observations
GPS VELOCITIES
GEOLOGY VELOCITIES
COMPARISON OF GPS AND GEOLOGY VELOCITIES
Processed GPS data
Conclusions

• GPS working groups strongly advise using the GPS data to constrain slip rates in the hazard maps.
• For California the GPS and Geology models are similar but the moment rate for gps is about 15% higher than the geology.
• For Utah the GPS and Geology models are differ by a factor of more than 1-3.
• The difference increase to the South
• Should we use the GPS data? This would imply higher hazard on the Southern Wasatch.
Discussion Points

- Collaboration with USGS on a consensus earthquake catalog
- Thinking through how to handle “background” earthquakes vis-à-vis fault sources
- Planned steps (redux)
Collaboration with USGS

Catalog compilation (1850 through 2010)

- Discussions started with Chuck Mueller in January, still shaping plans
- Scoping the bounds (larger than WGUEP area?) and magnitude threshold for unifying UUSS and USGS catalog entries, accounting for special studies of some mainshocks
- Eventual comparison of declustering: Gardner Knopoff method used by USGS vs. Veneziano and Van Dyck stochastic method
Steps (redux)

1. Conversion to Moment magnitude, $M_W$
   - Instrumentally-determined $M_W$
   - Conversion from macroseismic measure (e.g., $I_0$)
   - Conversion from other instrumental magnitudes
2. Uniform Magnitude Catalog

- Veneziano (EPRI, 1988) showed that earthquake recurrence rates can be biased due to uncertainties relating to the magnitude conversion process.

- In a rigorous analysis, $M^*$ (an adjusted magnitude) is used to correct this bias and produce a “uniform magnitude catalog” for recurrence calculations.
Steps (redux)

3. Catalog Declustering

- Gardner & Knopoff (1974) — uses simple time and distance windows to remove foreshocks and aftershocks
- EPRI (1986) [Veneziano & Van Dyck] — stochastic approach
Steps (redux)

5. Earthquake Recurrence Calculations

- State of practice is to use a maximum-likelihood approach (e.g., Weichert, 1980)
Example recurrence calculation using Weichert approach (from Feb 2010 WGUEP meeting)

N(3.0) = 0.32E+01, b = 0.72

Pechmann & Arabasz (1995)

Update for 1962.5–2006.5

Cumulative Annual Frequency

Magnitude

- observed
- N(3.0) = 0.30E+01, b = 0.78

(for reference)
Path Forward  (for discussion)

1. Need to decide/agree on scope and rigor of steps for analysis

2. At least basic attempt to move in direction of a consensus catalog with USGS

3. Revisit whether probability of $M \geq 5.0$ background earthquake is to be computed for entire WGUEP study region or on some gridded basis (as being done on USGS Web site)

4. Complete steps and analysis
end
## EARTHQUAKE TIMING (ka ± 2 sigma)

<table>
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<th>Event</th>
<th>Brigham City</th>
<th>Weber</th>
<th>Salt Lake City</th>
<th>Provo</th>
<th>Nephi</th>
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<tr>
<td>E2</td>
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<td>E3</td>
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<td>4.1 ± 0.3</td>
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<td>E4</td>
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<td>E5</td>
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## RECURRENCE (ky ± 2 sigma)

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<tr>
<td>Open mean</td>
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## SLIP RATE (mm/yr)

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Should the WGUEP Compute Time-Dependent Probabilities for Large Earthquakes on the Great Salt Lake Fault?

David A. Dinter and James C. Pechmann
Department of Geology and Geophysics
University of Utah
Major active normal faults in the Great Salt Lake region, northern Utah
Approach –
Analogous to trenching:

• Map active fault traces to determine lengths and identify segments

• Measure net vertical tectonic displacement from lake bottom topography and/or cross sections across fault

• Identify seismic event horizons

• Date event horizons to obtain earthquake
In our surveys, we typically use two seismic reflection systems simultaneously deployed from either side of a small boat.
The Geopulse “boomer” diaphragm, mounted on a pontoon sled, emits pulses at energies up to 280 joules with frequency content in the 700- to 1200-Hz range.
Active faults in the south arm, Great Salt Lake, Utah

- Two major segments of the GSL normal fault south of Promontory Point
  - Segment boundary is a 1-2-km left step W of White Rock Bay, N Antelope Island

- Fremont Island segment:
  - 20 km long (revised from 30 km)
  - No lakebed scarp along half of it (buried)

- Antelope Island segment:
  - 35 km long
  - Lakebed scarp, up to 3.6 m relief
  - Bends sharply SW at south end
  - Appears to merge with Oquirrh fault

- Numerous active intrabasin normal faults
  - Strikes oblique to GSLF
  - Lakebed scarps, up to 1.8 m relief
  - Probably coseismic with GSLF
South arm update:

- Acquired new south arm seismic data in 2005-6, primarily north of Carrington Island to Promontory Point stepover zone.

- Carrington fault is an independent seismogenic structure ~30 km long. Does not merge with GSL Events as large as M 6.8 Fresh scarp -> recent earthquake

- GSLF Fremont segment is shorter than previously mapped (~20 km) Does not curve NW to merge with Promontory segment. Left stepover zone ~ 7 km wide contains short faults probably coseismic with Promontory segment.
A.I. segment average vertical slip rate = 0.55 ±0.5/-0.25 mm/yr (max)

Squares: A.I. Segment
Circles: F.I. Segment.
Great Salt Lake fault, Antelope Island segment

Geopulse Line 98GSL11

Depth below lake level (m)

Two-way travel time (msec)

V.E. = 24:1

East Great Salt Lake fault
EH-A3; 640 B.P.
Lake bottom
EH-A2; 6224 B.P.

H0

GSL00-3
Scarp
Debris-flow fan
EH-A1; 9952 B.P.

WSW

ENE

200 m
Great Salt Lake fault, Fremont Island segment

Geopulse Line 98GSL36

EH-F3 (fault termination surface); 3204 B.P.

EH-F2 (onlap surface); 6466 B.P.

EH-F1 (onlap surface); < 11,481 B.P.

EGSLF east strand

EGSLF west strand

V.E. = 35:1

Depth below lake level (m)

Two-way travel time (msec)

0 400 m

WSW

H0

GSL00-1

GSL00-2

H0

Top salt

C

b

a

40
The DOSECC GLAD-1 mobile lacustrine drilling platform, 2000
<table>
<thead>
<tr>
<th>Earthquake</th>
<th>$^{14}$C yr BP (before 1950)</th>
<th>Calendar yr BP (before 1950) \cite{Stuiver98}; terrestrial calibration</th>
<th>Residence-corrected calendar years BP (before 1950)</th>
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<td>EH-A3</td>
<td>$&gt; 804 \pm 38$ $&lt; 1027 \pm 44$</td>
<td>$&gt; 706^{+81/-40}$ $&lt; 944^{+106/-147}$</td>
<td>586 $^{+201/-241}$</td>
<td>643 $^{+201/-241}$</td>
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<td>EH-A2</td>
<td>5,711 $\pm 50$</td>
<td>6491 $^{+163/-135}$</td>
<td>6170 $^{+236/-234}$</td>
<td>6227 $^{+236/-234}$</td>
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<td>EH-A1</td>
<td>9,068 $\pm 66$</td>
<td>10,219 $^{+178/-234}$</td>
<td>9898 $^{+247/-302}$</td>
<td>9955 $^{+247/-302}$</td>
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<td><strong>Fremont Island segment</strong></td>
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<tr>
<td>EH-F3</td>
<td>3,269 $\pm 47$</td>
<td>3471 $^{+161/-90}$</td>
<td>3150 $^{+235/-211}$</td>
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<td>EH-F2</td>
<td>5,924 $\pm 44$</td>
<td>6733 $^{+121/-90}$</td>
<td>6412 $^{+209/-211}$</td>
<td>6469 $^{+209/-211}$</td>
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<td>EH-F1</td>
<td>$&lt;10,155 \pm 72$</td>
<td>$&lt;11,748^{+580/-406}$</td>
<td>$&lt;11,427^{+605/-449}$</td>
<td>$&lt;11,484^{+605/-449}$</td>
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## Earthquake recurrence intervals, Great Salt Lake fault

<table>
<thead>
<tr>
<th>Earthquake pairs</th>
<th>Dates of occurrence (residence-corrected cal yr before 1950)</th>
<th>Recurrence interval (yr)</th>
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<tr>
<td>EH-A3 EH-A2</td>
<td>596 ±201/-241, 6170 ±236/-234</td>
<td>5584 ±219/-172</td>
</tr>
<tr>
<td>EH-A2</td>
<td>6170 ±236/-234</td>
<td>3728 ±223/-285</td>
</tr>
<tr>
<td>EH-A1</td>
<td>9898 ±247/-302</td>
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</tr>
<tr>
<td><strong>Fremont Island segment (M\text{\textsubscript{max}} = 6.6-6.7)</strong></td>
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<tr>
<td>EH-F3 EH-F2</td>
<td>3150 ±235/-211, 6412 ±209/-211</td>
<td>3262 ±151/-184</td>
</tr>
<tr>
<td>EH-F2 EH-F1</td>
<td>6412 ±209/-211, &lt;11,427 ±605/-449</td>
<td>&lt;5015 ±587/-424</td>
</tr>
</tbody>
</table>

**Average single-segment recurrence interval**

= 4200 ± 1400 years
North Arm provisional results

- Obtained 40 north arm crossings of GSLF in 2009, 2010
- Detailed active fault map in preparation
- Preliminary interpretation indicates:
  
  Two additional segments in the north arm:

  **Promontory segment** has a young scarp. Stepover faults at south end of Promontory Point also have fresh scarps; may be coseismic.

  **Rozelle segment** is partly buried, and is the northernmost segment of GSLF system.

  Hansel Valley fault to north has opposite dip direction.

  There is likely a tear-fault system in Spring Bay.
Example of North Arm Data, Great Salt Lake

Raw plot of “Ultrachirp” Line 09GSL2a, E-W crossing of GSLF Promontory segment in Great Salt Lake north arm. Note Holocene scarp at far right, auxiliary faults throughout basin.
Launching the survey boat in the Great Salt Lake north a
Maximum Magnitude Estimates, Great Salt Lake Fault
(from empirical relationships in Wells and Coppersmith, 1994)

<table>
<thead>
<tr>
<th>Faulting Parameter</th>
<th>Antelope Segment</th>
<th>Fremont Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Rupture Length</td>
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<td>6.6 ± 0.3</td>
</tr>
<tr>
<td>Rupture Area</td>
<td>6.9 ± 0.3</td>
<td>6.7 ± 0.3</td>
</tr>
</tbody>
</table>
Strawman Rupture Scenarios for the Great Salt Lake Fault

James C. Pechmann and David A. Dinter
Department of Geology and Geophysics
University of Utah

(with help from Susan S. Olig, URS Corp.)
End-to-End Segment Lengths

Antelope Island (AI)
35 (30-37) km
Large lakebed scarp

Fremont Island (FI)
22 (18-28) km
Half buried scarp

Promontory (P)
32 (28-36) km
Young scarp

Rozelle (R)
23 (19-27) km
Partly buried scarp
A.I. segment avg vertical slip rate = 0.55 \pm 0.5/-0.25 mm/yr (max)
### Maximum Magnitude Estimates, Great Salt Lake Fault (from M vs. SRL relations for normal faults, Wells and Coppersmith, 1994)

<table>
<thead>
<tr>
<th>Single-Segment Ruptures</th>
<th>Multi-Segment Ruptures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Segment</td>
<td>Length (km)</td>
</tr>
<tr>
<td>Rozelle (R)</td>
<td>23</td>
</tr>
<tr>
<td>Promontory (P)</td>
<td>32</td>
</tr>
<tr>
<td>Fremont Island (FlI)</td>
<td>22</td>
</tr>
<tr>
<td>Antelope Island (Al)</td>
<td>35</td>
</tr>
</tbody>
</table>
South arm update:

- Acquired new south arm seismic data in 2005-6, primarily north of Carrington Island to Promontory Point stepover zone.

- Carrington fault is an independent seismogenic structure ~30 km long.

  Does not merge with GSL

  Events as large as M 6.8

  Fresh scarp -> recent earthquake

- GSLF Fremont segment is shorter than previously mapped (~20 km)

  Does not curve NW to merge with Promontory segment.

  Left stepover zone ~ 7 km wide contains short faults probably coseismic with Promontory segment.
Great Salt Lake fault, Antelope Island segment

**V.E. = 24:1**

- East Great Salt Lake fault
- EH-A3; 640 B.P.
- Lake bottom
- EH-A2; 6224 B.P.
- H₀

Geopulse Line 98GSL11
Great Salt Lake fault, Fremont Island segment

Geopulse Line 98GSL36
# Earthquake dates, Great Salt Lake fault

<table>
<thead>
<tr>
<th>Earthquake Segment</th>
<th>14C yr BP (before 1950)</th>
<th>Calendar yr BP (before 1950) (^2); Stuiver et al., 1998 terrestrial calibration</th>
<th>Residence-corrected (^3) calendar years BP (before 1950) (^2)</th>
<th>Residence-corrected (^3) calendar years before 2007 (^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antelope Island segment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EH-A3</td>
<td>&gt; 804 ± 38</td>
<td>&gt; 706 +81/-40</td>
<td>586 +201/-241</td>
<td>643 +201/-241</td>
</tr>
<tr>
<td></td>
<td>&lt; 1027 ± 44</td>
<td>&lt; 944 +106/-147</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EH-A2</td>
<td>5,711 ± 50</td>
<td>6491 +163/-135</td>
<td>6170 +236/-234</td>
<td>6227 +236/-234</td>
</tr>
<tr>
<td>EH-A1</td>
<td>9,068 ± 66</td>
<td>10,219 +178/-234</td>
<td>9898 +247/-302</td>
<td>9955 +247/-302</td>
</tr>
<tr>
<td><strong>Fremont Island segment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EH-F3</td>
<td>3,269 ± 47</td>
<td>3471 +161/-90</td>
<td>3150 +235/-211</td>
<td>3207 +235/-211</td>
</tr>
<tr>
<td>EH-F2</td>
<td>5,924 ± 44</td>
<td>6733 +121/-90</td>
<td>6412 +209/-211</td>
<td>6469 +209/-211</td>
</tr>
<tr>
<td>EH-F1</td>
<td>&lt;10,155 ± 72</td>
<td>&lt;11,748 +580/-406</td>
<td>&lt;11,427 +605/-449</td>
<td>&lt;11,484 +605/-449</td>
</tr>
</tbody>
</table>
Earthquake recurrence intervals, Great Salt Lake fault

<table>
<thead>
<tr>
<th>Earthquake pairs</th>
<th>Dates of occurrence (residence-corrected cal yr before 1950)</th>
<th>Recurrence interval (yr)</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td><strong>Antelope Island segment</strong> (M_{\text{max}} = 6.9)</td>
<td></td>
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</tr>
<tr>
<td>EH-A3 EH-A2</td>
<td>596 +201/-241</td>
<td>5584 +219/-172</td>
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<td></td>
<td>6170 +236/-234</td>
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<td></td>
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<tr>
<td></td>
<td>6170 +236/-234</td>
<td>3728 +223/-285</td>
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<tr>
<td>EH-A2 EH-A1</td>
<td>9898 +247/-302</td>
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<tr>
<td><strong>Fremont Island segment</strong> (M_{\text{max}} = 6.6-6.7)</td>
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</tr>
<tr>
<td>EH-F3 EH-F2</td>
<td>3150 +235/-211</td>
<td>3262 +151/-184</td>
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<tr>
<td></td>
<td>6412 +209/-211</td>
<td></td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>6412 +209/-211</td>
<td>&lt; 5015 +587/-424</td>
</tr>
<tr>
<td>EH-F2 EH-F1</td>
<td>&lt; 11,427 +605/-449</td>
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</tr>
</tbody>
</table>

Average single-segment recurrence interval \(= 4200 \pm 1400\) years
Considerations Favoring Single-Segment Ruptures

• Fault geometry
• Rupture lengths of most recent events
• Relatively uniform offsets in each event

Considerations Favoring Multi-Segment Ruptures

• Some relatively short segment lengths
• Dates permit two combined ruptures of the Fremont Island and Antelope Island segments
<table>
<thead>
<tr>
<th>R</th>
<th>P</th>
<th>FI</th>
<th>AI</th>
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</thead>
<tbody>
<tr>
<td>R + P</td>
<td>FI</td>
<td>AI</td>
<td>Speculative</td>
</tr>
<tr>
<td>R</td>
<td>P + FI</td>
<td>AI</td>
<td>Unlikely</td>
</tr>
<tr>
<td>R</td>
<td>P</td>
<td>FI + AI</td>
<td>Allowed by dates for S half</td>
</tr>
<tr>
<td>R + P</td>
<td>FI + AI</td>
<td>Allowed by dates for S half</td>
<td></td>
</tr>
</tbody>
</table>

**COMMENTS**

- MRE ruptures
- Speculative
- Unlikely
- Allowed by dates for S half
- Allowed by dates for S half

Unsegmented
Rupture Scenarios

<table>
<thead>
<tr>
<th></th>
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<th>WS1</th>
<th>WS2</th>
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<tr>
<td>R</td>
<td>P</td>
<td>FI</td>
<td>AI</td>
<td></td>
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<td>0.75</td>
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<tr>
<td>R + P</td>
<td>FI</td>
<td>AI</td>
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<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>R</td>
<td>P + FI</td>
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<td>AI</td>
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<td>0.00</td>
<td>0.00</td>
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<tr>
<td>R</td>
<td>P</td>
<td>FI + AI</td>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>R + P</td>
<td>FI + AI</td>
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<td></td>
<td>0.05</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Unsegmented | 0.10 | 0.08
Maximum Magnitude Estimates, Great Salt Lake Fault
(from empirical relationships in Wells and Coppersmith, 1994)

<table>
<thead>
<tr>
<th>Faulting Parameter</th>
<th>Antelope Segment</th>
<th>Fremont Segment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Rupture Length</td>
<td>6.9 ± 0.3</td>
<td>6.6 ± 0.3</td>
</tr>
<tr>
<td>Rupture Area</td>
<td>6.9 ± 0.3</td>
<td>6.7 ± 0.3</td>
</tr>
<tr>
<td>FAULT NO.</td>
<td>FAULT NAME</td>
<td>RIFT TYPE</td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>730</td>
<td>Bear River fault zone</td>
<td>Independent (1.0)</td>
</tr>
<tr>
<td>2432</td>
<td>Drum Mountains fault zone and Crater Bench faults</td>
<td>Independent (0.2)</td>
</tr>
<tr>
<td>Not Applicable</td>
<td>Carrington fault</td>
<td>Independent (1.0)</td>
</tr>
<tr>
<td>2346</td>
<td>Crawford Mountains (west side) fault</td>
<td>Independent (1.0)</td>
</tr>
</tbody>
</table>
Table 1. Source Parameters For Working Group on Utah Earthquake Probabilities "Other" Faults (continued)

<table>
<thead>
<tr>
<th>FAULT NO.</th>
<th>FAULT NAME</th>
<th>RUPTURE MODEL</th>
<th>MAXIMUM RUPTURE LENGTH</th>
<th>MAXIMUM MAGNITUDE</th>
<th>DIP°</th>
<th>APPROXIMATE AGE OF YOUNGEST OFFSET</th>
<th>PROBABILITY OF ACTIVITY</th>
<th>RATE OF ACTIVITY</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3504</td>
<td>Curlew Valley faults</td>
<td>Independent single plane (1.0)</td>
<td>20</td>
<td>6.3 (0.2)</td>
<td>6.6 (0.6)</td>
<td>6.9 (0.2)</td>
<td>30 W (0.2)</td>
<td>55 W (0.6)</td>
<td>70 W (0.2)</td>
</tr>
<tr>
<td>2352a, 2352b, 2352c, 2378, 2377</td>
<td>East Cache fault zone (includes the James Peak and Broadmouth Canyon faults)</td>
<td>Unsegmented (0.3)</td>
<td>84</td>
<td>7.0 (0.2)</td>
<td>7.3 (0.6)</td>
<td>7.6 (0.2)</td>
<td>30 W (0.2)</td>
<td>55 W (0.6)</td>
<td>70 W (0.2)</td>
</tr>
<tr>
<td>2354a, 2354b</td>
<td>East Canyon fault (includes northern [12-16] and southern [12-17] sections)</td>
<td>Linked (1.0)</td>
<td>26</td>
<td>6.4 (0.2)</td>
<td>6.7 (0.6)</td>
<td>7.0 (0.2)</td>
<td>30 E (0.2)</td>
<td>55 E (0.6)</td>
<td>70 E (0.2)</td>
</tr>
<tr>
<td>3509</td>
<td>East Dayton – Oxford faults</td>
<td>Independent (1.0)</td>
<td>23</td>
<td>6.0 (0.2)</td>
<td>6.7 (0.6)</td>
<td>7.0 (0.2)</td>
<td>30 W (0.2)</td>
<td>55 W (0.6)</td>
<td>70 W (0.2)</td>
</tr>
<tr>
<td>FAULT NO.1</td>
<td>FAULT NAME</td>
<td>RUPTURE MODEL</td>
<td>MAXIMUM RUPTURE LENGTH2 (km)</td>
<td>MAXIMUM MAGNITUDE3 (M)</td>
<td>DIP4 (degrees)</td>
<td>APPROXIMATE AGE OF YOUNGEST OFFSET</td>
<td>PROBABILITY OF ACTIVITY4</td>
<td>RATE OF ACTIVITY5 (mm/yr)</td>
<td>COMMENTS</td>
</tr>
<tr>
<td>------------</td>
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<td>---------------</td>
<td>-----------------------------</td>
<td>------------------------</td>
<td>----------------</td>
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<td>--------------------------</td>
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<td>----------</td>
</tr>
<tr>
<td>2364c-</td>
<td>Eastern Bear Lake Segment, 2364b-Central Segment, 2364a-Northern Segment</td>
<td>Segmented (0.7)</td>
<td>Southern section – 32</td>
<td>6.8 (0.2)</td>
<td>7.1 (0.6)</td>
<td>30 W (0.4)</td>
<td>Late Holocene</td>
<td>1.0</td>
<td>0.4 (0.2)</td>
</tr>
<tr>
<td>2471, 2443, 2442, 2441, 2440</td>
<td>Faults along the western margin of Scipio Valley (from south to north includes: Red Canyon Grove faults, Maple Grove faults, Pavant Range fault, Scipio fault zone, and Scipio Valley faults)</td>
<td>Linked (1.0)</td>
<td>45 (0.3) (total length)</td>
<td>6.7 (0.2)</td>
<td>7.0 (0.6)</td>
<td>30 E (0.2)</td>
<td>Latest Quaternary (≤ 15 ka)</td>
<td>1.0</td>
<td>0.02 (0.2)</td>
</tr>
<tr>
<td>2445</td>
<td>Gunnison fault</td>
<td>Independent (1.0)</td>
<td>42</td>
<td>6.7 (0.2)</td>
<td>7.0 (0.6)</td>
<td>30 E (0.2)</td>
<td>Holocene (?)</td>
<td>0.8</td>
<td>0.05 (0.3)</td>
</tr>
<tr>
<td>2358, 2359</td>
<td>Hansel Valley fault (includes the east Hansel Mountains fault – Hansel Valley [valley bottom] faults?)</td>
<td>Linked (1.0)</td>
<td>27</td>
<td>6.6 (0.2)</td>
<td>6.8 (0.6)</td>
<td>30 E (0.2)</td>
<td>Historic (1934)</td>
<td>1.0</td>
<td>0.07 (0.2)</td>
</tr>
<tr>
<td>2439</td>
<td>Little Valley faults (link with Scipio faults, etc.?)</td>
<td>Independent (1.0)</td>
<td>20</td>
<td>6.3 (0.2)</td>
<td>6.6 (0.6)</td>
<td>70 W (0.3)</td>
<td>Latest Pleistocene (≤ 30 ka)</td>
<td>1.0</td>
<td>0.06 (0.5)</td>
</tr>
</tbody>
</table>
Table 1. Source Parameters For Working Group on Utah Earthquake Probabilities “Other” Faults (continued)

<table>
<thead>
<tr>
<th>FAULT NO.</th>
<th>FAULT NAME</th>
<th>RUPTURE MODEL</th>
<th>MAXIMUM RUPTURE LENGTH(^1) (km)</th>
<th>MAXIMUM MAGNITUDE(^1) (M)</th>
<th>DIP(^4) (degrees)</th>
<th>APPROXIMATE AGE OF YOUNGEST OFFSET</th>
<th>PROBABILITY OF ACTIVITY(^1)</th>
<th>RATE OF ACTIVITY(^1) (mm/yr)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2350</td>
<td>Main Canyon fault as “fault east of East Canyon,” or East Canyon [east side] fault(^2) in USGS database</td>
<td>Independent (1.0)</td>
<td>26</td>
<td>6.4 (0.2) 6.7 (0.6) 7.0 (0.2)</td>
<td>30 W (0.2) 55 W (0.6) 70 W (0.2)</td>
<td>Holocene</td>
<td>0.9</td>
<td>Recurrence intervals (0.7): 12,000 (0.2) 24,000 (0.3) 30,000 (0.3) 60,000 (0.2)</td>
<td>Although identified and mapped by Bryant (1990) and Coogan and King (1999), this fault is not included in Black et al. (2003) and was only recently included in the USGS Quaternary Fault and Fold Database. The Main Canyon fault bounds the east side of East Canyon Valley and the East Canyon fault bounds the west side. Previous studies had considered the nearby East Canyon fault to be the more active and dominant fault primarily based on thicker late Cenozoic deposits along the west side of the basin, and the geomorphic expression of bedrock scarps (Sullivan et al., 1988). However, in a recent paleoseismic study by Piety et al. (2008), they found evidence for three (or more?) late Quaternary faulting events occurring on the Main Canyon fault at 5-6 ka, 30-35 ka, and &gt;40-50 ka. In contrast, Piety et al. (2008) found no evidence for late Quaternary faulting on the East Canyon fault, although the age of youngest activity remains unconstrained, and the relation of the two faults remains ambiguous. Our characterization here is simplified after Anderson (2009) and considers the Main Canyon fault likely to be the dominant fault, but our slightly lower probability of activity acknowledges the small possibility the East Canyon may be dominant.</td>
</tr>
<tr>
<td>2353a, 2353b, 2353c</td>
<td>Morgan fault (includes northern, central, and southern sections)</td>
<td>Linked (1.0)</td>
<td>17</td>
<td>6.4 (0.2) 6.7 (0.6)(^5) 7.0 (0.2)</td>
<td>30 W (0.2) 55 W (0.6) 70 W (0.2)</td>
<td>Holocene</td>
<td>1.0</td>
<td>0.01 (0.3) 0.04 (0.4) 0.1 (0.3)</td>
<td>We grouped the northern, central, and southern sections defined by Sullivan and Nelson (1992) based on: (1) short section lengths; (2) along-strike patterns of topographic profiles; and (3) similar geomorphic expression (Sullivan et al., 1988). Slip rates based on data of Sullivan and Nelson (1992) and Sullivan et al. (1988).</td>
</tr>
<tr>
<td>2361</td>
<td>North Promontory fault</td>
<td>Independent (1.0)</td>
<td>26</td>
<td>6.5 (0.2) 6.8 (0.6)(^5) 7.1 (0.2)</td>
<td>30 W (0.2) 55 W (0.6) 70 W (0.2)</td>
<td>Latest Quaternary</td>
<td>1.0</td>
<td>0.02 (0.2) 0.25 (0.6) 1.0 (0.2)</td>
<td>Range-front fault bounding eastern Hansel Valley showing evidence for Holocene movement and multiple late Pleistocene events. Slip rate distribution based on data in McCalpin et al. (1992).</td>
</tr>
<tr>
<td>2369, 2398, 2399, 2407, 2420</td>
<td>Oquirrh-Great Salt Lake fault zone (modified from Wong et al., 2002; includes the East Great Salt Lake, Oquirrh, South Oquirrh Mountains, Tophill Hills, and East Tintic faults)</td>
<td>Unsegmented (0.2) Segmentation Model A (0.65): Segmentation Model B (0.35):</td>
<td>50 (1.5 times weighted-mean average segment length)</td>
<td>6.8 (0.2) 7.1 (0.6) 7.4 (0.2)</td>
<td>30 W (0.2) 45 W (0.6) 70 W (0.2)</td>
<td>Holocene</td>
<td>1.0</td>
<td>0.05, 0.5 (0.2) 0.2, 0.9 (0.6) 1.0, 2.5 (0.2)</td>
<td>Rupture lengths and segmentation models A and B revised from Wong et al. (2002) based on new data from Dinter and Pechmann (2005) and Olig et al. (2001). Note that the South Oquirrh Mountains fault includes the Mercut fault (No.7-14 of Hecker, 1993) as well as other associated Quaternary faults as mapped by Olig et al. (1999a). Note also that Dinter and Pechmann (2005) and Lund (2005) refer to the former East Great Salt Lake fault zone (#2369) as just the Great Salt Lake fault zone, and we use that nomenclature here. Recent revised mapping of the Great Salt Lake fault based on additional seismic reflection profiles in the northern arm of the lake indicate a newly identified segment boundary near the north end of Indian Cove that defines the Rozelle segment to the north (D. Dinter, University of Utah, written and digital communication, 2010). Shallower dips considered for the Great Salt Lake fault (i.e., the Rozelle Promontory, Antelope Island, and Fremont Island segments) based on seismic reflection and drill-hole data (Pechmann et al., 1987; Vivieros, 1986; Smith and Bruhn, 1984; Mohapatra and Johnson, 1998).</td>
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### Table 1. Source Parameters For Working Group on Utah Earthquake Probabilities “Other” Faults (continued)

<table>
<thead>
<tr>
<th>FAULT NO.</th>
<th>FAULT NAME</th>
<th>RUPTURE MODEL</th>
<th>MAXIMUM RUPTURE LENGTH (km)</th>
<th>MAXIMUM MAGNITUDE (M)</th>
<th>DIP (degrees)</th>
<th>APPROXIMATE AGE OF YOUNGEST OFFSET</th>
<th>PROBABILITY OF ACTIVITY</th>
<th>RATE OF ACTIVITY (mm/yr)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Northern Oquirrh - South Oquirrh Segment-61</td>
<td>6.9 (0.2)</td>
<td>30 W (0.2)</td>
<td>6.9 (0.2)</td>
<td>55 W (0.6)</td>
<td>Holocene</td>
<td>1.0</td>
<td>0.05 (0.3)</td>
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</tr>
<tr>
<td></td>
<td>Topliff Hills Segment-26</td>
<td>6.4 (0.2)</td>
<td>30 W (0.2)</td>
<td>6.4 (0.2)</td>
<td>55 W (0.6)</td>
<td>Holocene - ?</td>
<td>1.0</td>
<td>0.05 (0.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>East Tintic Segment-35</td>
<td>6.6 (0.2)</td>
<td>30 W (0.2)</td>
<td>6.6 (0.2)</td>
<td>55 W (0.6)</td>
<td>Mid to late</td>
<td>1.0</td>
<td>0.05 (0.3)</td>
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</tr>
<tr>
<td>2380</td>
<td>Porcupine Mountain faults</td>
<td>Independent (1.0)</td>
<td>30 W (0.2)</td>
<td>30 W (0.2)</td>
<td>55 W (0.6)</td>
<td>Late Quaternary</td>
<td>1.0</td>
<td>0.01 (0.5)</td>
<td>Fault geometry and length from Coogan and King (1999) and Bryant (1998). Note that even though Machette et al. (2001) measure an end to end length of 34.6 km from the same sources as used here, this shorter length would still result in the same preferred maximum magnitude of M 6.9. This fault offsets apparently young (Holocene-latest Pleistocene?) alluvial fans (J. King, UGS, personal communication, 4-3-00). Due to a lack of slip rate data, we assumed a distribution similar to the Morgan fault.</td>
</tr>
<tr>
<td>FAULT NO.</td>
<td>FAULT NAME</td>
<td>RUPTURE MODEL</td>
<td>MAXIMUM RUPTURE LENGTH1 (km)</td>
<td>MAXIMUM MAGNITUDE3</td>
<td>DIP4 (degrees)</td>
<td>APPROXIMATE AGE OF YOUNGEST OFFSET</td>
<td>PROBABILITY OF ACTIVITY5</td>
<td>RATE OF ACTIVITY6 (mm/yr)</td>
<td>COMMENTS</td>
</tr>
<tr>
<td>-----------</td>
<td>------------</td>
<td>---------------</td>
<td>-----------------------------</td>
<td>-------------------</td>
<td>--------------</td>
<td>----------------------------------</td>
<td>-------------------------</td>
<td>--------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>731</td>
<td>Reactivated Section of the Absaroka Thrust fault</td>
<td>Independent (1.0)</td>
<td>15</td>
<td>6.1 (0.2)</td>
<td>6.4 (0.6)</td>
<td>6.7 (0.2)</td>
<td>Holocene</td>
<td>0.7</td>
<td>0.4 (0.3)</td>
</tr>
<tr>
<td>729</td>
<td>Rock Creek fault</td>
<td>Independent (1.0)</td>
<td>41</td>
<td>Listric?</td>
<td>1.0</td>
<td>0.2 (0.1)</td>
<td>Holocene</td>
<td>0.2 (0.1) 0.7 (0.6) 1.0 (0.3) 0.6-1.5 ky?</td>
<td></td>
</tr>
<tr>
<td>2405</td>
<td>Sheepr Rock fault zone</td>
<td>Independent (1.0)</td>
<td>12</td>
<td>30 W (0.2)</td>
<td>55 W (0.6)</td>
<td>70 W (0.2)</td>
<td>Latest Quaternary - Holocene?</td>
<td>1.0</td>
<td>0.05 (0.3) 0.1 (0.4) 0.3 (0.3)</td>
</tr>
<tr>
<td>2387</td>
<td>Skull Valley (mid valley) faults</td>
<td>Linked (1.0)</td>
<td>32</td>
<td>6.5 (0.2)</td>
<td>6.8 (0.6)</td>
<td>7.1 (0.2)</td>
<td>Latest Quaternary</td>
<td>0.9</td>
<td>0.06 (0.2) 0.3 (0.6) 0.5 (0.2)</td>
</tr>
<tr>
<td>Not Applicable</td>
<td>Springline fault (of Helm, 1995). Now incorporated into the Skull Valley (mid valley) faults on the USGS database.</td>
<td>Independent (1.0) Or combine with Skull Valley faults above?</td>
<td>18</td>
<td>6.2 (0.2)</td>
<td>6.5 (0.6)</td>
<td>6.8 (0.2)</td>
<td>Quaternary (?)</td>
<td>0.7</td>
<td>0.06 (0.2) 0.2 (0.6) - High? 0.5 (0.2)</td>
</tr>
</tbody>
</table>

Length and location based on mapping of West (1994), which includes the Martin Ranch scarp. We assigned a slightly lower p(a) to account for the possibility that this structure may not be seismogenic and capable of independent rupture from the Bear River fault zone, as suggested by West (1994). Preferred slip rate based on West’s (1994) 0.5 to 0.7 mm/yr vertical estimate, even though this is not for a complete seismic cycle.

The Rock Creek fault is a high-angle, down-to-west normal fault within the Tunp Range; it may sole into the Laramide-age Tump thrust fault. Most of fault length is characterized by scarps on steep colluvial slopes. McCalpin (1993) stated that some scarps are as much as 25 m high. He excavated one trench across the fault. The most recent event is bracketed by radiocarbon ages of 3,280±70 and 3,880±60 14C yr BP (McCalpin and Warren, 1992), or roughly 3.6±0.3 ka, whereas the penultimate (older) event is about 4.6±0.2 ka. McCalpin (1993) provided these minimum and maximum recurrence intervals based on the occurrence of the two most recent paleoearthquakes. This equates to a permissible recurrence interval of about 0.6-1.5 ky. However, the late Quaternary recurrence interval must be quite variable: it has been about 3.6±0.3 ky since the last event and it was at least 10 ky before the penultimate event (15 ka is the inferred time of deposition of older faulted deposit at trench site).

Range-front scarps along the eastern side of the Sheeprock Mountains and Red Pine Mountain. The southern half of the fault zone is a single, continuous, north-northwest-trending fault trace paralleling the range front. At East Government Creek, the fault zone and range front change trend to the north-northeast, and the fault zone changes from a single trace without antithetic faulting to an en-echelon fault zone accompanied by antithetic faulting. Diffusion-equation modeling of the scarps, which probably represent multiple earthquakes (cumulative displacement <11.5 m), yielded an age of about 53 ka (Hanks and others, 1984). In contrast, Everitt and Kaliser (1980) concluded that scarp morphology suggests a possible Holocene age for the latest faulting event. The embayed character of the range front suggests a long period of inactivity preceding the recent episode of faulting (Everitt and Kaliser, 1980).

For simplicity these faults were modeled as a single, linked plane. Similar to the Springline fault, these faults may be dependent on the Stansbury fault. Therefore, a slightly lower p(a) was assigned although Geomatrix Consultants (1999) found definite evidence for repeated late Pleistocene offsets. Lower bound slip rate is based on analogy with the Stansbury fault. Other rates are based on late Pleistocene vertical slip rates of 0.2 (±0.1) and 0.06 (±0.01) mm/yr for the East and West faults, respectively (Geomatrix Consultants, 1999).

Although this postulated fault may actually be dependent on the Skull Valley faults (East and West faults of Geomatrix Consultants, 1999), and/or the Stansbury fault, for simplicity and because of its distance, we considered it only as an independent source and assigned a relatively lower p(a). Geometry, location, and slip rates based on data and estimates of Geomatrix Consultants (1999).
Table 1. Source Parameters For Working Group on Utah Earthquake Probabilities “Other” Faults (continued)

<table>
<thead>
<tr>
<th>FAULT NO.</th>
<th>FAULT NAME</th>
<th>RUPTURE MODEL</th>
<th>MAXIMUM RUPTURE LENGTH (km)</th>
<th>MAXIMUM MAGNITUDE (M)</th>
<th>DIP (degrees)</th>
<th>APPROXIMATE AGE OF YOUNGEST OFFSET</th>
<th>PROBABILITY OF ACTIVITY (yr)</th>
<th>RATE OF ACTIVITY (mm/yr)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2395</td>
<td>Stansbury fault</td>
<td>Unsegmented (0.3)</td>
<td>69</td>
<td>6.9 (0.2)</td>
<td>30 W (0.2)</td>
<td>Holocene (7)</td>
<td>1.0</td>
<td>0.06 (0.2)</td>
<td>Segment model modified after Helm (1995) and Geomatrix Consultants (1999). Maximum rupture lengths measured on Plate 6 of Geomatrix Consultants (1999). Slip rate distribution based on long-term (Miocene) vertical slip rates of 0.07 (± 0.02) mm/yr (Helm, 1995), late-Pleistocene vertical slip rates of 0.4 (± 0.1) mm/yr (Geomatrix Consultants, 1999) and comparison with the Oquirrh-East Great Salt Lake fault for the maximum. The surface trace of the Stamsbury fault is simple in the southern half of the fault (south of Pass Canyon) but complex to the north, suggesting the fault may consist of two independent sections. A down-to-the-south cross-fault at Pass Canyon forms the boundary between the sections (Helm, 1994 #4517). In the south, a single fault strand consisting of a main fault and a subsidiary anthetic fault cuts Quaternary alluvial fans and forms a narrow (about 20-m-wide) graben along most of the fault trace (Helm, 1994 #4517). Holocene scarps of the southern section appear younger than the Sheeprock [2405], Topliff Hill [2407] and Mercur [2399] fault scarps. Measured scarp heights are from 3.9 to 49.5 m.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segmented (0.7)</td>
<td>69</td>
<td>7.2 (0.6)</td>
<td>69 W (0.2)</td>
<td>Holocene (7)</td>
<td>(same for all segments)</td>
<td>0.06 (0.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Northern Segment</td>
<td>6.9 (0.2)</td>
<td>7.0 (0.2)</td>
<td>30 W (0.2)</td>
<td>Late Pleistocene (7)</td>
<td>1.0</td>
<td>0.5 (0.6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Central Segment</td>
<td>6.7 (0.2)</td>
<td>7.0 (0.6)</td>
<td>65 W (0.6)</td>
<td>Holocene (7)</td>
<td>(same for all segments)</td>
<td>1.0 (0.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Southern Segment</td>
<td>6.2 (0.2)</td>
<td>6.5 (0.6)</td>
<td>70 W (0.2)</td>
<td>Quaternary (7)</td>
<td>0.06 (0.2)</td>
<td>0.5 (0.6)</td>
<td></td>
</tr>
<tr>
<td>2413</td>
<td>Stinking Springs fault</td>
<td>Independent (1.0)</td>
<td>11</td>
<td>6.0 (0.2)</td>
<td>30 W (0.2)</td>
<td>Late Quaternary</td>
<td>1.0</td>
<td>0.04 (0.2)</td>
<td>Slip rate data are lacking for this poorly understood fault as much of the central portion lies underwater, so we assumed a slip rate distribution similar to the Strawberry fault based on a similar geomorphic expression (Nelson and Martin, 1982).</td>
</tr>
<tr>
<td>2412</td>
<td>Strawberry fault</td>
<td>Independent (1.0)</td>
<td>32</td>
<td>6.7 (0.2)</td>
<td>30 W (0.2)</td>
<td>Holocene</td>
<td>1.0</td>
<td>0.04 (0.2)</td>
<td>Maximum rupture length includes the southernmost suspected Quaternary fault trace of Hecker (1993). Trenches across a subsidiary fault exposed evidence for 2 to 3 earthquakes offsetting fan deposits estimated to be 15 to 30 ky based on soil development (Nelson and Martin, 1982; Nelson and Van Arsdale, 1986). Slip rate distribution based on data in Nelson and Van Arsdale (1986), with vertical offsets of 1 to 2 m per event and average recurrence of 5,000 to 15,000 years during the latest Quaternary, and longer-term Quaternary (&lt;150 to 300 ka) vertical slip rates of 0.03 to 0.06 mm/yr. Specifically, maximum rate of 0.5 mm/yr assumes 2 m of vertical slip and a recurrence interval of 5,000 years (adjusted to net slip for a 55º dip). Preferred rate of 0.2 mm/yr assumes 1.5 m of vertical slip and a recurrence interval of 10,000 years (also adjusted to net slip for a 55º dip). Minimum rate of 0.04 mm/yr based on longer term rate estimates. In contrast, the UQFPWG (Lund, 2005) assigned 5th, 50th, and 95th percentile slip rate values of 0.3, 0.1, and 0.3 mm/yr, but we consider this distribution to underestimate the large uncertainties of the limited paleoseismic data from a subsidiary fault (i.e., absolute age constraints for events and estimates of total slip are lacking, as well as data are for a subsidiary fault).</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>FAULT NO.</th>
<th>FAULT NAME</th>
<th>RUPTURE MODEL</th>
<th>MAXIMUM RUPTURE LENGTH$^1$ (km)</th>
<th>MAXIMUM MAGNITUDE$^2$ (M)</th>
<th>DIP$^3$ (degrees)</th>
<th>APPROXIMATE AGE OF YOUNGEST OFFSET</th>
<th>PROBABILITY OF ACTIVITY$^4$</th>
<th>RATE OF ACTIVITY$^5$ (mm/yr)</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2409</td>
<td>Utah Lake faults</td>
<td>Zone (1.0)</td>
<td>31</td>
<td>6.5 (0.2)</td>
<td>6.8 (0.6)</td>
<td>7.1 (0.2)</td>
<td>55 W (0.4)</td>
<td>90 (0.3)</td>
<td>55 W (0.3) Latest Pleistocene to Holocene (?) 0.7 0.1 (0.3) 0.35 (0.4) 0.5 (0.3) This complex anastomosing system of east and west dipping faults generally strikes north-south, but individual fault traces are poorly located. Because of this, we modeled the Utah Lake faults as a zone. Although seismic airgun surveys suggest offset of &lt;2 to 5 m of Lake Bonneville deposits (Brimhall and Merritt, 1981), we assigned a slightly lower p(a) to account for the possibility that the Utah Lake faults rupture dependently on the Provo segment of the Wasatch fault zone, given the geometric and possible seismogenic relation of the faults. Slip rates are based on &lt;2 to 5 m of vertical offset of regressive lake Bonneville deposits (Machette, 1992) (assumed to be 12 to 14.5 ka for these elevations).</td>
</tr>
<tr>
<td>2521b, 2521a, 2374, 2521c</td>
<td>West Cache fault zone</td>
<td>Unsegmented (0.3)</td>
<td>80</td>
<td>7.0 (0.2)</td>
<td>7.3 (0.6)</td>
<td>7.6 (0.2)</td>
<td>30 E (0.2)</td>
<td>55 E (0.6)</td>
<td>70 E (0.2) Holocene (same for all segments) 1.0 0.06 (0.3) 0.3 (0.4) 0.9 (0.3) Seismic reflection data indicates that the West Cache fault zone has significantly less cumulative offset than the East Cache fault zone (Evans, 1991; Evans and Oaks, 1996), suggesting that the former is antithetic to the latter (Sullivan et al., 1988). However, subsequent detailed mapping and trenching studies have shown that the latest Quaternary behavior of the two faults is distinctly different, implying generally independent behavior (Black et al., 2000). Therefore, we assigned a p(a) of 1.0. Fault trace geometry and lengths are after Black et al. (2003). Segmentation model is after Black et al. (2000). We included the Hyrum fault as a southern extension of the Wellsville segment in the unsegmented model (Black et al., 2000; Figure 1). Rate distributions used by Wong et al. (2002) were slightly modified here based on consensus rates of the UQFPWG (Lund, 2005). Slip rate distributions based on: (1) 9 m of vertical offset since 16.8 ka on the Clarkston segment (Solomon, 1999); (2) 2.9 m of vertical offset since 22.5 ka (Black et al., 2000), and 600 to 1200 m of vertical offset since the Miocene (Evans, 1991) on the Junction Hills segment; (3) 13.2 m of vertical offset of 100 to 200 ka deposits, and 4.4 m of vertical offset since 15.1 to 25 ka on the Wellville segment (Black et al., 2000).</td>
</tr>
<tr>
<td></td>
<td>West Cache fault zone</td>
<td>Segmented (0.7)</td>
<td>80</td>
<td>6.7 (0.2)</td>
<td>7.0 (0.6)$^6$</td>
<td>7.3 (0.2)</td>
<td>60 E (0.2)</td>
<td>60 E (0.2)</td>
<td>80 E (0.3) Early Holocene (same for all segments) 0.1 (0.3) 0.5 (0.4) 0.9 (0.3)</td>
</tr>
<tr>
<td></td>
<td>Clarkston fault-37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slip Rate (0.8): 0.04 (0.3) 0.12 (0.5) 0.9 (0.2) Recurrence Interval (0.2): 10,000 (0.5) 25,000 (0.5)</td>
</tr>
<tr>
<td></td>
<td>Junction Hills fault - 24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slip Rate (0.8): 0.06 (0.3) 0.12 (0.5) 0.9 (0.2) Recurrence Interval (0.2): 10,000 (0.5) 25,000 (0.5)</td>
</tr>
<tr>
<td></td>
<td>Wellsville fault - 20</td>
<td></td>
<td>6.6 (0.2)</td>
<td>6.9 (0.6)$^6$</td>
<td>7.2 (0.2)</td>
<td>55 E (0.3)</td>
<td>70 E (0.4)</td>
<td>80 E (0.3)</td>
<td>Holocene (same for all segments) 1.0 0.03 (0.2) 0.2 (0.6) - Low? 0.7 (0.2) Due to their close-proximity, similar dip, and for simplicity, we assumed that the Granger and Taylorsville faults of the West Valley fault zone merge at a shallow depth and that the primary moment release occurs on the Granger fault as it appears to have the greatest cumulative offset (Keaton et al., 1993). The West Valley fault zone is anithetic to, and is 3 to 13 km west of, the more-active Salt Lake City segment of the Wasatch fault zone. We allowed for both independent and dependent (linked or coseismic) rupture of the West Valley fault zone with the Salt Lake City segment of the Wasatch fault zone. We favored the latter in light of recent dates from trenches that suggest overlapping ages for: the youngest events on the Granger fault and the Salt Lake City segment, and the youngest event on the Taylorsville fault and the penultimate event on the Salt Lake City segment (Solomon, 1998; B.D. Black, UGS, written communication, 8-9-99). Steeper dips than typical range-bounding faults were assumed for this intrabasin graben-bounding fault zone. Slip rate distribution is based on data in Keaton et al. (1993) for a variety of time periods.</td>
</tr>
<tr>
<td>2386b, 2386a</td>
<td>West Valley fault zone</td>
<td>Independent (0.3)</td>
<td>16</td>
<td>6.4 (0.2)</td>
<td>6.7 (0.6)$^6$</td>
<td>7.1 (0.2)</td>
<td>55 E (0.3)</td>
<td>70 E (0.4)</td>
<td>80 E (0.3) Holocene 1.0 0.03 (0.2) 0.2 (0.6) - Low? 0.7 (0.2) Due to their close-proximity, similar dip, and for simplicity, we assumed that the Granger and Taylorsville faults of the West Valley fault zone merge at a shallow depth and that the primary moment release occurs on the Granger fault as it appears to have the greatest cumulative offset (Keaton et al., 1993). The West Valley fault zone is anithetic to, and is 3 to 13 km west of, the more-active Salt Lake City segment of the Wasatch fault zone. We allowed for both independent and dependent (linked or coseismic) rupture of the West Valley fault zone with the Salt Lake City segment of the Wasatch fault zone. We favored the latter in light of recent dates from trenches that suggest overlapping ages for: the youngest events on the Granger fault and the Salt Lake City segment, and the youngest event on the Taylorsville fault and the penultimate event on the Salt Lake City segment (Solomon, 1998; B.D. Black, UGS, written communication, 8-9-99). Steeper dips than typical range-bounding faults were assumed for this intrabasin graben-bounding fault zone. Slip rate distribution is based on data in Keaton et al. (1993) for a variety of time periods.</td>
</tr>
<tr>
<td></td>
<td>(includes the Granger and Taylorsville faults)</td>
<td>Linked synchronous rupture with Salt Lake City segment of the Wasatch fault zone (0.7)</td>
<td>16</td>
<td>6.4 (0.2)</td>
<td>6.7 (0.6)$^6$</td>
<td>7.1 (0.2)</td>
<td>55 E (0.3)</td>
<td>70 E (0.4)</td>
<td>80 E (0.3) Holocene 1.0 0.03 (0.2) 0.2 (0.6) - Low? 0.7 (0.2) Due to their close-proximity, similar dip, and for simplicity, we assumed that the Granger and Taylorsville faults of the West Valley fault zone merge at a shallow depth and that the primary moment release occurs on the Granger fault as it appears to have the greatest cumulative offset (Keaton et al., 1993). The West Valley fault zone is anithetic to, and is 3 to 13 km west of, the more-active Salt Lake City segment of the Wasatch fault zone. We allowed for both independent and dependent (linked or coseismic) rupture of the West Valley fault zone with the Salt Lake City segment of the Wasatch fault zone. We favored the latter in light of recent dates from trenches that suggest overlapping ages for: the youngest events on the Granger fault and the Salt Lake City segment, and the youngest event on the Taylorsville fault and the penultimate event on the Salt Lake City segment (Solomon, 1998; B.D. Black, UGS, written communication, 8-9-99). Steeper dips than typical range-bounding faults were assumed for this intrabasin graben-bounding fault zone. Slip rate distribution is based on data in Keaton et al. (1993) for a variety of time periods.</td>
</tr>
<tr>
<td>622</td>
<td>Western Bear Lake fault</td>
<td>Independent (single plane)</td>
<td>26 (versus total fault length of about 80 km)</td>
<td>6.6 (0.2)</td>
<td>6.9 (0.6)$^6$</td>
<td>7.2 (0.2)</td>
<td>40 E (0.4)</td>
<td>50 E (0.4)</td>
<td>60 E (0.2) Late Holocene 0.6 0.2 (0.9) 1.0 (0.1) Maximum rupture length based on total extent of scarpas on unconsolidated sediments (McCalpin, 1993). Probability of activity considers possibility that the western Bear Lake fault is dependent on the eastern Bear Lake fault and is not an independent seismic source, based on kinematic and geometric relations (Evans, 1991; Skeen, 1975; McCalpin et al., 1990). Dips based on cross-sections of Evans (1991). Slip rates based on data in McCalpin (1993).</td>
</tr>
</tbody>
</table>

---

$^1$ Maximum rupture length

$^2$ Maximum magnitude

$^3$ Dip

$^4$ Approximate age of youngest offset

$^5$ Probability of activity

$^6$ Rate of activity

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Table 1. Source Parameters For Working Group on Utah Earthquake Probabilities “Other” Faults (continued)

1. Fault number and nomenclature after Hecker (1993) with number in parentheses after Black et al. (2003) unless noted otherwise.
2. Measured straight-line, end to end on Hecker (1993) unless noted otherwise. Note that the same maximum seismogenic depth distribution of 12 km (0.2), 15 km (0.7), and 18 km (0.1) was assumed for all fault sources.
3. Preferred values estimated using the empirical relation of Wells and Coppersmith (1994) for all fault types. Unless otherwise noted, values are estimated based on maximum surface rupture length.
4. Average crustal dips. Most faults are assumed to be simple planes except those that are italicized, where a curvilinear model was used. Preferred dips are based on available subsurface data for Wasatch Front faults and basin geologies (e.g., Zoback 1983, 1992; Smith and Bruhn, 1984; Bruhn et al., 1992; Mubeey, 1998; Mohapatra and Johnson, 1998). Ranges are based on focal mechanisms for large normal faulting earthquakes worldwide (Jackson and White, 1989).
5. Probability of activity, p(a), the likelihood that a fault is an independent seismogenic structure and is still active within the modern stress field.
6. Rates of fault activity are typically average net slip rates (in mm/yr) except values shown in bold, which are recurrence intervals (in years). Recurrence models included characteristic, maximum moment, and exponential, with weights depending on the type of seismic source and rupture model (as shown in column 3). For longer, segmented faults the distribution is: characteristic – 0.7, maximum moment – 0.2, and truncated exponential – 0.1. For shorter, single-plane, independent faults the distribution is: characteristic – 0.6, maximum moment – 0.2, truncated exponential – 0.2. For faults modeled as zones, characteristic and truncated exponential models are equally weighted (0.5/0.5).
7. Based on the average of expected magnitudes estimated from: surface rupture length, and 3 m of average displacement per event (West, 1994). Note that although Machette et al. (2001) measured an end to end fault length of only 33.2 km based on mapping by West (1994), this would still result in the same average expected magnitude of $M_{\text{7.1}}$ as calculated here.
8. Based on average of expected magnitudes estimated from: rupture length, and average displacements per event of 0.85 and 1.65 m (McCalpin, 1994).
9. Based on average of expected magnitudes estimated from: rupture length, and inferred average displacements per event of 0.5 to 1.5 m (McCalpin and Forman, 1991) for the southern East Cache fault, and an average displacement per event of 1.8 to 2.4 m for the James Peak fault (Nelson and Sullivan, 1992).
10. Based on average of expected magnitudes estimated from: rupture length, and average displacements per event of 5 to 6.6 m (McCalpin, 1993).
11. Although displacement data are not available for this segment, maximum magnitudes were estimated similar to the southern segment assuming that behavior is analogous to the southern segment and other active faults in the region that show large displacements relative to segment or fault lengths (McCalpin, 1993).
13. Based on the average of expected magnitudes estimated from: rupture length, and maximum displacements per event of 2.6 m (McCalpin et al., 1992).
14. Based on the average of expected magnitudes estimated from: rupture length, and average displacements per event of 0.5 to 1.0 m (Sullivan et al., 1988; Sullivan and Nelson, 1992).
15. Based on the average of expected magnitudes estimated from: rupture length, and average displacements per event of 2.5 m (McCalpin et al., 1992).
16. Based on the average of expected magnitudes estimated from: rupture length, and average displacement per event of ~2 m (Dinter and Pechmann, 2005).
17. Based on the average of expected magnitudes estimated from: rupture length, and a maximum displacement per event of 5.5 m per event (Dinter and Pechmann, 2005).
18. Based on the average of expected magnitudes estimated from: rupture length, and a maximum displacement of 2.7 m (Olig et al., 1994; 1999) and the empirical displacement relation of Hemphill-Haley and Weldon (1999).
19. Based on the average of expected magnitudes estimated from: rupture length, and average displacements per event of 2.4 m (Olig et al., 1994).
20. Based on the average of expected magnitudes estimated from: rupture length, and average displacements per event of 1.3 to 2.4 m per event (Olig et al., 2001).
21. Based on the average of expected magnitudes estimated from: rupture length, and an average displacement per event of 2 to 3 m (Geomatics Consultants, 1999).
22. Based on the average of expected magnitudes estimated from: rupture length, and an average displacement per event of 1.5 to 2.0 m (Solomon and Keaton et al., 1993).
23. Based on the average of expected magnitudes estimated from: rupture length, and average displacements per event of 1.5 to 2.0 m (McCalpin, 1993).
1. Total of 49 faults/fault segments
2. Age of most recent deformation color coded.
3. Wasatch fault zone shown in black for reference.
1. Four faults previously recognized as segmented:
   a. East Bear Lake
   b. East Cache
   c. West Cache
   d. Morgan

2. URS, Inc. included the following closely related faults in their fault characterization table:
   a. East Hansel Mountains faults
   b. Hyrum fault
   c. EGSLFZ Rozelle segment (new)
   d. Morgan fault southern segment
   e. Red Canyon fault scarps
POSSIBLE ADDITIONAL FAULT GROUPINGS
CHIEFLY AFTER URS

1. Combine East Hansel Mountains faults with the Hansel Valley fault.
2. Add Hyrum fault to the West Cache fault zone.
3. Combine the James Peak and Broadmouth Canyon faults with the East Cache fault zone.
4. Combine the EGSLF, Oquirrh fault zone, Southern Oquirrh fault zone, Topliff fault zone, and East Tintic Mountains fault into a single very long fault zone.
5. Segment the Stansbury fault zone after Geomatrix Inc.
6. Combine the Scipio Valley faults, Scipio fault, Pavant Range fault, Maple Grove fault, and the Red Canyon fault scarps into a single fault zone.
7. Combine the Drum Mountains fault zone with the Crater Bench faults.

QUESTIONS
What about the:
1. Hansel Valley (valley floor) faults?
2. Little Valley faults?
3. Red Canyon fault scarps (just outside Wasatch Front Region boundary)
WGUEP “OTHER” FAULTS LIST

Bear River fault zone
Broadmouth Canyon faults
Carrington fault
**Crater Bench faults**
Crawford Mountains fault (west side)
Curlew Valley faults
**Drum Mountains fault zone**
**East Dayton – Oxford faults**
East Canyon fault
East Tintic Mountains fault (west side)
East Cache fault zone
  Northern section
  Central section
  Southern section
East Great Salt Lake fault zone
  Promontory section
  Fremont section
  Antelope Island section
Eastern Bear Lake Fault
  Northern section
  Central section
  Southern section
Gunnison fault
Hansel Valley fault
James Peak fault
Little Valley faults
Main Canyon fault (East Canyon east side faults)
Maple Grove faults
Martin Ranch fault (Reactivated Section of the Absaroka Thrust fault)
Morgan fault
  Northern section
  Central section
North Promontory fault
Oquirrh fault zone
Pavant Range fault
Porcupine Mountains fault
**Rock Creek fault**
Scipio fault zone
Scipio Valley faults
**Sheeprock fault zone**
Skull Valley (mid valley) faults
Southern Oquirrh Mountains fault zone
Stansbury fault zone
Stinking Springs fault
Strawberry fault
Topliff Hill fault zone
Utah Lake faults
West Cache fault zone
  Clarkston fault
  Junction Hills fault
  Wellsville fault
Western Bear Lake fault
West Valley fault zone
  Granger fault
  Taylorsville fault

*Not characterized by URS*
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<tr>
<th>Fault Zone / Segment</th>
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<tr>
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<td>Main Canyon fault (East Canyon east side faults)</td>
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<td>Granger fault</td>
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<td>Taylorsville fault</td>
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WGUEP GROUPED “OTHER FAULTS” LIST

Bear River fault zone
Carrington fault
**Crater Bench faults**
**Drum Mountains fault zone**
Crawford Mountains fault (west side)
Curlew Valley faults
East Dayton – Oxford faults
East Canyon fault
**East Cache fault zone**
  - Northern section
  - Central section
  - Southern section
James Peak fault
**Broadmouth Canyon faults**
**East Great Salt Lake fault zone**
  - Rozelle segment
  - Promontory segment
  - Fremont segment
  - Antelope Island segment
Oquirrh fault zone
**Southern Oquirrh Mountains fault zone**
Topliff Hill fault zone
**East Tintic Mountains fault (west side)**
Eastern Bear Lake Fault
  - Northern section
  - Central section
  - Southern section
Gunnison fault
**Hansel Mountains (east side) fault**
**Hansel Valley (valley floor) faults?**
**Hansel Valley fault**
Little Valley faults?
Scipio fault zone
Scipio Valley faults
Pavant Range fault
Maple Grove faults
**Red Canyon fault scarps?**
Main Canyon fault (East Canyon east side faults)
Martin Ranch fault (Reactivated Section of the Absaroka Thrust fault)
**Morgan fault**
  - Northern section
  - Central section
  - Southern section
North Promontory fault
Porcupine Mountains fault
Rock Creek fault
Sheeprock fault zone
Skull Valley (mid valley) faults
Stansbury fault zone
Stinking Springs fault
Strawberry fault
Utah Lake faults
**West Cache fault zone**
  - Clarkston fault
  - Junction Hills fault
  - Wellsville fault
  - Hyrum fault
Western Bear Lake fault
**West Valley fault zone**
  - Granger fault
  - Taylorsville fault
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<th>Rate of Sliding</th>
<th>Reference Interval</th>
<th>Approximate Age of Displacement</th>
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