**SUMMARY**
**SIXTH MEETING**
**WORKING GROUP ON UTAH EARTHQUAKE PROBABILITIES**
**Thursday & Friday, November 17 & 18, 2011**
**Utah Department of Natural Resources Building, Room 2000**
**1594 West North Temple, Salt Lake City**

## WELCOME AND INTRODUCTION

Working Group on Utah Earthquake Probabilities (WGUEP) Coordinator Bill Lund called the sixth WGUEP meeting to order at 8:30 a.m. After welcoming the Working Group members and UGS staff (attachment 1), Bill turned the meeting over to Ivan Wong (WGUEP Chairperson) who reviewed the meeting agenda (attachment 2) and recapped WGUEP progress to date.

## TECHNICAL PRESENTATIONS

The meeting then moved into a series of technical presentations and issue updates. PowerPoint presentations made at the meeting are available at http://geology.utah.gov/ghp/workgroups/pdf/wguep/WGUEP-2011C_Presentations.pdf.

### Thursday, November 17

- Update on Consensus Wasatch Front Earthquake Catalog – Walter Arabasz
- Strawman Recurrence Models – Ivan Wong
- Data Needs for Probability Calculations and Input Sensitivities – Patricia Thomas
- WGUEP: Wasatch Fault Zone Recurrence Rates and COVs – Chris DuRoss (two PowerPoints)
- Update on "Other Faults" Database – Bill Lund (no PowerPoint)
- Update on calculating M and $M_o$ for the Wasatch Fault Zone – Susan Olig/ Chris DuRoss

### Friday, November 18

- Path Forward on Use of Geodetic Data – Ivan Wong (no PowerPoint)
- Spatial Smoothing Issues – Mark Petersen (no PowerPoint)

- $M_{max}$ for Background Earthquakes – Ivan Wong (no PowerPoint)

- Modeling Graben-Bounding Faults in the NSHMs – Mike Hylland (two PowerPoints)

- Dip Angles for Basin and Range Normal Faults – Tony Crone

- Oquirrh-Great Salt Lake Fault Zone – Susan Olig/Jim Pechmann

## ISSUE DISCUSSIONS

Technical presentations and the ensuing discussions they generated are summarized below.

### Update on a Consensus Wasatch Front Earthquake Catalog

Walter Arabasz updated the WGUEP on his effort to compile a consensus Wasatch Front earthquake catalog. The principal points of Walter's presentation included:

- Methodology preview: magnitude uncertainties and rate calculations from seismicity.

- University of Utah Seismograph Stations (UUSS) magnitudes (historical – $M_{L\ (Io)}$; instrumental – $M_L$, $M_C$, and $M_w$).

- More on the comparison between UUSS and National Seismic Hazard Maps (NSHM) catalogs (and magnitudes).

- Next steps to closure.

Why Magnitude Uncertainties are Important

- Recurrence calculations for rigorous hazard and risk analyses require an adjustment for magnitude uncertainties because they introduce bias (*a*-values are systematically overestimated).

- Bias arises because errors in magnitude estimates are normally distributed while earthquake counts in magnitude bins are exponentially distributed.

- Magnitude uncertainties come from: (1) statistical average of measurements made at a number of stations, and (2) conversion from one magnitude scale to another; errors also occur from rounding.

Methodology Status

- Standard errors for magnitude estimates in the UUSS catalog can be provided for $M_{L\,(Io)}$, $M_L$, and $M_C$, and rounding values can be provided.

- Have to decide on approach to uniform magnitude ($M_W$) — Event-by-event conversion to $M_W$? Assume $M_L$ and $M_C$ sufficiently equivalent to $M_W$?

- Size estimates for pre-instrumental shocks ($M_{L\,(Io)}$) have relatively large uncertainty; intensity-magnitude relation will be examined with added data, and sizes of larger events re-examined.

- Assumption is that WGUEP earthquake catalog will be turned over to URS Corporation/U.S. Geological Survey (USGS) "analysts" for bias-corrected rate calculations and probabilities.

Walter then discussed and compared the UUSS and NSHM earthquake catalogs for the WGUEP region, and noted the discrepancy between the two catalogs in the number of independent main shocks (declustered using different methods) in the 4.0 ≤ **M** < 4.5 and 5.0 ≤ **M** < 5.5 bins (table 1).

***Table 1.*** *Comparison of UUSS and NSHM catalogs for the WGUEP region (1880 through 2010; independent main shocks **M** ≥ 4.0, non-tectonic events removed).*

| Magnitude Range | UUSS Catalog | NSHM Catalog |
|---|---|---|
| 4.0 ≤ **M** < 4.5 | 45 | 34 |
| 4.5 ≤ **M** < 5.0 | 5 | 4 |
| 5.0 ≤ **M** < 5.5 | 10 | 21 |
| 5.5 ≤ **M** < 6.0 | 4 | 4 |
| 6.0 ≤ **M** < 6.5 | 3 | 3 |
| 6.5 ≤ **M** < 7.0 | 1 | 1 |
| Total Number | 68 | 67 |

After accounting for time- and magnitude-dependent variations in catalog completeness, a similar discrepancy between the two catalogs was noted in the number of 4.67 ≤ **M** < 5.33 independent main shocks (table 2). The latter discrepancy between the two catalogs is likely due to the importation of events into the NSHM catalog from the Pancha and others (2006) catalog for the western United States (1850−1999) for **M** ≥ 4.8.

***Table 2.*** *Comparison of independent main shocks (**M** ≥ 4.0) in the UUSS and NSHM catalogs for the WGUEP region — accounting for completeness periods.*

| **Magnitude Range** | **Completeness Period** | **Yrs** | **UUSS Catalog** | **NSHM Catalog** |
|---|---|---|---|---|
| $4.00 \leq \mathbf{M} < 4.67$ | July 1962–Dec 2010 | 48.5 | 17 | 16 |
| $4.67 \leq \mathbf{M} < 5.33$ | Jan 1950–Dec 2010 | 61.0 | 7 | 17 |
| $5.33 \leq \mathbf{M} < 6.00$ | Jan 1938–Dec 2010 | 73.0 | 1 | 1 |
| $6.00 \leq \mathbf{M} < 6.67$ | Jan 1900–Dec 2010 | 111.0 | 3 | 3 |

Walter again presented figure 1 below, which outlines the path forward to achieve a unified UUSS–NSHM earthquake catalog.

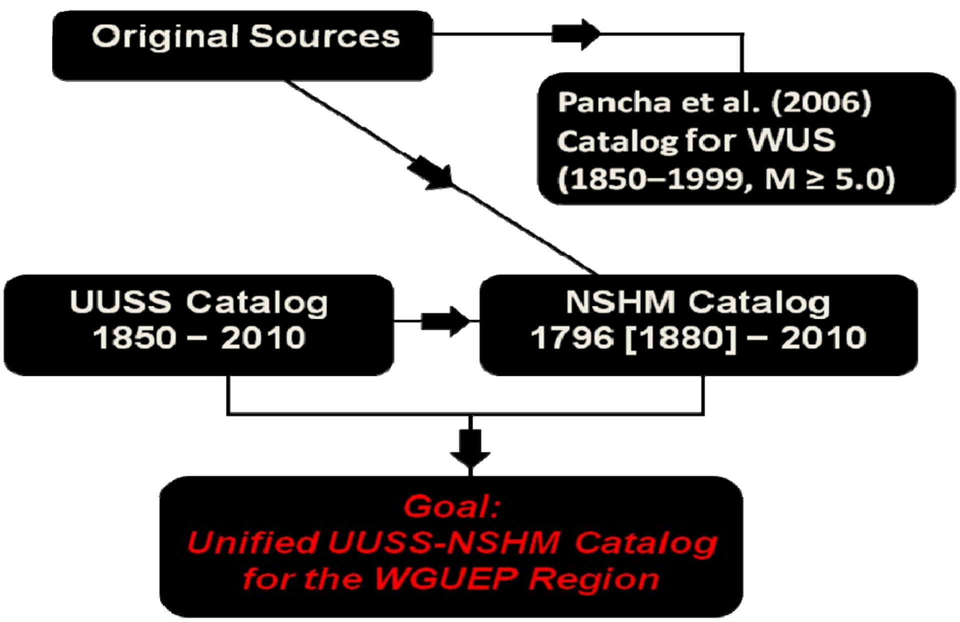


***Figure 1.*** *Path forward to achieve a unified UUSS–NSHM earthquake catalog.*

Next Steps to Closure

Walter presented the remaining six steps required to achieve closure on a consensus UUSS/NSHM earthquake catalog.

1. Identify parts of the WGUEP catalog (a) that will come directly from the UUSS instrumental catalog, and (b) that will represent a unified blending of UUSS and NSHM catalogs.

2. Verify periods of completeness using "Stepp" plots.

3. Revise or confirm the intensity-magnitude relation for pre-instrumental shocks in the Utah region with added data.

4. Decide on an approach to achieve "uniform **M**" in the catalog.

5. Determine values of σ and rounding errors for various magnitude estimates in the WGUEP catalog that will be needed by the analysts for bias corrections.

6. Reconcile differences in magnitudes between the NSHM and UUSS catalogs — based on careful checking of sources, compilation of available size estimates, and assessment of a preferred magnitude — to achieve a unified catalog.

## Update on Strawman Recurrence Models

At WGUEP Meeting 5, Ivan Wong reviewed the three recurrence models and their typical assigned weights traditionally used by the consulting industry when performing probabilistic seismic hazard analyses (PSHAs): $M_{max}$ (0.3), characteristic (0.6), and truncated exponential (0.1) (see figure 2 for recurrence model examples). Ivan noted that based on work being conducted by Abrahamson and Hecker, he expects that the truncated exponential model will soon be given no weight.

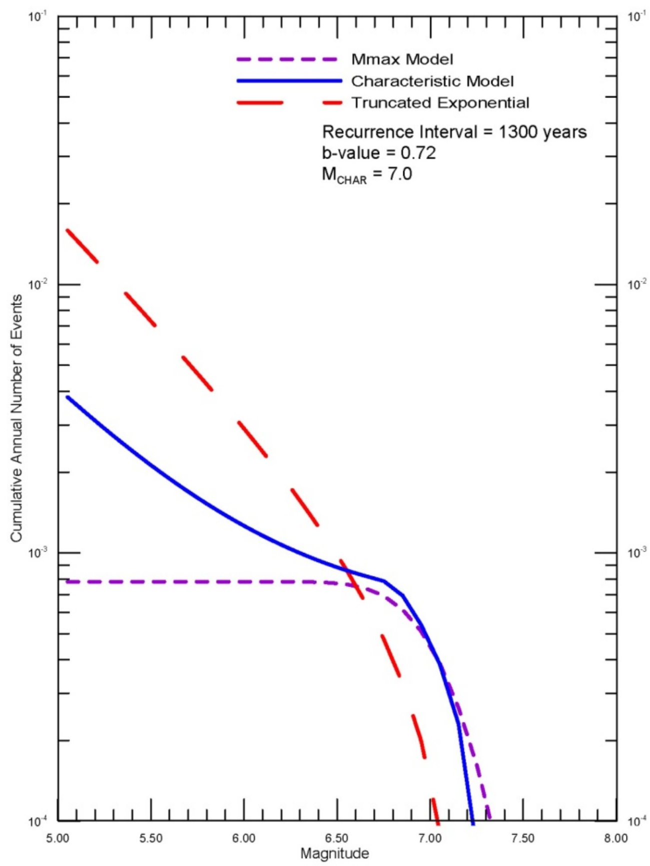


***Figure 2.*** *Recurrence model examples.*

A decision regarding which recurrence model(s) WGUEP should adopt was deferred at WGUEP Meeting 5 until WGUEP Meeting 6, at which time a "strawman" WGUEP recurrence model would be presented for the Working Group's consideration.

At Meeting 6, Ivan again reviewed the USGS NSHM recurrence model approach:

- Use both "characteristic" (actually maximum magnitude) and Gutenberg-Richter models,

- Both models have their $M_{min}$ at **M** 6.5 for faults,

- $M_{min}$ 6.5 came about because of mismatch of **M** 4-5 earthquakes in southern California,

- Background earthquakes are accommodated by smoothed seismicity. Gutenberg-Richter model has a $M_{max}$ of **M** 6.5, and

- $M_{max}$ for gridded seismicity is lowered over dipping faults to avoid overlap.

Ivan showed a figure presenting various recurrence models for the Salt Lake City segment of the Wasatch fault zone (WFZ) (figure 3). He then presented a table showing expected return periods for ≥ **M** 5, ≥ **M** 6, and ≥ **M** 7 earthquakes for the 100% $M_{max}$, 100% characteristic, and 50% $M_{max}$ / 50% characteristic models (table 3).

Ivan then presented a "strawman" WGUEP recurrence model developed by the Seismology Subgroup (Ivan, Jim Pechmann, and Walter Arabasz) for the Working Group's consideration:

- Wasatch fault zone and Oquirrh-Great Salt Lake faults
  0.9 maximum magnitude ($M_{min}$ 6.75?)
  0.1 truncated exponential ($M_{min}$ 6.75?)

- Other Faults
  0.8 maximum magnitude ($M_{min}$ 6.75?)
  0.2 truncated exponential ($M_{min}$ 6.75?)

- Background Seismicity
  1.0 truncated exponential (**M** 5.0 to $M_{min}$)

Considerable discussion ensued regarding the details of, and the awkward name for the USGS' "Characteristic" recurrence model used for the NSHMs. Discussion also followed on whether to change $M_{min}$ from **M** 6.75 to **M** 6.5. It was agreed that the WGUEP $M_{min}$ would be **M** 6.75. Earthquakes smaller than **M** 6.75 along the WFZ are assumed to occur at the same rate as background events. The background earthquake will not have a maximum magnitude of **M** 7.0, which differs from the USGS NSHM procedure.

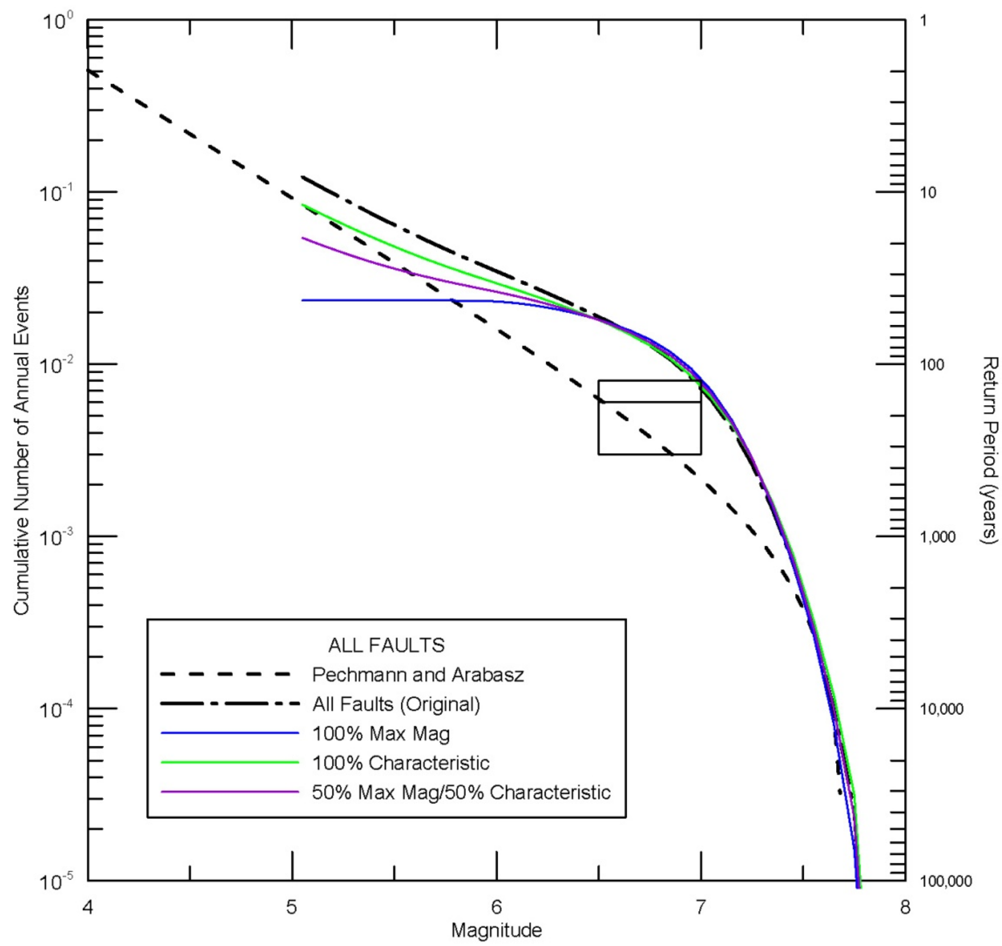


***Figure 3.*** *Recurrence models for the Salt Lake City segment of the WFZ. The black box represents the range in recurrence-interval estimates for large magnitude earthquakes determined by Hecker (1993) using paleoseismic data.*

***Table 3.*** *Expected return periods for ≥ **M** 5, ≥ **M** 6, and ≥ **M** 7 earthquakes for the 100% $M_{max}$, 100% characteristic, and 50% $M_{max}$ / 50% characteristic models.*

| Wasatch Fault Zone | Return Period (years) | | |
|---|---|---|---|
| | 100% $M_{max}$ | 100% Characteristic | 50% $M_{max}$/50% Char. |
| **M** 5 and greater | 98 | 24 | 39 |
| **M** 6 and greater | 98 | 72 | 86 |
| **M** 7 and greater | 200 | 222 | 215 |

## Data Needs for Probability Calculations and Input Sensitivities

Patricia Thomas discussed the approach and data needs for the WGUEP probability calculations and input sensitivities. The approach includes the following five steps:

1. Define fault segment attributes

2. Define rupture sources and rates

3. Define background seismicity

4. Define probability model parameters

5. Probability calculations

Model data needs include:

- Geometry
  - Segment endpoints
  - Seismogenic thickness
  - Dip
- Regional moment rate constraint?
- Mean characteristic magnitude models
- Average displacement for rupture sources
- Magnitude probability density models
- Fault rupture models (rupture sources, models, weights)
- Distribution of slip for multisegment ruptures
- Background seismicity parameters
- Probability models and weights
- Probability model parameters
  - Time since last event, coefficient of variation (COV)

Next, Patricia presented the results of her preliminary probability calculations including the following (see PowerPoint presentation at http://geology.utah.gov/ghp/workgroups/pdf/wguep/WGUEP-2011C_Presentations.pdf for details):

- Wasatch single segment model weighted mean $M_{char}$ magnitudes equally weighted using surface rupture length (SRL), area (A), average displacement (AD), and moment (Mo) magnitudes.
- Wasatch single segment model $M_{char}$ magnitudes for SRL, A, AD, and Mo.
- Moment-balanced weighted mean recurrence intervals for the WFZ single segment model.
- Moment-balanced recurrence intervals for the WFZ single segment model based on SRL, A, AD, and Mo showing sensitivity to $M_{char}$ and slip-rate relations.
- Implied slip rates from a-priori rates for the five central WFZ segments.
- Preliminary probability calculations for the WFZ single segment model using moment-balanced rates, a-priori rates (1/recurrence interval), and a closer look at probabilities for the Brigham City and Provo segments using both moment-balanced and a-priori slip rates.

Patricia then summarized the inputs required for the model (see above) and distributed a form (figure 4) showing required model inputs and the members of the Working Group responsible for providing those data.

| INPUT | Responsible Person | Completed? |
|---|---|---|
| Wasatch RI – single central 5 segments | Chris/Nico | |
| Wasatch RI – multisegment ruptures on central 5 segments | Nico/Chris | |
| Wasatch RIs – end segments, single & multisegment ruptures | | |
| Wasatch slip rates by segments | Mike/Chris | |
| Wasatch unsegmented model slip rates | | |
| Wasatch COV | | Done |
| O-GSL COV | Same as Wasatch | |
| O-GSL RIs | Susan/Jim | |
| O-GSL slip rates | | |
| Final MCHAR Relations and Weights<br>A-Faults<br>B/C-Faults<br>Unsegmented Wasatch (**M** 6.5-7.0)<br>Unsegmented O-GSL?<br>Antithetic Faults – only Area? | Susan | |
| Final MagRecur Models<br>A-Faults<br>B/C-Faults<br>Unsegmented | Ivan | Need $M_{min}$ for A/B/C faults |
| Seismogenic Thickness – BRP/CP/MRM physiographic provinces (km) | Jim/Ivan | Under further review<br>13 (0.3) 15 (0.4) 17 (0.3) |
| Fault Dips (degrees) | Tony | Done<br>35 (0.3) 50 (0.4) 65 (0.3) |
| Other Faults – length, slip rates/RIs, graben-bounding fault pair dips | Bill/Susan | |
| Antithetic Fault Parameters<br>Geometry of antithetic faults with distribution, weights of coseismic/independent branches | Mike/Bill | Need final parameters on Hansel Valley |
| Background Seismicity<br>Final parameters for uniform and grid points | Ivan/Mark | |
| Weights on time dependent /time independent | Chris and others | |
| Use of geodetic data | Jim/Mark/David | |
| Average displacement | Chris/Susan | |

***Figure 4.*** *Data needs for the WGUEP probability model and responsible WGUEP members.*

## Update on WFZ Recurrence Rates and COVs

Chris DuRoss summarized the WFZ rupture scenarios (and relative weights), seismic moment ($M_0$) release, and coefficients of variation (COVs) on recurrence discussed at WGUEP Meeting 5 (http://geology.utah.gov/ghp/workgroups/pdf/wguep/WGUEP-2011B_Summary.pdf). Chris also presented a composite COV for the WFZ.

Working Group members discussed the methods of determining average displacement for WFZ earthquakes and rupture sources, and agreed that per-earthquake displacement should be measured using an analytical half ellipse scaled to displacement observations (e.g., Chang and Smith, 2002). This method helps account for sparse displacement observations or those measured near mapped segment boundaries. Working Group members recommended a weighted mean for each earthquake source, that is, the mean of the mean displacement per earthquake on the source.

The composite COV determined for the WFZ is based on the following procedure:

1. Compile inter-event recurrence probability density functions (PDFs) in one place.
   - For example, Brigham City B4–B3, B3–B2, and B2–B1, plus Weber segment W4–W3, W3–W2, etc. (n = 16 inter-event recurrence intervals [RIs]).
   - RI PDFs used are those filtered for some minimum value (see DuRoss, 2011).
   - The elapsed time since the MRE on each segment is not included as a recurrence interval.

2. Sample recurrence data. In each simulation (n = 10 k).
   - For each of the 16 inter-event RI PDFs, randomly select a single recurrence value (e.g., B4–B3) and add to group of recurrence values.
   - Each simulation (sim) results in a set of 16 inter-event RIs.
   - Composite COV (per sim) = standard deviation (stdev) of all RIs / mean of all RIs.
   - A per-segment COV (per sim, per segment) = stdev of per-segment RIs / mean of per-segment RIs.

3. The composite COV values computed in each simulation are then compiled and plotted in probability space.

When broken out by segment (colored PDFs in figure 5), the COV estimates determined using the above method are nearly identical to those discussed at WGUEP meeting 5. Minor differences relate to using the inter-event RIs filtered for minimum recurrence. If these individual-segment COV PDFs are summed, the resulting PDF (black dashed line in figure 5) has a mean and 2σ uncertainty of 0.4 ± 0.4. The large range reflects the equal weight given to the COV determined for each segment. For example, the poorly constrained Nephi segment COV (based on two inter-event RIs) of 0.2 ± 0.4 and the relatively well constrained Weber segment COV (based on four inter-event RIs) of 0.4 ± 0.3 both account for 1/5 of the data, or 20%.

The composite COV is 0.5 ± 0.1 (2σ), which reflects the compiled 16 individual-event RIs and single COV calculation (per simulation). Using the example above, the two Nephi segment inter-event RIs now account for 2/16 or 12.5% of the data, whereas the four RIs for the Weber segment are 4/16 or 25% of the data. Thus, each inter-event recurrence interval is weighted equally. This method accounts for the full shape of each inter-event RI, but these uncertainties are minimized as the 16 RIs are combined. Using the full range of the data, the WFZ composite COV is 0.5 ± 0.2, similar to the global COV used by California earthquake-forecast working groups (e.g., the Working Group on California Earthquake Probabilities). However, the shape of the WFZ composite COV PDF suggests a symmetric distribution, rather than the asymmetric distribution used by the California working groups. Working Group members agreed to use the 0.5 ± 0.2 COV for the central WFZ (and other faults); however, additional discussion is needed regarding whether a symmetrical or asymmetric distribution should be applied.

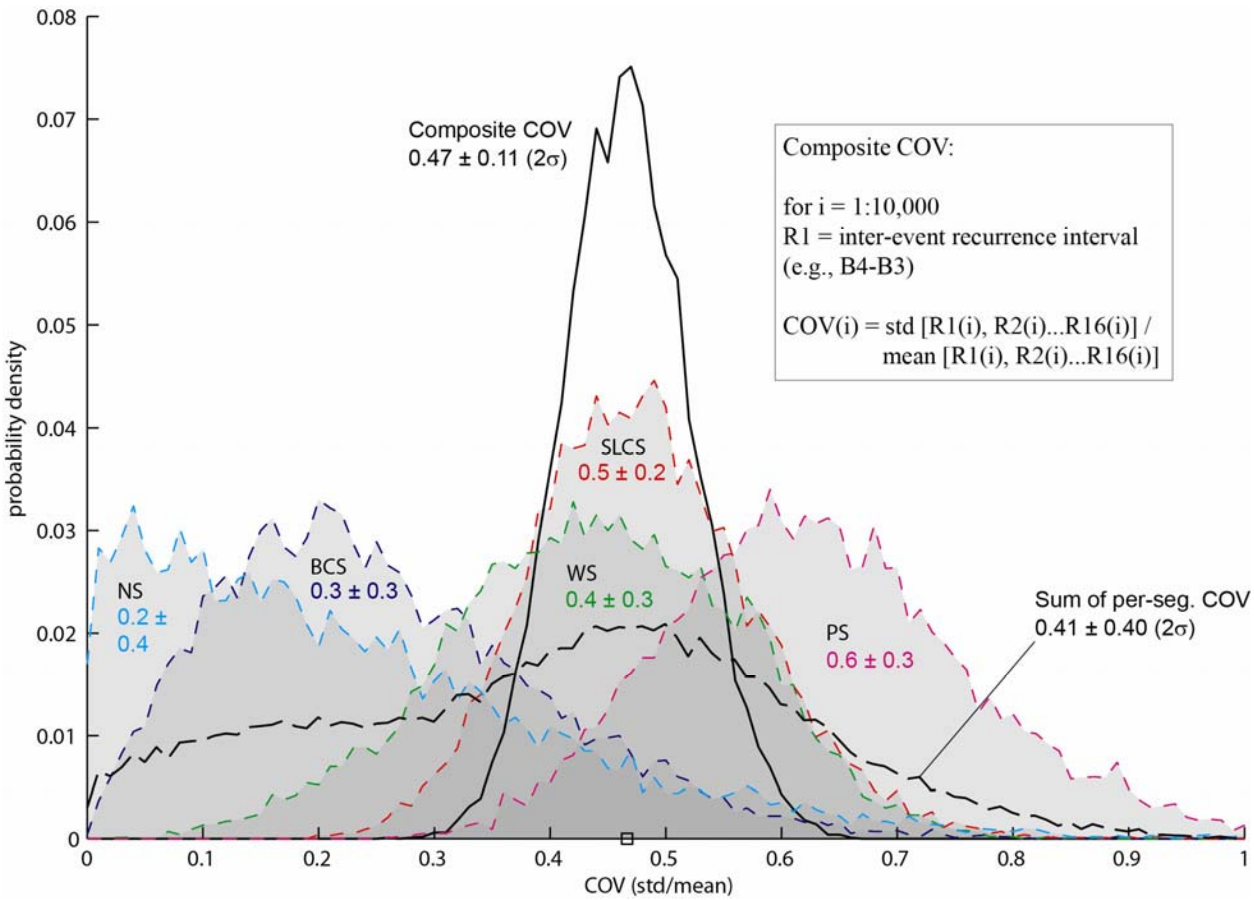

***Figure 5.*** *Composite COV for the five central segments of the WFZ.*

## Update on "Other Faults" Database

Bill Lund reviewed the current status of the Wasatch Front Region (WFR) "Other Fault" database (table 4). The USGS Quaternary Fault and Fold Database of the United States (QFFDUS) includes a total of 112 faults or fault sections within the WGUEP WFR, exclusive of the 10 segments of the WFZ. Of those 112 faults/fault segments, 53 have been retained in the "Other Fault" database and will be modeled in a time independent manner for the WGUEP earthquake forecast. The remaining 59 faults/fault sections have been eliminated from further consideration in the WGUEP modeling process through application of the following three screening criteria:

| Parameters | | Retained Faults | Deleted Faults |
|---|---|---|---|
| Total | 112 | 53 | 59 |
| <0.2 mm/yr | | 37 | 59 |
| > 0.2 mm/yr < 1.0 mm/yr | | 12 | – |
| > 1.0 mm/yr < 5.0 mm/yr | | 1 | – |
| Unknown | | 3 | – |
| Historical | | 1 | – |
| Latest Quaternary < 15 ka | | 37 | 4 |
| Late Quaternary < 130 ka | | 7 | 6 |
| Middle Quaternary < 750 ka | | 7 | 20 |
| Quaternary < 1.8 Ma | | 1 | 29 |
| 0 – 10 km | | 8 | 28 |
| 11 – 20 km | | 16 | 15 |
| 21– 30 km | | 13 | 7 |
| 31 – 40 km | | 6 | 6 |

***Table 4.*** *Parameters of faults exclusive of the ten WFZ segments within the WGUEP WFR as of 11/17/2011.*

1. Faults less than 15 km long if not linked – **M** 6.5 rule (faults less than 15 km long are considered unlikely to generate a ≥ **M** 6.5 earthquake, and therefore will be accommodated in the WGUEP earthquake forecast model as background earthquakes).

2. Faults categorized on the QFFDUS as < 750 ka or older if not plausibly linked to younger faults.

3. Wisdom of the group – which sometimes trumped criteria 1 and 2.

Although approaching final form, the "Other Fault" database remains under review and may undergo some additional modification before WGUEP Meeting 7 in February 2012. In particular, the Joes Valley and East Canyon faults presently in the database will receive additional careful scrutiny, as will the Snow Lake graben, which presently is not in the database, but which exhibits many characteristics similar to those of the Joes Valley faults.

## Update on Calculating Moment Magnitudes for WGUEP Faults

Significant epistemic uncertainties complicate the determination of earthquake moment magnitude for Basin and Range (BRP) normal faults. For example, for the central WFZ, a **M** discrepancy exists where **M** based on average displacement (AD) or seismic moment ($M_0$) exceeds that based on surface rupture length (SRL) or area (A). This difference in turn results in a significant discrepancy in $M_0$ release on the central WFZ, which affects moment-balanced models of earthquake recurrence and slip rate. However, for the WFZ, it is difficult to consistently reduce this discrepancy because of (1) consistently large vertical displacements per earthquake (using vertical displacement in **M** calculations and fault-parallel displacement in $M_0$

calculations), (2) insufficient data to consistently apply the average-displacement correction of Hemphill-Haley and Weldon (1999) and the limited effect of this method, (3) a poor basis for increasing SRLs beyond mapped segment boundaries, and (4) less robust normal-fault-type empirical relations (compared to all-fault-type relations; Wells and Coppersmith, 1994), which if used, help reduce the discrepancy. In addition, epistemic uncertainties may stem from the **M** regressions rather than the input data because of (1) a small-earthquake bias in historical catalogs and different scaling relations for small versus large earthquakes (Stirling and others, 2002), and (2) differences in **M** estimates depending on the strain-rate environment (Anderson and others, 1996).

The Basin and Range Province Earthquake Working Group II (BRPEWGII), which convened in November, 2011, prior to WGUEP Meeting 6, discussed the **M** discrepancy as related to BRP normal faults and its implications for the USGS NSHMs. Following a discussion of possible sources of the **M** discrepancy, the BRPEWGII recommended the following to the USGS:

> *To better address the epistemic uncertainties in determining $M_{max}$ (**M**) for BRP normal faults, the USGS should consider using the following multiple regression relations to determine $M_{max}$ for BRP faults in the NSHMs:*
>
> - *Wells and Coppersmith (1994) – SRL (all fault types)*
> - *Wells and Coppersmith (1994) – SRL (normal fault types)*
> - *Wells and Coppersmith (1994) – rupture area (A) (all fault types)*
> - *Stirling and others (2002) – censored instrumental (SRL)*
> - *Anderson and others (1996) – slip rate*

The WGUEP considered the BRPEWGII recommendation, and revised the regressions used in the two-category approach discussed at WGUEP Meeting 5 in June 2011, http://geology.utah.gov/ghp/workgroups/pdf/wguep/WGUEP-2011B_Summary.pdf). The Meeting 5 approach included the following regressions and weights:

| **Category A faults** (3+ paleoseismic sites) (June 2011) | Weight |
|---|---|
| • Wells and Coppersmith (1994) – SRL (all fault types) | 0.25 |
| • Wells and Coppersmith (1994) – A (all fault types) | 0.25 |
| • Wells and Coppersmith (1994) – AD adjusted using Hemphill-Haley and Weldon (1999) | 0.25 |
| • Hanks and Kanamori (1979) – $M_0$ | 0.25 |

| **Category B/C faults** (0–2 paleoseismic sites) (June 2011) | Weight |
|---|---|
| • Wells and Coppersmith (1994) – SRL (all fault types) | 0.5 |
| • Wells and Coppersmith (1994) – A (all fault types) | 0.5 |

At WGUEP Meeting 6, members considered the conclusions of the BRPEWGII and developed the following approach:

| **Category A faults** (2+ paleoseismic sites) (November 2011) | Weight |
|---|---|
| • Hanks and Kanamori (1979) – $M_0$ | 0.3 |
| • Stirling and others (2002) – SRL (censored instrumental) | 0.3 |
| • Wells and Coppersmith (1994) – SRL (all fault types) | 0.2 |
| • Wells and Coppersmith (1994) – A (all fault types) | 0.2 |

| **Category B/C faults** (all others) (November 2011) | Weight |
|---|---|
| • Stirling and others (2002) – SRL (censored instrumental) | 0.4 |
| • Wells and Coppersmith (1994) – SRL (all fault types) | 0.2 |
| • Wells and Coppersmith (1994) – A (all fault types) | 0.2 |
| • Anderson and others (1996) – slip rate | 0.2 |

The updated approach includes four regressions when paleoseismic data are available (category A faults). The greatest weight is given equally to the Hanks and Kanamori (1979) $M_0$ regression—a well-accepted regression that estimates **M** based on $M_0$, and thus accounts for AD and A—and the Stirling and others (2002) regression for SRL based on their censored-instrumental data. The Stirling and others (2002) regression accounts for potential differences in small versus large earthquakes and has the best fit to the relatively large WFZ magnitudes based on AD or $M_0$. The Wells and Coppersmith (1994) regression on AD (either with or without an adjustment based on Hemphill-Haley and Weldon [1999]) was not included because of the limited data used to define the regression, as well as issues related to different displacement measurement types (e.g., vertical and horizontal, versus net displacement). Relatively less weight is given to the Wells and Coppersmith (1994) all-fault-type regressions on SRL and A. Although normal faults may behave differently than strike-slip or reverse faults, the Wells and Coppersmith (1994) normal-fault-type regressions were not included, owing to the limited data used to determine the regressions (e.g., only 15 normal-faulting earthquakes have SRL information compared to 77 all-slip-type earthquakes).

For faults with little to no paleoseismic data (category B/C faults), four regressions are included to account for uncertainties arising from the apparent discrepancy between displacement- and length-based **M** estimates. The Stirling and others (2002) regression is given the most weight considering its good agreement with the WFZ $M_0$-based **M** estimates, and because it is the only regression present that appears to account for the **M** discrepancy. Equal, but less weight is given to the Wells and Coppersmith (1994) all-fault-type regressions on SRL and A, as well as the Anderson and other (1996) regression, which accounts for slip rate. Anderson and others (1996) found that including slip rate with SRL in the regression model provided a better fit to the data than just SRL alone, perhaps due to differences in fault behavior in different tectonic regimes (high versus low strain-rate environments). Normal-fault-type regressions (Wells and Coppersmith, 1994) were not included for reasons discussed above.

Further discussion is required on this topic to determine if the Working Group is comfortable with the weights assigned to the regressions recommended for the B and C category faults.

## Path Forward on Use of Geodetic Data

Based on a review of Christine Puskas' comparison of geodetic, historical earthquake, and geologic moment rates across the Wasatch Front (see WGUEP Meeting 5 Summary at http://geology.utah.gov/ghp/workgroups/pdf/wguep/WGUEP-2011B_Summary.pdf), Jim Pechmann concluded that for Christine's northern and central boxes, geodetic moment is a factor of two to three times (depending on the rupture model used) greater than geologic moment. For the southern box, geodetic moment is a factor of five to ten times greater than geologic moment. The reasons for these discrepancies remain unclear, but may be due in part to missed contributions to geologic moment rates from faults not included in the analysis. Based on Jim's review, the Working Group concluded at Meeting 5 that the geodetic data could provide an estimate of extension in a volume of crust across a region (WFR), and therefore provide a check on geologic rates. Additionally, areas with large discrepancies could be targeted for further study to resolve significant differences. However, the geodetic data are not sufficiently robust to allow geodetic extension to be partitioned among individual faults.

At Meeting 6, Ivan stated that geodetic data will likely not be a direct input to the WGUEP probability calculations. Mark Petersen noted that geodesists now expect geodetic data to be incorporated in earthquake probability analyses, and if we don't use the data available for the Wasatch Front, we will still need to acknowledge its existence and explain why we did not use it. Mark then turned the discussion to the high horizontal slip measured across the southern Wasatch Front. Tony Crone stated that the higher rates may be due to post seismic relaxation following an earthquake cluster, or possibly deformation of the more ductile rock units (salt and gypsum) found in the southern Wasatch Front area. Jim Pechmann questioned why we should assume that all of the horizontal slip is on the WFZ, and noted that we are really looking at a volume of crust with several Quaternary-active faults within it. David Schwartz stated the WGUEP should use the geodetic data as an upper bound and that we should convert available geologic slip rates to horizontal slip and then make a comparison of the horizontal slip data with the geodetic data to evaluate the size of the discrepancy. David volunteered to make the comparison. Patricia Thomas noted that the extension rates are within the uncertainty limits assigned to the WFZ geologic slip rates, and therefore will be covered in the probability calculations. Susan Olig wondered how much of the geodetic slip may be aseismic, and if there is a way to determine if aseismic slip is occurring, and if so, how much.

Ivan outlined a path forward that includes obtaining a robust slip rate for the WFZ and using that rate as a low-weight branch on the WFZ model. Jim, with the assistance of Mark, will analyze the difference between the geodetic and geologic rates and the Working Group can then decide how to proceed.

## Spatial Smoothing Issues

This discussion centered on whether the WGUEP wants to include a uniform background zone, in additional to Gaussian smoothing to account for non-stationarity in the historical record. That is, should we allow for the possibility that background earthquakes in the WFR could occur in locations where there have not been events in the historical record? Both approaches could be weighted as was done for the Salt Lake Valley microzonation maps developed by Wong and others (2002). The USGS smoothes background seismicity on the NSHMs using an isotropic smoothing function, except for three zones, where they use an anisotropic smoothing function: (1) Brawley seismic zone, (2) Creeping section, San Andreas fault, and (3) Mendocino seismic zone (all in California). The discussion then centered on whether the WGUEP should use isotropic, anisotropic, or a combination of the two in the WFR. Ivan stated that he would discuss that issue and also the appropriate smoothing kernel to use with Bob Youngs (Amec Geomatrix Consultants, Inc.).

## $M_{max}$ for Background Earthquakes

The discussion centered on what $M_{max}$ should be considered for the background earthquake. Previous studies in the Wasatch Front have generally used **M** 6.5 ± 0.25. The USGS uses a $M_{max}$ of **M** 7.0, which seems too high. The answer to the question depends on the minimum $M_{max}$ for faults, the evidence for which (scarps) could be observed at the surface after repeated earthquakes. The prevailing thinking was that **M** 6.5 was too low. Hence, at WGUEP Meeting 5 Ivan suggested a preliminary $M_{max}$ of **M** 6.75 ± 0.25 (see WGUEP Meeting 5 Summary at http://geology.utah.gov/ghp/workgroups/pdf/wguep/WGUEP-2011B_Summary.pdf).

Discussion then focused on whether a $M_{max}$ of **M** 6.5 or 6.75 is more appropriate for background earthquakes in the WFR; the WGUEP settled on **M** 6.75, because smaller events may not be observed in trenches and hence would go undetected.

## Modeling Graben-Bounding Fault Pairs

The WGUEP WFR includes a number of graben-bounding (antithetic) fault pairs (WFZ Salt Lake City segment/West Valley fault zone, WFZ Provo segment/Utah Lake faults, East Cache fault/West Cache fault zone, Hansel Valley fault/North Promontory fault, Joes Valley graben bounding faults, and Eastern Bear Lake fault/Western Bear Lake fault) that are too close together to avoid intersecting at depth.

- Faults closer than 17 km will intersect if both dip 60°
- Faults closer than 25 km will intersect if both dip 50°
- Faults closer than 36 km will intersect if both dip 40°

On past iterations of the NSHMs, antithetic fault pairs were each projected below their intersection to a depth of 15 km and earthquake magnitudes calculated for each fault based on area. This process overestimates hazard because if a "master" fault intersects and truncates its antithetic fault, the correspondingly smaller area of the antithetic fault would result in a lower earthquake magnitude and hazard.

The BRPEWGII also considered the issue of antithetic fault pairs as they apply to the next update of the NSHMs (Issue G2) and formulated the following recommendations to the USGS:

- *USGS should explore using metrics (such as length, topographic relief, and overlap) to guide selection of master and subsidiary faults.*

- *Evaluate dataset for overlapping relations to select master fault based on length.*
- *Evaluate using aspect ratio (length/width) for individual fault pairs.*
- *Where data allow, structural throw should be used rather than topographic relief.*
- *Evaluate using length x throw as a parameter for selecting master fault.*
- *Subsurface data (e.g., seismic reflection) should be used to guide master fault selection, where available.*
- *Where available data do not give a clear indication of master vs. subsidiary fault, model both alternatives using a logic tree approach.*
- *For truncated faults use rupture area (rather than SRL) to determine M.*

The WGUEP will review the BRPEWGII recommendations to the USGS regarding antithetic fault pairs for possible use in the WGUEP modeling process.

## Dip Angles for Basin and Range Normal Faults

The BRPEWGII also examined and discussed the issue of dip angle for BRP normal faults with respect to the next update of the NSHMs (Issue G4). Based on the recommendation from BRPEWGI (Lund, 2006), the current USGS NSHMs use a dip value of 50°±10° for normal faults in the BRP. The question considered by BRPEWGII was "is the 50° dip value and the ±10° uncertainty range valid and acceptable to cover the probable range of dips for BRP normal faults?" At the workshop, a review of geological, seismological, and geodetic data for faults in the BRP and in other selected regions worldwide provided insight into the dip of normal faults in continental crust. Following this review and discussion, the BRPEWGII formulated the following recommendations to the USGS:

- *Following a review of published data summarizing the dips of normal faults in the BRP and worldwide, the BRPEWGII concludes that a dip of 50° ± 15° best represents the range of dips for normal faults in the BRP. The BRPEWGII recommends this range be used in updates of the NSHMs; the 50° value defines the mean dip value and the ± 15° range represents the 5% and 95% percentiles.*

- *For those faults having geological, geophysical, seismological, or geodetic data that convincingly constrains a specific fault's dip within seismogenic depth, the NSHMs should use these fault-specific data to calculate the fault's hazard.*

- *The BRPEWGII recommends that the USGS evaluate the impact of increasing the range of recommended fault dips (from ± 10° to ± 15°) on the overall hazard.*

– *USGS should also evaluate whether the range in fault dips determined from global data is better represented by non-Poissonian distribution around the mean value versus assuming a simple Poissonian distribution*

The WGUEP will review the BRPEWGII recommendations to the USGS for possible use in the WGUEP modeling process.

## Oquirrh-Great Salt Lake Fault Zone

Susan Olig reviewed the current segmentation model for the Oquirrh-Great Salt Lake fault zone (O-GSLFZ) (figure 6):

**O-GSLFZ SEGMENTS**
Rozelle (RS) – 25 km
Promontory (PS) – 25 km
Fremont Is. (FIS) – 25 km
Antelope Is. (AIS) – 35 km
No. Oquirrh (NOS) – 30 km
So. Oquirrh (SOMS) – 31 km
Topliff Hills (THS) – 26 km
East Tintic (ETS) – 35 km

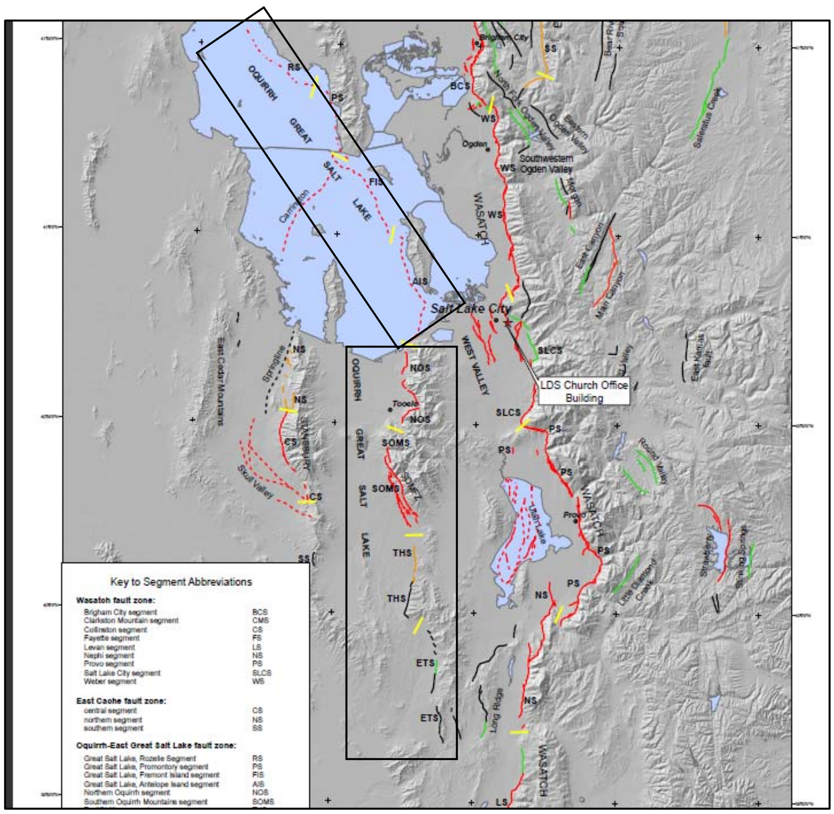


***Figure 6.*** *Boxes enclose the segments of the Oquirrh-Great Salt Lake fault zone.*

Susan then reviewed the timing information available for the most recent surface-faulting earthquake on each of the proposed O-GSLFZ segments (table 5), and the Great Salt Lake fault zone rupture scenarios and weights developed at WGUEP Meeting 4 (table 6). She then presented two new strawman rupture models with different weights for a combined O-GSLFZ (table 7).

Following discussion, the WGUEP expressed a general preference for the Strawman 2 weights, although Chris DuRoss felt that a rupture scenario that included an AI+NO multisegment rupture should also be included in the model. The possibility of having unsegmented rupture scenarios of various lengths was also discussed. Due to time constraints the discussion was cut short and Susan and Jim Pechmann were charged with revising the model to address the WGUEP discussion comments.

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**Table 5.** *Age of youngest surface-faulting along segments of the Oquirrh-Great Salt Lake fault zone.*

| | Fault Segment | Youngest Event | Penultimate Event | Older Events?[3] |
|---|---|---|---|---|
| *Great Salt Lake fault*[2] | Rozelle (RZ) | Holocene? | ?[3] | ?[3] |
| | Promontory (PY) | Holocene? | ?[3] | ?[3] |
| | Fremont Island (FI) | 3,150 (+240, -210) | 6,410 (+210, -210) | < 11,430 (+610, -450) |
| | Antelope Island (AI) | 590 (+200, -240) | 6,170 (+240, -230) | 9,900 (+250, -300) |
| | Northern Oquirrh (NO)[4] | 6330 ( 4960 to 7650) | 20,300 - 26,400 | > > 33,000 |
| | Southern Oquirrh (SO)[5] | 1,300 to **4,830**[6] | 20 to 50 ka[6] | shortly after 42 ± 8; shortly after 75 ± 10 ka; ca. 92 ± 14 ka[6] |
| | Topliff Hills (TH) | > 15,000[7] or < 15,000[8] | ?[3] | ?[3] |
| | East Tintic (ET) | > > 15,000 (middle to late Pleistocene)[9] | ?[3] | ?[3] |

***Table 6.*** *Great Salt Lake fault zone rupture scenarios and weights from WGUEP Meeting 4*

| Rupture Scenarios | WGUEP Weights |
|---|---|
| R, P, *FI, AI* | ***0.75*** |
| R, P, FI+AI | **0.1** |
| Unsegmented | **0.15** |

R = Rozelle segment, P = Promontory segment, FI = Fremont Island segment, AI = Antelope Island segment; italics indicates time-dependent model considered for that rupture source.

***Table 7.*** *Strawman Oquirrh-Great Salt Lake fault zone rupture model.*

| | Rupture Scenarios | Strawman 1 Weights | Strawman 2 Weights |
|---|---|---|---|
| **1** | RZ, PY, *FI, AI,* NO+SO, TH, ET | *0.40* | *0.25* |
| **2** | RZ, PY, *FI, AI,* NO, SO, TH, ET | *0.25* | *0.40* |
| **3** | RZ, PY, FI+AI, NO, SO, TH, ET | 0.10 | 0.10 |
| **4** | RZ, PY, *FI, AI,* NO, SO+TH, ET | 0.10 | 0.10 |
| **5** | Unsegmented (floating) | 0.15 | 0.15 |

RZ = Rozelle segment, PY = Promontory segment, FI = Fremont Island segment, AI = Antelope Island segment, NO = Northern Oquirrh, SO = Southern Oquirrh, TH = Topliff Hills, ET = East Tintic; italics indicates time-dependent model considered for that rupture source.

## TASK LIST

1. Complete revision of the historical earthquake catalog (Walter/Jim).
2. Decluster catalog and calculate recurrence for background seismicity correcting for magnitude bias (Mark/Walter/Ivan).
3. Finalize selection of recurrence models and weights (Ivan).

4. Finalize COV and uncertainties for WFZ – asymmetric or symmetric (Chris).
5. Finalize RIs for single and multi-segment ruptures on central WFZ (Chris/Nico).
6. Finalize slip rates for end segments of WFZ (Mike/Chris).
7. Finalize rupture model, RIs, slip rates, and COV for O-GSLFZ (Susan/Jim).
8. Finalize $M_{max}$ procedures (Susan).
9. Finalize seismogenic crustal thicknesses for west and east of WFZ (Jim/Ivan).
10. Finalize parameters for "Other Faults" (Bill).
11. Finalize parameters for antithetic rupture of Hansel Valley fault (Mike/Bill).
12. Finalize weights of time-dependent versus time-independent models for WFZ and O-GSLFZ (Chris/Susan/Jim).
13. Finalize average displacements for calculating **M** for central WFZ (Chris/Susan).
14. Compare geologic horizontal slip rates with geodetic rates across Wasatch Front (David/Jim/Mark).
15. Finalize approach for background seismicity (Ivan/Mark).

## REFERENCES

Presenters did not provide complete citations for the references given in their presentations and reported in these minutes.

## NEXT MEETING

The next WGUEP meeting is scheduled for February 16–17, 2012, at the Utah Department of Natural Resources Building (1594 West North Temple, Salt Lake City, Utah).

## ATTACHMENT 1

**Attendance**
**Working Group on Utah Earthquake Probabilities**
**Meeting 6**

Walter Arabasz, UUSS
Tony Crone, USGS
Chris DuRoss, UGS
Mike Hylland, UGS
Nico Luco, USGS
Bill Lund, UGS, Coordinator
Susan Olig, URS Corporation
James Pechmann, UUSS
Steve Personius, USGS
Mark Petersen, USGS
Dave Schwartz, USGS
Bob Smith, UUGG*
Patricia Thomas, URS Corporation
Ivan Wong, URS Corporation, Chair

*Member Absent

Others presenting or assisting the Working Group
Steve Bowman, UGS Liaison to WGUEP

## ATTACHMENT 2

## REVISED AGENDA*
## WORKING GROUP ON UTAH EARTHQUAKE PROBABILITIES
## MEETING #6
## Thursday/Friday, 17 & 18 November 2011
## Utah Department of Natural Resources Building, Room 2000 (2nd floor)
## 1594 West North Temple, Salt Lake City

**Thursday, 17 November**

| | | |
|---|---|---|
| 8:00 – 8:30 | Continental Breakfast | |
| 8:30 – 8:45 | Welcome | Bill |
| | Overview of Agenda | Ivan |
| | Update on Consensus Wasatch Front Earthquake Catalog | Walter/Jim |
| | Recurrence Models (Issue S1) | Ivan |
| | Overview of Methodology and Data Needs | Patricia |
| | Update on Final Wasatch Central Segment Recurrence Rates and COVs | Chris |
| | Update on Other Faults (Issue G3) | Bill |
| | Calculating $M_{max}$ for Faults (Issue G1) | Susan/Chris |
| 5:00 | Adjourn | |

**Friday, 18 November**

| | | |
|---|---|---|
| 7:30 – 8:00 | Continental Breakfast | |
| | Path Forward on Use of Geodetic Data | Ivan |
| | Spatial Smoothing (Issue S2) | Mark |
| | Modeling Antithetic Faults (Issue G2) | Mike |
| | Fault Dips (Issue G4) | Tony |
| | $M_{max}$ for Background Earthquakes | Ivan |
| | Historical Versus Geologic Rates (Issue S3) (Not discussed) | Ivan |
| | Oquirrh-Great Salt Lake Fault | Susan |
| | Open Discussion and Schedule | All |
| 3:00 | Adjourn | |

WGUEP Members

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

Other Participants

Steve Bowman, UGS

*Topic discussions at this meeting were free roaming. Topics discussed on the first and second day are listed above; however, discussion length and start and stop times were variable.