A Revised Earthquake Catalog and Unbiased Rate Calculations for Background Seismicity in the WGUEP Region

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(with thanks to Jim Pechmann and Relu Burlacu for various input and help)

UNIVERSITY OF UTAH SEISMOGRAPH STATIONS
THE UNIVERSITY OF UTAH

WGUEP
September 12, 2013

Outline

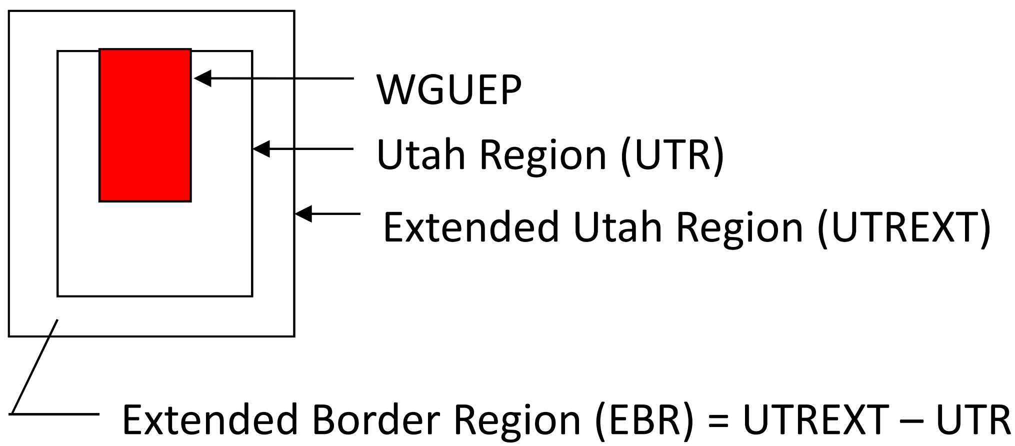
I. Introduction□the endgame
II. A uniform (and unified) earthquake catalog for the Utah region
III. Methodology for unbiased rate calculations
IV. Results
V. Remaining methodology issues

The Endgame

- Unified UUSS-USGS earthquake catalog → declustered; 1850 through Sept. 2012; for the entire Utah region, including the WGUEP region; USGS format used for NSHM
- Uniform catalog in terms of moment magnitude, M
- "Complete" catalog accounting for all significant events in diverse catalogs being considered
- For each event, magnitude uncertainty σ (aka sigM)
- For each event, rounding error
- For each event, the calculation of N*, an equivalent earthquake count, incorporating corrections for σ, used to compute unbiased earthquake recurrence parameters

Definition of domains

	UTREXT	UTR	WGUEP
top	43.50º N	42.50º N	42.50º N
bottom	36.00º N	36.75º N	39.00º N
left	-115.00º W	-114.25º W	-113.25º W
right	-108.00º W	-108.75º W	-110.75º W



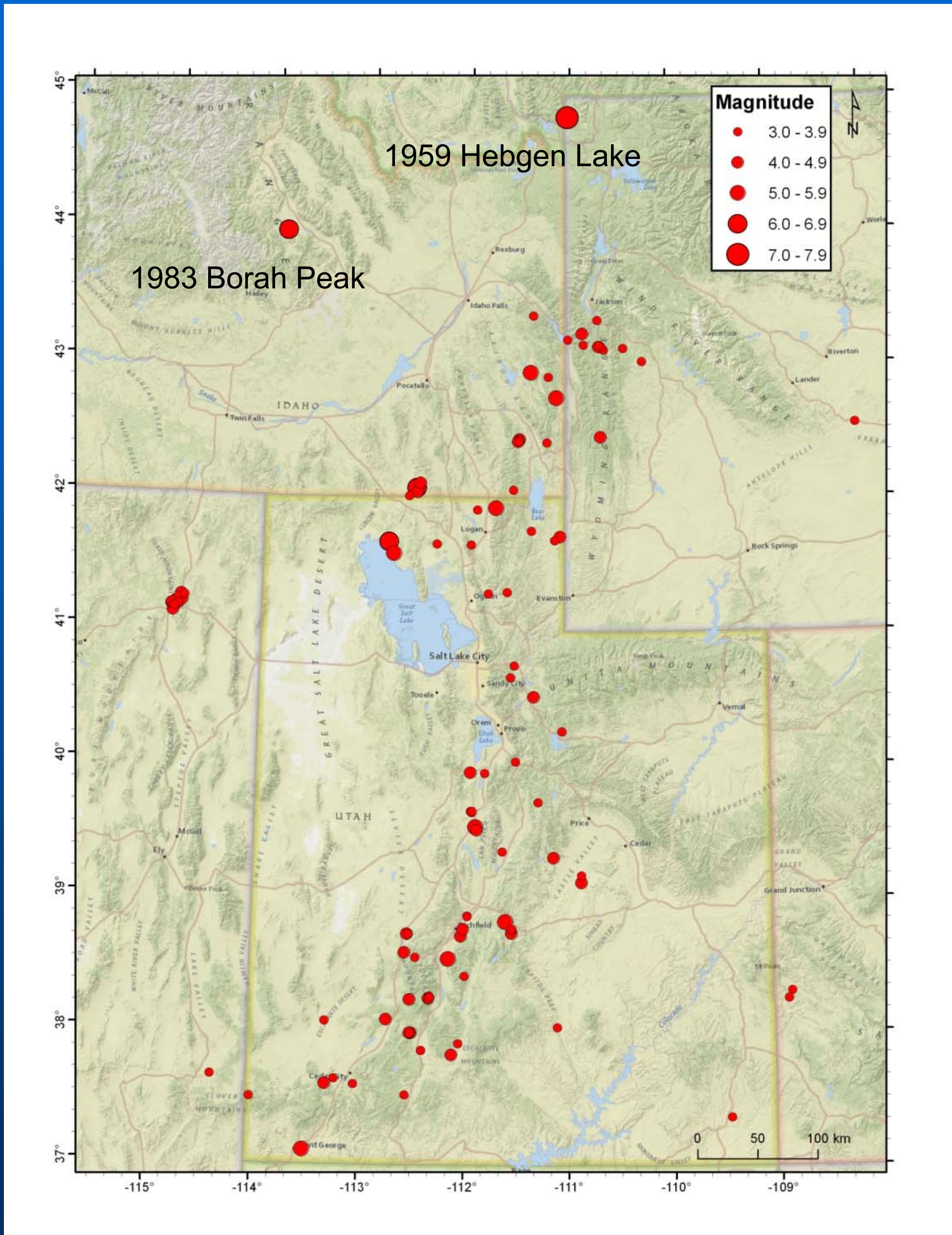
Overview of merged catalogs and sub-catalogs for the UTREXT

	UUSS (historical) ALL	**SRA** ALL	**NSHM** (wmm) M≥3.5 ALL	**UNR** M≥4.8 ALL	**Stover and Coffman** (1993) I_0 ≥6, M≥4.5	**UUSS** (instrumental) M≥2.45	**USGS/PDE** ALL
A. Jan 1850–Jun 1962	XXX	XXX	XXX	XXX	XXX		
B. July 1962–Dec 1986		XXX	XXX	XXX	XXX	XXX	XXX
C. Jan 1987–Sept 2012			XXX	XXX	XXX	XXX	XXX

Note: The NSHM/WMM catalog received from C. Mueller extended only through the end of 2010; C. Mueller (personal communication) confirmed that the USGS/PDE catalog would be the basis for extending it beyond 2010.

N=9678 event lines (excluding 866 MIS events ≥ M2.45)

Systematically merged, line-edited and culled → 5394 events in the UTREXT



109 EQS with M_{obs}

(incl. Hebgen Lake and Borah Peak Earthquakes)

Basis for Conversion Relationships

Global CMT	7
Whidden and Pankow (2012)	43
Whidden (unpublished)	9
Herrmann et al. (2011)/SLU MT catalog	30
Oregon State Univ. MT catalog	7
Pre-1989	
Doser (1989)	2
Patton and Zandt (1991)	8
Other (geometric mean of multiple M_0's	3
TOTAL	109

$3.17 \le \mathbf{M} \le 7.35$ (1934–2012)

$\mathbf{M} = 2/3 \log M_0 - 10.7$

Conversion Relationships (instrumental)

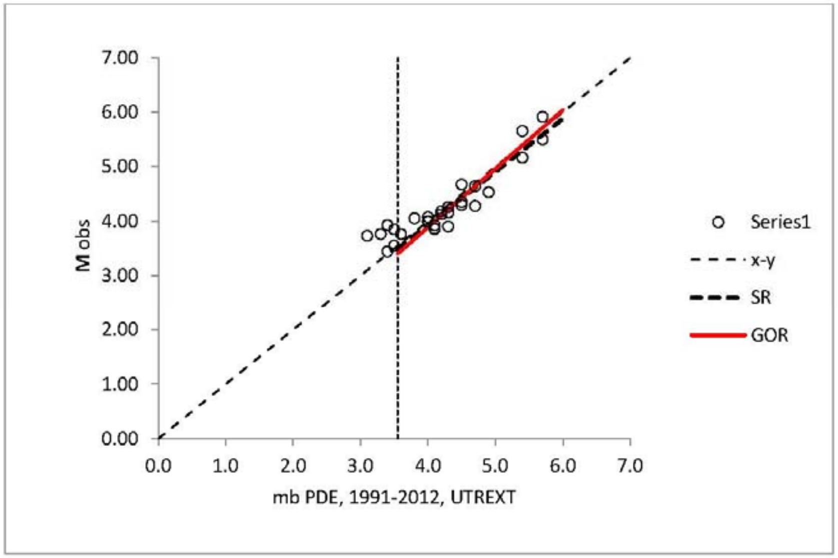
Size Measure		Conversion Relationship (CR)		$\sigma[\mathbf{M}\|X]$
Notation	Description and Applicable Period	CR ID	Relationship	
M_L UU1	M_L Univ. of Utah (1981–2012)	1	E[**M**] = 0.791 (M_L UU1) +0.851	0.14
M_L UU2	M_L Univ. of Utah (July 1962–Dec 1980)	2	Deduce M_L UU1 = M_L UU2 ± 0.24, where 0.24 $=\sigma_{MLUU1\|MLUU2}$, and use CR-1	0.28
M_C UU1	M_C Univ. of Utah (1981–2012)	3	E[**M**] = 0.929 (M_C UU1) + 0.227	0.22
M_C UU2	M_C Univ. of Utah (Oct 1974–Dec 1980)	4	Deduce M_L UU1 = M_C UU2 ± 0.27, where 0.27 $=\sigma_{MLUU1\|McUU2}$, and use CR-1	0.30
M_C UU3	M_C Univ. of Utah (JULY 1962–Sept 1974)	5	Deduce M_L UU1 = M_C UU3 ± 0.28, where 0.28 $=\sigma_{MLUU1\|McUU3}$, and use CR-1	0.31
M_L GS	M_L USGS, Utah Region, UTR (1974–2012)	6	Compute M_L UU1 = M_L GS – 0.11 and use CR-1	0.29
M_L GS	M_L USGS, Extended Border Region, EBR (1981–2012)	7	Compute M_L UU1 = M_L GS + 0.09 and use CR-1	0.28
m_b PDE1 > 3.5	m_b USGS/PDE (1991–2012), Extended Utah Region, UTREXT	8	E[**M**] = 1.078 (m_b PDE1) – 0.427	0.21
m_b PDE2 ≥ 3.5	m_b USGS/PDE (1978–1990)	9	Compute $M_{L(C)}$ UU = 1.088 m_b PDE2 – 0.652 and use CR-1	0.45
m_b PDE3 3.3–5.0	m_b CGS/USGS/PDE (1963–1977)	10	Compute $M_{L(C)}$ UU = 1.697 m_b PDE3 – 3.557 and use CR-1	0.56
m_b ISC	m_b ISC, Nsta ≥ 5 (1964–2012)	11	E[**M**] = 1.162 m_b ISC –0.740	0.30

Conversion Relationships (non-instrumental)

Size Measure		Conversion Relationship (CR)		$\sigma[\mathbf{M}\|X]$
Notation	Description and Applicable Period	CR ID	Relationship	
ln(FA)	ln(FA), in km^2, where FA is the total felt area (1850–2012)	12	$E[\mathbf{M}] = 0.645 + 0.345 \times \ln(FA) + 0.0018\ (FA)^{1/2}$	0.35
$I_0 \geq V$	Epicentral value of Modified Mercalli Intensity, MMI ≥ V (1850–2012)	13	$E[\mathbf{M}] = 0.764\ I_0 + 0.229$	0.5
$I_0 < V$	Epicentral value of MMI < V (1850–2012)	14	$E[\mathbf{M}] = 0.386\ I_0 + 2.126$	0.5
A_{VII}	Extent of area shaken, in km^2, at or greater than MMI VII (1850–2012)	15	$E[\mathbf{M}] = 1.619 \log_{10}(A_{VII}) + 0.802$	0.35
A_{VI}	Extent of area shaken, in km^2, at or greater than MMI VI (1850–2012)	16	$E[\mathbf{M}] = 1.341 \log_{10}(A_{VI}) + 0.535$	0.35
A_V	Extent of area shaken, in km^2, at or greater than MMI V (1850–2012)	17	$E[\mathbf{M}] = 1.445 \log_{10}(A_V) - 0.809$	0.35
A_{IV}	Extent of area shaken, in km^2, at or greater than MMI IV (1850–2012)	18	$E[\mathbf{M}] = 1.306 \log_{10}(A_{IV}) - 0.345$	0.35

Example CRs (instrumental)

mb USGS/PDE (1991–2012)

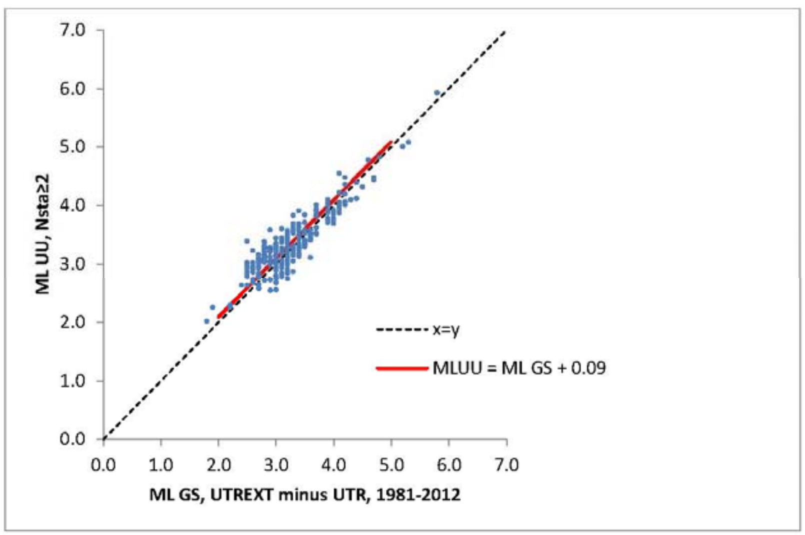


For mb PDE > 3.5, Utah Extended Region

General Orthogonal Regression (GOR)

E[**M**] = 1.078 (mb PDE1) – 0.427 σ[**M**| mb PDE1] = 0.21

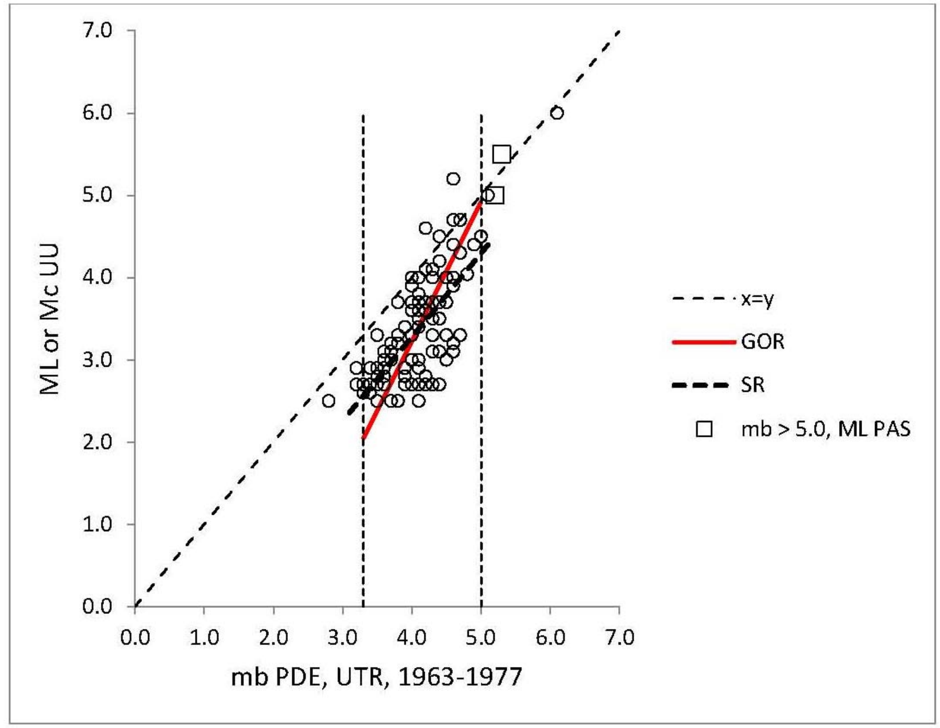
ML UU vs. ML GS, Extended Border Region



Offset Model

Compute M_L UU1 = M_L GS + 0.09 and use CR-1 σ[**M**|M_L GS] = 0.28

mb USGS/PDE (1963–1977)



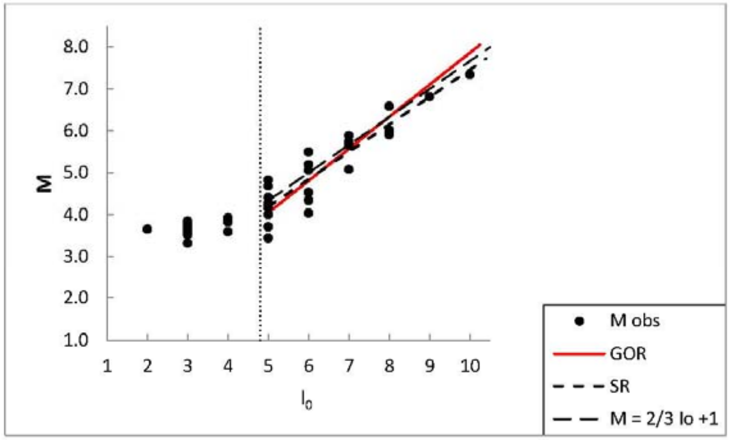
For 3.3 ≤ mb PDE ≤ 5.0, Utah Region

General Orthogonal Regression (GOR)

Compute M_L UU = 1.697 (mb PDE3) – 0.3557 and use CR-1

σ[**M**| mb PDE3] = 0.56

$I_0 \geq V$ (1850–2012)

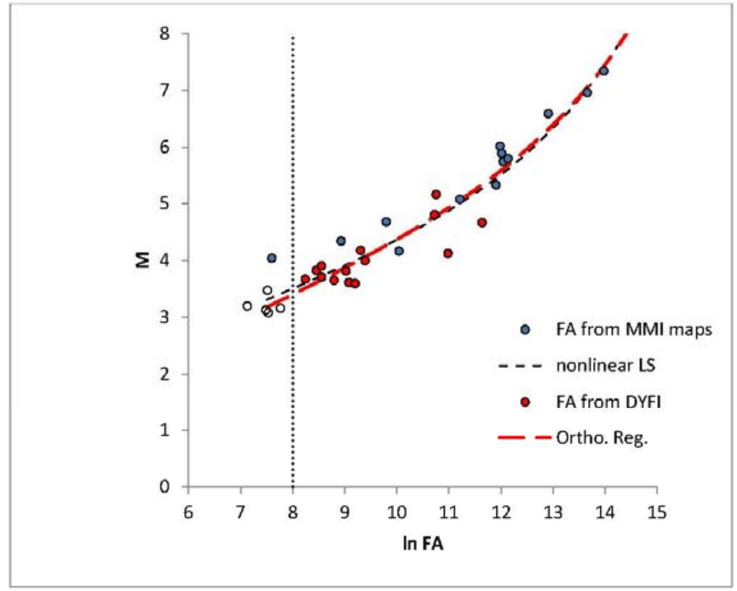


For $I_0 \geq V$, Utah Region (plus Hebgen Lake, Borah Peak, Draney Peak, Wells eqs)

General Orthogonal Regression

$E[\mathbf{M}] = 0.764\, I_0 + 0.229 \qquad \sigma[\mathbf{M}|I_0] = 0.5$

ln(FA) where FA = km^2 (1850–2012)



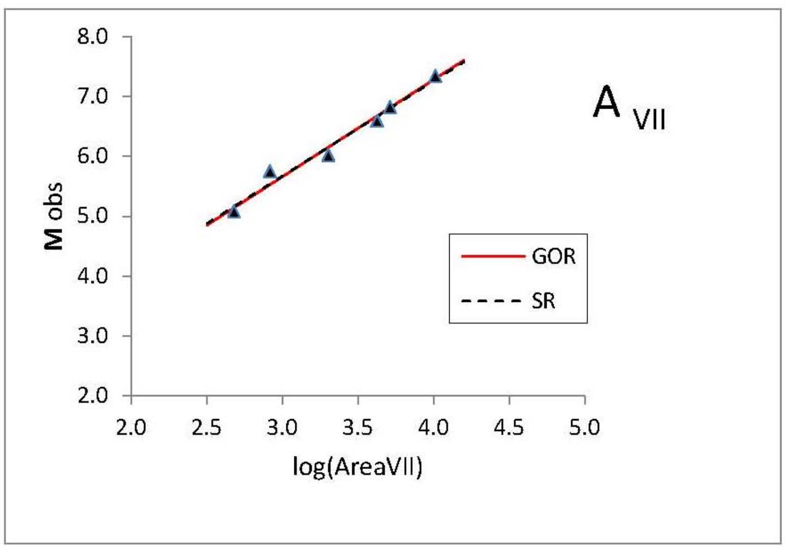
For ln(FA), Utah Region (plus Hebgen Lake, Borah Peak, Draney Peak eqs)

ln(FA) > 8 (i.e., FA > 3000 km^2)

Nonlinear least-squares estimation

$E[\mathbf{M}] = 0.645 + 0.345\ \ln(FA) + 0.0018\ SQRT\{FA\} \qquad \sigma[\mathbf{M}|\ \ln(FA)] = 0.35$

Note: Open circles are values of ln(FA) from DYFI and whose y-values are $E[\mathbf{M}|M_L\ UU]$; these data are below the truncation value of ln(FA) for the regression and are shown for illustration only.



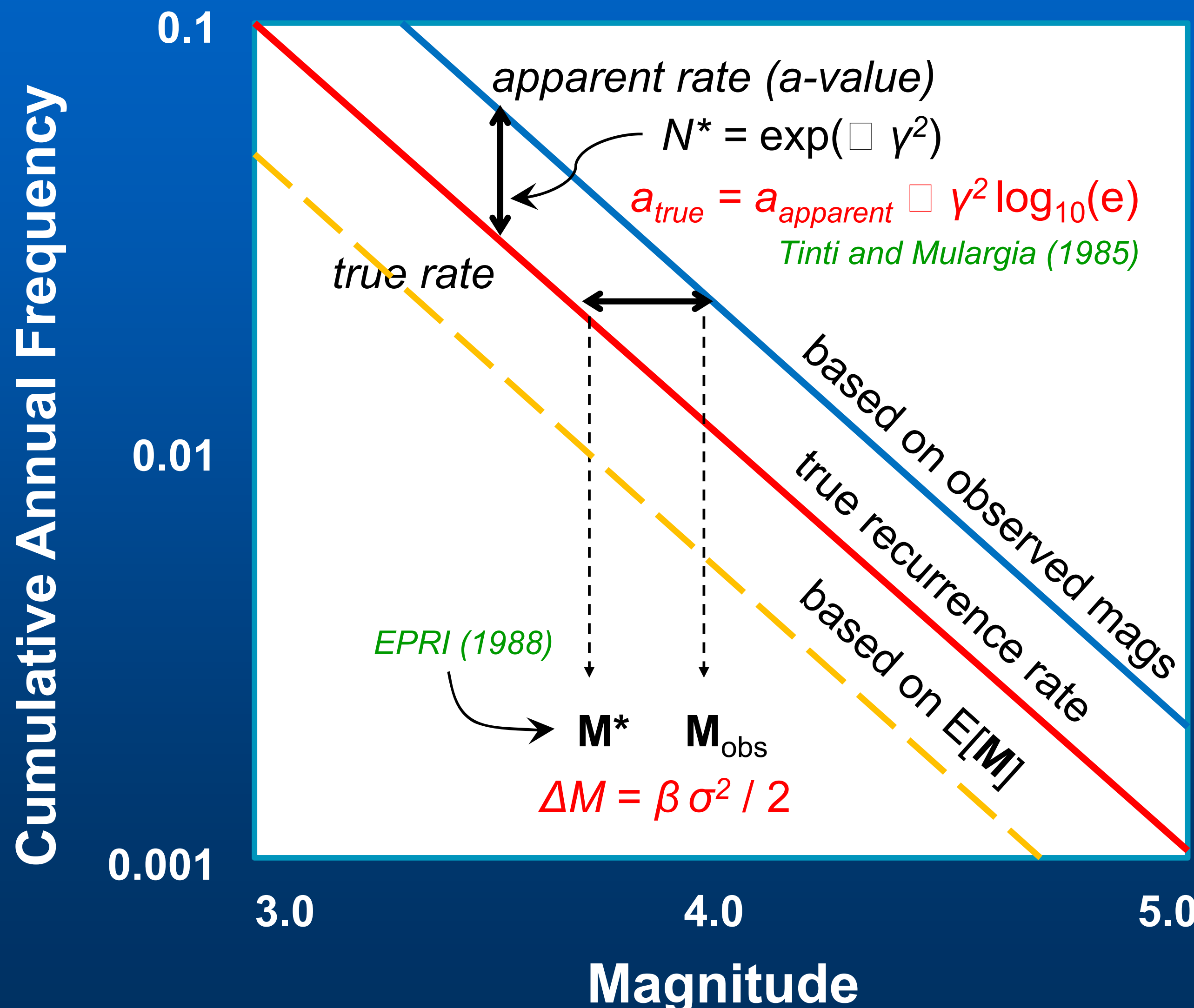
For A_{VII}, Utah Region (plus Hebgen Lake and Borah Peak)

General Orthogonal Regression

$E[\mathbf{M}] = 1.169\ \log_{10}(A_{VII}) + 0.802 \qquad \sigma[\mathbf{M}|A_{VII}] = 0.14$

Example CRs (non-instrumental)

METHODOLOGY: *Equivalent approaches to ensuring unbiased recurrence rates*



$\gamma^2 = \beta^2 \sigma^2 / 2$

where $\beta = b / \log_{10}(e)$

or $b \ln(10)$

Fine point:

E[M] = expected value of moment magnitude

Adapted from Youngs (2011)

METHODOLOGY (1 OF 2)

RULES FOR CALCULATING E[M] AND SIGMA
(EPRI, 1988; EPRI/DOE/NRC, 2012)

I. For Instrumentally Determined Moment Magnitudes

M	Moment magnitude
$\mathbf{M}_{obs}$	Observed moment magnitude (measured with error)
E[**M**]	Expected value of true moment magnitude
$\sigma[\mathbf{M}\vert\mathbf{M}_{obs}]$	Standard deviation of the normally distributed errors in the observed moment magnitudes (aka sig**M**)

$E[\mathbf{M}] = \mathbf{M}_{obs} - \beta\sigma^2 [\mathbf{M}|\mathbf{M}_{obs}]$, where $\beta = b\ln\{10\} = b/\log_{10}e$ (3.3.1-5) CEUS-SSC

Note: The second term is a bias correction for exponentially distributed magnitudes in discrete magnitude bins (e.g., Veneziano and Van Dyke, 1985; Tinti and Mulargia, 1985).

II. For Other Observed Size Measures (and Estimating M from Only One Size Measure X)

E[**M**|X] = [magnitude conversion relationship between **M** and some other size measure X]

$\sigma^2 [\mathbf{M}|X] = \sigma^2 [\mathbf{M}_{obs}|X] - \sigma^2 [\mathbf{M}|\mathbf{M}_{obs}]$ (3.3.1-8) CEUS-SSC

$\sigma[\mathbf{M}|X] = \mathrm{SQRT}\{\sigma^2_{regression} - \sigma^2_{y}\}$ *correction term (A)*

METHODOLOGY (2 OF 2)

III. For Other Observed Size Measures (and Estimating M from Multiple Size Measures), Use Variance Weighting (or more correctly, inverse-variance weighting)

$$\sigma^2\,[\mathbf{M}|\mathbf{X}] = \{\Sigma\, 1 / \sigma^2\,[\mathbf{M}|X_i]\}^{-1} \qquad \text{(3.3.1-10) CEUS-SSC}$$

combined variance, CV

Let the combined variance, $\sigma^2\,[\mathbf{M}|\mathbf{X}]$ = CV and the variance for a single size measure, $\sigma^2\,[\mathbf{M}|X_i]$ = SSMV. Then,

correction term (B)

$$\mathbf{E}[\mathbf{M}|\mathbf{X}] = \{\Sigma\, CV/SSMV * E[\mathbf{M}|X_i]\} + (R-1)\,\beta * CV \qquad \text{(3.3.1-9) CEUS-SSC}$$

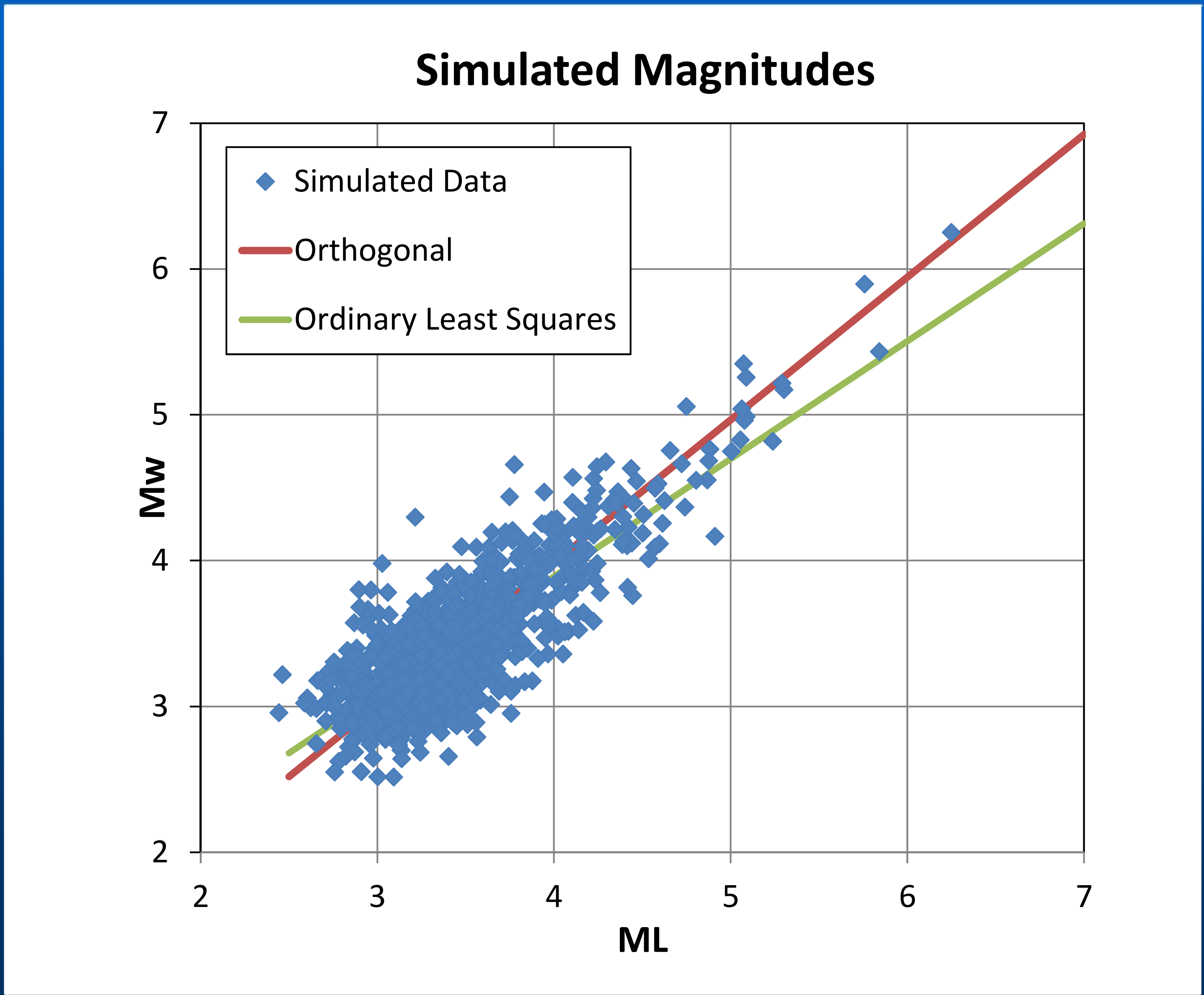
Note: According to the CEUS-SSC Report, the final term is needed "to adjust for bias introduced by the underlying exponential distribution in magnitude."

IV. For the Case of Converting a Size Measure X_1 to Another Size Measure X_2 and Then Estimating $E[M|X_2]$

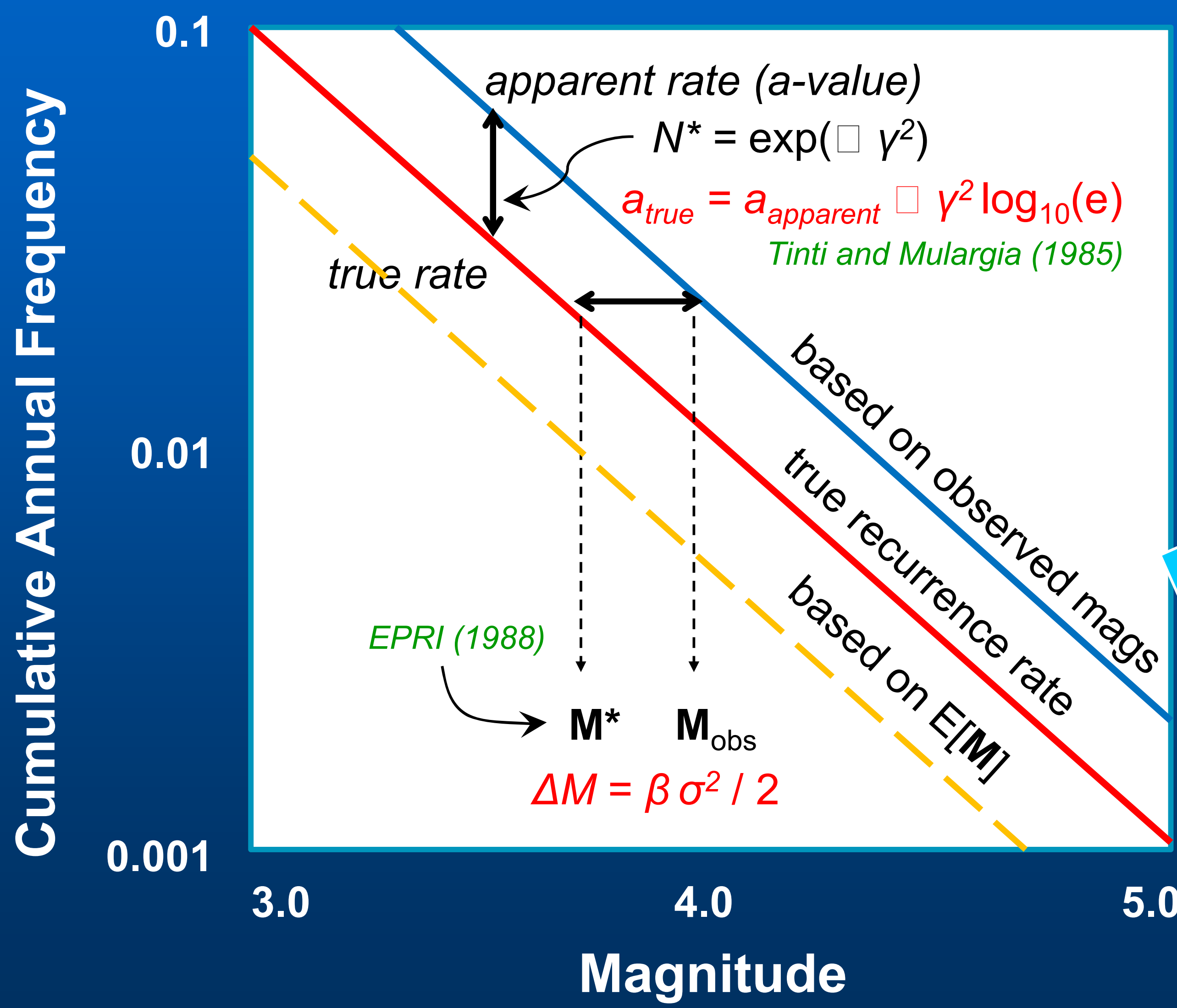
First convert $\mathbf{X_1}$ to $\mathbf{X_2}$, and then estimate $\mathbf{E}[\mathbf{M}|X_2]$.

$$\sigma_{M|X1} = SQRT\{\, (\sigma_{M|X2})^2 + (\sigma_{X2|X1})^2 \,\}$$

Methdology Refinement (after G. Toro, 9/5/2013, USGS Webinar on Magnitude Uncertainty)



Results of orthogonal regression are not E[M] but the equivalent of Mobs



$\gamma^2 = \beta^2 \sigma^2 / 2$
where $\beta = b / \log_{10}$)
or $b \ln (10)$

Fine point:
E[M] = expected value of the true magnitude

Adapted from Youngs (2011)

Back to the Drawing Board

- Instead of creating an “E[M] catalog, create a catalog consisting of $M_{observed}$ (and $M_{predicted}$)

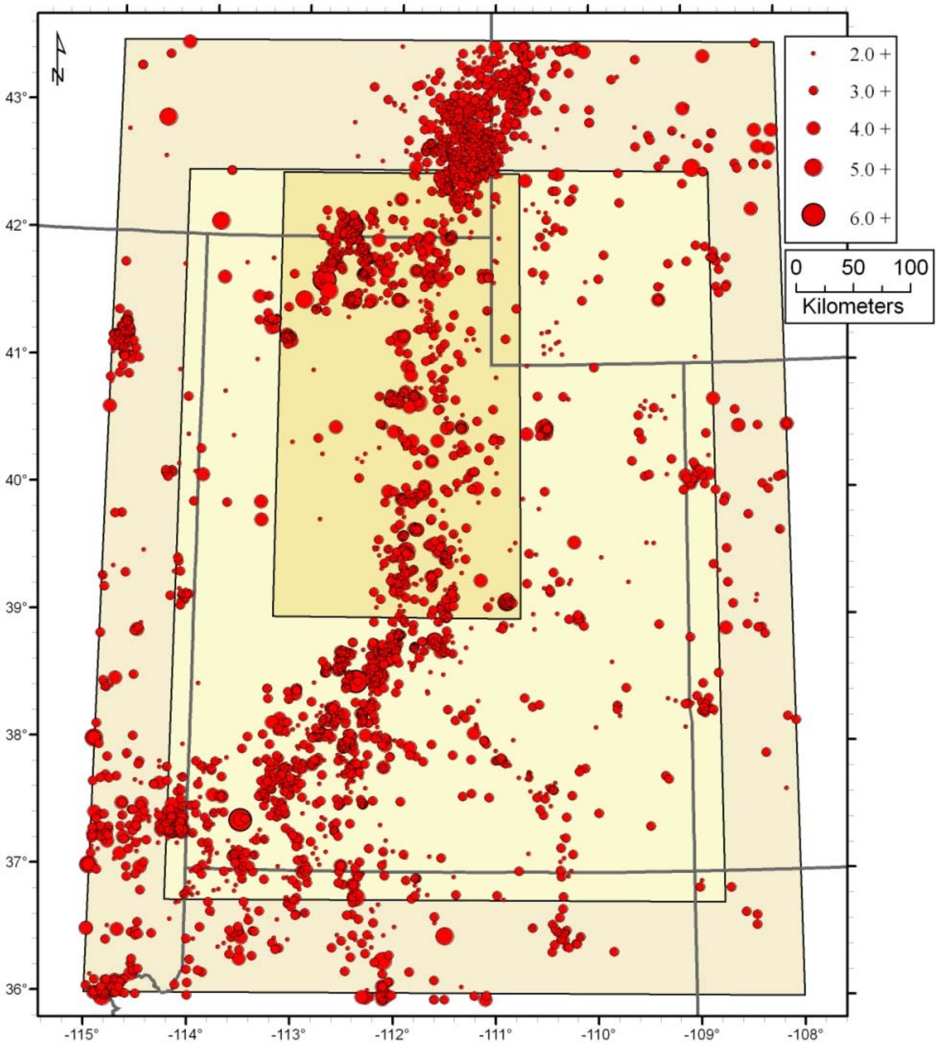
  ($M_{predicted}$ includes results of magnitude conversions based on orthogonal regressions and magnitudes assumed to be equivalent to $M_{observed}$)

- Use orthogonal regressions consistently
- Get to the “true rate” red line via N*
- The E[M] methodology can be used if one consistently uses least-squares regressions

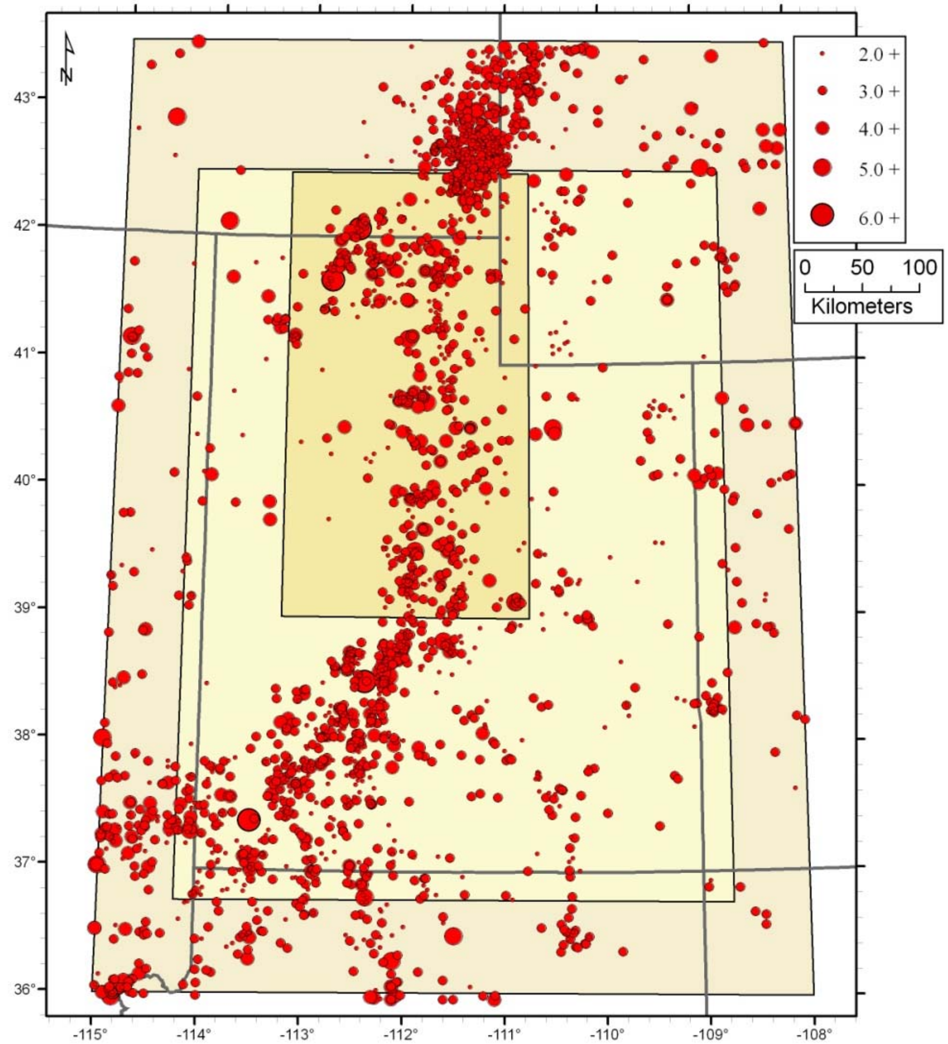
RESULTS

G-K declustering

Clustered (no MIS) N=5394 Declustered N= 2413

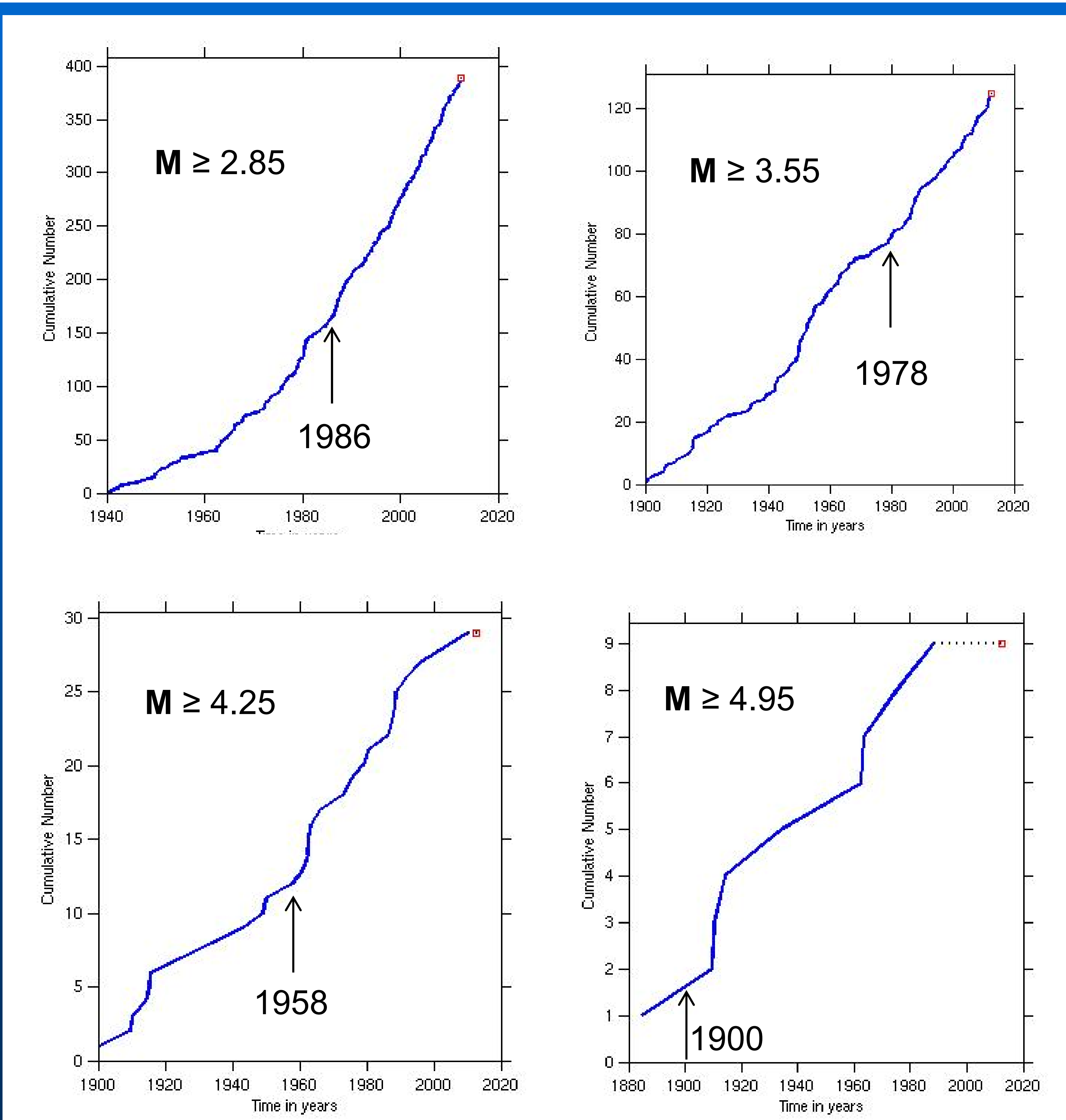


WGUEP N= 1160



WGUEP N= 655

Completeness WGUEP (declustered Catalog)



Completeness Periods

WGUEP REGION

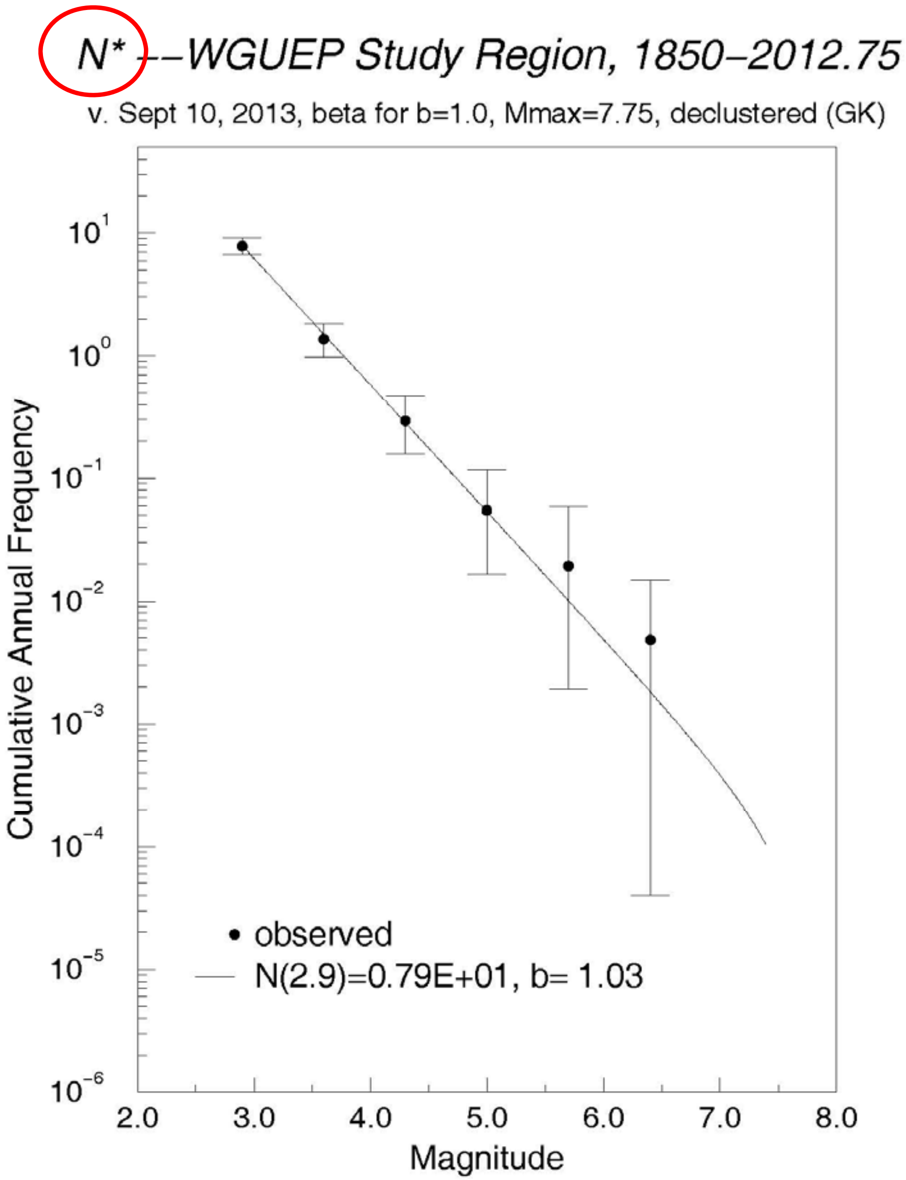
Magnitude Range	Range for Counts	Completeness Period Year (Start)	Year (End)	t (years)
$2.9 \leq M < 3.6$	2.85-3.54	**1986**	2012.75	26.75
$3.6 \leq M < 4.3$	3.55-4.24	**1978**	2012.75	34.75
$4.3 \leq M < 5.0$	4.25-4.94	**1958**	2012.75	54.75
$5.0 \leq M < 5.7$	4.95-5.64	**1900**	2012.75	112.75
$5.7 \leq M < 6.4$	5.65-6.34	*1880*	2012.75	132.75
$6.4 \leq M < 7.1$	6.35-7.04	*1850*	2012.75	162.75
$3.0 \leq M < 3.5$	2.95-3.44	**1986**	2012.75	26.75
$3.5 \leq M < 4.0$	3.45-3.94	**1978**	2012.75	34.75
$4.0 \leq M < 4.5$	3.95-4.44	**1966**	2012.75	46.75
$4.5 \leq M < 5.0$	4.45-4.94	**1915**	2012.75	97.75
$5.0 \leq M < 5.5$	4.95-5.44	**1900**	2012.75	112.75
$5.5 \leq M < 6.0$	5.45-5.94	*1880*	2012.75	132.75
$6.0 \leq M < 6.5$	5.95-6.44	*1850*	2012.75	162.75
$6.5 \leq M < 7.0$	6.45-6.94	*1850*	2012.75	162.75

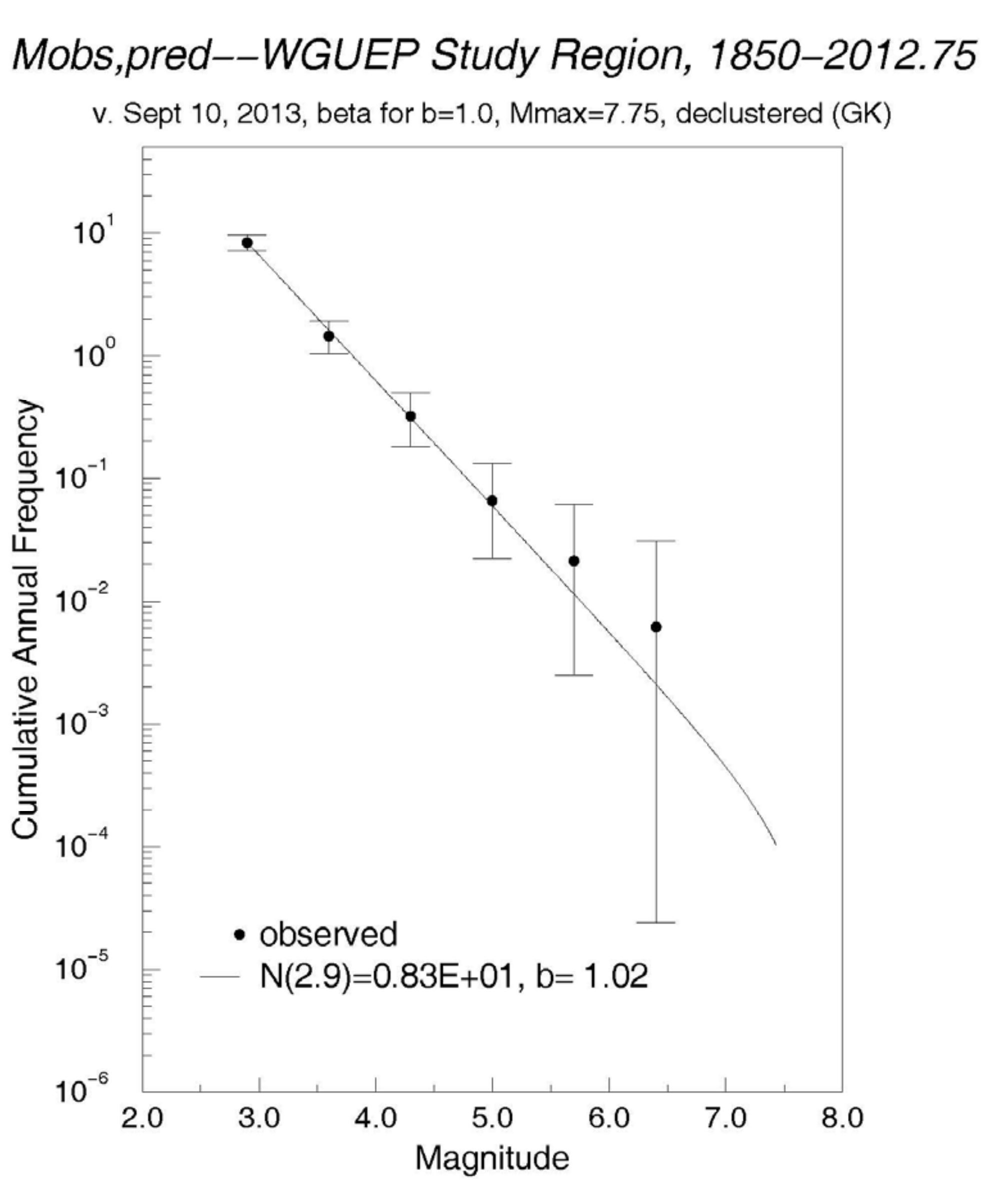
For start dates of completeness periods, bold date indicates it was picked from a plot of cumulative number vs. time; italicized date, from other arguments.

WGUEP Counts (and a look at the largest events)

Mobs or Mpred	Long W	Lat N	Year	Mo	Day	sigM	Mag Type method 2	N*		Completeness (color coded)	COUNTS Mobs or Mpred	SUM N*
4.69	-112.491	42.101	1978	11	30	0.125	Mobs	0.959				
4.81	-111.582	39.527	1876	3	22	0.500	Mpred|lo	0.515	4.25-4.94			
4.81	-111.959	41.224	1894	7	18	0.500	Mpred|lo	0.515	pink			
4.81	-112.650	40.500	1915	8	11	0.500	Mpred|lo	0.515				
4.81	-111.500	42.500	1924	11	25	0.500	Mpred|lo	0.515				
4.81	-111.849	40.749	1949	3	7	0.500	Mpred|lo	0.515				
4.83	-112.089	40.715	1962	9	5	0.128	Mpred|Xvar	0.957				
5.58	-111.400	42.300	1884	11	10	0.500	Mpred|lo	0.515	4.95-5.64			
5.58	-112.700	41.800	1909	10	6	0.500	Mpred|lo	0.515	green			
5.46	-111.800	40.700	1910	5	22	0.287	Mpred|Xnon	0.804				
5.00	-112.000	41.200	1914	5	13	0.287	Mpred|Xnon	0.804				
5.06	-111.909	39.533	1963	7	7	0.150	Mobs	0.942				
5.14	-110.890	39.133	1988	8	14	0.132	Mpred|Xvar	0.955	4.95-5.64		5	4.020
5.75	-111.733	41.917	1962	8	30	0.150	Mobs	0.942	5.65-6.34			
6.02	-112.525	42.063	1975	3	28	0.060	Mobs	0.991	purple		2	1.933
6.59	-112.795	41.658	1934	3	12	0.300	Mobs	0.788	6.35-7.04		1	0.788
									red			

Weichert recurrence parameters





Remaining Methodology Issues

- Adjusting σ from regressions

$$\sigma^2 [\mathbf{M}|X] = \sigma^2 [\mathbf{M}_{obs}|X] - \sigma^2 [\mathbf{M}|\ \mathbf{M}_{obs}] \qquad \text{(3.3.1-8) CEUS-SSC}$$

$$\sigma [\mathbf{M}|X] = \text{SQRT}\{\sigma^2_{regression} - \sigma^2_y\}$$

correction term (A)

- Adjusting variance weighting

correction term (B)

$$E[\mathbf{M}|\mathbf{X}] = \{\Sigma\ CV/SSMV * E[\mathbf{M}|X_i]\} + (R-1)\,\beta * CV \qquad \text{(3.3.1-9) CEUS-SSC}$$

Note: According to the CEUS-SSC Report, the final term is needed "to adjust for bias introduced by the underlying exponential distribution in magnitude."

- Corrections for rounding?
  (59 events in WGUEP region, M 3.0–5.5, affected)

Oquirrh Great Salt Lake Fault Zone (OGSLFZ) Wrap Up

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Oakland, CA 94612

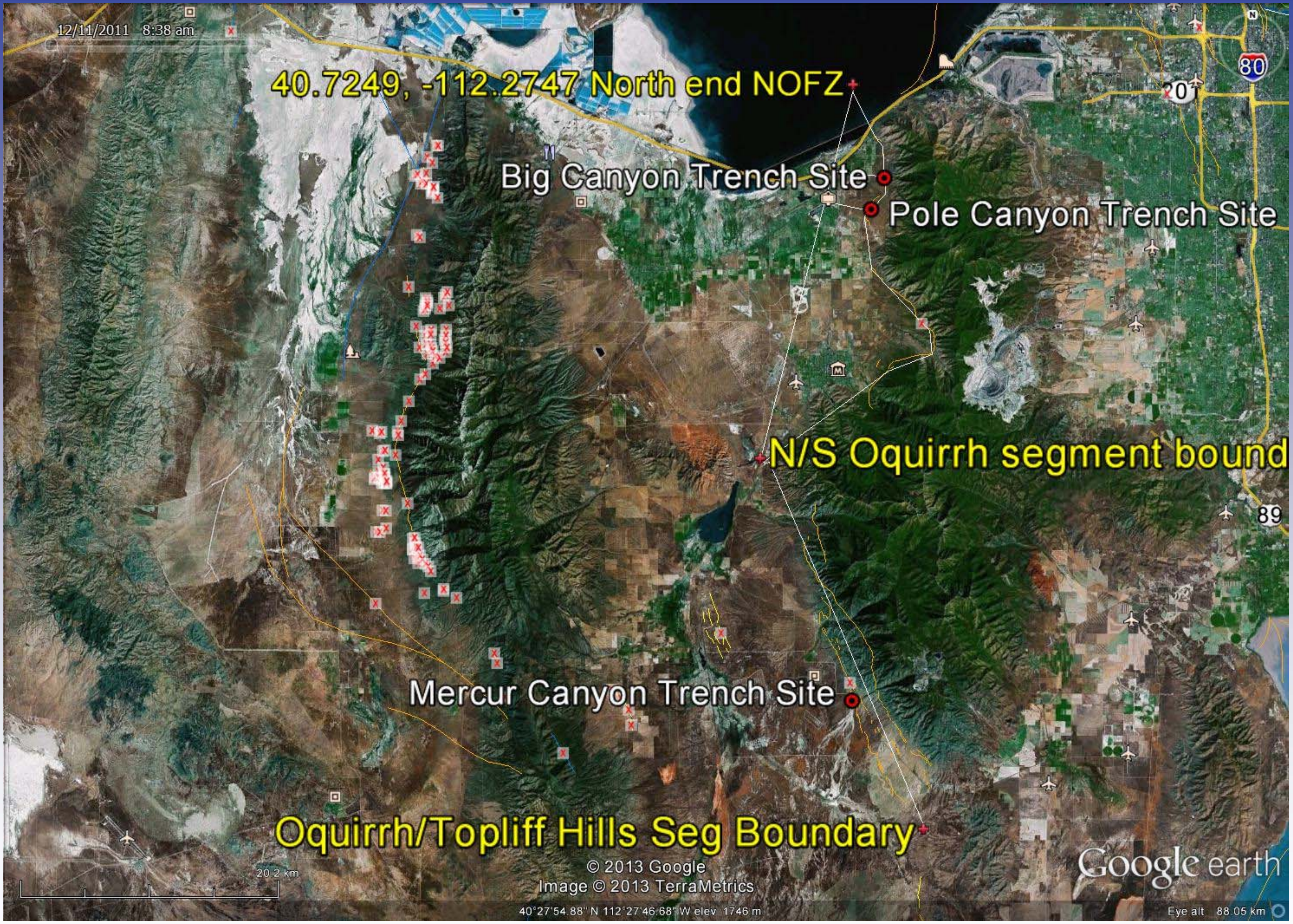
 WGUEP Meeting #10, 12 September 2013

URS

Outline

- Modeling displacements for Northern Oquirrh (NO) and Southern Oquirrh (SO) segments
- OxCal analysis of NO segment
- OxCal analysis of SO segment
- Approaches and weights used for calculating rates for the OGSLFZ

Trench Locations and Data Sources



- **NO segment: Olig et al. (1994; 1996)**
- **SO segment: Olig et al. (2001)**

Inputs – Displacements Per Site and Rupture Event

SO segment

Data for Mercur Canyon Site from Olig et al. (2001)

Event	Pref D*	Min D	Max D	Total Length (km)	Along Strike Distance (km)	Normalized site location
P1	1	0.75	1.25	31.2	19.5	0.625
P2	2	2	2.25			
P3	1.75	1	2			
P4	2.05	1.45	2.9			
P5	2.95	1.6	3.3			

NO segment

Data from Olig et al. (1994; 1996)

Event	Pole Canyon Site					
	Pref D*	Min D	Max D	Total Length (km)	Along Strike Distance (km)	Normalized site location
P1	2.7	2.2	3.3	29.75	8.96	0.301176
P2	2.3	1.9	2.9			
	Big Canyon Site					
P1	2.2	2	2.7	29.75	6.26	0.21042

URS

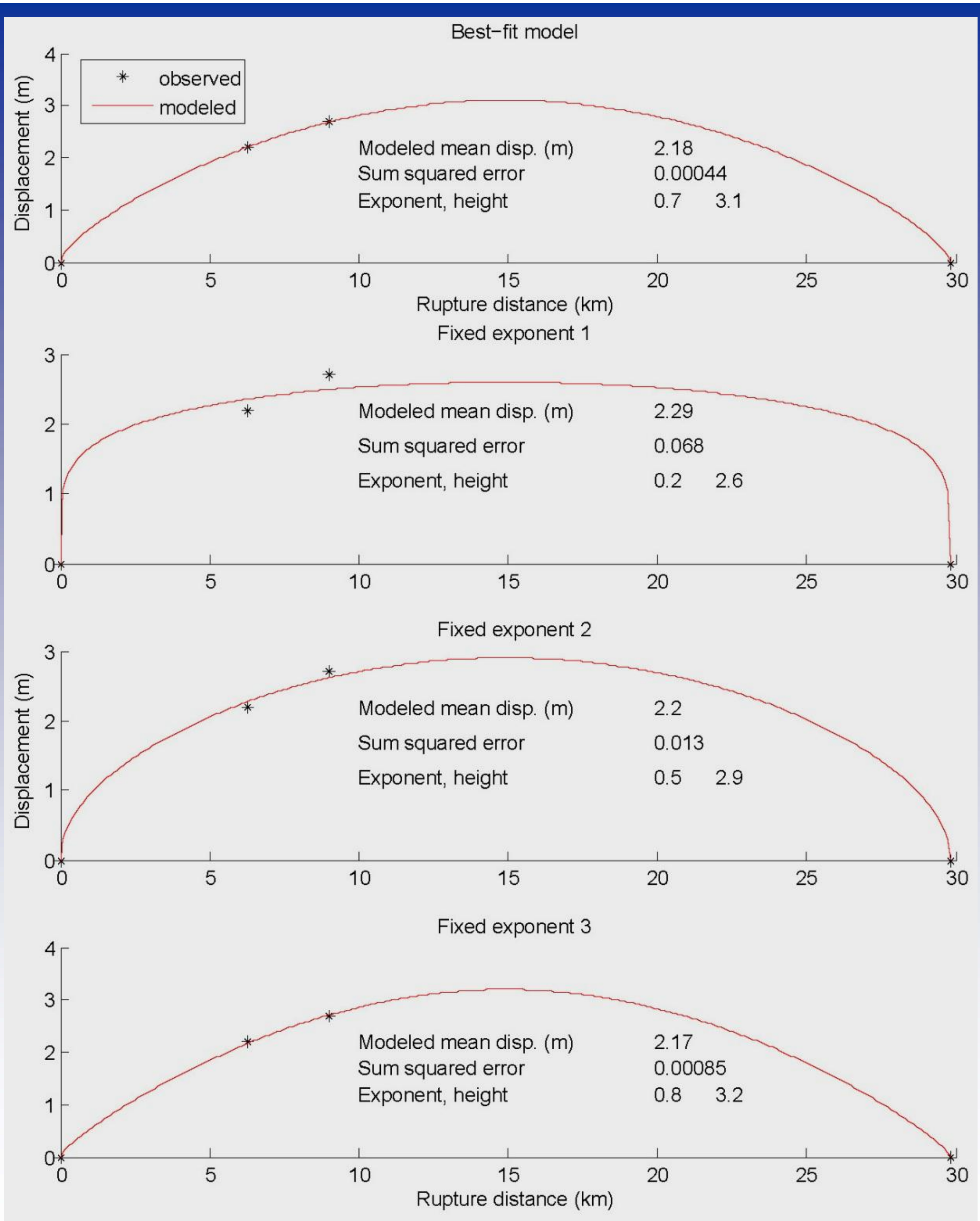
Inputs – Displacements Per Site and Rupture Event

NO+SO segments

Data from Olig et al. (1994; 1996;2001)

Event	Pole Canyon Site					
	Pref D*	Min D	Max D	Total Length (km)	Along Strike Distance (km)	Normalized site location
P1	2.7	2.2	3.3	60.95	8.96	0.147006
P2	2.3	1.9	2.9			
	Big Canyon Site					
P1	2.2	2	2.7	60.95	6.26	0.102707
	Mercur Canyon Site					
P1	1	0.75	1.25	60.95	49.27	0.808368
P2	2	2	2.25			

Example: Modeling Event P1 on NO Segment

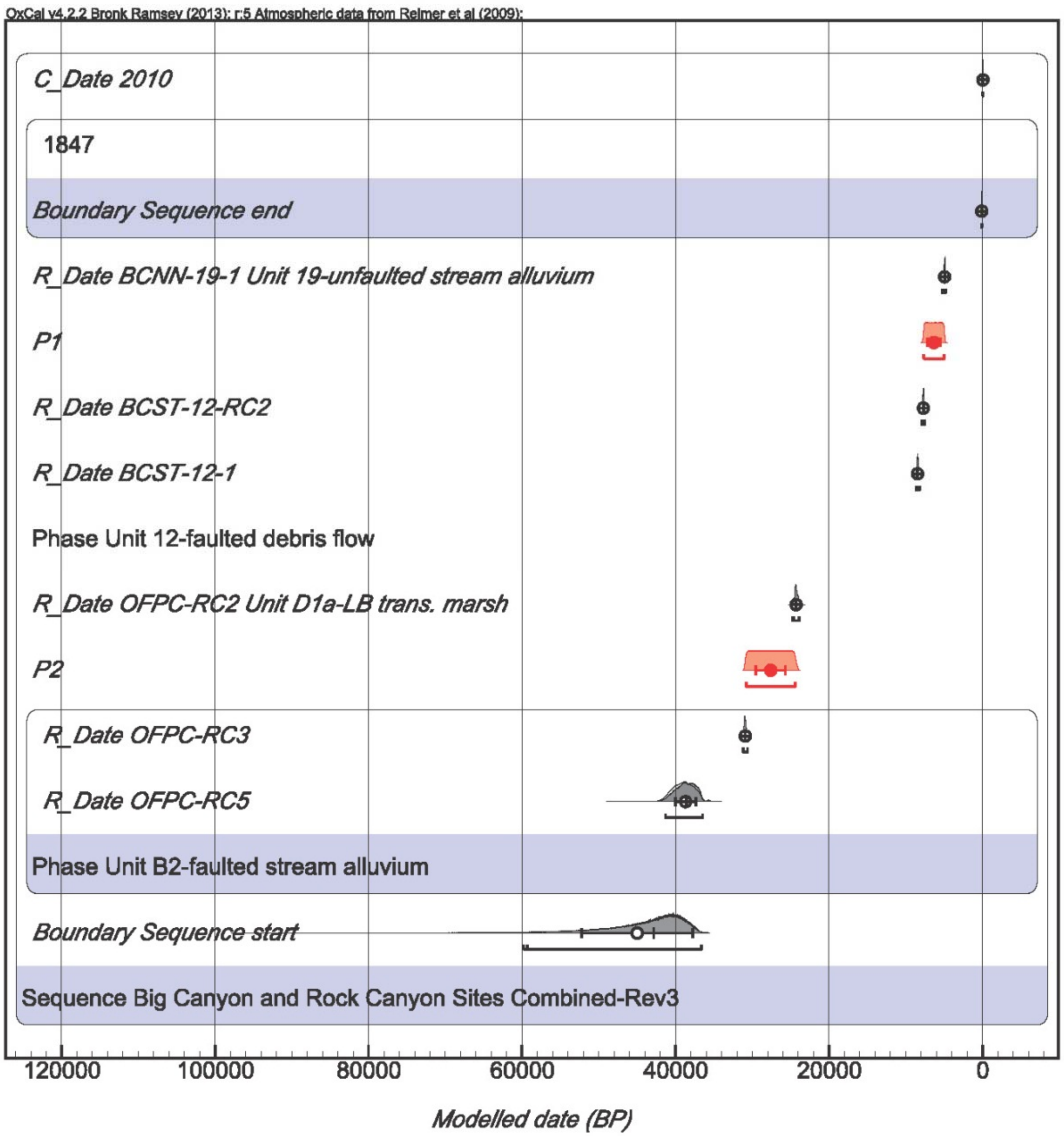


URS

Modeled Displacements for Rupture Sources of OGSLFZ

Rupture Source	Pref D (weighted 0.6)	Min D (weighted 0.2)	Max D (weighted 0.2)	No. of Obs.
SO	1.56	0.62	2.65	5
NO	2.075	1.61	2.67	3
SO+NO	2.055	1.68	2.52	5

OxCal Analysis – NO Segment



- **Based on data from Olig et al. (1994; 1996) (see Figures 15/18)**
- **Used similar approach to central WFZ, but no Matlab analysis required (P1 only dated at Big Canyon and P2 only dated at Pole Canyon)**
- **Total of six radiocarbon ages**
- **Used OxCal v4.2.2 (Bronk Ramsey, 2012) with calibration curve of Reimer et al. (2009)**

Timing Results for NO Segment*

Rupture Event	Mean	2σ	5th	50th	95th
P1	6.3	1.6	5.0	6.3	7.6
P2	27.6	3.8	24.4	27.6	30.8

** In thousands of years before 1950; from OxCal model NOFZbc_pc_comb 3*

- ***Mean closed recurrence interval ~21 ky***
- ***Maximum time (T): 30.9 ± 0.3 ka (from OFPC_RC3)***

URS

Comparison of Approach 1 versus 2 for NO Segment

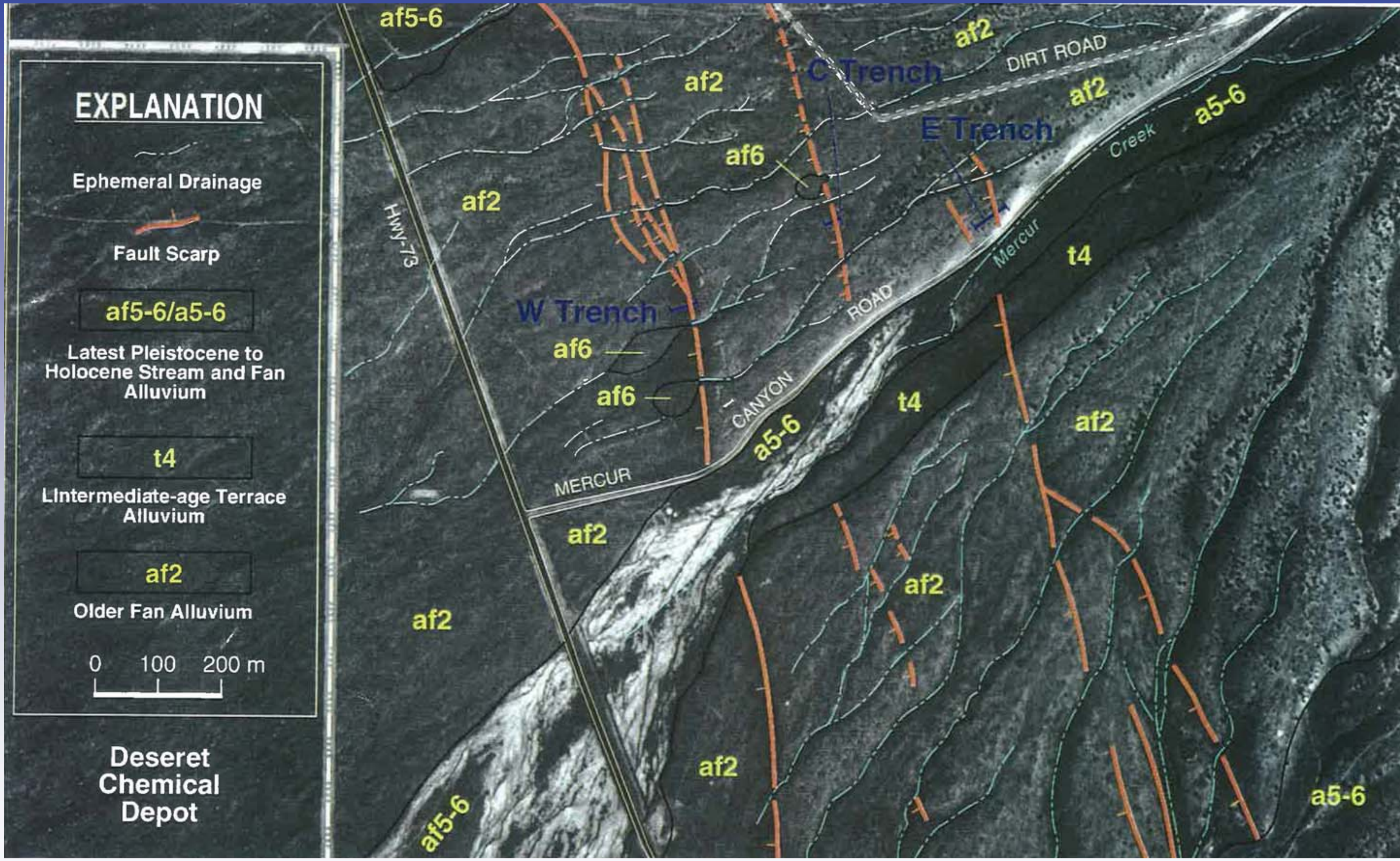
Rate Parameter	Approach 1*	Approach 2*
1/λ mean	10.3	15.5
1/λ 50%	11.6	31.0
1/λ 3.5%	43.8	106.5
1/λ 96.5%	4.6	6.0

** In thousands of years*

- **Approach 2 yields broader, more asymmetric results**

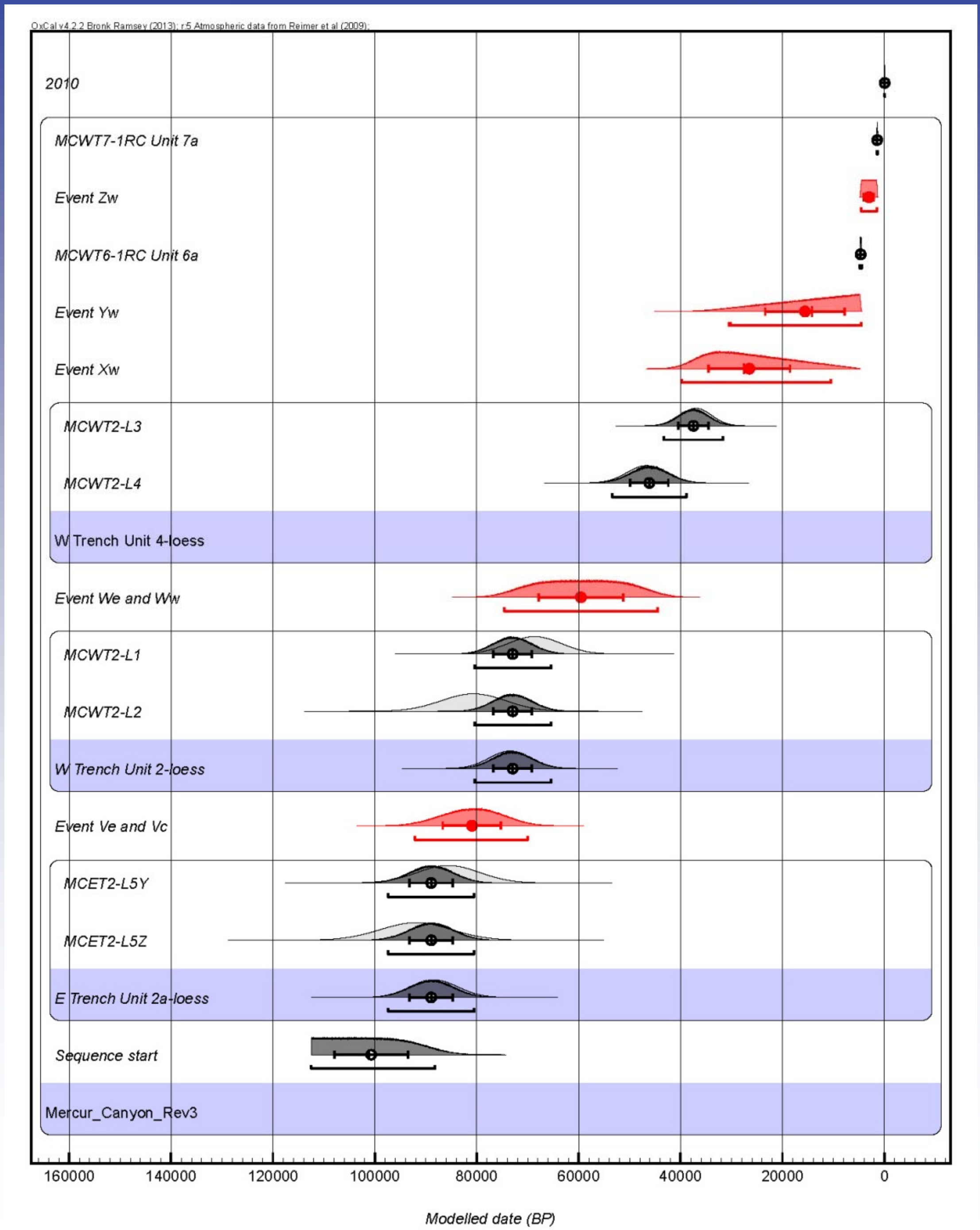
URS

Mercur Canyon Trench Site – 5 to 7 Events



- **W Trench – 4 events**
- **C Trench – At least 1 undated event (older?)**
- **E Trench – 2 events (1 undated; 1 older)**

OxCal Analysis – SO Segment



- Based on data from Olig et al. (2001) and unpublished OSL date
- Used similar approach to central WFZ, but no Matlab analysis required (only one trench site)
- Total of six OSL and two radiocarbon ages
- Used OxCal v4.2.2 (Bronk Ramsey, 2012) with calibration curve of Reimer et al. (2009)
- Assumes only 5 events

Timing Results for SO Segment*

Rupture Event	Mean	2σ	5th	50th	95th
P1	3.0	1.9	1.5	3.0	4.6
P2	15.6	15.6	4.6	14.2	30.5
P3	26.5	16.0	10.5	27.6	39.8
P4	59.6	16.6	44.4	59.5	74.6
P5 (?)	-	-	-	-	-
P6 (?)	-	-	-	-	-
P7	81	11.4	70.0	80.8	92.2

** In thousands of years before 1950; from OxCal model Mercur_Canyon_Rev3.*

- ***Can only use Approach 1***
- ***Mean closed recurrence interval ~13 to 19.5 ky***
- ***Maximum time (T): 88.9 ± 8.5 ka (from MCET2-L5Y and MCET2-L5Z)***

URS

Poisson Rates for OGSLFZ Sources – P1

Source	Approach	Recurrence (in yrs) or *Vertical Slip Rates (in mm/yr)**	Notes
RZ segment	Recurrence Intervals (1.0)	14103 (0.101) 6300 (0.244) 3724 (0.310) 2377 (0.244) 1468 (0.101)	Assumed similar to AI segment
PY segment	Recurrence Intervals (1.0)	14103 (0.101) 6300 (0.244) 3724 (0.310) 2377 (0.244) 1468 (0.101)	Assumed similar to AI segment
FI segment*	Recurrence Intervals (1.0)	16269 (0.101) 7267 (0.244) 4296 (0.310) 2742 (0.244) 1694 (().101)	Based on Approach 2 with N = 3 and T = 11488 yrs
AI segment*	Recurrence Intervals (1.0)	14103 (0.101) 6300 (0.244) 3724 (0.310) 2377 (0.244) 1468 (0.101)	Based on Approach 2 with N = 3 and T = 9959 yrs

URS

Poisson Rates for OGSLFZ Sources – P2

Source	Approach	Recurrence (in yrs) or *Vertical Slip Rates (in mm/yr)**	Notes
NO segment	Recurrence Intervals (0.6)	106538 (0.101) 36153 (0.244) 18453 (0.310) 10613 (0.244) 5983 (0.101)	Based on Approach 2 with N = 2 and T = 30971 yrs
	Slip Rates (0.4)	***0.05 (0.2)*** ***0.2 (0.6)*** ***0.4 (0.2)***	Based on consensus slip rates from the UQFPWG (Lund, 2005)
SO segment	Recurrence Intervals (0.6)	37291 (0.101) 22366 (0.244) 15698 (0.310) 11433 (0.244) 8004 (0.101)	Based on Approach 1 with N = 5 and T = 89011 yrs (distribution weighted 0.5)
		24106 (0101) 15704 (0.244) 11606 (0.310) 8817 (0.244) 6441 (0.101)	Based on Approach 1 with N = 7 and T = 89011 yrs (distribution weighted 0.5)
	Slip Rates (0.4)	***0.05 (0.2)*** ***0.2 (0.6)*** ***0.4 (0.2)***	Based on consensus slip rates from the UQFPWG (Lund, 2005)
TH segment	Slip Rates (1.0)	***0.05 (0.2)*** ***0.2 (0.6)*** ***0.4 (0.2)***	Assumed similar to the NO and SO segments based on descriptions and arguments in Everitt and Kaliser (1980)

URS

Poisson Rates for OGSLFZ Sources – P3

Source	Approach	Recurrence (in yrs) or *Vertical Slip Rates (in mm/yr)*	Notes
ET segment	Slip Rates (1.0)	***0.025 (0.2)*** ***0.1 (0.6)*** ***0.2 (0.2)***	Assumed half the rates of the NO and SO segments based on relatively poor geomorphic expression for this end segment (Black and Hecker, 1999b)
FI+AI segments	Recurrence Intervals (1.0)	14103 (0.101) 6300 (0.244) 3724 (0.310) 2377 (0.244) 1468 (0.101)	Used distribution of AI segment as it is better constrained and distributions are similar
NO+SO segments	Slip Rates (1.0)	***0.05 (0.2)*** ***0.2 (0.6)*** ***0.4 (0.2)***	Used slip rates and not recurrence because slip rate distributions are the same for each segment, whereas the timing of the youngest event on each segment does not overlap at 2 σ, and the timing of earlier events is broad
SO+TH segments	Slip Rates (1.0)	***0.05 (0.2)*** ***0.2 (0.6)*** ***0.4 (0.2)***	Used slip rates of SO segments as it is better constrained
Floating	Slip Rates (1.0)	GSLF segments: ***0.3 (0.2)*** ***0.6 (0.6)*** ***1.6 (0.2)*** Other segments: ***0.05 (0.2)*** ***0.2 (0.6)*** ***0.4 (0.2)***	Based on consensus slip rates from the UQFPWG (Lund, 2005)

URS

Calculation of Recurrence Intervals (a.k.a., Section 3.4)

Working Group on Utah Earthquake Probabilities Meeting

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Summary of Calculations

- **Time-independent (Poisson) mean recurrence *rates* (λ's) for ...**
  - Single-segment (SS) ruptures of central segments of WFZ (BC, W, SLC, P, & N)
  - Multi-segment (MS) ruptures of central segments of WFZ (BC+W, W+SLC, SLC+P+N, SLC+P, & P+N)
  - SS ruptures of Antelope & Fremont Island segments of GSLFZ (AI & FI)
  - Southern & Northern segments of OFZ (SO & NO)
- **Time-dependent (BPT) mean recurrence intervals (μ's) for COV's (α's) of 0.3, 0.5, & 0.7 and …**
  - SS rupture of BC, W, SLC, P, & N
  - SS ruptures of AI & FI

Summary of Calculations (continued)

- Poisson λ's calculated via CEUS SSC Section 5.3.3.1.**2** ("Earthquake Recurrence Intervals"), except for SO

  Exception: Included open time interval before oldest earthquake, in addition to open time interval since most recent earthquake.

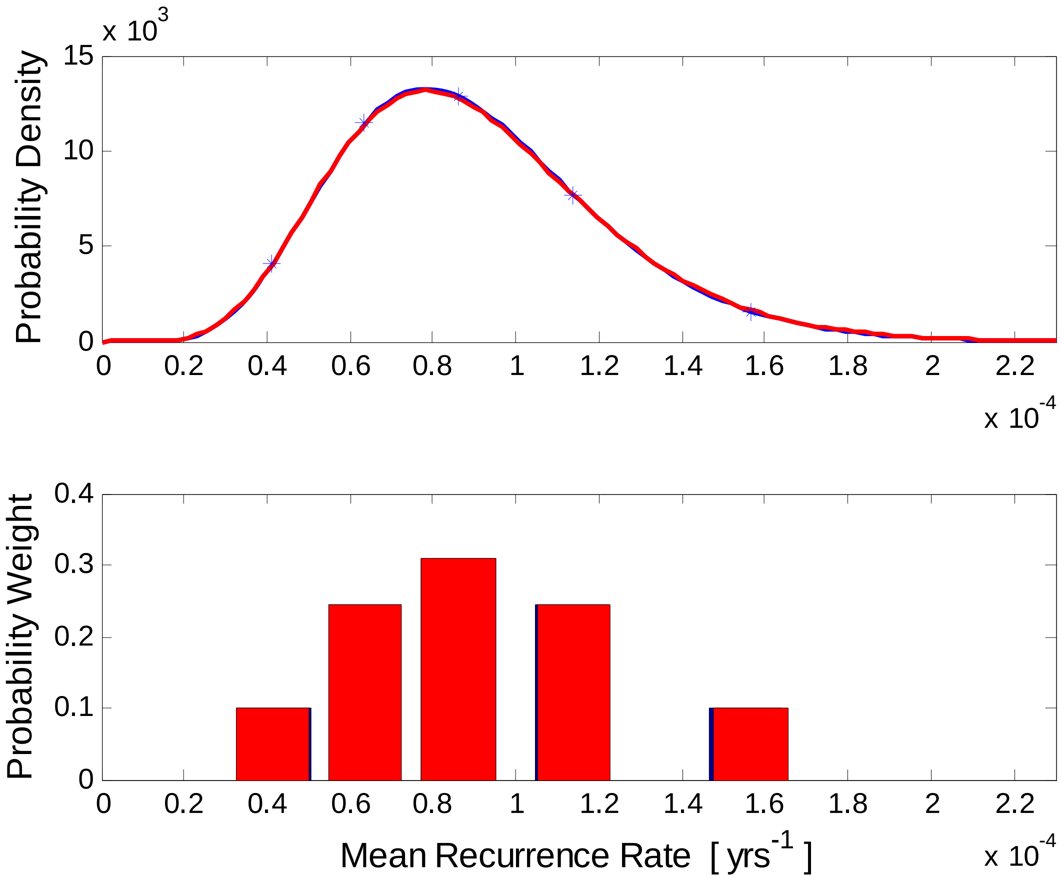
- For SO, Poisson λ's calculated via CEUS SSC Section 5.3.3.1.**1** ("Earthquake Count in a Time Interval)

- BPT μ's calculated via CEUS SSC Section 5.3.3.2 ("Estimation of Occurrence Rates for a Renewal Model")

  Exception: Same as above.

Summary of Calculations (continued)

- Impacts of CEUS SSC Section 5.3.3.3 ("Incorporating Uncertainty in the Input") found to be negligible in comparison to uncertainty arising from relatively small sample sizes of past earthquakes



N = 7 events
T = 89,011 yrs
σ_T = 4,270 yrs

Summary of Calculations (continued)

Microsoft Excel - PoissonRates

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Approach =	CEUS SSC Section 5.3.3.1.1														
2																
3	**Input**															
4	N =	7														
5	T =	89,011	years													
6																
7	**Output**															
8									*With uncertainty in T (calculated using Matlab) ...*							
9	$\lambda_{3.4893\%}$ =	4.15E-05	(weight = 0.101)		1 / $\lambda_{3.4893\%}$ =	24106	years		$\lambda_{3.4893\%}$ =	3.63E-05	(weight = 0.101)		1 / $\lambda_{3.4893\%}$ =	27561	years	
10	$\lambda_{21.1702\%}$ =	6.37E-05	(weight = 0.244)		1 / $\lambda_{21.1702\%}$ =	15704	years		$\lambda_{21.1702\%}$ =	6.24E-05	(weight = 0.244)		1 / $\lambda_{21.1702\%}$ =	16036	years	
11	$\lambda_{50\%}$ =	8.62E-05	(weight = 0.310)		1 / $\lambda_{50\%}$ =	11606	years		$\lambda_{50\%}$ =	8.68E-05	(weight = 0.310)		1 / $\lambda_{50\%}$ =	11526	years	
12	$\lambda_{78.8298\%}$ =	1.13E-04	(weight = 0.244)		1 / $\lambda_{78.8298\%}$ =	8817	years		$\lambda_{78.8298\%}$ =	1.17E-04	(weight = 0.244)		1 / $\lambda_{78.8298\%}$ =	8522	years	
13	$\lambda_{96.5107\%}$ =	1.55E-04	(weight = 0.101)		1 / $\lambda_{96.5107\%}$ =	6441	years		$\lambda_{96.5107\%}$ =	1.60E-04	(weight = 0.101)		1 / $\lambda_{96.5107\%}$ =	6268	years	
14	λ_{Mean} =	8.99E-05	= (N+1) / T		1 / λ_{Mean} =	11126	years		λ_{Mean} =	9.01E-05			1 / λ_{Mean} =	11100	years	
15	λ_{Mode} =	7.86E-05	= N / T		1 / λ_{Mode} =	12716	years		λ_{Mode} =	--			1 / λ_{Mode} =	#VALUE!	years	
16																
17																
18	**Input**															
19	N =	6														
20	T =	89,011	years													
21																
22	**Output**															
23									*With uncertainty in T (calculated using Matlab) ...*							
24	$\lambda_{3.4893\%}$ =	3.40E-05	(weight = 0.101)		1 / $\lambda_{3.4893\%}$ =	29405	years		$\lambda_{3.4893\%}$ =	2.98E-05	(weight = 0.101)		1 / $\lambda_{3.4893\%}$ =	33609	years	
25	$\lambda_{21.1702\%}$ =	5.41E-05	(weight = 0.244)		1 / $\lambda_{21.1702\%}$ =	18475	years		$\lambda_{21.1702\%}$ =	5.39E-05	(weight = 0.244)		1 / $\lambda_{21.1702\%}$ =	18560	years	
26	$\lambda_{50\%}$ =	7.49E-05	(weight = 0.310)		1 / $\lambda_{50\%}$ =	13346	years		$\lambda_{50\%}$ =	7.50E-05	(weight = 0.310)		1 / $\lambda_{50\%}$ =	13327	years	
27	$\lambda_{78.8298\%}$ =	1.01E-04	(weight = 0.244)		1 / $\lambda_{78.8298\%}$ =	9949	years		$\lambda_{78.8298\%}$ =	1.02E-04	(weight = 0.244)		1 / $\lambda_{78.8298\%}$ =	9819	years	
28	$\lambda_{96.5107\%}$ =	1.40E-04	(weight = 0.101)		1 / $\lambda_{96.5107\%}$ =	7130	years		$\lambda_{96.5107\%}$ =	1.45E-04	(weight = 0.101)		1 / $\lambda_{96.5107\%}$ =	6892	years	
29	λ_{Mean} =	7.86E-05	= (N+1) / T		1 / λ_{Mean} =	12716	years		λ_{Mean} =	7.88E-05			1 / λ_{Mean} =	12686	years	
30	λ_{Mode} =	6.74E-05	= N / T		1 / λ_{Mode} =	14835	years		λ_{Mode} =	--			1 / λ_{Mode} =	#VALUE!	years	
31																

GSLFZ AI / GSLFZ FI / OFZ NO / OFZ SO

Summary of Calculations (continued)

- Impacts of CEUS SSC Section 5.3.3.3 (“Incorporating Uncertainty in the Input”) found to be negligible in comparison to uncertainty arising from relatively small sample sizes of past earthquakes

Exception: For FI, uncertainty in timing of oldest earthquake (11,427 to 7,412 B.P.) is incorporated in calculation of BPT μ.

Earthquake Pairs	**Timing** (**terrestrially calibrated[2], residence corrected[3], calendar year B.P.[4]**)[5]	**Recurrence Interval (yr)**[5]
Antelope Island segment		
EH-A3 EH-A2	586 +201/-241 6170 +236/-234	5584 +219/-172
EH-A2 EH-A1	6170 +236/-234 9898 +247/-302	3728 +223/-285
Fremont Island segment		
EH-F3 EH-F2	3150+235/-211 6412 +209/-211	3262 +151/-184
EH-F2 EH-F1	6412 +209/-211 <11,427 +605/-449	<5015 +587/-424
Average single-segment recurrence interval = 4200 ± 1400 years[6]		

Summary of Calculations (continued)

Microsoft Excel - BPT_Intervals

Approach =	CEUS SSC Section 5.3.3.2				
Input					
t_0 =	3211	years			
t_1 =	3262	years			
$t_{2,min}$ =	1000	years			
$t_{2,max}$ =	5015	years			
t_f =	5015 - t_2	years			
Output *(calculated using Matlab)*					
	$\alpha = 0.3$	$\alpha = 0.5$	$\alpha = 0.7$		Weights
$\mu_{3.4893\%}$ =	2742	2659	2784	(years)	0.101
$\mu_{21.1702\%}$ =	3401	3696	4274	(years)	0.244
$\mu_{50\%}$ =	4028	4793	5984	(years)	0.310
$\mu_{78.8298\%}$ =	4764	6197	8318	(years)	0.244
$\mu_{96.5107\%}$ =	5882	8521	12395	(years)	0.101
μ_{Mean} =	4112	5029	6461	(years)	*= Weighted Mean*

Input					
t_0 =	3211	years			
t_1 =	3262	years			
t_2 =	5015	years			
t_f =	0	years			
Output *(calculated using Matlab)*					
	$\alpha = 0.3$	$\alpha = 0.5$	$\alpha = 0.7$		Weights
$\mu_{3.4893\%}$ =	3275	3186	3188		0.101
$\mu_{21.1702\%}$ =	3957	4330	4757		0.244
$\mu_{50\%}$ =	4609	5517	6382		0.310
$\mu_{78.8298\%}$ =	5379	6975	8130		0.244
$\mu_{96.5107\%}$ =	6550	8934	9618		0.101
μ_{Mean} =	4699	5693	6416	*(= Weighted Mean)*	

GSLFZ AI | GSLFZ FI

Summary of Calculations (continued)

Microsoft Excel - PoissonRates

	A	B	C	D	E	F	G
1	Approach =	CEUS SSC Section 5.3.3.1.2					
2							
3	**Input**						
4	N =	3					
5	T =	11488	years				
6							
7	**Output**						
8							
9	$\lambda_{3.4893\%}$ =	6.15E-05	(weight = 0.101)		$1 / \lambda_{3.4893\%}$ =	16269	years
10	$\lambda_{21.1702\%}$ =	1.38E-04	(weight = 0.244)		$1 / \lambda_{21.1702\%}$ =	7267	years
11	$\lambda_{50\%}$ =	2.33E-04	(weight = 0.310)		$1 / \lambda_{50\%}$ =	4296	years
12	$\lambda_{78.8298\%}$ =	3.65E-04	(weight = 0.244)		$1 / \lambda_{78.8298\%}$ =	2742	years
13	$\lambda_{96.5107\%}$ =	5.90E-04	(weight = 0.101)		$1 / \lambda_{96.5107\%}$ =	1694	years
14	λ_{Mean} =	2.61E-04	= N / T		$1 / \lambda_{Mean}$ =	3829	years
15	λ_{Mode} =	1.74E-04	= (N-1) / T		$1 / \lambda_{Mode}$ =	5744	years
16							
17							
18							

GSLFZ AI | GSLFZ FI