BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP II

UTAH GEOLOGICAL SURVEY

U.S. GEOLOGICAL SURVEY

WESTERN STATES SEISMIC POLICY COUNCIL

BRPEWGII GOALS

- **Bring together subject-matter experts to discuss evidence, evaluate issues, and define strategies for resolving eight key geologic (4) and seismologic (4) questions important to the next update of the National Seismic Hazard Maps.**
- **Where possible, establish a consensus recommendation(s) to the U.S. Geological Survey on each question for the next NSHM update.**
- **Where consensus is not possible, outline research programs to resolve outstanding technical issues that the USGS can use when setting research priorities.**

BRPEWGII MEMBERS

1. John Anderson* – University of Nevada Reno Seismological Laboratory
2. Walter Arabasz – University of Utah Seismograph Stations
3. Glenn Biasi – University of Nevada Reno Seismological Laboratory
4. Rich Briggs – USGS Denver
5. Jim Brune* – University of Nevada Reno Seismological Laboratory
6. Tony Crone* – USGS Denver
7. Craig dePolo – Nevada Bureau of Mines & Geology
8. Chris DuRoss* – Utah Geological Survey
9. Ryan Gold – USGS Denver
10. Kathy Haller* – USGS Denver
11. Suzanne Hecker – USGS Menlo Park
12. Mike Hylland* – Utah Geological Survey
13. David Love – New Mexico Bureau of Geology & Mineral Resources
14. William Lund** – Utah Geological Survey
15. Morgan Moschetti – USGS Denver
16. Chuck Mueller* – USGS Denver
17. Susan Olig* – URS Corp.
18. Phil Pearthree – Arizona Geological Survey
19. Jim Pechmann* – University of Utah Seismograph Stations
20. Steve Personius – USGS Denver
21. Mark Petersen* – USGS Denver
22. Bill Phillips – Idaho Geological Survey
23. Dave Schwartz* – USGS Menlo Park
24. Mike Stickney – Montana Bureau of Mines & Geology
25. Steve Wesnousky* – University of Nevada Reno
26. Chris Wills – California Geological Survey
27. Seth Wittke – Wyoming Geological Survey
28. Ivan Wong* – URS Corp.

**Issue discussion leader*
***Working Group Coordinator*

UTAH DNR GEOLOGICAL SURVEY

AGENDA
BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP II (BRPEWGII) MEETING
November 14-16, 2011
Utah Department of Natural Resources Building (1st Floor Meeting Rooms)
1594 West North Temple, Salt Lake City, Utah

Monday, November 14

12:00 – 1:00 Lunch [Room 1060, adjacent to meeting room]

1:00 – 3:30 **Issue S1:** How should the magnitude-frequency relations for a single Basin and Range Province (BRP) fault be characterized? Does existing seismological data help define this relationship? (**Discussion Leaders – David Schwartz and Jim Pechmann)** [Room 1050]

3:30 – 3:45 Break [Room 1060, adjacent to meeting room]

3:45 – 6:15 **Issue G1:** How should we calculate Mmax for BRP faults based on rupture lengths, fault areas, and available displacement data (Mmax of 7.5 currently is used in the NSHMs and is based on the magnitude of the 1959 Hebgen Lake earthquake)? What is the source or explanation of the discrepancy between M calculated using surface-rupture length versus using the average or maximum displacement (site bias, underestimation of surface rupture length, other?)? How should the discrepancy in the magnitude determined from these two measurements be handled in the NSHMs? (Discussion Leaders – **Susan Olig and Chris DuRoss**) [Room 1050]

Tuesday, November 15

7:00 – 7:30	Continental breakfast [Room 1010]
7:30 – 10:00	**Issue S2:** How should the "smoothing" of seismicity be handled in the NSHMs? The current NSHMs use a radial smoothing process, but recent precarious rock studies in California and western Nevada suggest that anisotropic smoothing (i.e. along faults) might be more appropriate? If anisotropic smoothing is used, should it be applied universally across the entire BRP? (**Discussion Leaders – Mark Petersen and Jim Brune**) [Room 1060]
10:00 – 10:15	Break [Room 1010]
10:15 – 12:30	**Issue G2:** How should antithetic fault pairs be modeled in the NSHMs? For example, what is the relation and seismogenic significance of fault pairs such as the East and West Cache faults, and strands of the Salt Lake City segment of the Wasatch fault and the West Valley fault zone? (**Discussion Leaders – Kathy Haller and Mike Hylland**
12:30 – 1:00	Lunch [Room 1010]
1:00 – 3:30	**Issue S3:** Does the rate of earthquakes represented on the NSHMs need to match the rate of historical earthquakes? If not, what level of mismatch is acceptable? (**Discussion Leaders – Chuck Mueller and Ivan Wong**) [Room 1060]
3:30 – 3:45	Break [Room 1010]
3:45 – 6:15	**Issue G3:** The USGS seeks guidance on how to estimate the uncertainty for the slip rates on BRP normal-slip faults, especially for faults that have little or no slip-rate data. The method used in California to estimate the uncertainty has varied the upper and lower bounds of the slip rate by plus-or-minus 50%. Thus the uncertainty bounds for a fault that has a slip rate of 5 mm/yr would be 7.5 mm/yr and 2.5 mm/yr. Do these bounding values encompass the fifth and ninety-fifth percentiles for this fault? (**Discussion Leaders – Kathy Haller and Steve Wesnousky**) [Room 1060]

Wednesday, November 16

7:30 – 8:00	Continental breakfast [Room 1060, adjacent to meeting room]
8:00 – 10:00	**Issue S4:** What are the sources and levels of uncertainty in the earthquake magnitudes contained in the seismicity catalogs used in the NSHMs? (**Discussion Leaders – Chuck Mueller and John Anderson**) [Room 1050]
10:00 – 10:15	Break [Room 1060]
10:15 – 12:30	**Discussion**
12:30 – 1:00	Lunch [Room 1060]
1:00 – 3:00	**Wrap-up Discussion:** Revisit issues as necessary, finalize consensus recommendations. [Room 1050]

Issue S1: Introduction and Specific Questions

Original Questions

- How should magnitude-frequency relations for a single Basin and Range Province (BRP) fault be characterized?
- Does existing seismological data help define this relationship?

Discussion Leaders
Dave Schwartz (USGS) and Jim Pechmann (UU)

Agenda

1:00 - 1:15	Session S1: Introduction and Specific Questions (Jim Pechmann, UU, and Dave Schwartz, USGS)
1:15 - 1:30	Models Used in the 2008 National Seismic Hazard Maps for Frequency-Magnitude Relations on Faults (Mark Petersen, USGS)
1:30 - 1:45	Evaluating Frequency-Magnitude Models for Individual Faults Using a Global Data Set of Slip at a Point (Suzanne Hecker, USGS)
1:45 - 2:00	Frequency-Magnitude Relations on Individual Faults as Inferred from Earthquake Catalogs and Paleoseismic Data (Steve Wesnousky, UNR)

Agenda (continued)

2:00 - 2:15 Observed Seismicity and Recurrence Modeling on the Wasatch Faults (Walter Arabasz, UU)

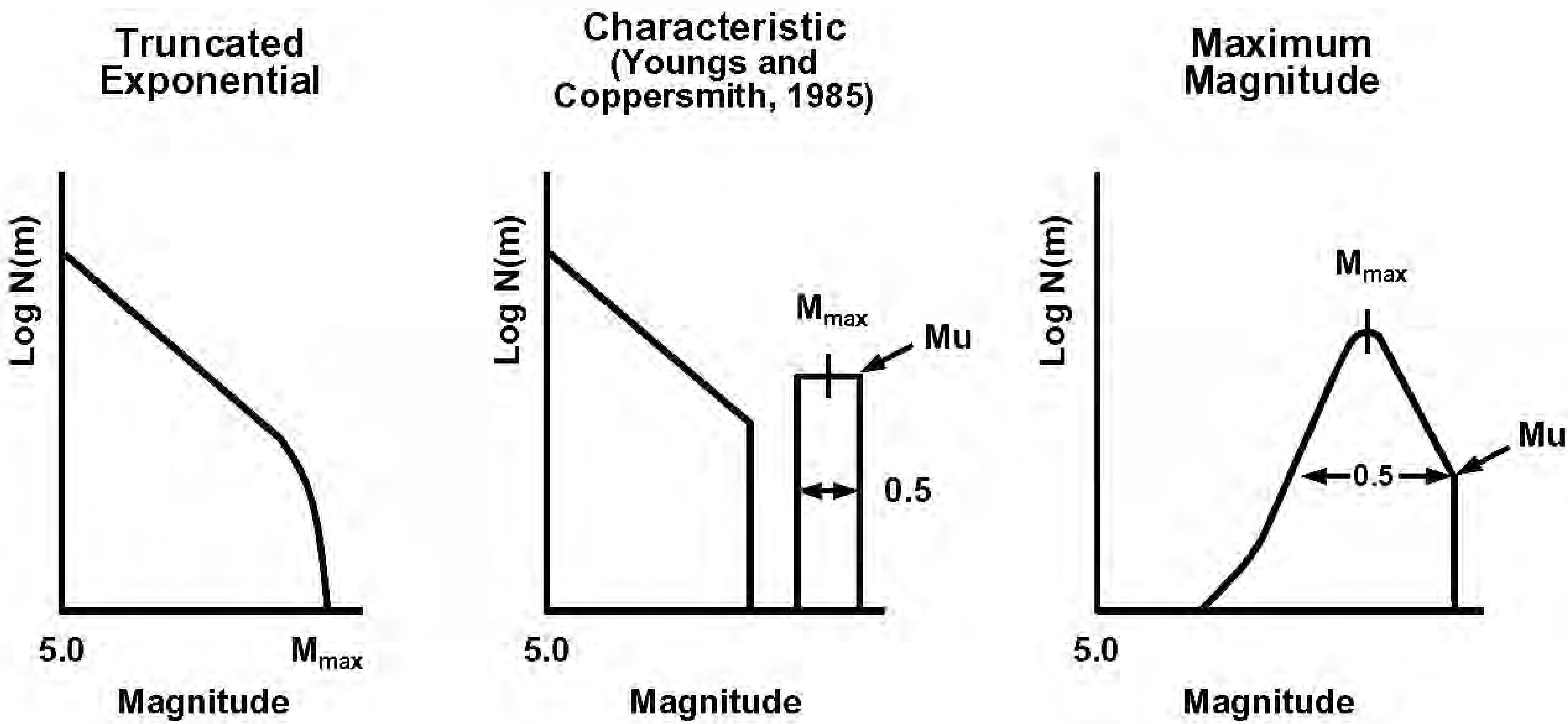
2:15 - 2:30 Fault-Specific Magnitude Frequency Distributions (Glenn Biasi, UNR)

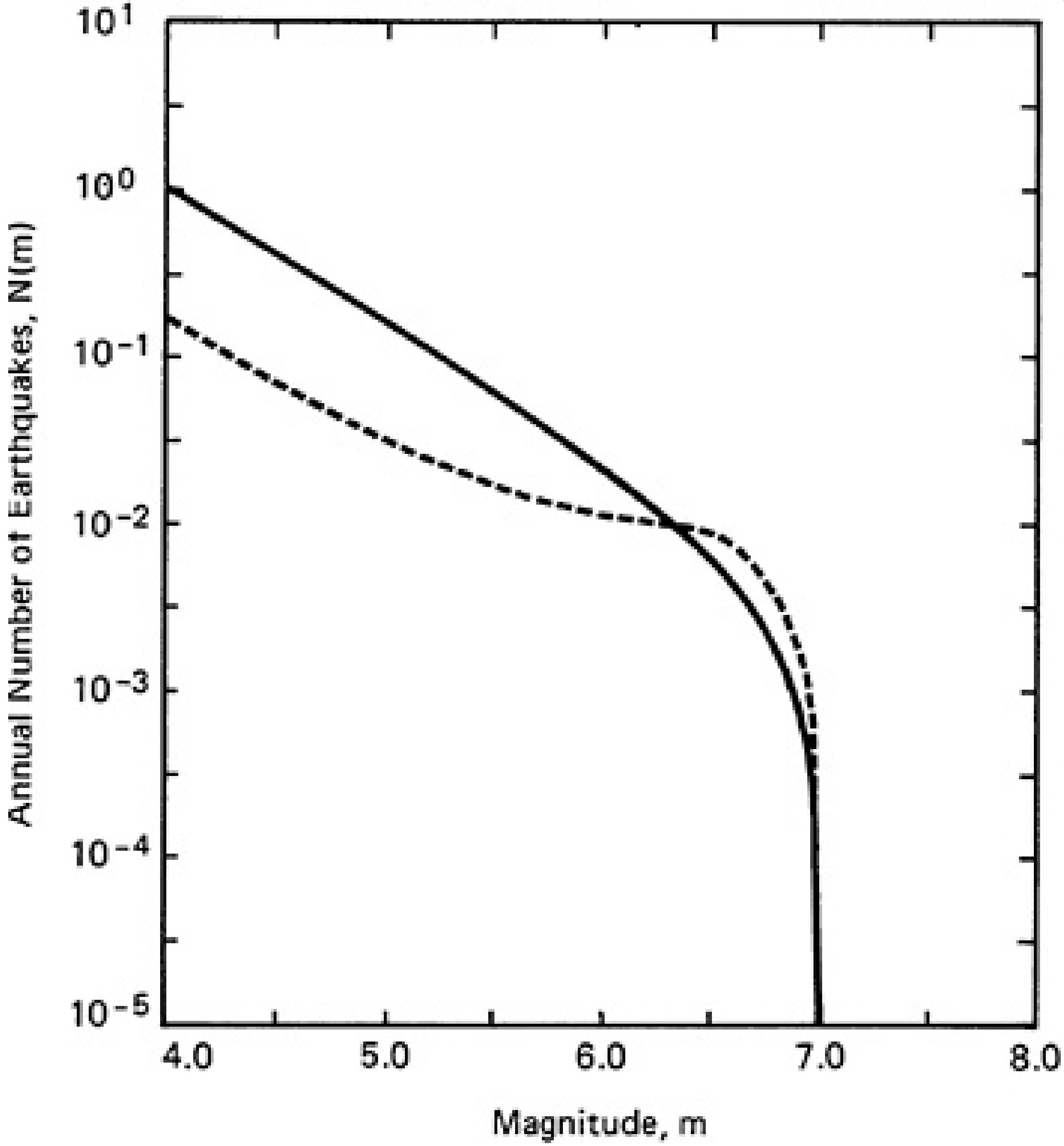
2:30 - 3:00 General Discussion

3:00 - 3:30 Discussion of Recommendations

3:30 - 3:45 Break

RECURRENCE MODELS





EXPLANATION

________ **Exponential magnitude distribution**

------------- **Characteristic earthquake model**

(Discrete)

From Youngs and Coppersmith (1985)

Typical Weightings for Frequency-Magnitude Models in PSHAs (Including Yucca Mountain) -—information from Ivan Wong

60% Youngs and Coppersmith Characteristic

30% Maximum Magnitude

10% Standard Gutenberg-Richter

0% USGS Gutenberg-Richter

2008 National Seismic Hazard Map Weightings for Frequency-Magnitude Models

Most BRP Faults

67% Maximum Magnitude

33% USGS Gutenberg-Richter

Wasatch Fault (Exception)

72% Maximum Magnitude

18% USGS Gutenberg-Richter

10% Floating M 7.4

No weight to the Standard Gutenberg-Richter or Youngs and Coppersmith characteristic models

Recommendations from the 2006 BRPEWGI Meeting (All Short-Term for the 2007 NSHMs)

1. The USGS "floating exponential" model should be validated to the extent possible, or at least made consistent with the paleoseismic and historical earthquake record in the BRP. The USGS model should also be compared with traditional magnitude-frequency models currently used in state-of-the-practice PSHAs. **(Not Done)**

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

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

Recommendations from the 2006 BRPEWGI Meeting (All Short-Term for the 2007 NSHMs; continued)

4. To avoid double-counting earthquakes in the range of M 6.5 to the characteristic earthquake magnitude, zones surrounding BRP faults should be removed from the areas included in the Gaussian smoothing of background seismicity. **(Done)**
5. The methodology used for constructing the NSHMs must be fully transparent. The USGS is urged to publish, if only as a short note, how recurrence modeling is performed for the NSHMs, especially for fault-specific sources. **(Partially done in 2008 NSHM documentation)**

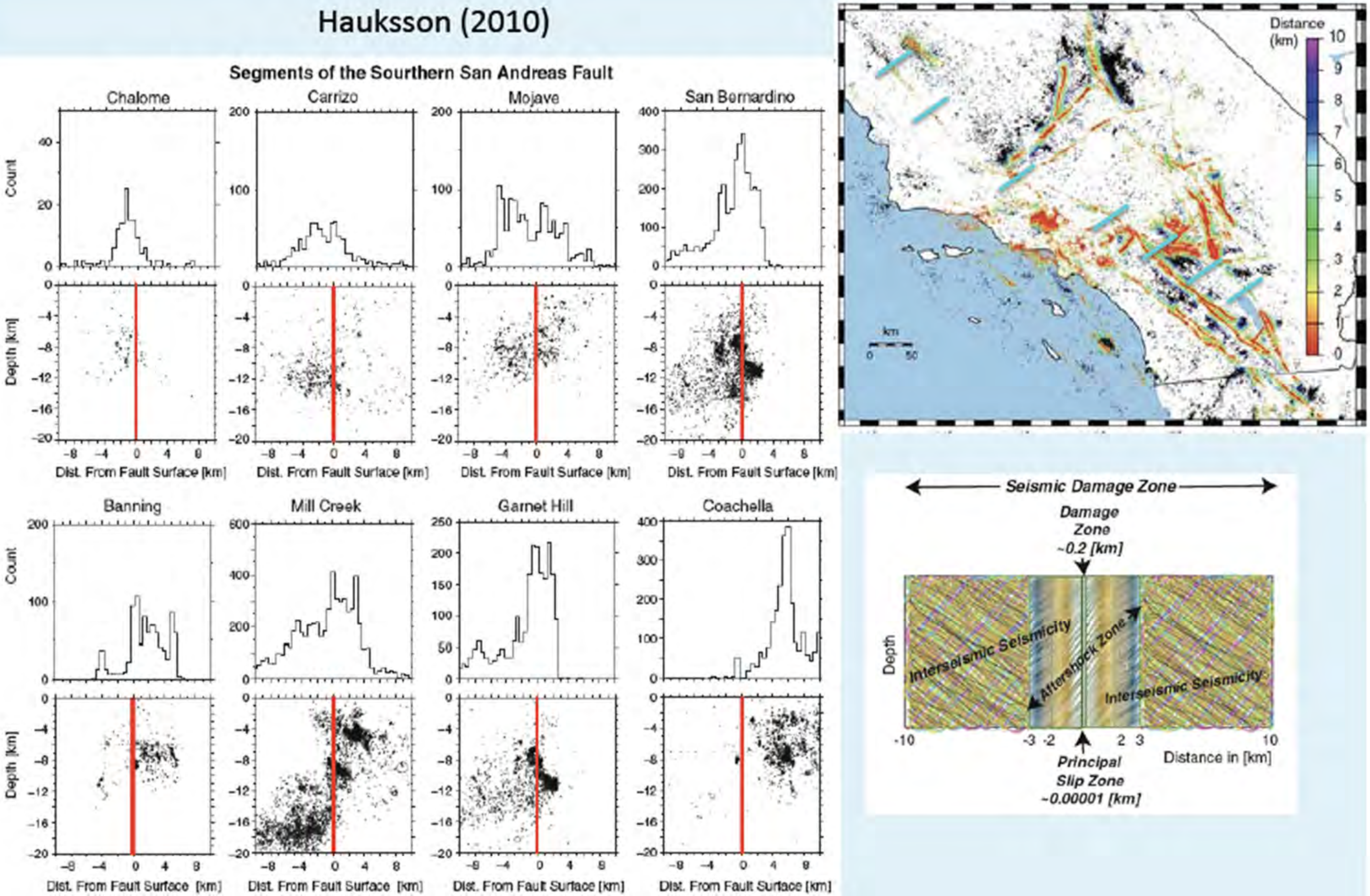
Frequency-Magnitude Distributions for BRP Faults: Specific Questions

1. Do moderate-size *independent* earthquakes below the threshold of surface faulting (M 5.0 to 6.5) occur at a higher rate on or near major Quaternary faults than elsewhere?

2. If so, should this increased rate be accounted for in the NSHMs by
(a) Extending the Gutenberg-Richter model down to M 5 (the minimum M for the PSHA calculations) and/or
(b) Giving some weight to the Youngs and Coppersmith (1985) characteristic model?

3. For larger earthquakes (M ≥ 6.5), is the 67% / 33% weight for the maximum magnitude versus G-R models (with the Wasatch fault exception) appropriate?

Hauksson (2010)



“The majority of small earthquakes do not occur on the same principal slip surfaces of late Quaternary faults in southern California as the major earthquakes.”

Observed Seismicity and Recurrence Modeling on the Wasatch Fault (Revisited)

Walter Arabasz

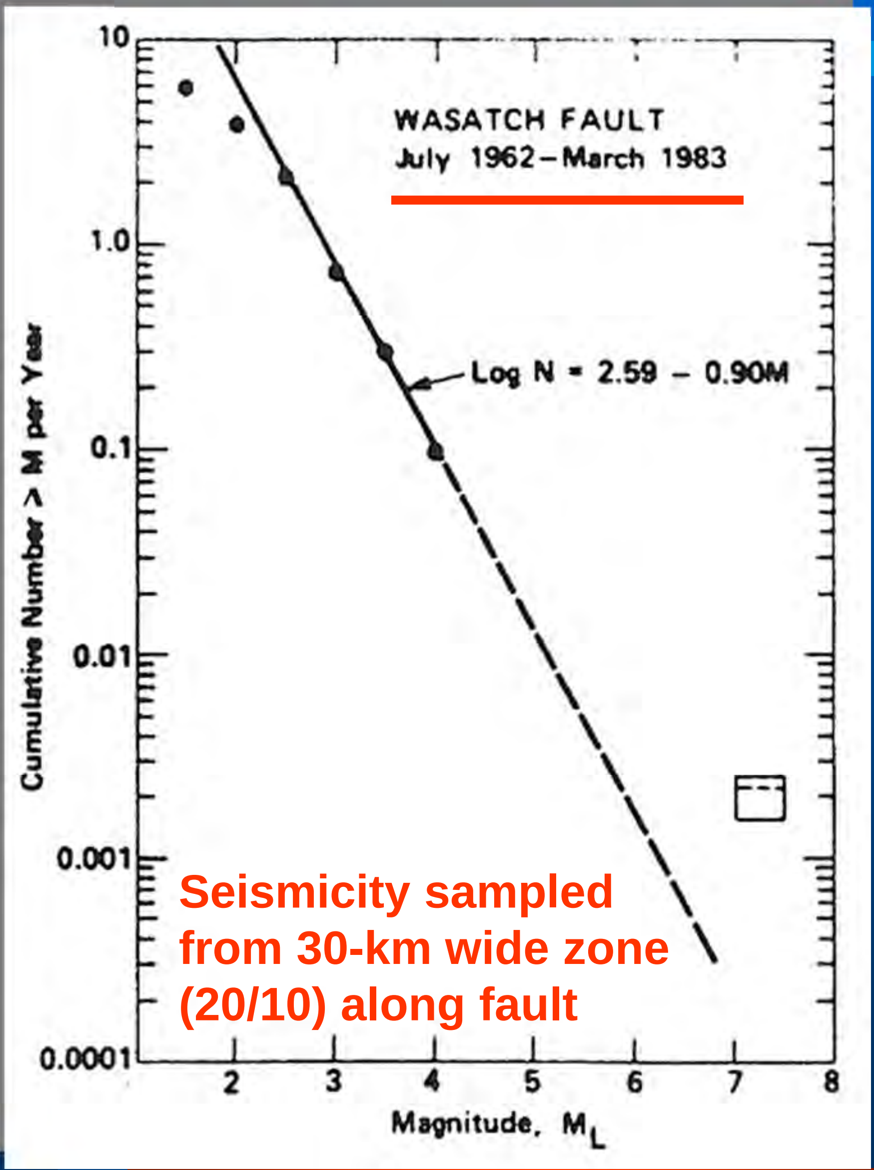
UNIVERSITY OF UTAH SEISMOGRAPH STATIONS
THE UNIVERSITY OF UTAH

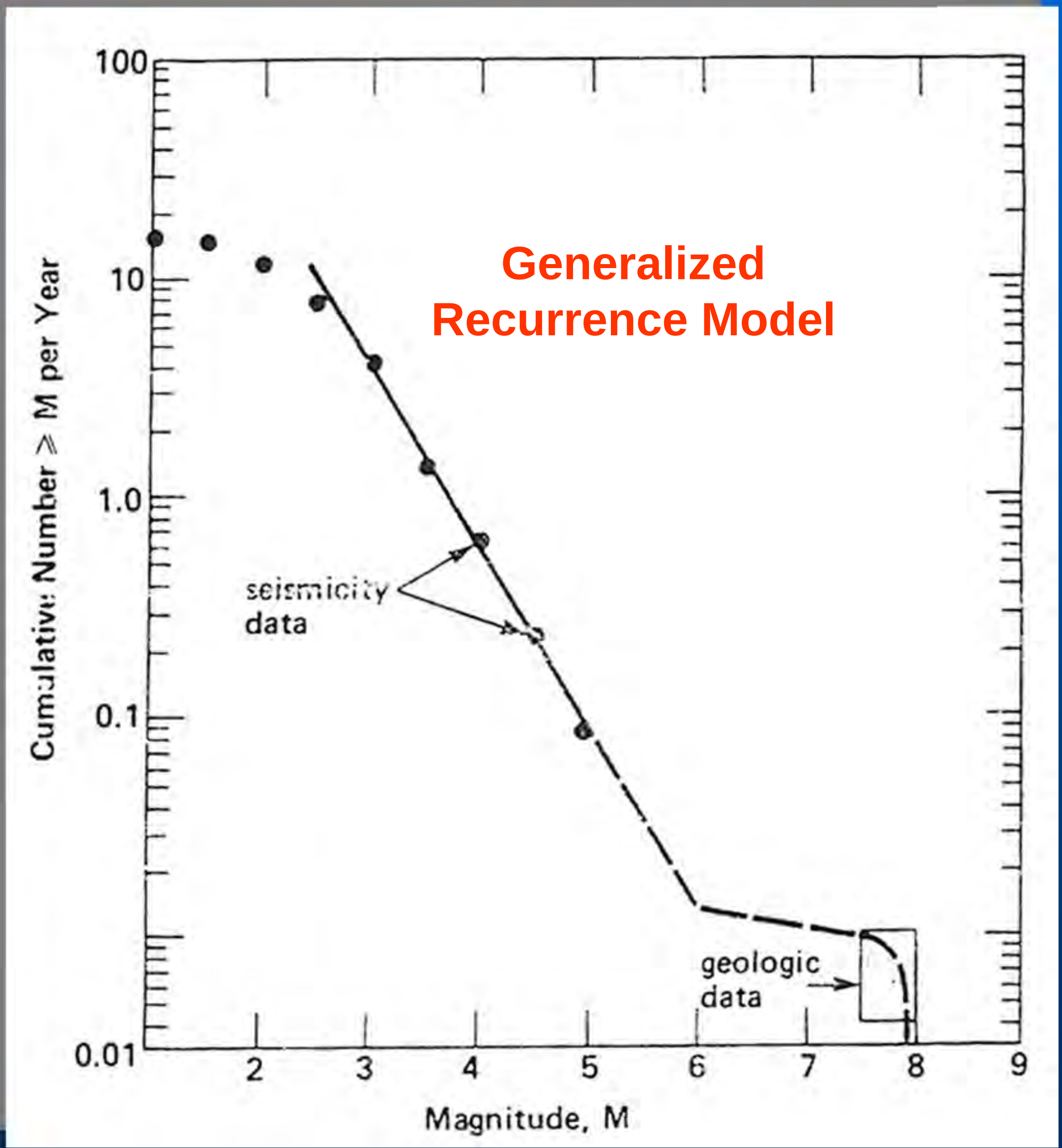
BRPEWG II
November 14, 2011

Towards Weighting Recurrence Models for the Wasatch Fault

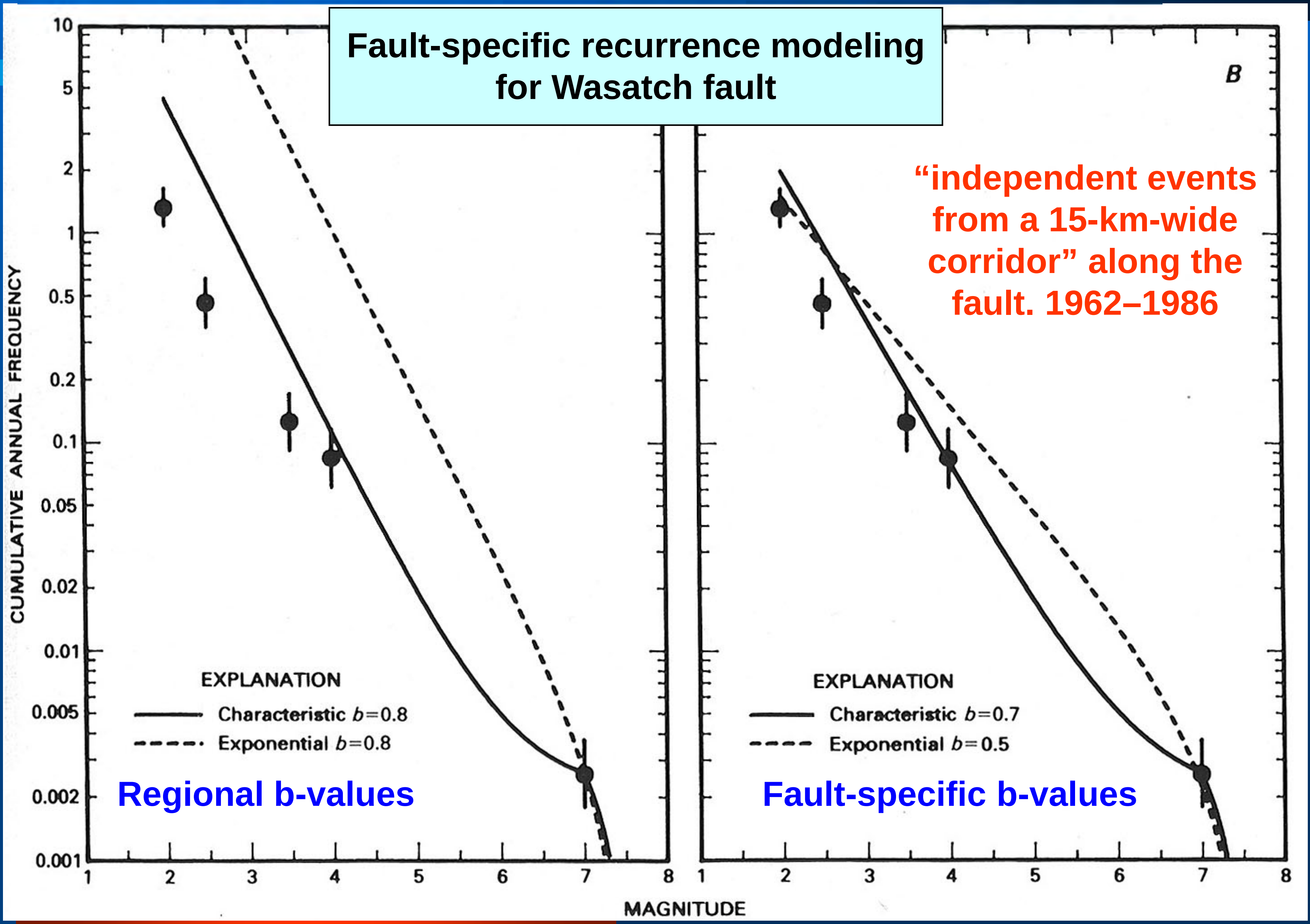
- What can we say from observational seismology?
- Keeping an eye on what we know and don't know
- Distinction between (1) discerning the true seismogenic behavior of the Wasatch fault and (2) appropriate modeling of observed/future seismicity

Schwartz & Coppersmith (1984)

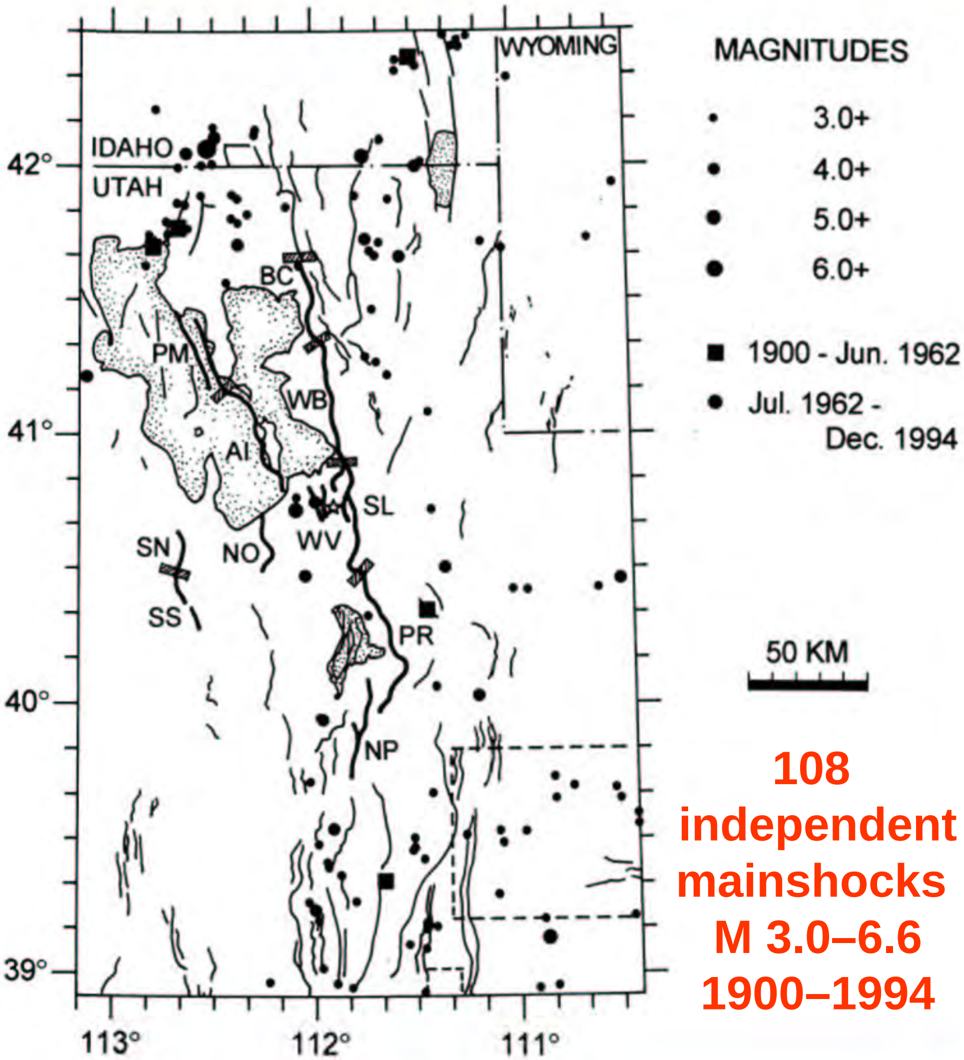




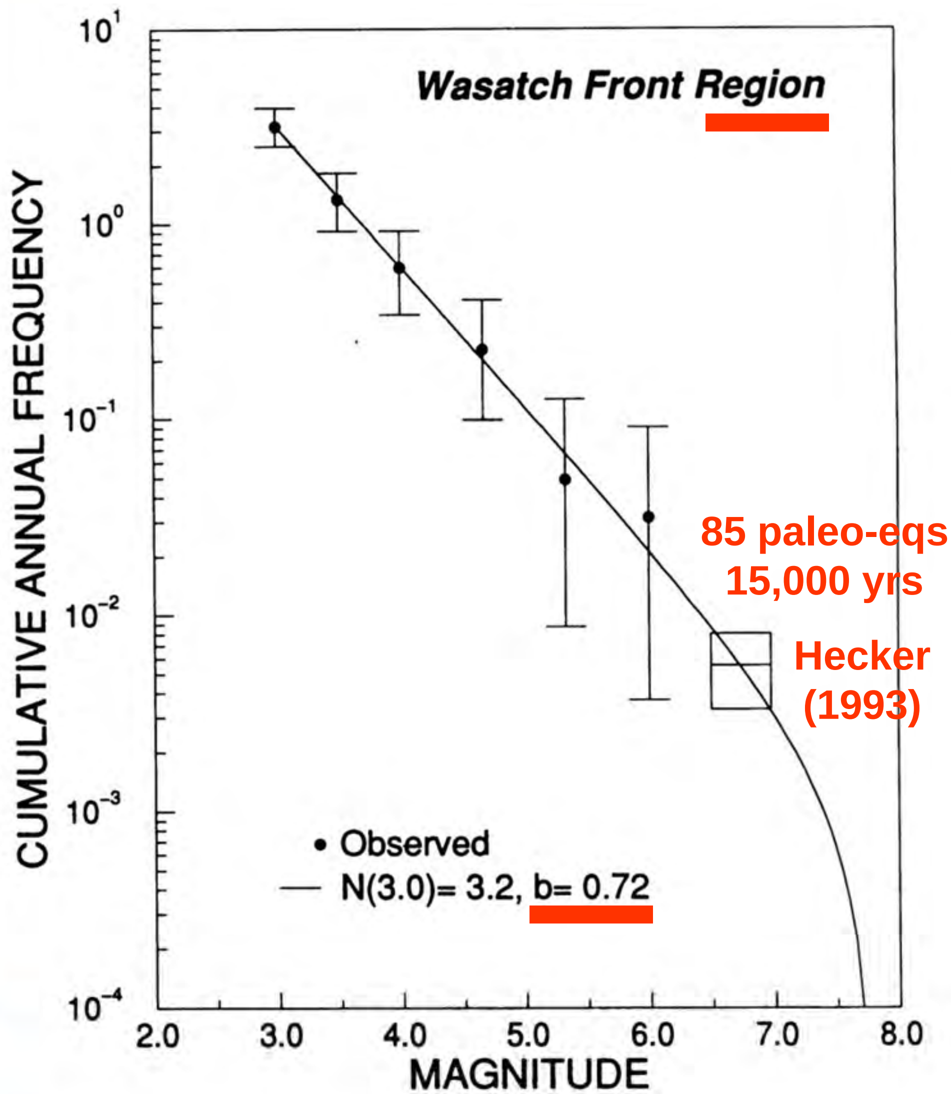
Youngs et al. (1987, 2000)



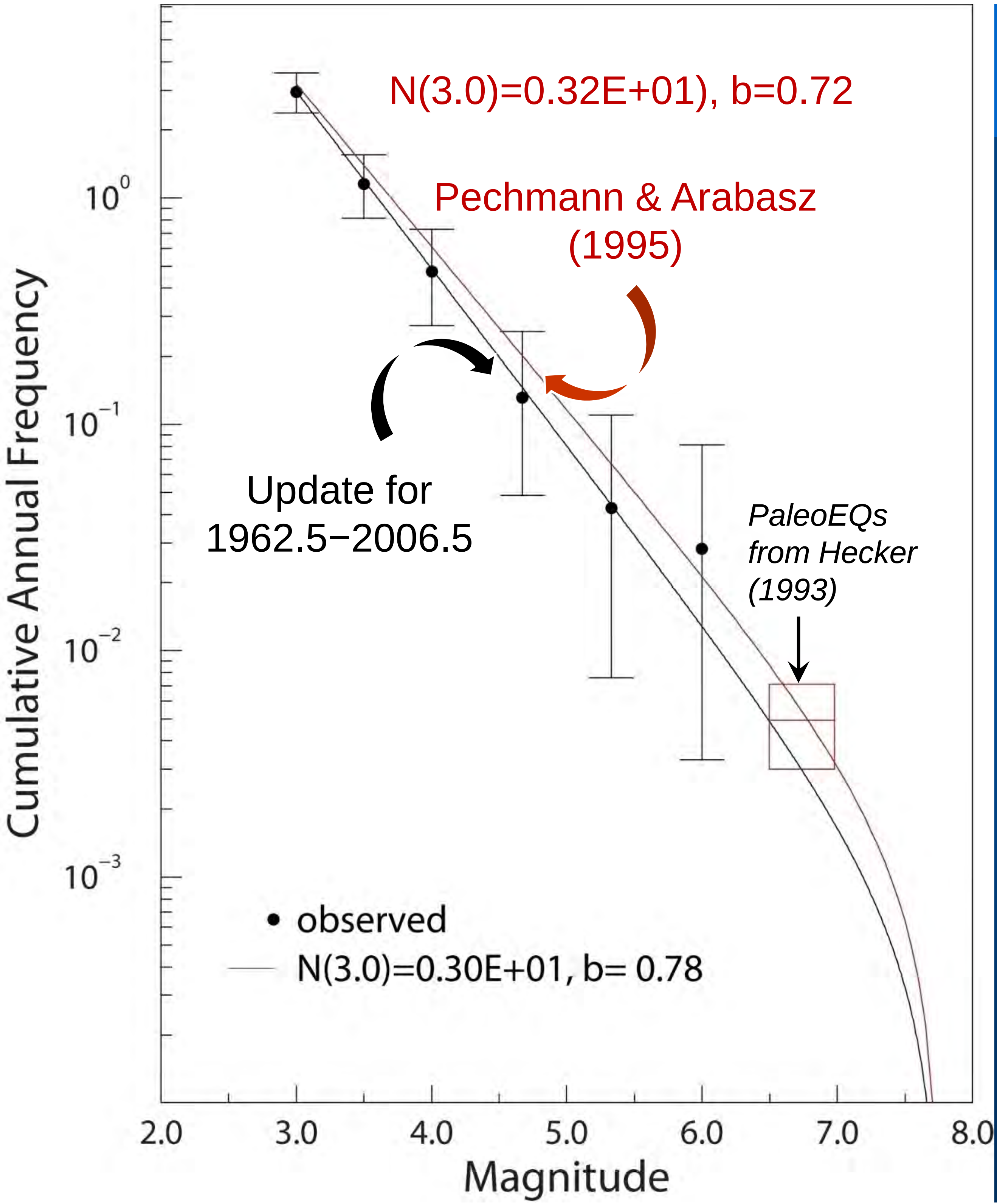
Pechmann & Arabasz (1995)



108 independent mainshocks M 3.0–6.6 1900–1994



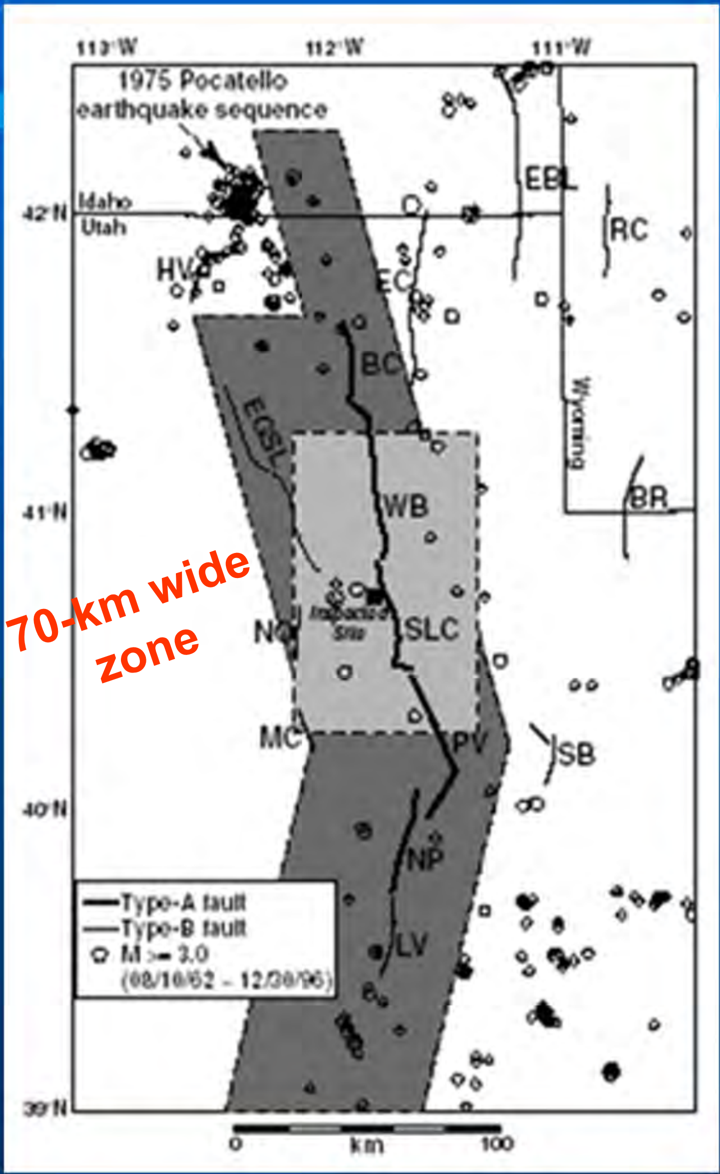
Recurrence modeling for Wasatch Front region

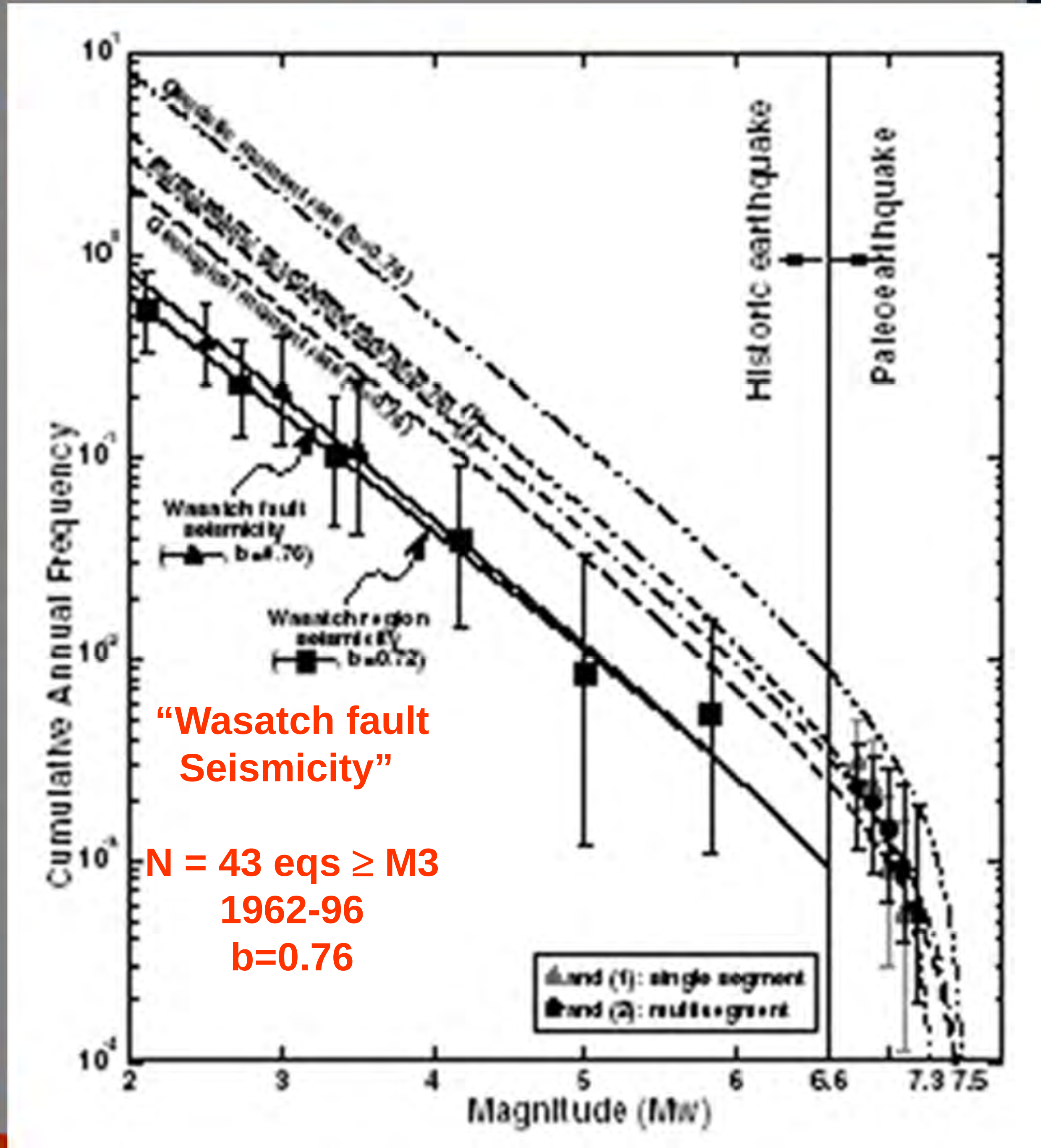


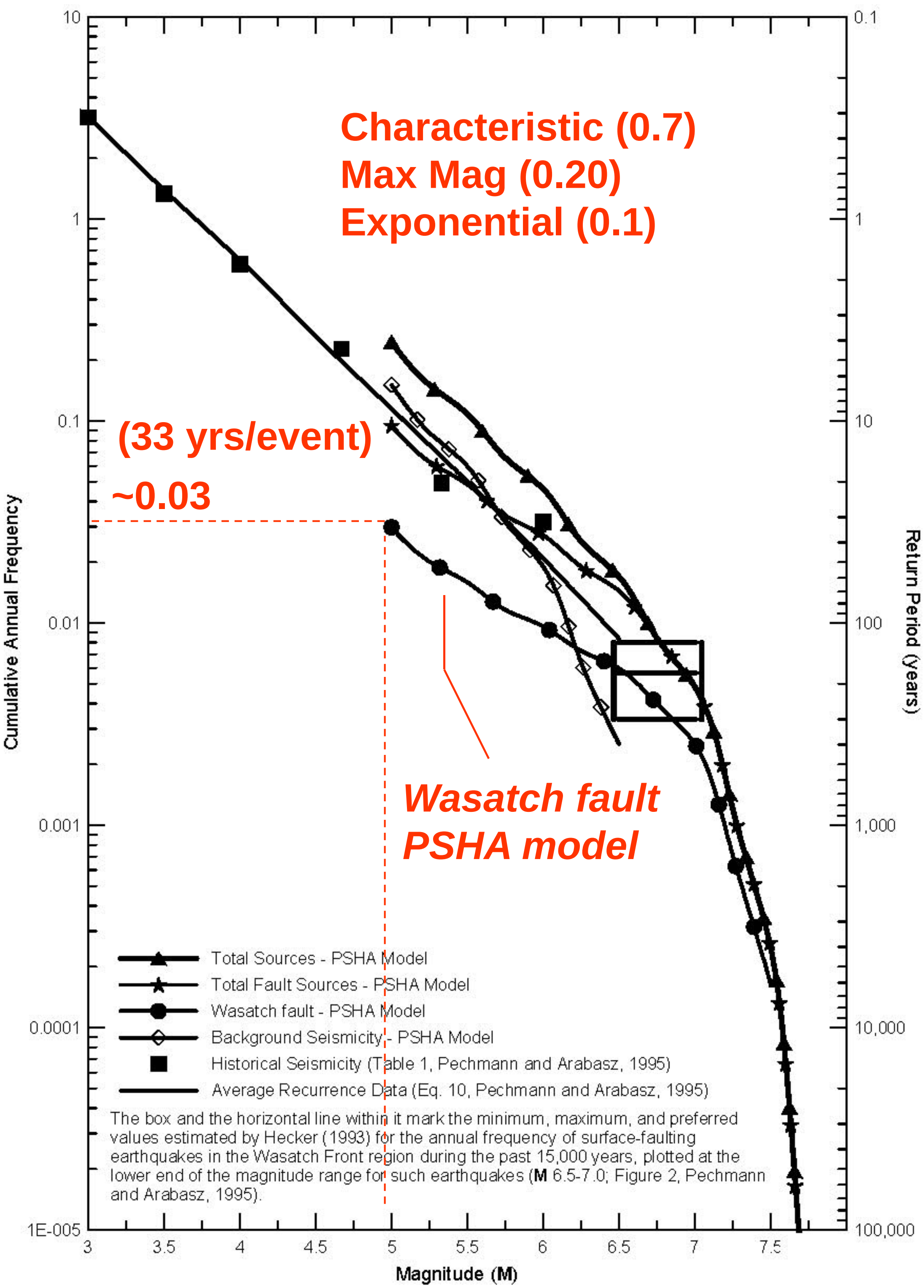
Update of Pechmann & Arabasz (1995) for Wasatch Front <u>region</u>

(from Feb 2010 WGUEP meeting)

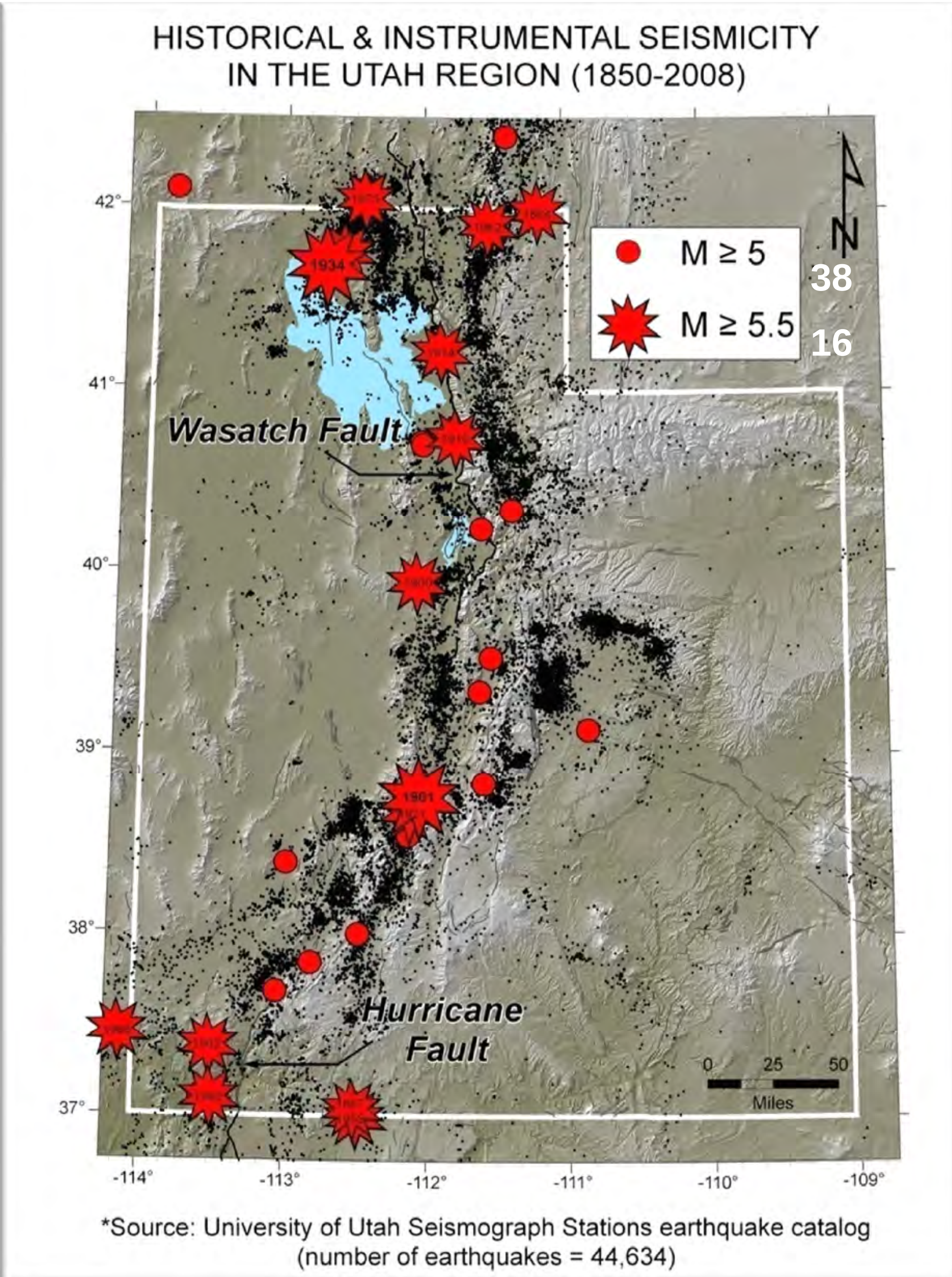
Chang & Smith (2002)



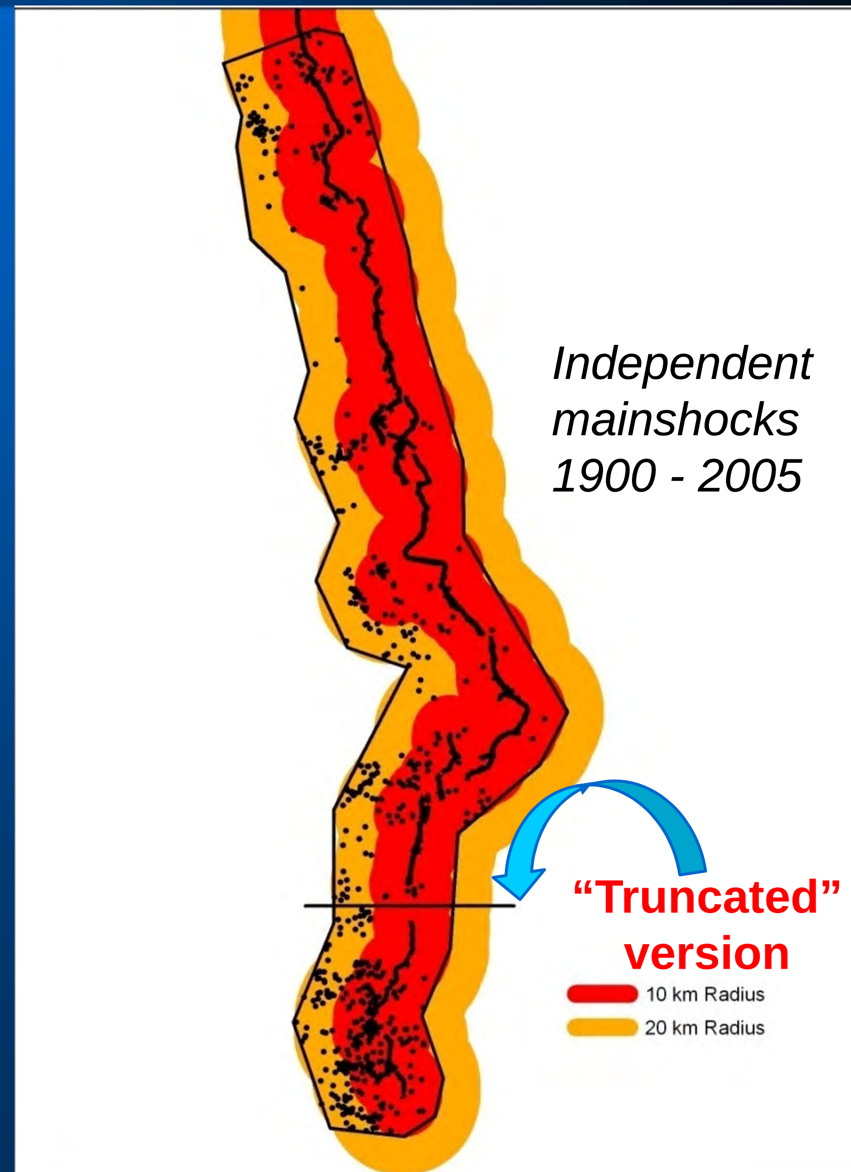




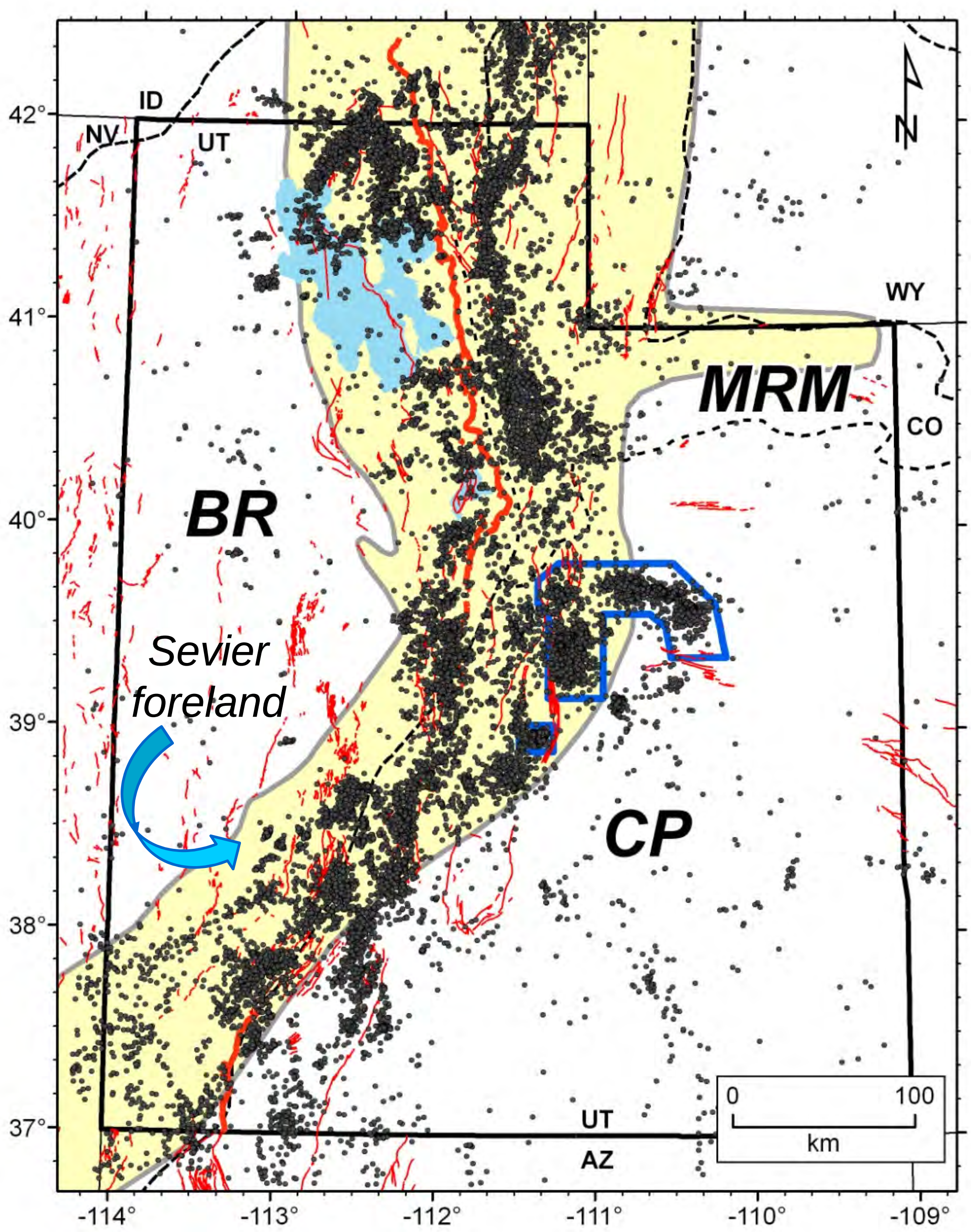
Wong et al. (2002)

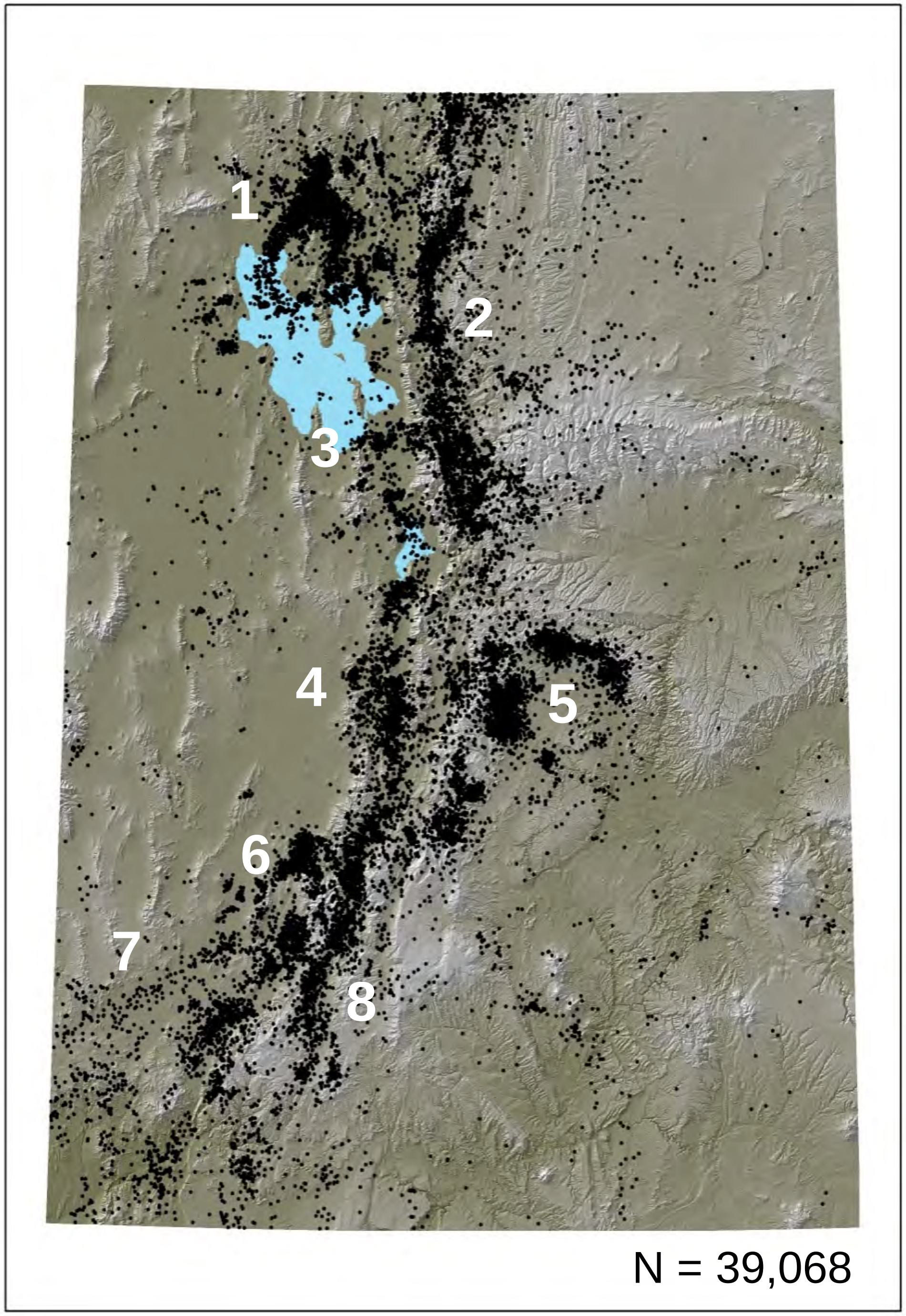


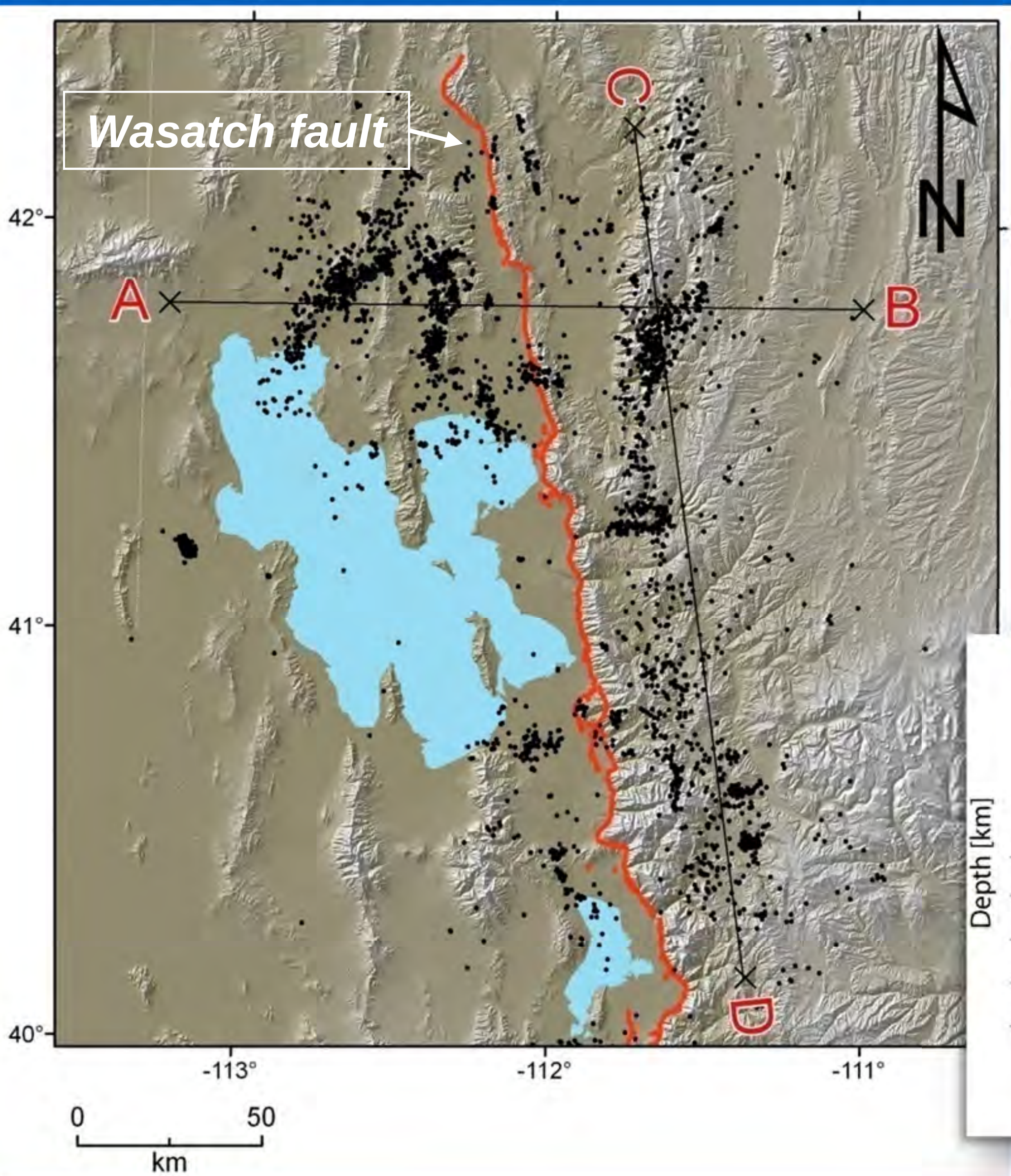
A closer look...

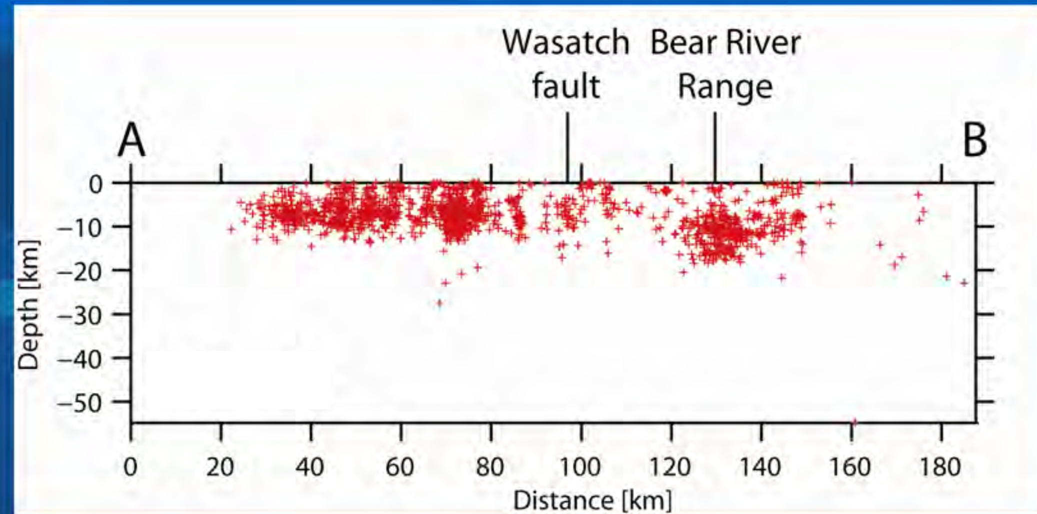


Seismicity of the Utah Region, 1981–2008

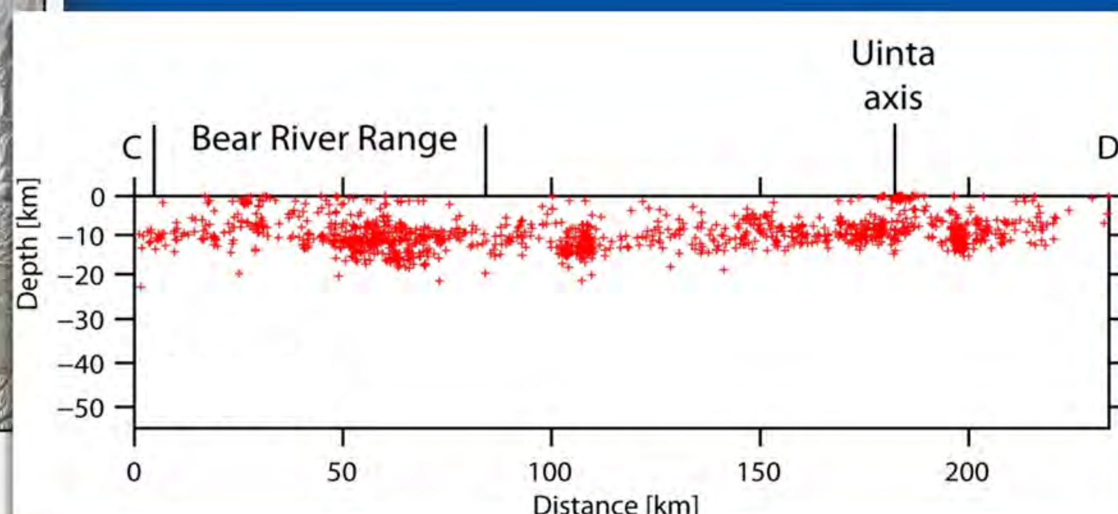






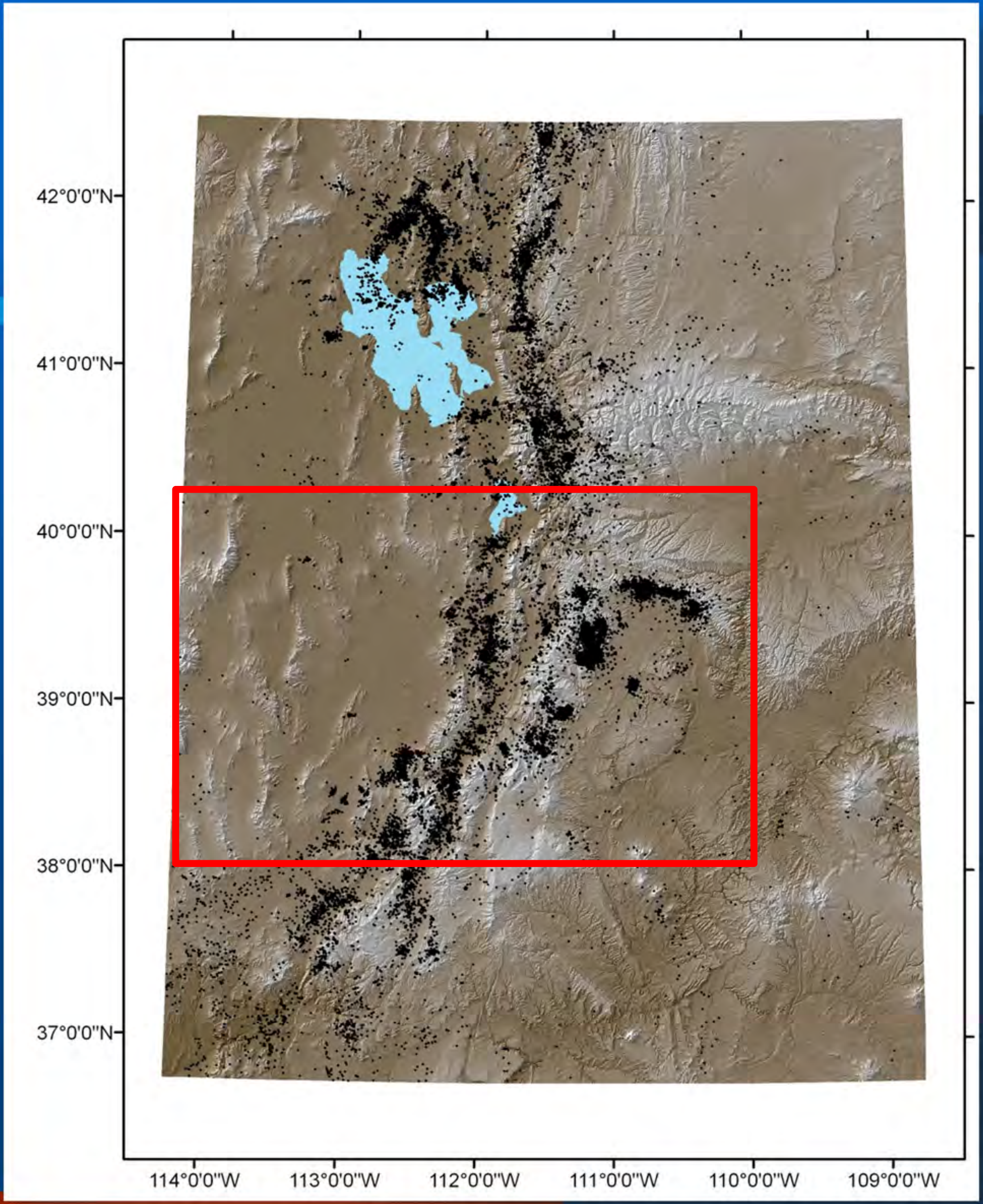


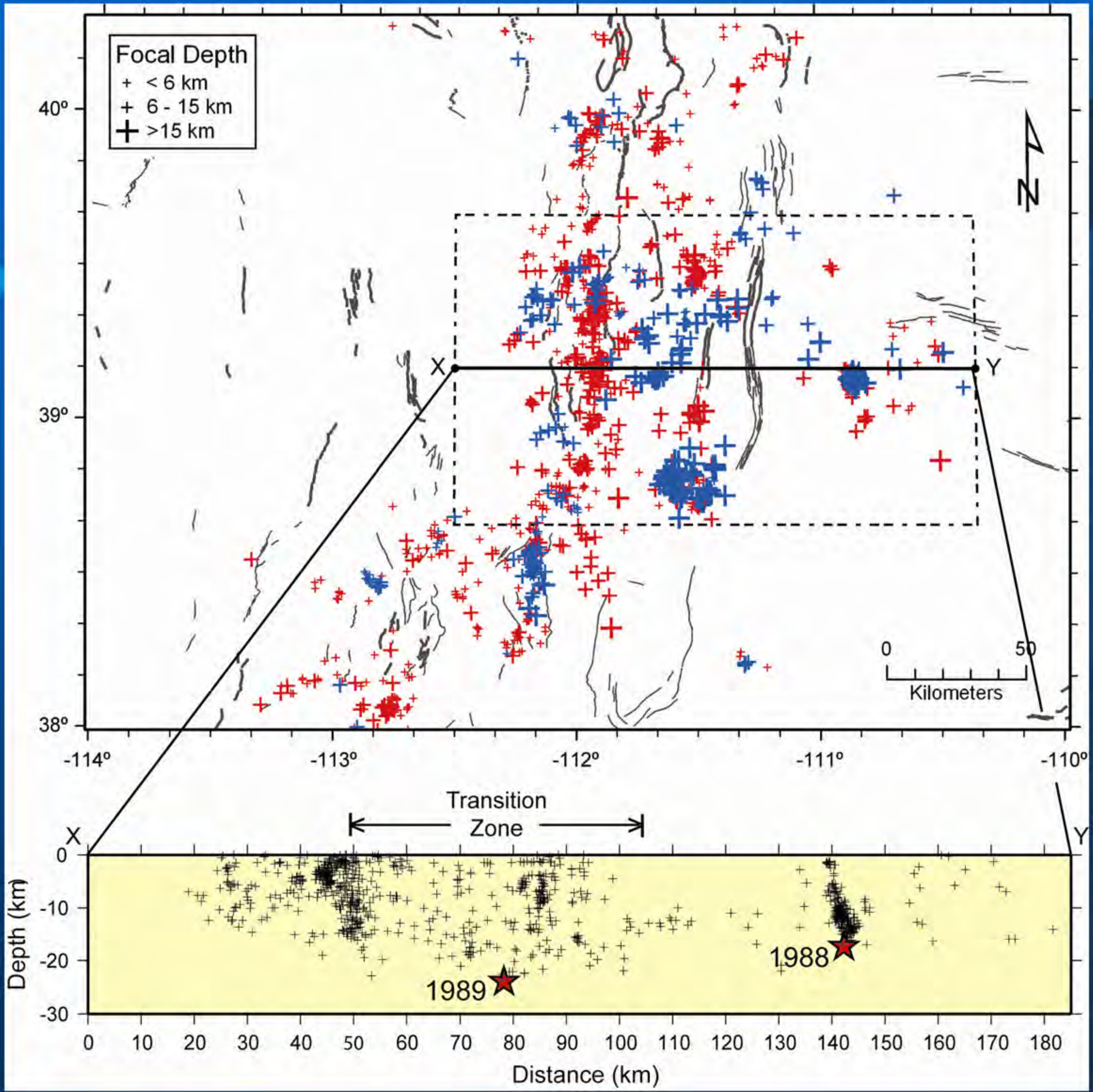
horizontal = vertical scales



Earthquakes with well-constrained and fair focal depths only
1981 - 2008

Central Utah





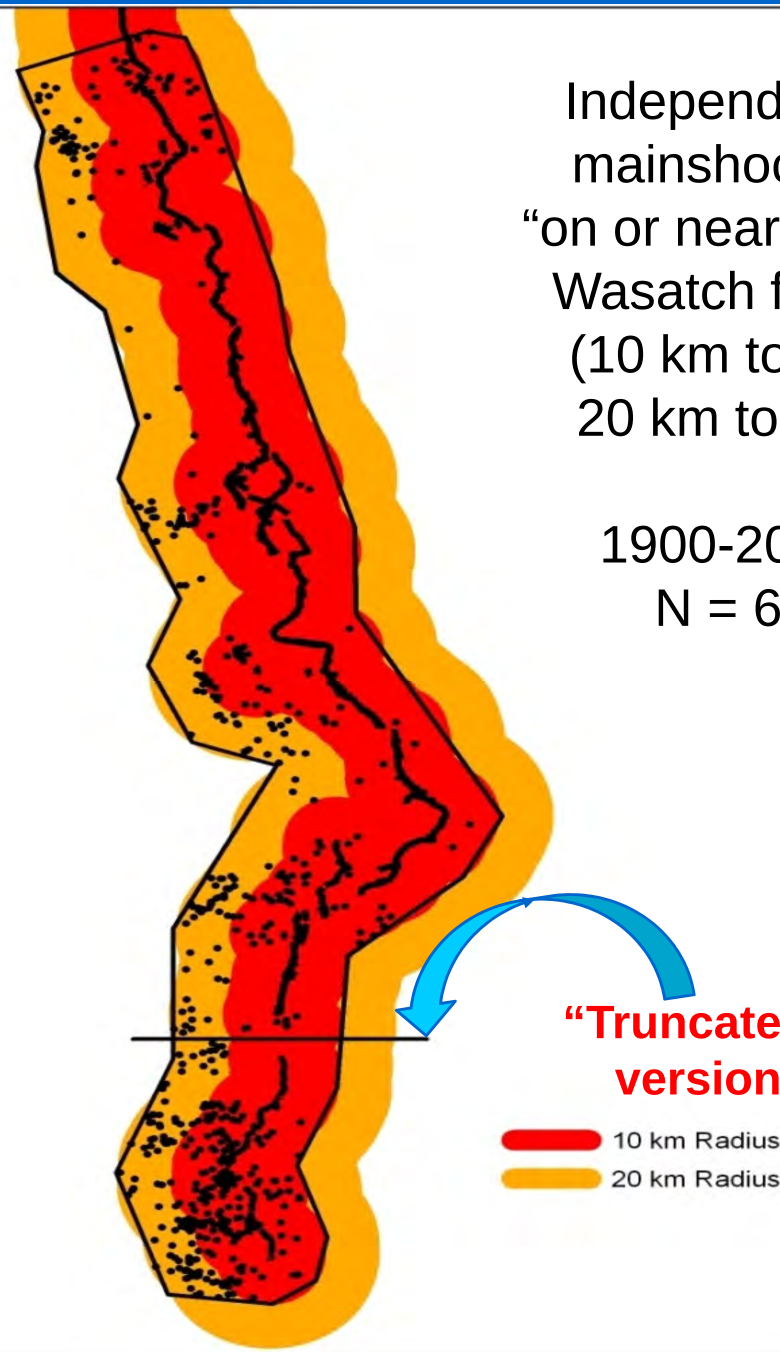
BLUE = "Well-constrained"

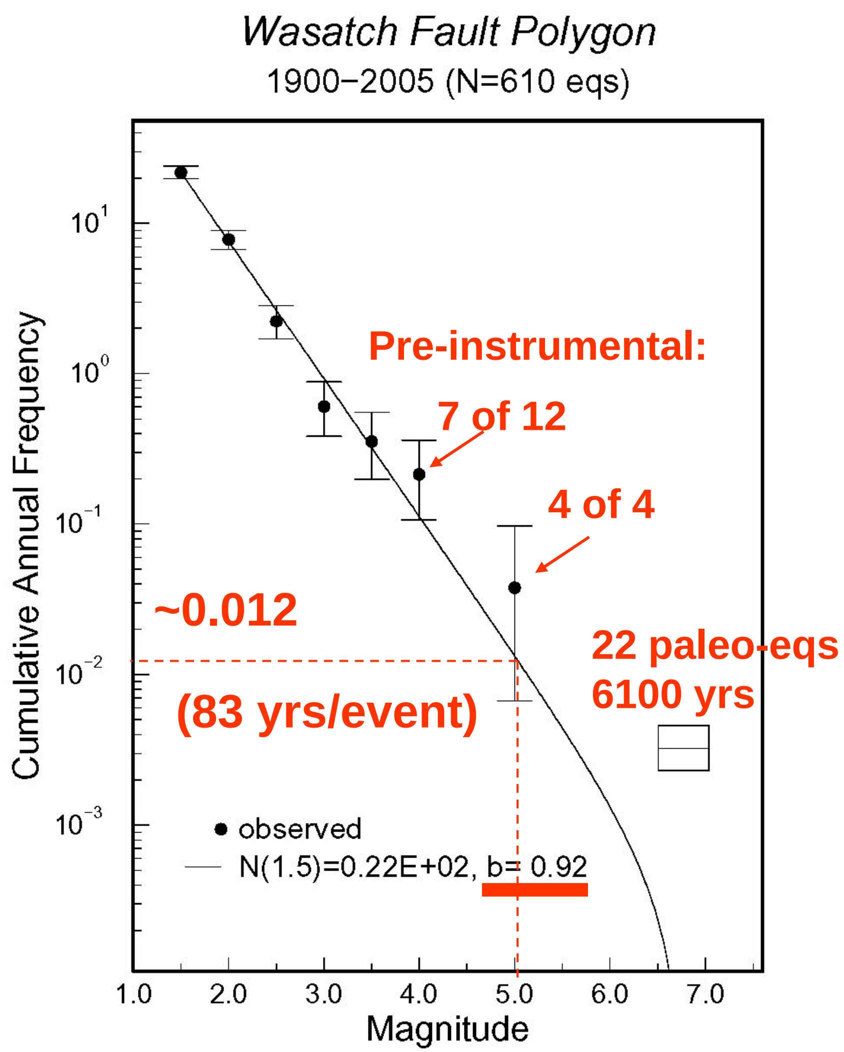
RED = "Fair"

Arabasz et al. (2007, UGA 36)

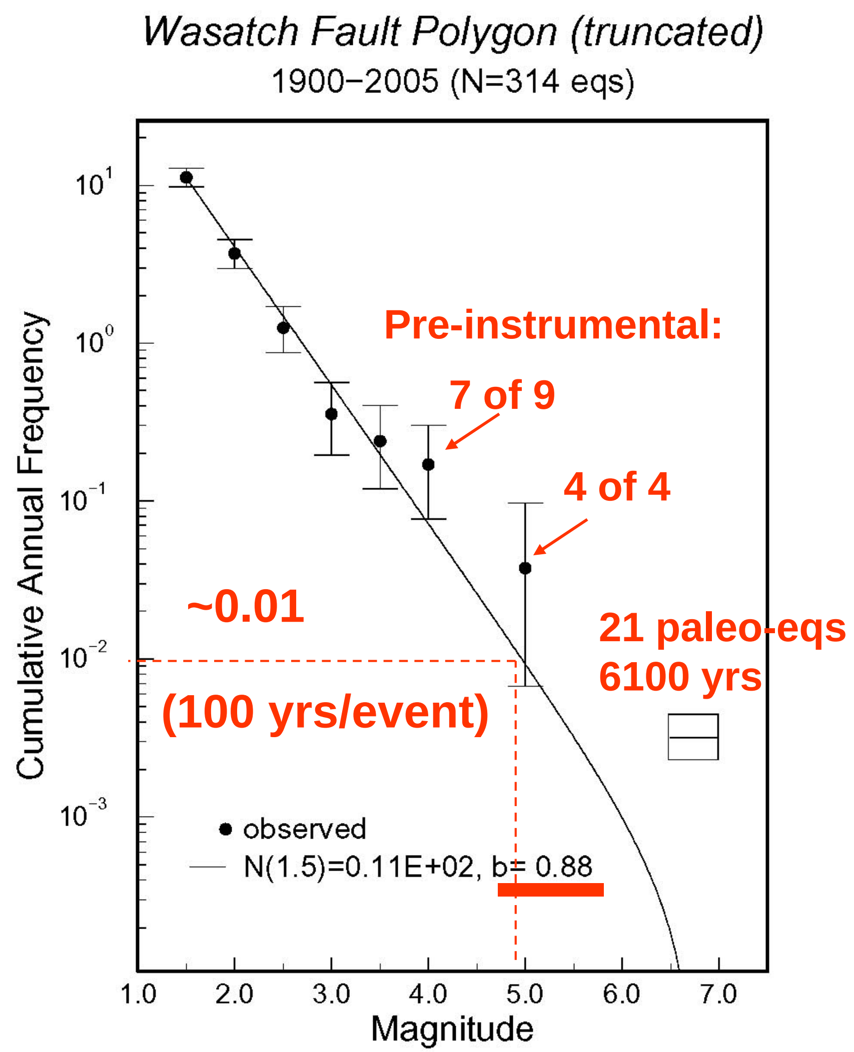
Independent mainshocks "on or near" the Wasatch fault (10 km to E, 20 km to W)

1900-2005
N = 610





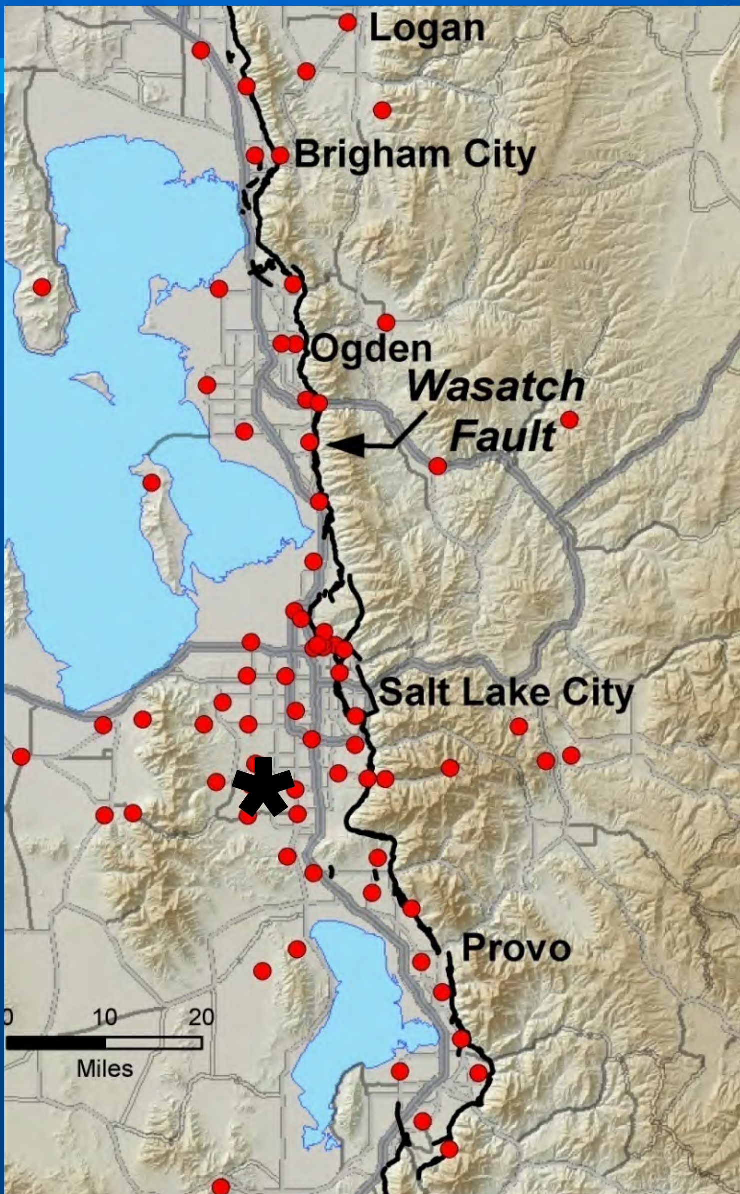
Wasatch Fault Polygon
1900−2005 (N=610 eqs)
Cumulative Annual Frequency
Magnitude
Pre-instrumental:
7 of 12
4 of 4
~0.012
(83 yrs/event)
22 paleo-eqs
6100 yrs
observed
N(1.5)=0.22E+02, b= 0.92

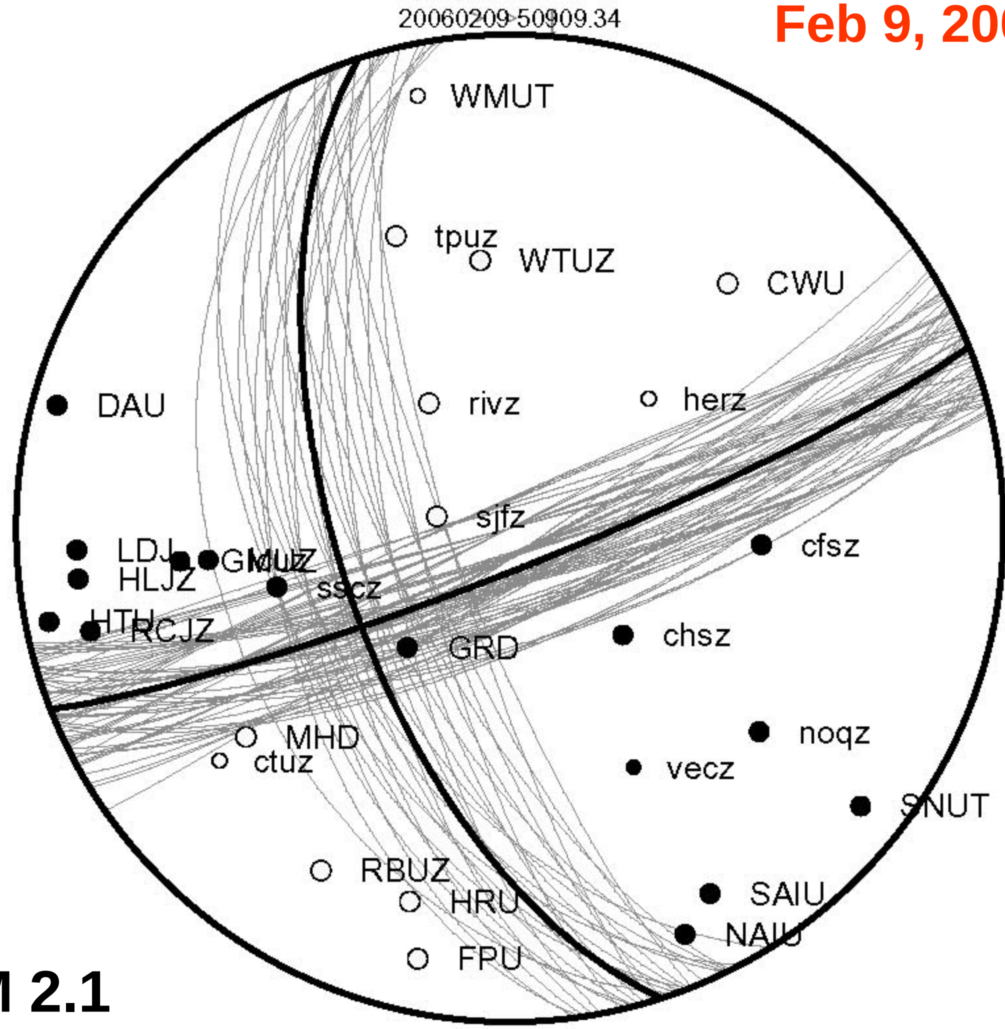


Wasatch Fault Polygon (truncated)
1900−2005 (N=314 eqs)
Cumulative Annual Frequency
Magnitude
Pre-instrumental:
7 of 9
4 of 4
~0.01
(100 yrs/event)
21 paleo-eqs
6100 yrs
observed
N(1.5)=0.11E+02, b= 0.88

Problematic spatial correlation
One example...

Note: Only 12% of EQs in UUSS catalog since 1981 have well-constrained focal depths





Feb 9, 2006

M 2.1
depth = 12.3 km

Conclusions (1 of 2)

- Data don't favor a truncated exponential model—but one can plausibly argue for this model for M ≥ 3 (Issue: Did pre-instrumental M4's and M5's occur on the Wasatch fault?)
- Observed seismicity is more consistent with the characteristic model—but the association of sampled instrumental seismicity with the Wasatch fault is uncertain
- Maximum magnitude model is viable if smaller earthquakes are part of adjoining background zones and not on the Wasatch fault

Conclusions (2 of 2)

- There's a distinction between (1) discerning the true seismogenic behavior of the Wasatch fault and (2) modeling of observed/future seismicity

—Weights for competing hypotheses do not have to be the same for both cases

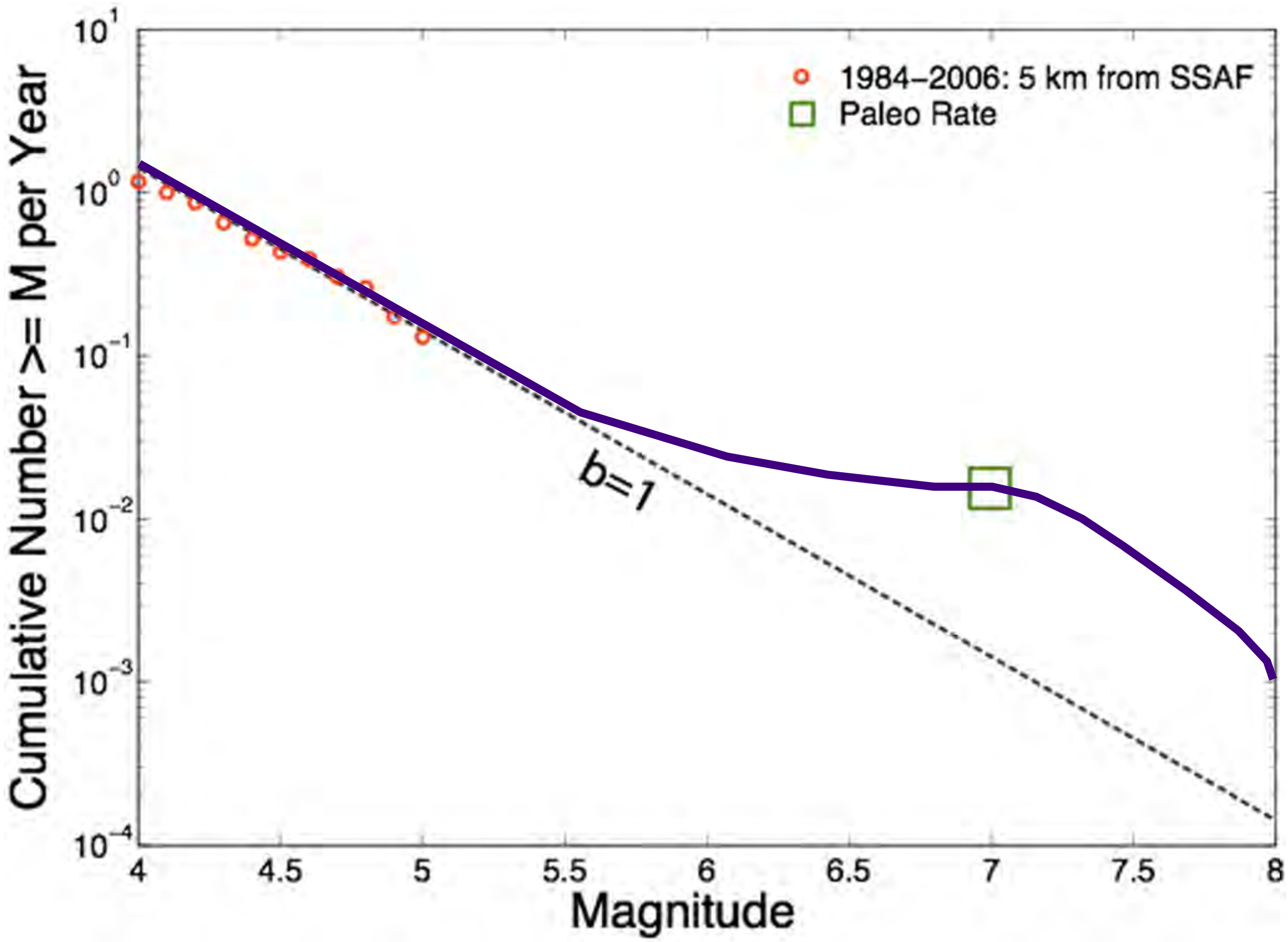
—Modeling of observed (and future) seismicity has to be mindful of double counting and <u>source</u> of rate information

—Seismicity can be modeled by Mmax or characteristic model for larger EQs on the Wasatch fault plus truncated exponential for adjoining background (appropriately accounting for threshold and upper-bound magnitudes and spatially-smoothed seismicity rate in the background)

Fault-Specific Magnitude-Frequency Distributions

Glenn Biasi
University of Nevada Reno

The Characteristic Magnitude Distribution

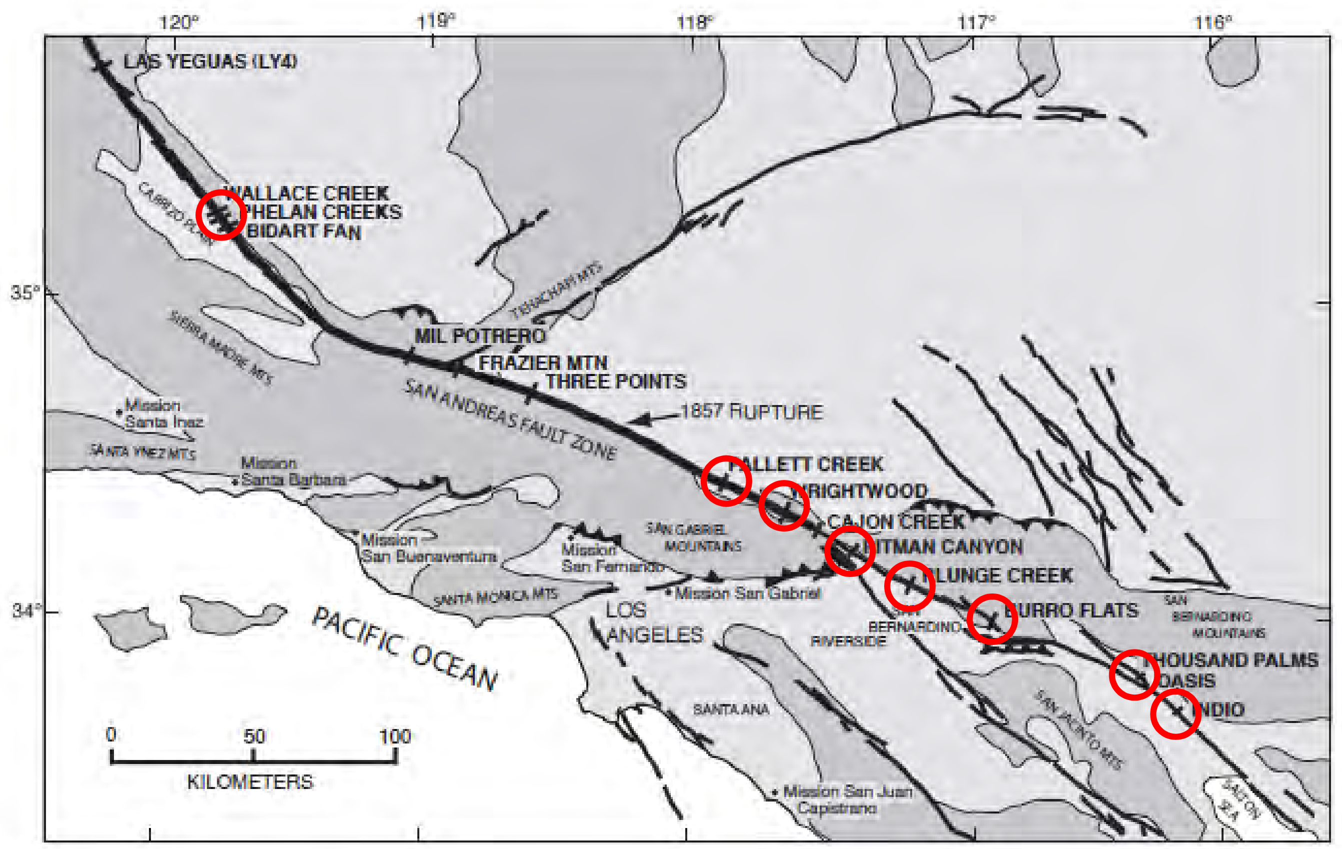


Hypothesizes that large earthquakes on faults occur at a higher rate than in the G-R distribution

This and several following slides from Page et al. 2008 AGU

Direct Magnitude-Frequency Estimation from Paleoseismic Data

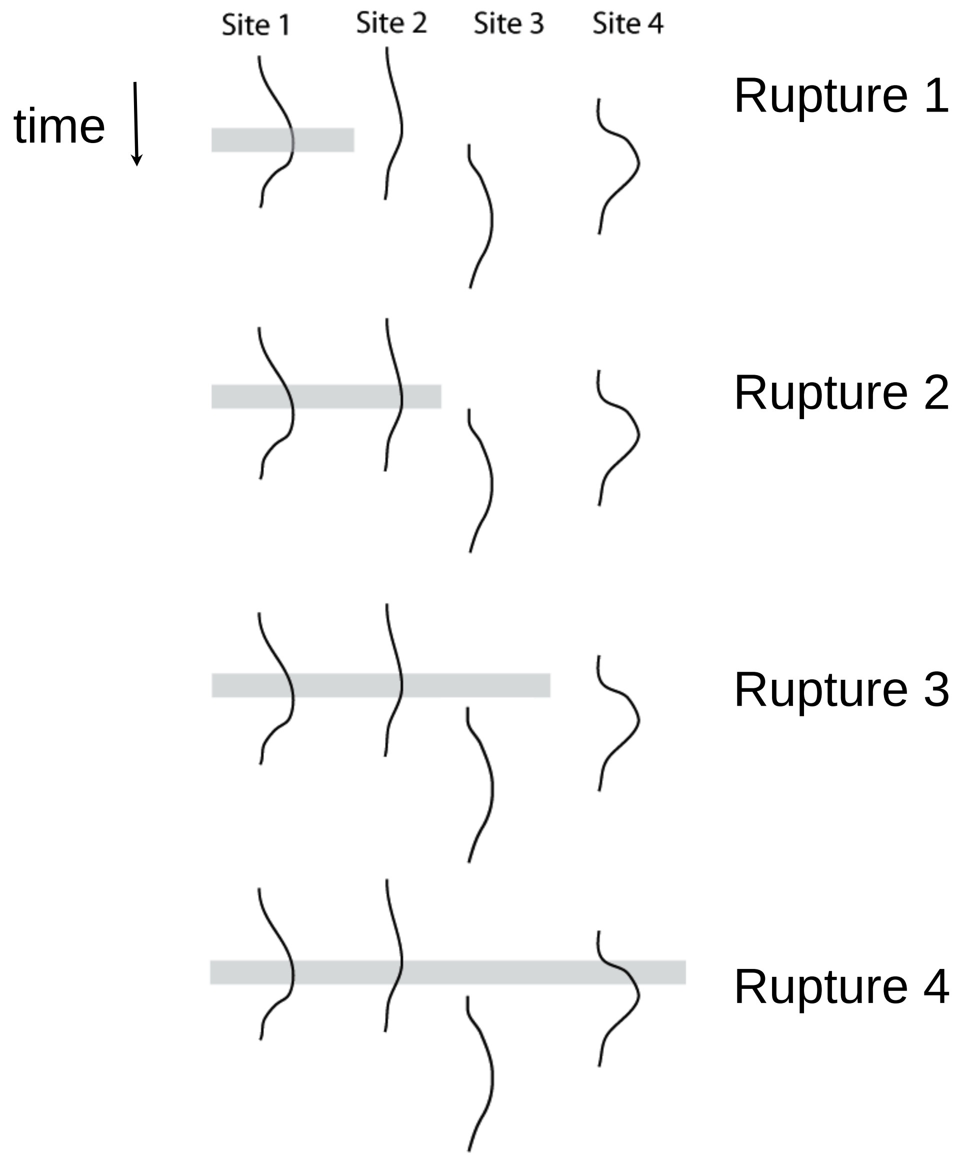
Approximate dates of events over last ~1000 years are available at 8 paleoseismic sites on the SSAF*



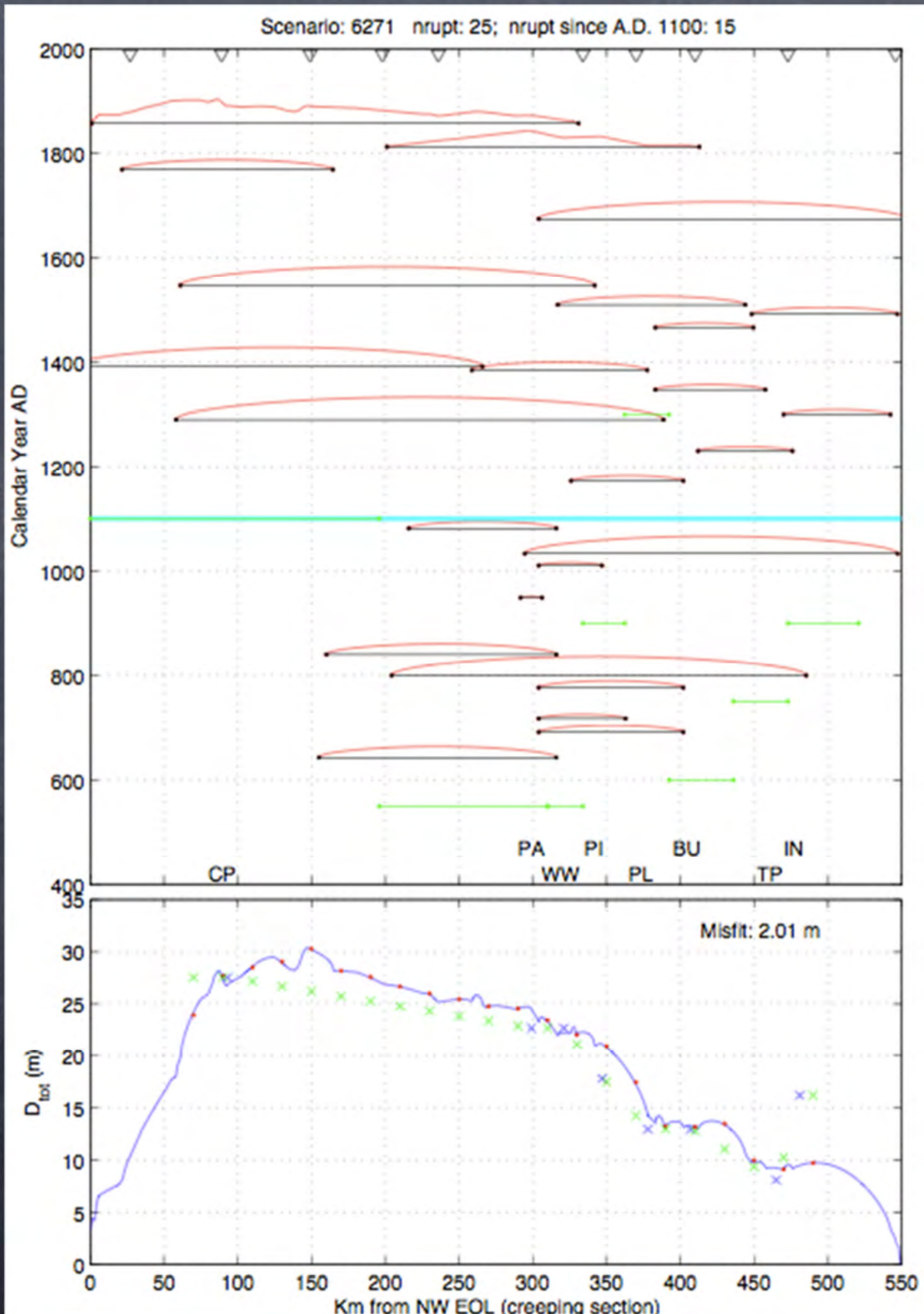
*Frazier Mountain would be added and some event dates changed if the analysis was repeated today.

The dates are linked in every way allowed by dating error to form all possible ruptures

"Stringing Pearls"



Slip and magnitude of each rupture is determined from length using the Hanks-Bakun relationship



Example rupture scenario for the southern San Andreas fault.

For magnitude-frequency study:

-- Collect good-fitting scenarios

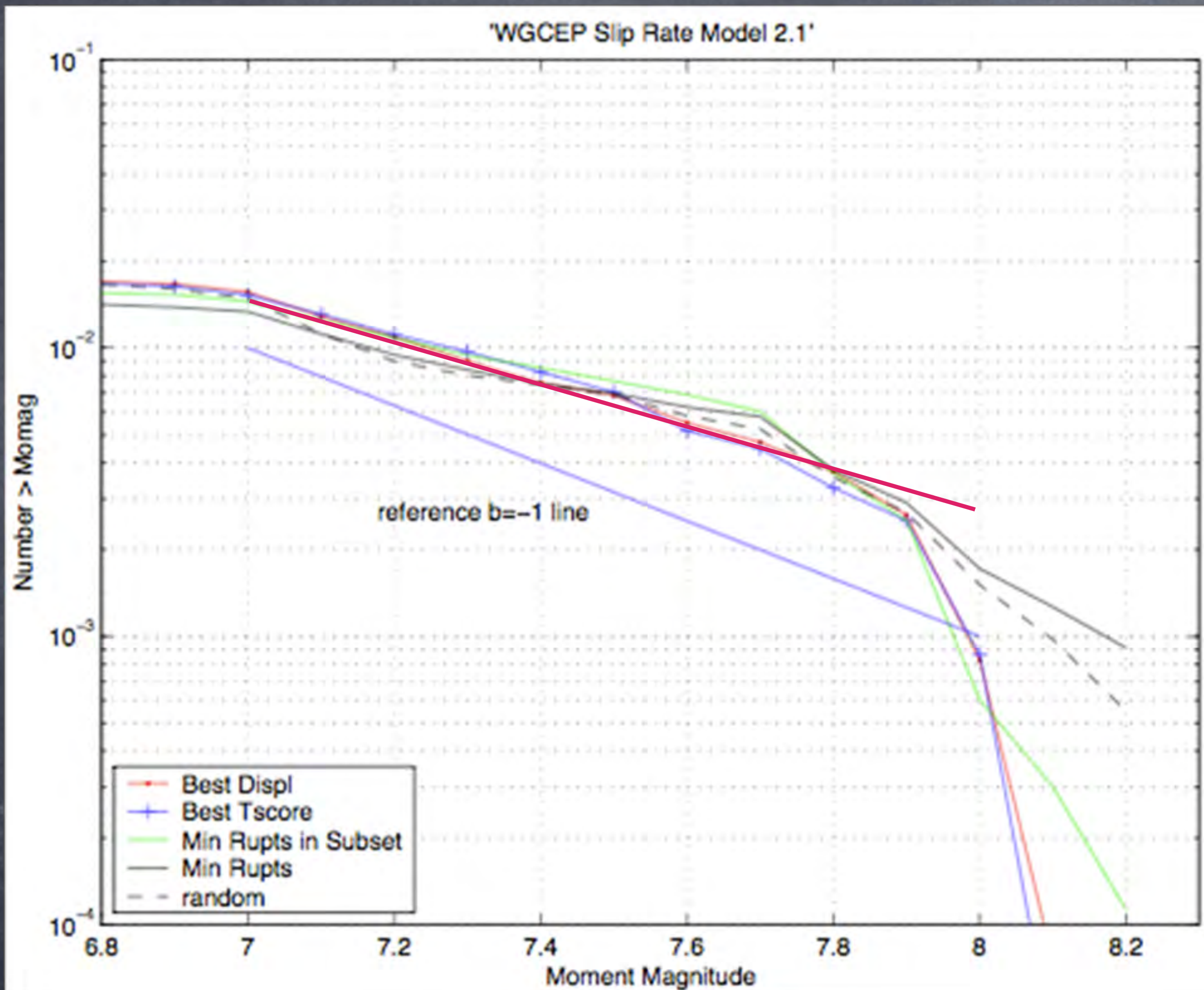
-- Estimate magnitude from length (the only "known")

-- Synthesize into magnitude-frequency curve for ground-rupturing earthquakes.

Red arches are displacement profiles.

Displacements for events after AD 1100 are summed to the blue line.

Green X's mark total displacement expected since 1100. Mean difference is 2.0 m.



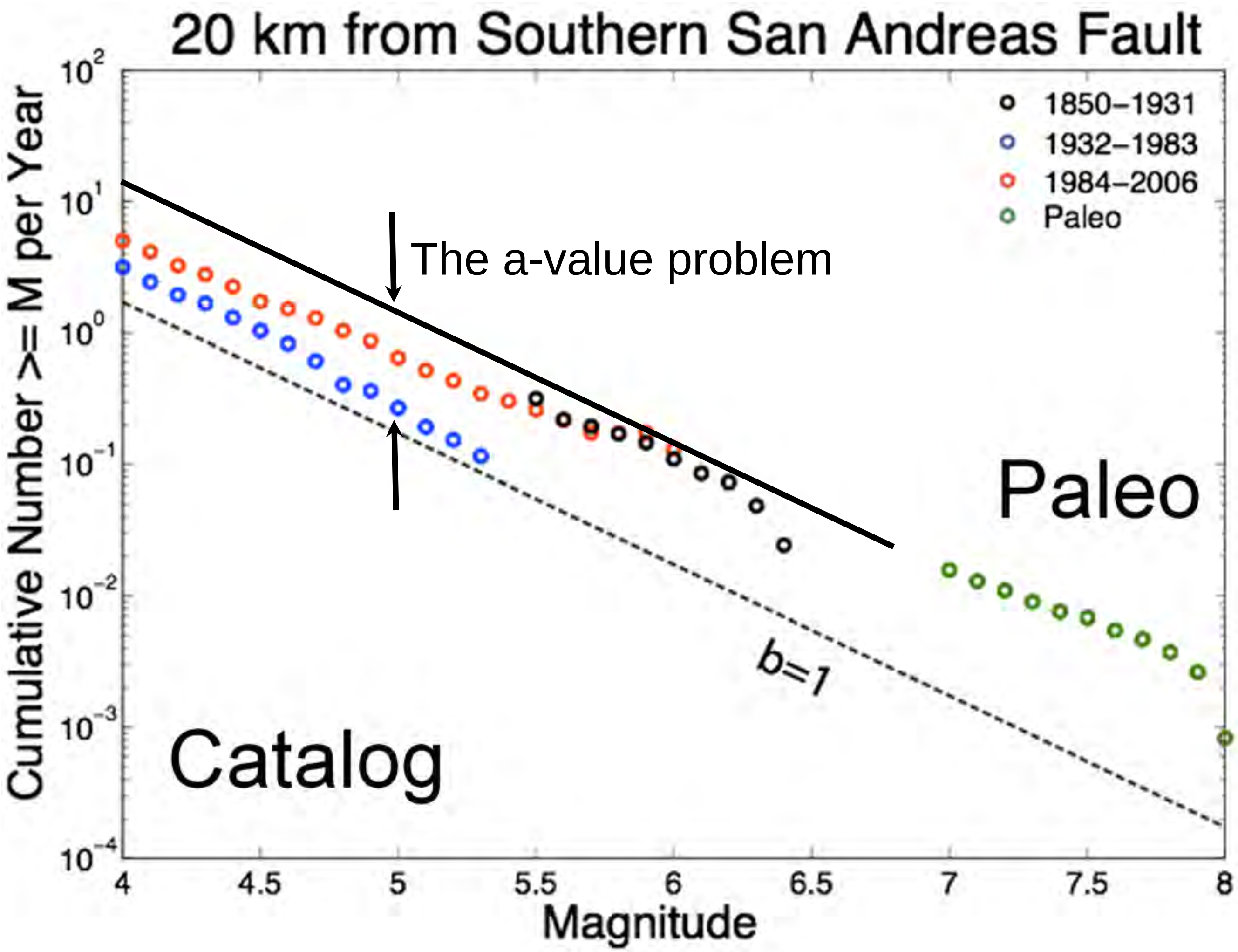
Magnitude-frequency curve for WGCEP slip rate model 2.1

100 best-fitting scenarios

Power-law shape

Slope b=-0.7 (and significantly less than 1.0)

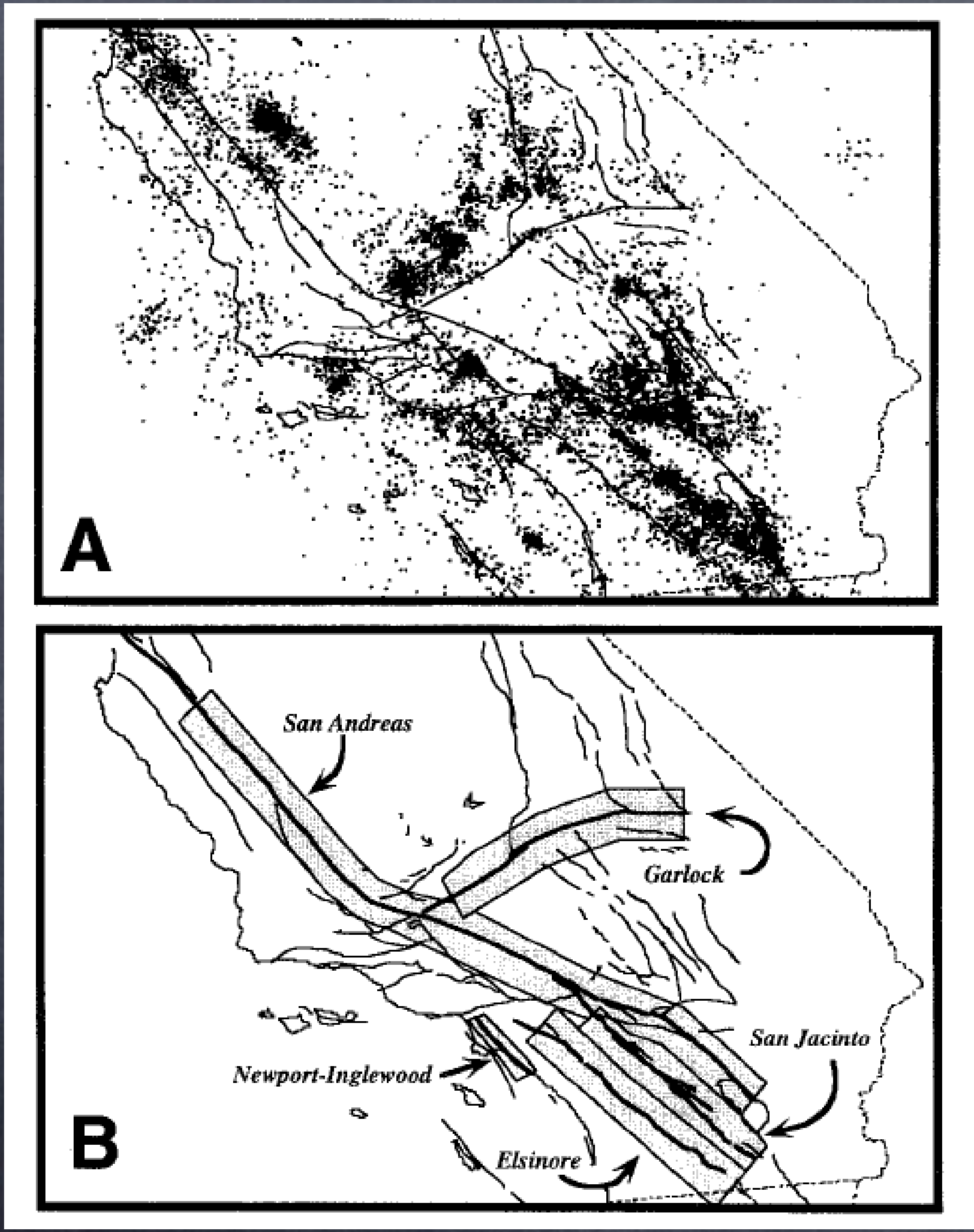
Compare with rates predicted by seismicity along the fault itself.



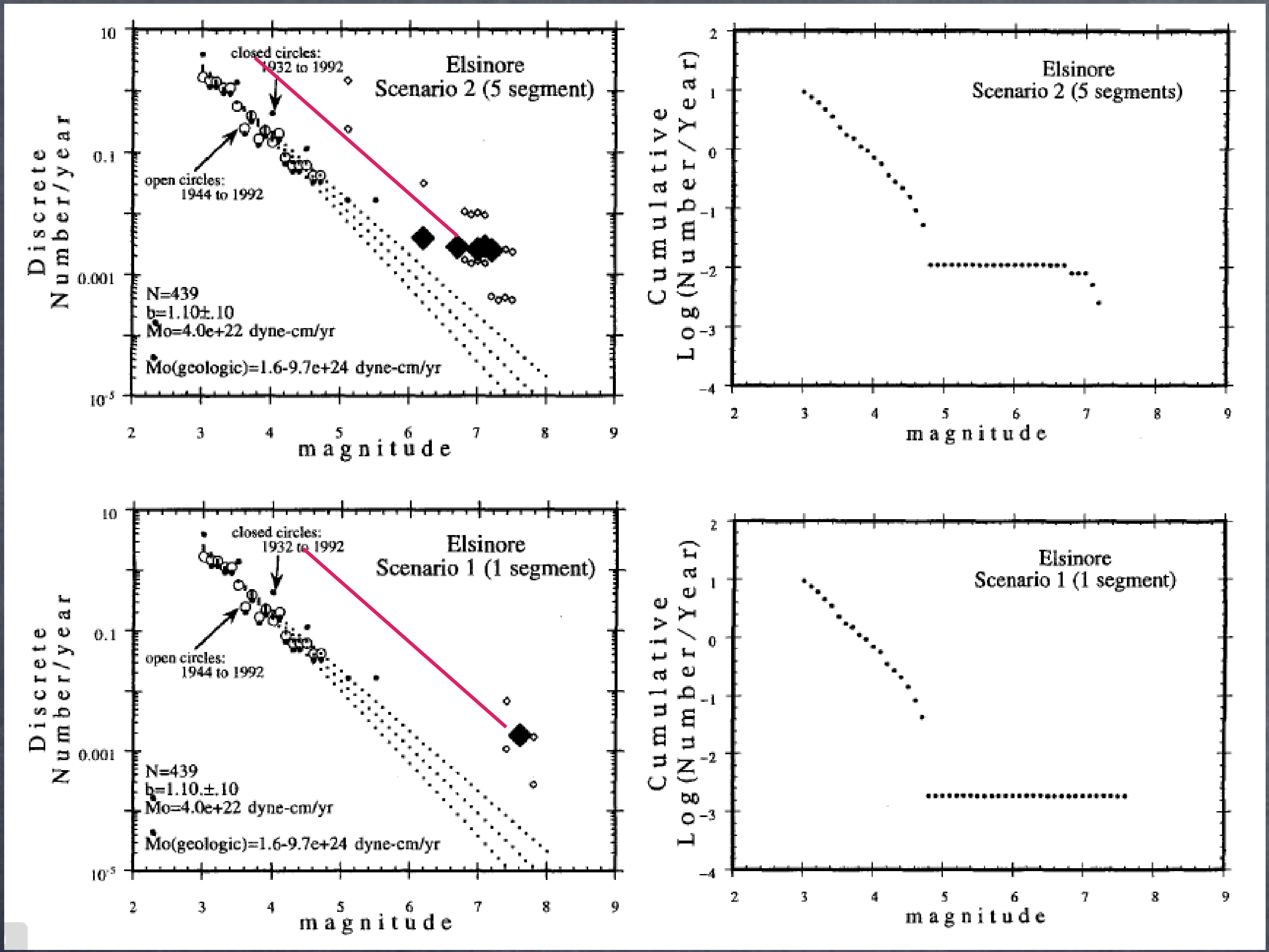
A-value deficit is clear.

Size of deficit depends on width of seismicity zone assumed to be “on the fault”

Deficit might be reduced, but not eliminated by including better aftershock counts (e.g., after 1857)

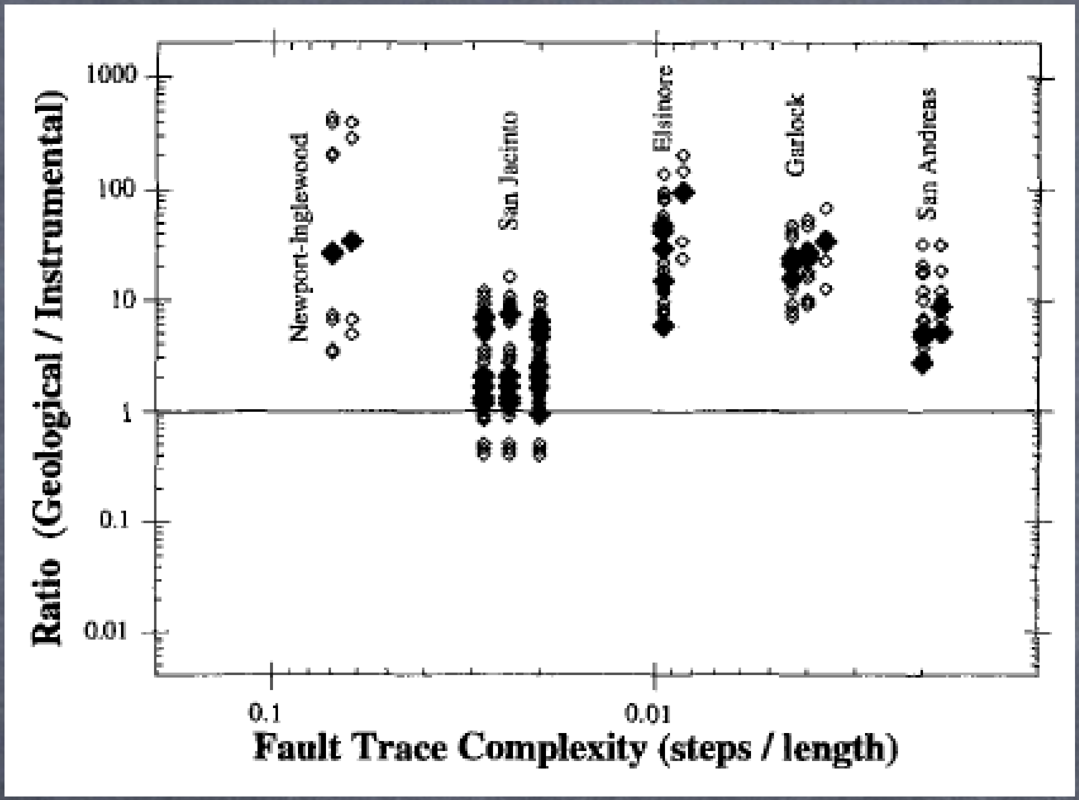


Wesnousky (1994 BSSA) studied magnitude-frequency relations for several SoCal faults (rectangular boxes)



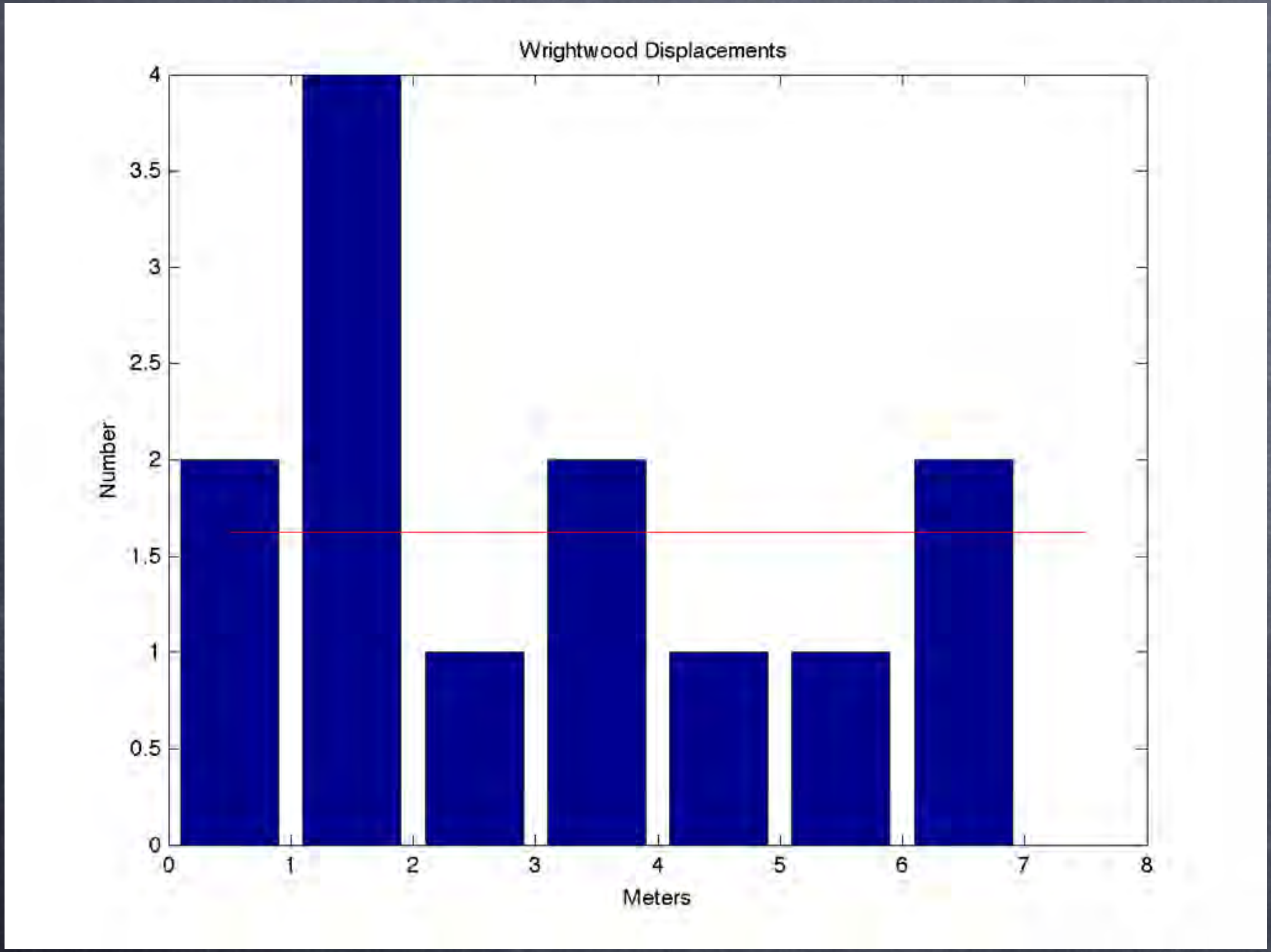
Elsinore fault example, upper as 5 segments, lower as one. Maximum likelihood annual occurrence rate from seismicity under-predicts geologic rate of large events. Catalog is either missing lots of 3<M<5 events, or is not stationary, or a characteristic model contributes.

Catalog under-predicts paleoseismic estimated rates on all faults considered.



- Preliminary and sophisticated attempts conclude that catalog seismicity under-predicts rates of large events in California
- Closing points by Wesnousky, 1994:
  - (1) the last 5 decades of seismicity are the best indicators of the next 50 years
  - (2) 50 years is about the period of interest in seismic hazard and engineering analysis
  - Therefore the characteristic recurrence model will serve better

Magnitude-frequency from displacement at a point

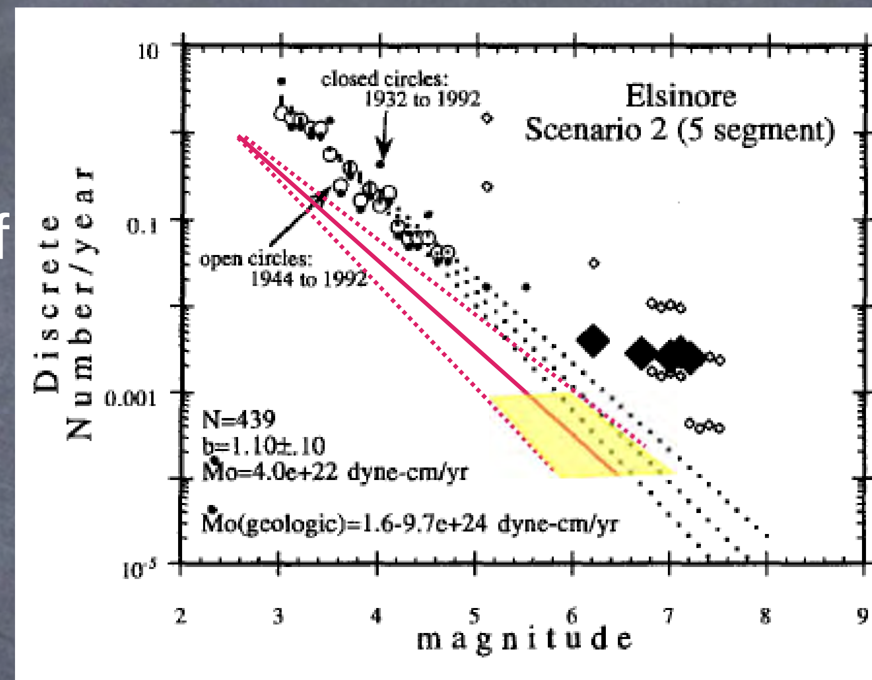


Expect a uniform distribution of displacements at a point if the magnitudes are GR that cause ground rupture.

Anecdotal evidence: 13 displacements from Wrightwood are fairly evenly distributed.

Basin and Range: Magnitude-frequency with low rates of seismicity and long recurrence times

- Uncertainties in the rate of small earthquakes will lead to rate uncertainties at recurrence intervals of 10^3 to 10^5 years.
- Individual, poorly located M4's could control the results
- Suggestion:
  - Compare seismicity rates with the geologic rate.
  - If they compare for M6+, use the result
  - If they differ, the geologic rate may be more stable.

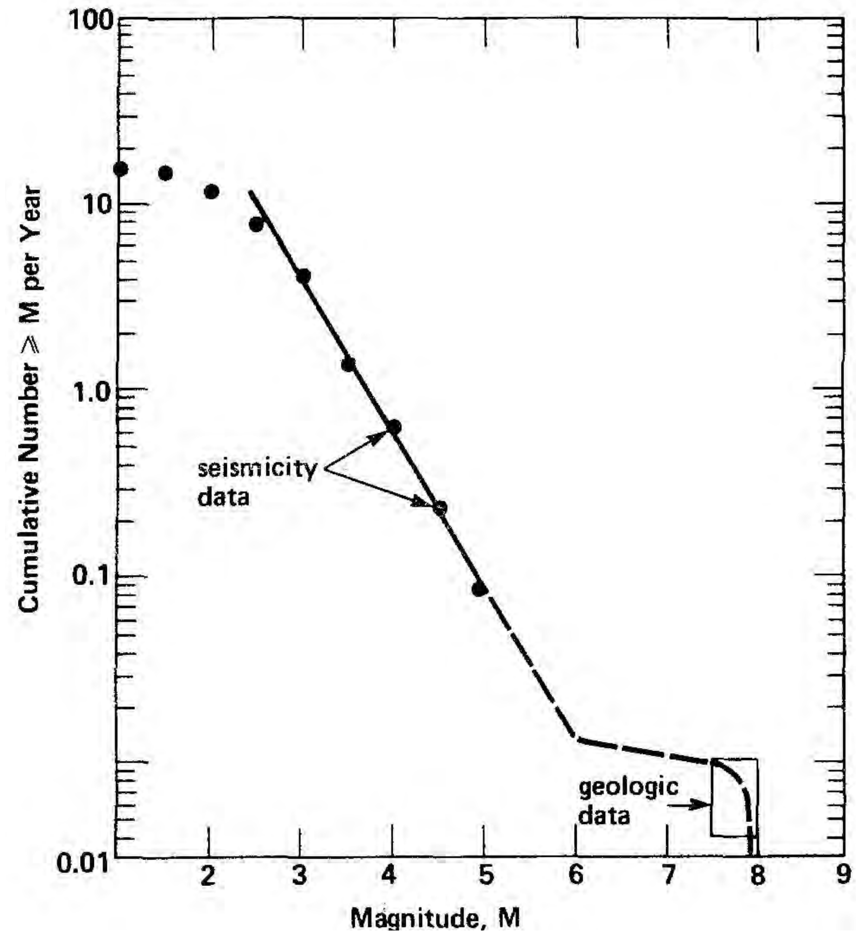


Example: One M2.5/yr on a fault. Extrapolate to 0.001 to 0.0001

Magnitude-frequency distribution for NSHM's

How we characterize M-f distributions in source models for faults and gridded background seismicity?

- Data: Geologic slip rates, paleoseismic recurrence, geodetic strain rate data, seismicity …
- Models: GR, Characteristic
- Uncertainty: Aleatory (natural variability) and epistemic (model uncertainty)
- Method: Use historic seismicity for earthquakes up to M 6.5 (near faults) or 7.0 (away from faults) and geologic data on faults

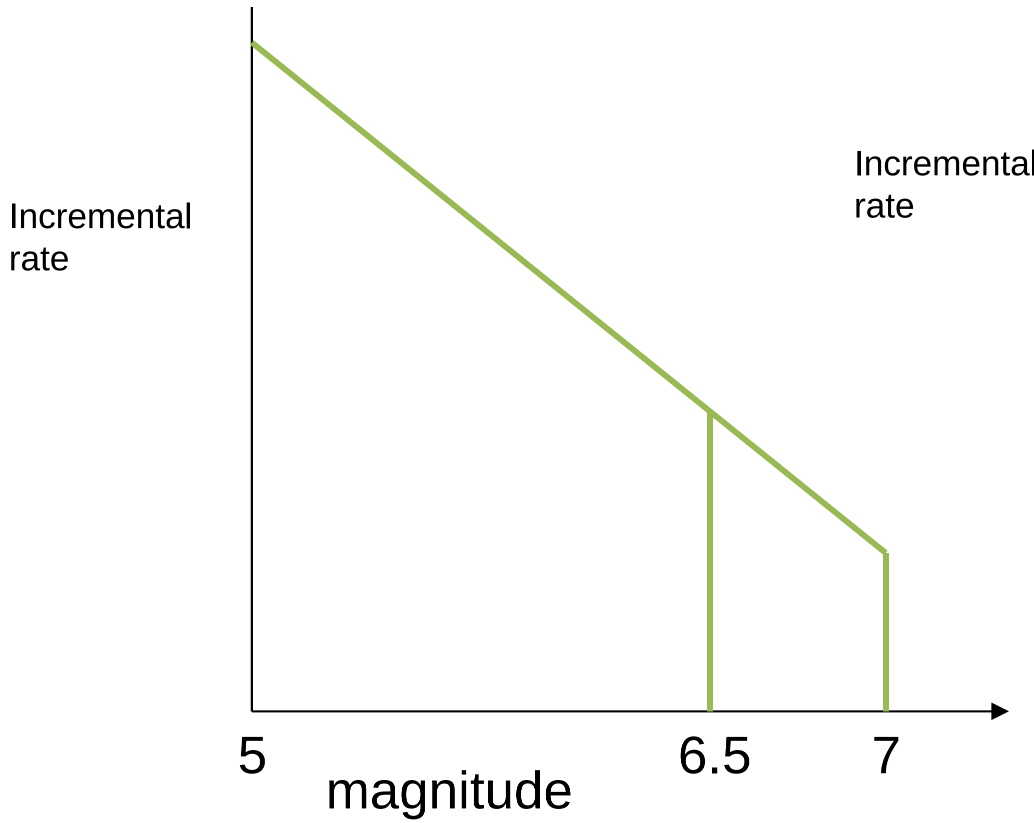


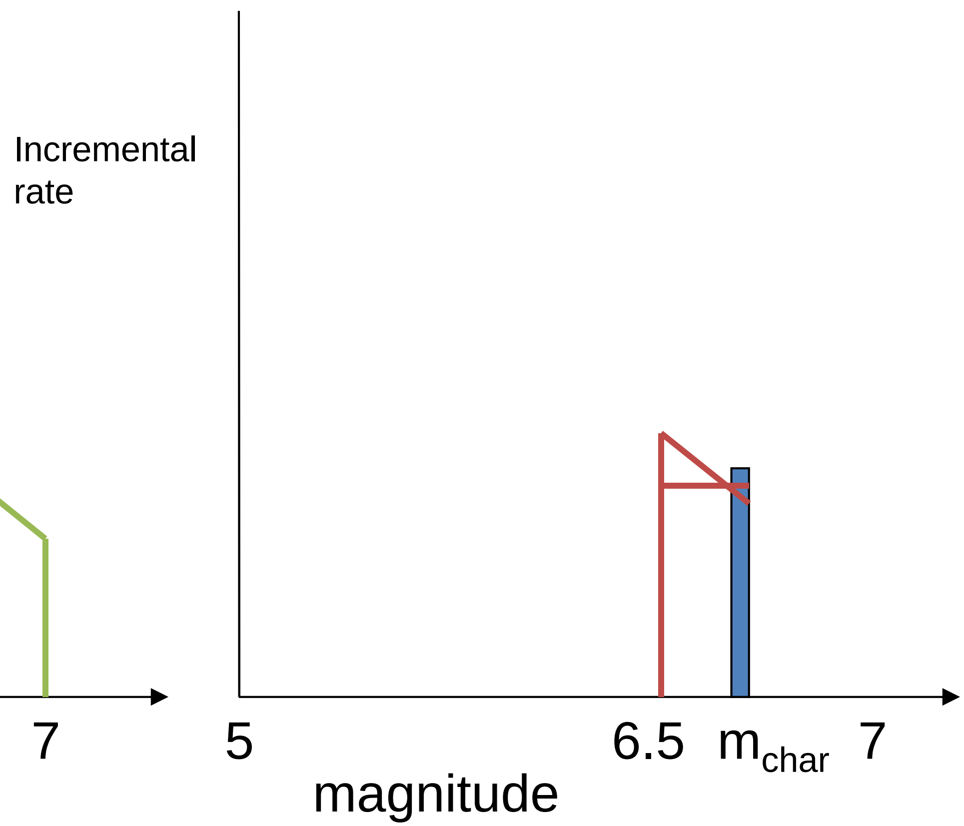
Youngs and Coppersmith, 1985;
Schwartz and Coppersmith, 1984

NSHM – conceptual model (no uncertainty)

•Background model: Use catalog to calculate 10^a for GR distribution.

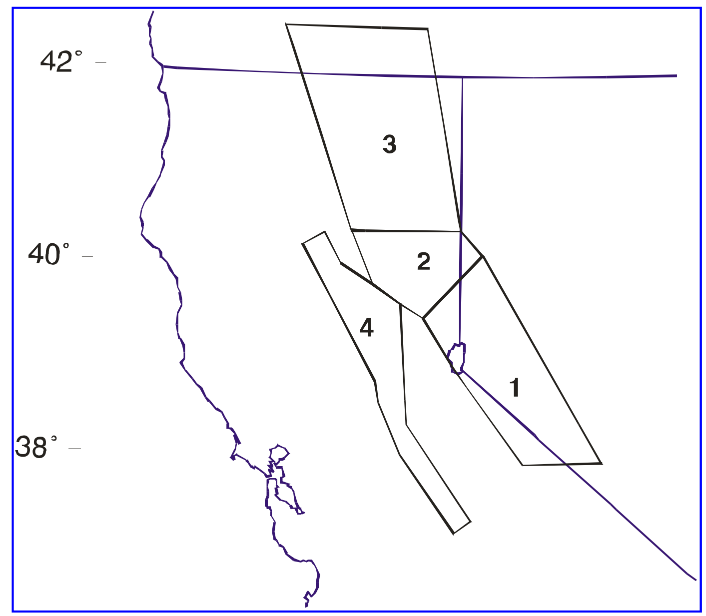
•Fault model: Use slip rates for calculating characteristic or floating partial-segment ruptures - GR (e.g., Wesnousky, Anderson).



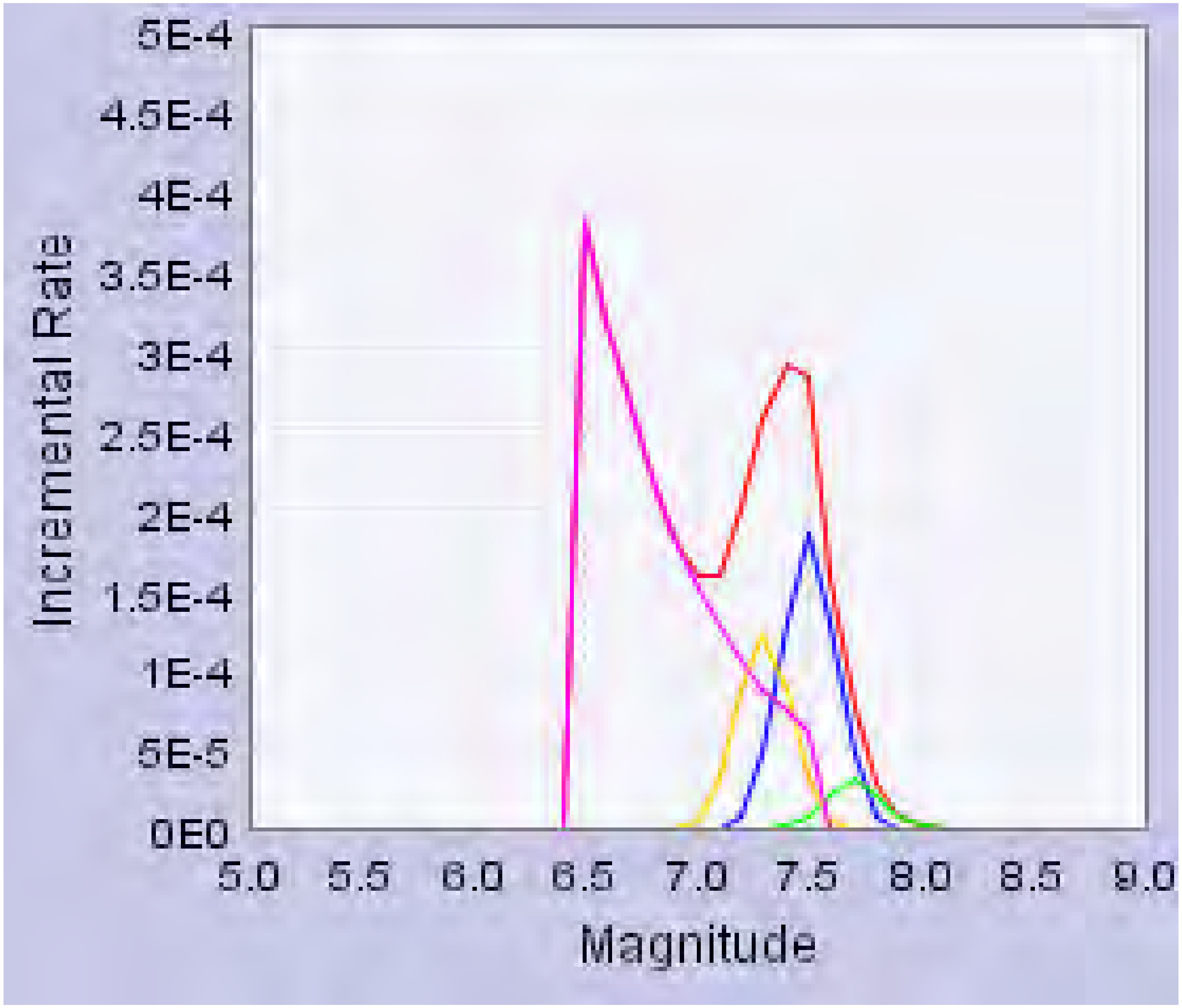


USGS National Seismic hazard map Magnitude-frequency distribution

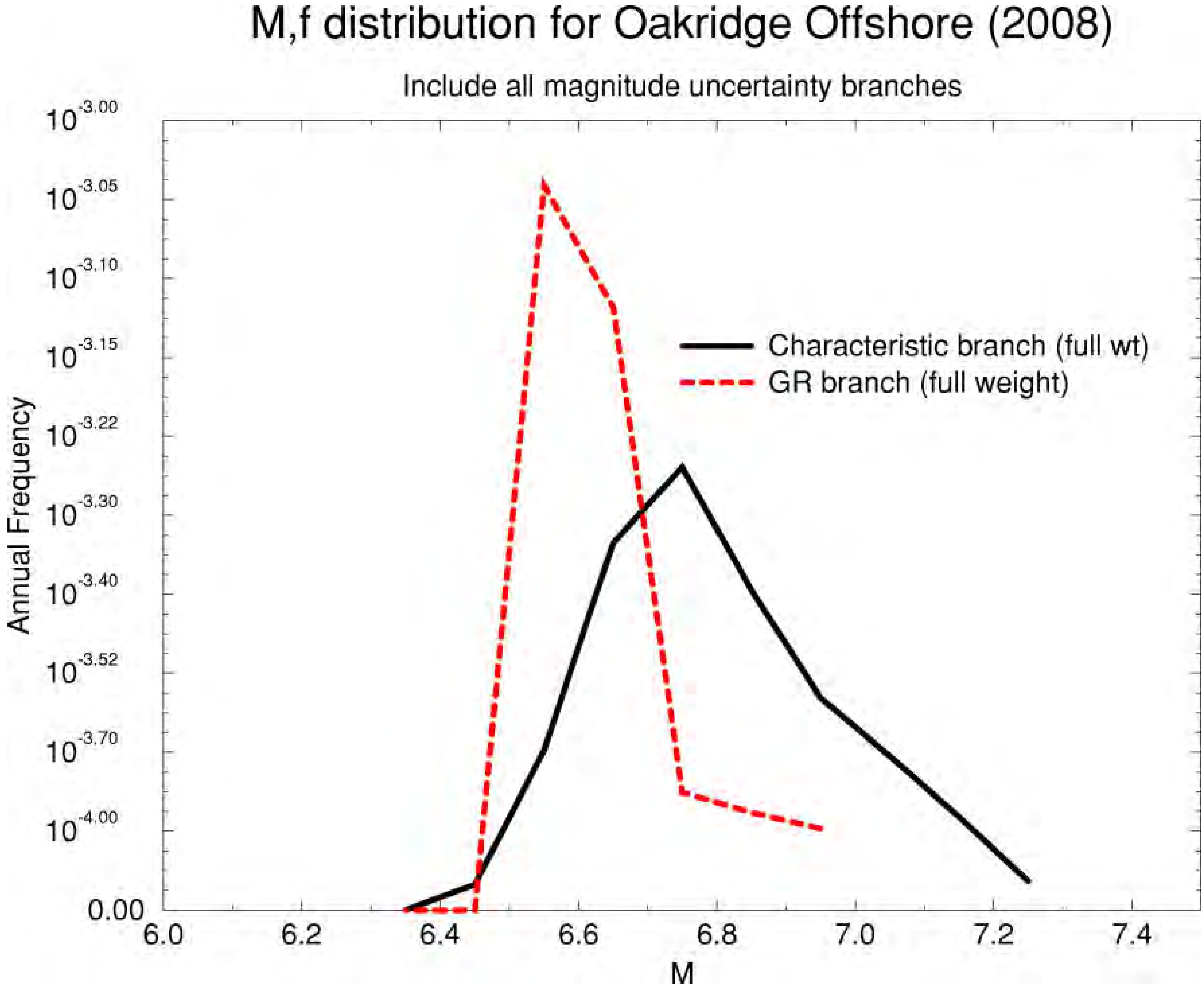
- Where geodetic data indicate significant strain but geology is not well defined we model shear zones.
- We use M 6.5 up to 7.6 on oriented line sources with recurrence defined by converting geodetic strain rates to moment rates.
- Geodetic models will be discussed at a workshop, summer 2012.



USGS Model for Faults (weights changed)



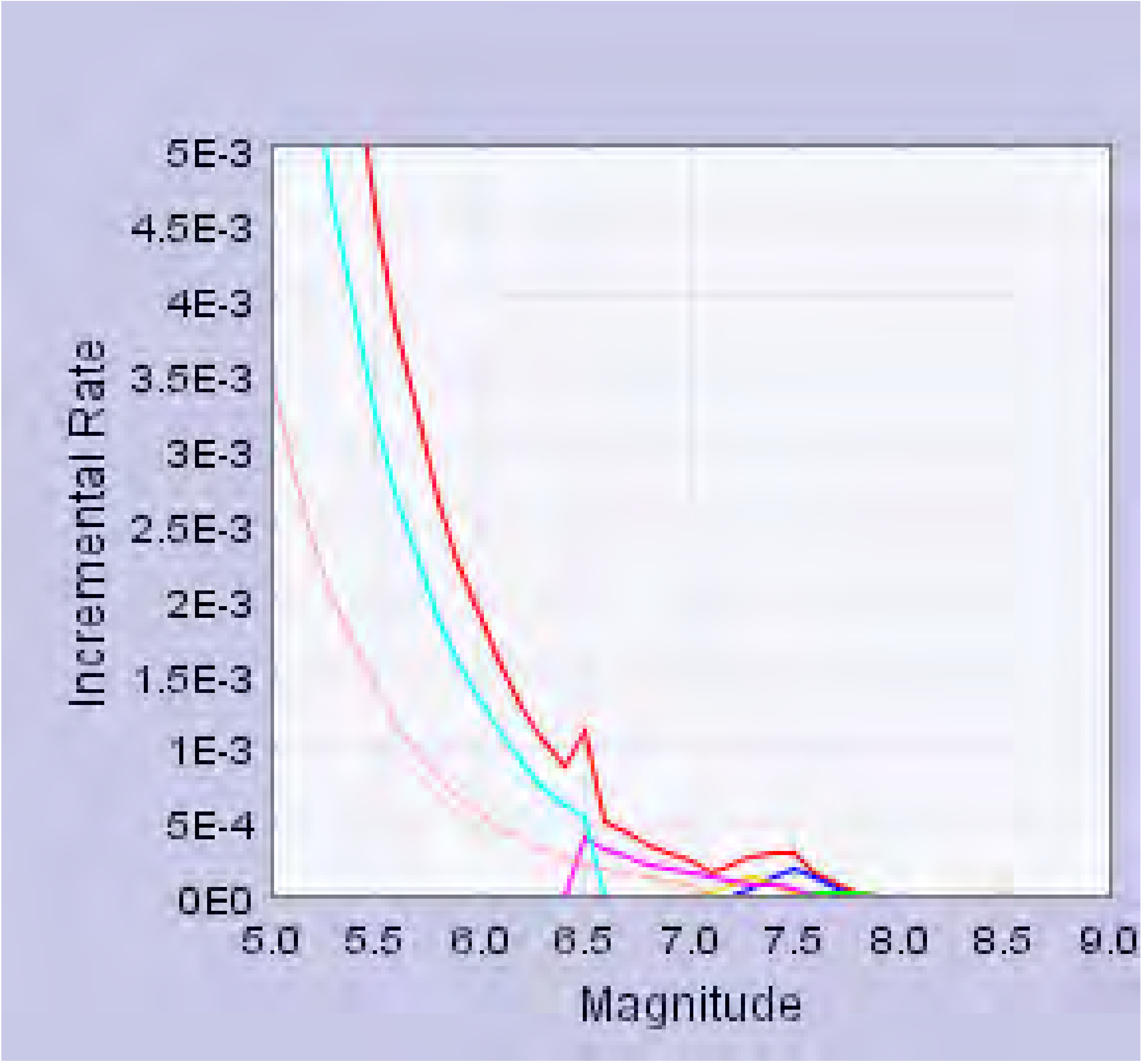
1. Moment rate 2E17/yr (2/3) split into three magnitudes – with additional aleatory variability σ = 0.12.
2. Moment rate 6.7E16/yr (1/3) used for floating ruptures (GR) maximum magnitude also split into three magnitudes, no additional aleatory variability.


M,f distribution for Oakridge Offshore (2008)
Include all magnitude uncertainty branches
Characteristic branch (full wt)
GR branch (full weight)
Annual Frequency
M
10^-3.00
10^-3.05
10^-3.10
10^-3.15
10^-3.22
10^-3.30
10^-3.40
10^-3.52
10^-3.70
10^-4.00
0.00
6.0
6.2
6.4
6.6
6.8
7.0
7.2
7.4

USGS National Seismic background source Magnitude-frequency distribution

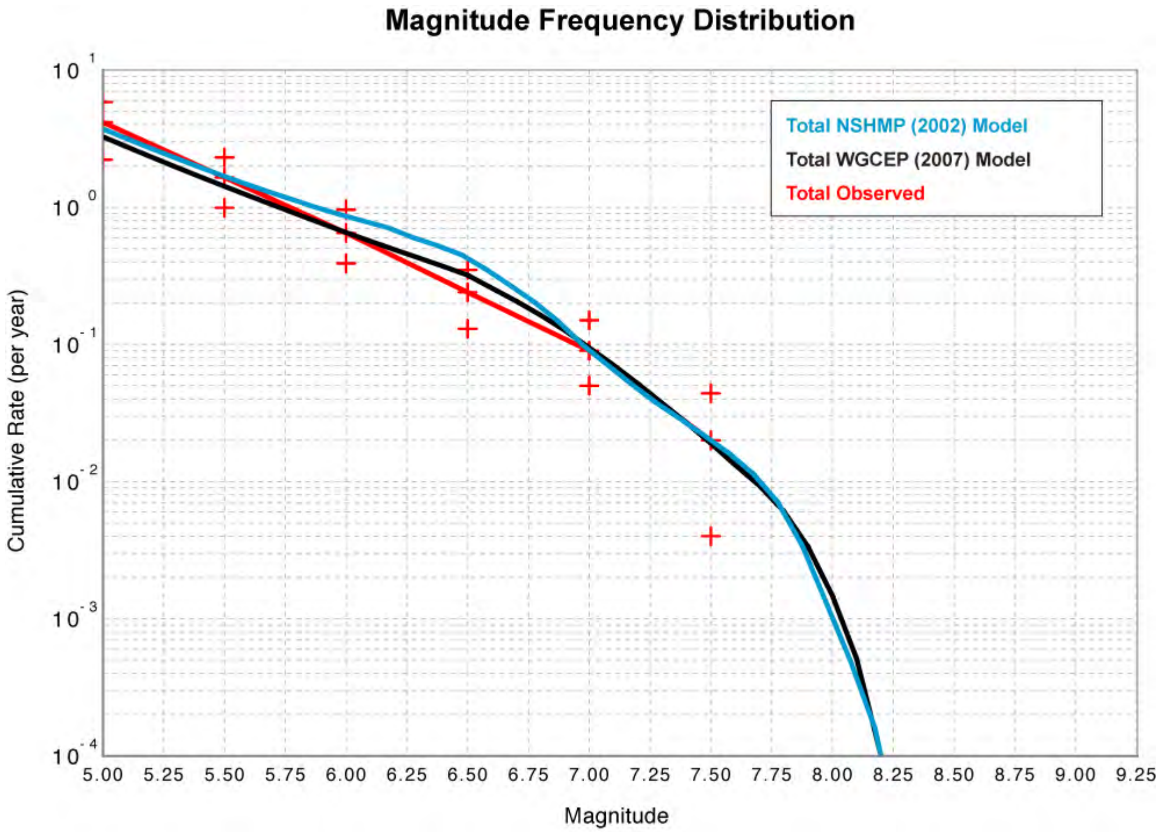
- To calculate random moderate size earthquakes use catalog to calculate 10^a values at evenly spaced grid points.
- Insures the number of earthquakes in the model $5 \leq M < 6.5$ is equal to the number in the catalog (with the exception of a few short faults with $M < 6.5$).
- Earthquakes are smoothed using a radial or anisotropic Gaussian smoothing operator with sigma about 32 km that extends out about 150 km.
- M 5-6 earthquakes are modeled as point sources and $M > 6$ are modeled as finite fault source with random or fixed strike.
- Described more in Session S2

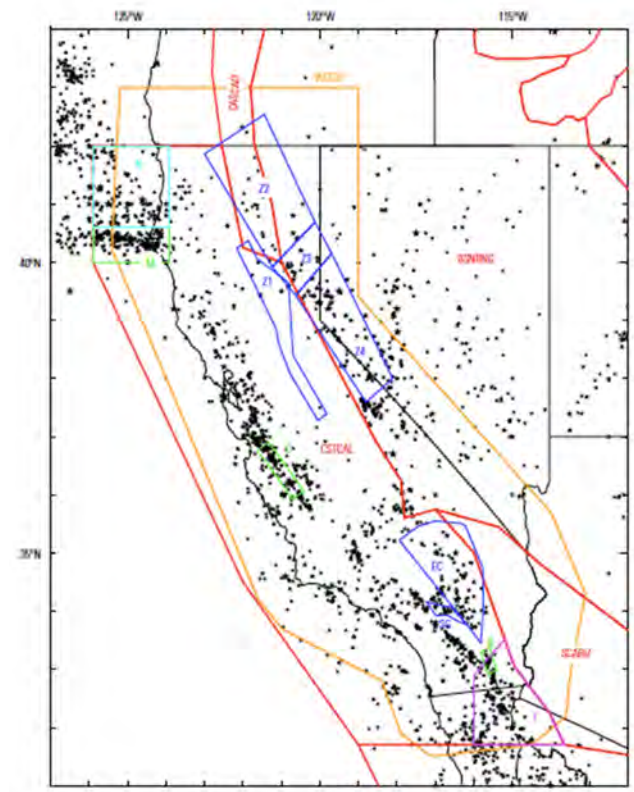
Source model



1. Moment rate 2E17/yr (2/3) split into three magnitudes
2. Moment rate 6.7E16/yr (1/3) used for floating ruptures (GR)
3. Moment rate 2E16/yr used for background earthquakes

M-f distribution and catalog rates

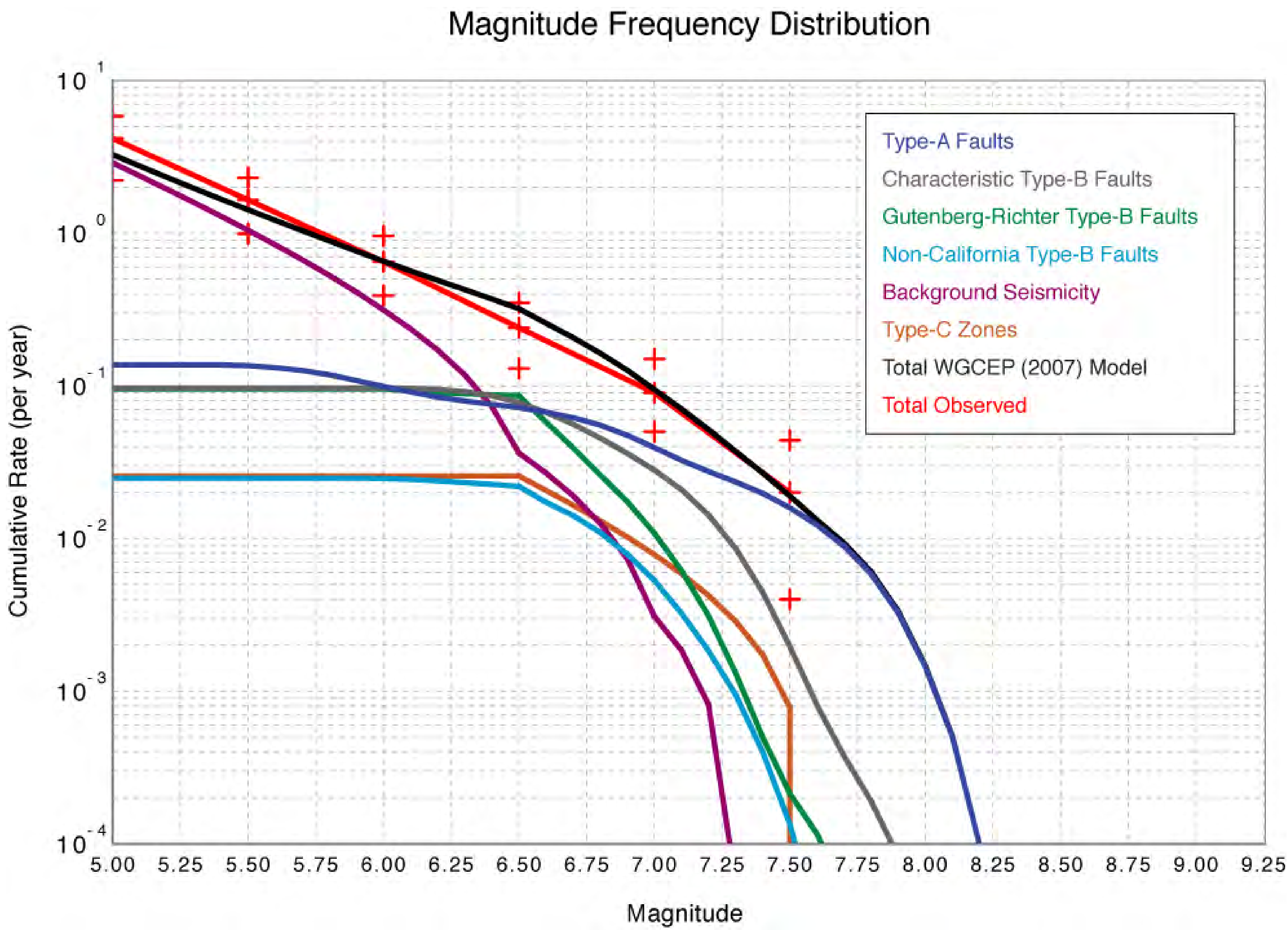




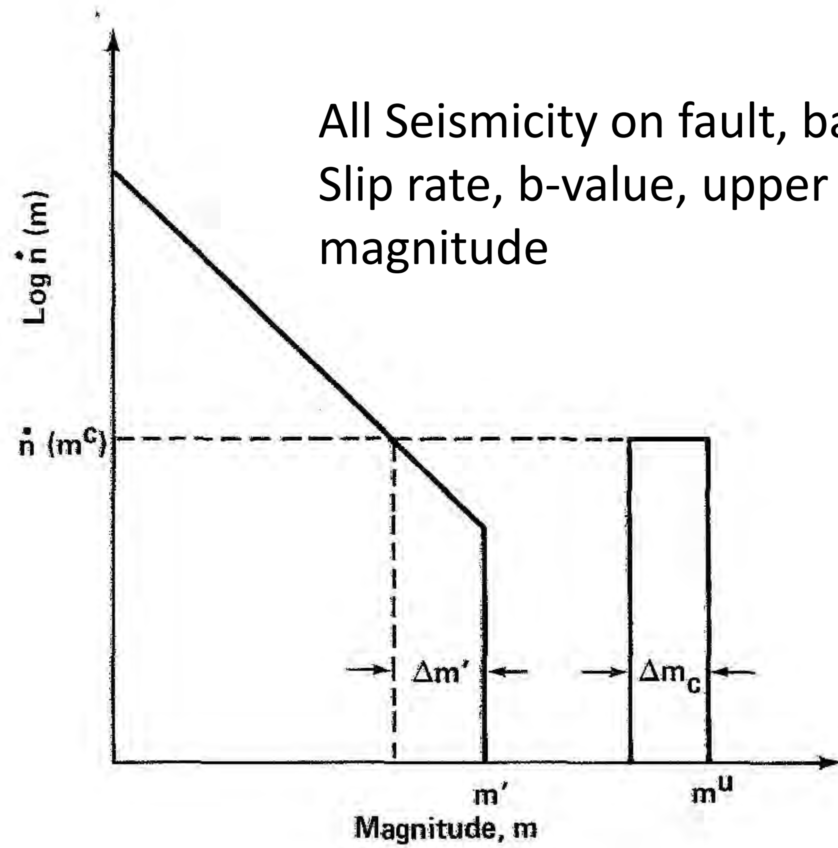
To solve the discrepancy between the model and catalog rate of earthquakes:

- GR b-value=0 option on Type-B faults (50% weight)
- A 10% slip-rate (or moment-rate) reduction applied to faults to account for off-fault deformation, smaller earthquakes, aftershocks and foreshocks.
- Inclusion of multi-segment ruptures on the larger sources
- Different weights for Char and GR
- The background seismicity GR distribution is reduced by a factor of 3 above M 6.5
- Regional GR b-value? (this was not changed in CA)

Contributions to hazard



Y&C model for determining WUS hazard

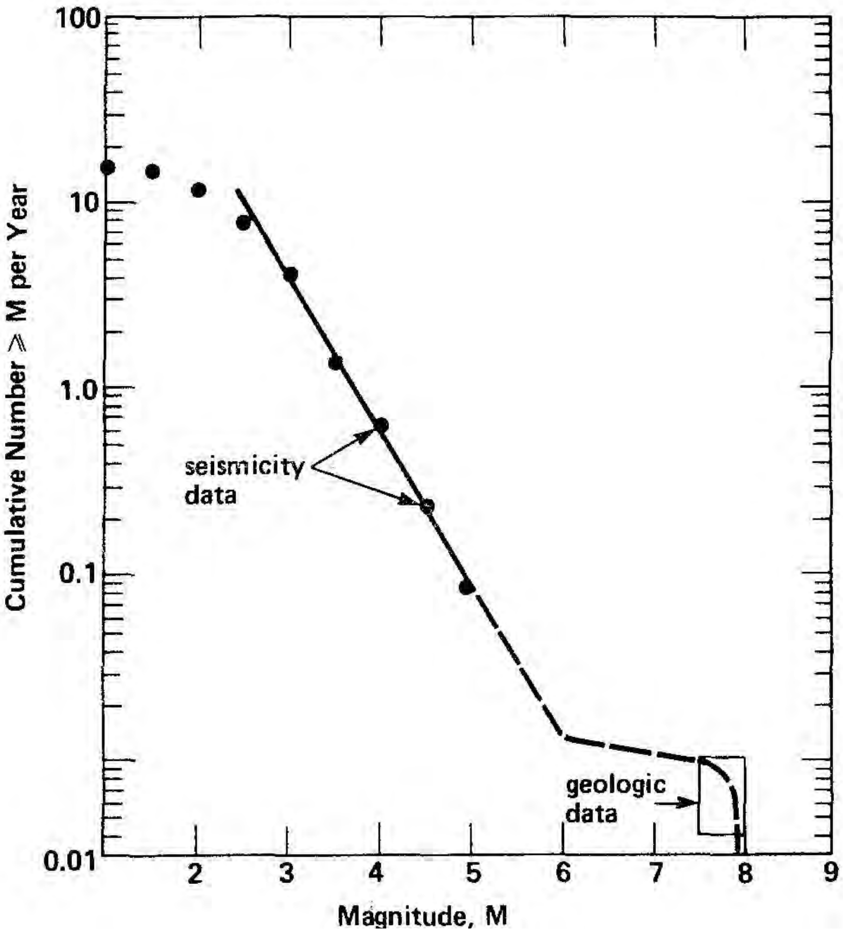


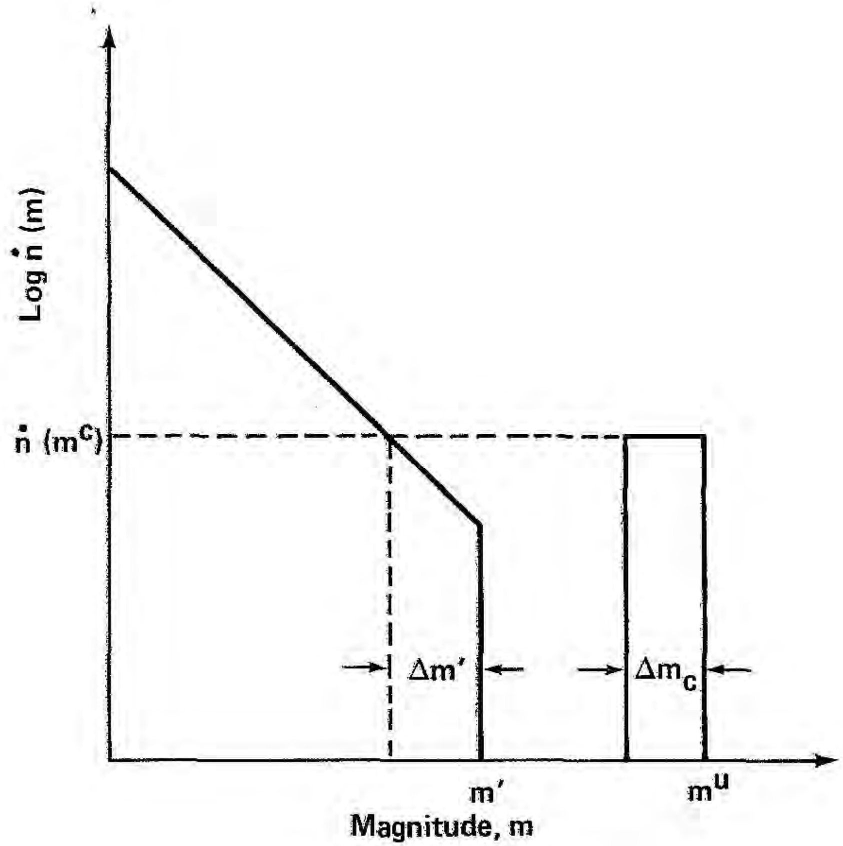
In addition to fault model –

•Need to have background seismicity model (based on earthquake catalog)

•Need to remove earthquakes that occur on faults from catalog.

Youngs and Coppersmith, 1985, fault characteristic or upper bound magnitude





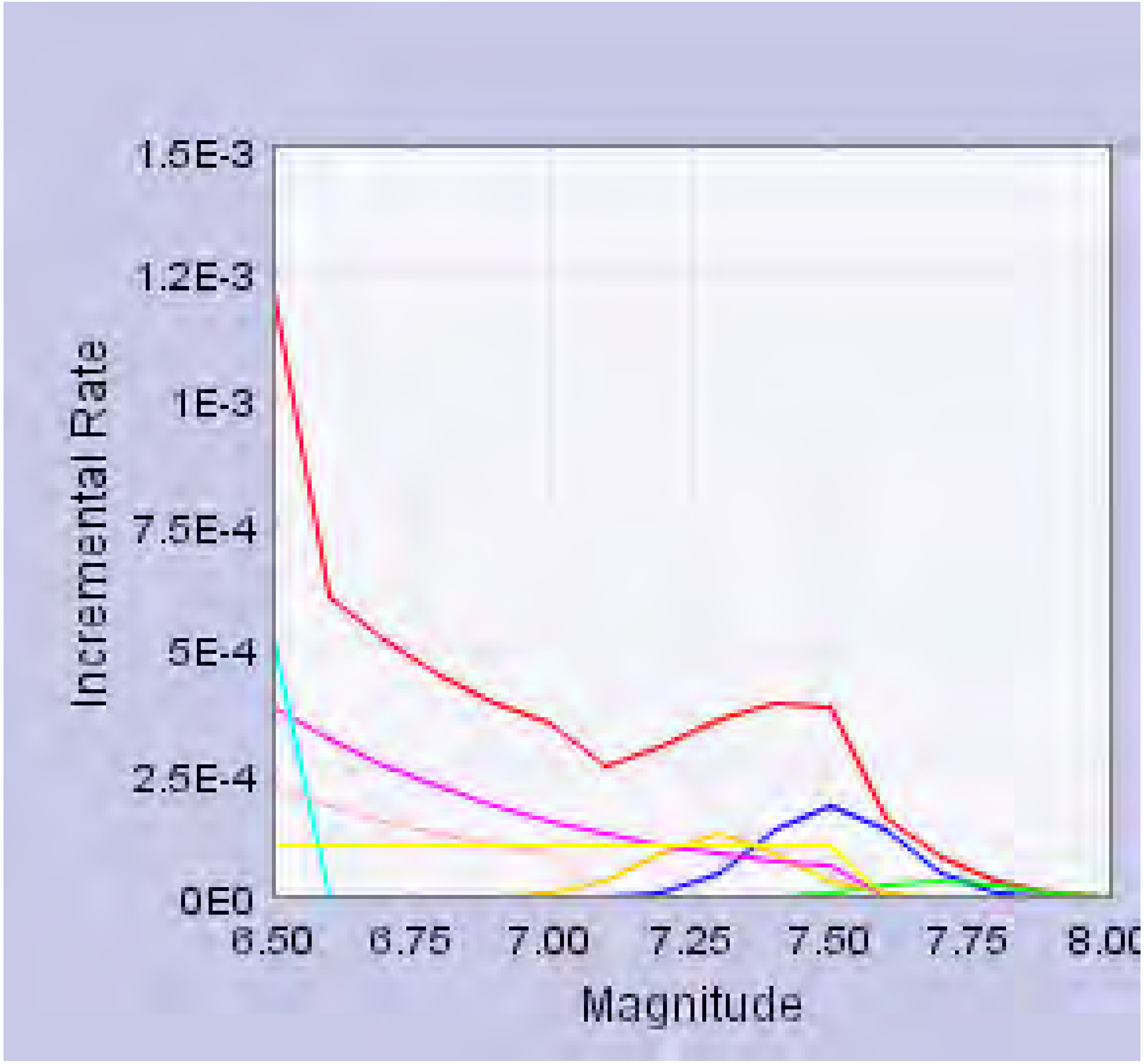
Youngs:
1. m_c=1/2 magnitude
2. $m'=m^u - \Delta m_c$
3. Flat portion of curve (m'-1)

How close is the seismicity to the fault?
(10 km?)

This model is used by the consulting industry.

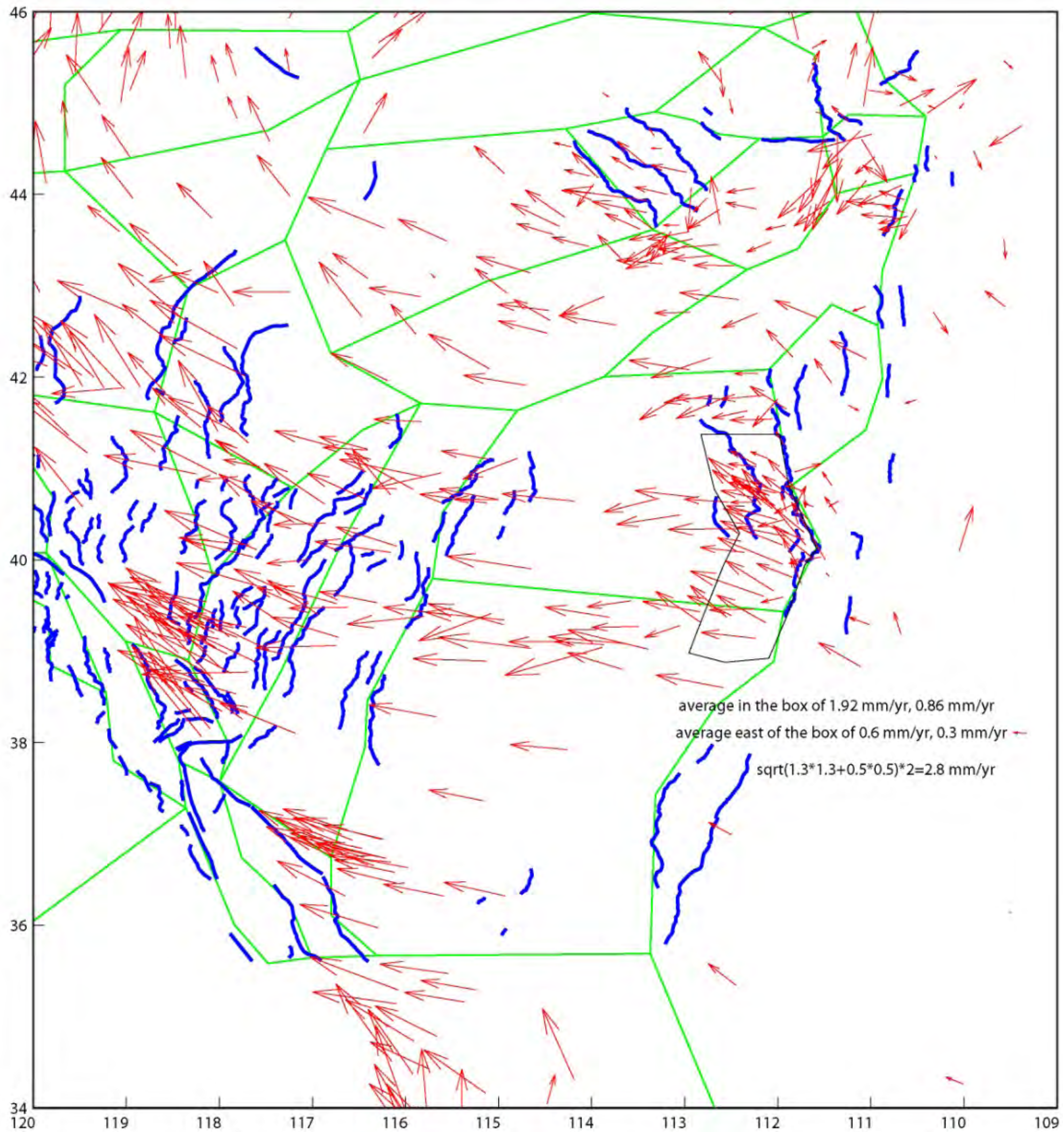
Model uncertainty

- Characteristic: +/- 0.2 epistemic (0.2, 0.6, 0.2 wts), sigma = 0.12 aleatory out two sigma.
- Floating ruptures: +/- 0.2 epistemic in magnitude, no aleatory.



1.5E-3
1.2E-3
1E-3
7.5E-4
5E-4
2.5E-4
0E0
Incremental Rate
6.50
6.75
7.00
7.25
7.50
7.75
8.00
Magnitude

GPS horizontal vectors in the WUS



Issue G1:
Calculating moment magnitudes for Basin and Range Province faults

Susan Olig (URS Corporation)
Chris DuRoss (UGS)

Basin and Range Province Earthquake Working Group II; November, 2011

DEFINING THE PROBLEM

ISSUE G1:

- "How should we calculate Mmax (*Mchar*) for BRP faults based on rupture lengths, fault areas, and available displacement data (Mmax of M 7.5 currently is used in the NSHMs and is based on the magnitude of the 1959 Hebgen Lake earthquake)?"

- "What is the source or explanation of the discrepancy between M calculated using surface-rupture length versus using the average or maximum displacement (site bias, underestimation of surface rupture length, other)? "

- "How should the discrepancy in the magnitude determined from these two measurements be handled in the NSHMs?"

PART 1: Capping Mmax *vs* PART 2: Best Approach for Estimating Mmax

OUTLINE

- ***Introduction***
  - Overview and background of G1 issue — ***Susan Olig & Chris DuRoss***
  - Current NHM approach used for estimating and capping Mmax — ***Kathy Haller***

- ***PART 1: Capping Mmax***
  - Historical observations, data limitations and uncertainties — ***Susan Olig***
  - Discussion and draft recommendation — ***All***

- ***PART 2: Best Approach for Estimating Mmax in the BRP (Better Understanding the M-SRL vs. M-D Discrepency in the BRP)***
  - Wasatch fault case study — ***Chris DuRoss***
  - Underestimating SRLs — ***Craig dePolo***
  - Overestimating displacements — ***Glen Biasi***
  - Large stress drops — ***Susanne Hecker***
  - Discussion and draft recommendation(s) — ***All***

History - BRPEWG I Recommendations

***Short Term** (2007 NSHMs):*

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

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

***Long Term**:*

- Develop new empirical regression relations among several other broad research objectives

BRPEWG I Recommendations Driven By:

- Discrepancy between M-SRL vs. M-D (e.g., Mason, 1996; Olig et al., 1997; Stirling et al., 2002)

- Observations that large historical BRP fault ruptures typically have included more than one segment (e.g., dePolo et al., 1991)

- Indications that paleo-displacements may be a better predictor of the size of expected Mmax (e.g., Hemphill-Haley and Weldon, 1999; Chang and Smith, 2002; Biasi and Weldon, 2006)

- Agreement that uncertainties need to be better addressed in estimating Mmax for NHM

BRPEWG II Issue G1 Driven By:

- Difficulty in implementing BRPEWG I recommendations (lots of questions about how, what, and who??)

- WGUEP Case Study
  - Highlighted different opinions about regressions and approaches (consensus not simple – even for Wasatch fault with lots of data)
  - Approach significantly affects Mmax (which affects hazard in multiple ways, including rates depending on how they are calculated)

Seismic Moment – Fundamental Measure of Earthquake Size

- $M_0 = \mu * A * AD$ (Aki, 1966)
  - M_0 = Seismic moment
  - μ = crustal rigidity/shear modulus (3 x 10^{11} dyne-cm)
  - Area (A) = surface-rupture length (SRL) * down-dip width (W)
  - AD = Average slip on fault *(average dislocation over area of fault surface)*

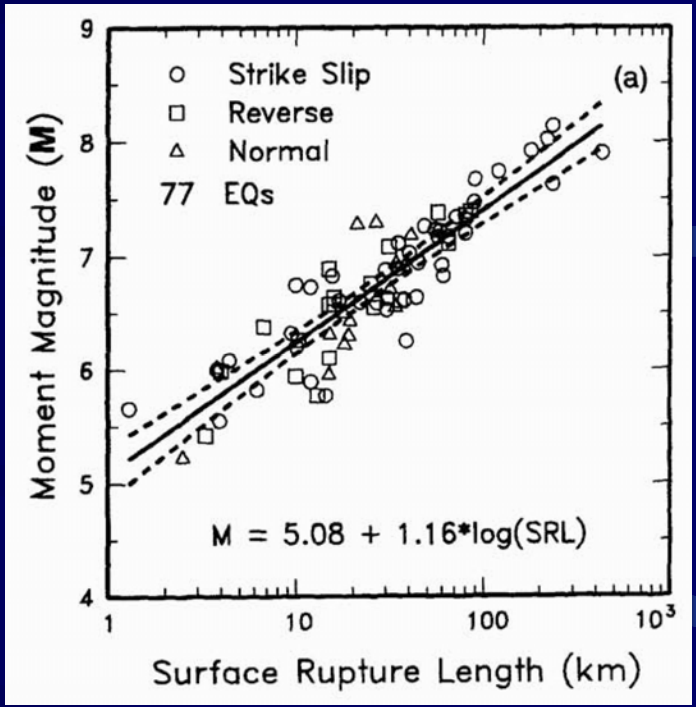
- Moment magnitude (**M**) (Hanks and Kanamori, 1979)
  - $\mathbf{M} = 2/3 \log M_0 - 10.7$

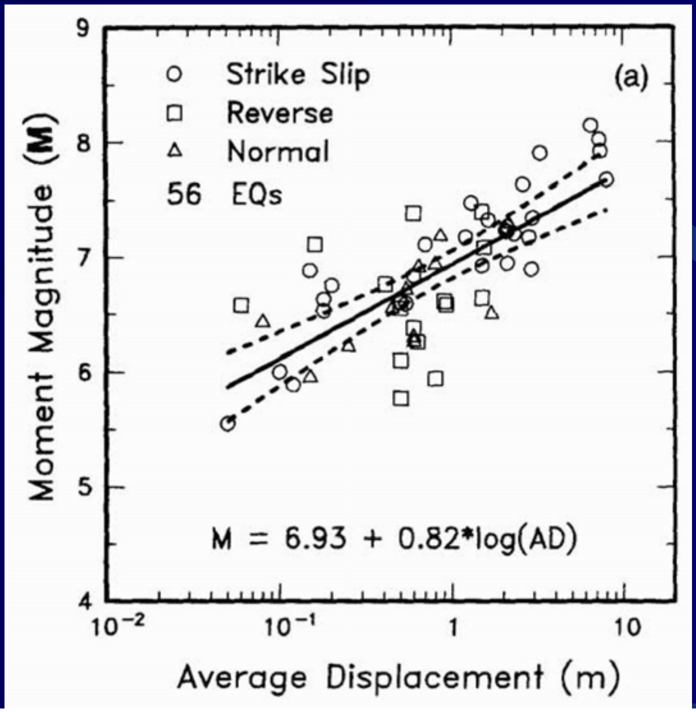
- Empirical linear regressions
  - $\mathbf{M} = a \log X + b$
  - X = fault parameter, e.g., SRL, W, A, D, SRL*D, A*D…
  - a, b = constants

Background – Wells and Coppersmith (1994) **M** Regressions

- WC94 all-slip-type regressions (recommended by WC- statistically more robust):
  - Area (A)
    M = 4.07 + (0.98 x log A); n = 148; r = 0.95
  - Surface rupture length (SRL)
    M = 5.08 + (1.16 x log SRL); n = 77; r = 0.89
  - Average displacement (AD)
    M = 6.93 + (0.82 x log AD); n = 56; r = 0.75

- WC94 normal slip regressions (consider because normal-slip events scale differently?)
  - Area
    M = 3.93 + (1.02 x log A); n = 22; r = 0.92
  - SRL
    M = 4.86 + (1.32 x log A); n = 15; r = 0.81
  - AD
    M = 6.78 + (0.65 x log AD); n = 12; r = 0.64





Potential Sources of **M-SRL and M-D** Discrepancies & Related Issues

1. Potential issues with the regressions
   a. Inconsistencies in defining and applying AD or SRL
   b. Scaling issues (Do large earthquakes scale differently than small earthquakes? Or do earthquakes in different tectonic environments scale differently? Or do different slip types scale differently?)
   c. Would multivariate (e.g., SRL * SR or SRL * D) regressions be better?

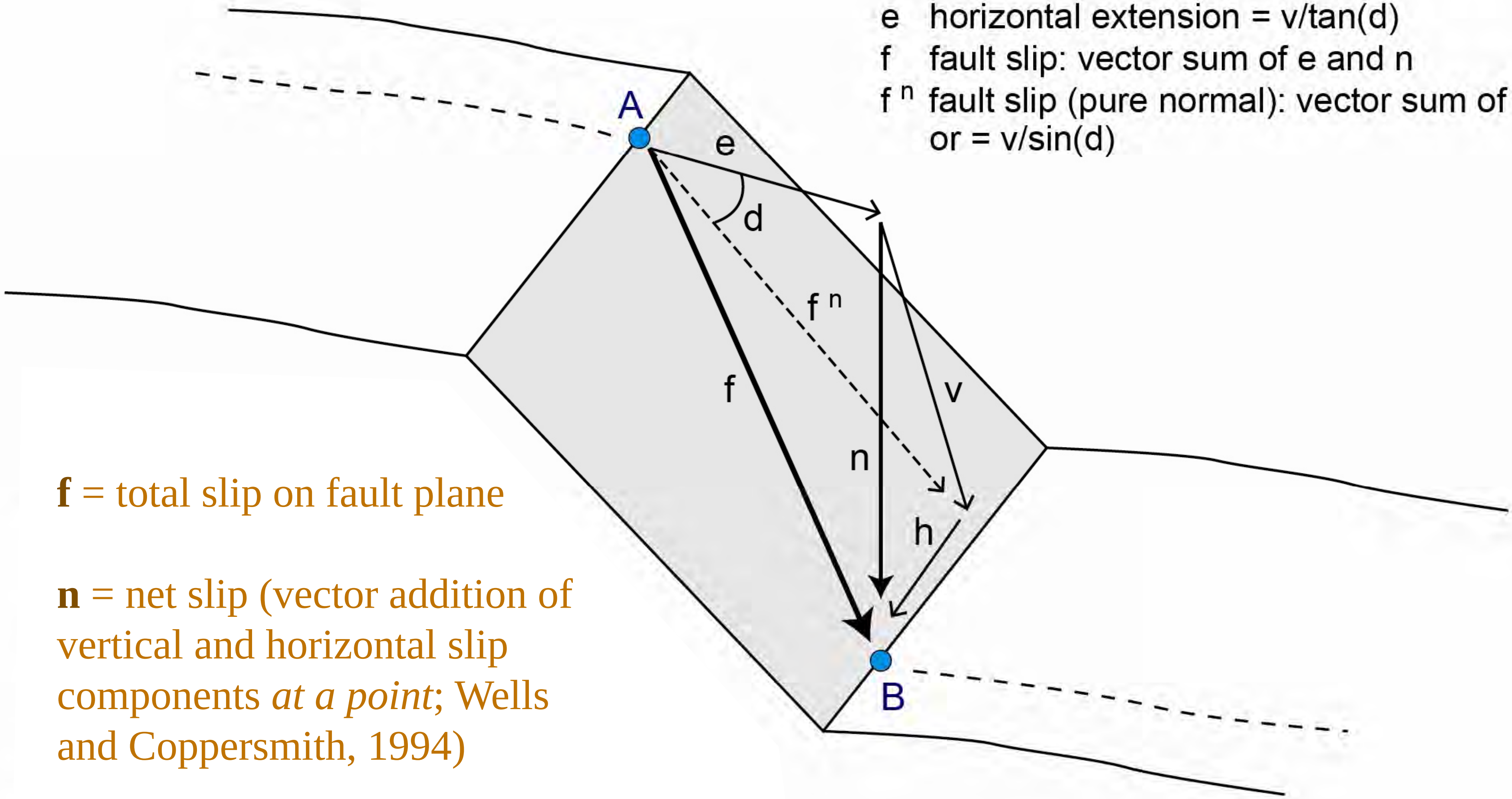
2. Underestimate surface rupture lengths (erosion/burial of small scarps, multisegment ruptures)
3. Overestimate displacements based on paleoseismic observations
4. Large stress drops
5. Other sources (uncertainty in fault dip and seismogenic depth)?

Issue 1. Inconsistencies in Inputs -What is AD?

M_0 relation uses **f** (if d <90°)

M regressions use **n** (or v, h)

- v vertical component of displacement
- h horizontal (lateral) component of displacement
- n net slip: vector sum of v and h (W&C, 1994)
- d fault dip
- e horizontal extension = v/tan(d)
- f fault slip: vector sum of e and n
- f^n fault slip (pure normal): vector sum of e and v, or = v/sin(d)



f = total slip on fault plane

n = net slip (vector addition of vertical and horizontal slip components *at a point*; Wells and Coppersmith, 1994)

Slip Vector Diagram

Issue 1. How do Surface and Subsurface Displacements Compare?

- Ratio of AD subsurface/AD surface ranges from 0.25 – 6.0

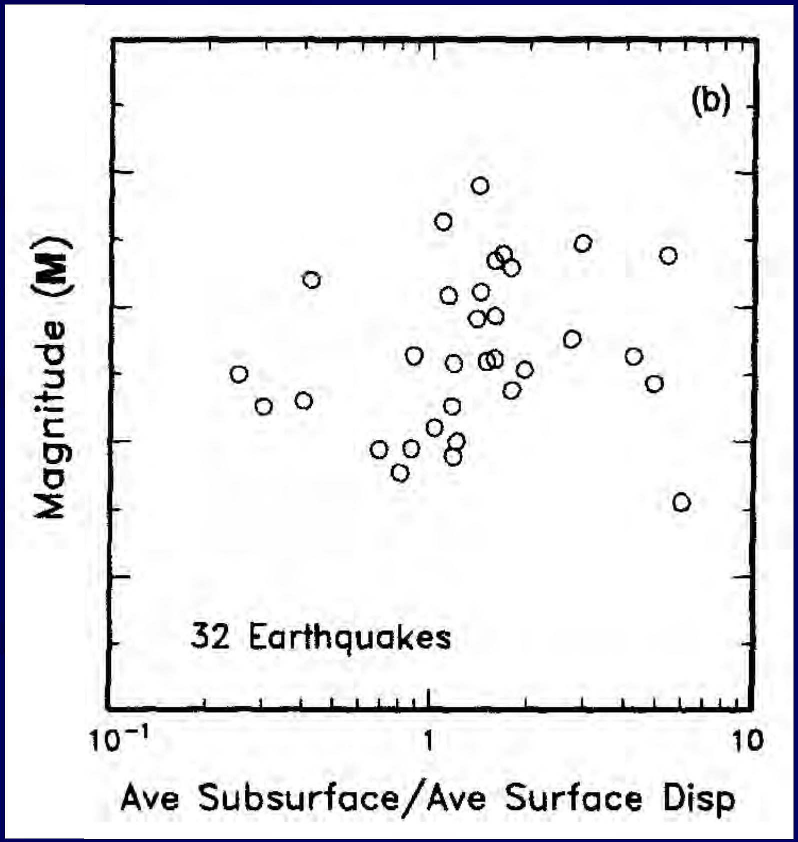


Fig. 6b from Wells and Coppersmith (1994)

Issues 1. Preinstrumental vs. Instrumental data bias

- Relations using preinstrumental (incl. prehistoric) data (blue dashed) result in larger **M** estimates than those based on instrumental relations (including WC94)

Stirling et al., 2002

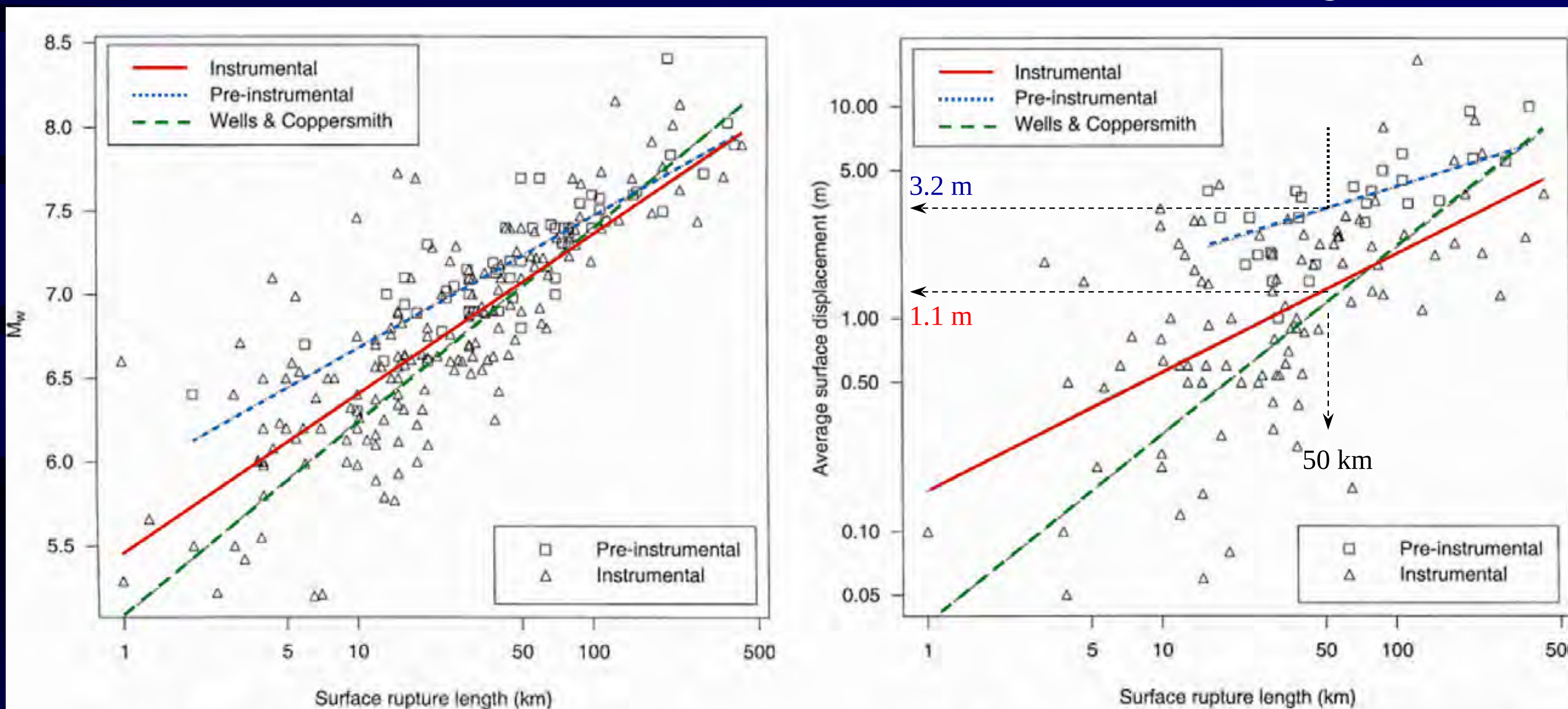


Figure 1. Regressions of magnitude versus surface rupture length for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters a and b for each of the regressions.

Figure 3. Regressions of average surface rupture displacement versus surface rupture length for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters a and b for each of the regressions.

Issues 1. Preinstrumental vs. instrumental data bias & scaling issues with size

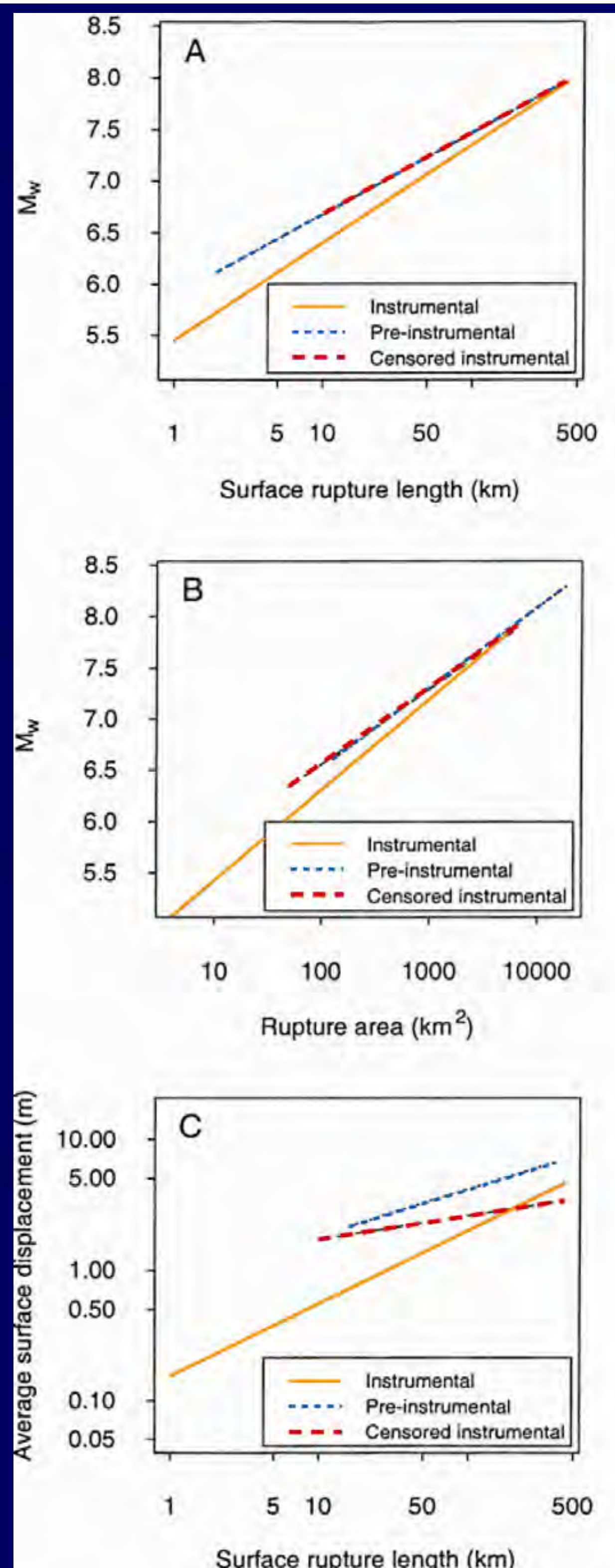
- Differences in regressions can be accounted for by the natural censoring of small events in the preinstrumental record

  (Red line: instrumental data censored for AD < 1 m, SRL < 5 km)

- Remaining (minor) differences between preinstrumental and censored instrumental (for D vs. SRL)
  - Overestimated AD (small scarps not included)
  - Underestimated SRL (small scarps not included)

- “Large earthquakes have different scaling relationships to those of smaller earthquakes”

Stirling et al., 2002

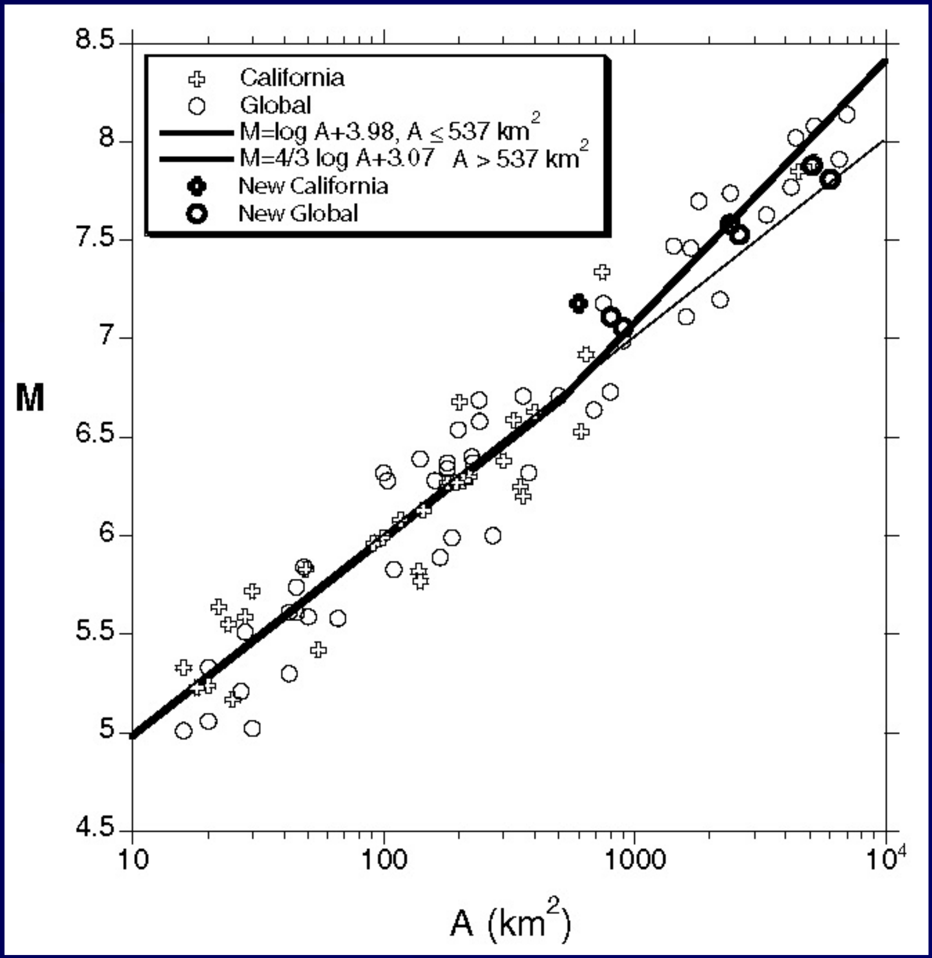


Issue 1. Do Large Earthquakes Have Different Scaling Relationships from Small earthquakes?

- Studies indicate a bilinear model better fits the data for strike-slip earthquakes with constant stress-drop scaling for smaller events and L-model scaling for larger events (Hanks & Bakun, 2002; 2008; Leonard, 2011)

- What regression is used in NHM for large strike-slip faults in the western BRP?

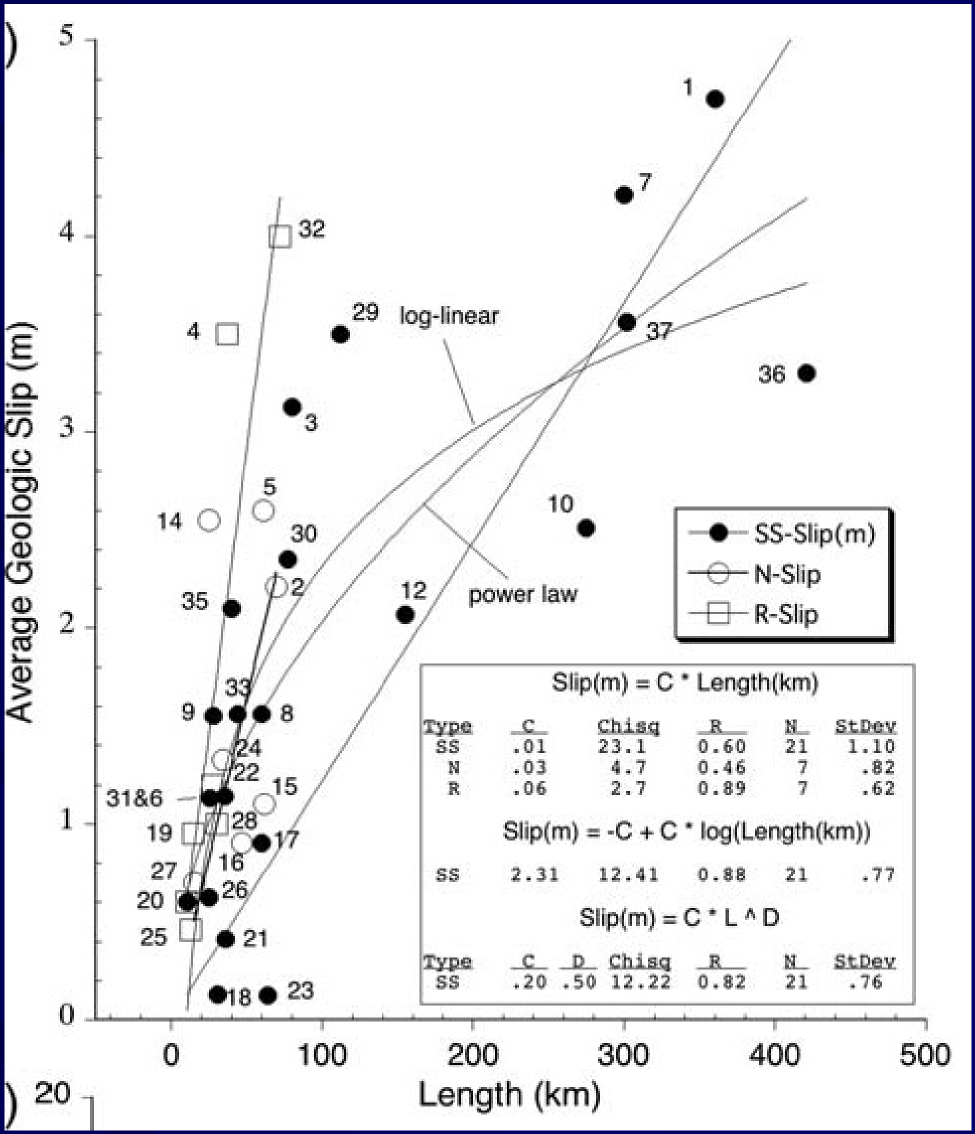
- Do large normal slip earthquakes also scale differently from small events?



From Hanks and Bakun (2008)

Issue 1. Scaling for AD vs. SRL

- Log-linear or power-law curves better fit strike-slip earthquakes (Wesnousky, 2008)
- Normal earthquakes are reasonably well fit by a straight line with slope between that of reverse and strike-slip (Wesnousky, 2008; WC 1994)
- Relationships for all fault types are dominated by strike-slip events- should we be using regressions for normal-slip events?



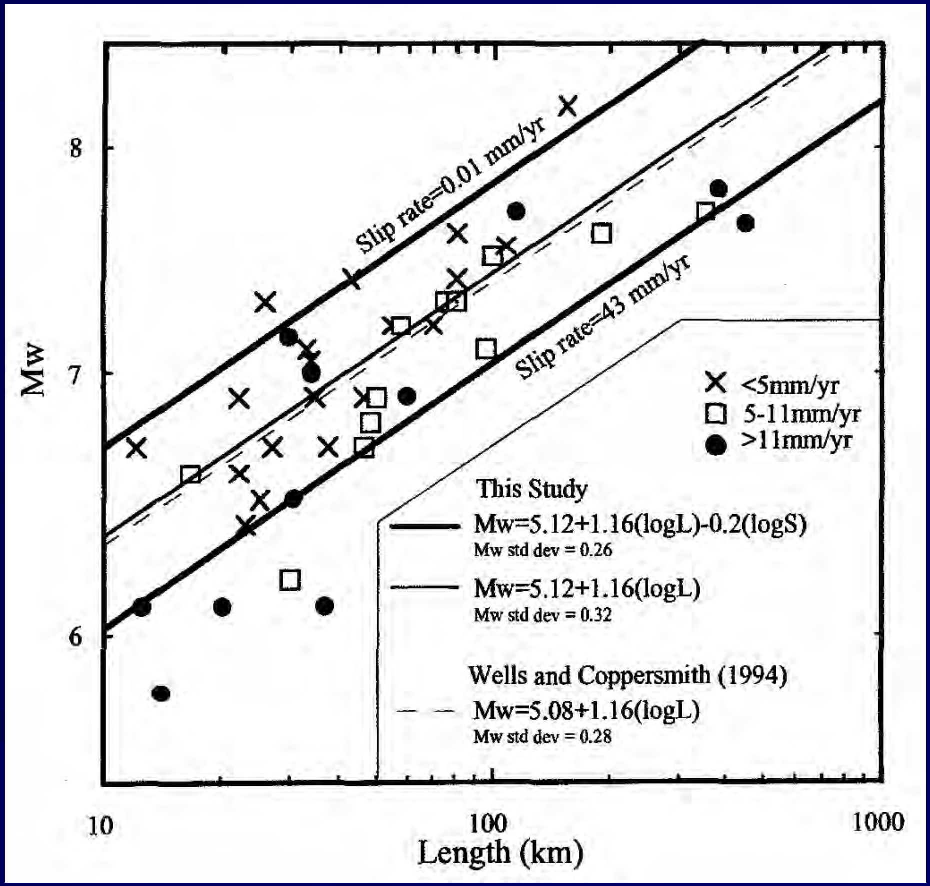
From Wesnousky (2008)

1. Scaling Issues – Tectonic environment, Strain Rate & Stress Drop

- Anderson et al. (1996) found that including slip rate (SR) with length (SRL) in the regression model provides a better fit to the data than just SRL alone (6 of the 43 total earthquakes where in BRP)

- Low SR → larger M_W (They suggest this is due to higher stress drop in low strain rate environments)

- Leonard (2011) also found differences between intraplate-dip-slip (SCR), interplate-dip slip and interplate –strike slip events



From Anderson et al. (1996)

Regression Issue 1. Should D and SRL be used in a multivariate analysis?

- Bonilla et al. (1984)
  - Found that correlating SRL*MD gave the most robust relationships (highest correlation coefficient and lowest standard deviation)

2404 M. G. BONILLA, R. K. MARK, AND J. J. LIENKAEMPER

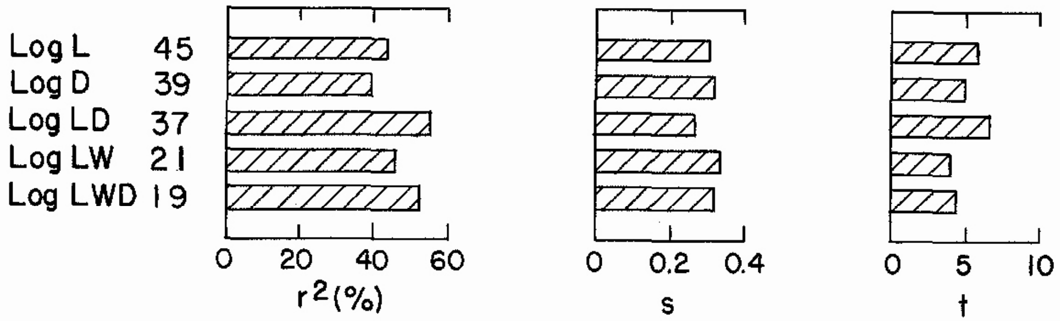


FIG. 7. Comparison of correlations of M_S with various rupture parameters. Regressions are of M_S on the given parameter, using ordinary least squares $M_S \geq 6$. Number of data points in each group is shown to *right* of parameter column. *L*, surface rupture length; *D*, maximum surface displacement; *W*, rupture width (downdip); r^2, coefficient of determination; *s*, standard deviation of M_S; *t*, *t* statistic. The *t* probability for the set log *LW* is 0.001, and is 0.000 for all the others.

- Mason (1996) also found more robust statistical correlation when AD and SRL were correlated.

DISCUSSION QUESTIONS

1. Should the NHM keep the present M 7.5 cap on Mmax or use a different distribution?

2. Given the discrepancies between M-SRL and M-D, what is the best approach for determining Mmax for BRP faults in the NHM? Is it the same for both strike-slip and normal faults?

   a. If we systematically underestimate SRL, can the amount be quantified for prehistoric ruptures?

   b. Does D scale with SRL or W for BRP faults? Different scaling for small vs. large earthquakes? Is a BRP region -specific relation needed?

   c. Can we blame large stress drops for the SRL-D discrepancy? If so, what to do about it? Use SRL-Slip Rate empirical relations (e.g., Anderson et al., 1996)?

DISCUSSION QUESTIONS

d. If we systematically overestimate AD, should we even be using AD regression relations as recommended by BRPEWG I? If so, which M-D regressions should be used? How should they be weighted? What criteria and guidelines can BRPEWG II recommend for applying these consistently in a straightforward approach for all BRP faults in the NHM?
   - W&C94: M(AD)
   - HHW99: M(AD-corrected)
   - H&K79: M(M0= m*A*AD)
   - B&W06: M(AD)

e. Formal recommendation to develop new **M** regressions? Layout path forward?
   - Update/revise WC94 catalog
   - Different scaling parameters (SRL*AD?) (SRL * SR?)
   - Censoring of small events (Stirling et al., 2002)
   - Regional regressions or slip type?

RECOMMENDATIONS

Short-Term Recommendations

Part 1 –

Part 2 –

Long-Term Recommendations

Part 1 –

Part 2 –

2. Underestimated SRLs

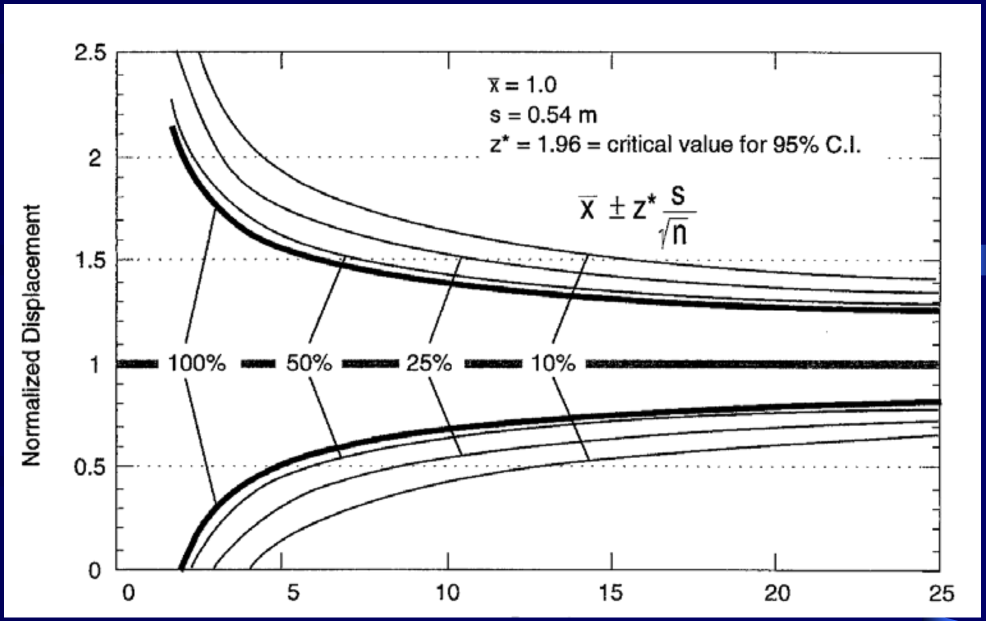
- Multisegment ruptures are common (dePolo and Slemmons, 1991) but usually do not have enough paleoseismic data to characterize these for NHM

- Wells and Coppersmith (1994)
  - SRL = 75% of subSRL (aftershock zone)

- Burial and erosion of smaller scarps near rupture endpoints – Underestimate SRL by ~25% if small displacements (equal to 0–10% of MD) are removed by weathering/erosion (10 normal fault ruptures) (McCalpin and Slemmons, 1996)

3. Overestimated Displacement

- D more reliable measure of **M** than SRL
  - Because of scarp preservation and field sampling issues, tend to overestimate AD, underestimate SRL

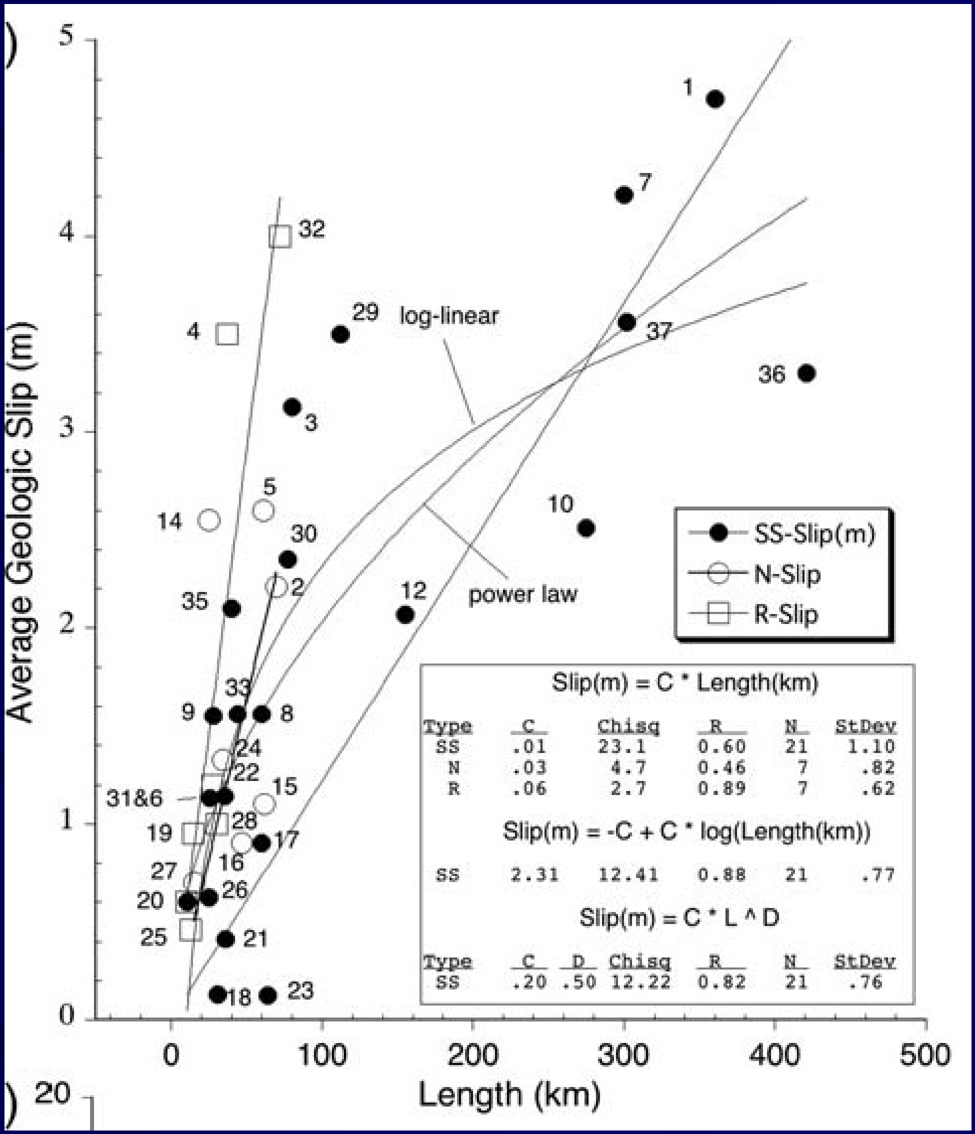


- Analytical model
  - Uncertainty decreases with sample size (large when <3, ideal # is 5–10)
  - For fixed # samples, uncertainty <u>increases</u> with % of fault rupture sampled
  - For small # samples or fault %, sample mode consistently overestimates sample mean

- Application to Paleoearthquakes
  - Correction to AD based on # samples and % of rupture sampled
  - Area sampled – based on mapped trace or D-SRL regression?
  - "We would hesitate to use less than 3–5 measurements because of the extremely large uncertainties"

Issue 1b. Scaling for AD vs. SRL

- Log-linear or power-law curves better fit strike-slip earthquakes
- Normal earthquakes are reasonably well fit by a straight line with slope between that of reverse and strike-slip
- Relationships for all fault types are dominated by strike-slip events- should we be using regressions for normal-slip events?



From Wesnousky (2008)

Issue G1 – Part 1: Capping Mmax
(Putting a Lid on Mmax for Long, Unsegmented, Normal-Slip BRP Faults)

Susan Olig (URS Corporation)
Chris DuRoss (UGS)

Basin and Range Province Earthquake Working Group II; November, 2011

Largest Normal-Slip Earthquakes

- 1959 Hebgen Lake, MT: M_W 7.3
- *1954 Dixie Valley-Fairview Peak, NV: M_W 6.9 & 7.2**
- 1915 Pleasant Valley, NV: M_W 7.2
- 1887 Sonora, Mexico: M_W 7.4 – 7.6
- *1872 Owens Valley, CA: M_W 7.6**

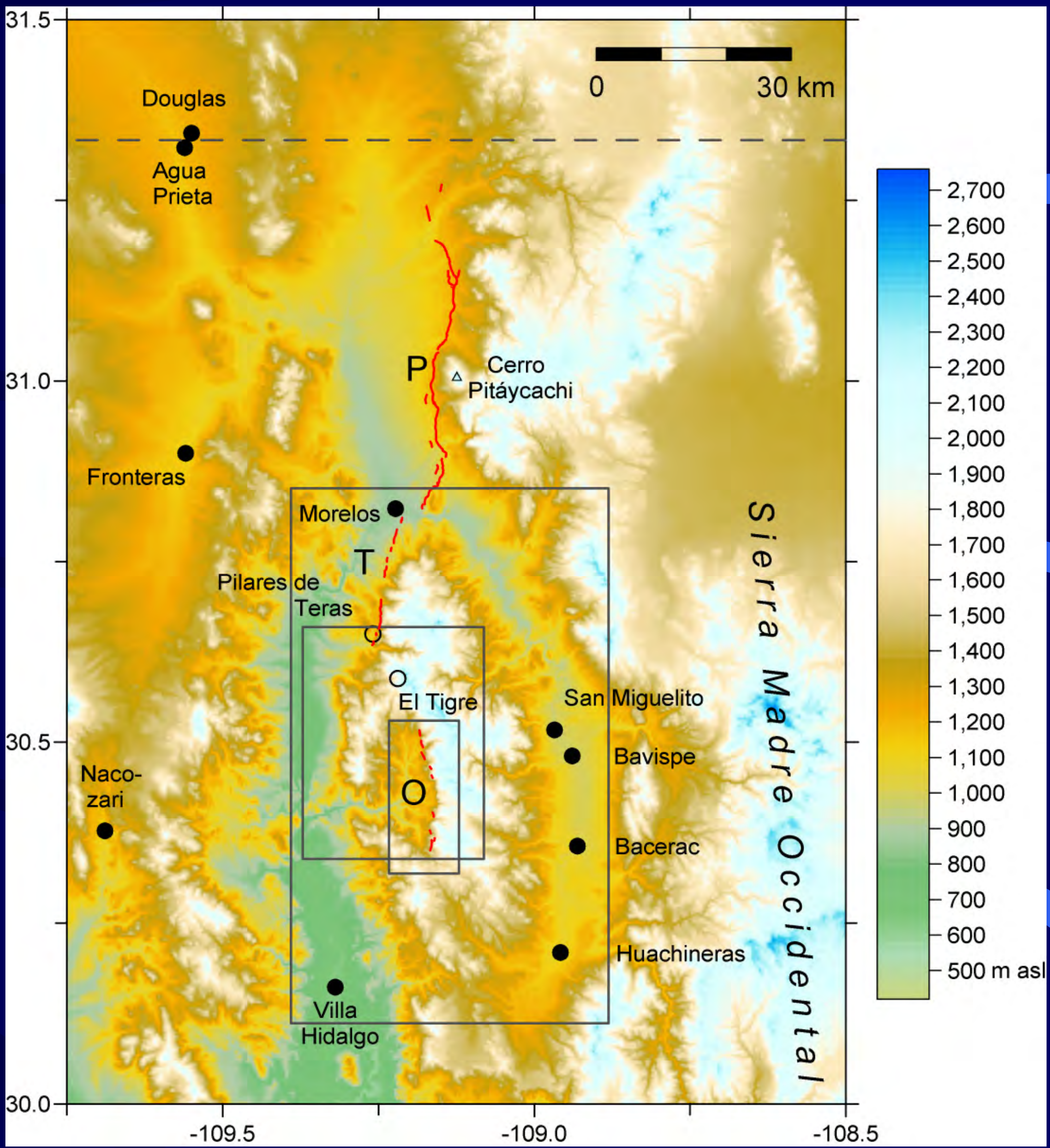
* *Included significant strike-slip component*

3 May 1887 Sonora (Pitaycachi) Earthquake

Previous Parameters (W&C 1994):	Revised Parameters (Suter and Contreras, 2002; Suter, 2006; Bakun, 2006):
M_W 7.31	M_W 7.5 ± 0.3
SRL = 75 km	SRL = 102 km
MD = 4.5 m	MD = 5.1 m
AD = 1.9 m	AD = 1.1 – 2.7 m
	SR = 0.06 mm/yr

1887 Sonora Earthquake

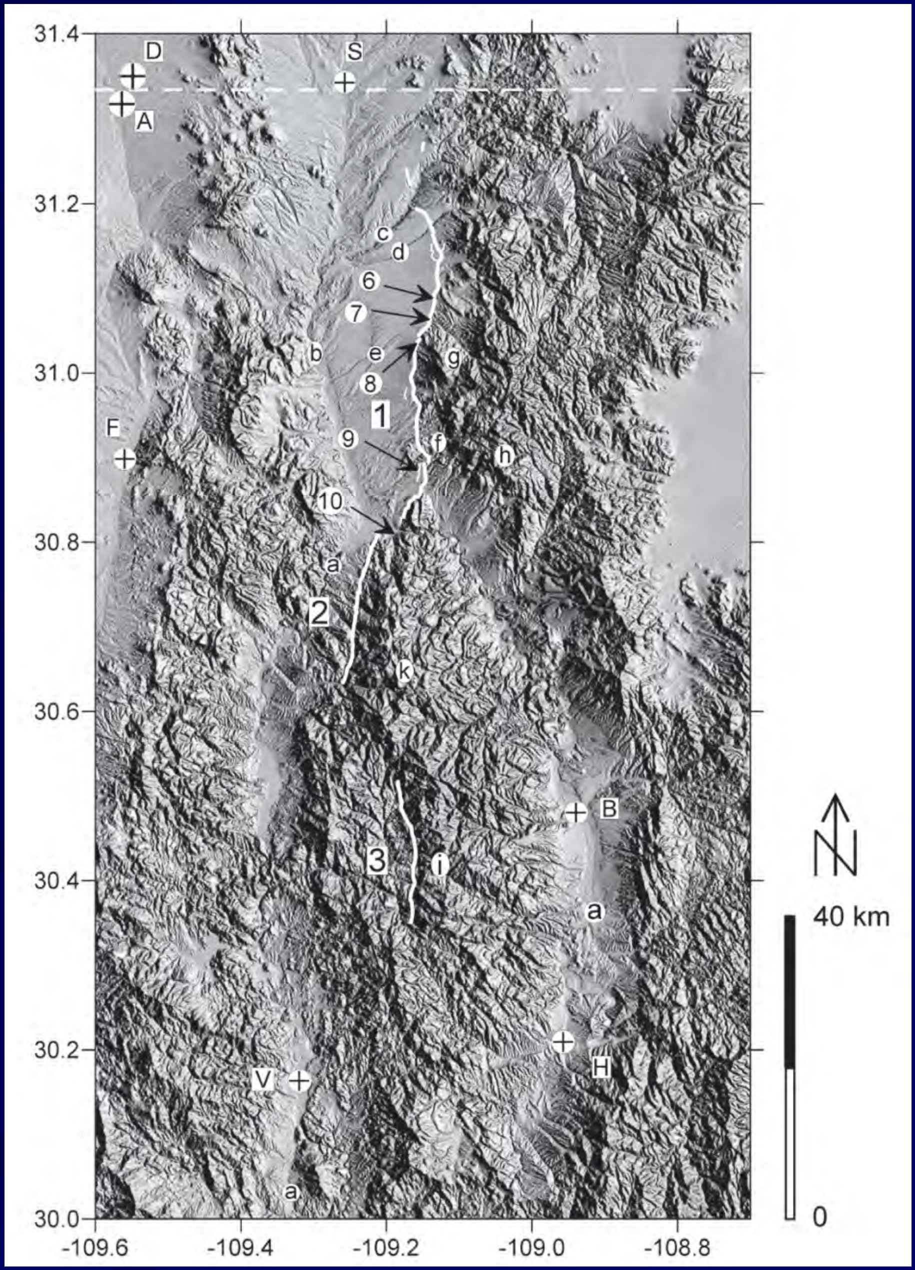
- Part of a 300-km-long N-S striking down-to-the-west normal fault along western flank of Sierra Madre Occidental in Sonoran BRP
- Ruptured 3 “segments” (Pitaycachi – 44 km; Teras – 21 km; & Otates – 19 km)



From Suter (2008)

1887 Sonora Earthquake

- Maximum vertical slip 5.1 m; horizontal slip negligible
- Average vertical slip:
  Pitaycachi – 2.3 m
  Teras – 1.1 m
  Otates – 1.9 m



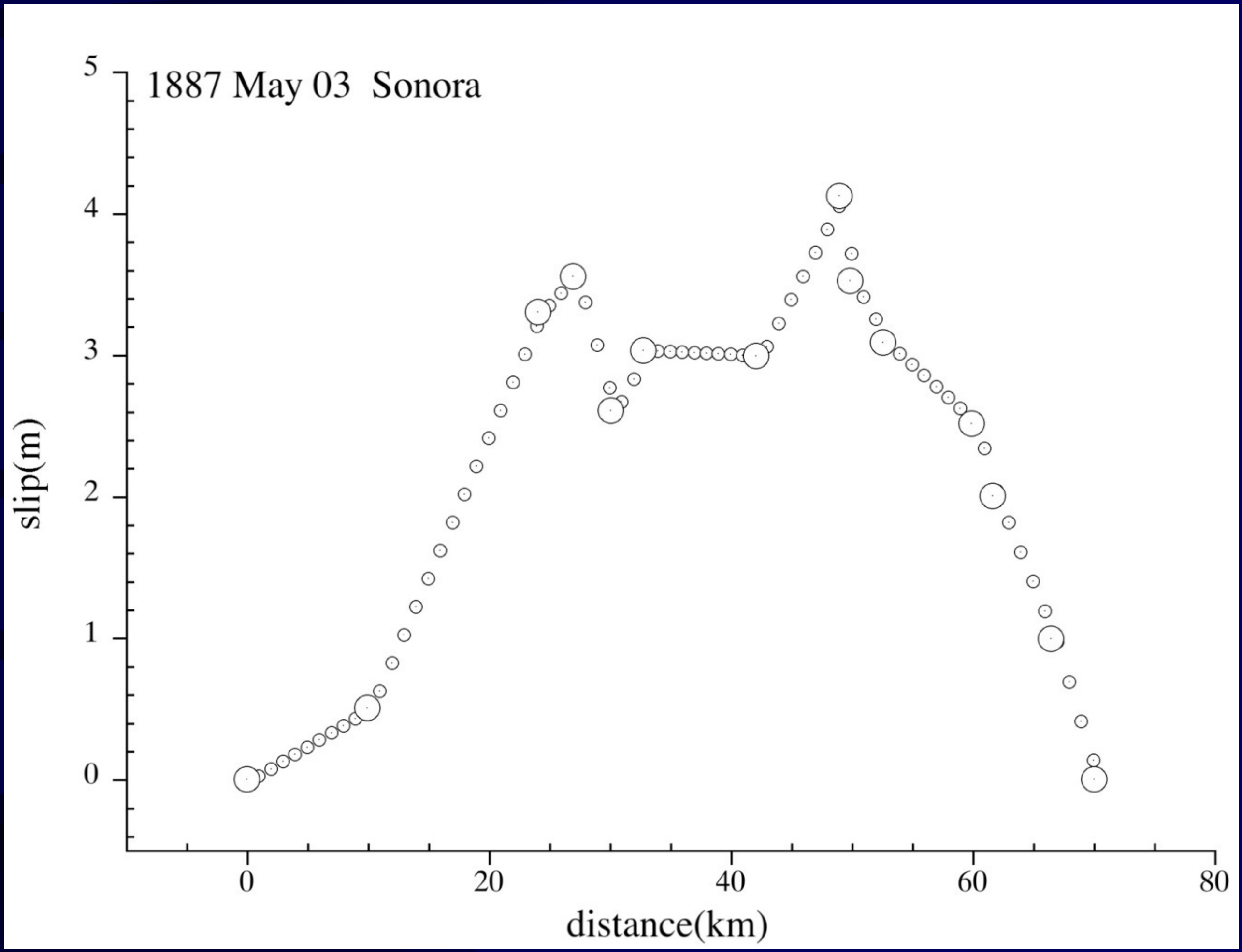
From Suter (2008)

1887 Sonora Earthquake

Scarp is ~4.4 m high.

Photo by Camillus Fly; From Suter (2006)

1887 Sonora Earthquake



AD = 2.2 m

From Wesnousky (2008)

Magnitude Estimates – 1887 Sonora Earthquake

Regression/Analysis	Input Parameter(s)	Estimated M_W
WC-SRL -All -Normal	SRL = 102 km	7.4 ± 0.28 7.5 ± 0.34
Anderson et al. (1996)	SRL = 102 km; SR = 0.06 mm/yr	7.7
WC-RA -All -Normal	Dip = 74°; Depth = 16 km A = 1697 km^2	7.2 ± 0.24 7.2 ± 0.25
WC-MD -All -Normal	5.1 m	7.2 ± 0.40 7.1 ± 0.34
WC-AD -All -Normal	2.2 m	7.2 ± 0.39 7.0 ± 0.33
Hanks & Kanamori (1979) $M_O = A * AD * \mu$	A = 1697 km^2; AD = 2.2 m $\mu = 3x10^{11}$ dyne/cm^2	7.3 (7.5 for 50° dip)
Bakun (2006)	Intensity	7.5 (7.2-7.7)
Suarez & Hough (unpublished)	Intensity	7.6

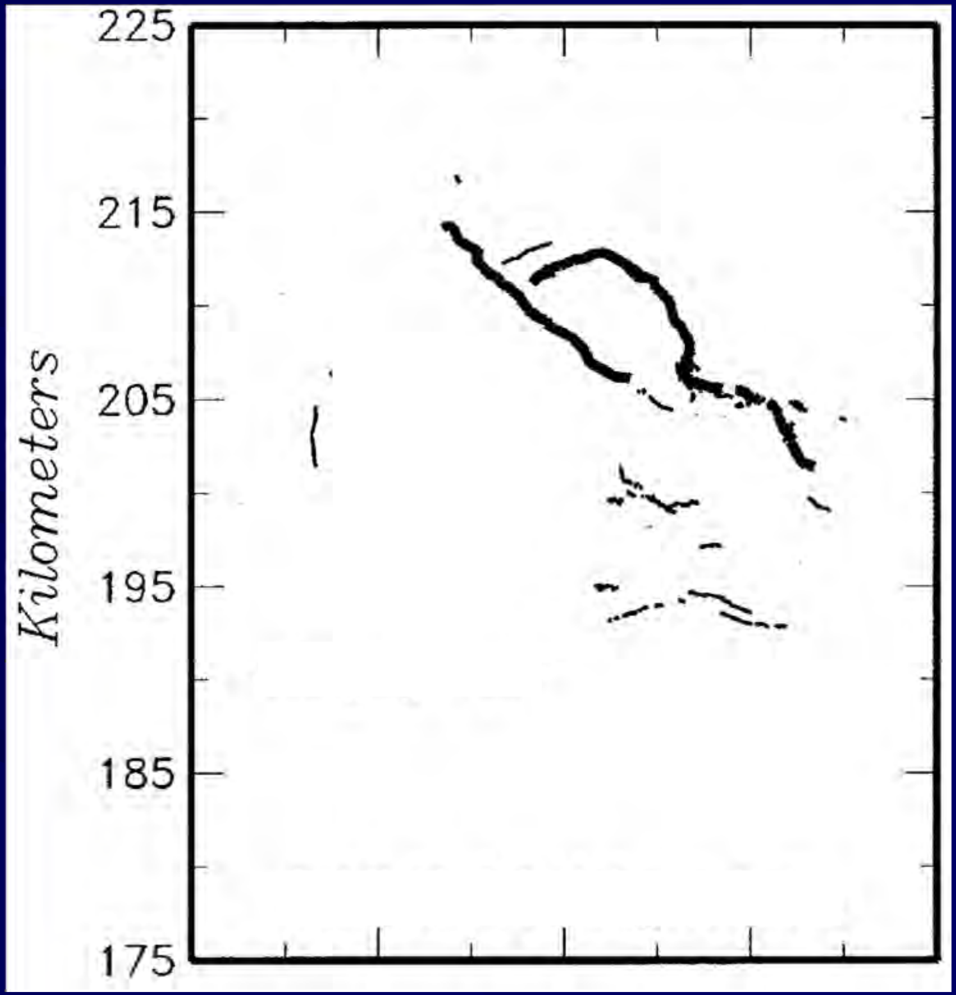
18 August 1959 Hebgen Lake, MT Earthquake

- M_S 7.5 (Abe, 1982)
- M_O 1.0 x 10^{27} dyne-cm (Doser, 1985)
- M_W 7.3 (Arabasz et al., 1992)

1959 M_W 7.3 Hebgen Lake Earthquake

- Complex rupture included:
  - Red Canyon fault
  - Hebgen fault
  - Unnamed faults in Hebgen Lake basin
  - West Fork fault
  - Short section of Madison fault

- SRL = 27 km



From Pezzopane and Dawson (1996)

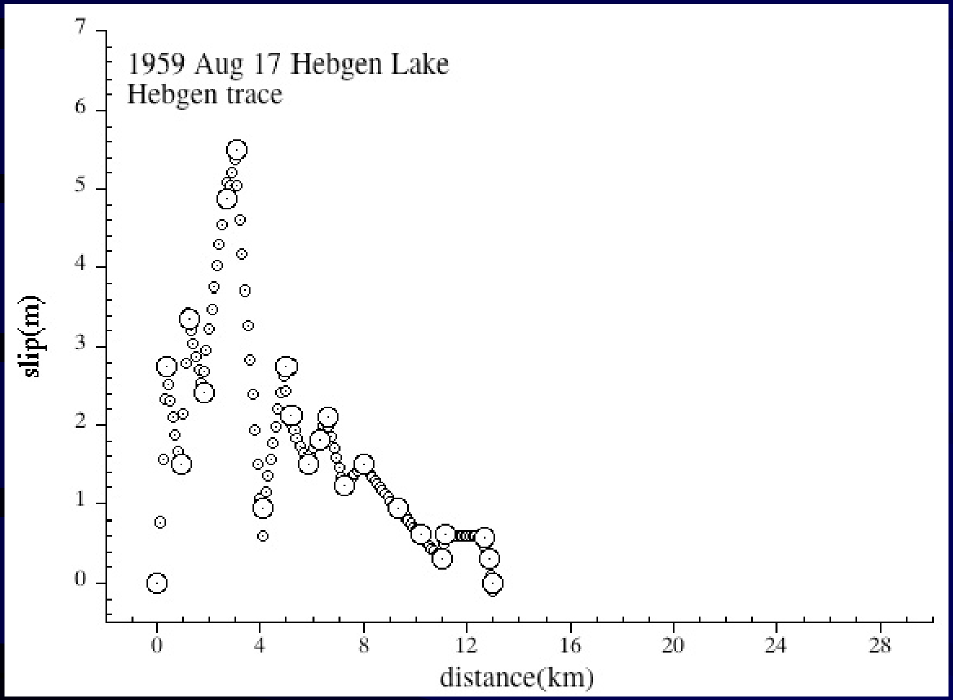
1959 Hebgen Lake Earthquake

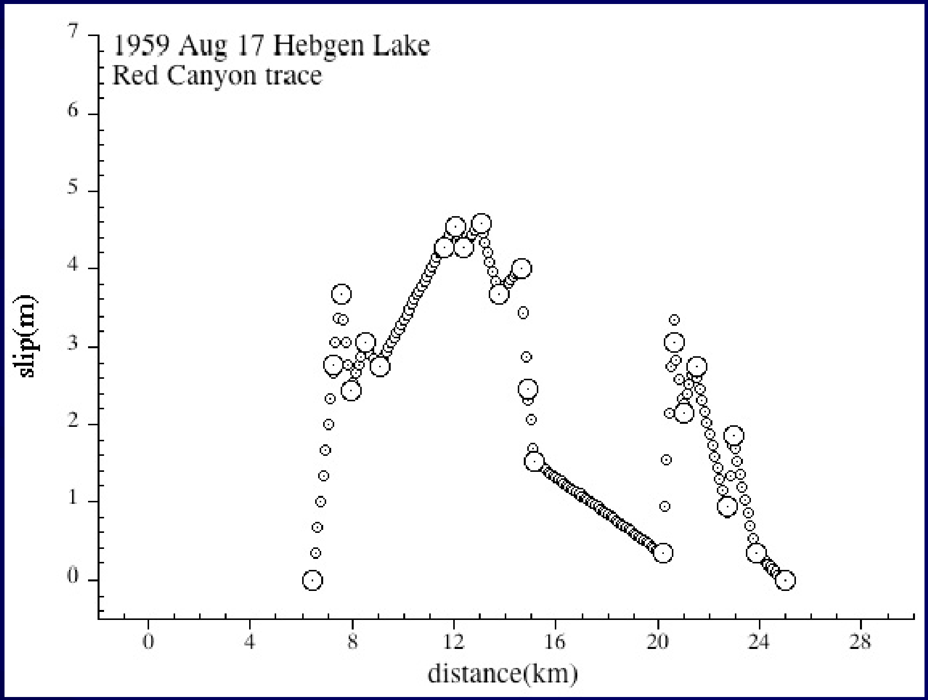
- MD = 6.7 m
  (Meyers and Hamilton, 1964)
- MD = 5.4 m
  (Witkind, 1964

Red Canyon fault scarp – 5.8 ft displacement.

Photo by J.R. Stacy from http://libraryphoto.cr.usgs.gov

1959 Hebgen Lake Earthquake





AD = 2.5 m (Wesnousky, 2008)

Data Limitations and Uncertainties for Normal-Slip Earthquakes Worldwide

- Worldwide historic earthquake record has very few large (M_W > 7.0) events – 9

  (Largest – M_W 7.5 1887 Sonora; Next –M_W 7.4 1912 Marmara, Turkey)

- Even fewer events have been instrumentally recorded – 6

  (Largest – M_W 7.29 1959 Hebgen Lake; Next –M_W 7.28 1946 Ancash, Peru)

- Limited observations of the short historical record even more problematic in low strain-rate environments (typical for extensional terranes)

- Consider paleoseismic estimates? (e.g., Mason [1996] estimated paleomagnitudes of Ms 6.8 to 7.5 for several dozen faults in ISB; Largest normal-slip earthquake paleomagnitude estimated by Stirling et al. [2002] was M_W 7.5 for Waiochau, New Zealand event)

Discussion – Issue G1: Part 1

1a. Should the upper bound Mmax of MW 7.5 for long unsegmented faults be revised in NHM?

1b. What uncertainties are recommended (i.e., what values and weights to characterize full distribution)?

Issue G1:

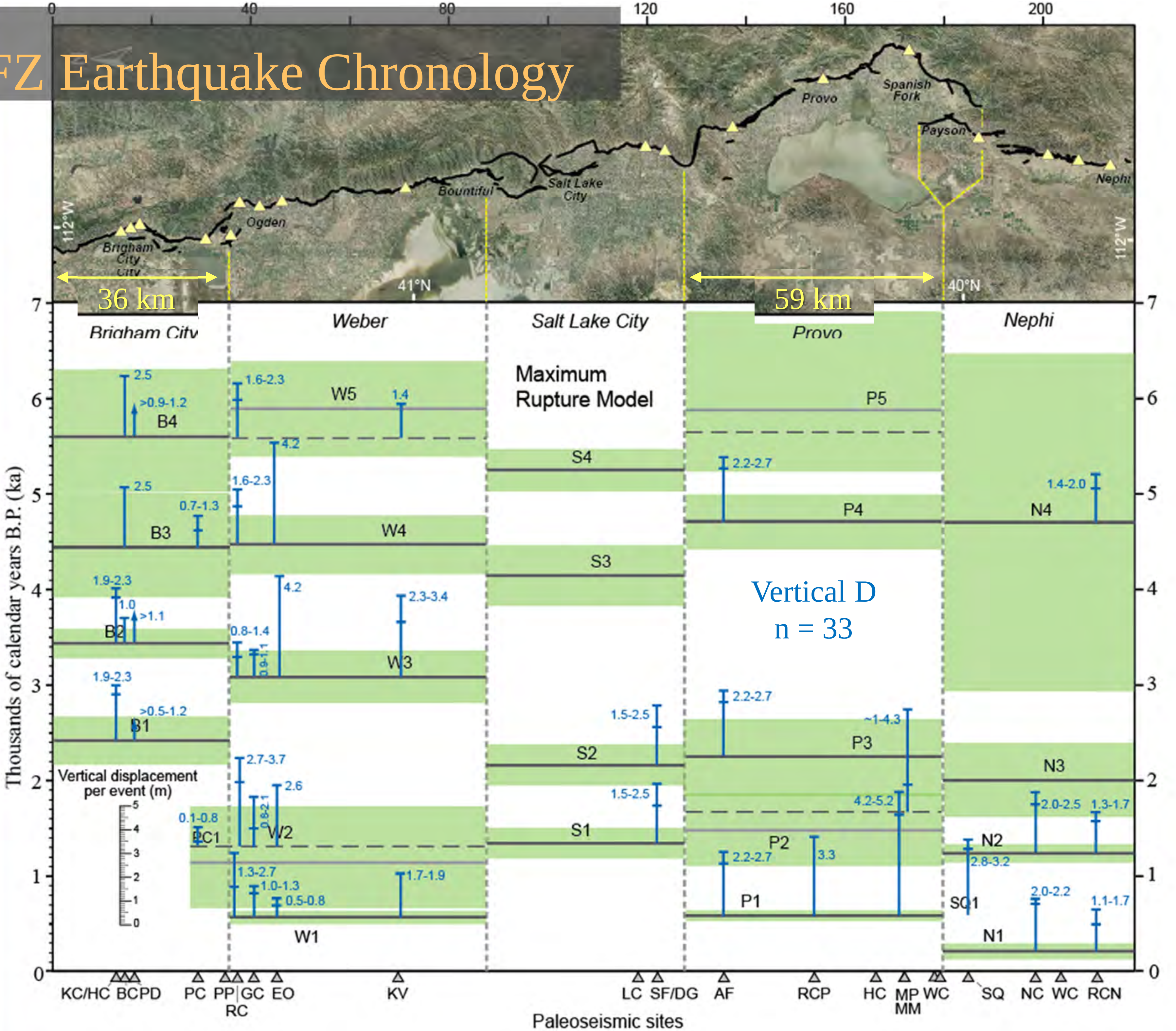
Calculating moment magnitudes for Basin and Range Province faults

Case Study: Wasatch Fault Zone (WFZ)

Chris DuRoss (UGS)

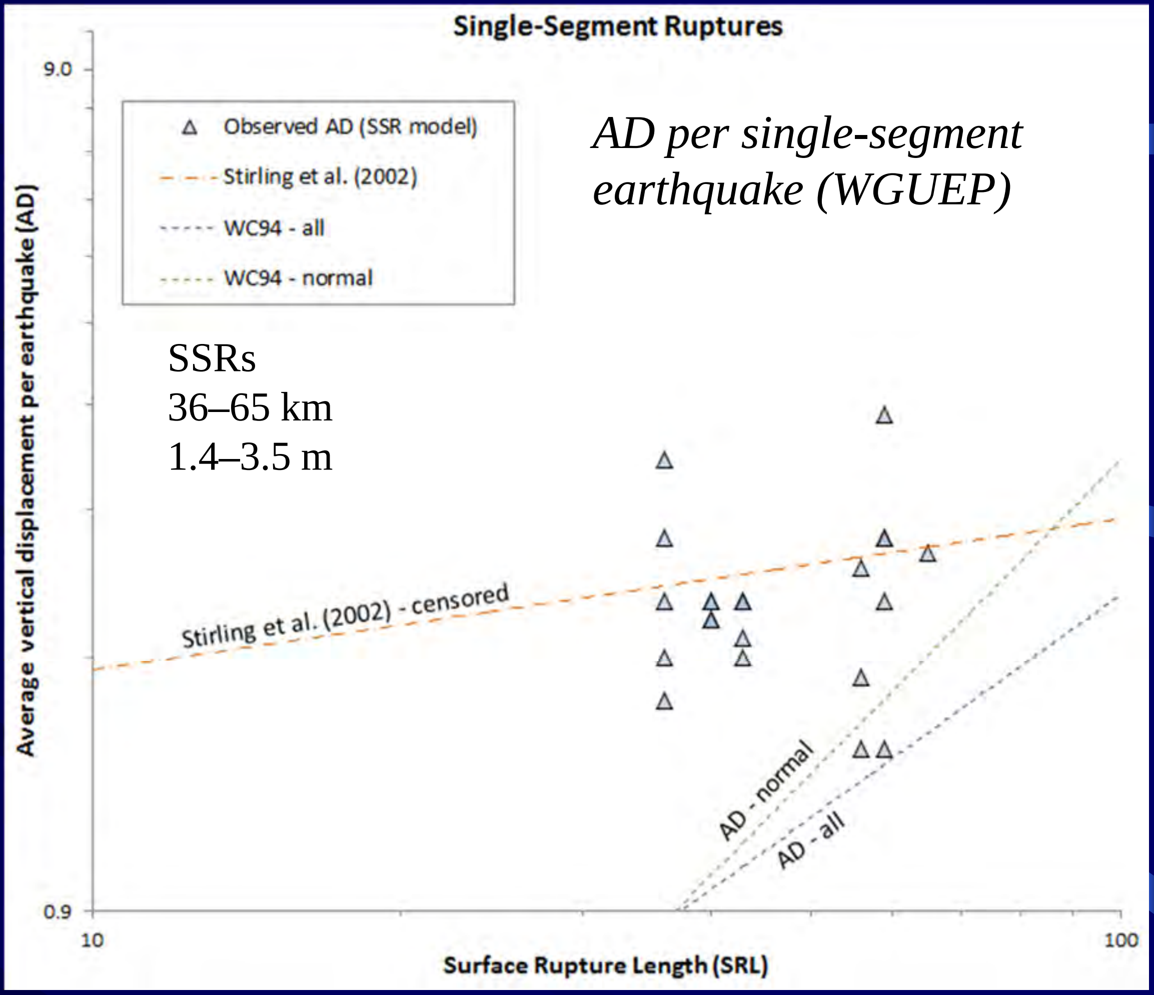
Basin and Range Province Earthquake Working Group II; November, 2011

WFZ Earthquake Chronology



Large Per-Event Displacements

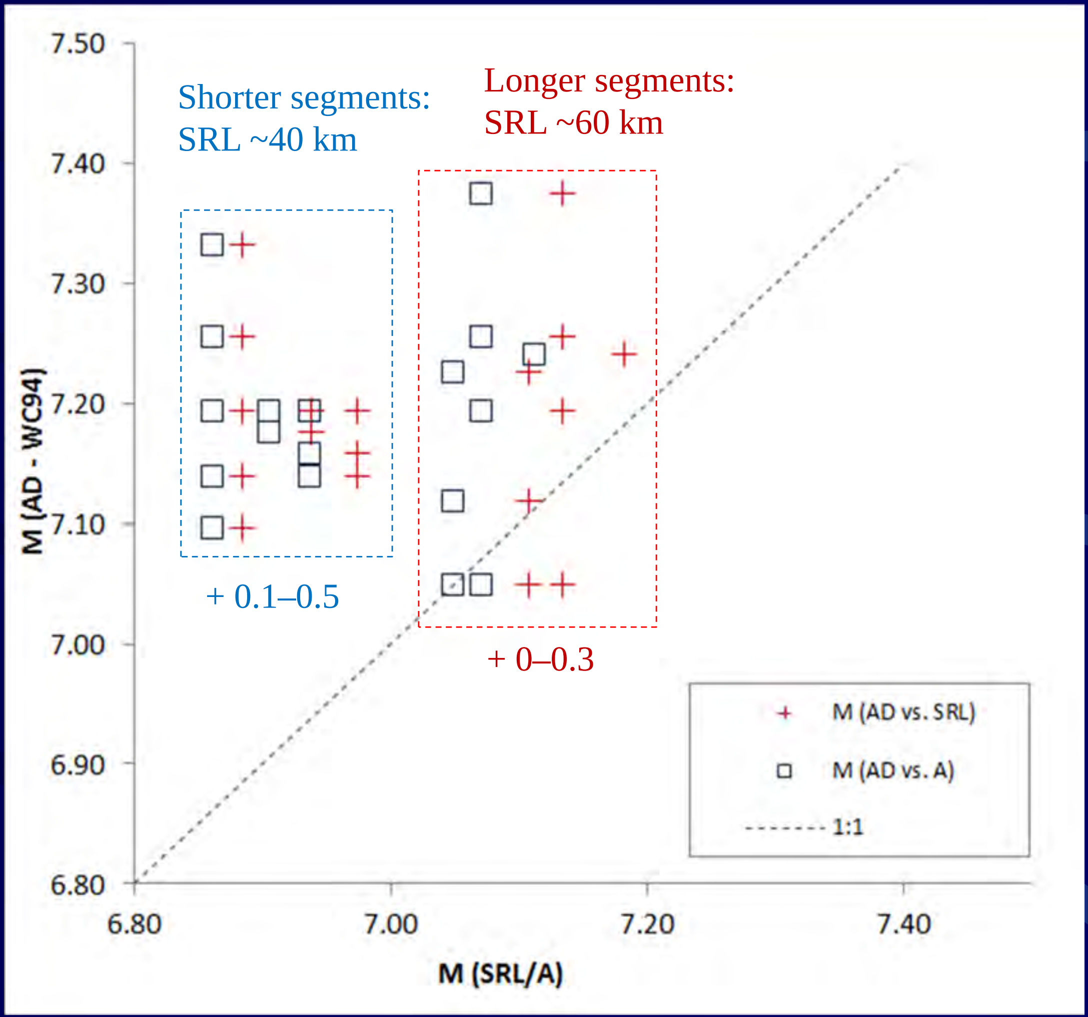
- For single-segment earthquakes, the average displacement (AD) per surface rupture length (SRL) is consistently larger than WC94-based estimates
  - Greater discrepancy for shorter segments
  - Corresponds well with regression of Stirling et al. (2002) censored for small D/SRL earthquakes



SRL

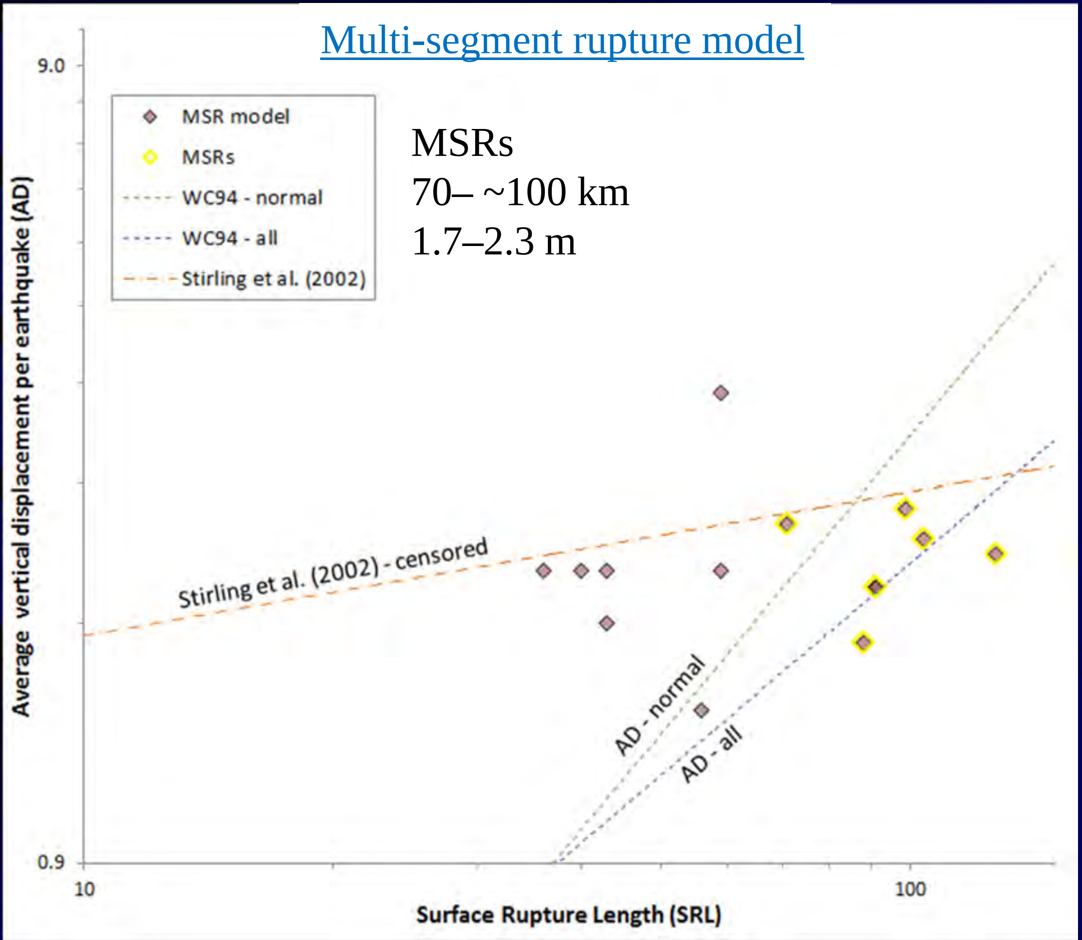
M Discrepancy – Single-Segment Ruptures

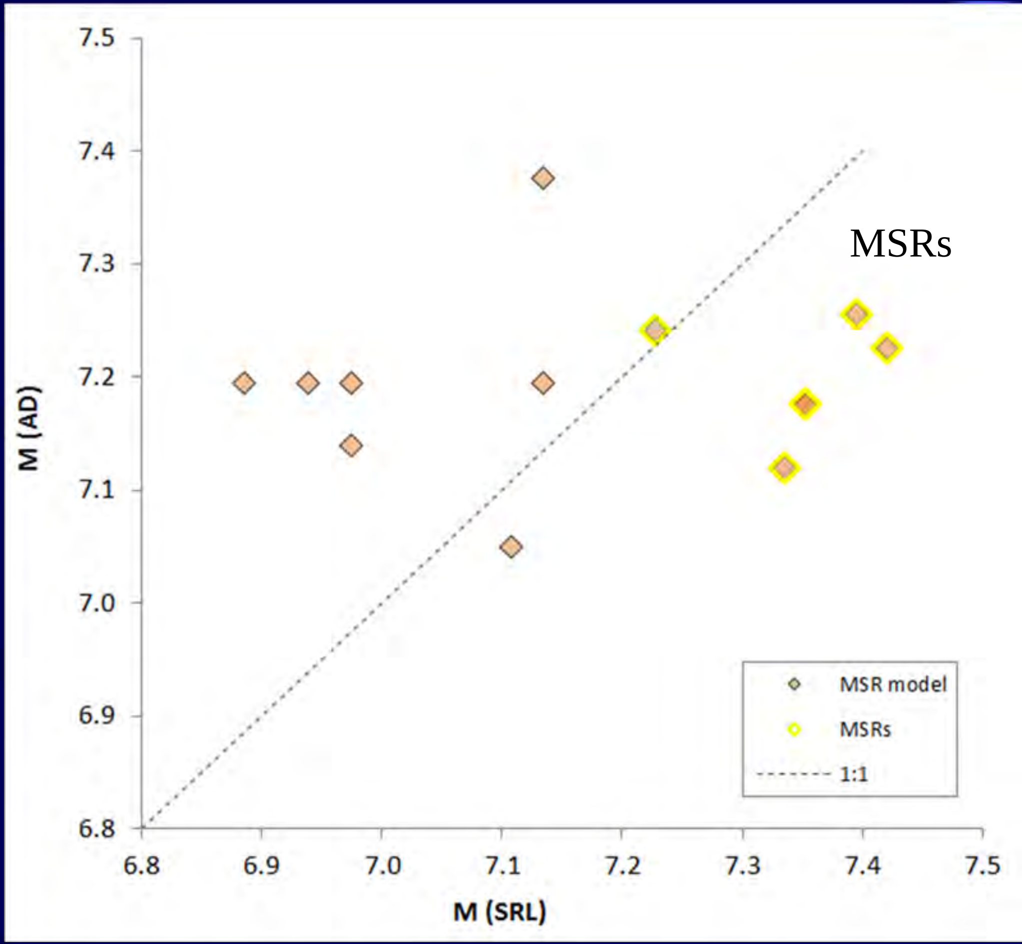
- For single-segment earthquakes, **M**(AD) consistently greater than **M**(SRL or A)
  - Discrepancy greatest for shorter segments



Multi-Segment Ruptures

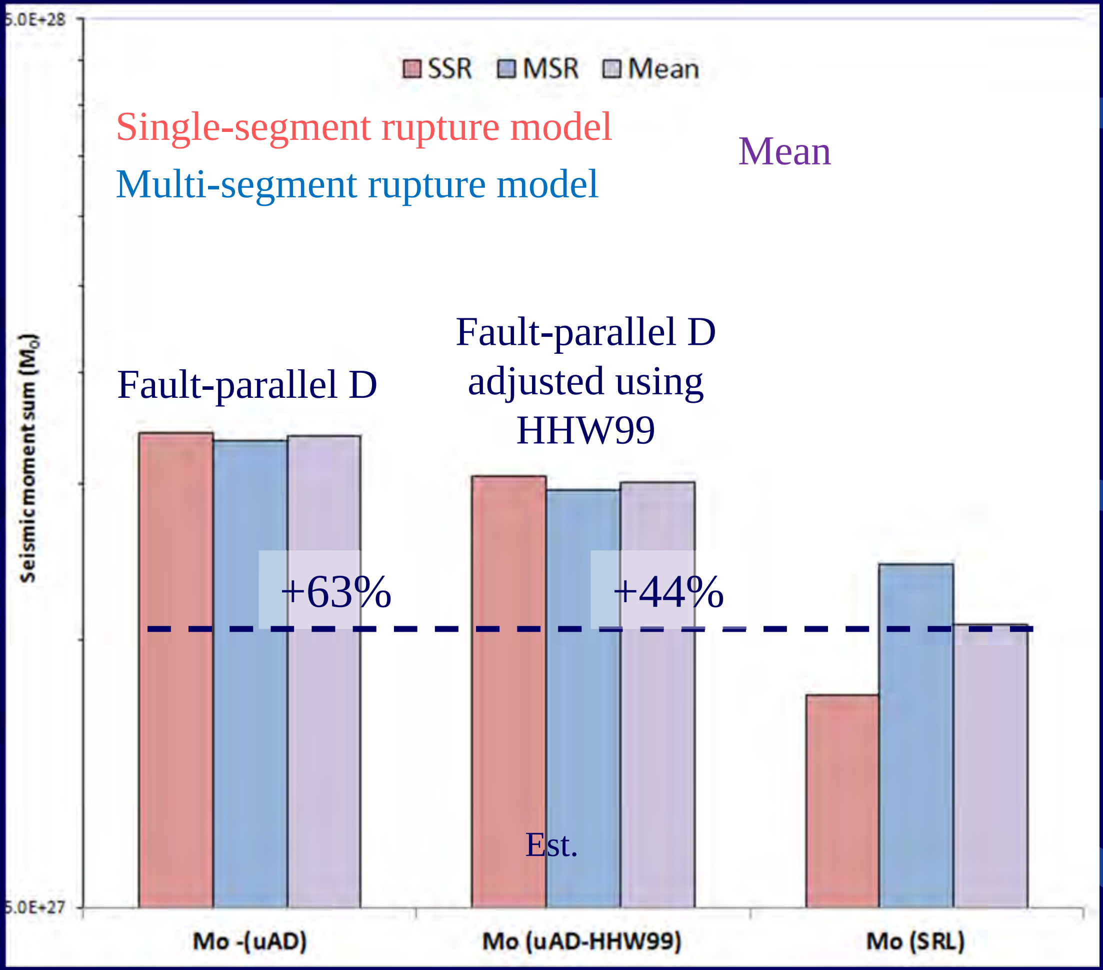
- **M** discrepancy less of an issue for MSRs (using observed displacements)





Why Important

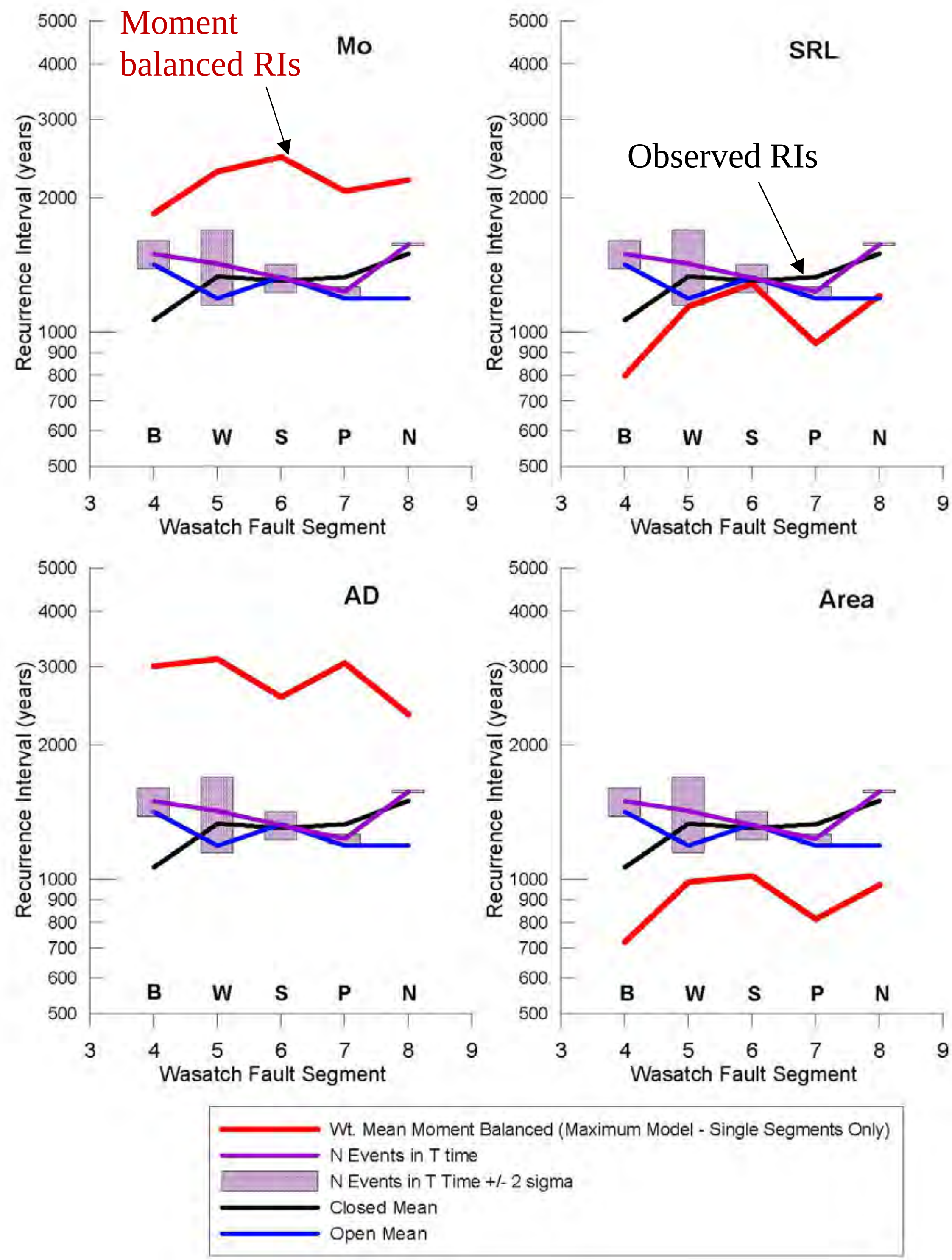
- ~40–60% more moment released on WFZ using ADs ($M_0 = \mu * A * AD$) compared to only using SRLs



Sum of M_0 release for single- and multi-segment rupture models (WGUEP)

Why Important

- To moment balance, need longer recurrence intervals (RIs) to account for larger displacements/greater M_0 release
  - RIs ~2000-3000 yr using **M**(AD or M0)
  - RIs ~700-1000 yr using **M**(SRL or A)
  - Observed RIs ~1000-1500 yr

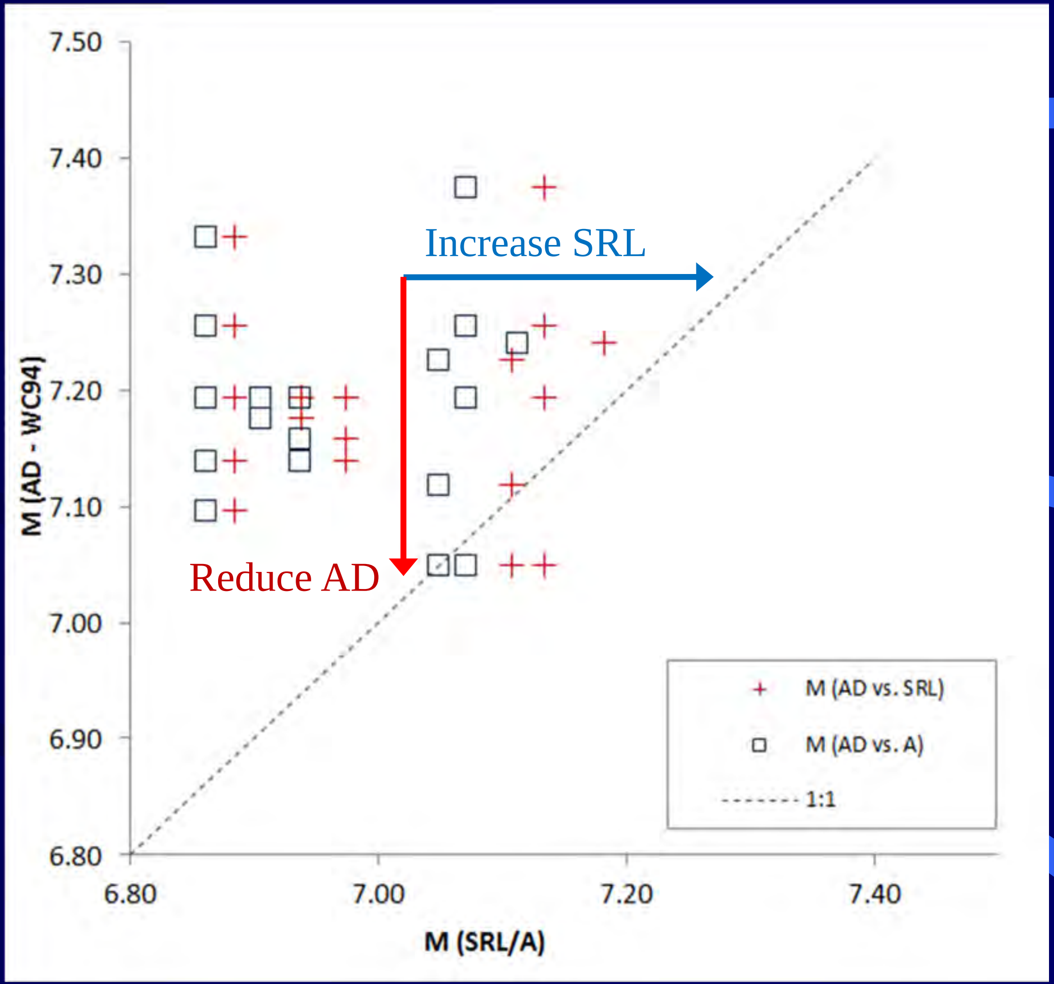


From Patricia Thomas (URS). Moment-balanced recurrence intervals for the single-segment rupture model (WGUEP)

Reducing the **M** Discrepancy

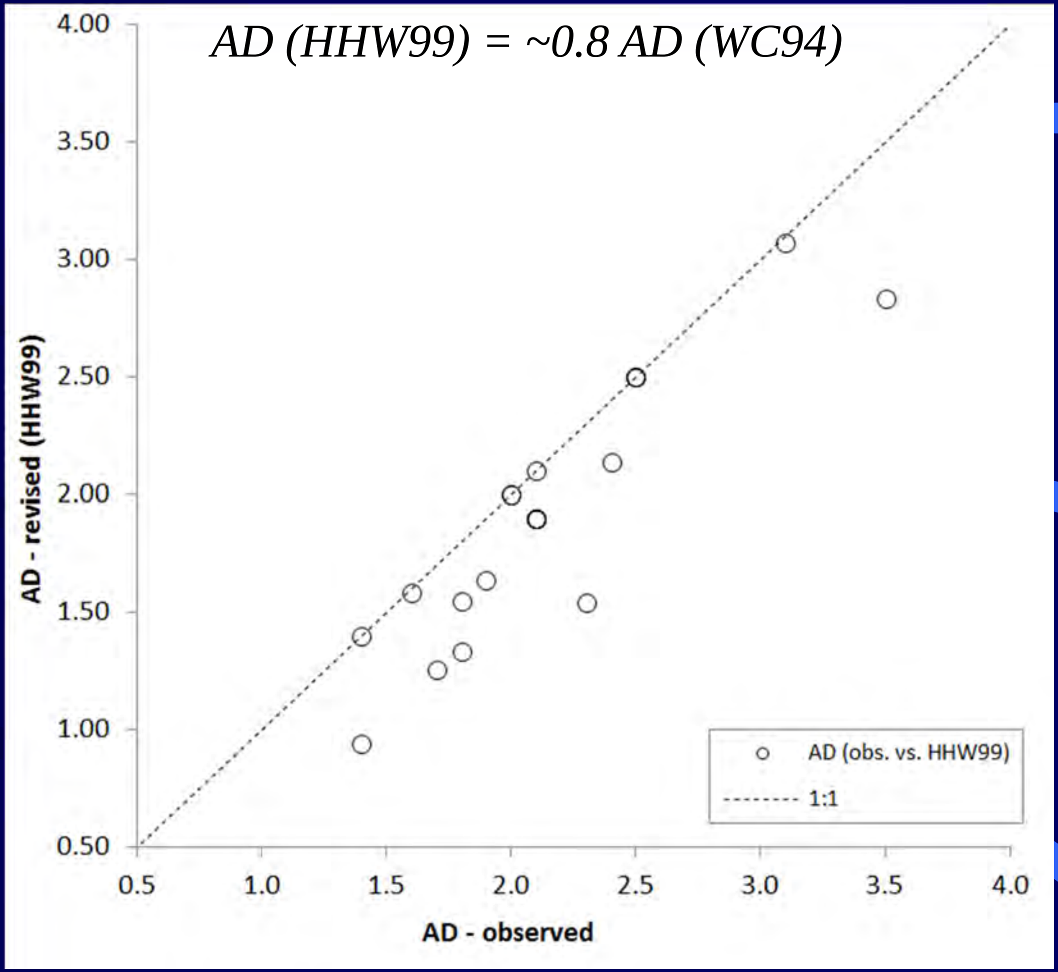
- Ways to reduce the **M** discrepancy
  - Reduce AD
  - Increase SRL

- Other options
  - Ignore (cite large stress drops)
  - Take mean of all available **M** estimates
  - Use different or acquire new regressions



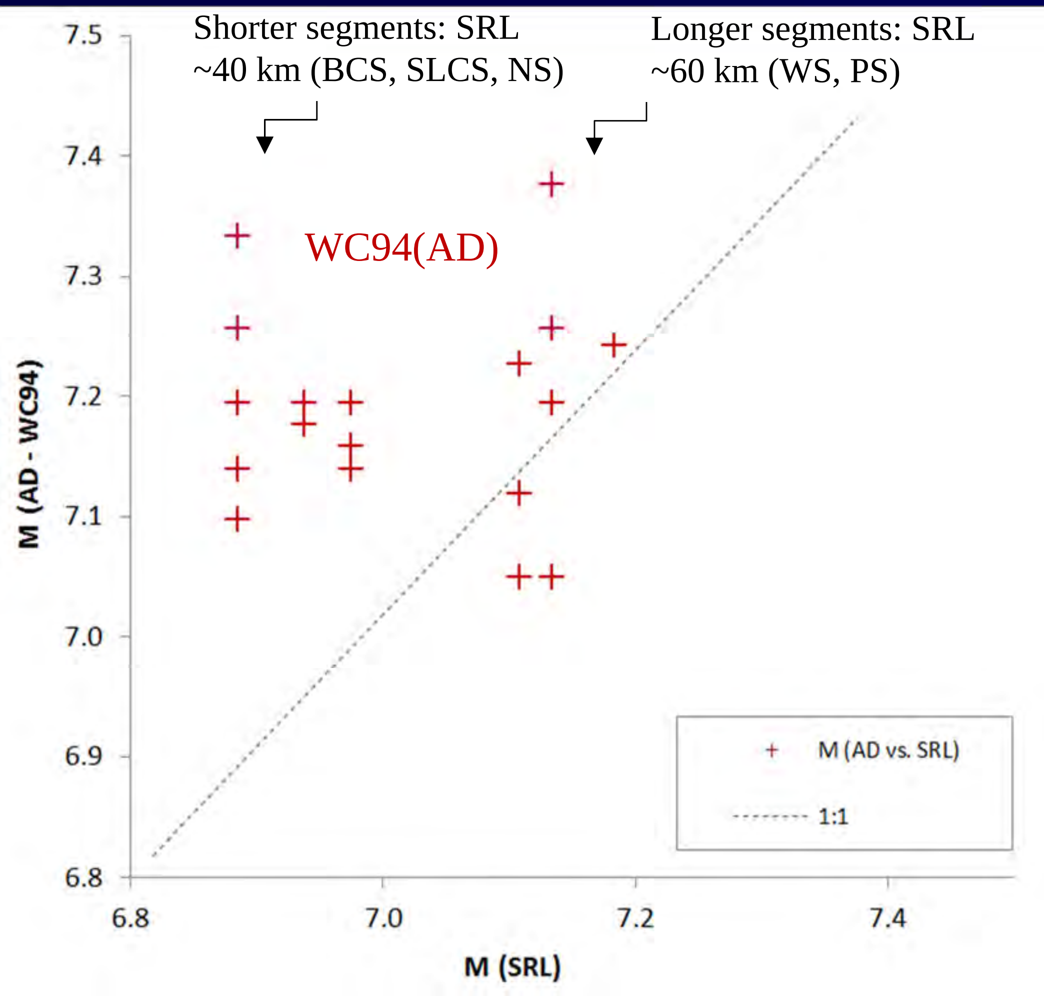
Revising Displacement

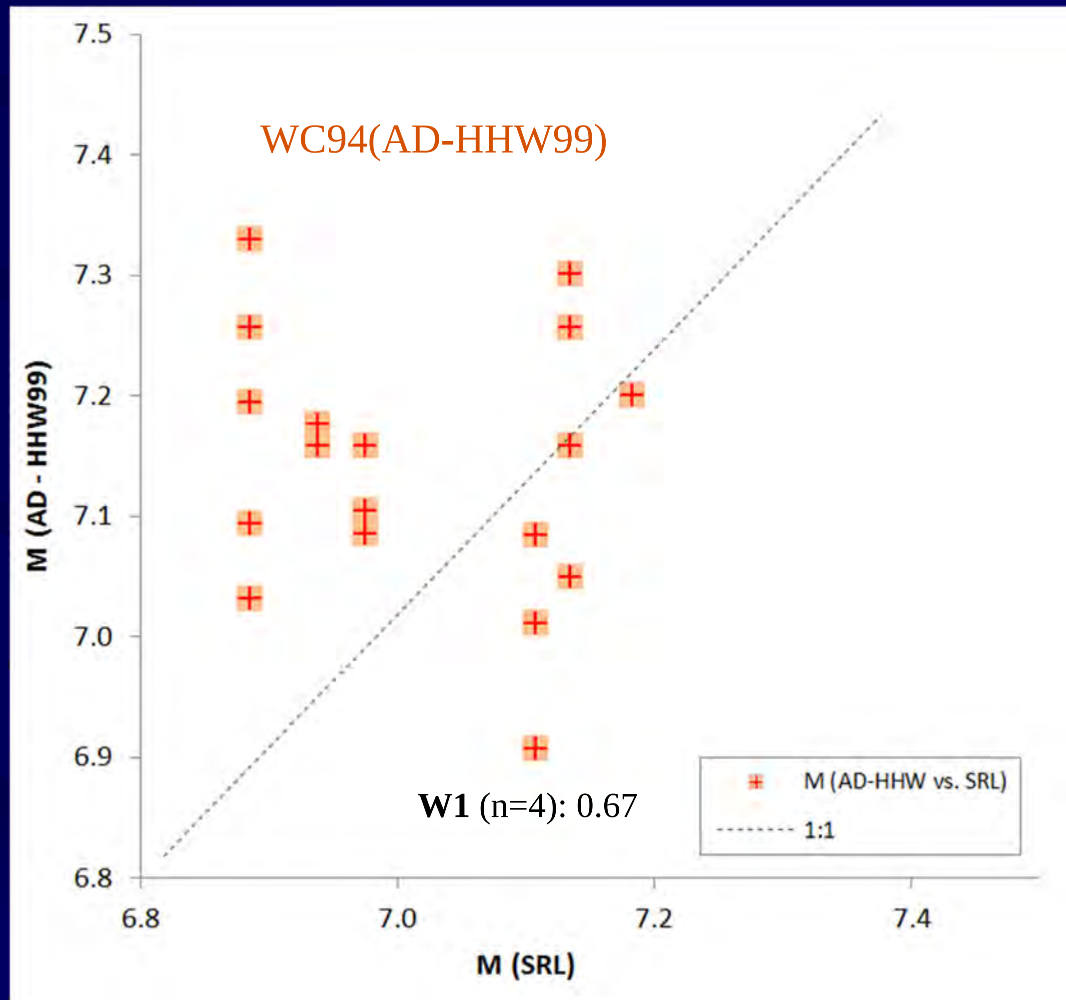
- Scale mean displacements using Hemphill-Haley and Weldon (1999) (HHW99)
  - Because of SRL preservation and sampling issues, observed AD > true AD; correct using # obs. and % of fault sampled
  - 10/22 events have sufficient data (2+ obs); correction value (MVCDS) ranges from 0.67–0.99 (mean 0.8)



Revising Displacement

- HHW99 AD correction has minor effect on **M** discrepancy
  - Most significant change: W1 (1.4 to 0.9 m), W3 (2.3 to 1.5 m)
  - Minor to no change with shorter SRL segments (BCS, SLCS, NS)

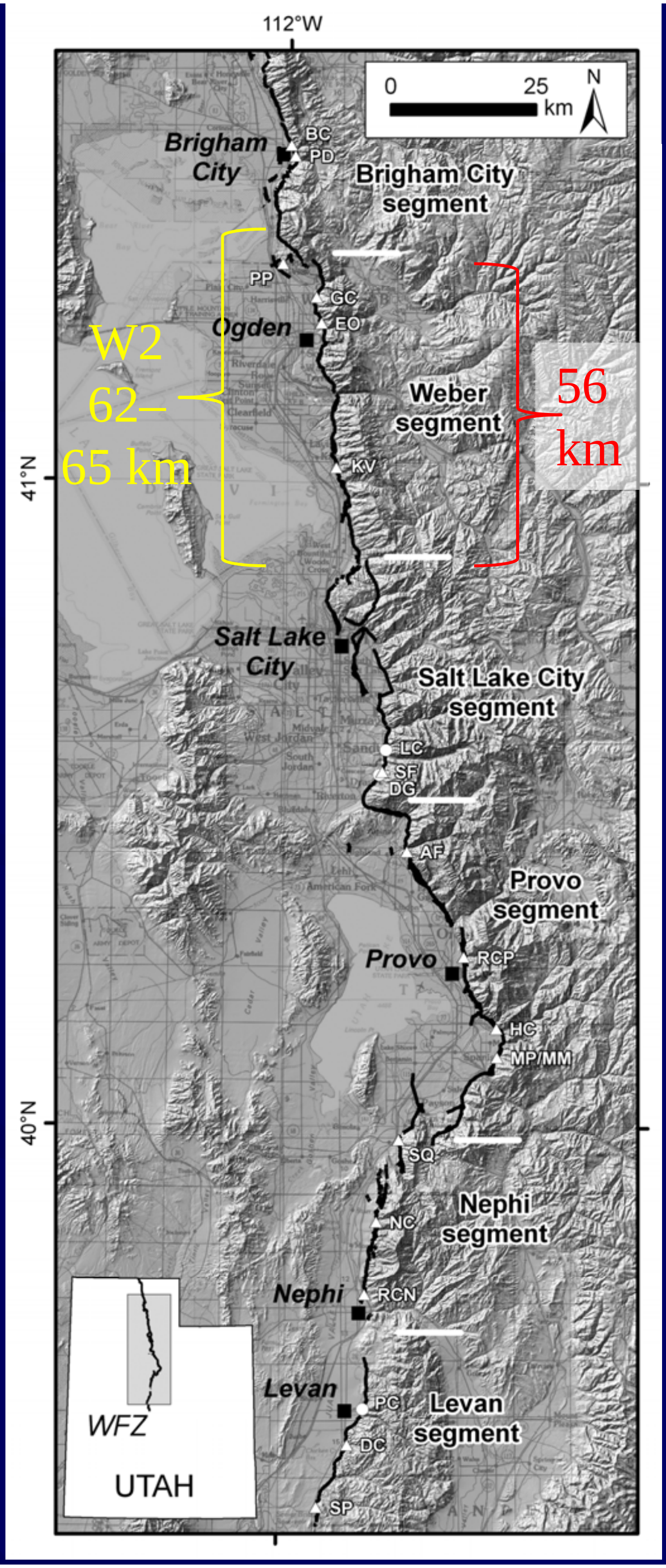




Revising SRL

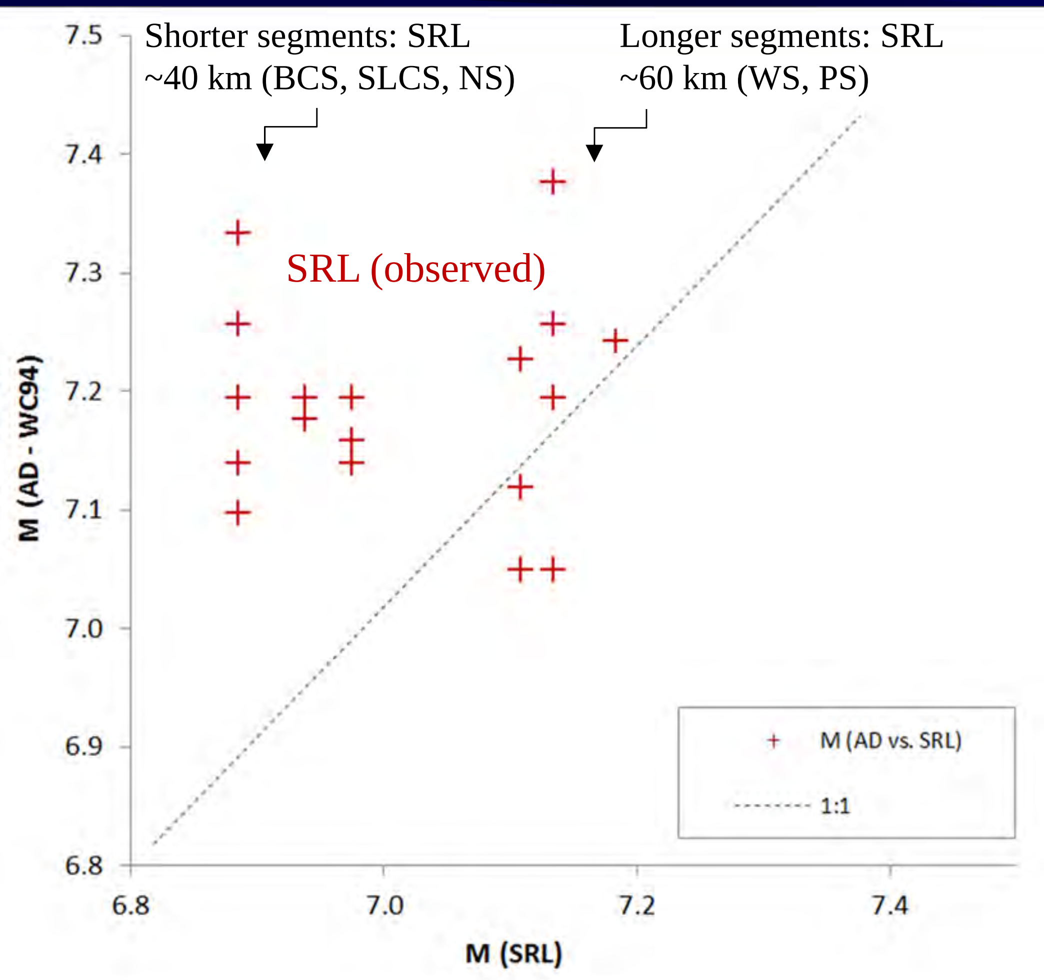
- Do WFZ single-segment ruptures consistently extend beyond the mapped segment boundaries?

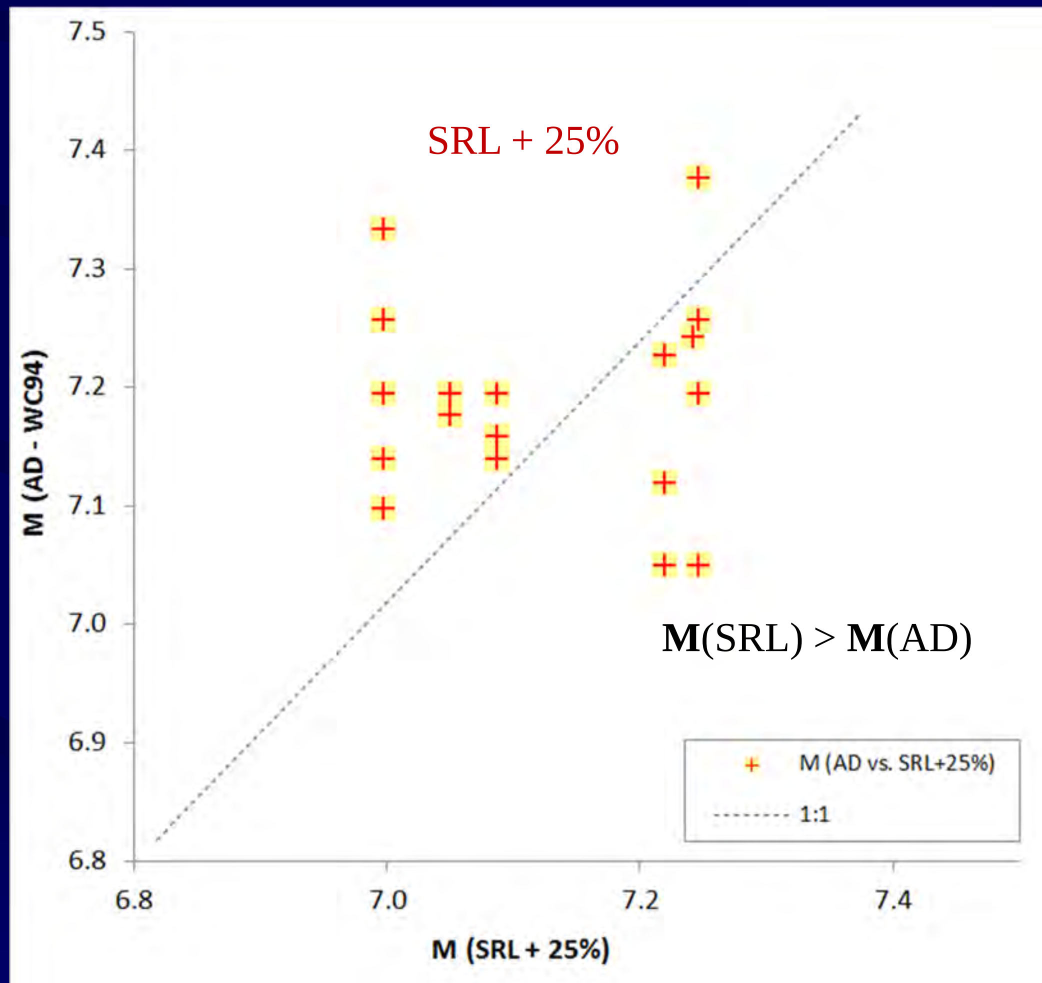
- Example: spill-over rupture Weber segment (WS) earthquake W2
  - Rupture north across segment boundary onto southern ~8 km of Brigham City segment
  - WS SRL increased 6–9 km (11–16%) (62–65 km vs. 56 km)



Revising SRL

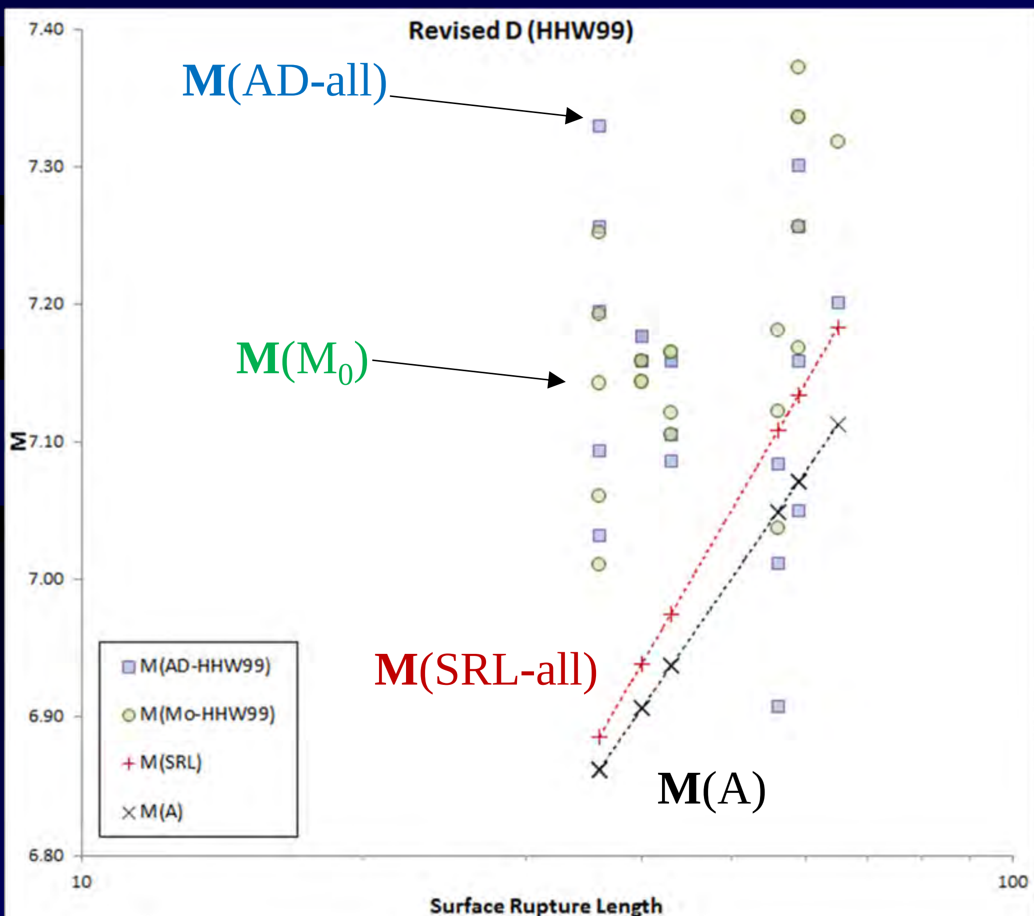
- What if we underestimated single-segment SRLs by 25%?
  - Double the Weber-Brigham City segment spill over = ~27%
  - McCalpin and Slemmons (1996): underestimate SRL by ~25% if scarps having $\leq$ 10% of maximum displacement ($\leq$ ~40 cm) are removed, buried, or obscured

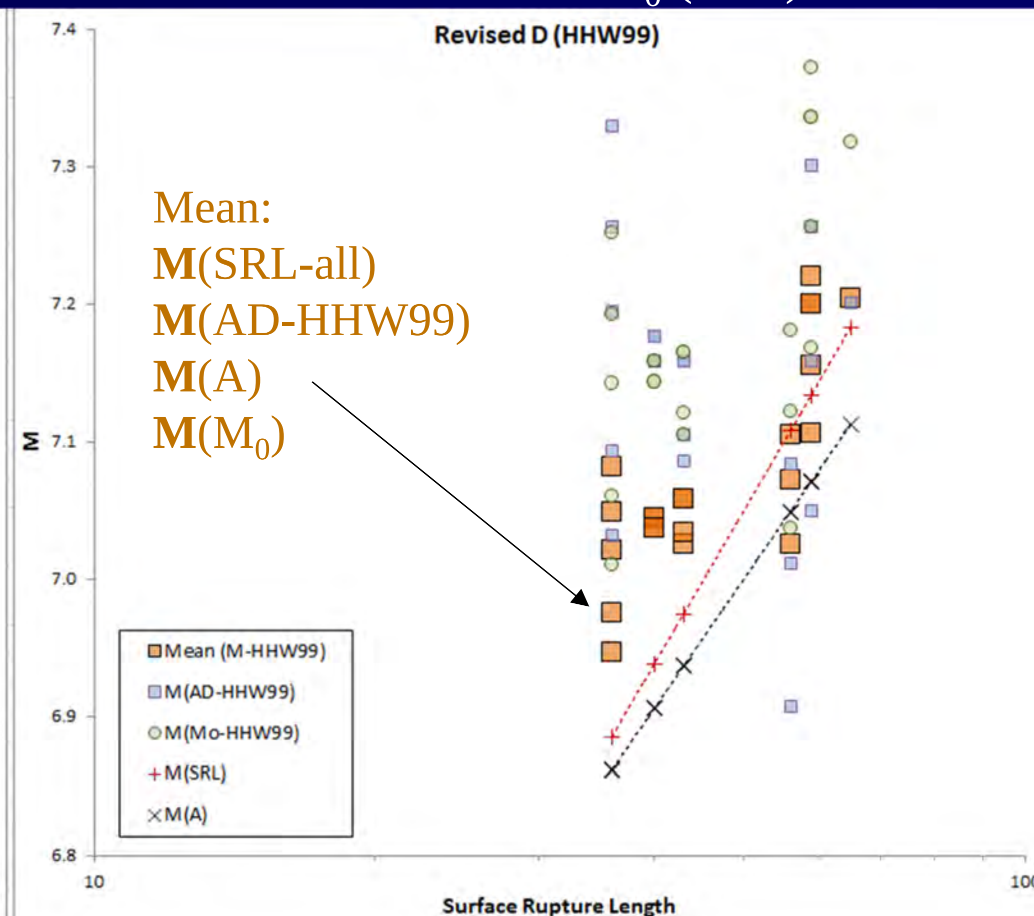




Other Options

- Weighting Scheme (using revised AD):
  - W&C94 – A (0.25)
  - W&C94 – SRL-all (0.25)
  - HHW99 – AD (0.25)
  - Hanks and Kanamori – M_0 (0.25)*

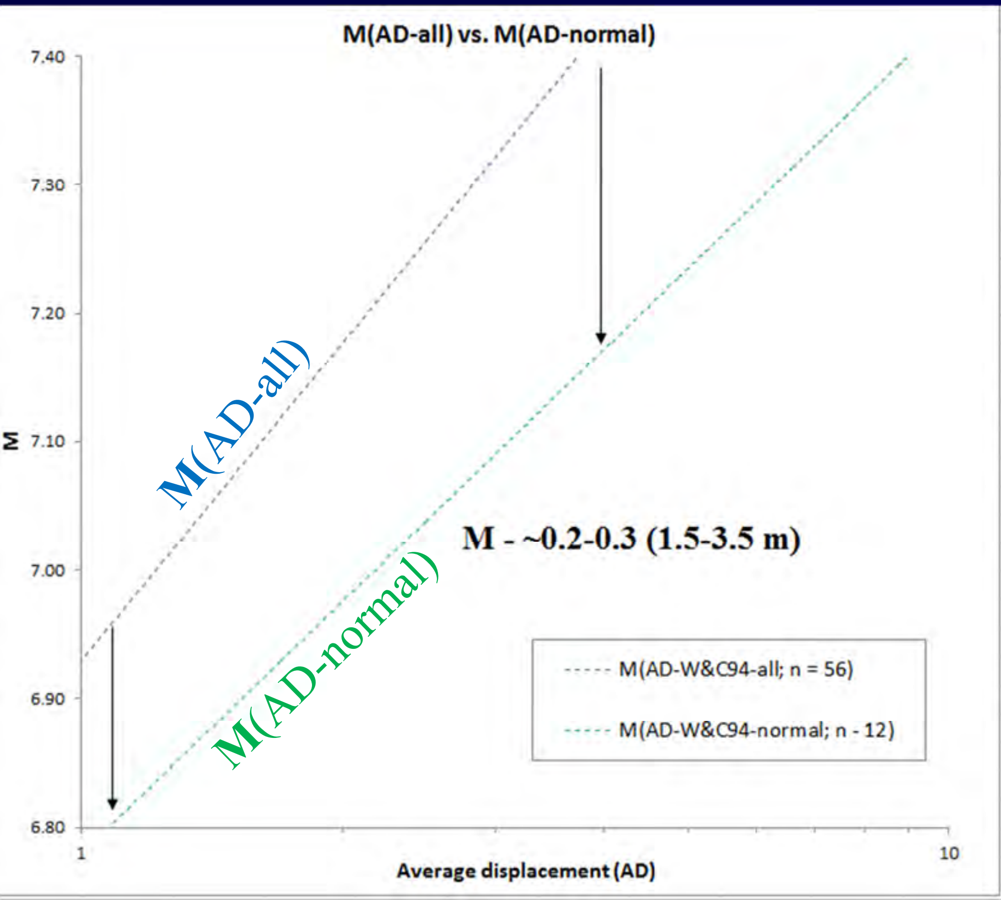


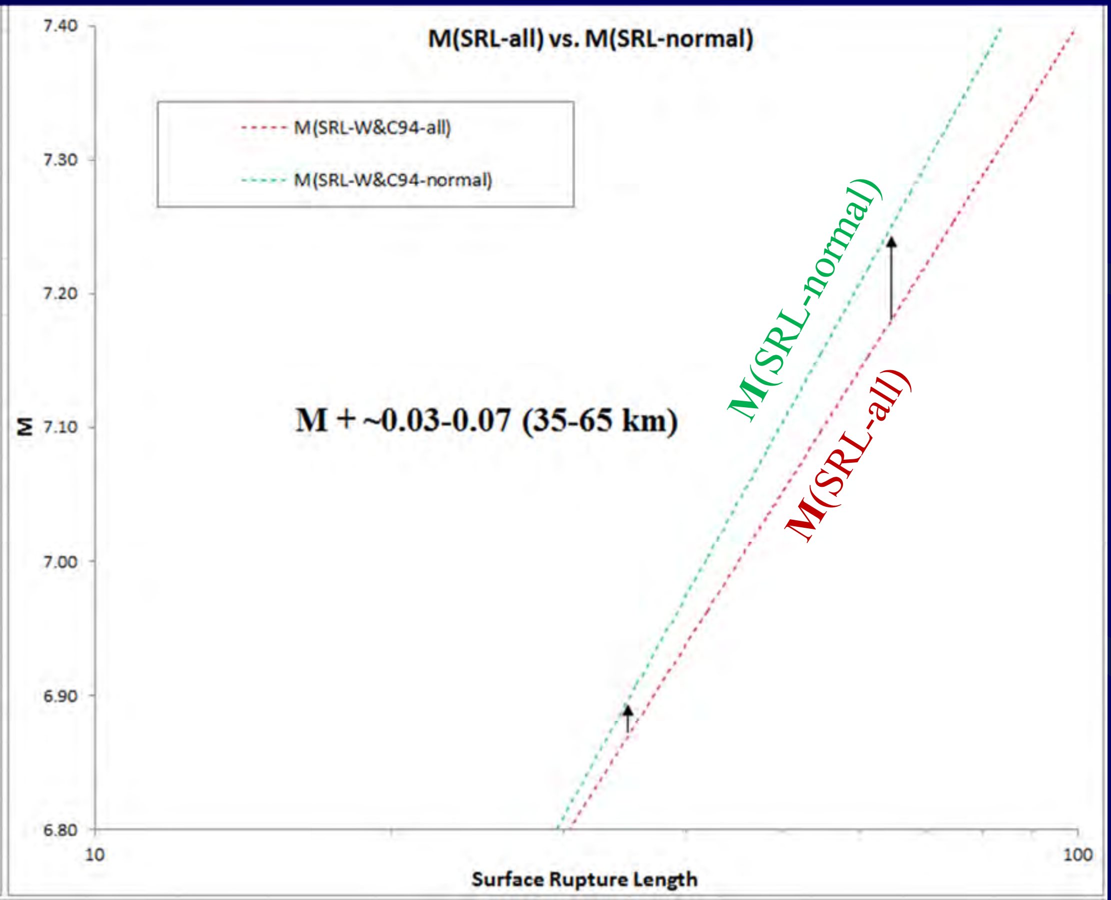


***M** (M_0) = 2/3 log(M_0) – 10.7; M_0 = μ*A(SRL*W)*AD (AD converted to fault-parallel slip)

Other Options

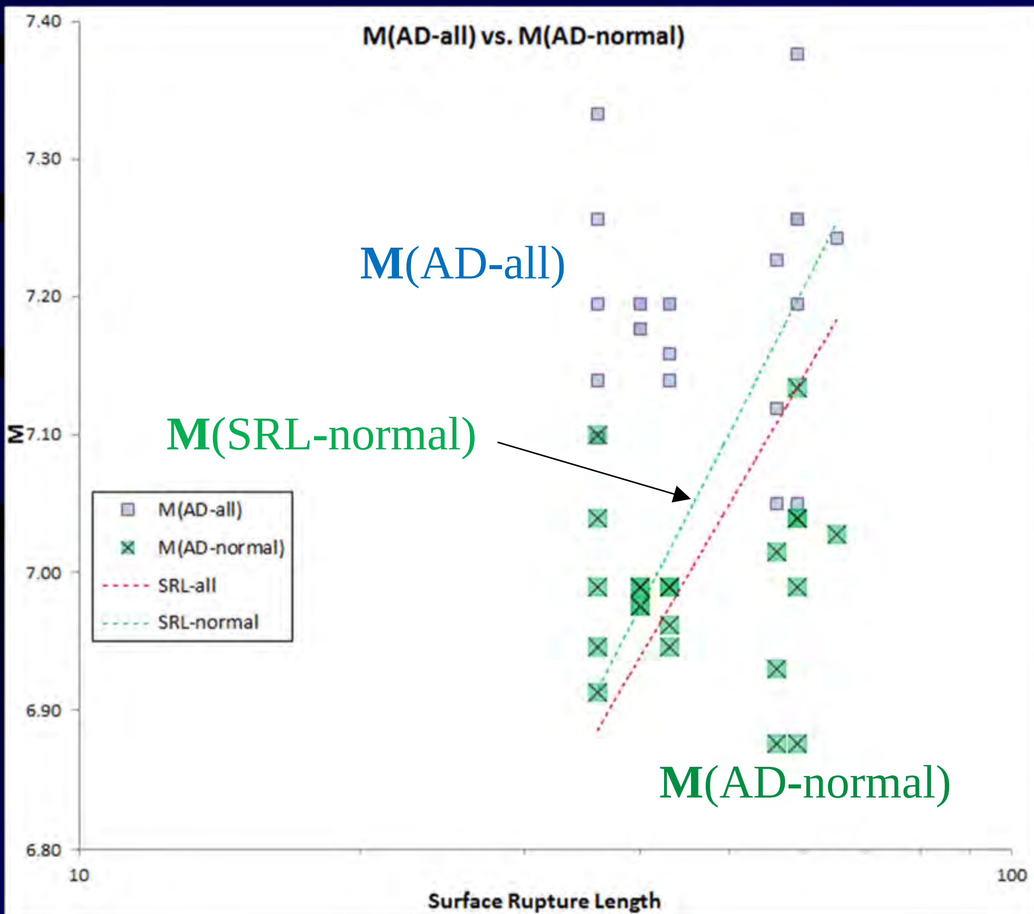
- Other regressions? W&C94 – Normal-fault regressions?
  - **M**(AD-all) > **M**(AD-normal)
  - **M**(SRL-all) < **M**(SRL-normal)

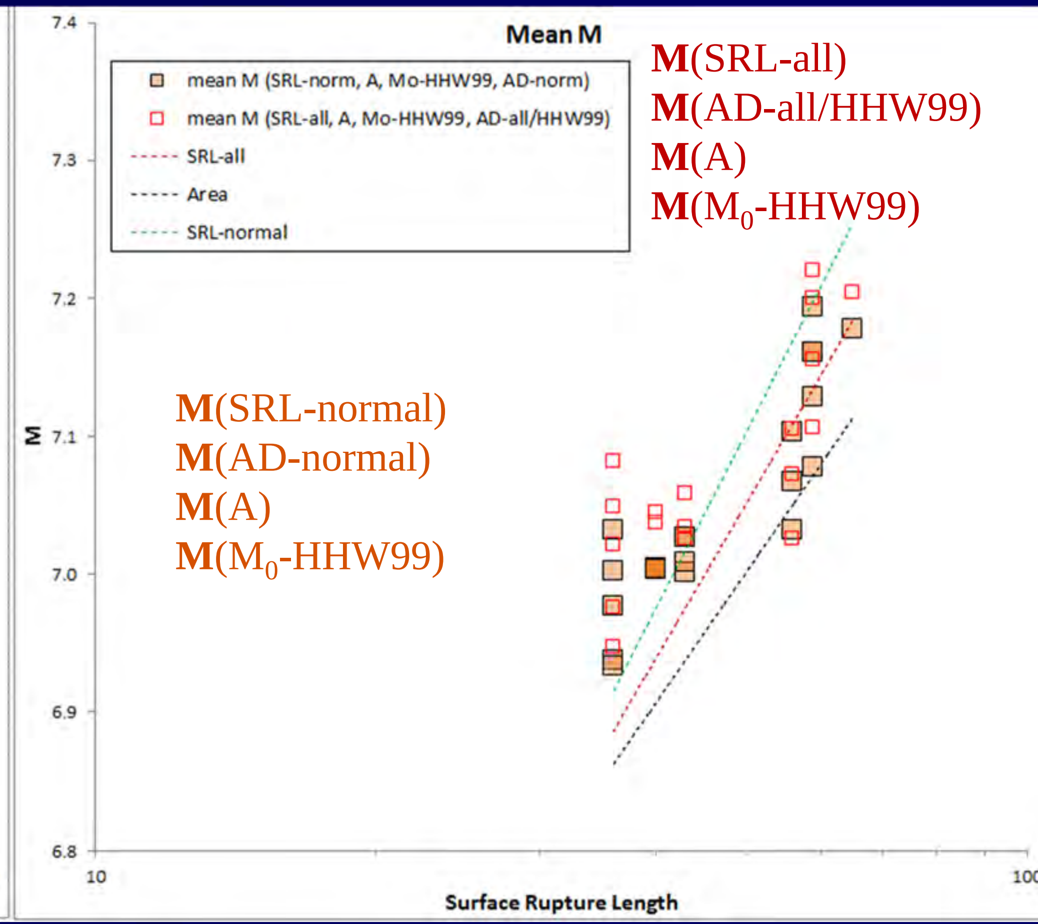




Other Options

- Other regressions? W&C94 – Normal-fault regressions?
  - Discrepancy reduced for shorter segments
  - M(SRL) > M(AD) for longer segments, larger displacements





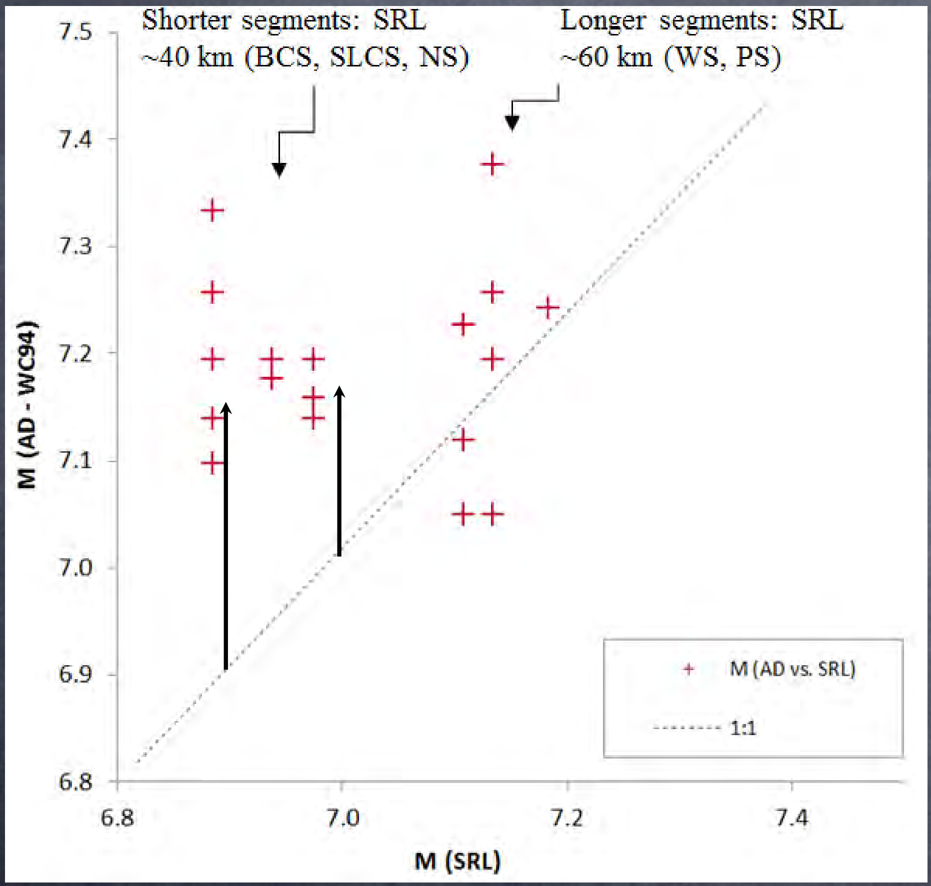
Conclusions

- WFZ **M** discrepancy
  - For single-segment ruptures, and especially SRLs < ~50 km, larger AD per SRL than predicted by WC94,
  - **M**(AD) exceeds **M**(SRL or A) by 0.1–0.5 M units
- Difficult to consistently reduce the **M** discrepancy
  - Insufficient data to consistently apply HHW99 (and has limited effect)
  - Increasing SRL helps (especially for shorter segments), but hard to justify
  - Using normal-fault-type regressions helps reduce discrepancy for shorter SRLs, but for longer segments **M**(SRL) > **M**(AD)
  - <u>Best approach</u>: equal weighting of different **M** regressions?
- Other potential factors
  - Regression issues? Small vs. large, dip-slip vs. strike slip, regional vs. global?
  - L vs. W scaling? (D saturate at SRL = W?)
  - Large stress drops?

Pre-Historic Earthquake Displacement

Glenn Biasi
University of Nevada Reno

Wasatch Example



Magnitude bias from average displacement for shorter segments.

How much length is needed?

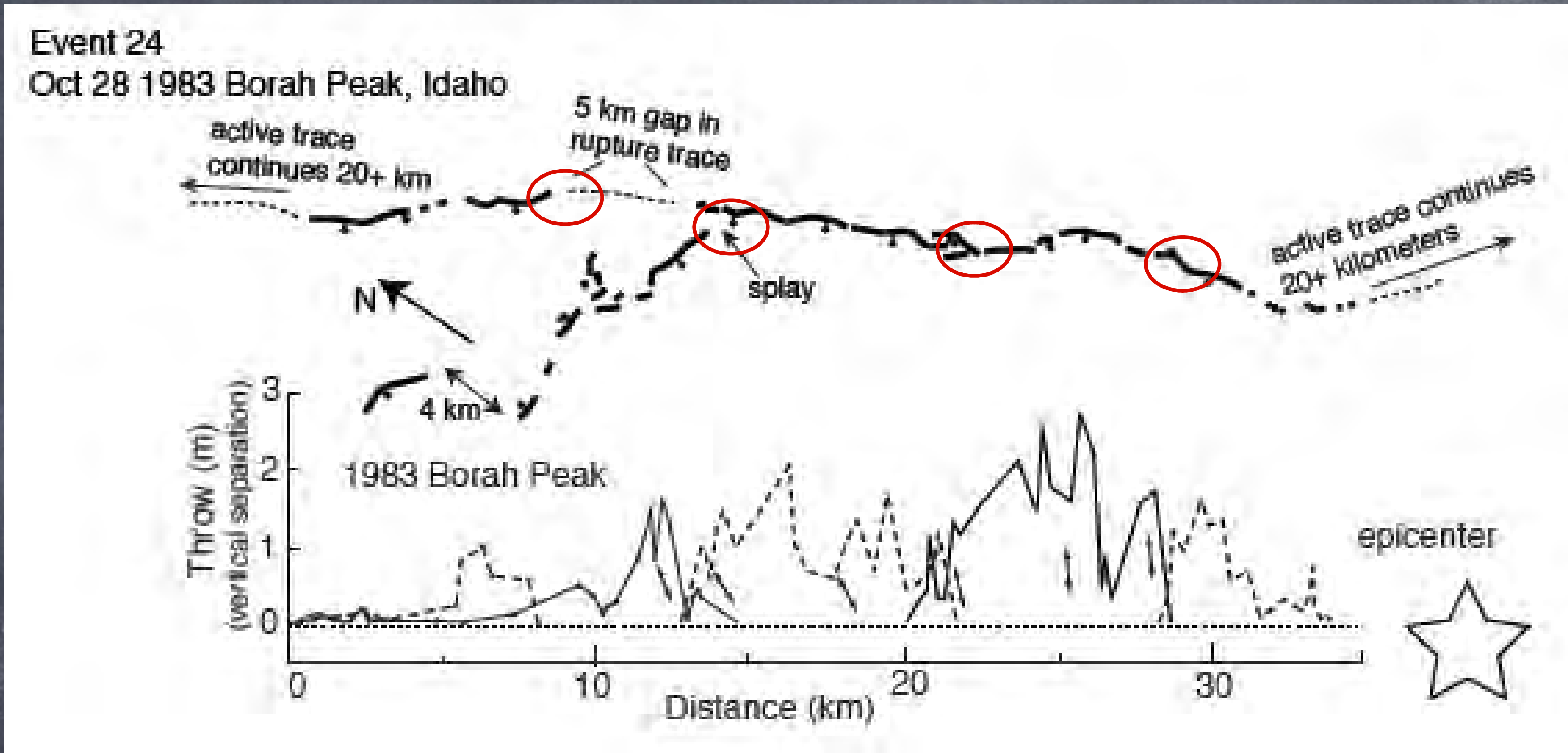
$M_{AD} - M_{SRL} =\sim 0.2$

$L_{AD} = 1.4 * L_{SRL}$

or

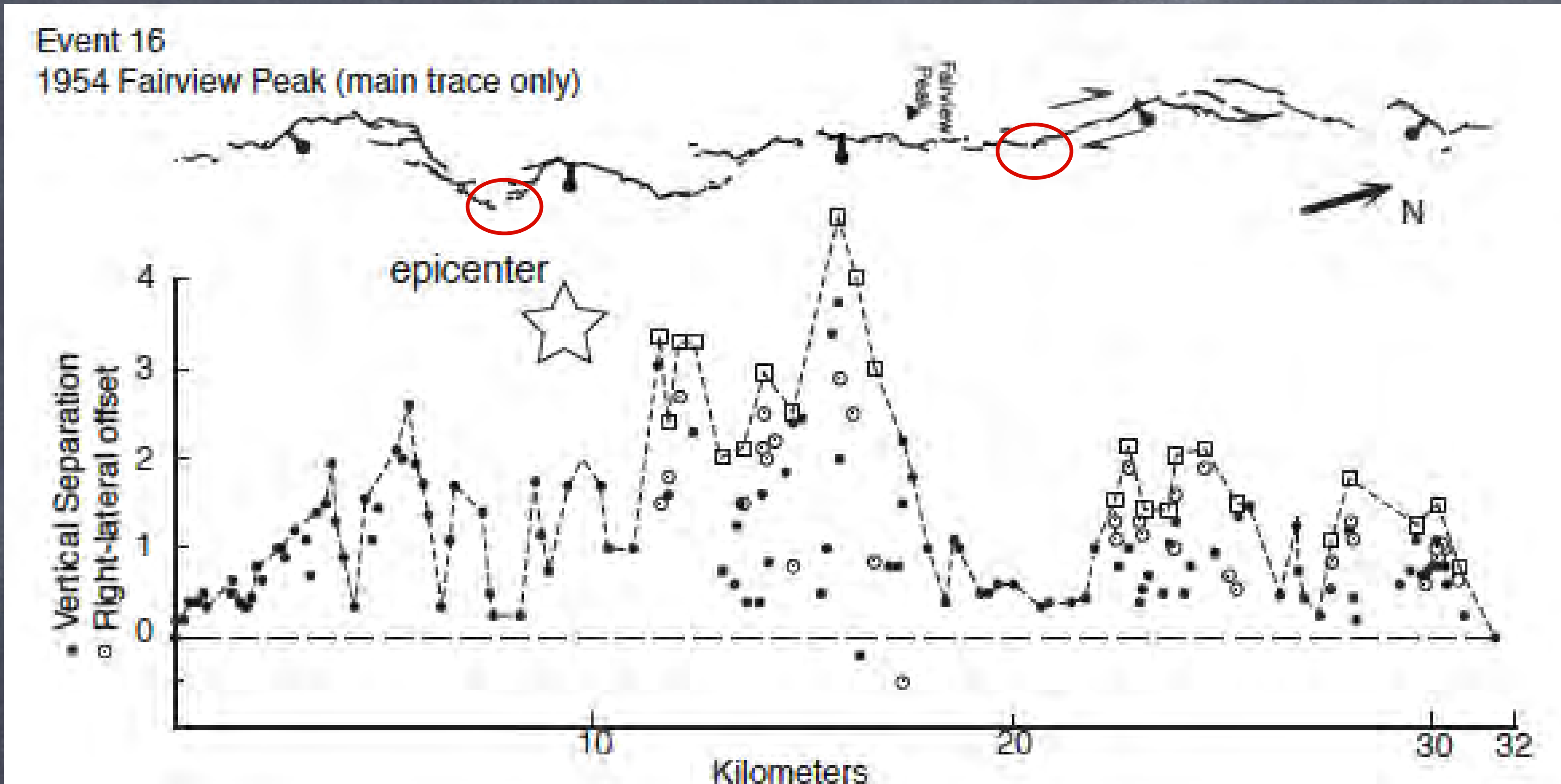
$AD_{true} = AD_{obs}/1.4$

The extra 0.4 displacement has to be over the full L.

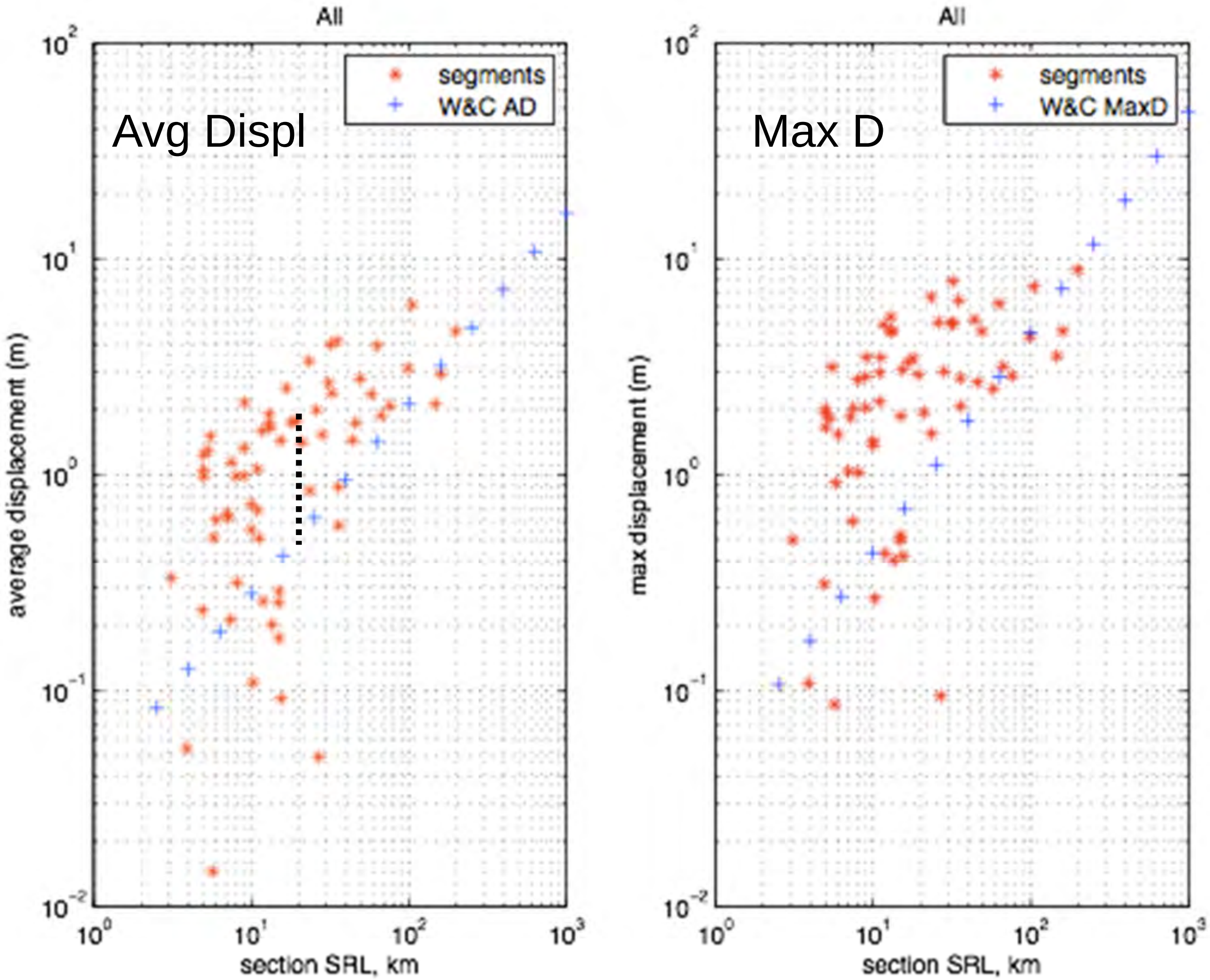


Event 24 from Wesnousky (BSSA, 2008)

Possibility suggested by study of mapped ruptures...



Event 16
1954 Fairview Peak (main trace only)
Fairview Peak
N
epicenter
Vertical Separation
Right-lateral offset
4
3
2
1
0
10
20
30
32
Kilometers



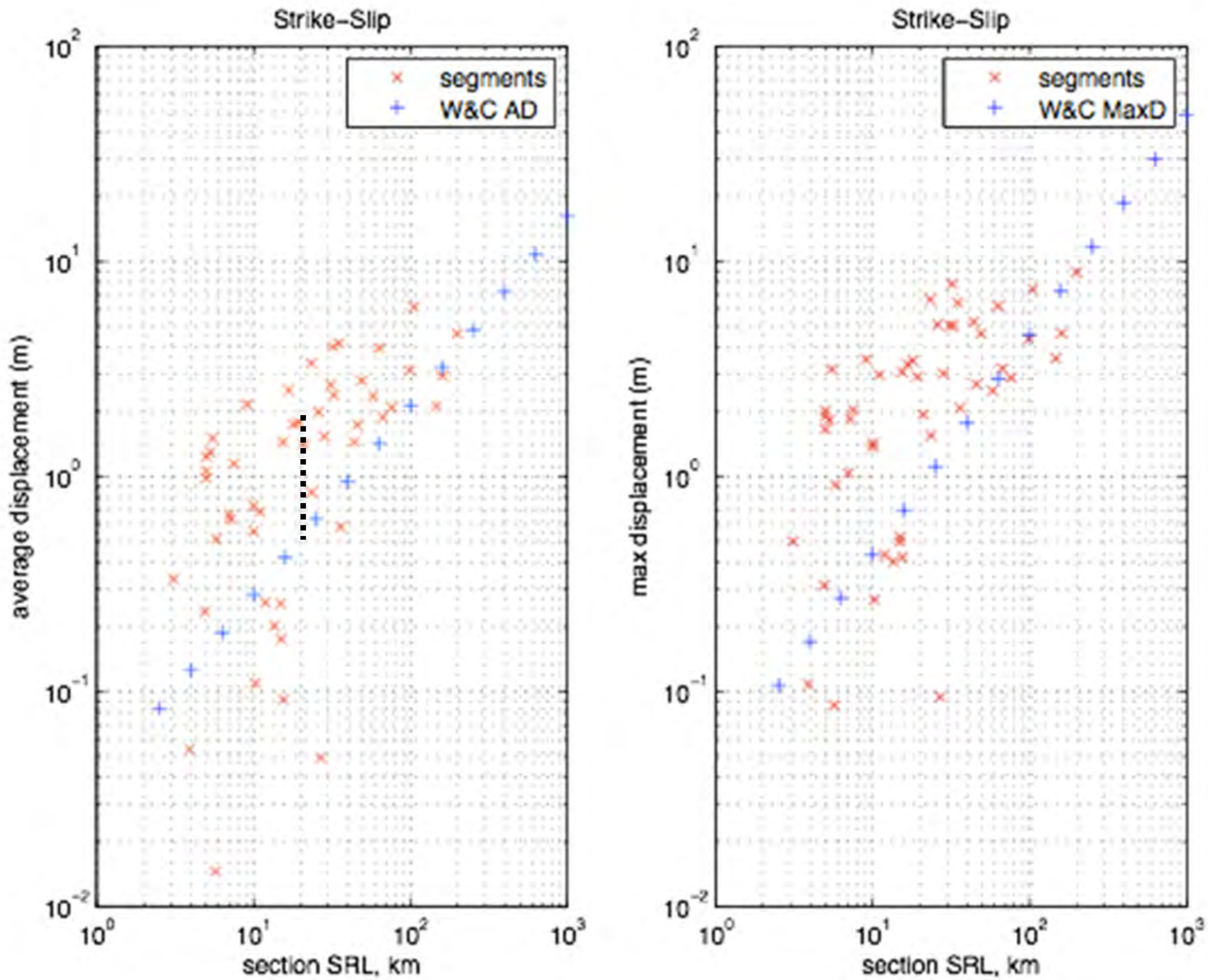
Plot rupture section displacements versus their lengths

Dashed: 0.4 factor scale bar

Sub-section average and maximum displacements plot above expectations for their W&C length.

Somehow most sections adjust their individual displacements to correspond to the final event magnitude. Large ruptures are not made by just linking shorter sections that just happened to be ready to go.

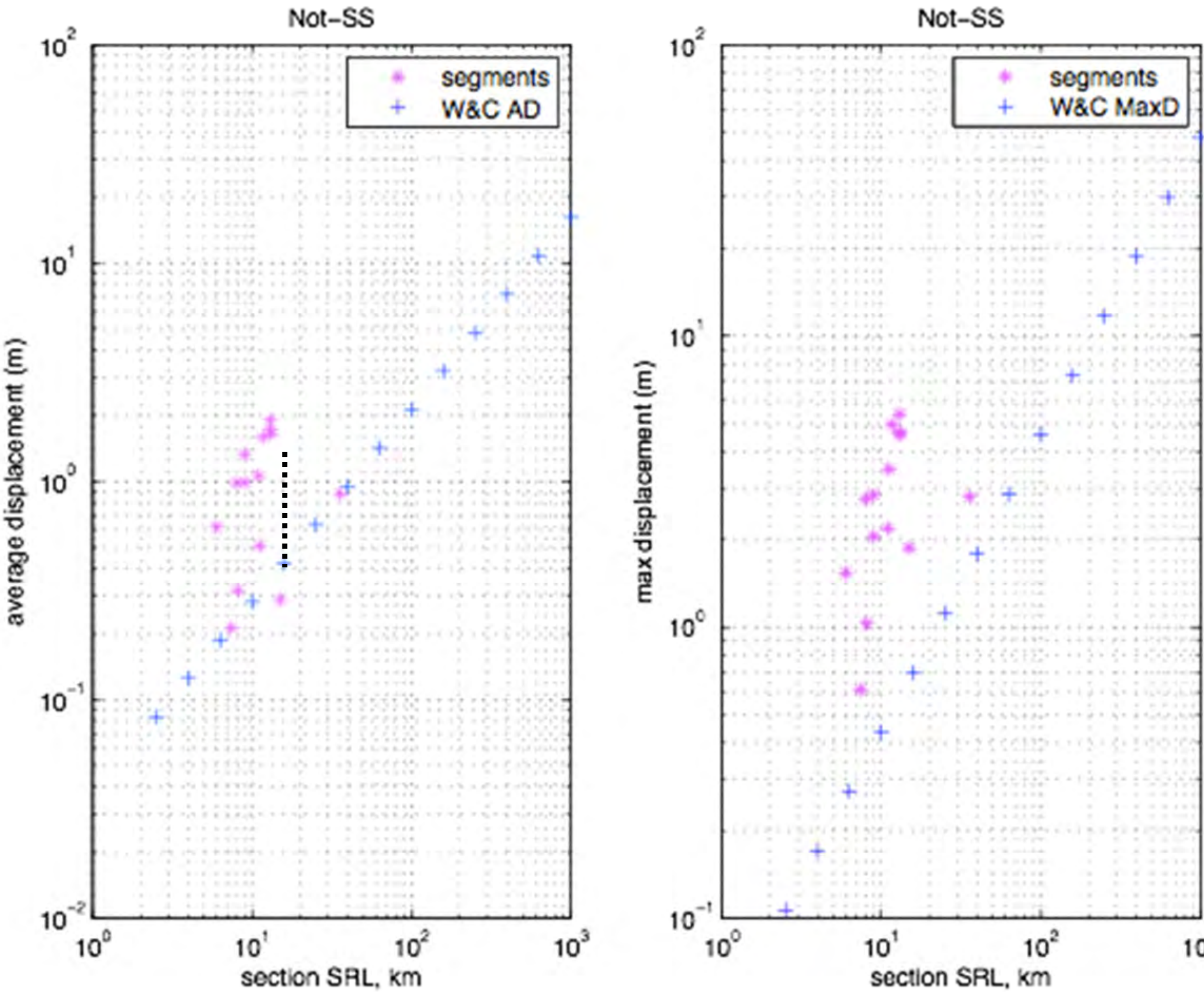
Displacements have to be assigned after any fault-to-fault links are done.



Plot section AD vs. length

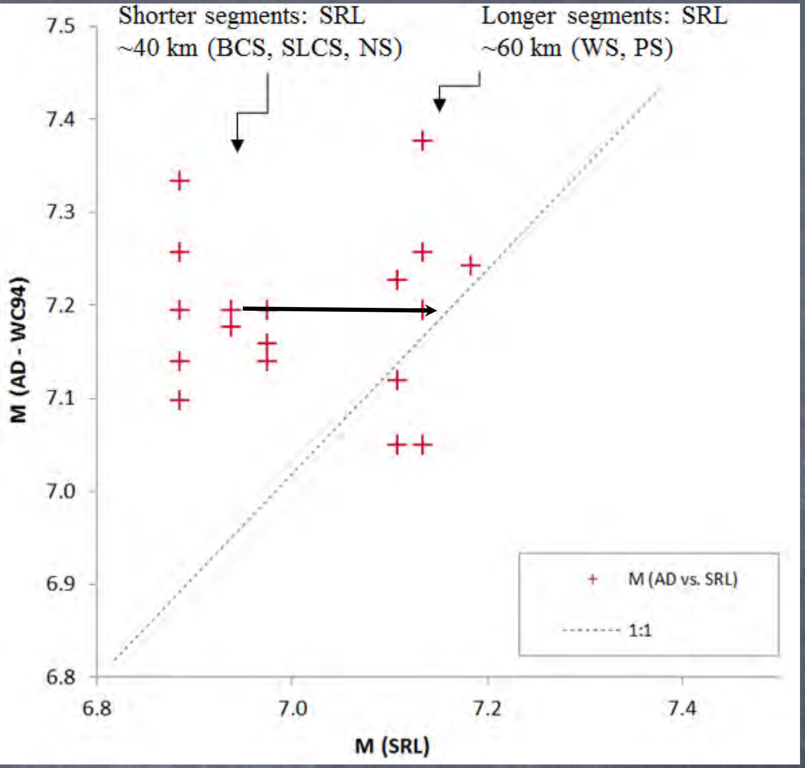
Strike-slip events with subsegments in Wesnousky 2008.

Dashed line: 0.4 factor increase in AD

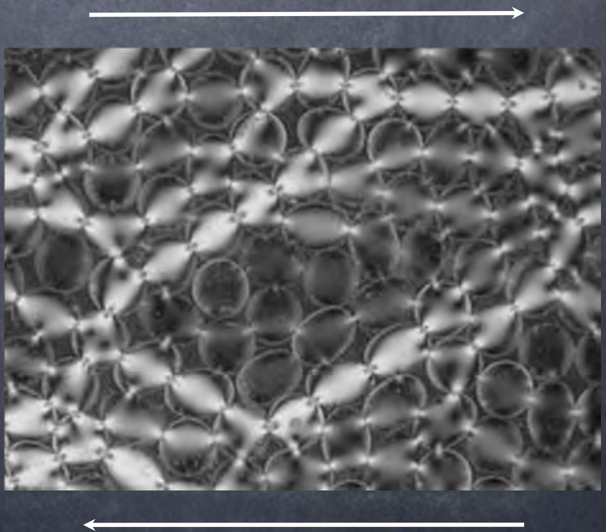


Non-strike-slip events

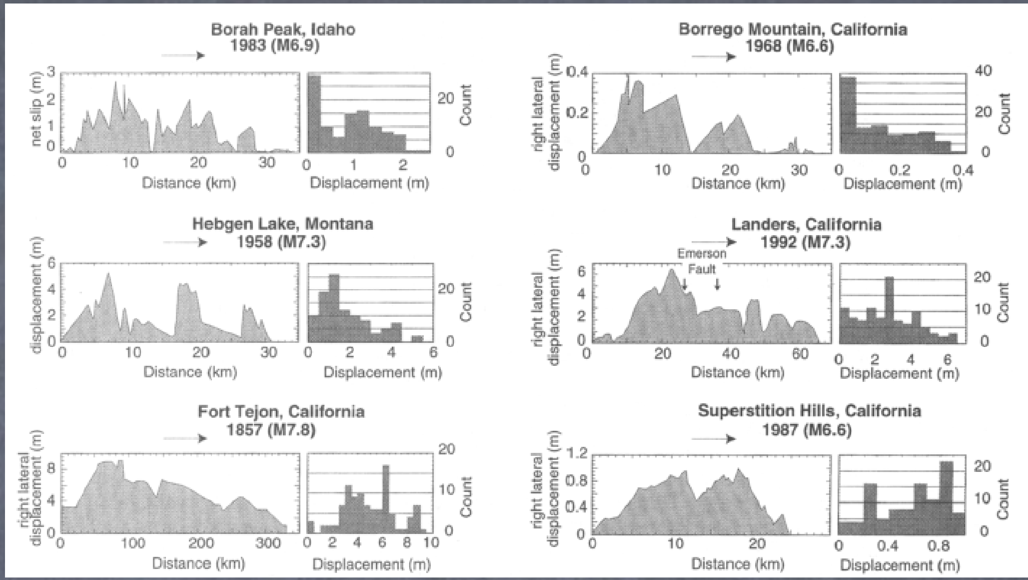
- M(AD)>M(L)? Maybe sections are part of larger ruptures.
    - Dynamic stress release for large earthquakes may “extract” or ”push” greater offsets.
    - Large earthquakes may sense a larger stress environment and scale displacements to that.



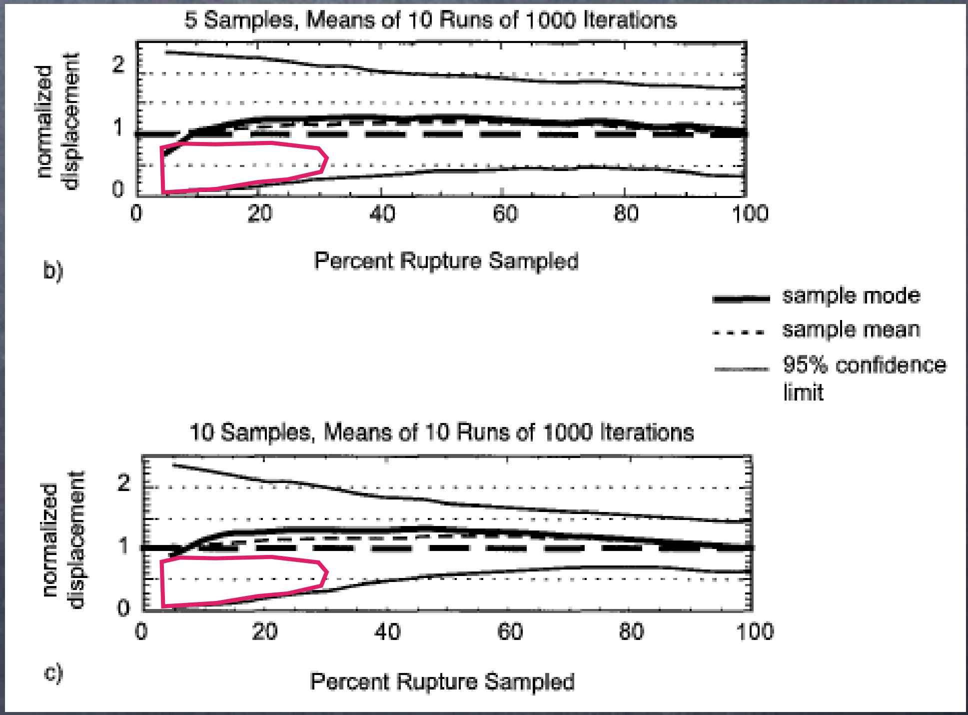
About the larger stress environment: (e.g., Daniels and Hayman, JGR, 2008). Force chains in granular media under strike-slip shear. Photo is detail of larger system. Lighter grains bear more force. Shows support paths in grain-supported media. Note different path lengths. Larger AD on multi-section ruptures may reflect broader stress trajectory of the system.



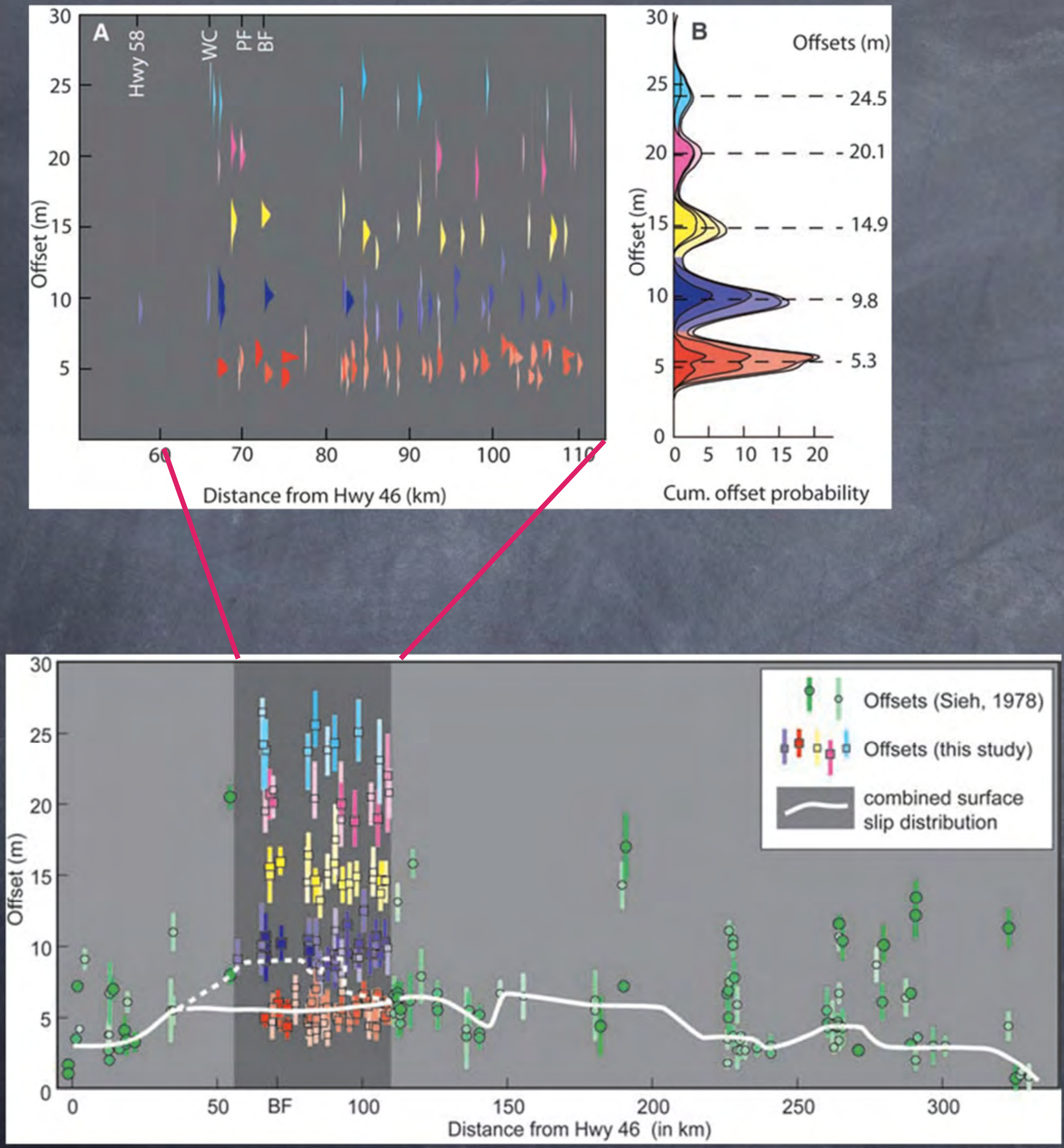
- Displacement from random sampling in rupture profiles
- Sampling BRP ruptures will rarely fit assumptions of HH&W 1999
    - Rupture extent is not a given
    - Rarely sample unless the surface expression is already clear.
    - Random in the profile, amplitude: Larger offsets are preserved longer.
    - Potential for overestimation is real.



Hemphill-Haley and Weldon, 1999, Figs 1, 10



Red: Qualitative region removed by biased sampling.



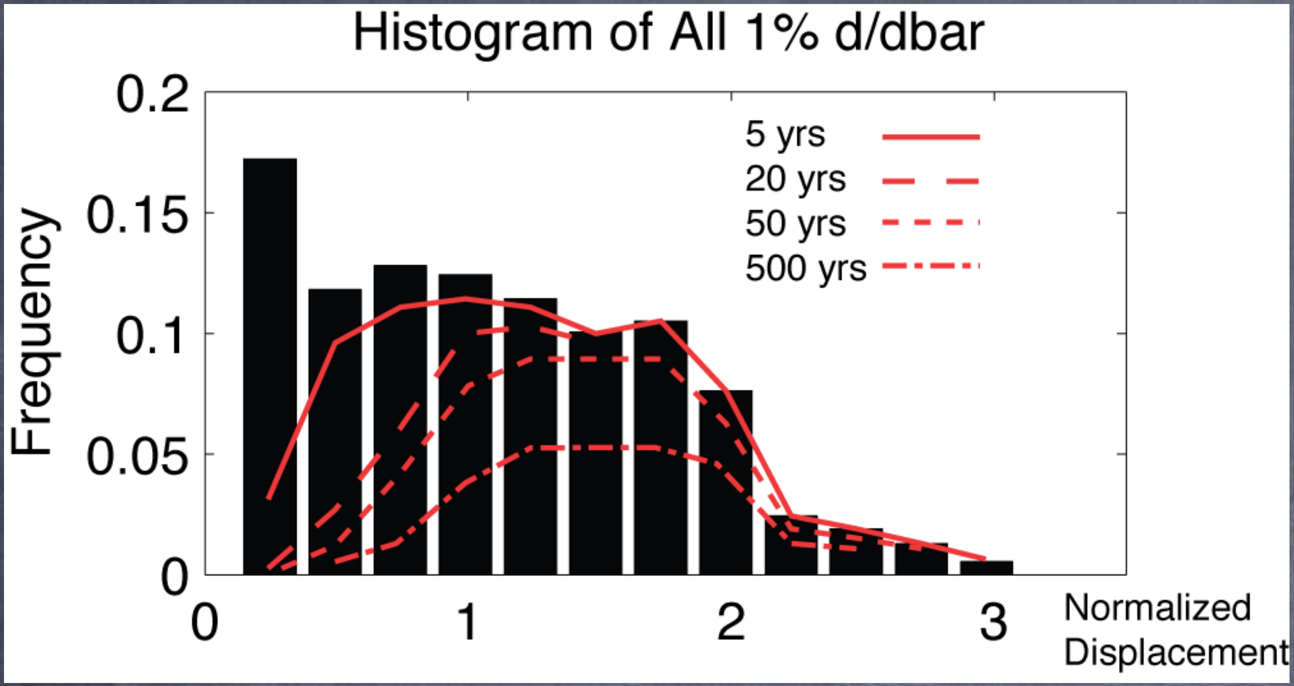
Zielke et al., 2010, Science

-- LiDAR is changing the rules on the number of displacement observations in ruptures

-- Even this quality of data would not resolve the length to better than about a factor of 2.

-- There is more evidence for characteristic slip than in the past.

P(M|Dobs): Biasi and Weldon (2006)

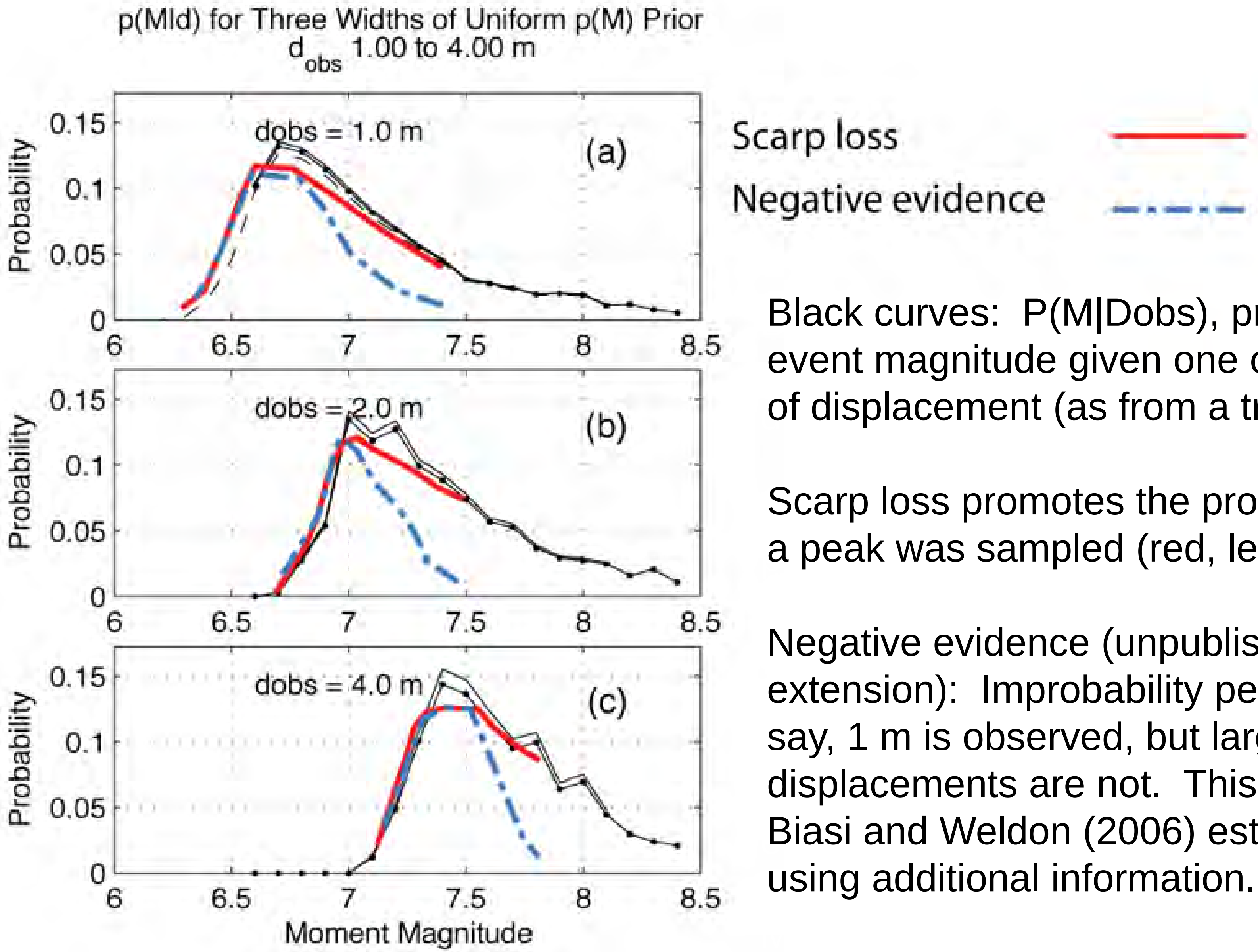


Histogram: sampling displacement at random while the displacements are still clear and abundant.

In time small displacements are preferentially removed. Effect is to increase the sample mean.

Above case assumes mean displacement of a meter. Scarp loss is conceptual, and in practice could be site specific.

Lines describing loss of scarp to be sampled depend on the average displacement. If the mean is 2 m instead of 1 m, less of the smaller than average sampling space is lost.



Black curves: P(M|Dobs), probability of event magnitude given one observation of displacement (as from a trench)

Scarp loss promotes the probability that a peak was sampled (red, left shift)

Negative evidence (unpublished extension): Improbability penalty that, say, 1 m is observed, but larger displacements are not. This improves Biasi and Weldon (2006) estimates by using additional information.

Magnitude will be overestimated if these effects are not considered.

Conclusions

- M(AD) > M(L) could be an indication of multiple-segment events - favors larger magnitudes.
- Magnitude from one or a few observed displacements can be fuzzy
  - Want to understand the biases in sampling before attempting HH&W magnitude uncertainties.
  - Sampling will never be as random as assumed in HH&W.
- Magnitude distribution from single displacement is an option.
- Scarp loss causes P(M|Dobs) to shift to smaller magnitudes since larger scarps are preferentially preserved and observed.
- Probability of non-detection is an asset for narrowing M(D) estimates - improbability of evidence for larger offsets all being lost.

Estimating Surface Lengths for Prehistoric Ruptures in the Basin and Range Province

Craig M. dePolo
Nevada Bureau of Mines and Geology

Need to identify and characterize earthquake segments

Data set is mapped Quaternary faults

Basin and Range Province Faults

- Commonly structurally complex
- Can be challenges identifying active faults and the extent of faults

Structurally Complex

- Preconditioned crust (Paleo-Meso),
- Tertiary volcanic activity,
- Many Quat. faults developed in Miocene,
- Changes in stress regime since Miocene,

  (Walker Lane belt)
- Young faults still linking up.

Challenges Identifying Active Fault Traces

- Blind, incomplete, and variable surface ruptures (distributed faulting, folding, variations in surface displacement),
- Erosion (fluvial, lacustrine, human),
- Burial (alluvial, eolian, lacustrine, human),
- Bedrock ruptures.

Measuring Potential Surface Rupture Length

- Use good dividers for paper maps,
- Main faults only (represent earthquake),
- Straight-line distance through complexity,

- All about identifying the rupture endpoints of earthquake segments.

Historical Earthquakes

Longer (>15-20 km) BRP ruptures are complex and are made up of multiple geometric and structural segments and/or multiple faults.

Number of Geometric or Structural Segments Versus Total Rupture Length (km) for Basin and Range Province Earthquakes

one fault segment common

<15-20<

two fault segments common

<30-50<

three segments common

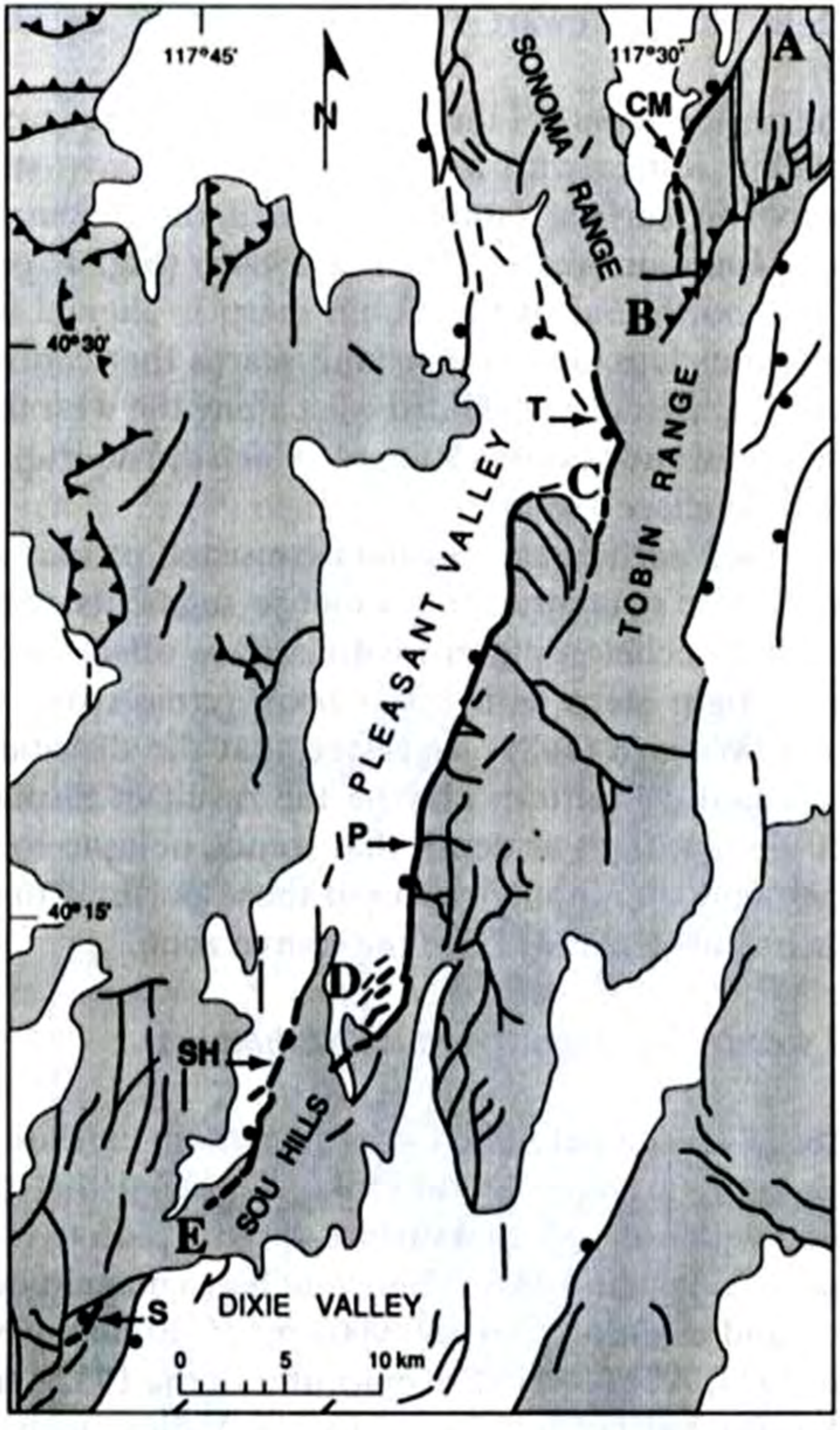
<60-110<

four segments common

mod. from dePolo and others (1991)

Analyzing a fault

- Type of fault (sense of displacement),
- Identify and characterize discontinuities,
- Divide fault into segments,
- Characterize fault endpoints,
- Develop earthquake segment models (L),
  (multiple models to handle uncertainties)
- Weigh the relative likelihood of models.



1915 Pleasant Valley earthquake

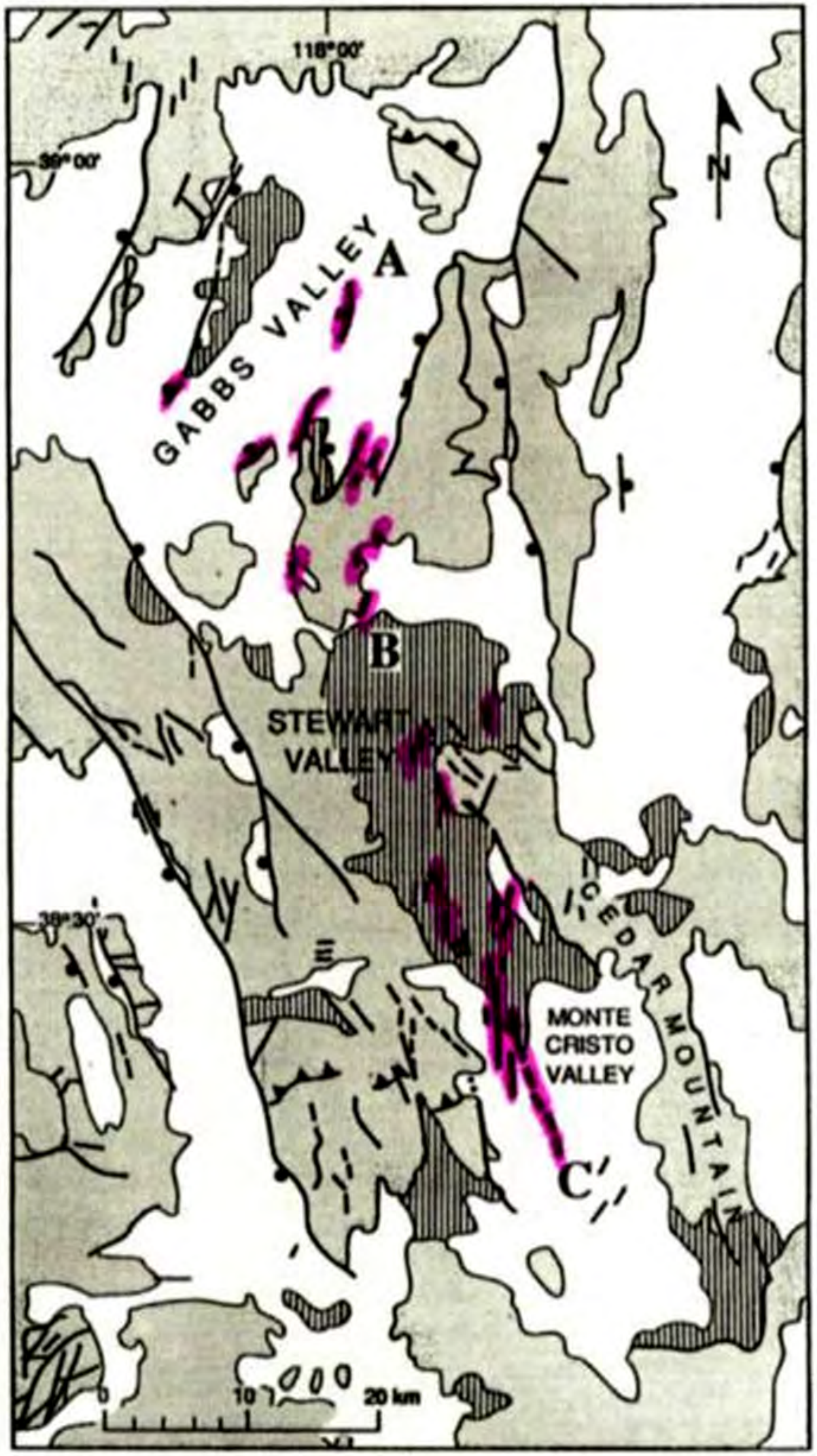
Logic Tree for Earthquake Segment Models

Fault X

- one segment (L= a) ___
- two segments (L= b) ___
- three segments (L= c) ___
- endpoint models ___

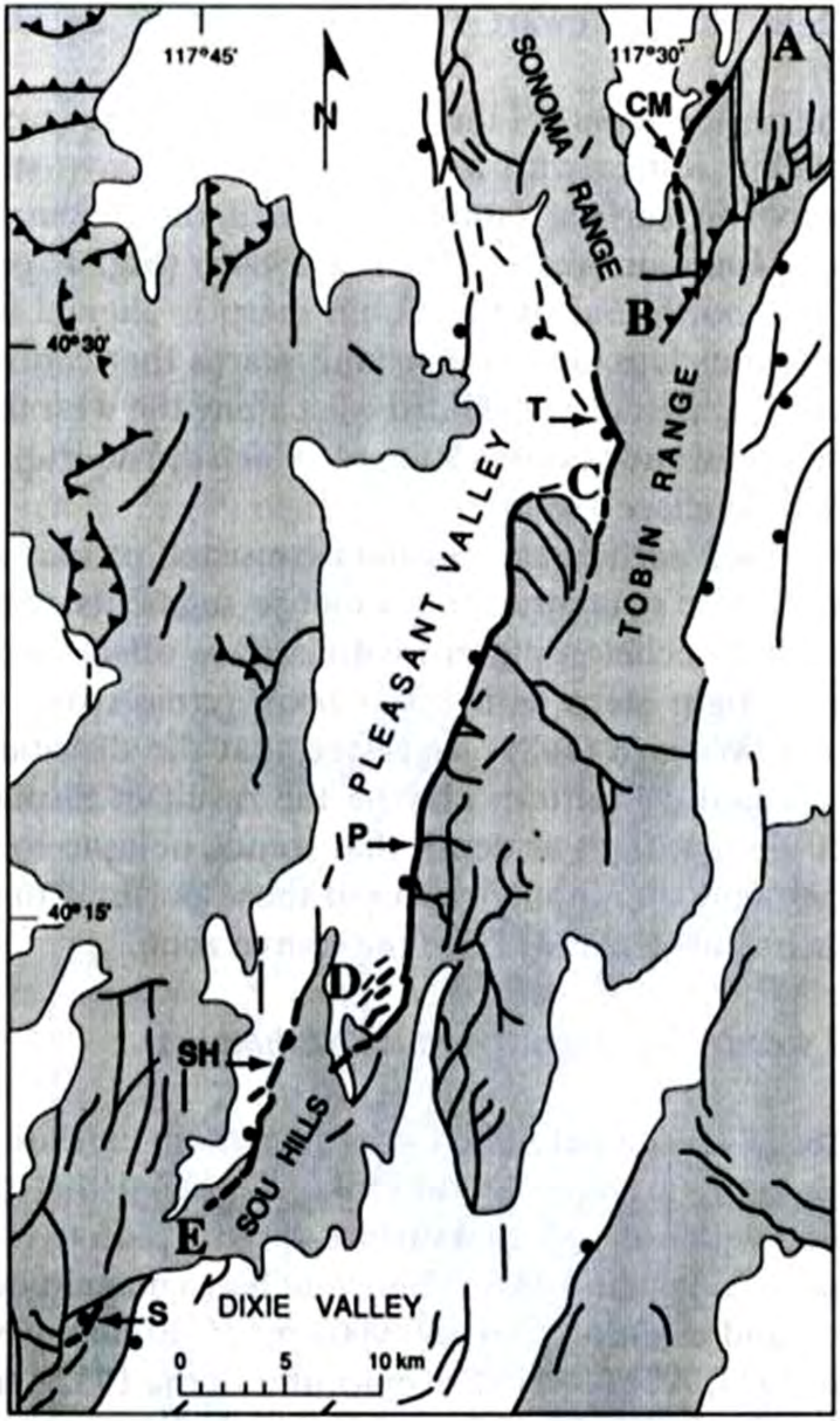
Weighing Logic Tree Branches
(Earthquake Segment Models)

- Paleoseismic information,
- Probability of discontinuity failure,
  - scale of discontinuity
  - type of discontinuity
  - character of discontinuity
  - number of discontinuities
- Historical analog.



1932 Cedar Mountain Earthquake

Mw 7.1



1915 Pleasant Valley earthquake

Date	L(km)	M_w	M_{length}	M_{Dmax}	D_{max}(m)
1872	110	7.6	7.45*	7.32	7
1887	102	7.5	7.41*	7.21	5.1
1915	62	7.3	7.16	7.25*	5.8
1959	28	7.3	6.76	7.24*	5.5
1954d	67	7.1	7.19*	7.23	5.3
1932	75	7.1	7.26*X	6.91* (7.01)	2 (2.7)
1954e	42	6.9	6.96*	7.11	3.7
1954c	53	6.9	7.08*	6.69	1
1983	36	6.8	6.89*	7.01	2.7
1934-H	10	6.6	6.24	6.47*	0.5
1954a	18	6.3	6.54	6.40*	0.4(?)
1934-E	1.7	6.1	5.35	6.47*	0.5(?)
1954b	6.5	6.0	6.02*	6.40	0.4
1950	9.5	5.6	6.21*	6.53	0.6

Calcs. using Wells and Coppersmith (1994) relations for all eqs.
* closer to eq. value.
X doubtful could be measured w/o event

Important Points:

- Type of fault is important for earthquake modeling,
- Larger BRP earthquakes are cascading failures of segments (2-4 segs; 3 disconts. max.),
- Develop and relatively weigh multiple earthquake segment scenarios,
- Maximum surface displacement can help scale paleoearthquakes – use it.

Date	L(km)	M_w	M_{length}	M_{Dmax}	D_{max}(m)
1872	110	7.6			
1887	102	7.5			
1915	62	7.3	7.16	7.25*	5.8
1959	28	7.3	6.76	7.24*	5.5
1954d	67	7.1	7.19*	7.23	5.3
1932	75	7.1	7.26*X	6.91* (7.01)	2 (2.7)
1954e	42	6.9	6.96*	7.11	3.7
1954c	53	6.9	7.08*	6.69	1
1983	36	6.8	6.89*	7.01	2.7
1934-H	10	6.6	6.24	6.47*	0.5
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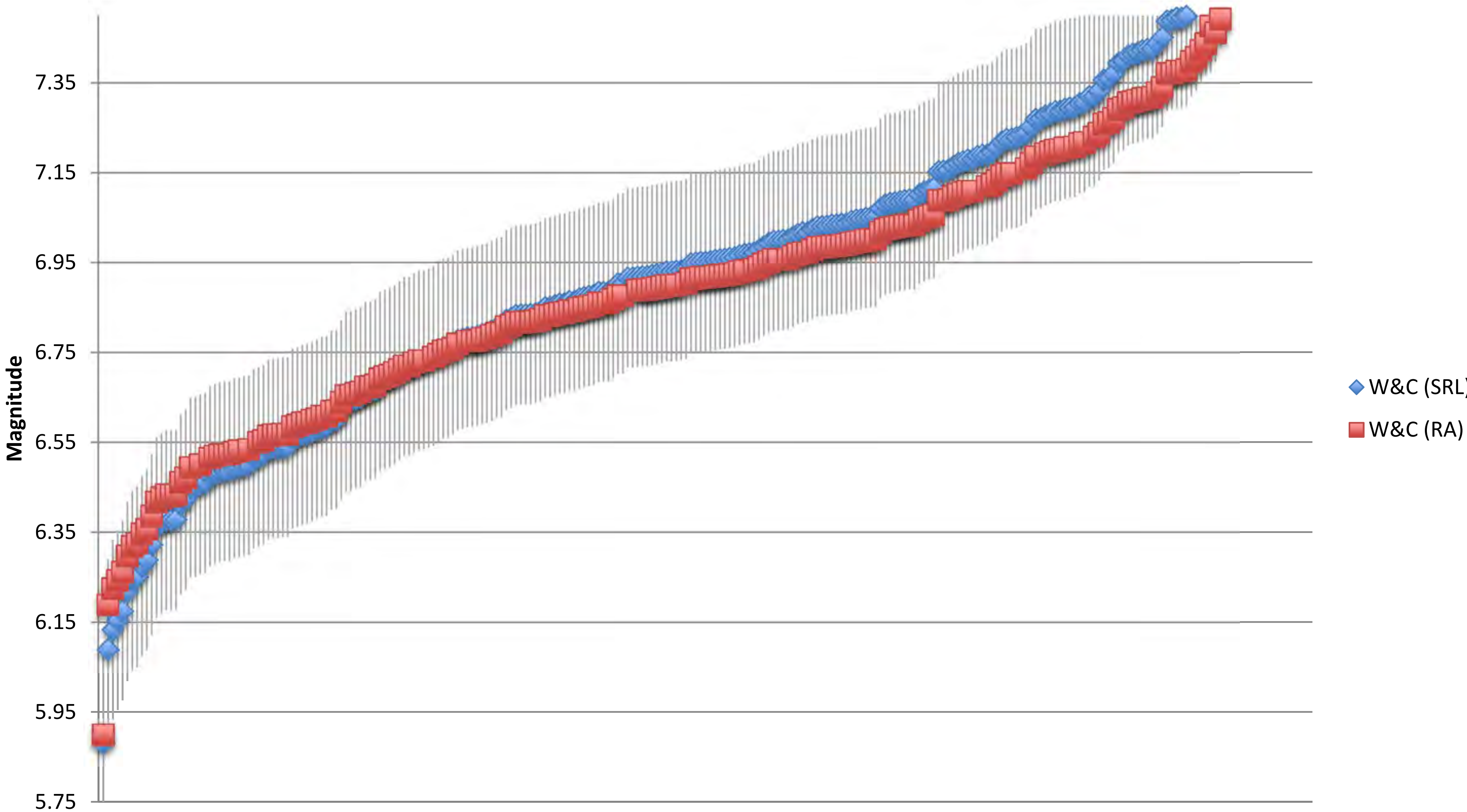
1934-E	1.7	6.1	5.35	6.47*	0.5(?)
1954b	6.5	6.0	6.02*	6.40	0.4
1950	9.5	5.6	6.21*	6.53	0.6

Calcs. using Wells and Coppersmith (1994) relations for all eqs.
* closer to eq. value.
X doubtful could be measured w/o event

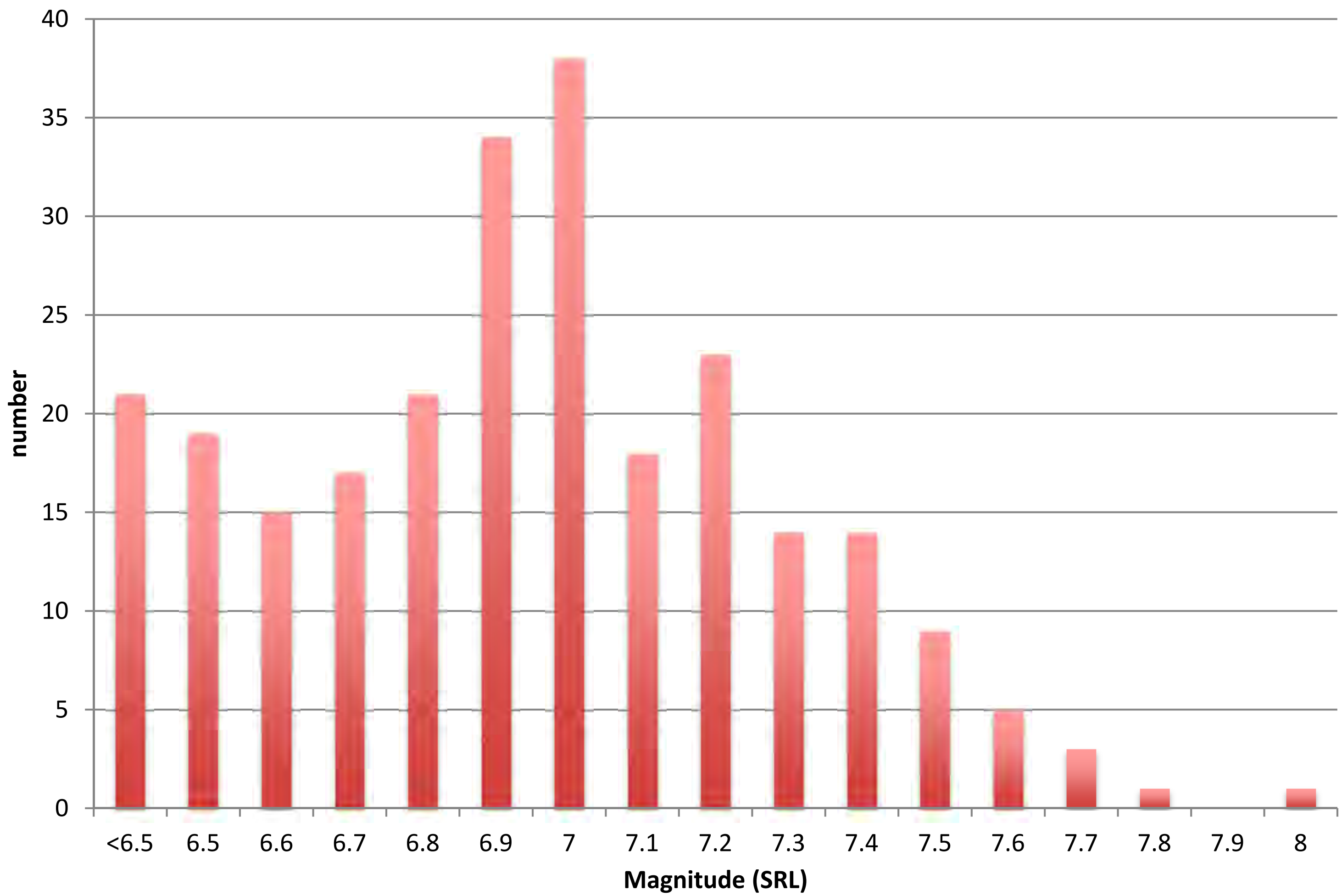
Magnitude in the NSHM

- Maximum M and characteristic magnitude based on Wells and Coppersmith (1994) M *versus* surface rupture length (ALL)
  - M = 5.08 +1.16*log(SRL)
- Additional epistemic uncertainty ±0.2 M
- Additional aleatoric uncertainty
- SRL (N) yields average difference of -0.024 M
  - M = 4.86 +1.32*log(SRL)
  - Standard errors are 3X larger than ALL

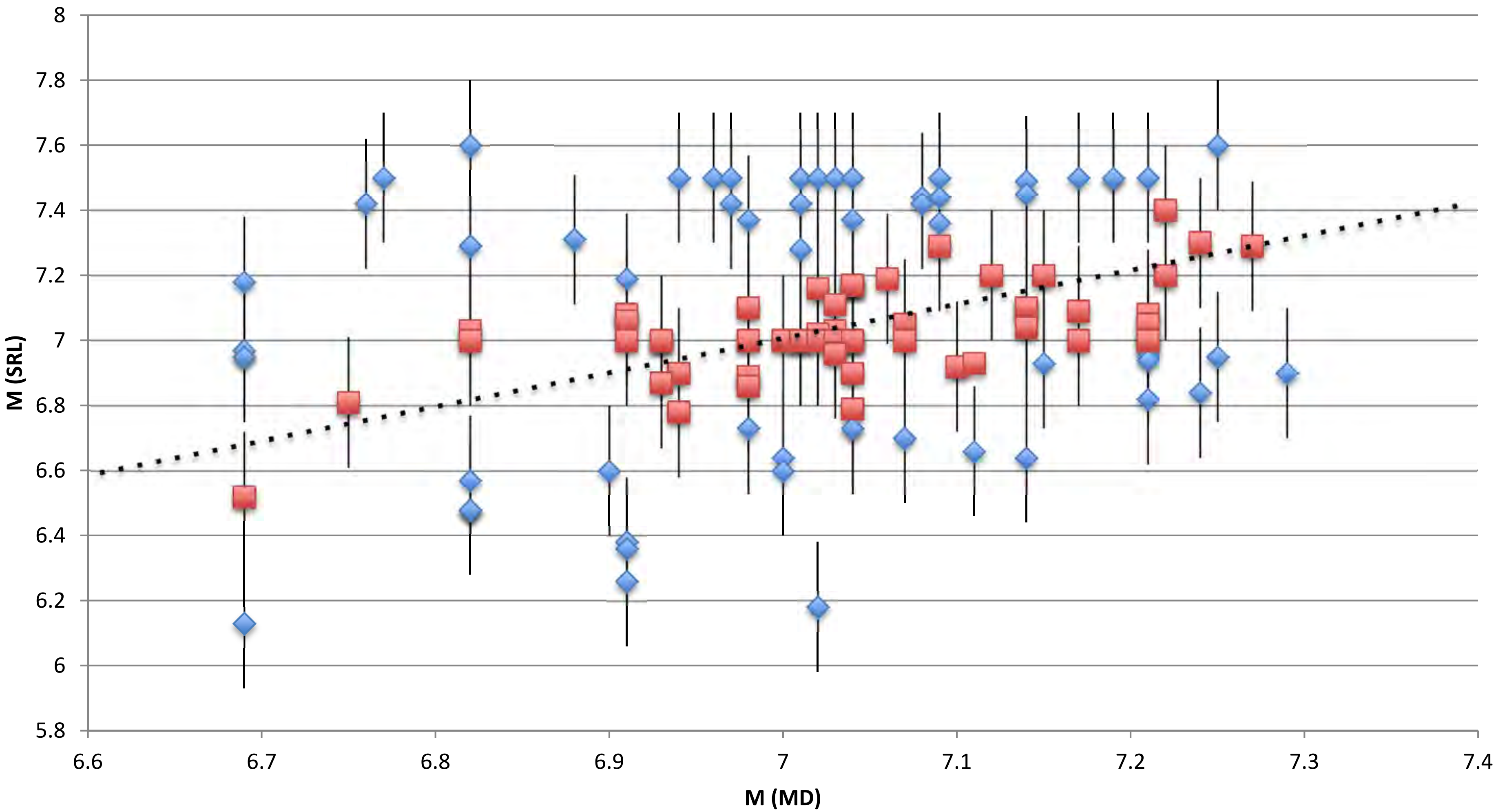
Magnitude-scaling relations



Frequency of Mchar (SRL)

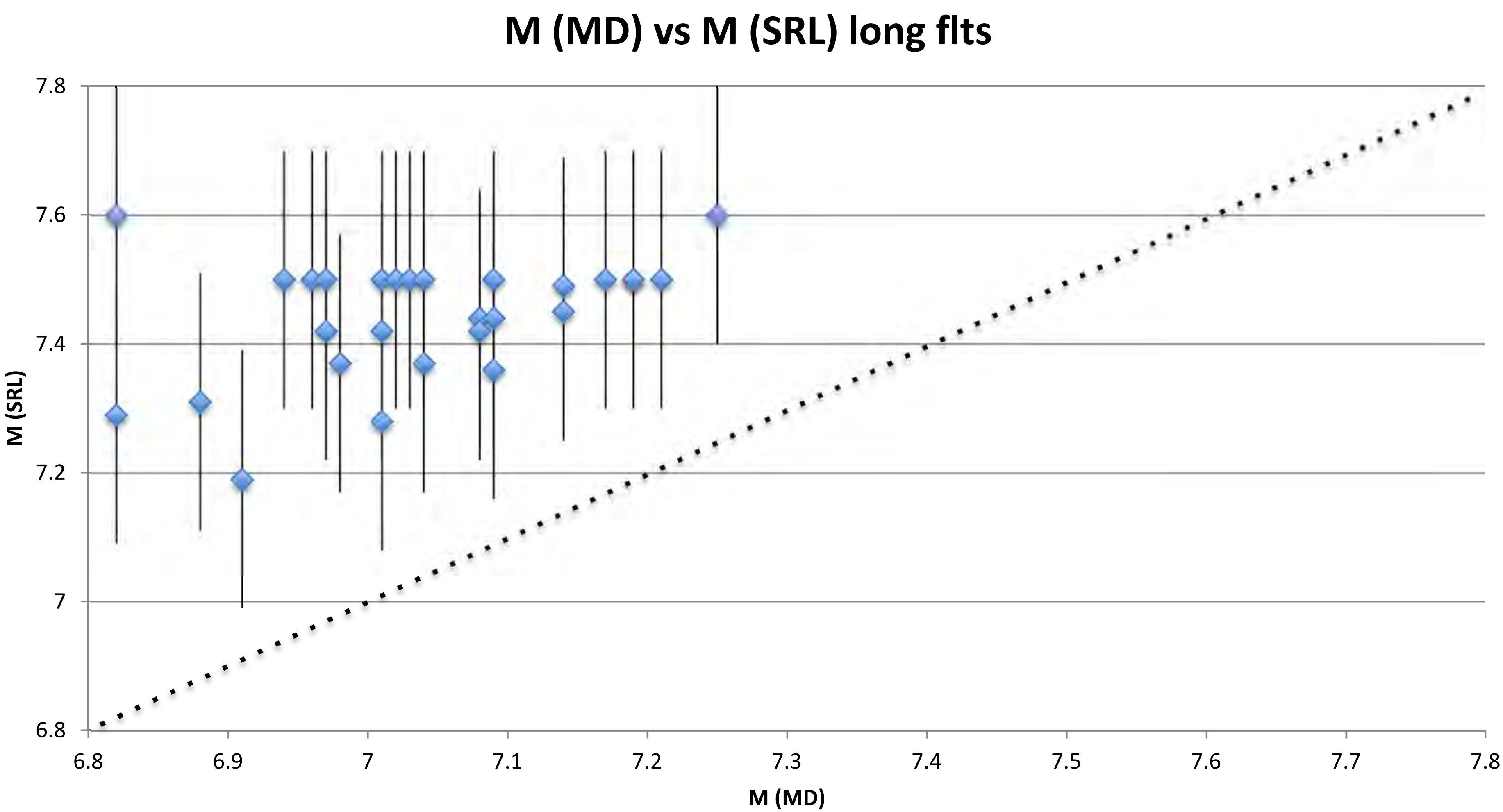


M(SRL) *versus* M(MD)

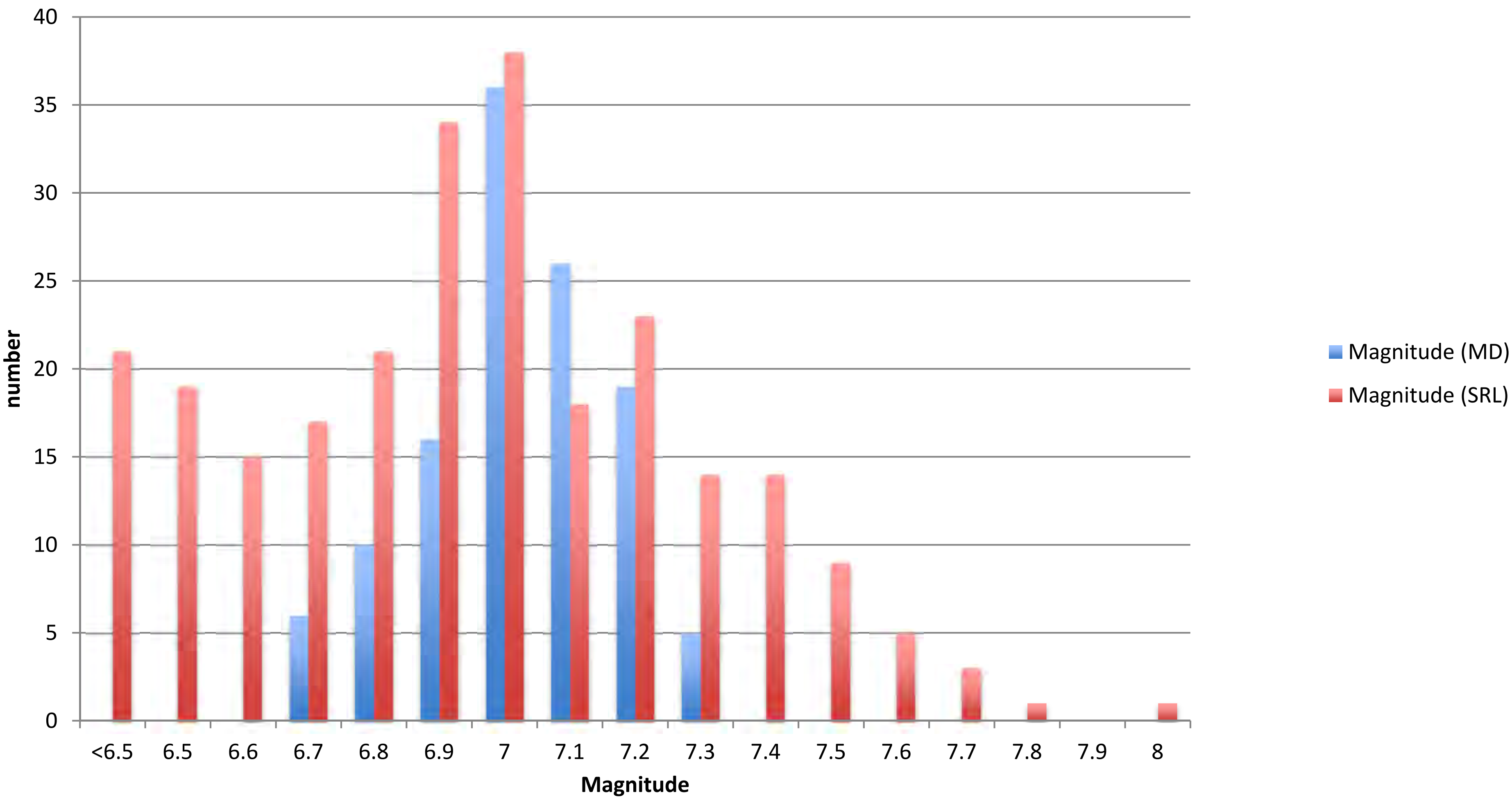


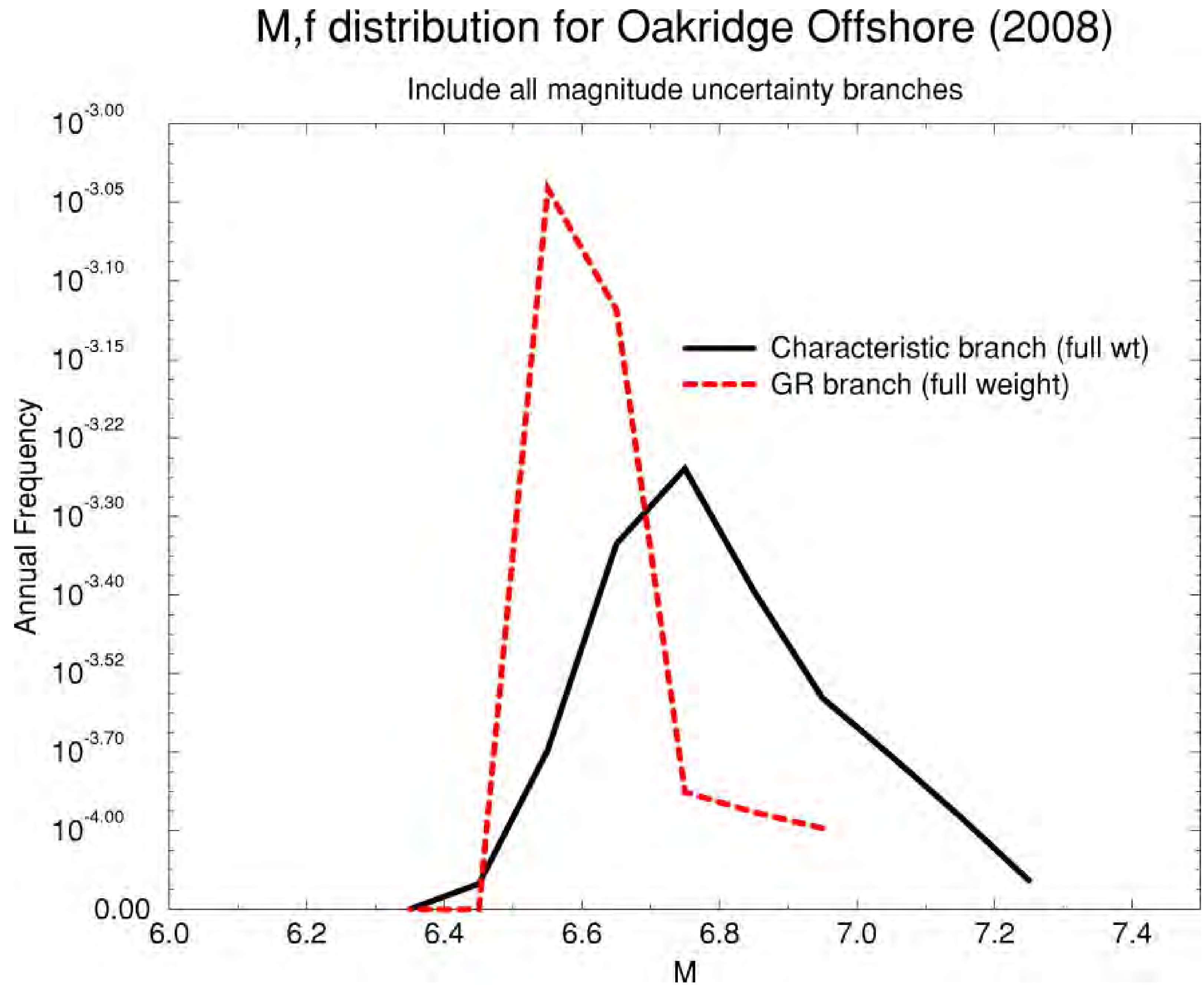
Maximum displacement data from S. Hecker Feb 2010

M (MD) *versus* M (SRL) long flts



M(MD) *versus* M(SRL)





M,f distribution for Oakridge Offshore (2008)
Include all magnitude uncertainty branches
Annual Frequency
$10^{-3.00}$
$10^{-3.05}$
$10^{-3.10}$
$10^{-3.15}$
$10^{-3.22}$
$10^{-3.30}$
$10^{-3.40}$
$10^{-3.52}$
$10^{-3.70}$
$10^{-4.00}$
0.00
6.0
6.2
6.4
6.6
6.8
7.0
7.2
7.4
M
Characteristic branch (full wt)
GR branch (full weight)

BRPEWG Issue S2: Smoothing parameters for NSHM

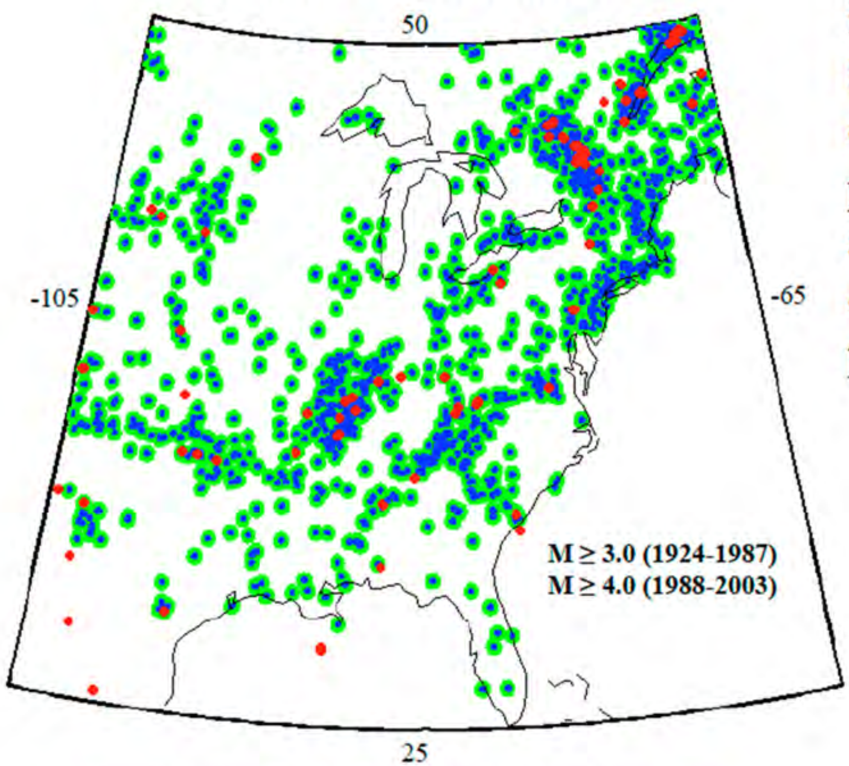
How should the smoothing of seismicity be handled in the NSHMs? The current seismic hazard maps use a radial smoothing process but recent precarious rock studies in CA and W NV suggest that anisotropic smoothing (i.e., along faults) might be more appropriate. If anisotropic smoothing is used should it be applied universally across the entire Basin and Range province.

Morgan Moschetti and Mark Petersen

S2 Discussion Outline

- How and why do we include smoothed seismicity models?
- Implementation of smoothing in the 2008 NSHMs
- Issues with smoothing (anisotropy)
- Potential model for extending anisotropic smoothing across IMW

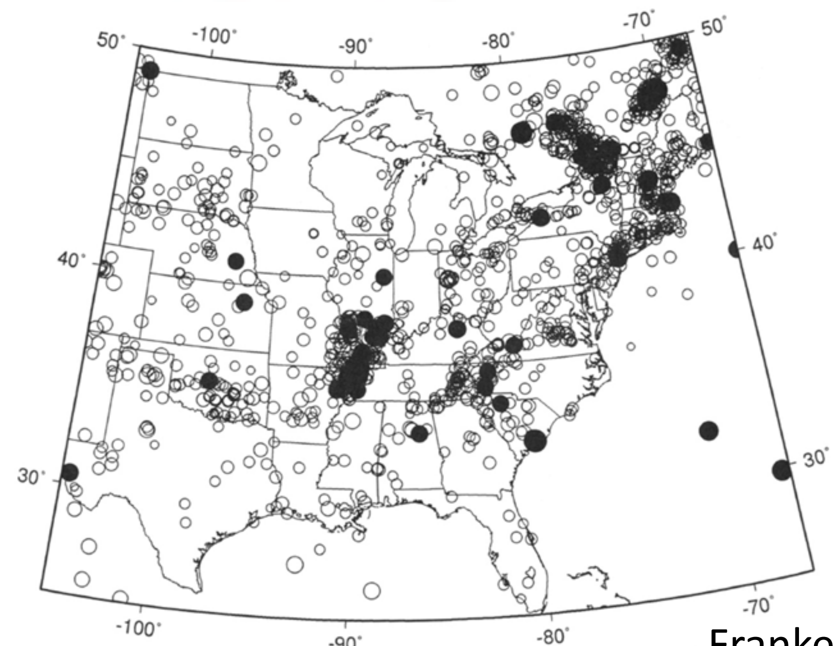
Historical seismicity models, CEUS



(Kafka – see Kafka,2002)

Future large earthquakes in the CEUS have about 86% probability of occurring within 36 km of past earthquakes, and about 60% probability of occurring within 14 km of past earthquakes.

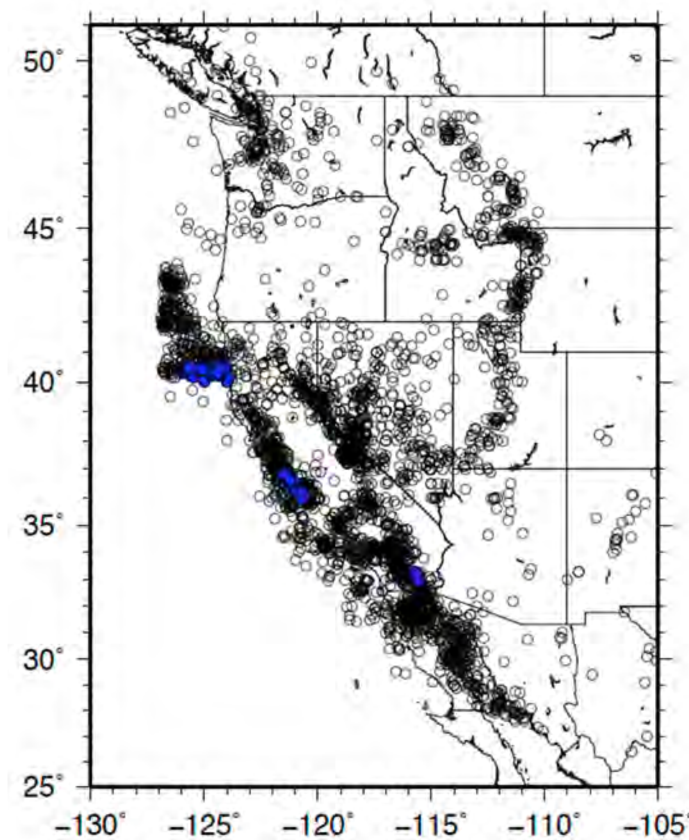
- Kafka (2005)



Frankel, 1995

History of smoothed background seismicity in the NSHMs

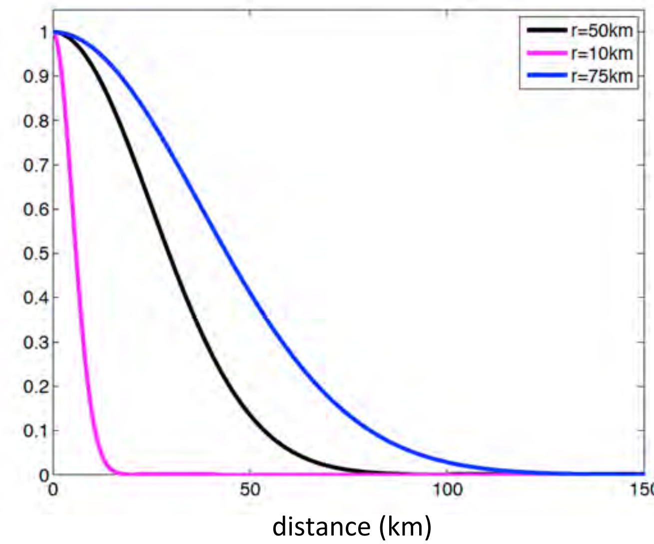
- Smoothed background seismicity replaced source zones in the 1996 NSHMs (see Frankel, 1995 and Frankel et al., 1996)
- 2008 NSHMs: we calculate 10^a values from earthquake catalogs at grid points.
- Background seismicity is smoothed using isotropic smoothing function except for three zones where we use an anisotropic smoothing function: (1) Brawley seismic zone; (2) Creeping section, SAF; and (3) Mendocino seismic zone.

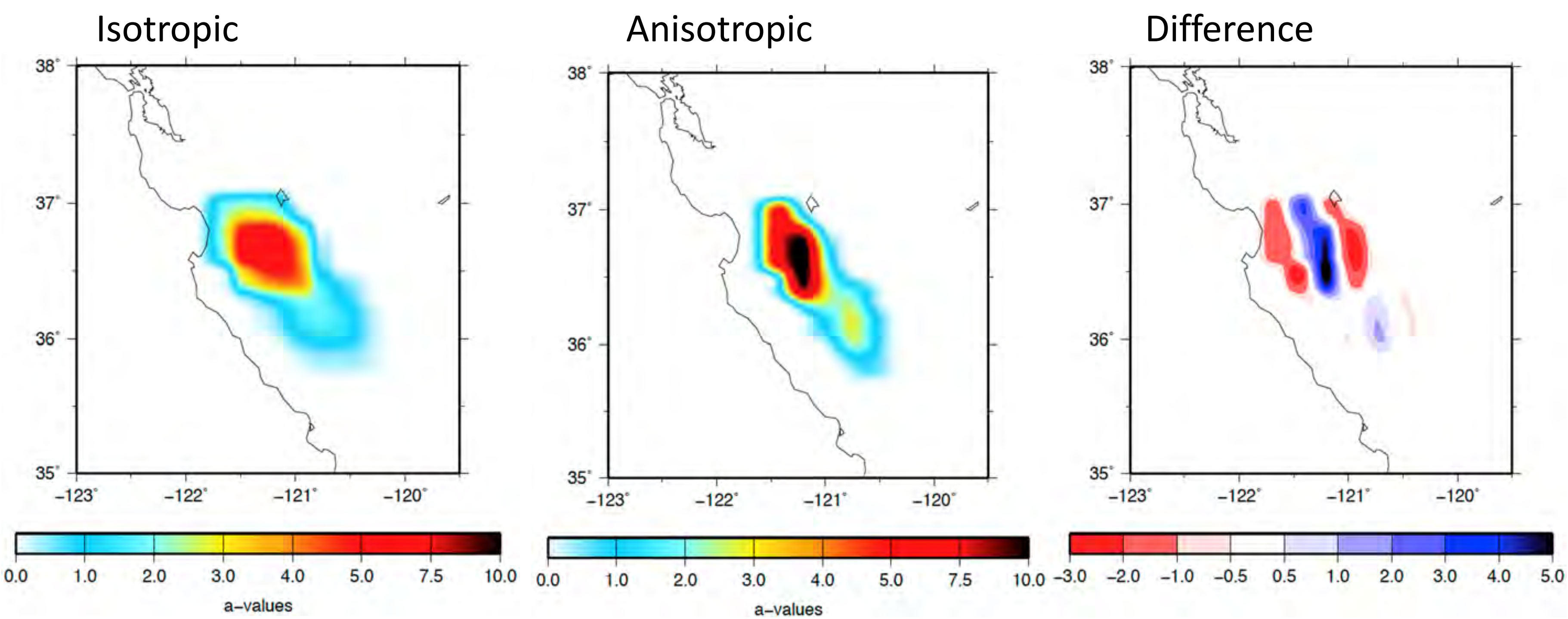


Smoothing parameters

2-D Gaussian (see Frankel, 1996):

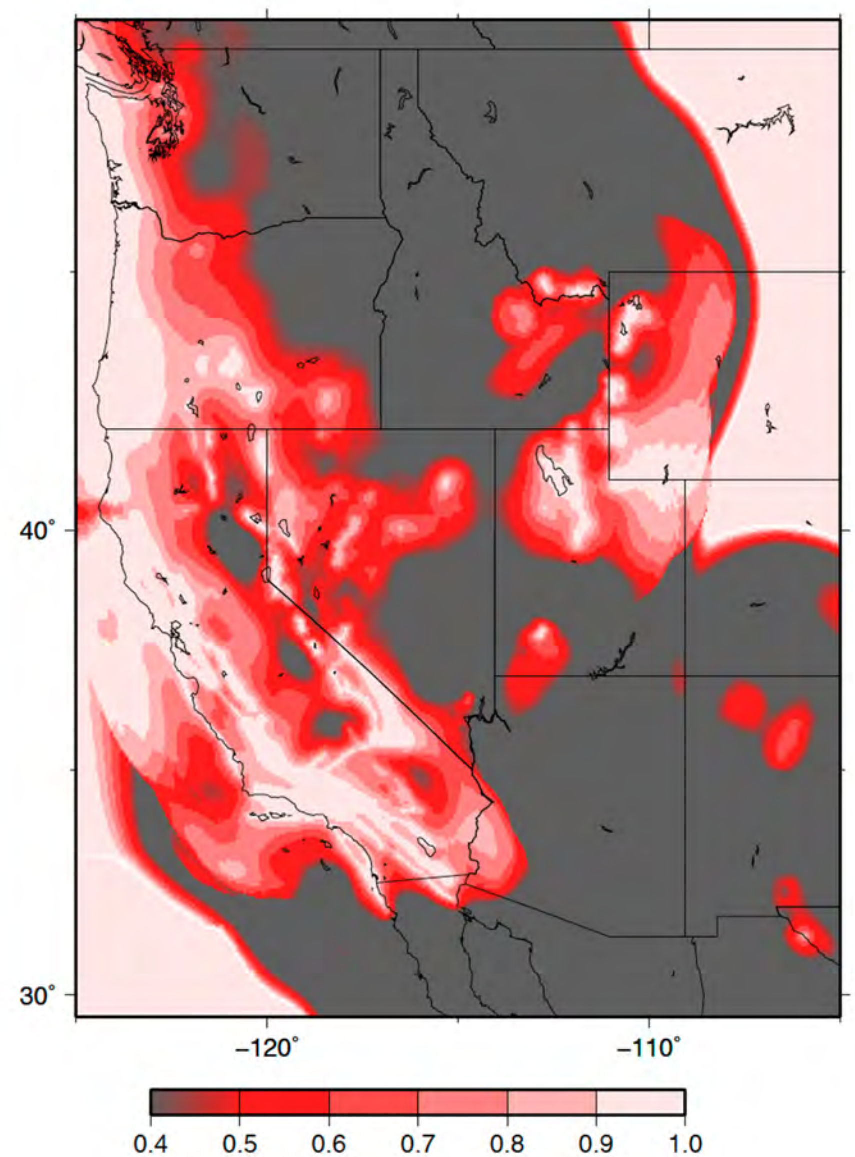
- 50 km “correlation distance”
- 75 km along-strike (major axis), 10 km perpendicular direction (minor axis).
- Example from creeping section, SAF





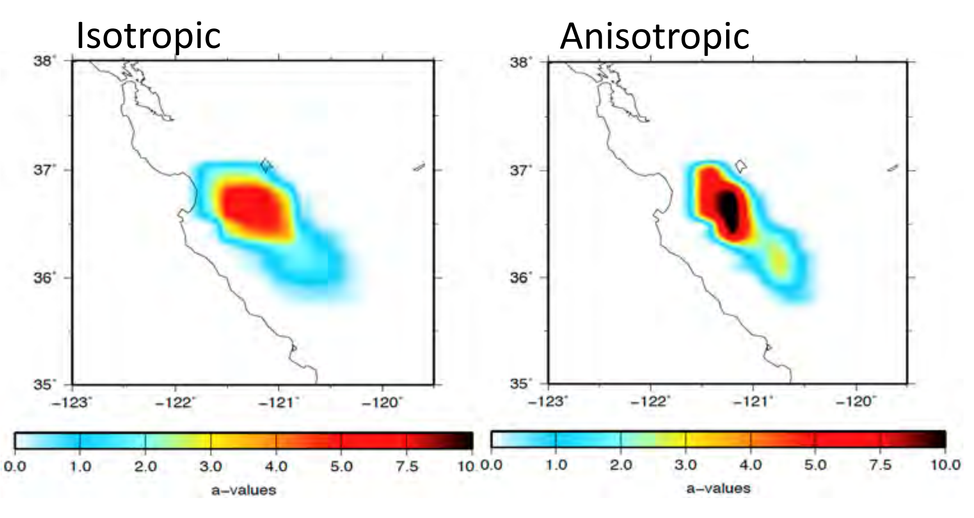
Where does smoothed seismicity influence the hazard most?

- Ratio of PGA (2%50yrs) for 2008 NSHM, version III input with and without background (gridded) seismicity
- Fault model sources dominate near faults in CA, western NV, Cascadia, Wasatch.
- Background seismicity contributes more than 60% to PGA hazard across large areas of BRP.
- No CEUS sources



Methods of smoothing

- Isotropic
- Anisotropic
- Other methods (Adaptive weighting – Stock and Smith; Penalized likelihood – Toro; Felzer – UCERF3)



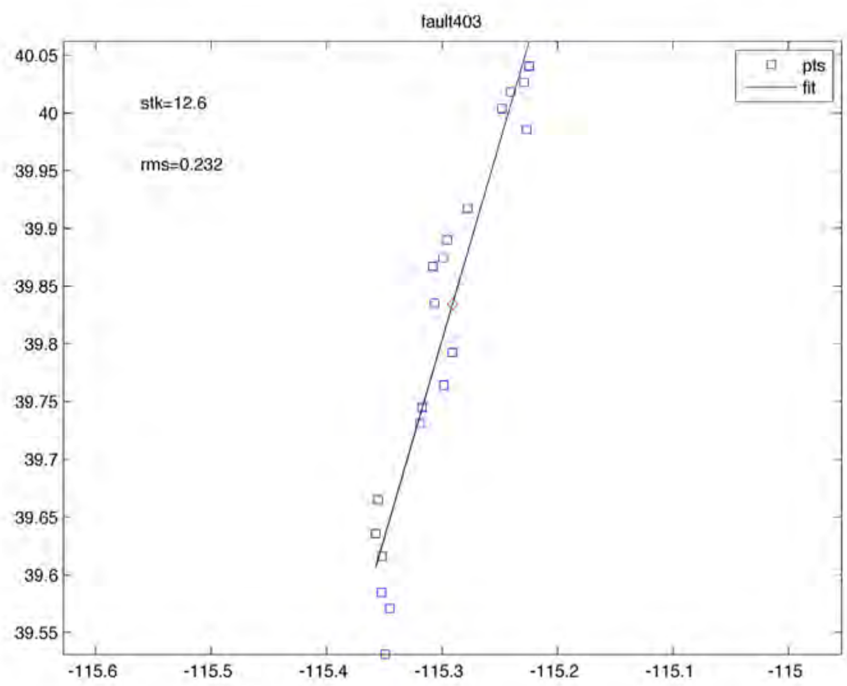
Possible models for NSHM

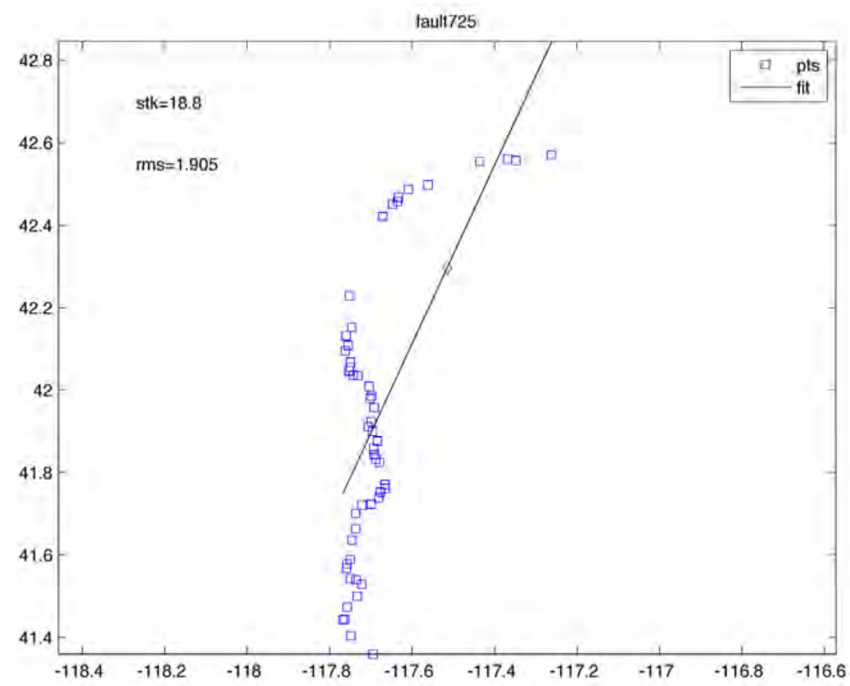
1. Isotropic with three anisotropic zones (2008 NSHM model)
2. Isotropic with additional anisotropic zones (based on PBRs, etc.) (as discussed in 2010 UNR-PBR workshop)
3. Anisotropic and Isotropic logic tree

Developing uniform anisotropically-smoothed agrids

- Extend 2008 NSHM methodology for anisotropic smoothing across the western US (i.e., smooth seismicity with anisotropic kernels for given strike)
- Calculate spatially-varying fault strike parameters
- Smooth extracted catalogs using standard smoothing parameters (75/10 km) and spatially-varying strike parameters.
- Results – look at changes in a-values and PGA, for western US and for two regional test cases.

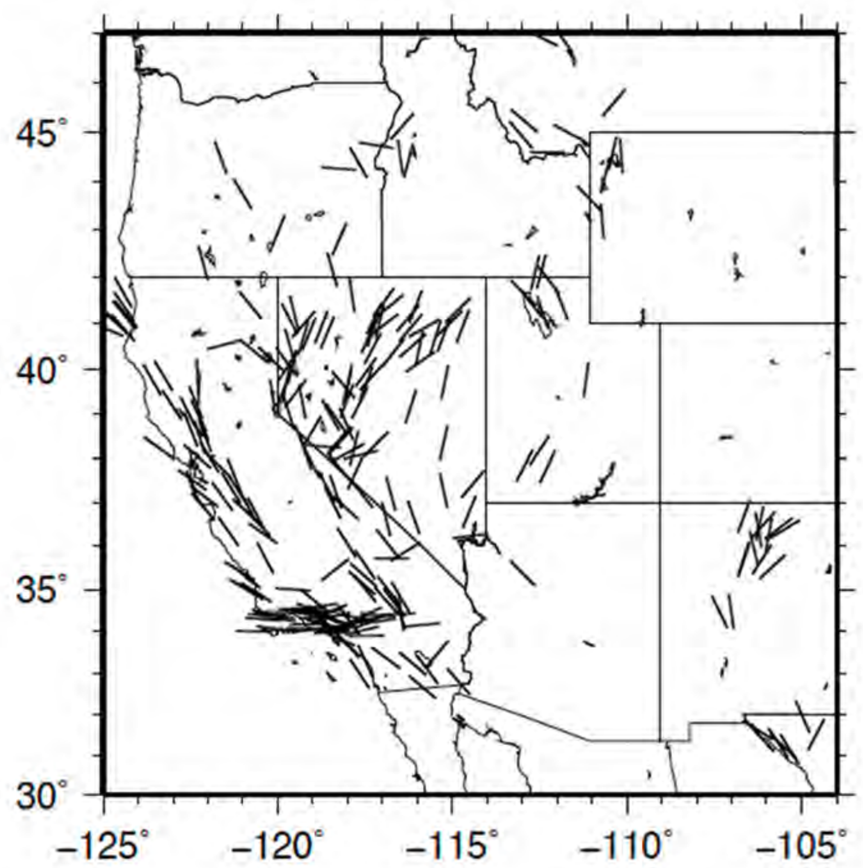
Developing uniform anisotropically-smooth agrids: individual line segment fits to faults in NSHM database





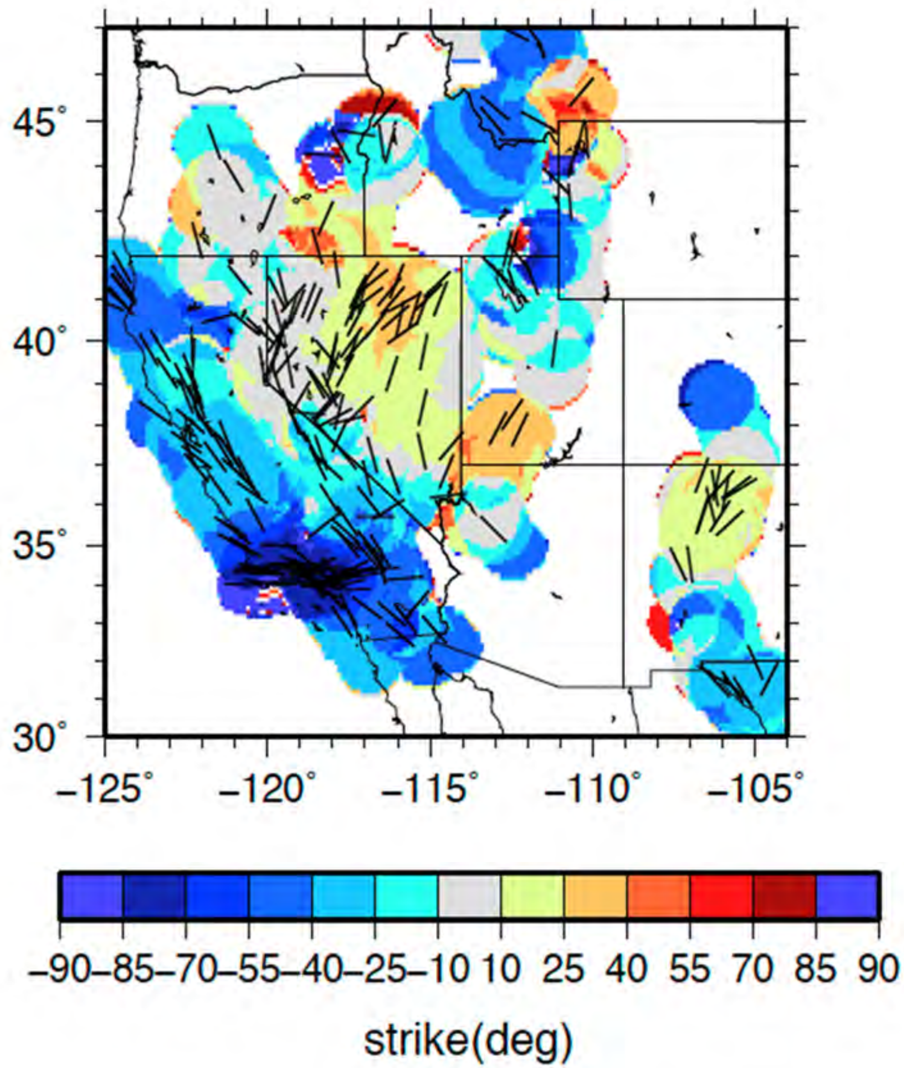
- Fit all faults with line segments and calculate “fault data point” separation residual
- Reject fit faults with large residuals (rms>0.3)

Developing regional anisotropically-smoothed agrids: regional line segment fits to faults in NSHM database



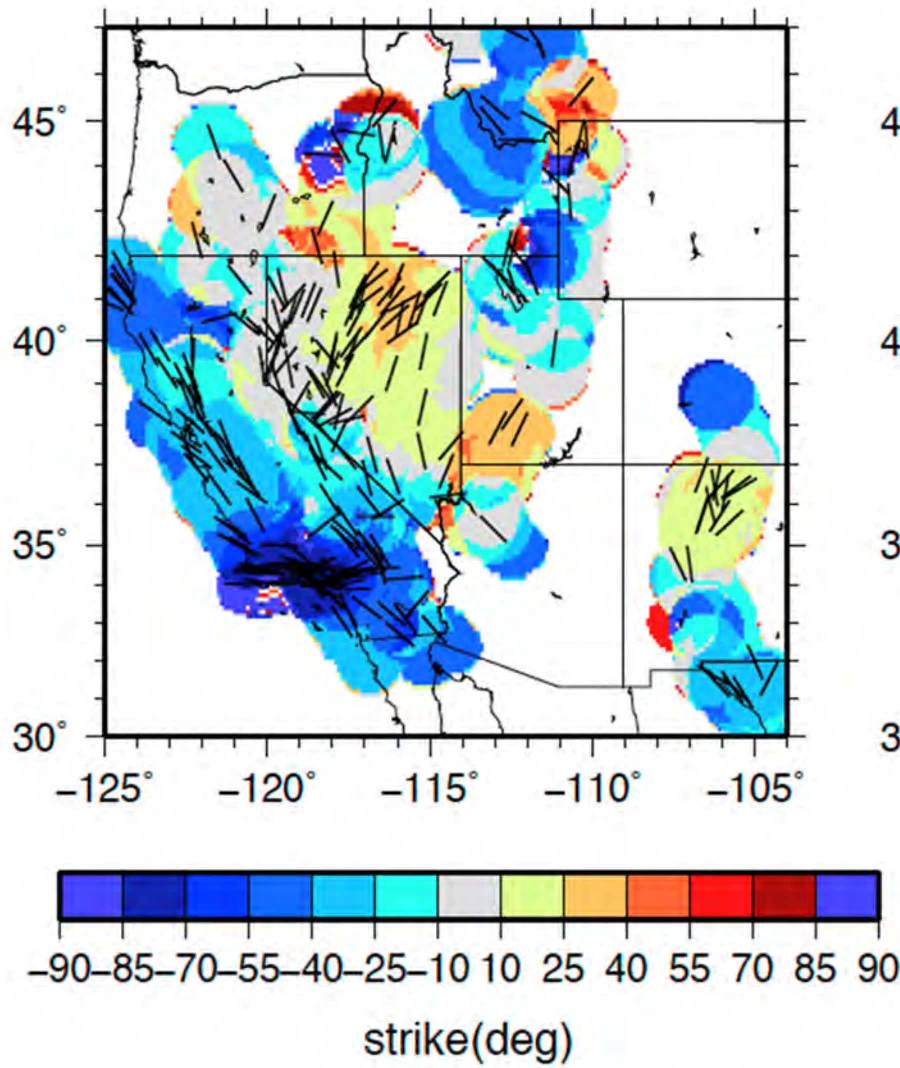
- Distribution of accepted line fits to fault sources modeled in NSHMP.
- Use these faults to determine spatially varying strike parameters for anisotropic smoothing.
- Search within fixed radius to define anisotropic fabric across the map (r=100km).

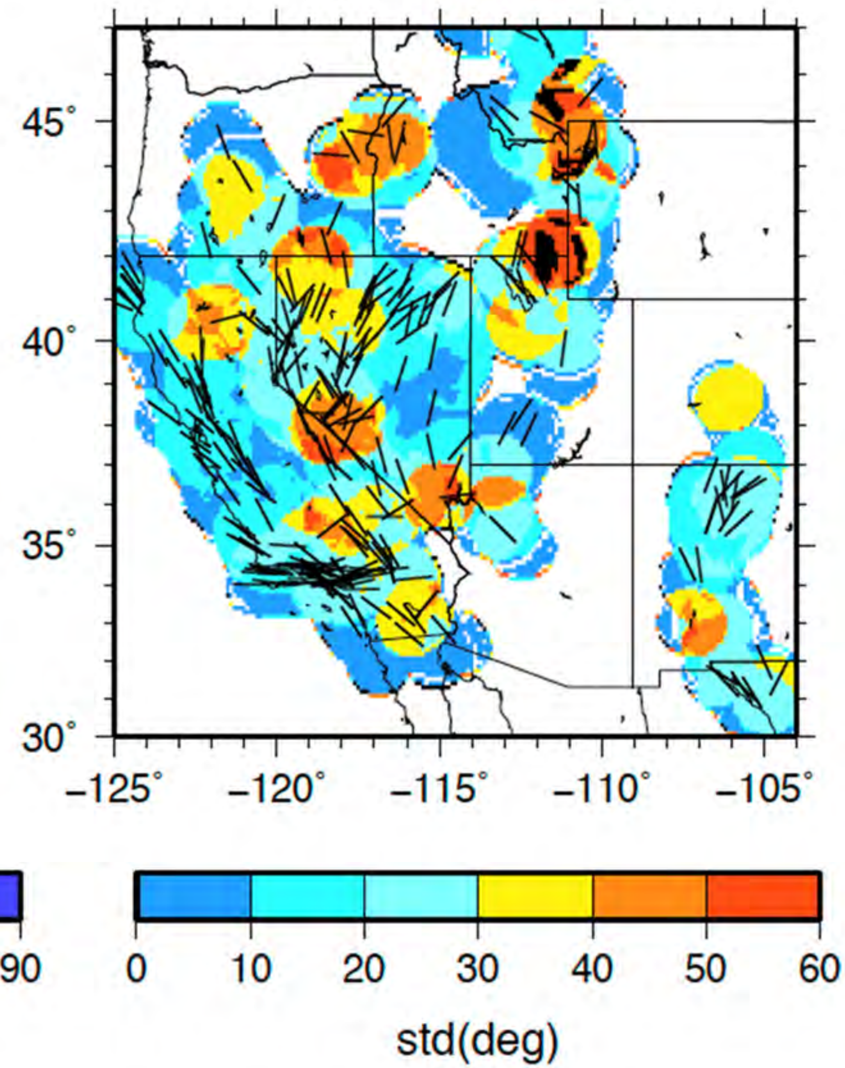
Developing uniform anisotropically-smooth agrids: spatially-varying fault strikes (r=100 km)



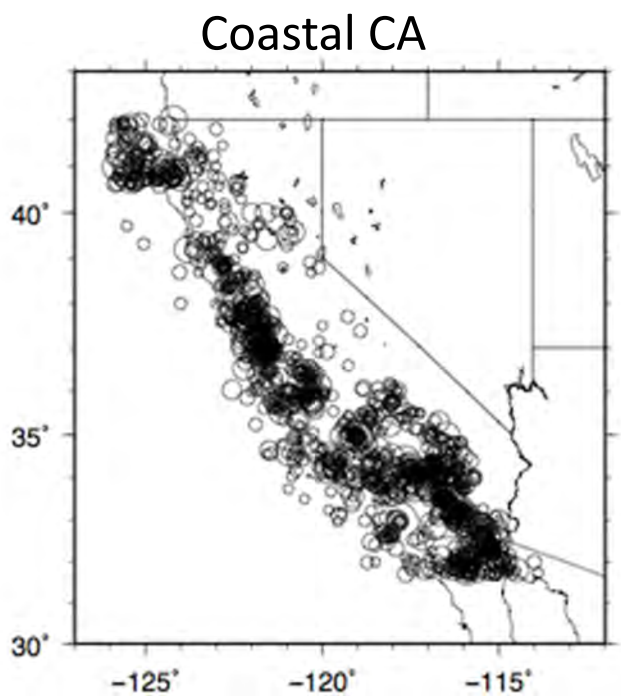
- Mean strike values at all grid points for background seismicity calculations – strike values for anisotropic smoothing.
- NNE orientations in BRP rotating to NNW-NW in Walker Lane and coastal CA. EW orientations in Transverse Ranges
- “Conflicting” fault strikes
- Uncertainties in the measurements may be used to account for large variations in strike.

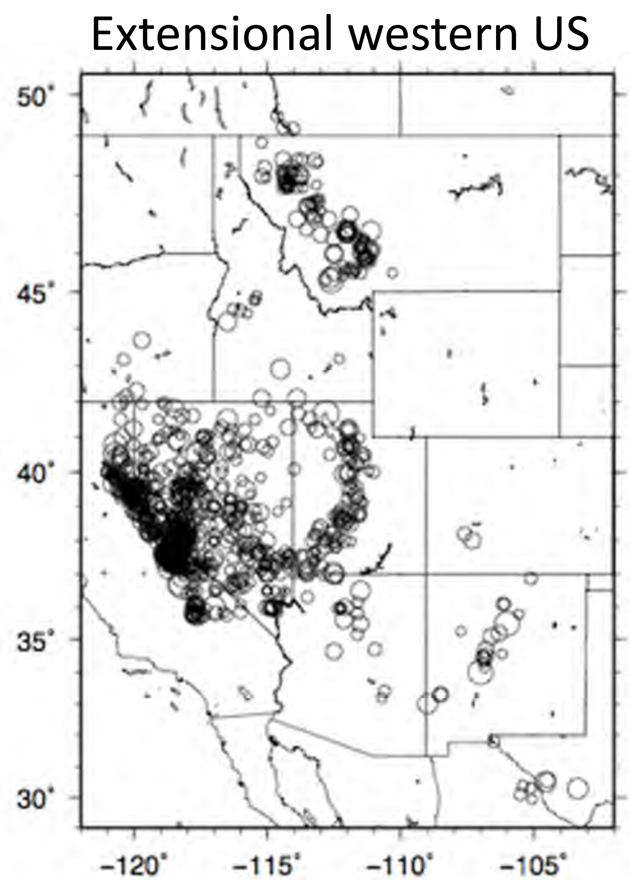
Developing uniform anisotropically-smooth agrids: spatially-varying fault strikes (r=100 km)





Developing uniform anisotropically-smooth agrids: earthquake catalogs

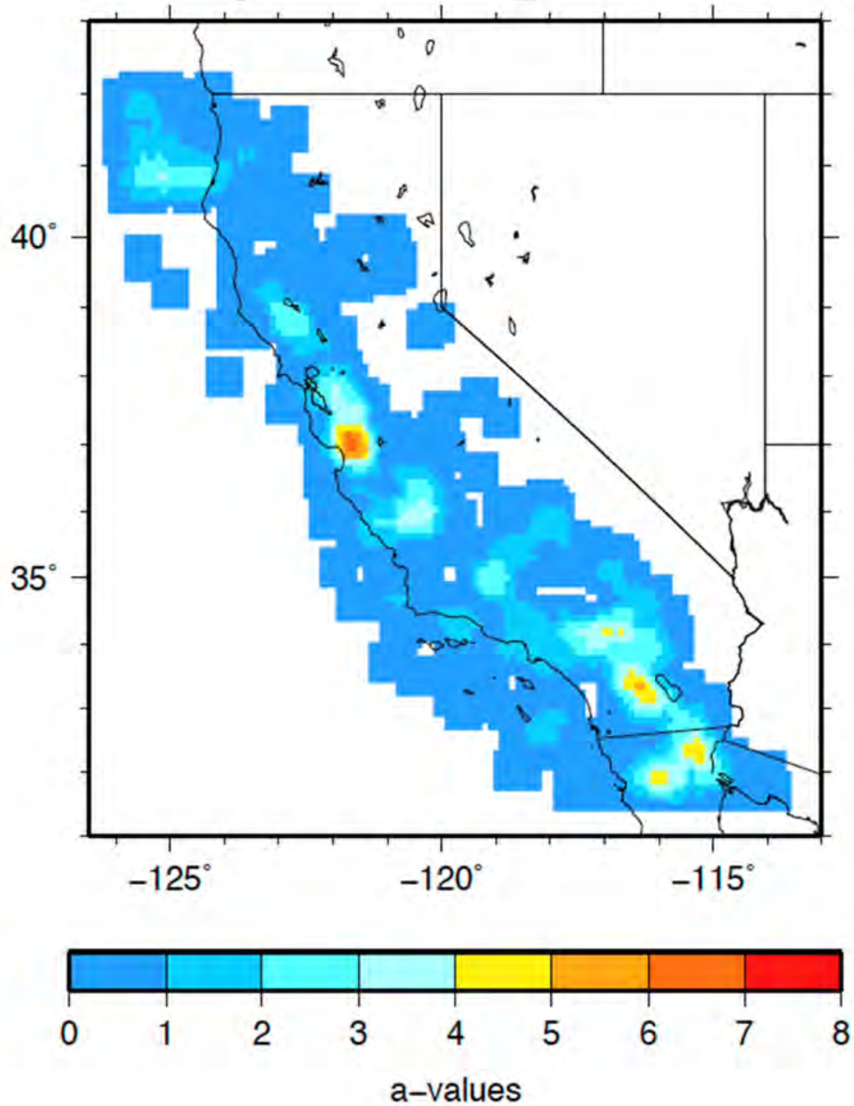




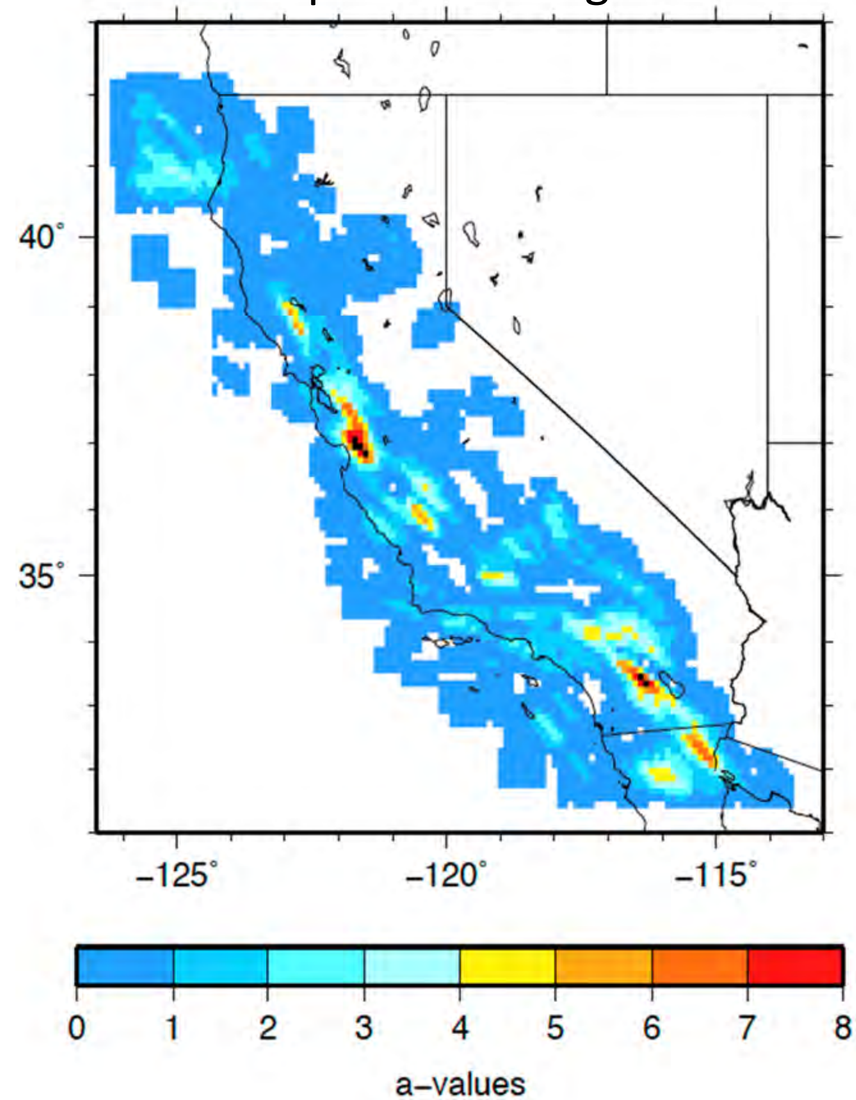
- Smoothing background seismicity from multiple catalogs to allow for different GMPEs (strike-slip/reverse for coastal CA and strike-slip/normal for extensional WUS)

Effects of smoothing method on a-values, coastal CA

Isotropic smoothing

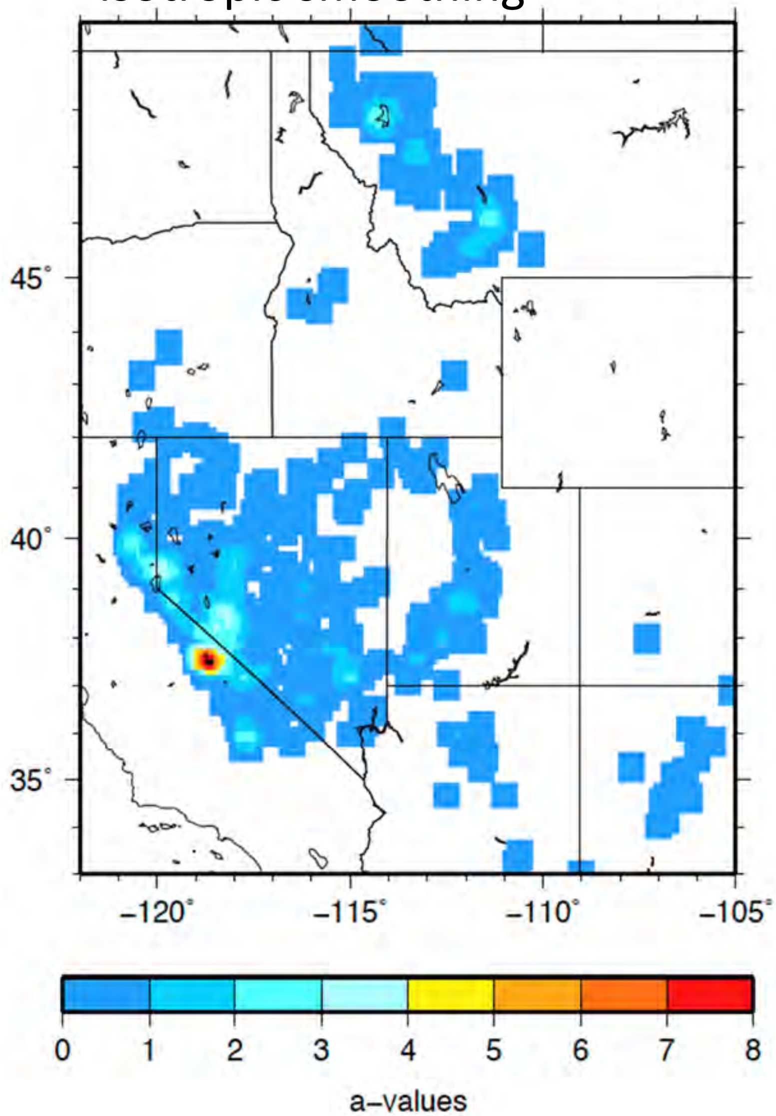


Anisotropic smoothing

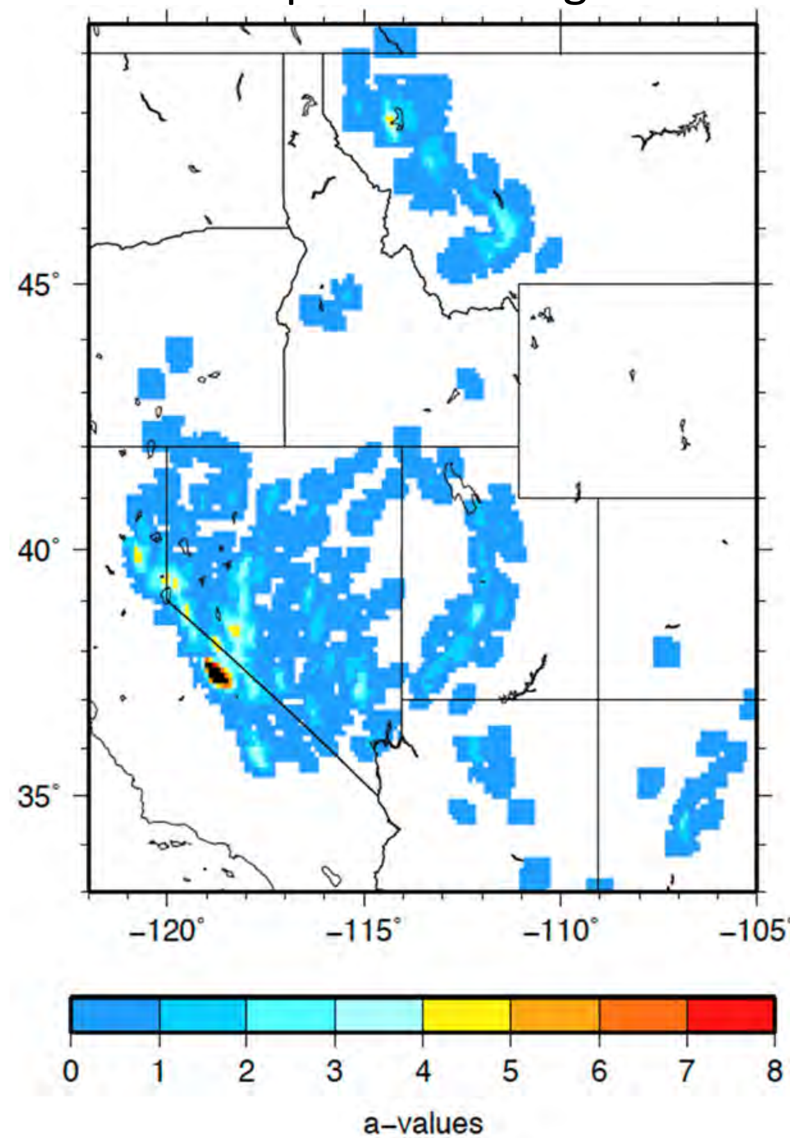


Effects of smoothing method on a-values, extensional WUS

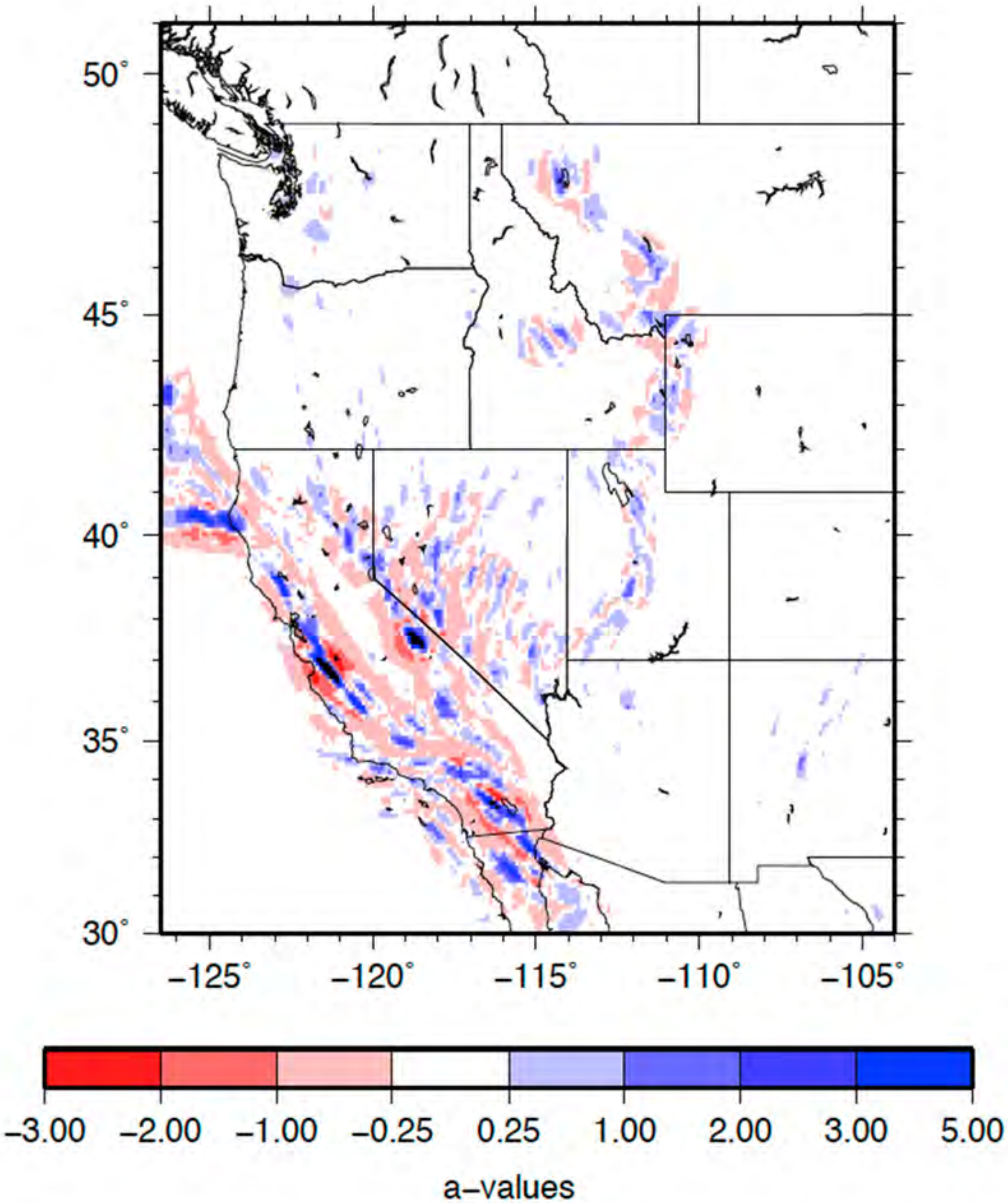
Isotropic smoothing



Anisotropic smoothing

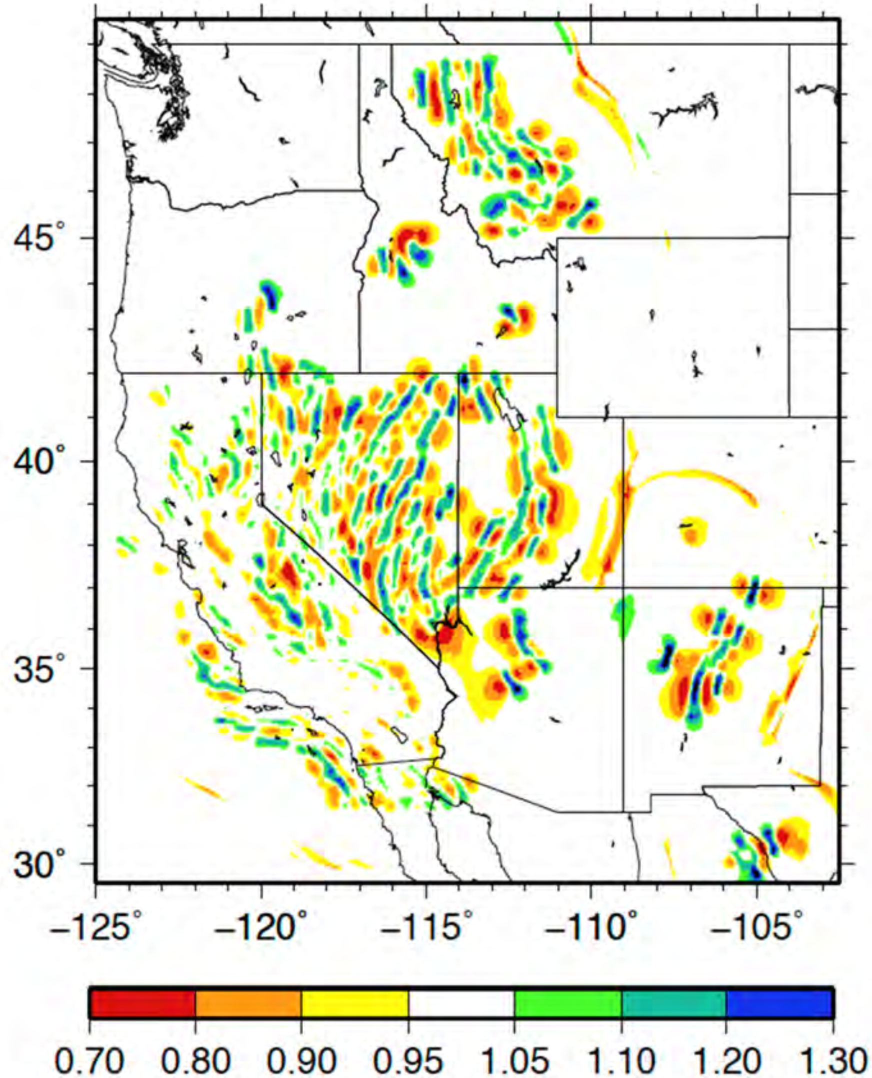


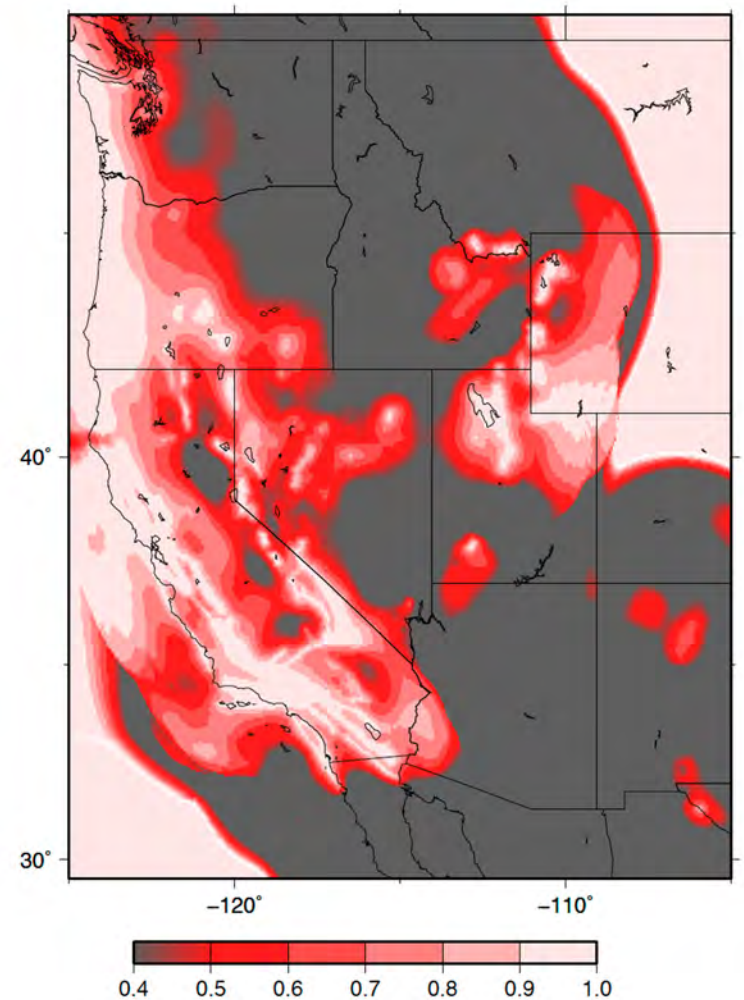
Developing anisotropically smoothed a-grids: difference in a-values



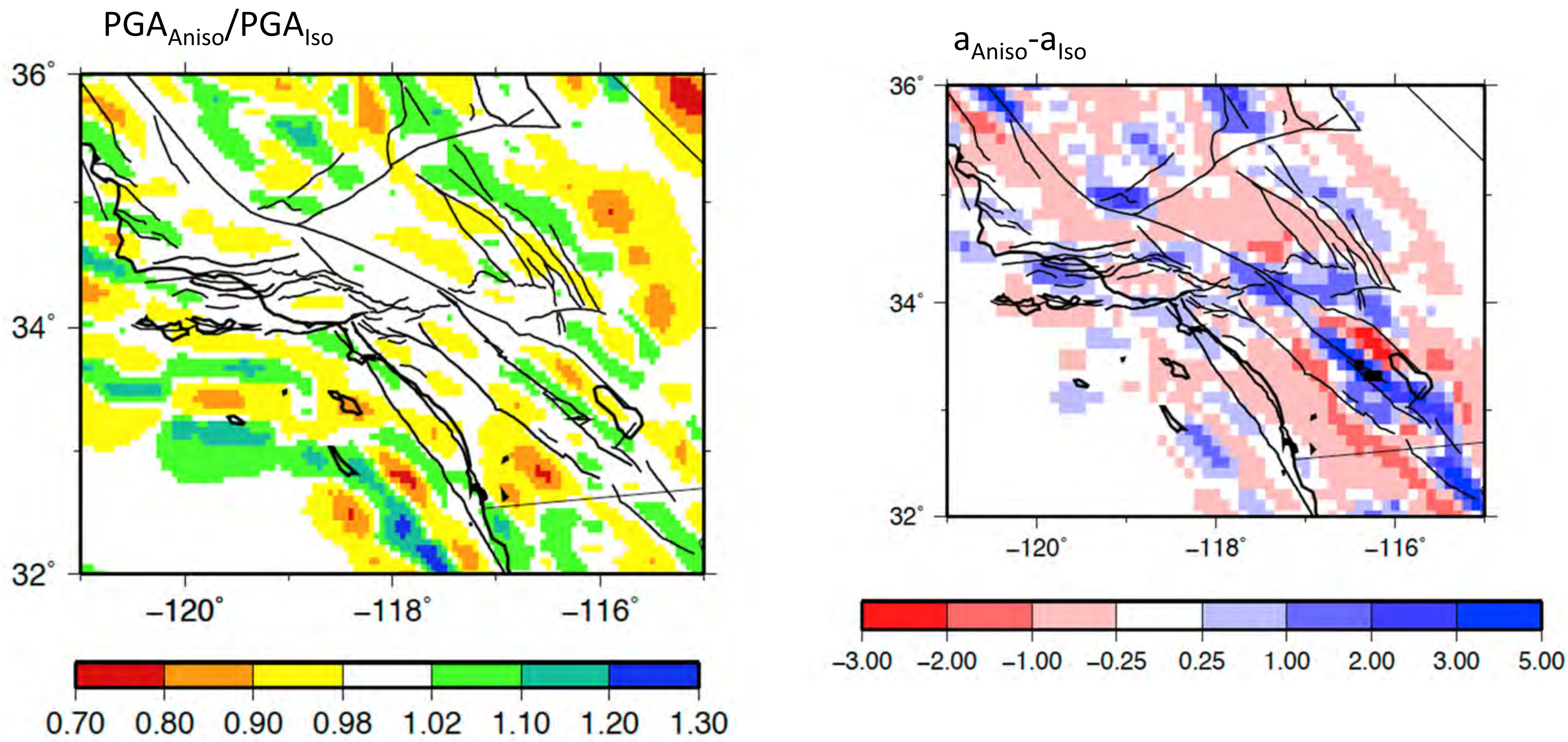
- At locations where seismicity exists in the catalog and where a strike direction is inferred from fabric,

Developing uniform anisotropically-smoothed a-grids: PGA ratio, 2%50y



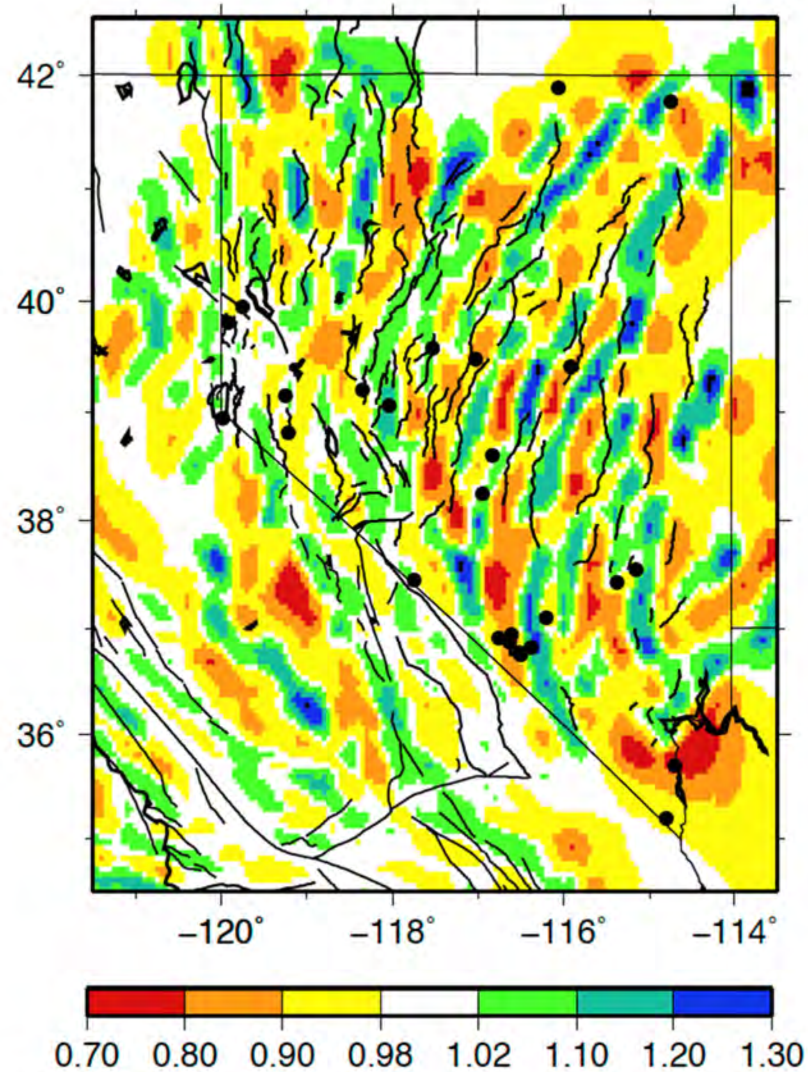


PGA ratio, 2%50y, southern CA

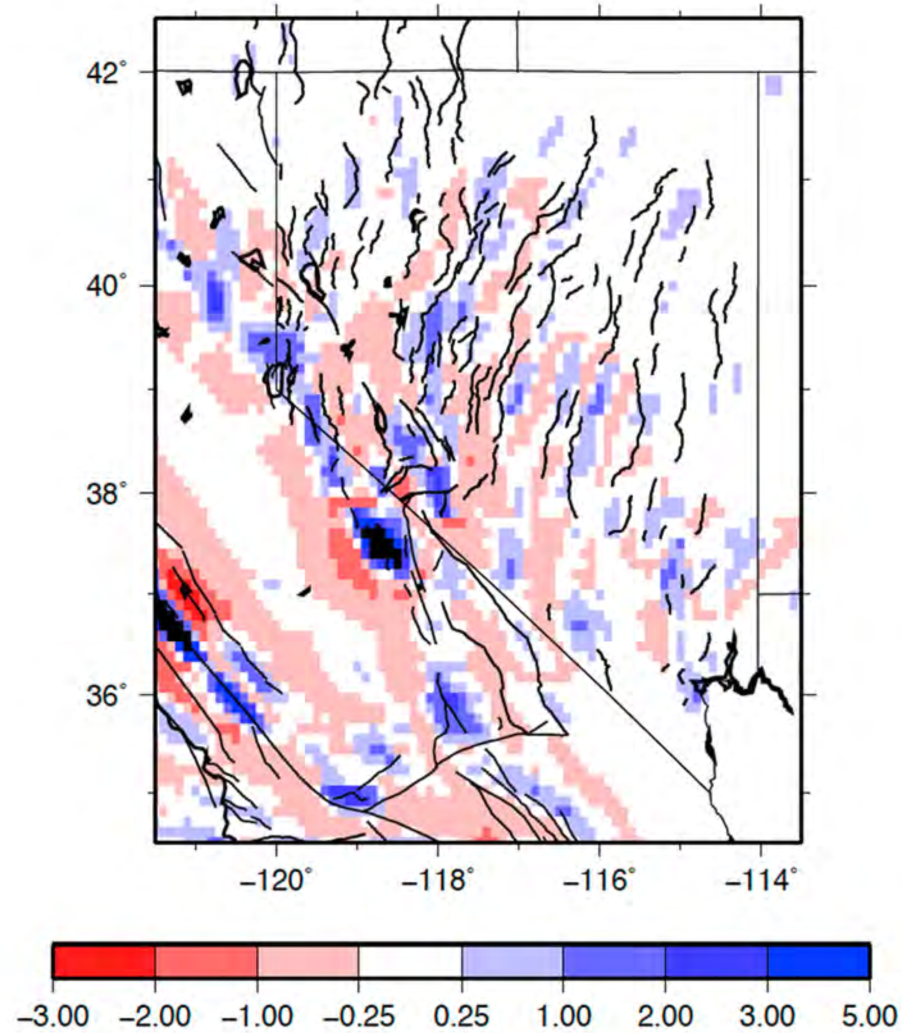


PGA ratio, 2%50y, Nevada

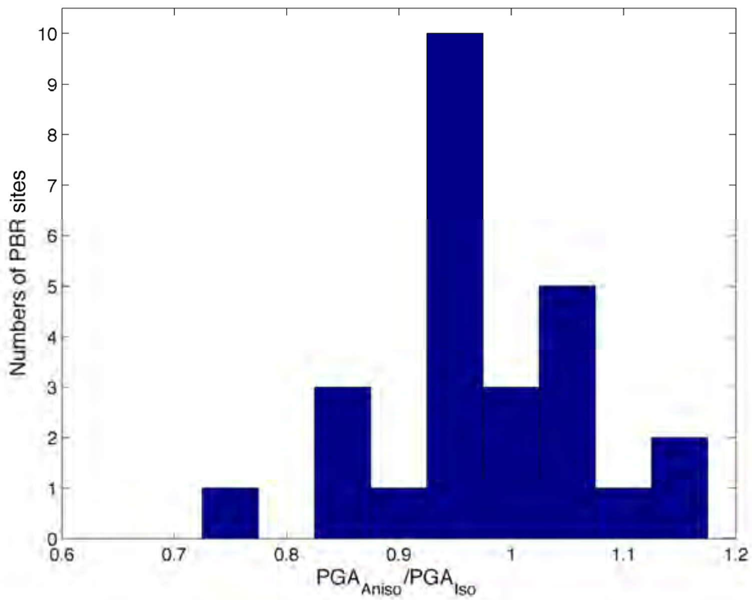
PGA_{Aniso}/PGA_{Iso}

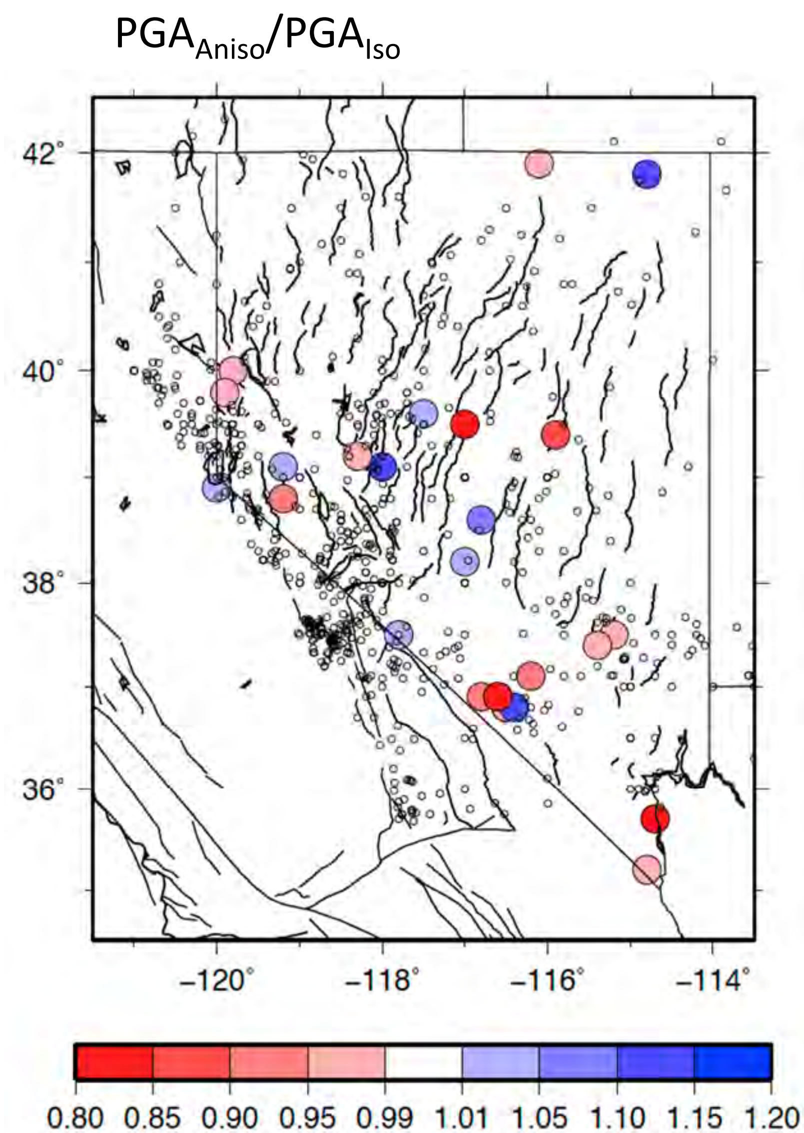


$a_{Aniso}-a_{Iso}$



PGA ratio, 2%50y – perturbations at Nevada PBR sites

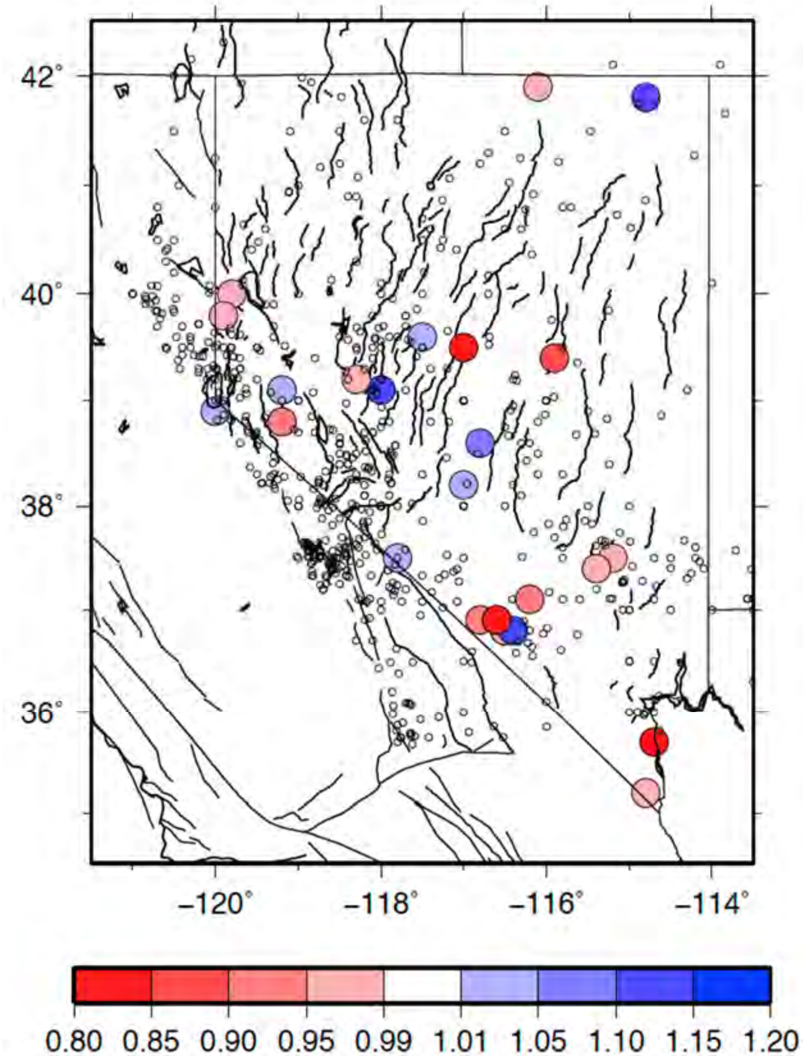




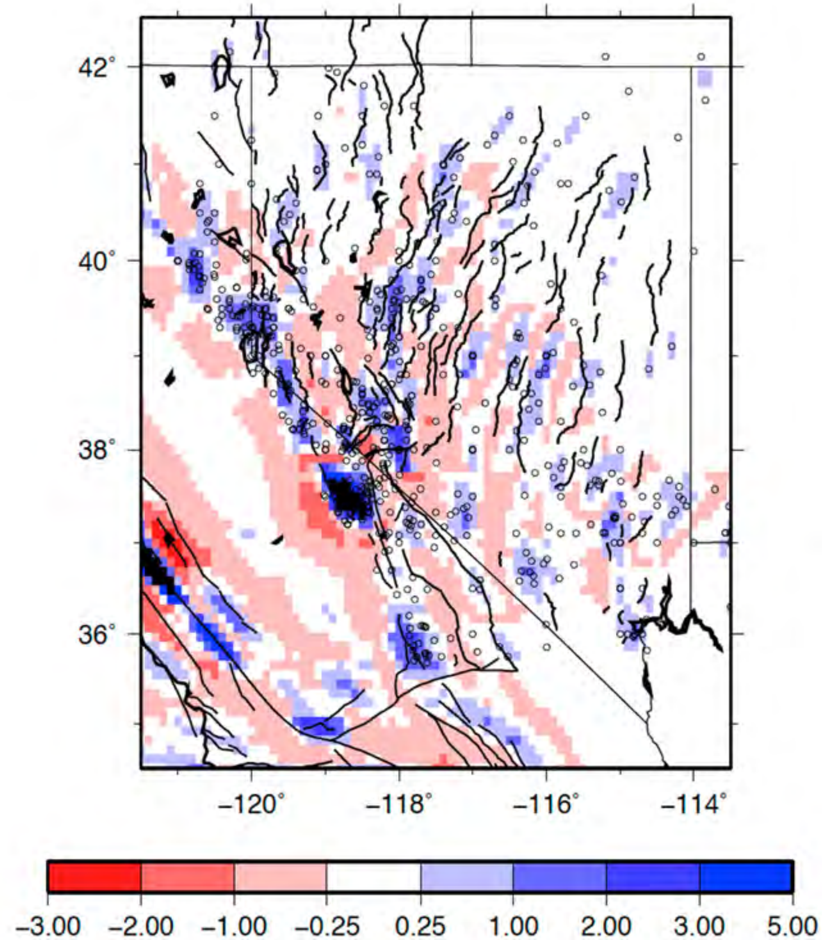
- PGA ratios: 0.75-1.14
- At PBR sites in NV, 17 sites show reduction in PGA, 8 show increase.
- Consider different smoothing for dip-slip faults?

PGA ratio, 2%50y– perturbations at Nevada PBR sites

PGA_{Aniso}/PGA_{Iso}



Δa



Recommendations

- Use combination of anisotropic and isotropic smoothing
- Conduct sensitivity studies for different parameters (e.g., r=50 km, logic tree for mean/mean+/-std weighting on fault strike)
- Test logic tree results using precarious rock data

PBRs and Seismic Hazard

aleatory, epistemic, standard deviation, sigma—characteristic, Gutenberg-Richter, creep, rupture depth, background,

-- all unknown, need data

Rupture rise time, slip weakening distance, rupture velocity, direction of rupture, background stress, frictional stress, dynamic stress history,

Assumed Background Seismicity as a Partial Explanation for Discrepancies Between Precariously Balanced Rocks and 2008 California Seismic Hazard Maps

By

James N. Brune (UNR)

Glenn Biasi (UNR)

Lisa Grant Ludwig (UCI)

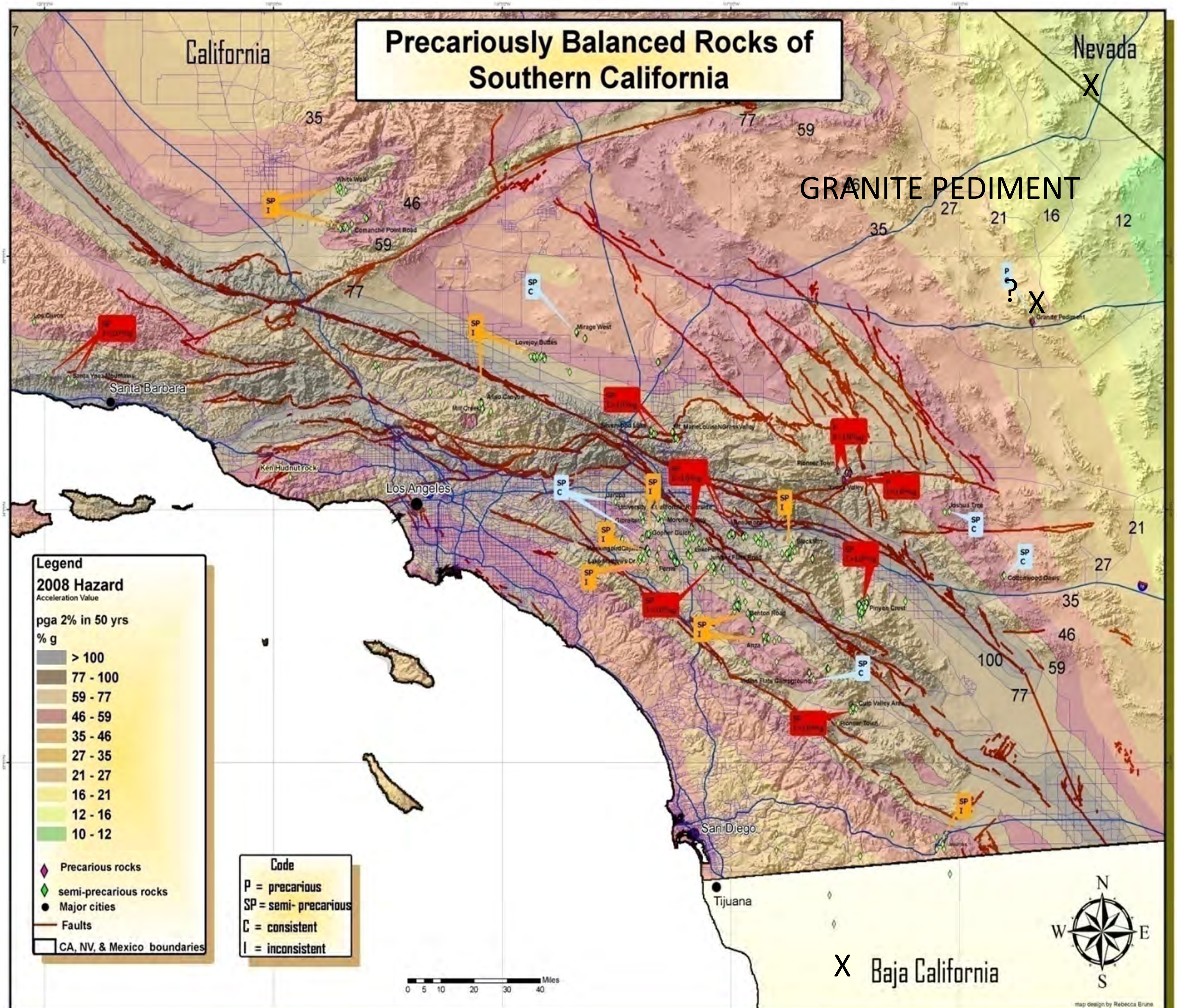
Dylan Rood (UCSB and UCI)

Dylan Rood 20 ka cosmogenic

Figure 3: Field-test to determine the quasi-static toppling acceleration of "Tooth" rock.

PBR PROBLEMS

- 1. Test the ergodic assumption (randomness)
- 2. Test attenuation relationships
- 3. Test random background earthquake assumptions.
- 4. Determine directions of rupture propagation.
- 5. Constrain hanging wall-foot wall ground motions.
- 6. Constrain step-over ground motions.
- 7. Test UCERF assumptions (Fault activity, fault dips).
- 8. Test frequency of supersonic ruptures.

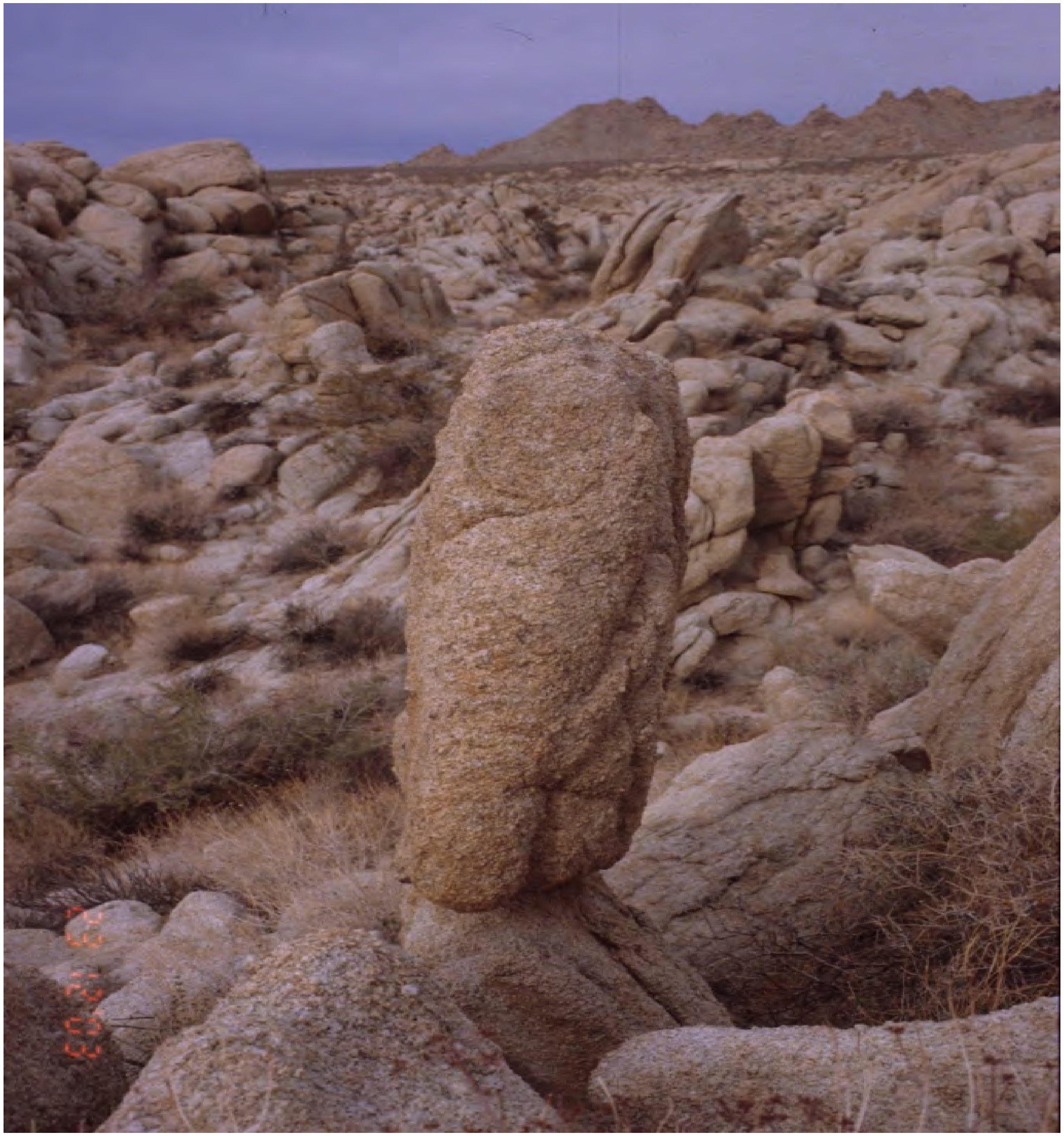

Precariously Balanced Rocks of Southern California
California
Nevada
GRANITE PEDIMENT
Baja California
Santa Barbara
Los Angeles
San Diego
Tijuana
Legend
2008 Hazard
Acceleration Value
pga 2% in 50 yrs
% g
> 100
77 - 100
59 - 77
46 - 59
35 - 46
27 - 35
21 - 27
16 - 21
12 - 16
10 - 12
Precarious rocks
semi-precarious rocks
Major cities
Faults
CA, NV, & Mexico boundaries
Code
P = precarious
SP = semi- precarious
C = consistent
I = inconsistent
Miles
0 5 10 20 30 40
N
E
S
W

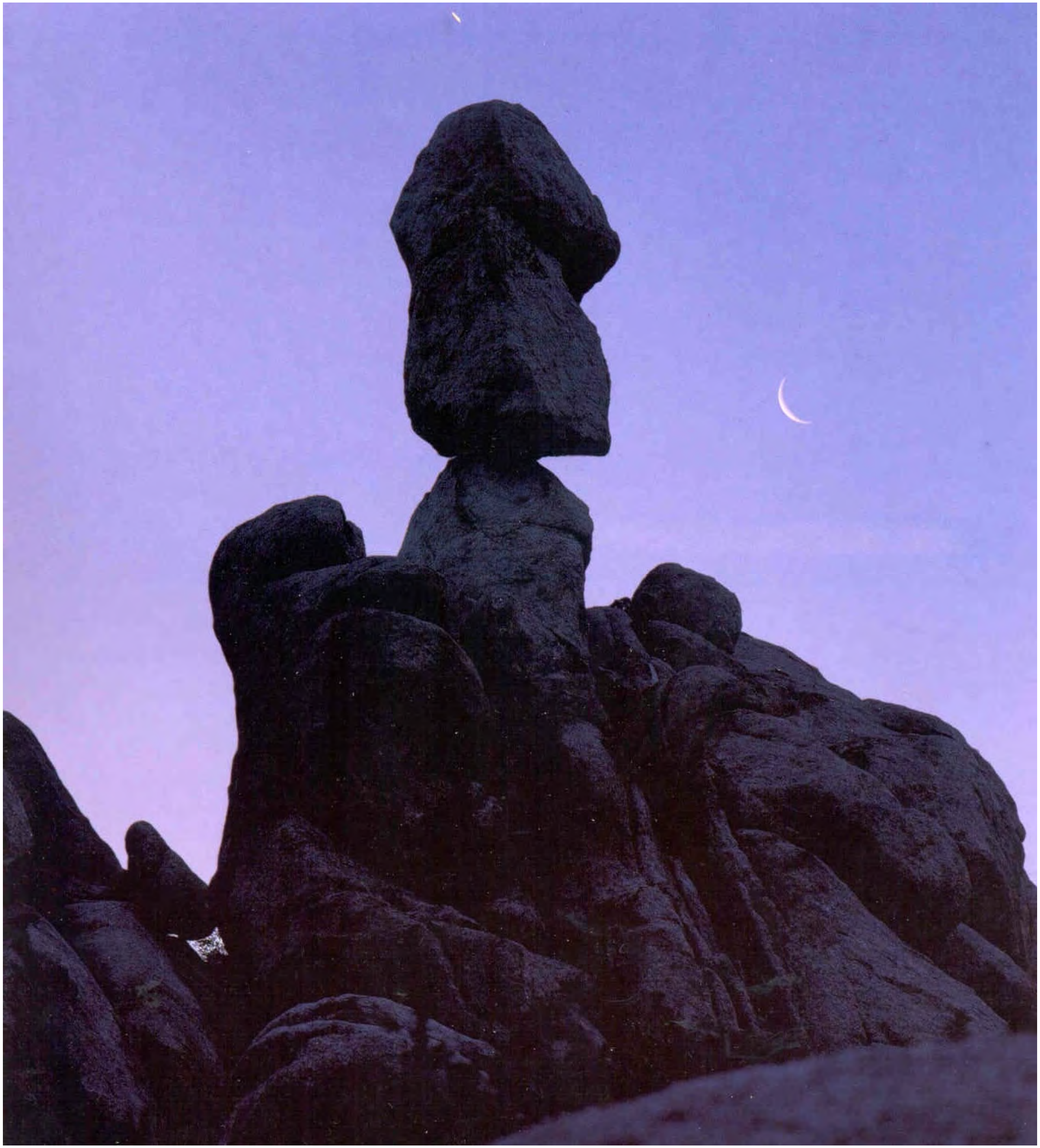

JAN 26 2007

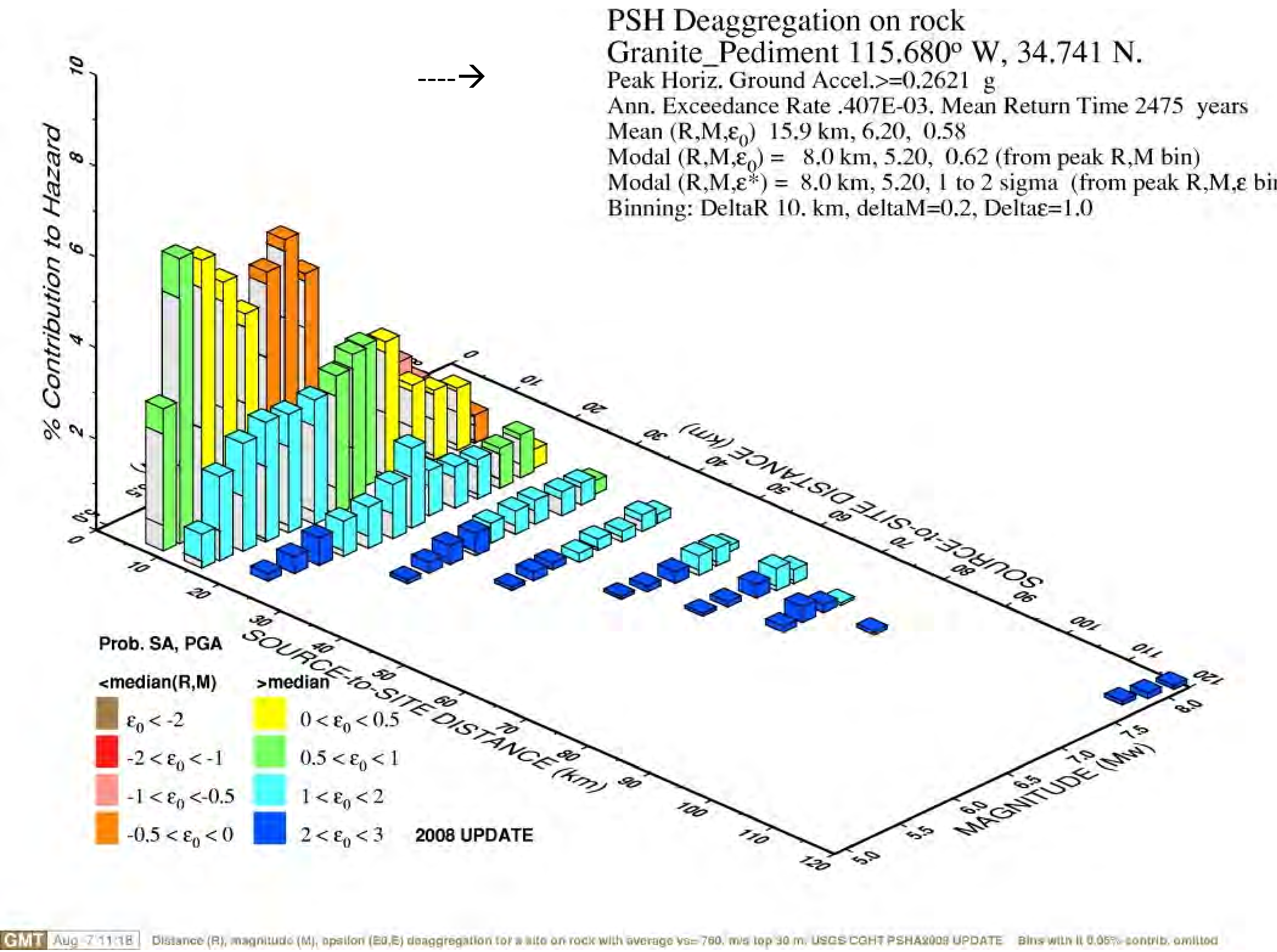

NOV 24 2004


5 2'03

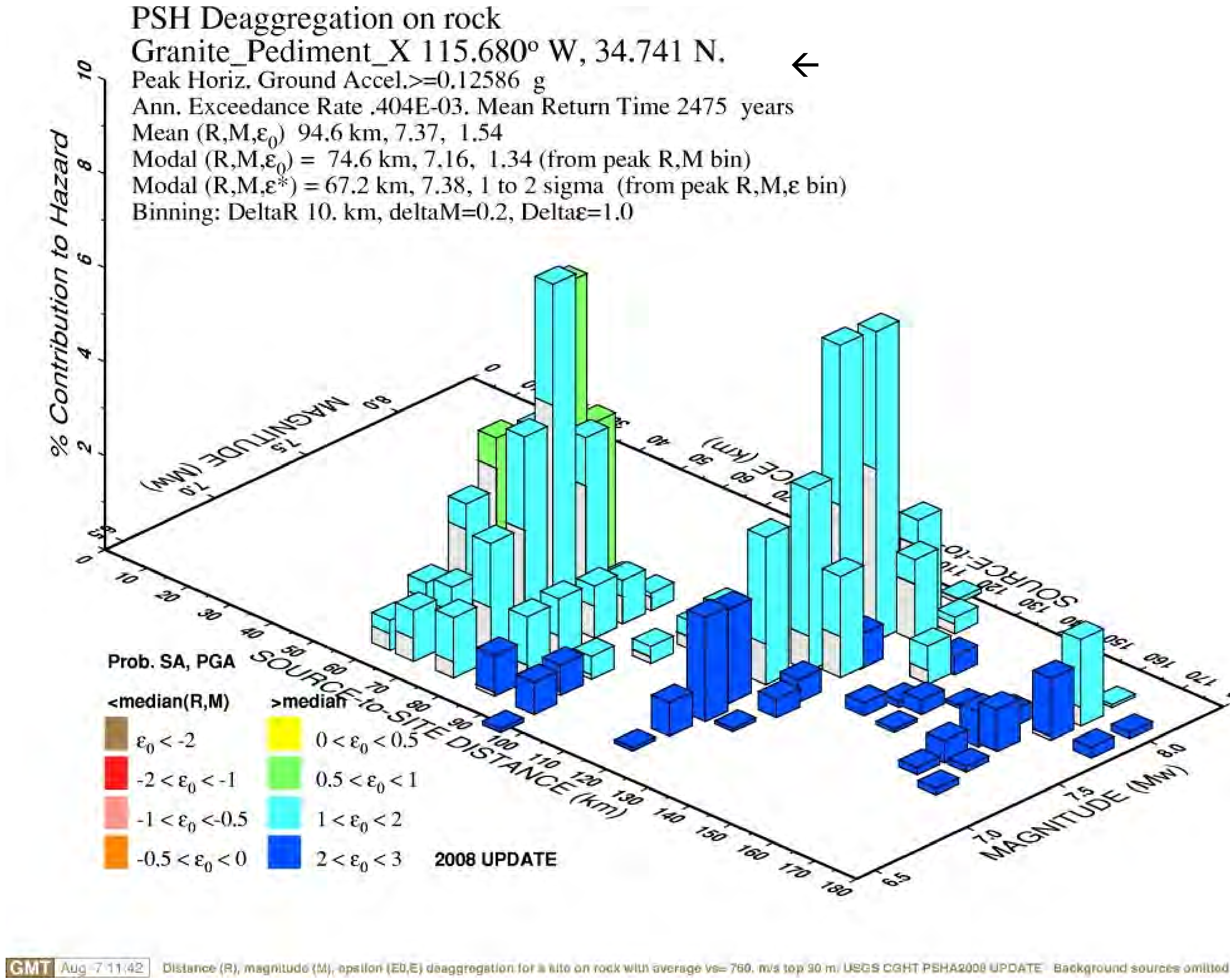
Granite Pass 06-94



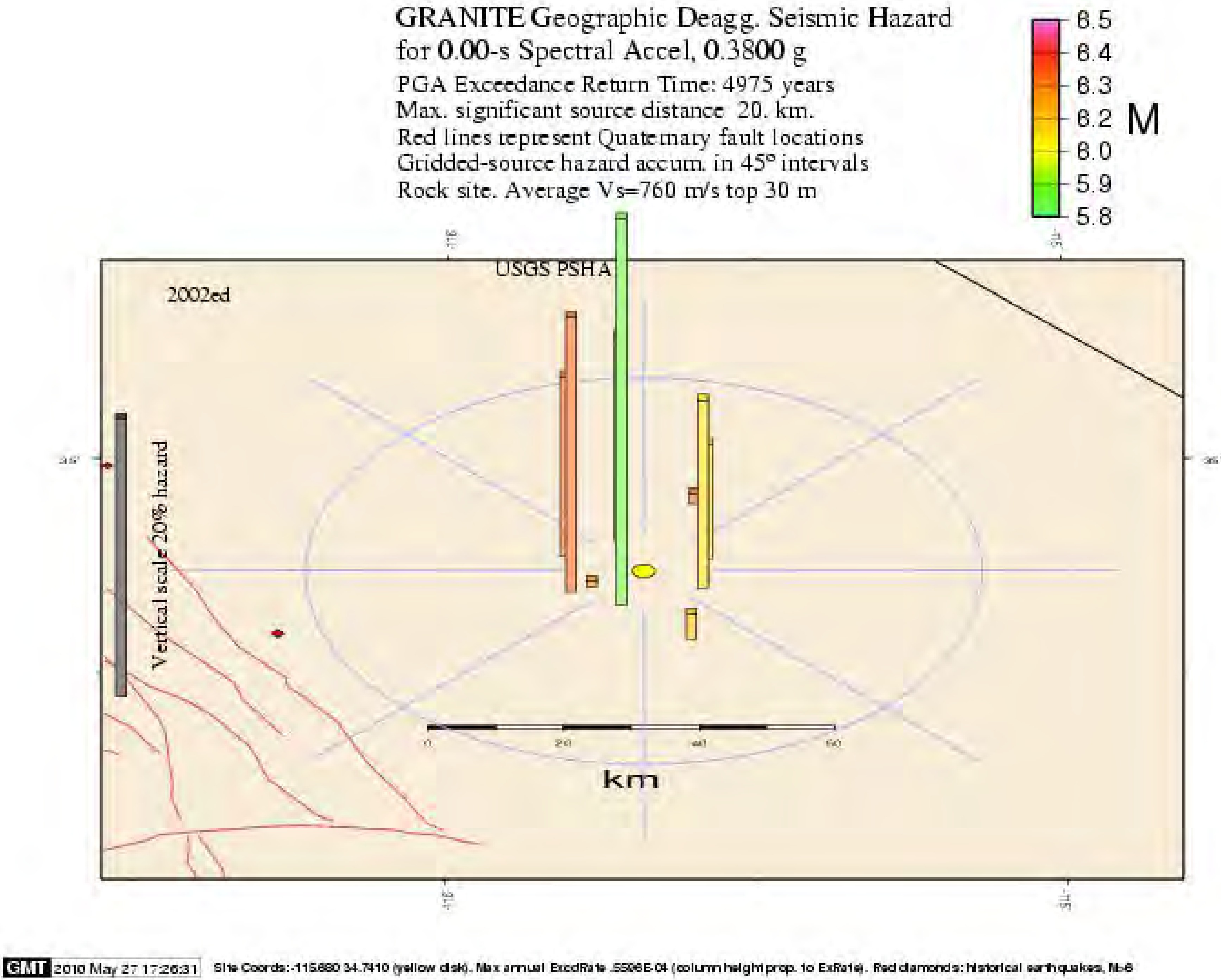




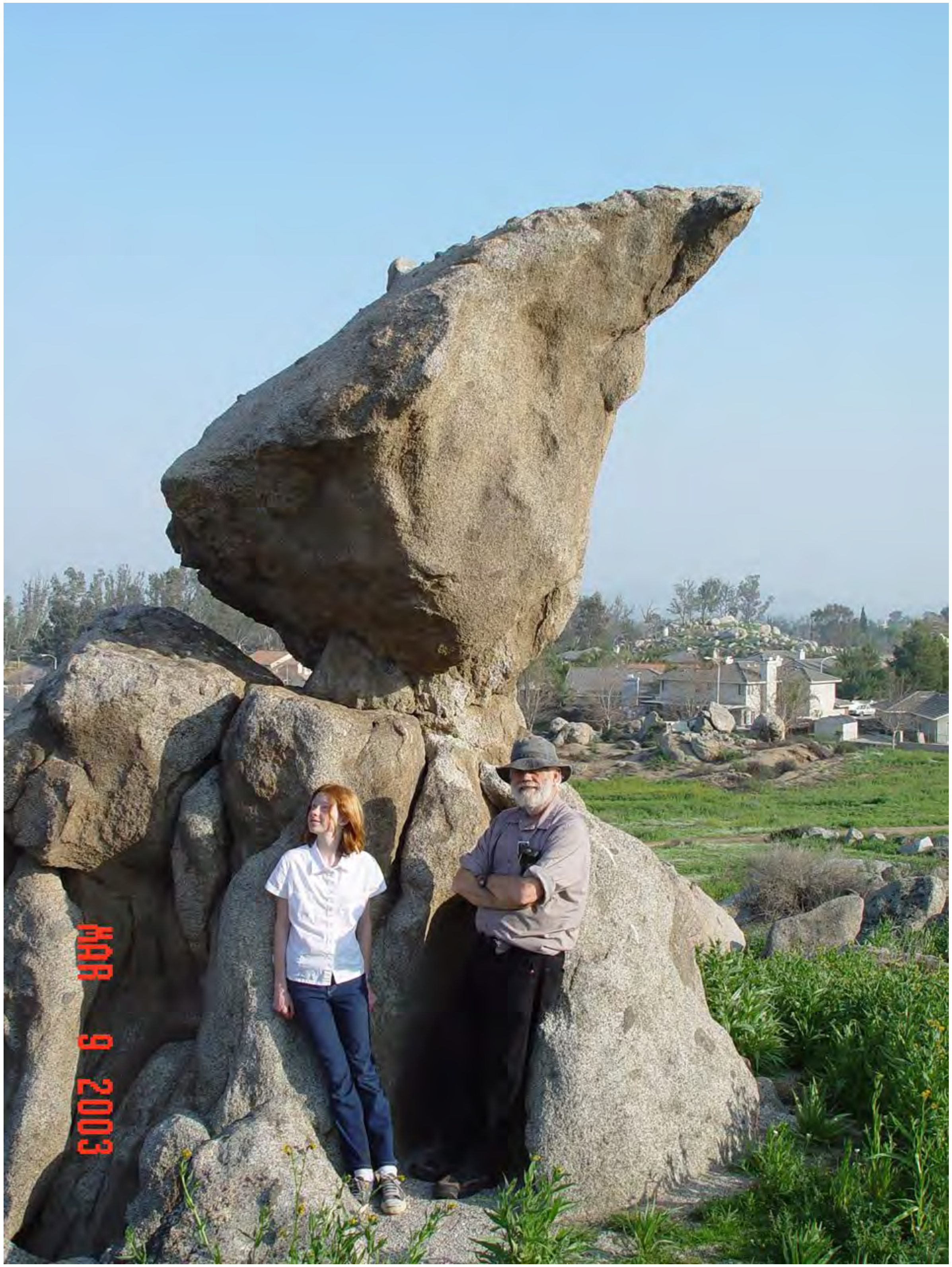
PSH Deaggregation on rock
Granite_Pediment 115.680° W, 34.741 N.
Peak Horiz. Ground Accel.>=0.2621 g
Ann. Exceedance Rate .407E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 15.9 km, 6.20, 0.58
Modal (R,M,ε0) = 8.0 km, 5.20, 0.62 (from peak R,M bin)
Modal (R,M,ε*) = 8.0 km, 5.20, 1 to 2 sigma (from peak R,M,ε bin
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
SOURCE-to-SITE DISTANCE (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
2008 UPDATE
GMT Aug 7 11:18 Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs=760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

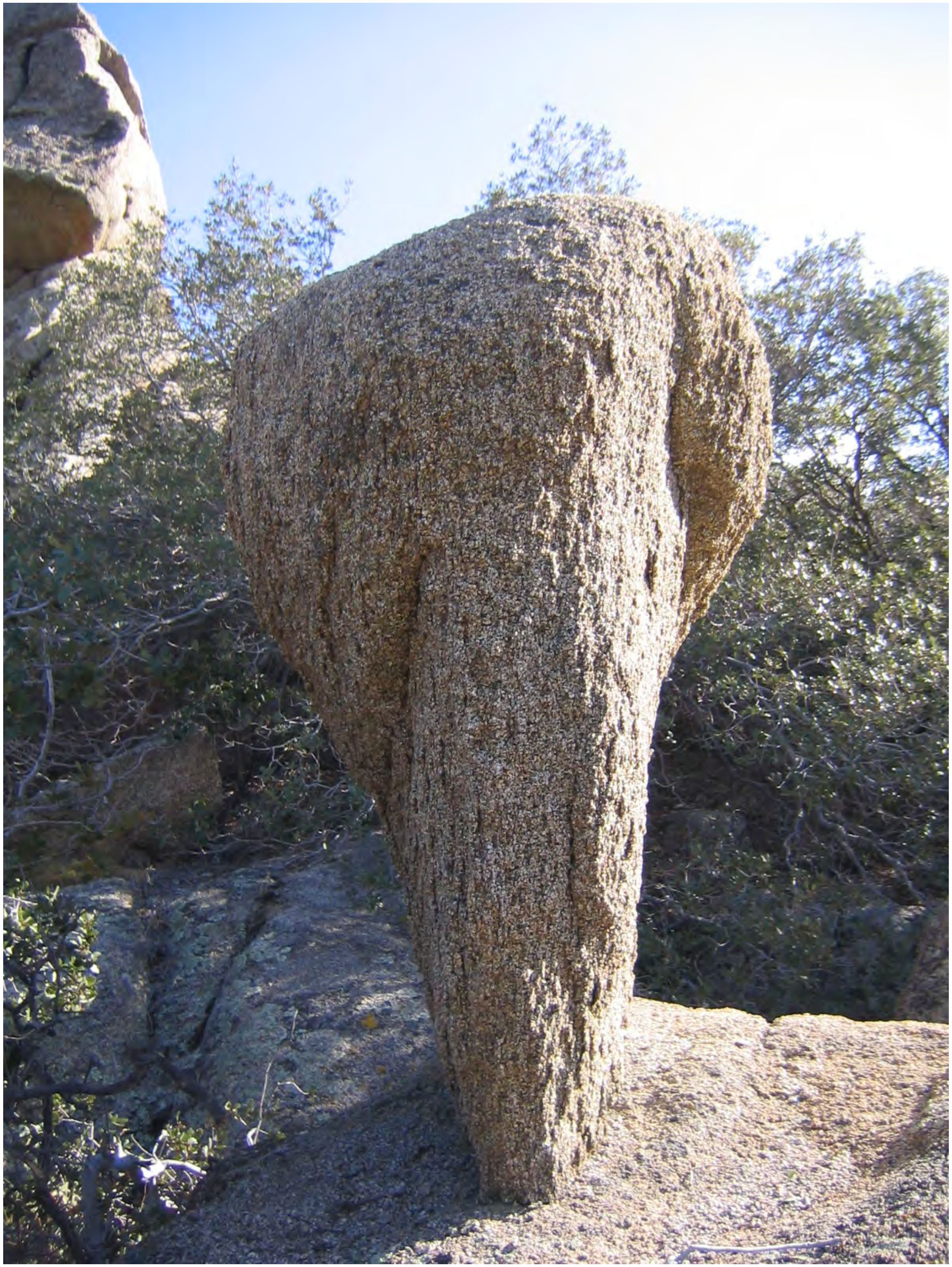


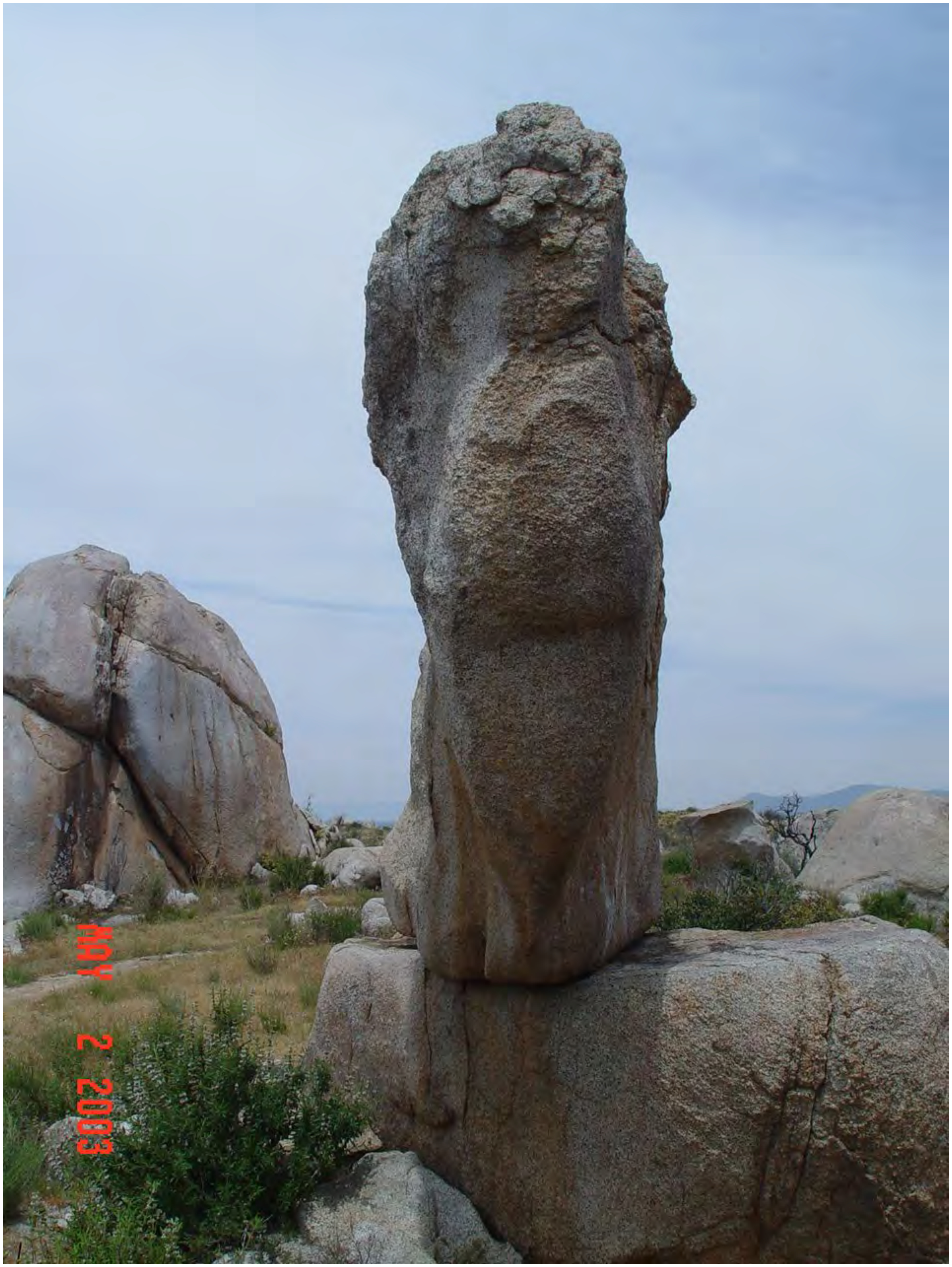
PSH Deaggregation on rock
Granite_Pediment_X 115.680° W, 34.741 N.
Peak Horiz. Ground Accel.>=0.12586 g
Ann. Exceedance Rate .404E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 94.6 km, 7.37, 1.54
Modal (R,M,ε0) = 74.6 km, 7.16, 1.34 (from peak R,M bin)
Modal (R,M,ε*) = 67.2 km, 7.38, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
SOURCE-to-SITE DISTANCE (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
2008 UPDATE
GMT Aug 7 11:42
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Background sources omitted


GRANITE Geographic Deagg. Seismic Hazard
for 0.00-s Spectral Accel, 0.3800 g
PGA Exceedance Return Time: 4975 years
Max. significant source distance 20. km.
Red lines represent Quaternary fault locations
Gridded-source hazard accum. in 45° intervals
Rock site. Average Vs=760 m/s top 30 m
6.5
6.4
6.3
6.2
6.0
5.9
5.8
M
USGS PSHA
2002ed
Vertical scale 20% hazard
0
20
40
60
km
GMT 2010 May 27 17:26:31
Site Coords: -115.880 34.7410 (yellow disk). Max annual ExcdRate .5506E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6

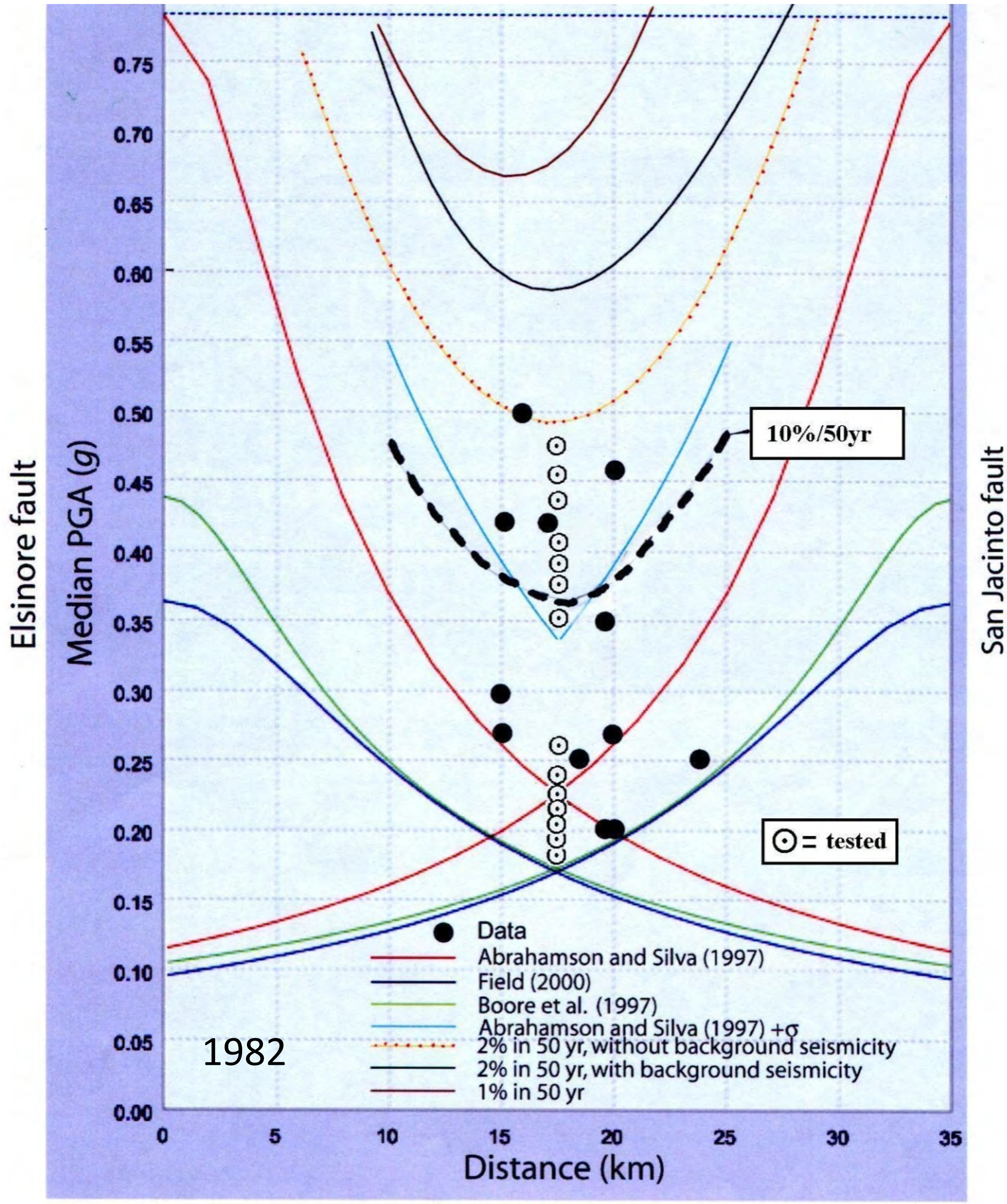
Riverside-Aguanga Line of Precarious Rocks


MAR 9 2003

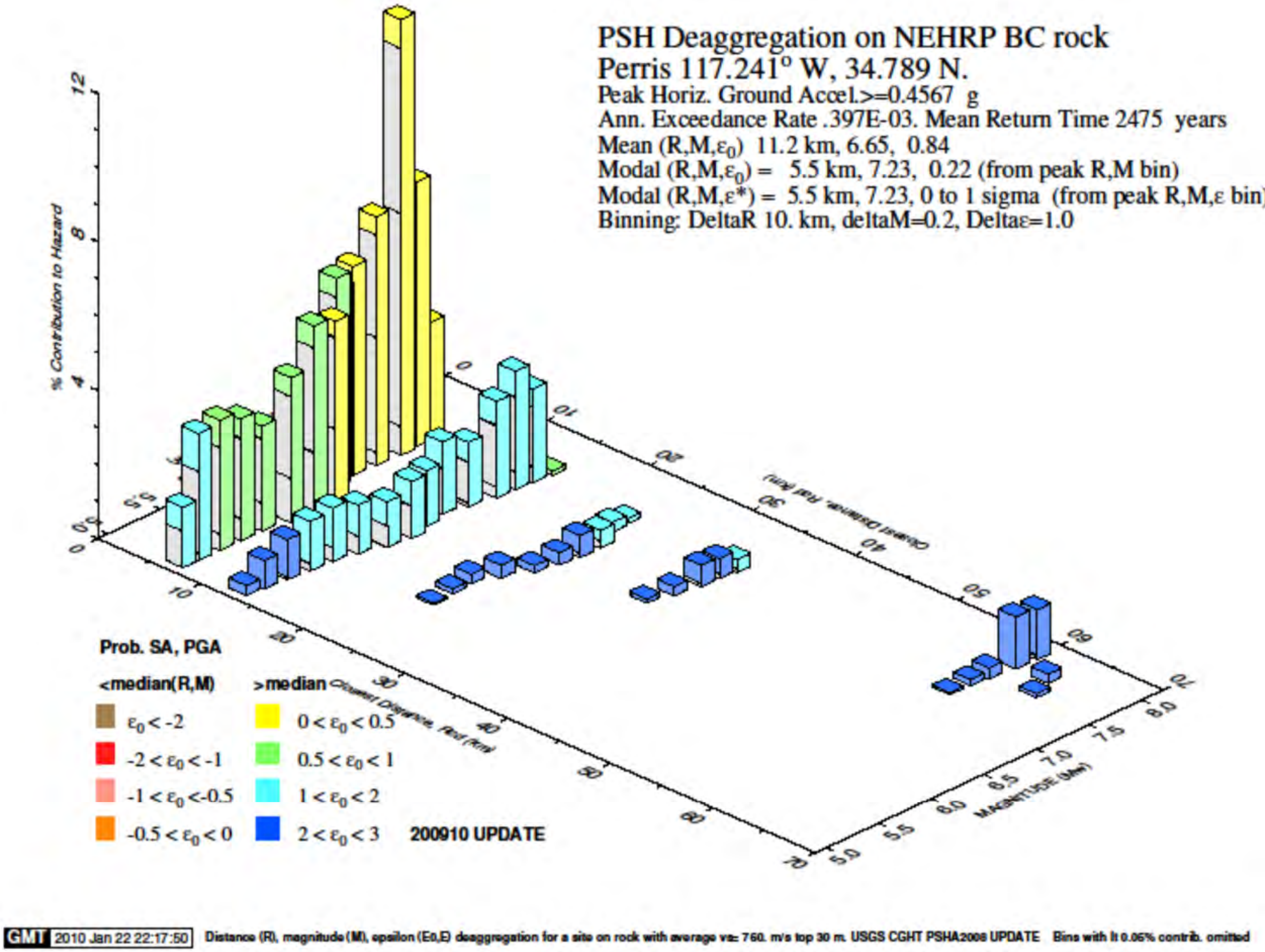



MAY 2 2003


MAY 17 2003

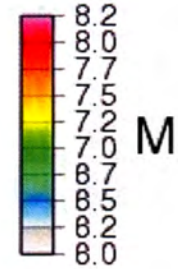


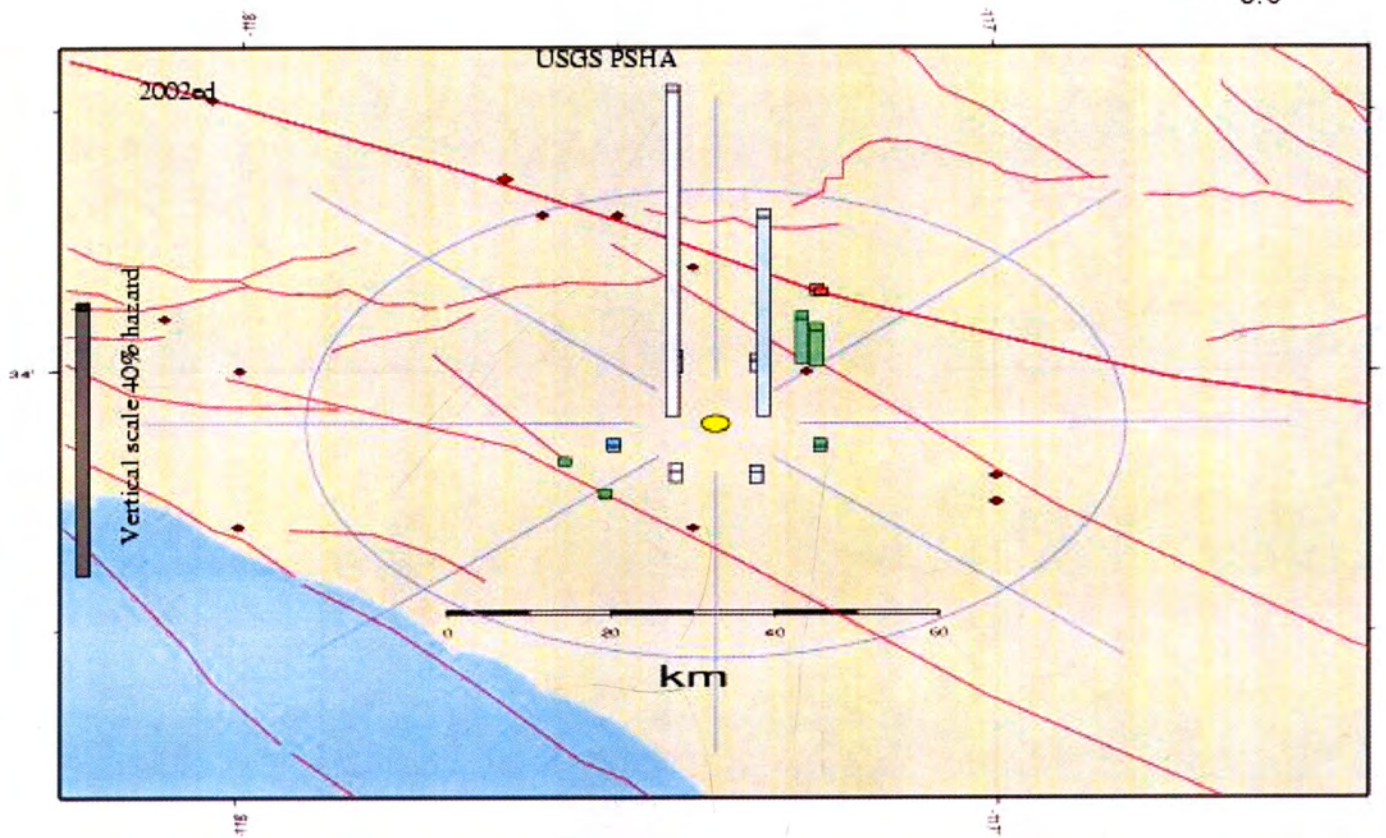
Elsinore fault
Median PGA (g)
San Jacinto fault
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
Distance (km)
10%/50yr
= tested
Data
Abrahamson and Silva (1997)
Field (2000)
Boore et al. (1997)
Abrahamson and Silva (1997) +σ
2% in 50 yr, without background seismicity
2% in 50 yr, with background seismicity
1% in 50 yr
1982

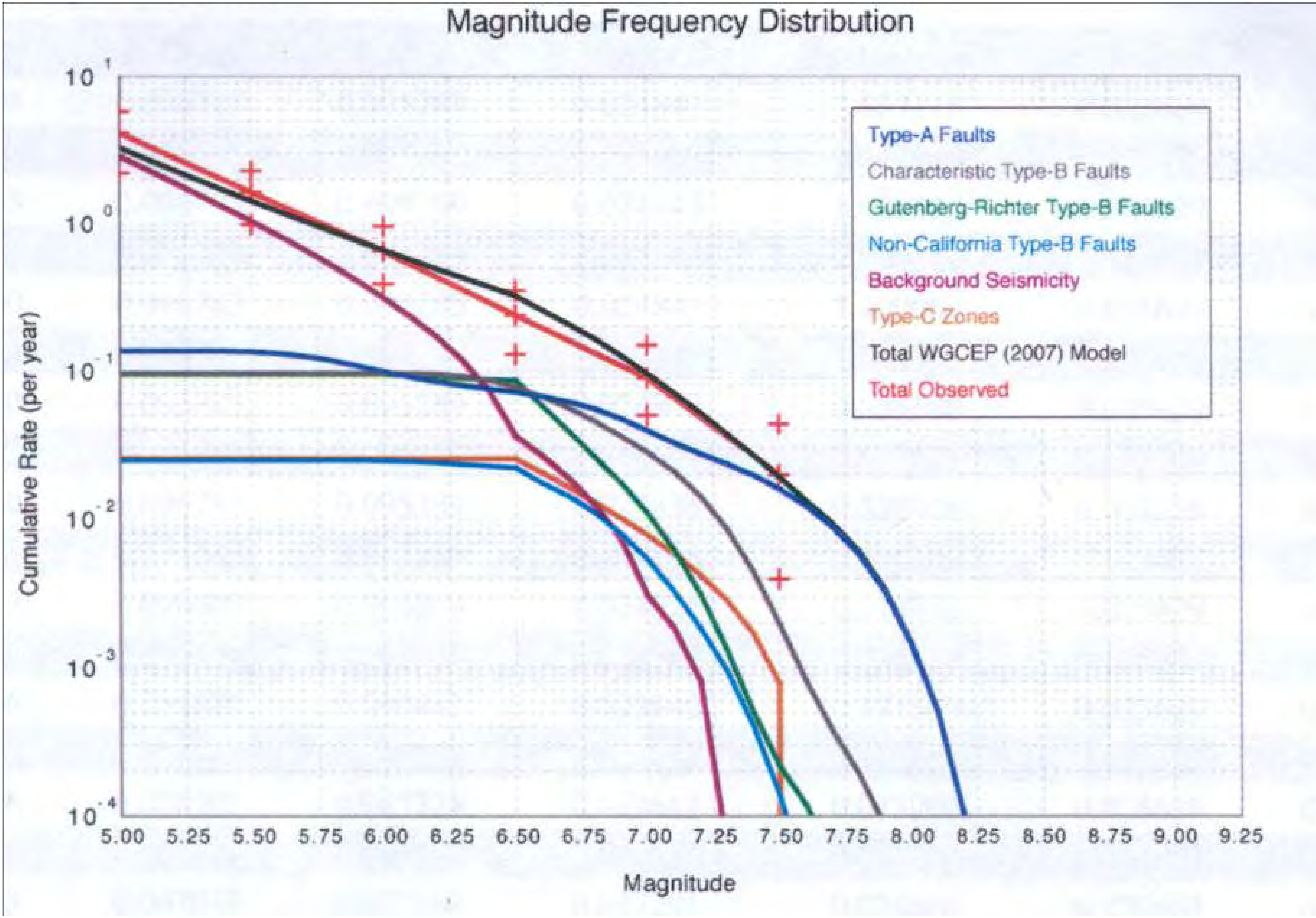

PSH Deaggregation on NEHRP BC rock
Perris 117.241° W, 34.789 N.
Peak Horiz. Ground Accel.>=0.4567 g
Ann. Exceedance Rate .397E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 11.2 km, 6.65, 0.84
Modal (R,M,ε0) = 5.5 km, 7.23, 0.22 (from peak R,M bin)
Modal (R,M,ε*) = 5.5 km, 7.23, 0 to 1 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2010 Jan 22 22:17:50
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.06% contrib. omitted

gopher Geographic Deagg. Seismic Hazard
for 0.00-s Spectral Accel, 0.7282 g

PGA Exceedance Return Time: 4975 years
Max. significant source distance 31. km.
Red lines represent Quaternary fault locations
Gridded-source hazard accum. in 45° intervals
Rock site. Average Vs=760 m/s top 30 m







Magnitude Frequency Distribution
Cumulative Rate (per year)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
5.00 5.25 5.50 5.75 6.00 6.25 6.50 6.75 7.00 7.25 7.50 7.75 8.00 8.25 8.50 8.75 9.00 9.25
Magnitude
Type-A Faults
Characteristic Type-B Faults
Gutenberg-Richter Type-B Faults
Non-California Type-B Faults
Background Seismicity
Type-C Zones
Total WGCEP (2007) Model
Total Observed

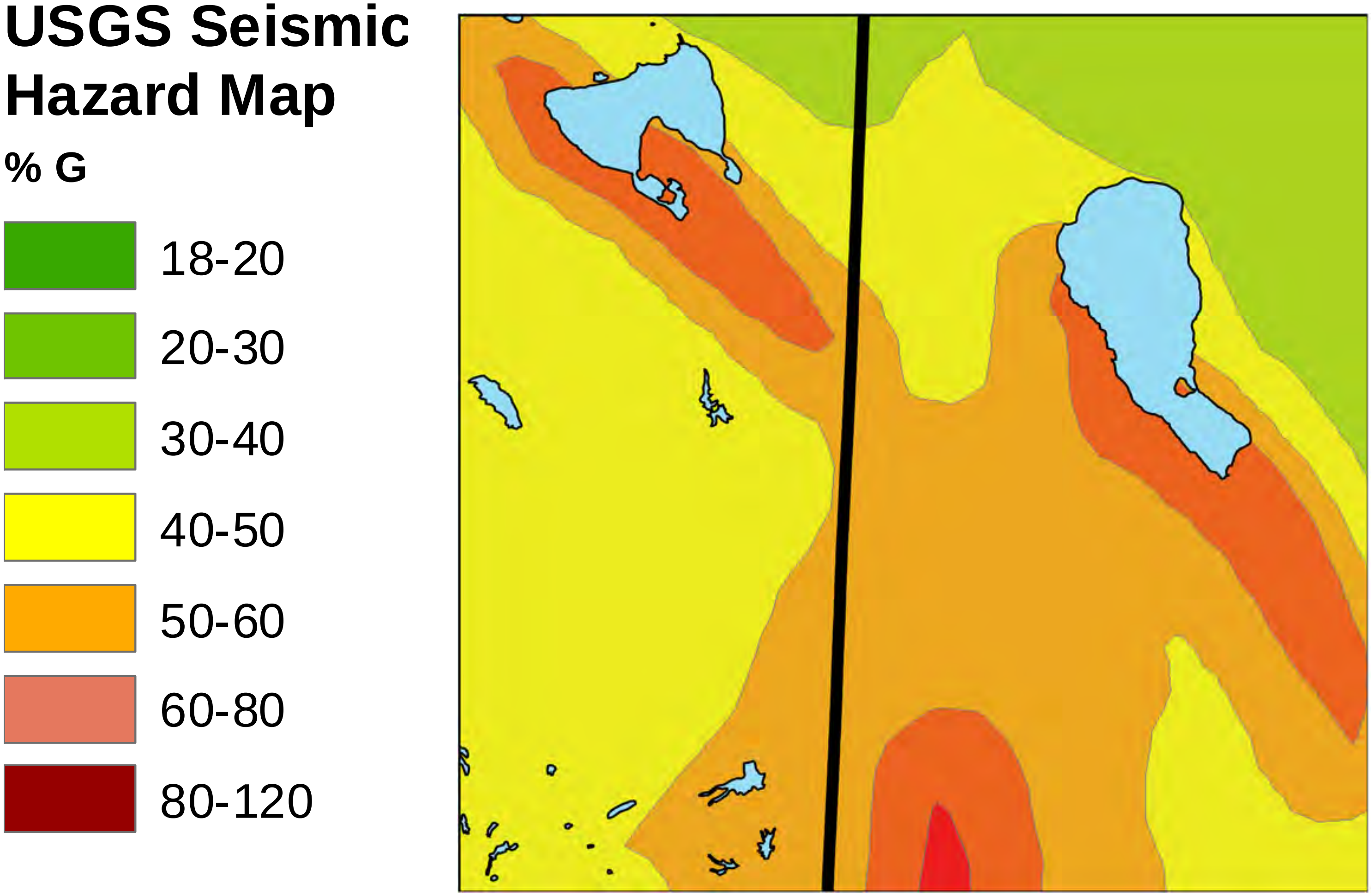

MAY 29 2003

Vicinity Map

USGS
Seismic Hazard Map

Map 1-4: USGS Seismic Hazard Map

% G

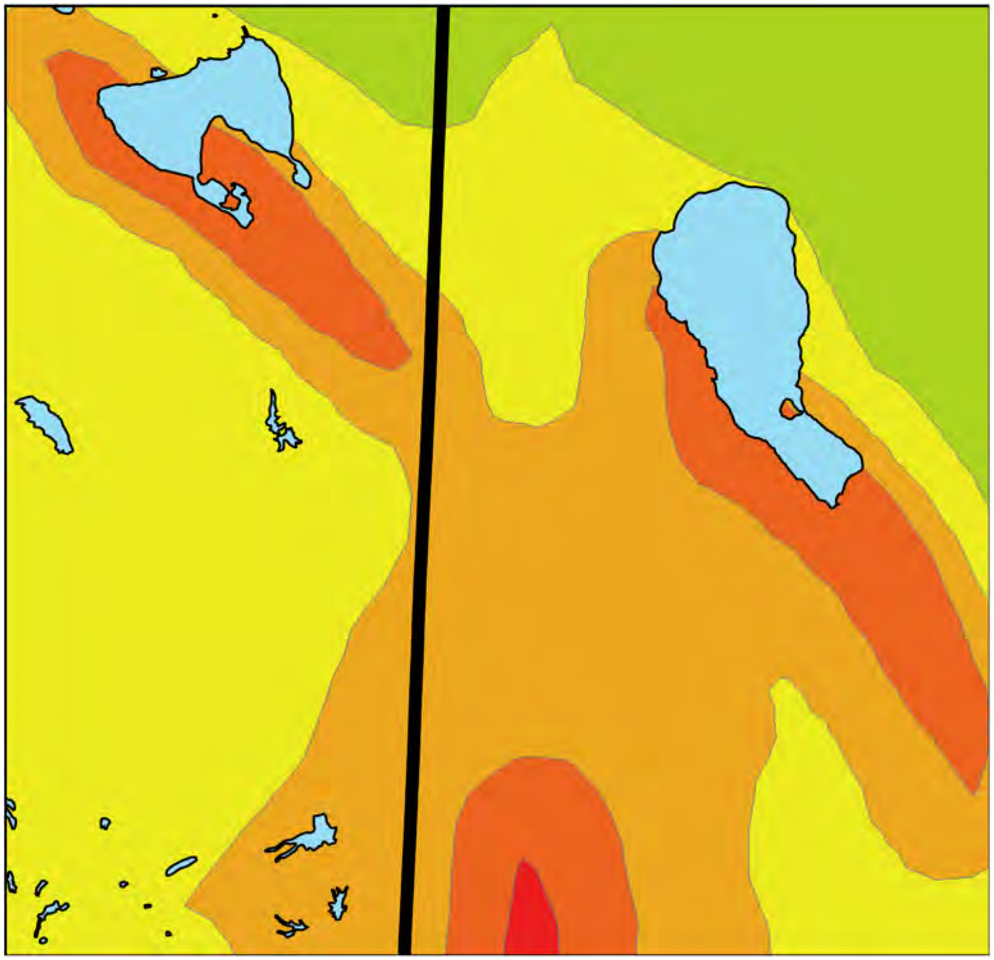


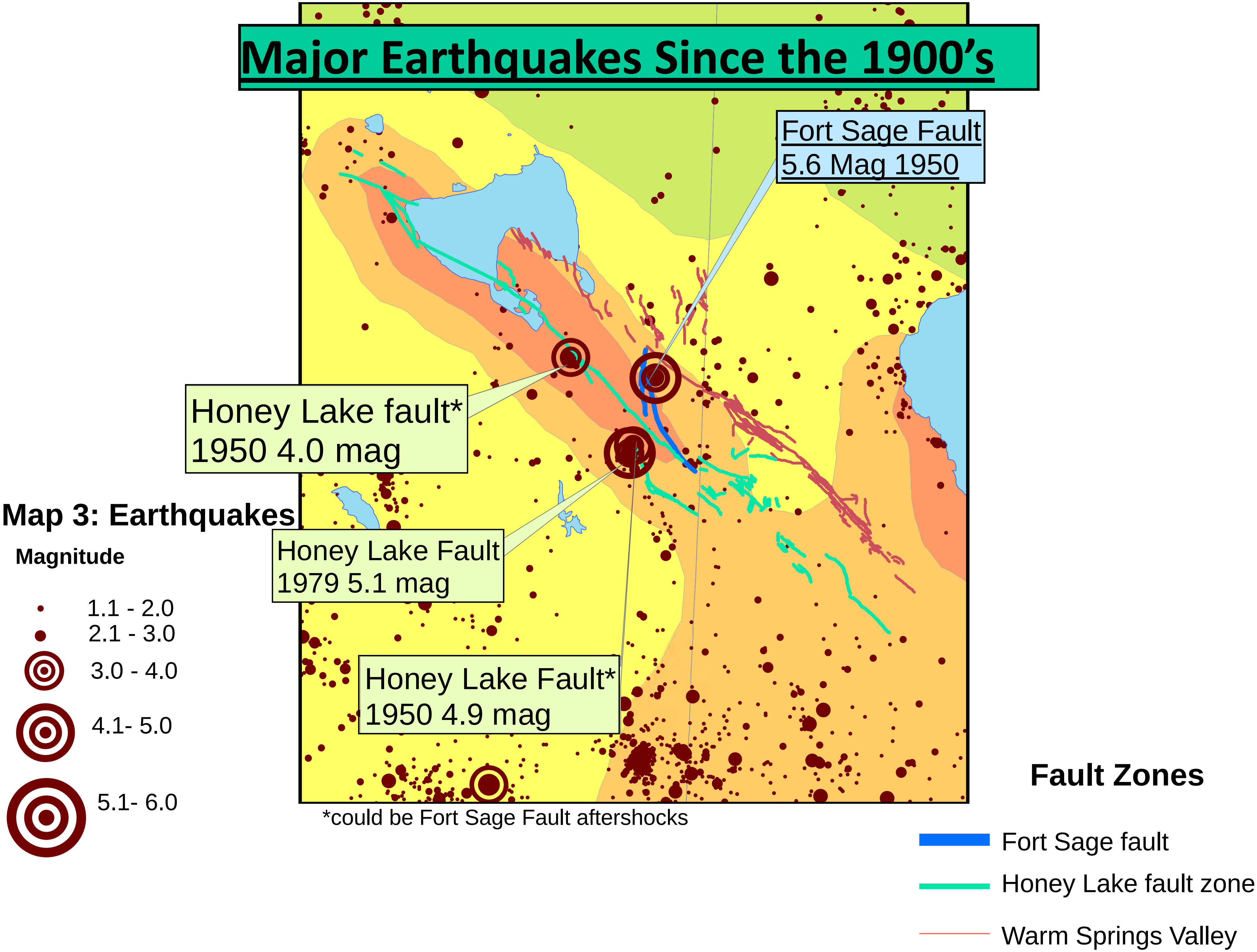
USGS
Seismic Hazard Map

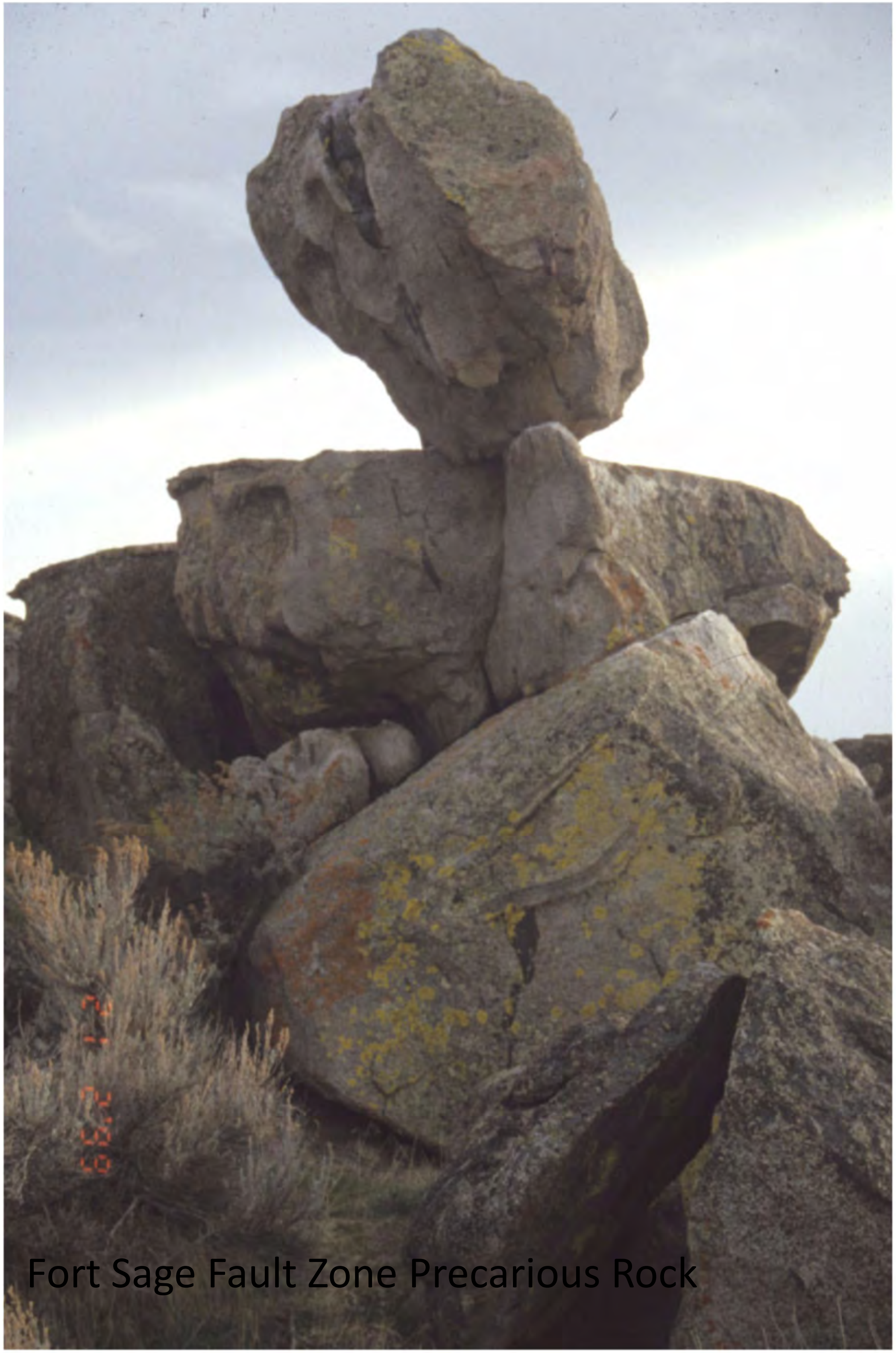
Map 1-4:
USGS Seismic Hazard Map

% G

	18-20
	20-30
	30-40
	40-50
	50-60
	60-80
	80-120




Major Earthquakes Since the 1900's
Fort Sage Fault
5.6 Mag 1950
Honey Lake fault*
1950 4.0 mag
Honey Lake Fault
1979 5.1 mag
Honey Lake Fault*
1950 4.9 mag
*could be Fort Sage Fault aftershocks
Map 3: Earthquakes
Magnitude
1.1 - 2.0
2.1 - 3.0
3.0 - 4.0
4.1- 5.0
5.1- 6.0
Fault Zones
Fort Sage fault
Honey Lake fault zone
Warm Springs Valley

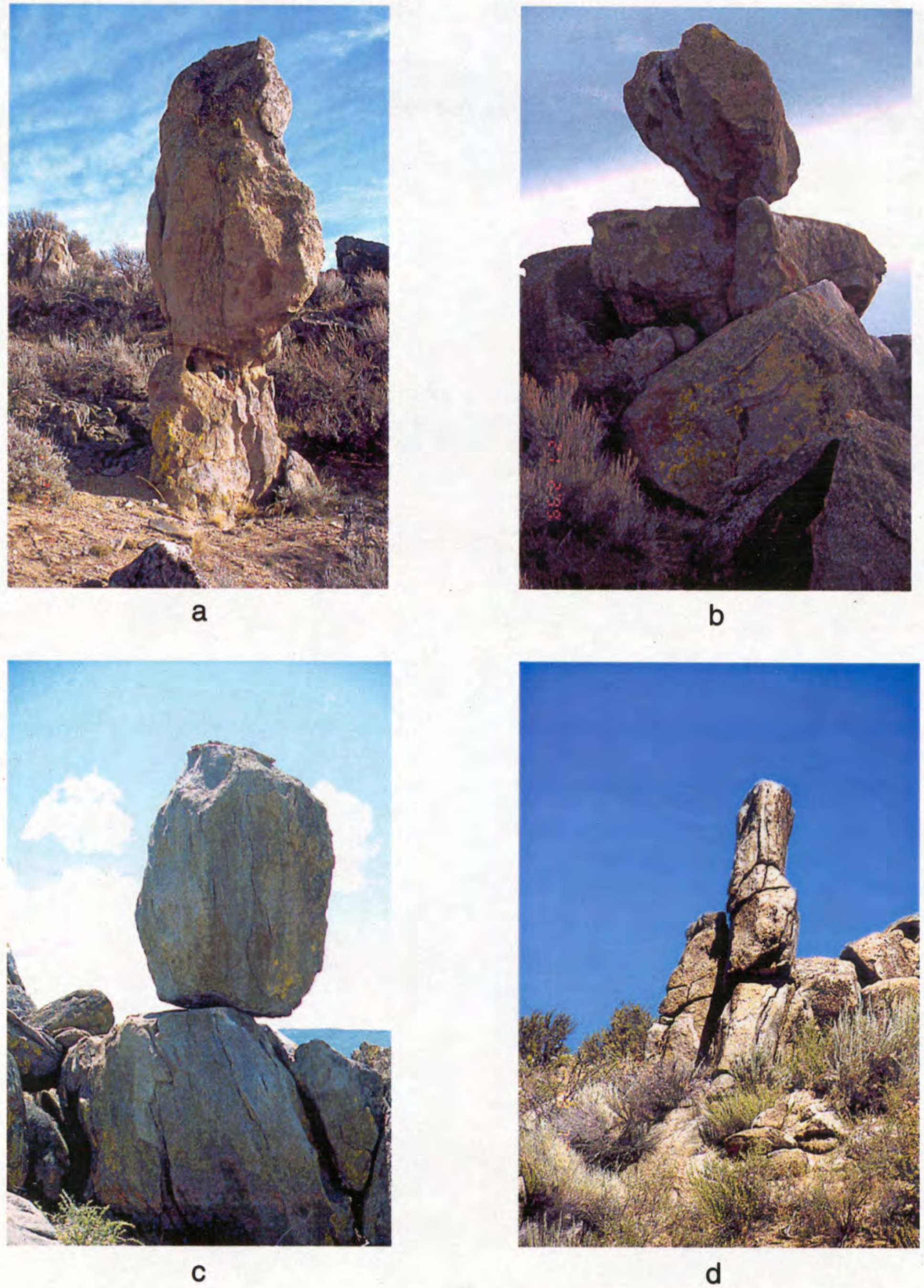


Fort Sage Fault Zone Precarious Rock

Photo by Jim Brune

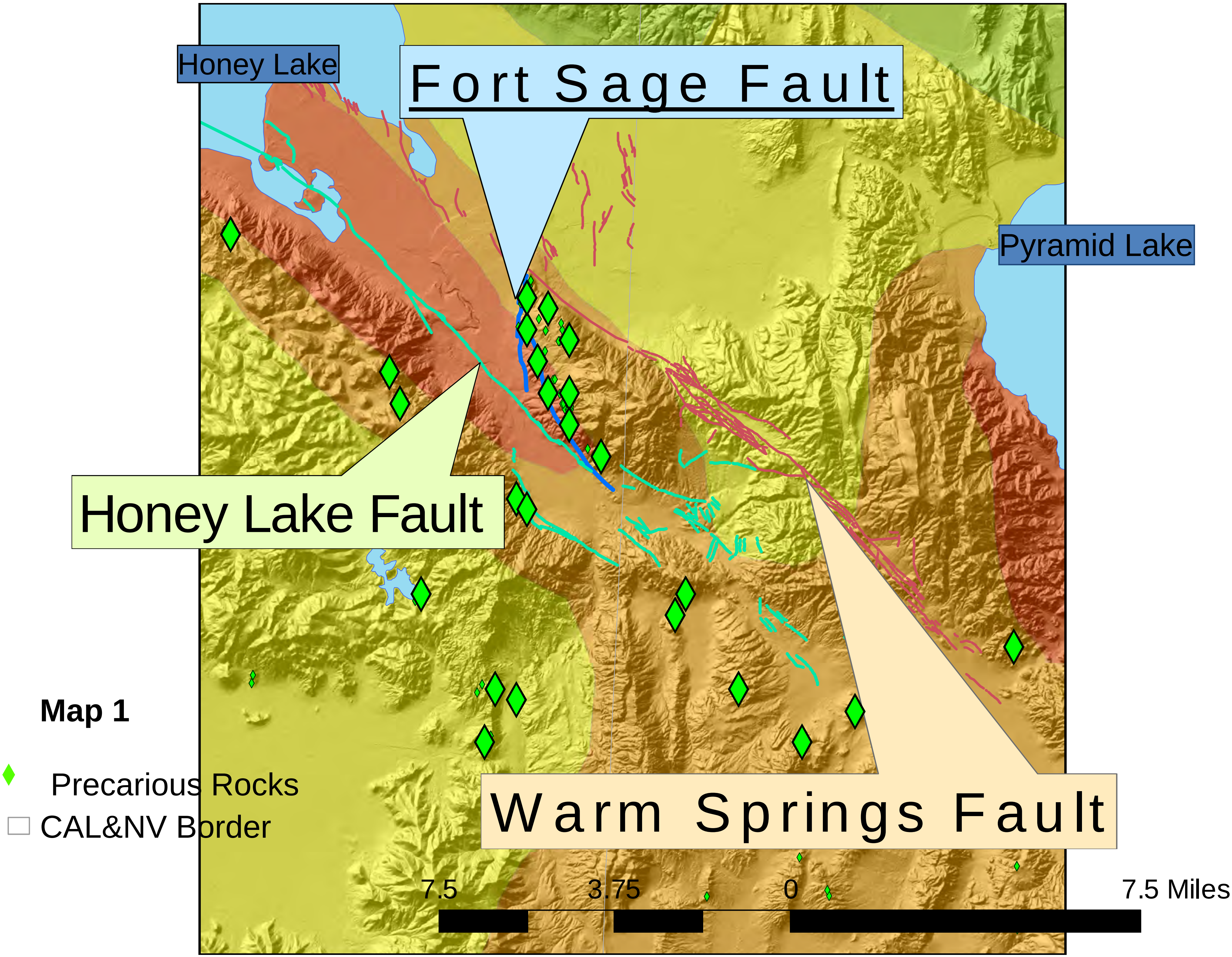
Fort Sage Fault Zone Precarious Rock

Fort Sage
Mountains



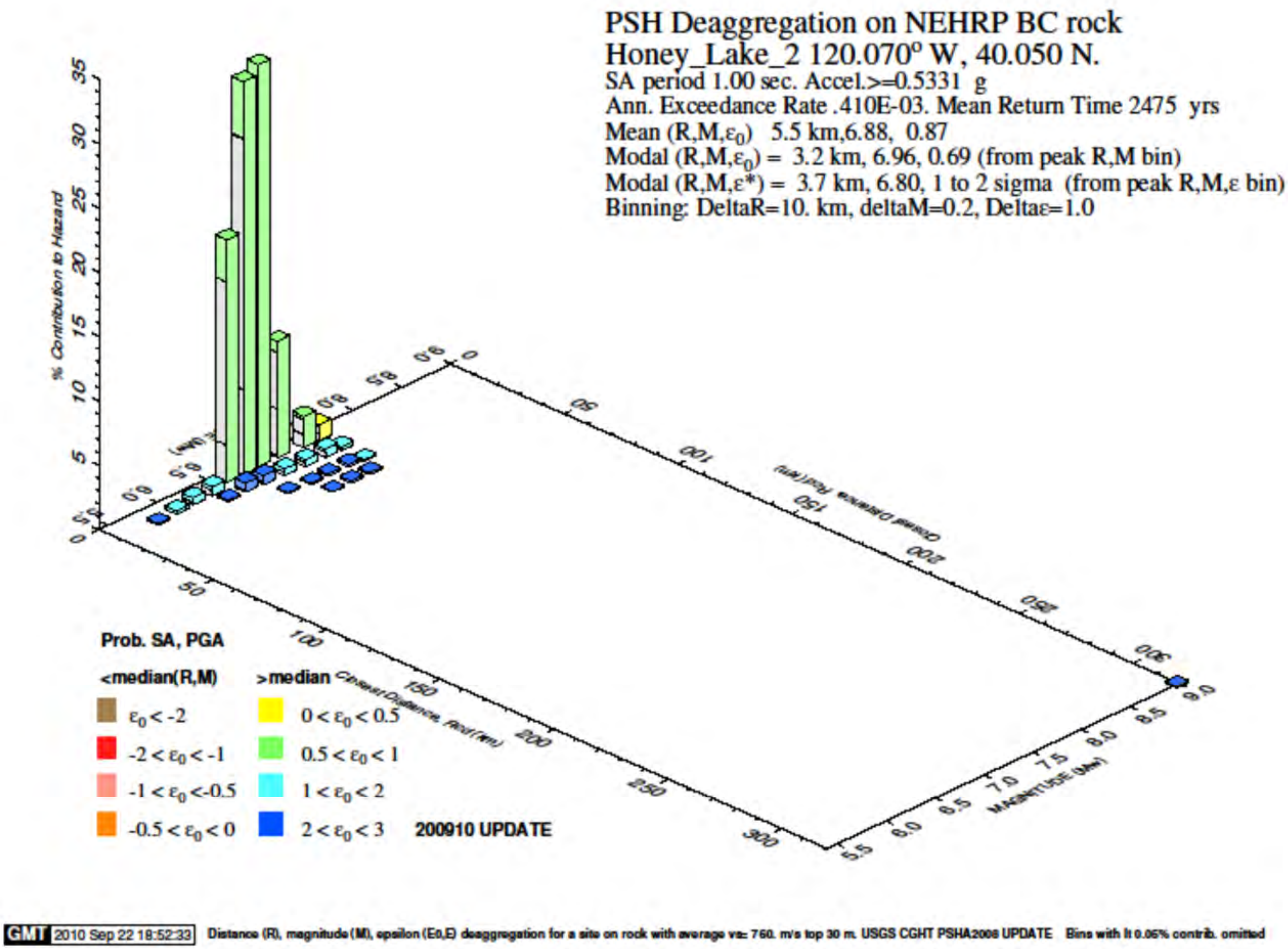
Examples of precarious rocks found in the vicinity of Honey Lake fault.

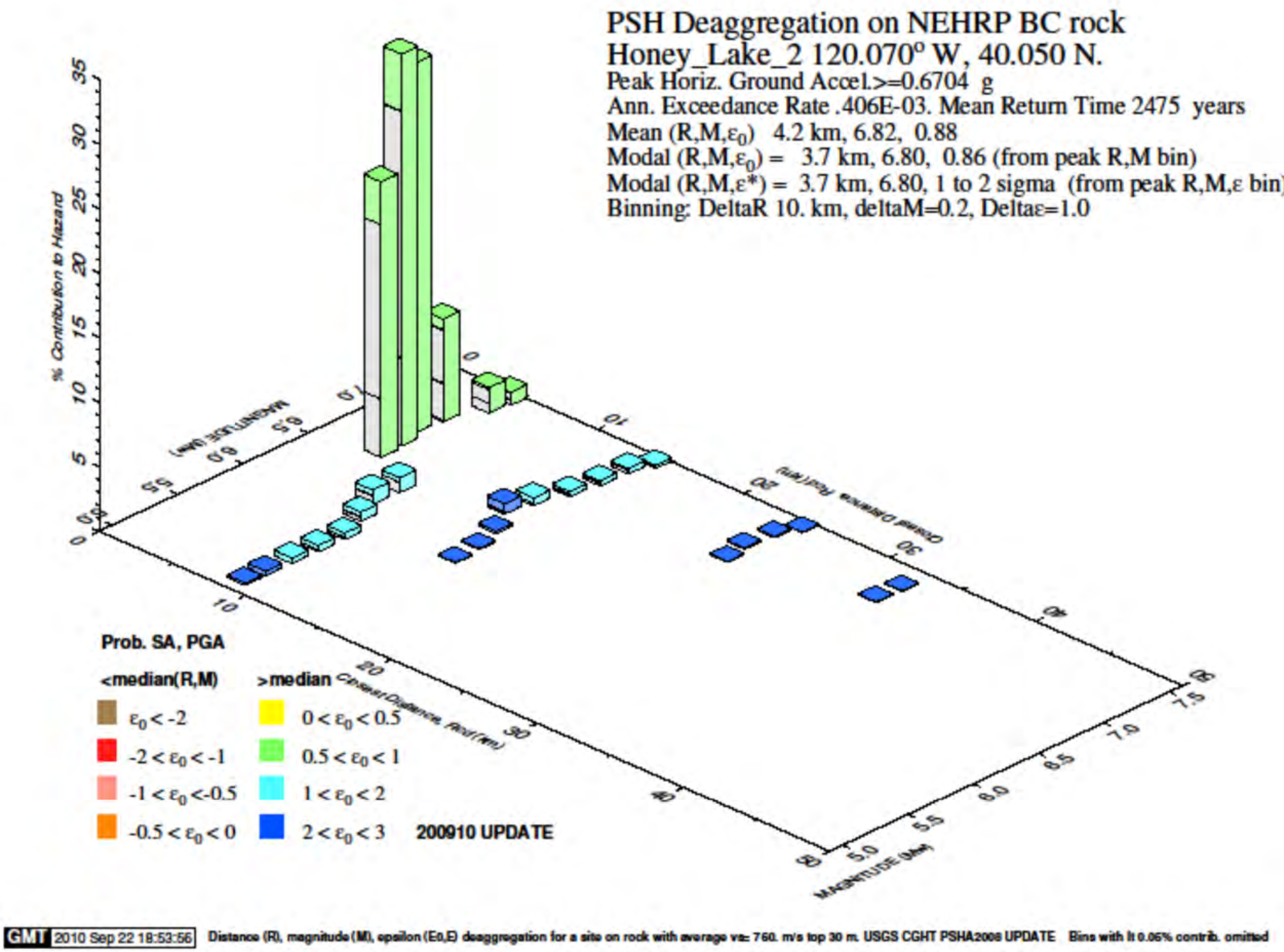
Constraints on Normal and Trans-tensional Faulting

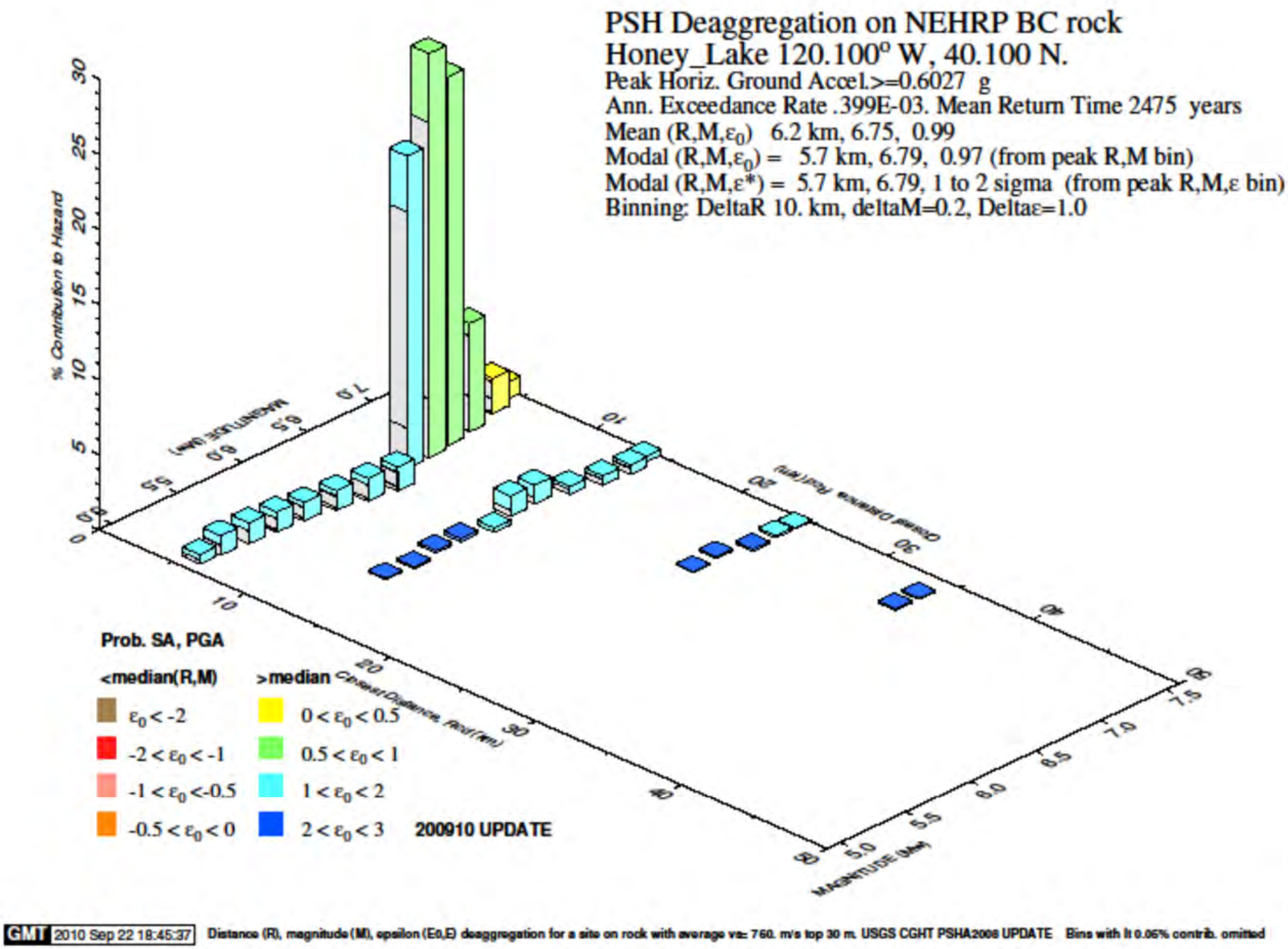

Honey Lake
Fort Sage Fault
Pyramid Lake
Honey Lake Fault
Warm Springs Fault
Precarious Rocks
CAL&NV Border
7.5
3.75
0
7.5 Miles

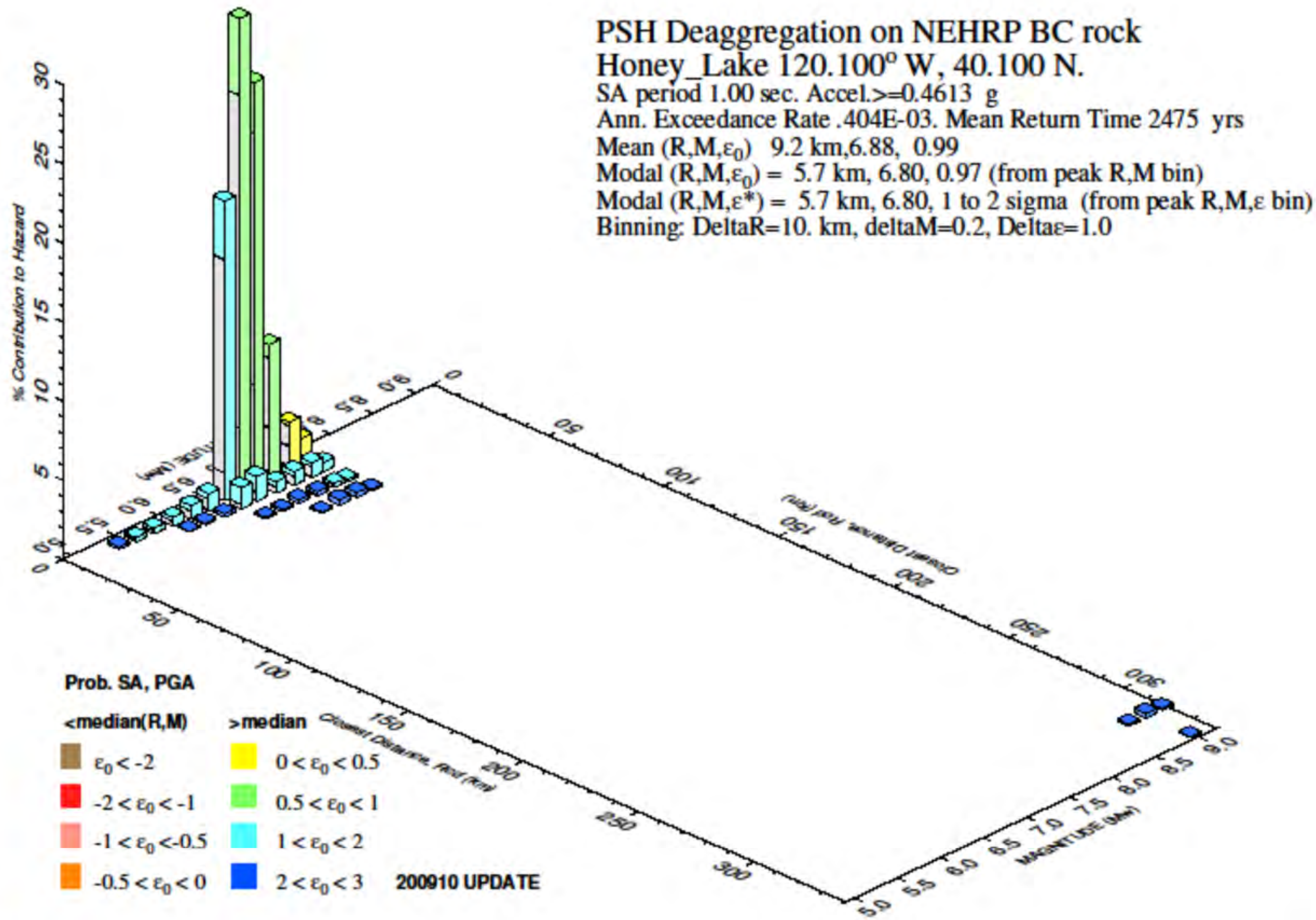
Map 1

Avalanches ?
?
?
?
?
?
?


PSH Deaggregation on NEHRP BC rock
Honey_Lake_2 120.070° W, 40.050 N.
SA period 1.00 sec. Accel.>=0.5331 g
Ann. Exceedance Rate .410E-03. Mean Return Time 2475 yrs
Mean (R,M,ε0) 5.5 km,6.88, 0.87
Modal (R,M,ε0) = 3.2 km, 6.96, 0.69 (from peak R,M bin)
Modal (R,M,ε*) = 3.7 km, 6.80, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2010 Sep 22 18:52:33 Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted


PSH Deaggregation on NEHRP BC rock
Honey_Lake_2 120.070° W, 40.050 N.
Peak Horiz. Ground Accel.>=0.6704 g
Ann. Exceedance Rate .406E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 4.2 km, 6.82, 0.88
Modal (R,M,ε0) = 3.7 km, 6.80, 0.86 (from peak R,M bin)
Modal (R,M,ε*) = 3.7 km, 6.80, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2010 Sep 22 18:53:56
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.06% contrib. omitted


PSH Deaggregation on NEHRP BC rock
Honey_Lake 120.100° W, 40.100 N.
Peak Horiz. Ground Accel.>=0.6027 g
Ann. Exceedance Rate .399E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 6.2 km, 6.75, 0.99
Modal (R,M,ε0) = 5.7 km, 6.79, 0.97 (from peak R,M bin)
Modal (R,M,ε*) = 5.7 km, 6.79, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2010 Sep 22 18:45:37
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

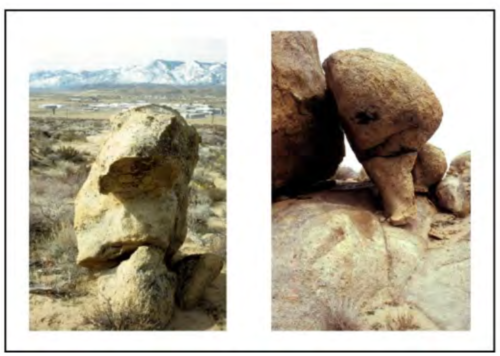


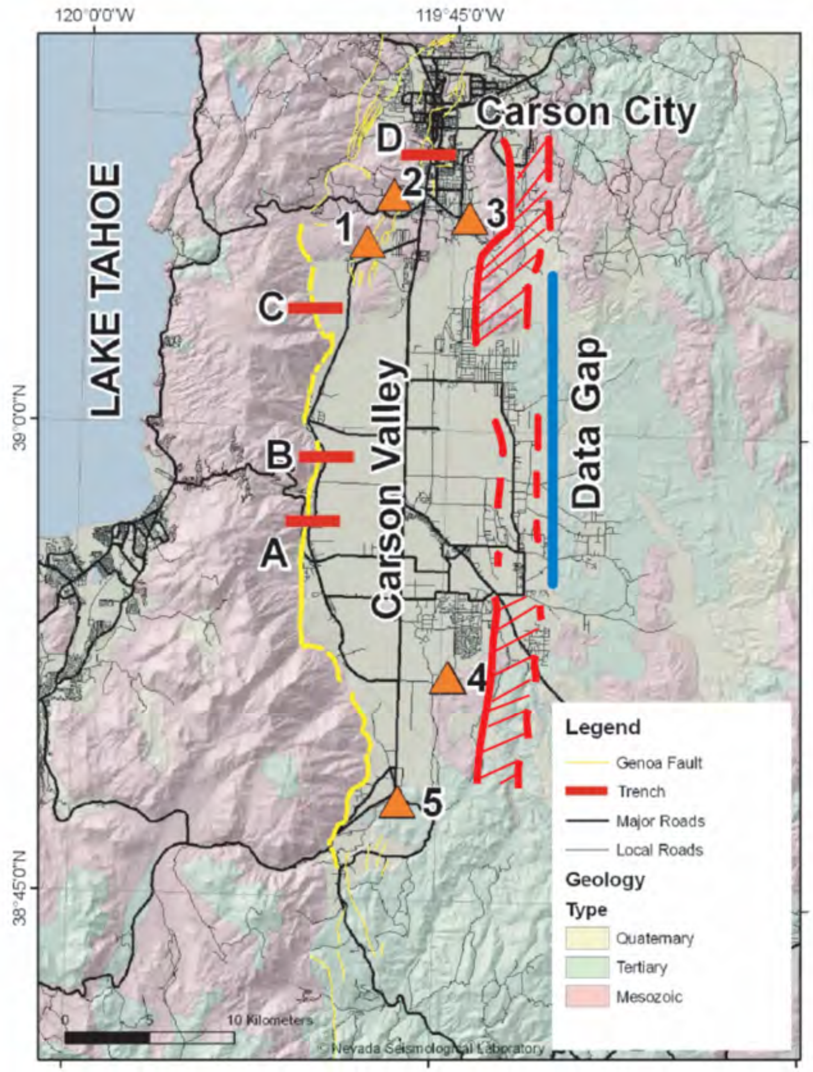
GMT 2010 Sep 22 18:47:26 Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.06% contrib. omitted

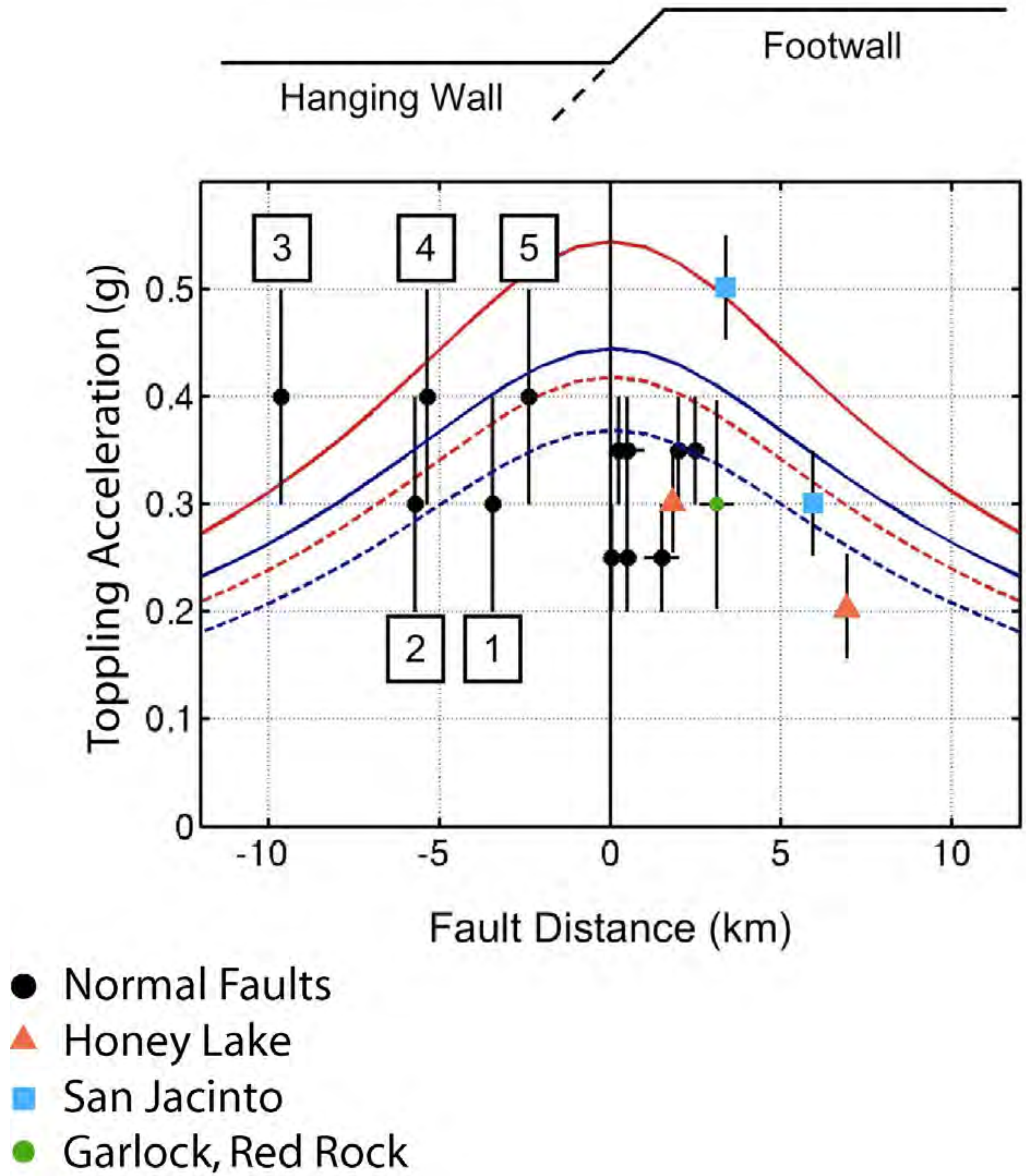
1

2

3



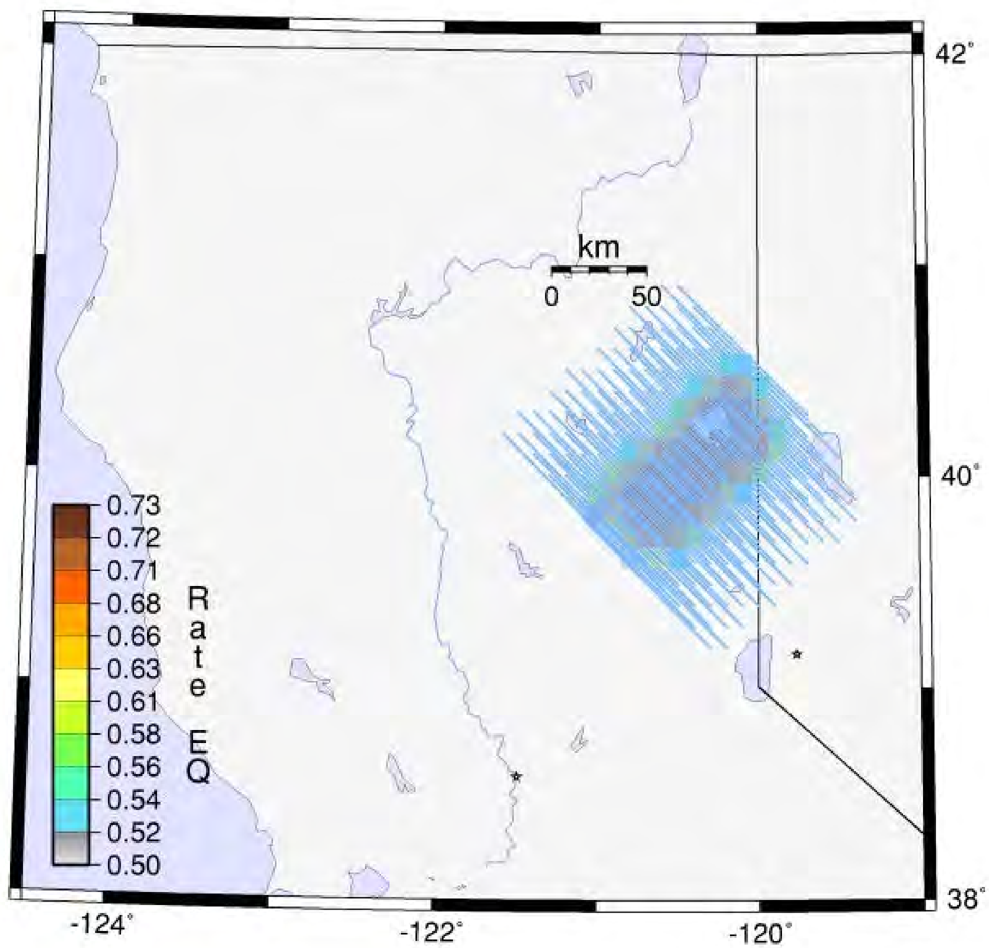

120°0'0"W
119°45'0"W
39°0'0"N
38°45'0"N
LAKE TAHOE
Carson City
Carson Valley
Data Gap
A
B
C
D
1
2
3
4
5
Legend
Genoa Fault
Trench
Major Roads
Local Roads
Geology
Type
Quaternary
Tertiary
Mesozoic
0
5
10 Kilometers
©Nevada Seismological Laboratory



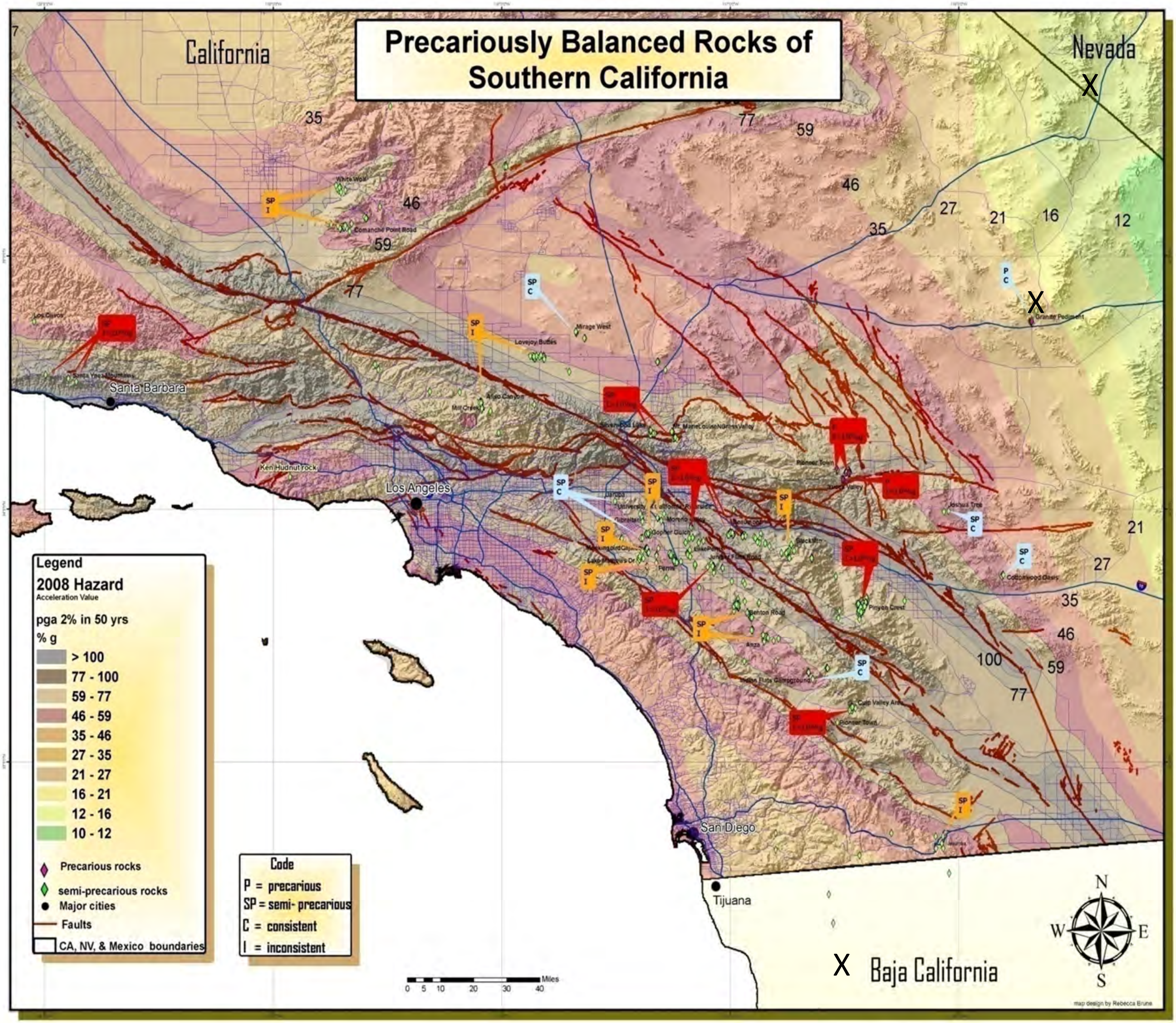
Footwall
Hanging Wall
Toppling Acceleration (g)
0
0.1
0.2
0.3
0.4
0.5
-10
-5
0
5
10
Fault Distance (km)
3
4
5
2
1
Normal Faults
Honey Lake
San Jacinto
Garlock, Red Rock

Background Seis.

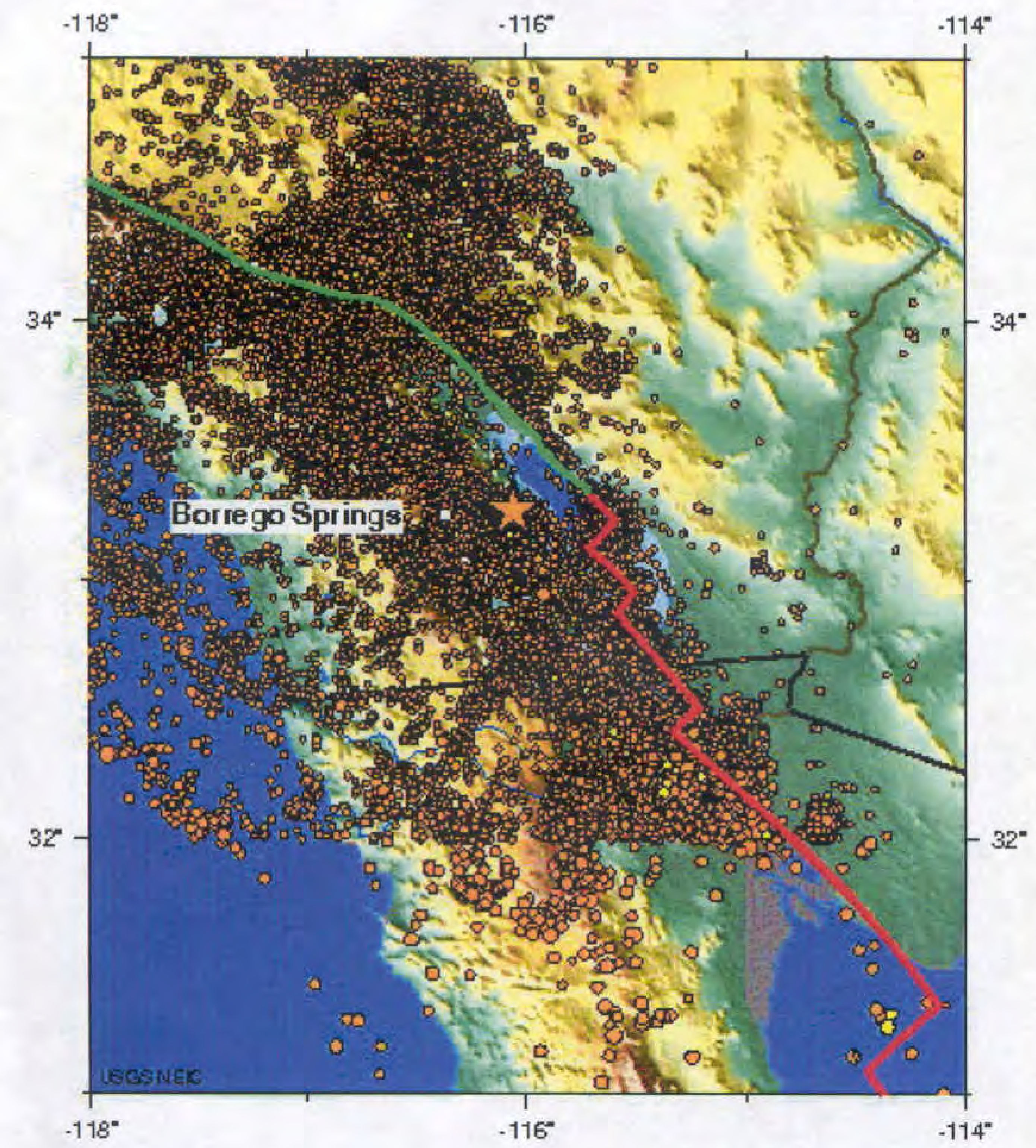
2007 SHEAR3 agrid



2010 Jan 29 13:55:03 2007 rates for WUS shearzone sources. Blue lines virtual flts. Area3new.agrid CA-NV.

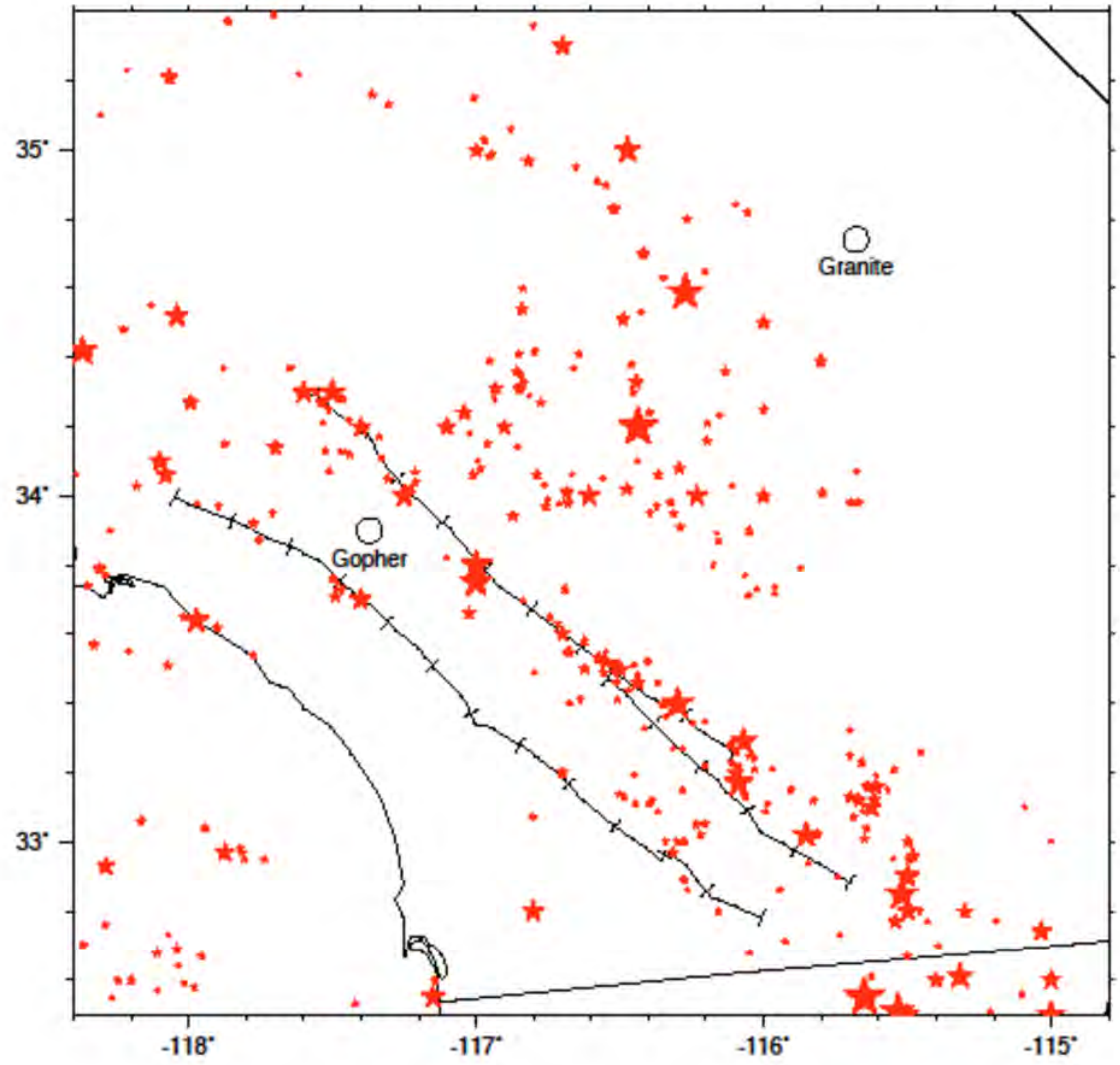


Precariously Balanced Rocks of Southern California
California
Nevada
Baja California
Santa Barbara
Los Angeles
San Diego
Tijuana
Legend
2008 Hazard
Acceleration Value
pga 2% in 50 yrs
% g
> 100
77 - 100
59 - 77
46 - 59
35 - 46
27 - 35
21 - 27
16 - 21
12 - 16
10 - 12
Precarious rocks
semi-precarious rocks
Major cities
Faults
CA, NV, & Mexico boundaries
Code
P = precarious
SP = semi- precarious
C = consistent
I = inconsistent
Miles
0 5 10 20 30 40
N
E
S
W
map design by Rebecca Brune

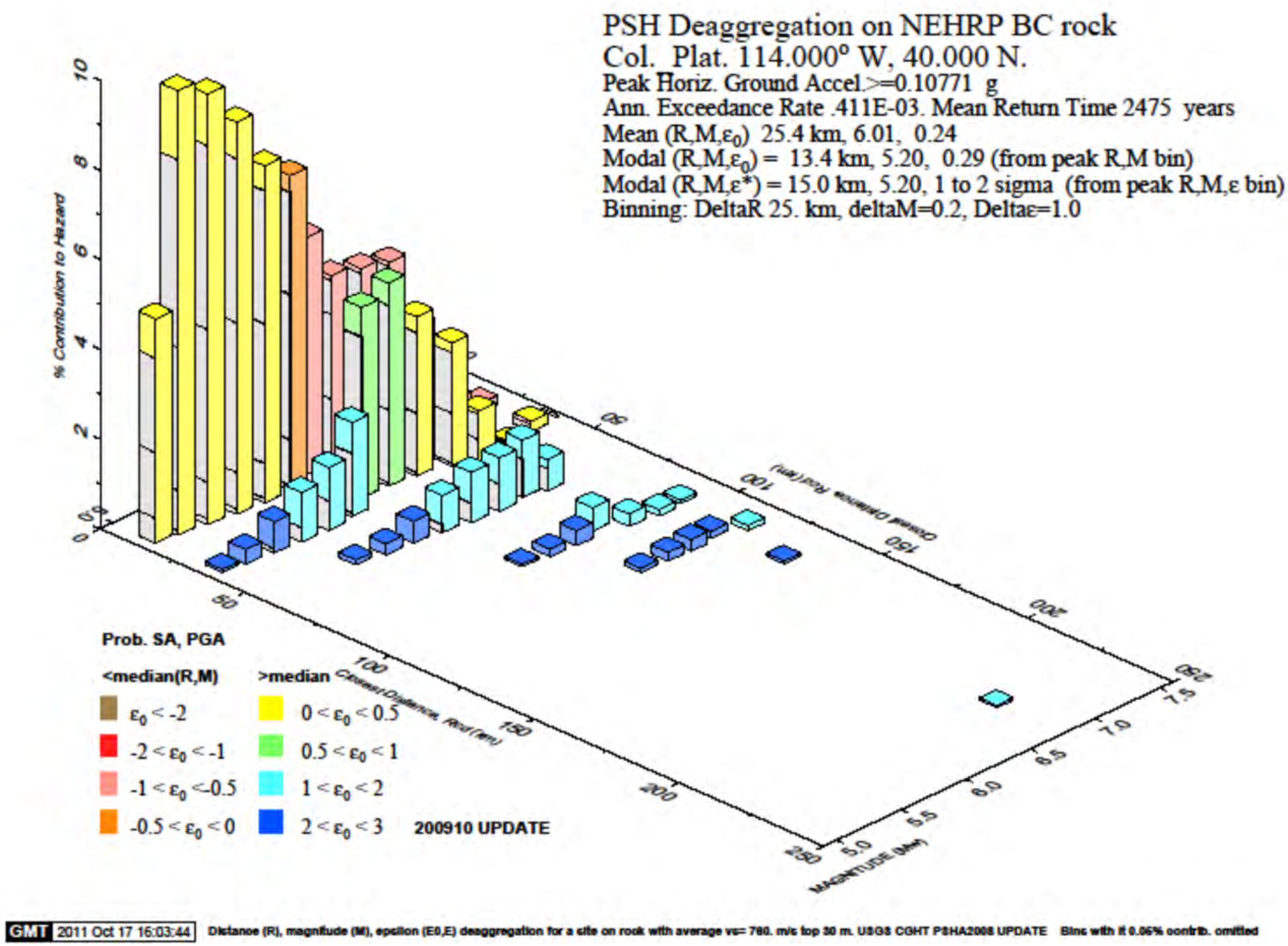


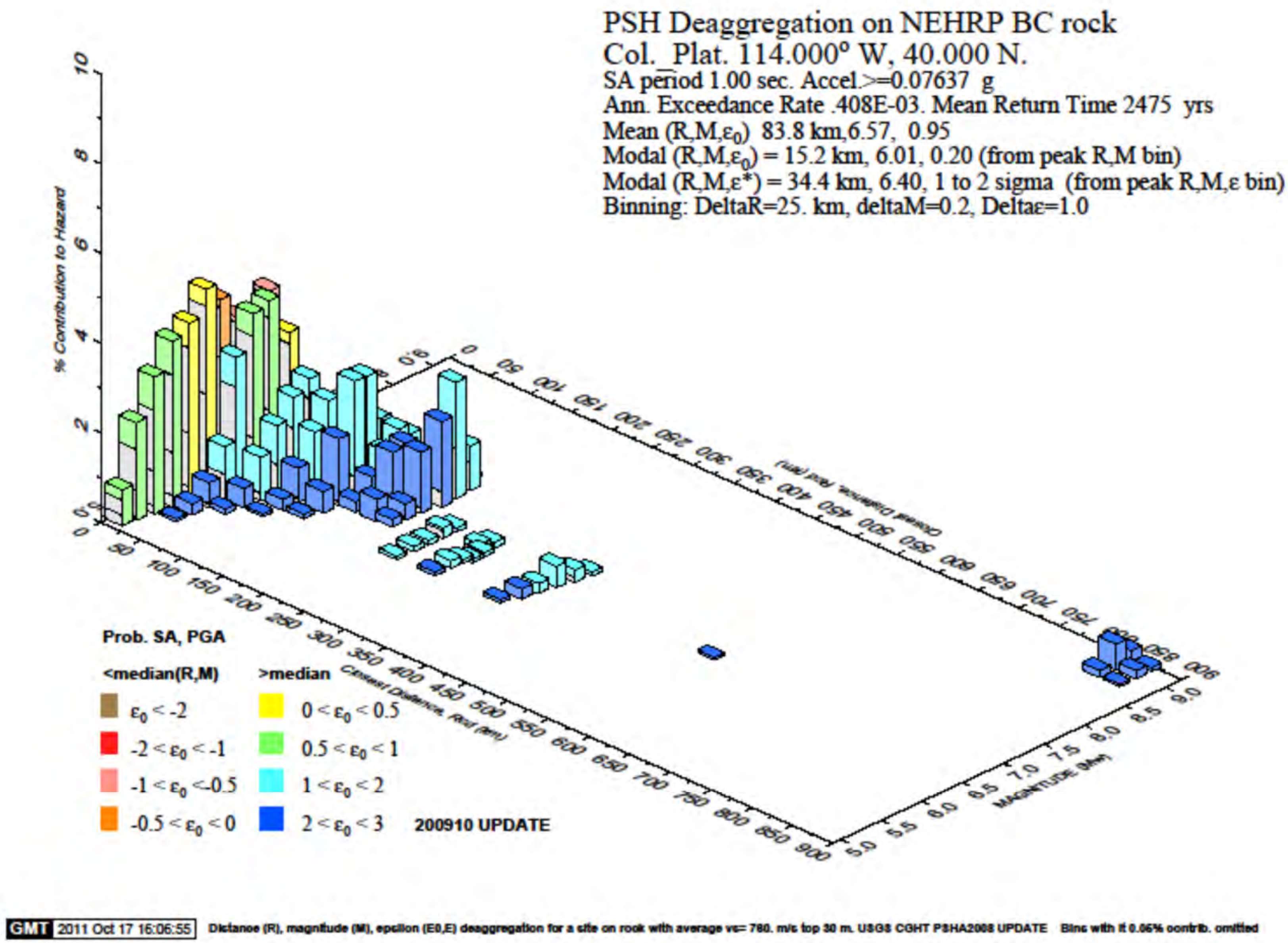
-118°
-116°
-114°
34°
34°
Borrego Springs
32°
32°
USGS NEIC
-118°
-116°
-114°

Catalog used for 2008 NSHM (wmm.cch): M>=4 (accounting for completeness)

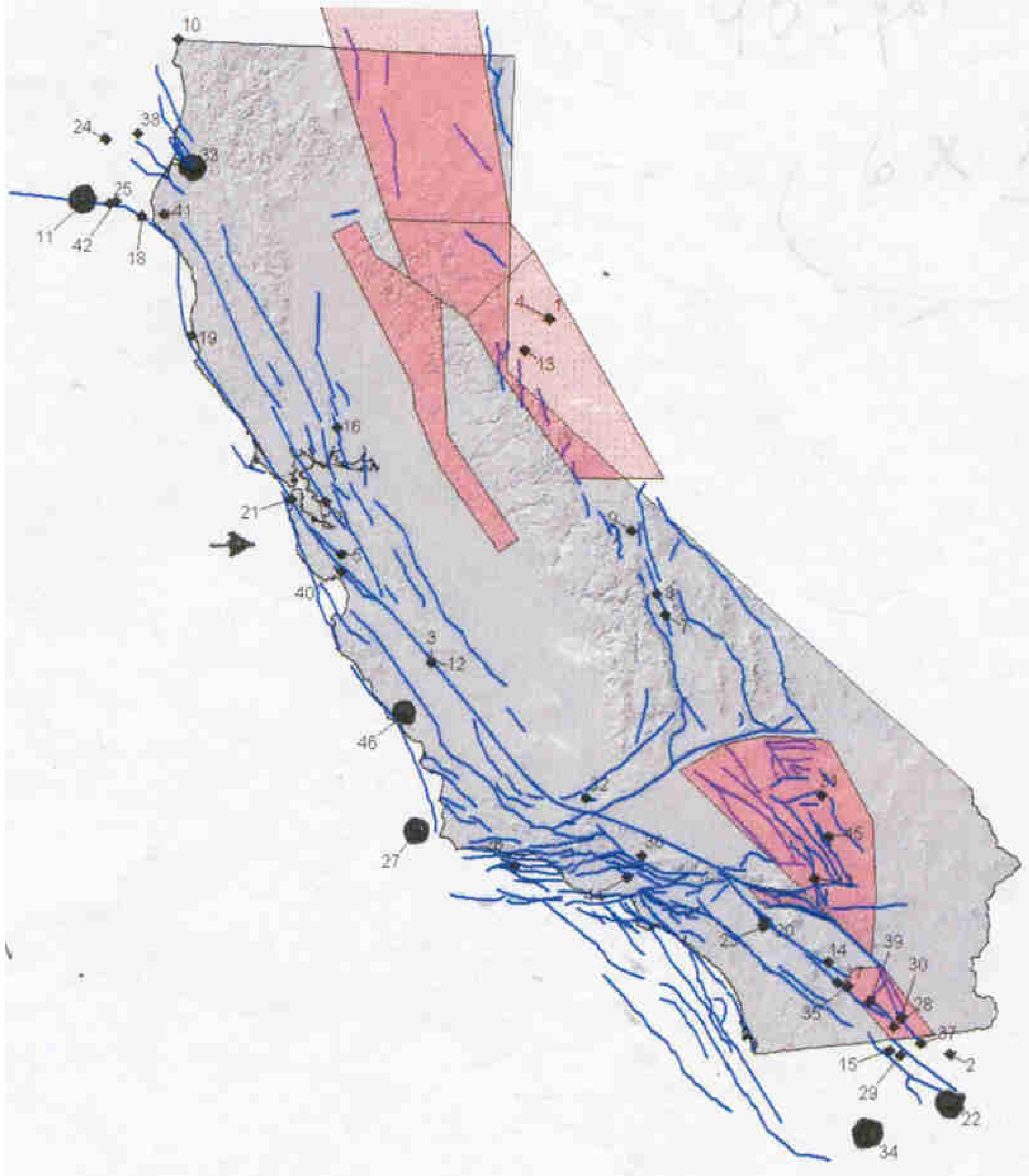


Colorado Plateau



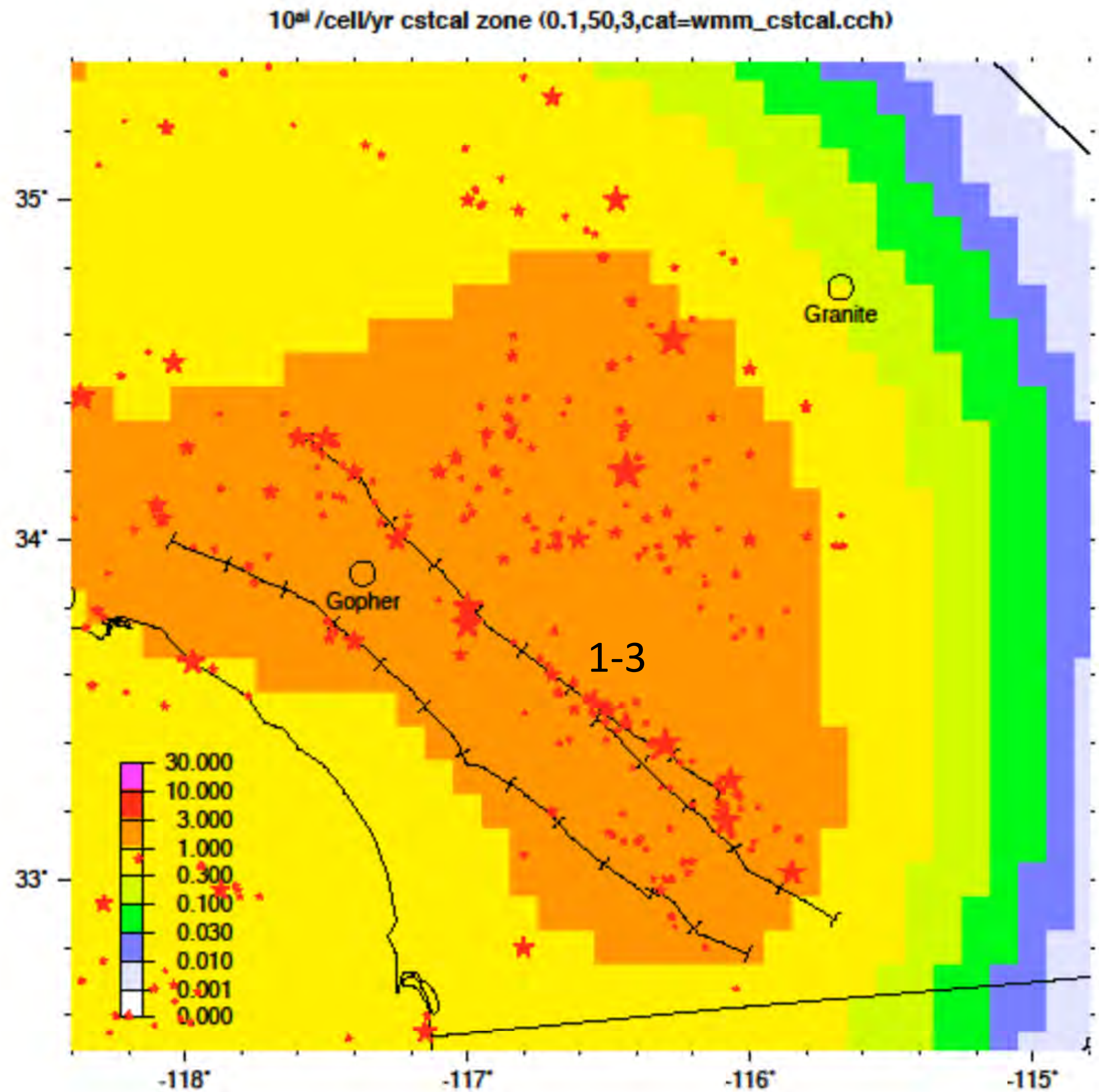


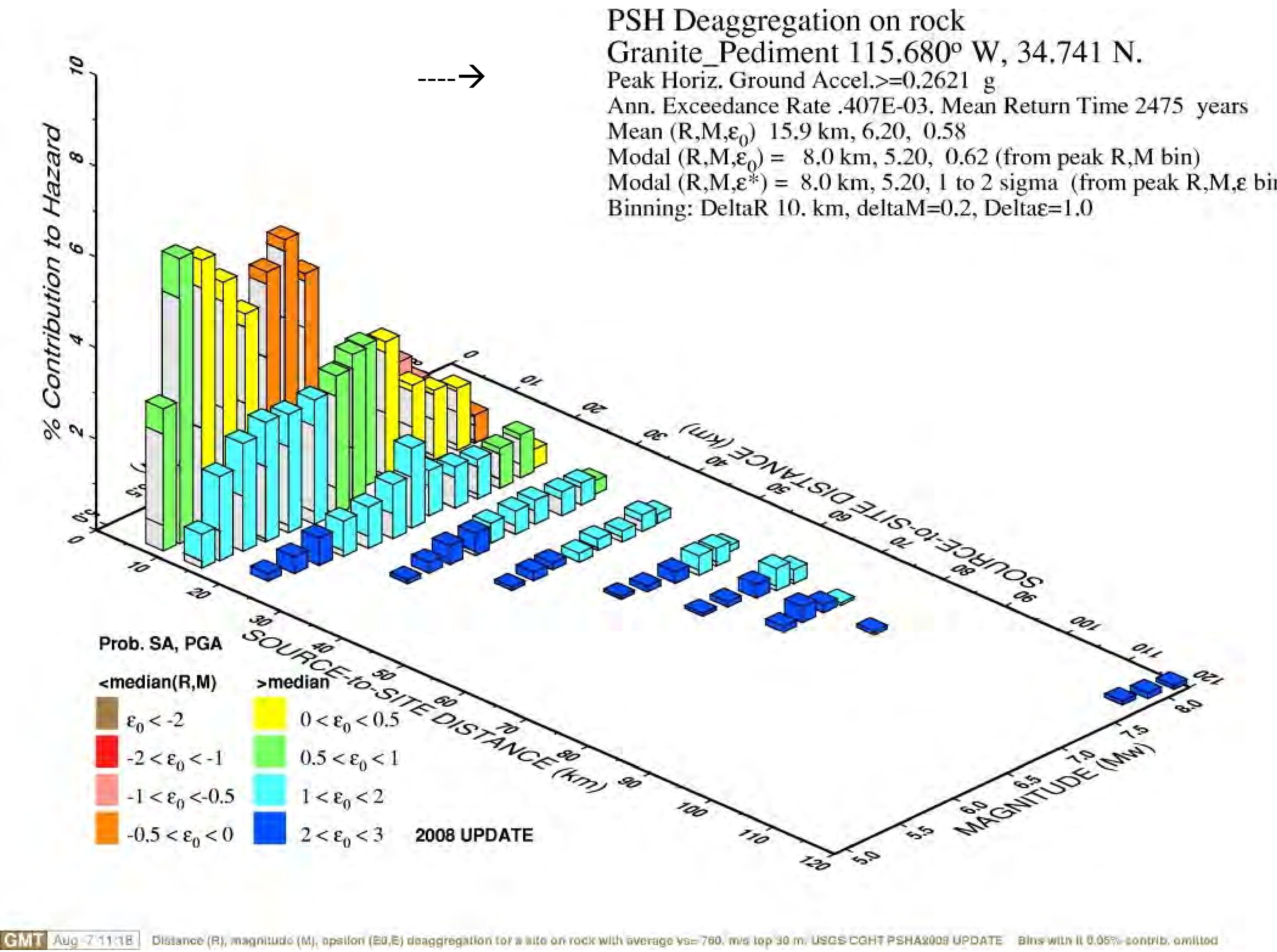
PSH Deaggregation on NEHRP BC rock
Col._Plat. 114.000° W, 40.000 N.
SA period 1.00 sec. Accel.>=0.07637 g
Ann. Exceedance Rate .408E-03. Mean Return Time 2475 yrs
Mean (R,M,ε0) 83.8 km,6.57, 0.95
Modal (R,M,ε0) = 15.2 km, 6.01, 0.20 (from peak R,M bin)
Modal (R,M,ε*) = 34.4 km, 6.40, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=25. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2011 Oct 17 16:06:55
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

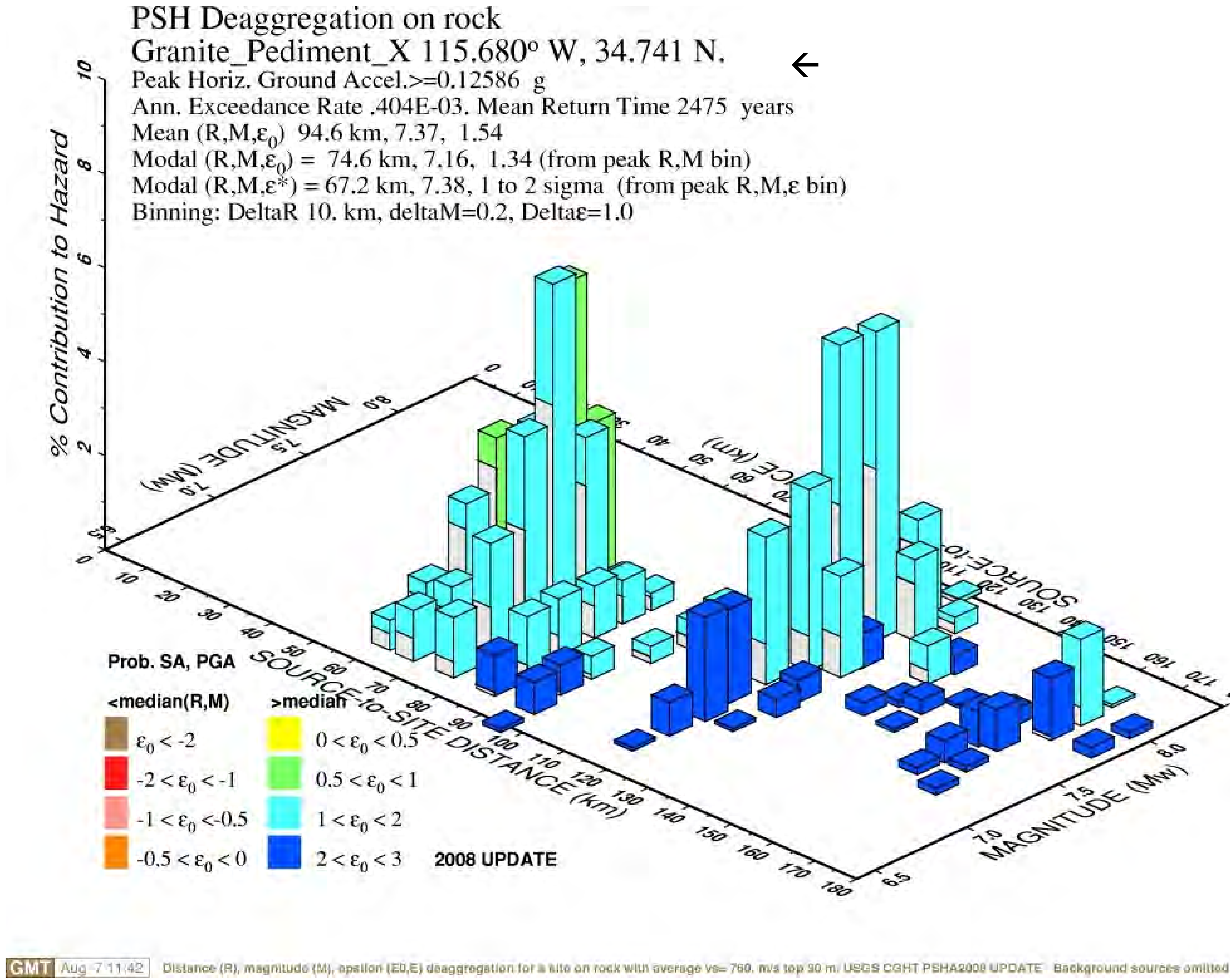


10
24
38
33
25
11
42
18
41
4
1
13
19
16
21
40
3
12
8
7
46
32
27
26
36
23
20
14
39
30
35
28
37
2
15
29
22
34

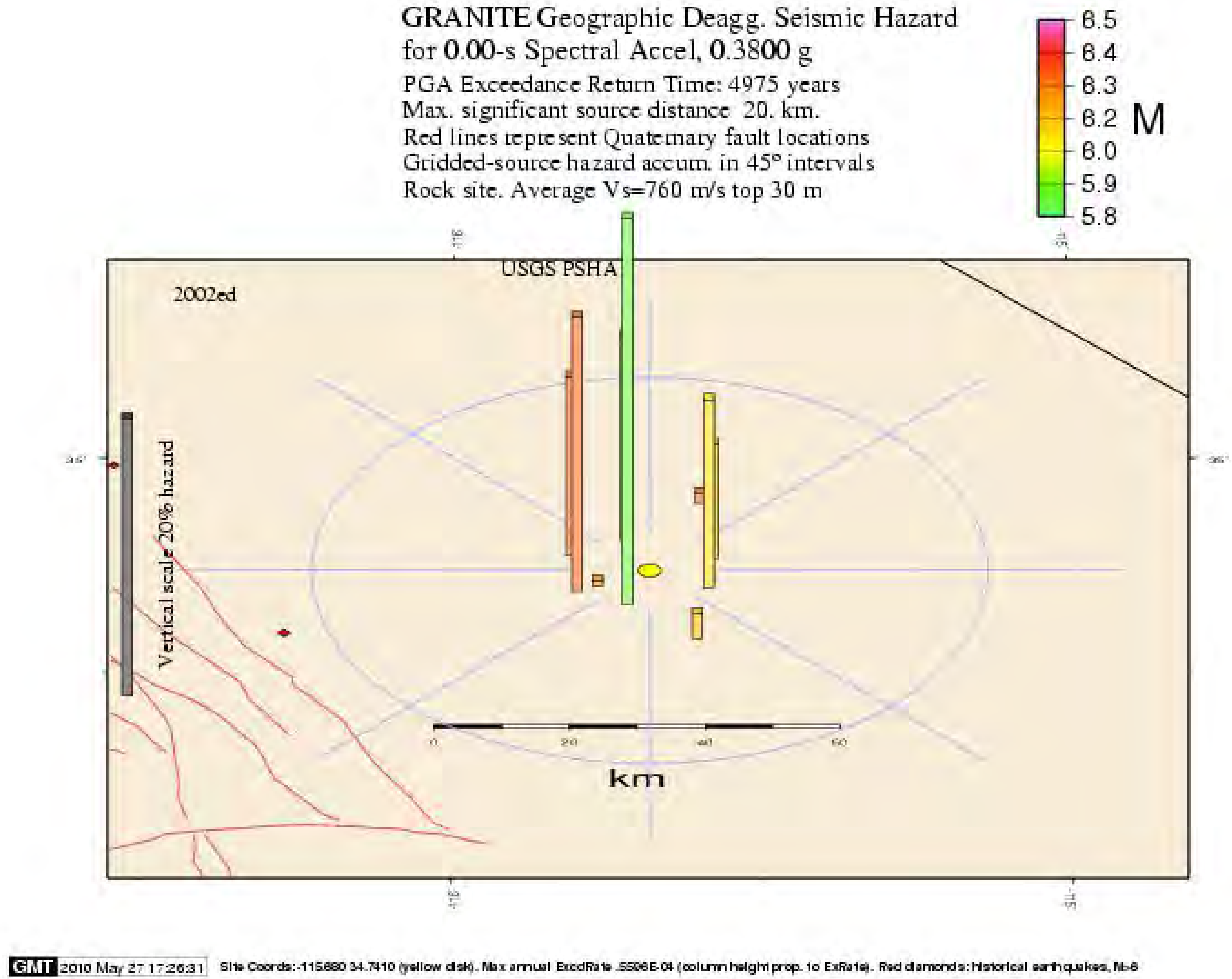
50 km smoothing



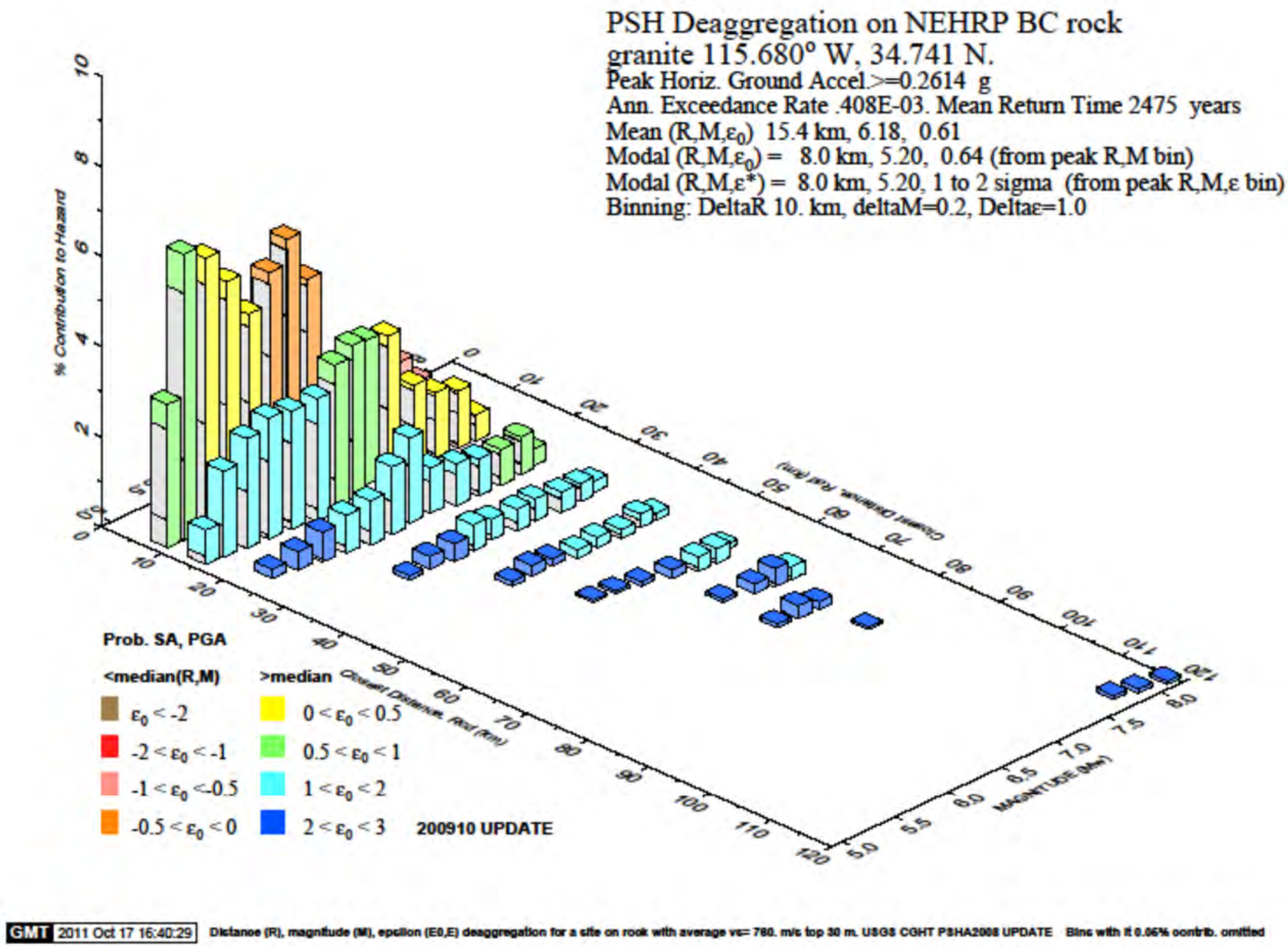

PSH Deaggregation on rock
Granite_Pediment 115.680° W, 34.741 N.
Peak Horiz. Ground Accel.>=0.2621 g
Ann. Exceedance Rate .407E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 15.9 km, 6.20, 0.58
Modal (R,M,ε0) = 8.0 km, 5.20, 0.62 (from peak R,M bin)
Modal (R,M,ε*) = 8.0 km, 5.20, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
SOURCE-to-SITE DISTANCE (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
2008 UPDATE
GMT Aug 7 11:18
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs=760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

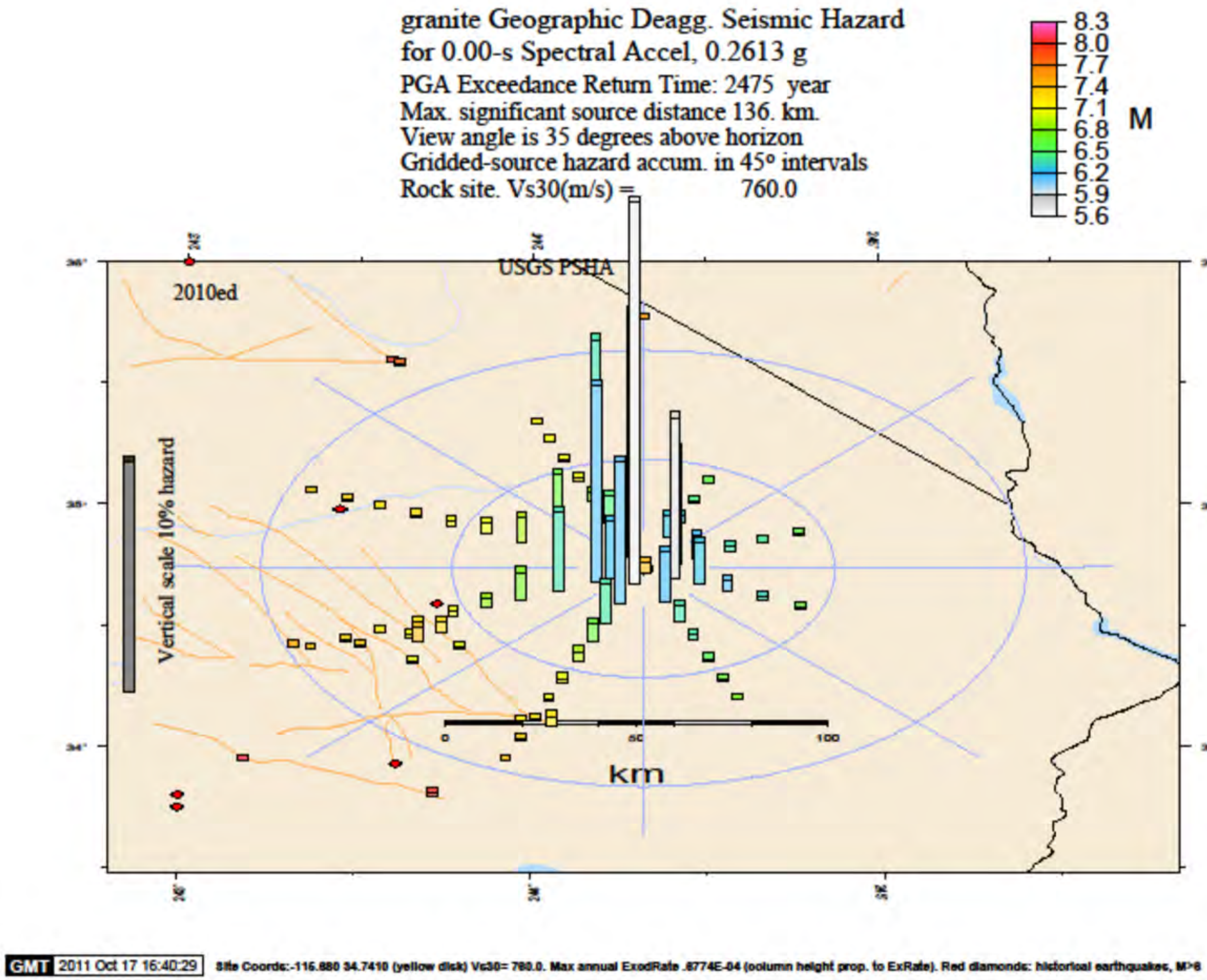


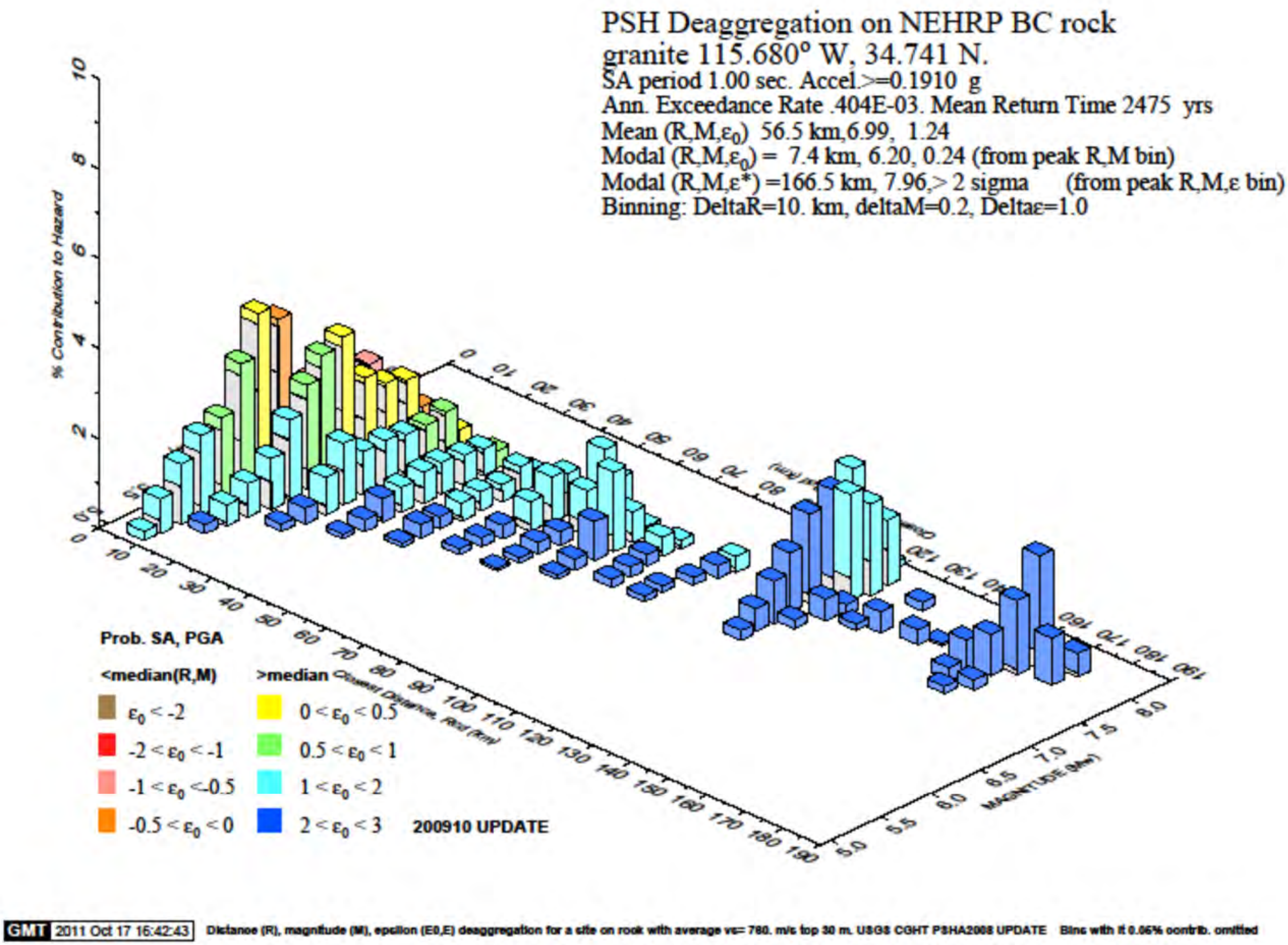
PSH Deaggregation on rock
Granite_Pediment_X 115.680° W, 34.741 N.
Peak Horiz. Ground Accel.>=0.12586 g
Ann. Exceedance Rate .404E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 94.6 km, 7.37, 1.54
Modal (R,M,ε0) = 74.6 km, 7.16, 1.34 (from peak R,M bin)
Modal (R,M,ε*) = 67.2 km, 7.38, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
SOURCE-to-SITE DISTANCE (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
2008 UPDATE
GMT Aug 7 11:42
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Background sources omitted

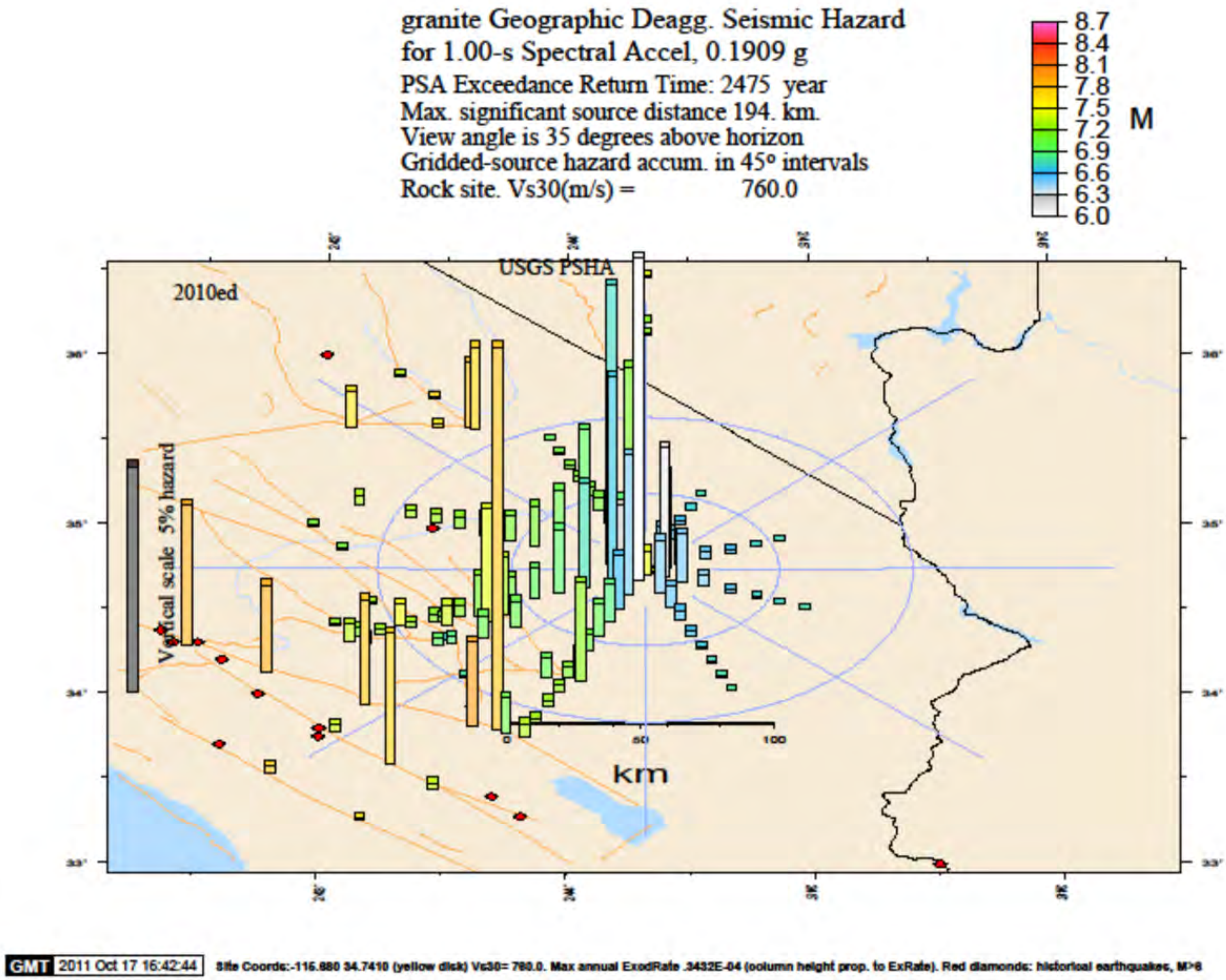


GRANITE Geographic Deagg. Seismic Hazard
for 0.00-s Spectral Accel, 0.3800 g
PGA Exceedance Return Time: 4975 years
Max. significant source distance 20. km.
Red lines represent Quaternary fault locations
Gridded-source hazard accum. in 45° intervals
Rock site. Average Vs=760 m/s top 30 m
6.5
6.4
6.3
6.2
6.0
5.9
5.8
M
USGS PSHA
2002ed
Vertical scale 20% hazard
0
20
40
60
km
GMT 2010 May 27 17:26:31
Site Coords: -115.880 34.7410 (yellow disk). Max annual ExcdRate .5506E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6


PSH Deaggregation on NEHRP BC rock
granite 115.680° W, 34.741 N.
Peak Horiz. Ground Accel.>=0.2614 g
Ann. Exceedance Rate .408E-03. Mean Return Time 2475 years
Mean (R,M,ε0) 15.4 km, 6.18, 0.61
Modal (R,M,ε0) = 8.0 km, 5.20, 0.64 (from peak R,M bin)
Modal (R,M,ε*) = 8.0 km, 5.20, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2011 Oct 17 16:40:29
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

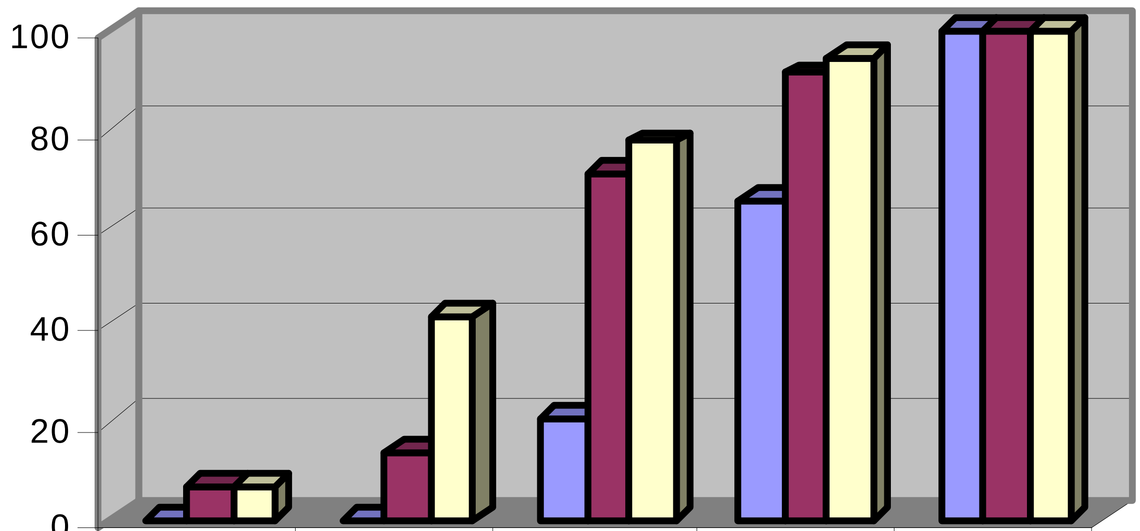

granite Geographic Deagg. Seismic Hazard
for 0.00-s Spectral Accel, 0.2613 g
PGA Exceedance Return Time: 2475 year
Max. significant source distance 136. km.
View angle is 35 degrees above horizon
Gridded-source hazard accum. in 45° intervals
Rock site. Vs30(m/s) = 760.0
8.3
8.0
7.7
7.4
7.1
6.8
6.5
6.2
5.9
5.6
M
USGS PSHA
2010ed
Vertical scale 10% hazard
0
50
100
km
GMT 2011 Oct 17 16:40:29
Site Coords:-116.880 34.7410 (yellow disk) Vs30= 760.0. Max annual ExcdRate .8774E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6


PSH Deaggregation on NEHRP BC rock
granite 115.680° W, 34.741 N.
SA period 1.00 sec. Accel.>=0.1910 g
Ann. Exceedance Rate .404E-03. Mean Return Time 2475 yrs
Mean (R,M,ε0) 56.5 km,6.99, 1.24
Modal (R,M,ε0) = 7.4 km, 6.20, 0.24 (from peak R,M bin)
Modal (R,M,ε*) =166.5 km, 7.96,> 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 < -0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2011 Oct 17 16:42:43
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted



granite Geographic Deagg. Seismic Hazard
for 1.00-s Spectral Accel, 0.1909 g
PSA Exceedance Return Time: 2475 year
Max. significant source distance 194. km.
View angle is 35 degrees above horizon
Gridded-source hazard accum. in 45° intervals
Rock site. Vs30(m/s) = 760.0
8.7
8.4
8.1
7.8
7.5
7.2
6.9
6.6
6.3
6.0
M
USGS PSHA
2010ed
Vertical scale 5% hazard
0
50
100
km
GMT 2011 Oct 17 16:42:44
Site Coords:-116.880 34.7410 (yellow disk) Vs30= 760.0. Max annual ExcdRate .3432E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6

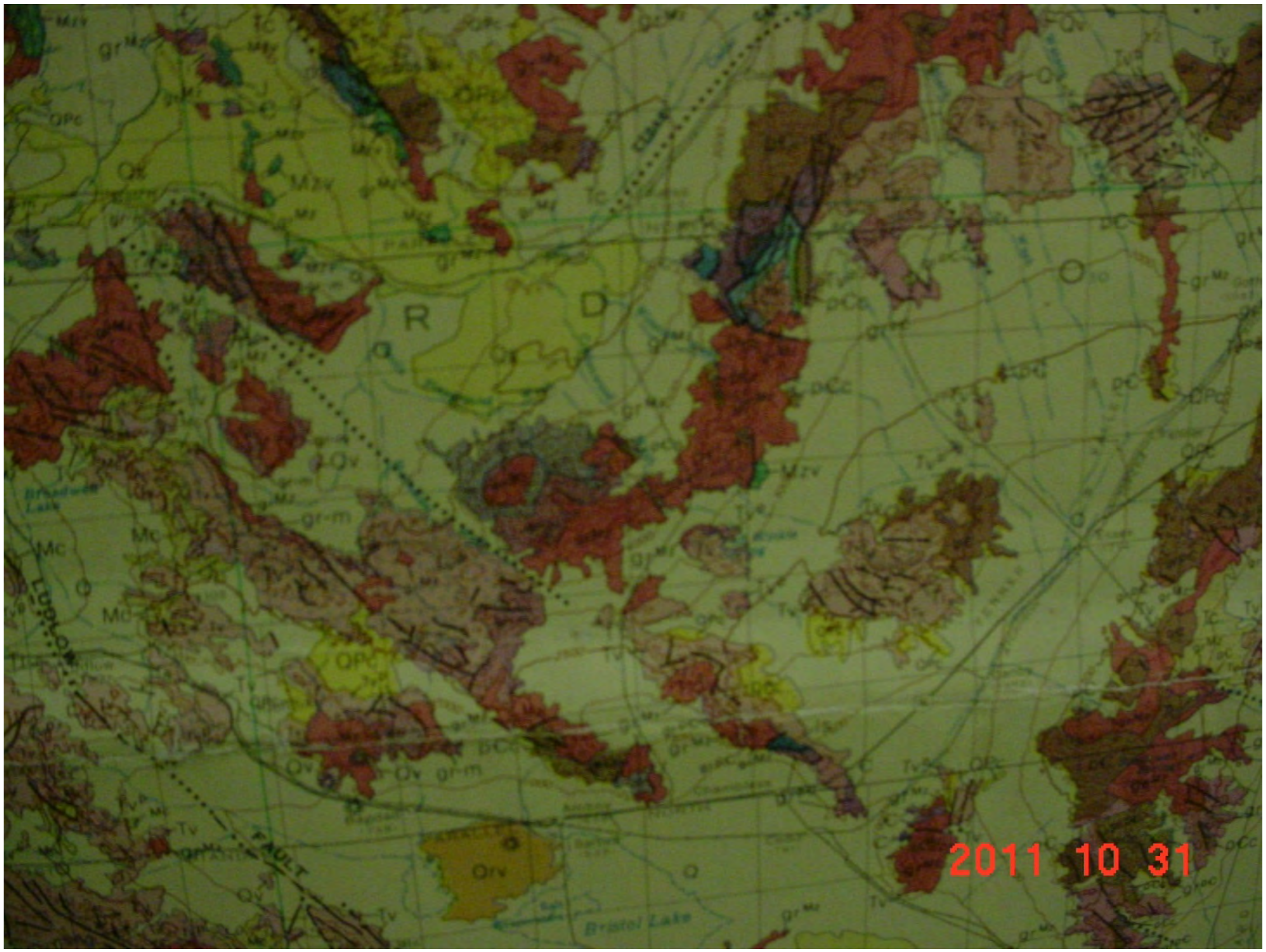
Normalized to 100



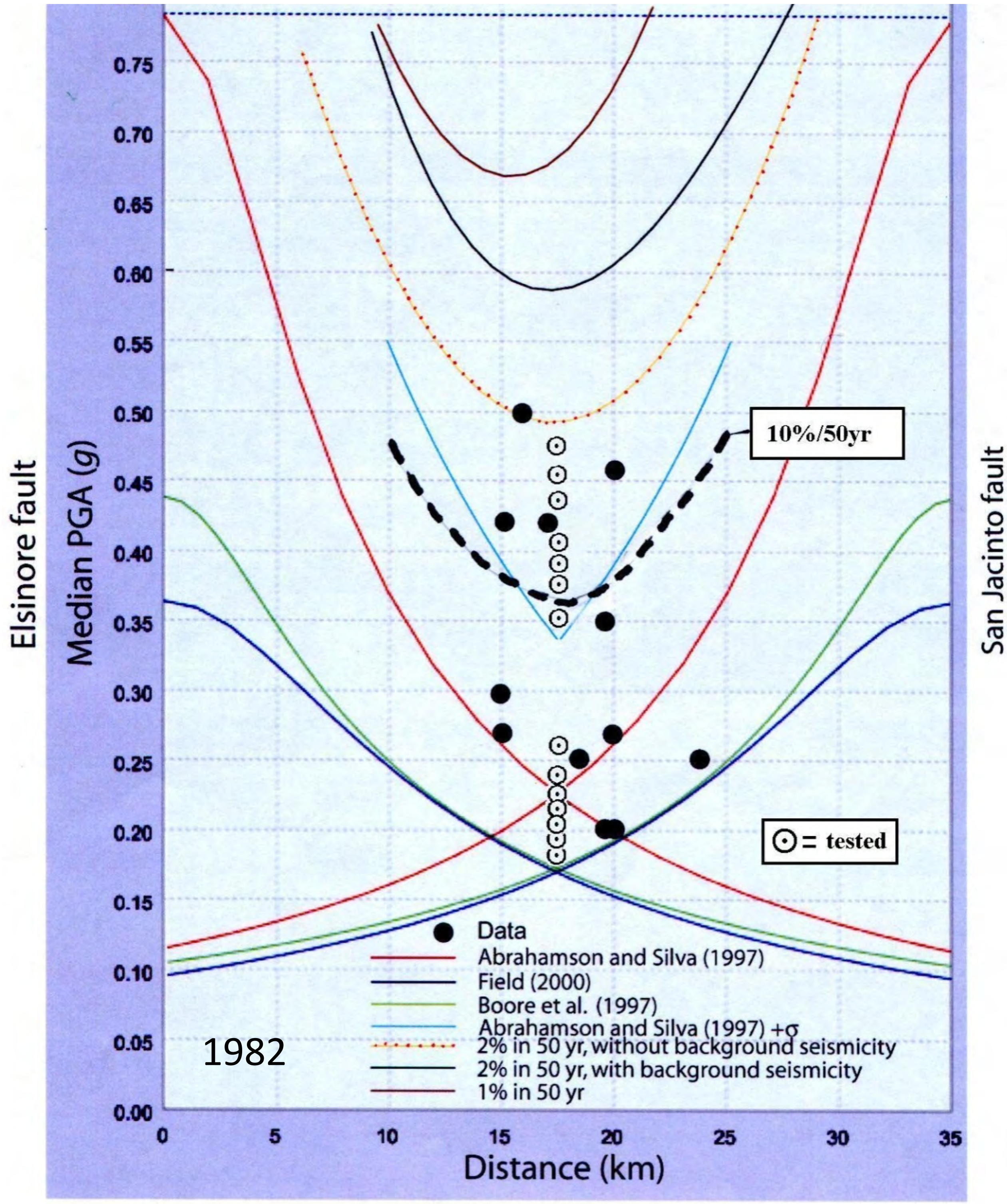
	0.1	0.2	0.3	0.4	0.5
LoveJoy	0	0	21	66	100
Victorville	7	14	70	91	100
Granite Pediment	6.82	42.05	77.27	94.32	100.00

α

Granite Geology

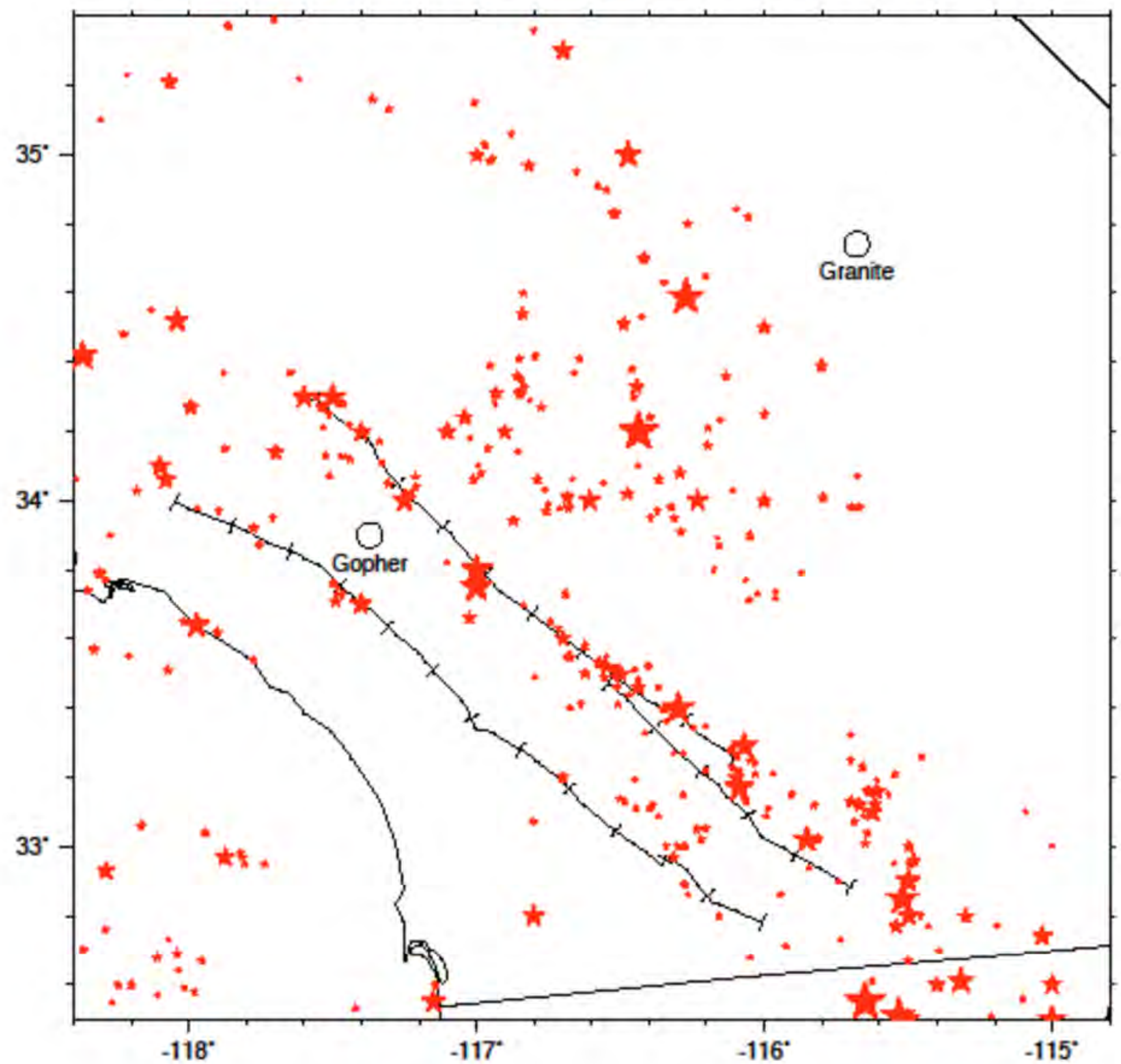


Riverside-Aguanga Line of Precarious Rocks



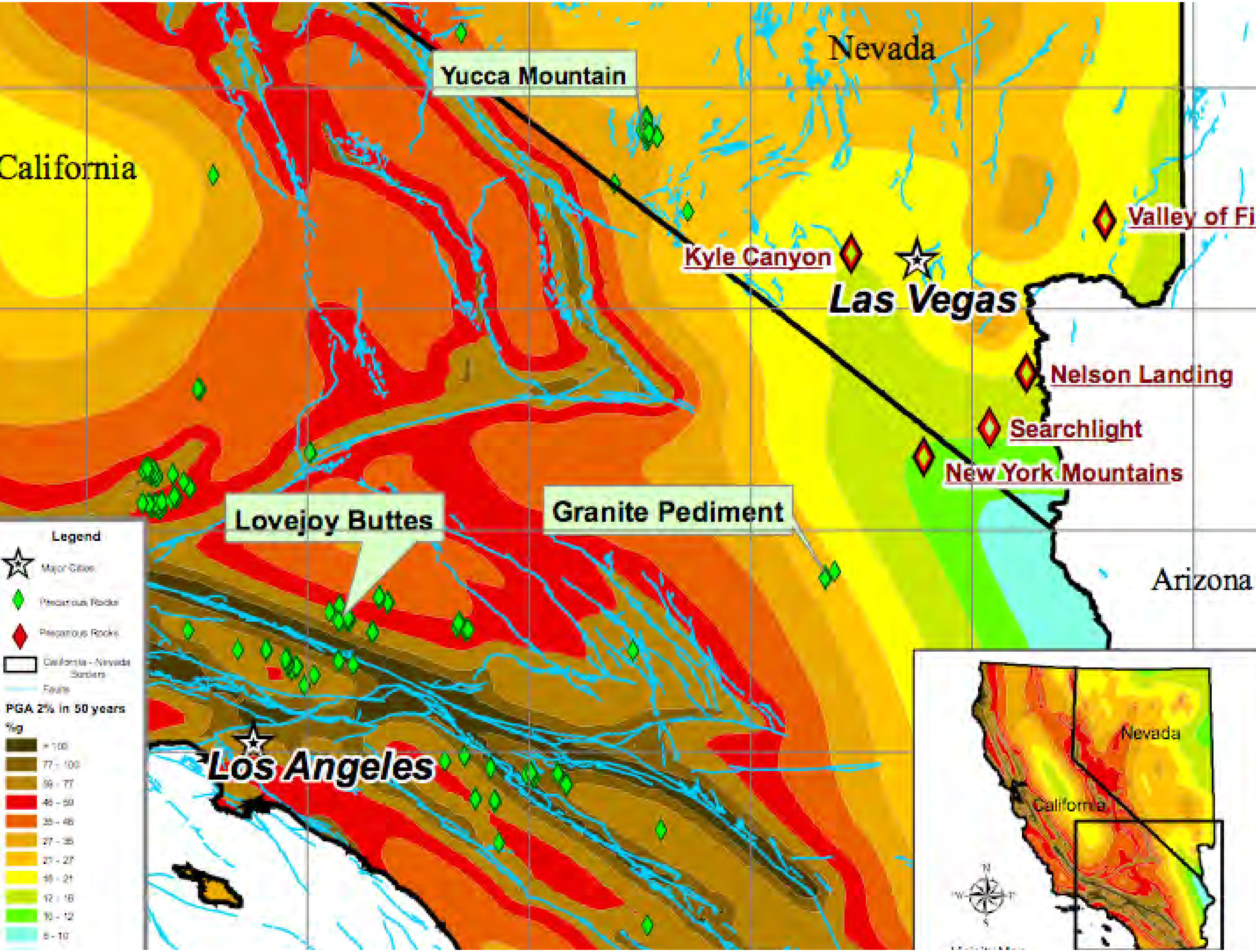
Elsinore fault
Median PGA (g)
San Jacinto fault
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0
5
10
15
20
25
30
35
Distance (km)
10%/50yr
= tested
Data
Abrahamson and Silva (1997)
Field (2000)
Boore et al. (1997)
Abrahamson and Silva (1997) +σ
2% in 50 yr, without background seismicity
2% in 50 yr, with background seismicity
1% in 50 yr
1982

Catalog used for 2008 NSHM (wmm.cch): M>=4 (accounting for completeness)

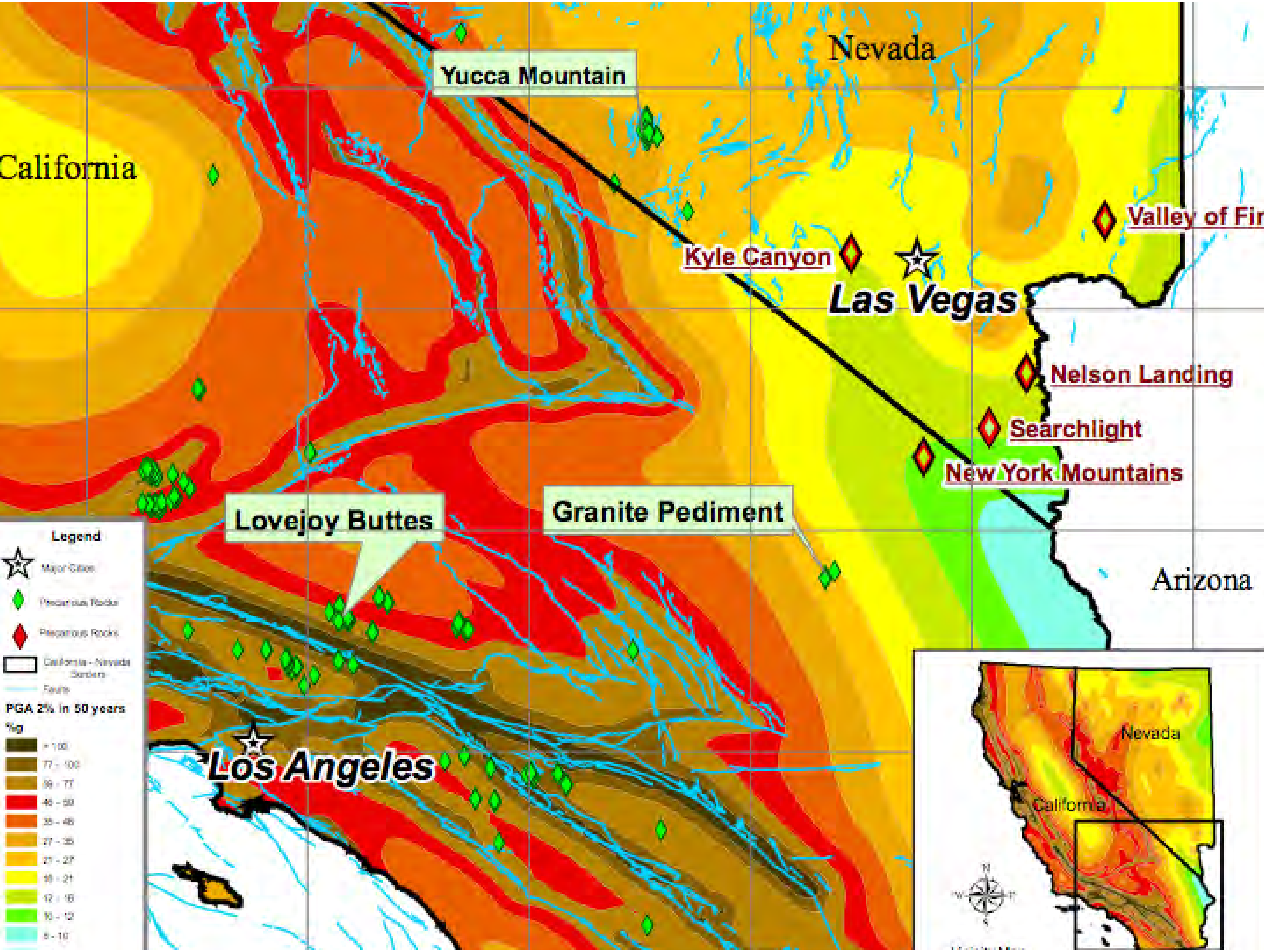


HAZARD ON SOLID ROCK

LAS VEGAS AREA

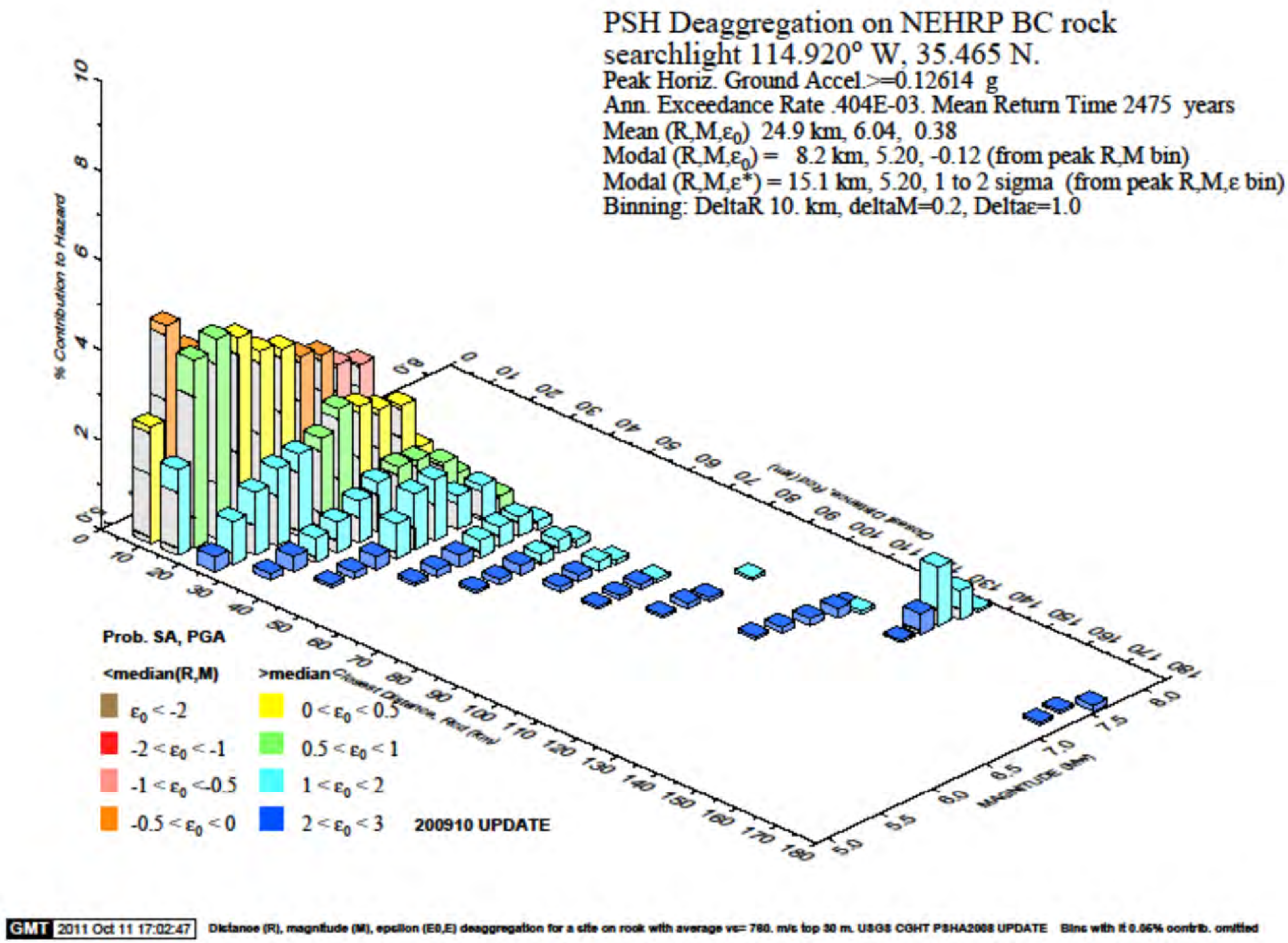


Nevada
Yucca Mountain
California
Kyle Canyon
Las Vegas
Valley of Fir
Nelson Landing
Searchlight
New York Mountains
Granite Pediment
Lovejoy Buttes
Arizona
Los Angeles
Legend
PGA 2% in 50 years
%g
Nevada
California

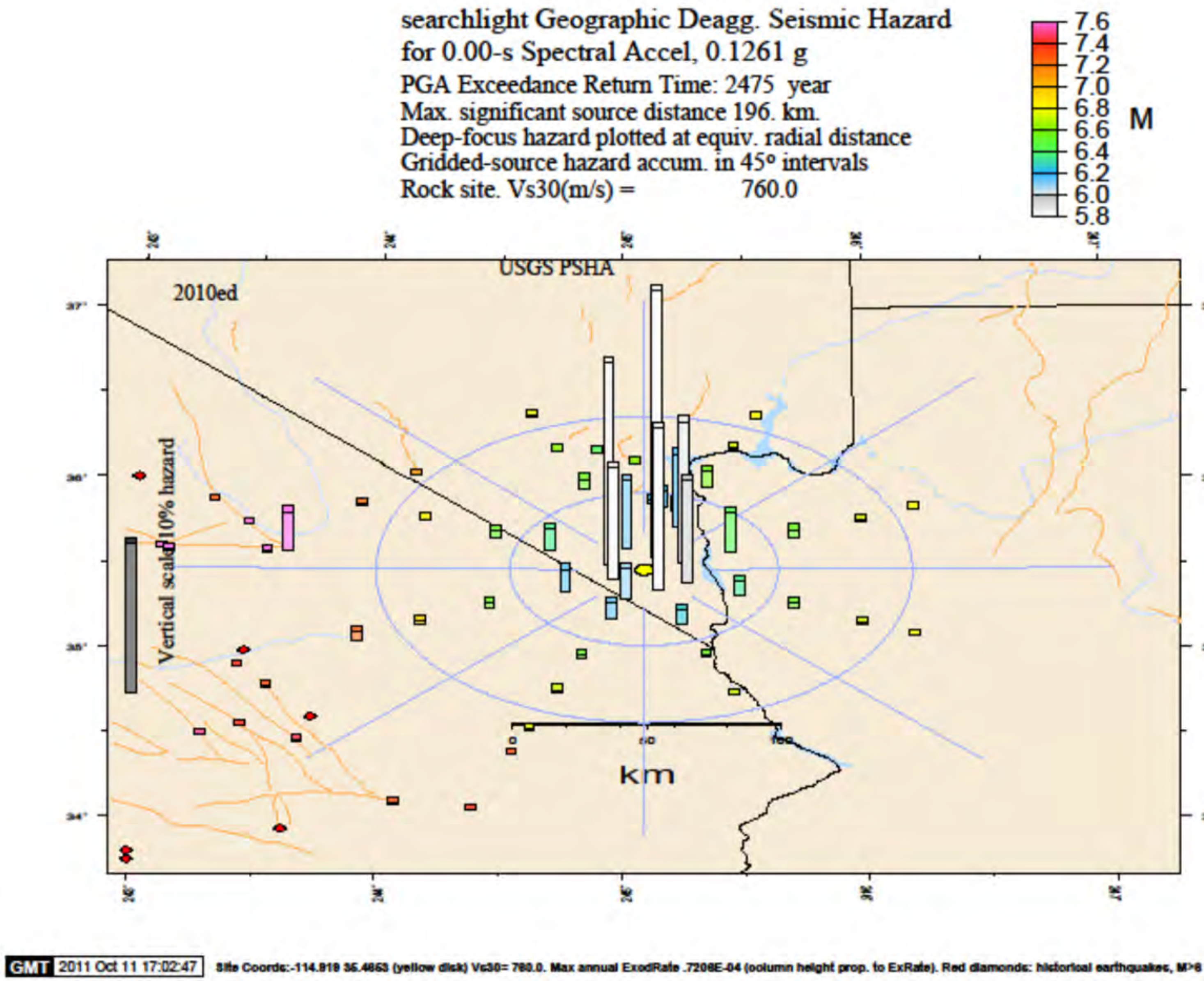


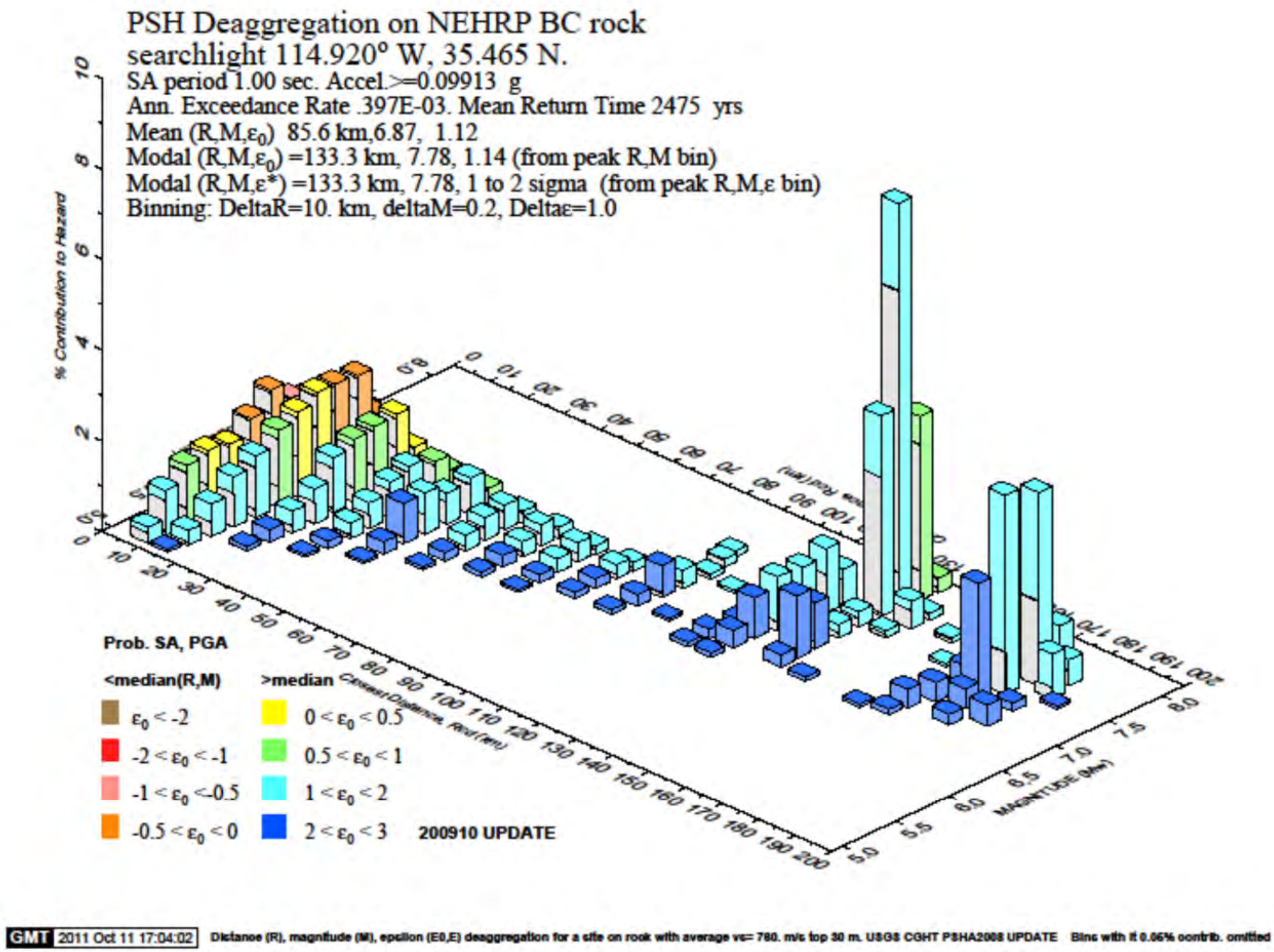
Nevada
Yucca Mountain
California
Valley of Fir
Kyle Canyon
Las Vegas
Nelson Landing
Searchlight
New York Mountains
Granite Pediment
Lovejoy Buttes
Arizona
Los Angeles
Legend
PGA 2% in 50 years
%g
Nevada
California

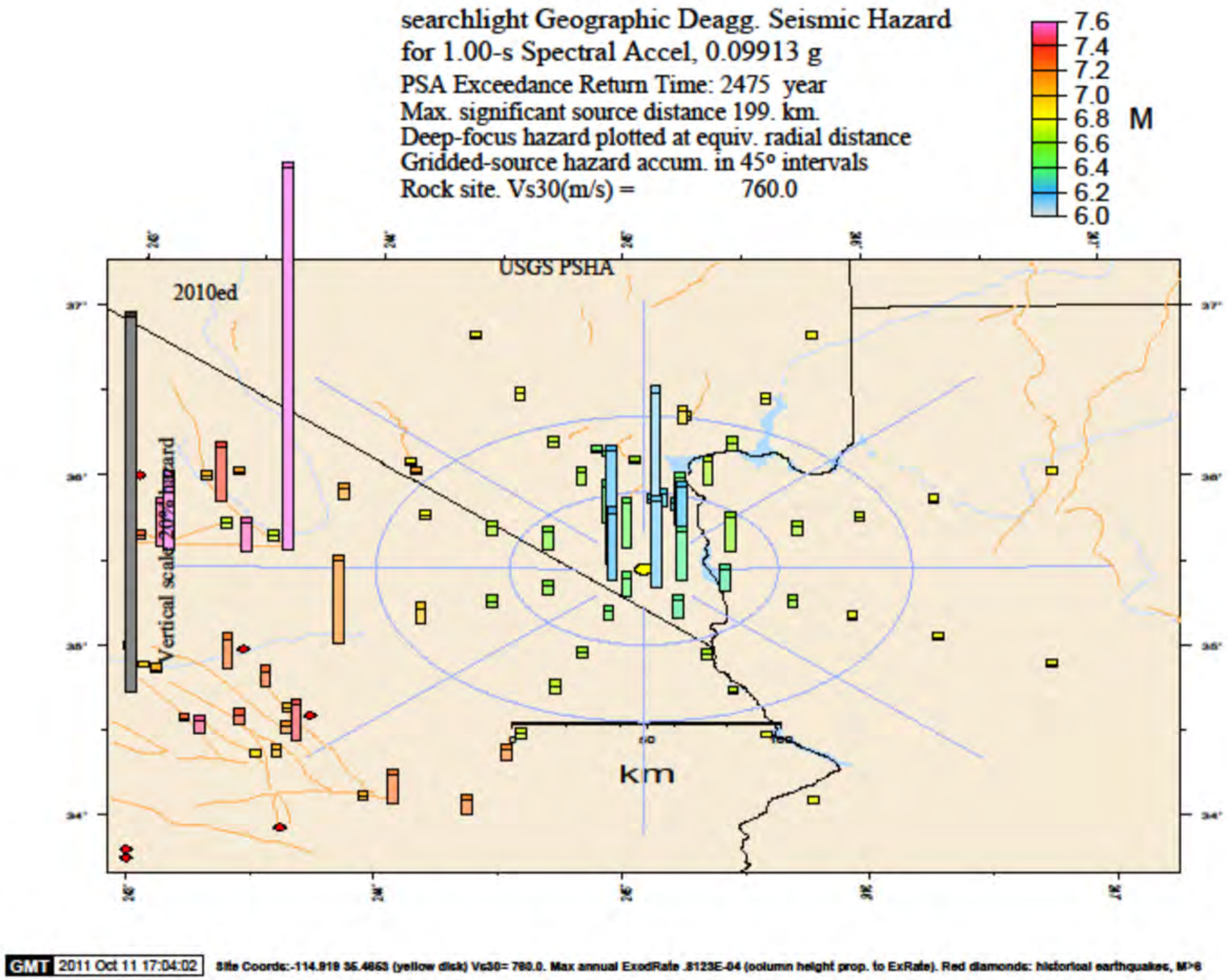
SEARCHLIGHT

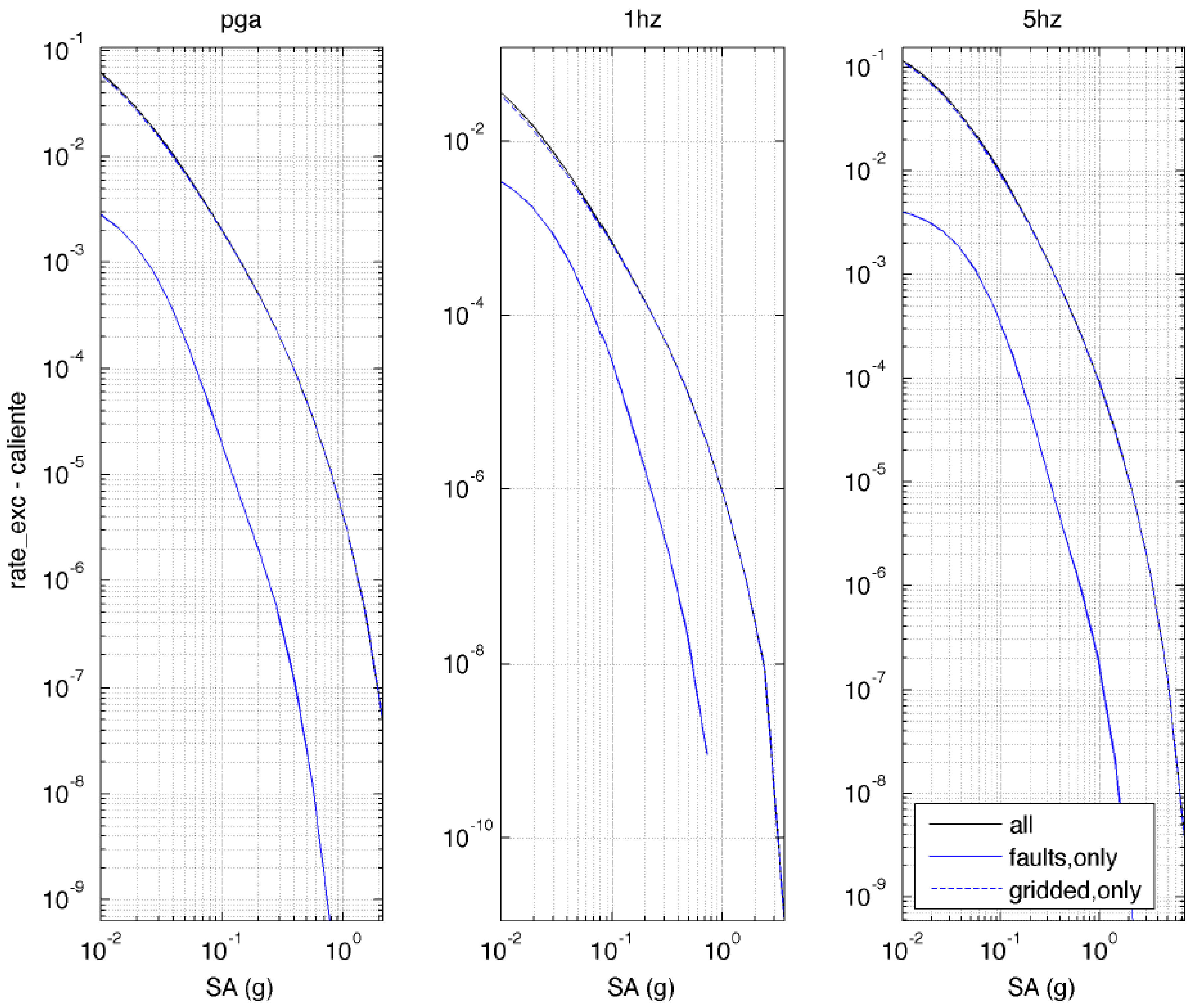


PSH Deaggregation on NEHRP BC rock
searchlight 114.920° W, 35.465 N.
Peak Horiz. Ground Accel.>=0.12614 g
Ann. Exceedance Rate .404E-03. Mean Return Time 2475 years
Mean (R,M,ε_0) 24.9 km, 6.04, 0.38
Modal (R,M,ε_0) = 8.2 km, 5.20, -0.12 (from peak R,M bin)
Modal (R,M,ε*) = 15.1 km, 5.20, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR 10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
$\varepsilon_0 < -2$
$-2 < \varepsilon_0 < -1$
$-1 < \varepsilon_0 < -0.5$
$-0.5 < \varepsilon_0 < 0$
$0 < \varepsilon_0 < 0.5$
$0.5 < \varepsilon_0 < 1$
$1 < \varepsilon_0 < 2$
$2 < \varepsilon_0 < 3$
200910 UPDATE
GMT 2011 Oct 11 17:02:47
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

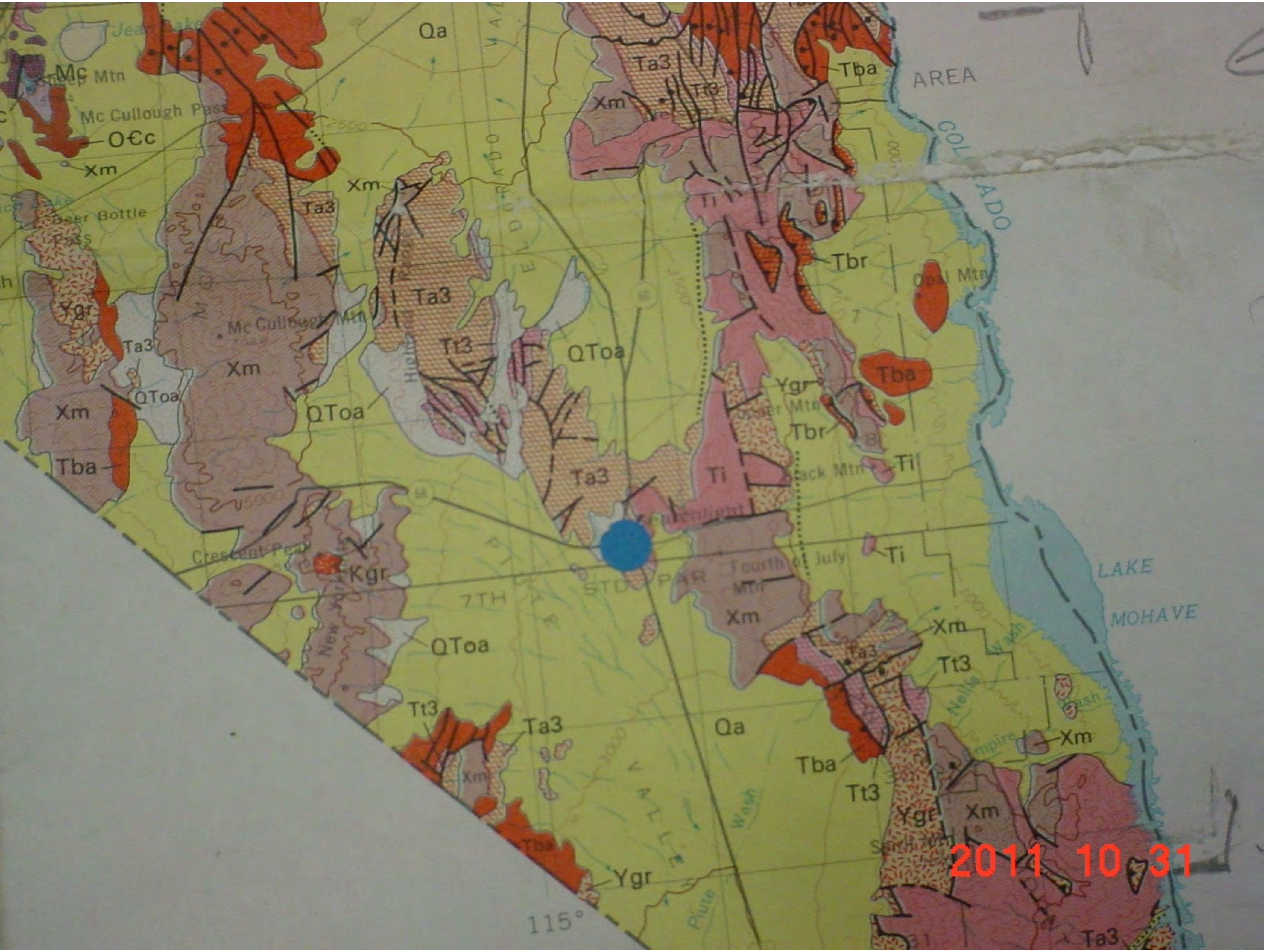

searchlight Geographic Deagg. Seismic Hazard
for 0.00-s Spectral Accel, 0.1261 g
PGA Exceedance Return Time: 2475 year
Max. significant source distance 196. km.
Deep-focus hazard plotted at equiv. radial distance
Gridded-source hazard accum. in 45° intervals
Rock site. Vs30(m/s) = 760.0
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
M
USGS PSHA
2010ed
Vertical scale 10% hazard
km
GMT 2011 Oct 11 17:02:47
Site Coords:-114.919 35.4653 (yellow disk) Vs30= 760.0. Max annual ExcdRate .7206E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6


PSH Deaggregation on NEHRP BC rock
searchlight 114.920° W, 35.465 N.
SA period 1.00 sec. Accel.>=0.09913 g
Ann. Exceedance Rate .397E-03. Mean Return Time 2475 yrs
Mean (R,M,ε0) 85.6 km,6.87, 1.12
Modal (R,M,ε0) =133.3 km, 7.78, 1.14 (from peak R,M bin)
Modal (R,M,ε*) =133.3 km, 7.78, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 < -0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
MAGNITUDE (Mw)
GMT 2011 Oct 11 17:04:02
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted


searchlight Geographic Deagg. Seismic Hazard
for 1.00-s Spectral Accel, 0.09913 g
PSA Exceedance Return Time: 2475 year
Max. significant source distance 199. km.
Deep-focus hazard plotted at equiv. radial distance
Gridded-source hazard accum. in 45° intervals
Rock site. Vs30(m/s) = 760.0
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
M
USGS PSHA
2010ed
Vertical scale 20% hazard
km
GMT 2011 Oct 11 17:04:02
Site Coords:-114.919 35.4653 (yellow disk) Vs30= 760.0. Max annual ExcdRate .8123E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6

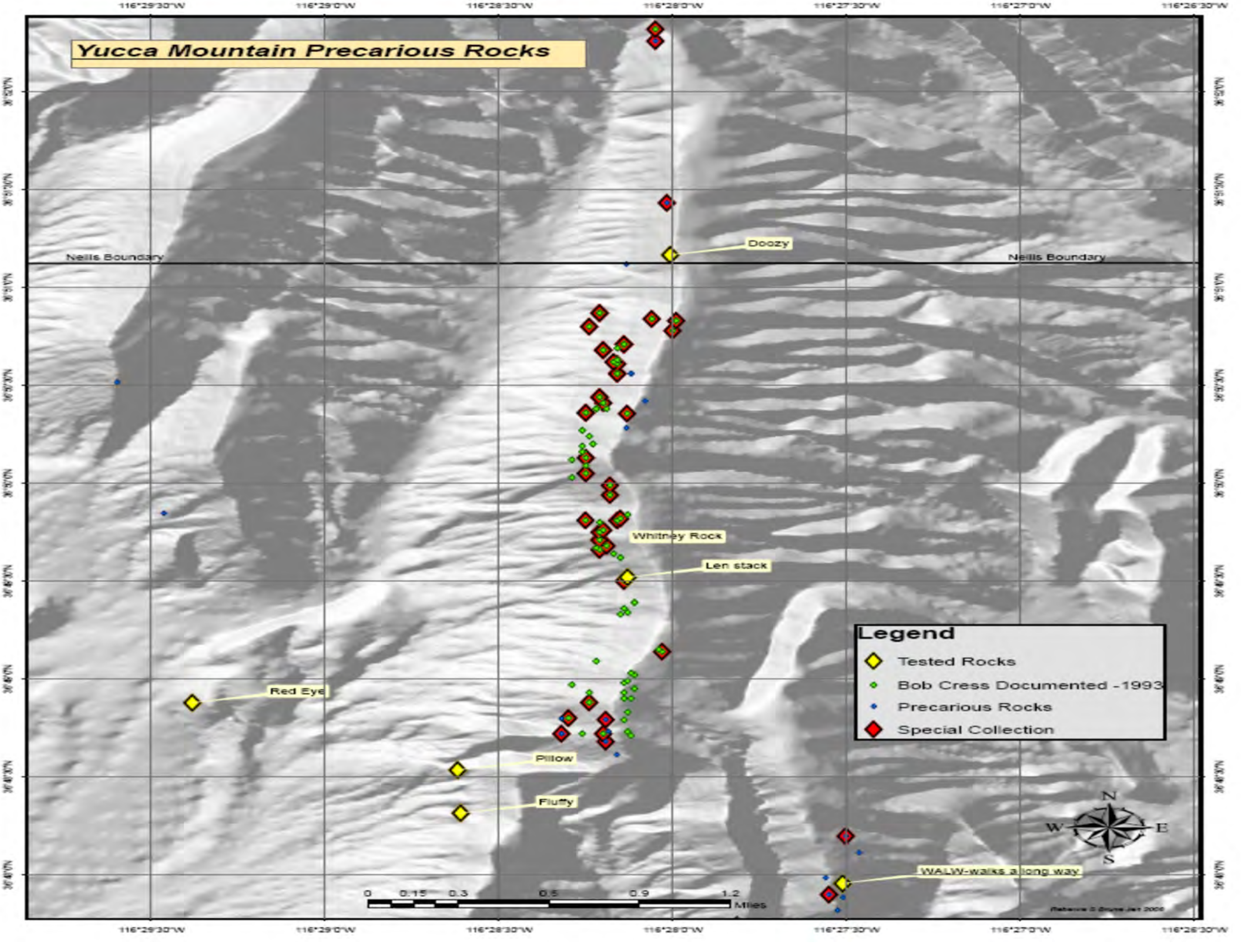


pga
1hz
5hz
rate_exc - caliente
SA (g)
SA (g)
SA (g)
all
faults,only
gridded,only



Qa
Mc
Sheep Mtn
Mc Cullough Pass
O€c
Xm
Ta3
Beer Bottle Pass
Ygr
Ta3
Mc Cullough Mtn
Xm
QToa
Xm
Tba
QToa
Xm
Ta3
Tt3
QToa
Ta3
Crescent Peak
Kgr
7TH
STD PAR
QToa
Tt3
Ta3
Ygr
115°
AREA
Tba
Ta3
Tt3
Xm
COLORADO
Ti
Tbr
Opal Mtn
Tba
Ygr
Tbr
Ti
Black Mtn
Ti
Searchlight
Ti
Fourth of July Mtn
Xm
Xm
Ta3
Tt3
Qa
Tba
Tt3
Ygr
Xm
Xm
Ta3
LAKE
MOHAVE
Piute Wash
2011 10 31

YUCCA MOUNTAIN


Yucca Mountain Precarious Rocks
116°29'30"W
116°29'0"W
116°28'30"W
116°28'0"W
116°27'30"W
116°27'0"W
116°26'30"W
Nellis Boundary
Nellis Boundary
Doozy
Whitney Rock
Len stack
Red Eye
Pillow
Fluffy
WALW-walks a long way
Legend
Tested Rocks
Bob Cress Documented -1993
Precarious Rocks
Special Collection
N
E
S
W
0
0.15
0.3
0.6
0.9
1.2
Miles

Rock varnish
>10.5 Ka

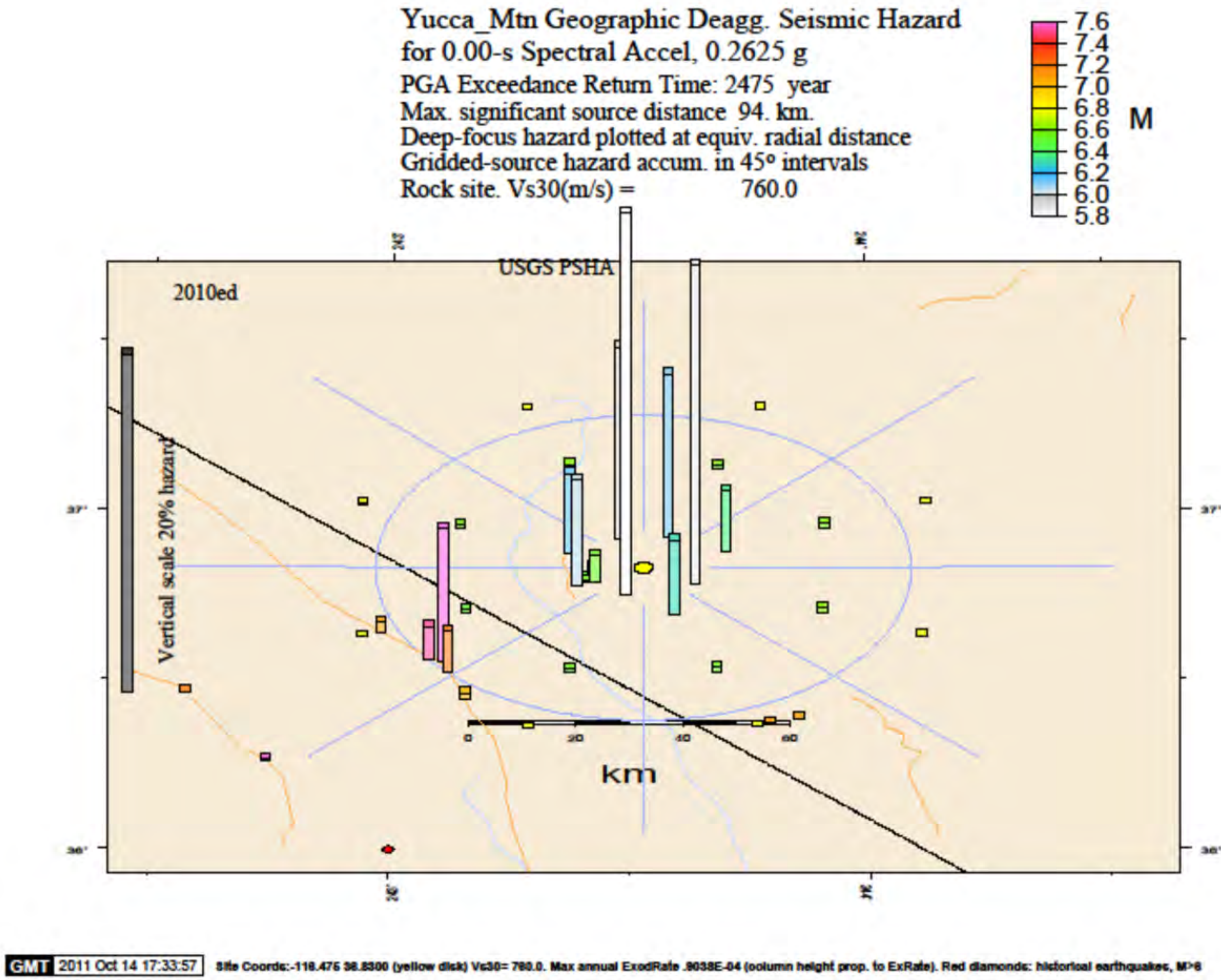
Pedestal
cosmogenic
age
242 ka

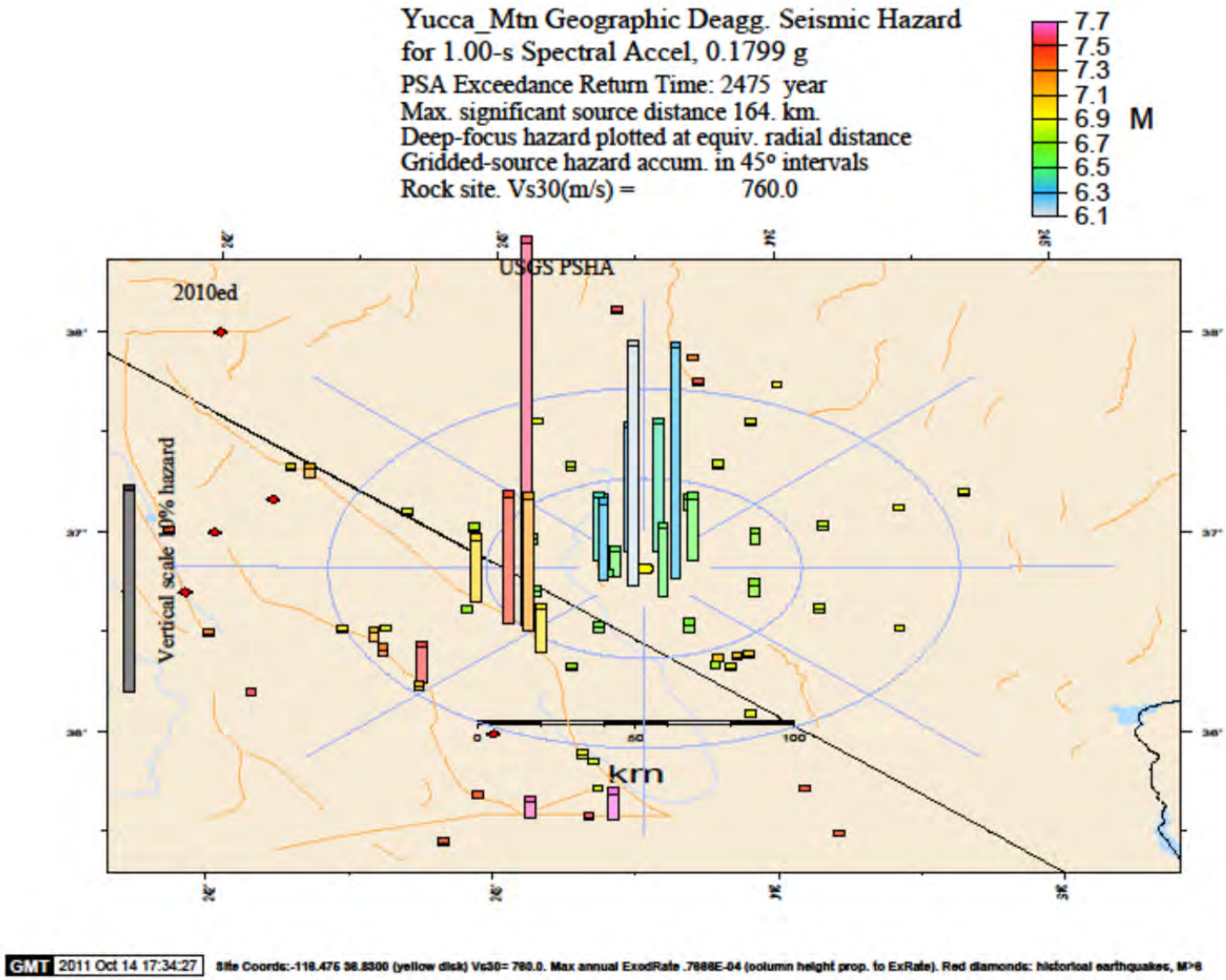
VADA Seismological Laboratory

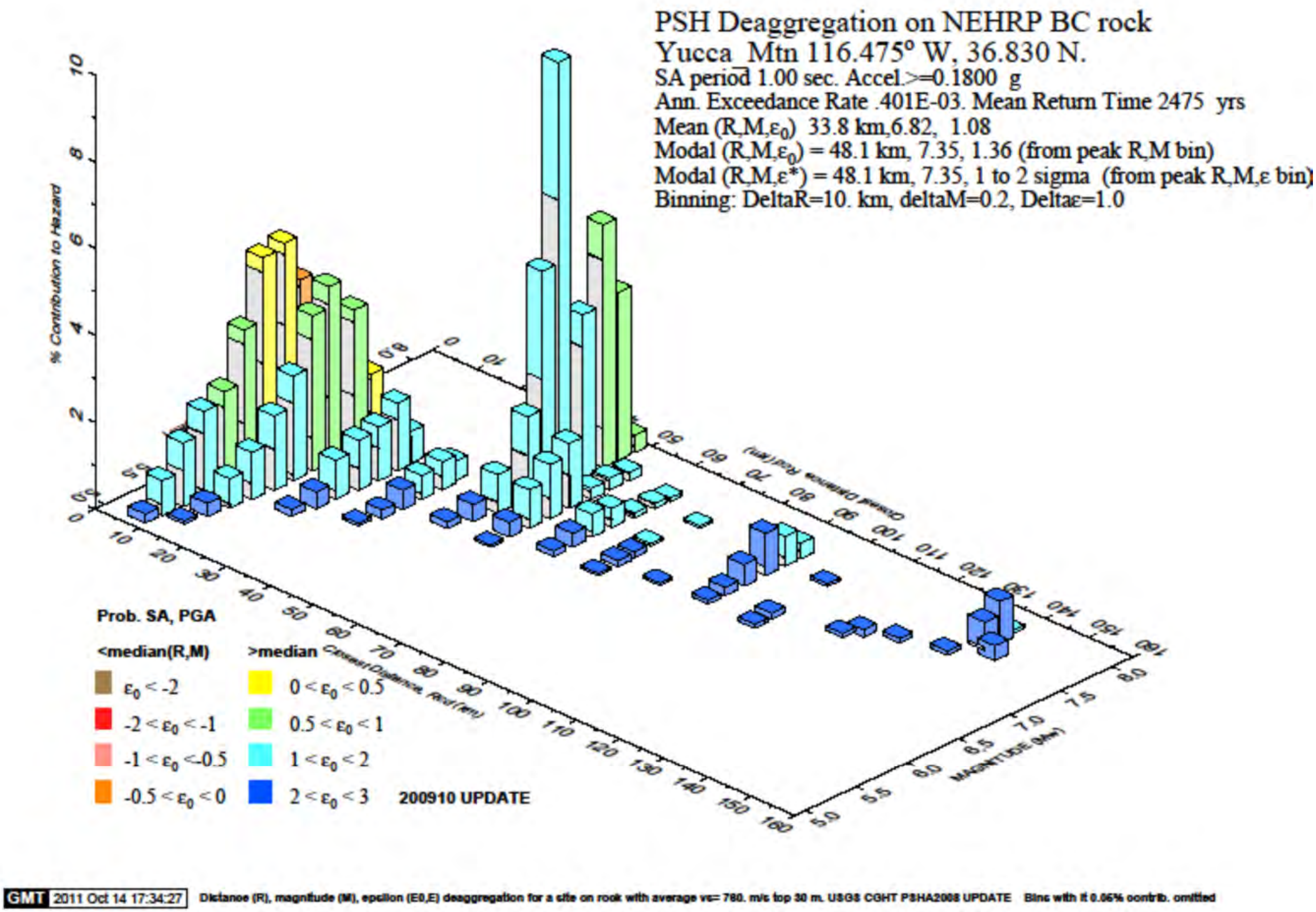
Fracture age ~10Ma

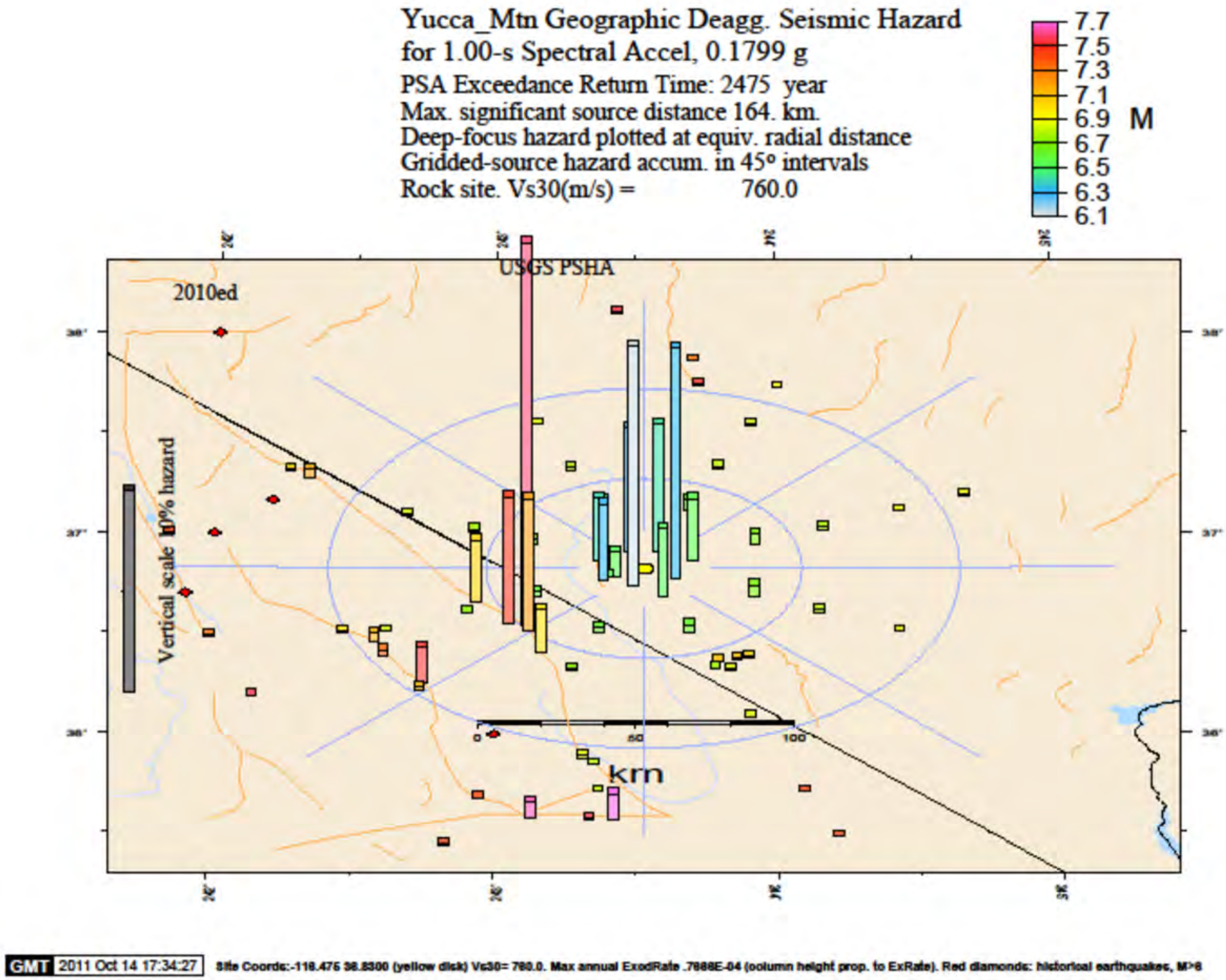
Not shattered

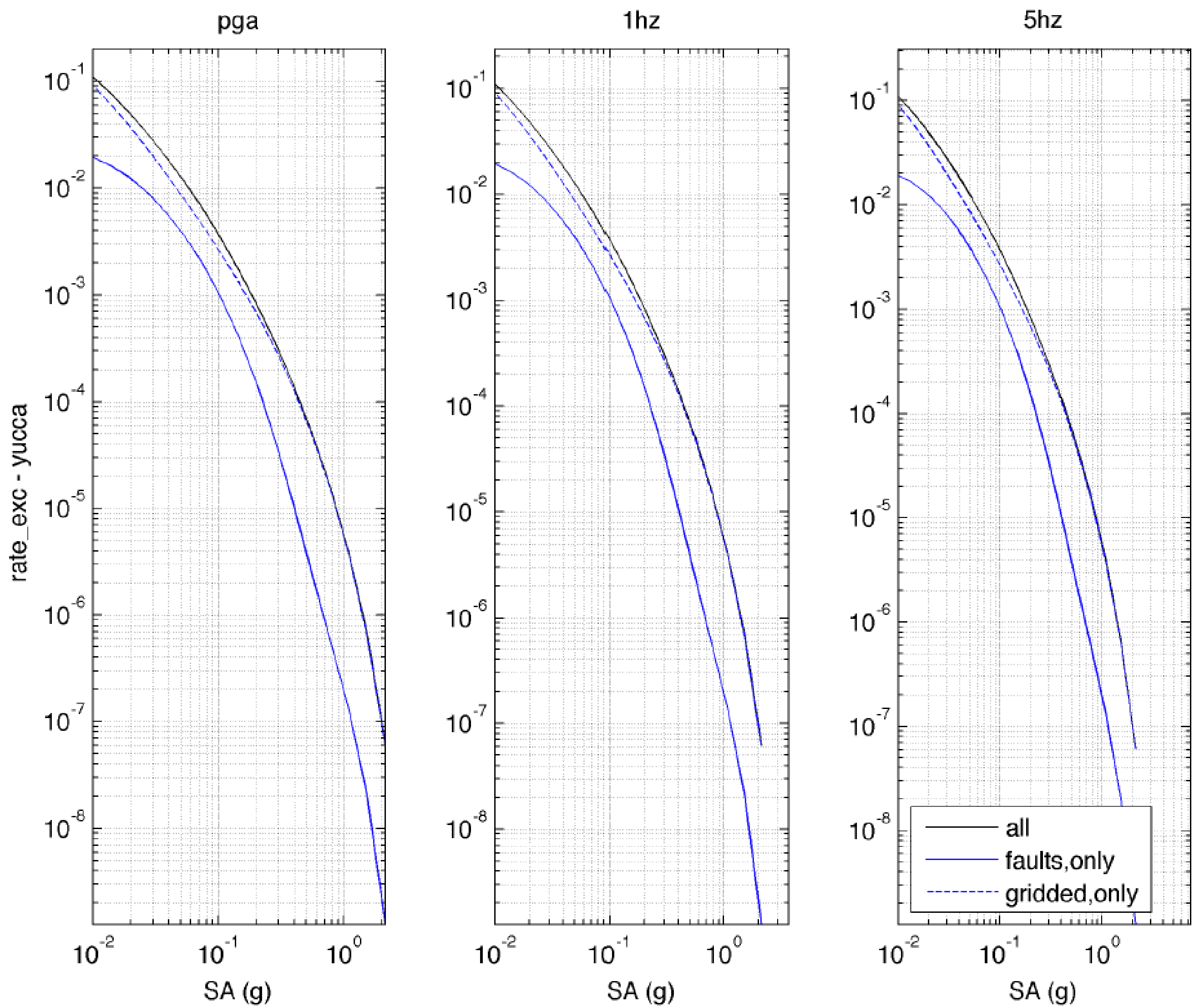
Rock Stack 100 ka


Yucca_Mtn Geographic Deagg. Seismic Hazard
for 0.00-s Spectral Accel, 0.2625 g
PGA Exceedance Return Time: 2475 year
Max. significant source distance 94. km.
Deep-focus hazard plotted at equiv. radial distance
Gridded-source hazard accum. in 45° intervals
Rock site. Vs30(m/s) = 760.0
7.6
7.4
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
M
USGS PSHA
2010ed
Vertical scale 20% hazard
0
20
40
60
km
GMT 2011 Oct 14 17:33:57
Site Coords:-116.475 36.8300 (yellow disk) Vs30= 760.0. Max annual ExcdRate .9038E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6

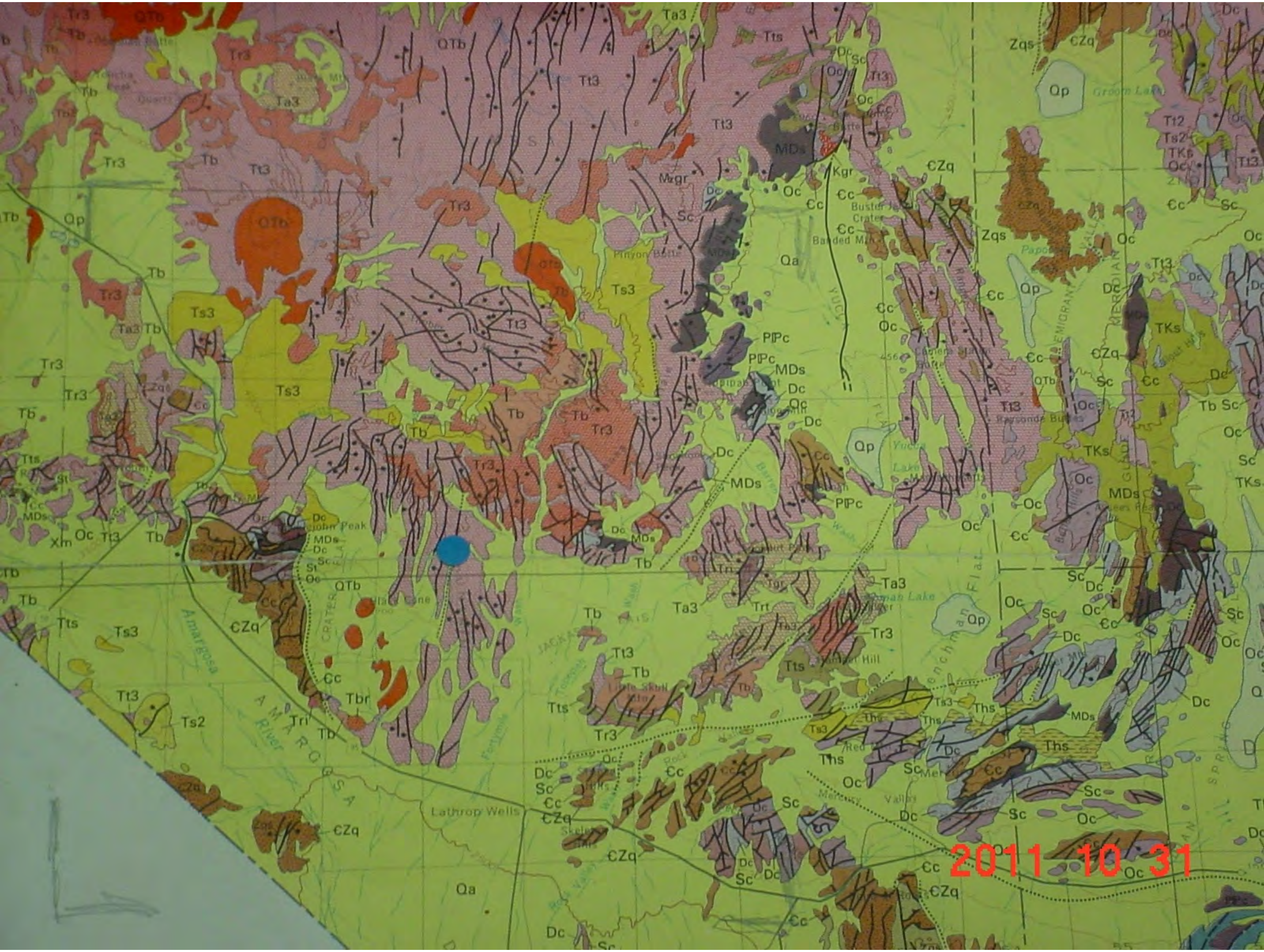

Yucca_Mtn Geographic Deagg. Seismic Hazard
for 1.00-s Spectral Accel, 0.1799 g
PSA Exceedance Return Time: 2475 year
Max. significant source distance 164. km.
Deep-focus hazard plotted at equiv. radial distance
Gridded-source hazard accum. in 45° intervals
Rock site. Vs30(m/s) = 760.0
7.7
7.5
7.3
7.1
6.9
6.7
6.5
6.3
6.1
M
USGS PSHA
2010ed
Vertical scale 10% hazard
0
50
100
km
GMT 2011 Oct 14 17:34:27
Site Coords:-116.475 36.8300 (yellow disk) Vs30= 760.0. Max annual ExcdRate .7686E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6


PSH Deaggregation on NEHRP BC rock
Yucca_Mtn 116.475° W, 36.830 N.
SA period 1.00 sec. Accel.>=0.1800 g
Ann. Exceedance Rate .401E-03. Mean Return Time 2475 yrs
Mean (R,M,ε0) 33.8 km,6.82, 1.08
Modal (R,M,ε0) = 48.1 km, 7.35, 1.36 (from peak R,M bin)
Modal (R,M,ε*) = 48.1 km, 7.35, 1 to 2 sigma (from peak R,M,ε bin)
Binning: DeltaR=10. km, deltaM=0.2, Deltaε=1.0
% Contribution to Hazard
Closest Distance, Rcd (km)
MAGNITUDE (Mw)
Prob. SA, PGA
<median(R,M)
>median
ε0 < -2
-2 < ε0 < -1
-1 < ε0 <-0.5
-0.5 < ε0 < 0
0 < ε0 < 0.5
0.5 < ε0 < 1
1 < ε0 < 2
2 < ε0 < 3
200910 UPDATE
GMT 2011 Oct 14 17:34:27
Distance (R), magnitude (M), epsilon (E0,E) deaggregation for a site on rock with average vs= 760. m/s top 30 m. USGS CGHT PSHA2008 UPDATE Bins with lt 0.05% contrib. omitted

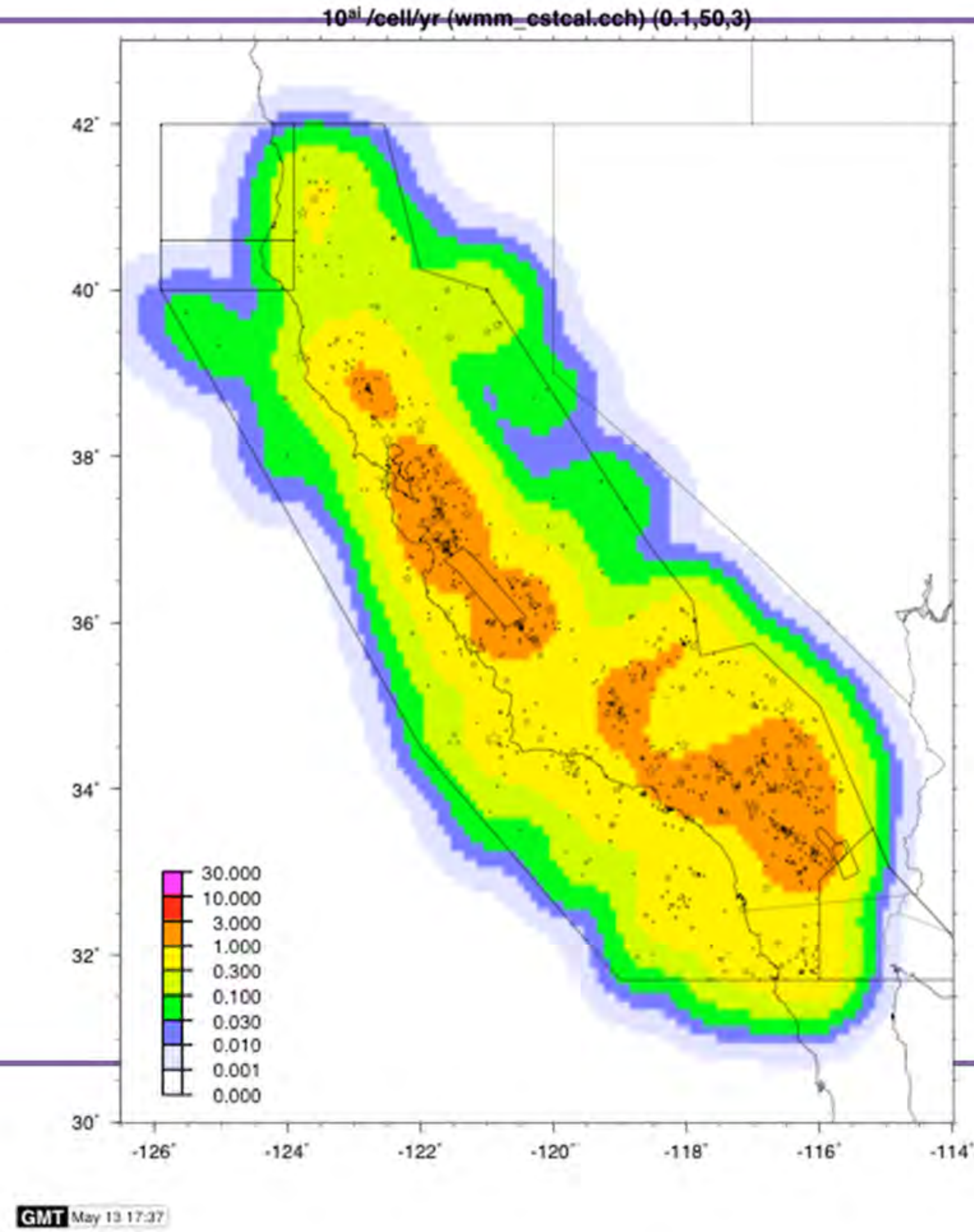

Yucca_Mtn Geographic Deagg. Seismic Hazard
for 1.00-s Spectral Accel, 0.1799 g
PSA Exceedance Return Time: 2475 year
Max. significant source distance 164. km.
Deep-focus hazard plotted at equiv. radial distance
Gridded-source hazard accum. in 45° intervals
Rock site. Vs30(m/s) = 760.0
7.7
7.5
7.3
7.1
6.9
6.7
6.5
6.3
6.1
M
USGS PSHA
2010ed
Vertical scale 10% hazard
0
50
100
km
GMT 2011 Oct 14 17:34:27
Site Coords:-116.475 36.8300 (yellow disk) Vs30= 760.0. Max annual ExcdRate .7686E-04 (column height prop. to ExRate). Red diamonds: historical earthquakes, M>6



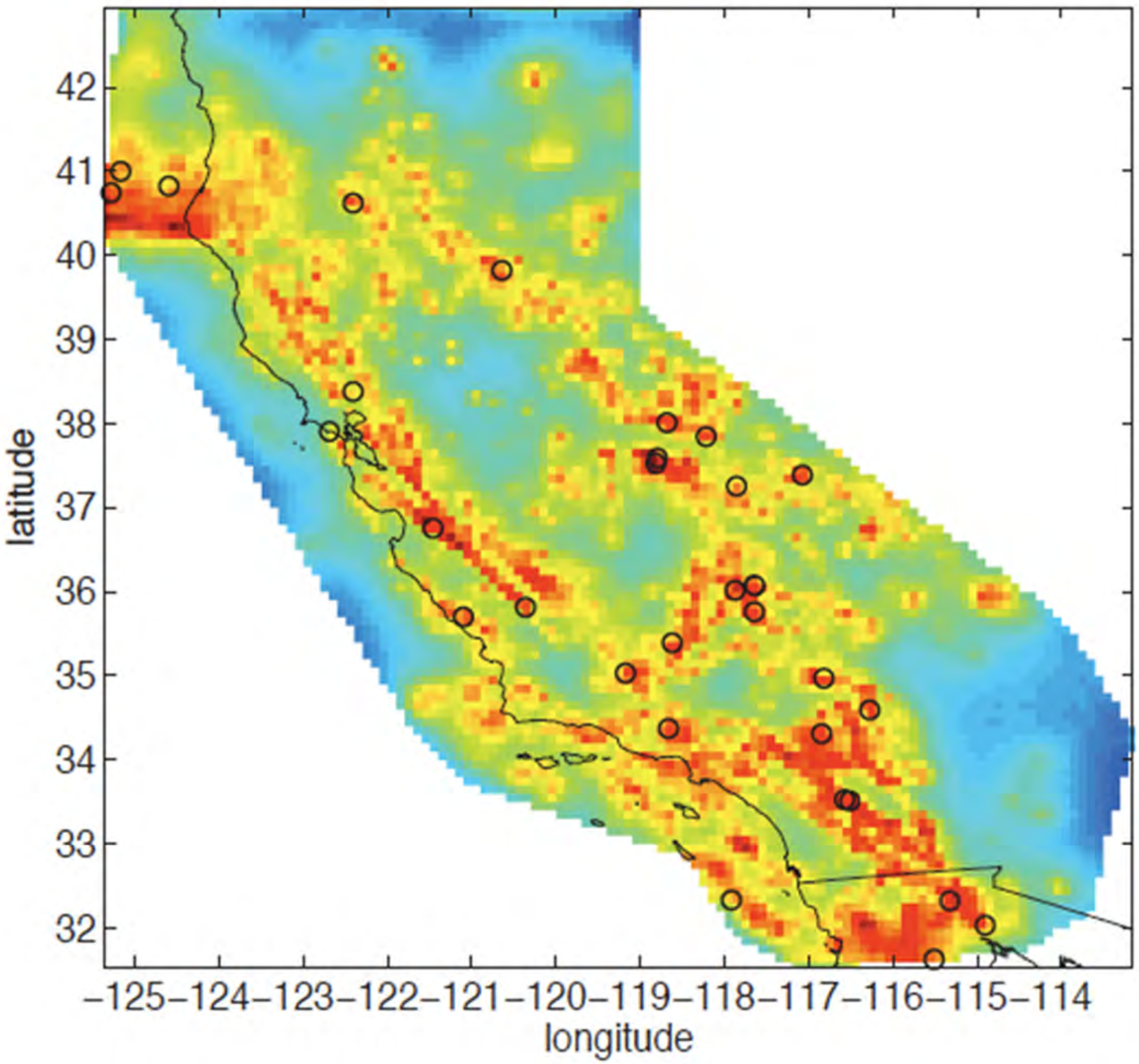
pga
1hz
5hz
rate_exc - yucca
SA (g)
SA (g)
SA (g)
all
faults,only
gridded,only



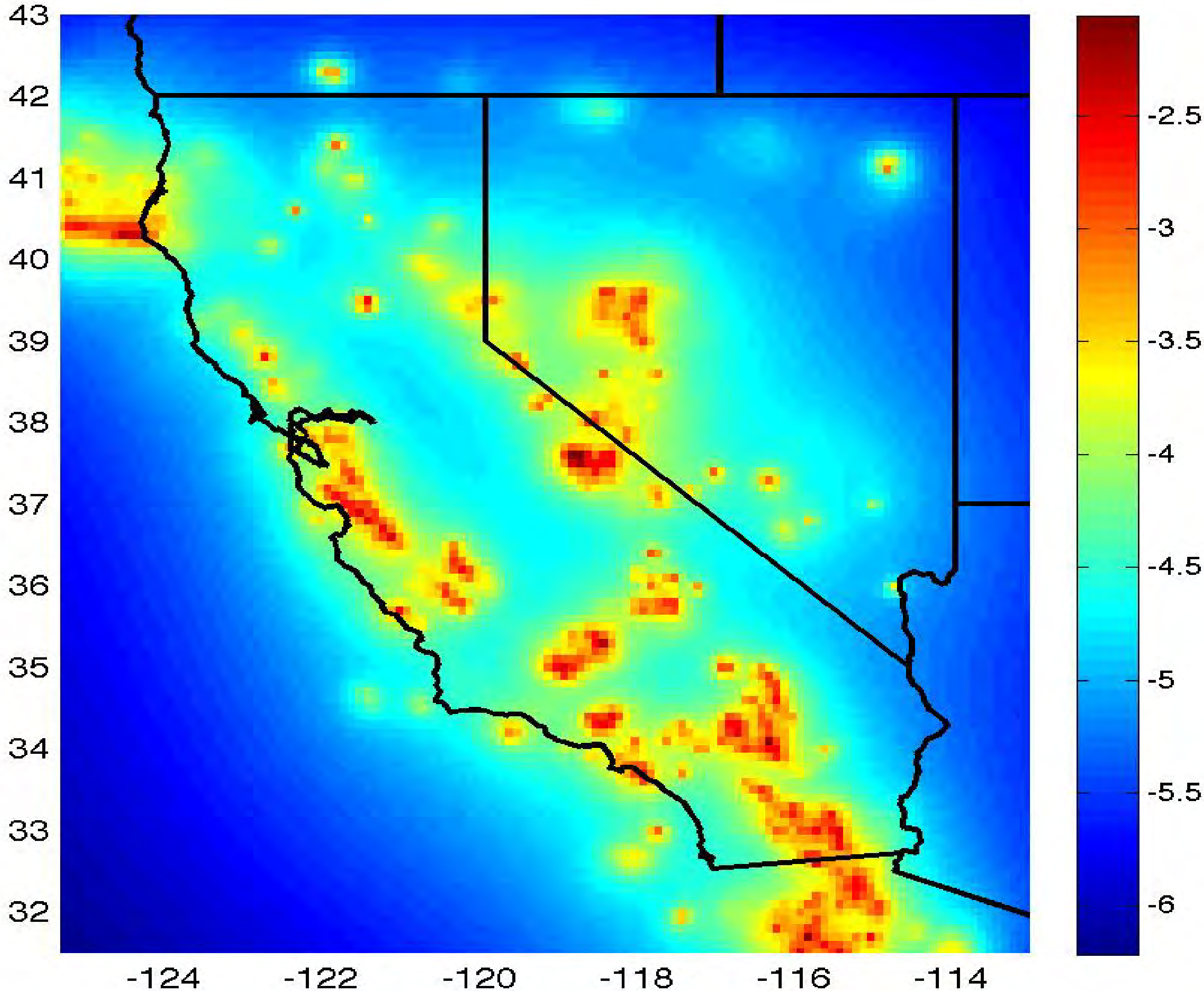
Groom Lake
Pinyon Butte
Buster Jack Crater
Banded Mtn
Yucca Lake
Lathrop Wells
Amargosa
A M A R G O S A
River
Mercury
Jackass
Frenchman Flat
2011 10 31



10^{ai} /cell/yr (wmm_cstcal.cch) (0.1,50,3)
42°
40°
38°
36°
34°
32°
30°
-126°
-124°
-122°
-120°
-118°
-116°
-114°
30.000
10.000
3.000
1.000
0.300
0.100
0.030
0.010
0.001
0.000
GMT May 13 17:37



42
41
40
39
38
37
36
35
34
33
32
latitude
−125−124−123−122−121−120−119−118−117−116−115−114
longitude


43
42
41
40
39
38
37
36
35
34
33
32
-124
-122
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-3
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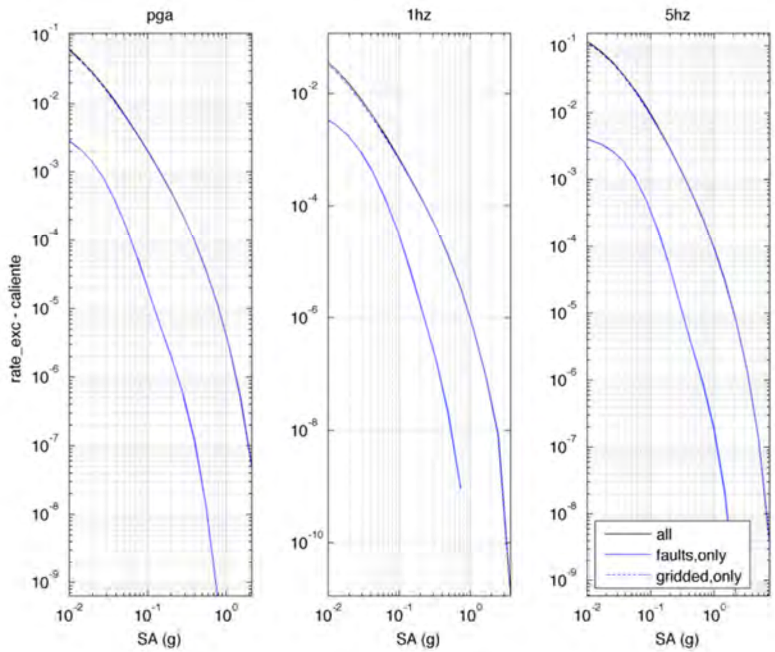
-6


pga
1hz
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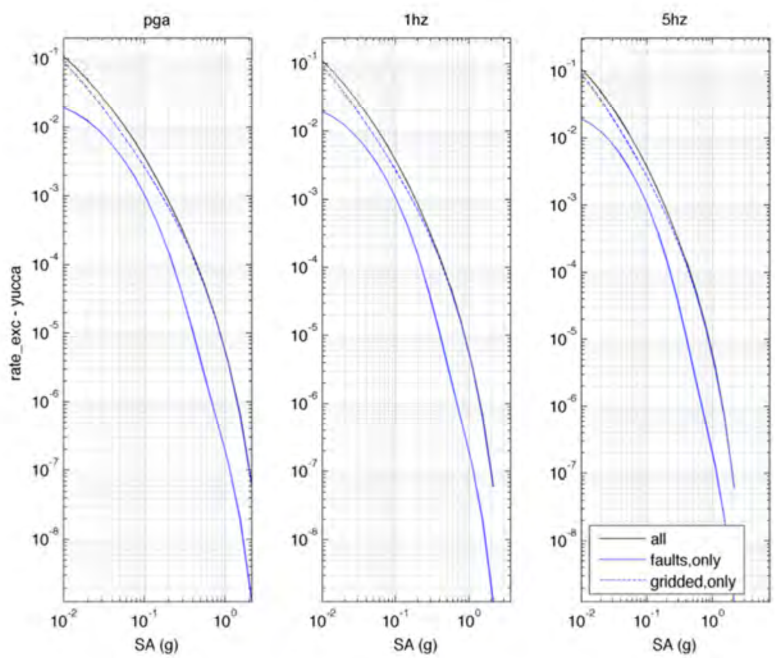
rate_exc - caliente
SA (g)
all
faults,only
gridded,only


pga
1hz
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rate_exc - yucca
SA (g)
all
faults,only
gridded,only

PRELIMINARY SUGGESTIONS

1. Reduce smoothing distance to 20 km

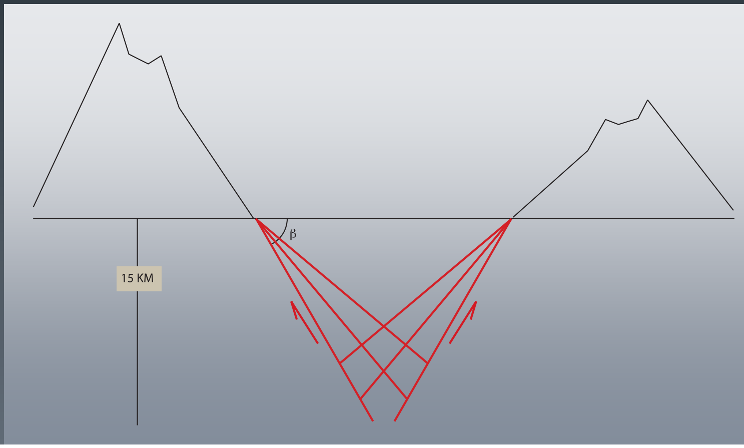
2. Eliminate small earthquakes along faults from background.

3. Mmax for a given period (2500 yrs?) should be based on geology (with epistemic uncertainty)

4. Define two types of background seismicity zones as
    A. areas where active faults exist, but are poorly mapped (e.g., Offshore)
    B. areas without known active faults (e.g. SC-ARIZ BZ)

Modeling Graben-bounding Faults in the NSHMs

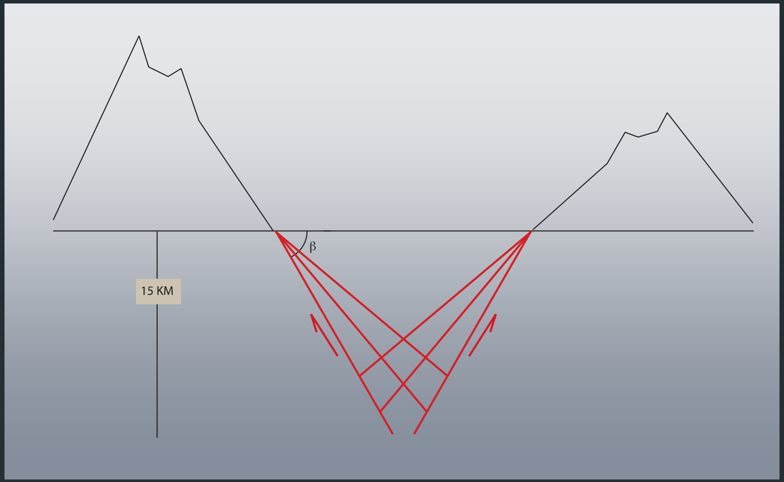
BRPEWGII Meeting
Issue G2
Discussion Leaders: Kathy Haller and Mike Hylland



The question:

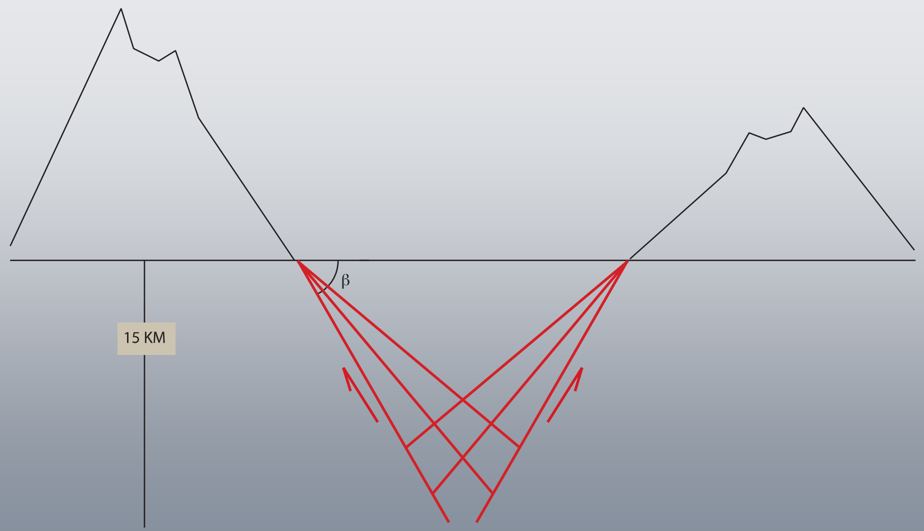
- How should antithetic fault pairs be modeled in the NSHMs? For example, what is the relation and seismogenic significance of fault pairs such as the East and West Cache faults, and strands of the Salt Lake City segment of the Wasatch fault and the West Valley fault zone?

The problem:



- Graben-bounding pairs are too close to avoid faults 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°
- Both sources were projected below their intersection to a depth of 15 km in prior hazard maps
- Some source pairs that dip 40° in the 2008 model intersect at depths as shallow as 1.6 km

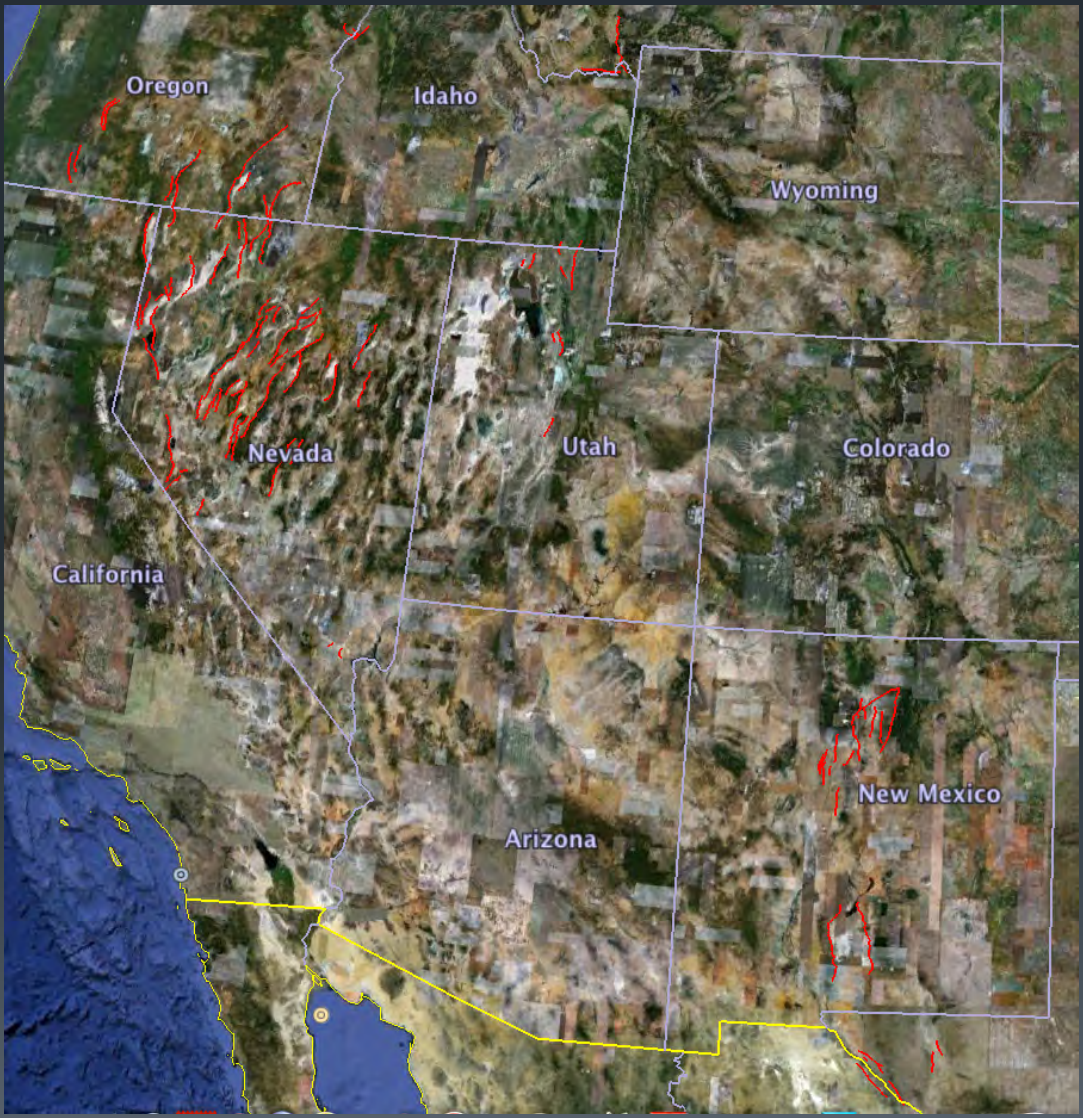
How we got here:



@ 60° dip, faults < 17 km apart will intersect
@50° dip, <25 km
@40° dip, <36 km

- Change in modeling assumptions in the 2008 maps to include dip uncertainty for normal faults increased the number of intersecting fault pairs

Intersecting pairs in 2008 model

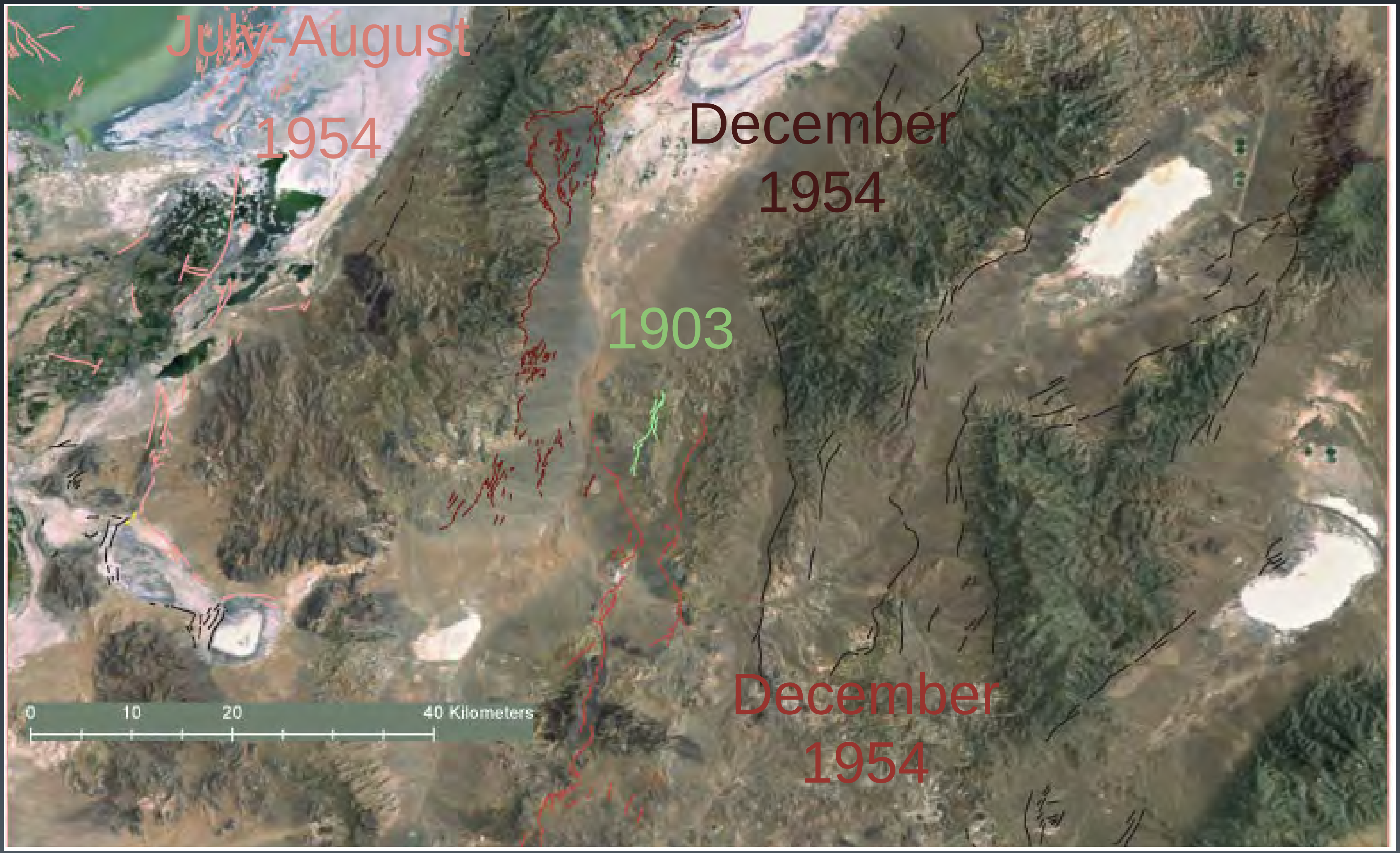


Key questions:

- Do graben-bounding fault pairs move together, separately, or both?
- Can we tell which fault is the master fault?
- Are some alternatives unviable--what is the minimum width for a fault to be considered capable of generating independent earthquakes?
- What method do we use to determine M on truncated faults?

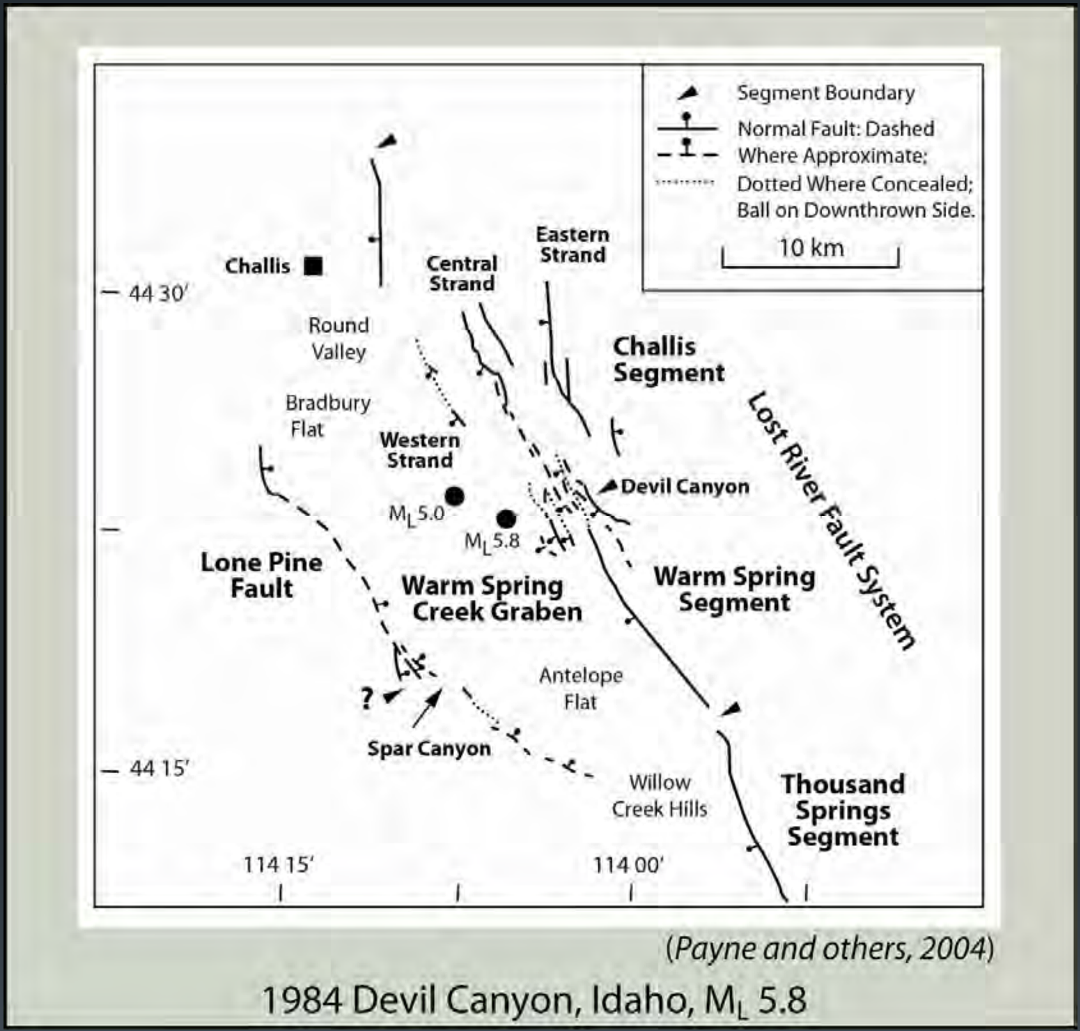
Historical Analogs for Antithetic Faulting in the Basin and Range

Central Nevada Seismic Zone (1903 and 1954)



Historical Analogs for Antithetic Faulting in the Basin and Range

Devil Canyon, Idaho (August 1984)



1984 Devil Canyon, Idaho, M_L 5.8

M 5.8 main shock considered a late aftershock of the M 7.3 Borah Peak earthquake (Oct. 1983)

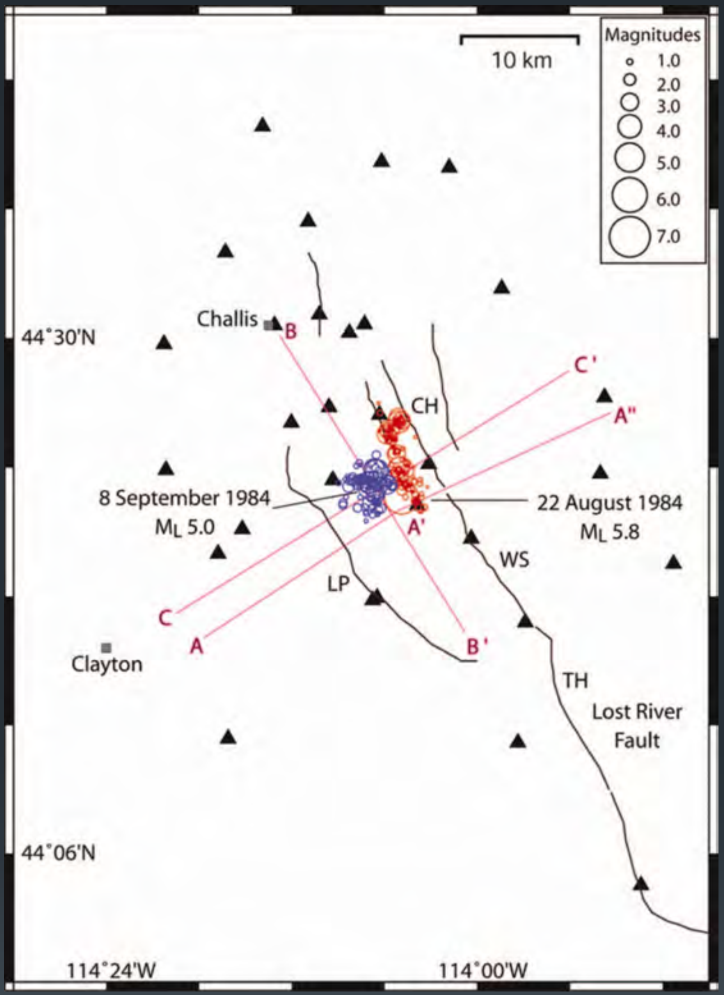
- Down-to-southwest normal slip on Challis segment of Lost River fault

M 5.0 aftershock occurred 17 days after the M 5.8 main shock

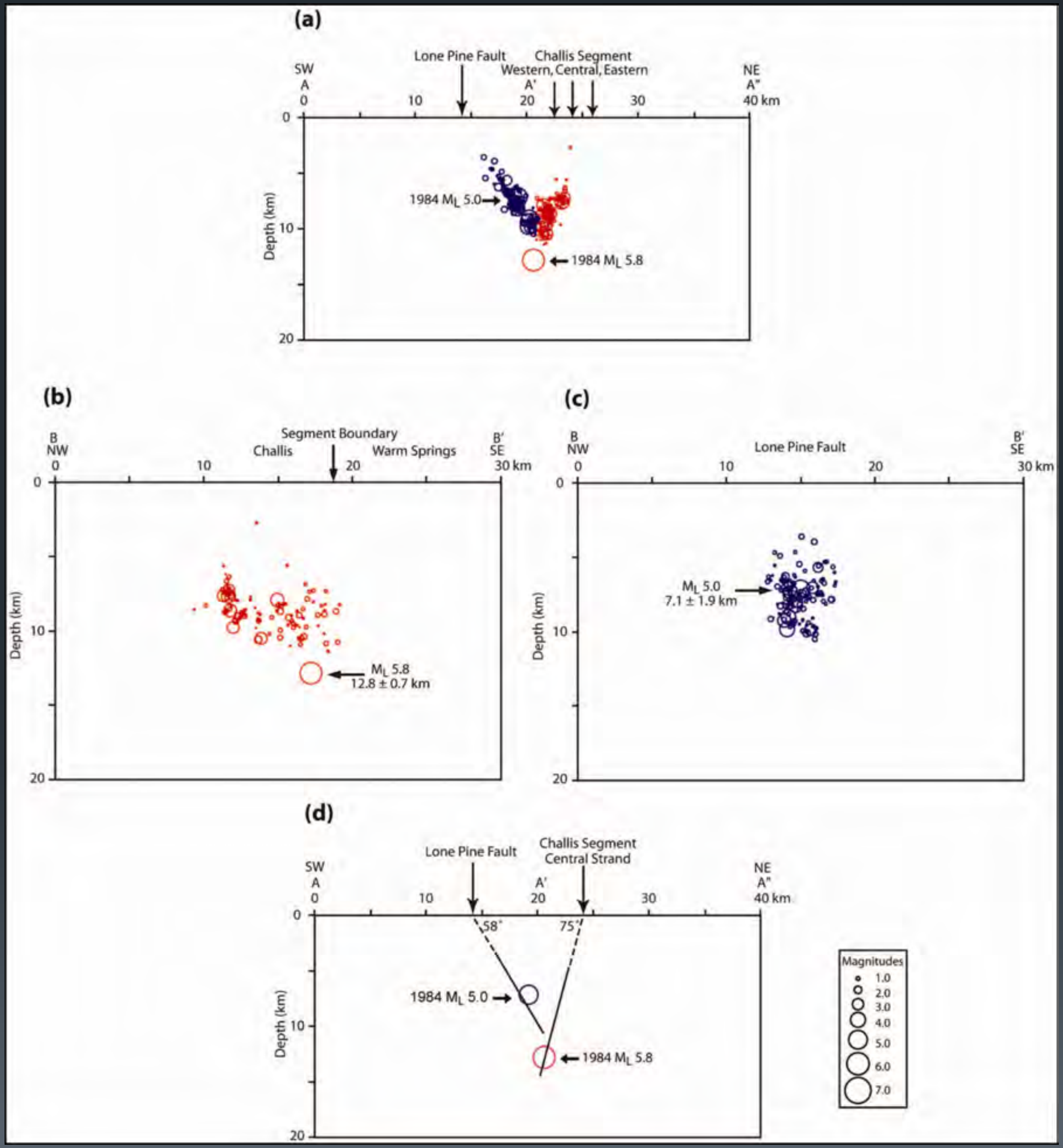
- Involved normal slip on antithetic Lone Pine fault

Historical Analogs for Antithetic Faulting in the Basin and Range

Devil Canyon, Idaho (August 1984)



(Payne and others, 2004)



Antithetic faulting considered triggered slip

- separate earthquake with its own moment release

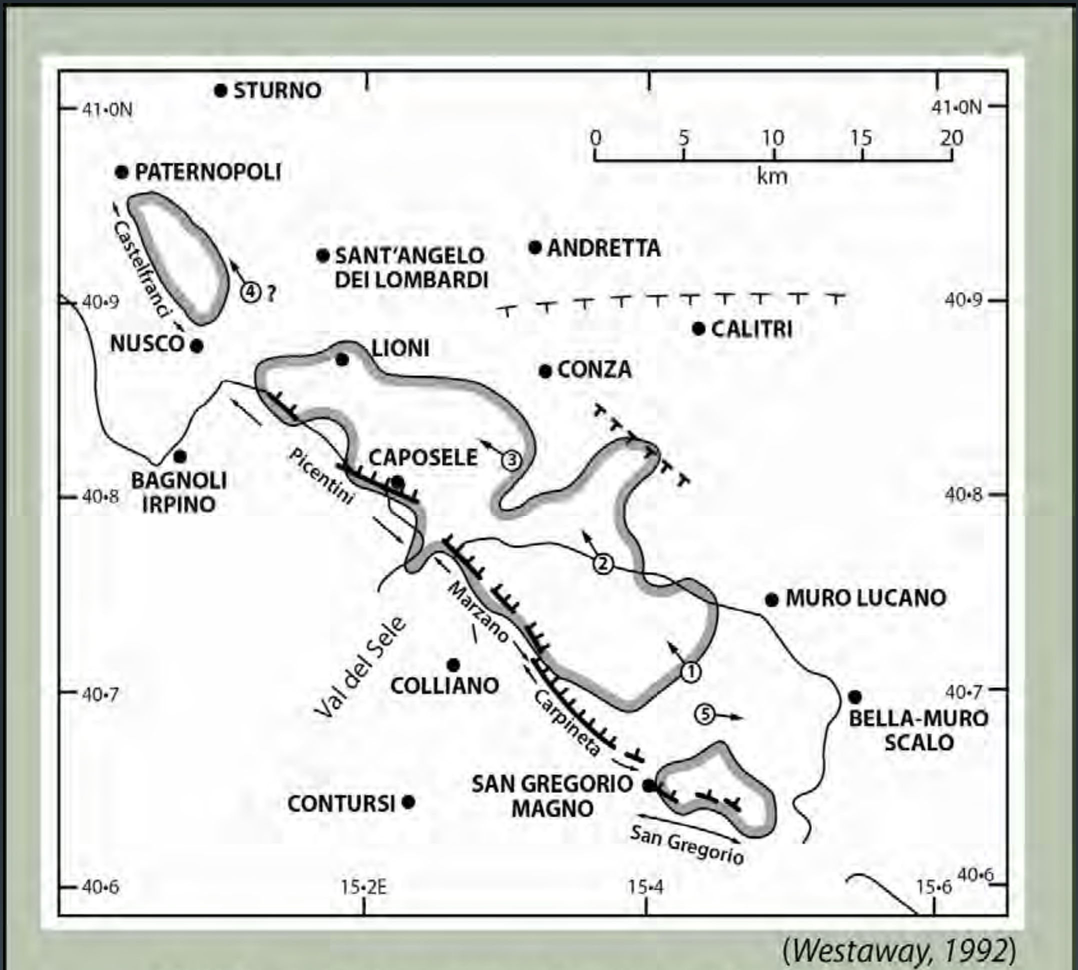
Antithetic slip restricted to Challis fault hanging wall

Small earthquake (M5), no surface rupture

(Payne and others, 2004)

Historical Analogs for Antithetic Faulting in the Basin and Range

Irpinia (Campania-Basilicata), Italy (November 1980)



1980 Irpinia (Campania-Basilicata), Italy, M_S 6.9

M 6.9 earthquake comprising numerous sub-events

- Rupture initiated as down-to-northeast normal slip on Carpineta fault
- At ~40 s, normal slip occurred on antithetic intrabasin fault

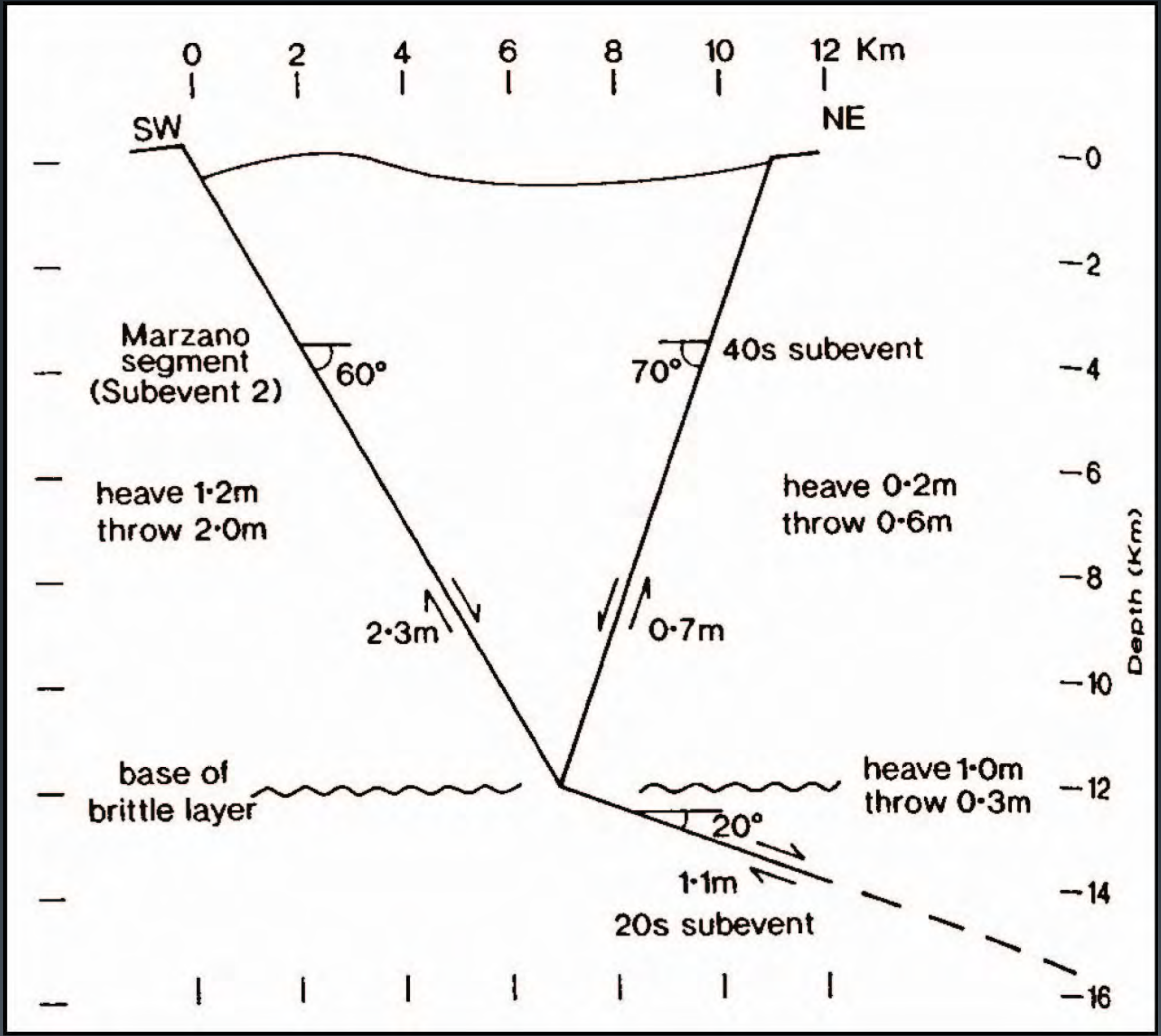
Historical Analogs for Antithetic Faulting in the Basin and Range

Irpinia (Campania-Basilicata), Italy (November 1980)

Antithetic faulting considered coseismic

- contributed moment (~12%) to the earthquake as a whole

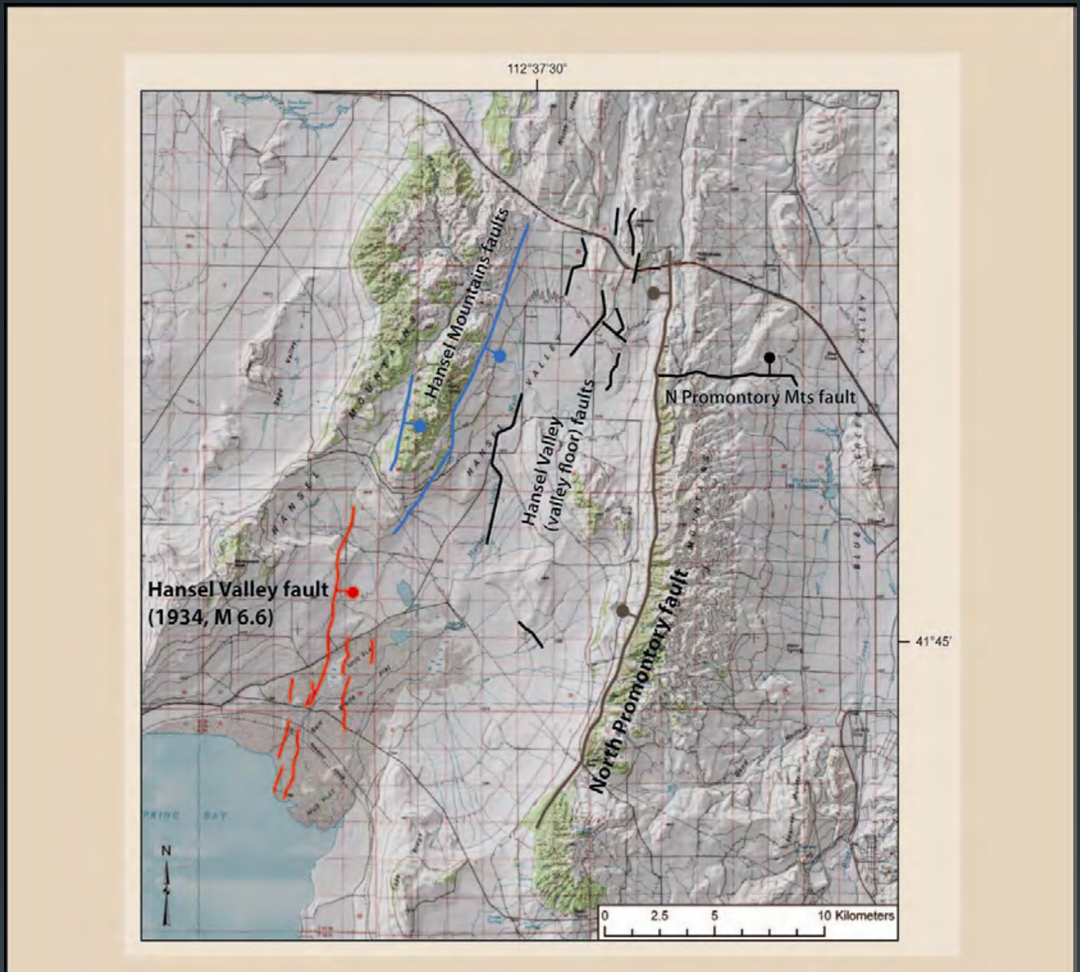
No surface rupture associated with antithetic faulting



(Westaway, 1992)

Historical Analogs for Antithetic Faulting in the Basin and Range

Hansel Valley, Utah (March 1934)



1934 Hansel Valley, Utah, M 6.6

M 6.6 earthquake involving mostly down-to-east surface faulting (but strike-slip focal mechanism)

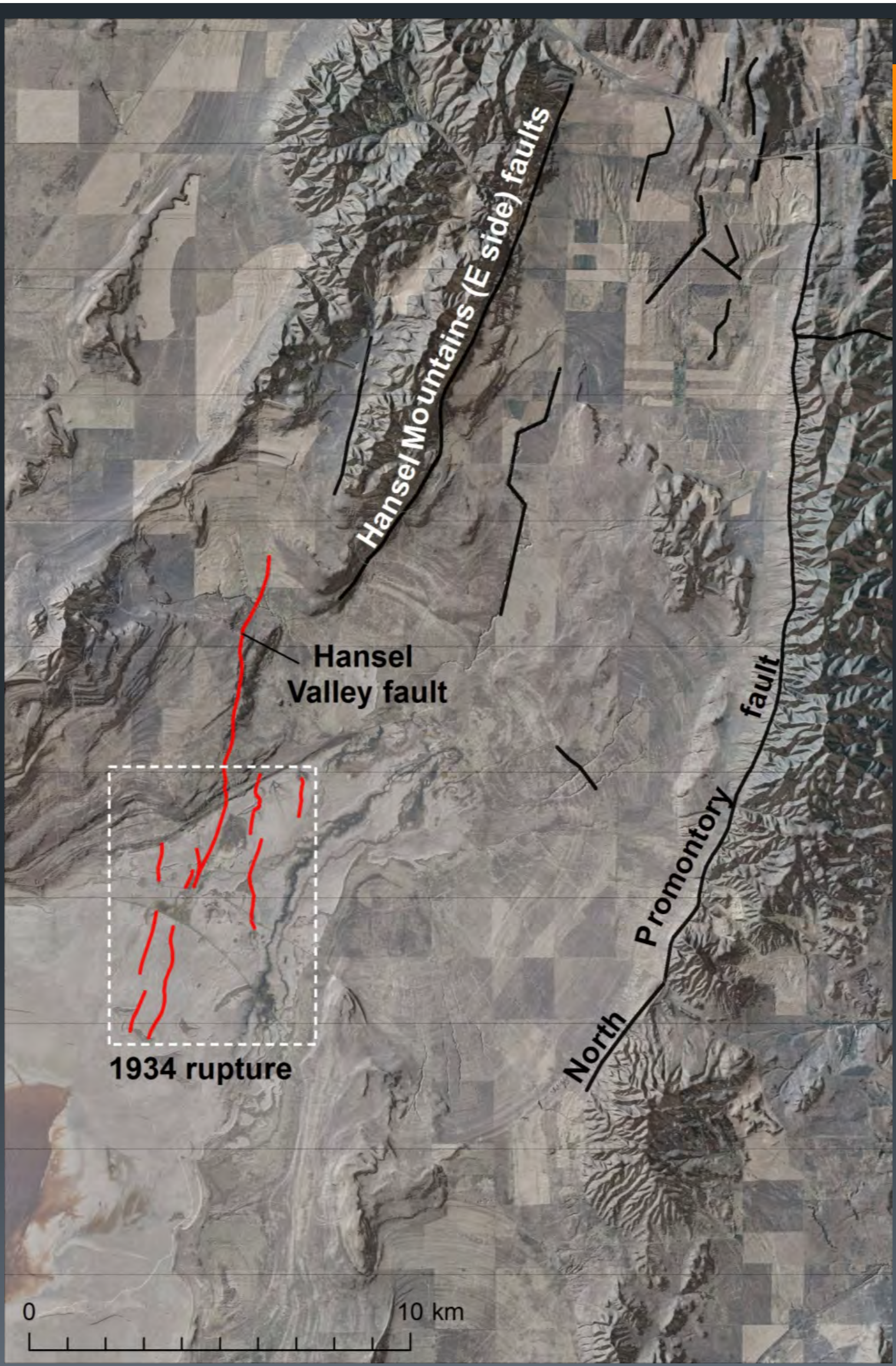
- No rupture documented along North Promontory fault, to which Hansel Valley fault is antithetic

Antithetic faulting appears to have been independent

- Absence of movement of the main range-bounding fault

1934 M 6.6 Hansel Valley Earthquake: Analog for Antithetic Fault Rupture?

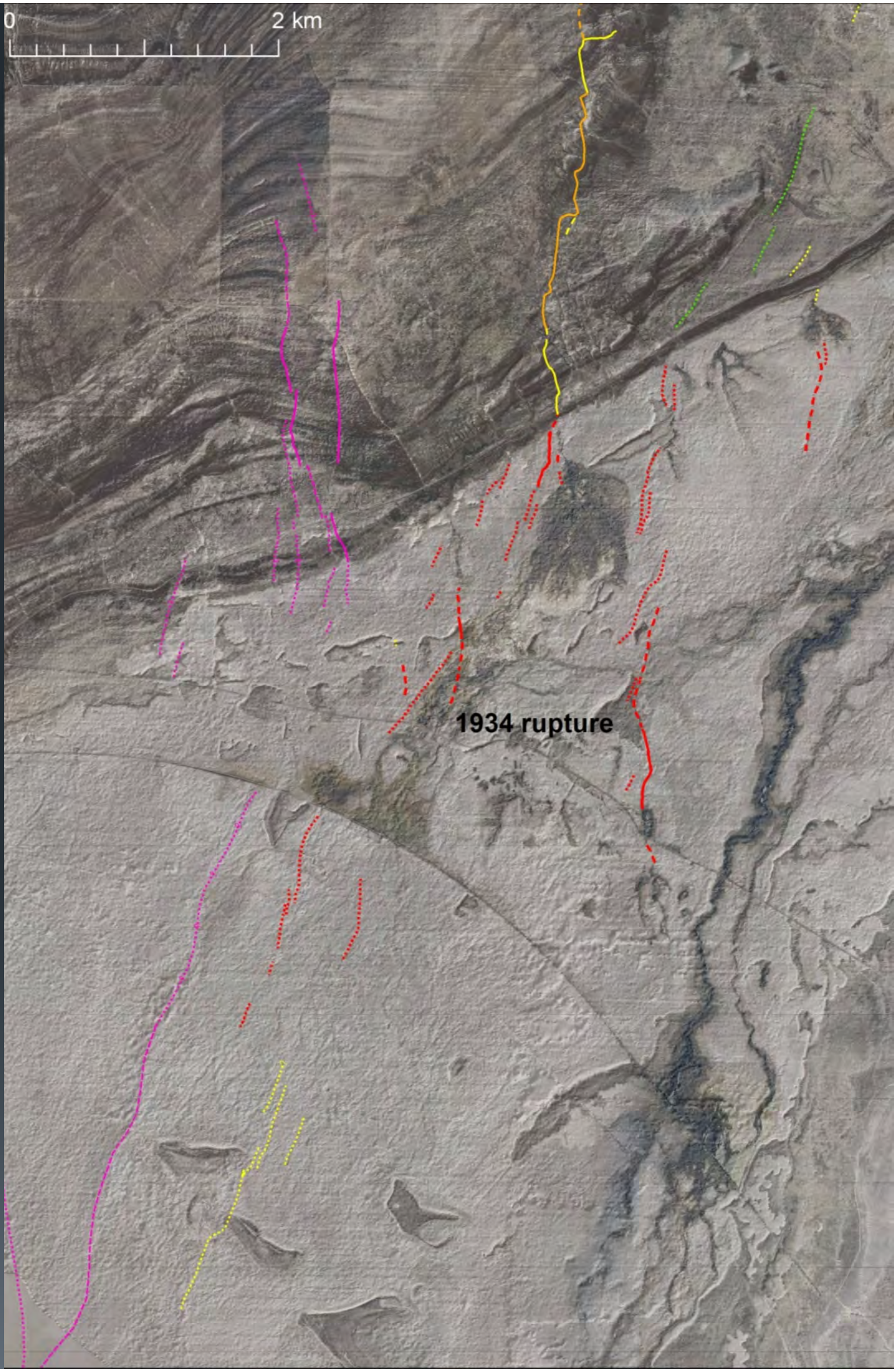
Chris DuRoss
Mike Hylland



Working Group on Utah Earthquake Probabilities
June, 2011

Geologic Observations

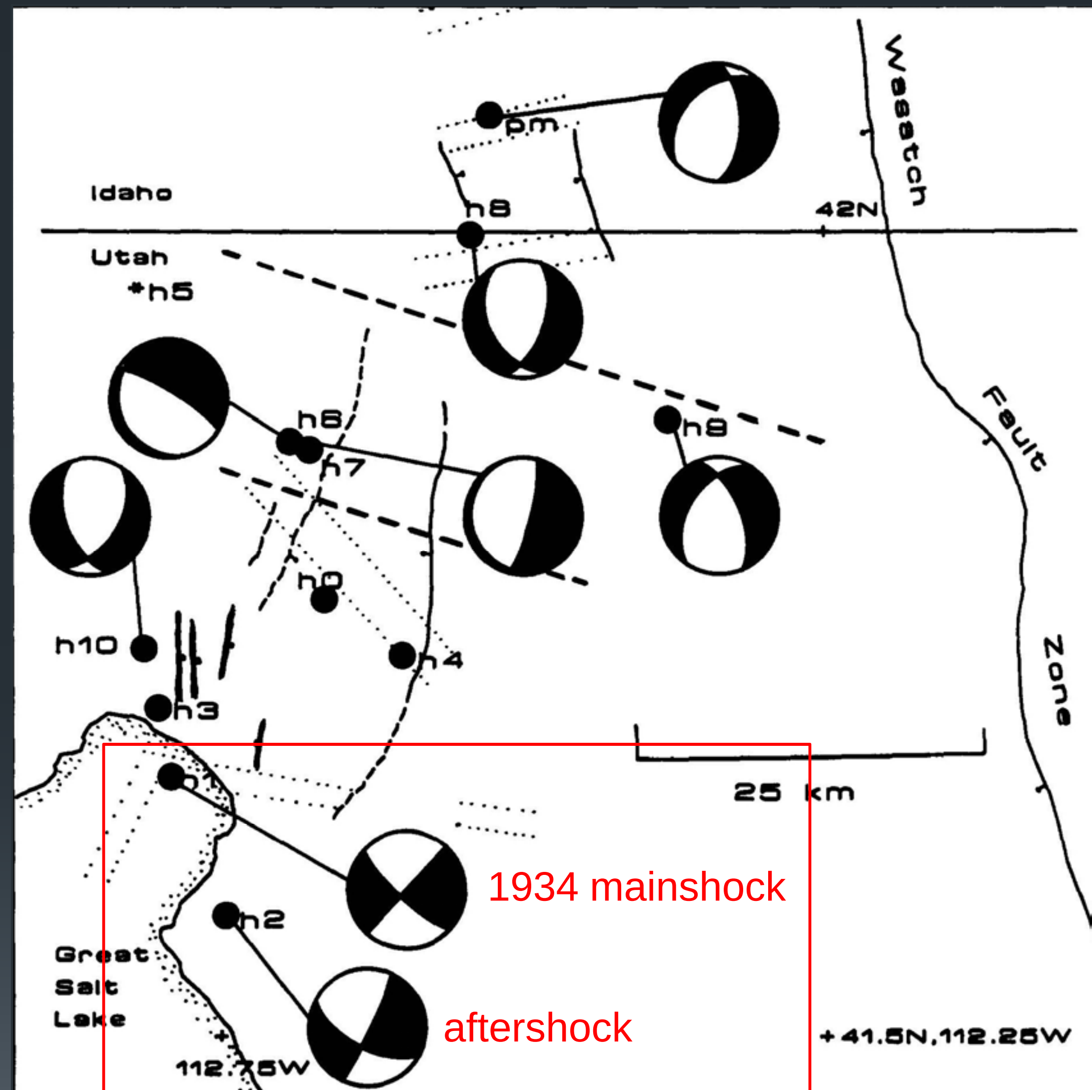
- 5–8-km-long, NE-oriented zone of ground cracks and minor surface faulting
- Down-to-the-east scarps related to 1934 earthquake
  - Maximum vertical displacement: ~50 cm, mostly down to the east
  - Maximum strike-slip displacement: ~25 cm (poorly documented)
- No reports of rupture along prehistoric rupture to the north, which has evidence of larger displacements (1+ m)




0
2 km
1934 rupture

Seismologic Observations

- Left-lateral strike-slip on near-vertical, NE oriented fault
- Rupture length: ~11 km using rupture time and velocity; NE propagation?
- Average horizontal slip: 2.3 m using seismic moment (M_0 = rigidity*area*slip)
- Average vertical slip: 20–25 cm using focal mechanism



Doser (1989)

Other puzzle pieces

- Bathymetry and shoreline data (1850–1934):
  - 1-m increase in water depth, no change to south
  - ~2-m decrease in relative shoreline elevation

- Re-leveling of railroad grade (after 1934)
  - ~0.3–0.4 m of subsidence east of rupture.

Other puzzle pieces

- 1909 M ~6 Hansel Valley earthquake
  - No report of surface rupture, but newspaper report of waves passing over 3.5-m high railroad trestle
  - A: Bathymetry & shoreline data (1850–1934) could include displacement from this event
  - B: Linear shoreline south of 1934 rupture (and epicenter) suggests down-to-the-west faulting.
  - C: Lineaments and down-to-the-west scarps east of 1934 rupture related to 1909 earthquake?

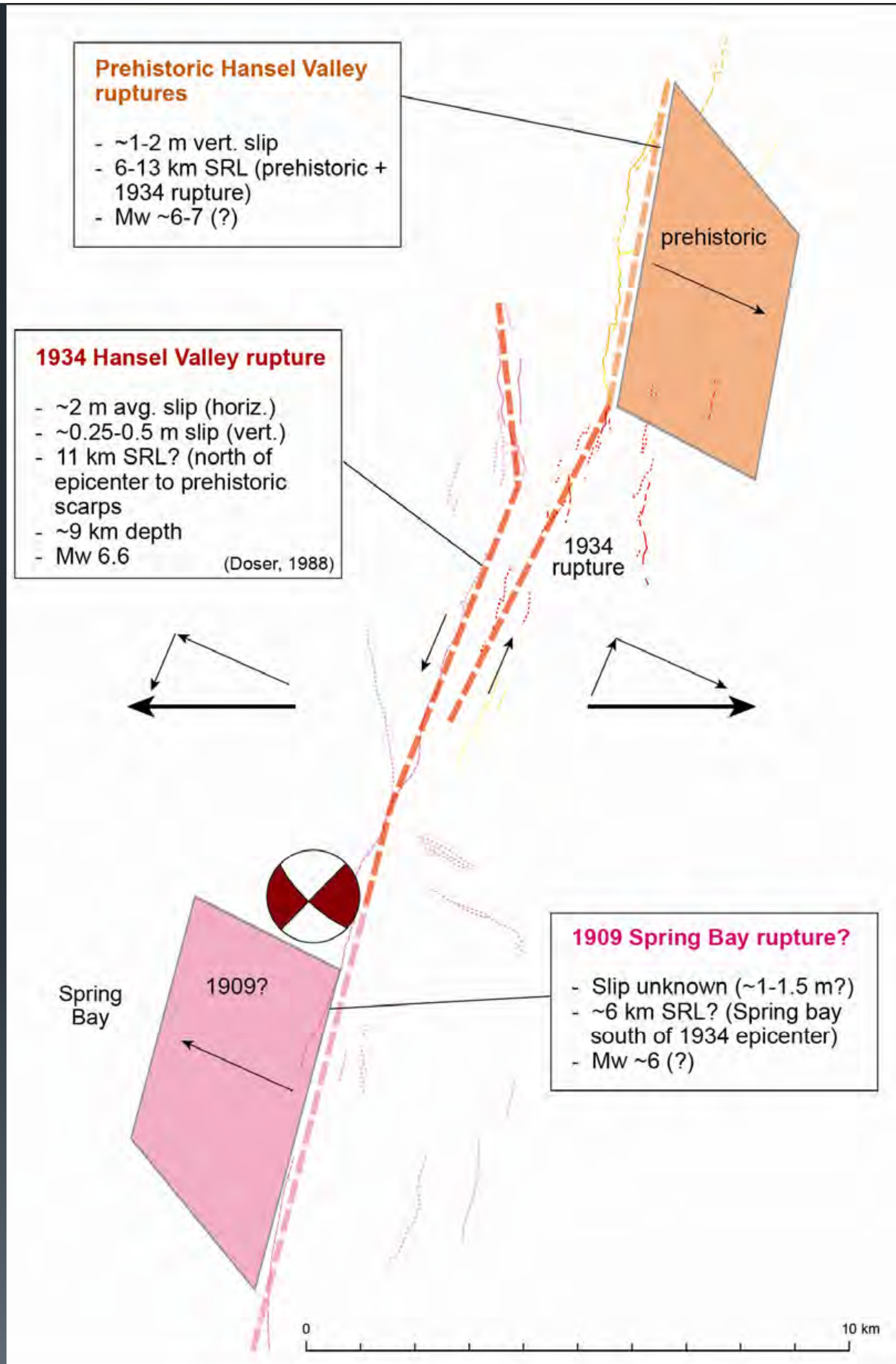
Remaining Questions

- Was the1934 M 6.6 earthquake a normal or strike slip event?
  - Normal surface rupture (~5–8-km L, 0.5 m vertical D)
  - Strike-slip focal mechanism (~11-km L, ~2 m horizontal D)
- Did the 1934 event occur as a strike slip event, only initiating normal faulting (or non-tectonic slip?) near the northern end of the rupture?
- How does the 1909 M~6 earthquake fit in? Did this event rupture faults in Spring Bay?

Speculation…

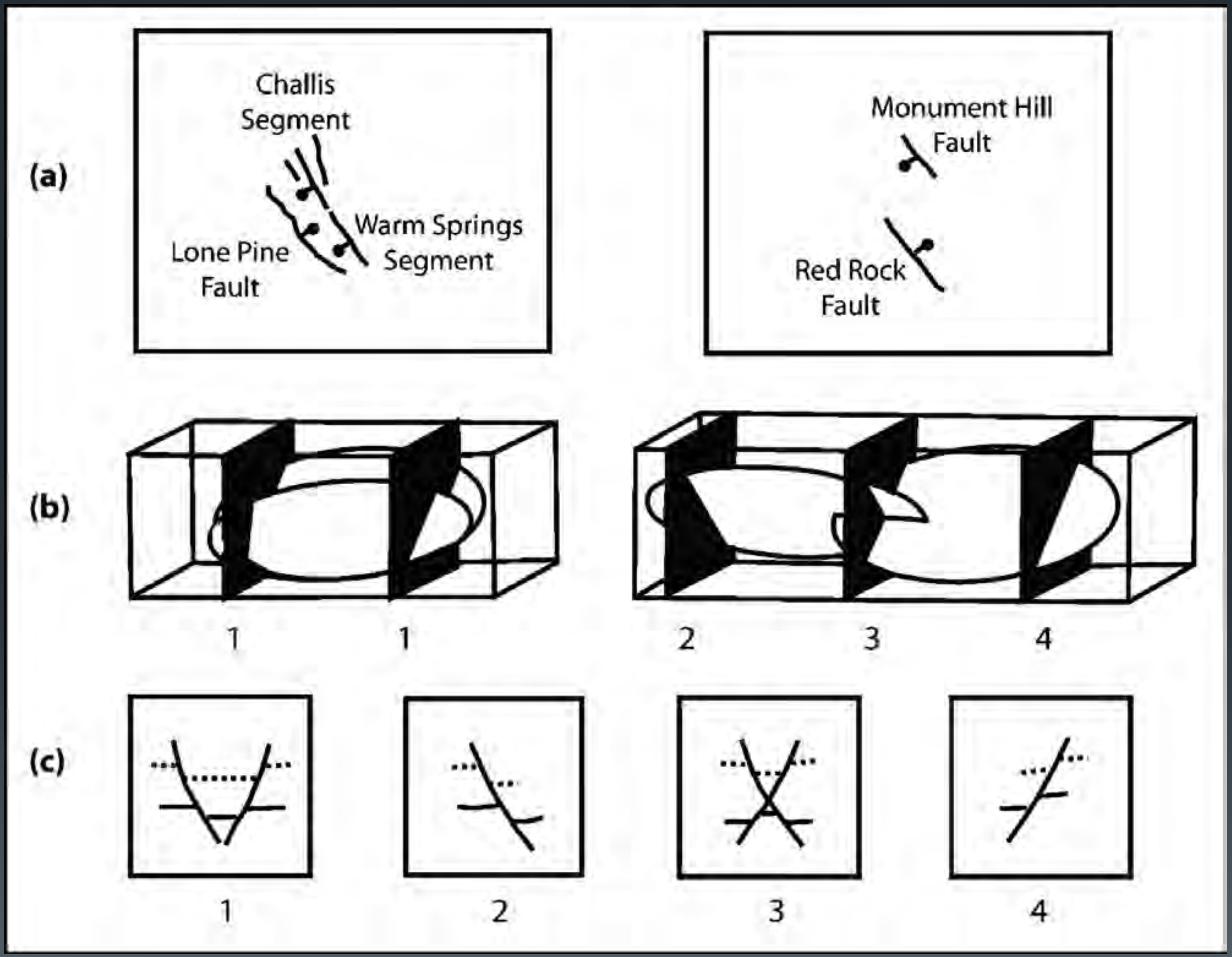
- Possible kinematic model: the 1934 earthquake was a dominantly strike-slip event that released strain accumulated between two normal faults.

- Bottom line: The 1934 earthquake has too many remaining questions to be a well-behaved poster child for antithetic-fault rupture.



Conjugate Normal Fault Systems
Insights from 2D, 3D Modeling and Lab Experiments

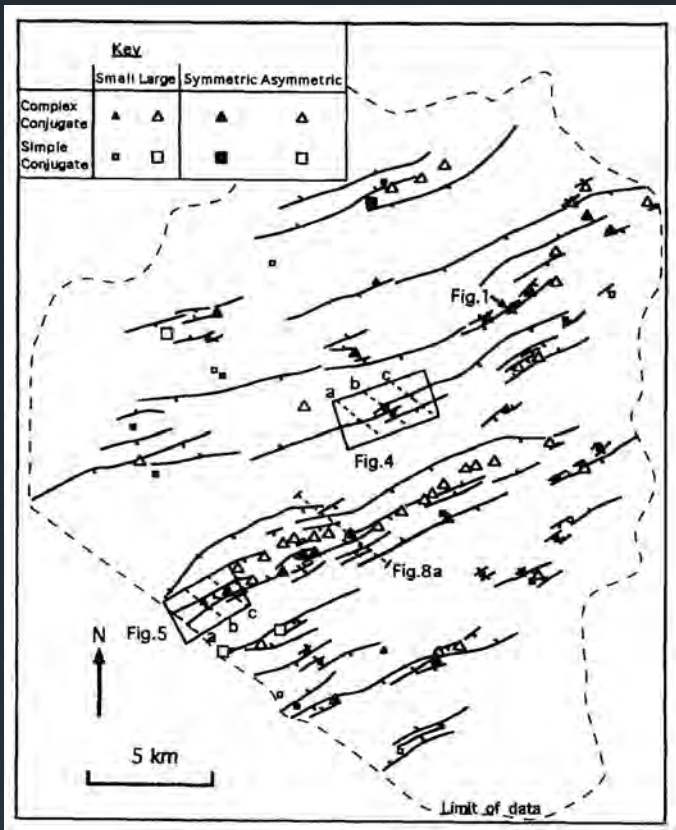
How is strain accommodated on conjugate normal fault systems, particularly near fault terminations and in overlap zones?



(Payne and others, 2004, after Nicol and others, 1995)

Conjugate Normal Fault Systems

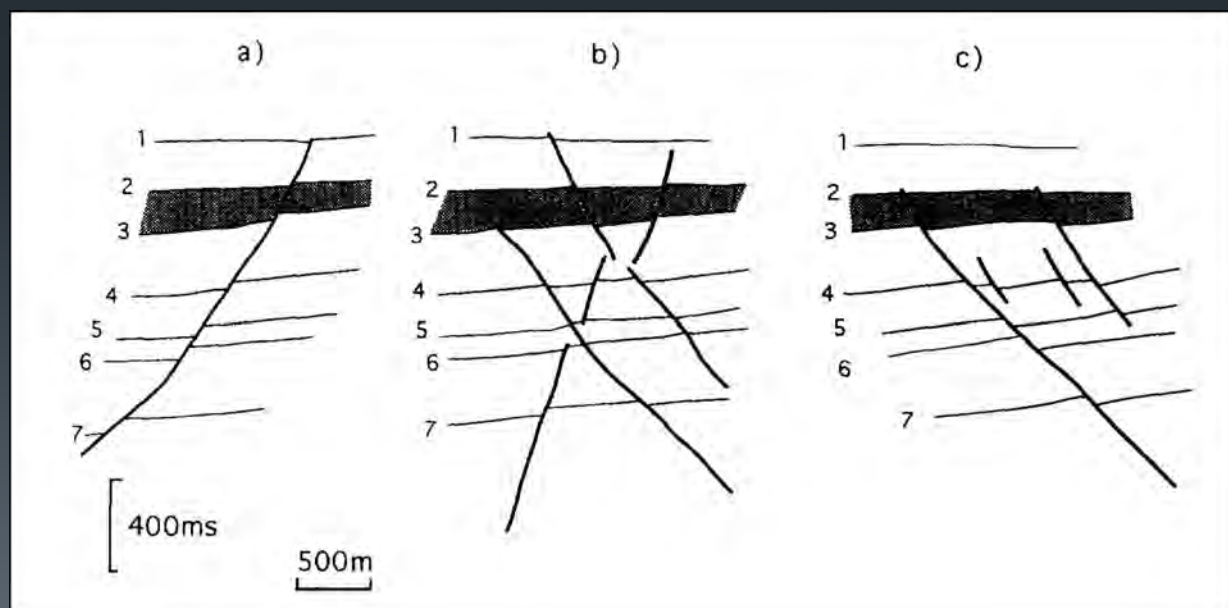
Insights from 2D, 3D Modeling and Lab Experiments



(Nicol and others, 1995)

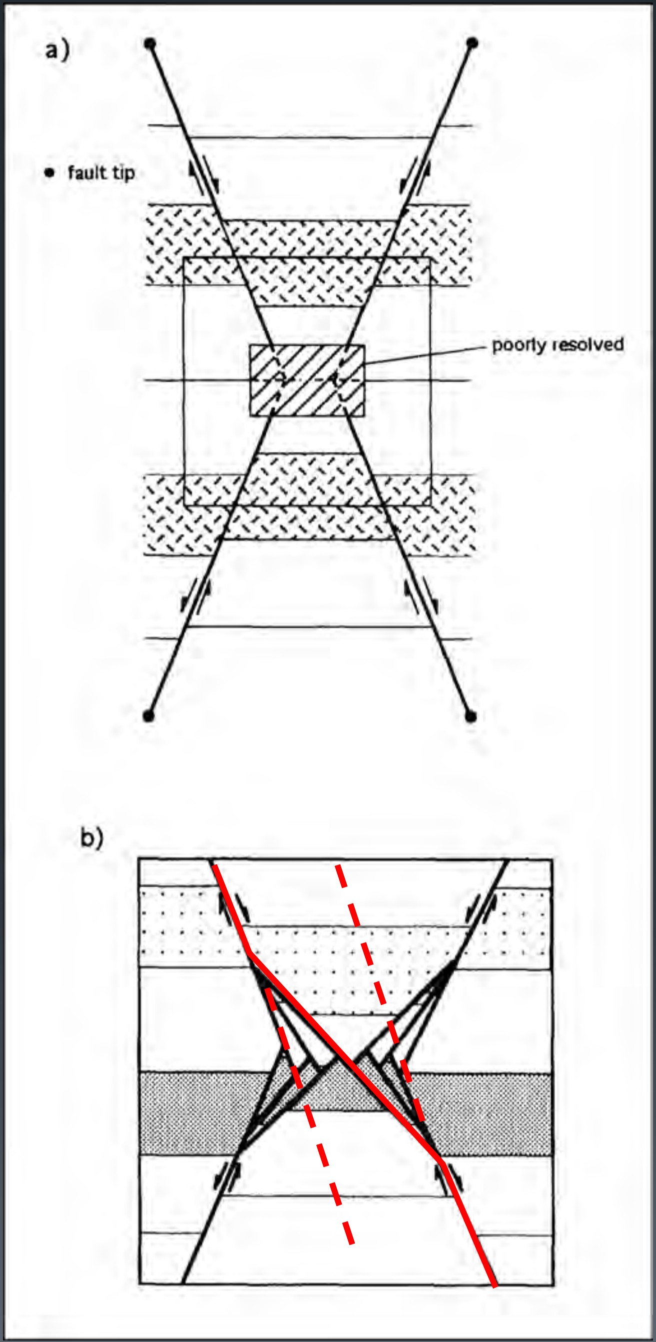
Example: Timor Sea

• Normal faults, up to 10s of kilometers long, throws up to 400 m
• Crossing conjugate normal faults imaged by 2D, 3D seismic reflection in upper 3.5 km of crust
• Faults accommodate extension associated with subduction of Australian plate
• Many larger faults originated by reactivation and upward propagation of Late Jurassic normal faults



(Nicol and others, 1995)

Conjugate Normal Fault Systems
Insights from 2D, 3D Modeling and Lab Experiments



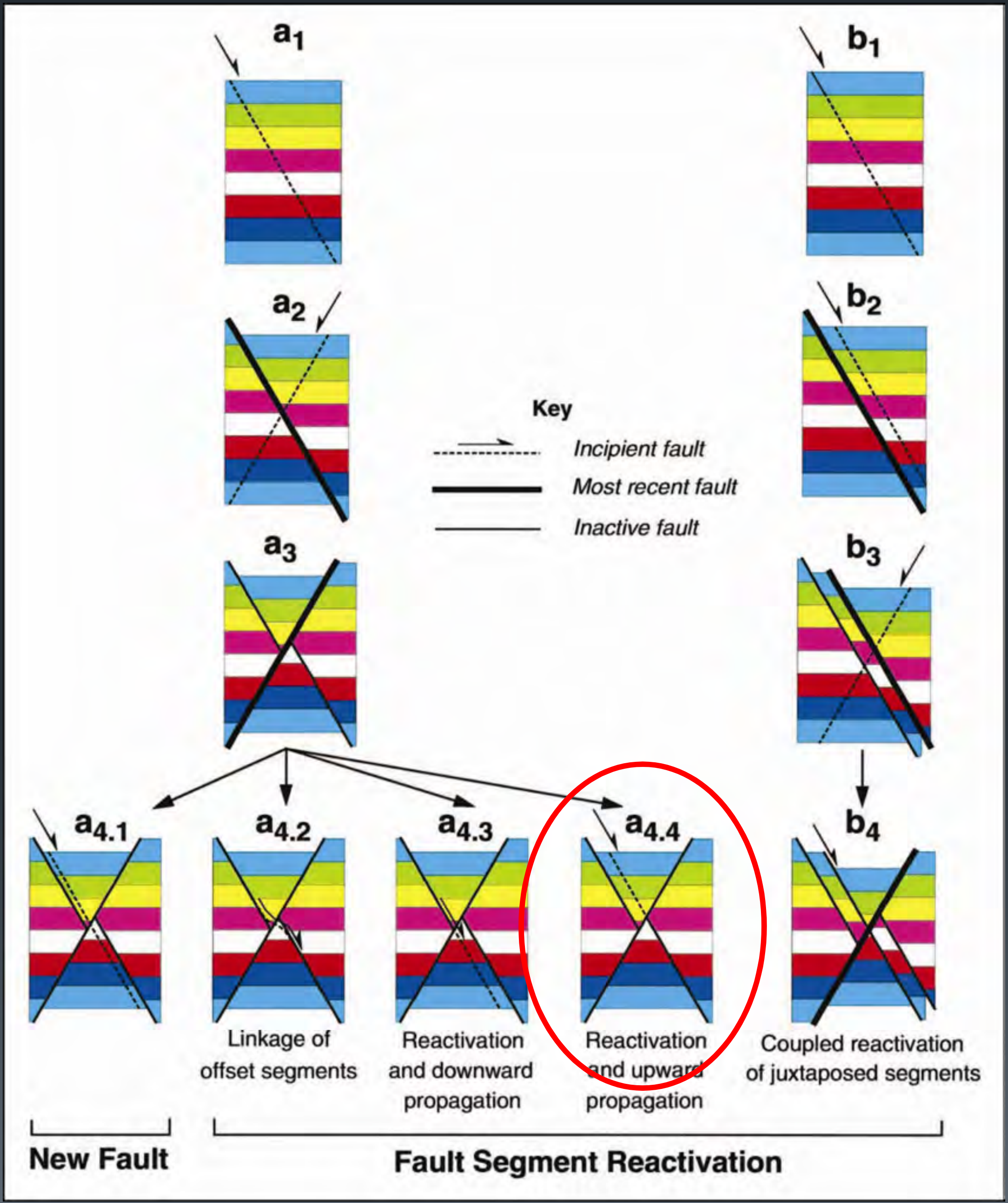
(Nicol and others, 1995)

Kinematic Model (Nicol and others, 1995, after Horsfield, 1980)

- Inter-fault volumes undergo significant ductile strain
- "Ductile" is scale-dependent term
  - "Concept of brittle deformation (rigid blocks translated along faults) is valid only for the microscopic scale"
- In intersection zone, cumulative displacement is distributed among numerous individual slip surfaces; new surface generated in each slip event
- Radius of curvature of bends in fault surface is limiting factor; i.e., eventually new fault will form
- Slip on main faults considered simultaneous (on geologic time scale)

Conjugate Normal Fault Systems

Insights from 2D, 3D Modeling and Lab Experiments



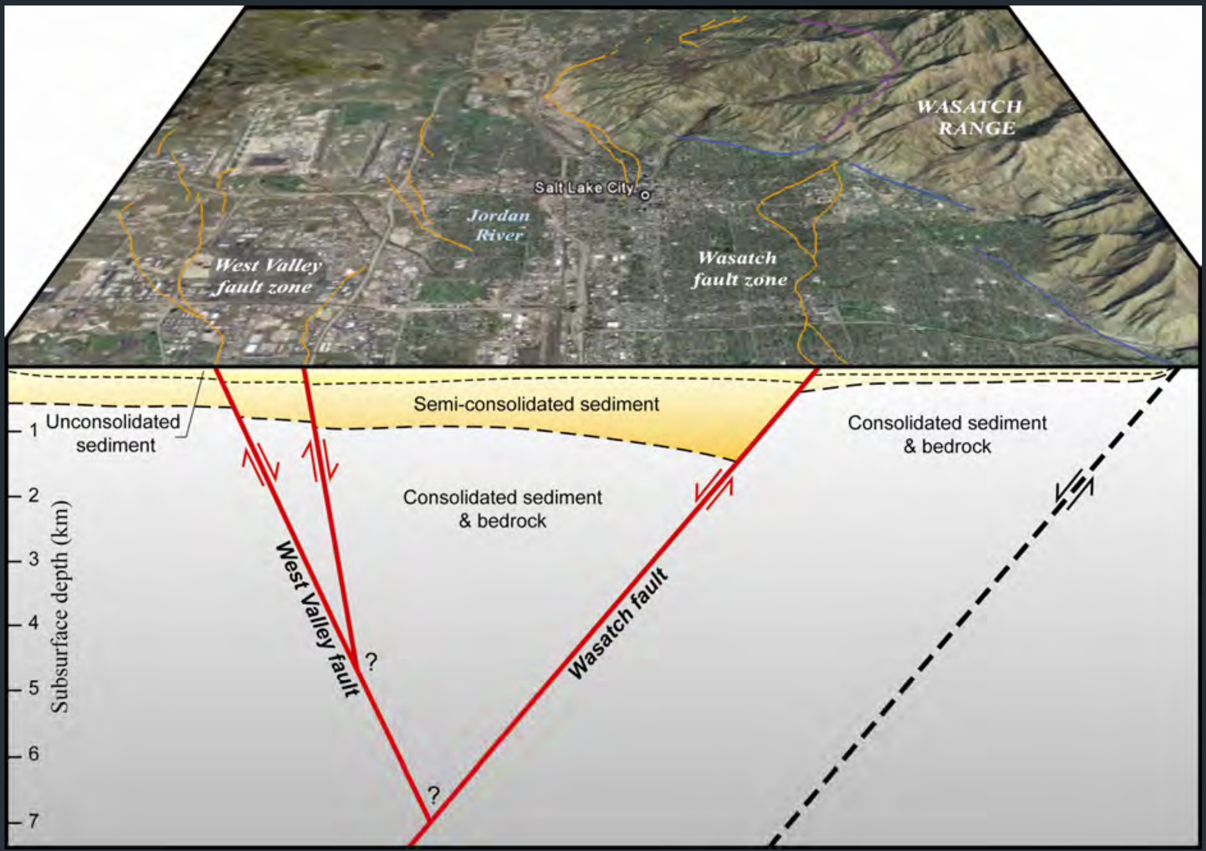
(Ferrill and others, 2000)

2D Modeling of Ferrill and others (2000)

- Simultaneous movement of conjugate fault pairs requires volume change in intersection area
- Alternating sequential movement is preferred model
- Several outcrop-scale examples provided

Conjugate Normal Fault Systems

Insights from 2D, 3D Modeling and Lab Experiments

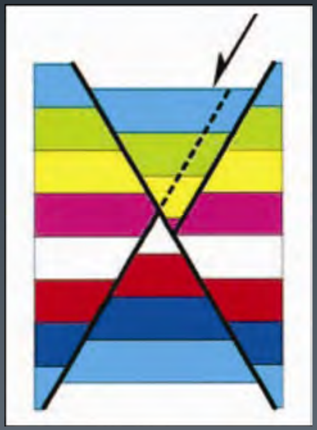


West Valley Fault Zone – Salt Lake City Segment

Crossing conjugate normal faults, or listric master fault (with splays) and truncated antithetic fault in hanging wall?

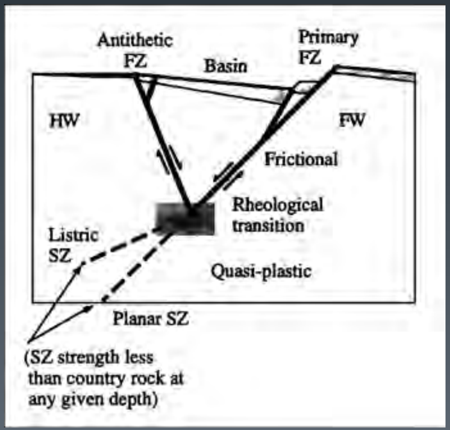
Pertinent questions:

- Fault dip
- Depth to intersection zone
- Horizontal separation of fault traces vs. vertical offset of faults
- Reactivation of pre-existing structure
- Map patterns of fault traces



(Ferrill and others, 2000)

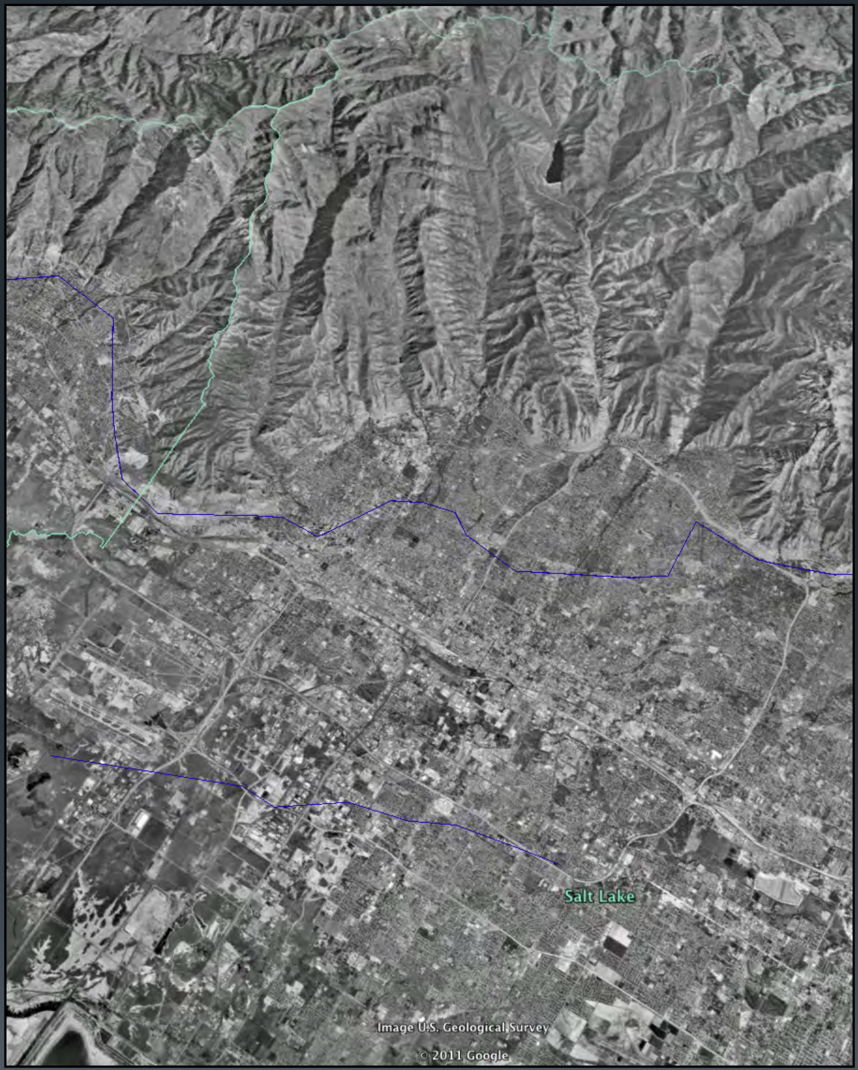
Or?



(Bruhn and Schultz, 1996)

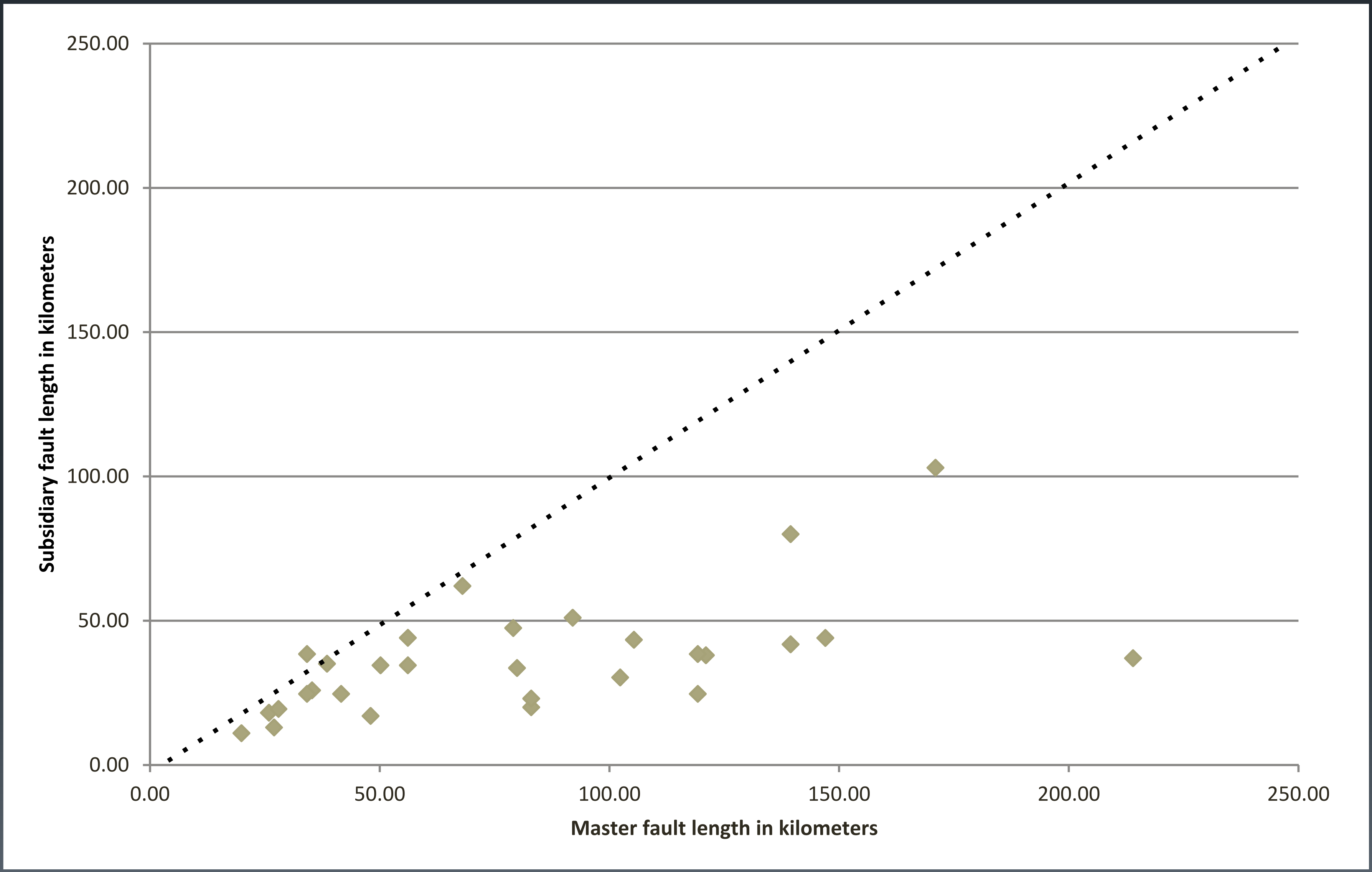
Metrics to differentiate master and subsidiary faults

- Fault length
- Percent of along-strike overlap
- Topographic relief
- Short-term slip rate based on paleoseismology is not always diagnostic

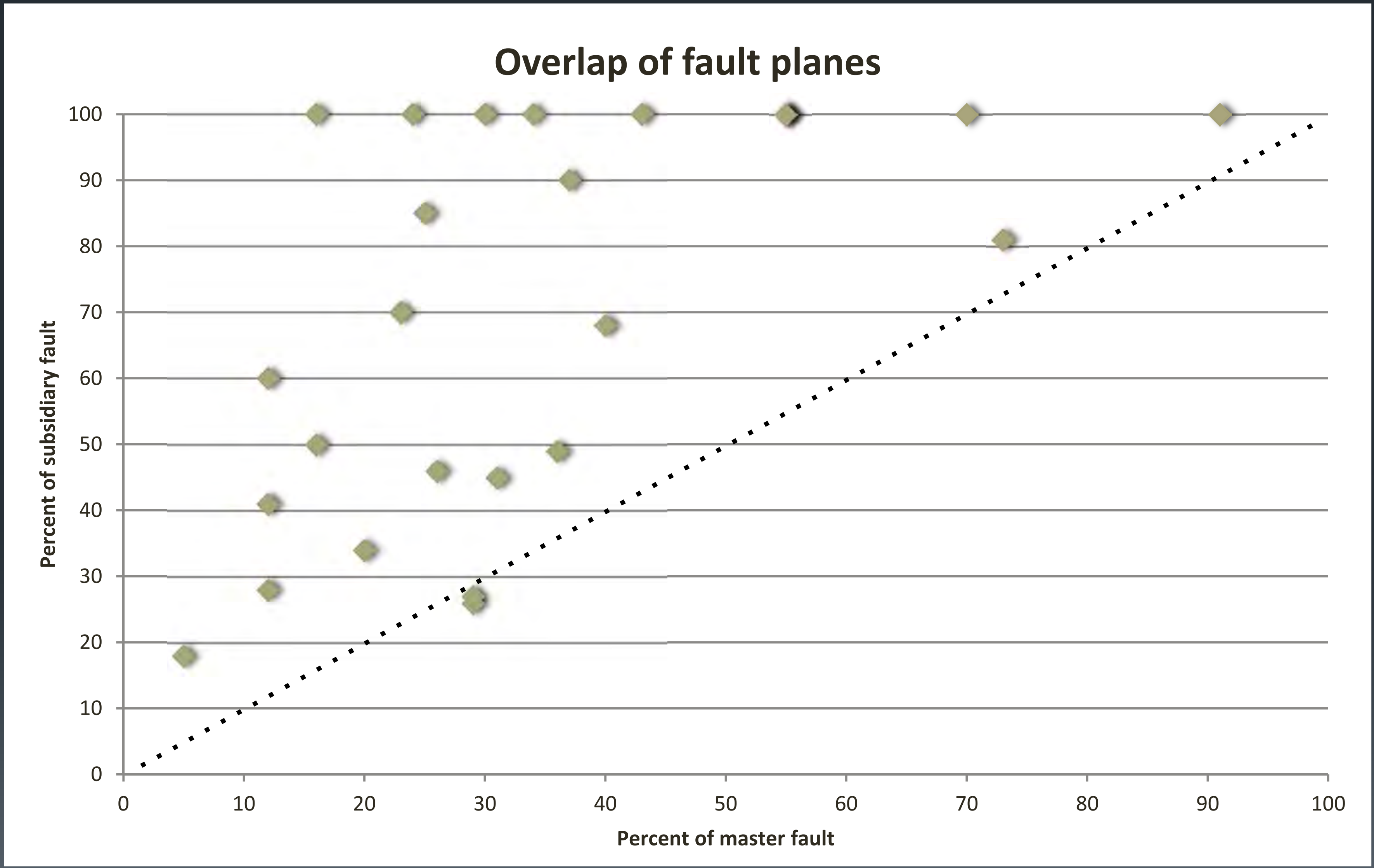


SLC segment of the Wasatch and West Valley sources

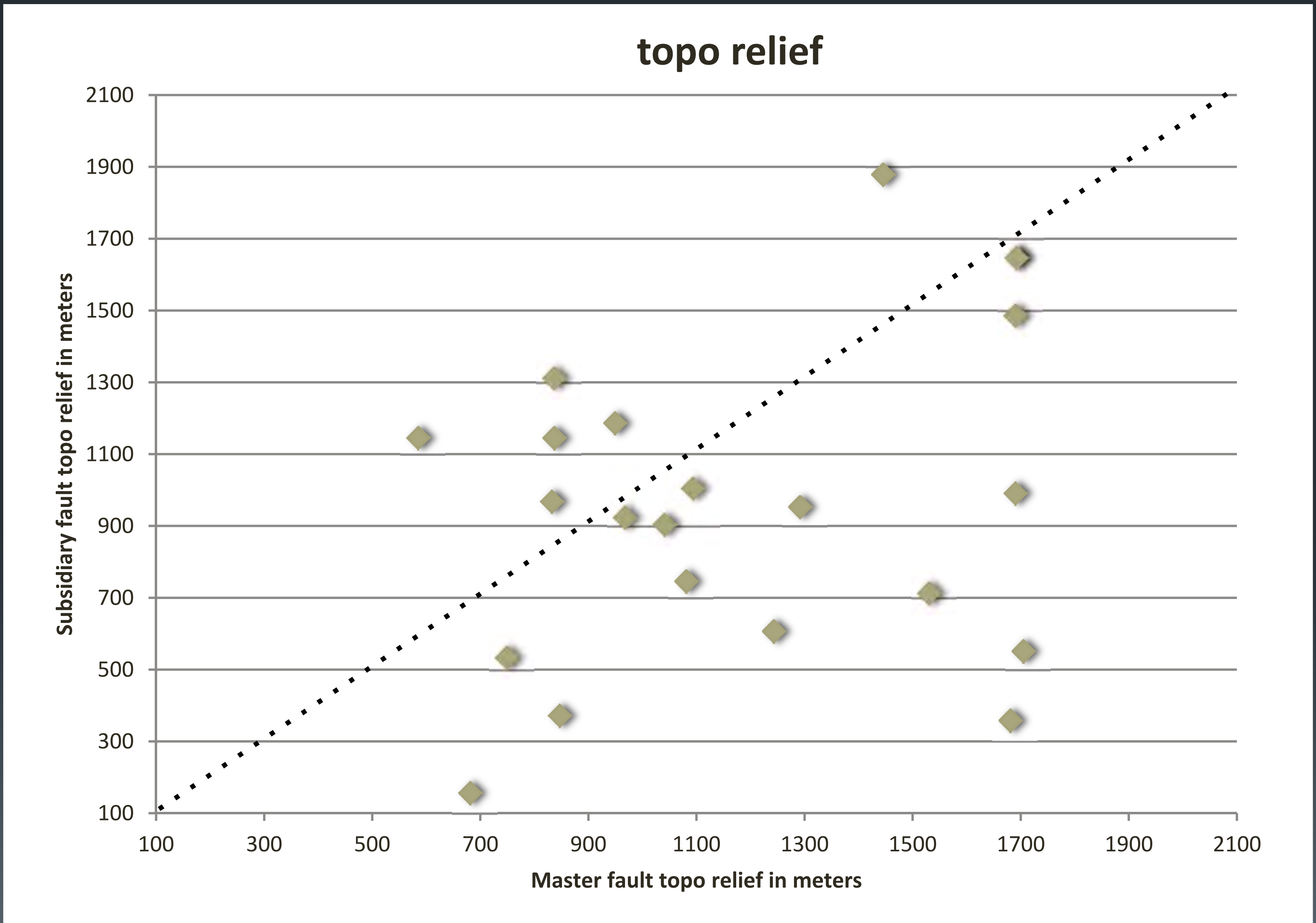
Fault length



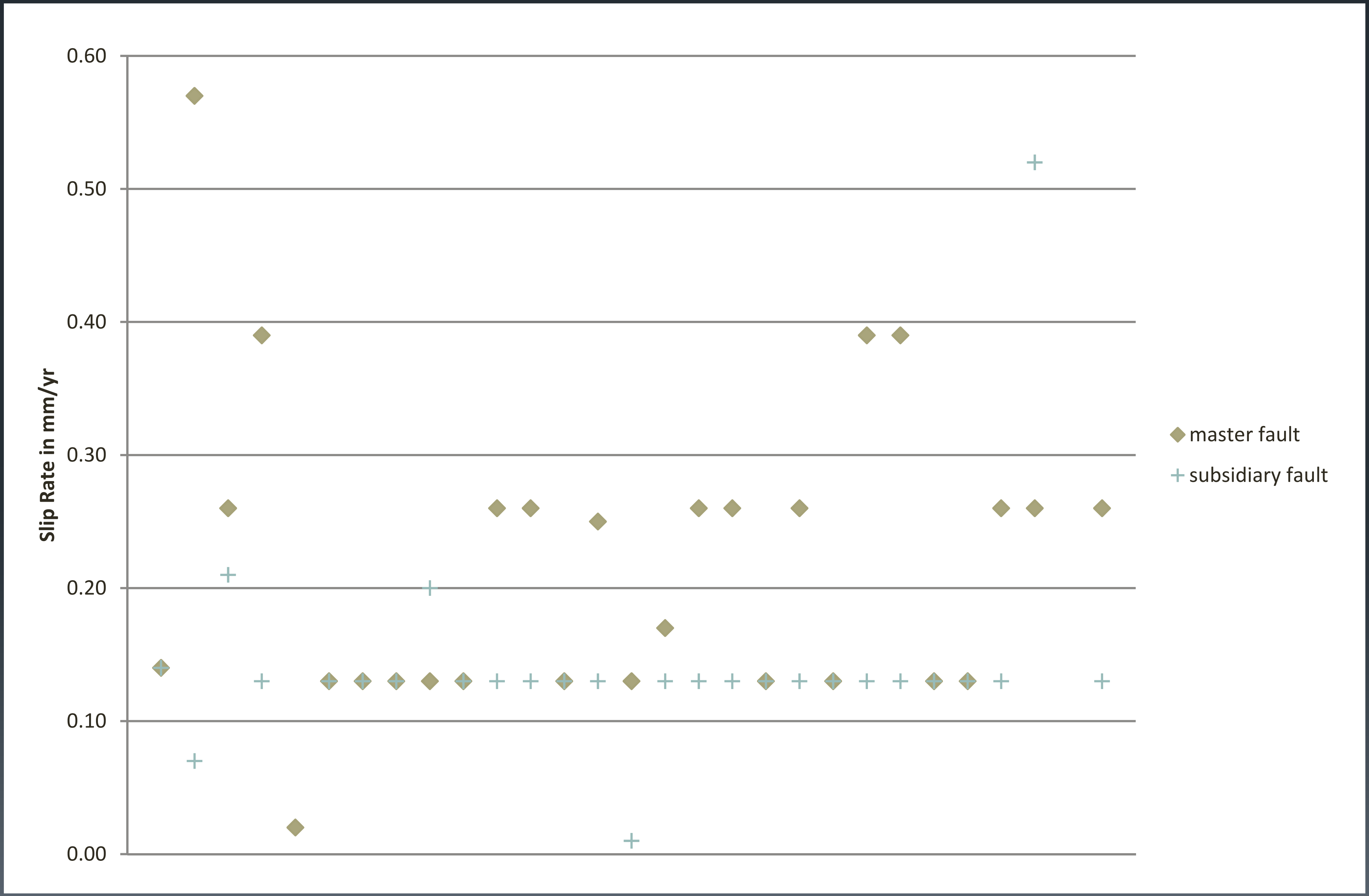
Overlap of fault planes



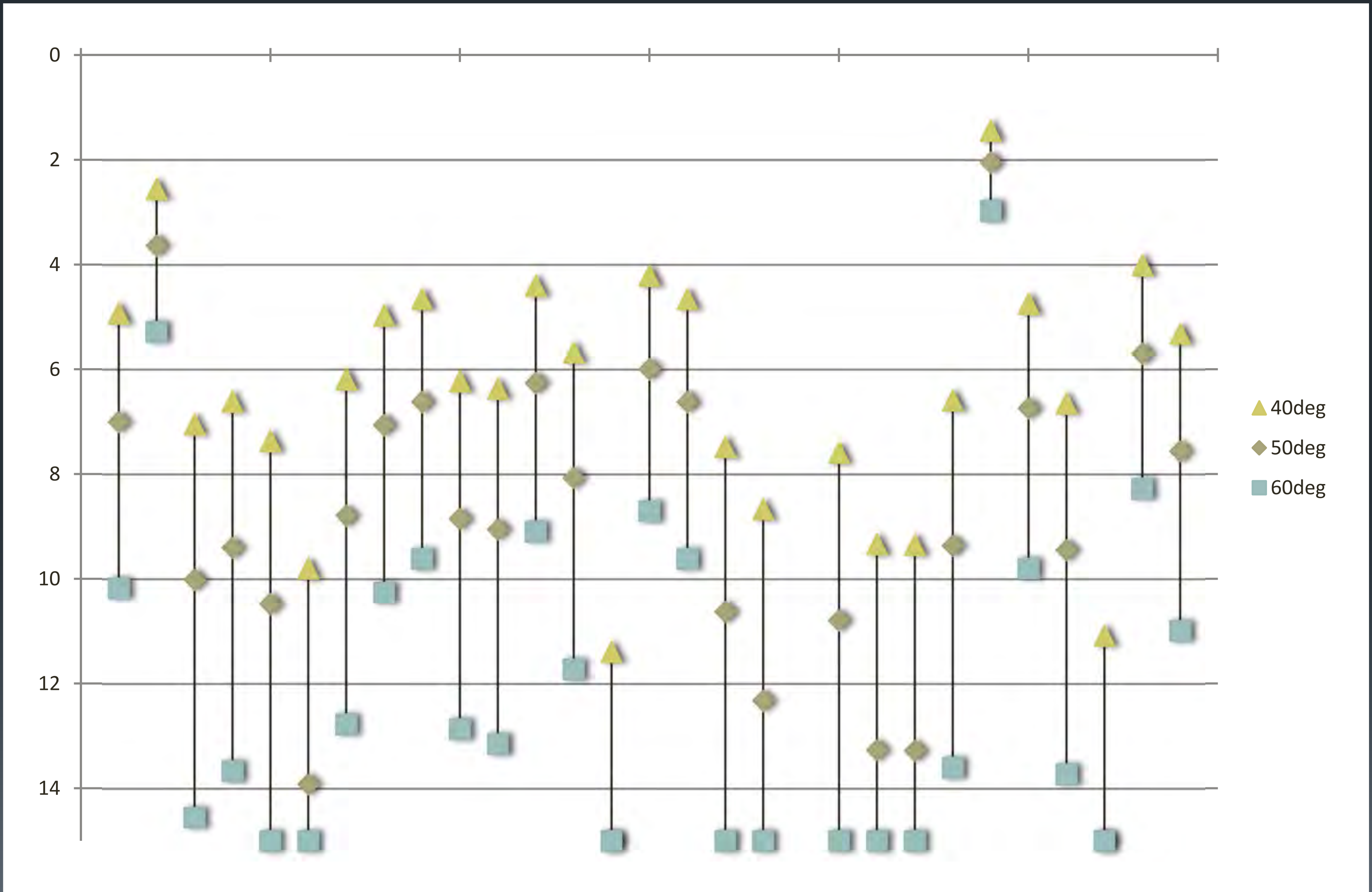
Topographic relief



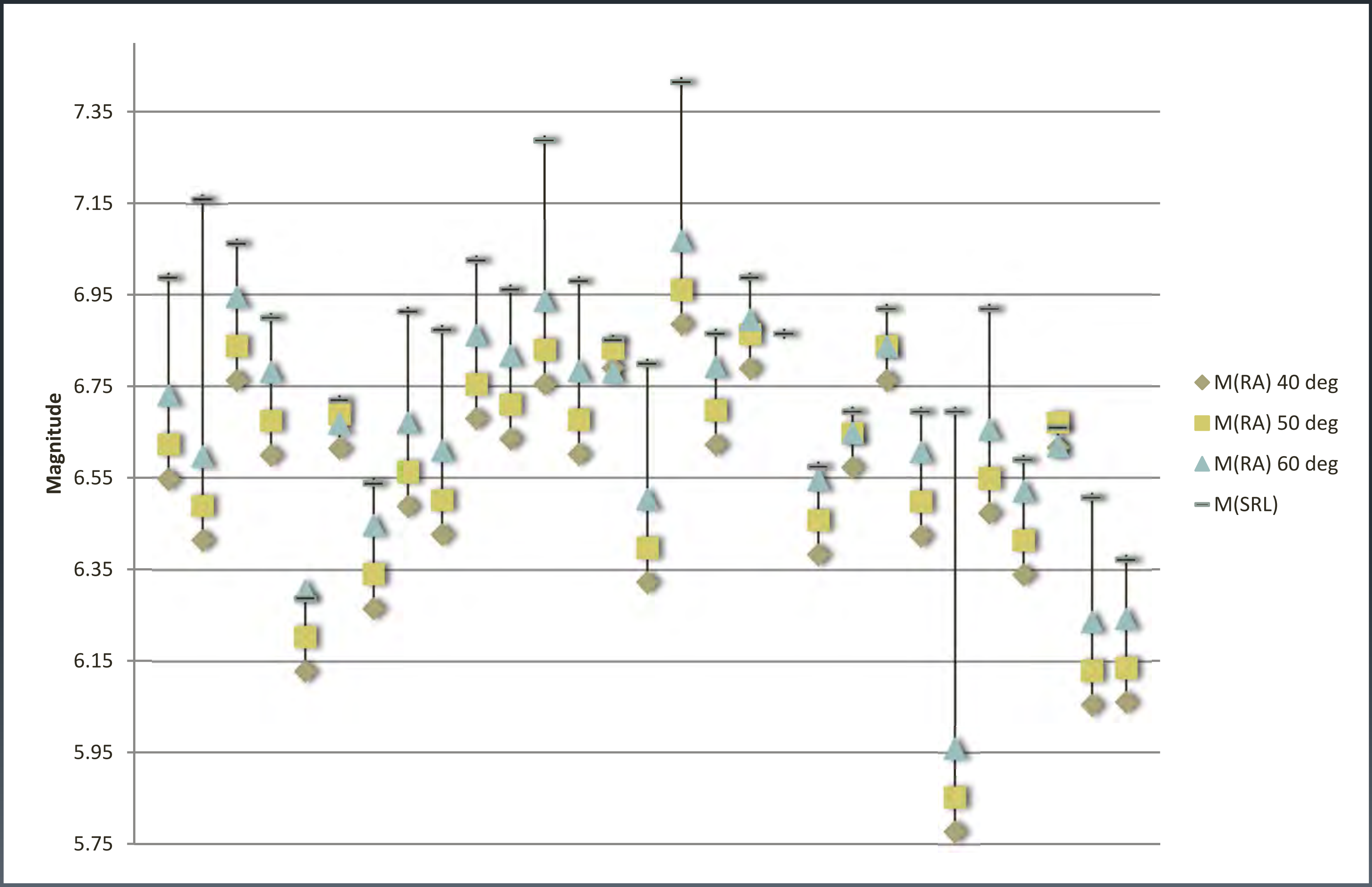
Assigned slip rate



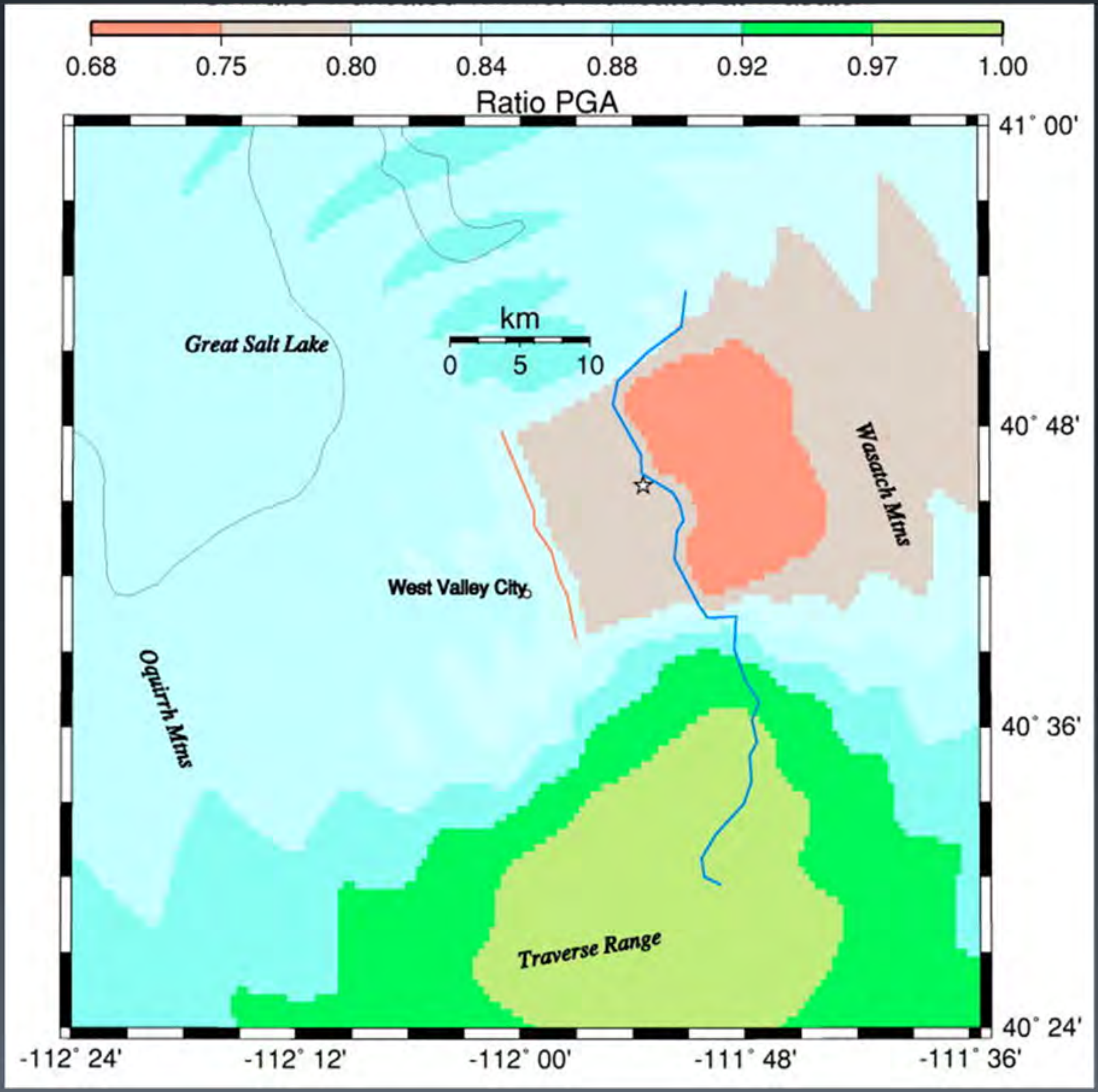
Depth of truncation



Magnitude comparison



Sensitivity study
SLC segment and West Valley fault zone



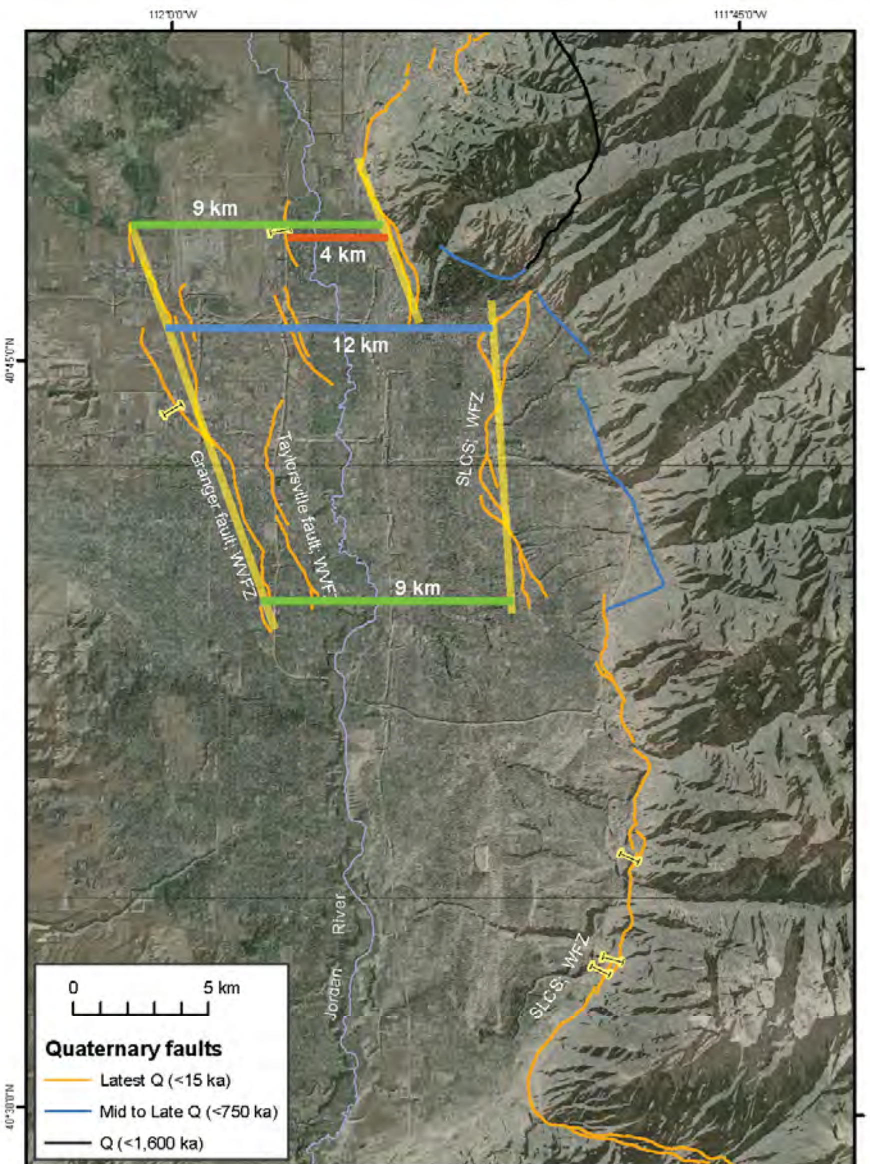
Conclusions

- Historical record suggests that graben-bounding faults do not behave in a predictable manner
- It is possible that none of these historic earthquakes provide an analogy for the seismic potential of the West Valley fault
- If one source is truncated, the hazard will noticeably decrease in the surrounding area

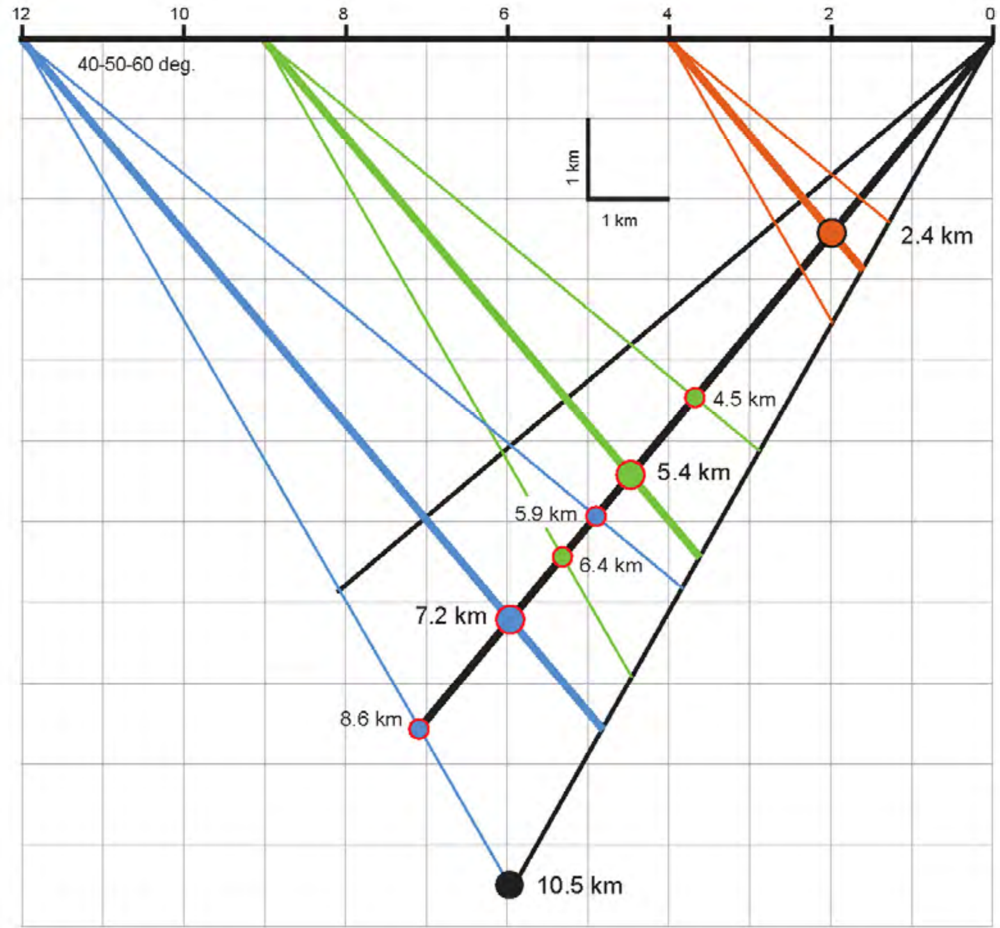
Discussion

- Are graben-bounding pairs properly modeled in the NSHMs?
- What other sensitivity studies are needed?
- Should the USGS modify how M is assigned to the truncated fault?
- Should there be a minimum M?

Consensus recommendation(s) to the USGS



112°0'0"W
111°45'0"W
40°45'0"N
40°30'0"N
9 km
4 km
12 km
9 km
Granger fault; WVFZ
Taylorsville fault; WVF
SLCS; WFZ
SLCS; WFZ
Jordan River
0
5 km
Quaternary faults
Latest Q (<15 ka)
Mid to Late Q (<750 ka)
Q (<1,600 ka)



12
10
8
6
4
2
0
40-50-60 deg.
1 km
1 km
2.4 km
4.5 km
5.4 km
5.9 km
6.4 km
7.2 km
8.6 km
10.5 km

Topic S3 – Does the Rate of Earthquakes Represented on the NSHMs Need to Match the Rate of Historical Earthquakes?

BRPEWG II

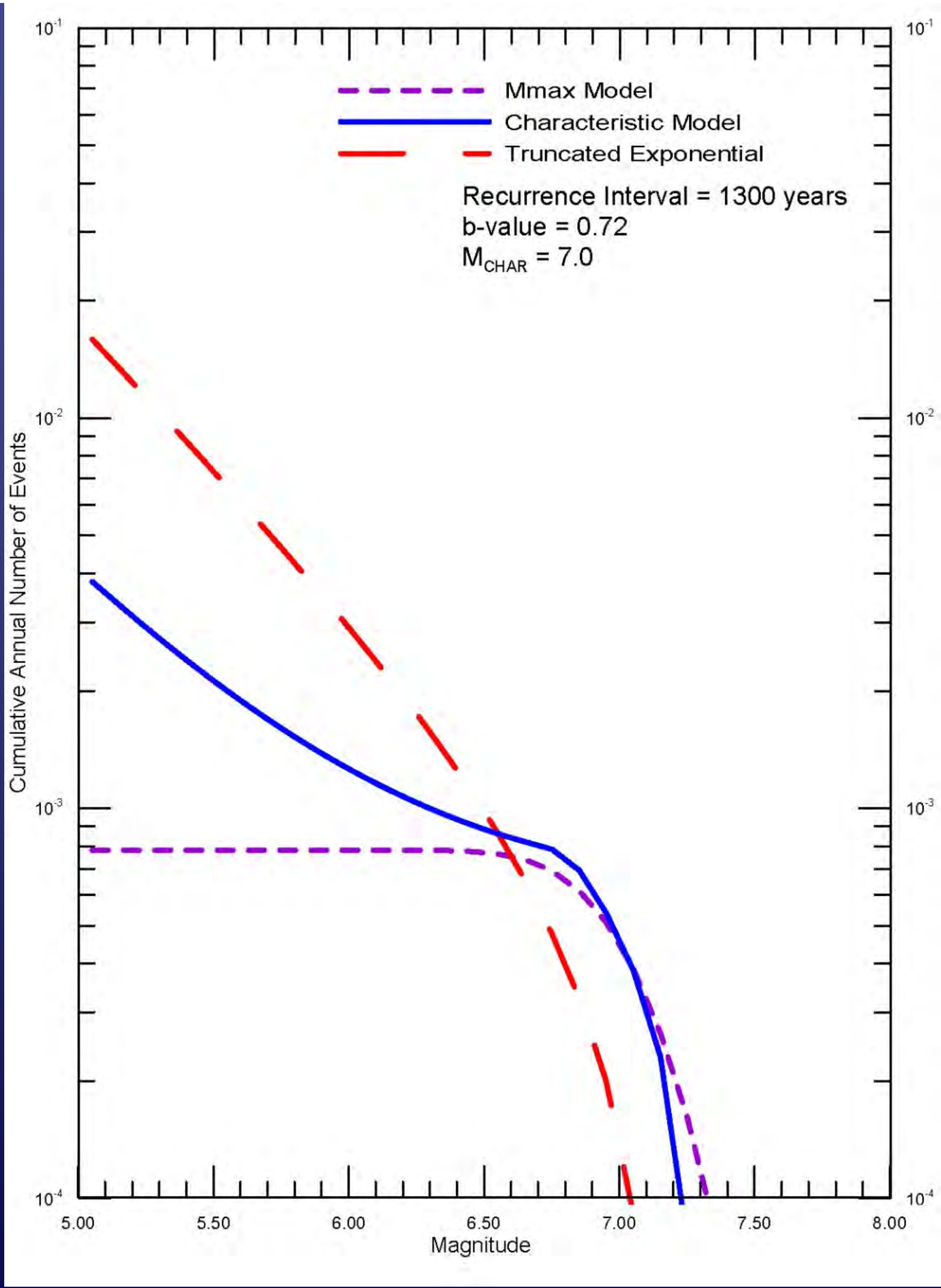
Ivan G. Wong
Seismic Hazards Group
URS Corporation
Oakland, CA

Salt Lake City, UT 14 November 2011

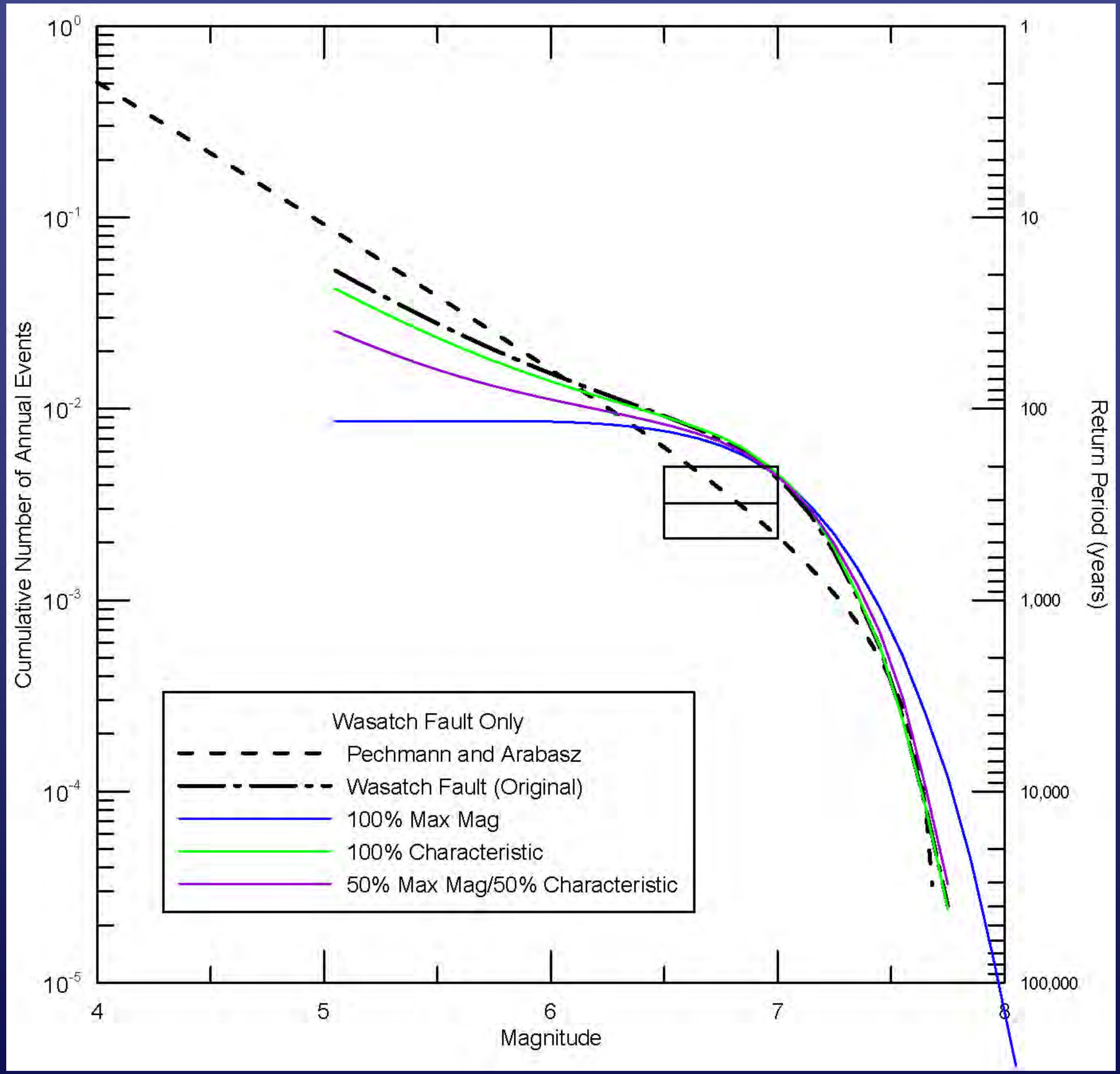
Potential Issues

- Comparison is made over the Intermountain U.S. Should such a comparison be made given very strong regional variations (e.g., Yellowstone)?
- Variable historical earthquake catalog completeness in Intermountain U.S.
- Historical records in Intermountain U.S. do not sample a complete seismic cycle anywhere.
- Are USGS recurrence models for faults an issue?
- Is USGS background Mmax too high?

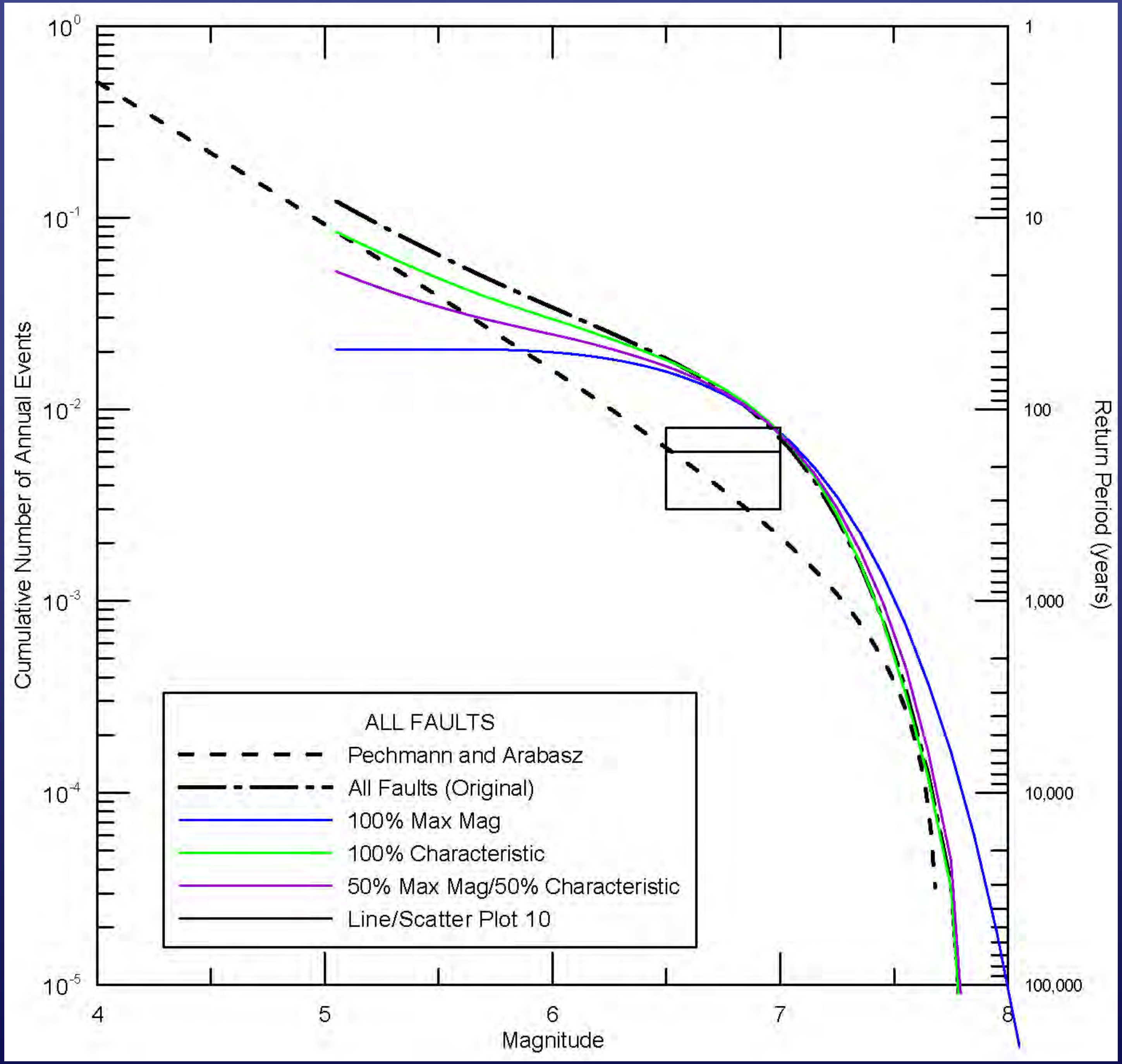
Earthquake Recurrence Models



Recurrence for the Wasatch Fault



Recurrence for the Wasatch Front



Wasatch Front Observations

- The Wasatch Front historical seismicity record is consistent with the paleoseismic record for large surface-faulting earthquakes.
- The seismic source characterization for both the Wasatch fault and the Wasatch Front overpredict the recurrence of M 7 earthquakes compared to the historical record.
- There are few moderate earthquakes (**M** 6-6.5) in the Wasatch Front catalog. Catalog incomplete?

Wasatch Front Observations

- Given the short duration of the historical record, should we expect a good comparison between the historical record and the predicted rate of moderate to large earthquakes?
- If yes, are we overestimating the slip rates of faults in the Wasatch Front????

BRPEWG II - Topic S3

Does the rate of earthquakes represented on the NSHMs need to match the rate of historical earthquakes?

Discussion Leaders: Ivan Wong & Chuck Mueller

USGS WUS hazard model

Faults (slip-rate or recurrence data)

- IMW: ~ 300 crustal faults
- PNW: crustal + megathrust
- CA: WGCEP

Distributions for M_{char} >= 6.5

Distribution for dip: 40, 50, 60 deg

67% char & 33% GR for CA+IMW

Shallow Seismicity (d < 35 km)

1) Declustered catalog M_w >= 4

2) Completeness:

Coastal CA: 1933, 1900, 1850

Other WUS: 1963, 1930, 1850

3) b = 0.80

4) 10^a grids (Weichert):

- Coastal CA
- Extensional WUS
- Non-extensional WUS

Adjust for mag uncertainty & rounding

Background “floor” in 5 zones

5) 50-km smoothing (+ anisotropic)

M_{max} = 7.0 mostly, < 7.0 near faults

Deep Seismicity

Geodetic Sources

Ground-motion relations

Crustal: NGA

Megathrust: Zhao + Youngs + AB03

In-slab: Geomatrix + BA00

&

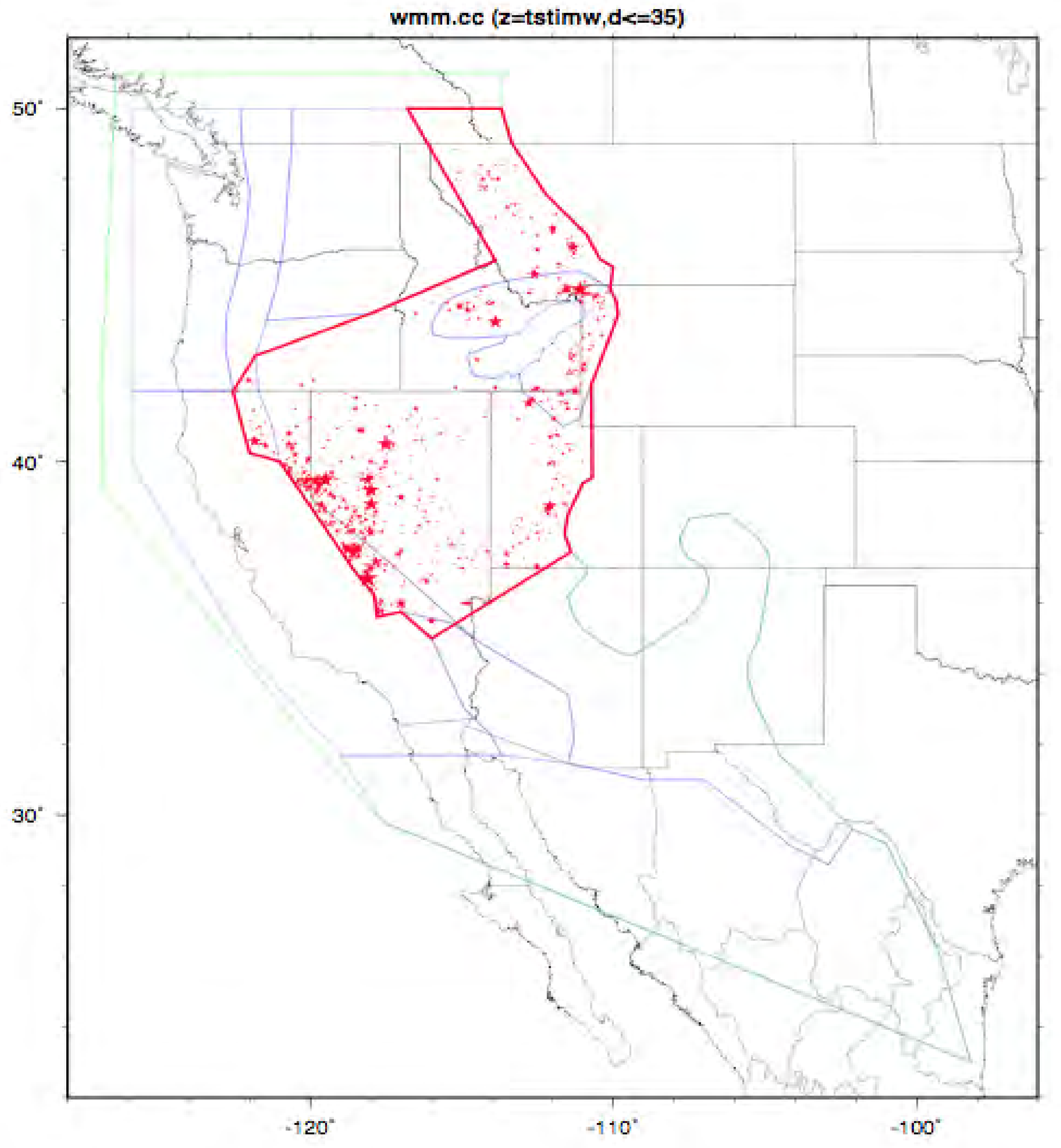
Site condition: 760–m/s

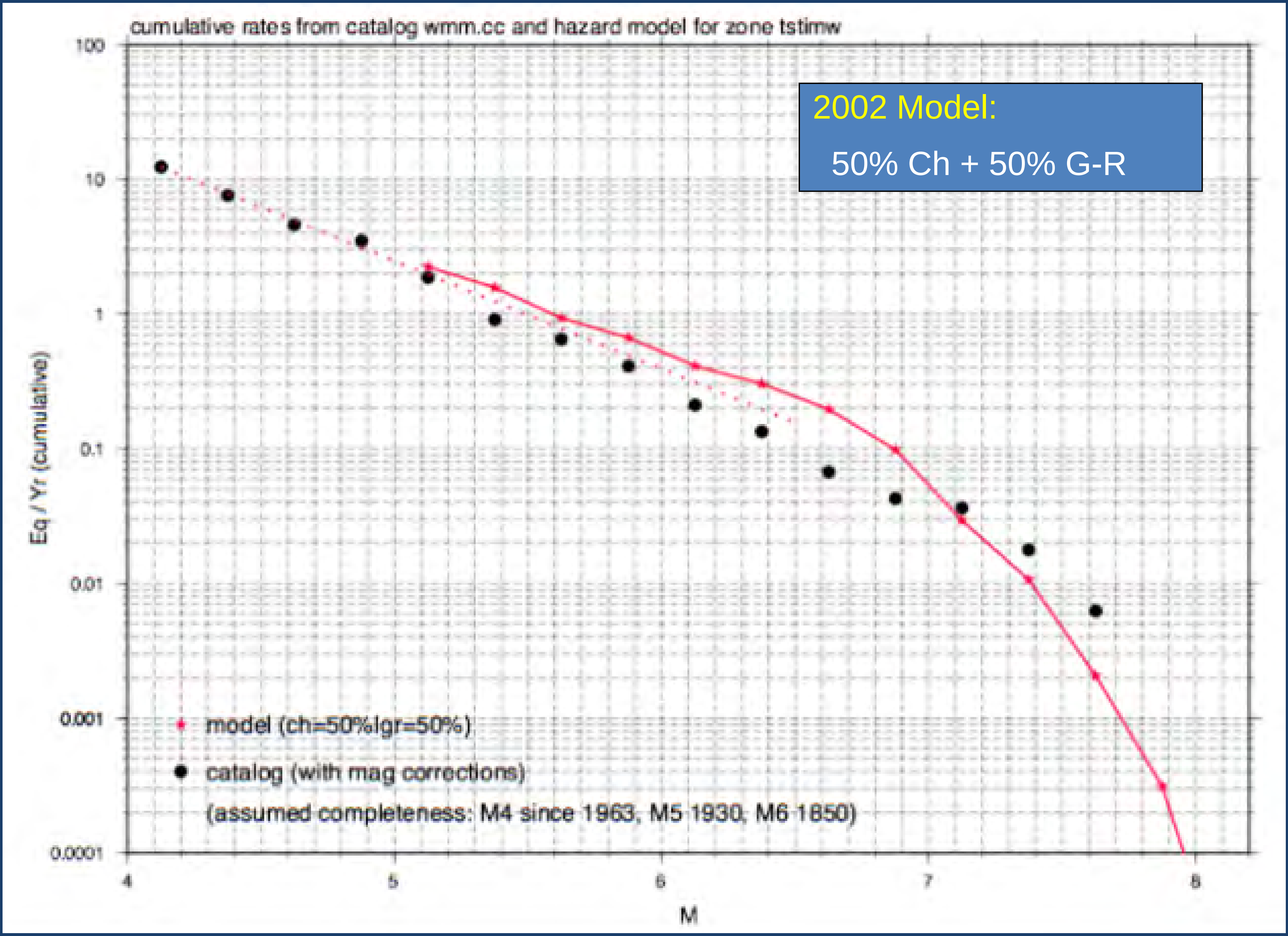
Pre-2008 California bulge

- 2008 “fix”:
  - Reduce moment rate on A & B faults 10% to account for aseismic slip or aftershocks
  - 1/3 factor on background seismicity for M_w 6.5+
  - These changes (+ fault changes) reduce the model rate, bringing it within the 95% confidence limits of the historical rate
- Possible future fix (WGCEP): link faults together to shift moment out of the M ~6.5 range

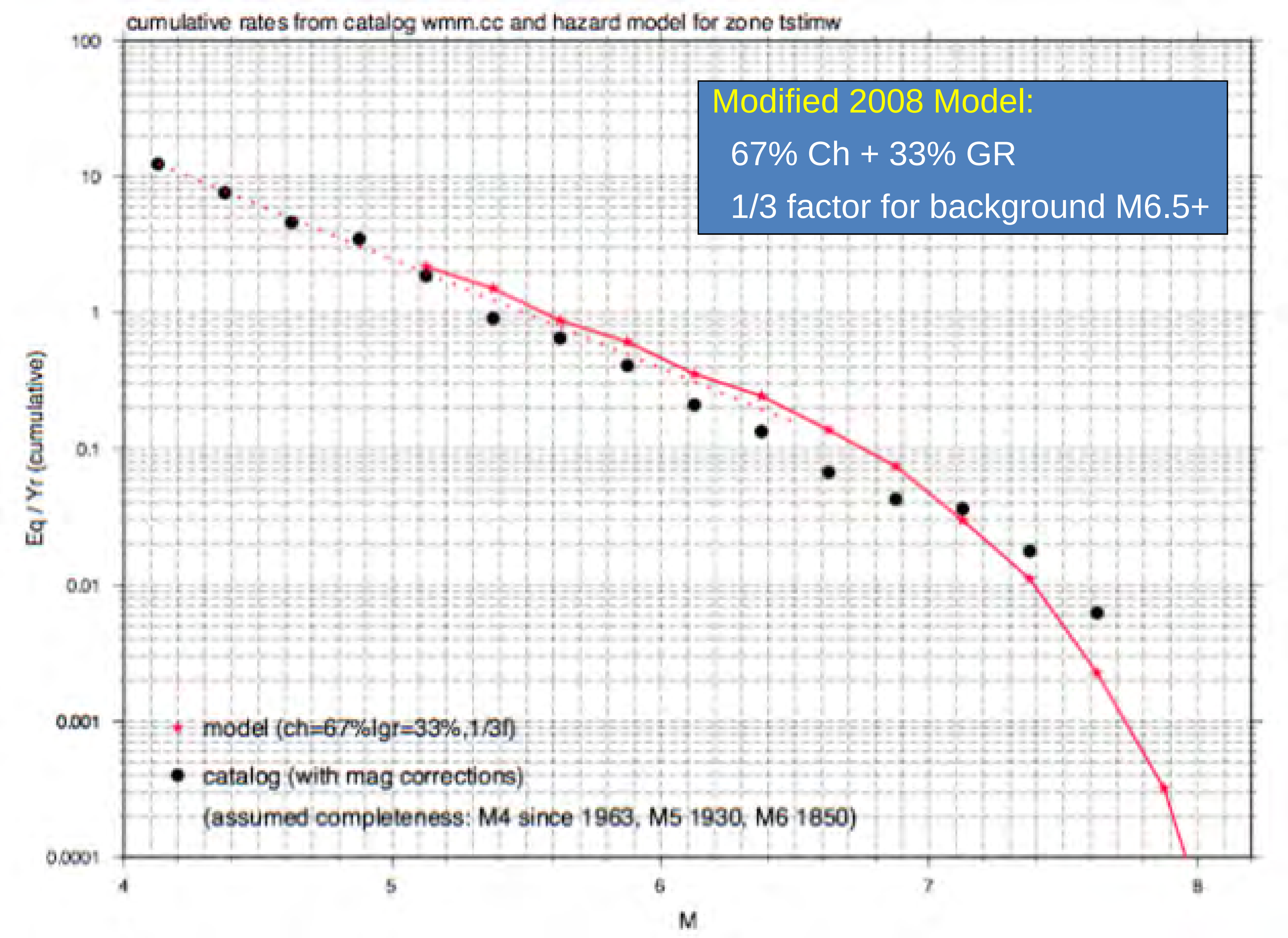
This got us wondering: Do we have a bulge problem in the intermountain west?

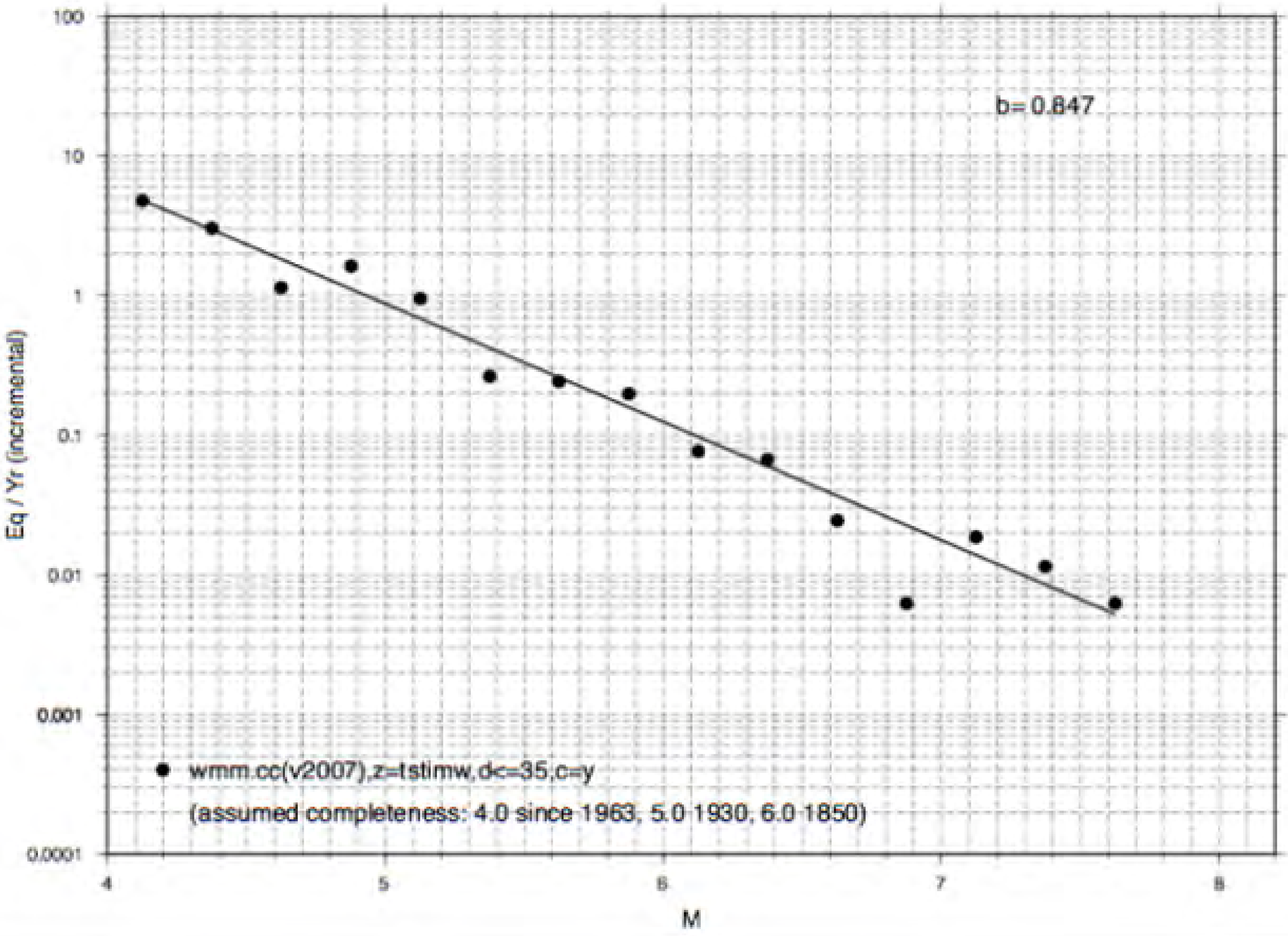
Compare model & historical earthquake rates in WUS test zone (standard sanity check on any seismic hazard model…)


wmm.cc (z=tstimw,d<=35)
50˚
40˚
30˚
-120˚
-110˚
-100˚

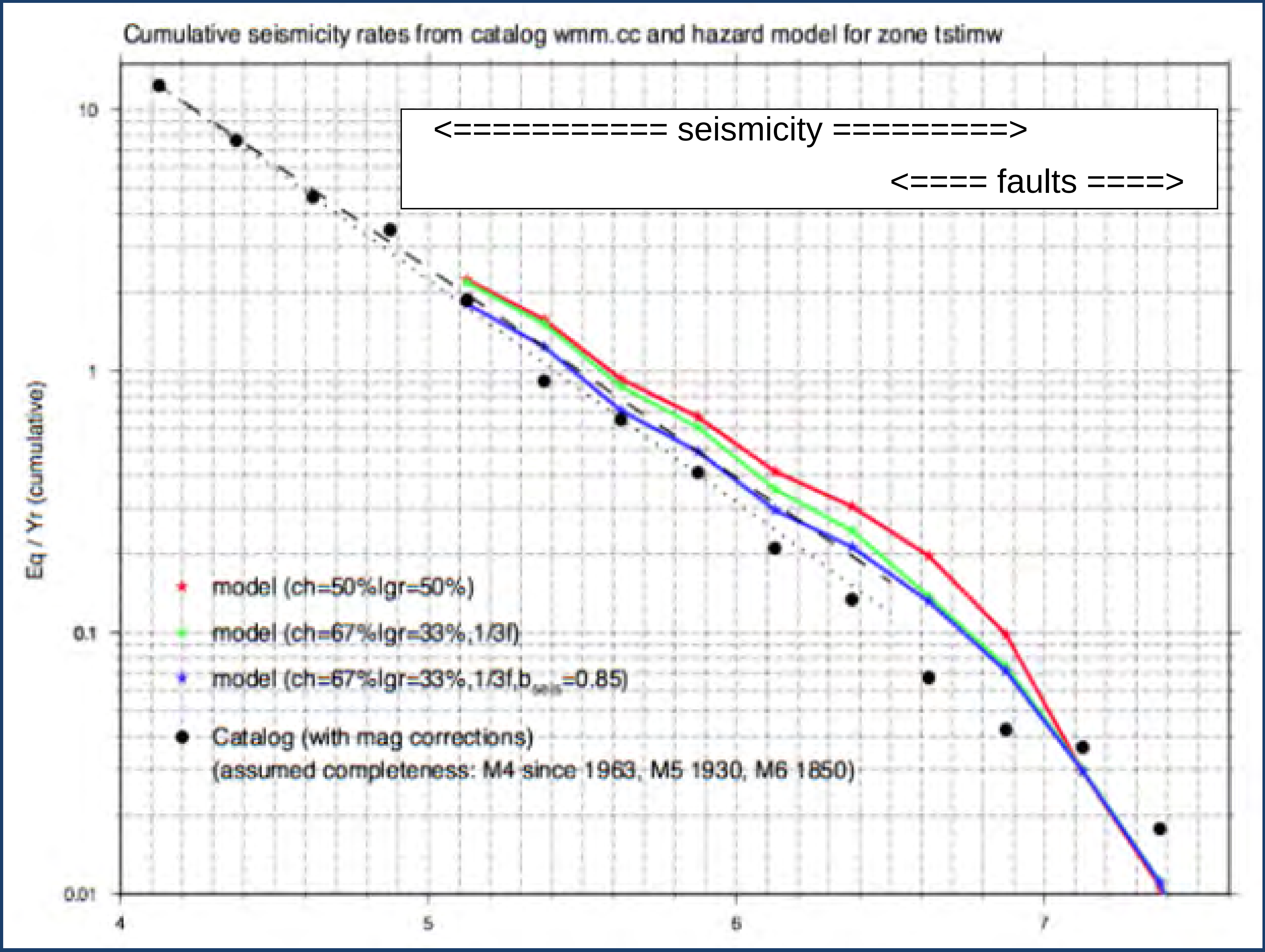


cumulative rates from catalog wmm.cc and hazard model for zone tstimw
2002 Model:
50% Ch + 50% G-R
Eq / Yr (cumulative)
100
10
1
0.1
0.01
0.001
0.0001
4
5
6
7
8
M
model (ch=50%lgr=50%)
catalog (with mag corrections)
(assumed completeness: M4 since 1963, M5 1930, M6 1850)


cumulative rates from catalog wmm.cc and hazard model for zone tstimw
Modified 2008 Model:
67% Ch + 33% GR
1/3 factor for background M6.5+
Eq / Yr (cumulative)
100
10
1
0.1
0.01
0.001
0.0001
4
5
6
7
8
M
model (ch=67%lgr=33%,1/3f)
catalog (with mag corrections)
(assumed completeness: M4 since 1963, M5 1930, M6 1850)



b= 0.847
Eq / Yr (incremental)
100
10
1
0.1
0.01
0.001
0.0001
4
5
6
7
8
M
wmm.cc(v2007),z=tstimw,dc=35;c=y
(assumed completeness: 4.0 since 1963, 5.0 1930, 6.0 1850)



Cumulative seismicity rates from catalog wmm.cc and hazard model for zone tstimw
<=========== seismicity =========>
<==== faults ====>
Eq / Yr (cumulative)
10
1
0.1
0.01
4
5
6
7
model (ch=50%lgr=50%)
model (ch=67%lgr=33%,1/3f)
model (ch=67%lgr=33%,1/3f,b$_{seis}$=0.85)
Catalog (with mag corrections)
(assumed completeness: M4 since 1963, M5 1930, M6 1850)

Observations & Interpretation

- ✓ 2002 model bulge: factor of ~3 near M 6.5
- ✓ Changing Ch / G-R from 50% / 50% to 67% / 33% + the 1/3 factor on seismicity for M > 6.5 reduces model bulge to factor of ~2
- ✓ Changing *b* from 0.80 to 0.85 reduces model rate for M < ~6.5, but doesn't change it for M > 6.5. Does this suggest that, compared to California, the contribution of seismicity relative to faults for M > 6.5 is smaller? If so the 1/3 factor on seismicity M > 6.5 that reduced the bulge in California might be less effective in IMW.

Questions:

- ✓ Should we worry about a bulge?
- ✓ How will potential changes to the model already being considered affect rates ~ M 6.5? (changing dips?, fixing fault intersections?, getting characteristic magnitudes from area rather than SRL for some faults?, b = 0 branch for G-R?, other?)
- ✓ Should we reduce the G-R percentage further?
- ✓ Should we regionalize *b* values?
- ✓ Other fixes?

Addressing Slip-Rate Uncertainty in the NSHM

BRPEWG II meeting
Issue G3
Discussion Leaders: Steve Wesnousky
Kathy Haller

The Question

- The USGS seeks guidance on how to estimate the uncertainty for the slip rates on BRP normal-slip faults, especially for faults that have little or no slip-rate data. The method used in California to estimate the uncertainty has varied the upper and lower bounds of the slip rate by plus-or-minus 50%. Thus the uncertainty bounds for a fault that has a slip rate of 5 mm/yr would be 7.5 mm/yr and 2.5 mm/yr. Do these bounding values encompass the fifth and ninety-fifth percentiles for this fault?

Outline

- Review UQFWG slip-rate uncertainties
- Sensitivity studies of UQFWG determinations
- Slip-rate uncertainties for IMW sources
- Examples of paleoseismic records suggesting clustering

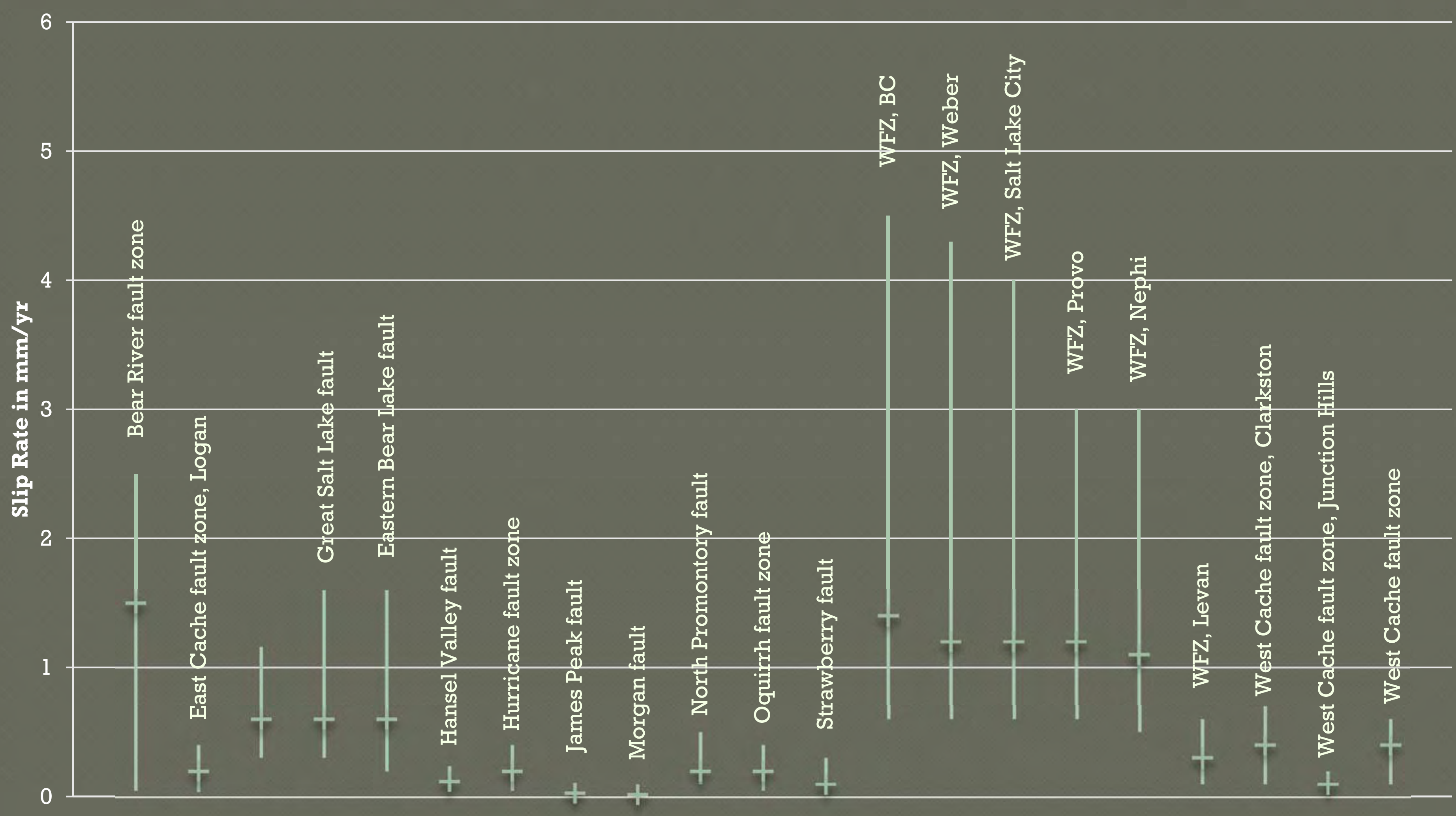
UQFWG uncertainties

- Working group reviewed all faults in Utah that had been trenched prior to 2003 and reported min, max, and preferred slip rates for 21 sources
- Slip rate uncertainty represents 5 and 95 percentiles
- The range of the model compares average slip rates that cover different time periods and/or different offset markers along a given fault

UQFWG uncertainties

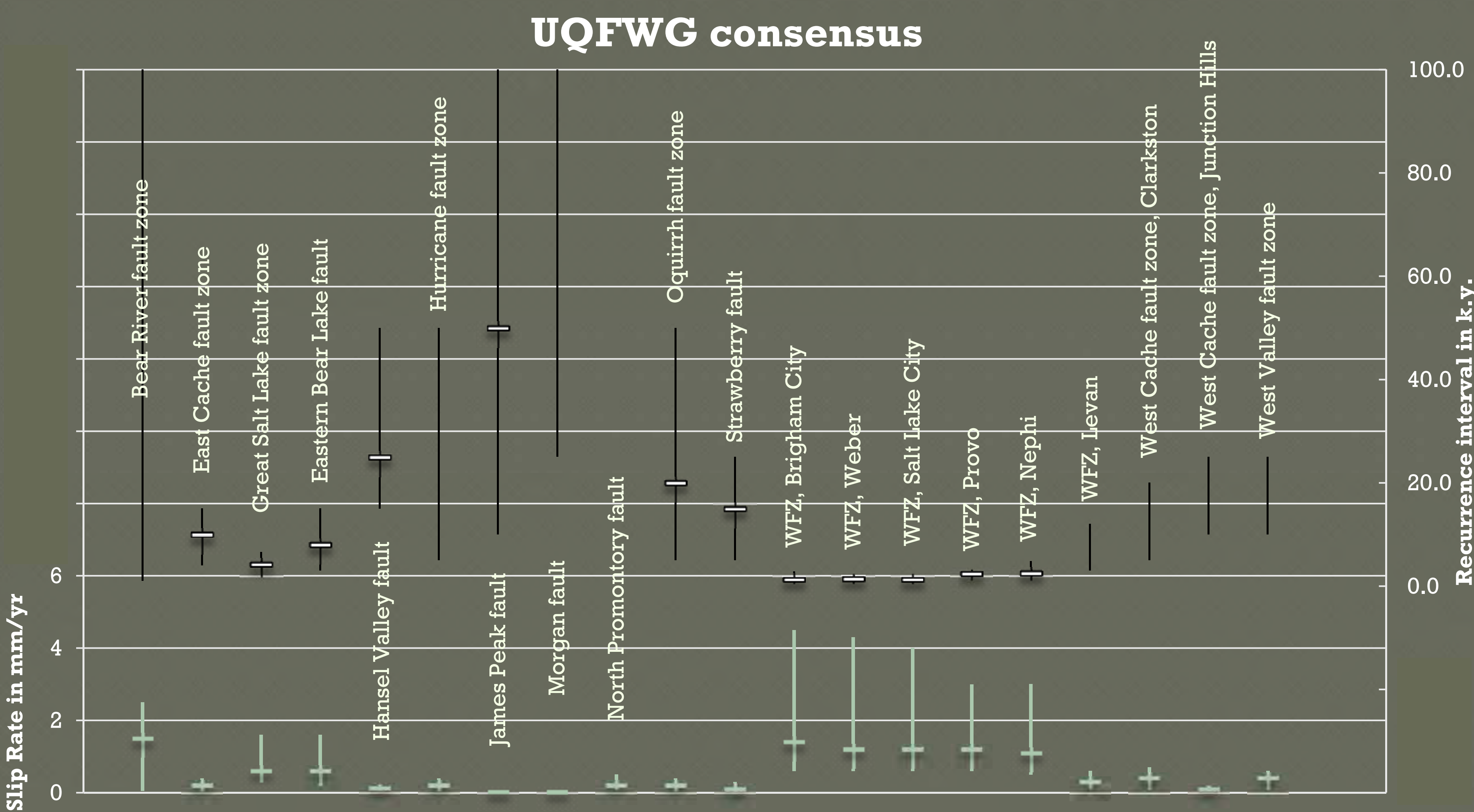
- Reported uncertainties reflect consensus view of clustering
- Minimum slip rates are from out of cluster series
- Maximum slip rate are from in-cluster series

UQFWG consensus slip rates



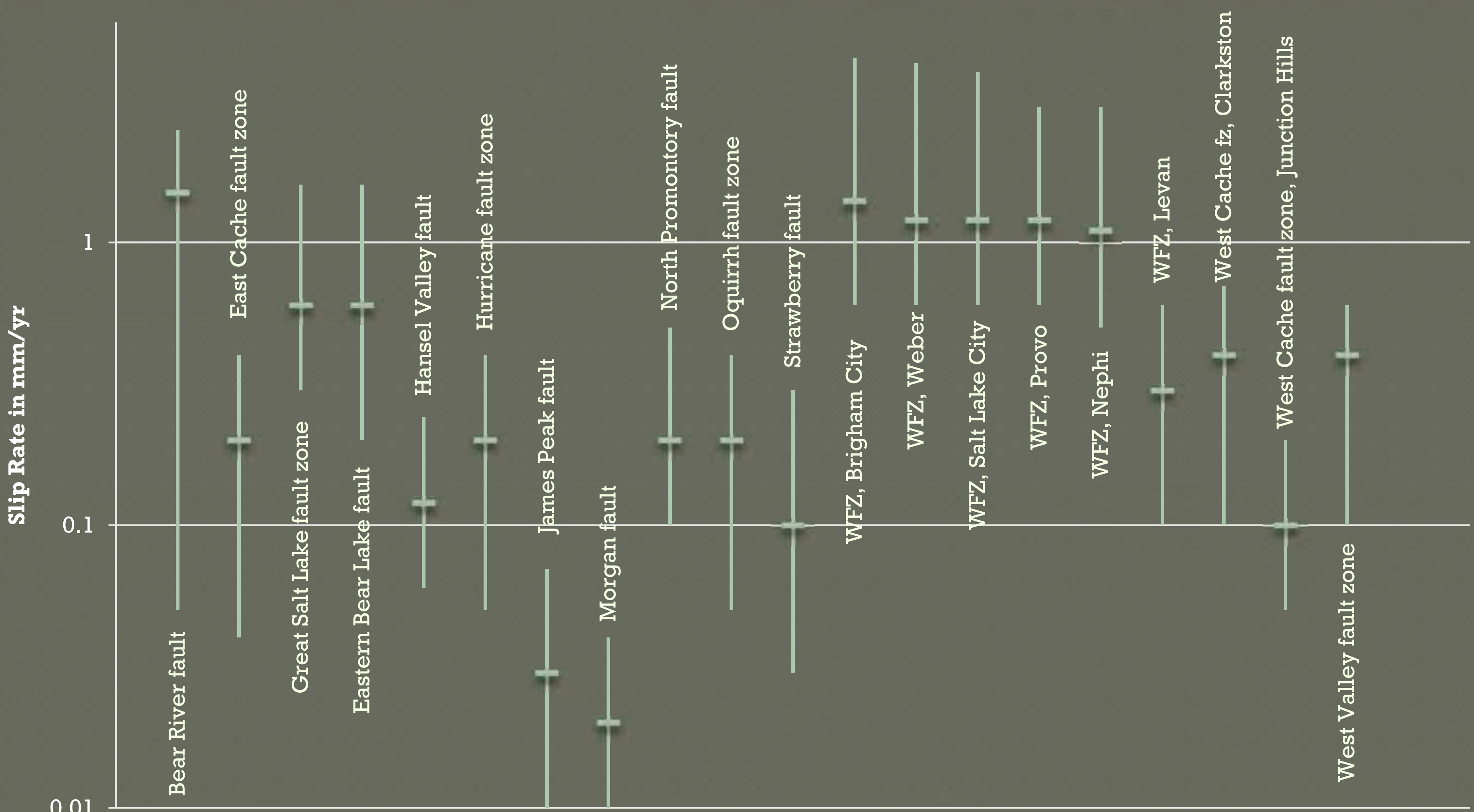
Data from Lund 2005

Consensus slip rate and recurrence intervals



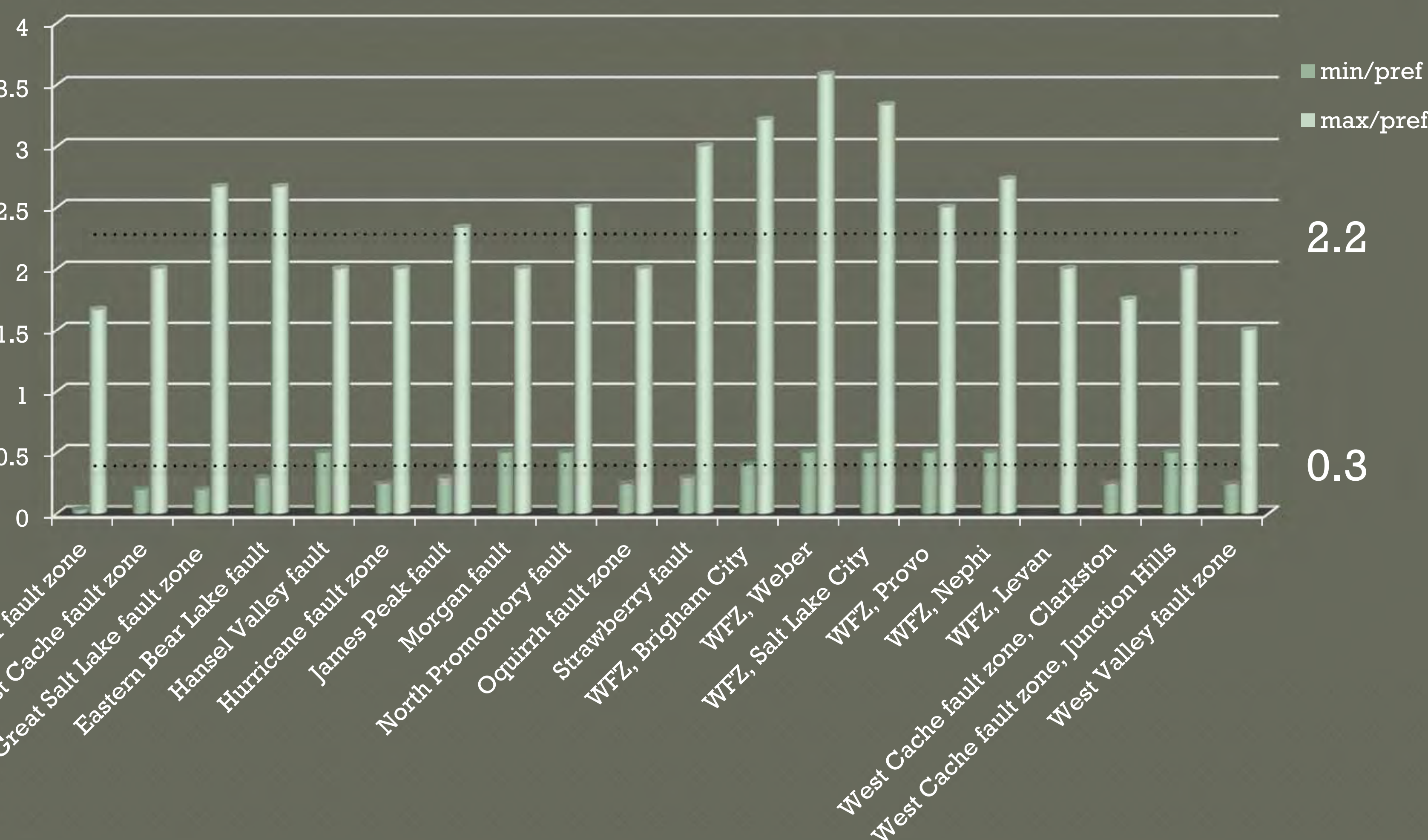
Data from Lund 2005

Log of slip rate

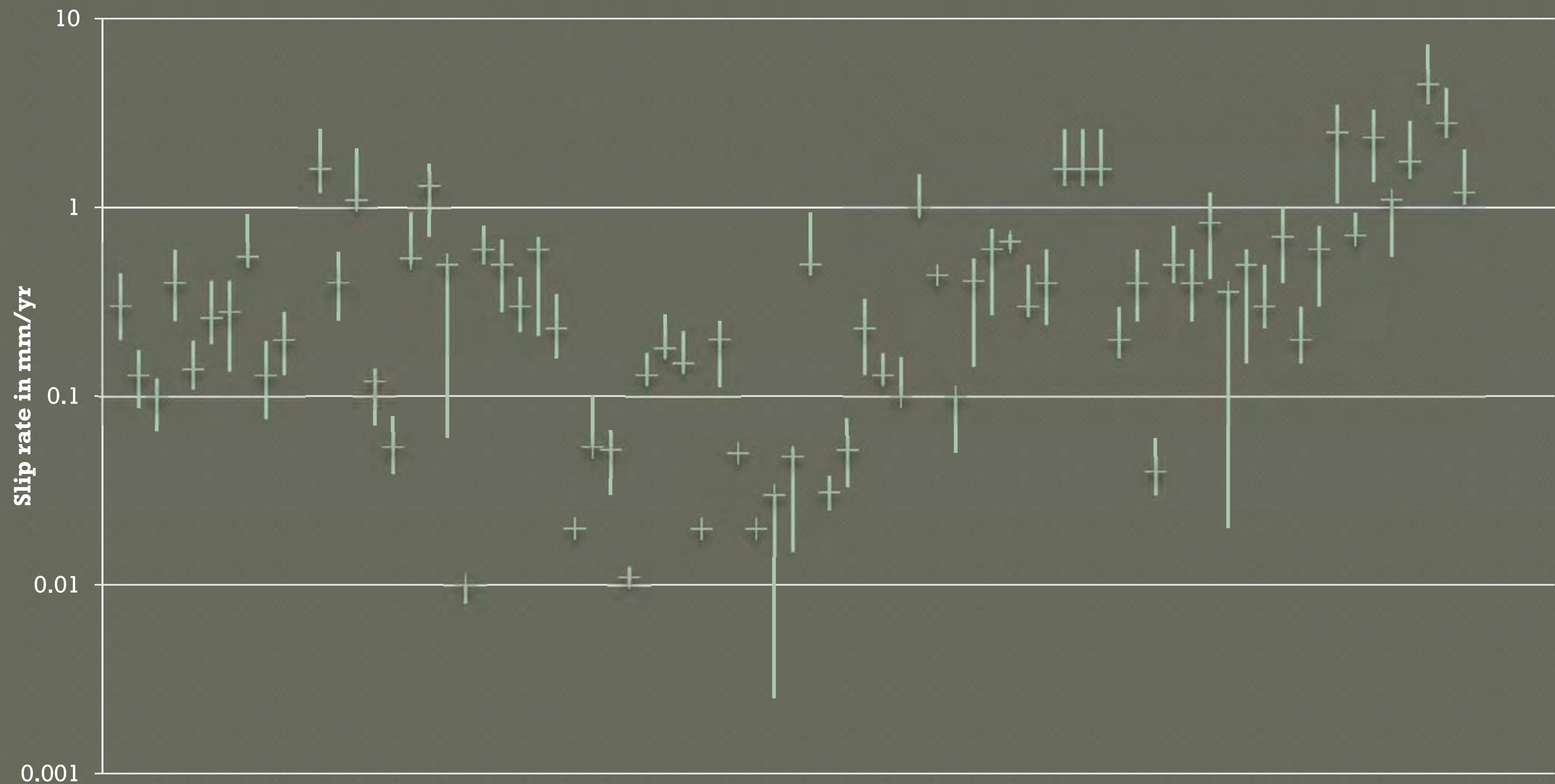


Data from Lund 2005

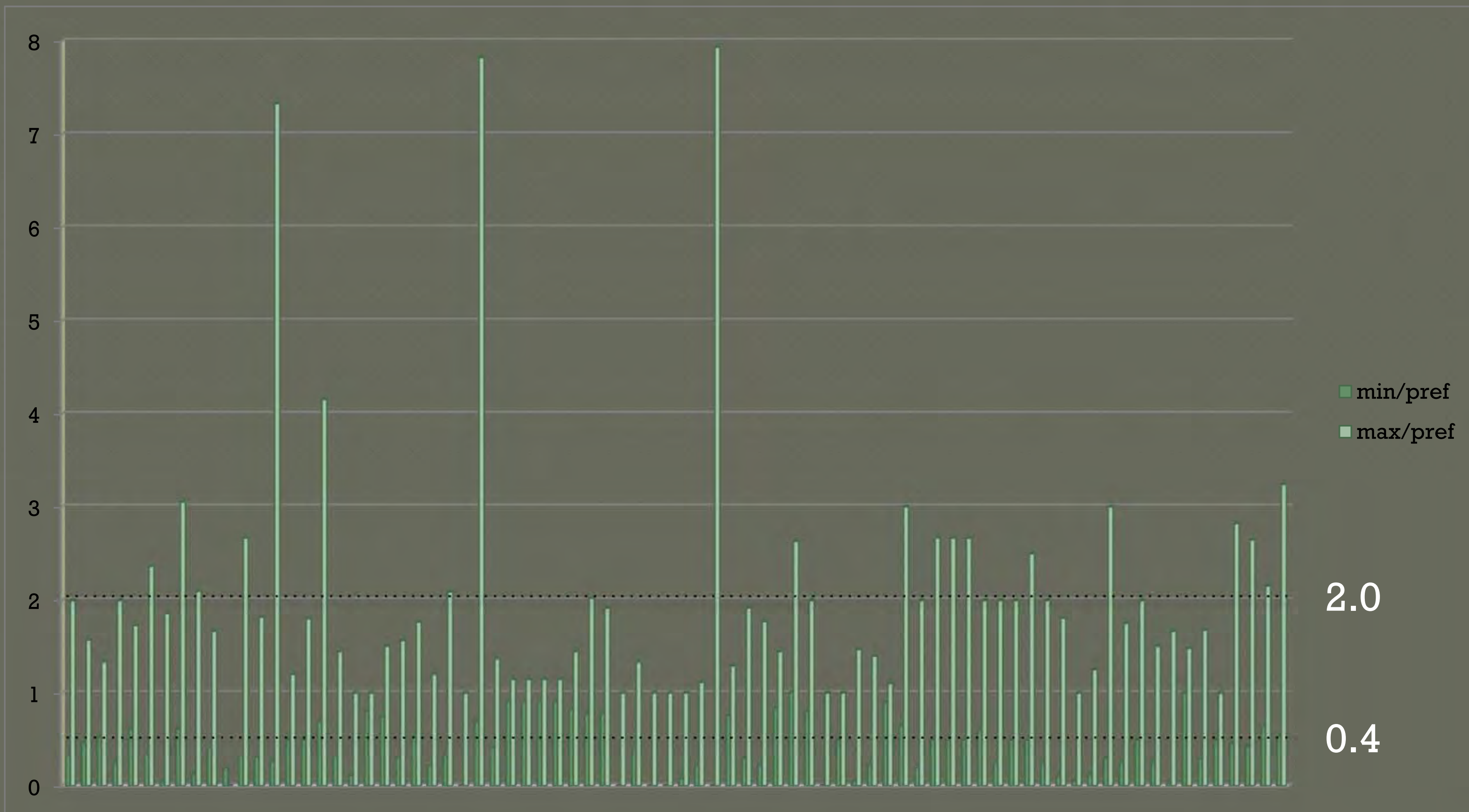
UQFWG slip-rate ratio



IMW slip-rate uncertainties



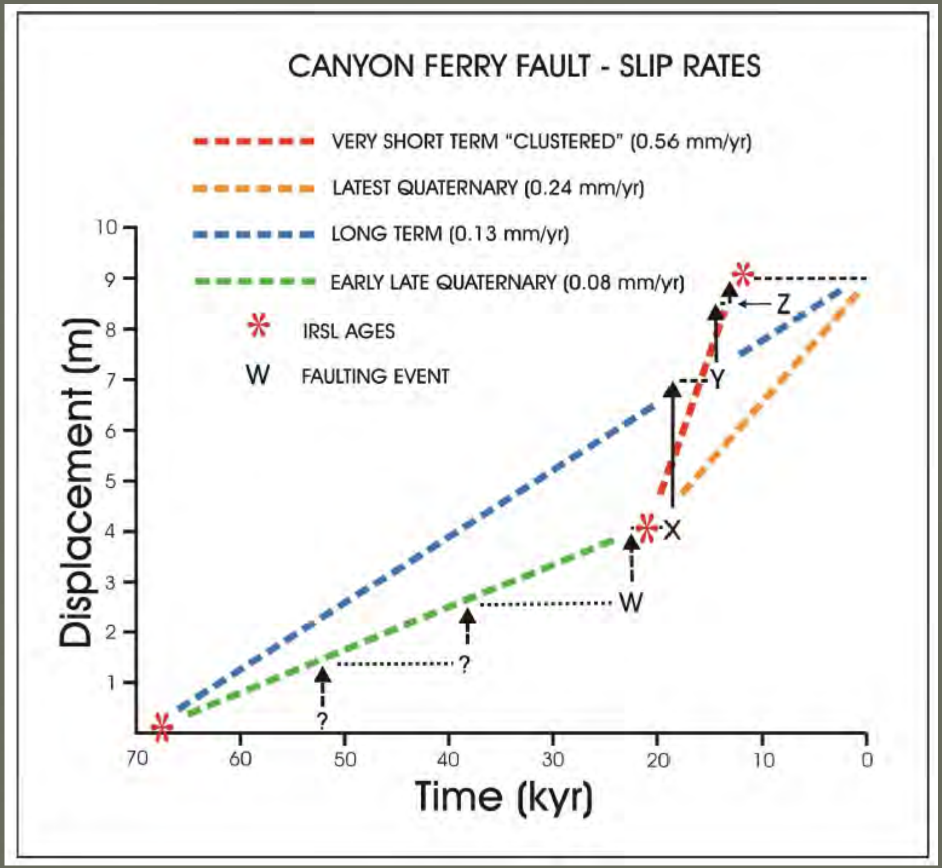
IMW slip-rate ratio



Clustering or Poisson

- "preponderance of evidence that some faults don't have regularly spaced events in time"—Zechar and Frankel 2009
- "For short series (fewer than 10 intervals) sample means tend to reflect the median of an asymmetric recurrence distribution possibly leading to an overestimate of the hazard.." –Parsons 2008
- Faults will yield different long-term slip rates depending on how far back (how many earthquakes) we are able to extend the paleoseismic record.

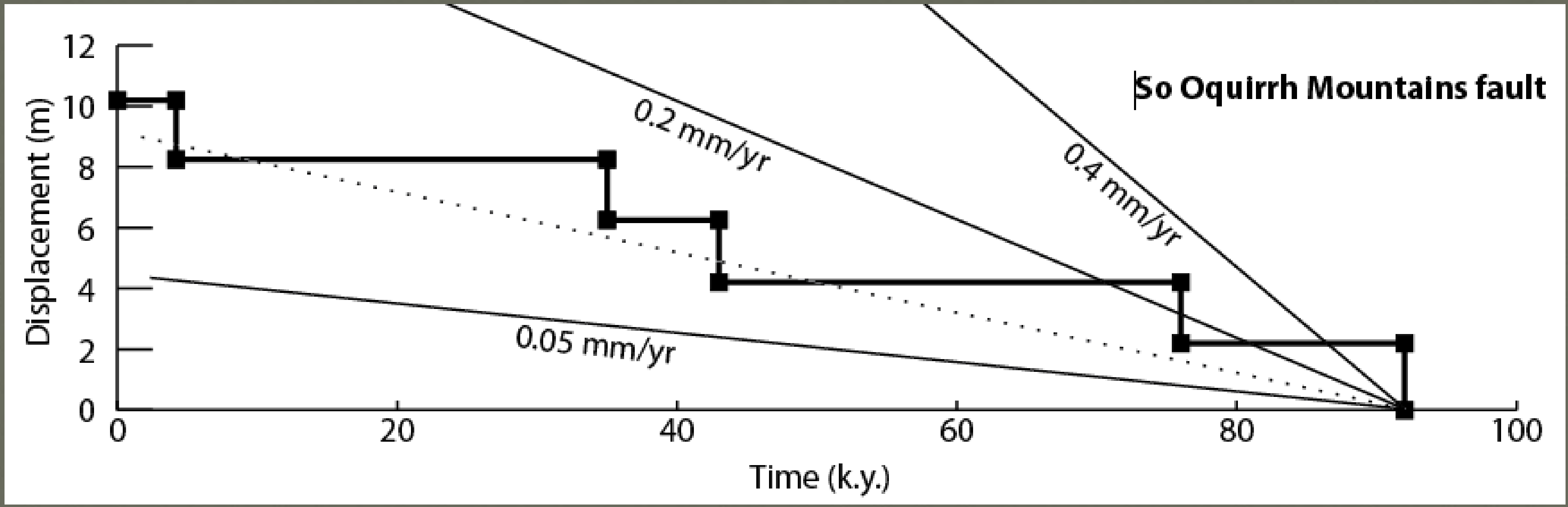
Clustering and slip rate



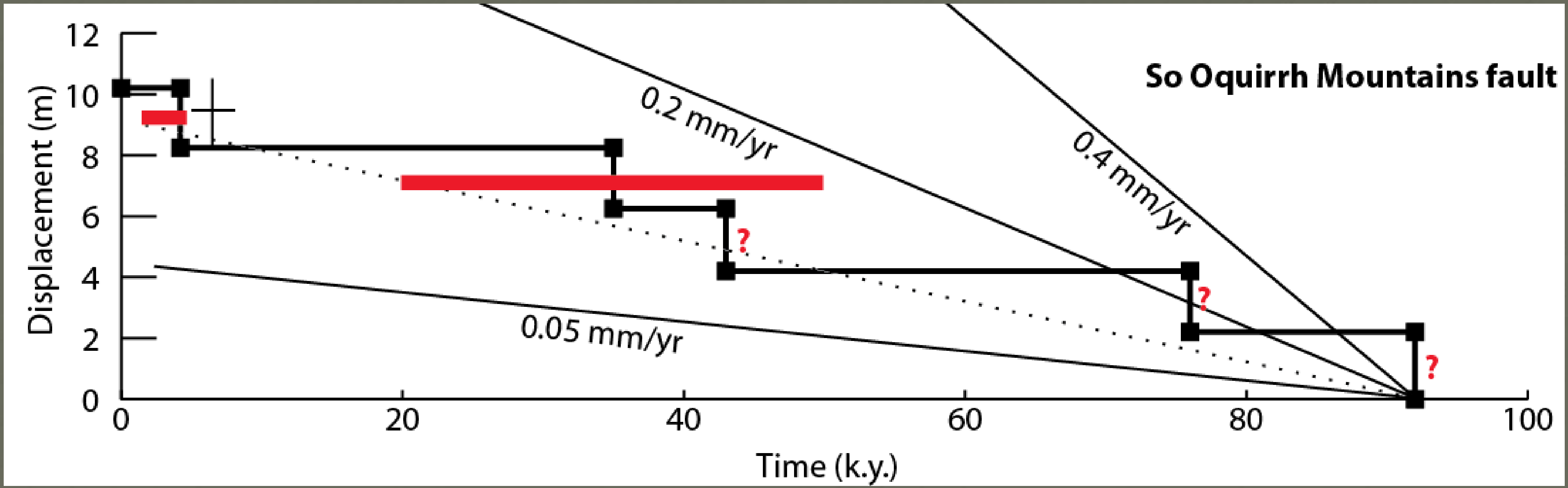
from Anderson and others 2004

- In cluster slip rate 0.56 mm/yr spanning 12% of the record
  2-3 events total offset 5 m
- Out of cluster slip rate 0.8 mm/yr spanning 70% of the record unknown number of events total offset 4.1 m

Slip-predictable model

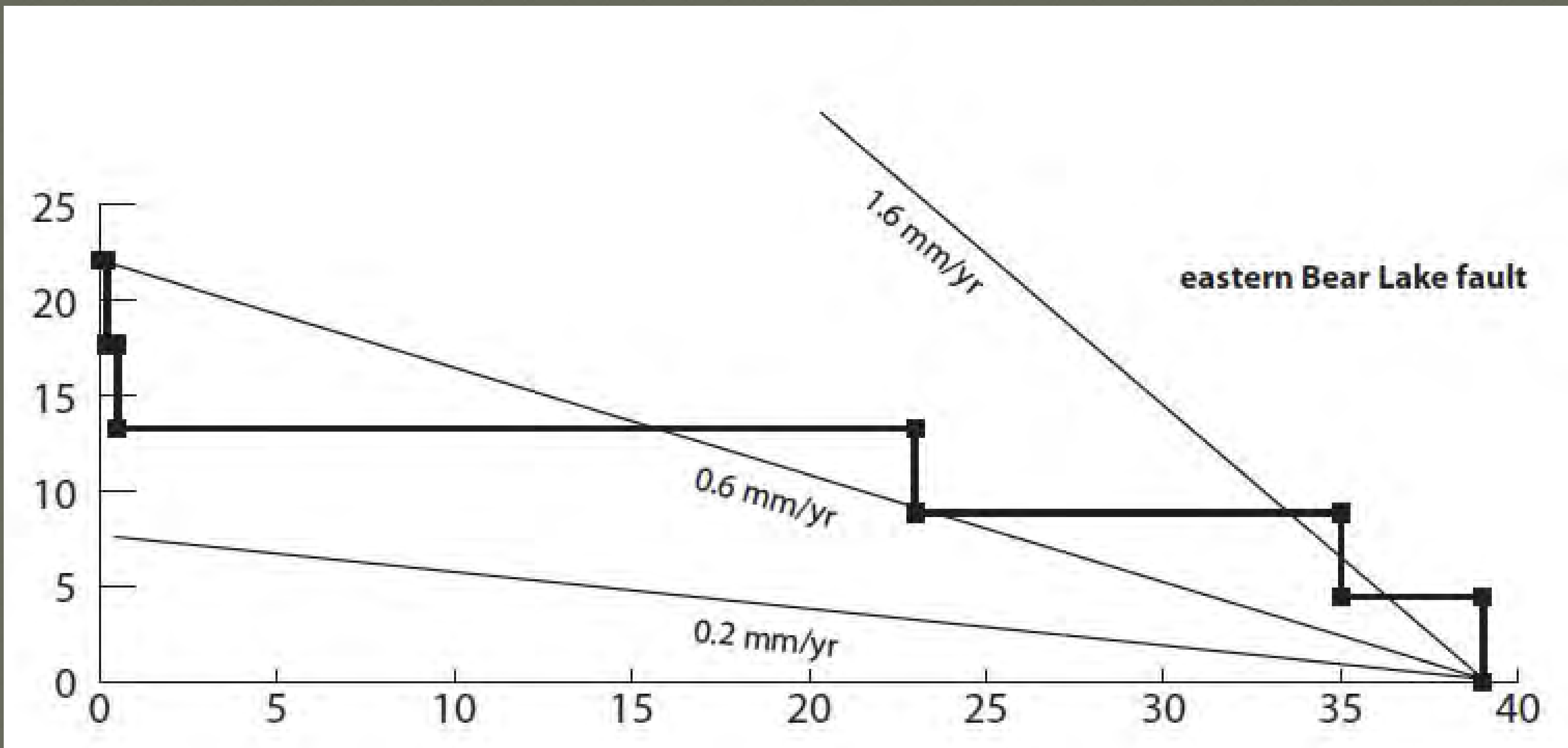


Data uncertainty



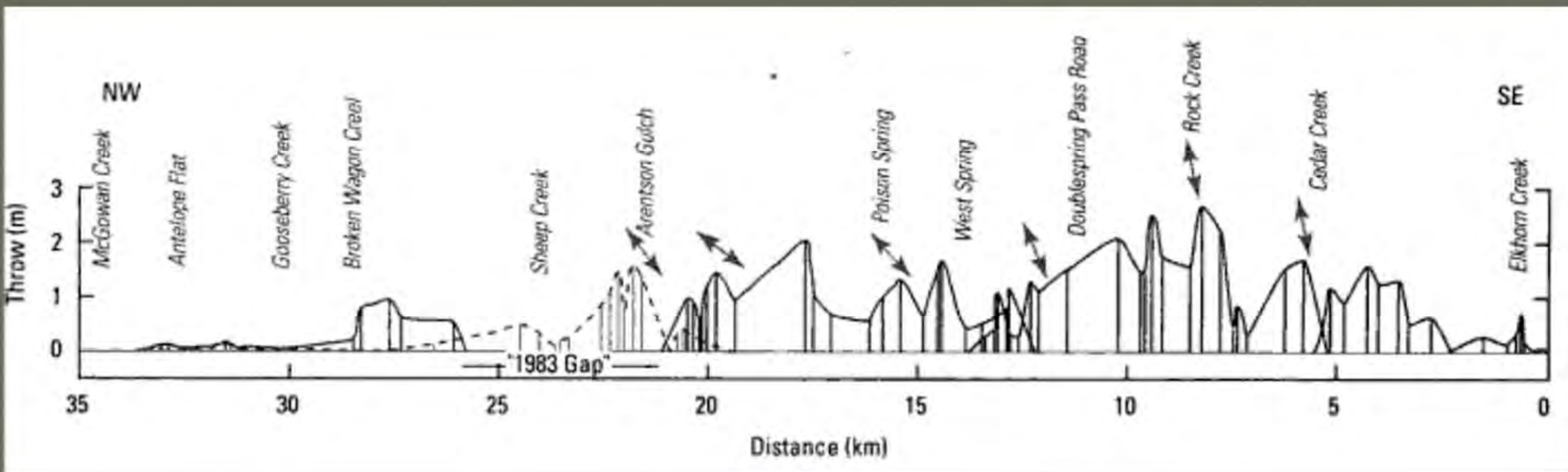
Event timing from Lund 2005

Another slip-predictable model



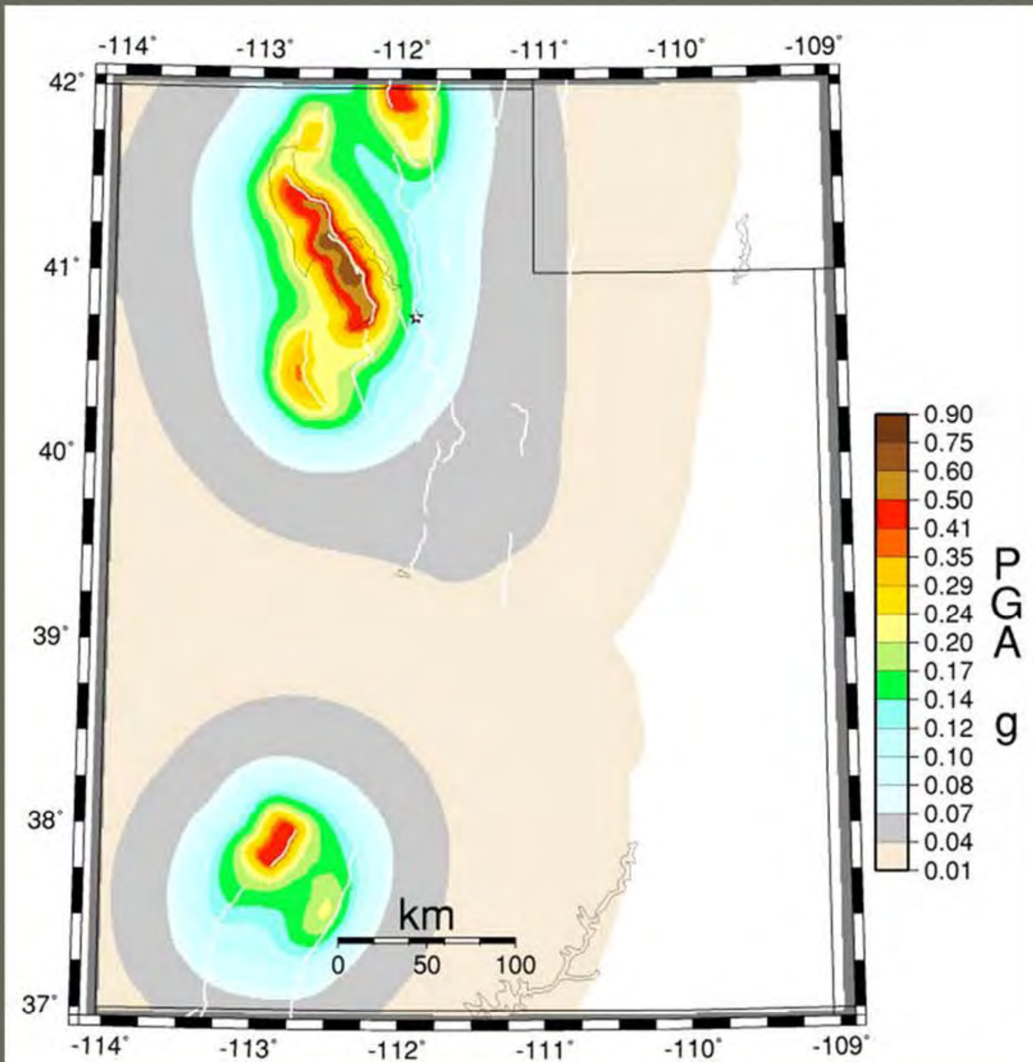
Event timing from Lund 2005

Have we addressed distribution of slip?



- "Skewed distributions are particularly common when mean values are low, variance is large, and values cannot be negative"
- "What is the difference between normal and log-normal variability? Both forms of variability are based on a variety of forces acting independently of one another. A major difference, however, is that the effects can be additive or multiplicative, thus leading to normal or log-normal distributions, respectively."
- --Limpert, Stahel, and Abbt 2001

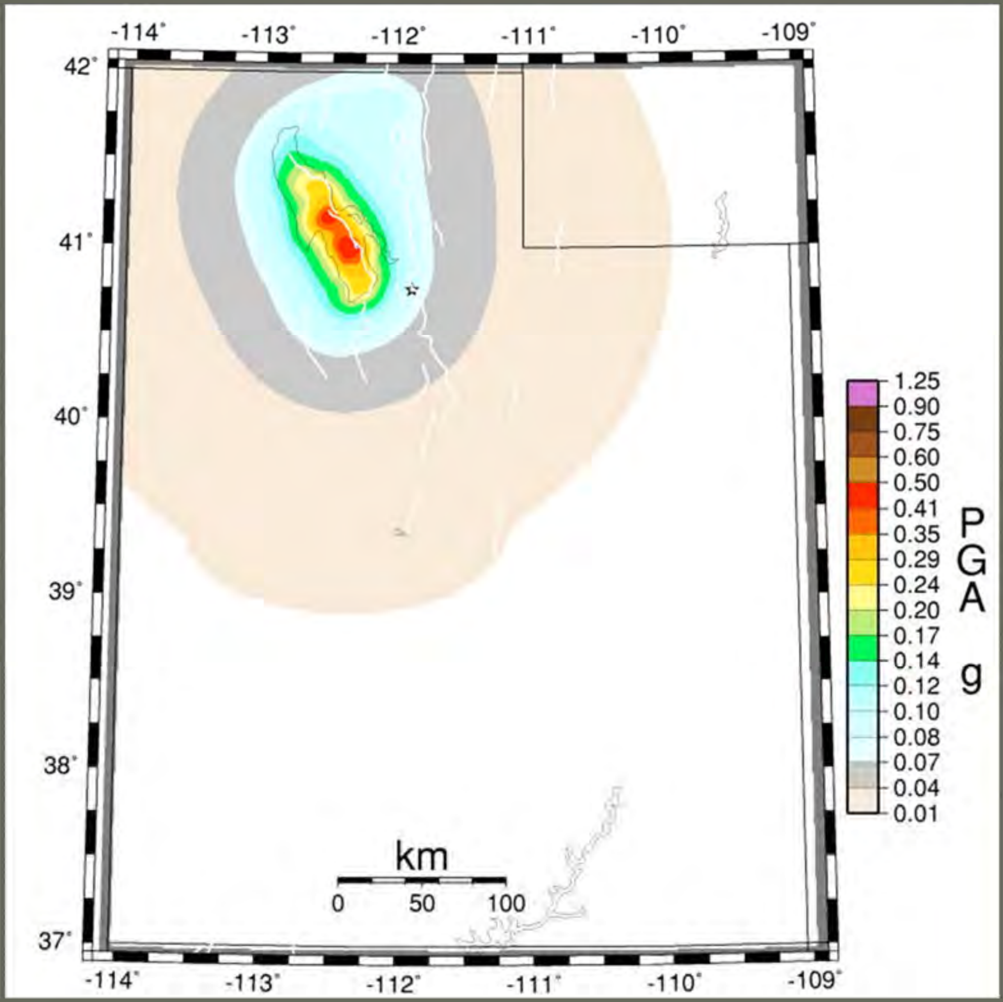
Preferred slip rates—UQFWG



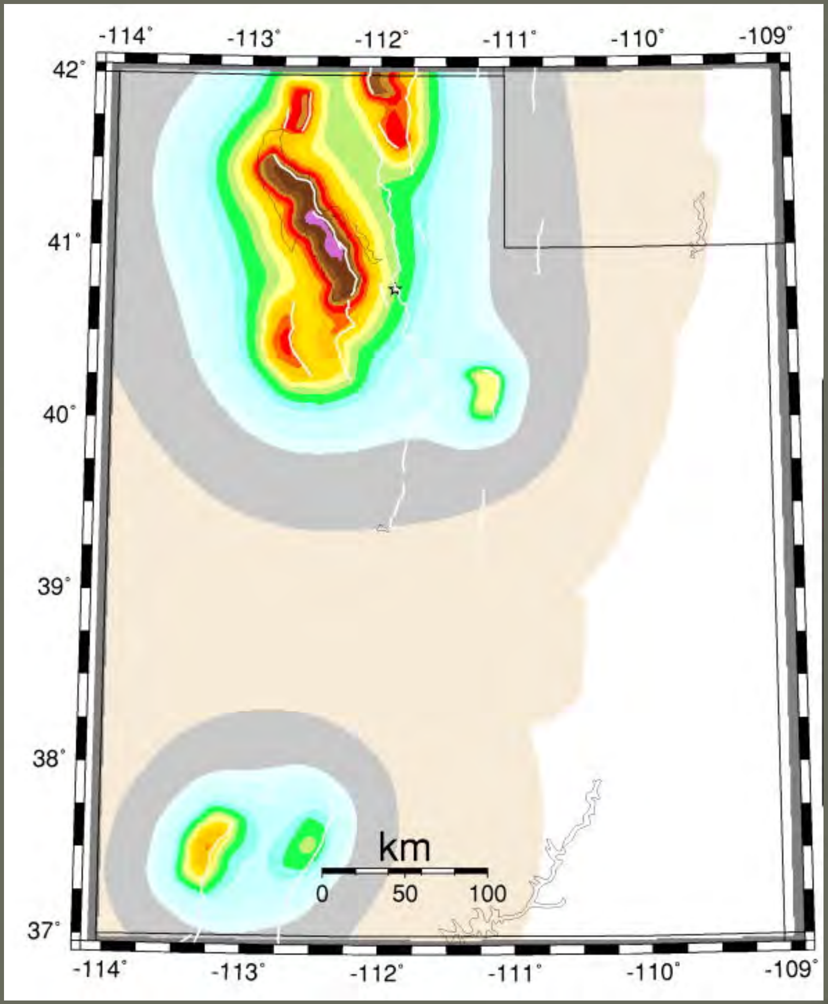
- PGA 2% in 50 yr
- Includes 1/3 GR and 2/3 Char
- 760 m/sec Vs30
- Sources (white lines) have ±10° dip uncertainty

Alternative slip rates—UQFWG

5 PERCENTILE SLIP RATE



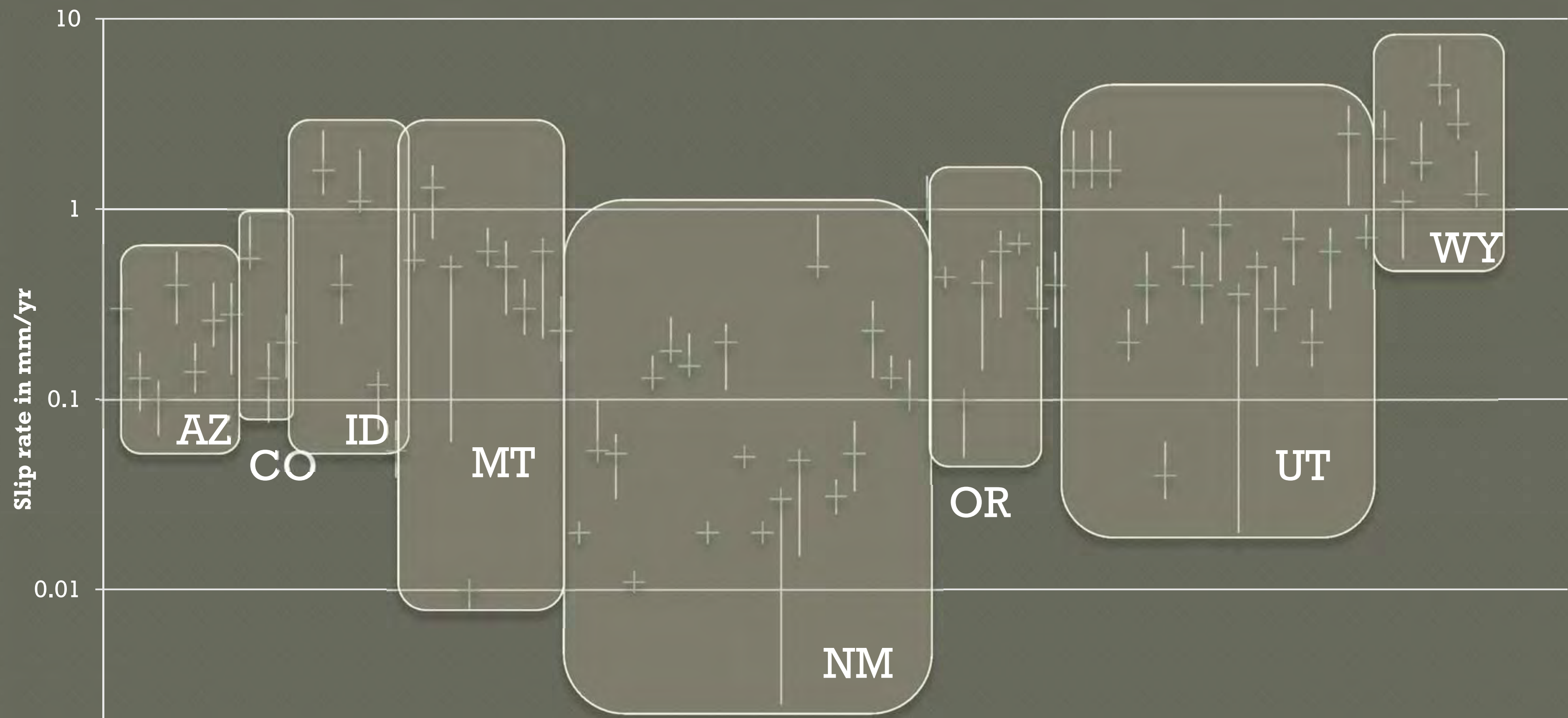
95 PERCENTILE SLIP RATE



Discussion

- Should we expect slip rate uncertainty to have normal distributions?
- UQFWG estimates and uncertainty compiled for surrounding states demonstrate considerable spread, but are in broad agreement. Does assigning ±50% make sense for IMW slip-rate uncertainties?
- Which paleoseismic records are long enough to evaluate clustering?

IMW slip-rate uncertainties



BRP EWG II
Introduction to Issue S4

Magnitude Uncertainty

John G. Anderson
Chuck Mueller

NEVADA Seismological Laboratory

Issue S4

- Issue S4: What are the sources and levels of uncertainty in the earthquake magnitudes contained in the seismicity catalogs used in the NSHMs?

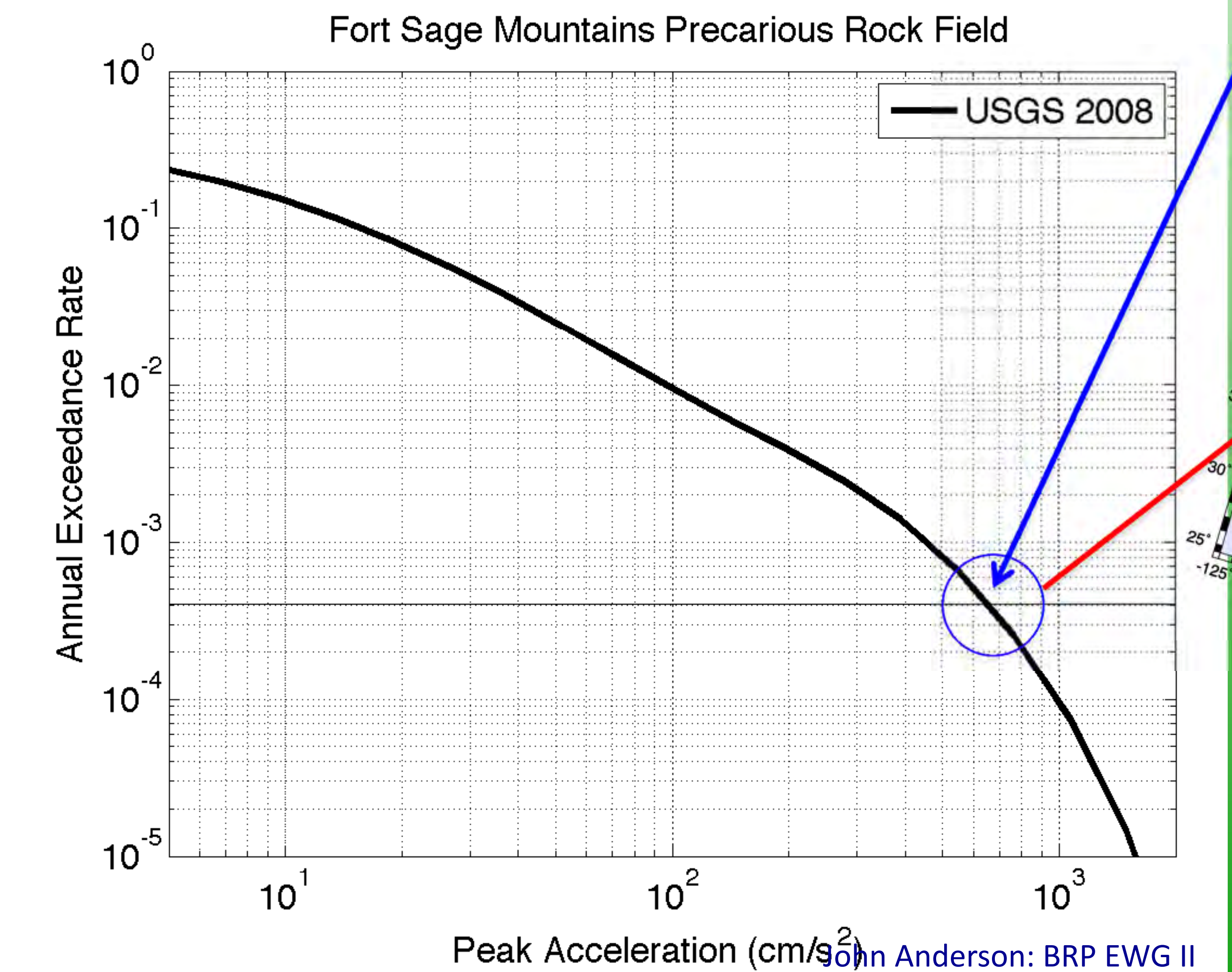
Outline of presentations

- Introduction: Anderson
- Introduction: Chuck Mueller
- Utah: Walter Arabasz
- Montana: Mike Stickney
- Nevada: John Anderson & Glenn Biasi
- Suggested path forward: Anderson et al.

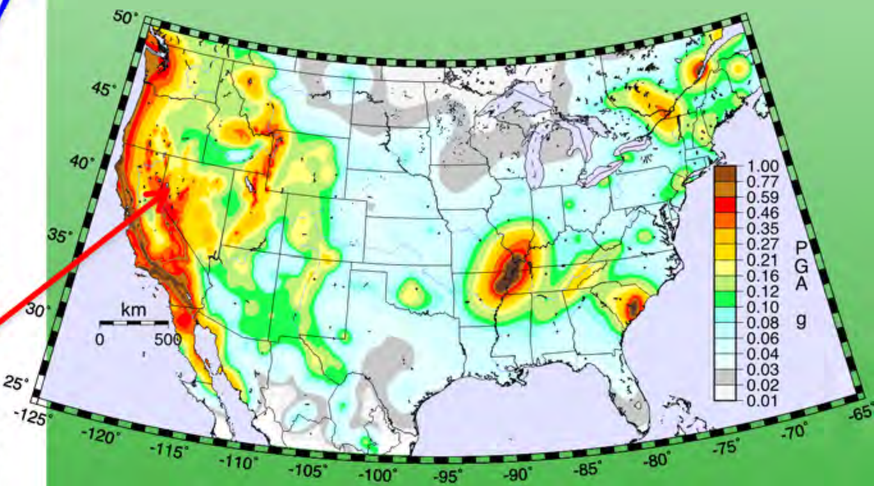
Why do the sources and levels of uncertainty matter?

National Hazard Map finds annual exceedance rate

$$\lambda_C(Y)$$



Contour these points to generate a hazard map.



Quality of hazard map depends on quality of $\lambda_C(Y)$

Source: USGS web site

PSHA Methodology

General integral to calculate $\lambda_C(Y)$:

$$\lambda_C(Y) = \iint n(M, r_{flt})\Phi(y \geq Y \mid \hat{Y}(M, r_{flt}), \sigma_T)\, dM\, dr_{flt}$$

$n(M, r_{flt})$ Seismicity model

$\Phi(y \geq Y \mid \hat{Y}(M, r_{flt}), \sigma_T)$ Ground motion prediction equation

Magnitude uncertainties can introduce a systematic bias into the seismicity model.

For a perfectly calibrated, unbiased magnitude scale …

- Inherent variability in M from variable amplitudes at contributing stations
- Roundoff in catalog preparation

- Both introduce a systematic bias in n(M)

Source of bias in M_W

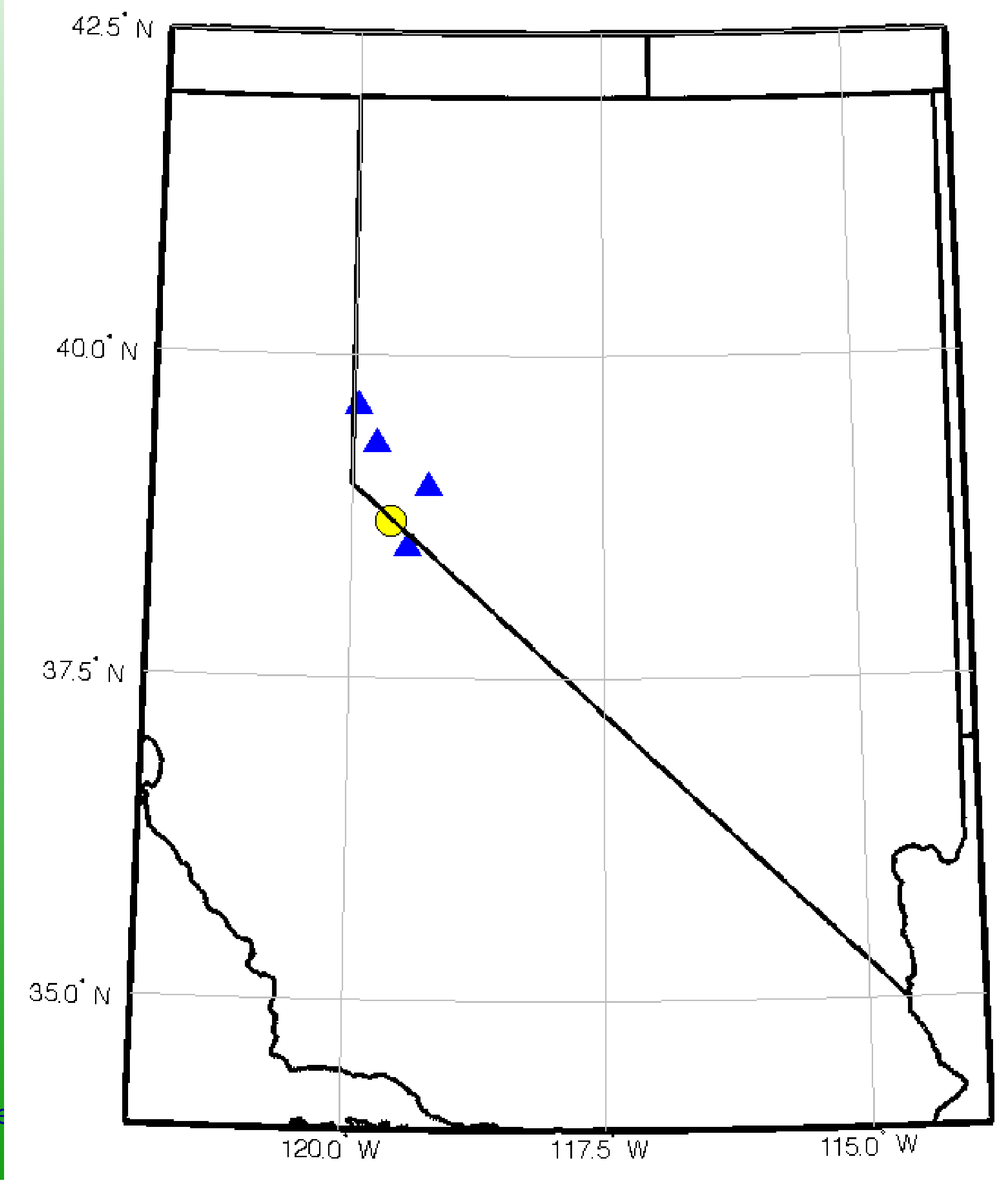
- Systematic bias in $M_{network}$ might depend on
  - Distance
  - Coverage
  - Calibration of instruments
- Conversion from $M_{network}$ to M_W
  - Bias in conversion equations
  - Correlation coefficient smaller than 1.0

Estimating $M_{network}$

- Network magnitude may be m_{coda}, m_L, or M_W.
- Consider an example of estimating M_W
  - Locate earthquake
  - Calculate synthetic Wood-Anderson response at several stations
  - Apply distance correction to find $M_{L,i,c}$ for component c at station i.
  - $$M_W = \frac{1}{N}\sum_{i,c}^{N} M_{W,i,c}$$
  - This gives an unbiased estimate of the magnitude.

Example

- Station Magnitudes:
  - 2.84
  - 3.12
  - 2.59
  - 3.63
- Mean: 3.05
- $\sigma = 0.45$
- $\sigma_v = 0.32$



John Ande

Continuing the example

- $M = 3.05$
- $\sigma_v = 0.32$
- For b=1, how many quakes with magnitude
  - $M-\sigma_v$: 2.79
  - $M+\sigma_v$: 0.36
  - So: about 8 times as many earthquakes that are 1 sigma smaller than are 1 sigma larger than 3.05.
- This event might have M=3.05, but if it is not exactly that, there is a larger chance that its magnitude is smaller than that it is larger.

Tinti and Mulargia (1985)

- For a region in which N(M)=a-bM, with uncertainty σ_ν,
- What is observed is: $$\log N = a - bM + \frac{b^2 \sigma_\nu^2}{2 \log e}$$
- This gives the basis for adjusting the background seismicity rate

BRPEWG II - Topic S4

What are the sources and levels of uncertainty in the earthquake magnitudes contained in the seismicity catalogs used in the NSHMs?

Discussion Leaders: John Anderson & Chuck Mueller

Why it matters – Case 1

- Measurement uncertainty => biased rates
- Example: With uncertainty and an exponential freq-mag distribution, a reported magnitude 5 eqk is more likely to be true 4.9 than 5.1
- Decrease *a* by a factor that depends on *b* and measurement *sigma* (Tinti&Mulargia, Felzer):

$$a^* = a - 0.5*\ln(10) * b^2 * sigma^2$$

$$(m^* = m - 0.5*\ln(10) * b * sigma^{2)}$$

Why it matters – Case 2

- Conversion uncertainty => biased rates
- Convert I_e to m, and consider the rate of eqks with m > some m_t. Simple conversion will only count eqks with I_e > corresponding I_t. With uncertainty, however, smaller eqks can contribute $m > m_t$, and with an exponential freq-mag distribution these far outnumber large eqks (which do the opposite).
- Increase *a* by the same factor (but with conversion *sigma*) (Veneziano&VanDyck, McGuire):

$$a^* = a + 0.5*\ln(10) * b^2 * sigma^2$$

$$(m^* = m + 0.5*\ln(10) * b * sigma^2)$$

Simulation Example …

Example from McGuire (2004): What is the rate of earthquakes with $m > 4.6$?

Assume:

1) Earthquakes are designated by epicentral intensity, I_e (convenient to use decimal values)
2) Convert I_e to magnitude: $m_c = 1.3 + 0.6 I_e$ (G-R, from global data)
3) *beta* = 2.0 (b=0.87) and *sigma* = 0.6, so $m^* = m_c + 0.5*2*0.6^2$ (=> b=0.87*0.6=0.52 for I_e)

MMI	I_e	n	m_c	n [m_c>4.6] "deterministic"				
III	2.6-3.4	699	2.9-3.3	0				
IV	3.6-4.4	211	3.5-3.9	0				
V	4.6-5.4	63	4.1-4.5	0				
VI	5.6-6.4	19	4.7-5.1	19				
VII	6.6-7.4	6	5.3-5.7	6				
VIII	7.6-8.4	2	5.9-6.3	2				
total		1000		27				

Example from McGuire (2004): What is the rate of earthquakes with $m > 4.6$?

Assume:

1) Earthquakes are designated by epicentral intensity, I_e (convenient to use decimal values)
2) Convert I_e to magnitude: $m_c = 1.3 + 0.6 I_e$ (G-R, from global data)
3) *beta* = 2.0 (b=0.87) and *sigma* = 0.6, so $m^* = m_c + 0.5*2*0.6^2$ (=> b=0.87*0.6=0.52 for I_e)

MMI	I_e	n	m_c	n [m_c>4.6] "deterministic"	prob [m>4.6]	n [m>4.6] "exact"		
III	2.6-3.4	699	2.9-3.3	0	0.006	4		
IV	3.6-4.4	211	3.5-3.9	0	0.06	13		
V	4.6-5.4	63	4.1-4.5	0	0.29	18		
VI	5.6-6.4	19	4.7-5.1	19	0.63	12		
VII	6.6-7.4	6	5.3-5.7	6	0.83	5		
VIII	7.6-8.4	2	5.9-6.3	2	0.99	2		
total		1000		27		54		

Example from McGuire (2004): What is the rate of earthquakes with m > 4.6?

Assume:

1) Earthquakes are designated by epicentral intensity, I_e (convenient to use decimal values)
2) Convert I_e to magnitude: $m_c = 1.3 + 0.6 I_e$ (G-R, from global data)
3) *beta* = 2.0 (b=0.87) and *sigma* = 0.6, so $m^* = m_c + 0.5*2*0.6^2$ (=> b=0.87*0.6=0.52 for I_e)

MMI	I_e	n	m_c	n [m_c>4.6] "deterministic"	prob [m>4.6]	n [m>4.6] "exact"	m^*	n [m^*>4.6] "approx"
III	2.6-3.4	699	2.9-3.3	0	0.006	4	3.2-3.7	0
IV	3.6-4.4	211	3.5-3.9	0	0.06	13	3.8-4.3	0
V	4.6-5.4	63	4.1-4.5	0	0.29	18	4.4-4.9	29
VI	5.6-6.4	19	4.7-5.1	19	0.63	12	5.0-5.5	19
VII	6.6-7.4	6	5.3-5.7	6	0.83	5	5.6-6.1	6
VIII	7.6-8.4	2	5.9-6.3	2	0.99	2	6.2-6.7	2
total		1000		27		54		56

Why it matters — Case 3

- From ~1900–1940 in California it was observatory practice(?) to round magnitudes to the nearest 1/2 or 1/4 mag unit
- Adjust rates by “unrounding” into a binned exponential freq-mag distribution

USGS WUS hazard model

<u>Faults (slip-rate or recurrence data)</u>

- IMW: ~ 300 crustal faults
- PNW: crustal + megathrust
- CA: WGCEP

Distributions for M_{char}

67% char & 33% GR for CA+IMW

<u>Shallow Seismicity (d < 35 km)</u>

1) Declustered catalog M_w >= 4
2) Completeness:

   Coastal CA: 1933, 1900, 1850

   Other WUS: 1963, 1930, 1850
3) *b* = 0.80
4) 10^a grids (Weichert):
   - Coastal CA
   - Extensional WUS
   - Non-extensional WUS

   Adjust for mag uncertainty & rounding

   Background “floor” in 5 zones
5) 50-km smoothing (+ anisotropic)

M_{max} = 7.0 mostly, < 7.0 near faults

<u>Deep Seismicity</u>

<u>Geodetic zones</u>

<u>Ground-motion relations</u>

Crustal: NGA

Megathrust: Zhao + Youngs + AB03

In-slab: Geomatrix + BA00

&

<u>Site condition</u>: 760–m/s

WUS catalog

Source catalogs in preference order:

Pancha etal (2006): ~200 eqks, M_w 4.8+, 1855-1999 (new M_w estimates; we like this kind of study <=> 2006 IMW wksp)

CGS updated (Felzer&Cao,2007): ~2070 eqks, M_w&m_L 4+, 1769-2006 (controls hazard from seismicity in CA)

Engdahl & Villasenor (2002): 18 eqks, mag 5.5+, 1900-1999

Stover & Coffman (1993): ~110 eqks, mag 4.5+ and/or MMI VI+, 1769-1989

Stover, Reagor & Algermissen: ~150 eqks, mag 3.0+, 1857-1986 (includes many smaller eqks than Stover & Coffman)

PDE: ~550 eqks, mag 3.2+, 1960-2006 (updates since 1996)

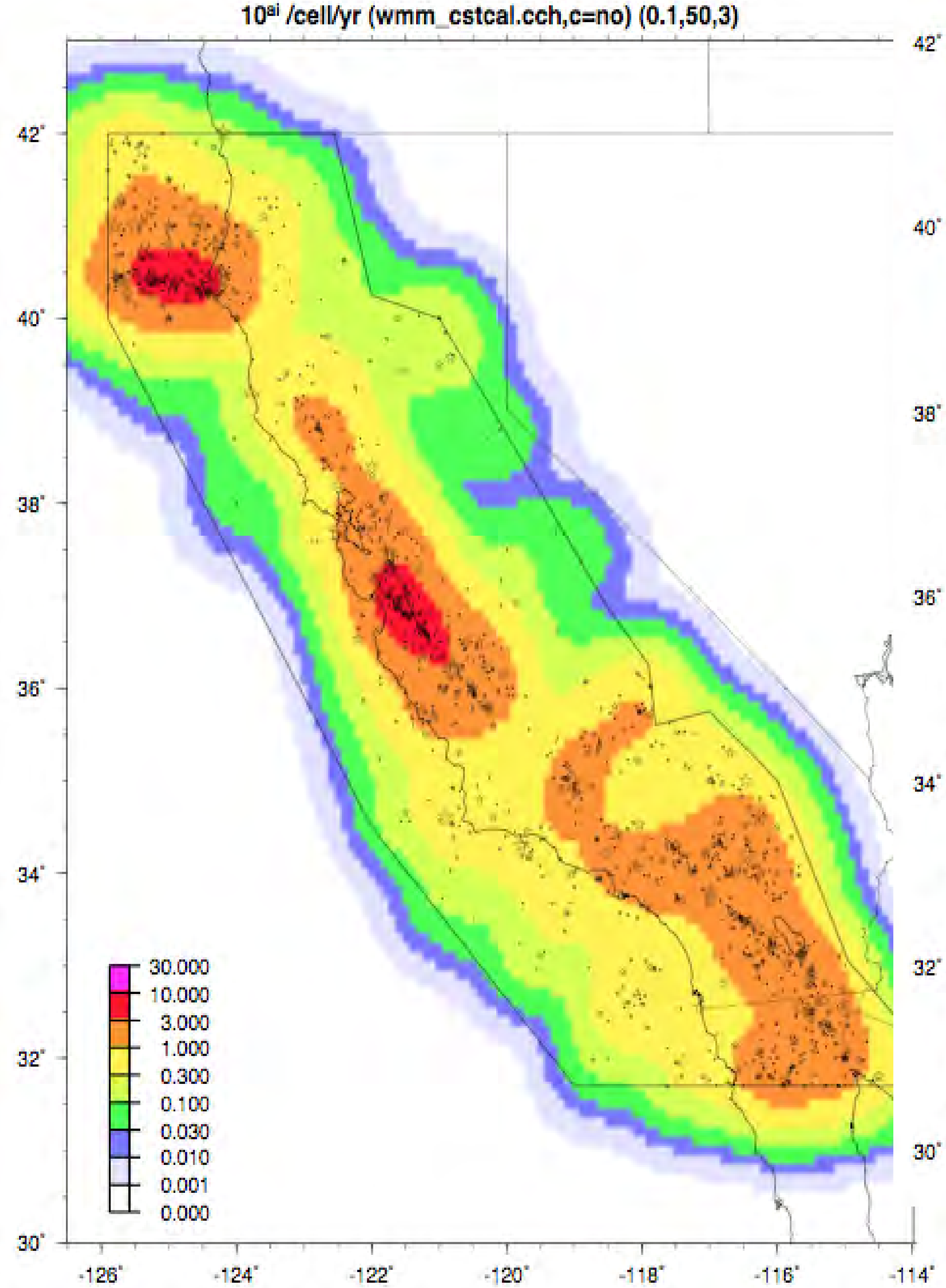
DNAG: ~150 eqks, mag 4+, 1808-1985

WUS catalog

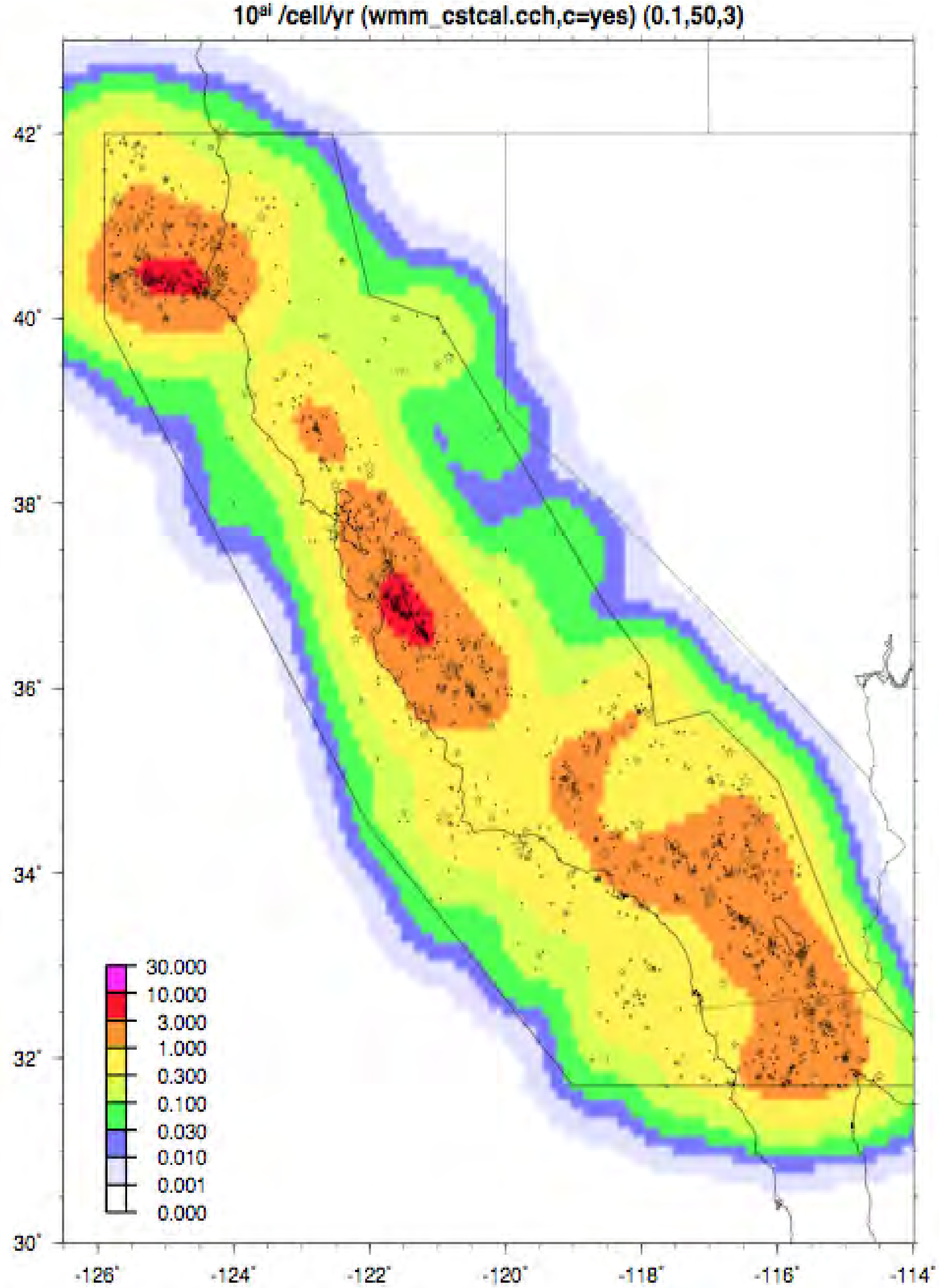
1) Convert magnitude to M_w as needed
2) Concatenate, sort, remove duplicates
3) Decluster and delete non-tectonic events
4) We don’t make an M* catalog; adjust rates (“agrid”) instead

We <u>do</u> correct for Case 1 (measurement *sigma*)

- ✓ This is right for directly measured M_w. Is it OK for M_w assumed equal to directly measured m_L or m_b or M_S?
- ✓ For WUS we borrow crude, era-based *sigma* estimates from Felzer's California work: *sigma* = ~ 0.1 since 1964, ~ 0.2 since 1932, and ~ 0.3 pre-1932. (Felzer uses these generic values when eqk-specific *sigma i*sn't available.) Rates decrease ~ 2-15%.
- ✓ This sort of granularity in time is probably fine.
- ✓ But do we need better *sigmas*? Regional variations? Magnitude-range variations?

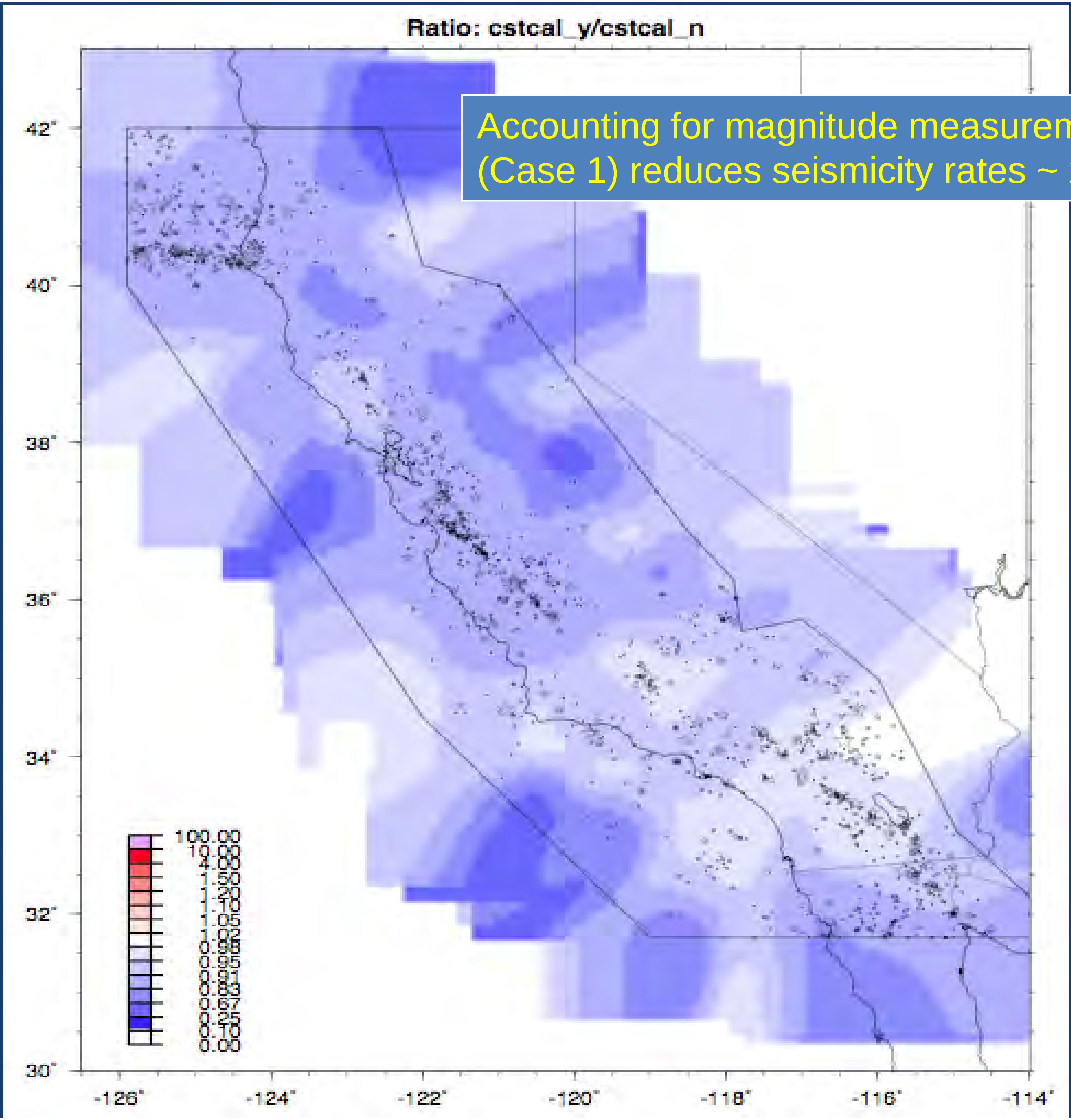


10^ai /cell/yr (wmm_cstcal.cch,c=no) (0.1,50,3)
42°
40°
38°
36°
34°
32°
30°
-126°
-124°
-122°
-120°
-118°
-116°
-114°
30.000
10.000
3.000
1.000
0.300
0.100
0.030
0.010
0.001
0.000



10^ai /cell/yr (wmm_cstcal.cch,c=yes) (0.1,50,3)
42°
40°
38°
36°
34°
32°
30°
-126°
-124°
-122°
-120°
-118°
-116°
-114°
30.000
10.000
3.000
1.000
0.300
0.100
0.030
0.010
0.001
0.000

Accounting for magnitude measurement uncertainty (Case 1) reduces seismicity rates ~ 2 to 15 %



McGuire’s comment on Case 1…

“Veneziano and Van Dyck (EPRI, 1986) also provide a procedure for incorporating the uncertainty caused by direct estimates of an instrumental magnitude. Because instrumental values of *sigma* are generally small, this correction is small, and it is accurate to use $m^* = m$ for direct instrumental measurements…”

We <u>do not</u> correct for Case 2 (conversion *sigma*)

This would require keeping track of the magnitude conversions used in the development of the WUS moment-magnitude catalog, and estimating their uncertainties. (Perhaps borrow conversion *sigma* values from CEUS-SSC: m_b=0.24, M_S=0.20, FA=0.22, I_0=0.5, M_C&M_D&M_L=0.22–0.25, M_L(GSC)=0.42).

We do correct for rounding

- ✓ For 1900–1941 & listed magnitude = x.0 or x.5 ,we “unround” into a binned exponential distribution (0.01 mag-unit bins, from -0.25 to +0.25 mag units)
- ✓ Felzer uses an alternative monte-carlo approach

PDE

Since 1983, NEIC m_b and M_S average magnitudes have been computed using a 25% trimmed mean, because studies have shown that the distributions are heavy-tailed and non-Gaussian (too many data points outside a normal standard deviation). This is reflected by the observation that individual station magnitudes vary by one order of magnitude or more from the mean. We believe that this is largely due to focal mechanism and geologic structure, rather than to errors in the data.

Contributed local magnitudes and locations are edited for gross errors, but are otherwise published as received. We usually have no information about the uncertainties of these solutions.

[Paraphrased from: Earthquake Bulletins and Catalogs at the USGS National Earthquake Information Center by Sipkin, Person & Presgrave (May 2000) (earthquake.usgs.gov/regional/neic/neic_bulletins.php)]

- As of Jan 2012, the PDE will be replaced by a massive upgrade of the ANSS catalog: graphical user interface, clickable access to information about each eqk
- Upcoming Herrmann, Benz & Ammon BSSA paper: Moment-tensor solutions for ~ 160 IMW earthquakes M_W 3.5+; about 5 eqks 1960-1990, but most are in the broadband era since ~1995.

Questions:

- ✓ Modern observatory practice; modern estimates of measurement *sigma*?
- ✓ Historical observatory practice; historical estimates of measurement *sigma*? Was rounding used in WUS outside of California?
- ✓ Case 1: Is Case 1 as broadly applicable as we assume? Are the generic uncertainty estimates from California good enough? Regional variations? Magnitude-range variations?
- ✓ Case 2: Should we implement it? If so, what conversion *sigmas* to use?

(And always keep in mind: we're focused on mag > 4.)

University of Utah Earthquake Catalog — Magnitude “Uncertainties” and Comparison with the NSHM Catalog

Walter Arabasz

University Of Utah
Seismograph Stations
The University of Utah

BRPEWG II
November 16, 2011

Outline

I. Why are magnitude uncertainties important?

II. Overview of the University of Utah Seismograph Stations (UUSS) earthquake catalog

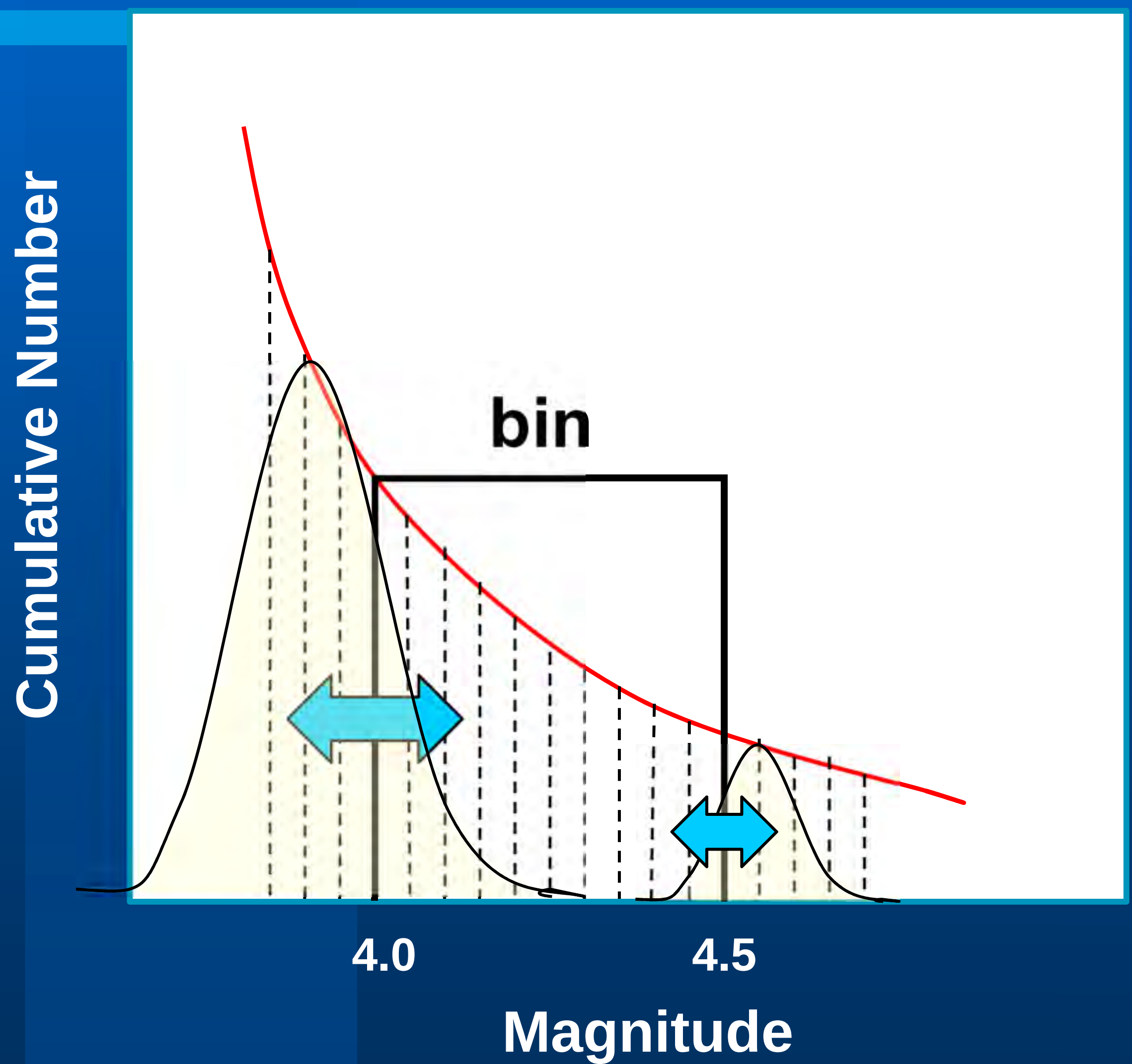
III. UUSS magnitudes
(historical: $M_{L\ (I_o)}$; instrumental: M_L, M_C, and M_W)

IV. Preliminary comparison between UUSS and NSHM catalogs (and magnitudes)

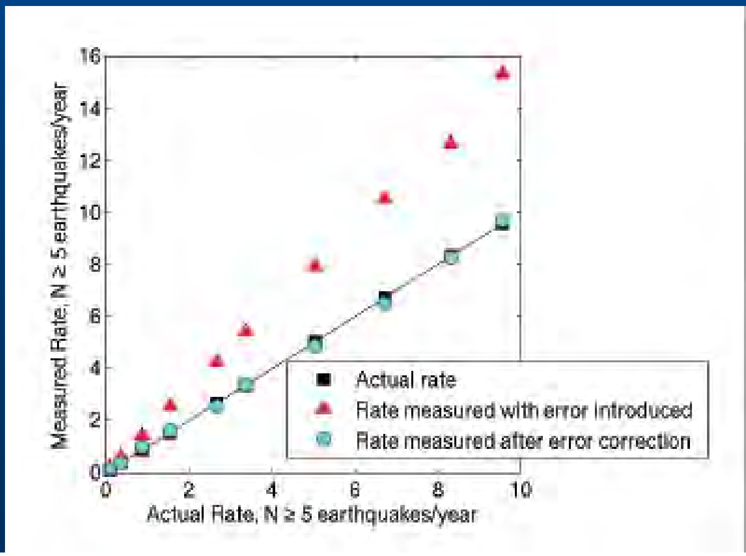
Why are magnitude uncertainties important?

- Recurrence calcs 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 from rounding

"observed" counts > true counts

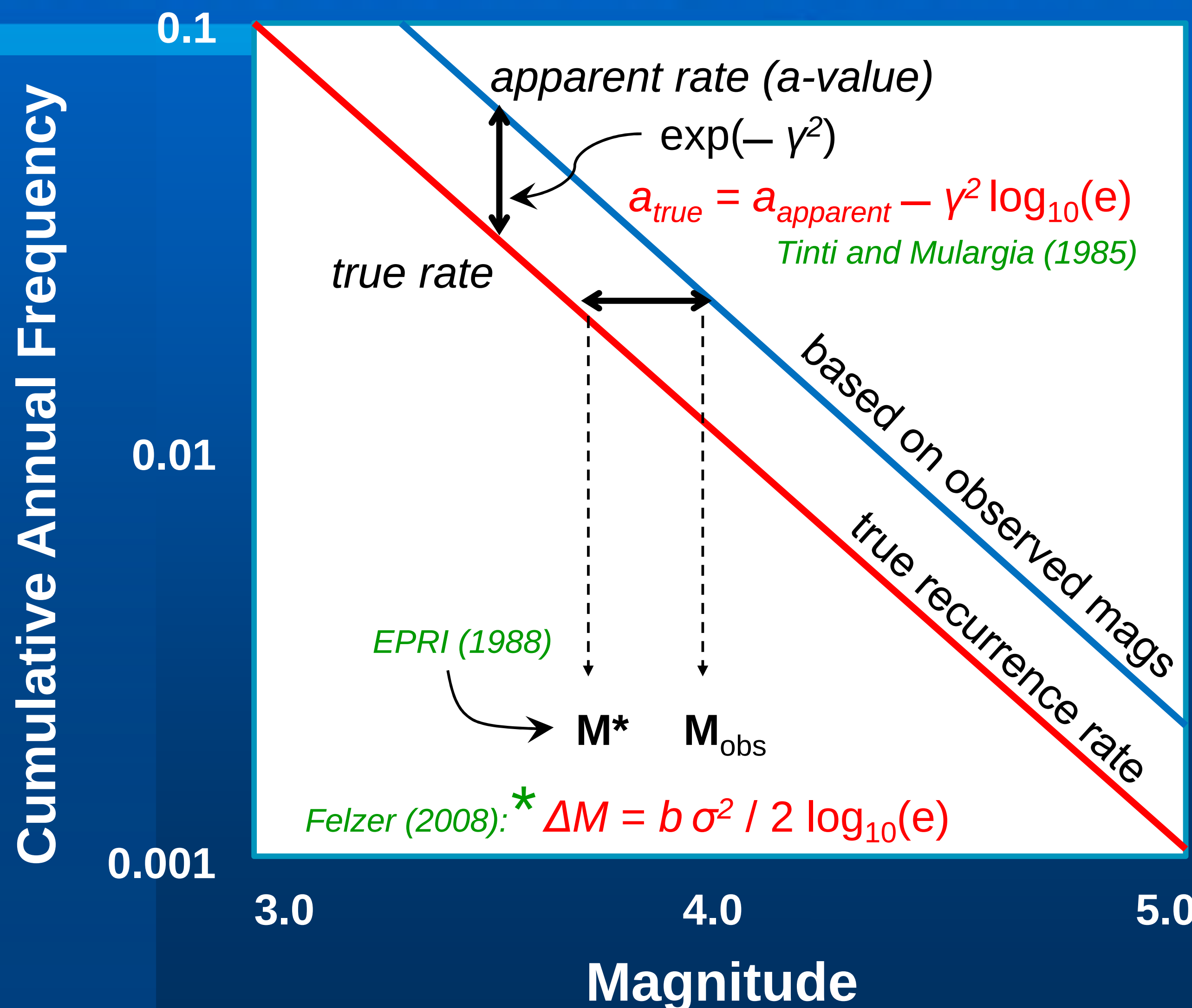


If Gaussian error is added to true magnitudes, **a net increase in the observed counts in a bin** results due to relative change in counts across the left-hand side of the bin compared to the right-hand side



Example from Felzer (2008) →

Equivalent approaches to ensuring unbiased recurrence rates



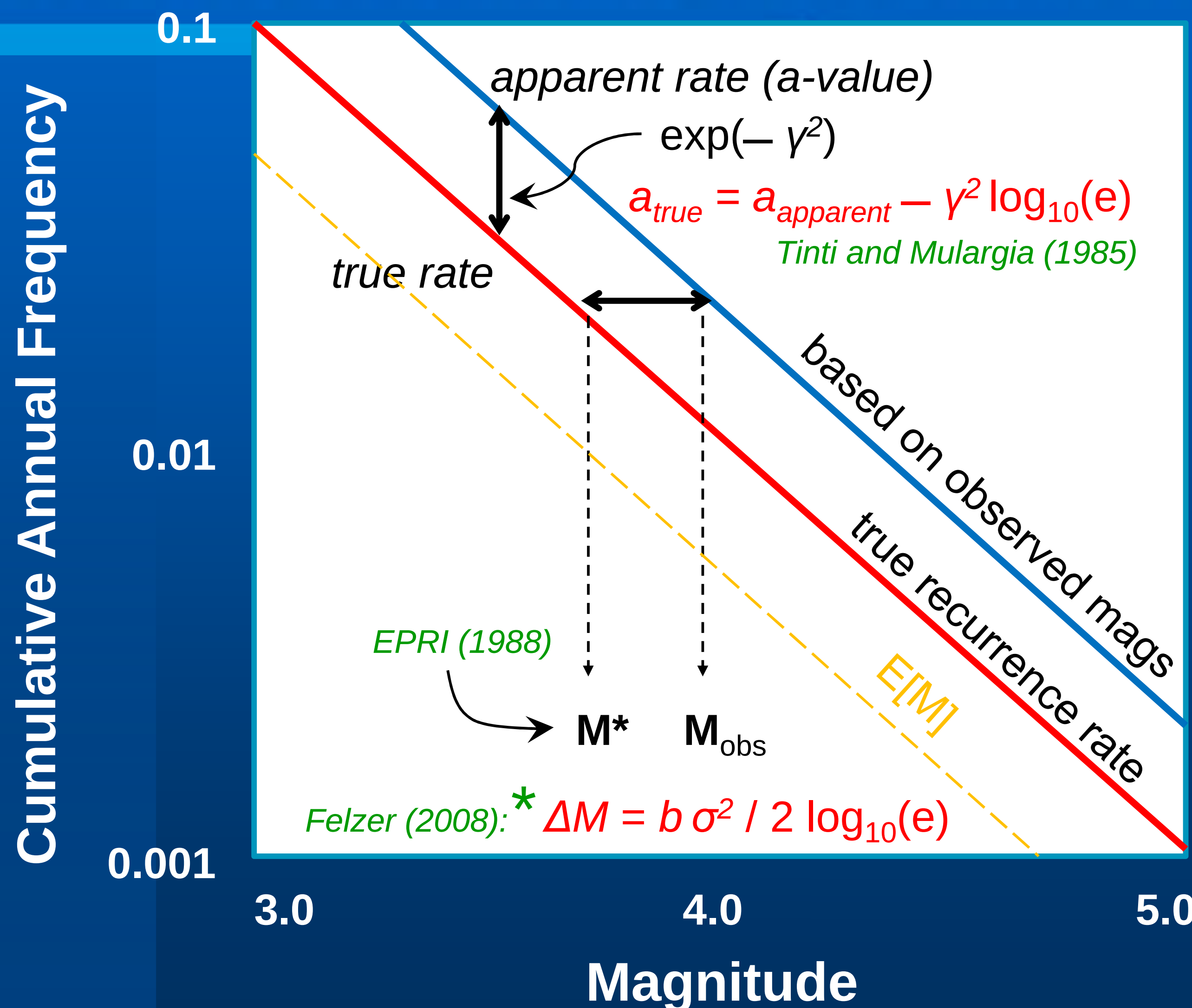
$\gamma^2 = \beta^2 \sigma^2 / 2$

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

Adapted from Youngs (2011)

**** Published equation incorrectly shows b^2***

Equivalent approaches to ensuring unbiased recurrence rates



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

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

Fine point:

E[M] = expected value of the true magnitude

Adapted from Youngs (2011)

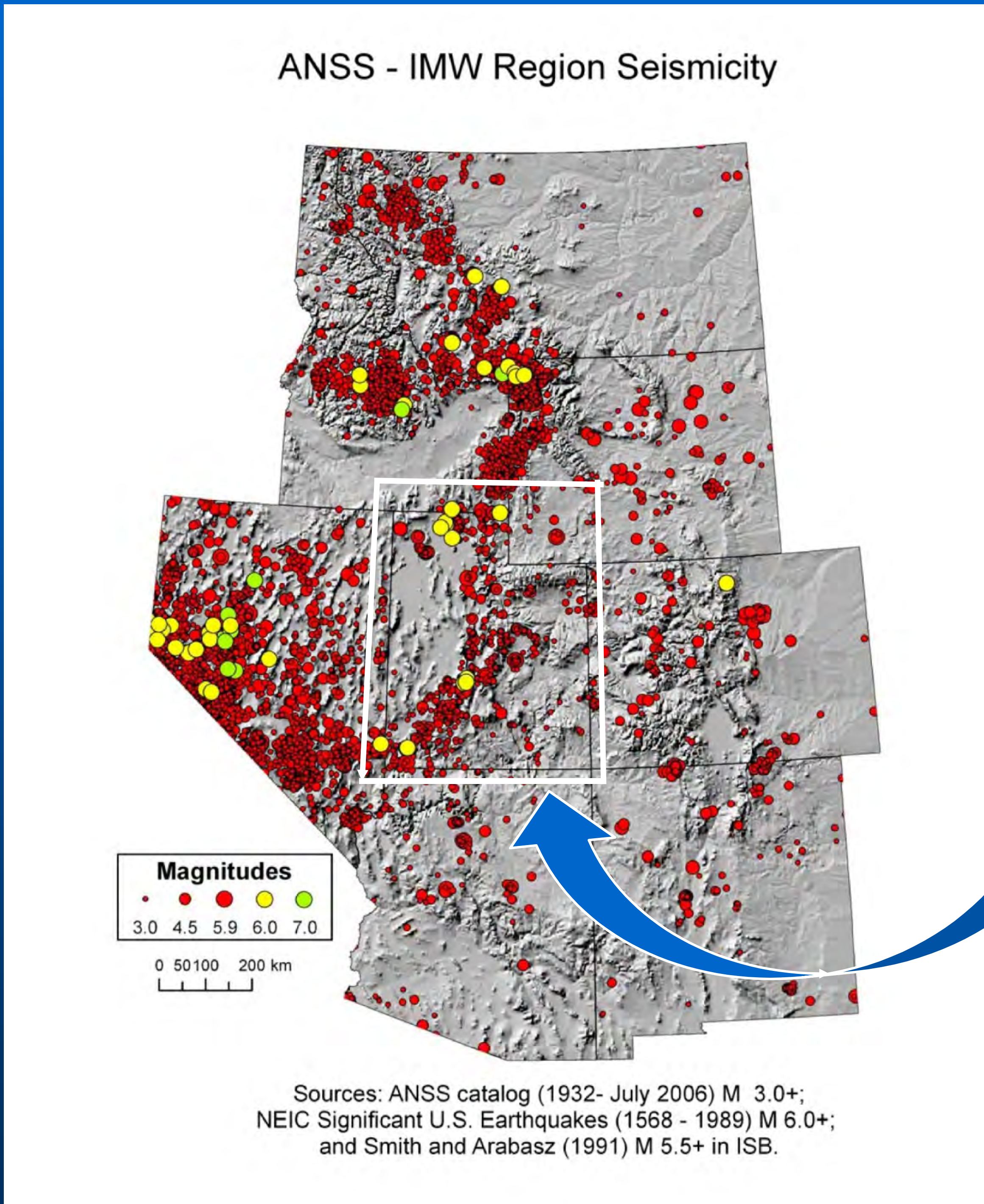
*** Published equation incorrectly shows b^2***

Need σ and *b*-value for the bias correction

- For an adopted scale (say M_W or $M_L \approx M_W$) and for observed magnitudes: need to know $\sigma_{stations}$, the standard error of estimate of magnitude based on measurements at multiple stations.
- When converting from one magnitude scale to another, need to know $\sigma_{regression}$, the std error of estimate for the regression.

In this case, for the normally-distributed magnitude errors

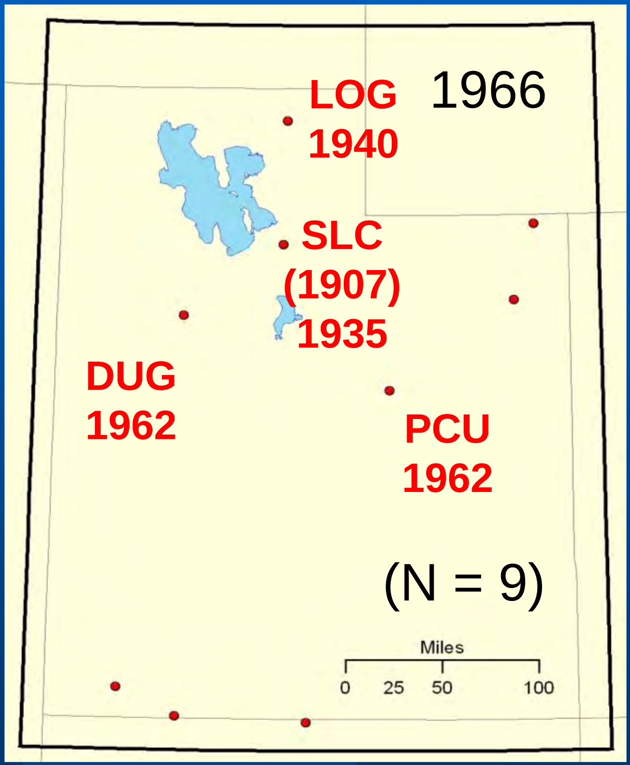
$$\sigma = \sqrt{\sigma_{regression}^{\ 2} - \sigma_{stations}^{\ 2}}$$



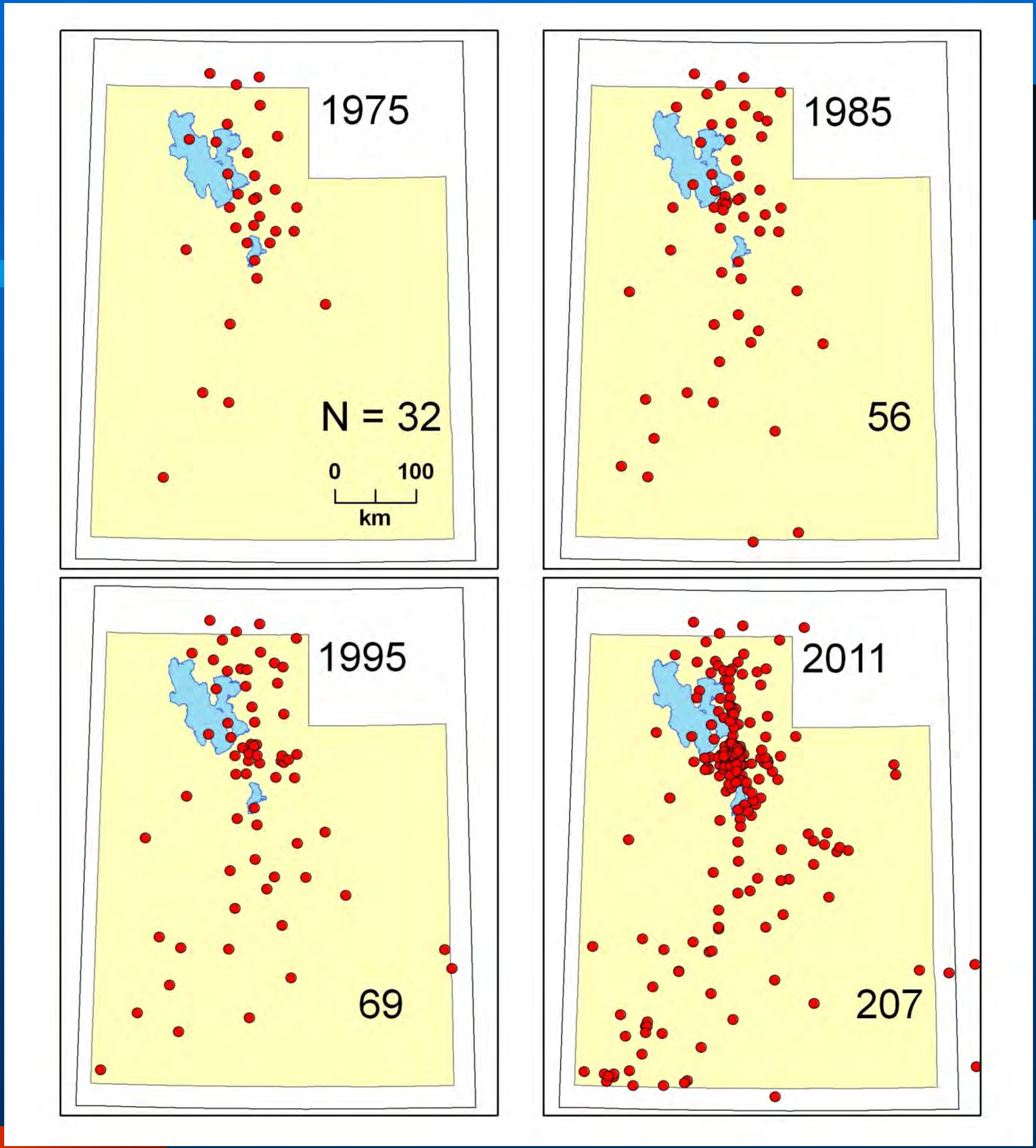
"Utah Region" corresponding to bounds of UUSS earthquake catalog

1850 to present

Seismographic Coverage



Wood-Andersons at LOG (1955), PCU(1962), DUG (1963), SLC (1976)



UUSS Earthquake Catalog

- **Historical Catalog:** 1850 - June 1962
  - —Mostly based on felt reports
  - —Some instrumental locations and magnitudes from the U.S. Coast and Geodetic Survey, others
- **Instrumental Catalog:** July 1962 - present
  - —From analog records (photographic paper, or develocorder film): July 1962 -1980
  - —From digital records: 1981 - present

Magnitudes in UUSS Catalog

- **Historical Catalog** (1850– June1962)
  - —Most magnitudes estimated from maximum Modified Mercalli Intensity (INT) using
    M_{I_o} = (2/3) INT + 1 (Gutenberg and Richter, 1956; validated for Utah by USGS, 1976)
- **Instrumental Catalog** (July 1962 – present)
  - —Preferred magnitude is local magnitude, M_L , determined from maximum peak-to-peak amplitudes on Wood-Anderson seismograms
  - —The vast majority of the magnitudes are coda magnitudes, M_C, determined from signal durations on short-period vertical records
  - —M_W now routinely determined for M ~ 3.4 and larger

Magnitude-Intensity Relation for Utah

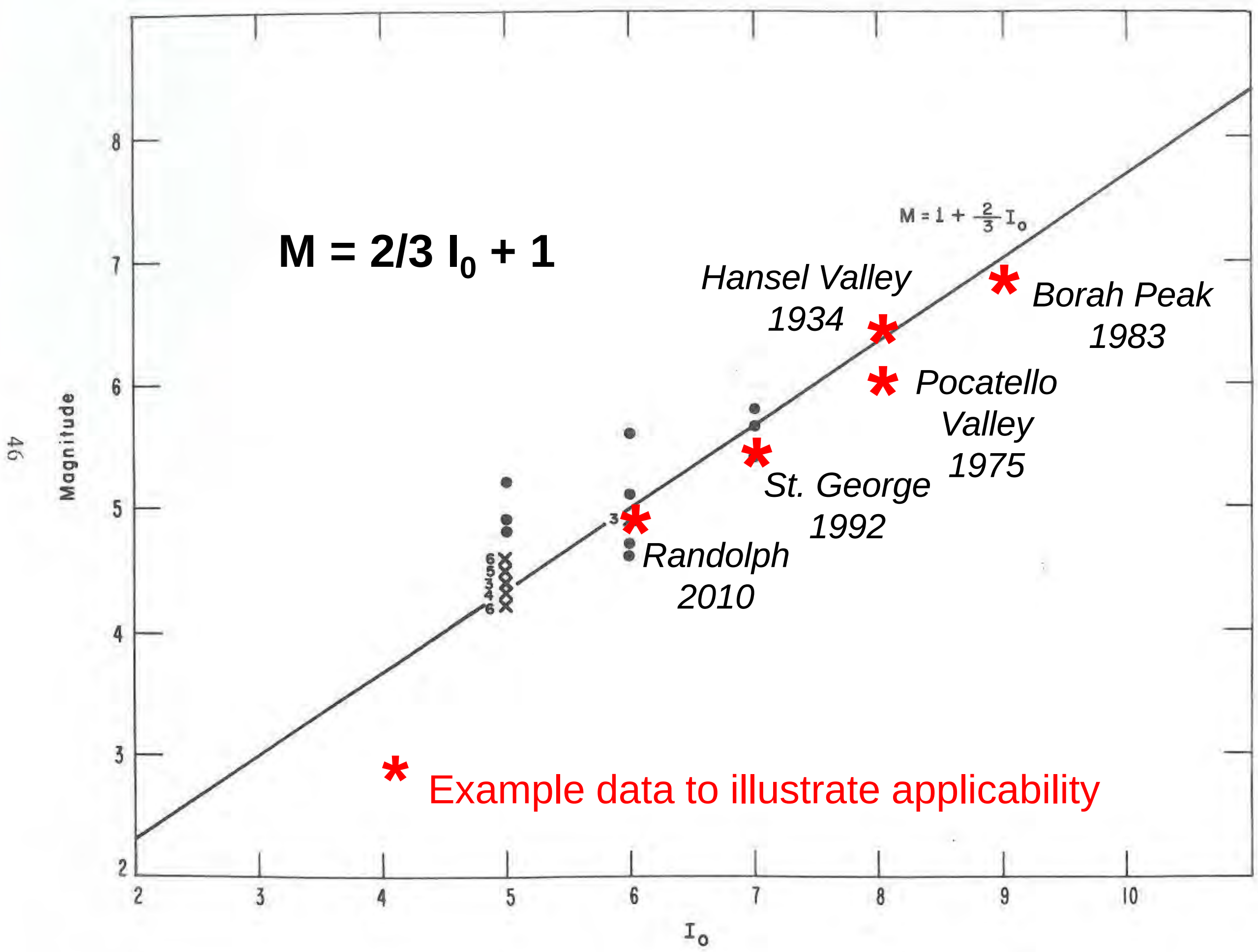
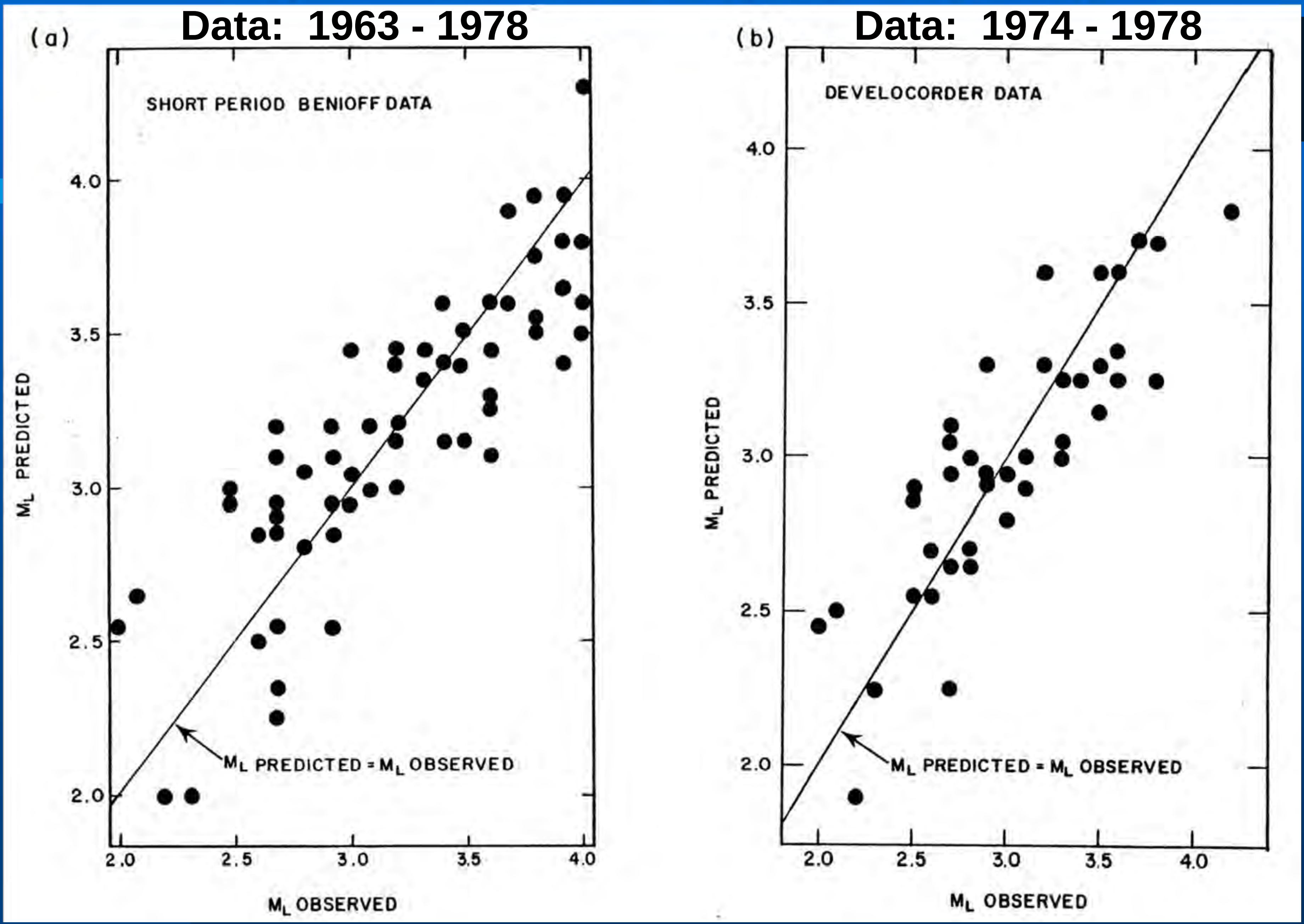


Figure 11.--Graph showing magnitude versus maximum intensity for Utah earthquakes. The line shows the Gutenberg-Richter relation. The numbers indicate the number of overlapping data points.

Base figure from Rogers et al. (USGS Open-file Rept. 76-89, 1976)

M_C Calibrations (pre-digital)

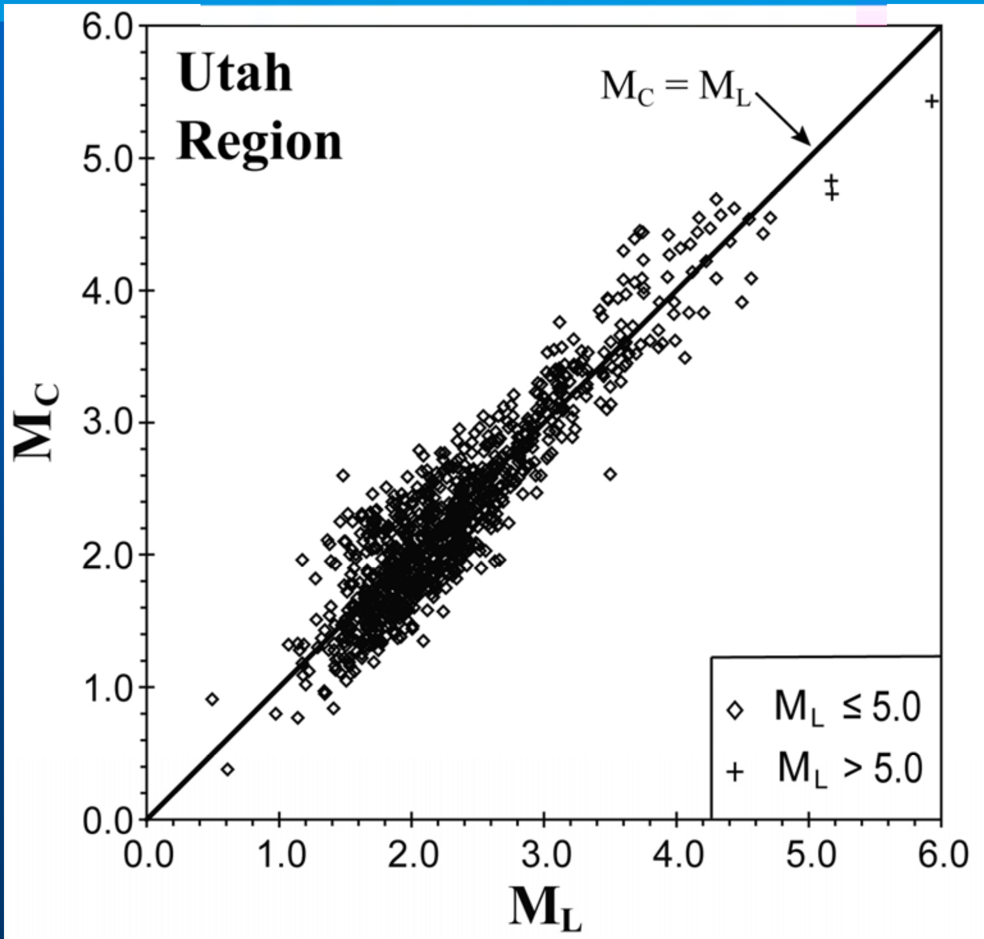


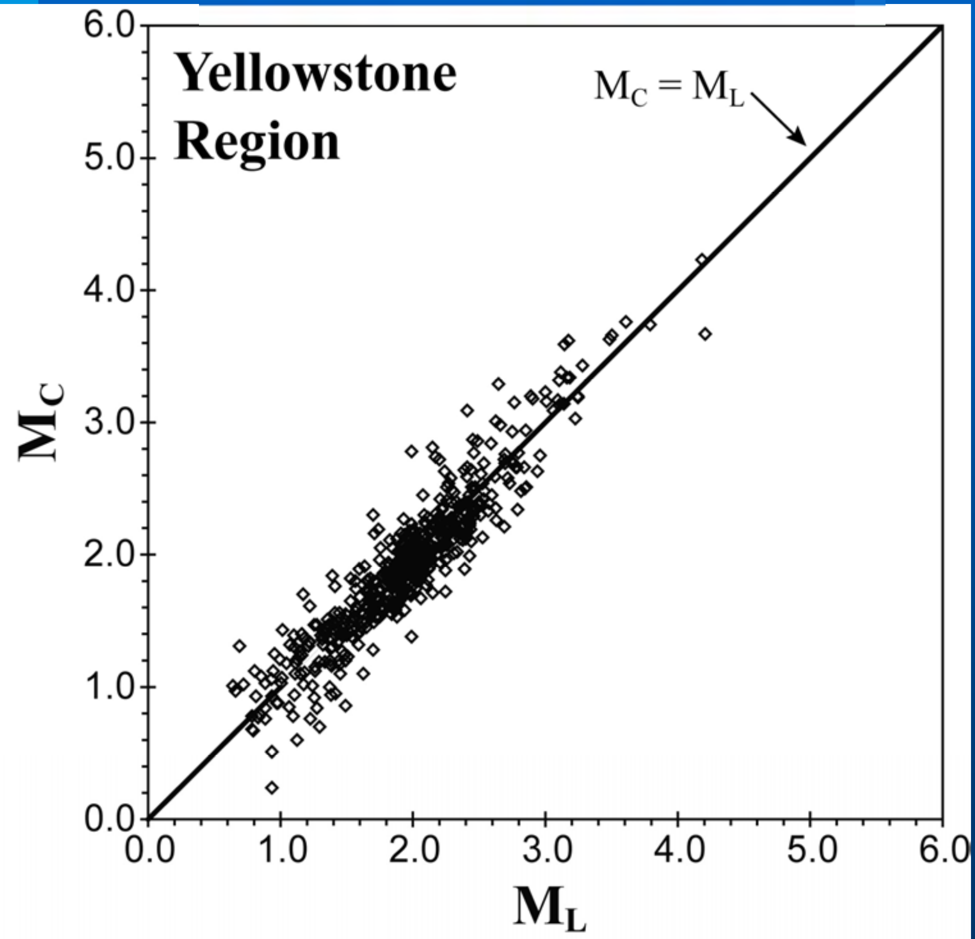
From Griscom and Arabasz (1979)

M_C Calibrations (digital)

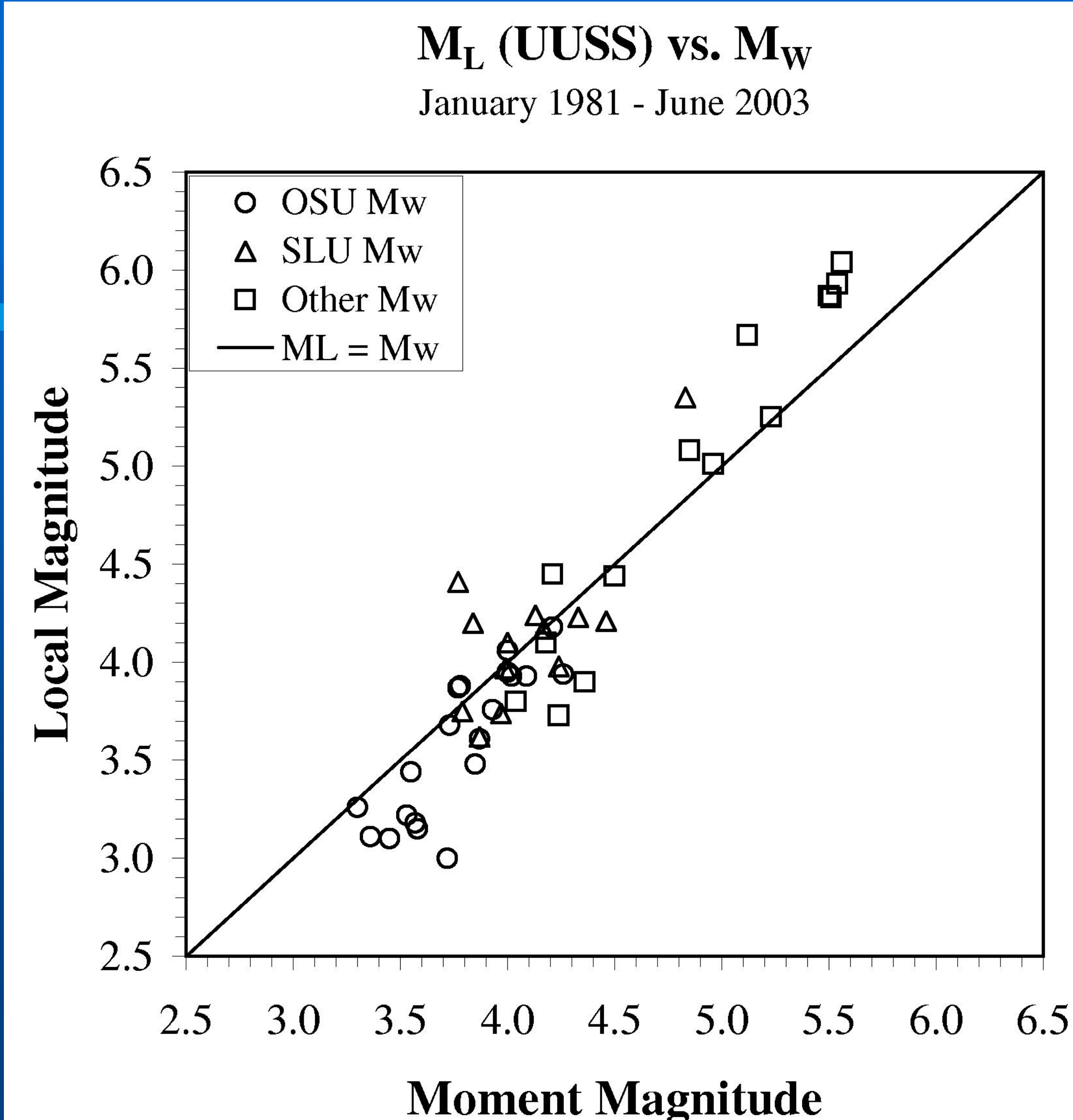
Data: 1981 - 2001

Data: 1995 - 2001

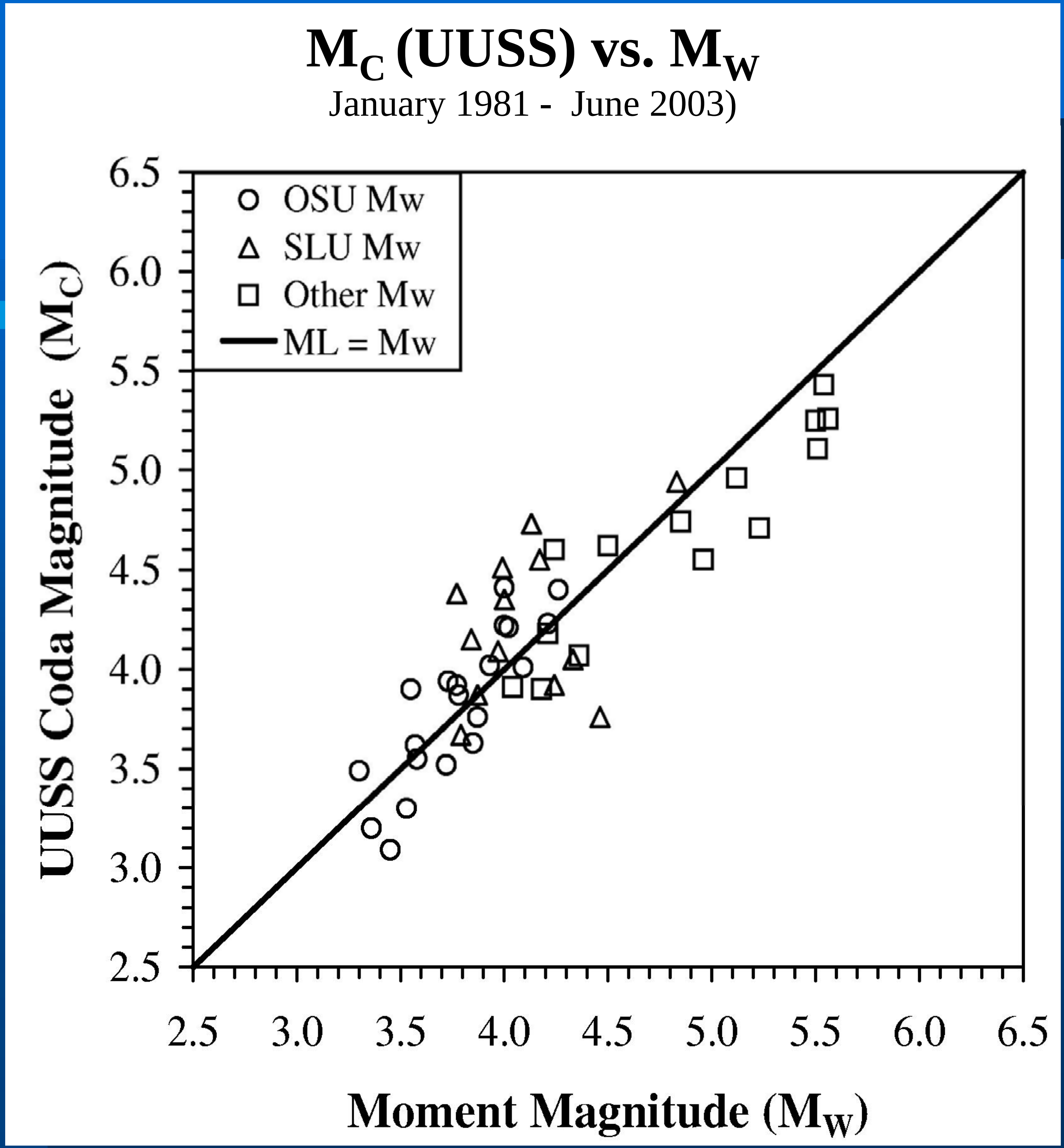




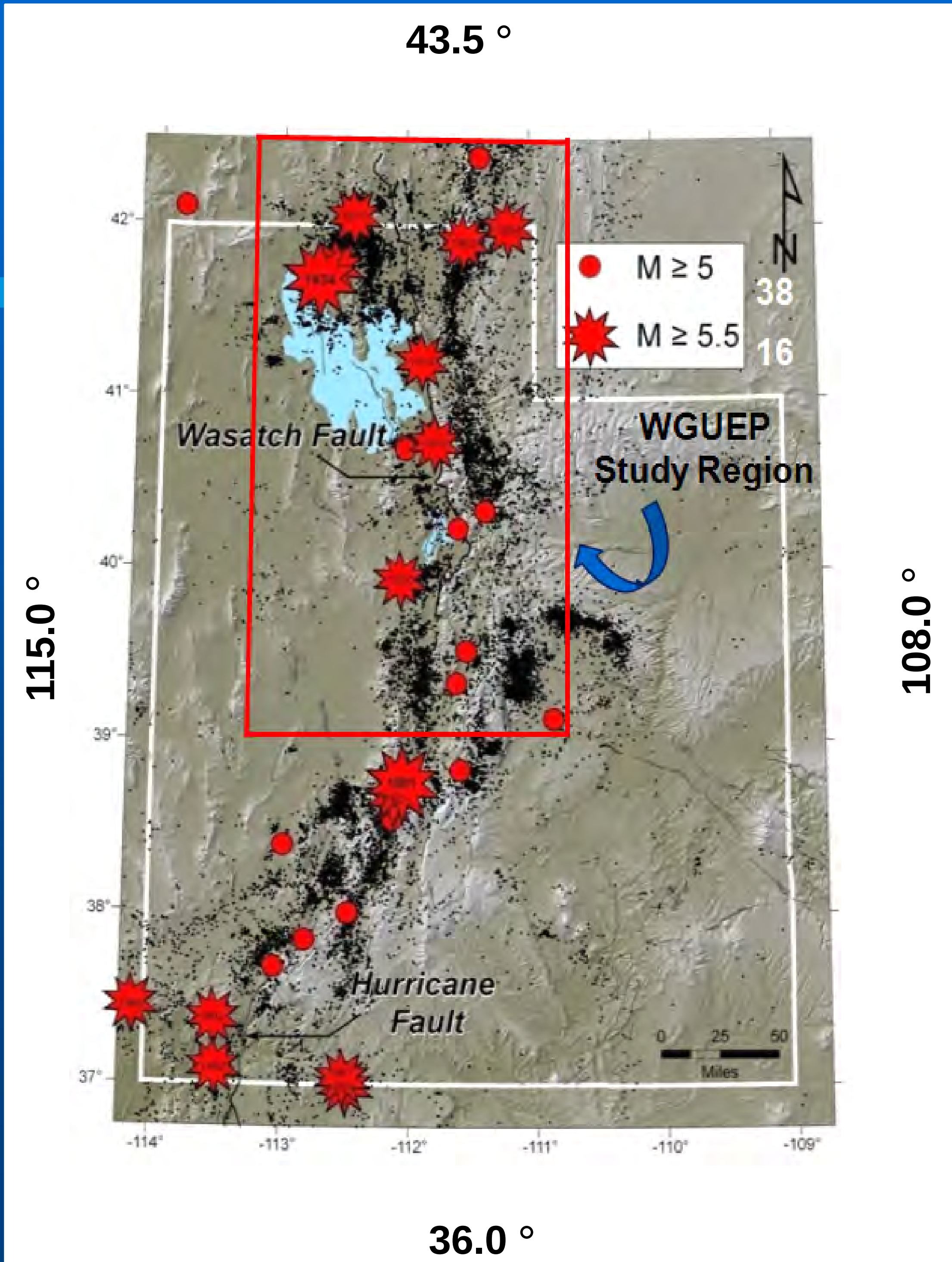
From Pechmann et al. (2007)



from Pechmann et al. (2007)



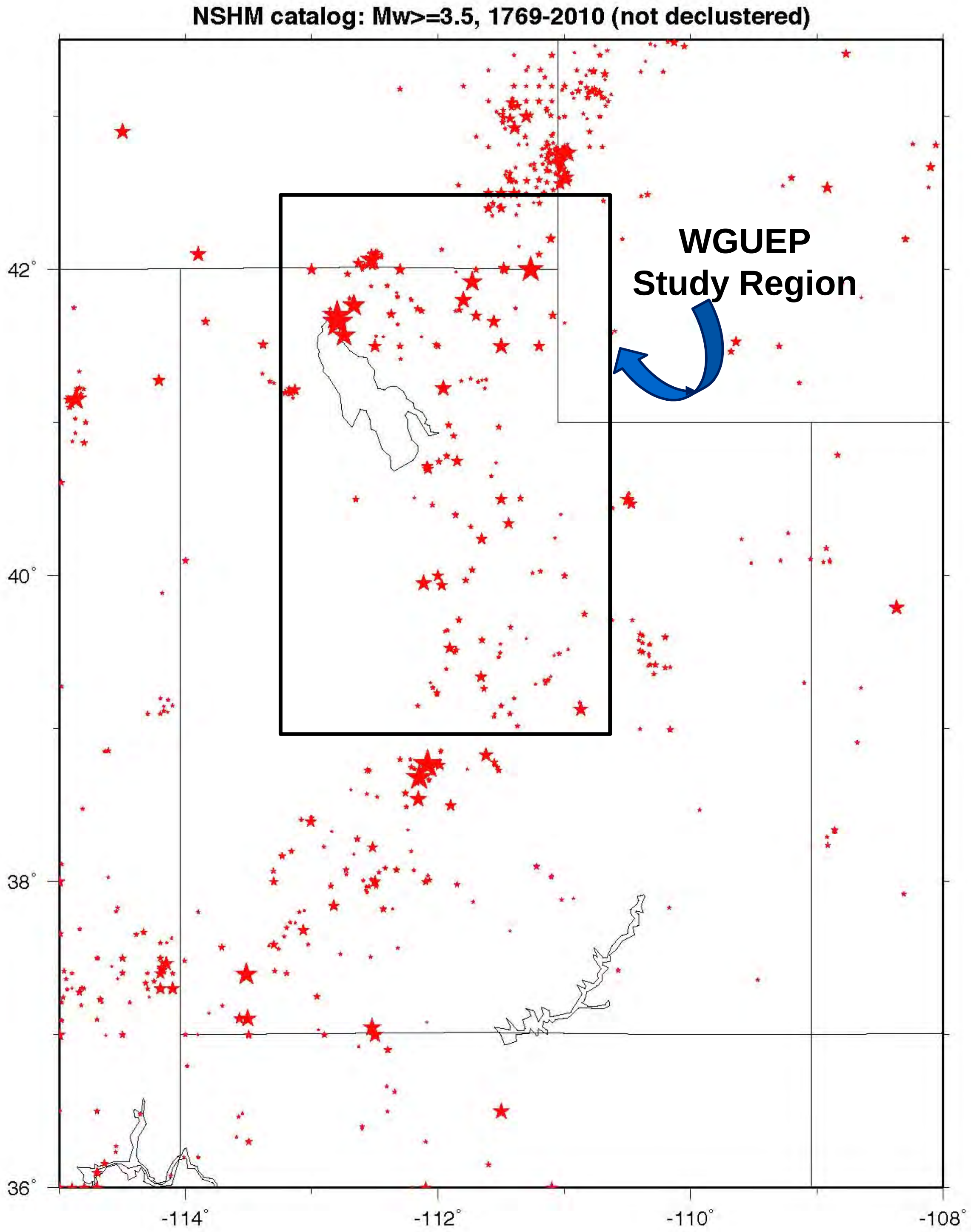
from Pechmann et al. (2007)



"extended Utah region"

NSHM catalog request

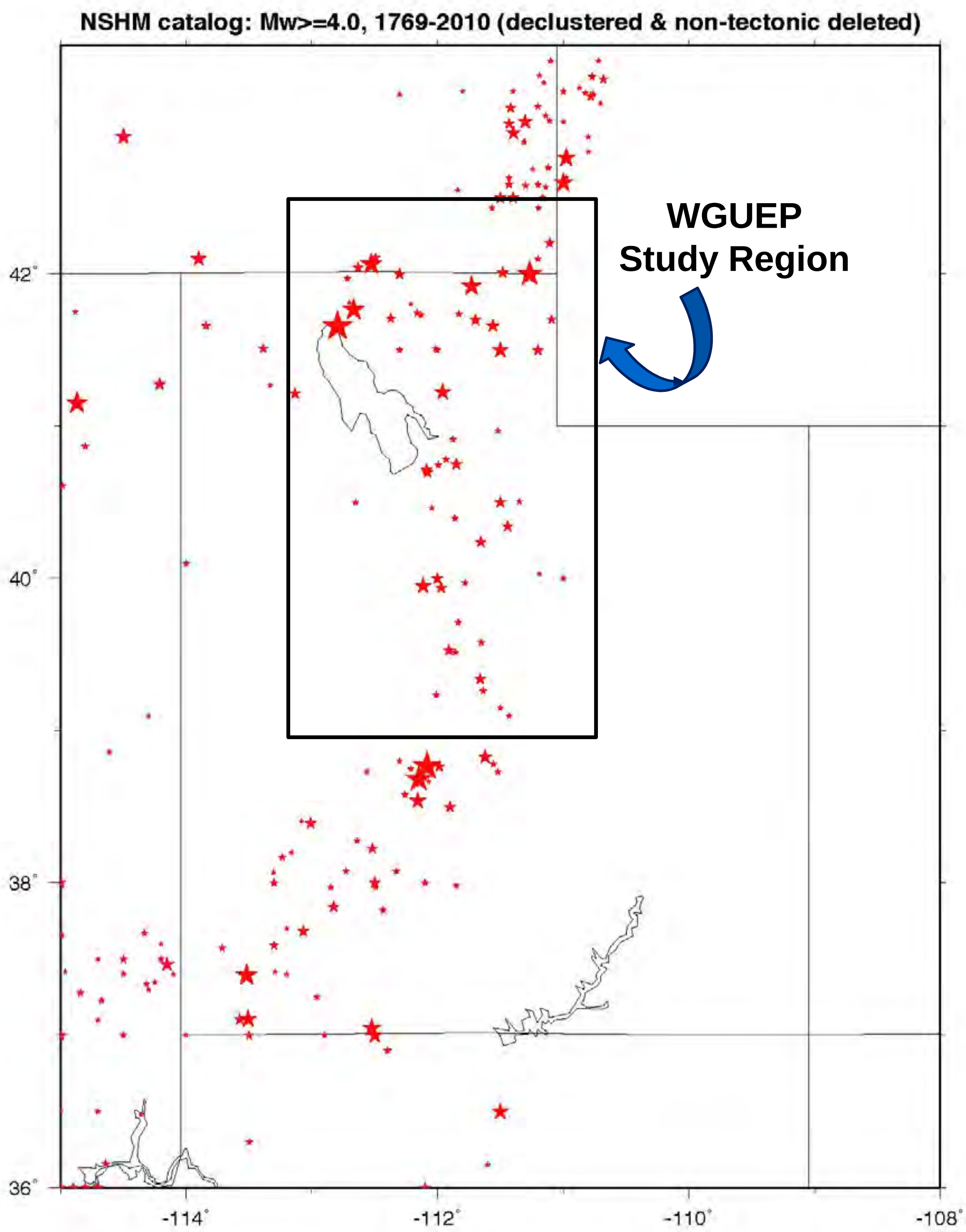
lat 36.0° – 43. 5° N
long 108.0° – 115.0° W



NSHM Catalog
Mw ≥ 3.5
1769 [1880]−2010
Not declustered

N *total area* = 788

N *WGUEP region* = 203



NSHM Catalog
Mw ≥ 4.0
1769 [1880]−2010
Declustered
Non-tectonic events deleted

N *total area* = 202

N *WGUEP region* = 67

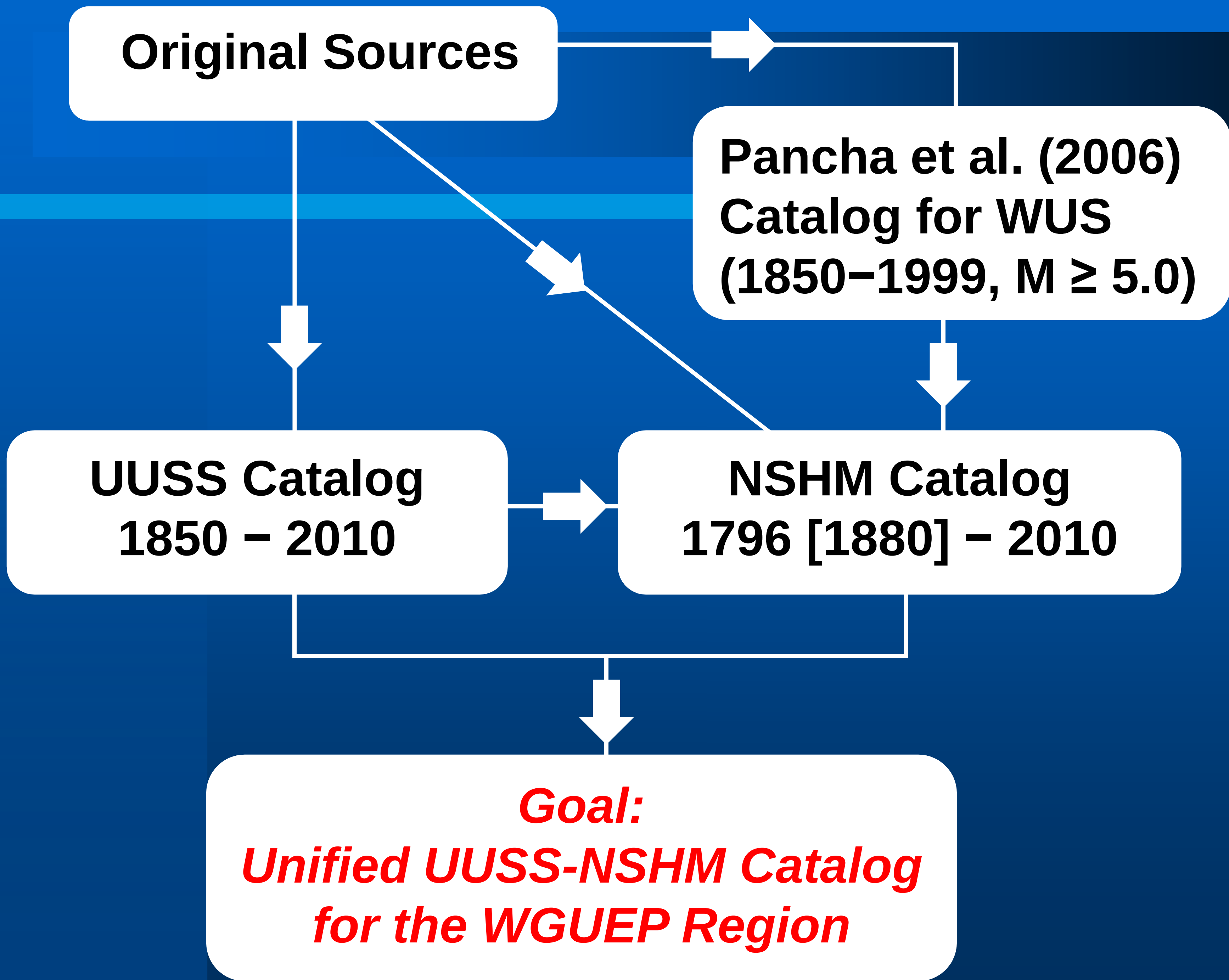
Comparison of UUSS and NSHM catalogs for the WGUEP region . . .

(1880 through 2010; independent mainshocks M ≥ 4.0, non-tectonic events removed)

Magnitude Range	UUSS Catalog	NSHM Catalog
$4.0 \le M < 4.5$	45	34
$4.5 \le M < 5.0$	5	4
$5.0 \le M < 5.5$	10	21
$5.5 \le M < 6.0$	4	4
$6.0 \le M < 6.5$	3	3
$6.5 \le M < 7.0$	1	1
Total Number	68	67

Comparison of independent mainshocks ($M \geq 4.0$) in the UUSS and NSHM catalogs for the WGUEP Region — *accounting for completeness periods*

Magnitude Range	Completeness Period	Yrs	Number UUSS Catalog	Number NSHM Catalog
$4.00 \leq M < 4.67$	July 1962−Dec 2010	48.5	17	16
$4.67 \leq M < 5.33$	Jan 1950−Dec 2010	61.0	7	17
$5.33 \leq M < 6.00$	Jan 1938−Dec 2010	73.0	1	2
$6.00 \leq M < 6.67$	Jan 1900−Dec 2010	111.0	3	2


Original Sources
Pancha et al. (2006)
Catalog for WUS
(1850–1999, M ≥ 5.0)
UUSS Catalog
1850 – 2010
NSHM Catalog
1796 [1880] – 2010
Goal:
Unified UUSS-NSHM Catalog
for the WGUEP Region

Example Comparison of NSHM and UUSS Catalogs

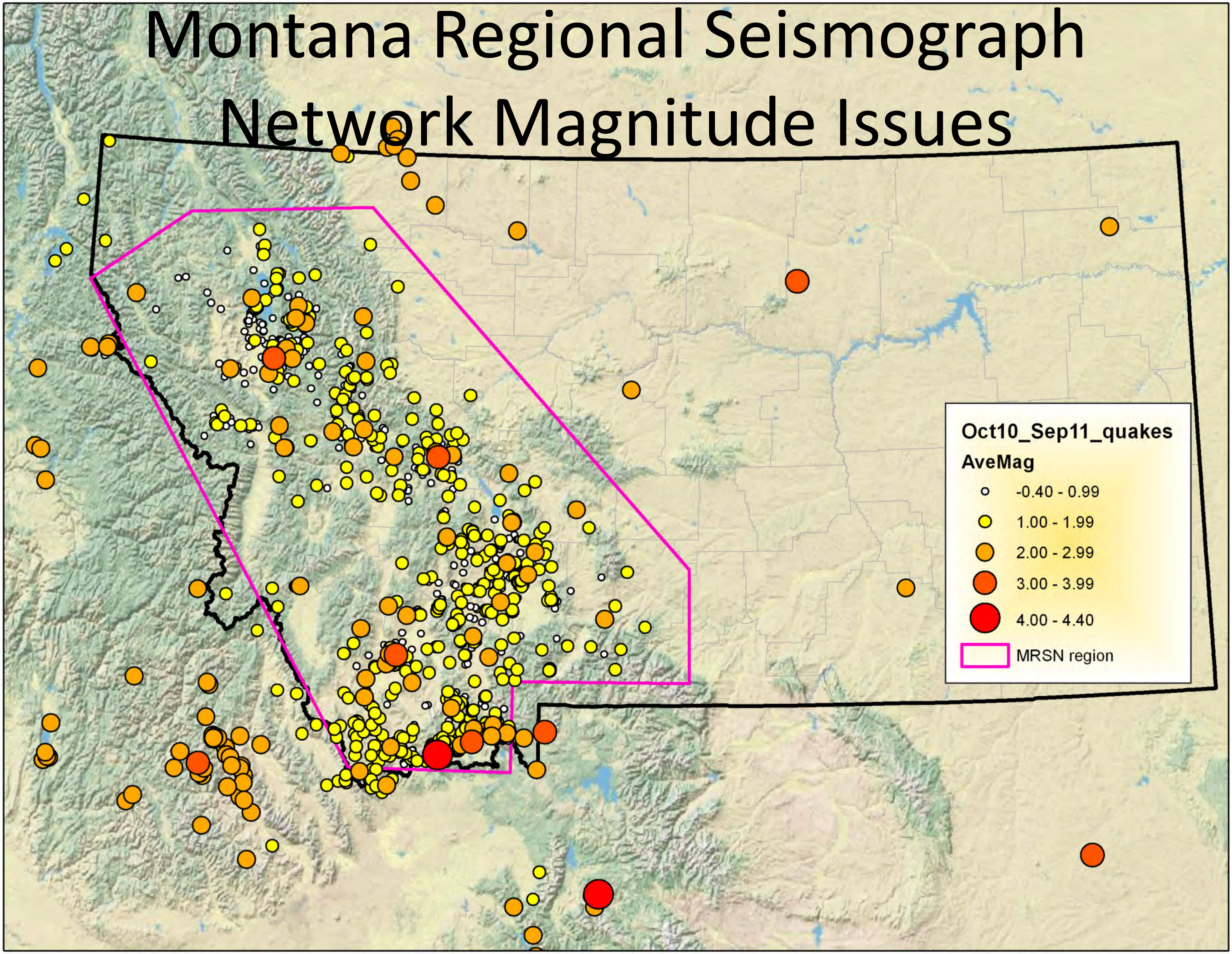
	NSHM→		← Pancha et al. (2006)			UUSS		
1966	5.21	UNR|mw	5.20899001	Mw	D&S 1982	4.6	ML	
1963	5.03	UNR|mw	5.03230178	Mw Surf	Patton 85	4.4	ML	
1964	5.02	UNR|mw	5.01883286	Mw	D&S 1982	4.1	ML	
1950	5.00	UNR|mw	5	MLEPB	EPB	3.0	X	NOAA (no mag)
1953	5.00	UNR|mw	5	MLEPB	EPB	4.3	I	
1957	5.00	UNR|mw	5	MLEPB	EPB	3.0	X	NOAA (no mag)
1958	5.00	UNR|mw	5		UTHist	5.0	I	
1960	5.00	UNR|mw	5	MLEPB	EPB	3.0	X	NOAA (no mag)
1961	5.00	UNR|mw	5		UTHist	5.0	I	
1962	5.00	UNR|mw	5.00470666	Mw	D&S 1982	5.2	ML	
1980	5.00	UNR|mw	5	mb GS	PDE	4.4	Mc	
1988	5.00	UNR|mw	5	mb GS	USHIS	4.32	Mc	
1987	4.99	UNR|mw	4.99	Mw SorB	W&C	4.71	Mc	
1973	4.95	UNR|mw	4.94900929	Mw	D&S 1982	4.2	Mc	
1987	4.80	UNR|mw	4.8	Mc	CNSS UW			Duplicate
1989	4.80	UNR|mw	4.8	*W	Utregion	4.8	ML	

Conclusions

- Standard errors for magnitude estimates in UUSS catalog can be documented for M_{lo}, M_L, and M_C, and rounding values can be provided; decision whether to convert to M_W event by event via regression
- Size estimates for pre-instrumental shocks have relatively largest uncertainty; intensity-magnitude relation needs to be examined with added data, and sizes of larger events re-examined
- Differences in magnitudes between NSHM and UUSS catalogs need to be reconciled, requiring careful checking and perhaps calculating preferred magnitude from variance-weighting of values from different available magnitude scales

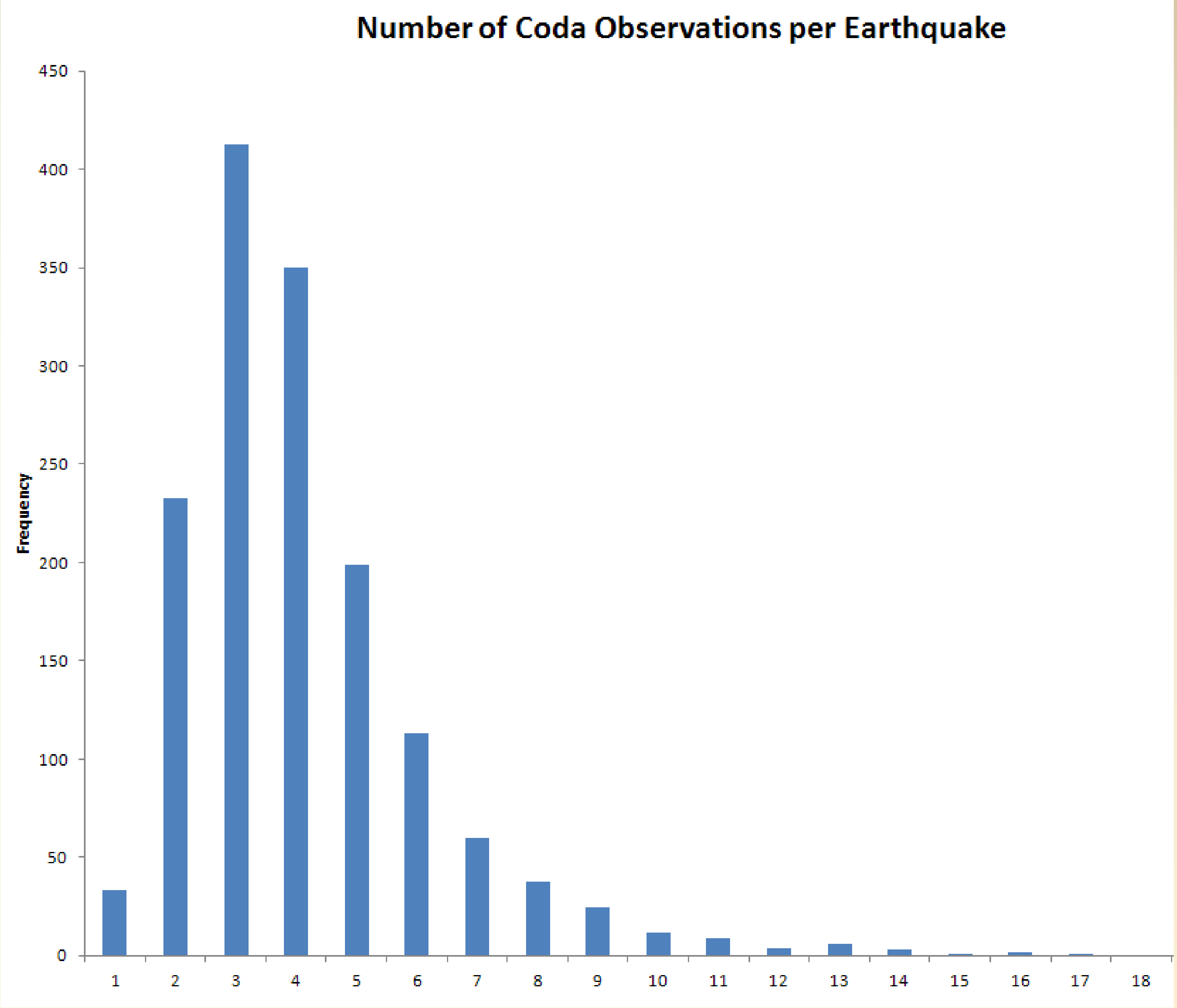
end

Montana Regional Seismograph Network Magnitude Issues

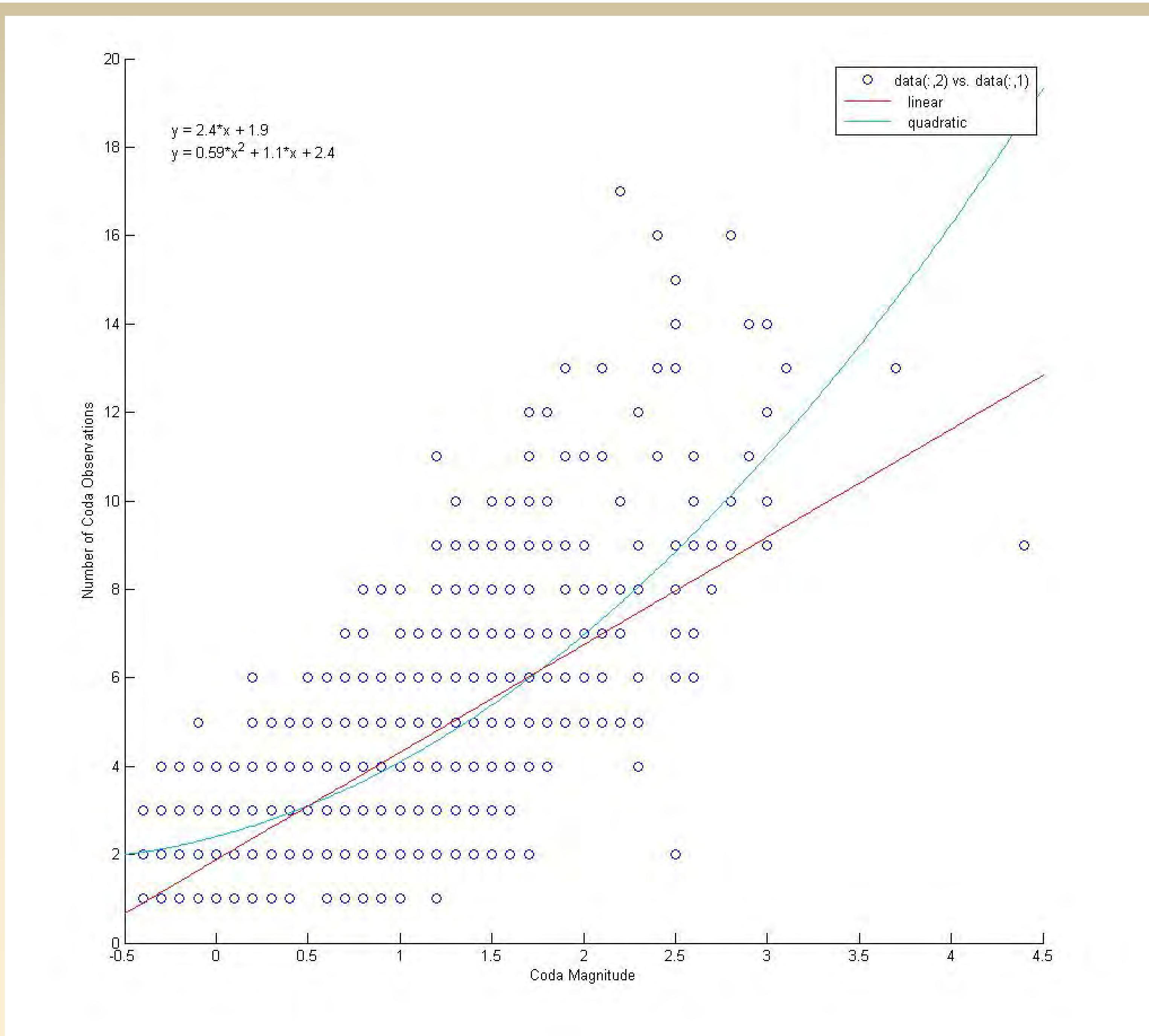


Three issues affecting magnitude estimates

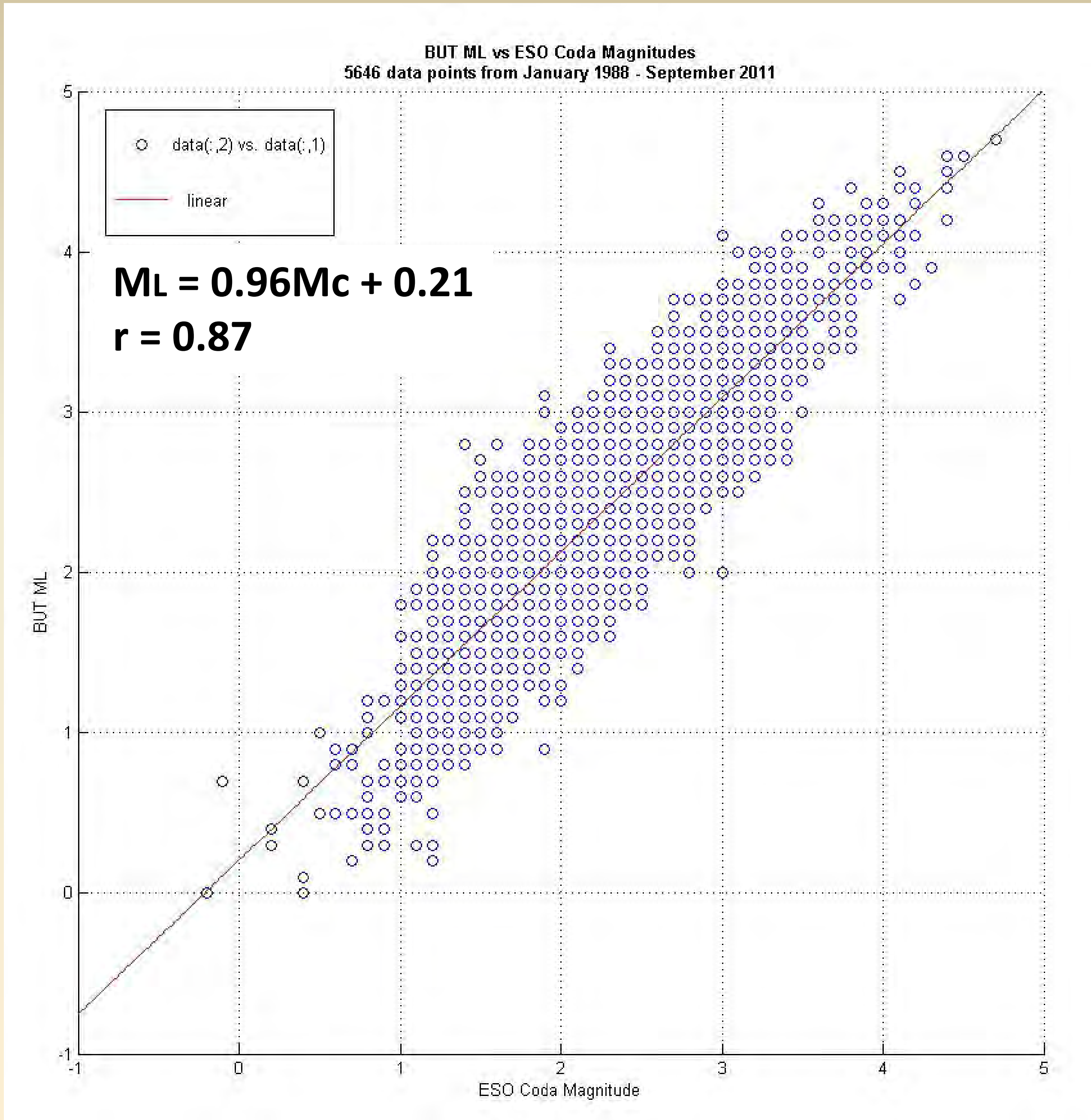
- Variability of M estimates for a single event
- Number of measurements used to determine M for a single event
- Number of stations available for M estimates as a function of time



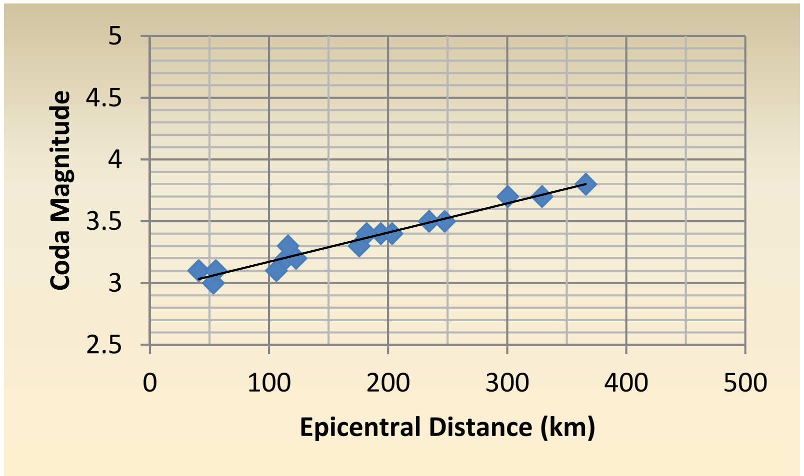
Histogram of the number of coda duration measurements used for magnitude determination for 1502 earthquakes within the MRSN region from 10/ 2010 – 9/2011



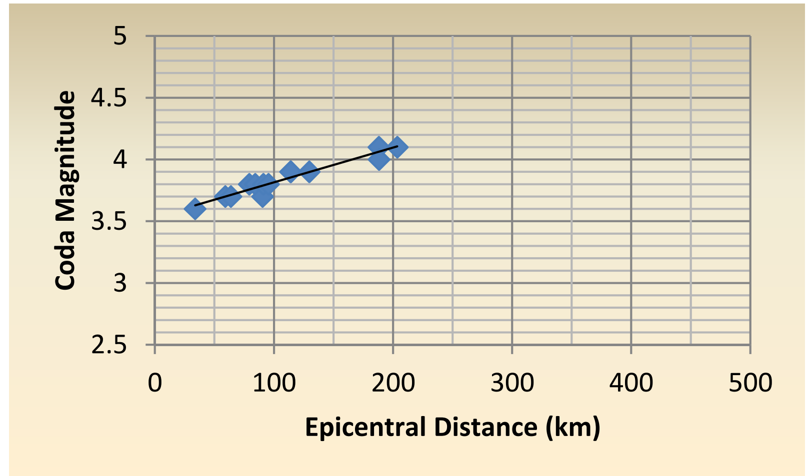
Number of coda observations used for magnitude determinations for Earthquakes occurring 10/2010 – 9/2011 (1502 observations)



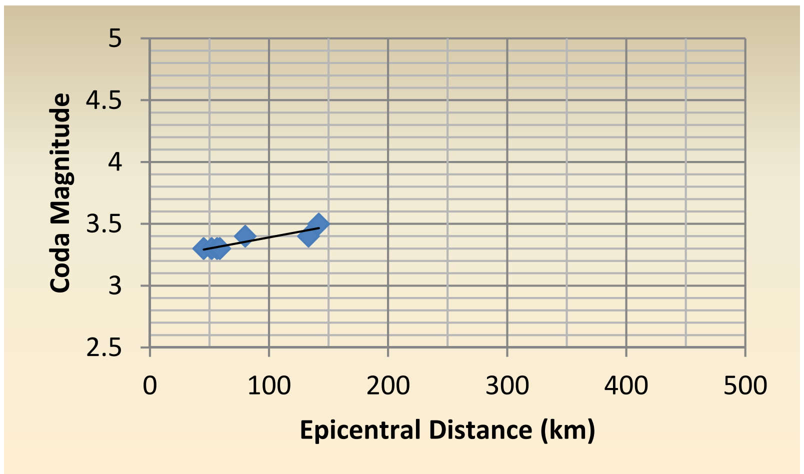
5647 earthquakes within 300 km of BUT that have magnitude determinations from both coda durations and BUT ML since January 1988



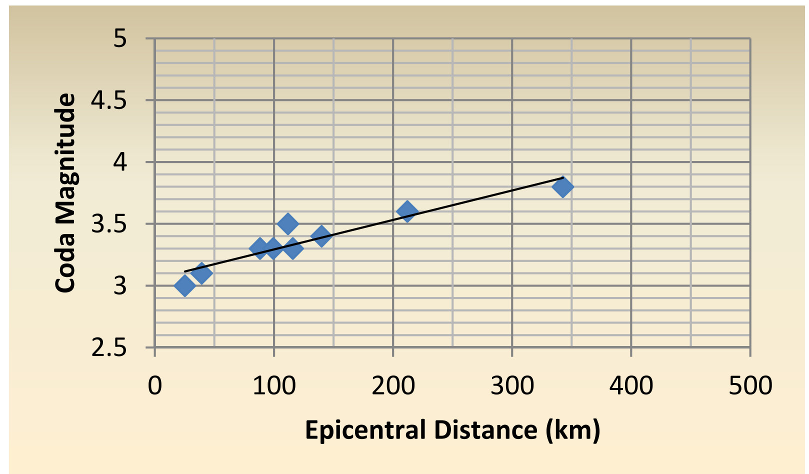
Coda Magnitude
5
4.5
4
3.5
3
2.5
0
100
200
300
400
500
Epicentral Distance (km)



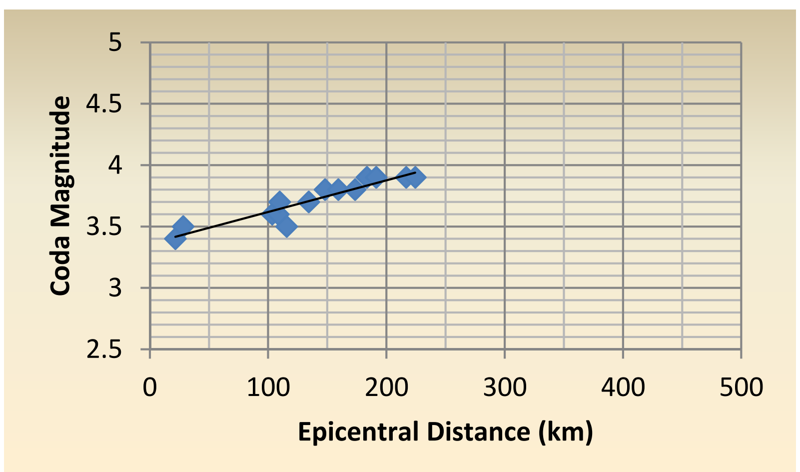
Coda Magnitude
5
4.5
4
3.5
3
2.5
0
100
200
300
400
500
Epicentral Distance (km)



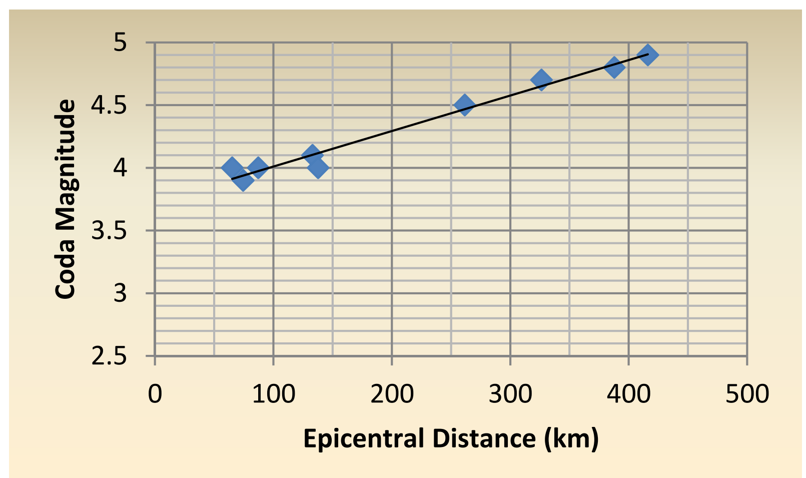
Coda Magnitude
5
4.5
4
3.5
3
2.5
0
100
200
300
400
500
Epicentral Distance (km)



Coda Magnitude
5
4.5
4
3.5
3
2.5
0
100
200
300
400
500
Epicentral Distance (km)



Coda Magnitude
5
4.5
4
3.5
3
2.5
0
100
200
300
400
500
Epicentral Distance (km)



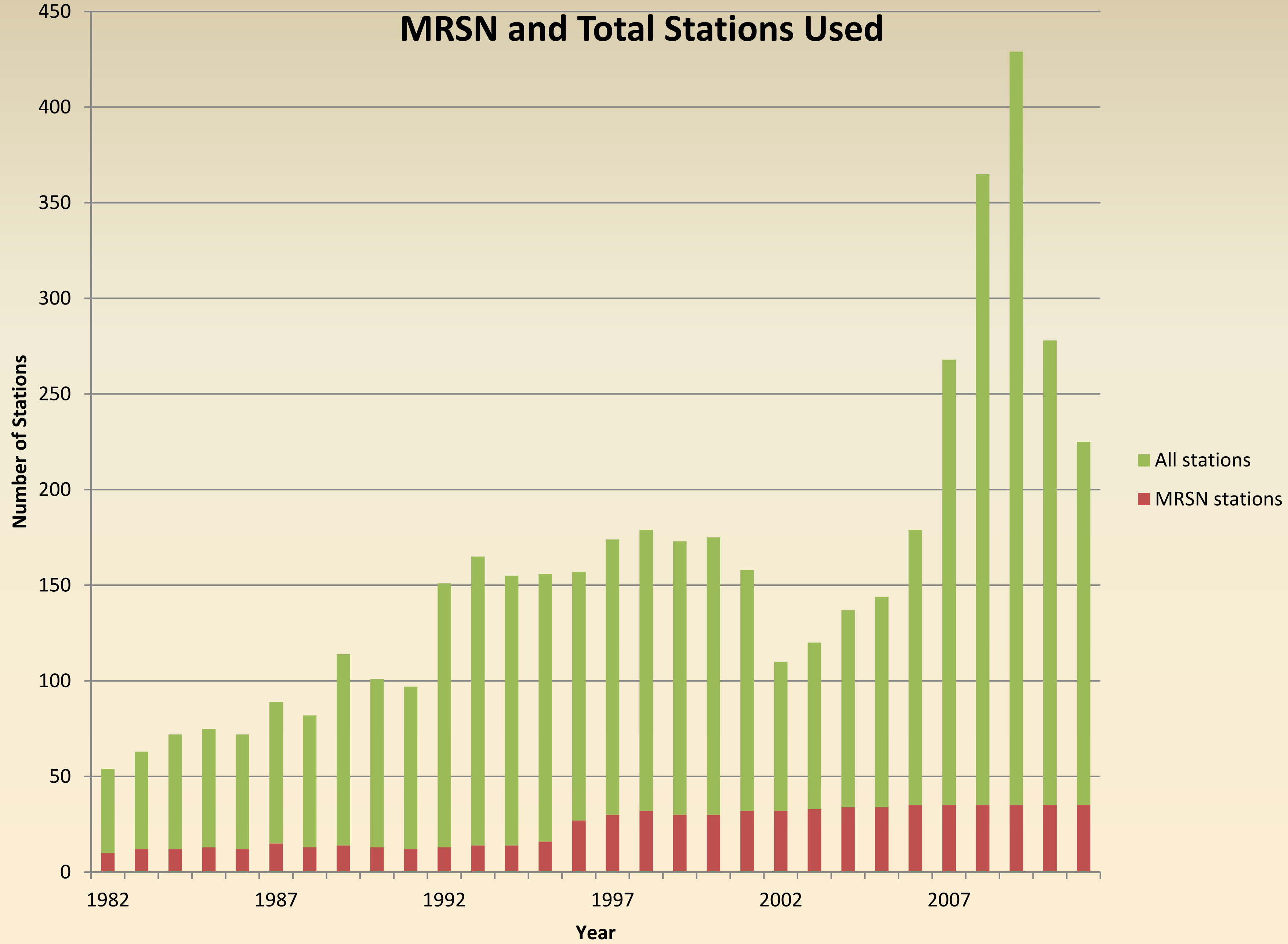
Coda Magnitude
5
4.5
4
3.5
3
2.5
0
100
200
300
400
500
Epicentral Distance (km)

Coda magnitude relation:

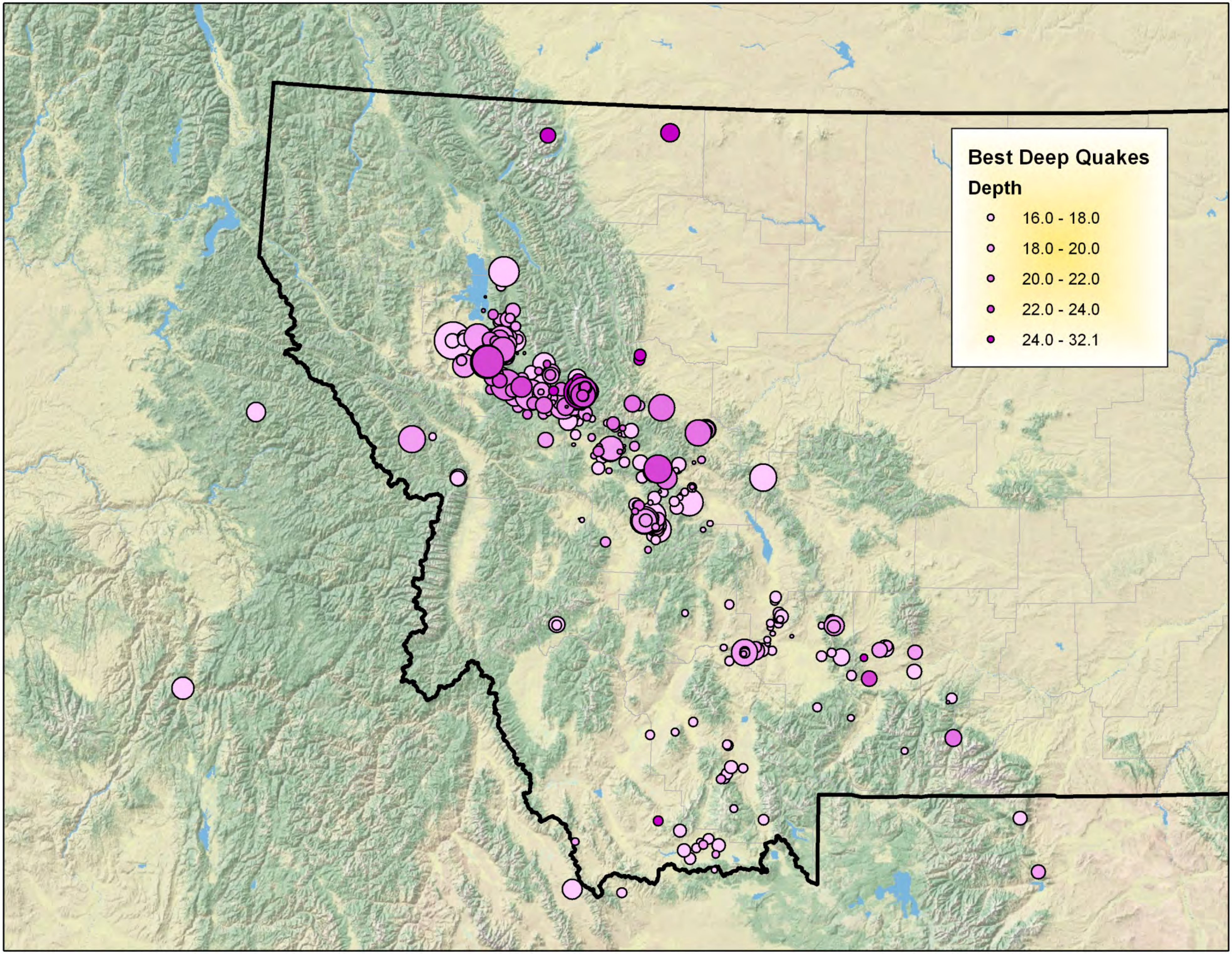
$$Mc = -2.50 + 2.275 \log \text{Duration} + 0.0029 \text{ Distance}$$

Average slope of
Epicentral Distance vs. Coda Magnitude curves
for 6 sample events:

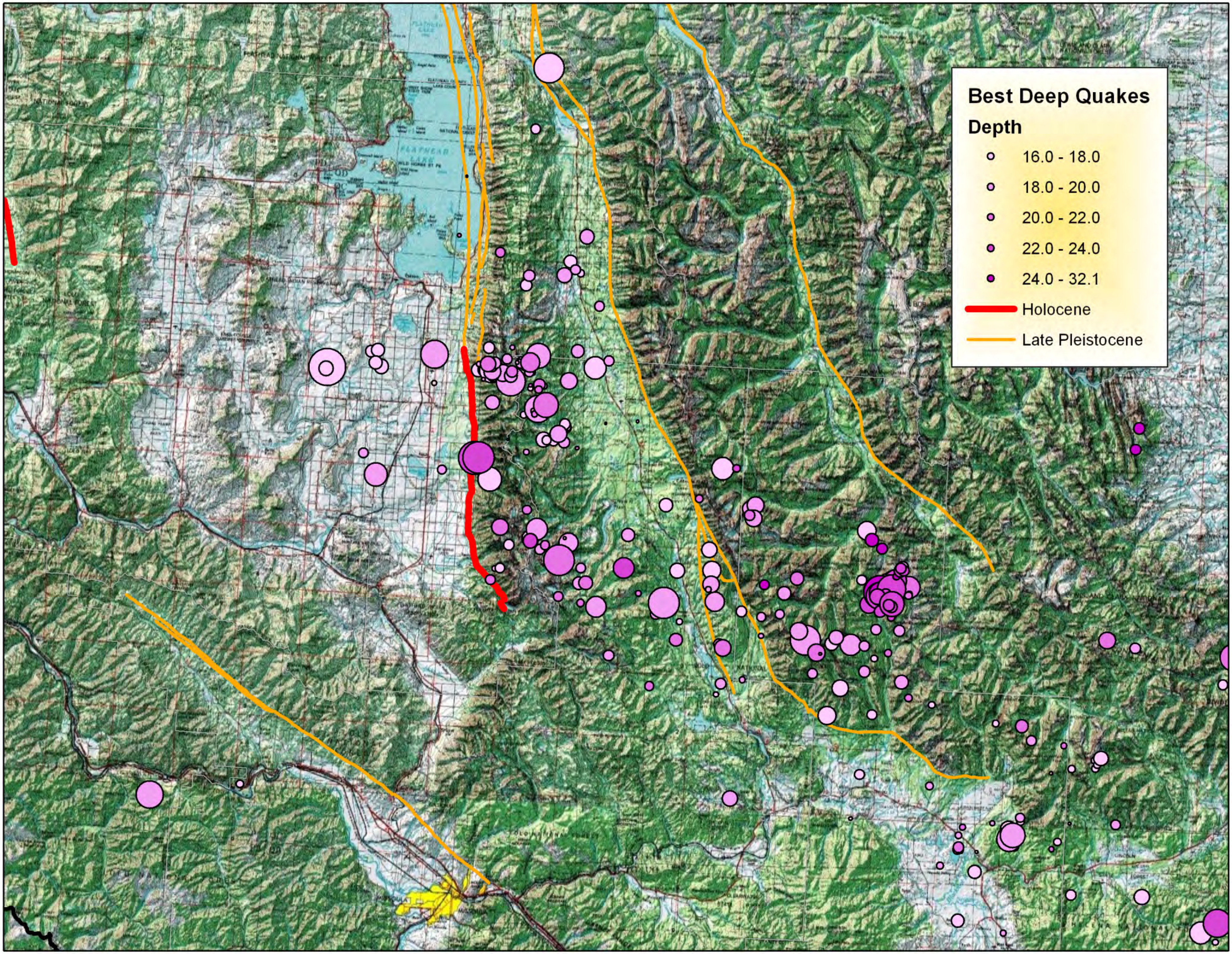
0.0025 magnitude units per km
or
.25 magnitude units per 100 km



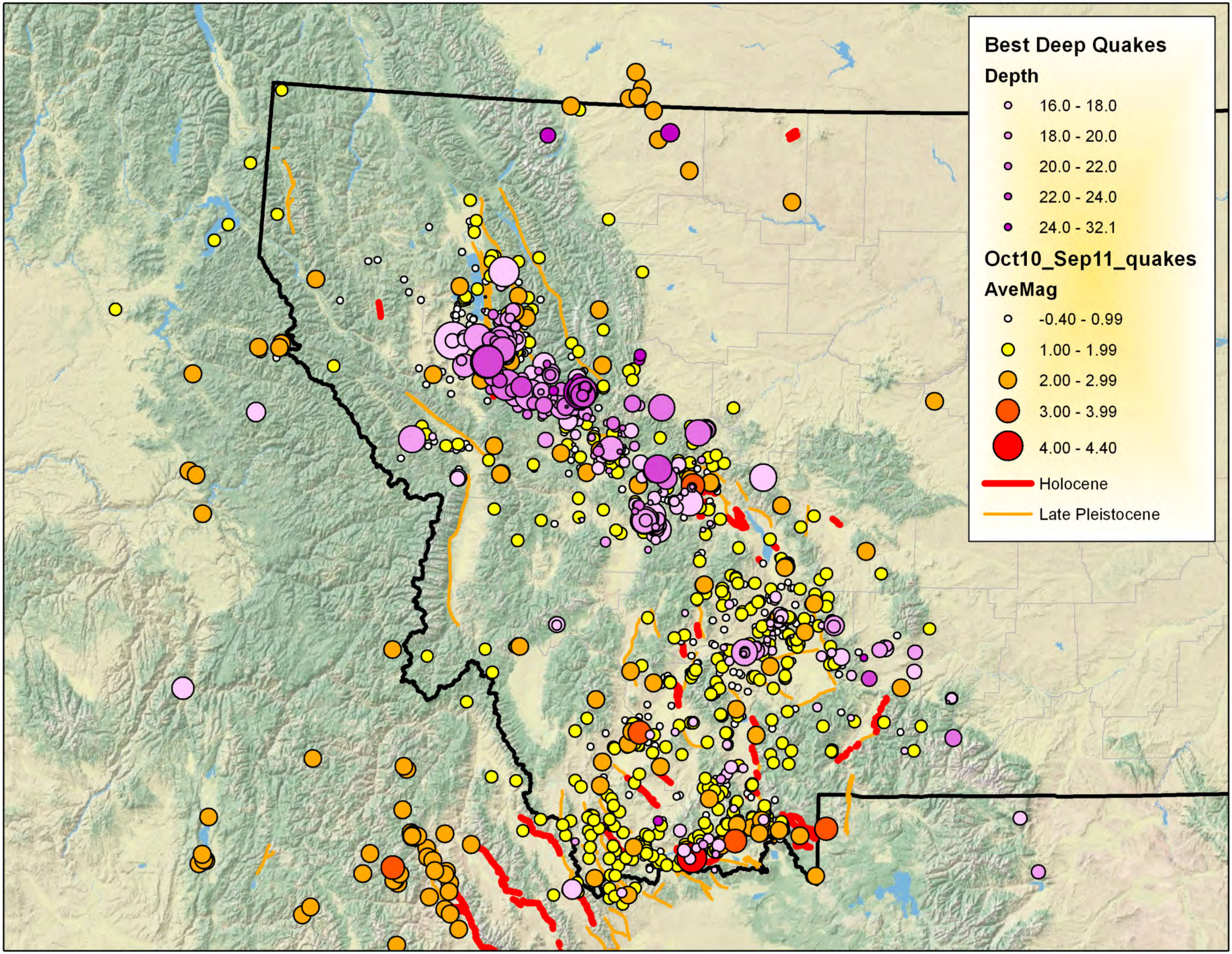
MRSN and Total Stations Used
Number of Stations
450
400
350
300
250
200
150
100
50
0
1982
1987
1992
1997
2002
2007
Year
All stations
MRSN stations



Best Deep Quakes
Depth
16.0 - 18.0
18.0 - 20.0
20.0 - 22.0
22.0 - 24.0
24.0 - 32.1



Best Deep Quakes
Depth
16.0 - 18.0
18.0 - 20.0
20.0 - 22.0
22.0 - 24.0
24.0 - 32.1
Holocene
Late Pleistocene



Best Deep Quakes
Depth
16.0 - 18.0
18.0 - 20.0
20.0 - 22.0
22.0 - 24.0
24.0 - 32.1
Oct10_Sep11_quakes
AveMag
-0.40 - 0.99
1.00 - 1.99
2.00 - 2.99
3.00 - 3.99
4.00 - 4.40
Holocene
Late Pleistocene

BRP EWG II
Issue S4

Nevada's Catalog

John G. Anderson, Glenn Biasi

Acknowledgements: USGS,

Ken Smith, Diane dePolo, Tom Rennie, et al.

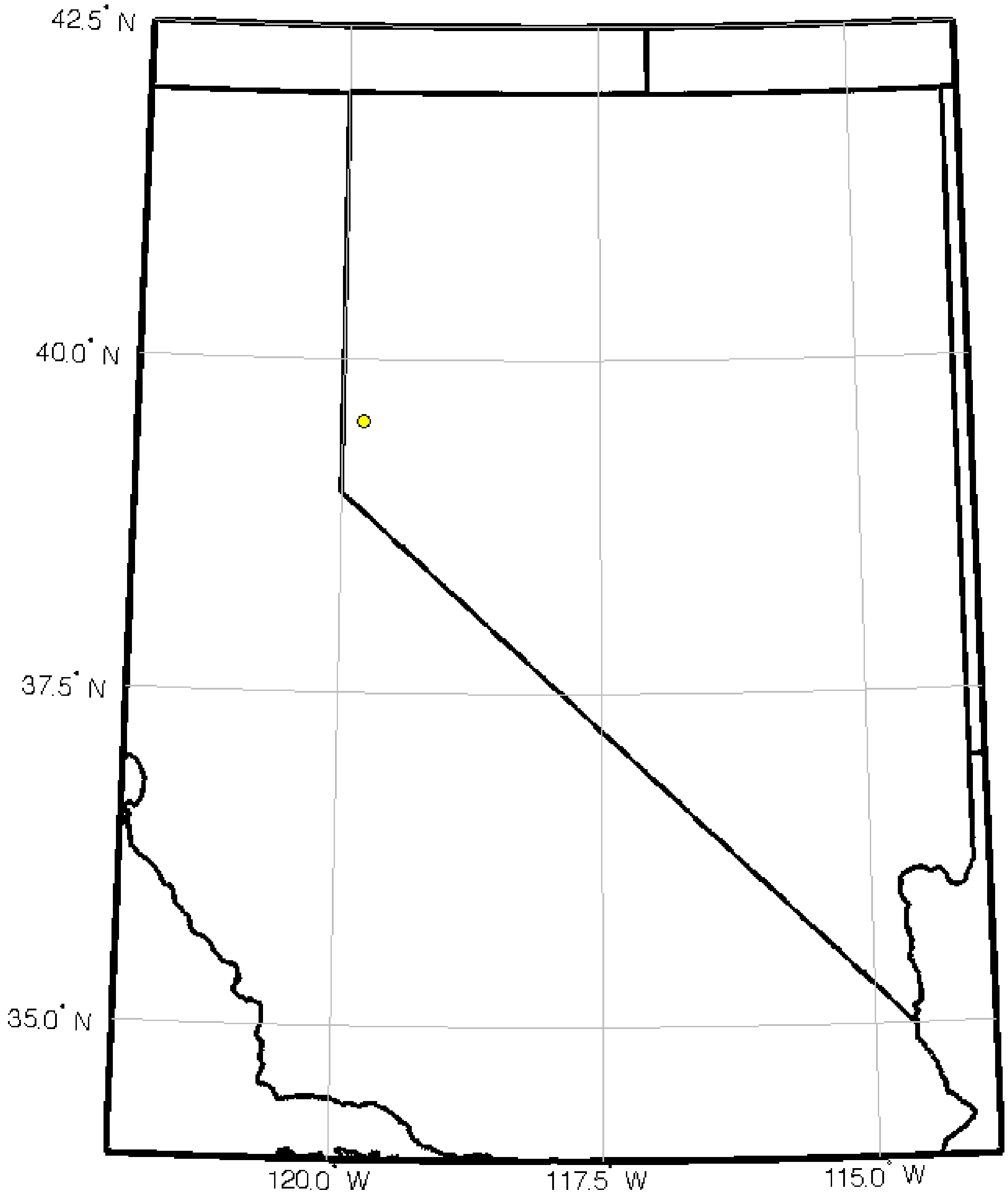
Issue S4

- Issue S4: What are the sources and levels of uncertainty in the earthquake magnitudes contained in the seismicity catalogs used in the NSHMs?

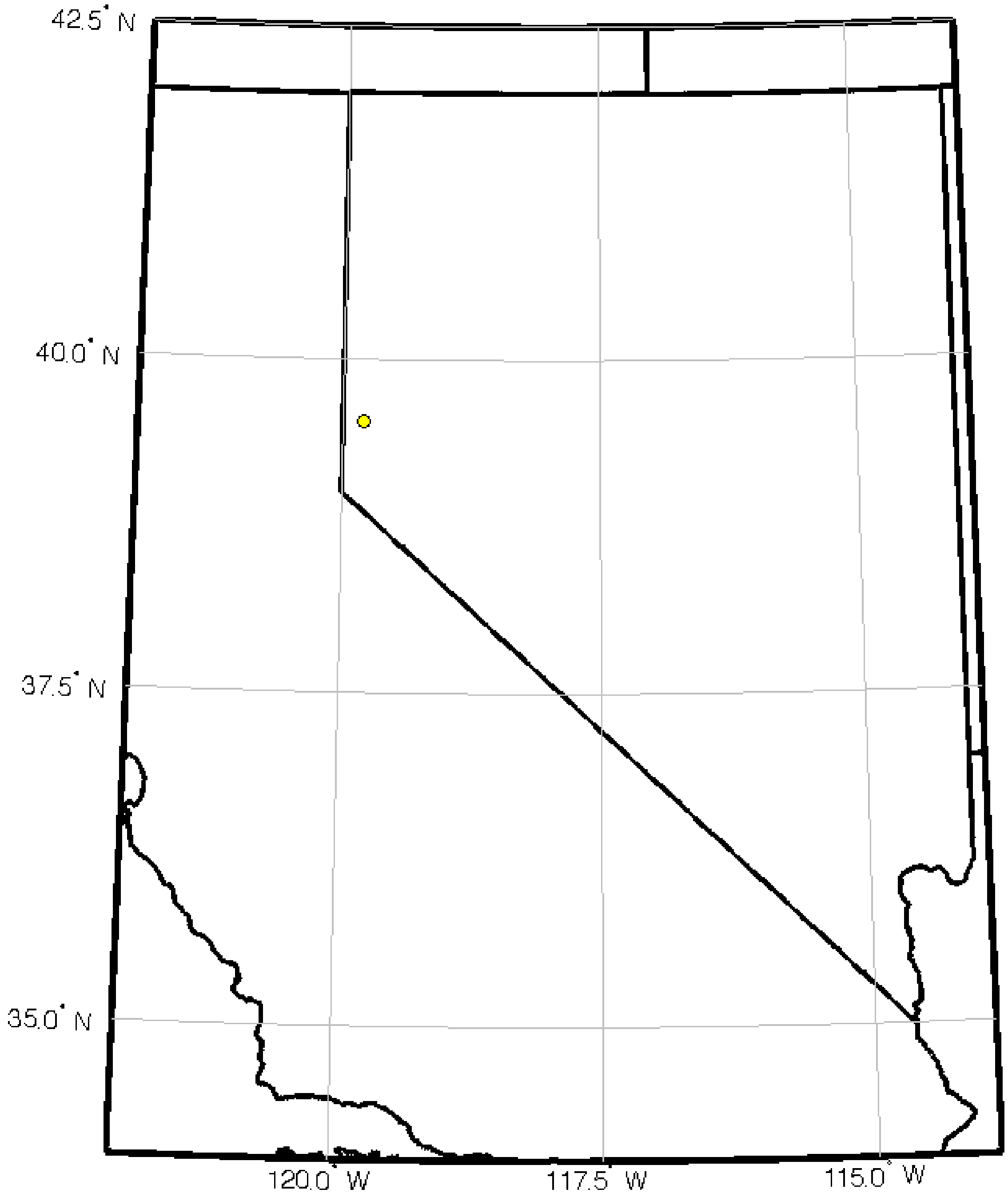
Outline

- History of Nevada monitoring
- Current status
- Uncertainties over time looking backwards

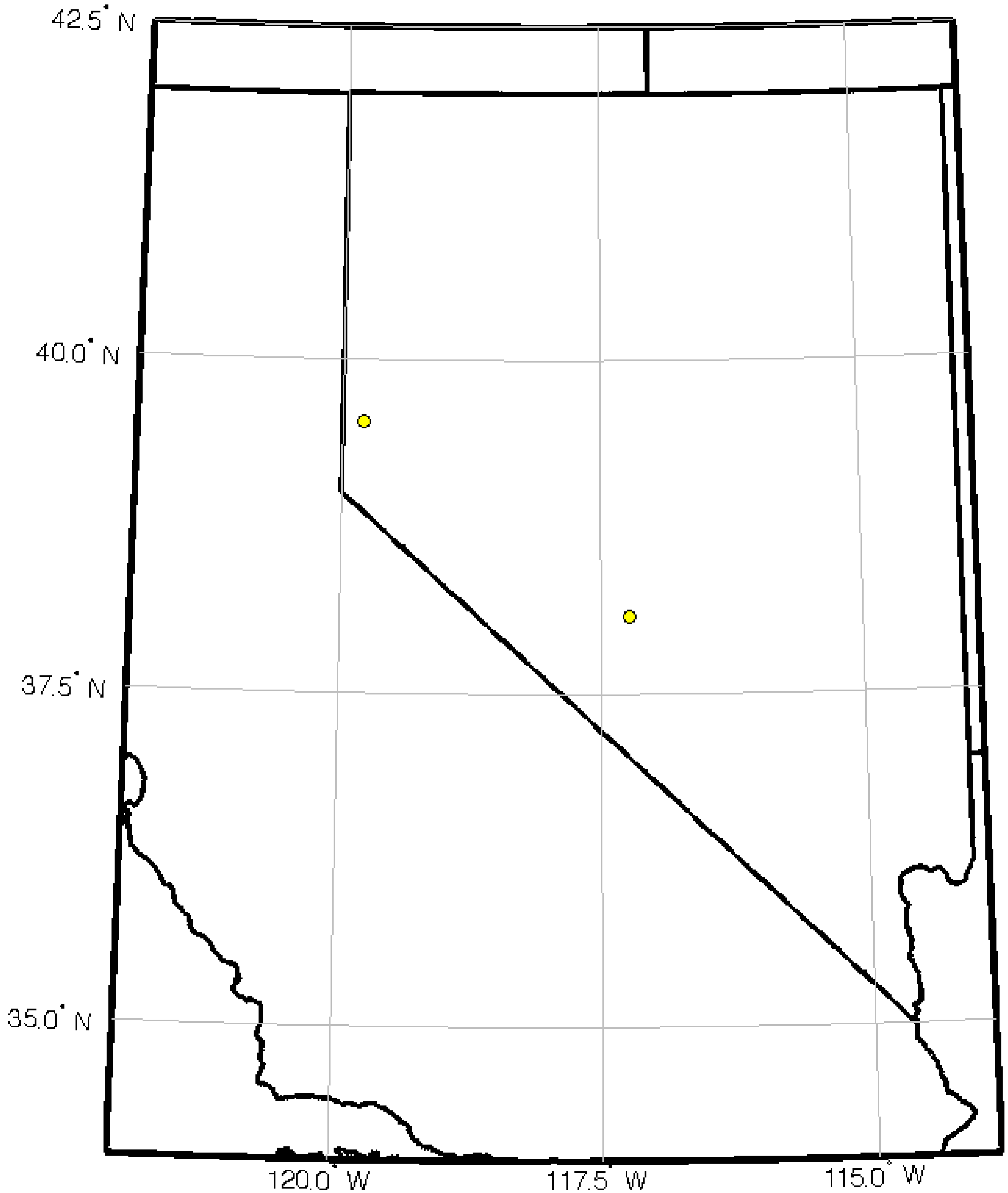
1917



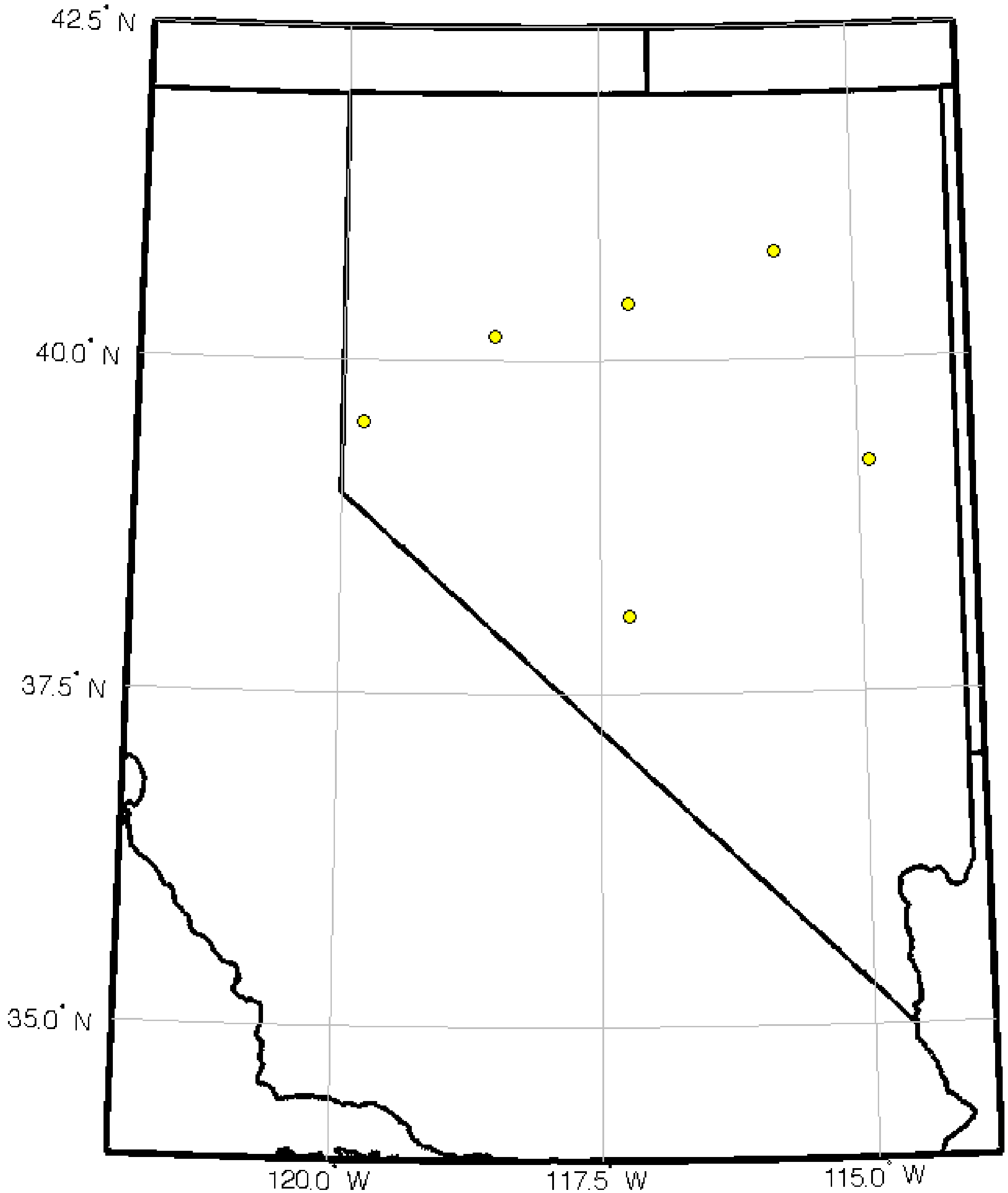
1963



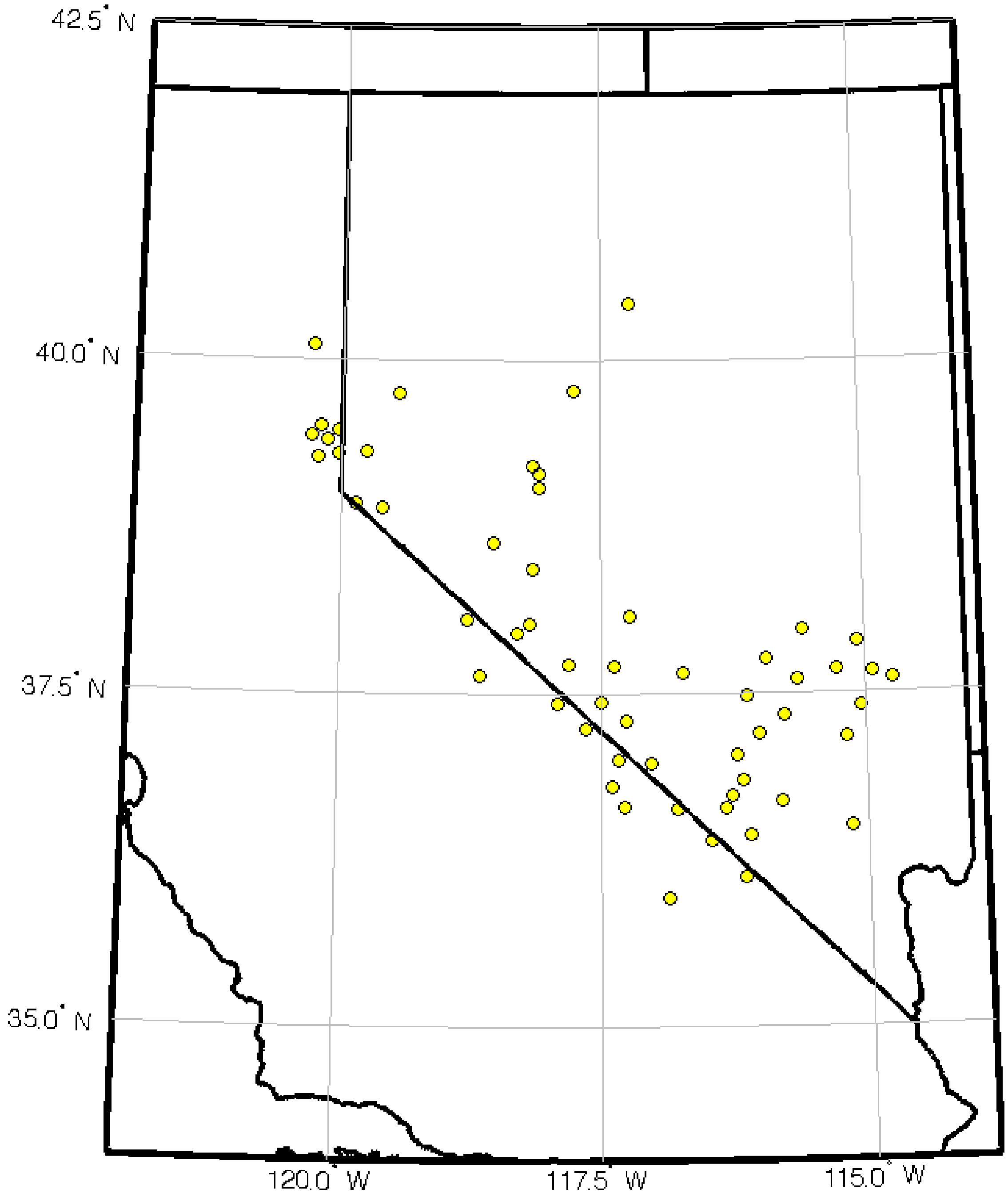
1964



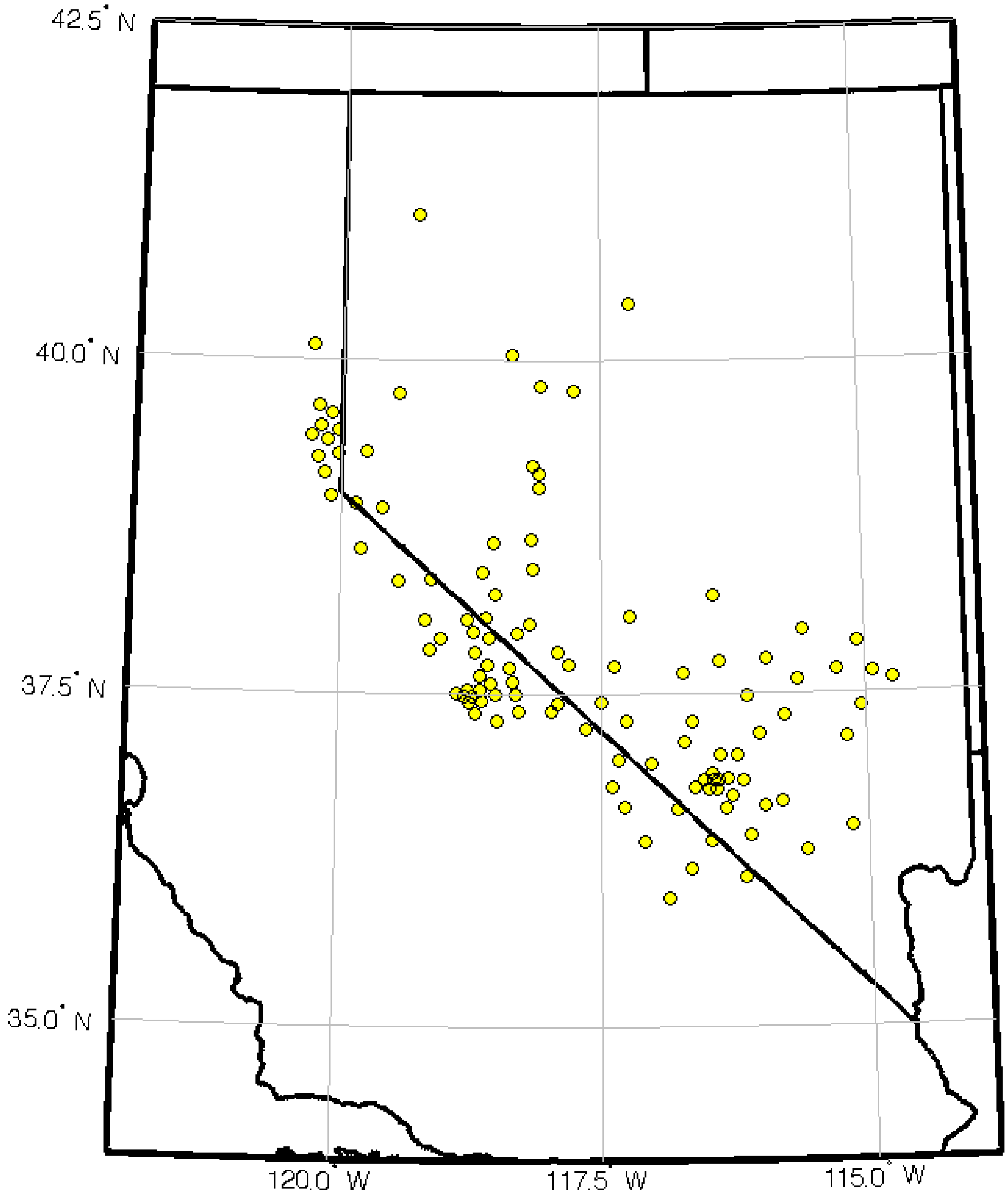
1970



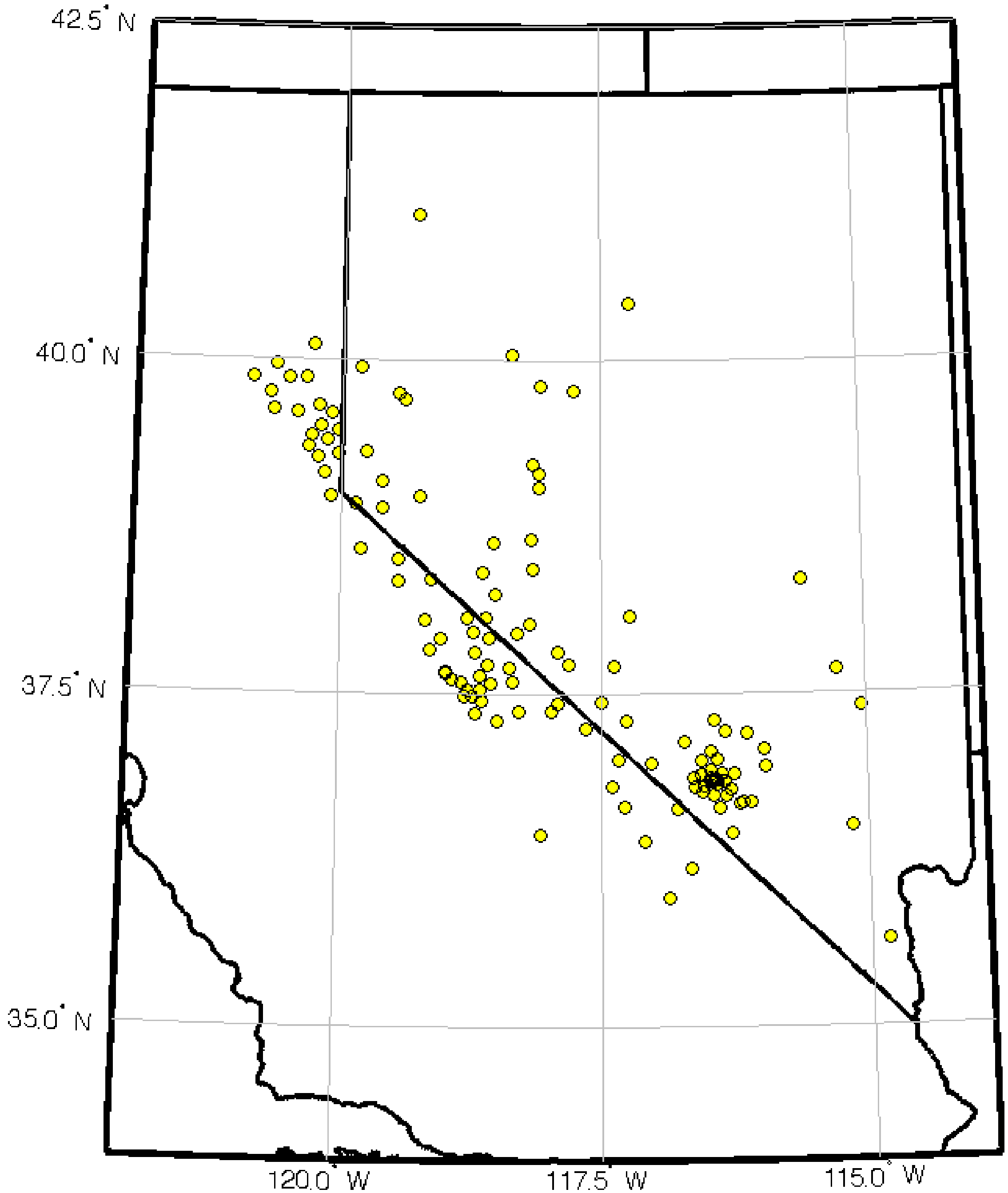
1980



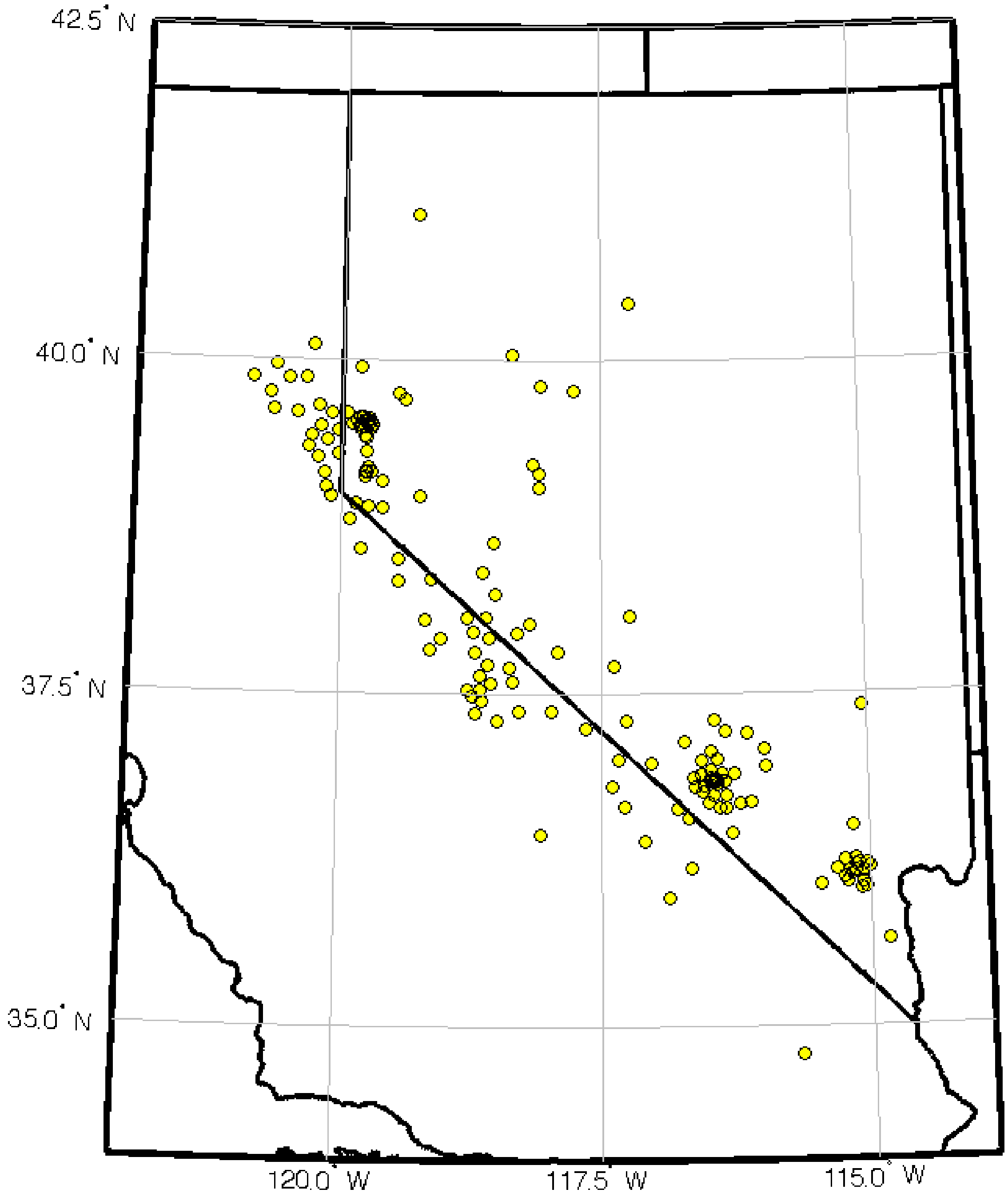
1990

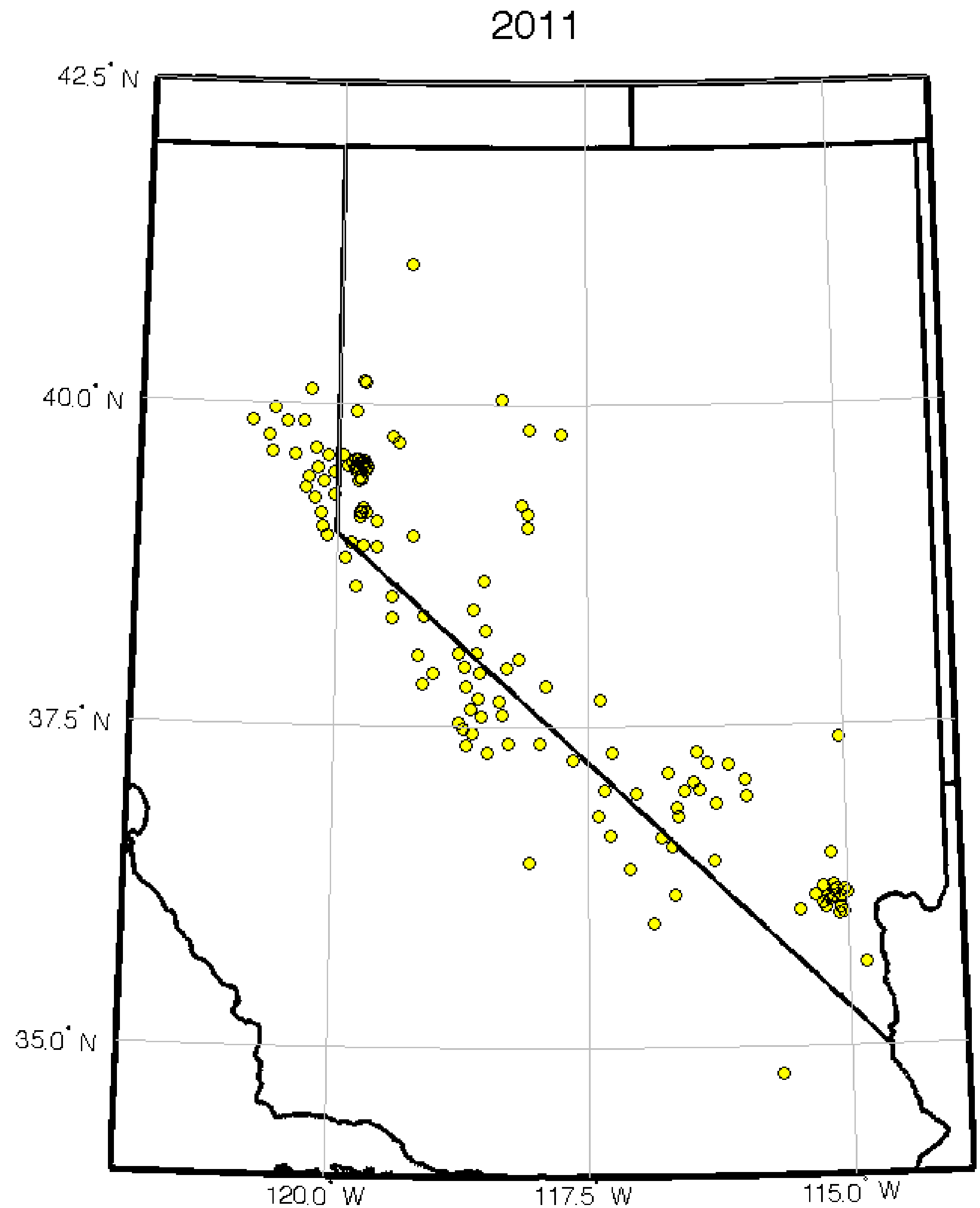


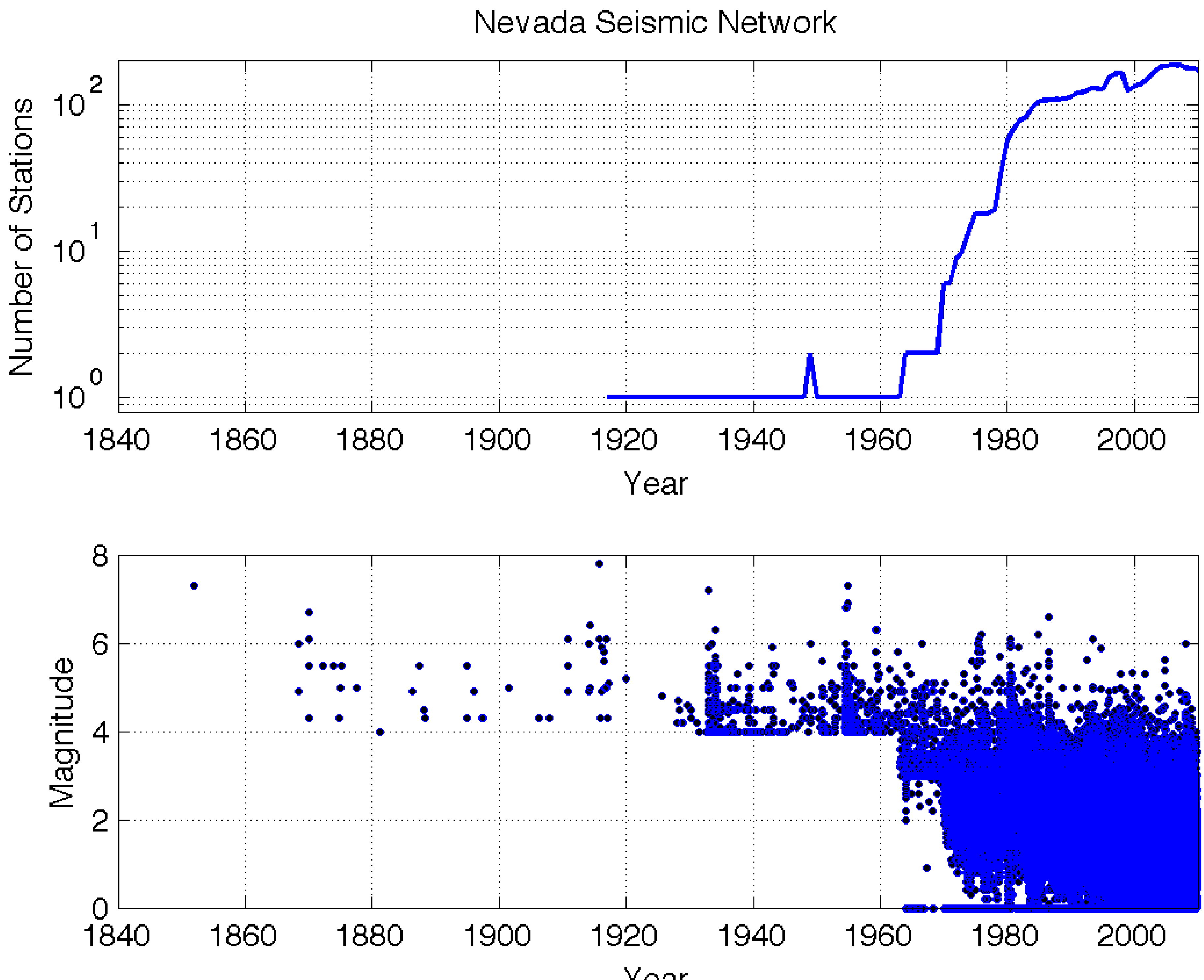
2000

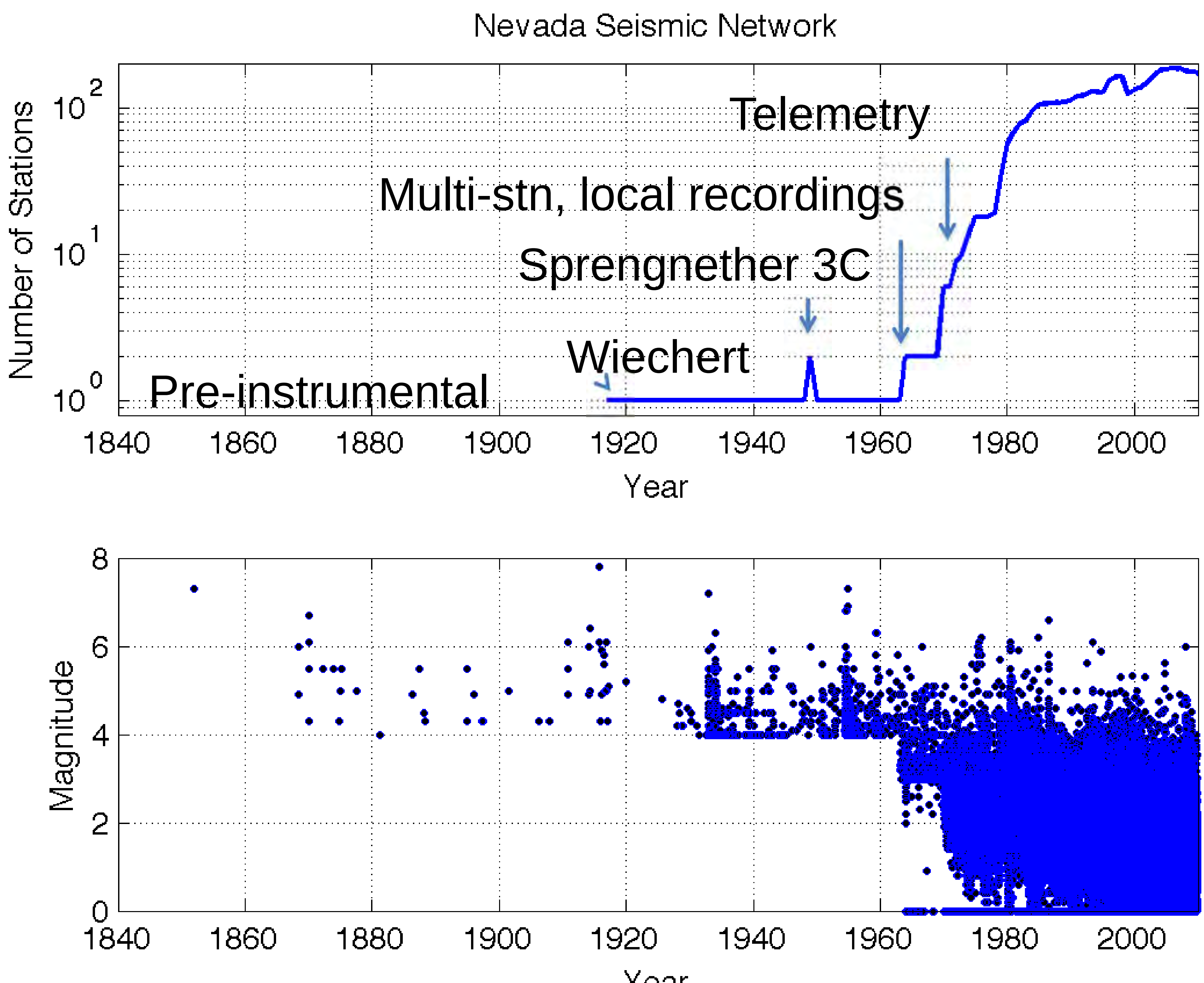


2010




2011
42.5° N
40.0° N
37.5° N
35.0° N
120.0° W
117.5° W
115.0° W


Nevada Seismic Network
Number of Stations
10^2
10^1
10^0
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year
Magnitude
8
6
4
2
0
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year

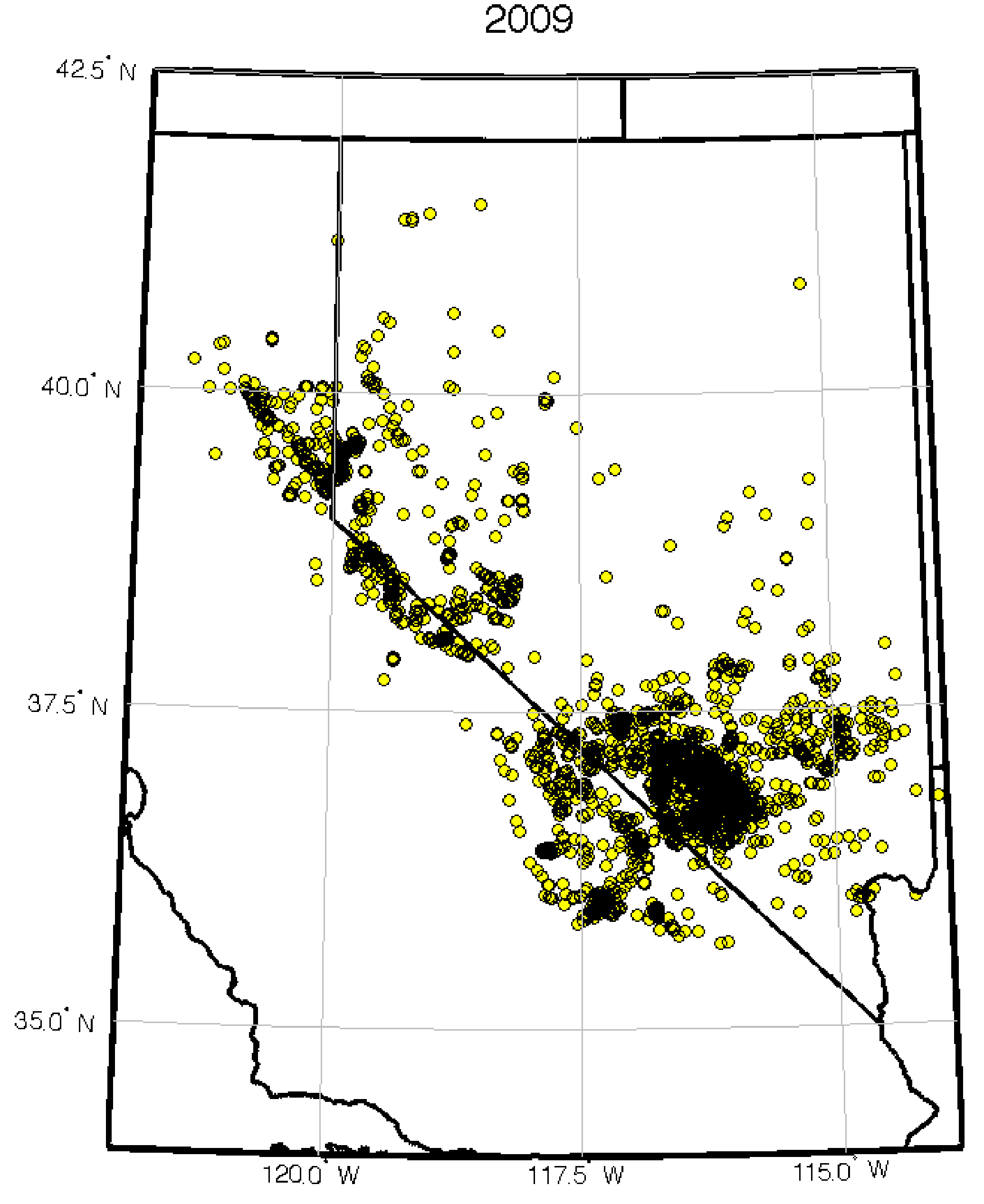


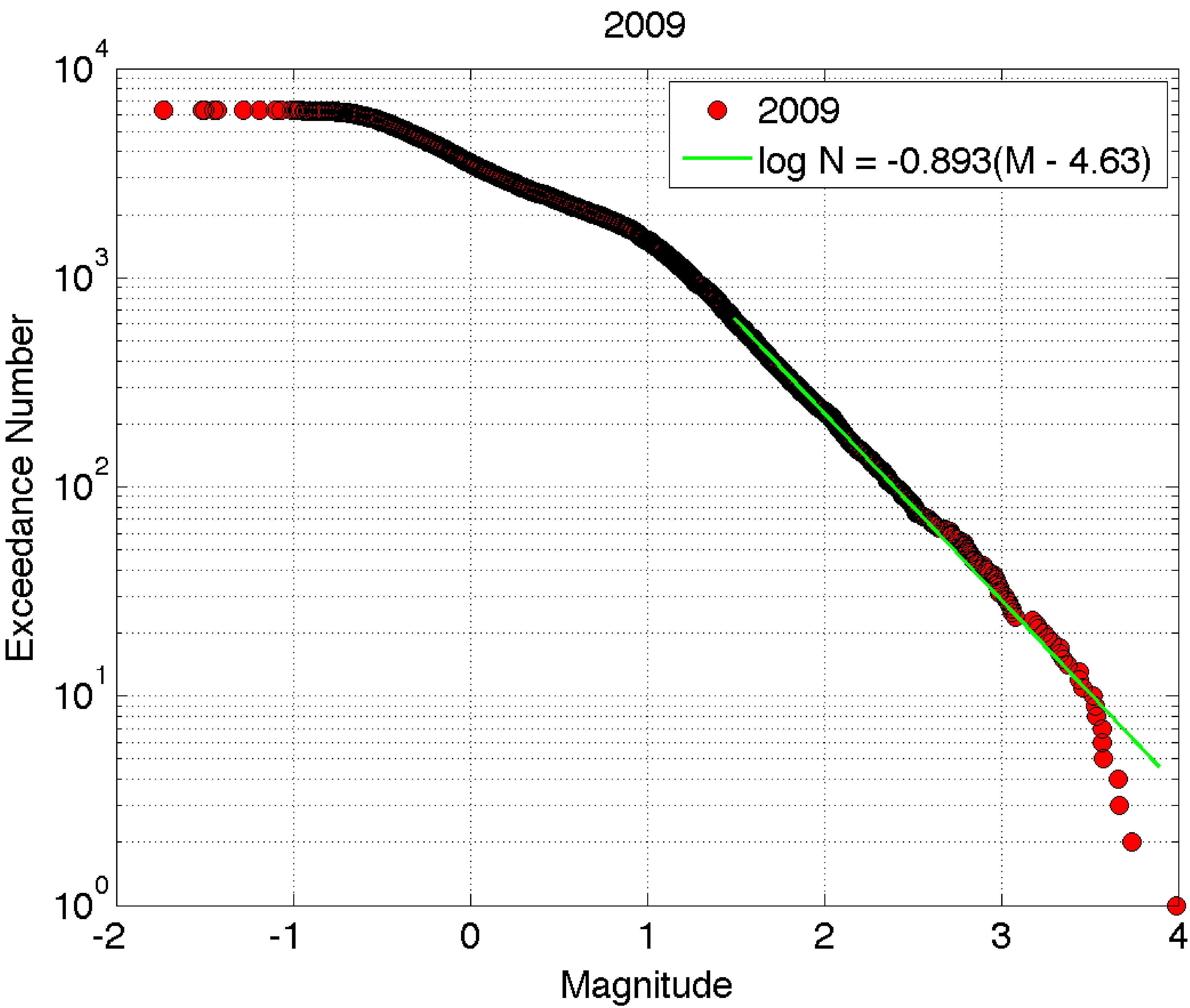
Nevada Seismic Network
Number of Stations
Telemetry
Multi-stn, local recordings
Sprengnether 3C
Wiechert
Pre-instrumental
Year
Magnitude
Year

Case Study 2009

- "Local" events only
- Relatively quiet year
- Magnitude scale: M_L
- Uses Richter distance term & M=2080
- YMP network operating
- 6296 earthquakes

John Anderson

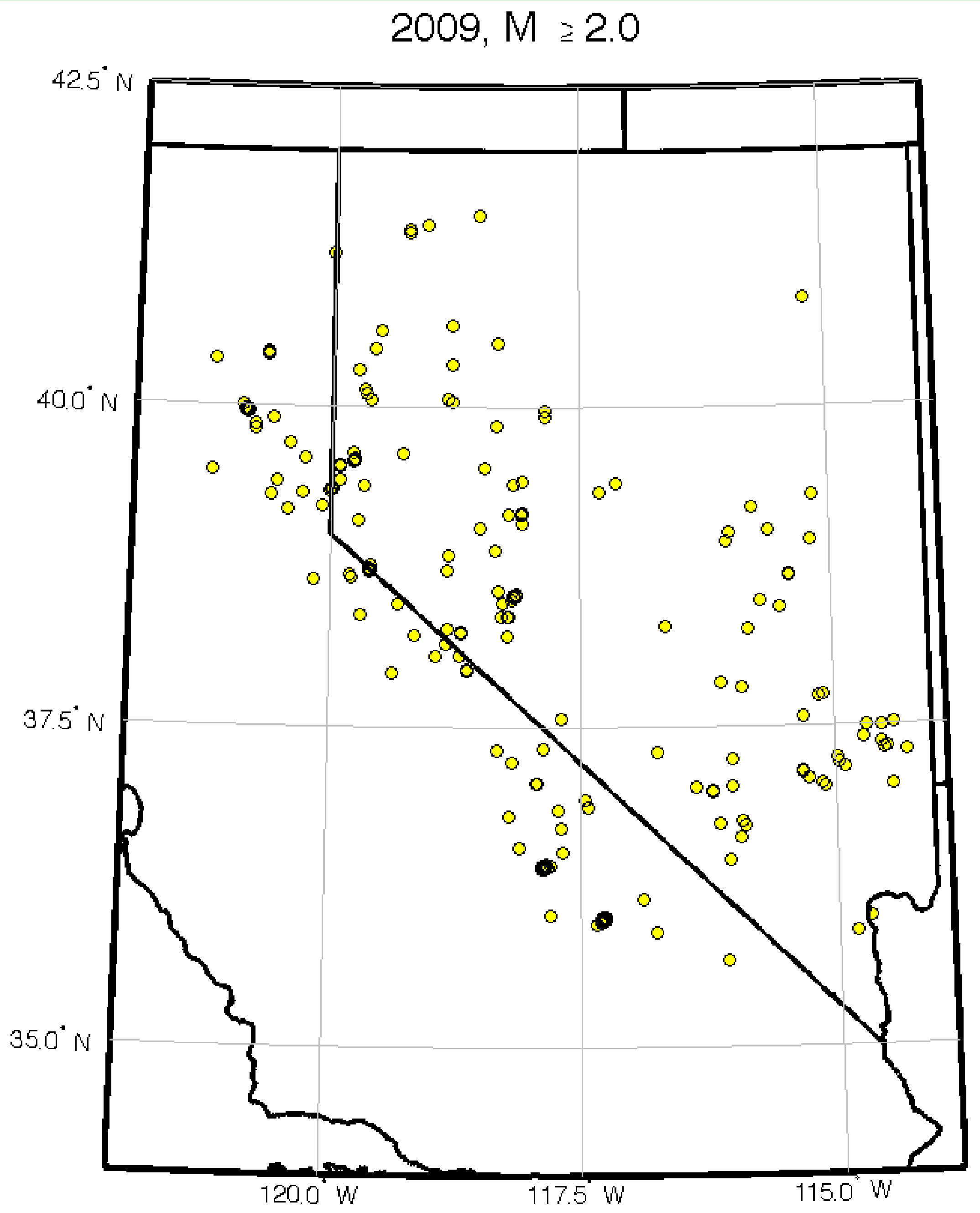


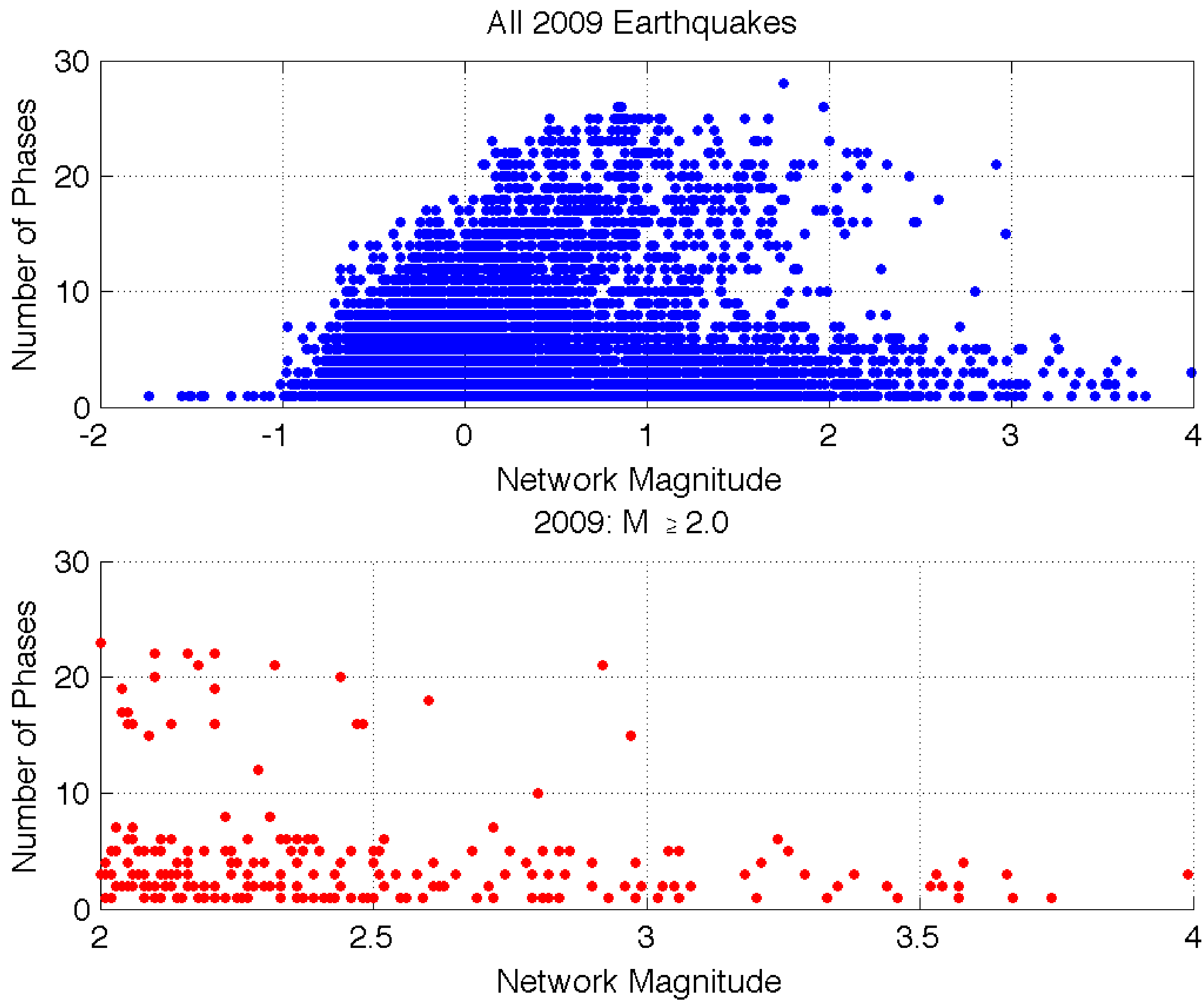

2009
Exceedance Number
Magnitude
2009
log N = -0.893(M - 4.63)
10^4
10^3
10^2
10^1
10^0
-2
-1
0
1
2
3
4

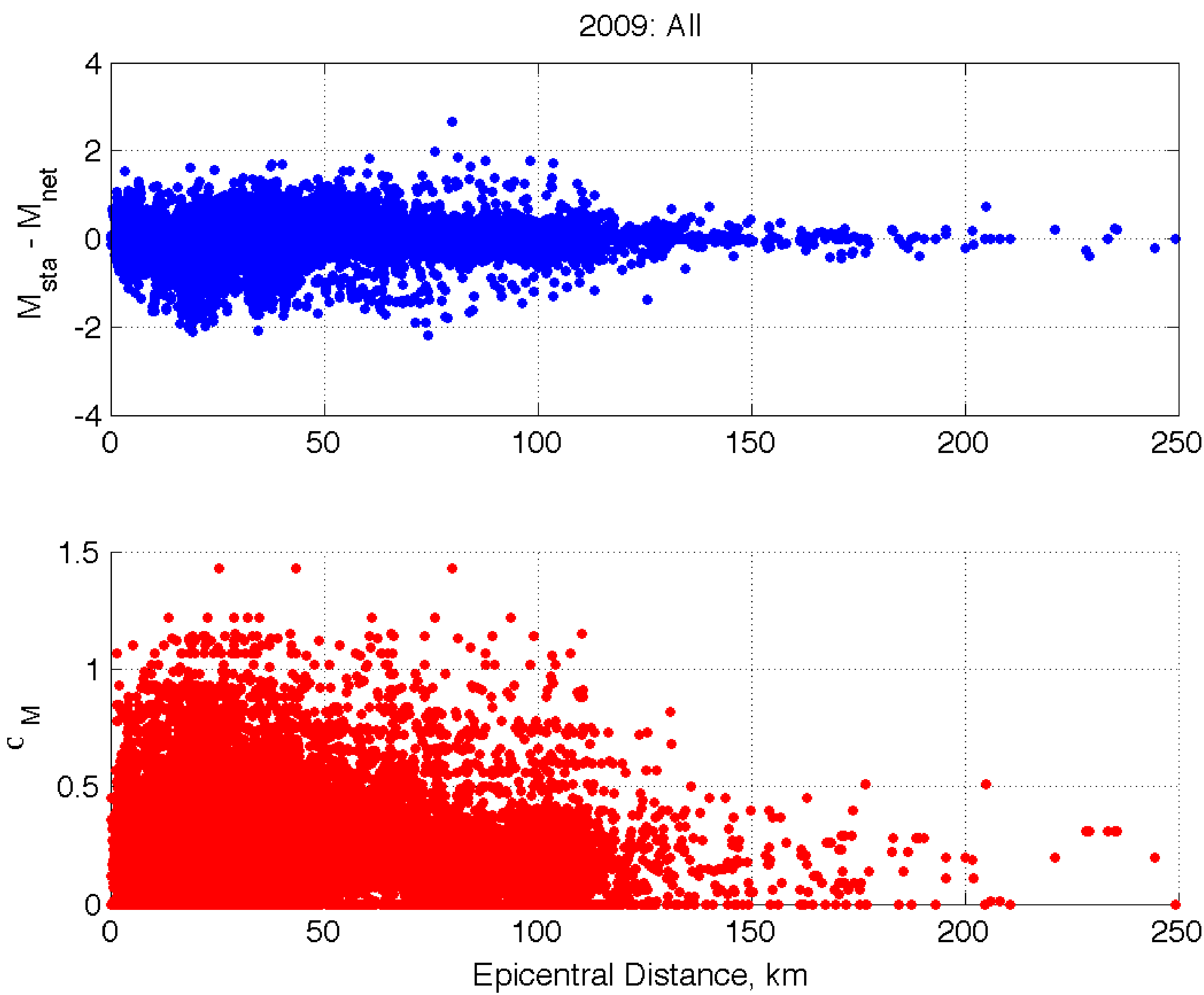
2009, M≥2.0

- 230 earthquakes
- Larger fraction in northern Nevada, not picked on the YMP net.

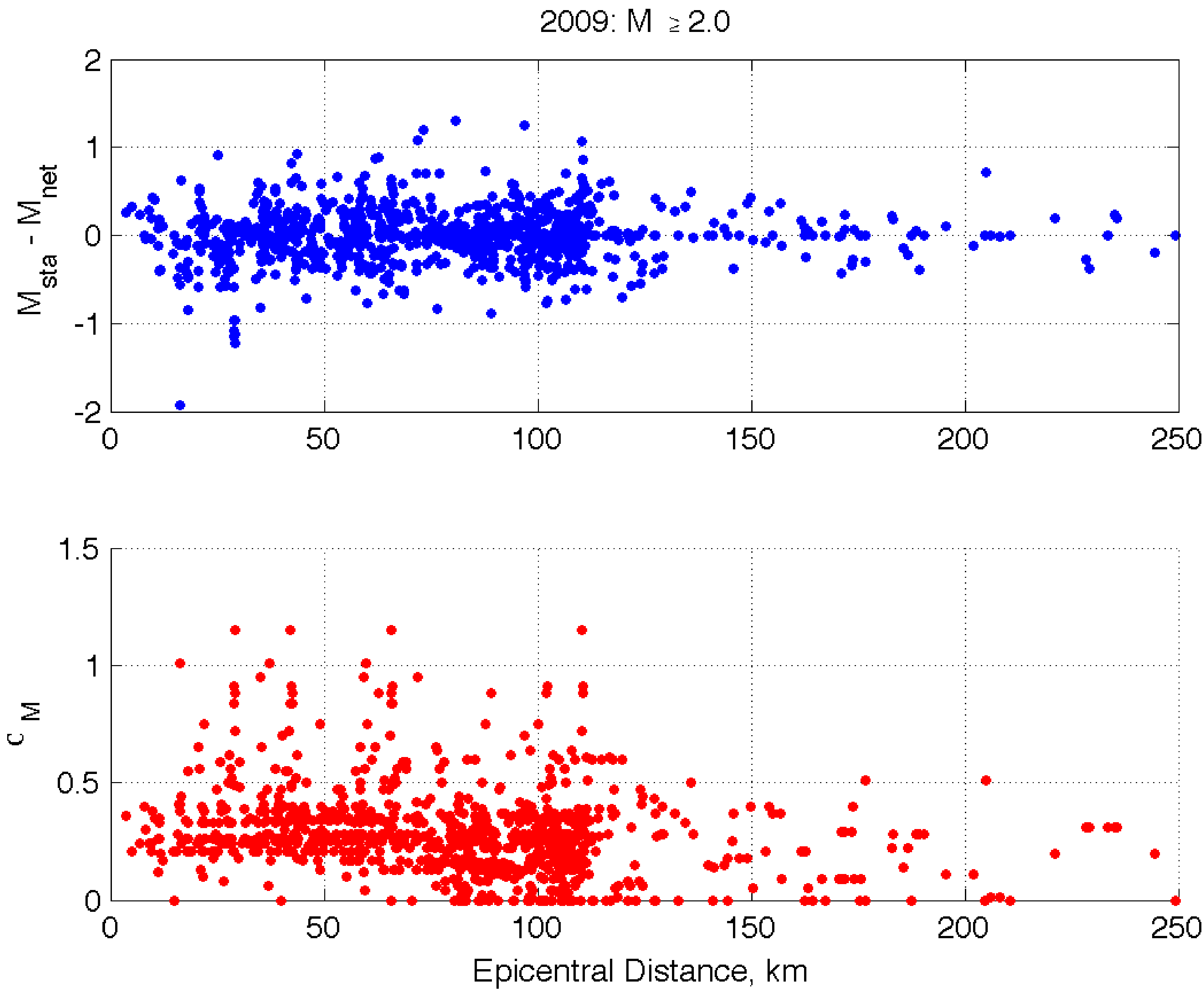
John Anders



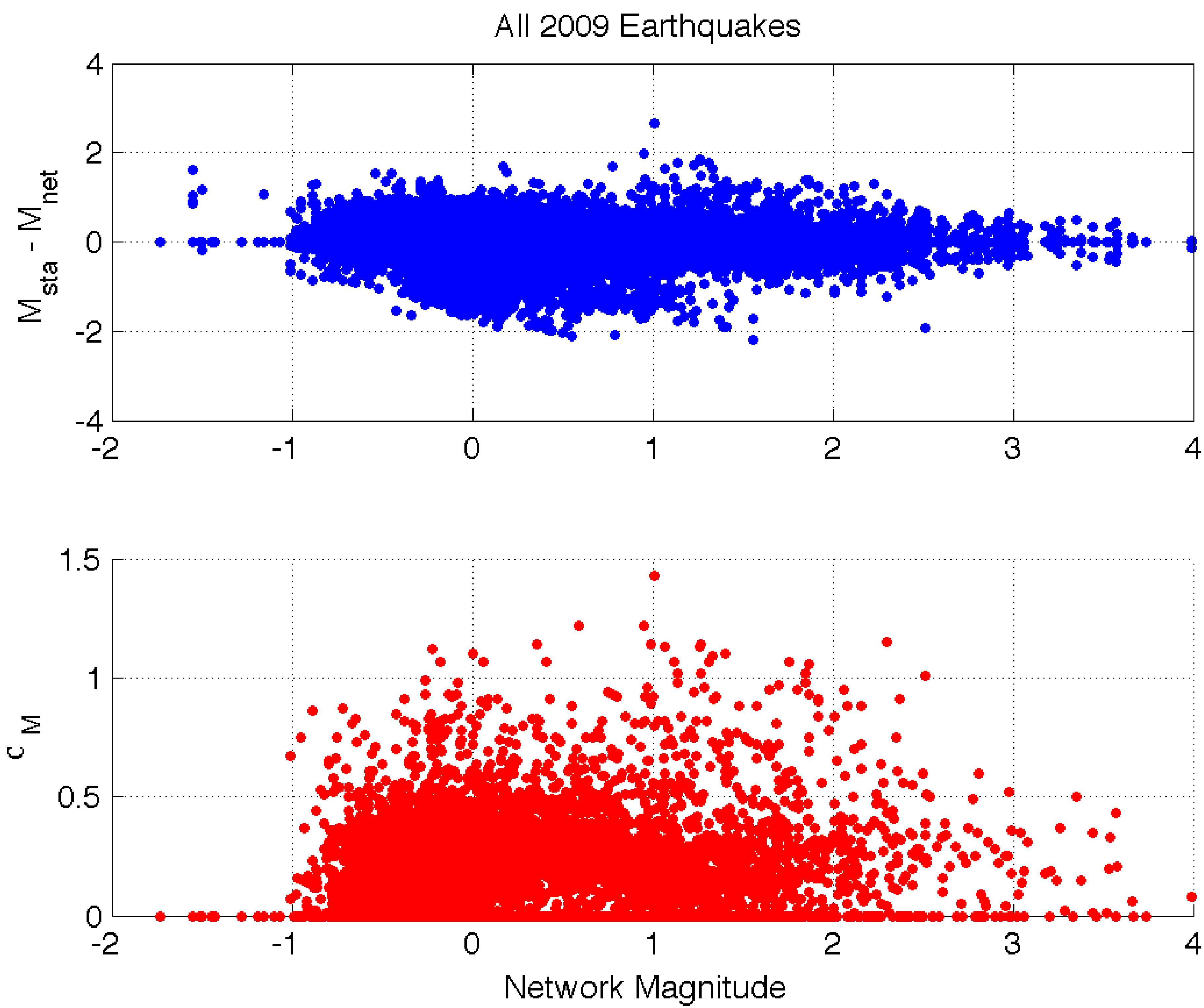

All 2009 Earthquakes
Number of Phases
Network Magnitude
2009: M ≥ 2.0
Number of Phases
Network Magnitude



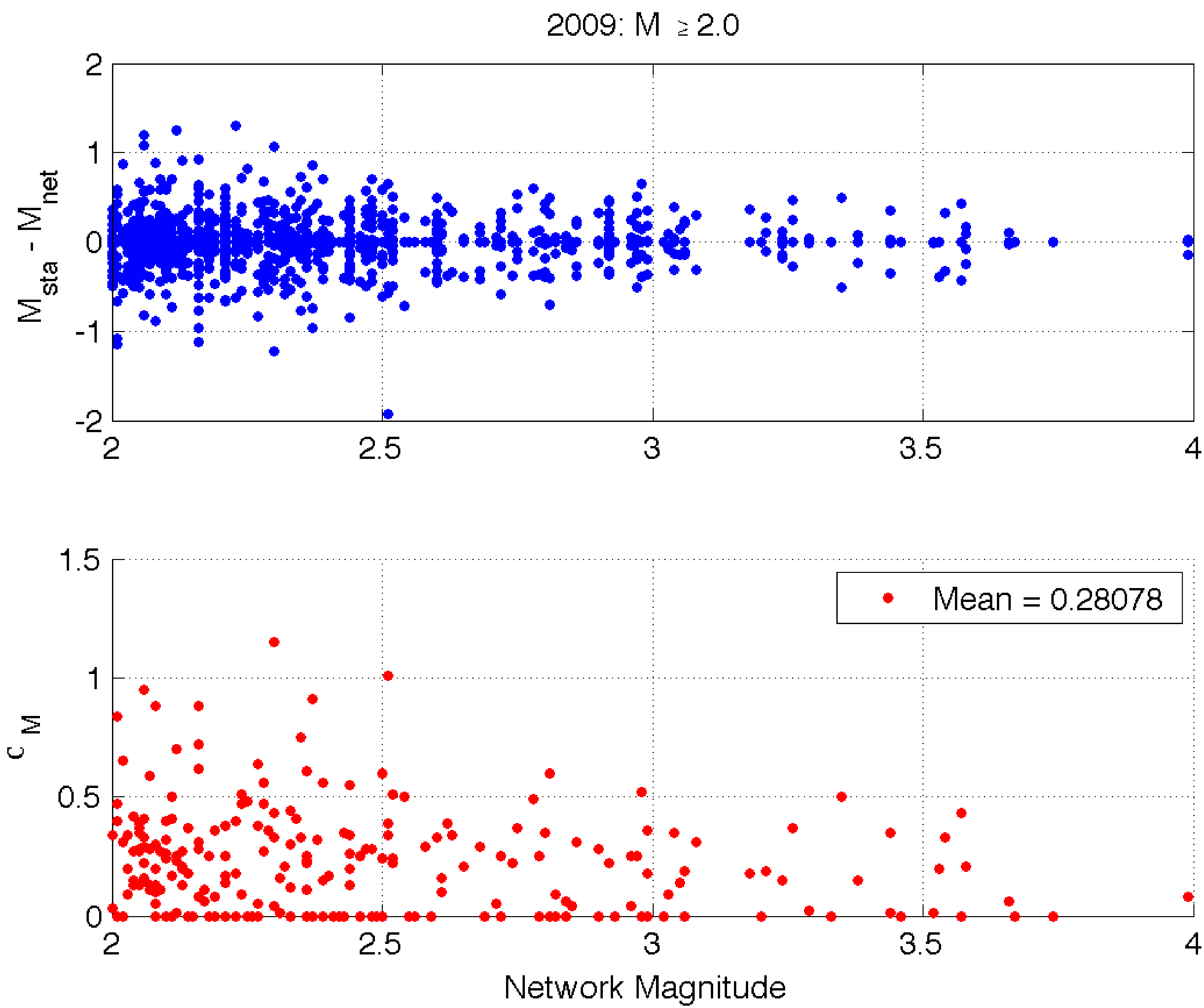
2009: All
$M_{sta} - M_{net}$
4
2
0
-2
-4
0
50
100
150
200
250
c_M
1.5
1
0.5
0
0
50
100
150
200
250
Epicentral Distance, km



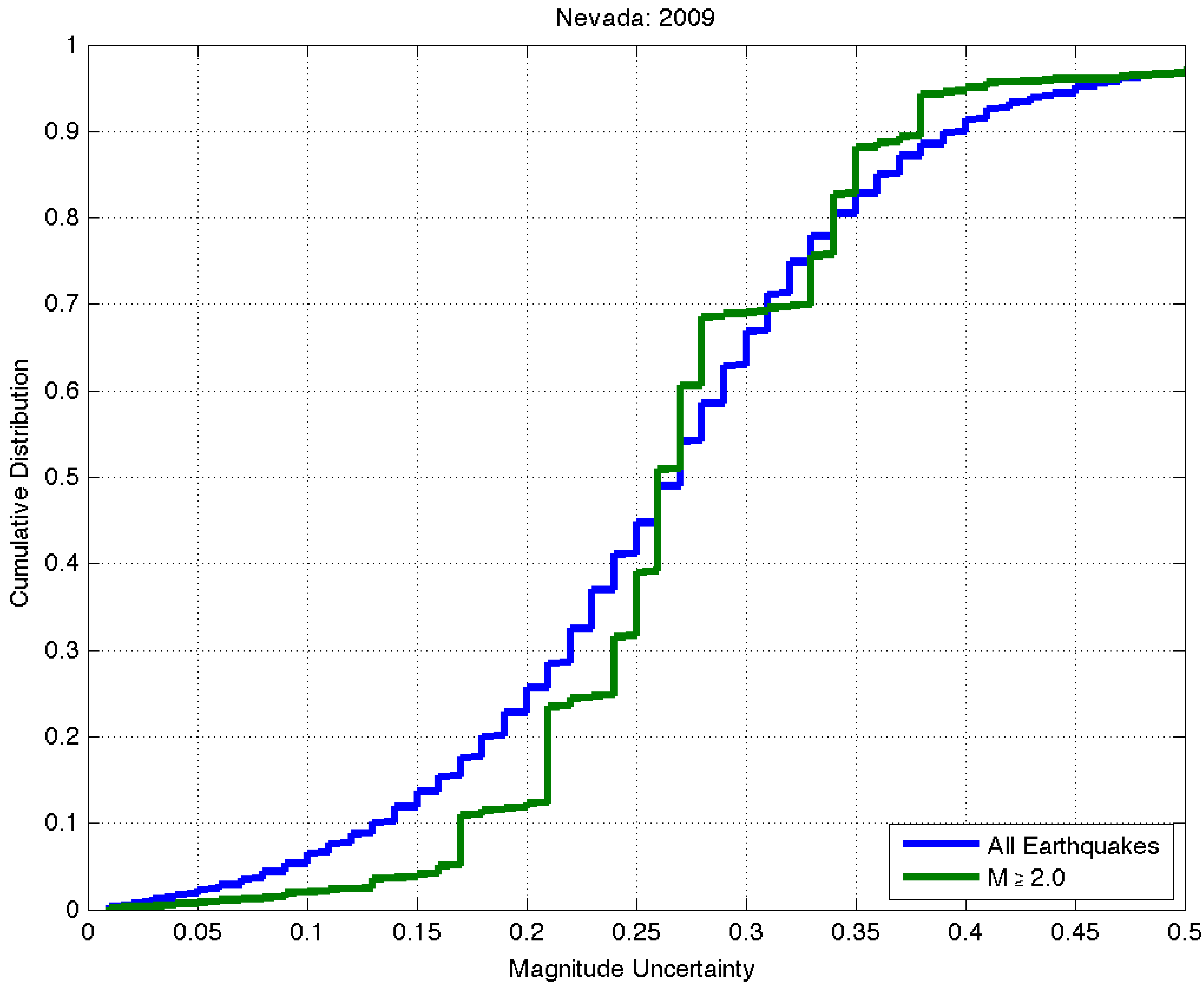
2009: M ≥ 2.0
M_{sta} - M_{net}
c_M
Epicentral Distance, km
0
50
100
150
200
250
2
1
0
-1
-2
1.5
1
0.5
0



All 2009 Earthquakes
$M_{sta} - M_{net}$
c_M
Network Magnitude



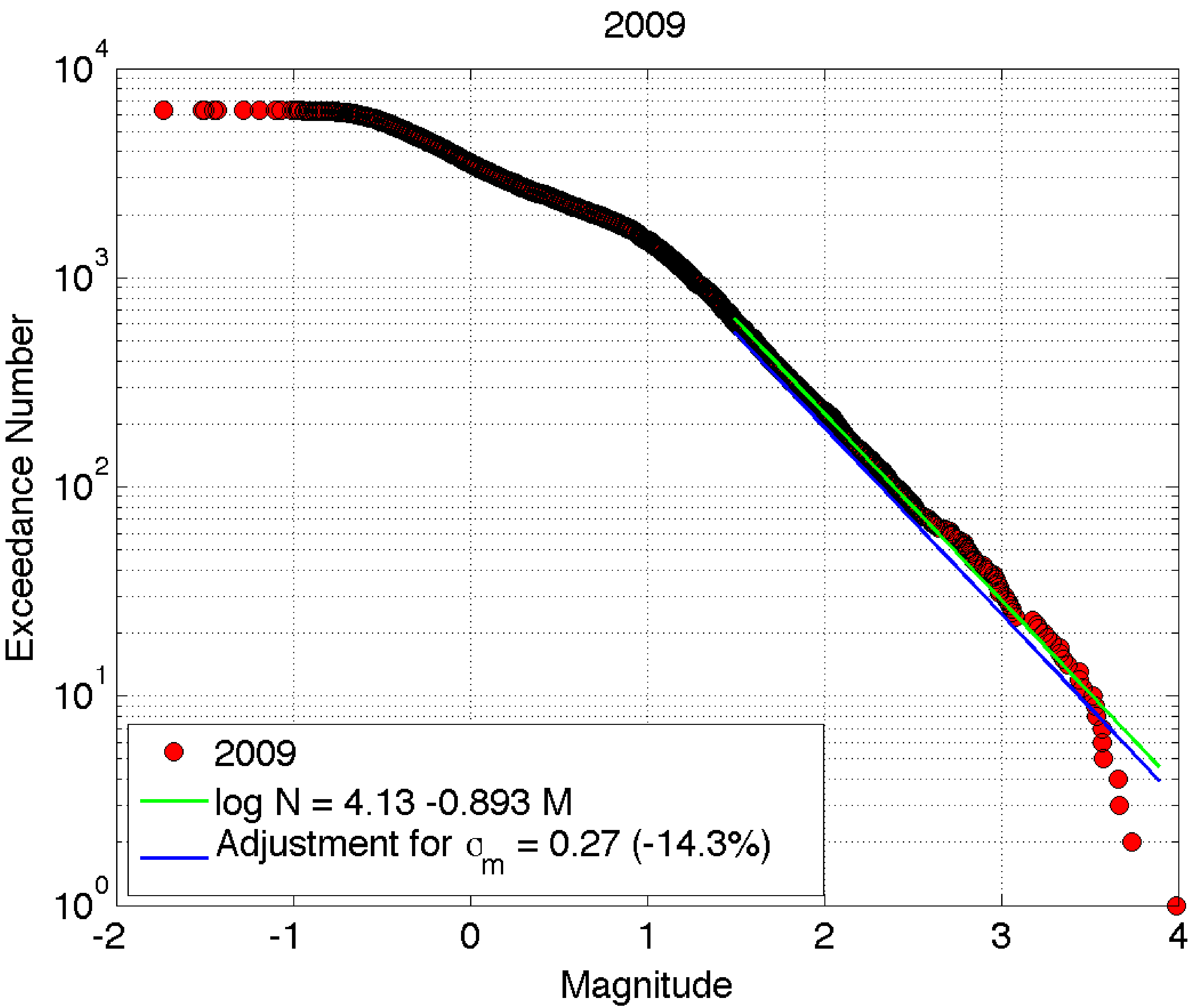
2009: M ≥ 2.0
$M_{sta} - M_{net}$
c_M
Mean = 0.28078
Network Magnitude

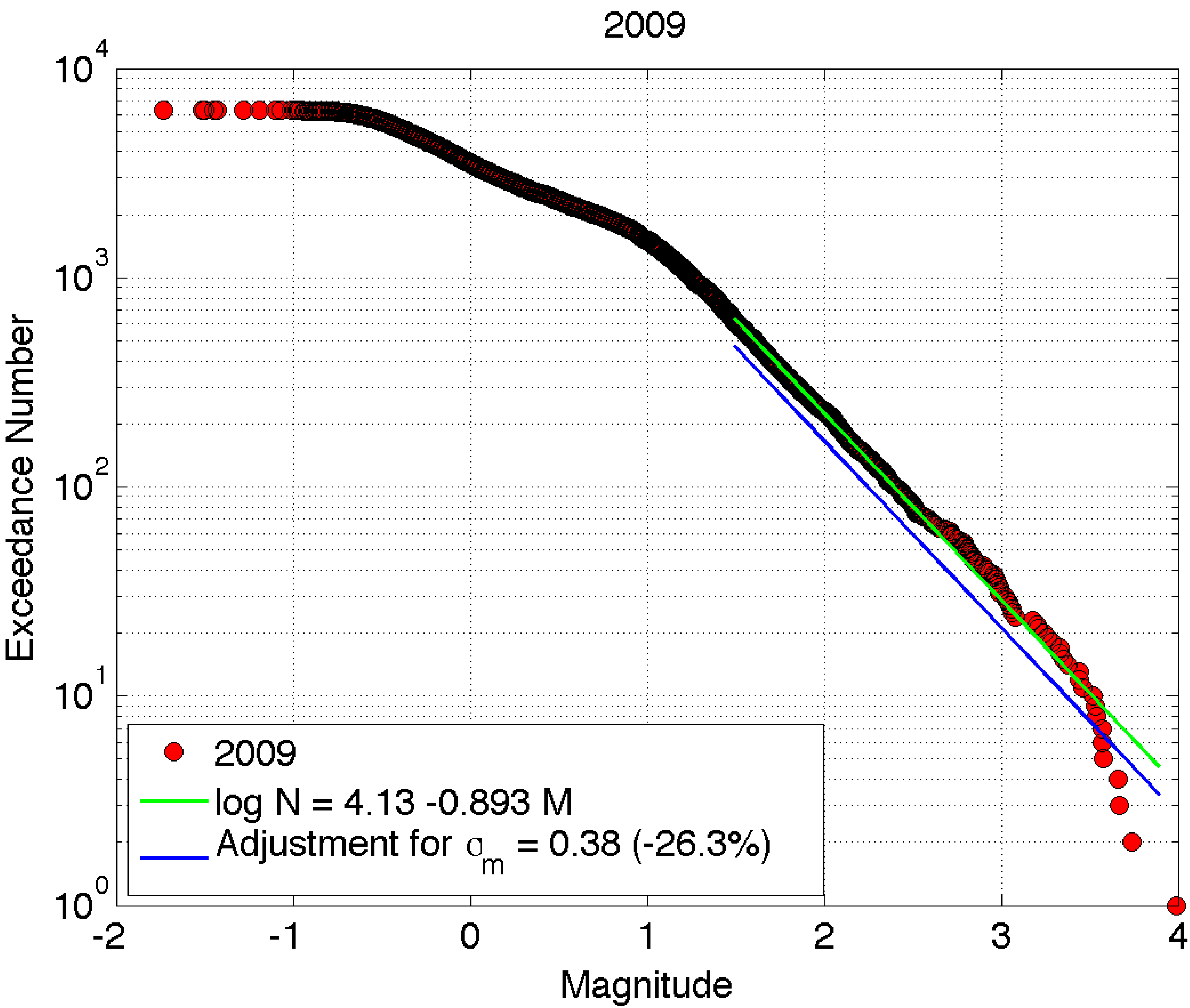


Nevada: 2009
Cumulative Distribution
Magnitude Uncertainty
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.05
0.15
0.25
0.35
0.45
All Earthquakes
M ≥ 2.0

Tinti and Mulargia (1985)

- For a region in which N(M)=a-bM, with uncertainty σ_v,
- What is observed is: $\log N = a - bM + \frac{b^2 \sigma_\nu^2}{2 \log e}$
- This gives the basis for adjusting the background seismicity rate


2009
Exceedance Number
Magnitude
10^4
10^3
10^2
10^1
10^0
-2
-1
0
1
2
3
4
2009
log N = 4.13 -0.893 M
Adjustment for σ_m = 0.27 (-14.3%)



2009
Exceedance Number
Magnitude
10^4
10^3
10^2
10^1
10^0
-2
-1
0
1
2
3
4
2009
log N = 4.13 -0.893 M
Adjustment for σ_m = 0.38 (-26.3%)

Notes

- No obvious distance dependence in residuals.
- The correlation of M_L, as determined in 2009, with magnitude scales used in the past is, at present, not known.
- The network does not use station corrections to determine magnitudes at this time. Use of station corrections may begin in the near future.

Summary

- The Nevada network was analyzed for 2009
- In 2009, the network estimated M_L
- The median uncertainty in network magnitude, as estimated by the network software, was 0.27.
- 90% of events with M>=2.0 had magnitude uncertainty under 0.38.

Summary

- Early Nevada magnitudes.
  - Suggest median uncertainty of 0.4.
  - Since 1990, decrease uncertainty to 0.27.

BRP EWG II
Issue S4

Possible Recommendations

John G. Anderson
Chuck Mueller

NEVADA Seismological Laboratory

Issue S4

- Issue S4: What are the sources and levels of uncertainty in the earthquake magnitudes contained in the seismicity catalogs used in the NSHMs?

Answer to immediate question

- Since USGS primarily uses the PDE catalog (unless there is a specialized regional study) to determine background seismicity, the question of source and level of uncertainty needs to be answered by USGS for many US regions including Walker Lane and IMW.
- For the Nevada catalog, uncertainties on M_L in recent years appear to be ~0.27. More research is needed to extend this result to prior years.

Some Thoughts

- The quality of locations within regional networks is generally superior to PDE, but regional network coverage is far from uniform at this time.
- There is a need to review regional catalogs "the right way".

Some thoughts (continued)

- All networks in the region should be encouraged to:
  - Use of station corrections in magnitude determinations.
  - Carefully document changes in magnitude determination practices, and whenever changes are made, to develop a correlation between the old and new system.
  - Assign version numbers to catalogs for quality control.

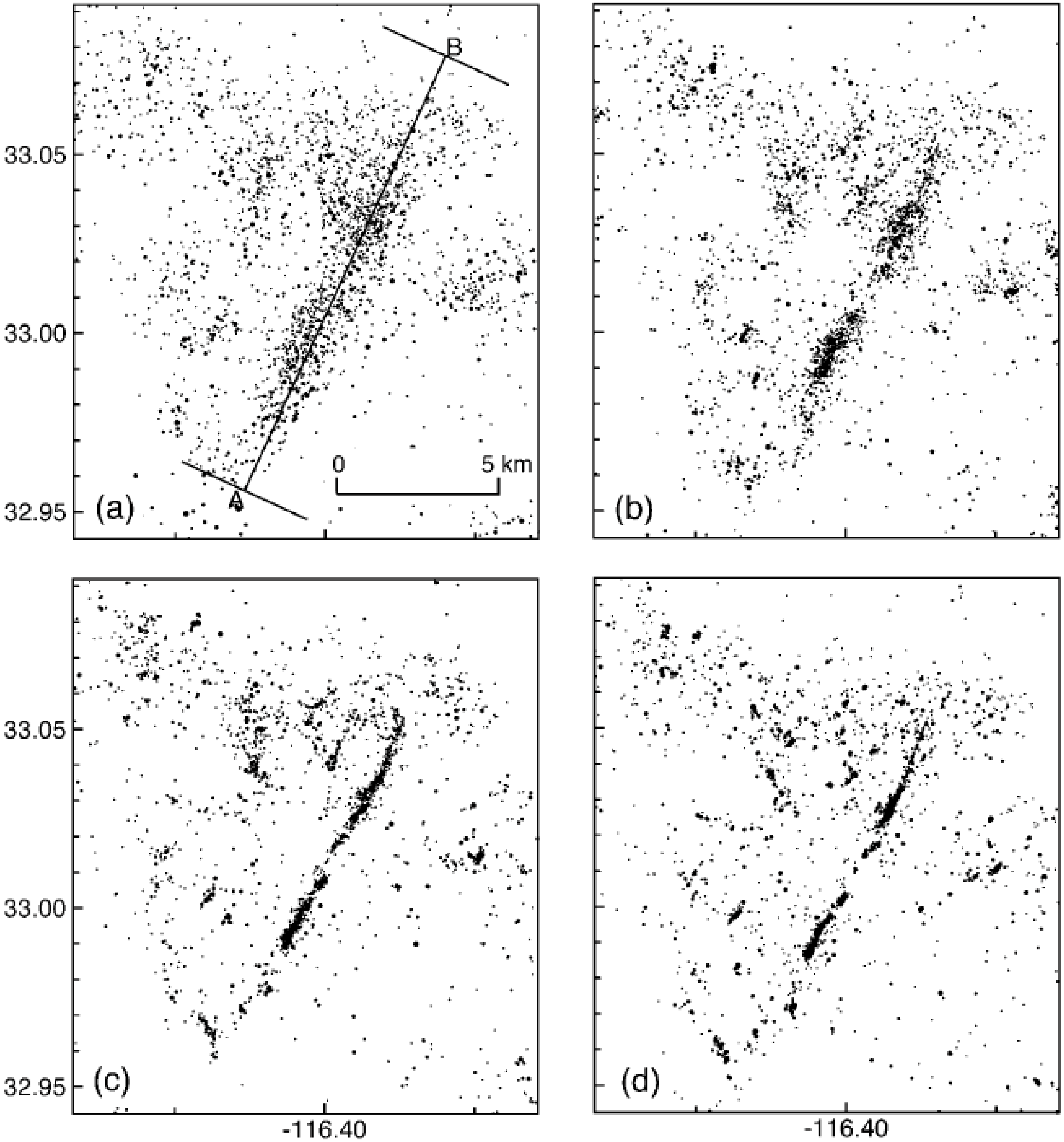
Some thoughts (continued)

- Efforts to improve regional catalogs should be encouraged, including
  - Review magnitudes, starting with the largest events. Thoughtfully assign uncertainties to reviewed magnitudes.
  - Use state-of-the-art techniques to relocate events.

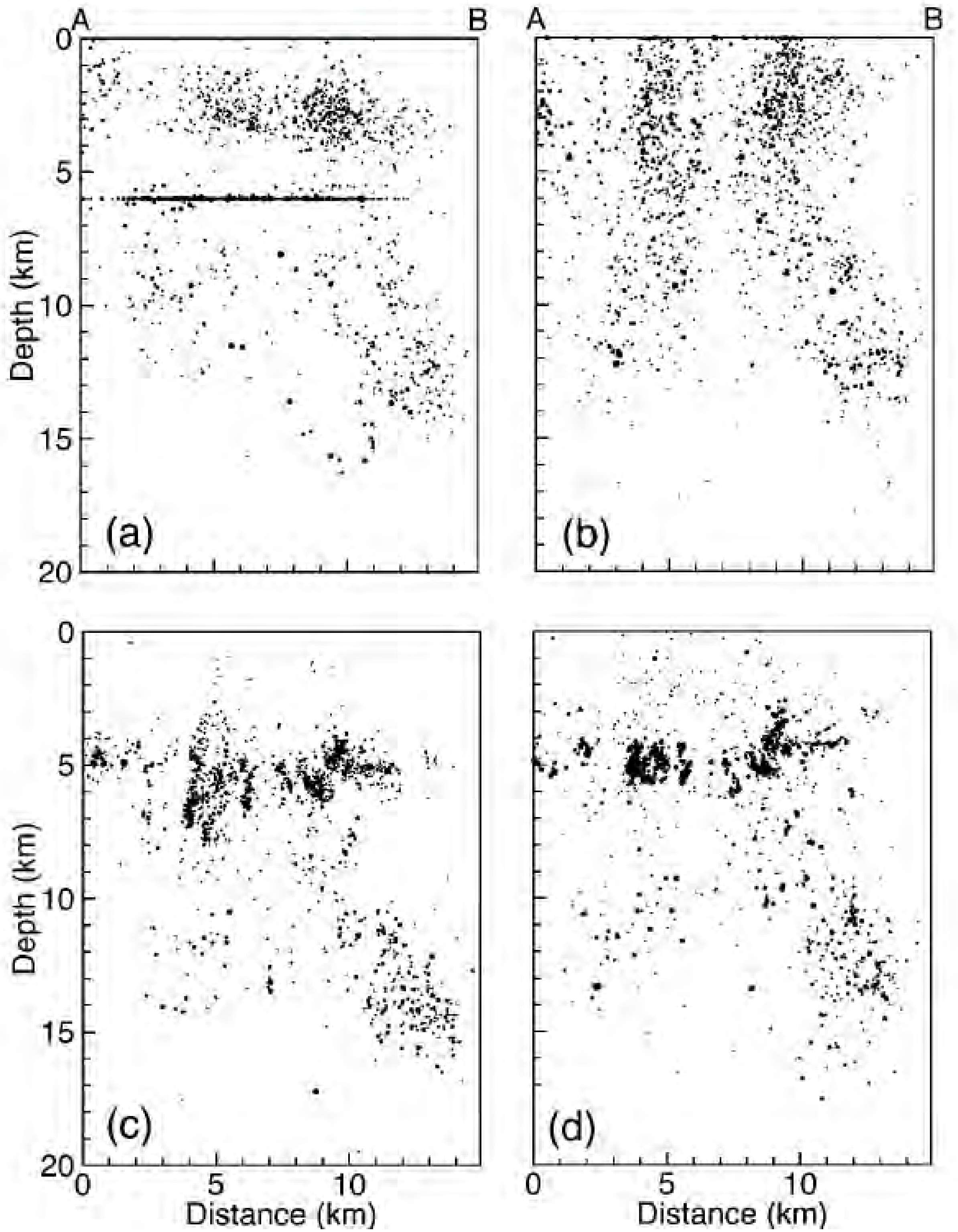
Bulletin of the Seismological Society of America, Vol. 95, No. 3, pp. 904–915, June 2005, doi: 10.1785/0120040168

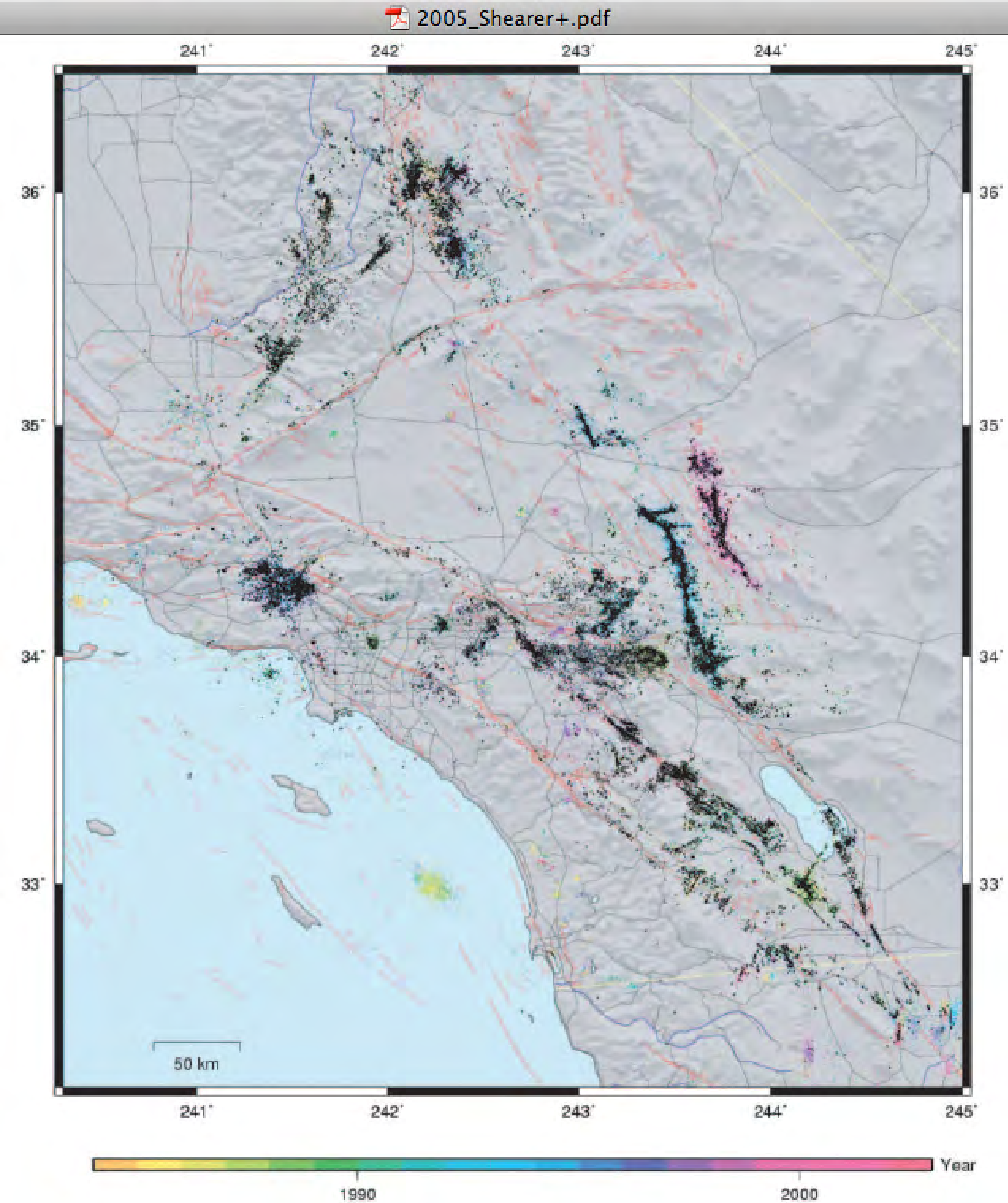
Southern California Hypocenter Relocation with Waveform Cross-Correlation, Part 2: Results Using Source-Specific Station Terms and Cluster Analysis

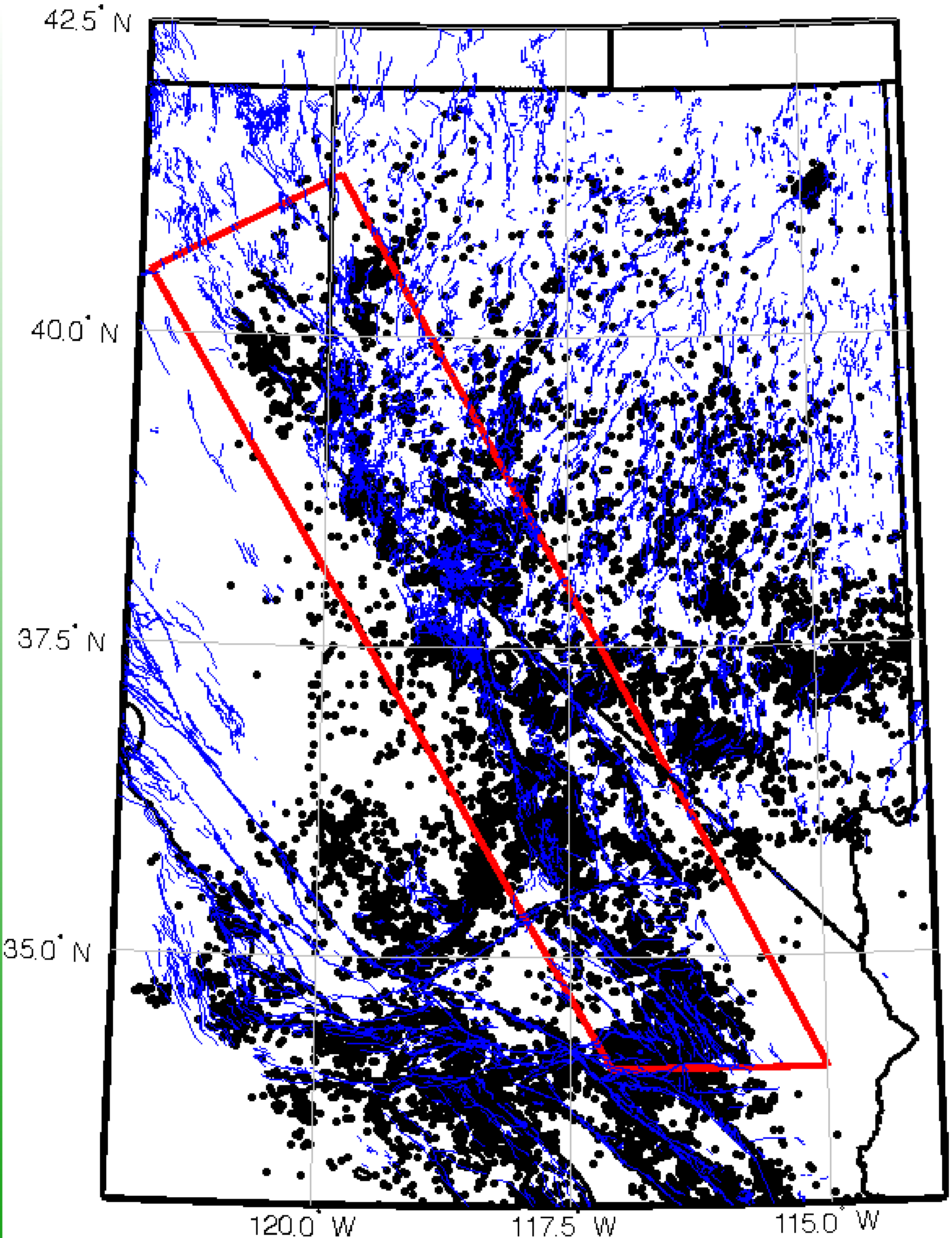
by Peter Shearer, Egill Hauksson, and Guoqing Lin


33.05
33.00
32.95
(a)
(b)
(c)
(d)
A
B
0
5 km
-116.40
-116.40

2005_Shearer+.pdf




2005_Shearer+.pdf
241°
242°
243°
244°
245°
36°
35°
34°
33°
50 km
Year
1990
2000

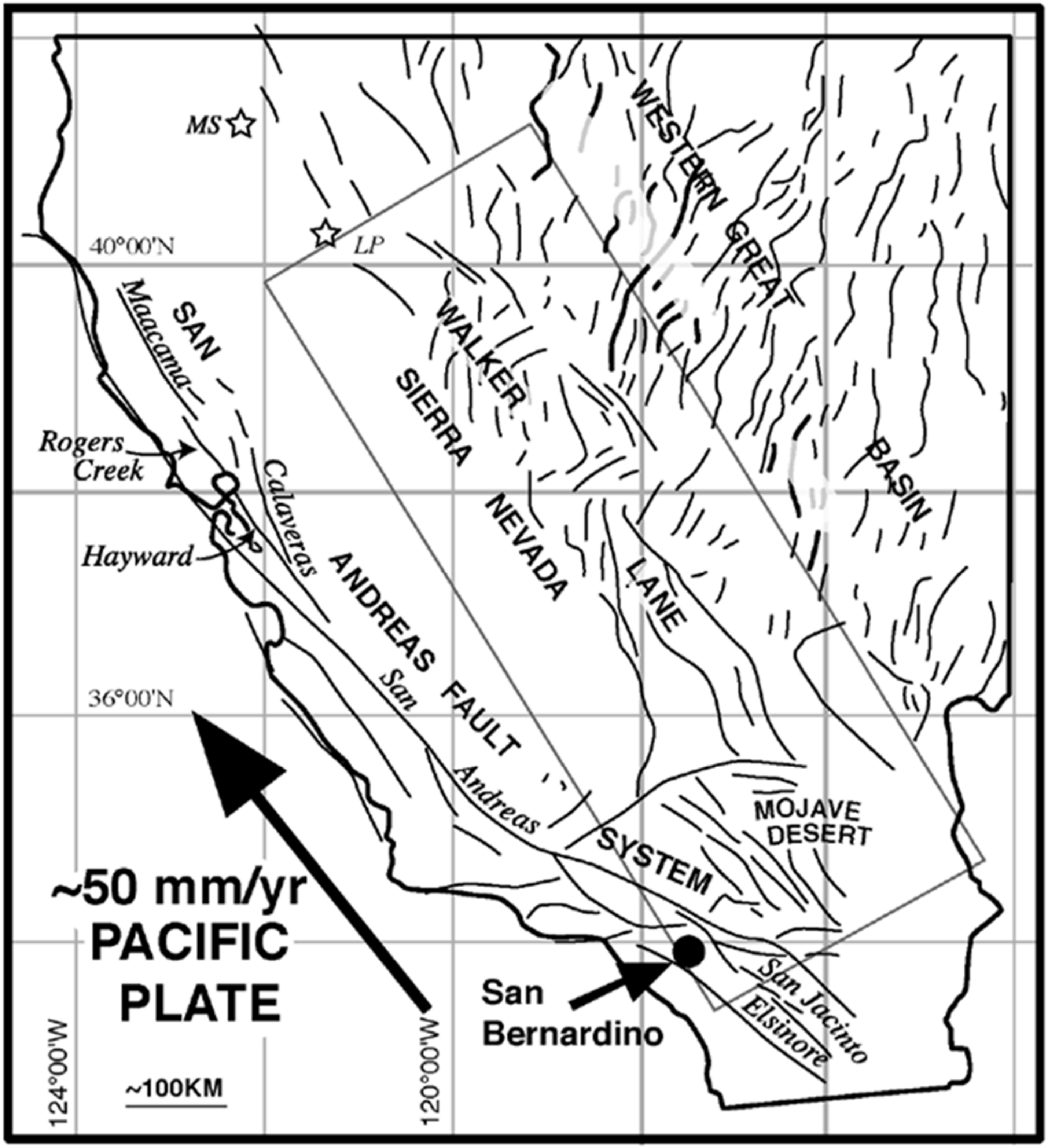

42.5° N
40.0° N
37.5° N
35.0° N
120.0° W
117.5° W
115.0° W

Recommendations

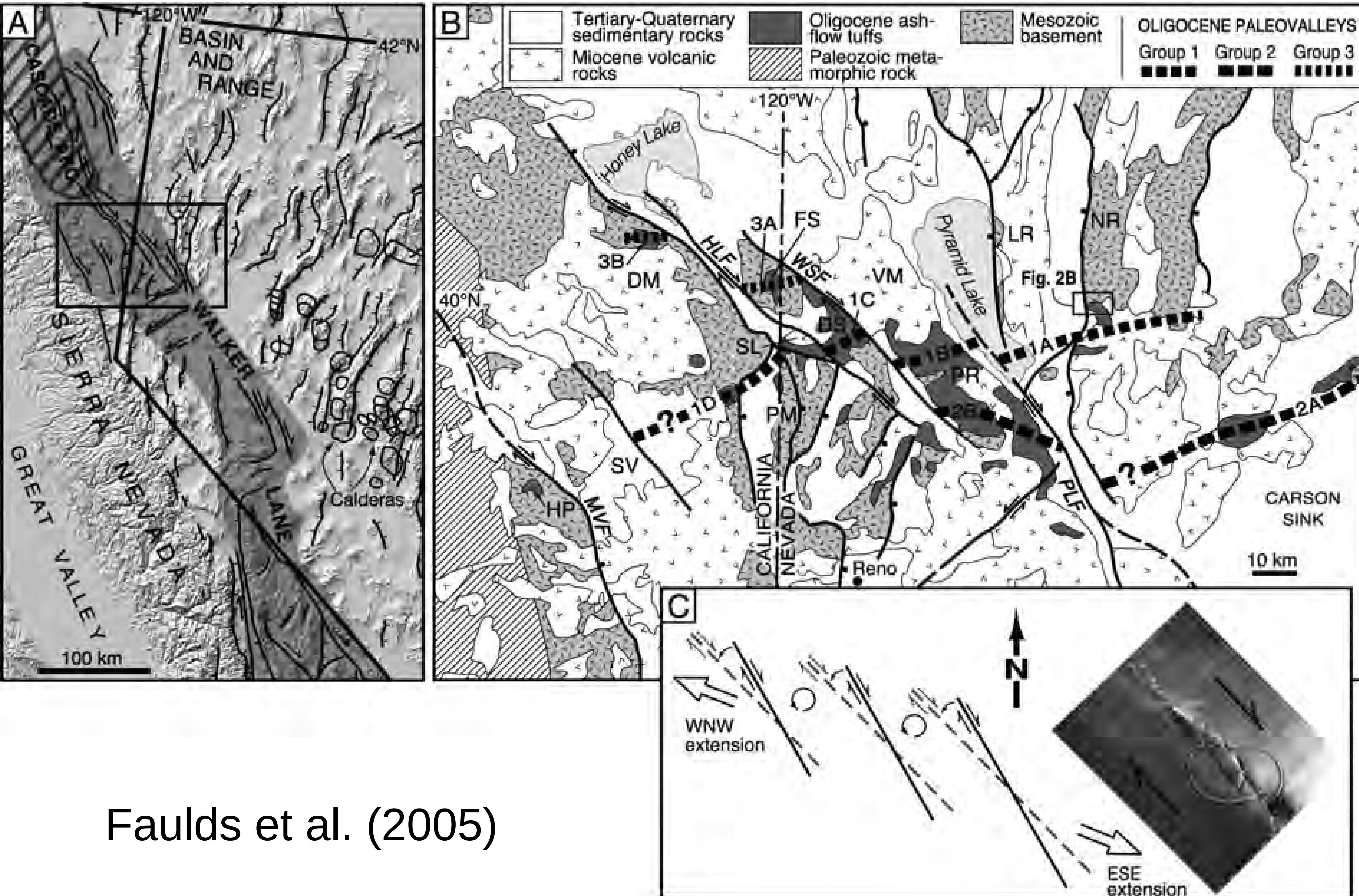
- All networks in the region need to develop statistical relationships between current and past magnitude scales to M_W
- Regional and national catalogs need to be compared.

Possible Recommendations

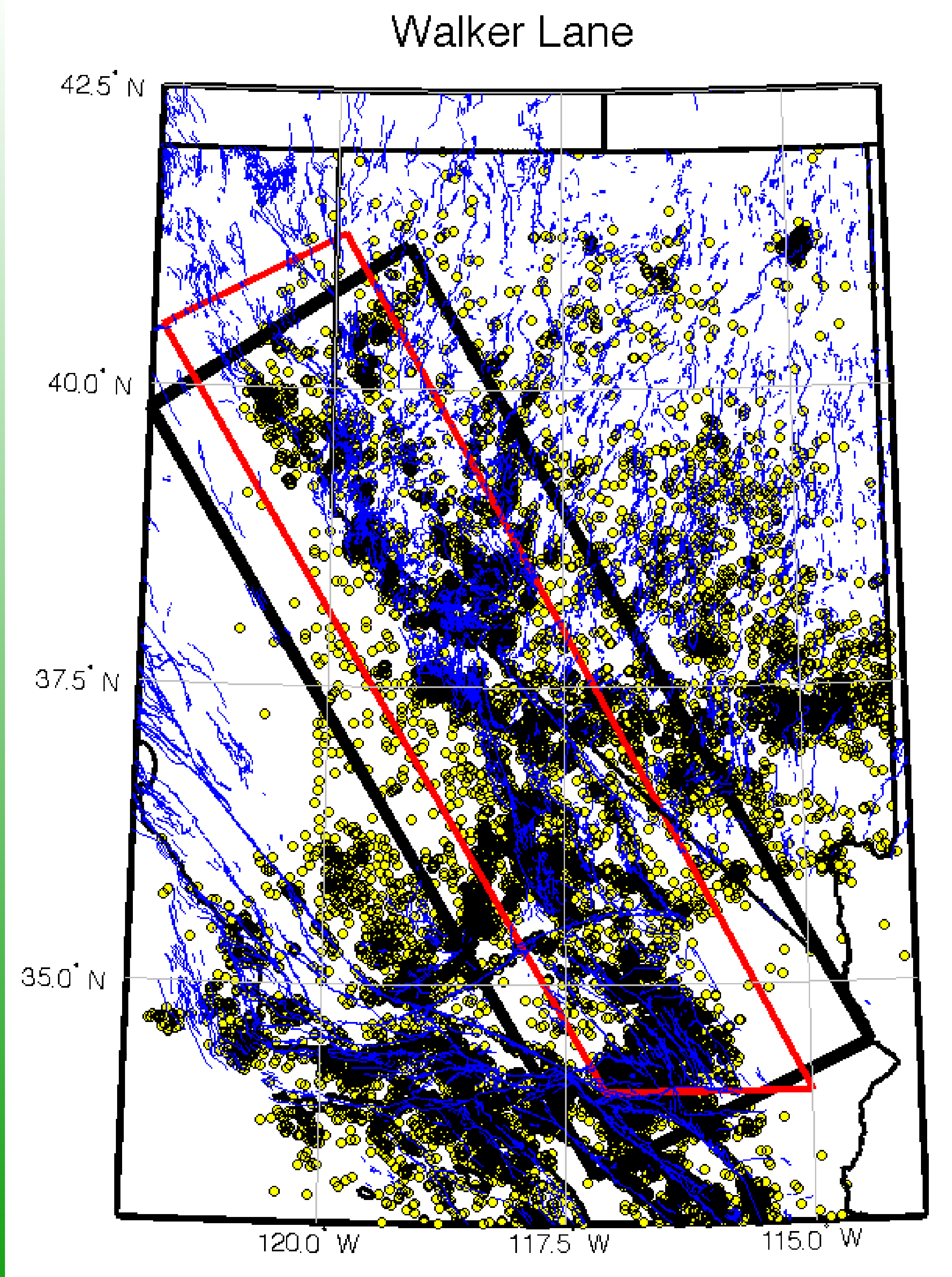
- Walker Lane is different from the Basin and Range province.
- Thus there may be reason to treat it separately.



Wesnousky (2005)



Faulds et al. (2005)



Walker Lane

- Different tectonic style
- Most seismicity

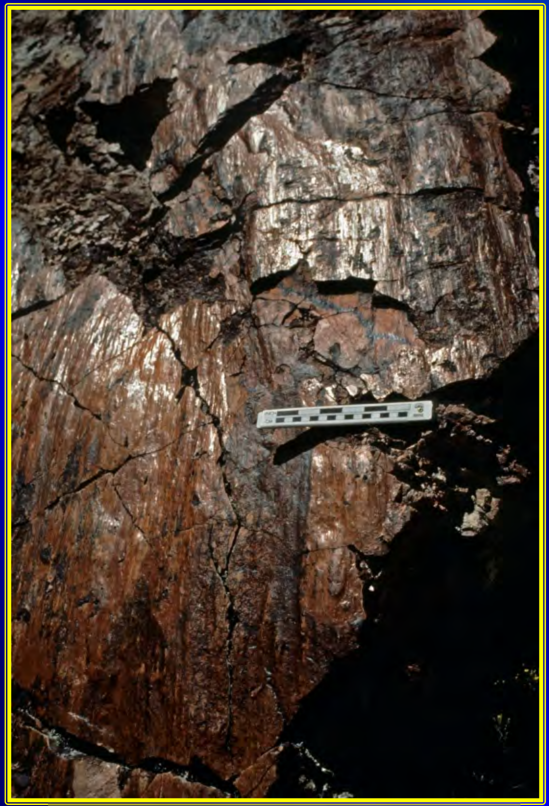
Dip Angles for Basin and Range Normal Faults

Yumu Shan fault, China

BRPEWG II

Discussion Topic Geology 4

Anthony Crone
U.S. Geological Survey



Dixie Valley fault, Nevada

USGS science for a changing world

Statement of the Issue:

Based on the recommendation from BRPEWG I, the current USGS NSHMs use a dip of 50°±10° for normal faults in the Basin and Range Province (BRP).

Is the 50° dip value and the ±10° uncertainty range valid and acceptable to cover the probable range of dips for BRP normal faults?

Historical Perspective:

NSHMs previously used value of 60° for dip of normal faults with no uncertainty range.

Topic arose in BRPEWG I discussion of geodetic vs. geologic deformation rates in the Province. Issue was not discussed in specific detail, but issue arose as part of spontaneous discussion.

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

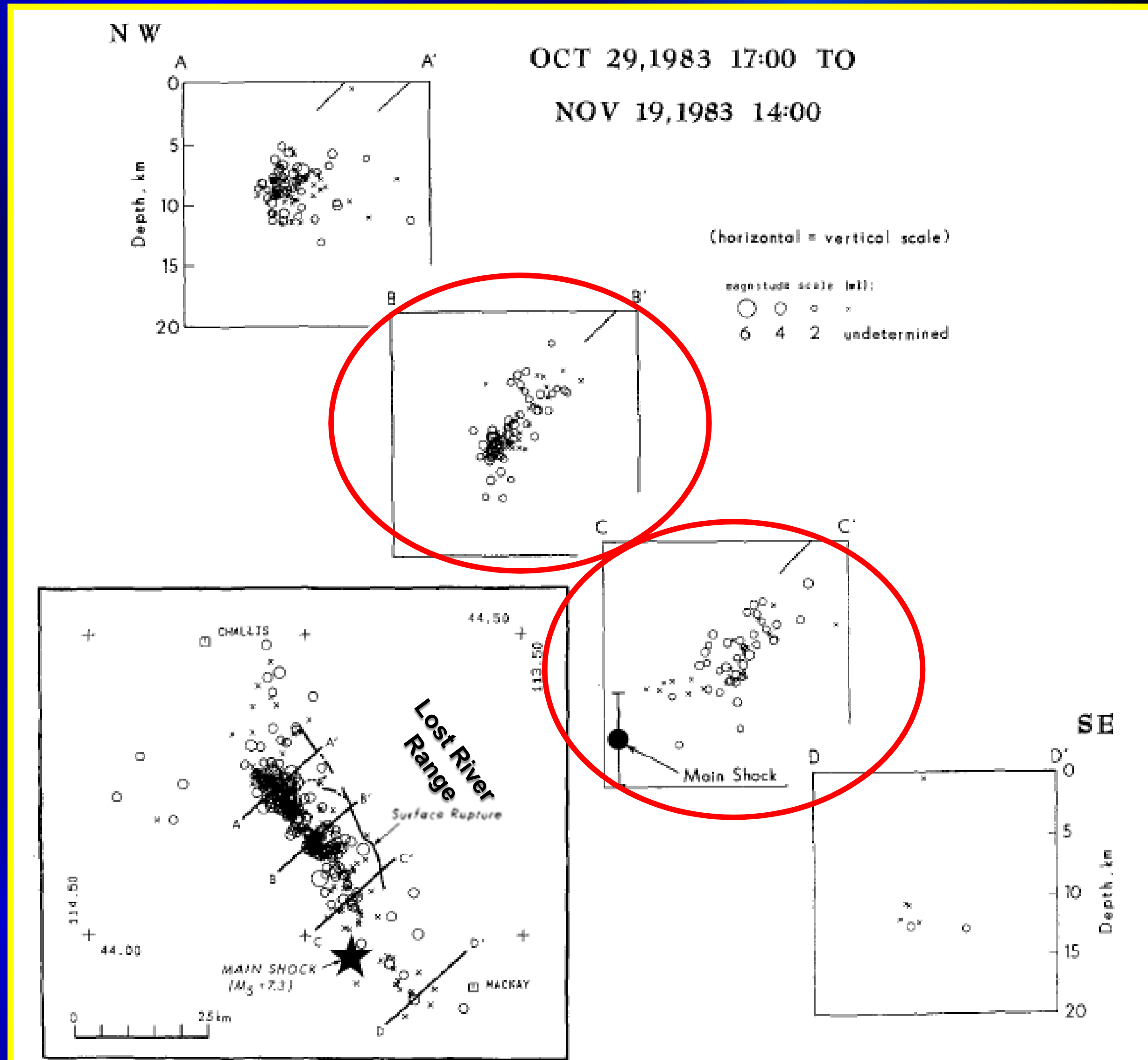
1983 Borah Peak, Idaho Earthquake

- Ms 7.3, Mw 6.9, Oct. 28, 1983.
- 34 km of surface rupture on Lost River fault.
- Unilateral rupture.
- Well-defined aftershock pattern.
- Geodetically measured coseismic deformation.

USGS science for a changing world

1983 Borah Peak, Idaho Earthquake

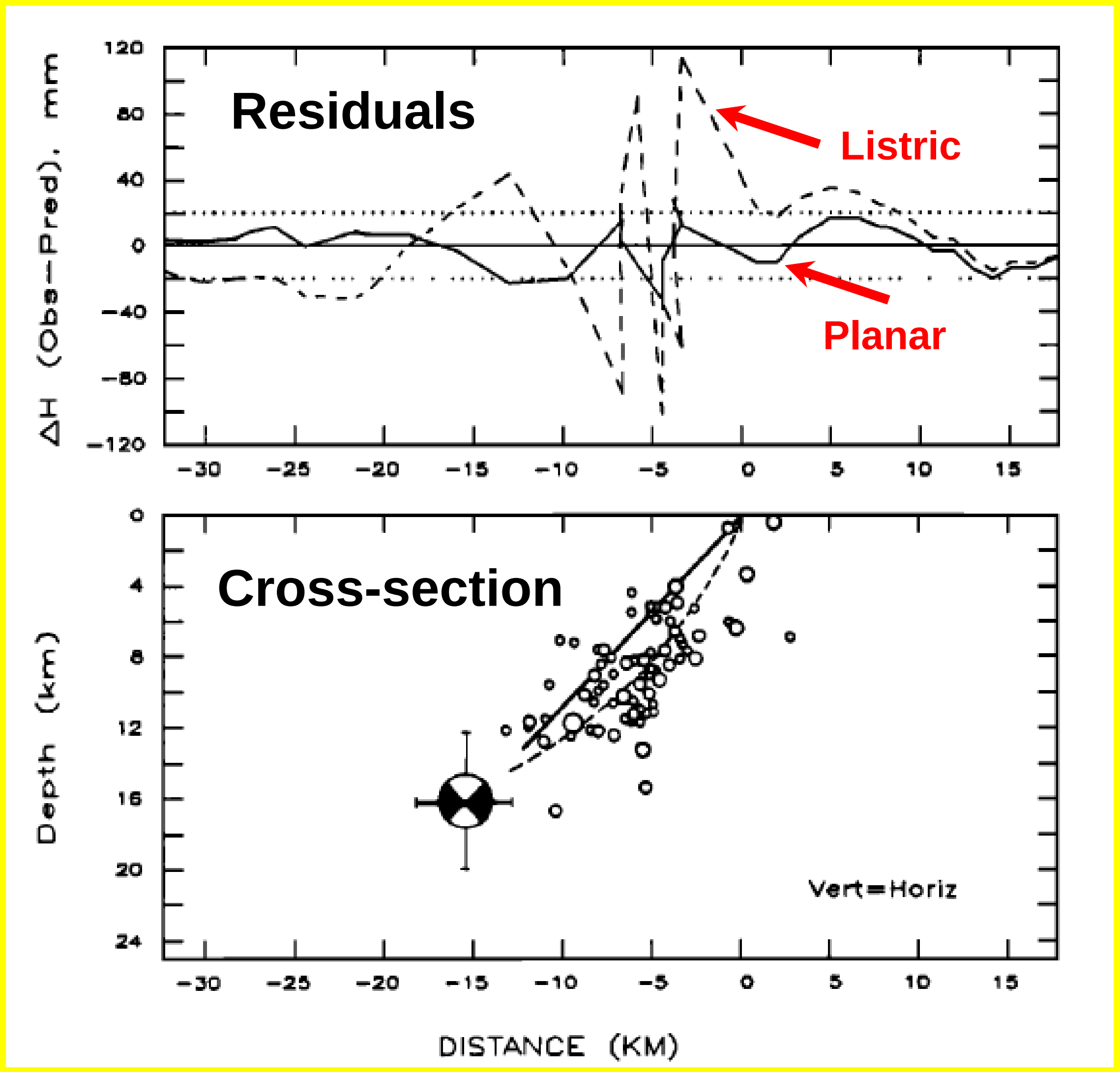
- Richins et al., 1987, BSSA.
- Main shock depth: 16 ± 4 km.
- 421 aftershocks define rupture area.
- Aftershocks in central and southern part of area define plane that dips at about 45°.
- Aftershock projection intersects surface at ruptures.



USGS science for a changing world

1983 Borah Peak, Idaho Earthquake

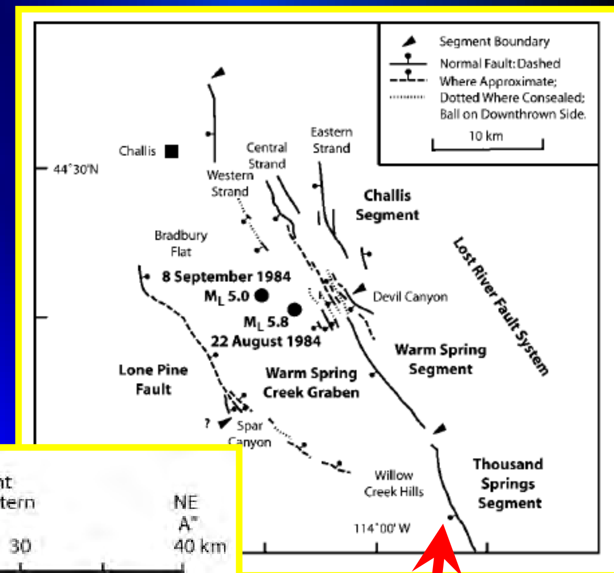
- Stein and Barrientos, 1985, BSSA.
- Solid line: planar fault; Dashed line: listric fault.
- Best fit: planar fault.
- Preferred dip: 47 ± 2° SW.
- Depth: 13.3 ± 1.2 km.



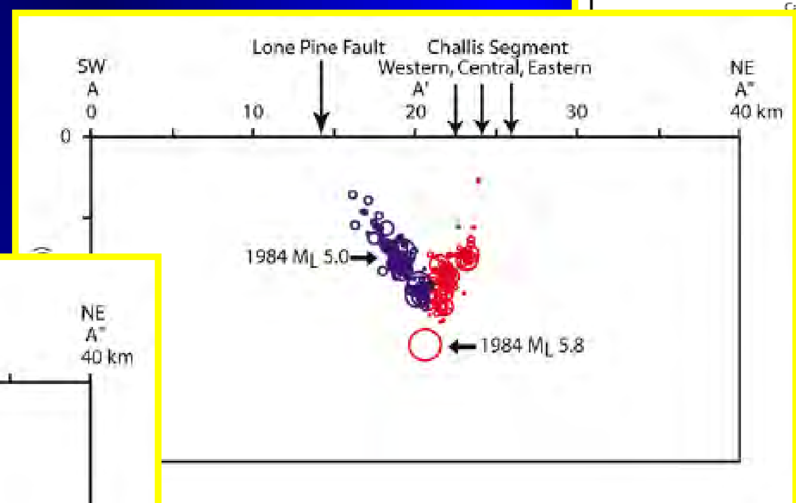
USGS
science for a changing world

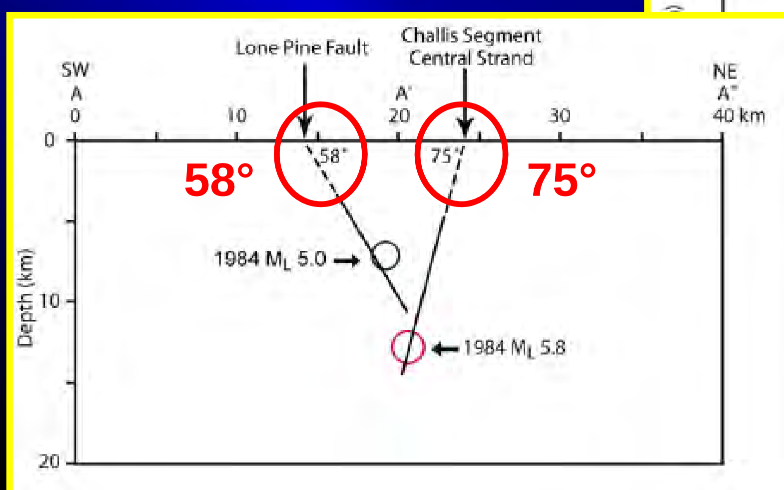
1984 Devils Canyon, Idaho Sequence

- **Payne et al., 2004, BSSA.**
- **Late aftershock (August, 1984; M_L 5.8) sequence of Borah Peak earthquake.**
- **Located 237 events on Challis segment; north of main Borah Peak ruptures.**



1983 rupture



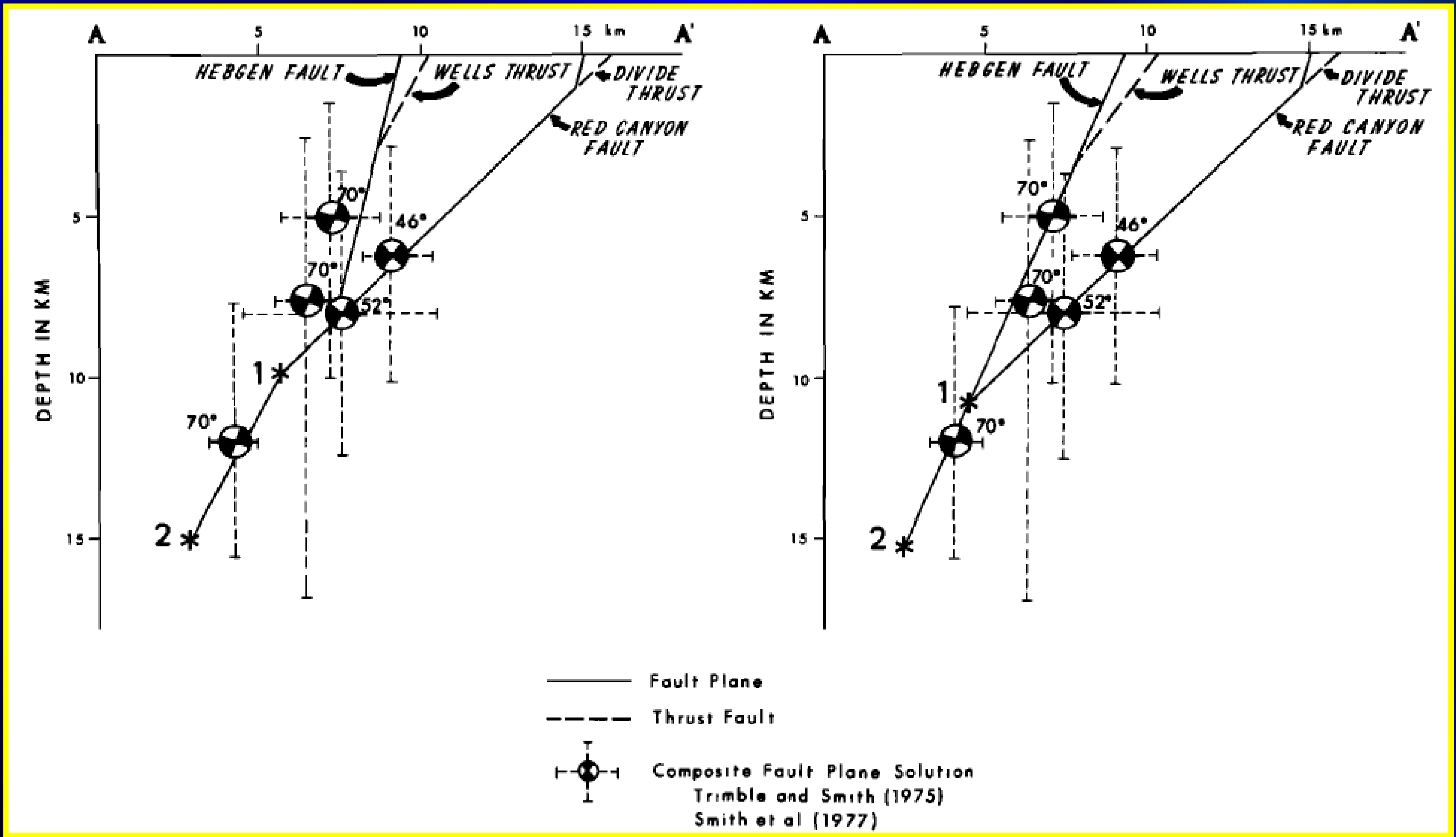


1959 Hebgen Lake, Montana Earthquake

- Ryall, 1962, BSSA.
- Based on analysis of P-waves
- Preferred fault plane-- Strike: N 80° ± 10° W; Dip: 54° ± 8°.

- Doser, 1985, JGR.
- Analyzed data from two subevents of main shock and three significant aftershocks.
- Variety of possible interpretations based on focal mechanisms, but short-period data indicate earthquake first ruptured faults dipping at 60 ± 5° S.
- Rupture may have propagated onto a 42 ± 5° fault (Laramide structure?).

1959 Hebgen Lake, Montana Earthquake

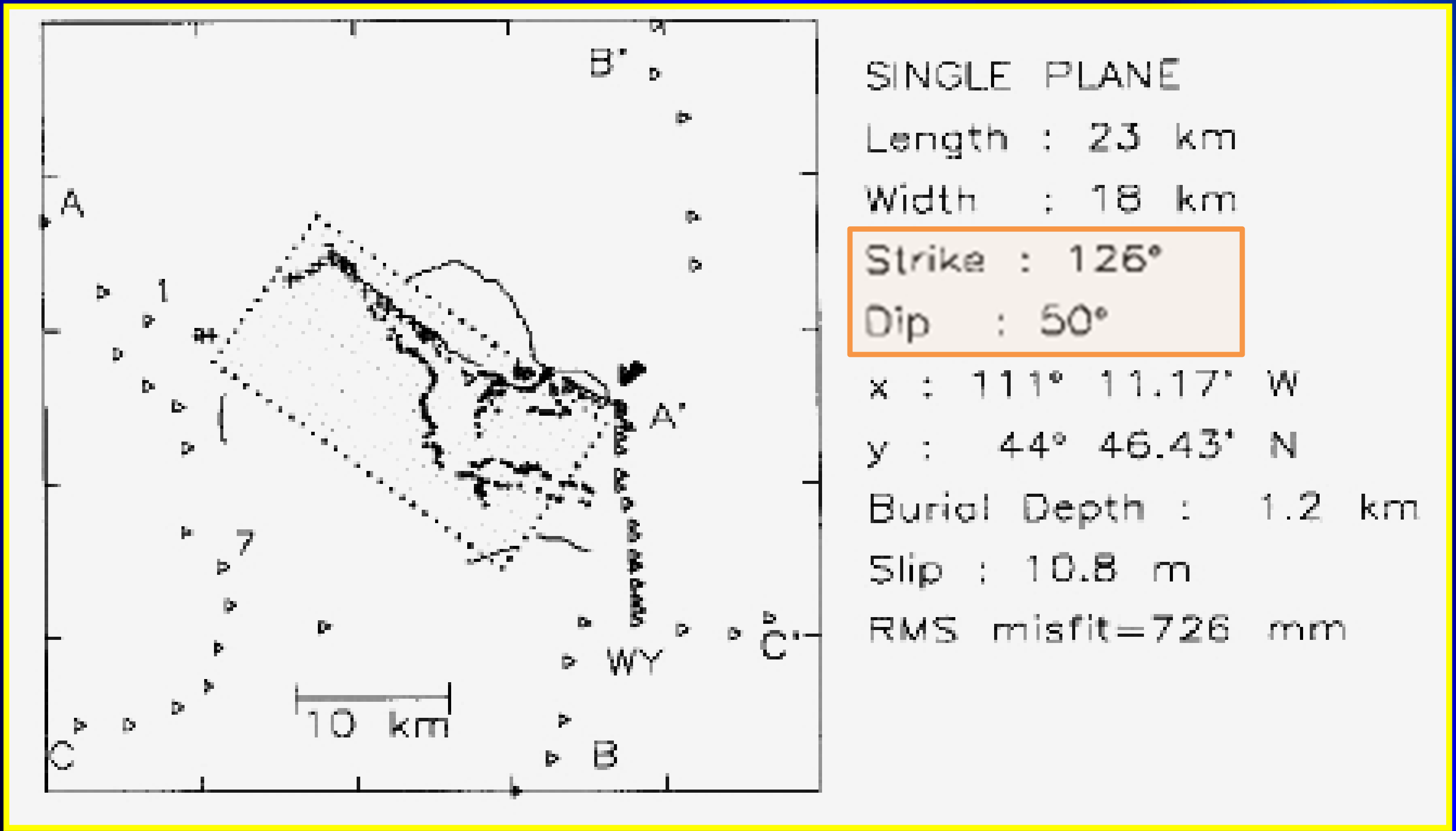


Doser, 1985, JGR.

1959 Hebgen Lake, Montana Earthquake

- Barrientos et al., 1987, BSSA.
- Analyzed deformation using geodetic leveling and lake shoreline changes.
- Developed elastic half-space models of single-plane and double-plane fault systems.
- Listric fault models did not improve the variance of fit at the 90% confidence level in a statistically significant way.

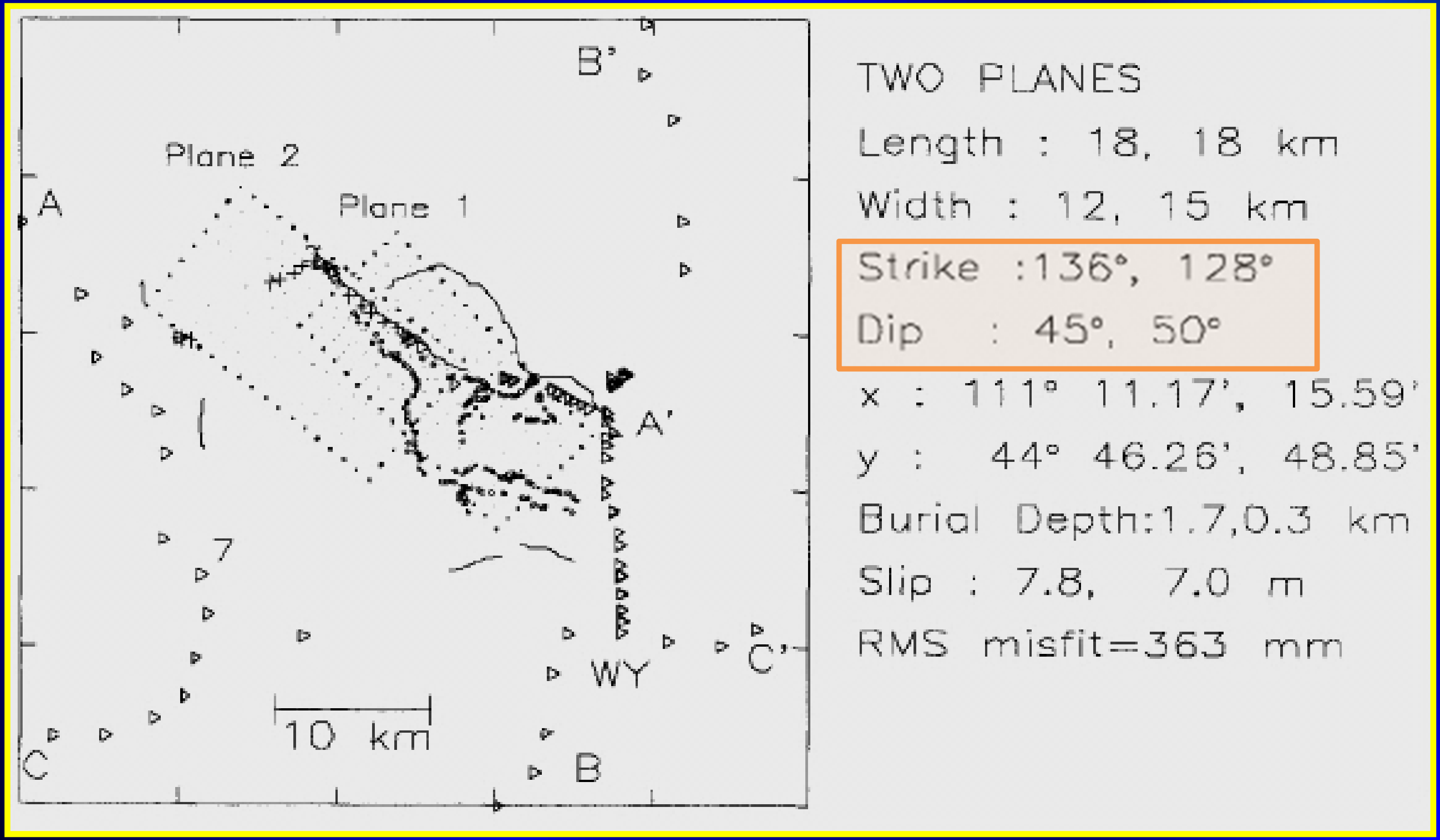
1959 Hebgen Lake, Montana Earthquake



Single-plane fault model

Barrientos et al., 1987, BSSA

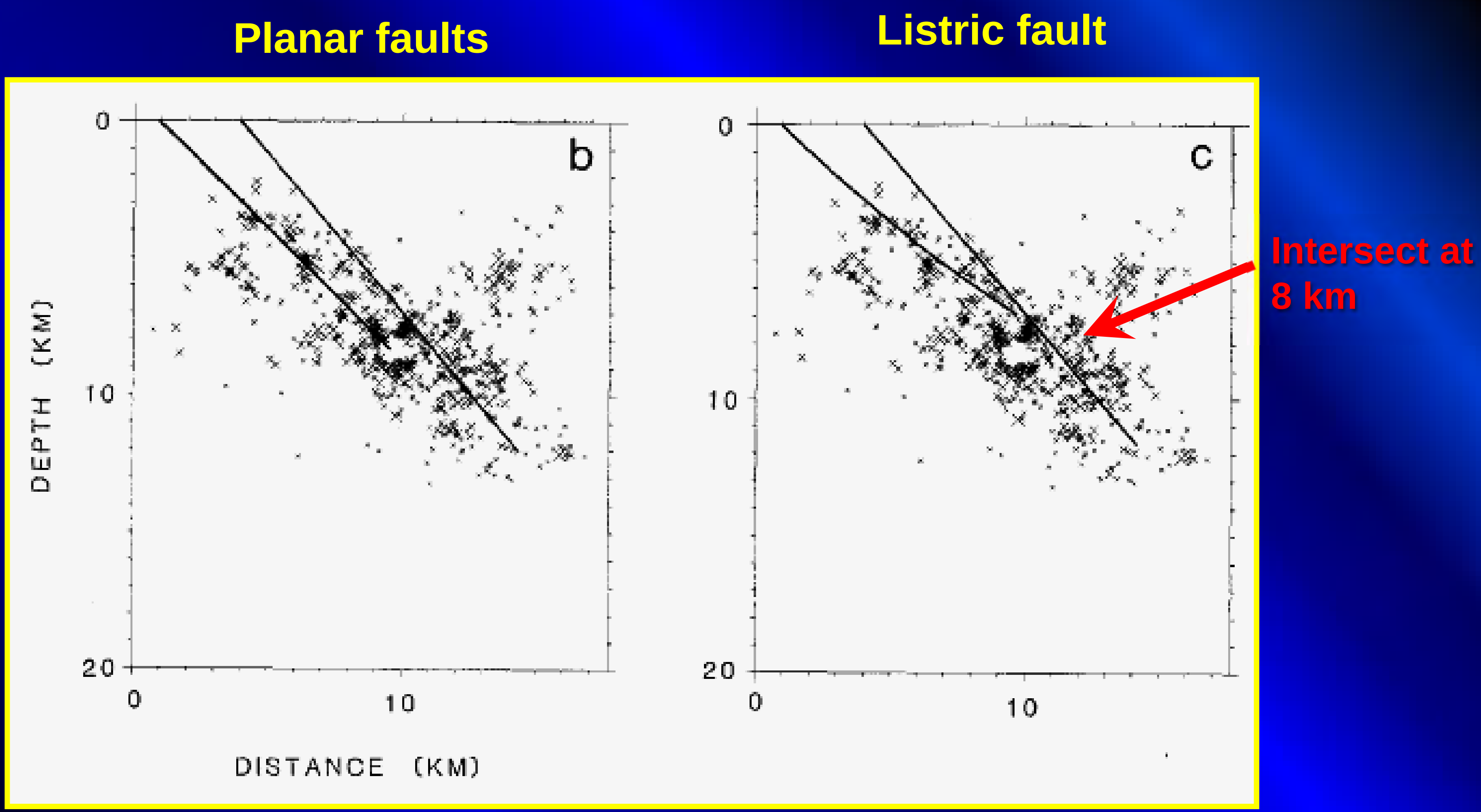
1959 Hebgen Lake, Montana Earthquake



Double-plane fault model

Barrientos et al., 1987, BSSA

1959 Hebgen Lake, Montana Earthquake



Double-plane fault model and seismicity: 1973-1981

Barrientos et al., 1987, BSSA

1954 Fairview Peak, Nevada Earthquake

- **Romney, 1957, BSSA.**
- **Analyzed P-wave first motions: "The solution obtained implies a fault striking N 11° W and dipping 62° to the east."**

2009

- **Slemmons, 1957, BSSA.**
- **"The faults in bedrock are everywhere normal, with dips of *55°* to *75°* east. Alluvium and soil, however, always breaks more steeply and the dips of the fault planes do not reflect the true dip of the fault plane in bedrock."**

1957

From Slemmons, 1957

1954 Dixie Valley-Fairview Peak Summary

Summary of Surface Rupture Characteristics for Faults Activated during the 1954 Fairview Peak and Dixie Valley Earthquakes

Fault	Rupture length (km)	Average Strike	Dip	VS_{max} (m)	VS_{avg} (m)	SS_{max} (m)	SS_{avg} (m)	u_{max} (m)	u_{avg} (m)	M_0^g(max) (× 10^{26} dyne cm)	M_0^g(avg) (× 10^{26} dyne cm)	M_w(max)	M_w(avg)
Dixie Valley fault	42.0	017°	30°–50° E	2.80	0.90	—	—	3.66	1.17	9.04	2.89	7.27	6.94
Fairview fault zone	31.6	015°	50°–70° E	3.80 (3.80)	1.20	2.90	1.00	5.26	1.71	8.63	2.80	—	—
Gold King fault	8.5	005°	50°–70° W	1.00	0.45	—	—	1.15	0.52	0.51	0.23	—	—
Louderback Mtns fault	14.0	345°	60°–80° W	0.80 (0.70)	0.20	1.70	0.50	1.86	0.54	1.25	0.36	—	—
Phillips Wash fault	6.2	027°	50°–70° E	0.48 (0.30)	0.25	0.80	0.60	0.87	0.67	0.28	0.22	—	—
West Gate fault	10.0	003°	50°–70° W	1.15 (0.65)	0.40	1.20	0.60	1.41	0.76	0.73	0.39	—	—
Fairview Peak event totals										11.40	4.00	7.34	7.03

From Caskey et al, 1996

Dixie Valley, 2005

USGS
science for a changing world

Northern Dixie Valley, Nevada

- **Okaya and Thompson, 1985, Tectonics.**
- **Interpreted reflection profiles in northern part of valley related to geothermal development.**
- **“Calculated fault dip from hand migration is 50°.”**

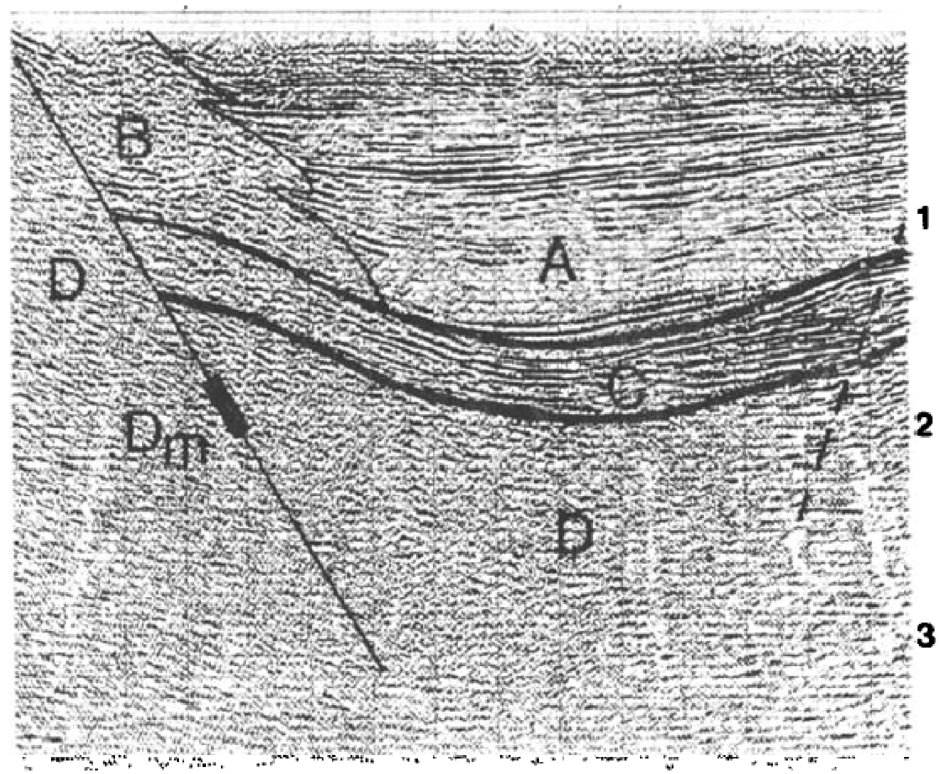


Fig. 3. Seismic line SRC-3, (top) stacked and (bottom) interpreted finite difference migration. Reflection symbols: A, lacustrine and playa deposits; B, alluvial fan; C, Tertiary volcaniclastic sequence; D, Mesozoic basement; D_e, steeply dipping fault plane reflections; D_m, hand migration of event D_e. Calculated fault dip from the hand migration is 50^0.

Northern Dixie Valley, Nevada

- **Okaya and Thompson, 1985, Tectonics.**
- **Modeled gravity data to define basin and fault geometry.**

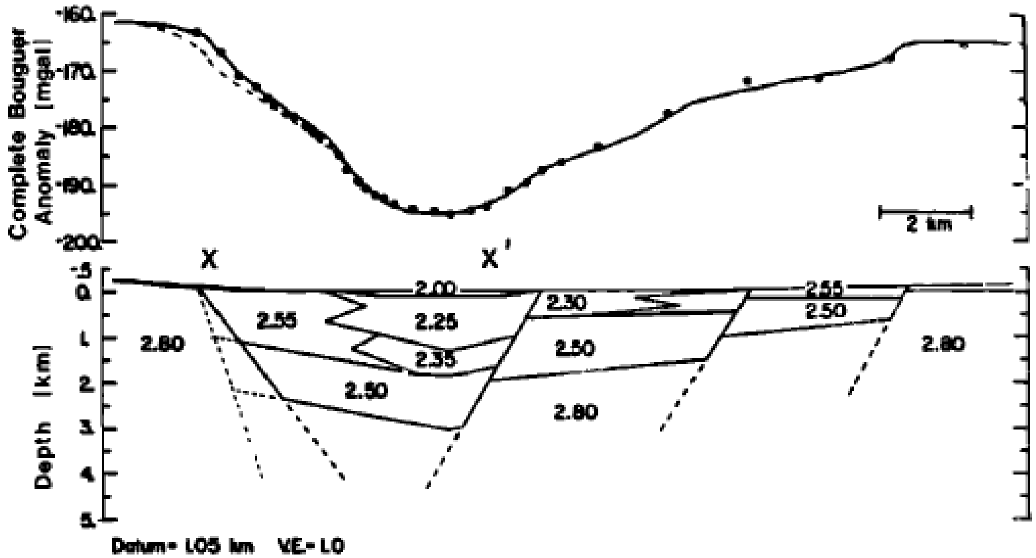


Fig. 4. Gravity model across Dixie Valley. (top) Observed stations (points) and calculated curve. Dashed alternative curve represents values from a fault with dip of 70°. (bottom) model of Dixie Valley; densities in gm/cm^3, depths in km. X-X' represents the projection of seismic line SRC-3 onto the model. Stillwater Range-front fault dip is 50°; thin dashed lines represent projection of the model for a dip of 70°. Other faults dip at 60°. Densities: lacustrine/playa range = 2.00 to 2.35 gm/cm^3; alluvial fan = 2.55 gm/cm^3; Tertiary volcaniclastic sequence = 2.50 gm/cm^3; Mesozoic basement = 2.80 gm/cm^3.

USGS science for a changing world

Northern Dixie Valley, Nevada

- **Okaya and Thompson, 1985, Tectonics.**
- **Preferred model of fault geometry and basin development.**

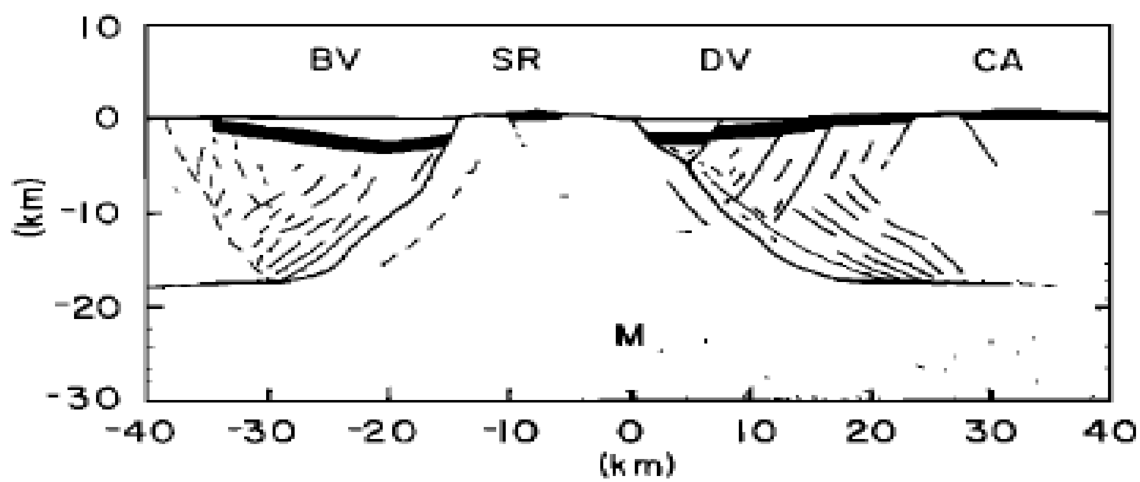
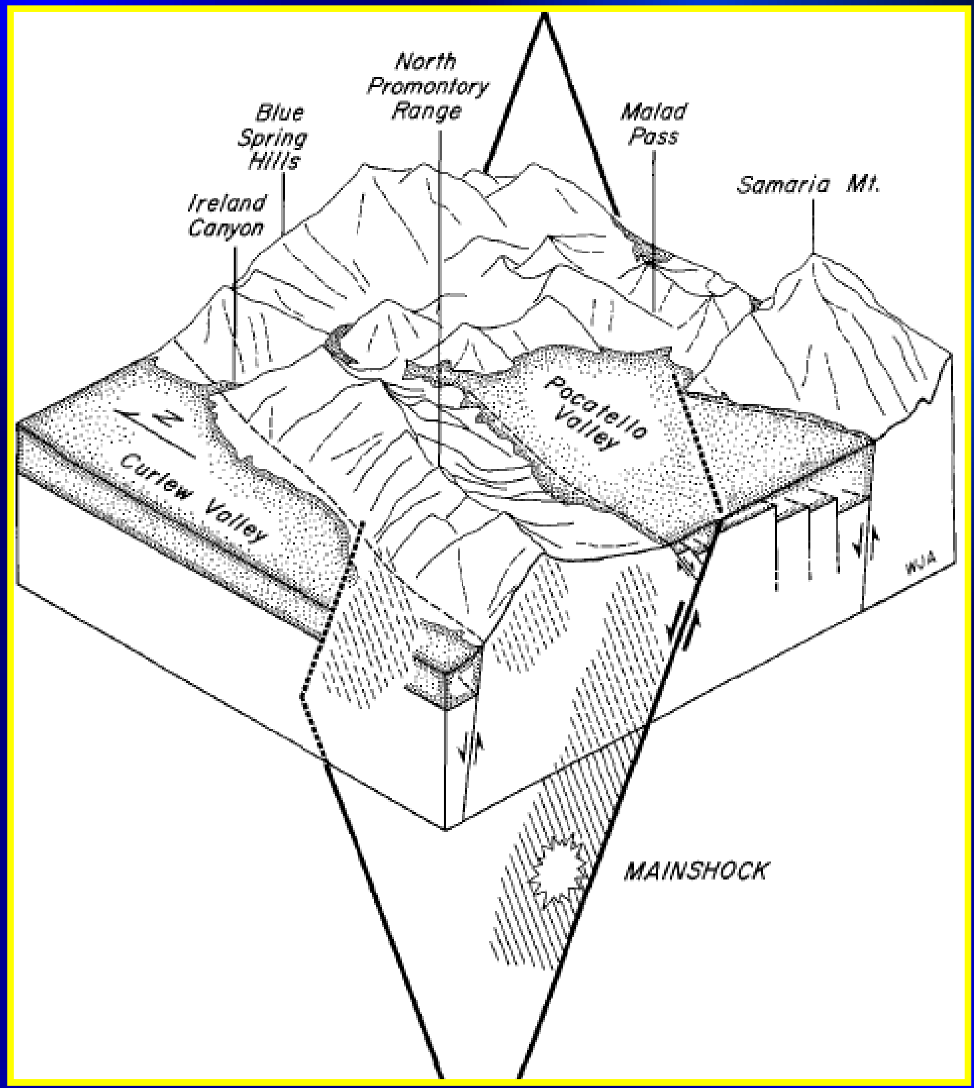


Fig. 15. Combination of rigid and nonrigid models to describe late Cenozoic extensional faulting in the Dixie Valley re gion. Many small faults associated with nonrigid deformation accommodate faulting and sagging of Dixie Valley in the lower to intermediate crust. Intrusion of the crust is not shown but plays a major role in the development of the basin.

science for a changing world

1975 Pocatello Valley, Idaho Earthquake

- **Arabasz et al., 1981, BSSA.**
- **Analyzed M 6.0 main shock and 587 aftershocks. Oblique-slip rupture on previously unrecognized, NW-dipping normal fault.**



1975 Pocatello Valley, Idaho Earthquake

- Arabasz et al., 1981, BSSA.
- "The fault plane outlined in Figure 7 is schematically shown dipping 45°NW. Various dip information, including the dip of the main shock nodal plane (39°), an average dip from the hypocentral cross sections (50°), and the dip from dislocation modeling (60°), illustrate the uncertainty involved in fixing the location of the fault at depth. A dip of 39 ° at 8.7-km depth is not incompatible with steeper dips higher in the crust if normal faults in the Basin and Range are listric, i.e., flatten with depth."
- Seems to emphasize the uncertainty in defining the fault location and geometry at depth.

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Wasatch Fault, Utah

- **Zoback, 1992, USGS Prof. Paper 1500**
- **Interpreted structure from 30-km-long, east-west, seismic-reflection profile across Wasatch fault near Nephi.**
- **Used data on surface geology, gravity, and petroleum exploration wells to constrain the subsurface structure.**

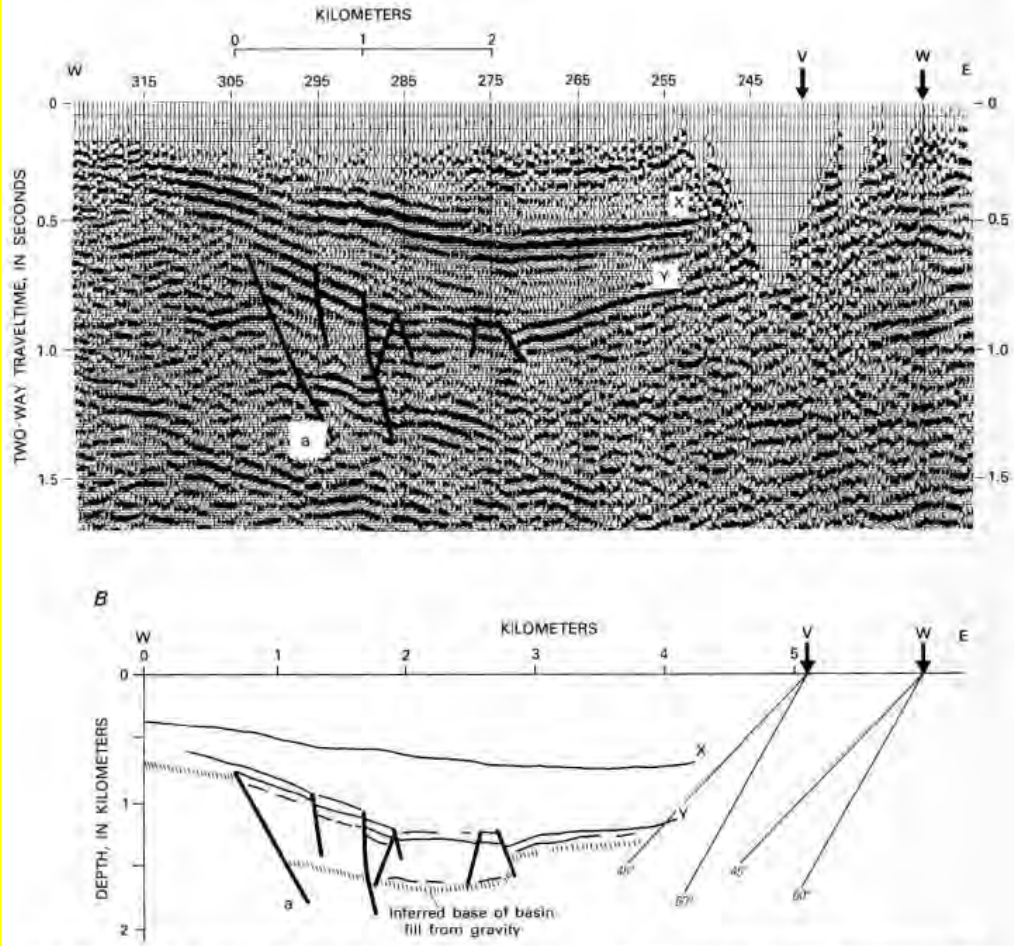

FIGURE 6.—*A*, Detail of seismic reflection profile in Juab Valley showing basin fill. V and W mark possible surface locations of the Wasatch fault zone described in text. Vibrator points are numbered across the top of the section. A major fault on the western side of the basin is labeled a. Reflectors X and Y are discussed in the text. Heavy solid lines are interpreted faults. *B*, Prominent reflectors in basin (true-depth cross section). Projections of planar faults having dips of 45° and 60° and reaching the surface at locations V and W are shown. Vertical and horizontal scales are equal.

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Wasatch Fault, Utah

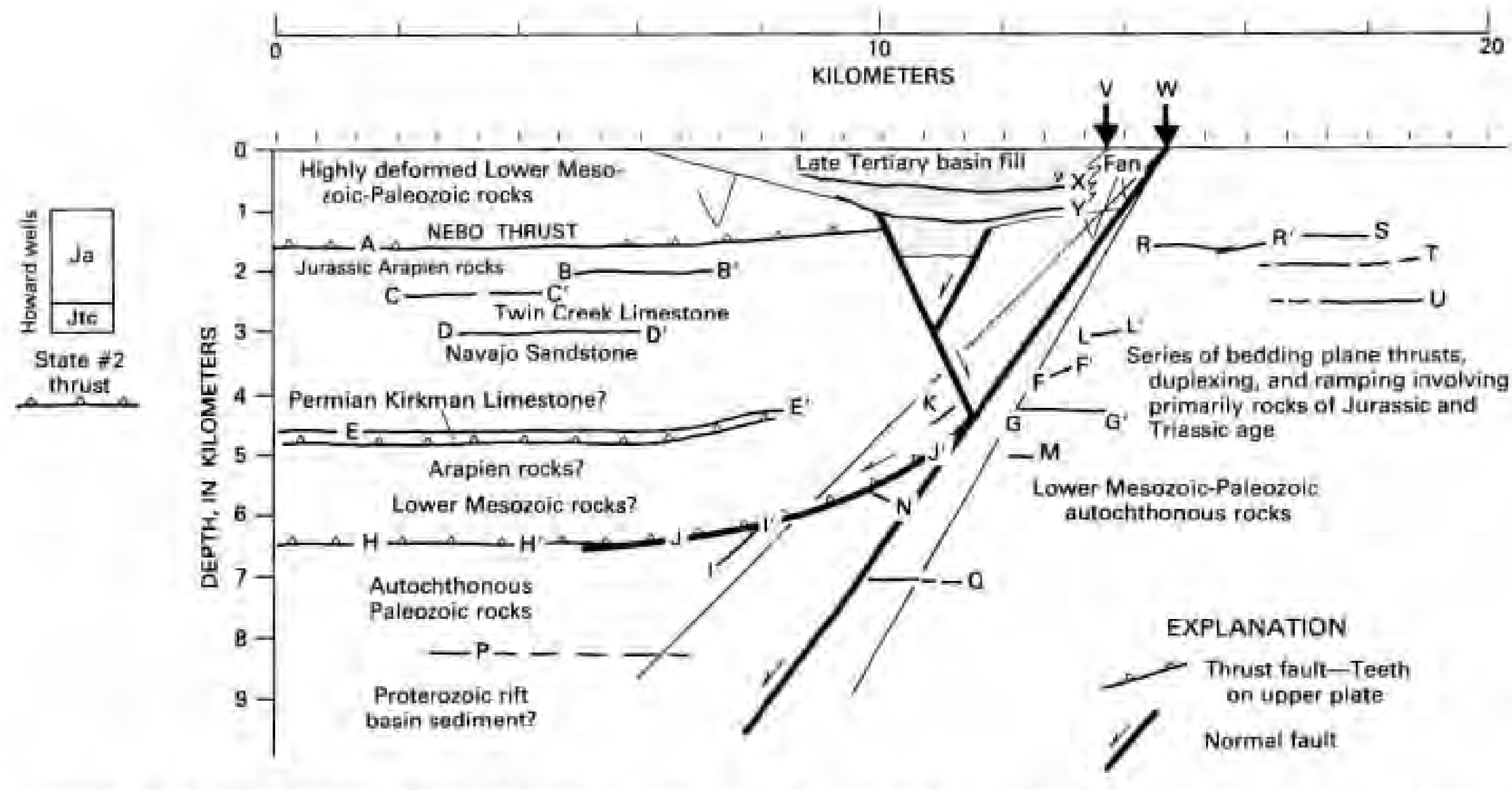


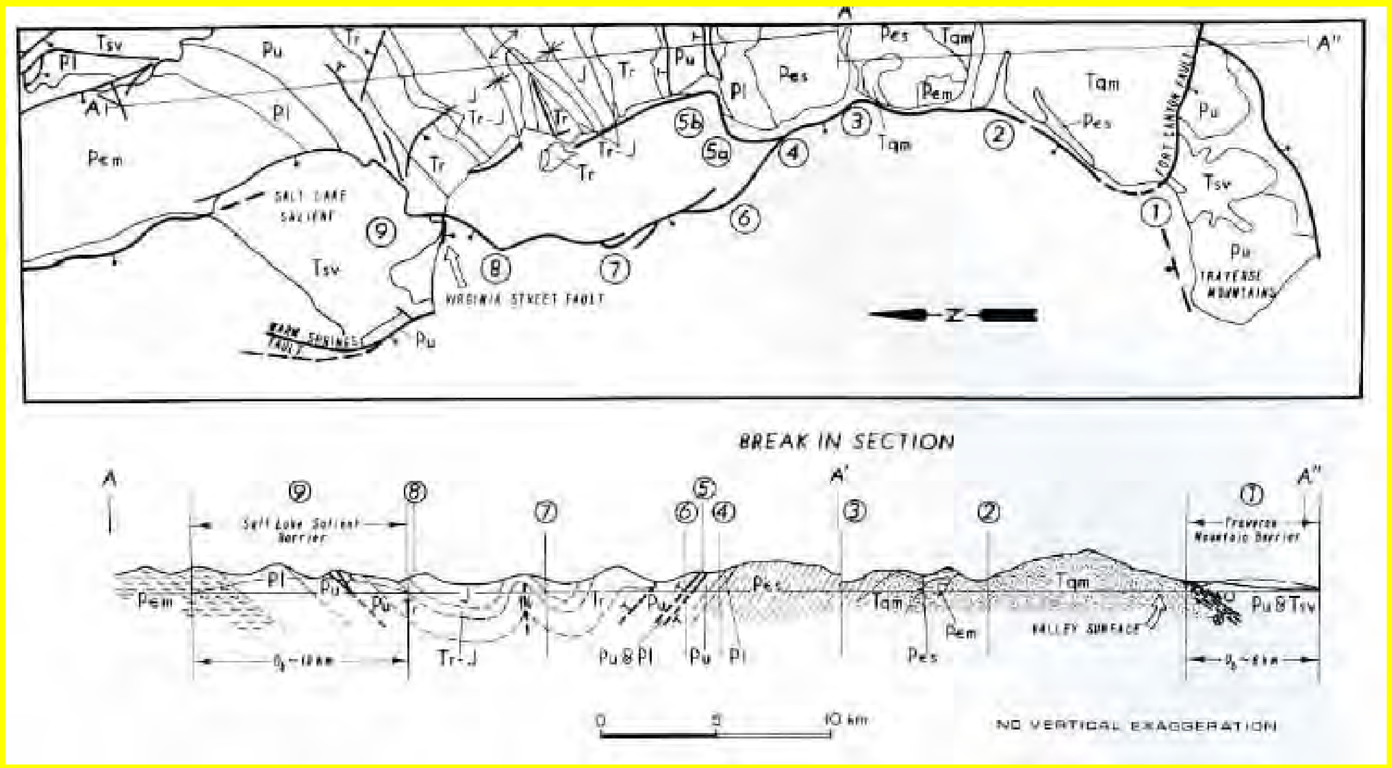
FIGURE 8.—Geologic interpretation of the western half of the true-depth line drawing shown in figure 5B. Heavy lines are seismic reflections. Inferred stratigraphic contacts are indicated.

From Zoback, 1992

"the absence of reverse drag in the basin sediments suggest a planar, relatively steeply dipping (50°-55°) geometry for the Wasatch fault zone at this locality."

Wasatch Fault, Utah

- Bruhn, Gibler, and Parry, 1987, Geol. Soc. Spec. Pub. 28.
- Focus on Salt Lake City segment; divide the segment into 3- to 12-km-long linear sections. Used fault orientation and slickenside data to determine orientation of paleostress field.



Wasatch Fault, Utah

- **Bruhn, Gibler, and Parry, 1987, Geol. Soc. Spec. Pub. 28.**
- **Based on geometry of intersection between sections, they defined conservative and non-conservative barriers.**
- **"…we construct a preliminary model of the fault zone utilizing information about the strike of fault sections, the inferred slip direction in the fault zone, and the characteristics of the palaeo-stress tensor."**
- **Dip values of 35-65°.**

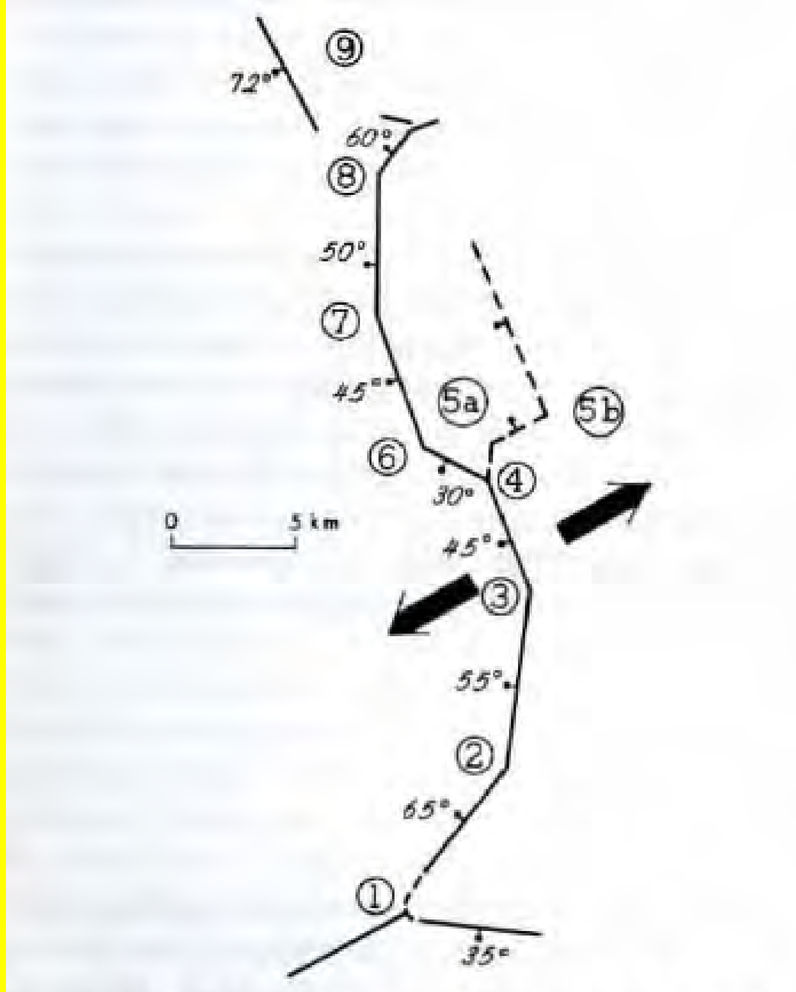
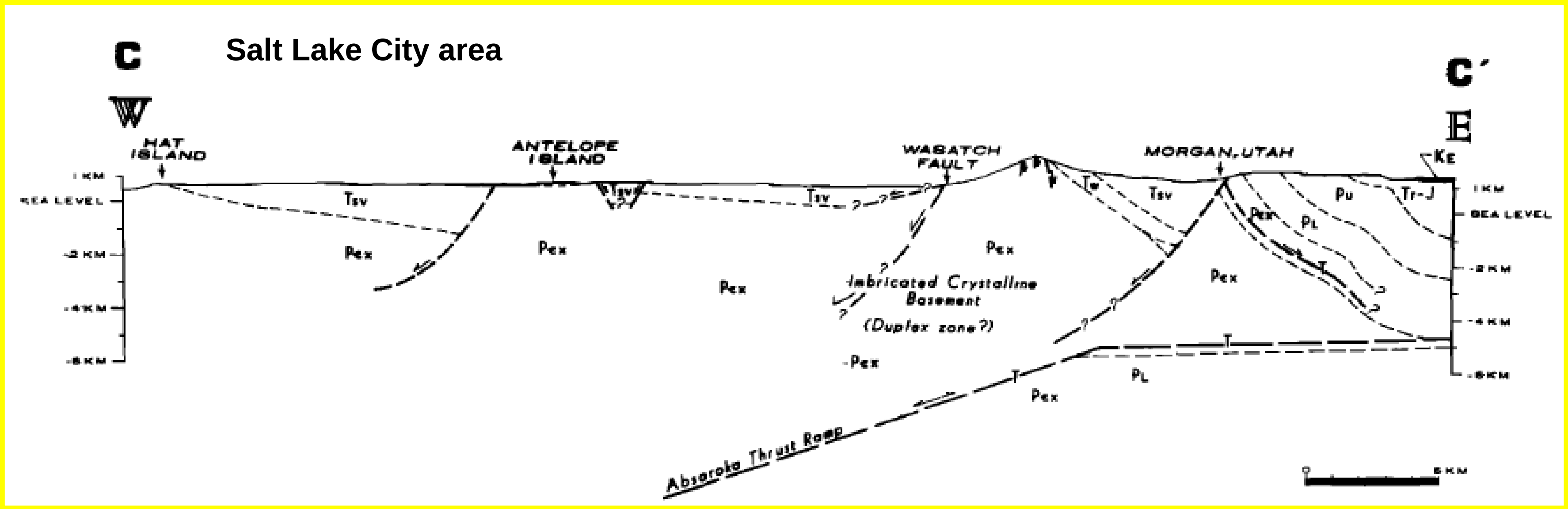


FIG. 8. Map of surface fault trace in the Salt Lake segment with preferred dip angles based on geometrical modelling. Numbers of barriers same as those in Fig. 2 and Table 1. See text for discussion.

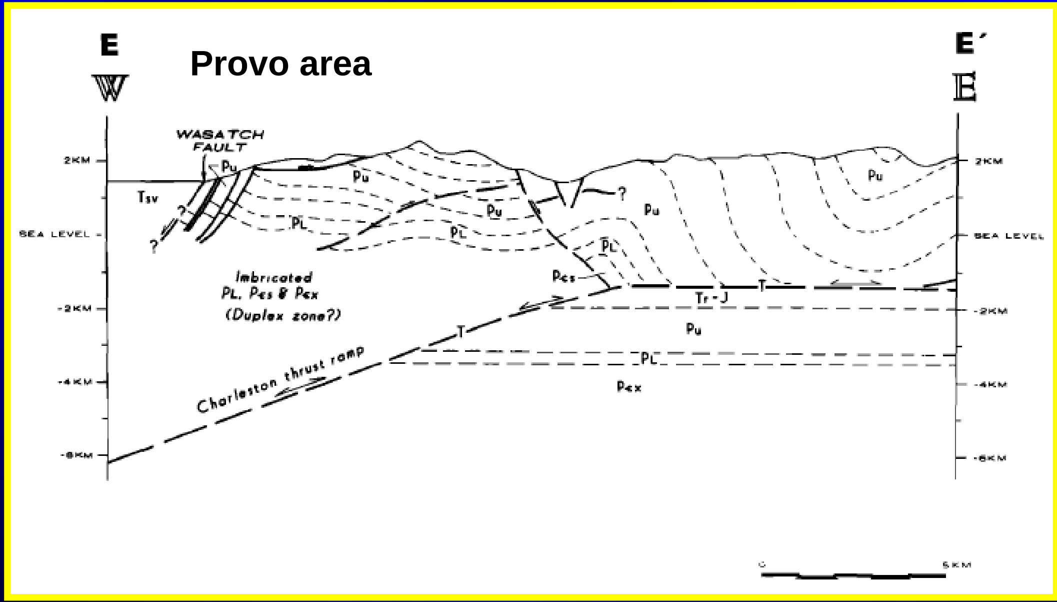
Wasatch Fault, Utah

- Smith and Bruhn, 1984, JGR.
- Interpreted more than 1500 km of reflection data and developed structural cross sections.
- "Our data and interpretations have revealed the following styles of Cenozoic deformation: (1) steep- to low-angle dip, normal faulting along the Wasatch fault, (2) low-angle dip and listric normal faulting possibly associated with movement on preexisting thrusts, (3) the occurrence of asymmetric, mostly eastward tilted Tertiary basins that are bounded by low- to moderate-dipping planar and listric faults….."
- "An important observation, based on interpretations of seismic reflection profiles, is that normal fault zones dip more gently in the subsurface than their associated scarps in unconsolidated surficial deposits."

Wasatch Fault, Utah



From Smith and Bruhn, 1984



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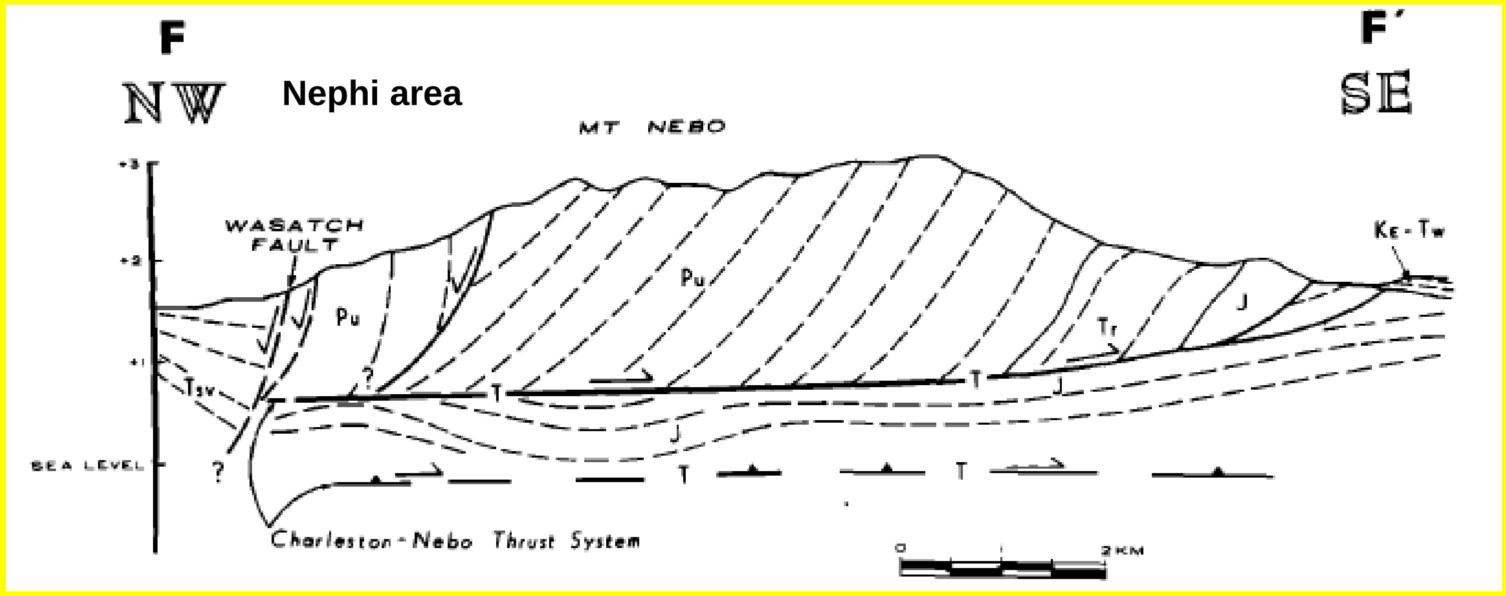
Wasatch Fault, Utah



"Reactivation of Mesozoic and early Tertiary thrust faults could be important on some segments of the Wasatch fault zone, but the evidence is generally ambiguous. The Levan segment may flatten into the Pavant thrust fault just west of the Gunnison Plateau [Standlee, 1982], and the Ogden and Provo segments cut the back limbs of ramp anticlines above the inferred positions of north trending frontal thrust ramps in the subsurface. However, we do not know if the faults merge into these ramps at depth. On the other hand, normal faults in the Salt Lake segment and southern most part of the Nephi segment do not appear to be located directly above north trending thrust ramps based on our interpretations."

From Smith and Bruhn, 1984

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Wasatch Fault, Utah

- **Chang and Smith, 2002, BSSA.**
- **"for the purpose of analytic stress modeling, the Wasatch and nearby faults were discretized into rectangular patches 10 km long, dipping 55 W, and extending from the surface to 15 km deep with rake angles of 90 (pure normal fault)."**
- **Chang et al., 2006, JGR.**
- **Best agreement between GPS and geologic deformation rates are for fault dip of about 55°.**

Table 3. Comparison of Deformation Rates Across the Wasatch Fault From GPS and Geologic Determinations

Dip of the Wasatch Fault	Dip of Simple Shear Plane (Antithetic Fault)	Vertical Displacement Rate from GPS Data,[a] mm/yr	Geologic Fault Slip Rate (0–10 ka),[b] mm/yr	Comparison of GPS Rate with Geologic Rate[c]
$\theta = 30°$	$\alpha = 55°E - 80°E$	0.5–1.0	1.7 ± 0.5	GPS < Geologic
	$\alpha = 90°$	0.7–1.2	1.7 ± 0.5	GPS < Geologic
$\theta = 55°$	$\alpha = 55°E - 80°E$	0.9–2.3	1.7 ± 0.5	Consistent
	$\alpha = 90°$	1.7–2.9	1.7 ± 0.5	Consistent
$\theta = 70°$	$\alpha = 55°E - 80°E$	1.1–3.7	1.7 ± 0.5	Consistent
	$\alpha = 90°$	3.3–5.5	1.7 ± 0.5	GPS > Geologic

[a] Vertical displacement rates were converted from the GPS-derived horizontal extension rates across the Wasatch fault, 1.6 ± 0.4 mm/yr, using equation (3).
[b] Holocene (0–10 ka) geologic slip rates of 1.7 ± 0.5 mm/yr for the Wasatch fault were determined by *Friedrich et al.* [2003].
[c] Comparison of the two rates was based on 1σ error ranges.

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Western U.S. Cordillera

- Doser and Smith, 1989, BSSA.
- Evaluated source parameters for 50 earthquakes (M≥5.5—7.8) between 1918 and 1988 in domain that spans the "from western cordillera of the United States, a predominantly extensional regime located east of the San Andreas fault system and west of the Great Plains."
- Includes mainshocks and large aftershocks,and events that have strong evidence of major strike-slip motion; i.e. 1932 Cedar Mtn. NV, 1986 Chalfant Valley, CA.
- "Finally, this study gives an indication of what might be expected from a magnitude ≥7.0 earthquake in the western cordillera. Faulting would likely extend to depths of 12 to 16 km near the base of the brittle/ductile transition on a planar fault dipping 40° to 70°. Surface rupture would extend for a distance ≥16 km with a total displacement > 1.0 m. The rupture would likely be unilateral and consist of two or more subevents, with no individual subevent having a rupture length >20 km."

Normal Faulting in Continental Crust

- **Jackson and White, 1992, J. Struct. Geol.**
- **Consider dip errors to be in the range of 10-15°.**
- **Conclude that: "The great majority [of faults] have dips in the range 30-60°, and dips significantly less than 20° have not been observed."**

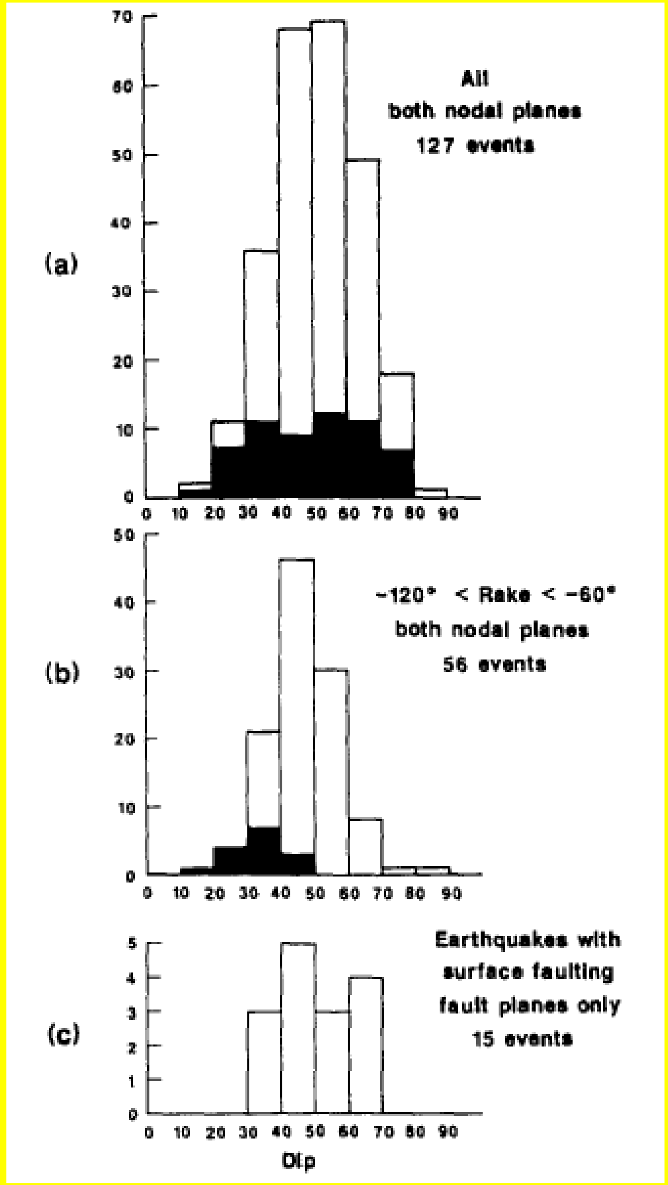

Fig. 1. Dips of nodal planes for large ($m_b \geq 5.2$) continental normal faulting earthquakes, measured from fault plane solutions. This figure includes data from Greece, western Turkey, Italy, the Gulf of Suez, Tibet, NE China, SW China, Mongolia, East Africa, and the western U.S.A. The black region in (a) includes dips from moment tensor inversions carried out at Harvard (the method of Dziewonski & Woodhouse 1983), and published by the United States Geological Survey. The black region in (b) includes dips that have been deliberately drawn to be as gentle as possible (i.e. minimizing the strike-slip component): they could be steeper.

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Normal Faulting in Continental Crust

- **Collettini and Sibson, 2001, GEOLOGY**
- **Updated data from Jackson and White by adding data from 13 additional events.**
- **Data are for: M >5.5 events in upper continental crust**
  Near-pure normal slip
  Dips of preferred nodal plane from focal mech., wave-form models, geodetic models, surface ruptures, aftershocks.
- **Only used data for which rupture plane can be unambiguously determined.**

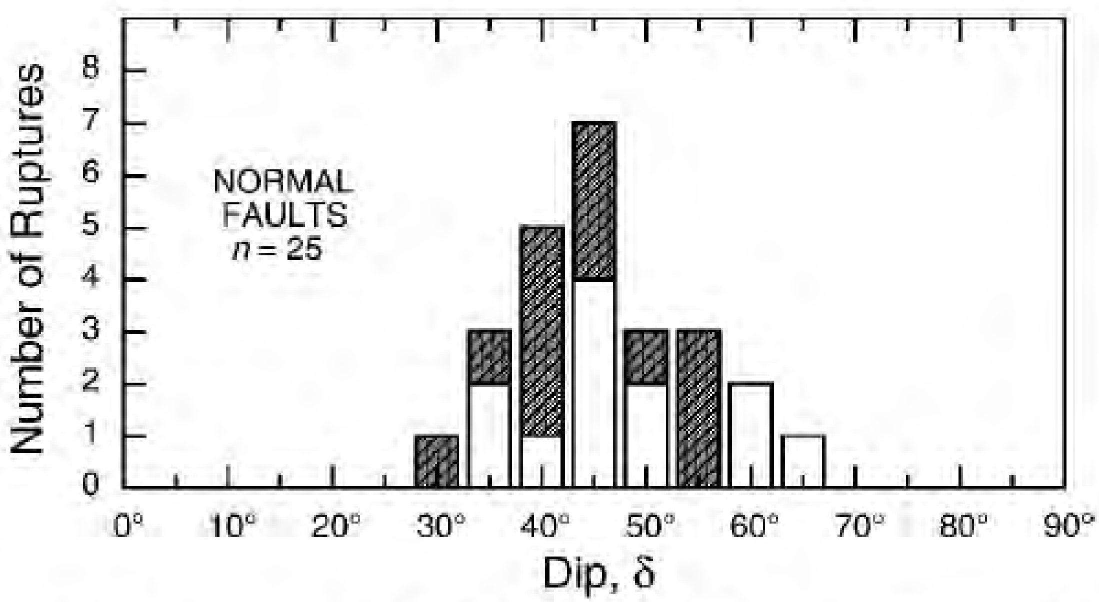


Figure 1. Histogram of active normal fault dips, from compilation of Jackson and White (1989) (no pattern) and Table 1 (pattern).

Normal Faulting in Continental Crust

- **Collettini and Sibson, 2001, GEOLOGY**
- **“The dip distribution for positively discriminated normal slip ruptures extends over the range, 65° > β > 30°, with a marked peak at β ≈ 45°. There is still no definite examples of M 5.5 normal-slip earthquakes on faults dipping less than 30° according to the selection criteria we have employed.”**

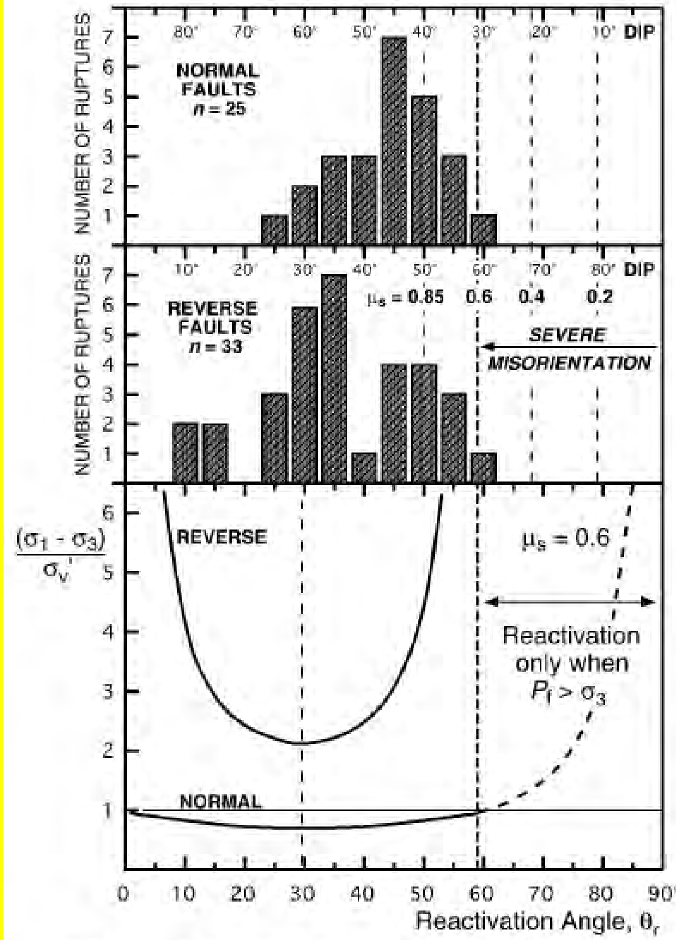
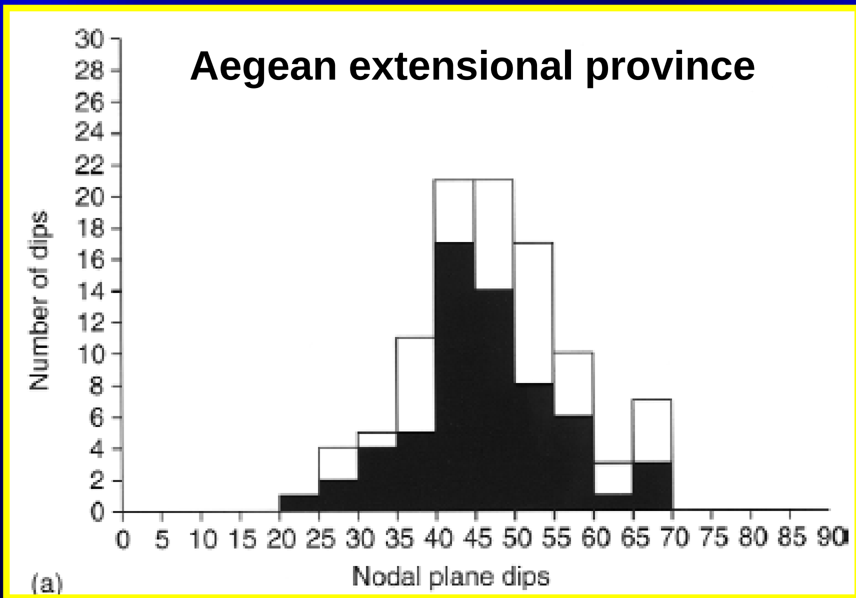
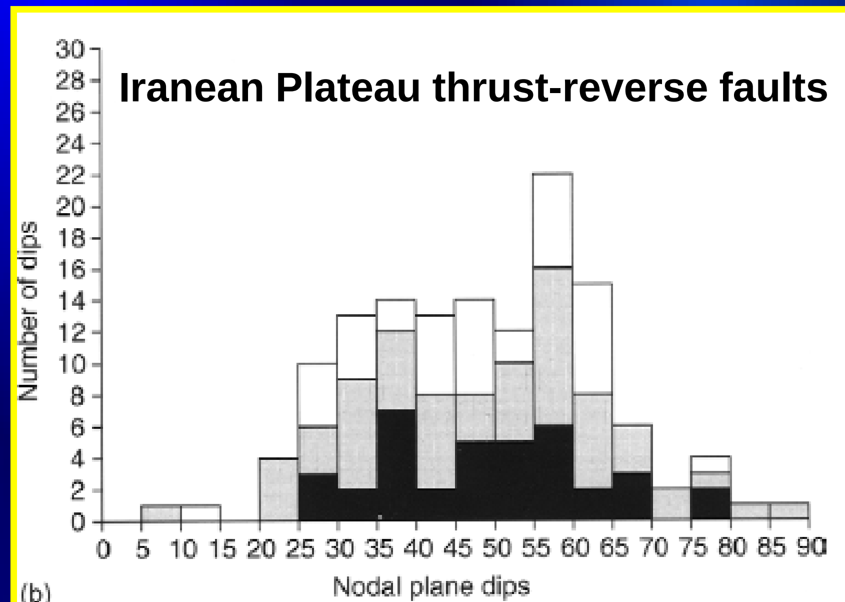


Figure 3. Dip distributions for normal and reverse fault ruptures replotted in terms of inferred reactivation angle, θ_r. Reverse fault data are from Sibson and Xie (1998), with addition of U.S. Geological Survey CMT dip estimates of 29° for 1999 M 7.6 Chi-chi, Taiwan, and 9° for M 6.5 Chamoli, India, ruptures. Vertical dashed lines represent lockup angles for various friction coefficients, μ_s. At base of diagram, frictional reactivation parameter $(\sigma_1 - \sigma_3)/\sigma_v'$ is plotted as function of θ_r for normal and reverse faults having $\mu_s = 0.6$.

Normal Faulting in Continental Crust

- **Jackson, 2002, Int. Assoc. Seismol. & Phys. Earth's Interior, v. 81A.**





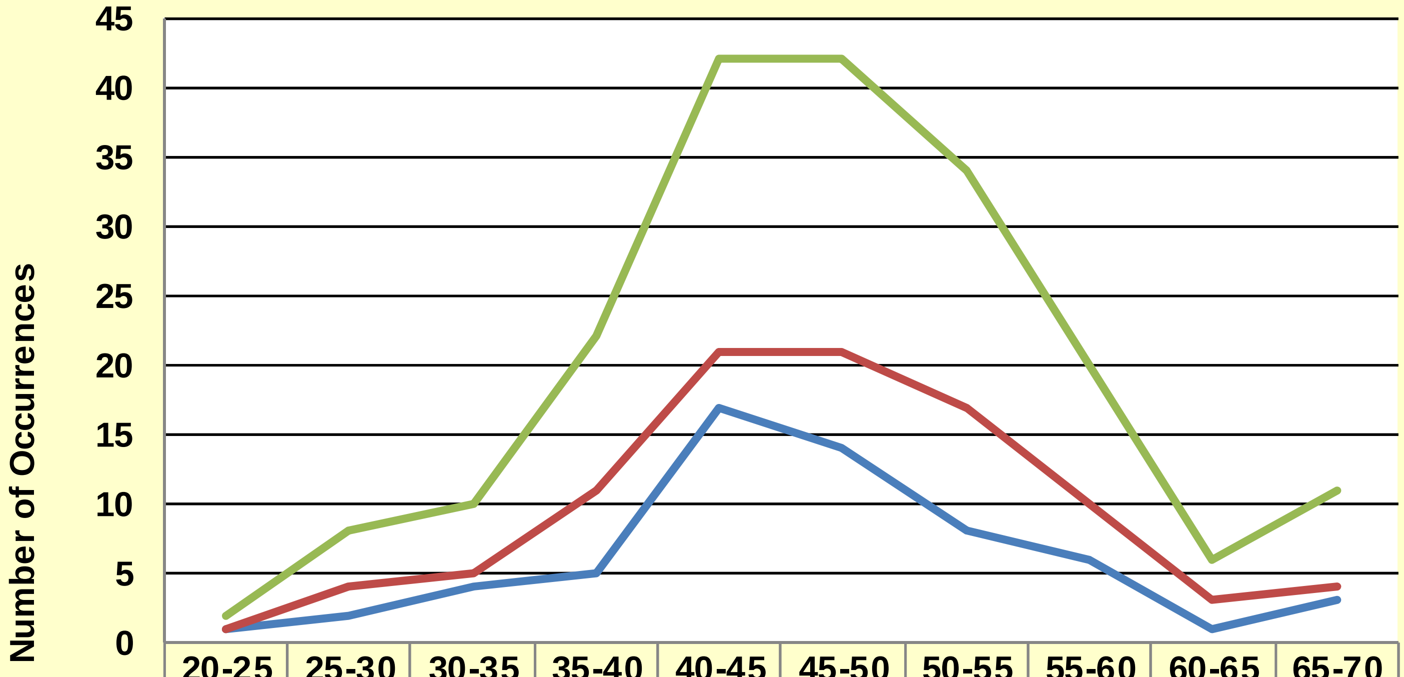
- **Mw ≥ 5.3**
- **Black: body wave modeling**
- **White: Harvard CMT**

- **Mw ≥ 5.3**
- **Black: body wave modeling**
- **Gray: Harvard CMT**
- **White: first-motion mechanisms**

Normal Faulting in Continental Crust

- **Jackson, 2002, Int. Assoc. Seismol. & Phys. Earth's Interior, v. 81A.**

Normal Fault Dip Angles



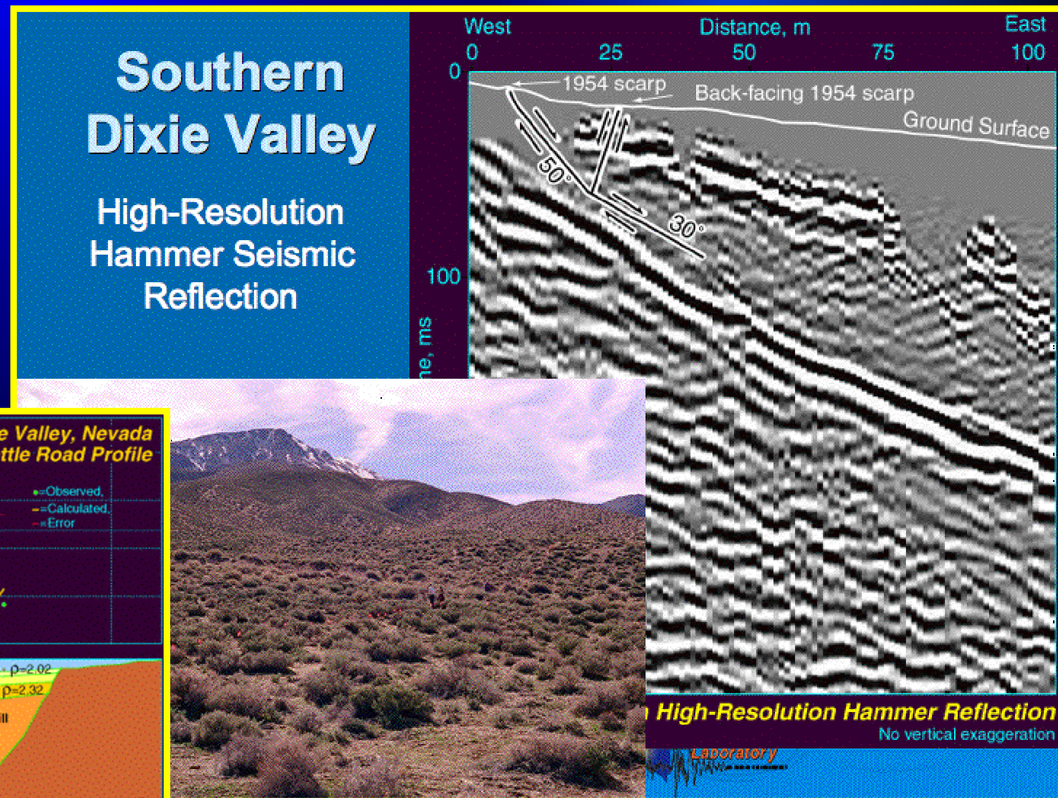
	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70
Total	1	4	5	11	21	21	17	10	3	7
CMT	0	2	1	6	4	7	9	4	2	1
Body wave	1	2	4	5	17	14	8	6	1	3

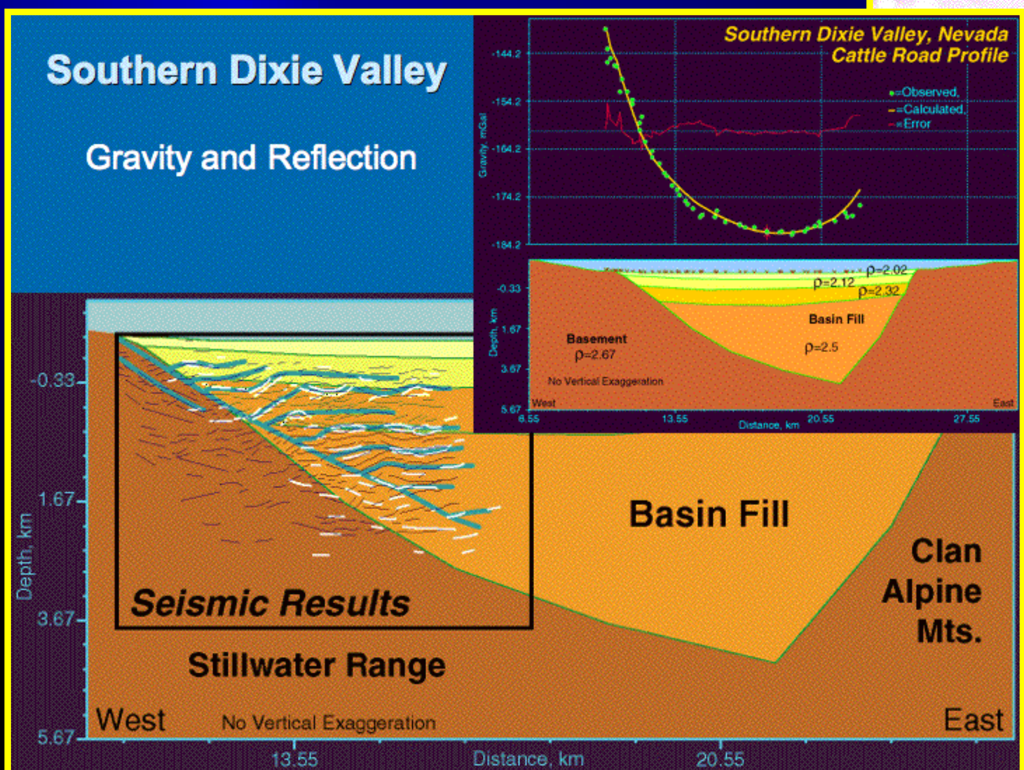
Low-Angle Normal Faults: Can they be active?

- High-angle normal faults can rotate during their slip history to lower angles. Low-angle normal faults appear to have an significant role in continental extension of the B & R.
- Sevier Desert detachment:
  - ✓ Considerable discussion about it being an active low-angle (11°) structure, but additional work (Wills and Anders, 1999) raises questions about the interpretations of the detachments.
- Dixie Valley, Nevada:
  - ✓ Evidence that southern part of the Dixie Valley fault may have low dip angle.

Dixie Valley, Nevada

Fault dip of 50° at surface but flattens to 30° in shallow subsurface.





From J. Louie, UNR; http://crack.seismo.unr.edu/ftp/pub/louie/talks/AGU07-NS23A-07.html

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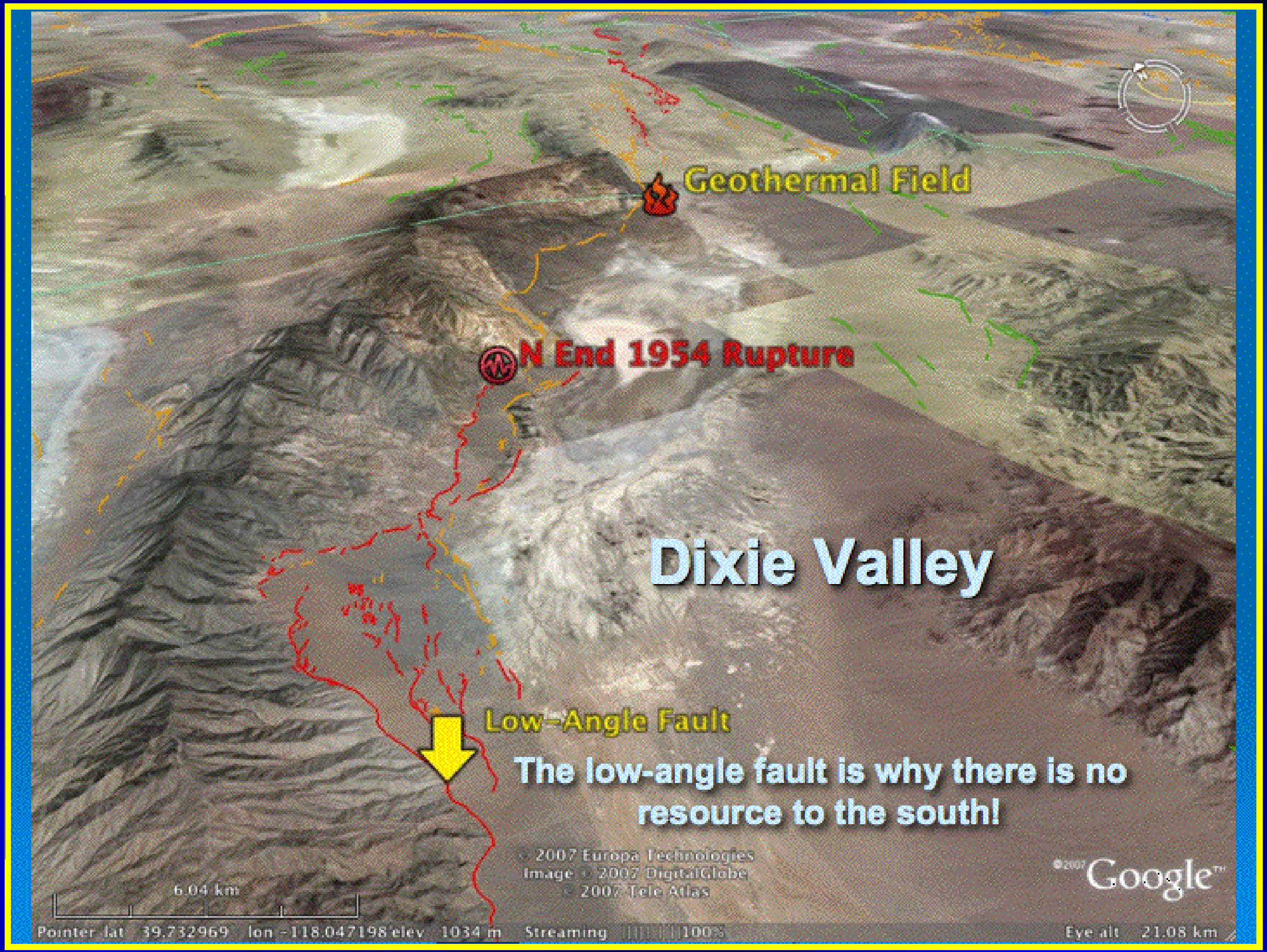
Dixie Valley, Nevada

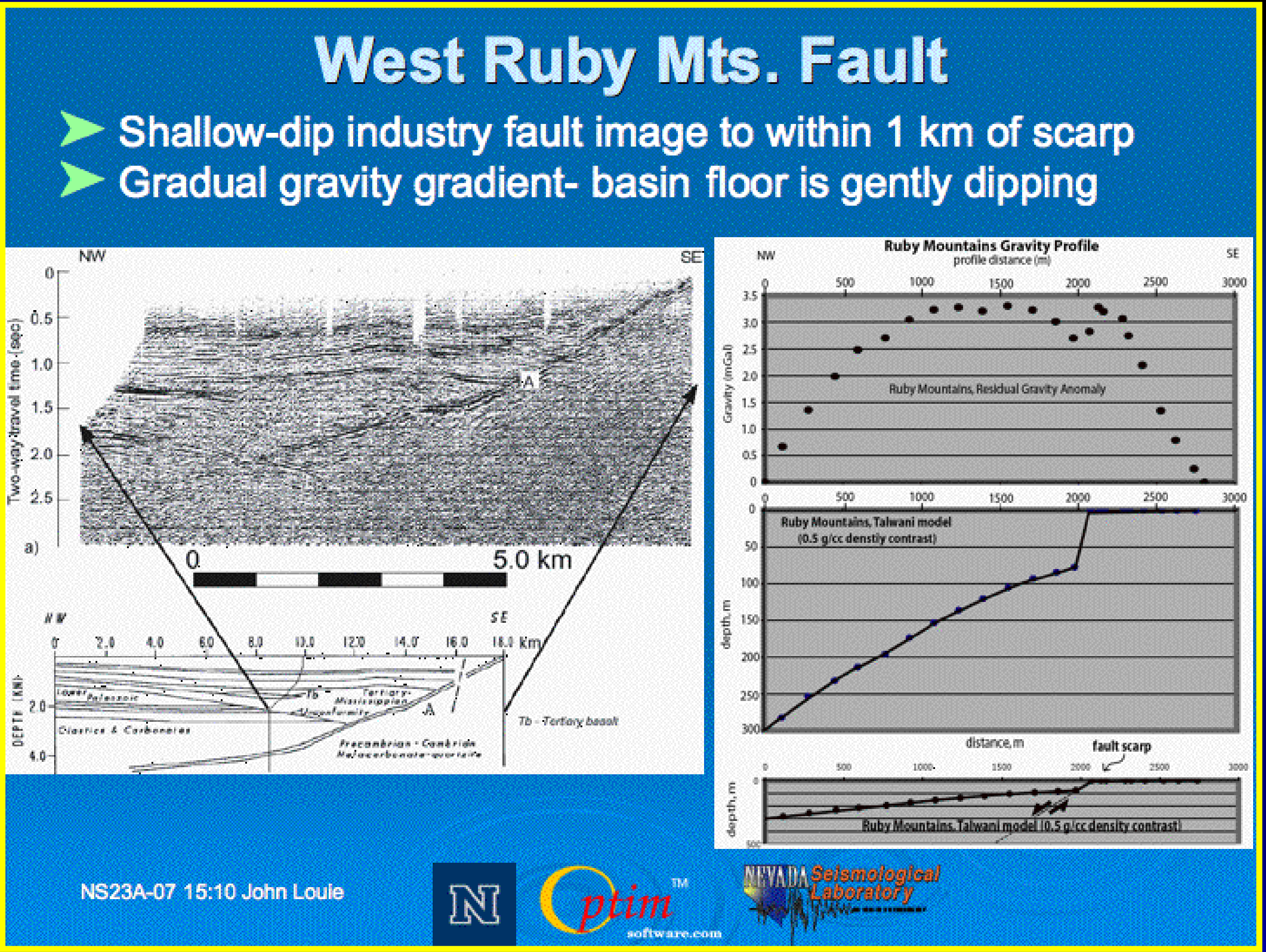
Suggests that the reason geothermal production exists in northern Dixie Valley is related to steeper fault to north compared to no geothermal and shallower dipping fault in southern part of valley.



From J. Louie, UNR; http://crack.seismo.unr.edu/ftp/pub/louie/talks/AGU07-NS23A-07.html

West Ruby Mts., Nevada

Additional example of range-front normal fault that apparently has shallow dip.



From J. Louie, UNR; http://crack.seismo.unr.edu/ftp/pub/louie/talks/AGU07-NS23A-07.html

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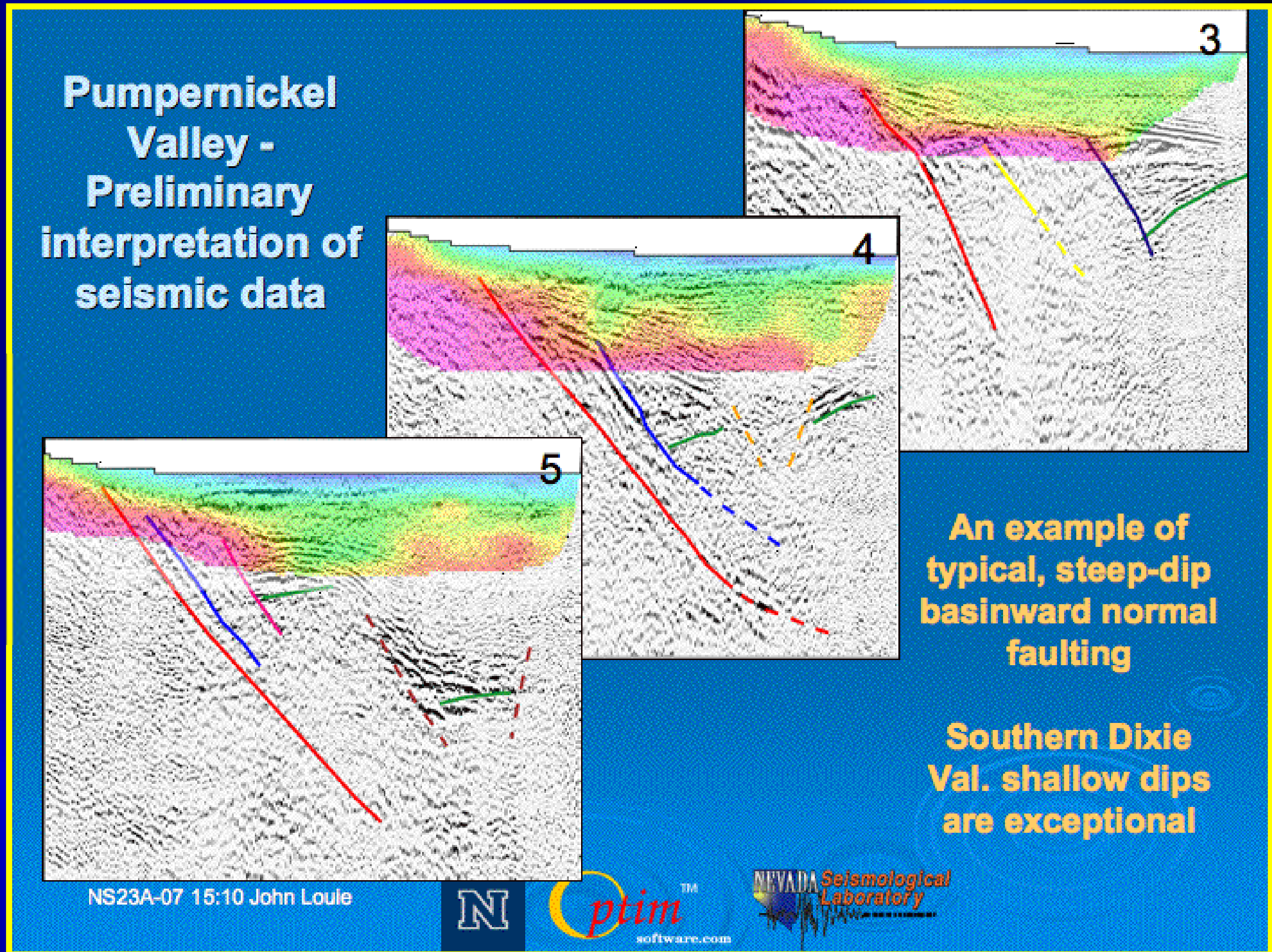
Pumpernickel Valley, Nevada

Example of a more typical geometry of range-bounding normal fault.



From J. Louie, UNR; http://crack.seismo.unr.edu/ftp/pub/louie/talks/AGU07-NS23A-07.html

Thomas Creek, Carson Range-Front, Nevada

Sarmiento et al., 2011, BSSA

Trench north of Thomas Creek on the eastern flank of the Carson Range near Reno exposed a low-angle feature.

Thomas Creek,
Carson Range-Front, Nevada

"…sharp, planar, low-angle failure surface dipping 33° E, lending to the possibility that the active normal fault is characterized by a dip much lower than expected from standard frictional considerations."

Sarmiento et al., 2011, BSSA

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Seismogenic Low-Angle Normal Fault

- **Abers et al. 1997, JGR.**
- **Woodlark-D'Entrecasteaux rift system, Papua, New Guinea.**
- **Some normal-faulting mechanisms have dips of less than 20°.**
- **Region of high extension rates: 35-40 mm/yr. (5-10 times greater than B & R rates).**
- **Geologic and tectonic setting very different than the B & R.**

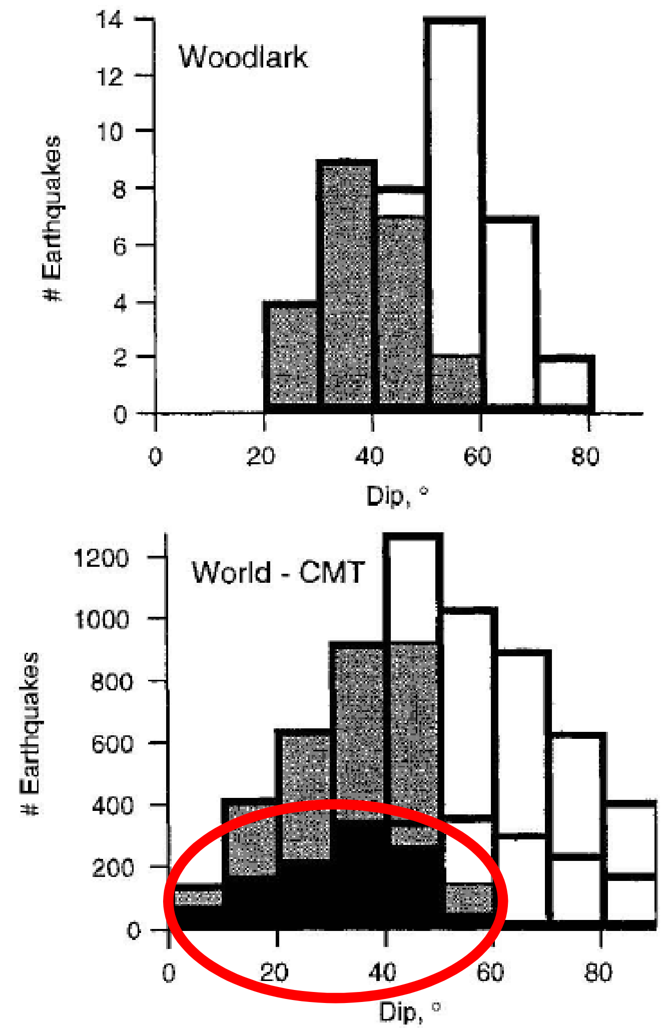
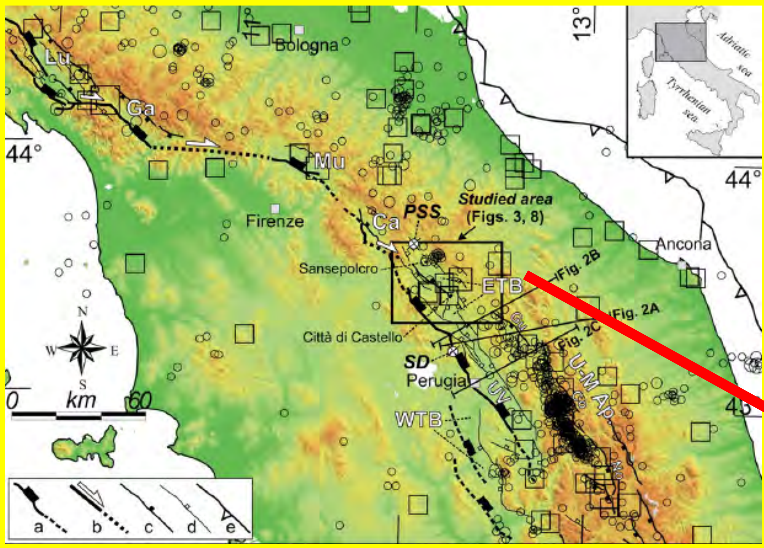


Figure 10. Histograms showing dips of nodal planes for normal-faulting mechanisms (P axis plunge >45°). Histogram for shallower-dipping plane is shaded, steeper plane is open. (top) Results presented here combined with CMT solutions for the region. (bottom) Global CMT catalog 1977-1995; black shading denotes events with $M_0 > 10^{17.5}$ N m ($M_W > 5.67$).

Seismogenic Low-Angle Normal Fault



Brozzetti et al., 2009, Tectonophysics

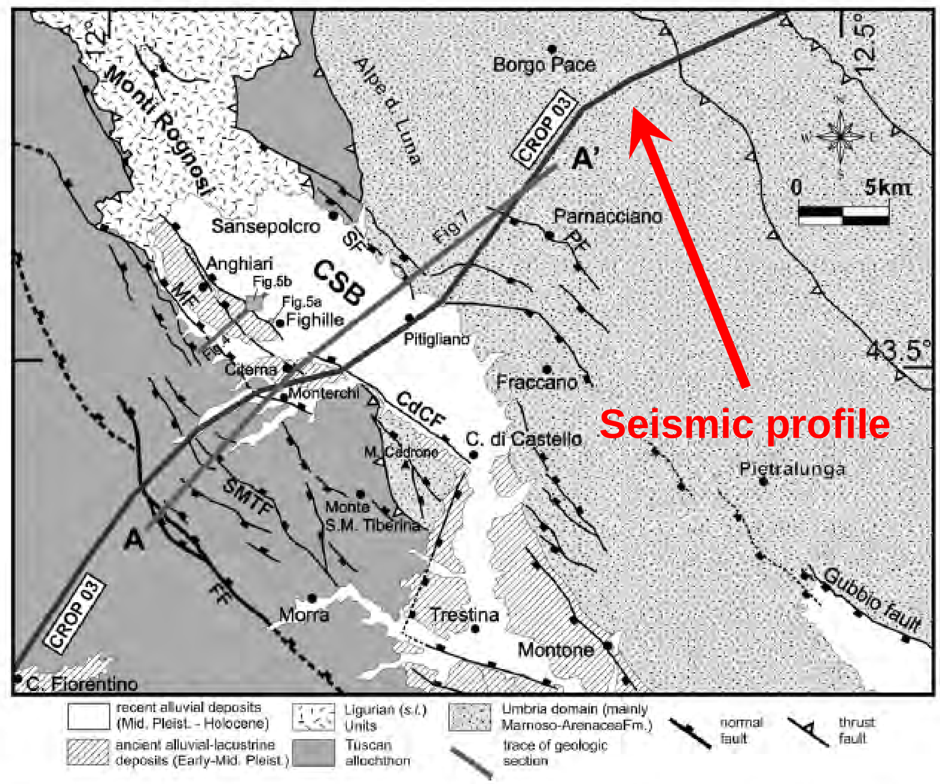


Fig. 3. Simplified geological map of the northern Tiber Valley showing the outcropping tectonic units and the Plio-Quaternary Città di Castello–Sansepolcro basin (CSB) deposits. The traces of the studied segment of the CROP 03 seismic profile (Fig. 6) and of the interpretative geological section (Fig. 7) are shown. FF = M. Favalto fault; SMTF = Monte Santa Maria Tiberina fault; CdCF = Città di Castello fault; SF = Sansepolcro fault; PF = Parnacciano fault.

- Low-angle normal fault system; Città di Castello–Sansepolcro basin (CSB), northern Apennines, Italy.
- Low level of instrumental seismicity recorded in CSB, and several damaging historical earthquakes; 1352, 1389, 1458, 1789, 1917.

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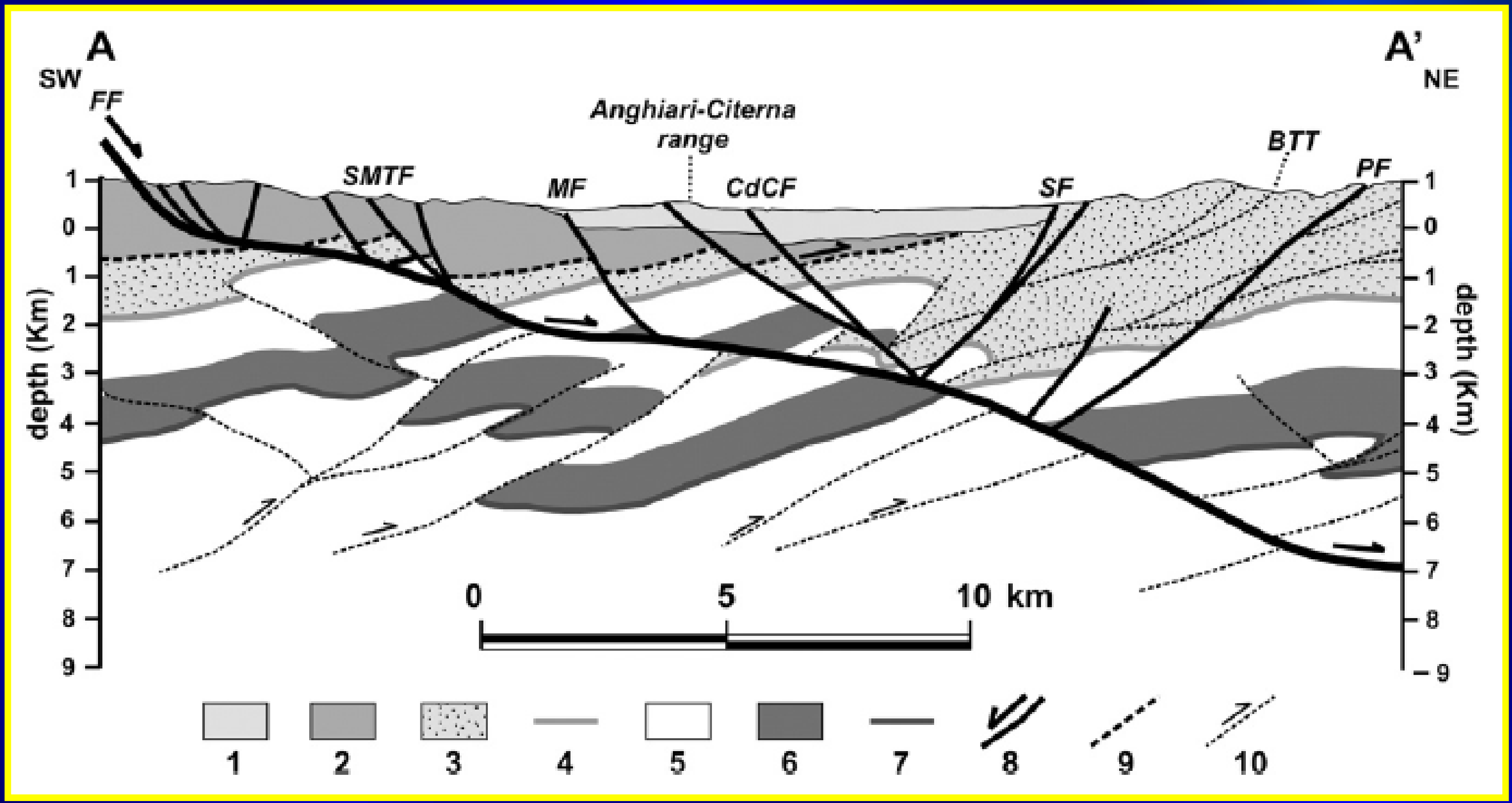
Seismogenic Low-Angle Normal Fault

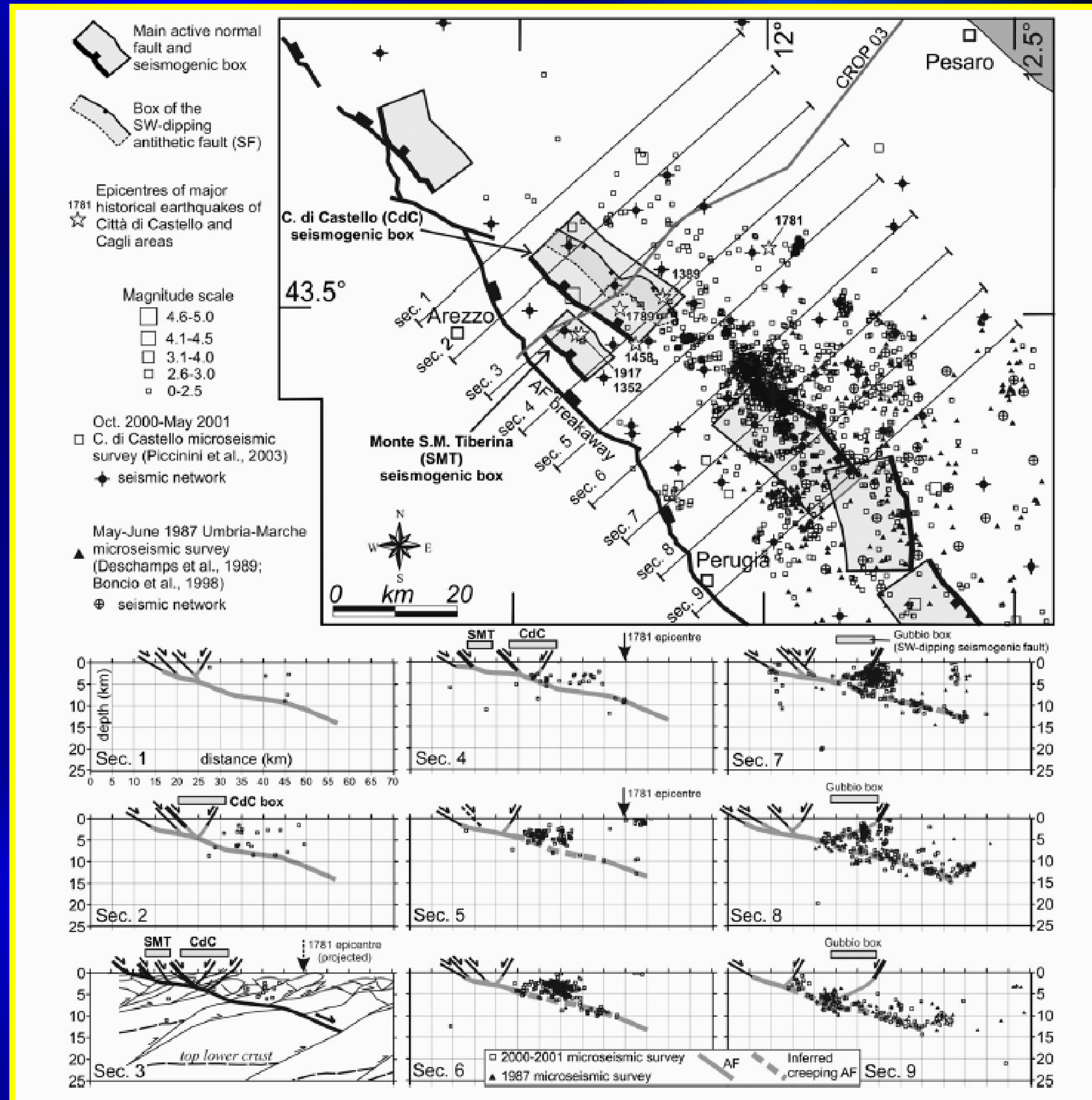


Brozzetti et al., 2009, Tectonophysics

- Deep seismic reflection profile: shows geometry of the Plio-Quaternary extensional structures. Low-angle east-dipping reflectors are expression of Altotiberina fault; regional extensional detachment on which both east- and west-dipping high-angle faults, sole out.
- Displacement along the AF is ~4.5 km; system still active, responsible for seismicity in the area.

Seismogenic Low-Angle Normal Fault

- **Based on instrumental seismicity and intensity data of five largest historical earthquakes (intensity IX to IX–X), they propose two main seismogenic structures: the Monte Santa Maria Tiberina (M_{max}=5.9) and Città di Castello (M_{max} up to 6.5) normal faults.**
- **Both are synthetic splays of the AF detachment, dipping to NE at moderate (45–50°) to low (25–30°) angles and cutting upper crust up to the surface.**
- **Conclude that low-angle normal faults (at least with dips of 25–30°) may be seismogenic.**



Brozzetti et al., 2009, Tectonophysics

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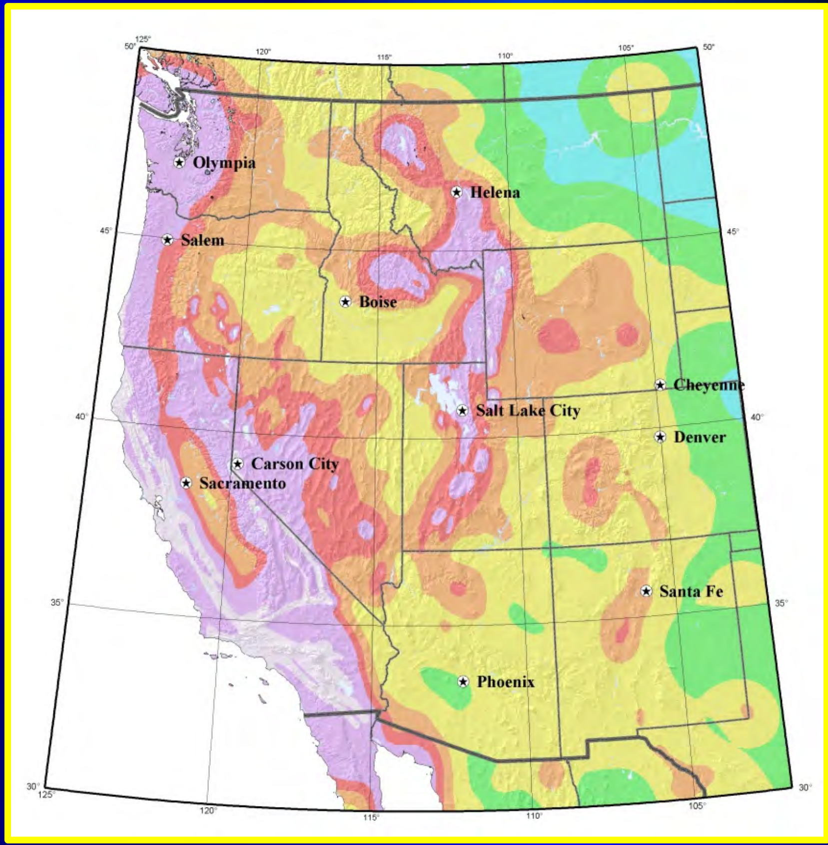
Effects of Dip Angle on the NSHM

- **Original treatment of B&R normal faults (2002): 60° dip for all faults.**
- **Revised fault dips for B&R faults used in 2008 NSHM:**

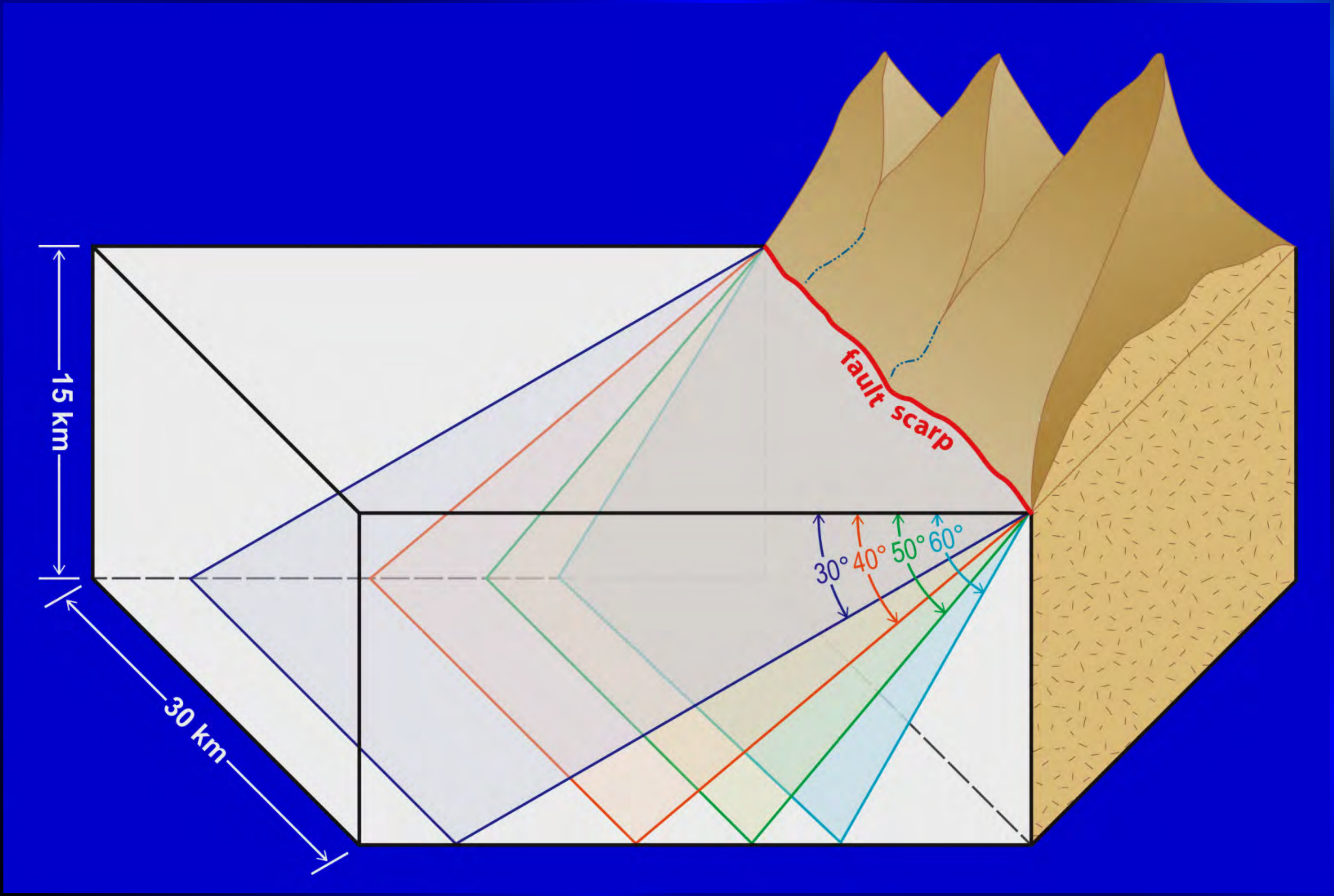
Dip angle:	**40°**	**50°**	**60°**
Weight:	**20%**	**60%**	**20%**

- **Hazard increases by about 30%.**
- **Lower dip angles have larger effect on hazard.**
- **Seek to define fault dips that fall in the 5-95% range (2 σ).**



Effects on Fault Dip on Rupture Area

Decrease in dip angle results in non-linear increase in fault area



Effects on Fault Dip on Rupture Area

Parameters for Faults of Varying Dip Angle

Thickness of seismogenic crust: 15 km
Rupture length: 30 km

Dip Angle (degrees)	Fault Area (km^2)	Δ Area (km^2) from prior dip angle	Increase from prior dip angle	Δ Area (km^2) from 60° dip	Increase from 60° dip
60	519.6	–	–	–	–
50	587.4	67.8	13.0%	67.8	13.0%
40	700.1	112.7	19.2%	180.5	34.7%
30	900.0	119.9	28.6%	380.4	73.2%

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Statement of the Issue:

Based on the recommendation from BRPEWG I, the current USGS NSHMs use a dip of 50°±10° for normal faults in the Basin and Range Province (BRP).

Is the 50° dip value and the ±10° uncertainty range valid and acceptable to cover the probable range of dips for BRP normal faults?

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