WORKING GROUP ON UTAH EARTHQUAKE PROBABILITIES

Photo courtesy of Deseret News, Salt Lake City, UT

Cache Valley earthquake, 1962

February 10 & 11, 2010

WGUEP Members

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

WGUEP AGENDA
Wednesday, February 10, 2010

7:30 – 8:00	Continental Breakfast	
8:00 – 8:15	Welcome and Introductions	Bill Lund
8:15 – 9:00	Purpose, Tentative Scope of Work, SSHAC Process, and Schedule	Ivan Wong
9:00 – 9:30	Overview of UCERF2	Mark Petersen
9:30 – 10:15	Issues Associated with UCERF2	David Schwartz
10:15 – 10:30	Break	
10:30 – 11:00	Discussion on UCERF2	Mark Petersen/David Schwartz
11:00 – 12:00	Overview of Wasatch Fault	Chris DuRoss
12:00 – 1:00	Lunch	
1:00 – 2:00	Overview of Forecast Model Inputs	Ivan Wong
2:00 – 3:00	Overview of Utah Quaternary Fault Working Group Model	Bill Lund
3:00 – 3:15	Break	
3:15 – 4:15	Review of Wasatch Time-Dependent Probabilities	Susan Olig
4:15 – 5:00	Discussion	
5:00	Adjourn	

WGUEP AGENDA
Thursday, February 11, 2010

7:30 – 8:00	Continental Breakfast	
8:00 – 9:00	Overview of Seismicity Catalog	Walter Arabasz/Jim Pechmann
9:00 – 9:30	Incorporation of Background Seismicity into Forecast	Walter Arabasz/Jim Pechmann
9:30 – 9:45	Break	
9:45 – 10:45	Overview of Geodetic Data	Bob Smith
10:45 – 11:30	Incorporation of Geodetic Rates into Forecast	Bob Smith
11:30 – 12:30	Lunch	
12:30 – 3:00	Issues (integration of geodetic data, segmentation, multi-segment rupture, recurrence models, etc.)	Ivan Wong
3:00 – 3:15	Break	
3:15 – 4:00	Path Forward	All
4:00	Adjourn	

Overview of WGUEP Process

Working Group on Utah Earthquake Probabilities

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

Salt Lake City, UT
10 February 2010

Introduction

- Define Study Region
- Scope of Work
- SSHAC Process
- Schedule

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Introduction (cont.)

- The level of information on past earthquakes along the Wasatch fault, along with regional seismicity and geodetic data, is now sufficiently robust to provide the basis for making probabilistic estimates of future large earthquakes within the Wasatch Front.

- The methodologies necessary to estimate probabilities have been developed and refined by the various California Working Groups, and their experience can now be applied in Utah.

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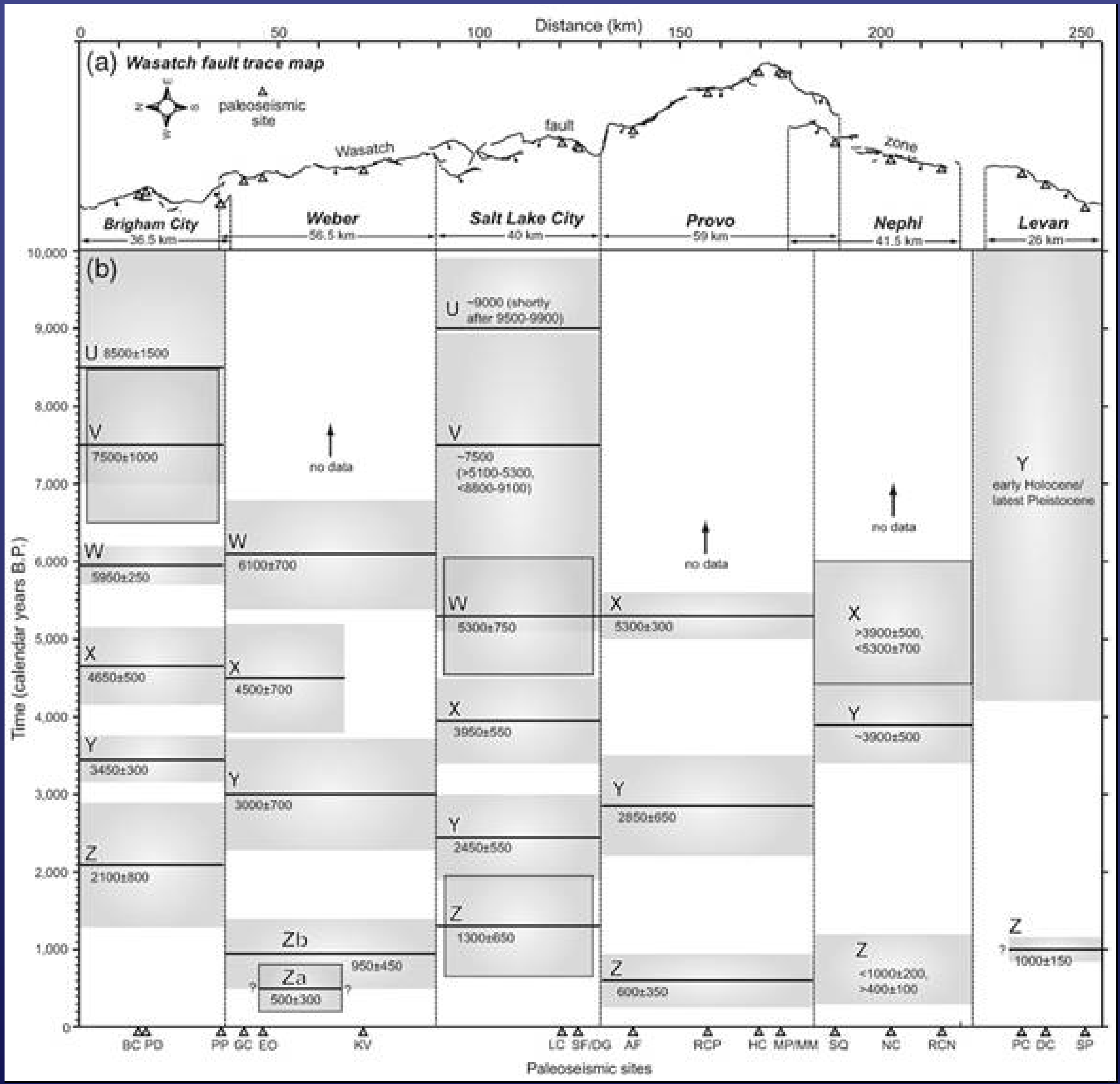
Paleoearthquake Space-Time Diagram for the Central Wasatch Fault



DuRoss, 2008

Introduction (cont.)

- There are both critical scientific and hazard-mitigation needs for a formal and consensus-based estimate of earthquake probabilities along the Wasatch Front.
- An earthquake forecast can be can be directly incorporated into site-specific probabilistic seismic hazard analyses (PSHA) for the design and safety evaluation of critical structures and facilities.

Introduction (cont.)

- Wasatch Front urban hazard maps are planned by the U.S. Geological Survey (USGS), and time-dependent probabilities can also be incorporated into the PSHAs that will form the bases of those maps.
- Earthquake probabilities will also eventually be incorporated into the USGS National Hazard Maps and the National Earthquake Hazard Reduction Program (NEHRP) building code provisions (Wong and others, 2007).

Introduction (cont.)

- A consensus-based estimate of earthquake probabilities for the Wasatch Front developed and reviewed by the earth science community can be incorporated into public policy that will drive greater and more sustained earthquake mitigation efforts in Utah.

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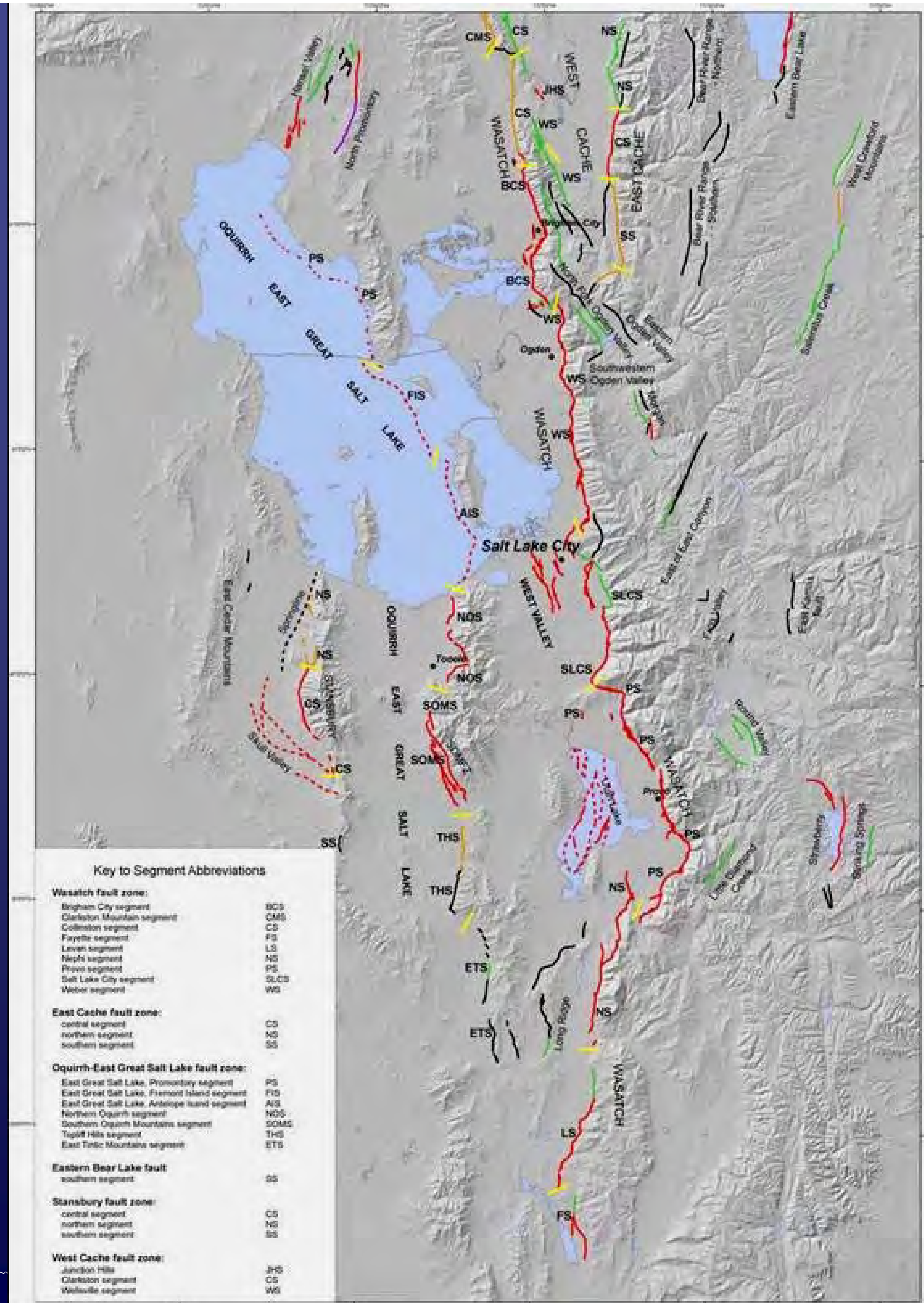
Proposed Study Region



Time-Independent Versus Time-Dependent Models

- Time-independent forecast is where probability of each earthquake rupture is completely independent of the timing of all others.

- Time-dependent models are based on the concept of stress renewal: the probability of a fault rupture drops immediately after a large earthquake releases tectonic stress on the fault and rises again as the stress is regenerated by continuous tectonic loading.

Approach

- This analysis will also include both time-dependent and time-independent probabilities for other faults in the Wasatch Front region (e.g., East Great Salt Lake fault) as well as the probability of background earthquakes.
- The California working groups emphasized 30-year probabilities, which is an appropriate interval given the high slip rate along the San Andreas transform plate boundary. In contrast, deformation rates along the Wasatch Front are an order of magnitude lower than California.

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Approach (cont.)

- An approach similar to that taken by the various California Working Groups will be followed.
- We will convene a series of workshops and meetings over a two-year period to review and develop model components. A SSHAC Level 2 process will be followed.

Scope of Work

- Calculate time-dependent probabilities of large earthquakes on major faults where the “requisite” information is available on the expected mean frequency of earthquakes and the elapsed time since the most recent large earthquake.
- Where such information is lacking on less well-studied faults, time-independent probabilities are estimated.

Scope of Work (cont.)

- Consequently we will calculate the probability of a large earthquake (**M** ≥ 6.5) in the Wasatch Front region for a range of intervals varying from annually to 100 years.
- Epistemic uncertainties in all input parameters will be explicitly addressed by the WGUEP.

Degrees of PSHA Issues and Levels of Study

ISSUE DEGREE	DECISION FACTORS	STUDY LEVEL
A Non-controversial and/or insignificant to hazard		**1** TI evaluates/weights models based on literature review and experience; estimates community distribution
B Significant uncertainty and diversity, controversial, and	➤ Regulatory concern ➤ Resources available ➤ Public perception	**2** TI interacts with proponents and resource experts to identify issues and interpretations; estimates community distribution
C Highly contentious, significant to hazard, and highly complex		**3** TI brings together proponents and resource experts for debate and interaction; TI focuses debate and evaluates alternative interpretations; estimates community distribution
		4 TFI organizes panel of experts to interpret and evaluate; focuses discussions; avoids inappropriate behavior on part of evaluators; draws picture of evaluators' estimate of the community's composite distribution; has ultimate responsibility for project

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Approach (cont.)

- Four models* will be implemented in the forecast process:

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

* Epistemic uncertainties in all model input parameters will be explicitly address by the WGUEP.

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Products

- The WGUEP will calculate the probability of a large earthquake (M $\geq$ 6.5) in the Wasatch Front Region for a range of intervals varying from annually to 100 years.

- The earthquake probabilities that will be estimated are:

  1. Segment-specific for the Wasatch fault
  2. Total for the Wasatch fault
  3. Fault-specific for other major faults in the area
  4. Total for the Wasatch Front region.

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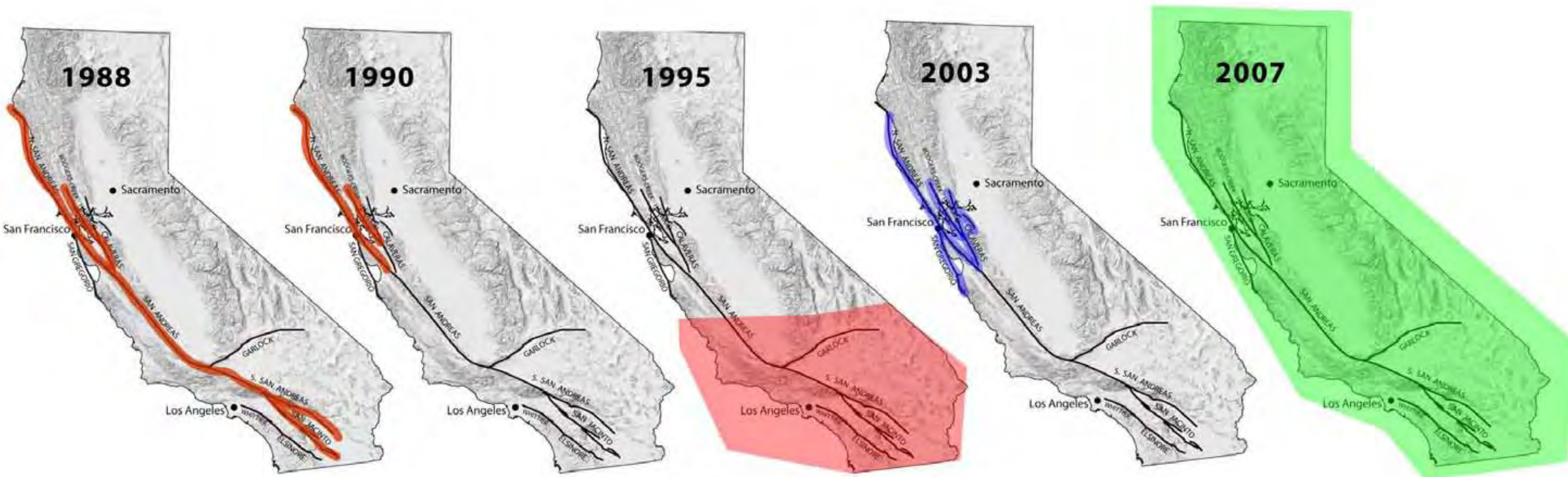
Products (cont.)

- The final forecast will undergo a formal internal USGS review, and will be sent to the National Earthquake Prediction Council for review and comment as well.
- Media release of the WGUEP results will be handled by the UGS. Project results will be presented at meetings for the general public and at professional and scientific society meetings.

Schedule

Meeting	Purpose
1	Kickoff: Review WGCEP process and WGUEP scope of work.
2	Develop rupture scenarios for the Wasatch fault.
3	Develop time-dependent and independent recurrence rates for the Wasatch fault.
4	Develop time-independent recurrence rates for other Wasatch Front faults.
5	Review preliminary earthquake probability calculations.
6	Review and adopt final results.

Comparisons: Uniform California Earthquake Rupture Forecast 2



STUDY AREAS

of the

Working Groups on California Earthquake Probabilities (WGCEPs)

Fault	WGCEP 1995 (S. CA)	WGCEP 2003 (SF Bay area)	WGCEP 2007 Mean [min-max range]
Southern San Andreas	53%		59% [22%-94%]
Hayward Rodgers Creek		27% [10%-58%]	31% [12%-67%]
San Jacinto	61%		31% [14%-54%]
North San Andreas		23% [3%-52%]	21% [6%-39%]
Elsinore	24%		11% [5%-25%]
Calveras		11% [3%-27%]	7% [1%-22%]
Garlock			6% [3%-12%]

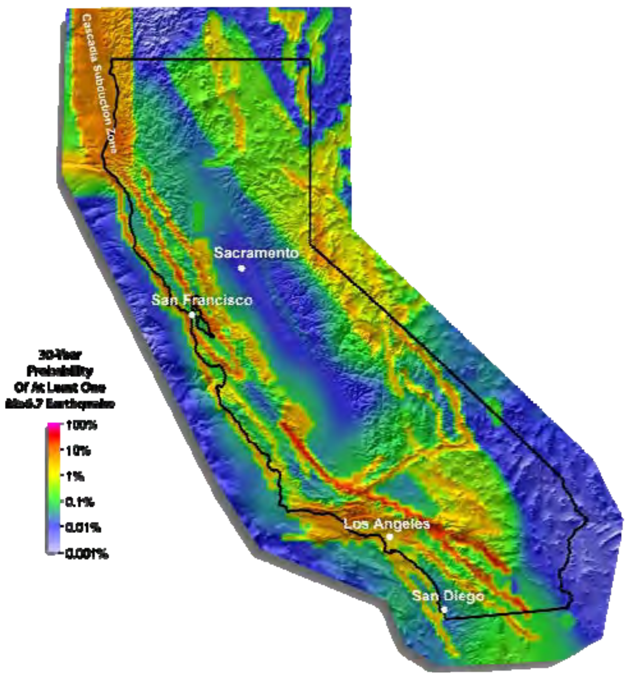
Uniform California Earthquake Rupture Forecast 2 (UCERF 2)

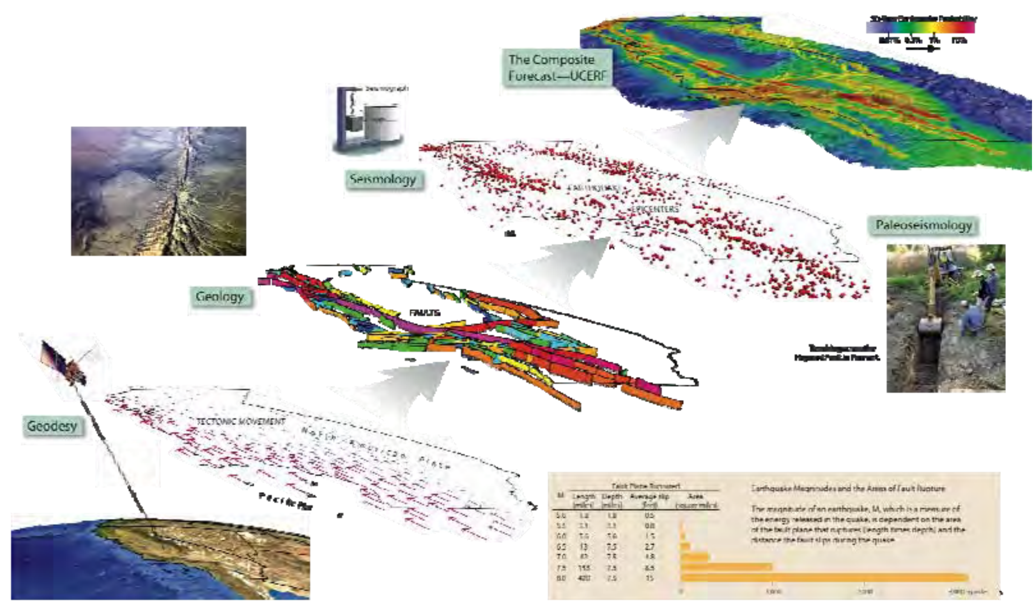
by the

Working Group on California Earthquake Probabilities (WGCEP)

& the

National Seismic Hazard Mapping Program (NSHMP)





SCEC an NSF+USGS center

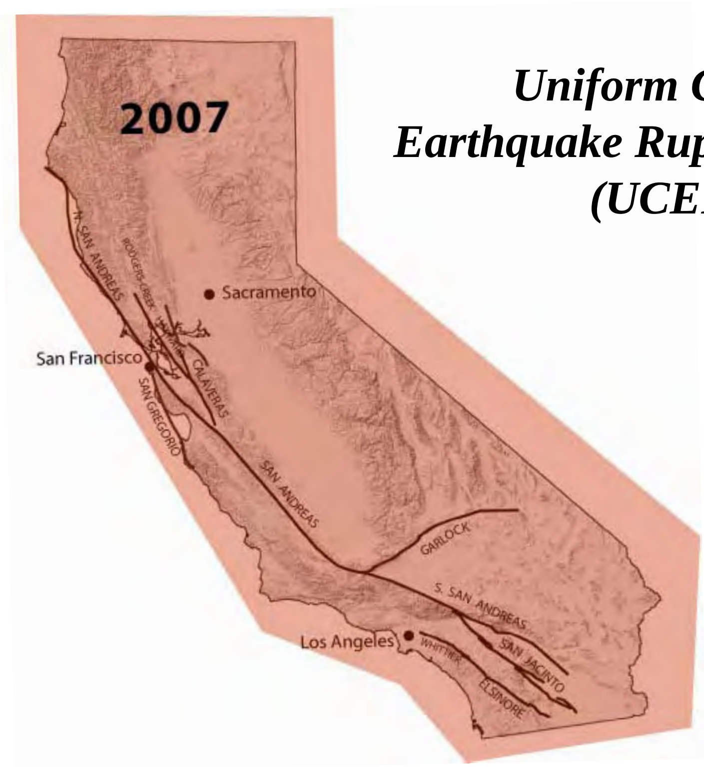
USGS science for a changing world

CGS CALIFORNIA GEOLOGICAL SURVEY

CEA CALIFORNIA EARTHQUAKE AUTHORITY

WGCEP-2007 Goal:

To provide the California Earthquake Authority (CEA) with a uniform, statewide, time-dependent earthquake rupture forecast that uses “best available science” and is endorsed by the USGS, CGS, and SCEC



Uniform California Earthquake Rupture Forecast 2 (UCERF 2)

Coordinated with the 2007 USGS National Seismic Hazard Mapping Program (same time-independent model)

SCEC an NSF + USGS center

USGS science for a changing world

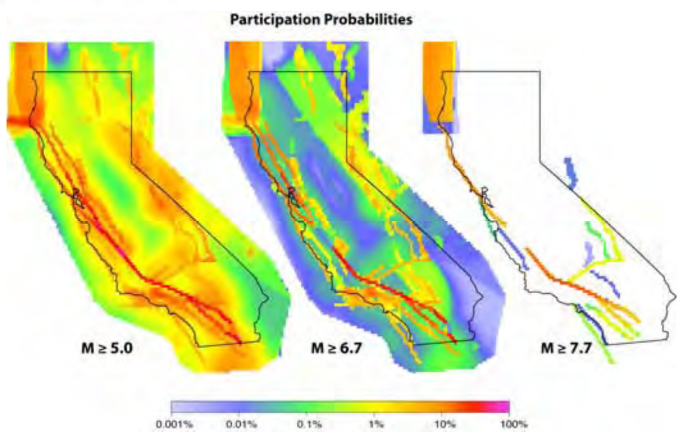
CGS California Geological Survey

The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2)

2007 Working Group on California Earthquake Probabilities (WGCEP) and the USGS National Seismic Hazard Mapping Program (NSHMP)

April, 2008

USGS Open File Report 2007-1437

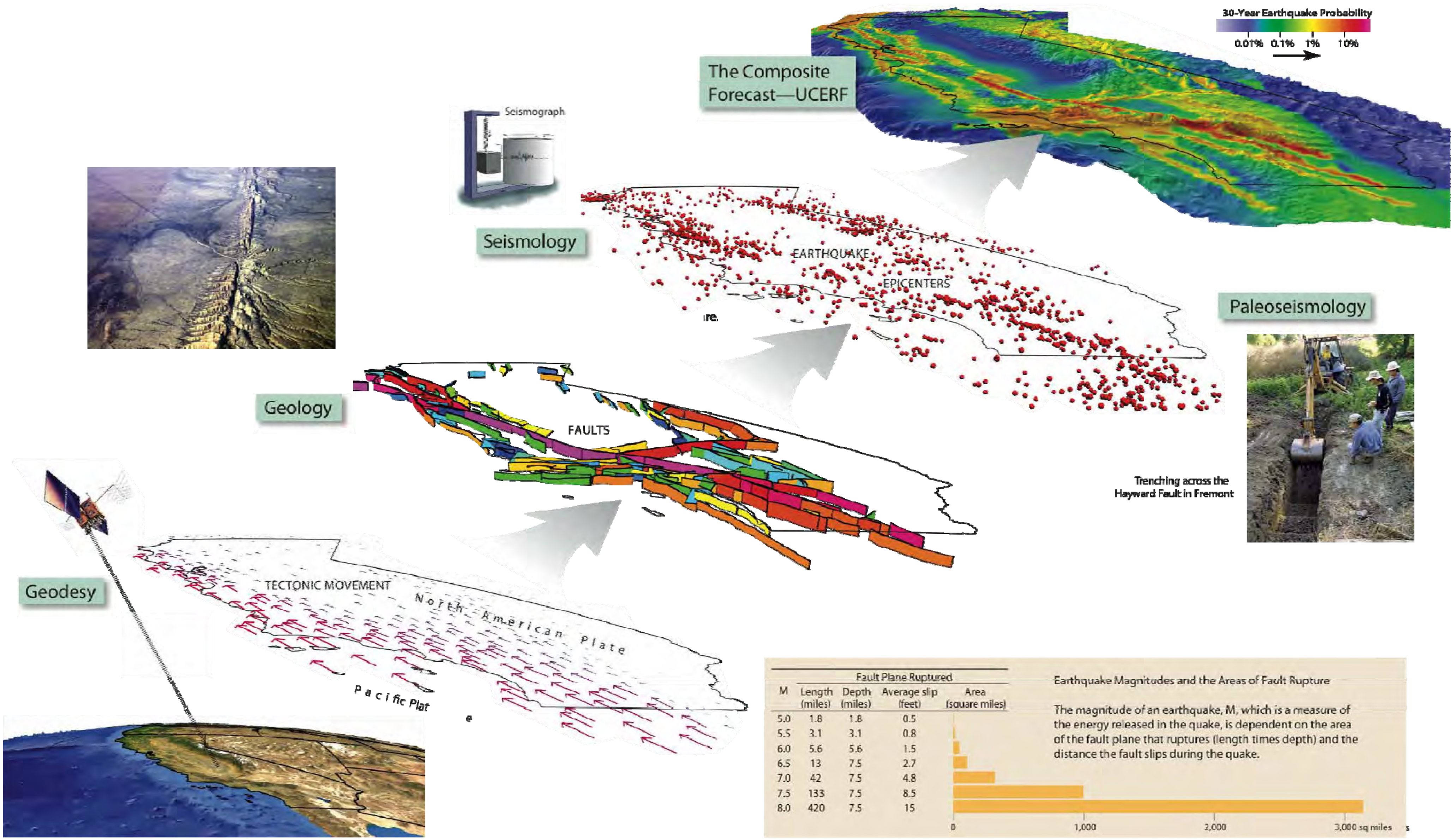


Primary Authors:

Edward Field	U. S. Geological Survey, Pasadena, CA
Timothy Dawson	U. S. Geological Survey, Menlo Park, CA
Karen Felzer	U. S. Geological Survey, Pasadena, CA
Arthur Frankel	U. S. Geological Survey, Golden, CO
Vipin Gupta	SCEC/ University of Southern California
Thomas Jordan	University of Southern California
Thomas Parsons	U. S. Geological Survey, Menlo Park, CA
Mark Petersen	U. S. Geological Survey, Golden, CO
Ross Stein	U. S. Geological Survey, Menlo Park, CA
Ray Weldon	SCEC/University of Oregon
Chris Wills	California Geological Survey

Report also reviewed by both the *National* and *California Earthquake Prediction Evaluation Councils* (*NEPEC* and *CEPEC*)

UCERF Ingredients



Earthquake Magnitudes and the Areas of Fault Rupture

The magnitude of an earthquake, M, which is a measure of the energy released in the quake, is dependent on the area of the fault plane that ruptures (length times depth) and the distance the fault slips during the quake.

M	Length (miles)	Depth (miles)	Average slip (feet)	Area (square miles)
5.0	1.8	1.8	0.5	
5.5	3.1	3.1	0.8	
6.0	5.6	5.6	1.5	
6.5	13	7.5	2.7	
7.0	42	7.5	4.8	
7.5	133	7.5	8.5	
8.0	420	7.5	15	

Fault Plane Ruptured; Area axis: 0, 1,000, 2,000, 3,000 sq miles

Important Lessons from Previous WGCEPs:

1) Everything takes longer than you expect

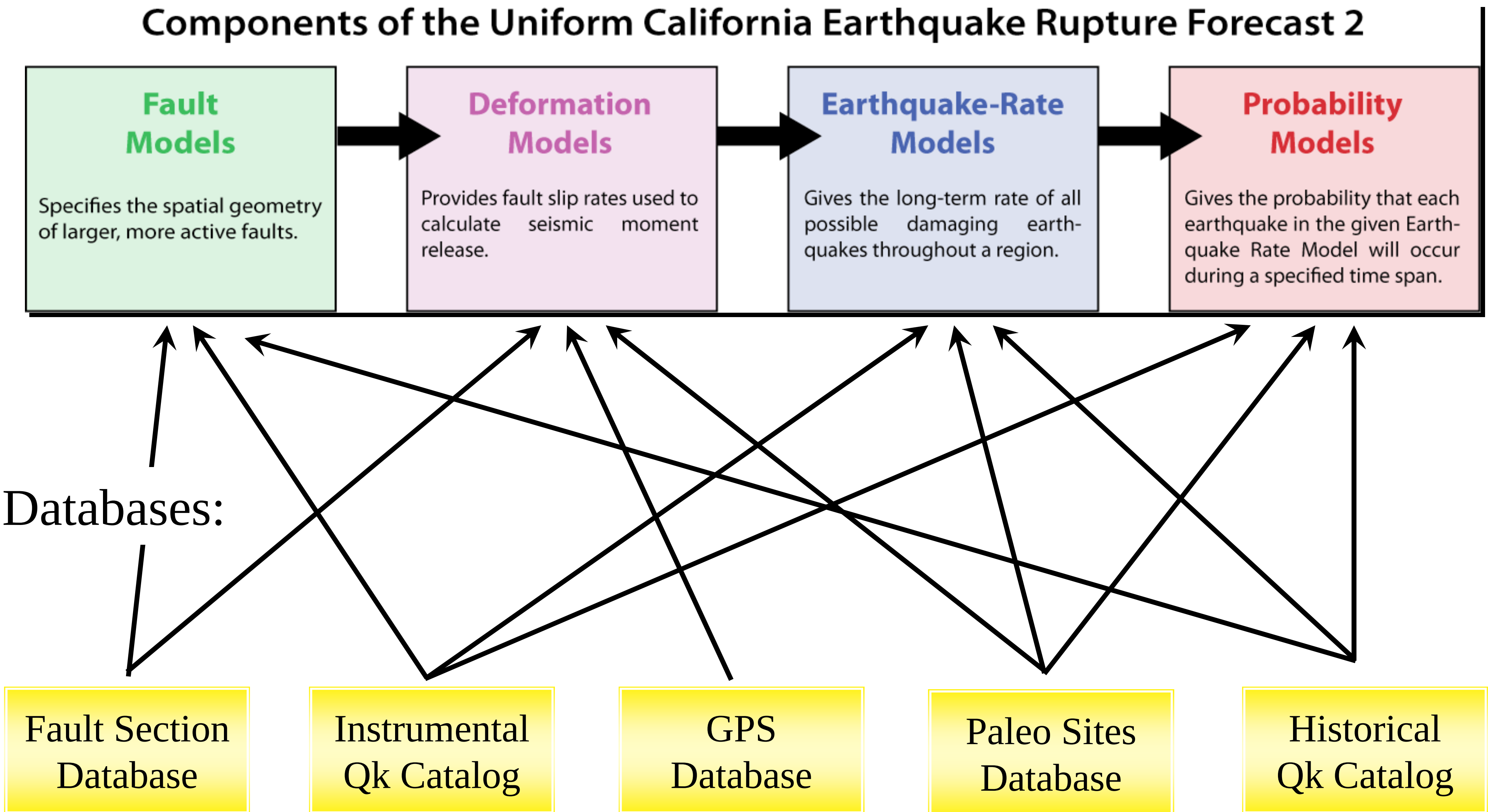
2) There will be problems with the final model

Thus:

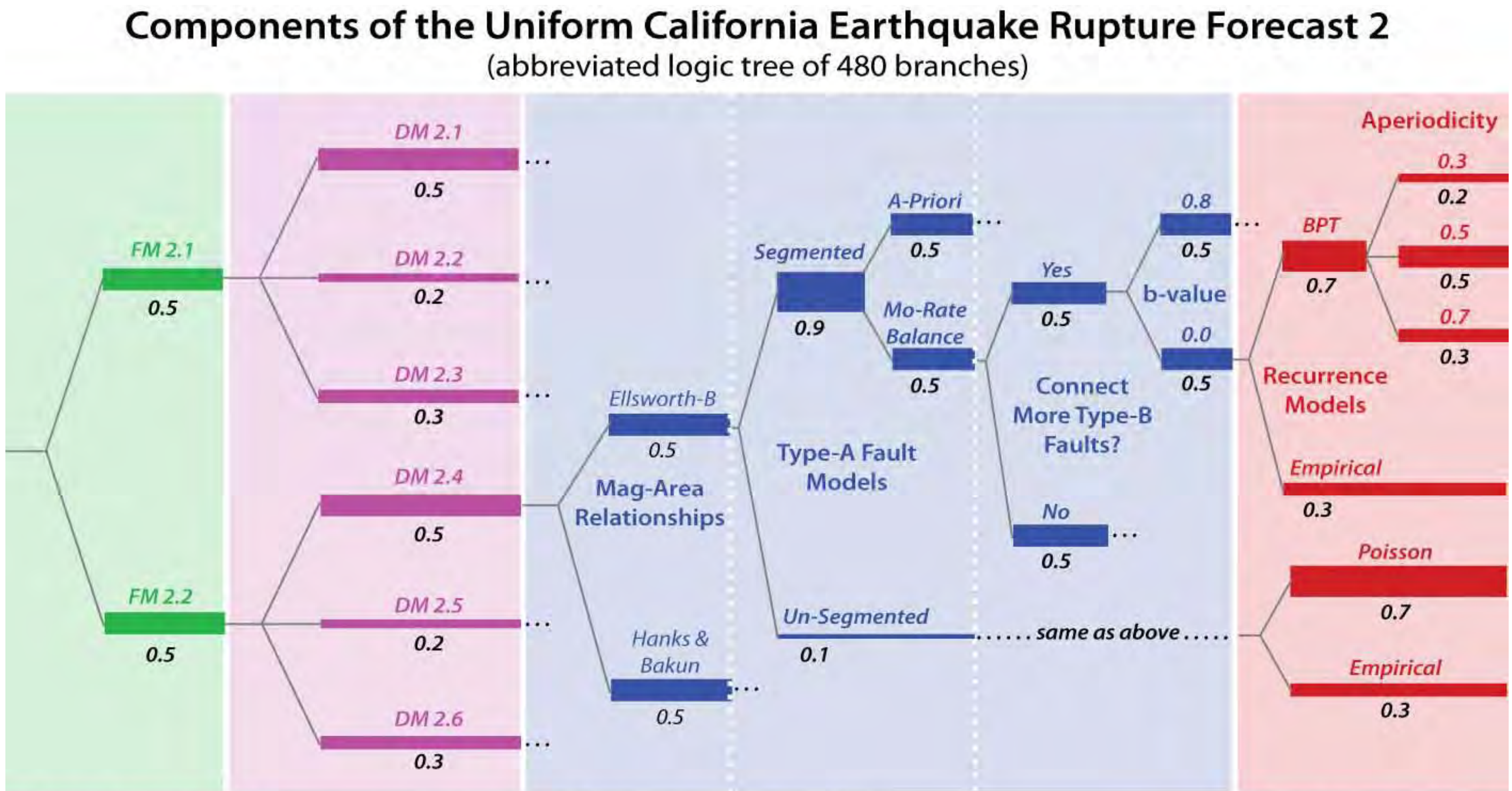
Plan for both the near and long term (e.g., build a living, extensible infrastructure that can adapt to new science, data, or seismic events)

(allowing others to more easily pick up where we left off)

UCERF2 Model Construction



UCERF2 Model Construction



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

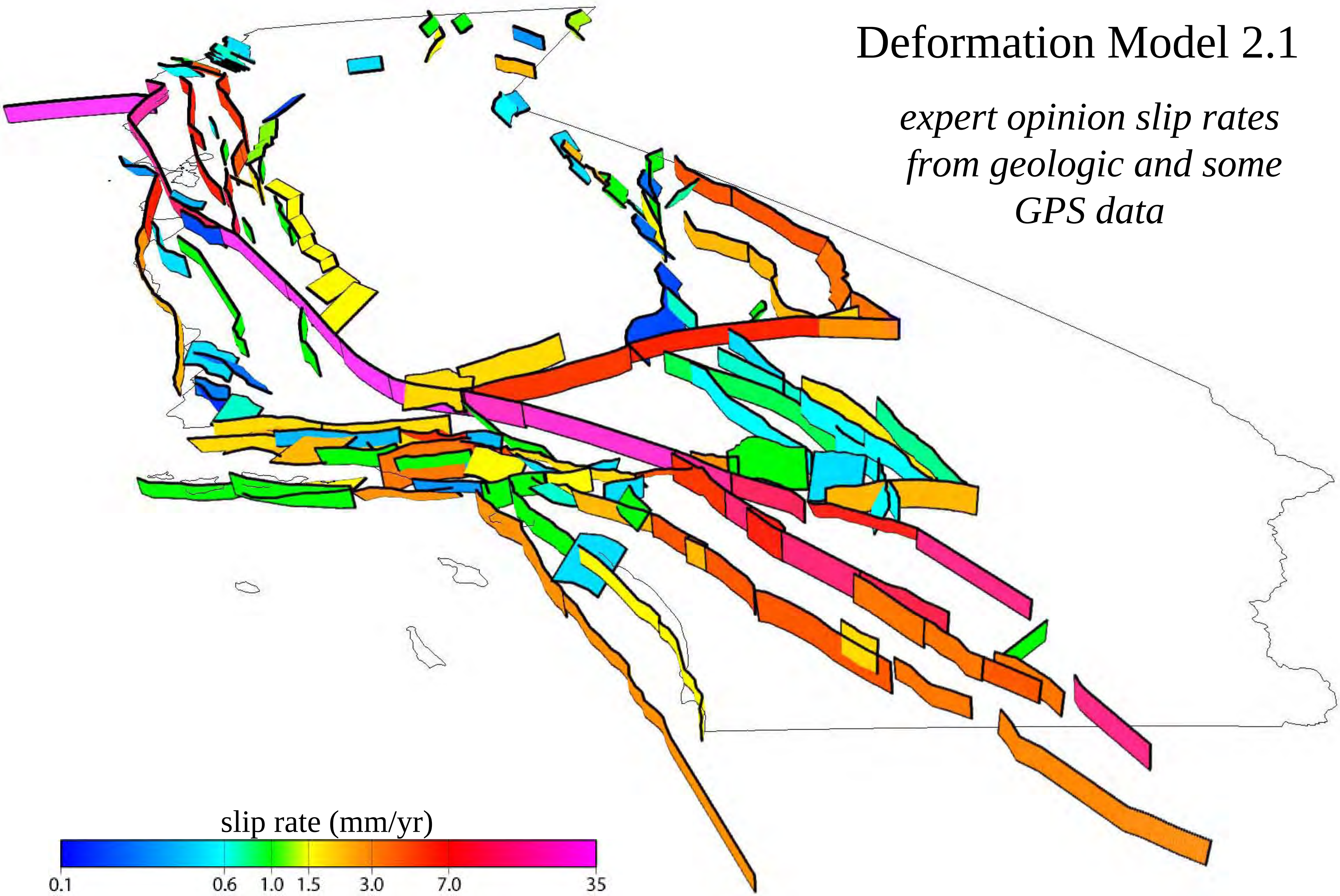
B. Deformation Models
Provides fault slip rates used to calculate seismic moment release.

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

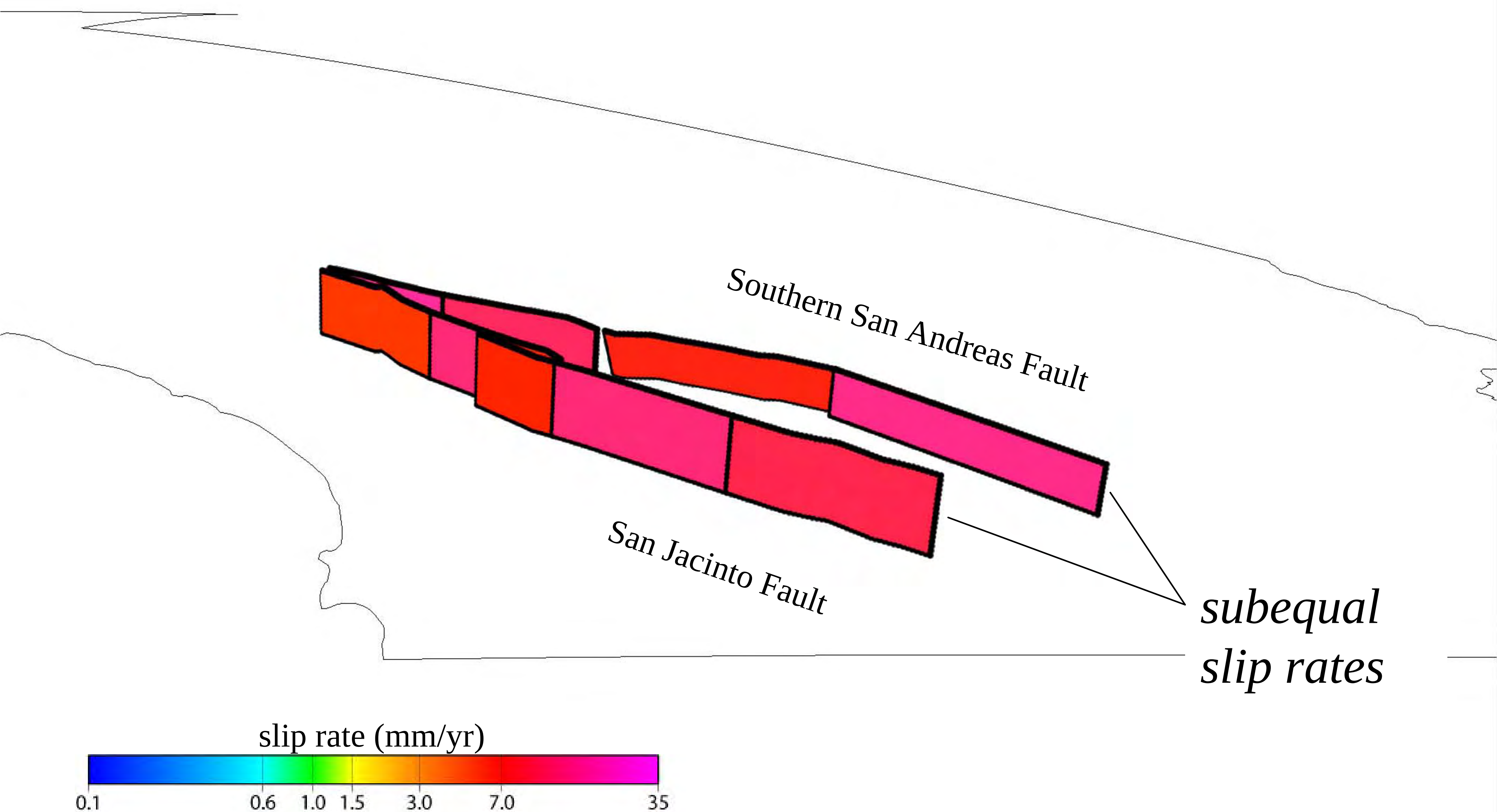
D. Probability Models
Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

Deformation Model 2.1

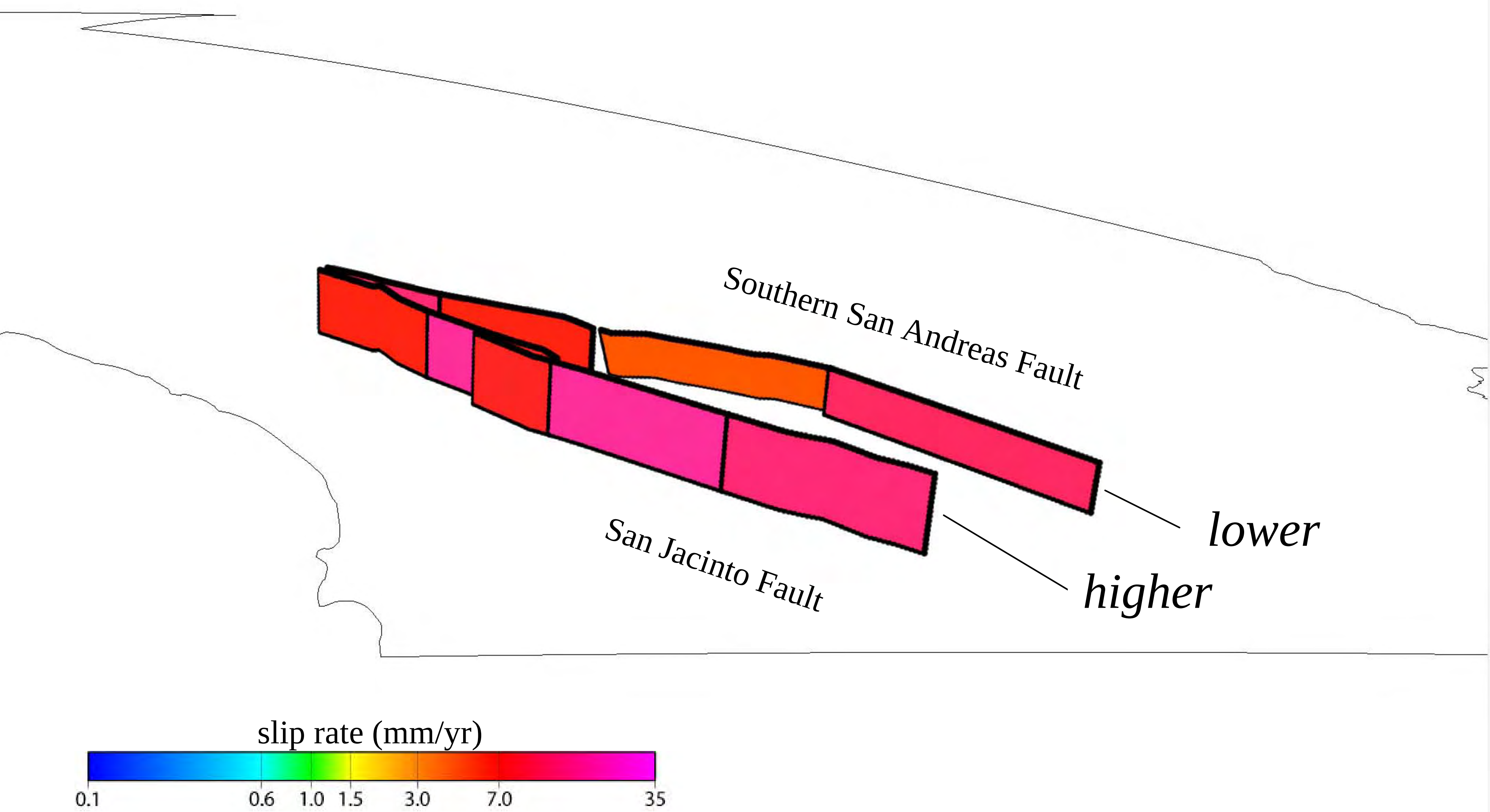
expert opinion slip rates from geologic and some GPS data



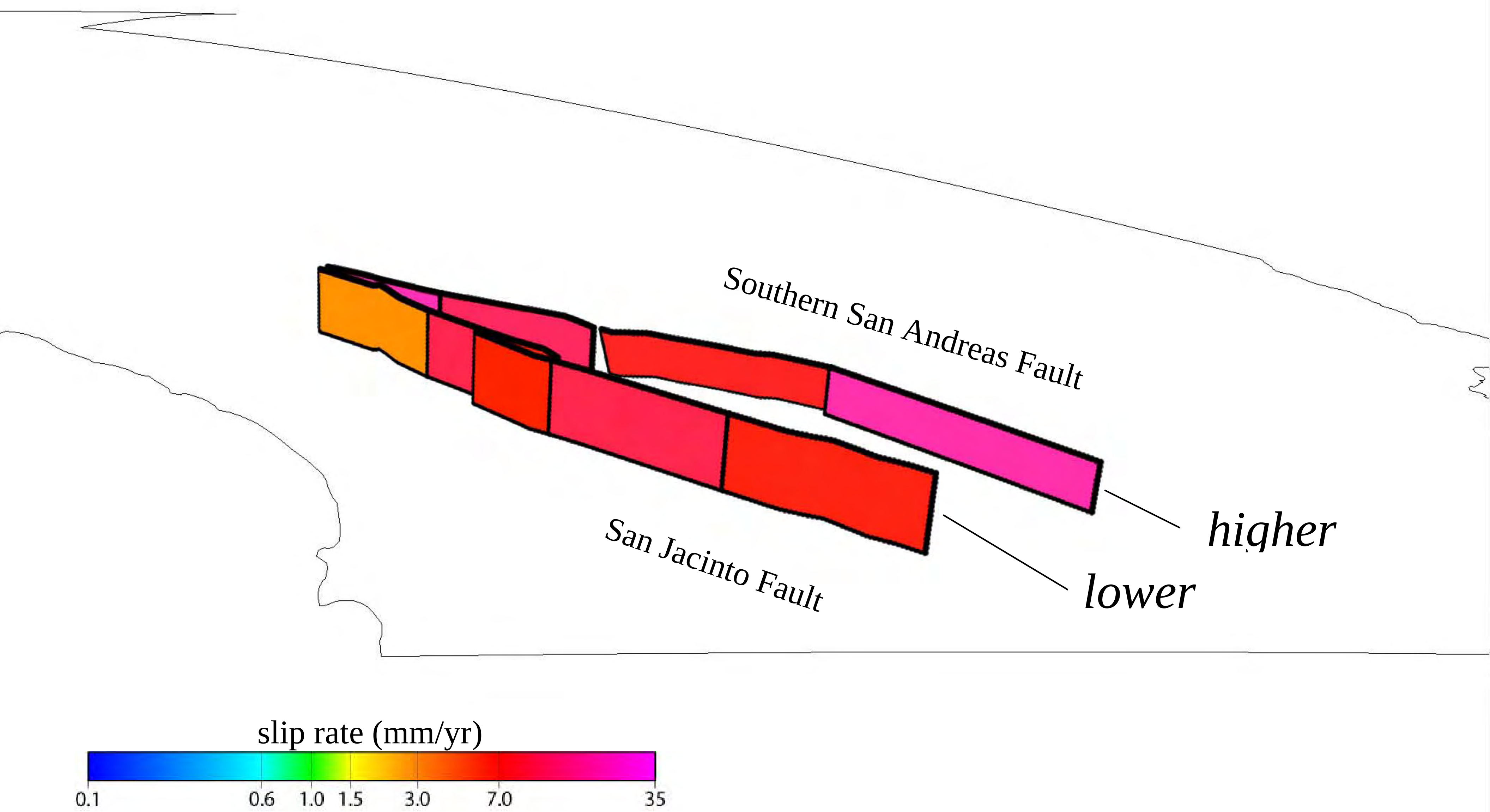
Unique to Deformation Model 2.1



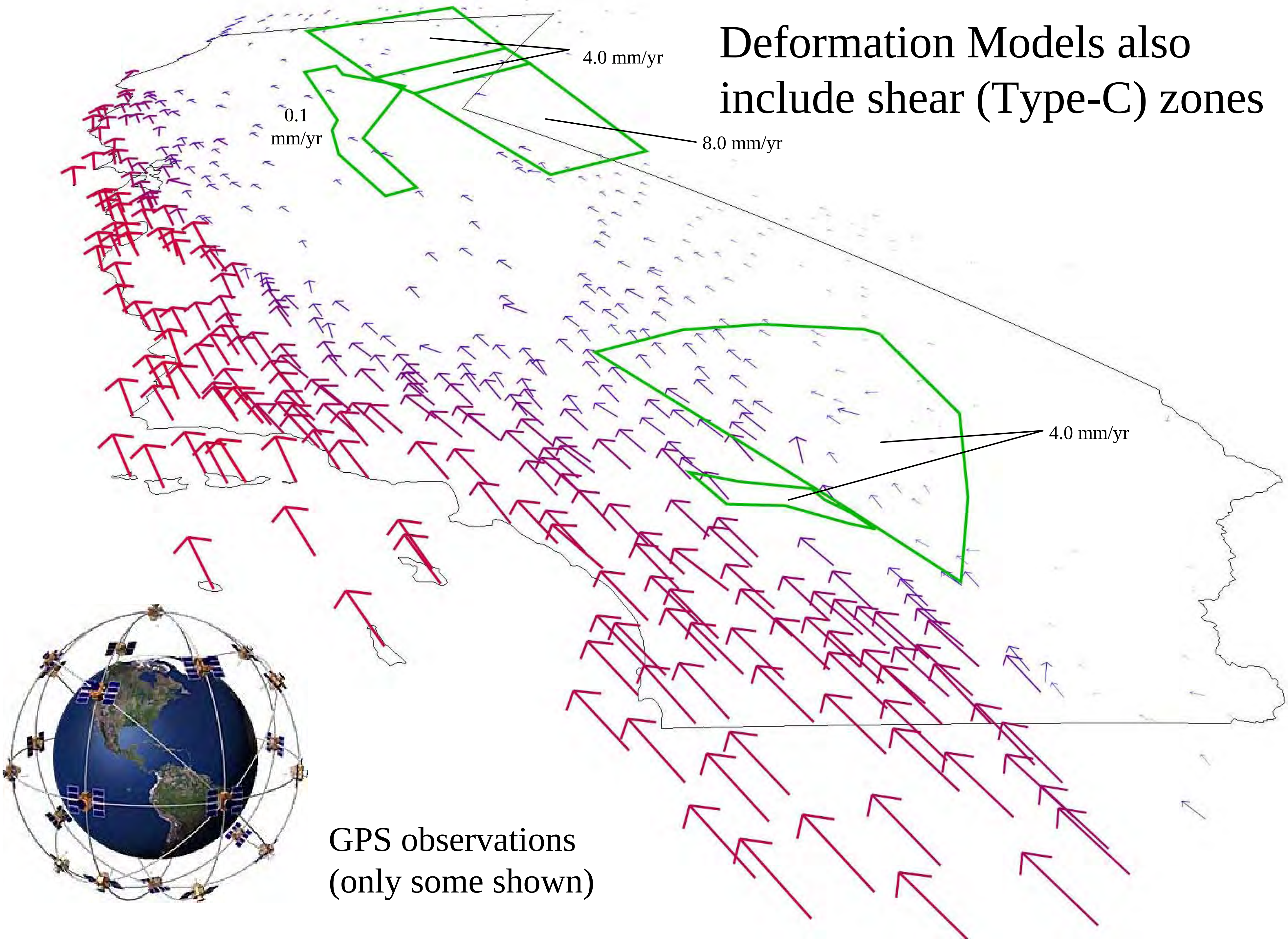
Unique to Deformation Model 2.2



Unique to Deformation Model 2.3



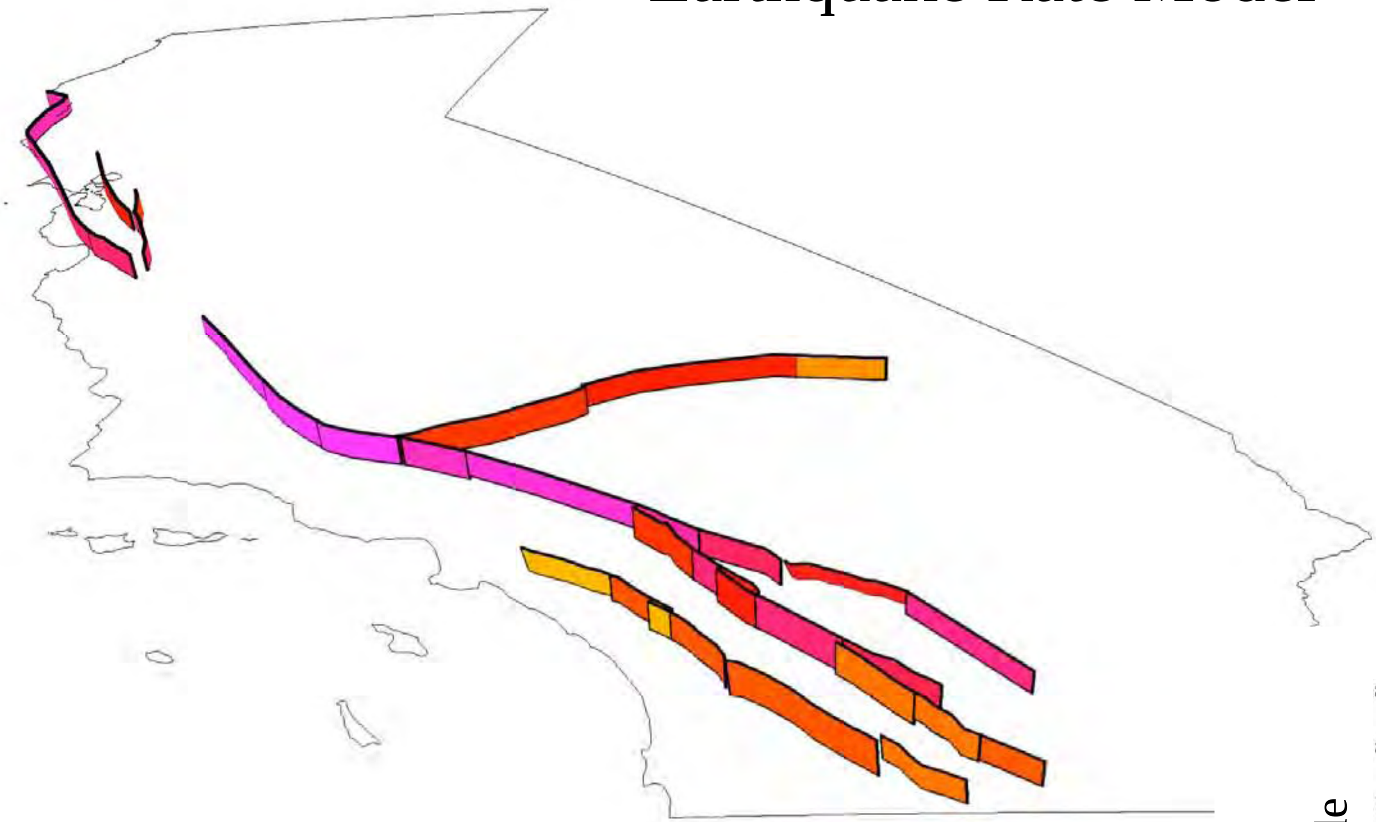
Deformation Models also include shear (Type-C) zones

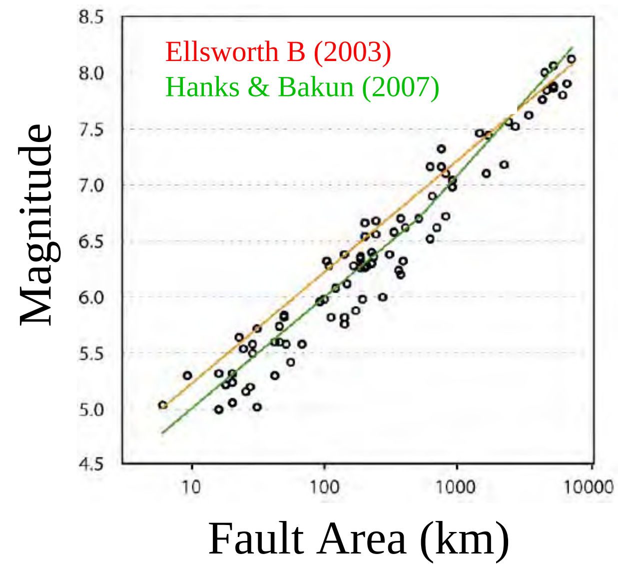


GPS observations (only some shown)

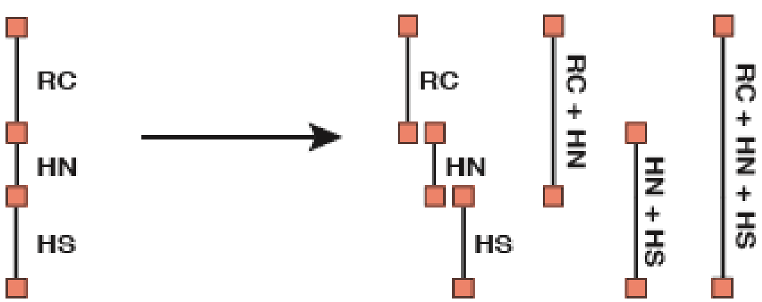
Earthquake Rate Model

Type-A Faults

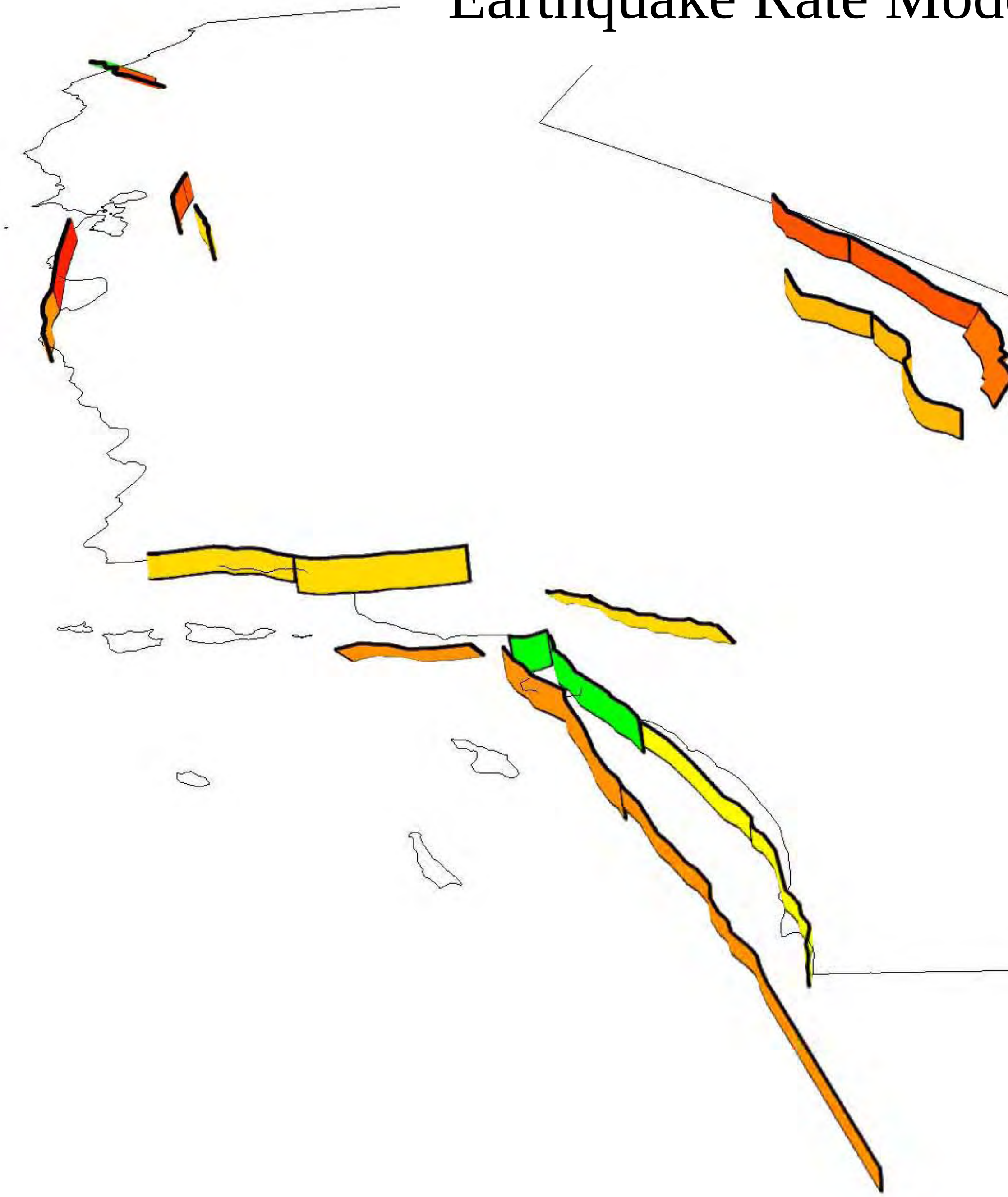




Faults are assumed to rupture as one or more segments



Earthquake Rate Model

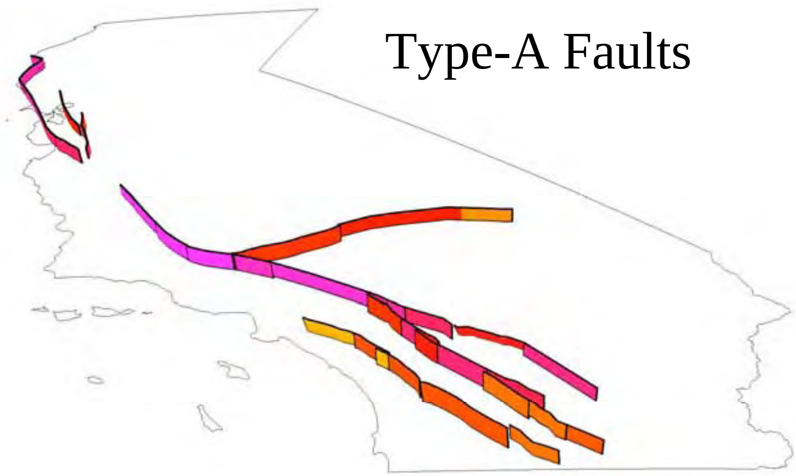


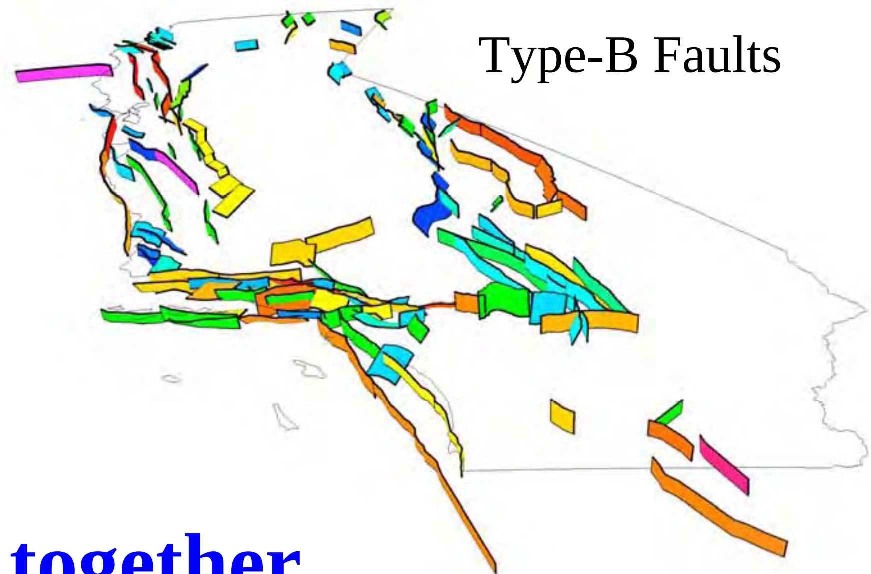
Type-B Faults

These Type-B faults have the option of being connected

Fault Name	Fault Model	Fault Sections
Palos Verdes	2.1 & 2.2	Palos Verdes Coronado Bank
Newport Inglewood	2.1 (alt 1) & 2.2 (alt 2)	Rose Canyon Newport-Inglewood (Offshore) Newport-Inglewood, alt 1 (or alt 2)
Santa Monica	2.1 (alt 1) & 2.2 (alt 2)	Anacapa-Dume, alt 1 (or alt 2) Santa Monica, alt 1 (or alt 2)
Santa Ynez	2.1 & 2.2	Santa Ynez (West) Santa Ynez (East)
Sierra Madre	2.1 & 2.2	Sierra Madre (San Fernando) Sierra Madre
Death Valley	2.1 & 2.2	Death Valley (No of Cucamongo) Death Valley (No) Death Valley (Black Mtns Frontal) Death Valley (So)
Panamint Valley	2.1 & 2.2	Hunter Mountain-Saline Valley Panamint Valley
Little Salmon	2.1 & 2.2	Little Salmon (Onshore) Little Salmon (Offshore)
Oak Ridge	2.2	Oak Ridge (Offshore), west extension Oak Ridge (Offshore) Oak Ridge (Onshore)
Pitas Point	2.2	Pitas Point (Upper) Ventura-Pitas Point

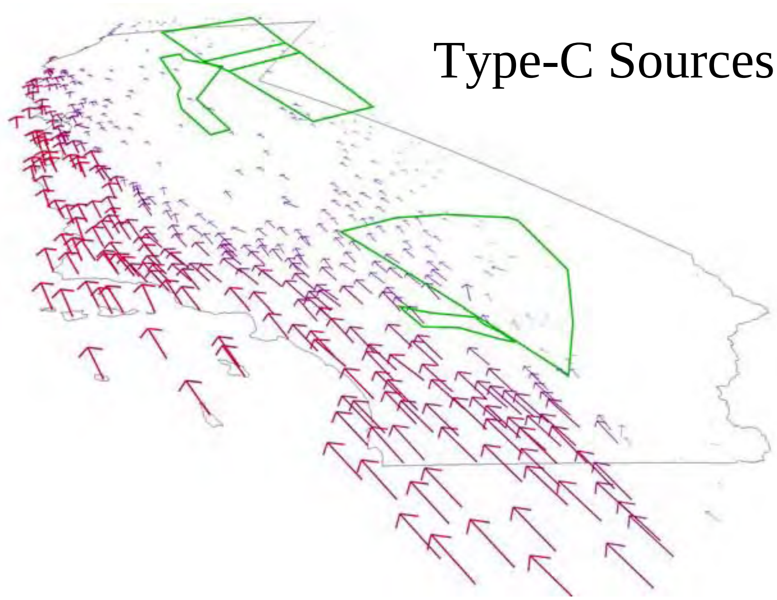
Earthquake Rate Model

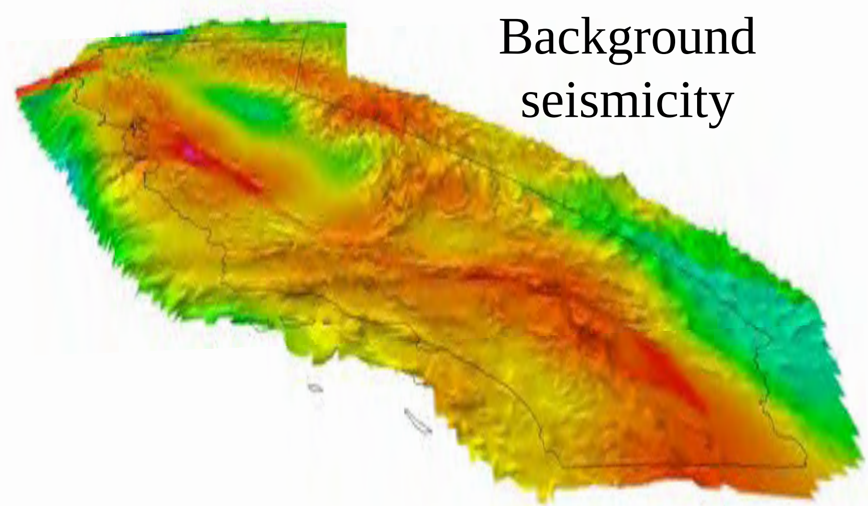




Quake rates on known faults

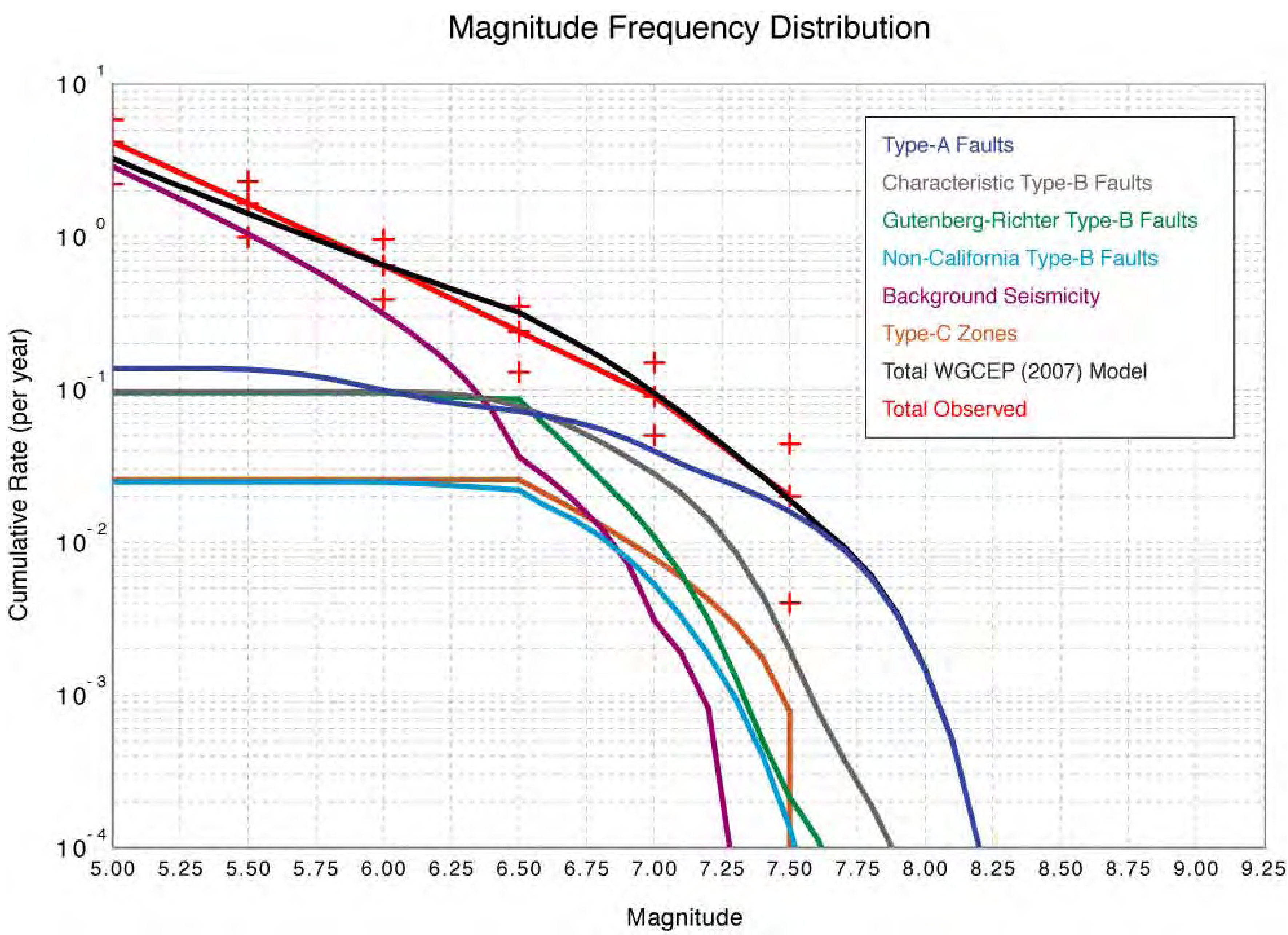
Putting it all together …



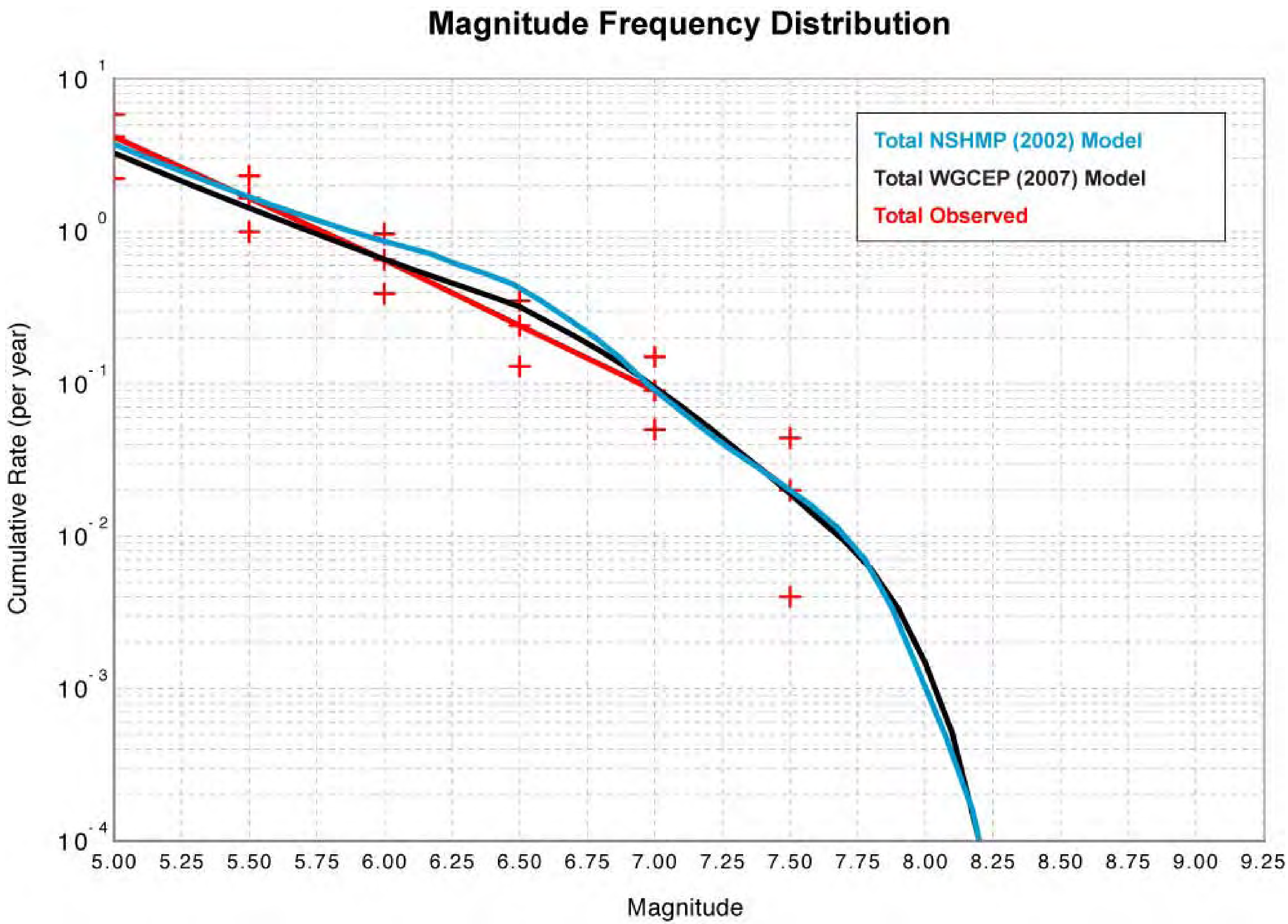


Quake rates elsewhere

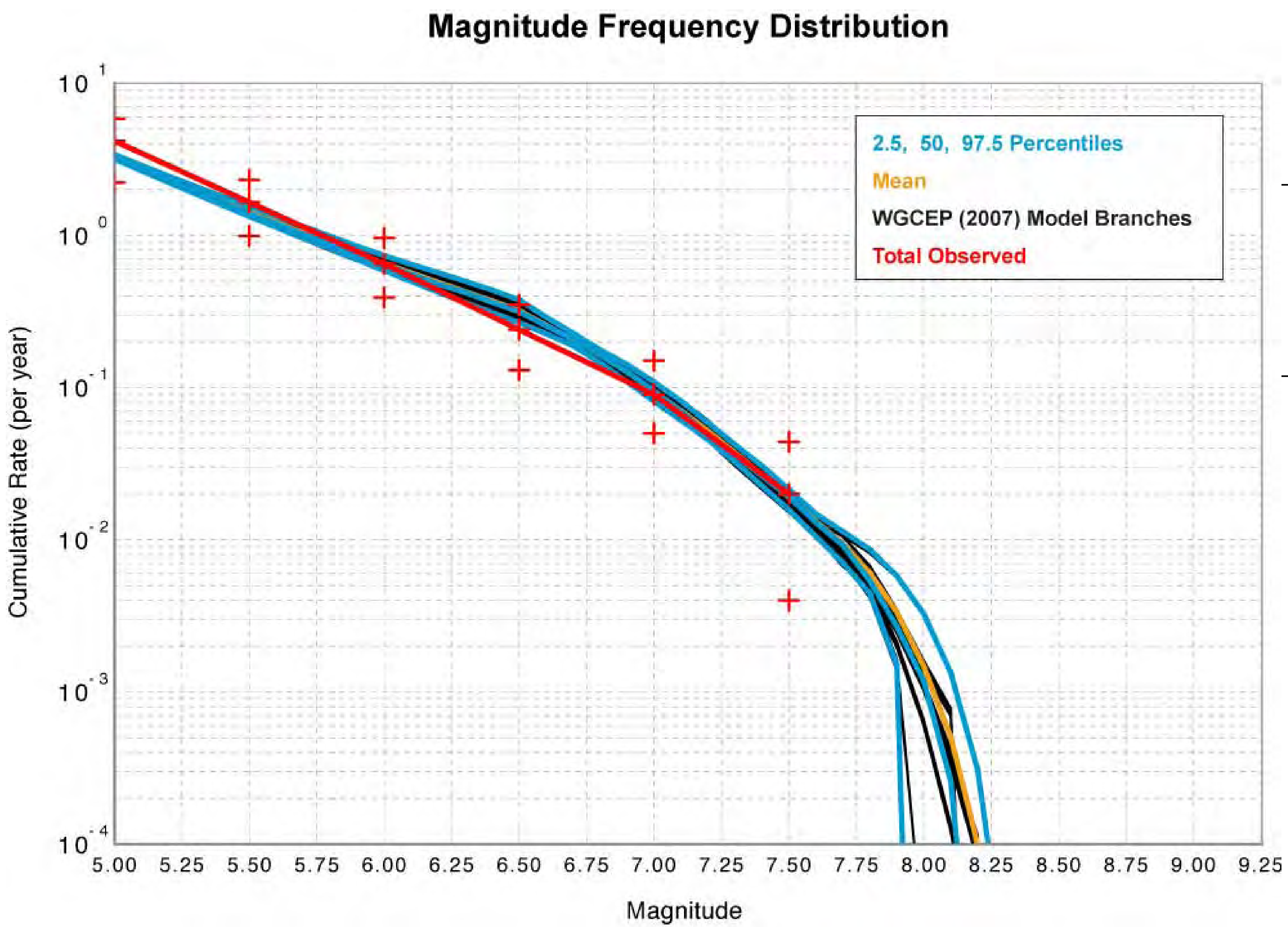
Earthquake Rate Model

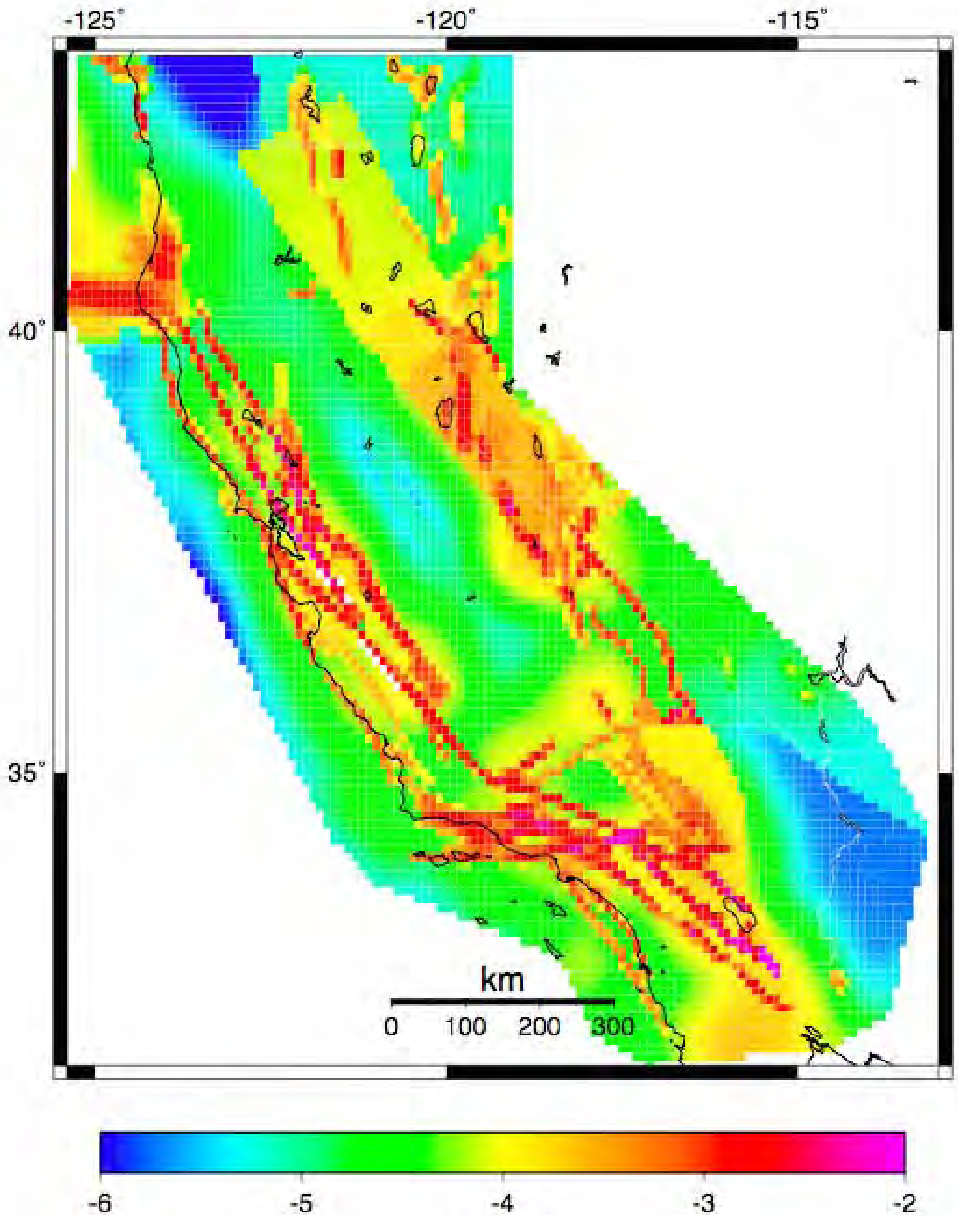


Earthquake Rate Model

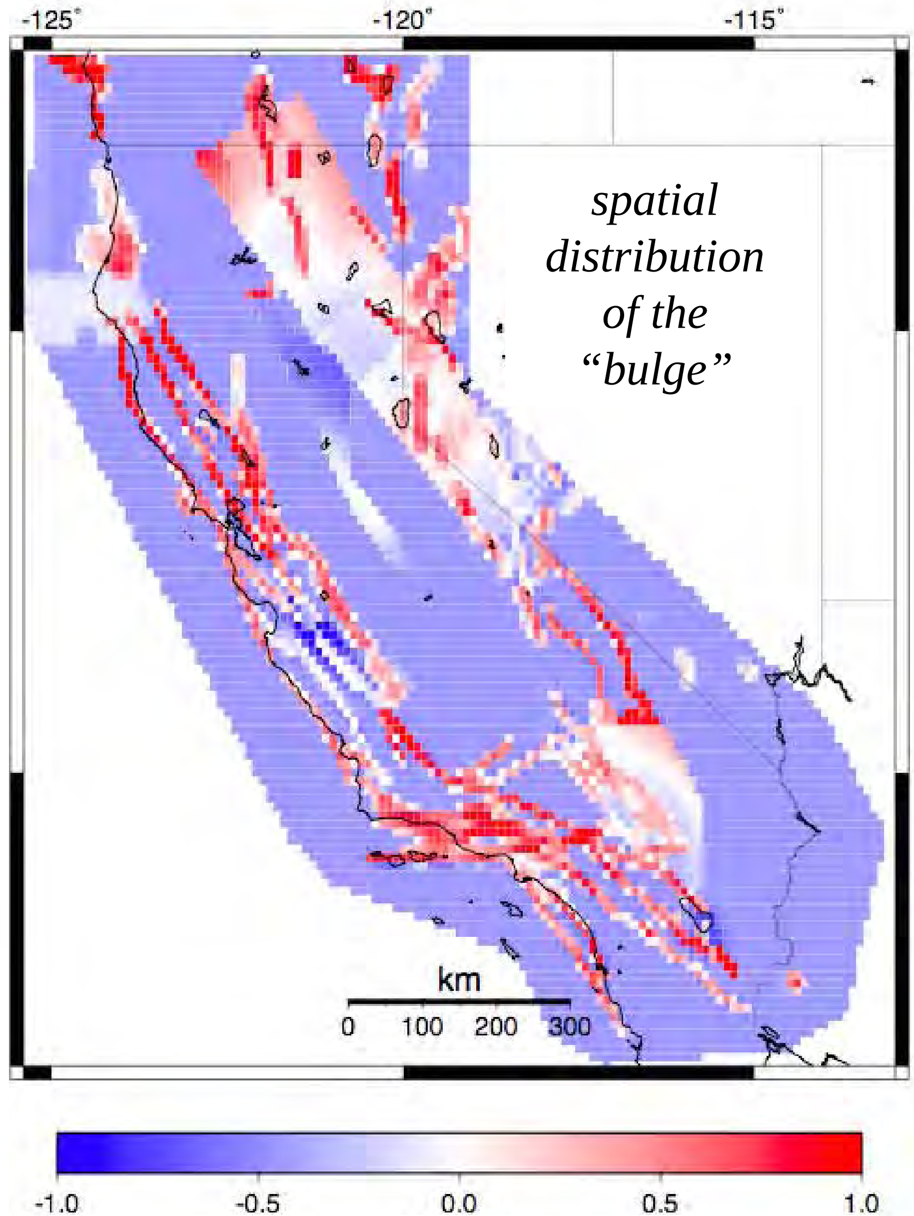


Earthquake Rate Model





Log$_{10}$ of predicted number of M≥6.5 events in 5 yrs in each 0.1 by 1.0 degree bin (RELM test format)



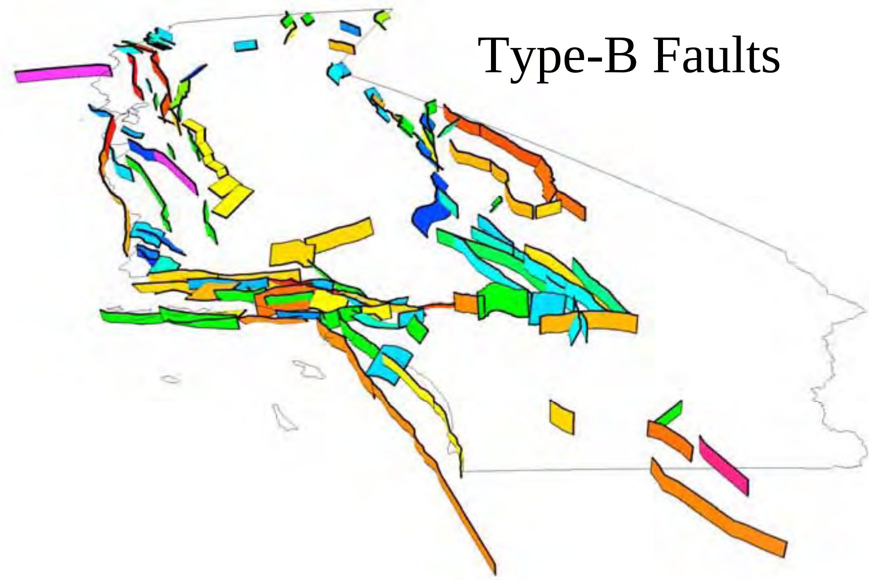
Log$_{10}$ of the ratio of the predicted rate of M≥6.5 events divided by that extrapolated from M=5 using b=0.8

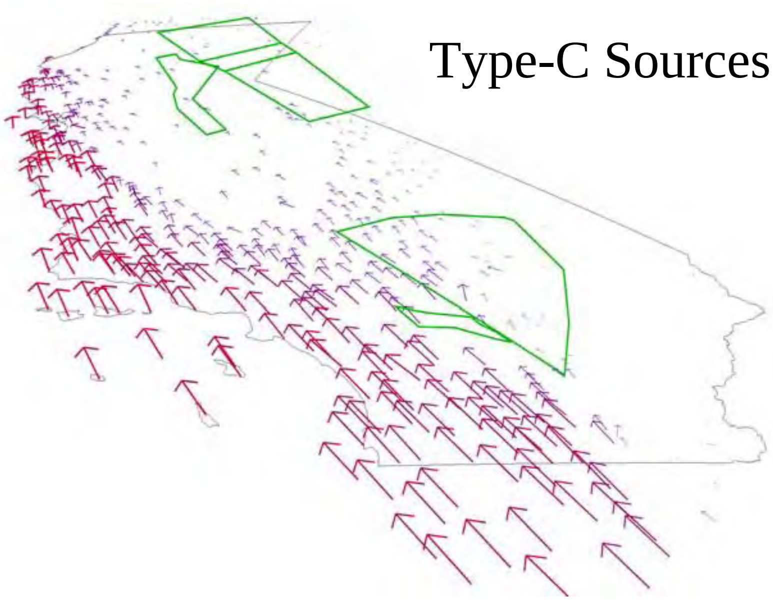
Earthquake Probability Model

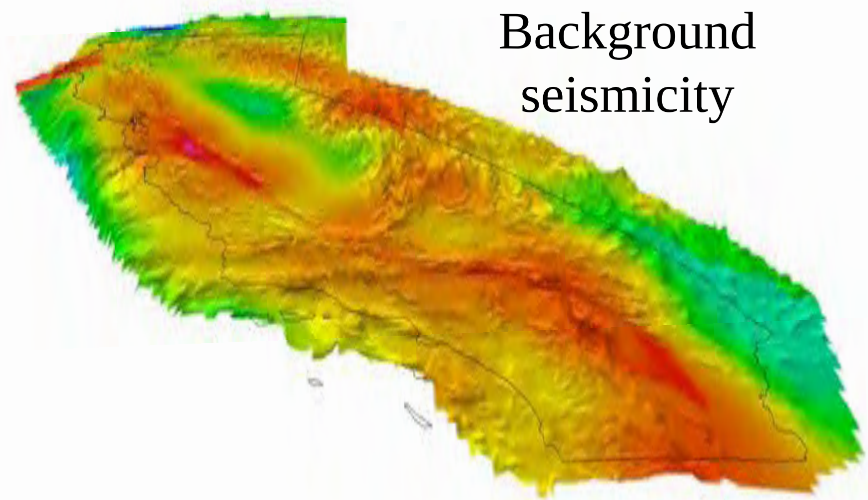
These are modeled as time independent (Poisson) earthquake sources

$P = 1 - \exp^{-R*T}$

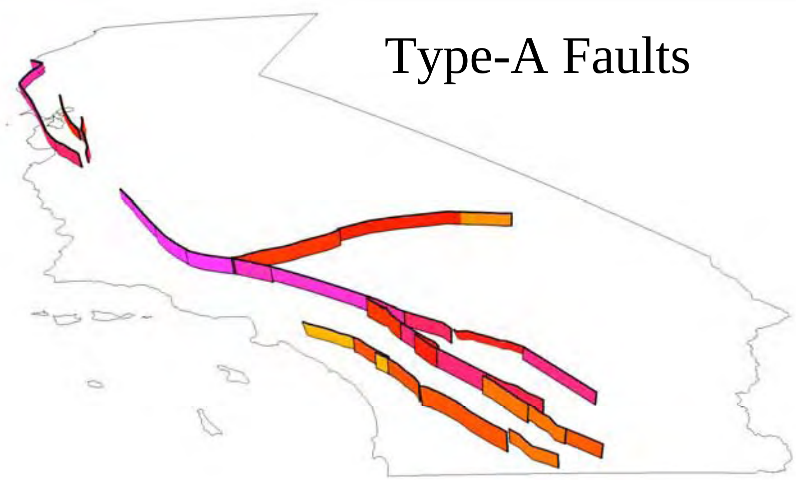
where R = earthquake rate
& T = the forecast duration

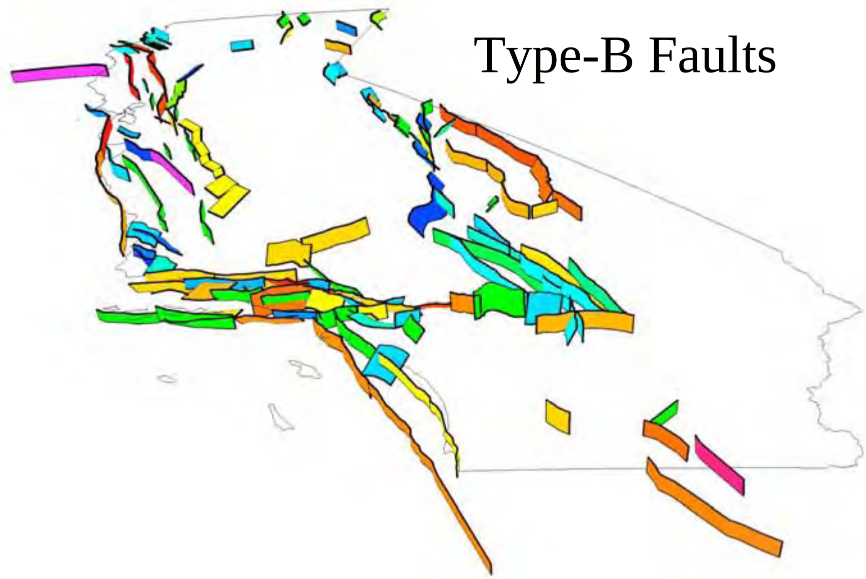






Earthquake Probability Model

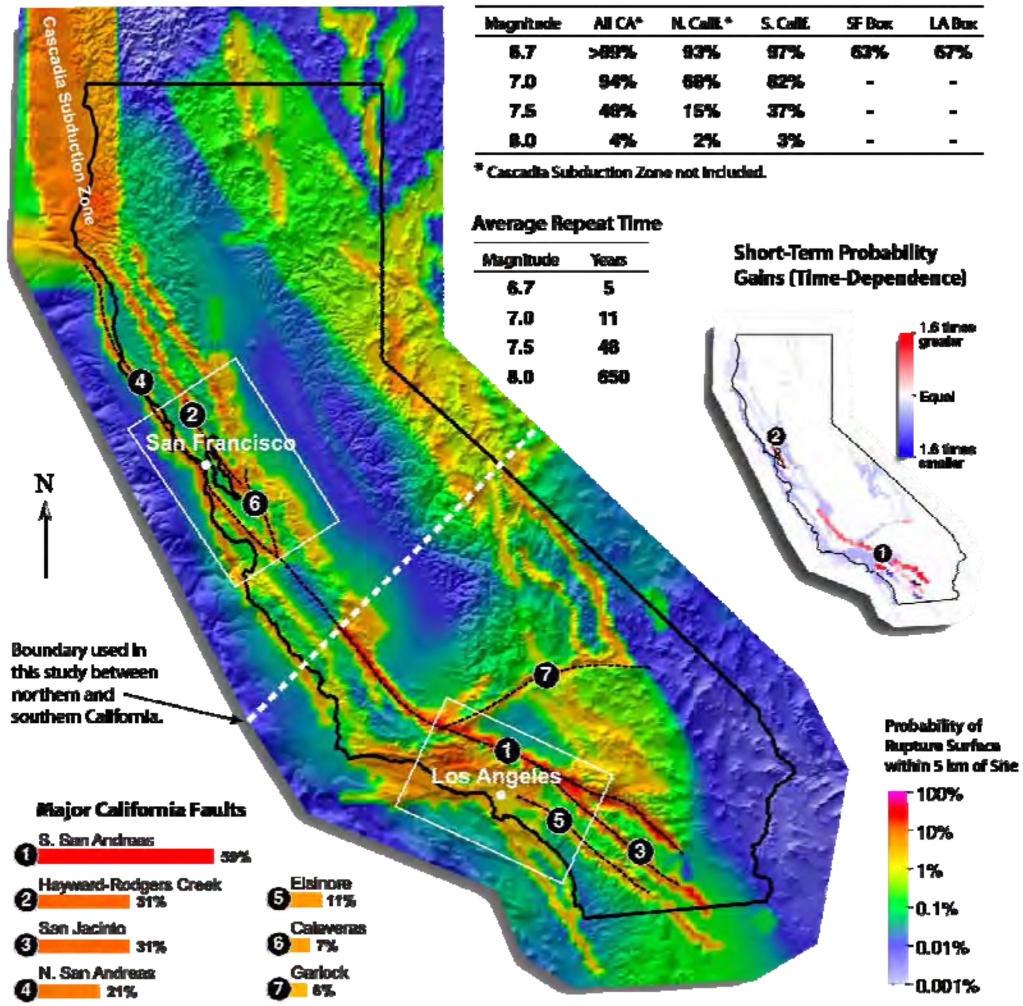




An "Empirical" probability model is also applied to Type-A & -B Faults

A Poisson model where long-term rates are scaled by any differences between recent and long-term seismicity rates

Summary of results:



Uniform California Earthquake Rupture Forecast (UCERF)

By the Working Group on California Earthquake Probabilities**

http://www.scec.org/ucerf

30-Year Probabilities of One or More Earthquake Ruptures Occurring

Magnitude	All CA*	N. Calif.*	S. Calif.	SF Box	LA Box
6.7	>99%	93%	97%	63%	67%
7.0	94%	68%	82%	-	-
7.5	46%	15%	37%	-	-
8.0	4%	2%	3%	-	-

* Cascadia Subduction Zone not included.

Average Repeat Time

Magnitude	Years
6.7	5
7.0	11
7.5	48
8.0	650

Short-Term Probability Gains (Time-Dependence)

Major California Faults

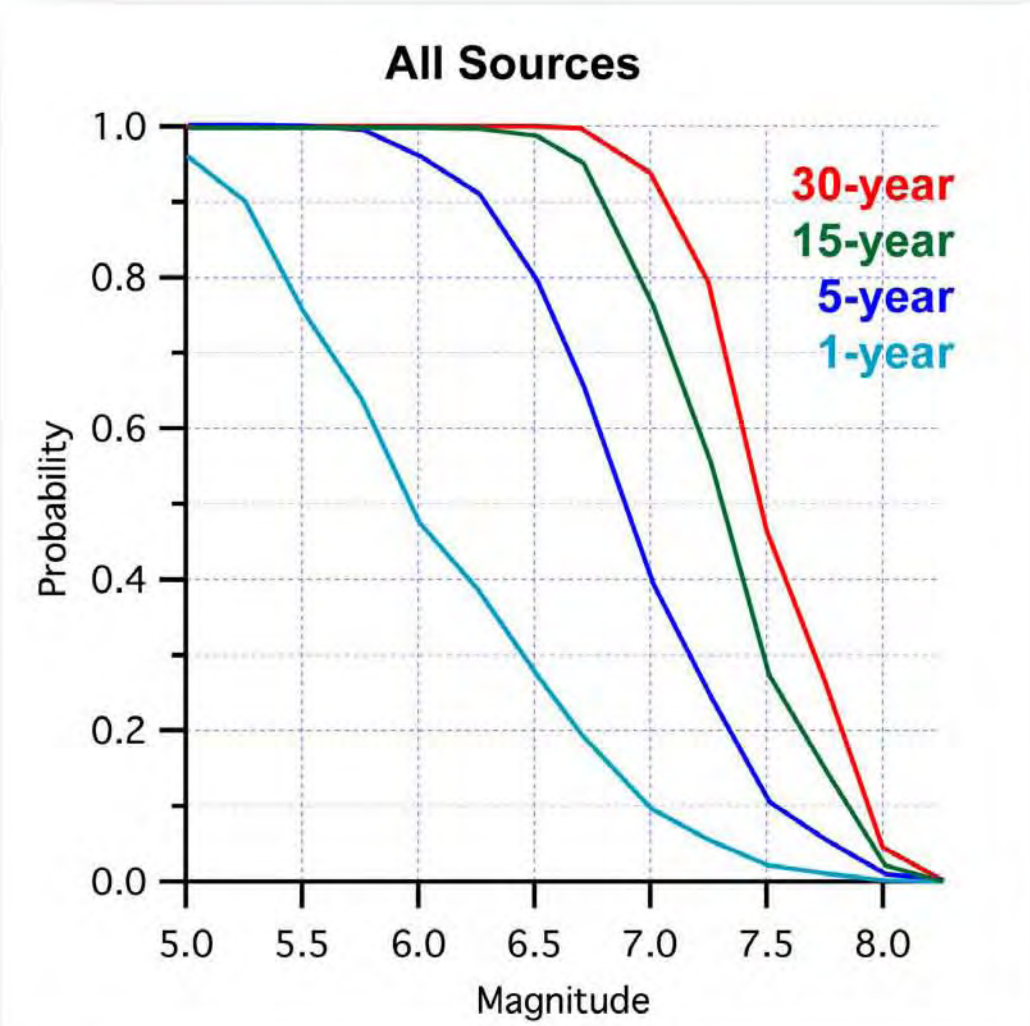
1. S. San Andreas 59%
2. Hayward-Rodgers Creek 31%
3. San Jacinto 31%
4. N. San Andreas 21%
5. Elsinore 11%
6. Calaveras 7%
7. Garlock 6%

** A multi-disciplinary collaboration of scientists and engineers, organized by the Southern California Earthquake Center, U.S. Geological Survey, and the California Geological Survey to develop the first comprehensive framework for comparing earthquake likelihoods throughout all of California.

S O U T H E R N   C A L I F O R N I A   E A R T H Q U A K E   C E N T E R

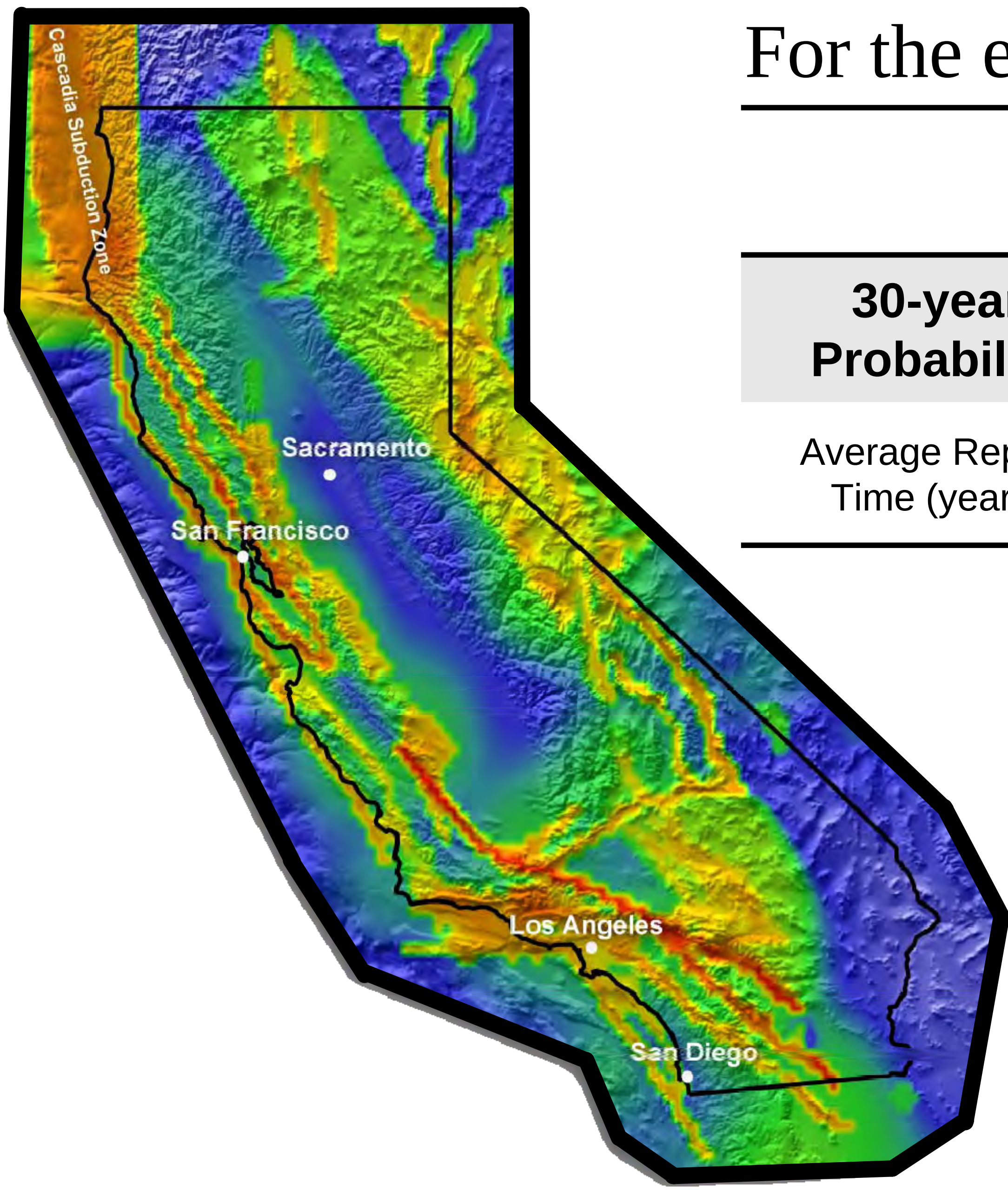
Working Group on California Earthquake Probabilities (WGCEP 2007)

Uniform California Earthquake Rupture Forecast: v. 2



30-yr probability

M ≥ 6.7: p= 99.7%
M ≥ 7.0: p= 94%
M ≥ 7.5: p= 46%
M ≥ 8.0: p= 4.5%



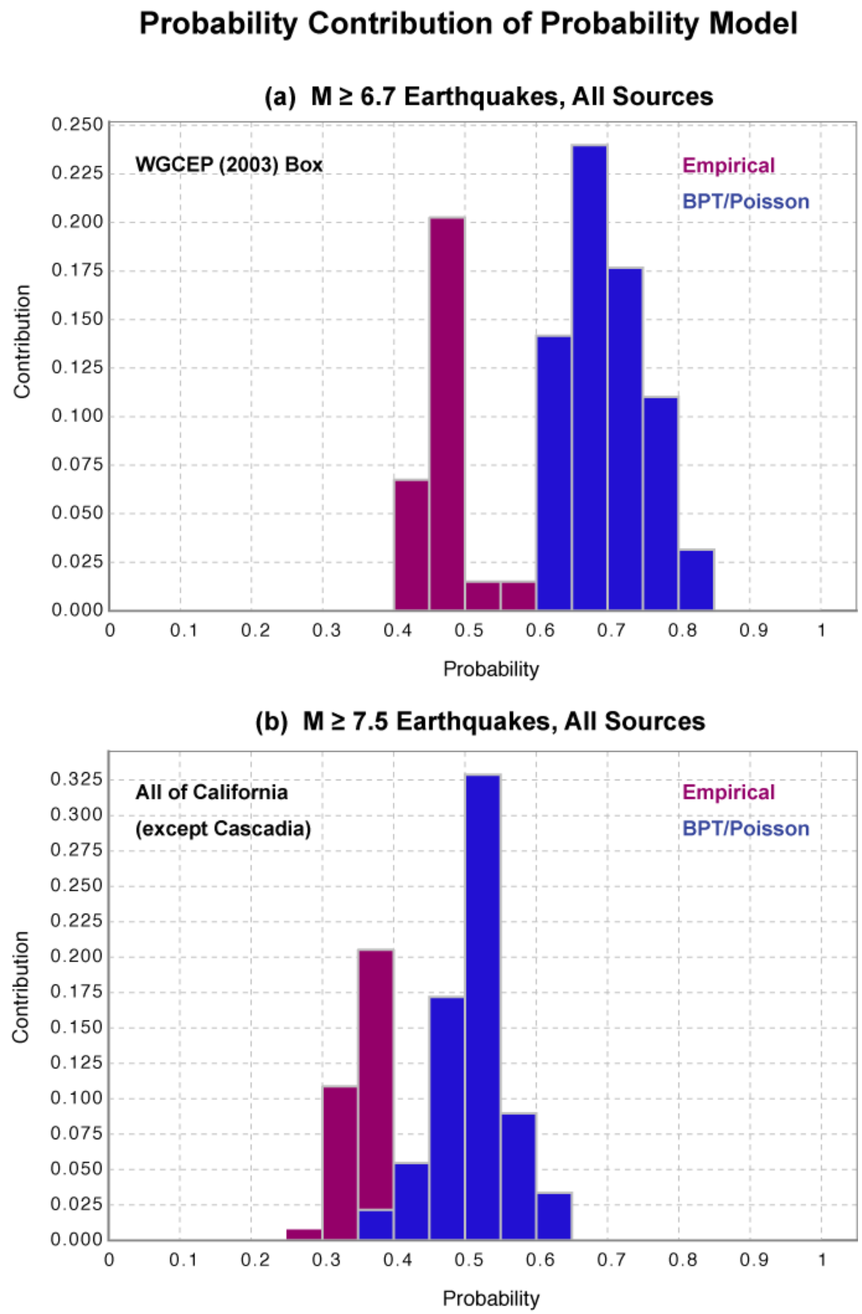
For the entire California Region

	Magnitude ≥6.7	≥7.0	≥7.5	≥8.0
30-year Probability	>99%	94%	46%	4%
Average Repeat Time (years)	5	11	48	650

~3 M≥5 per year

One M≥6 every ~1.5 years

The most important epistemic uncertainty:

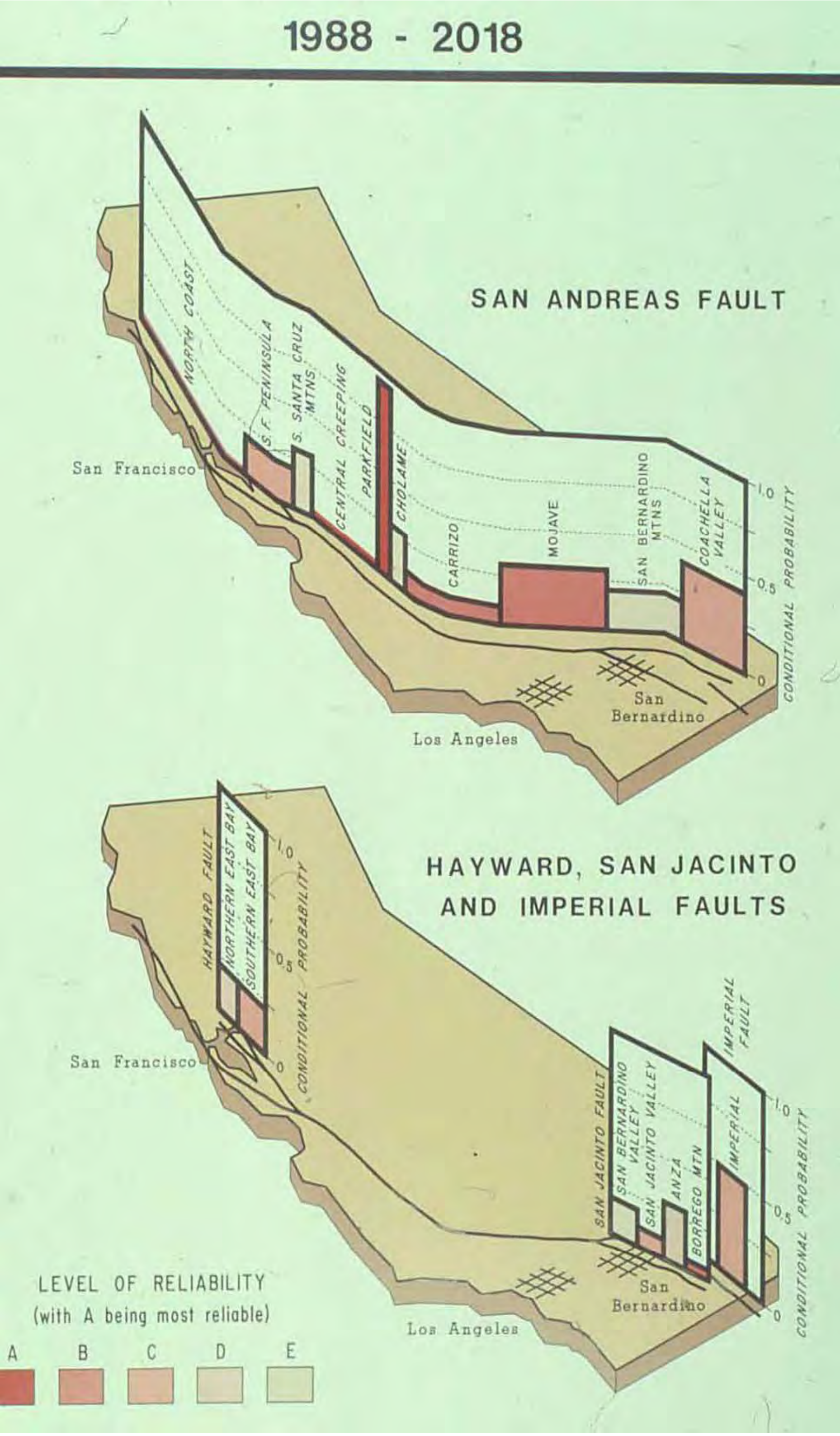


Significant Changes

- Better representation of faults
- Deformation models w/ SAF-SJF slip-rate tradeoff and geodetic strain across the Mojave
- Garlock treated as Type-A fault.
- Two new Type-C zones added to southern California
- Inclusion of more paleoseismic data & more rigorous moment balancing in the development of Type-A fault-rupture models.
- A more thorough analysis of observed seismicity rates throughout the state of California
- GR b-value=0 option on Type-B faults
- 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 San Jacinto and Elsinore faults (lowering rates and increasing ave magnitudes)
- Some previously distinct B-Fault sources have been combined into larger sources
- The background seismicity GR distribution is reduced by a factor of 3 above M 6.5
- Self-consistency analysis of conditional time-dependent probability calculations
- Uniform application of conditional, time-dependent probabilities throughout the state
- Division of WGCEP (2003) faults into type A vs B for statewide consistency
- Full coordination with NSHMP
- Deployed in a modular, extensible, living framework that includes analysis tools

Future Improvements (UCERF3)

1) Utilize kinematically consistent deformation models that include GPS observations (& off-fault deformation)
2) Clarify the distribution of slip during large earthquakes
3) Interpretation of the “Empirical Model”
4) Relax segmentation assumptions & include “fault-to-fault” rupture possibilities (while honoring slip-rate and paleoseismic event-rate data)
5) Apply self consistent elastic-rebound-motivated renewal models
6) Include earthquake clustering/triggering effects (more important than elastic rebound?)
7) Reduce model complexity
8) Develop tools to evaluate the loss implications of alternative models (to honor all logic tree branches and/or to allow scientists to trim branches)

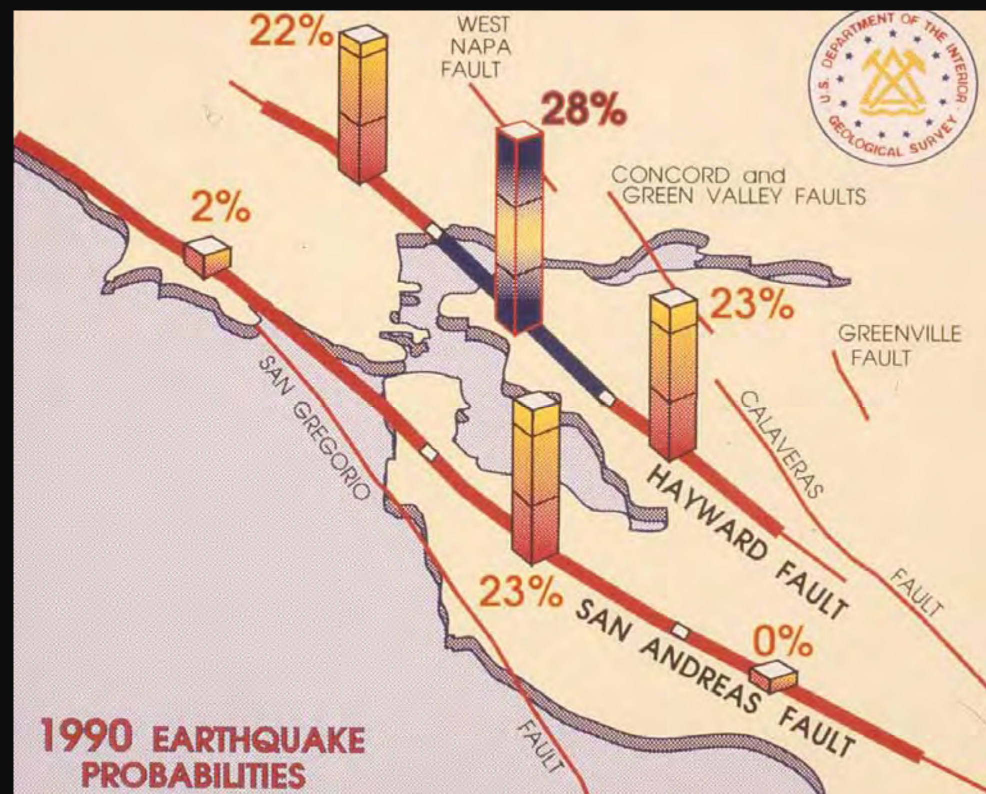


WG 88

50%
(1988-2018)

WG 90

67%
(1990-2020)



Working Group 2002 study

- We constructed a long-term model for large-earthquake production in the SFBR

  - balances slip rates and plate tectonic rates
  - accounts for overlapping ruptures, fault creep, earthquake interactions, and other complexities
  - provides magnitudes and rates of earthquakes

- We then calculated short-term earthquake probability forecasts
  - gives probabilities for faults, fault segments, and the Bay region
  - for a range of time intervals and earthquake magnitudes

- Results are applicable to hazard and loss calculations, and scenario planning

Working Group 2002
Oversight Committee and Participants

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David Schwartz, USGS (co-chair)
Norm Abrahamsen, PG&E
William Bakun, USGS
William Ellsworth, USGS
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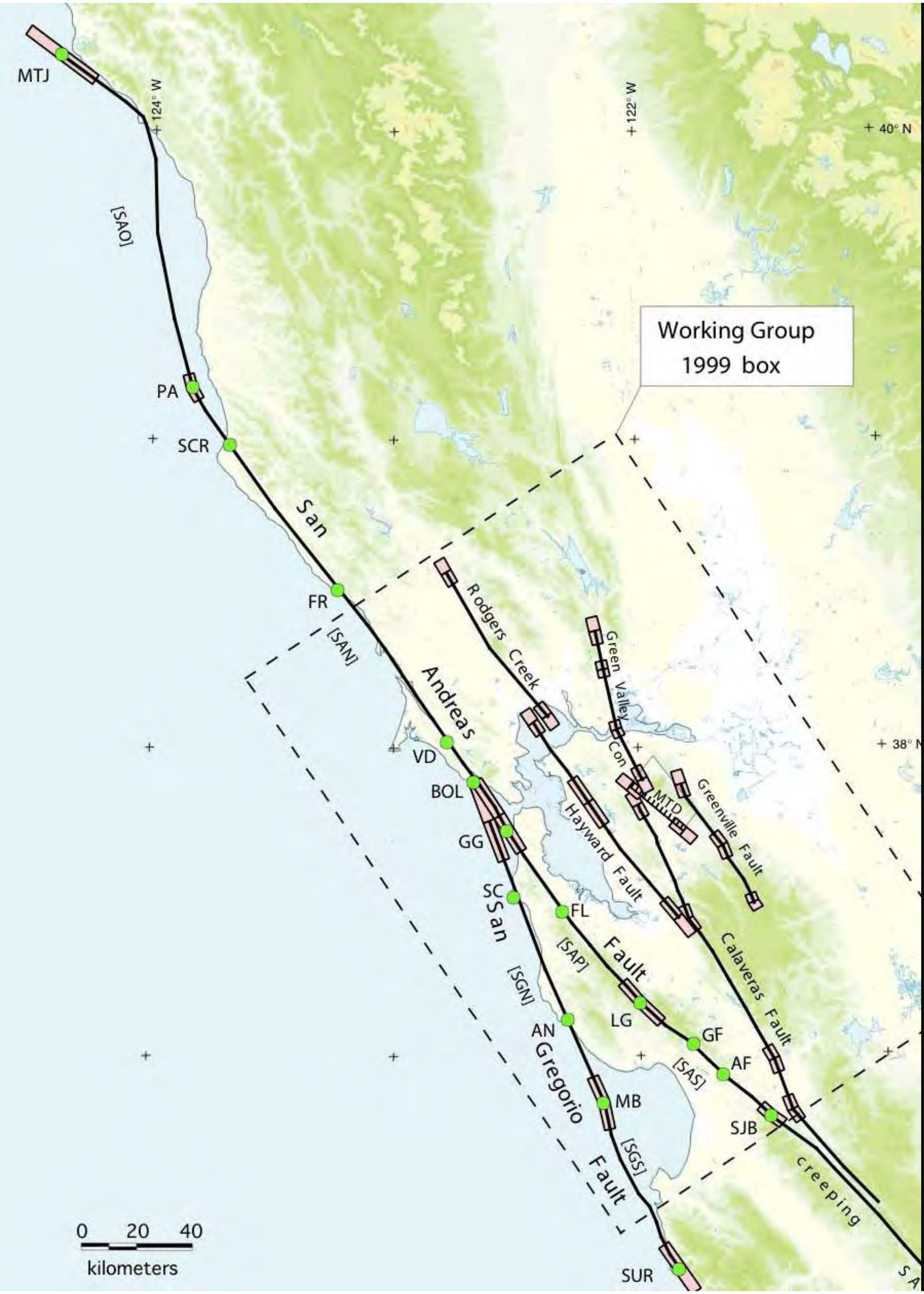


MTJ
124° W
122° W
40° N
38° N
[SAO]
Working Group
1999 box
PA
SCR
San
FR
[SAN]
Andreas
VD
BOL
GG
SC
San
FL
[SAP]
Fault
[SGN]
AN
Gregorio
LG
GF
AF
[SAS]
MB
SJB
[SGS]
Fault
Rodgers Creek
Green Valley
Con
MTD
Greenville Fault
Hayward Fault
Calaveras Fault
creeping
SUR
0 20 40
kilometers

San Francisco Bay Area

Earthquake Model

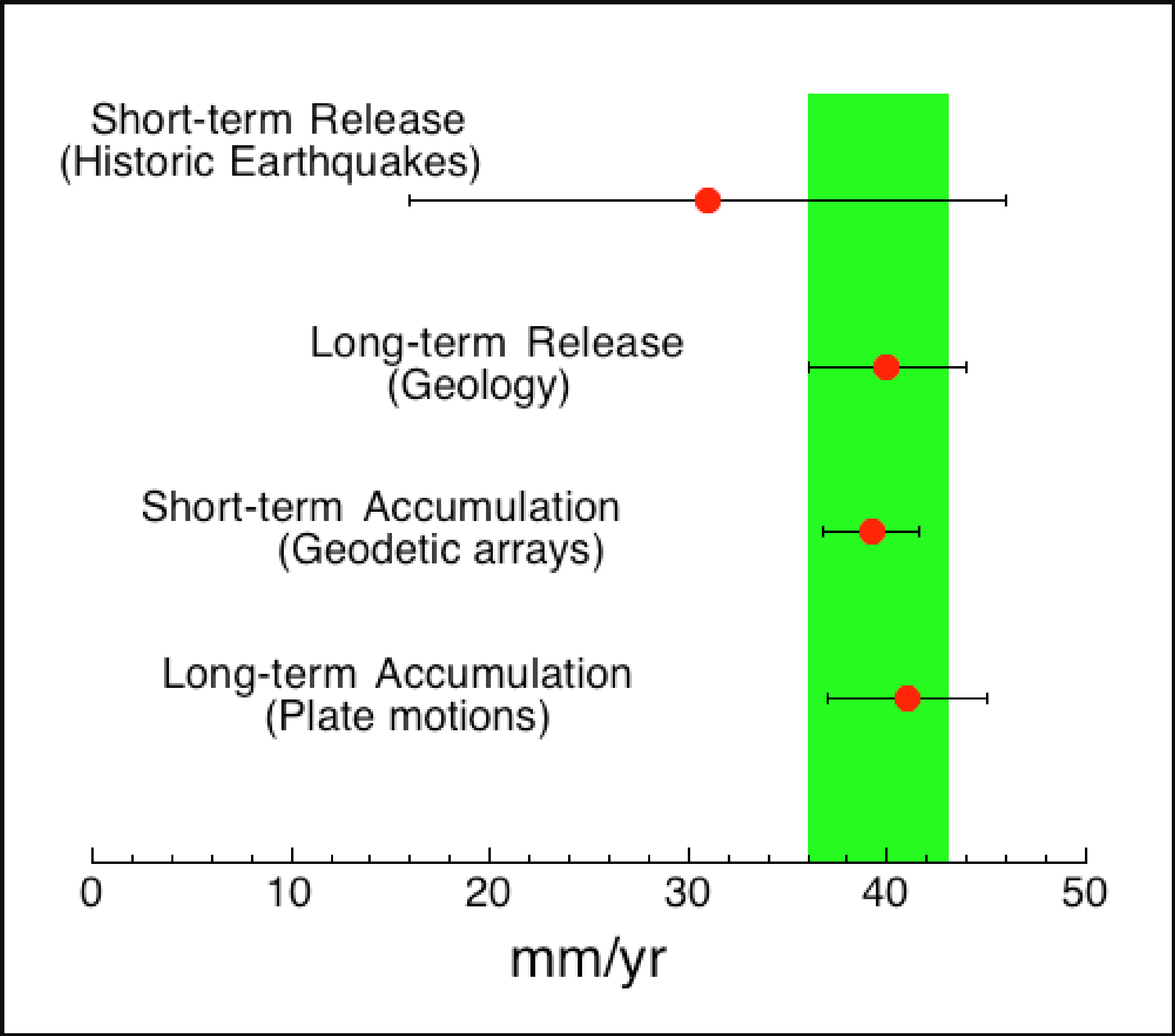
What goes in...must come out

AVERAGE long-term

earthquake recurrence

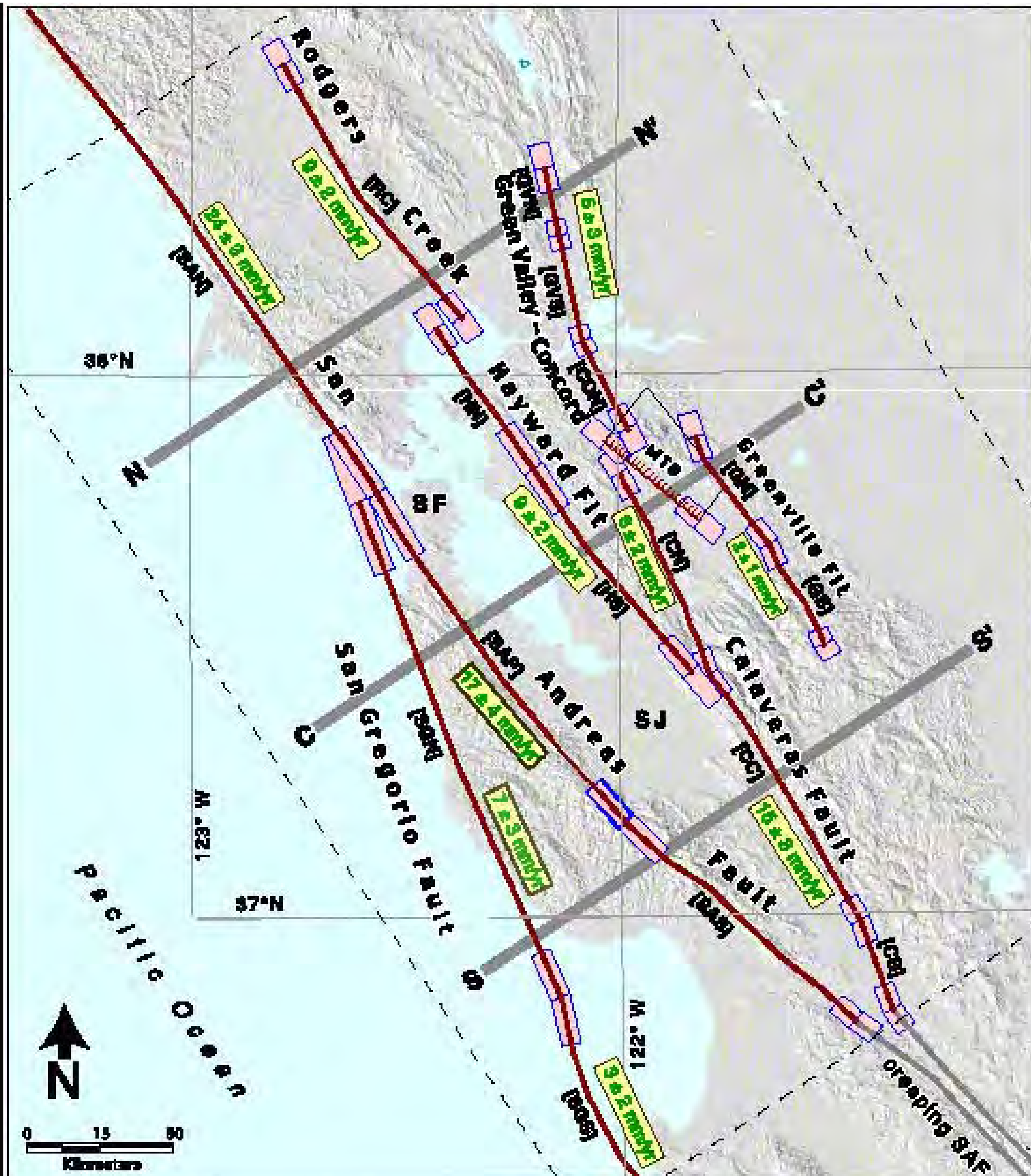
- -Plate Motions
- -GPS rates
- -Paleoseismology
- -Historical Seismicity
- -Fault Interactions
- -Expert Opinion

Four measures of SFBR rates



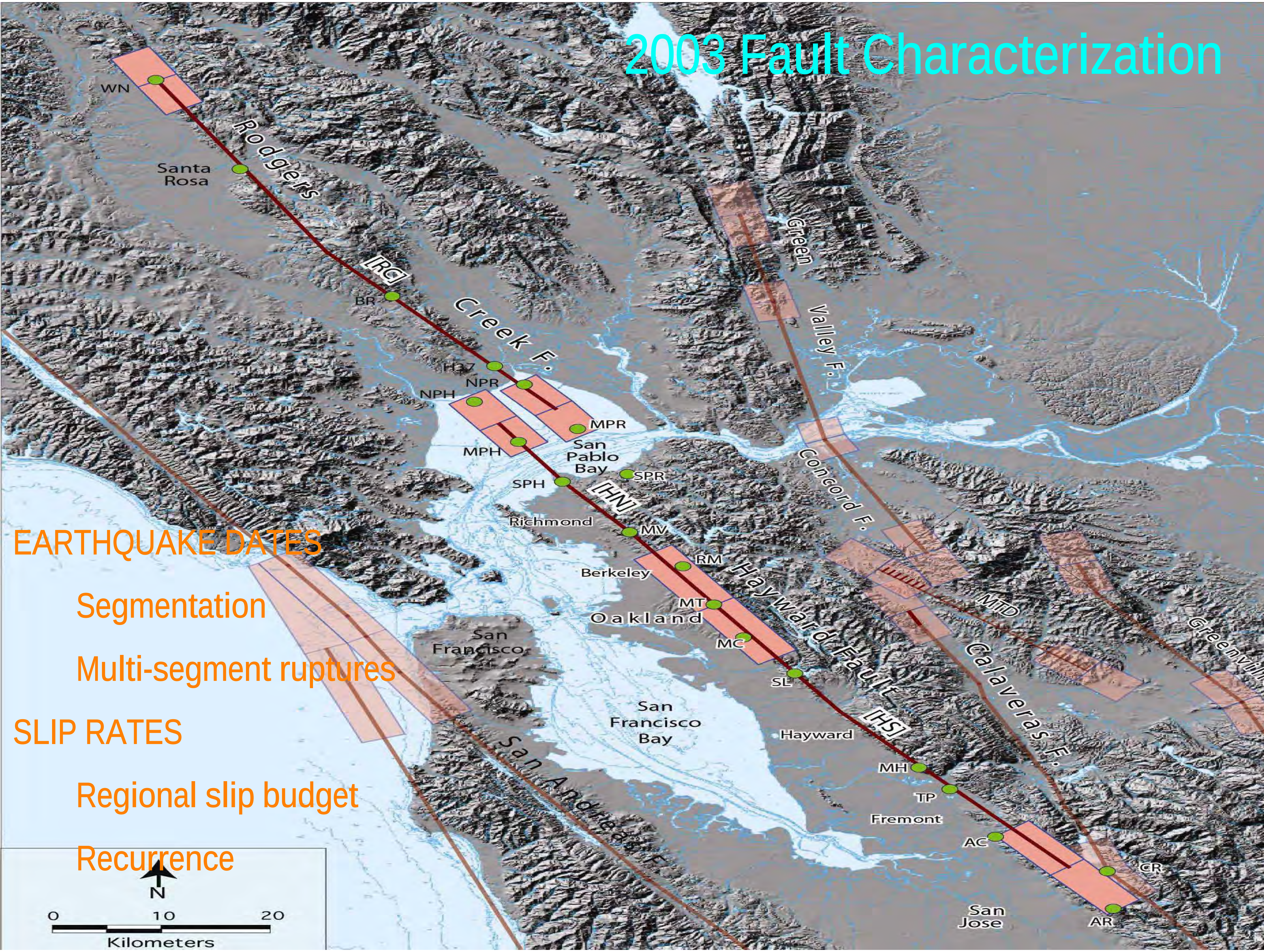
San Francisco Bay Area Faults

- A network of faults
- Fault segments fail alone or in combination
- Each fault segment has a length and slip rate
- Summed slip rates constrained to 36-43 mm/yr

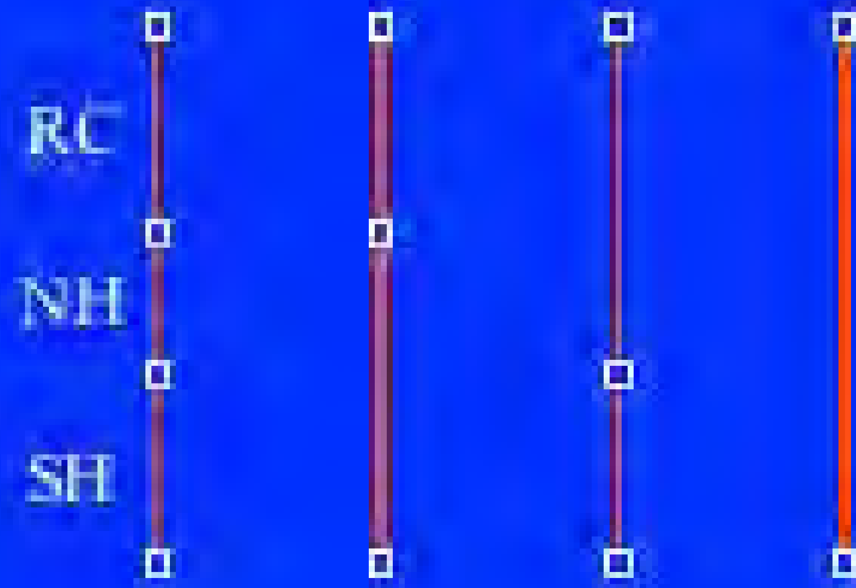


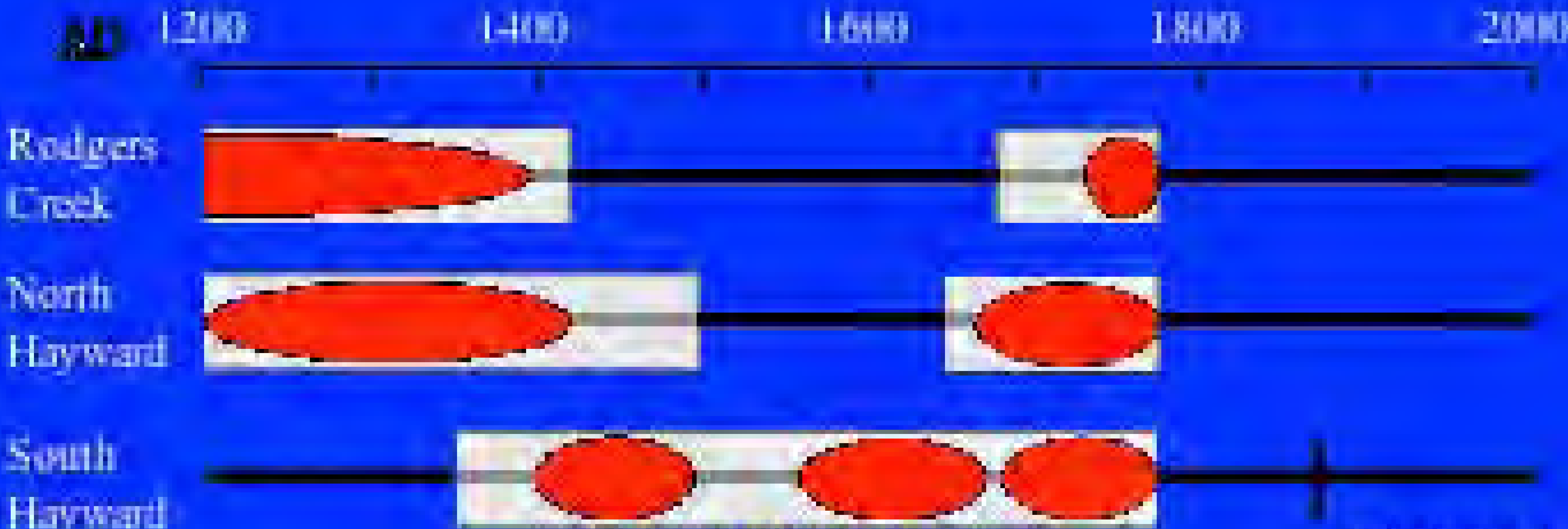
2003 Fault Characterization

- EARTHQUAKE DATES
  - Segmentation
  - Multi-segment ruptures
- SLIP RATES
  - Regional slip budget
  - Recurrence

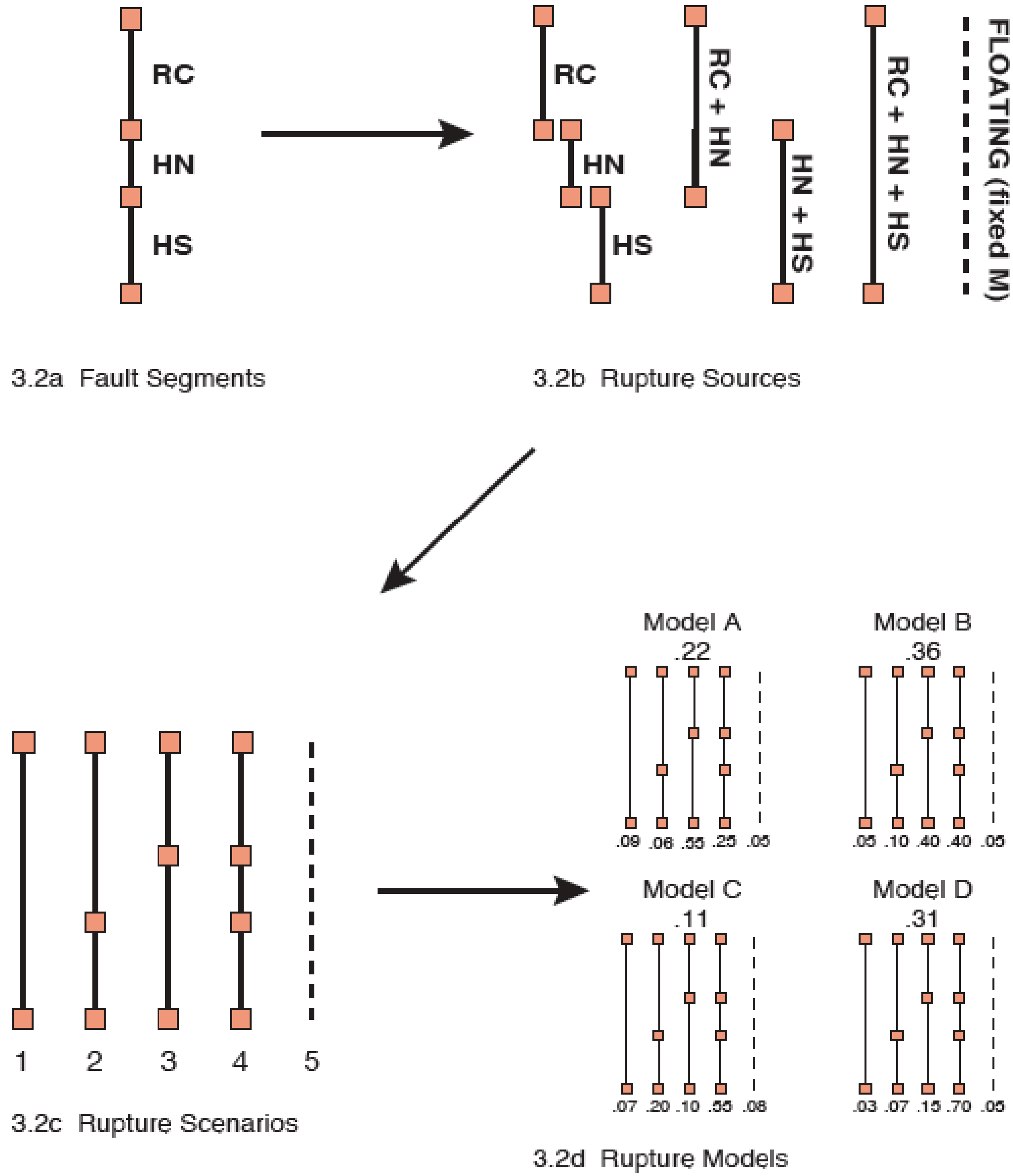


Paleoearthquake chronologies to evaluate possible rupture scenarios: Hayward-Rodgers Creek Fault Zone

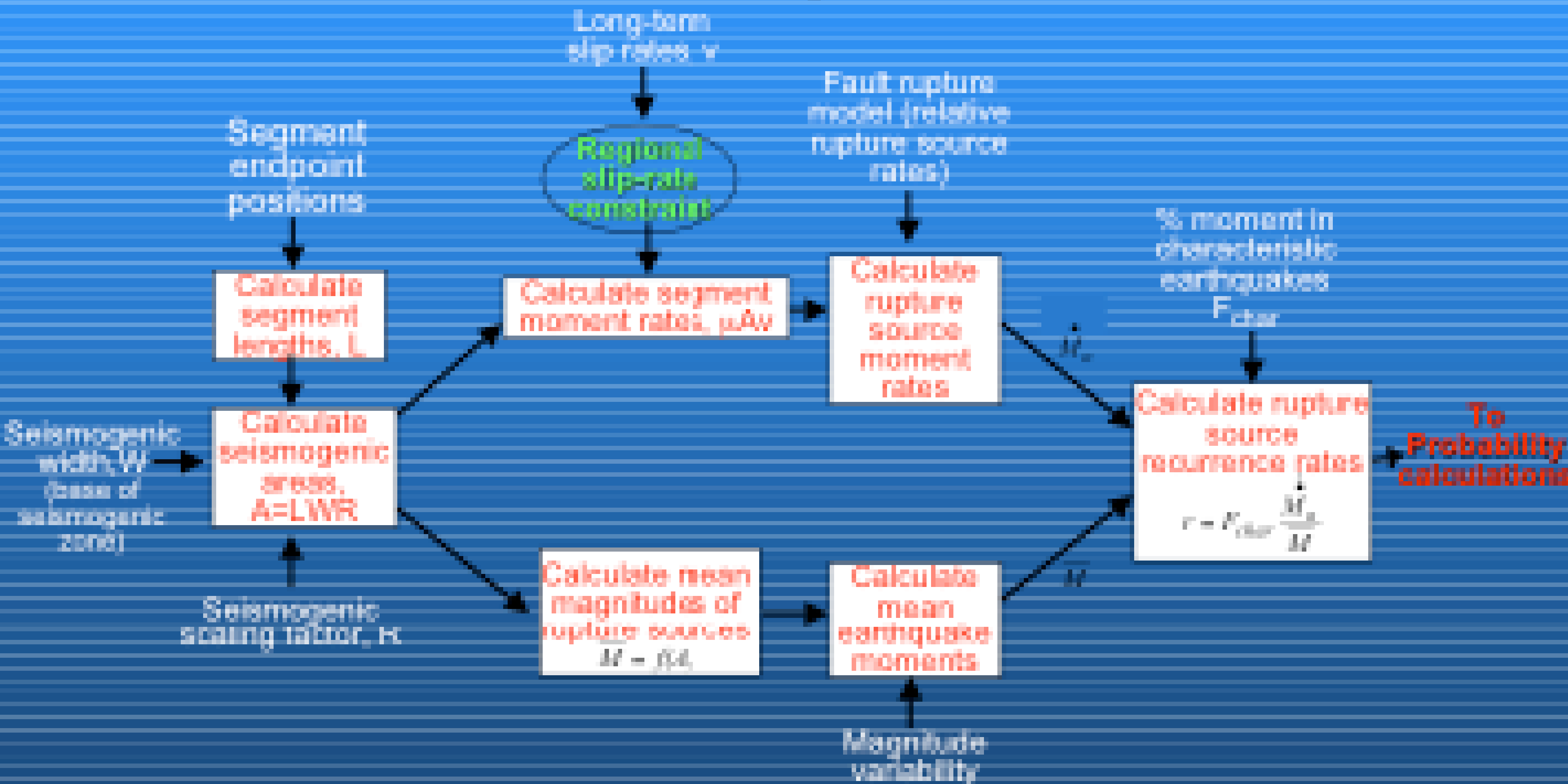




Earthquake Hazards Reduction Program


RC
HN
HS
RC
HN
HS
RC + HN
HN + HS
RC + HN + HS
FLOATING (fixed M)
3.2a Fault Segments
3.2b Rupture Sources
1
2
3
4
5
3.2c Rupture Scenarios
Model A
.22
.09 .06 .55 .25 .05
Model B
.36
.05 .10 .40 .40 .05
Model C
.11
.07 .20 .10 .55 .08
Model D
.31
.03 .07 .15 .70 .05
3.2d Rupture Models

1. Calculation Sequence for SFBR Earthquake Model



Rupture Rates

Table 4.8. Long-term magnitudes and occurrence rates of rupture sources. For reference, recurrence intervals are also listed; these are simply calculated as the inverse of the occurrence rate statistics listed in the center columns.

		Mean magnitude			Occurrence rate (/yr)			Recurrence interval (yr)		
Fault Name	Rupture Source	Mean	2.5%	97.5%	Mean	2.5%	97.5%	Mean	2.5%	97.5%
San Andreas	SAS	7.03	6.84	7.22	0.0007	0	0.0015	1402	646	–
	SAP	7.15	6.95	7.32	0.0005	0	0.0010	2017	967	–
	SAN	7.45	7.28	7.61	0.0001	0	0.0008	7180	1316	–
	SAO	7.29	7.12	7.44	0.0002	0	0.0011	4540	897	–
	SAS+SAP	7.42	7.26	7.56	0.0010	0.0002	0.0029	1037	343	4863
	SAP+SAN	7.65	7.48	7.79	0	0	0	–	–	–
	SAN+SAO	7.70	7.53	7.86	0.0012	0.0004	0.0035	809	282	2772
	SAS+SAP+SAN	7.76	7.59	7.92	0.00002	0	0.0001	42489	8240	–
	SAP+SAN+SAO	7.83	7.65	8.01	0.0001	0	0.0004	13046	2676	–
	SAS+SAP+SAN+SAO	7.90	7.72	8.10	0.0026	0.0012	0.0042	378	239	808
	floating	6.90	6.90	6.90	0.0009	0.0001	0.0019	1104	536	7723
Hayward/RC	HS	6.67	6.36	6.93	0.0034	0.0012	0.0069	292	144	830
	HN	6.49	6.18	6.78	0.0032	0.0011	0.0069	312	146	907
	HS+HN	6.91	6.68	7.12	0.0024	0.0009	0.0047	413	211	1100
	RC	6.98	6.81	7.14	0.0040	0.0023	0.0063	250	159	438
	HN+RC	7.11	6.94	7.28	0.0005	0	0.0013	2086	766	–
	HS+HN+RC	7.26	7.09	7.42	0.0003	0.0001	0.0007	3524	1511	19158
	floating	6.90	6.90	6.90	0.0003	0.0001	0.0006	3524	1706	7294
Calaveras	CS	5.79	0.00	6.14	0.0075	0	0.0158	134	63	–
	CC	6.23	5.75	6.68	0.0054	0.0025	0.0097	184	103	397
	CS+CC	6.36	5.87	6.75	0.0018	0	0.0065	541	155	–
	CN	6.78	6.58	6.97	0.0035	0.0015	0.0065	284	154	685
	CC+CN	6.90	6.68	7.11	0.0001	0	0.0011	10958	924	–
	CS+CC+CN	6.93	6.72	7.14	0.0006	0	0.0018	1555	543	–
	floating	6.20	6.20	6.20	0.0030	0.0009	0.0077	331	130	1158
	floating CS+CC	6.20	6.20	6.20	0.0120	0.0025	0.0285	83	35	405
Concord/GV	CON	6.25	5.75	6.67	0.0014	0.0002	0.0038	690	264	5374
	GVS	6.24	5.75	6.65	0.0007	0.0001	0.0018	1527	551	12725
	CON+GVS	6.58	6.13	6.91	0.0005	0.00003	0.0016	2158	640	40002
	GVN	6.02	5.45	6.49	0.0017	0.0002	0.0043	582	231	4474
	GVS+GVN	6.48	6.03	6.81	0.0009	0.0001	0.0024	1125	411	10866
	CON+GVS+GVN	6.71	6.34	7.00	0.0017	0.0003	0.0050	580	199	2888
	floating	6.20	6.20	6.20	0.0026	0.0001	0.0126	386	80	9327
San Gregorio	SGS	6.96	6.75	7.17	0.0007	0	0.0023	1403	444	–
	SGN	7.23	7.04	7.41	0.0012	0	0.0034	828	295	–
	SGS+SGN	7.44	7.27	7.58	0.0008	0	0.0021	1202	483	–
	floating	6.90	6.90	6.90	0.0008	0.0004	0.0014	1220	733	2833
Greenville	GS	6.60	6.37	6.83	0.0010	0.0004	0.0019	976	515	2622
	GN	6.66	6.41	6.88	0.0010	0.0004	0.0018	1040	550	2824
	GS+GN	6.94	6.74	7.13	0.0005	0.0002	0.0009	1994	1063	5393
	floating	6.20	6.20	6.20	0.0002	0.0001	0.0003	5897	3131	15835
Mt Diablo	MTD	6.65	6.42	6.89	0.0026	0.0006	0.0053	389	189	1609

Rupture sources

Fault segments

Table 4.9. Long-term earthquake recurrence rates and recurrence intervals for SFBR fault segments. Rates include earthquakes on all fixed and floating rupture sources that affect a given segment. For reference, recurrence intervals are also listed; these are simply calculated as the inverse of the occurrence rate statistics listed in the center columns.

		Recurrence rate (/yr)			Recurrence interval (yr)		
Fault Name	Segment	Mean	2.5%	97.5%	Mean	2.5%	97.5%
San Andreas	SAS	0.0045	0.0028	0.0064	224	156	363
	SAP	0.0044	0.0027	0.0063	229	160	377
	SAN	0.0045	0.0025	0.0065	223	153	397
	SAO	0.0044	0.0025	0.0065	225	154	405
Hayward/RC	HS	0.0062	0.0035	0.0101	161	99	283
	HN	0.0065	0.0037	0.0105	155	95	273
	RC	0.0049	0.0029	0.0073	205	136	345
Calaveras	CS	0.0134	0.0026	0.0245	75	41	390
	CC	0.0185	0.0094	0.0326	54	31	106
	CN	0.0054	0.0030	0.0085	187	117	339
Concord/GV	CON	0.0046	0.0015	0.0084	219	118	646
	GVS	0.0048	0.0015	0.0089	210	112	665
	GVN	0.0050	0.0016	0.0094	201	106	622
San Gregorio	SGS	0.0019	0.0007	0.0031	540	319	1441
	SGN	0.0026	0.0011	0.0043	392	232	926
Greenville	GS	0.0016	0.0006	0.0030	623	330	1677
	GN	0.0016	0.0006	0.0029	644	343	1748
Mt Diablo	MTD	0.0026	0.0006	0.0053	389	189	1609

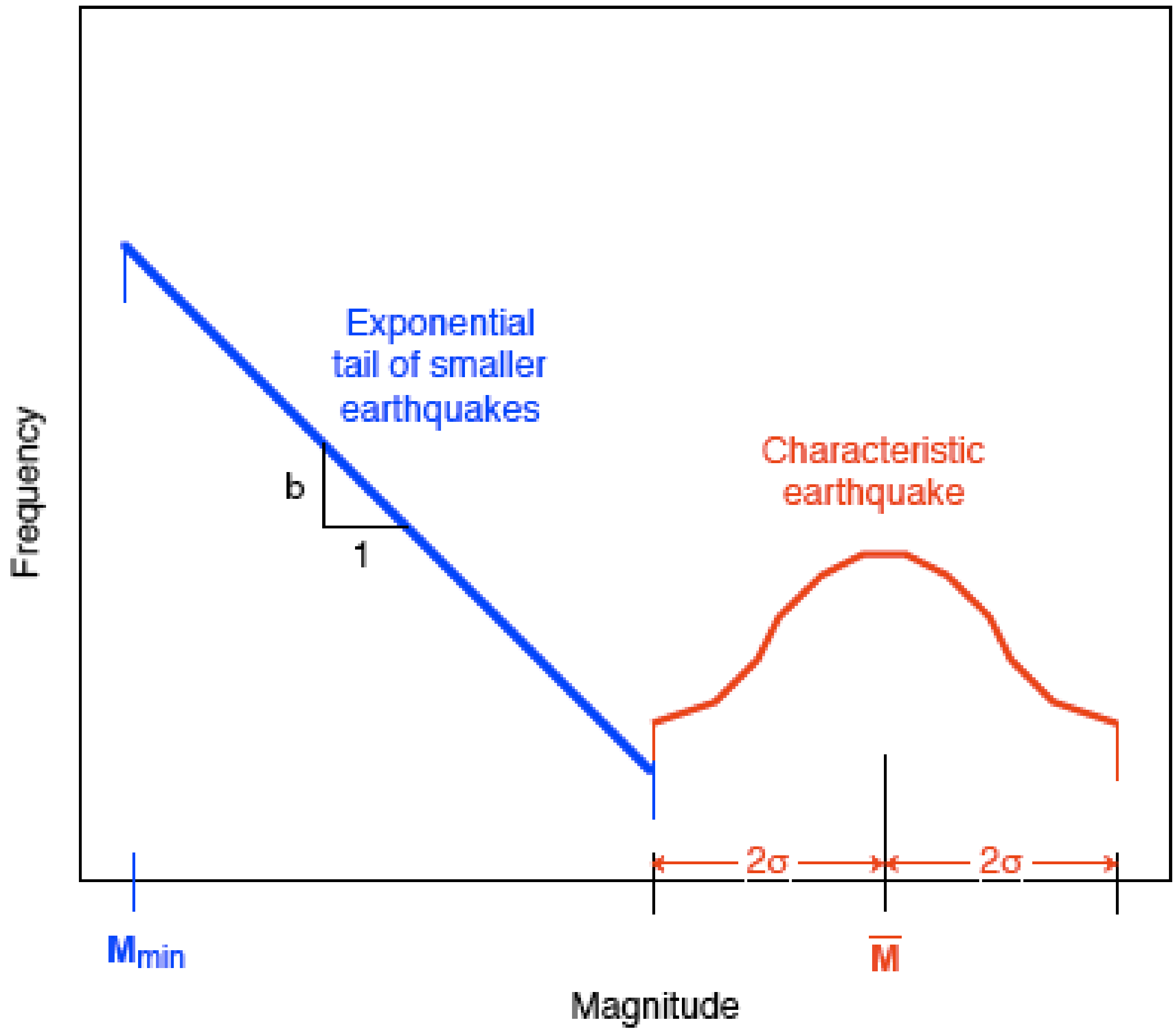
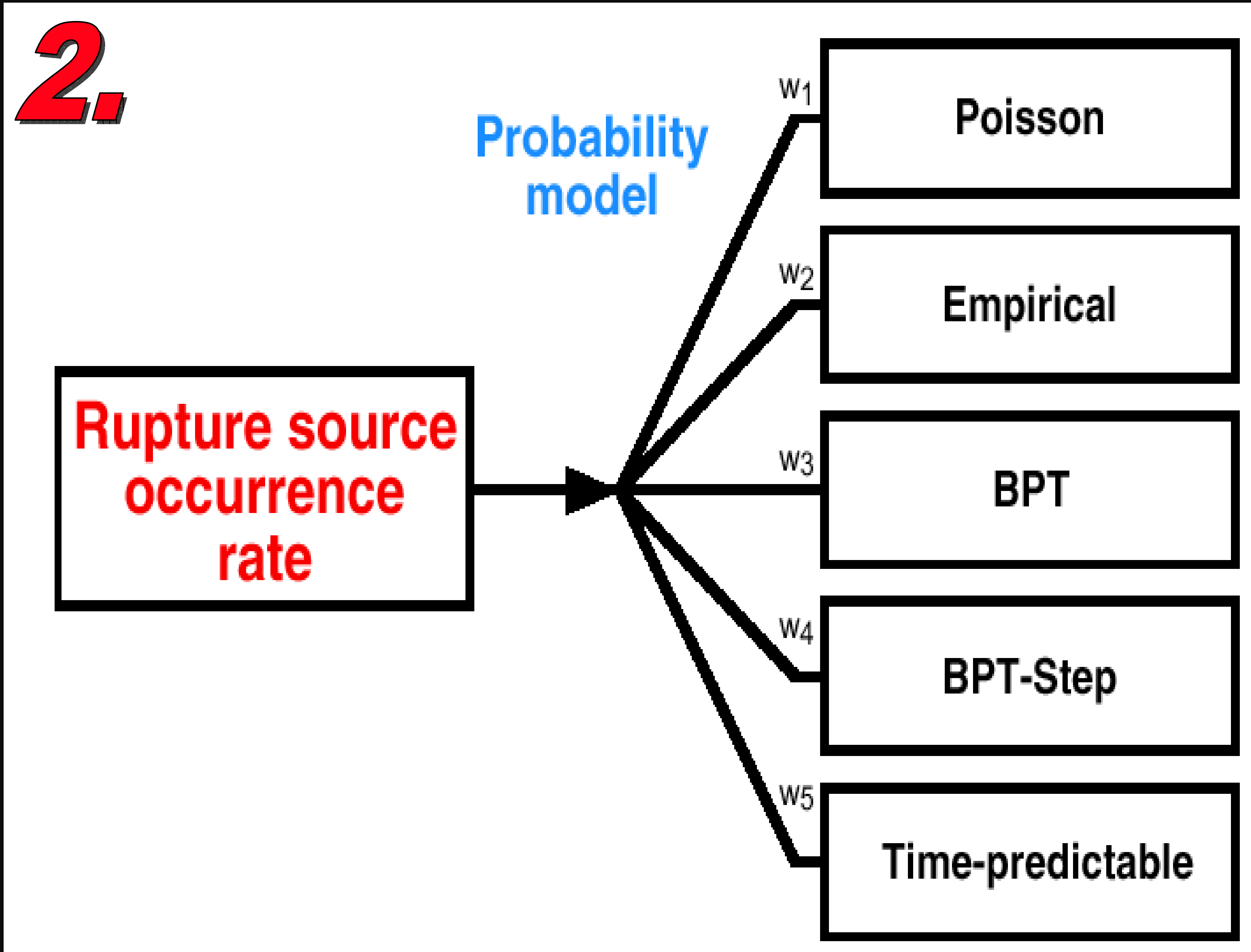
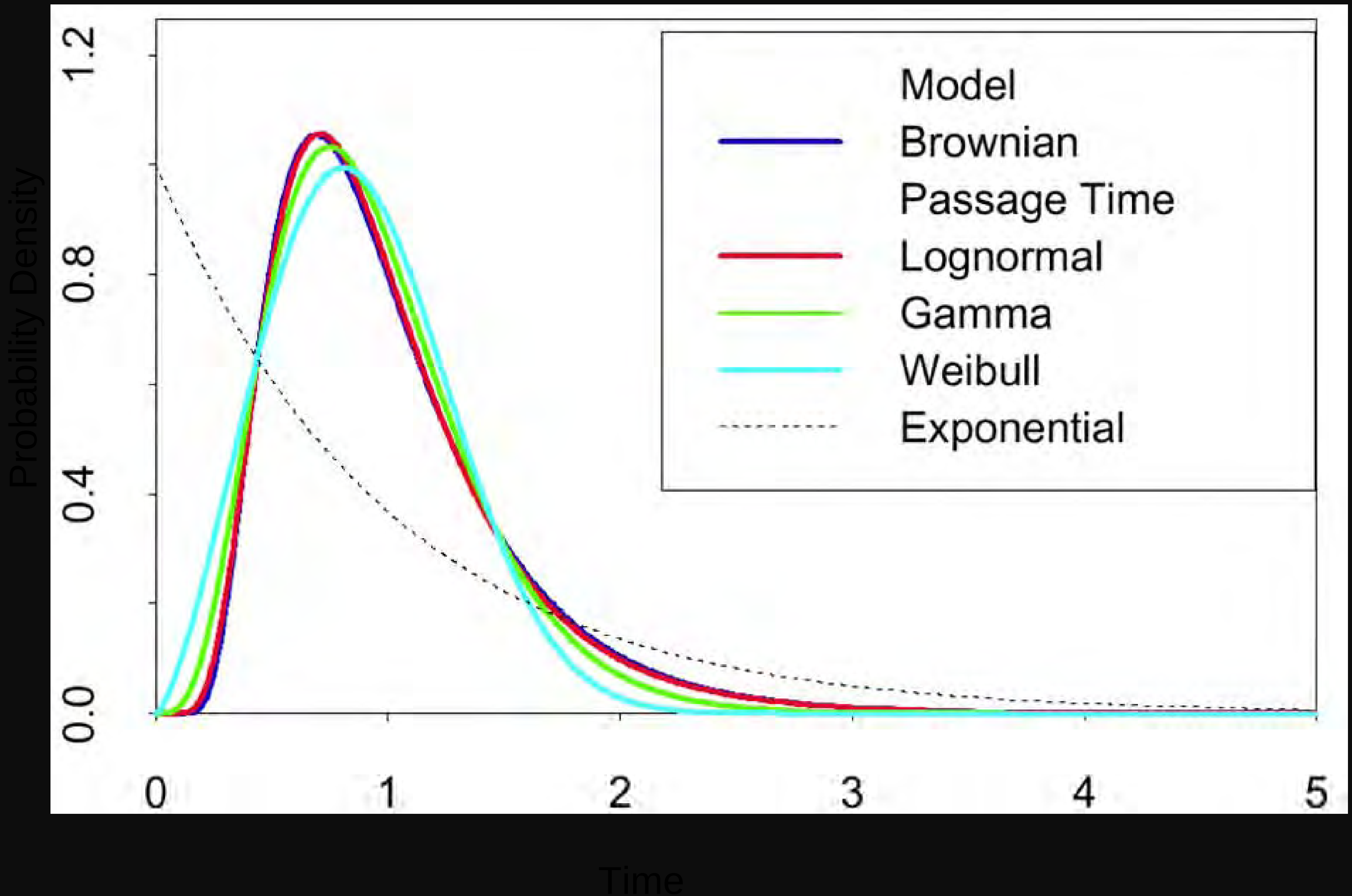


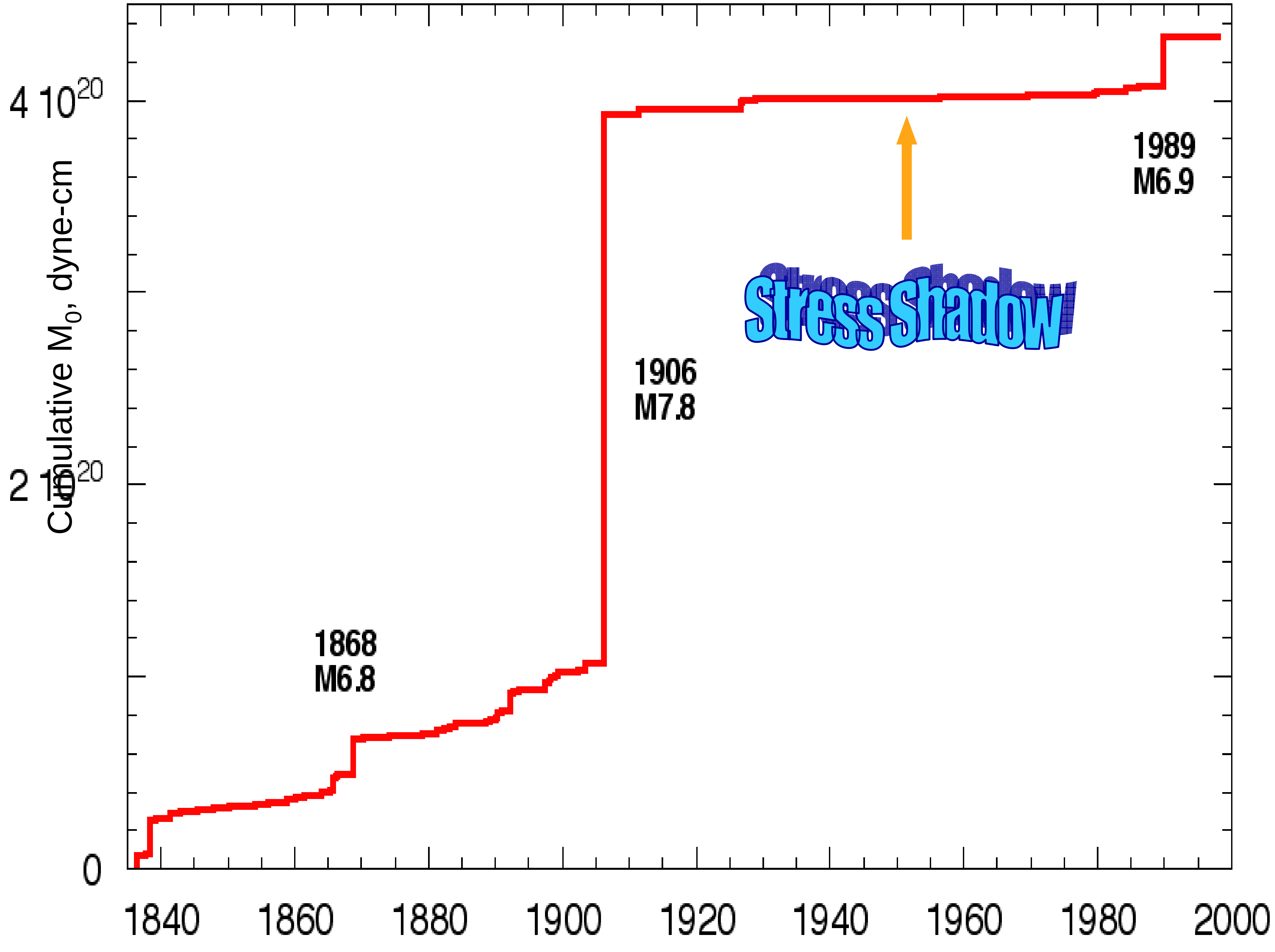
Figure 4.1. Illustration of a magnitude pdf (probability density function) for a WG99 fault containing a single rupture source. The characteristic rupture (which breaks the entire seismogenic area of the source) has a mean magnitude and a natural variability about that mean defined by +/- two standard deviations (where sigma = 0.12). A portion of the moment rate of the fault is expended in an exponential distribution of smaller earthquakes, where the exponential is defined by a b value and magnitude bounds as shown.

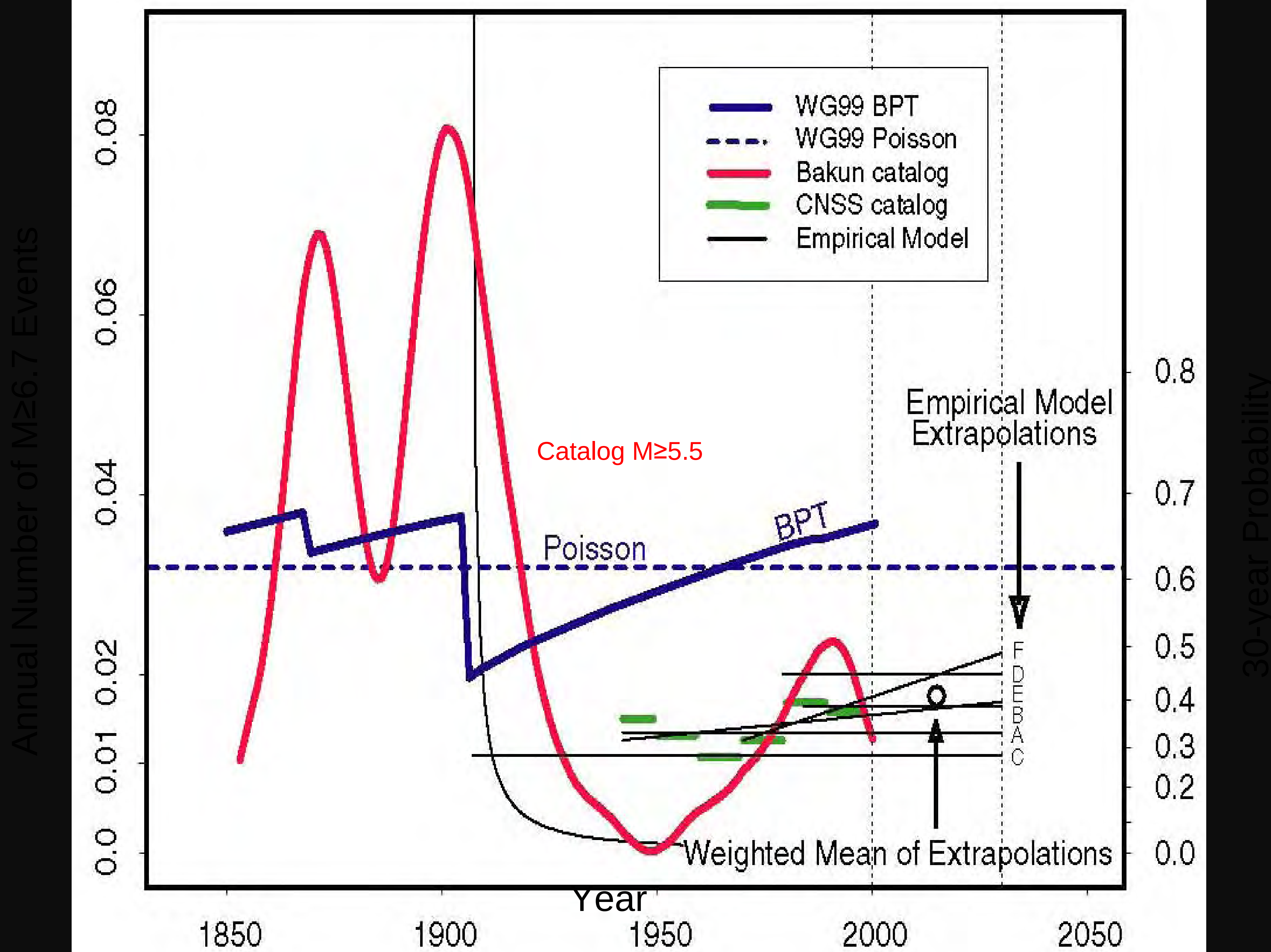

2.
Probability model
Rupture source occurrence rate
w1
w2
w3
w4
w5
Poisson
Empirical
BPT
BPT-Step
Time-predictable

Recurrence model pdf's
Mean=1, Aperiodicty=0.5



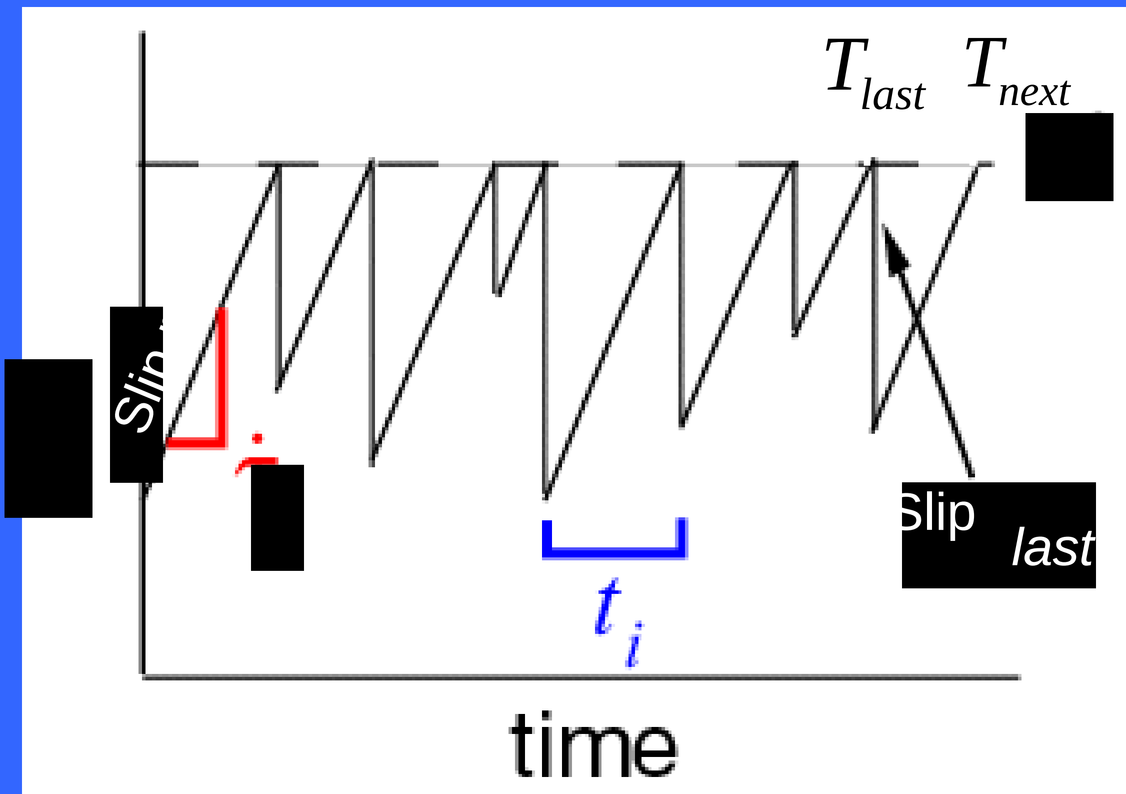
Moment Accumulation in the SF Bay Region




WG99 BPT
WG99 Poisson
Bakun catalog
CNSS catalog
Empirical Model
Catalog M≥5.5
Poisson
BPT
Empirical Model
Extrapolations
F
D
E
B
A
C
Weighted Mean of Extrapolations
Annual Number of M≥6.7 Events
30-year Probability
Year
0.0
0.01
0.02
0.04
0.06
0.08
0.0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1850
1900
1950
2000
2050

Time-predictable model

Shimazaki and Nakata, 1980



$$T_{next} - T_{last} = \frac{\text{Slip}_{last}}{\text{Slip rate}}$$

San Andreas fault only

Thatcher, 1997 slip model

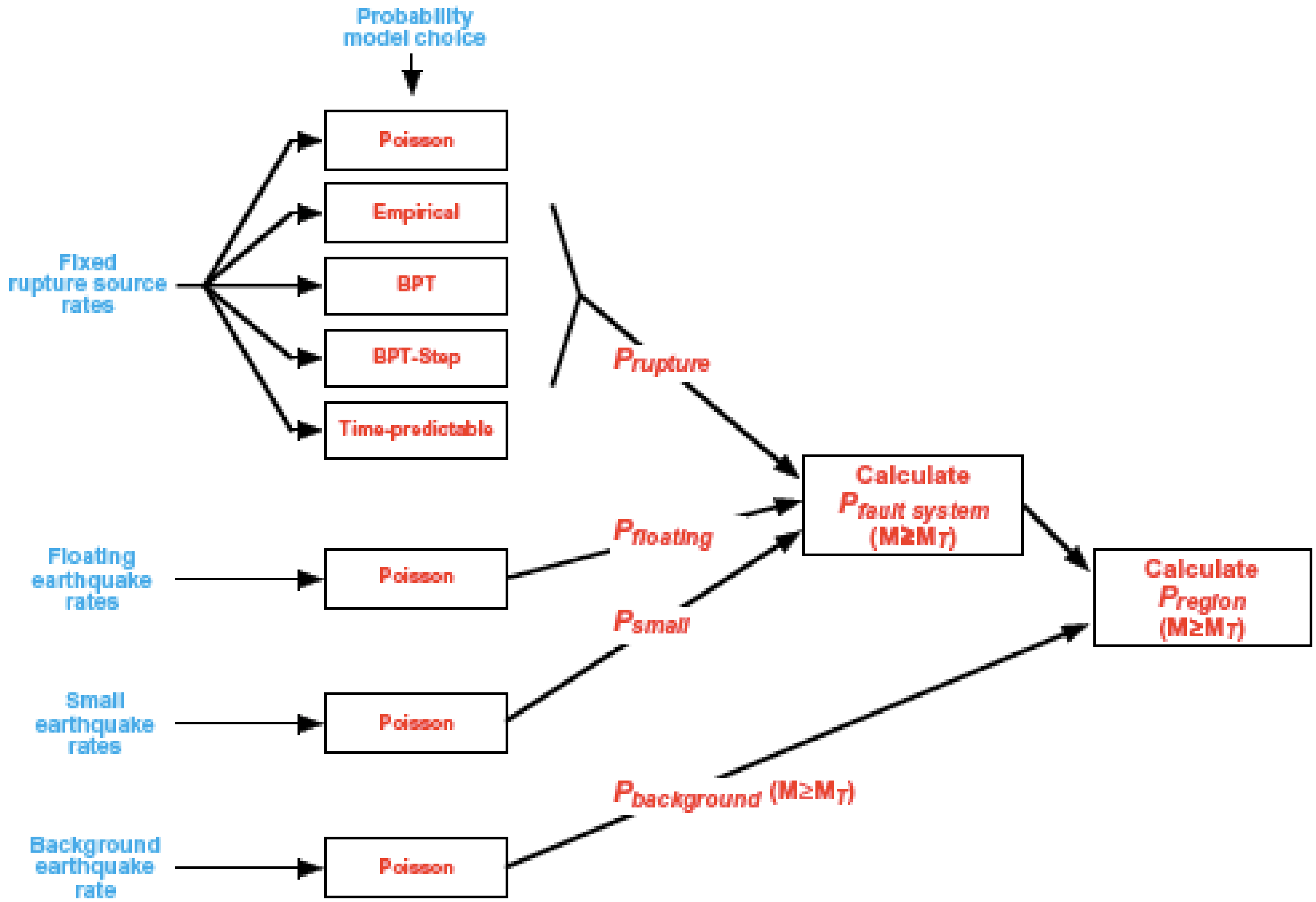
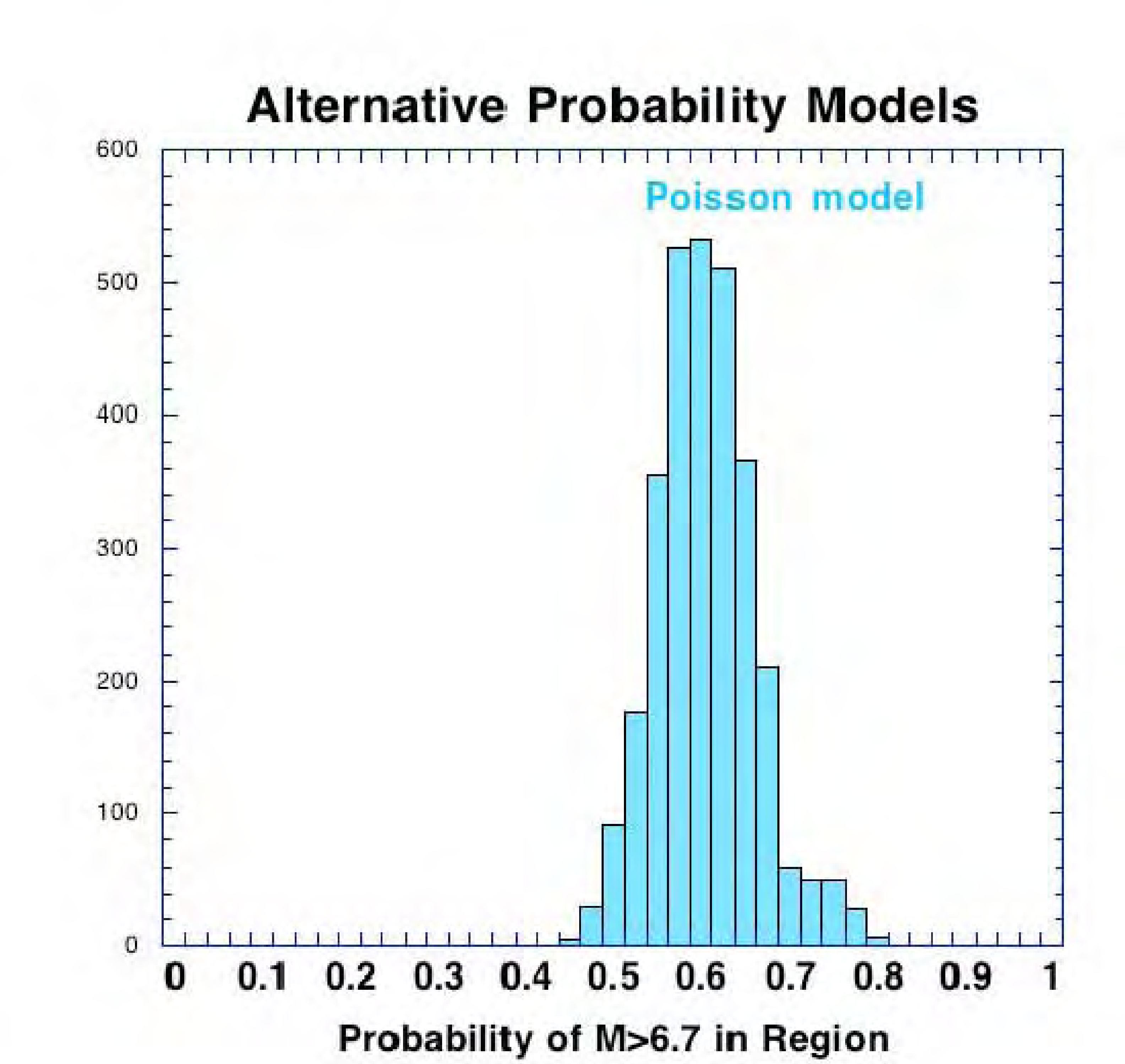
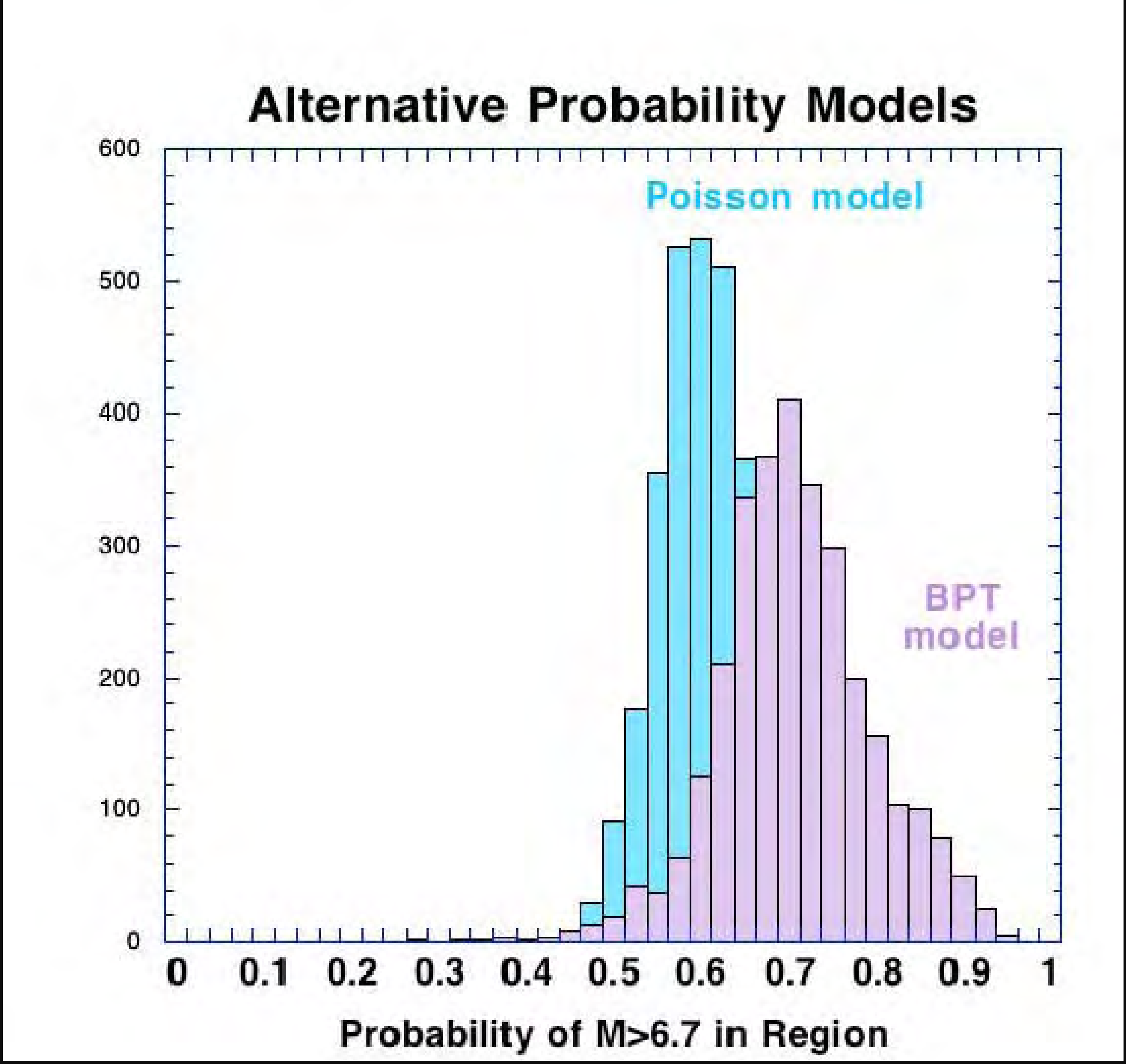


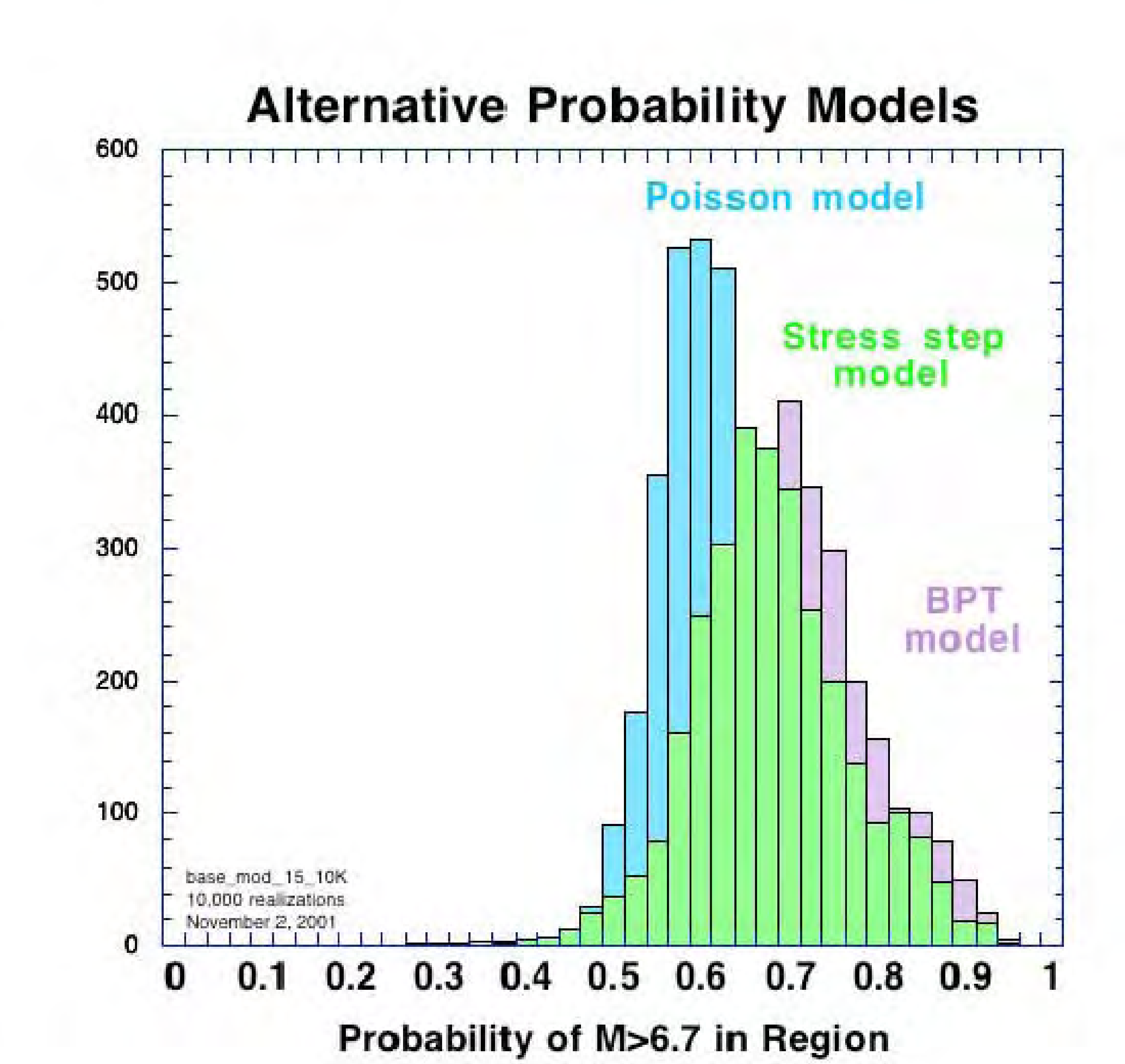
Figure 5.1. Final steps in the calculation sequence, in which time-dependent effects enter into the WG02 model. Long-term rates of fixed rupture sources, floating earthquakes, small earthquakes and background earthquakes are input to a suite of five probability models. Fixed rupture sources are input to all probability models, according weights determined by expert opinion. The other earthquake sources are input only to the Poisson model. Resulting probabilities for the fixed rupture sources, floating sources and small earthquakes are combined for each fault system, for events with magnitude $M \geq M_T$. Finally, the probability of background earthquakes is combined with the probabilities for fault systems to give the regional earthquake probability.



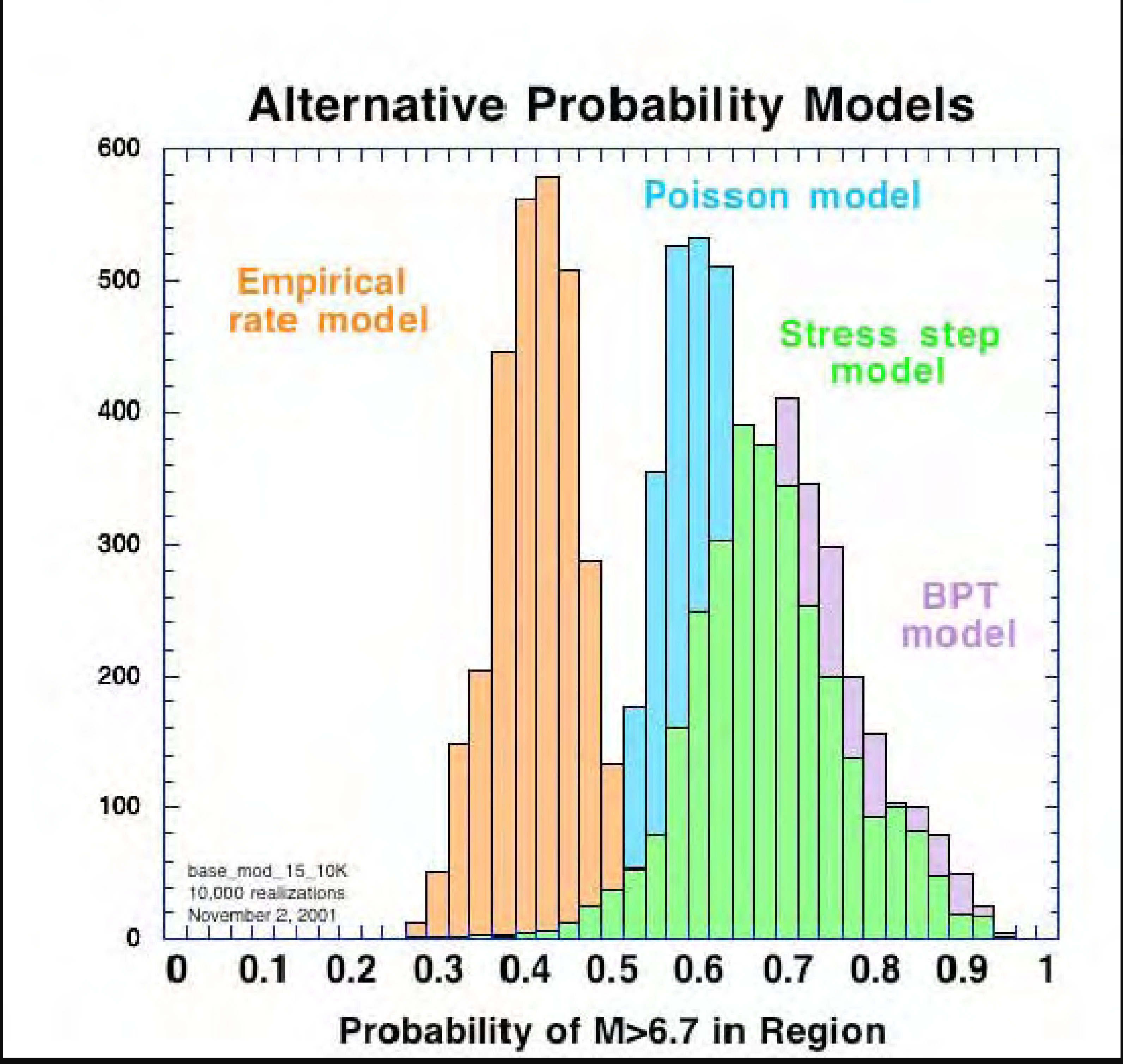
Alternative Probability Models
Poisson model
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability of M>6.7 in Region



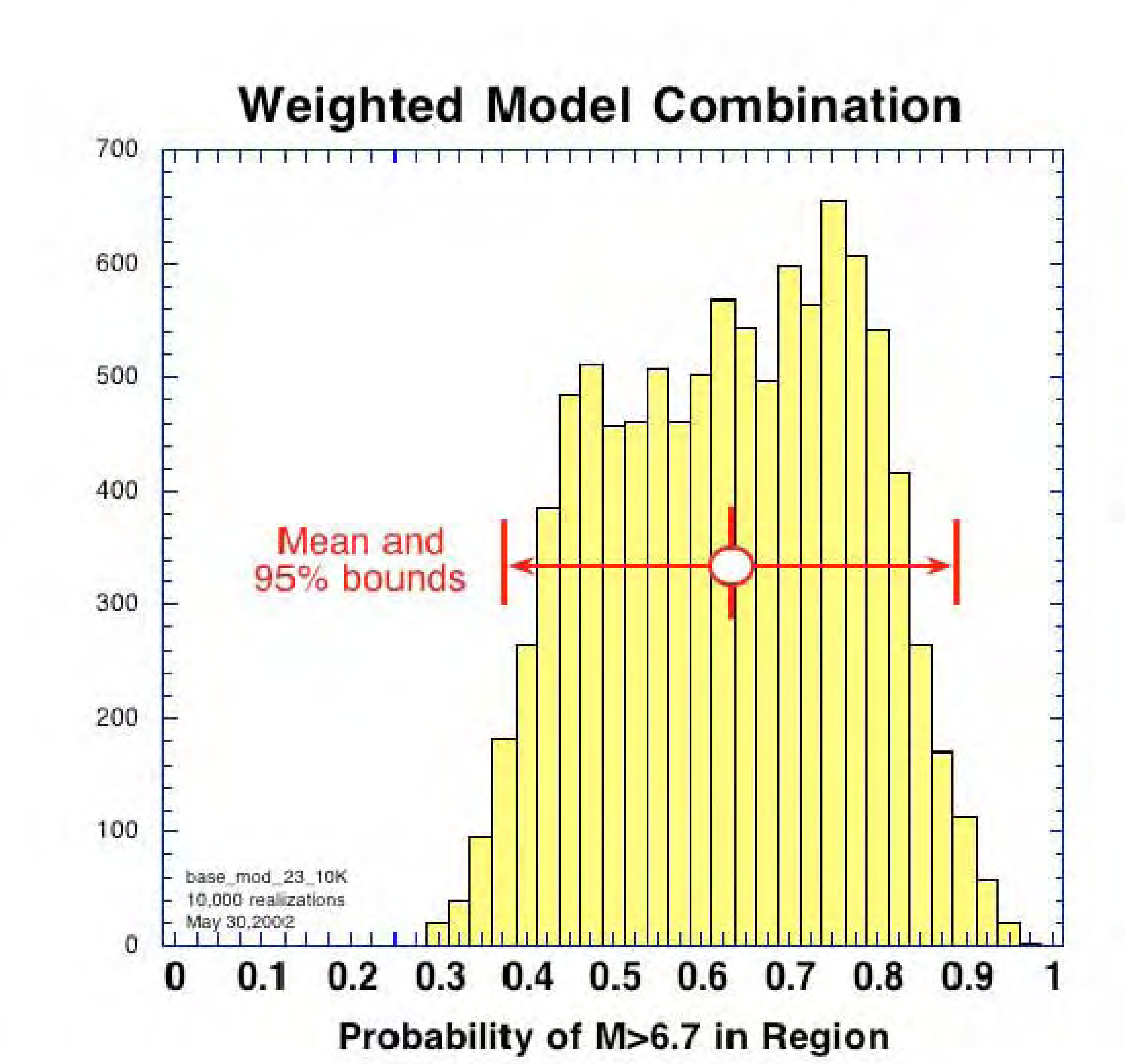
Alternative Probability Models
Poisson model
BPT model
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability of M>6.7 in Region



Alternative Probability Models
Poisson model
Stress step model
BPT model
base_mod_15_10K
10,000 realizations
November 2, 2001
0
100
200
300
400
500
600
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability of M>6.7 in Region



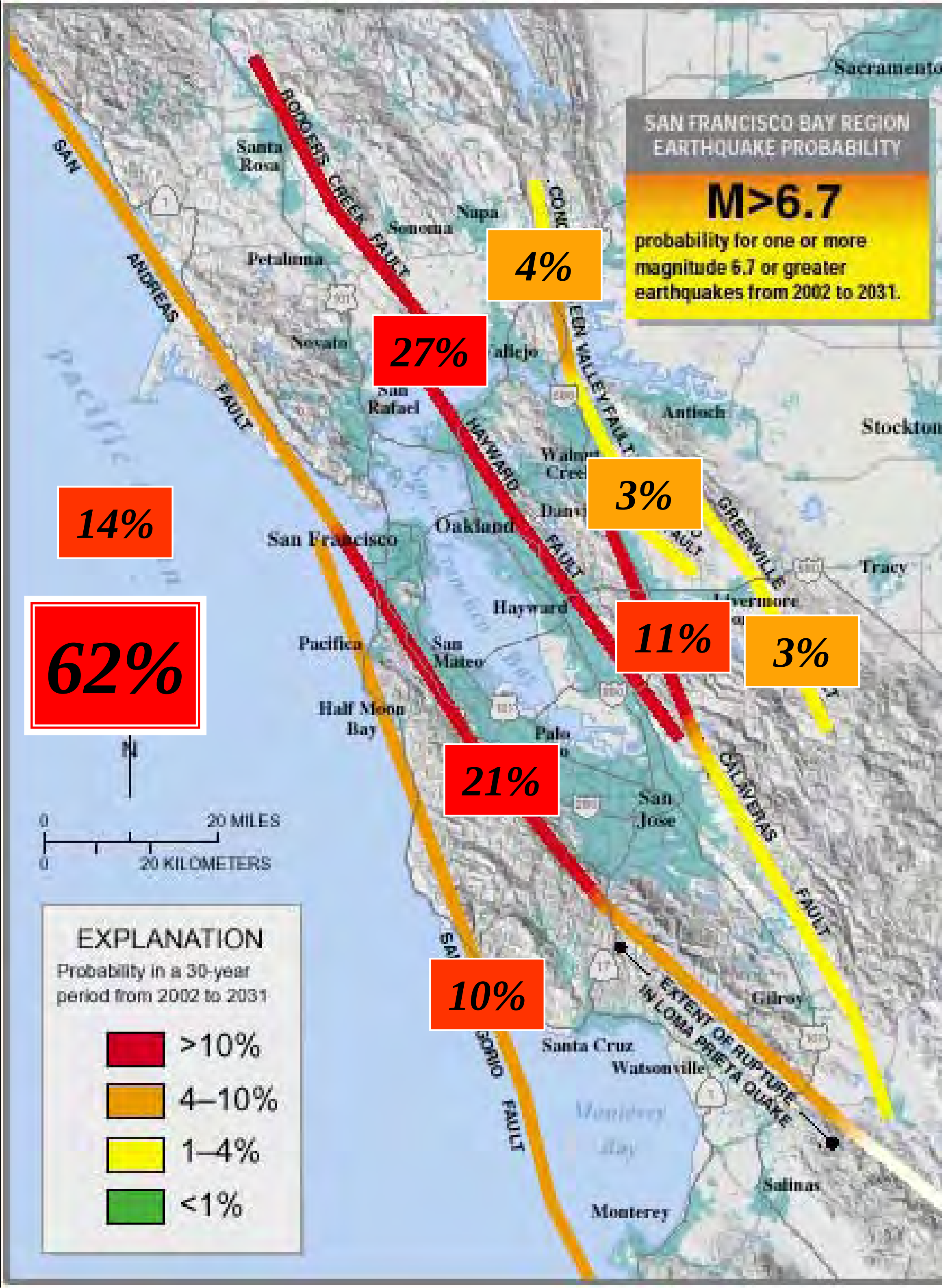
Alternative Probability Models
Poisson model
Empirical rate model
Stress step model
BPT model
base_mod_15_10K
10,000 realizations
November 2, 2001
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Probability of M>6.7 in Region


Weighted Model Combination
700
600
500
400
300
200
100
0
Mean and
95% bounds
base_mod_23_10K
10,000 realizations
May 30,2002
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Probability of M>6.7 in Region

San Francisco Bay Region Earthquake Probabilities

Probability for one or more M6.7 or greater earthquakes from 2002 to 2031

USGS Open-File Report 03-214



USGS science for a changing world

30-year Probabilities at Different Magnitude Thresholds

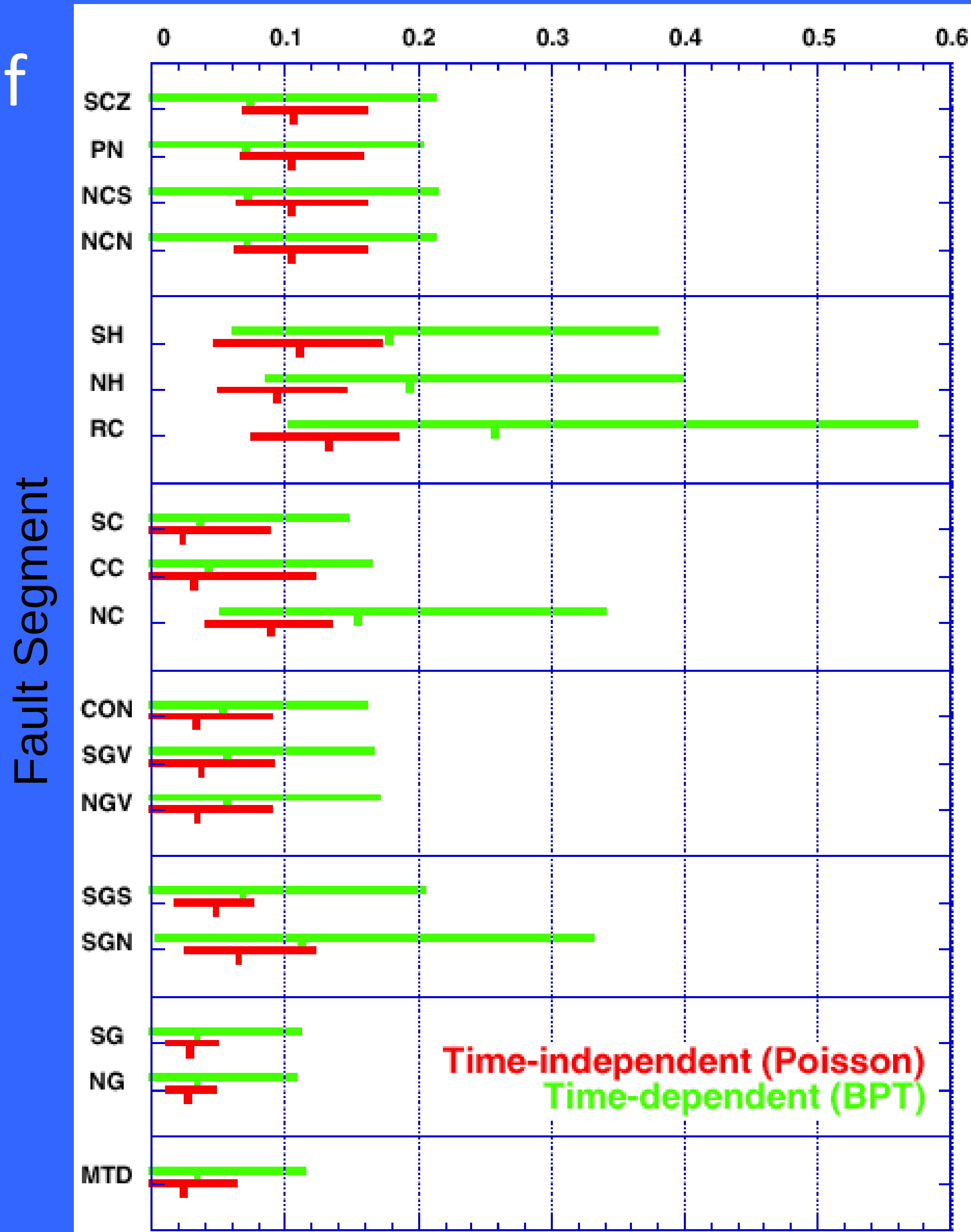
< M6.7	***80%-96%***
≥ M6.7	***62%***
≥ M7	***35%***
≥ M7.5	***10%***

USGS
science for a changing world

30-year Probability of Rupture, M>6.7

Red: **Any** 30 year interval (on average)

Green: The **next** 30 years (2002-2031)

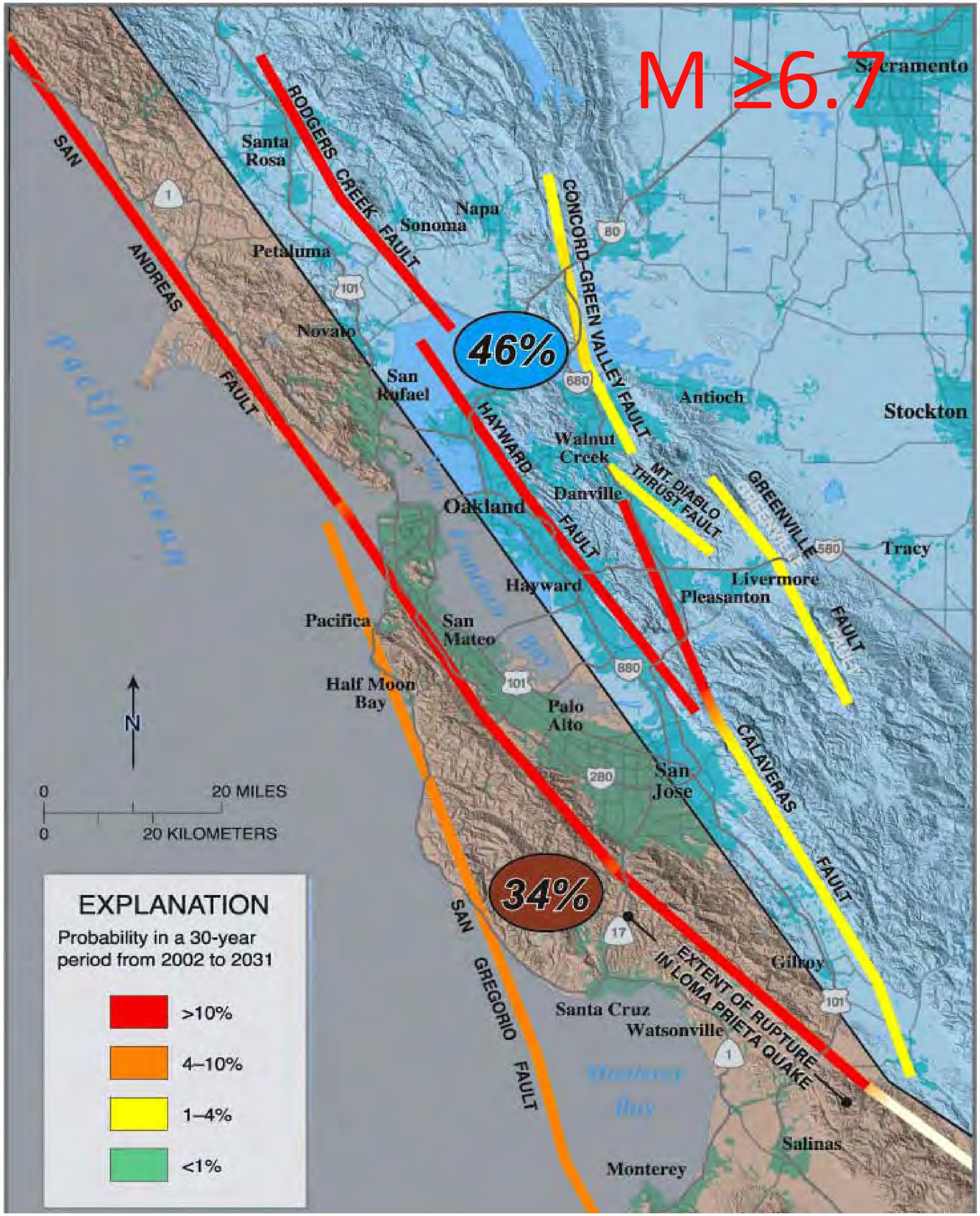


Probabilities for Other Exposure Times

Table 6.2. Probability of $M \geq 6.7$ earthquakes in the SFBR in various exposure times

Exposure Time (years from 2002)	Weighted Models	Poisson Model (Time-independent)
1	0.04 [0.02 - 0.08]	0.03 [0.02 - 0.04]
5	0.16 [0.07 - 0.32]	0.14 [0.11 - 0.18]
10	0.29 [0.14 - 0.49]	0.26 [0.21 - 0.33]
20	0.49 [0.27 - 0.74]	0.46 [0.37 - 0.55]
30	0.62 [0.38 - 0.85]	0.60 [0.51 - 0.70]
100	–	0.96[1] [0.92 - 0.99]

1. Equivalently, the number of $M \geq 6.7$ earthquakes expected in the SFBR in 100 years is 3.1 [2.4 – 4.1]


M ≥6.7
Sacramento
Santa Rosa
Napa
Sonoma
Petaluma
Novato
San Rafael
Antioch
Stockton
Walnut Creek
Danville
Oakland
Tracy
Livermore
Pleasanton
Hayward
Pacifica
San Mateo
Half Moon Bay
Palo Alto
San Jose
Gilroy
Santa Cruz
Watsonville
Salinas
Monterey
Pacific Ocean
SAN ANDREAS FAULT
RODGERS CREEK FAULT
CONCORD–GREEN VALLEY FAULT
HAYWARD FAULT
MT. DIABLO THRUST FAULT
GREENVILLE FAULT
CALAVERAS FAULT
SAN GREGORIO FAULT
EXTENT OF RUPTURE IN LOMA PRIETA QUAKE
46%
34%
1
80
101
680
580
880
280
17
N
0
20 MILES
0
20 KILOMETERS
EXPLANATION
Probability in a 30-year period from 2002 to 2031
>10%
4–10%
1–4%
<1%

Conclusions from Working Group 2002

- Damaging earthquakes are likely in the coming years and decades
- 62% chance of a Northridge-sized event in 30 years
- Moderate-sized (M>6) quakes very likely (80–90+%)
- M>7.5 earthquakes less likely but possible (10%)
- Shaking hazard is high throughout the region
- Potential shaking is strongest along the Bay margins

WG03 (OFR 03-214)

All faults characterized using same method

Segmentation models; multi-segment ruptures

Uncertainty in segment boundaries, overlapping ruptures, ± L

Rupture scenarios weighted by expert groups from available data

Floating (unsegmented) earthquake based on historical seismicity

Recurrence was modeled; slip rates drive recurrence

Recurrence, MRE, and range of P models give time-dependent probability

UCERF 08 (OFR 07-1437)

Faults modeled as A faults and B faults for statewide consistency; classification based on level of available recurrence data

A faults: segmented, multi-segment rupture scenarios, fixed boundaries:recurrence from paleoseismic data: use of MRE; time-dependent probabilities

B faults: no segmentation ; Mmax from rupture area: 67% of moment in Mmax, 33% in exponential distribution to M6.5; recurrence from slip rate; time-independent probabilities

Greenville, Concord-Green Valley, San Gregorio, Mt. Diablo re-classified as B faults

FAULT	WG 03 2002-2031	UCERF 08 2007-2036
San Andreas	21	21
Hayward-Rodgers Creek	27	31
Calaveras	11	7
San Gregorio	10	6
Greenville	3	3
Concord-Green Valley	4	3
Mt. Diablo	3	1
Background	14	--
Bay Area Cumulative	62	63

Products: What are you going to give the public?

Community buy-in: subgroups, broader involvement

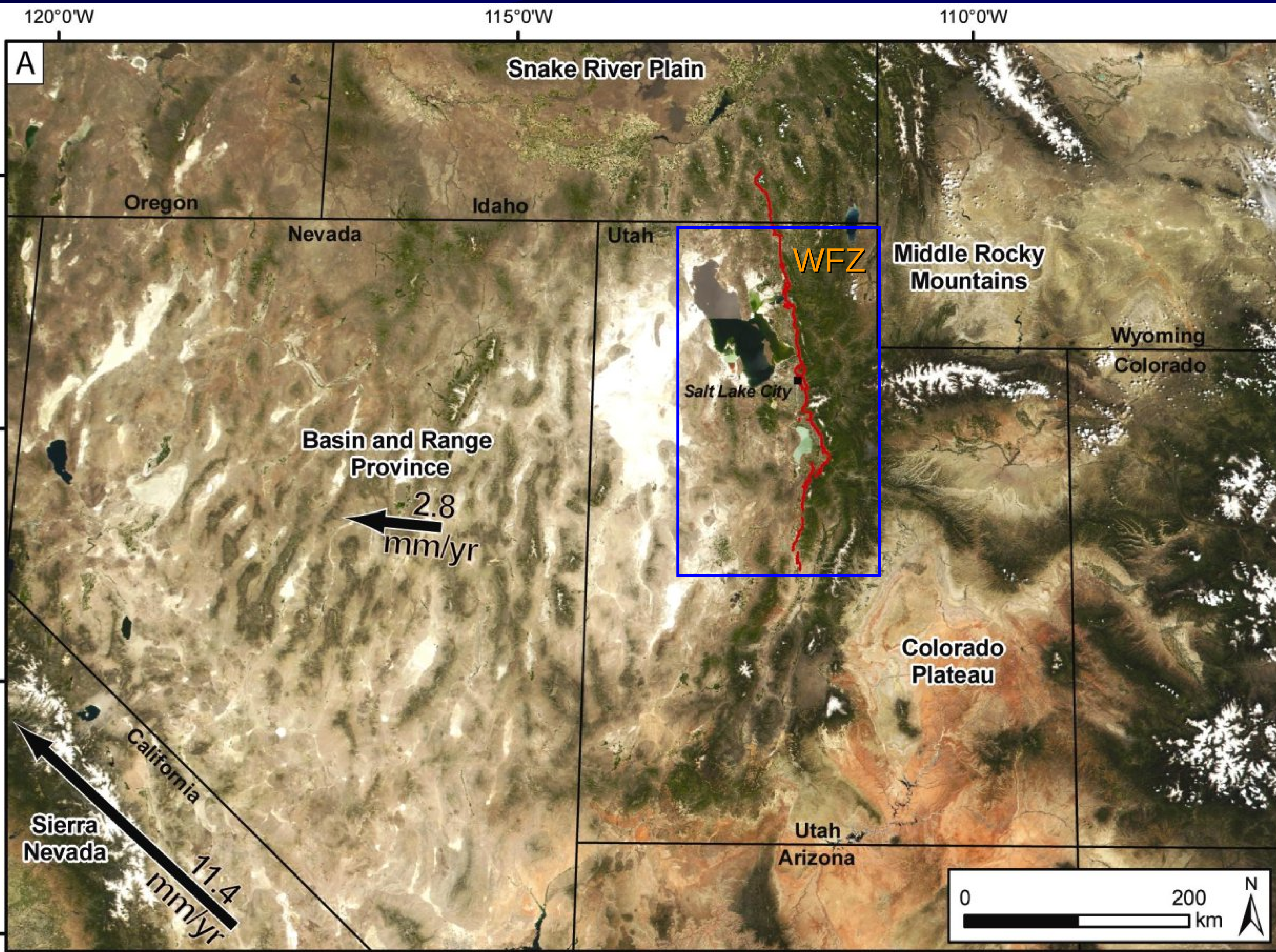
Transparency/reproducibility

Review process

Overview of the Wasatch Fault Zone

Chris DuRoss (UGS)

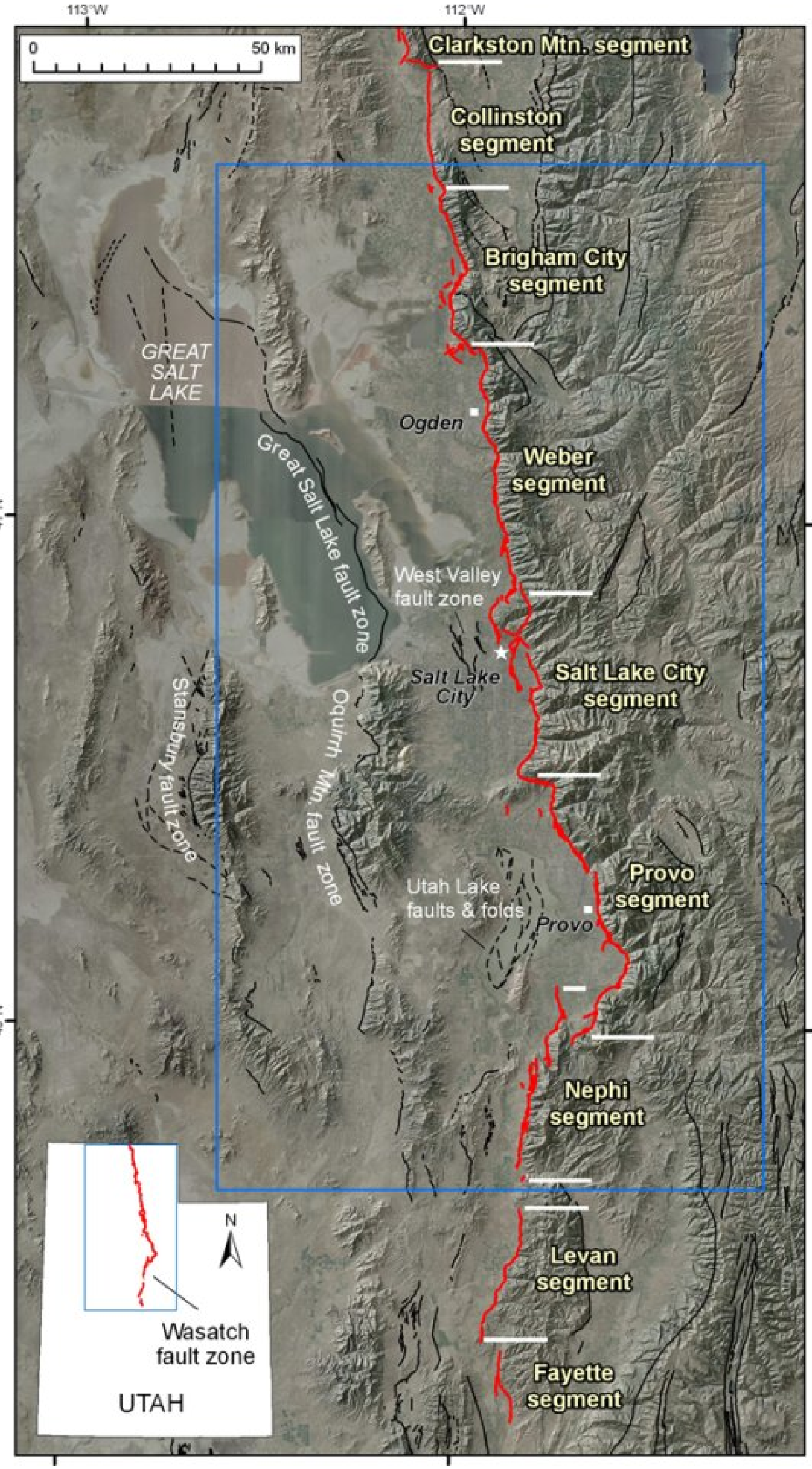
2010 Working Group on Utah Earthquake Probabilities


120°0'W
115°0'W
110°0'W
42°0'N
40°0'N
38°0'N
36°0'N
A
Snake River Plain
Oregon
Idaho
Nevada
Utah
WFZ
Middle Rocky
Mountains
Wyoming
Colorado
Salt Lake City
Basin and Range
Province
2.8
mm/yr
California
Sierra
Nevada
11.4
mm/yr
Colorado
Plateau
Utah
Arizona
0
200
km
N

Wasatch fault zone

- Length
  - 340 km (straight line)
  - 383 km (surface trace)

- 10 segments
  - Northern segments
    - No Holocene surface faulting
  - Central segments (outlined in blue)
    - Repeated Holocene earthquakes
  - Southern segments
    - Some Holocene faulting, but not multiple Holocene events(?)



Outline

I. Central segments
  - Fault geometry & length
  - Paleoseismic data (most recent earthquake [MRE], recurrence and slip-rate estimates)
  - Questions/issues

II. Southern segments

III. Northern segments

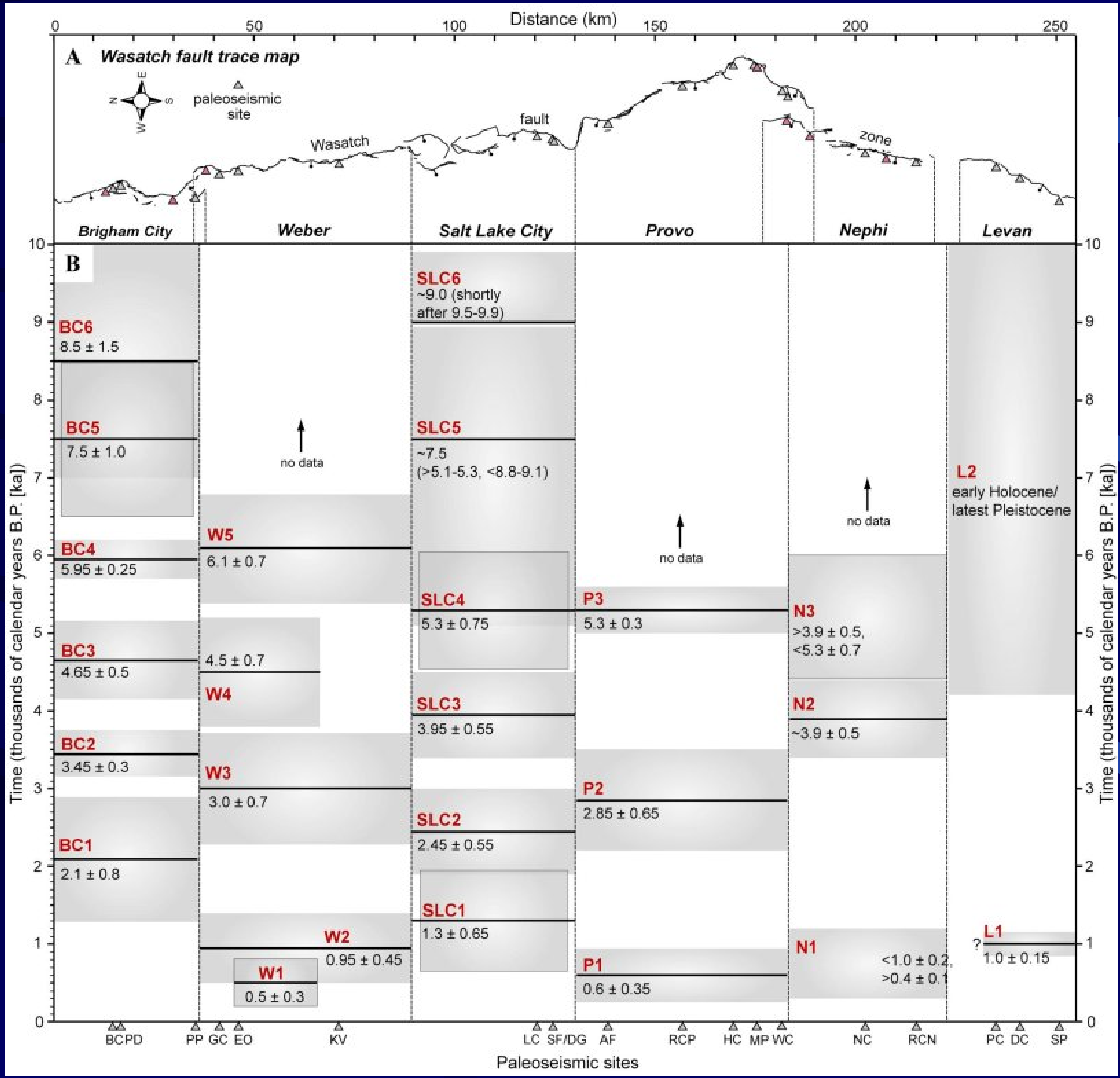
Central segments

Central segments

- 35–60 km long
- Subsurface dip
  - 30–50° (bedrock faults, seismic data) (Gilbert 1928; Smith & Bruhn, 1984)
  - 60–90° (fault trenching)
- Paleoseismic evidence
  - Repeated Holocene earthquakes
  - Average repeat time ~300 yr (~20 earthquakes in 5.6 ky)

WFZ earthquake history (~2004)

- Utah Quaternary Fault Parameters WG (Lund, 2005)
  - Consensus earthquake times
  - Average recurrence (per segment): 1.3–2.5 ky
  - Average slip rate (per segment): 1.1–1.4 mm/yr



New WFZ investigations (2004–present)

- 3 published trench reports
  - Weber segment (1)
  - Nephi segment (2)

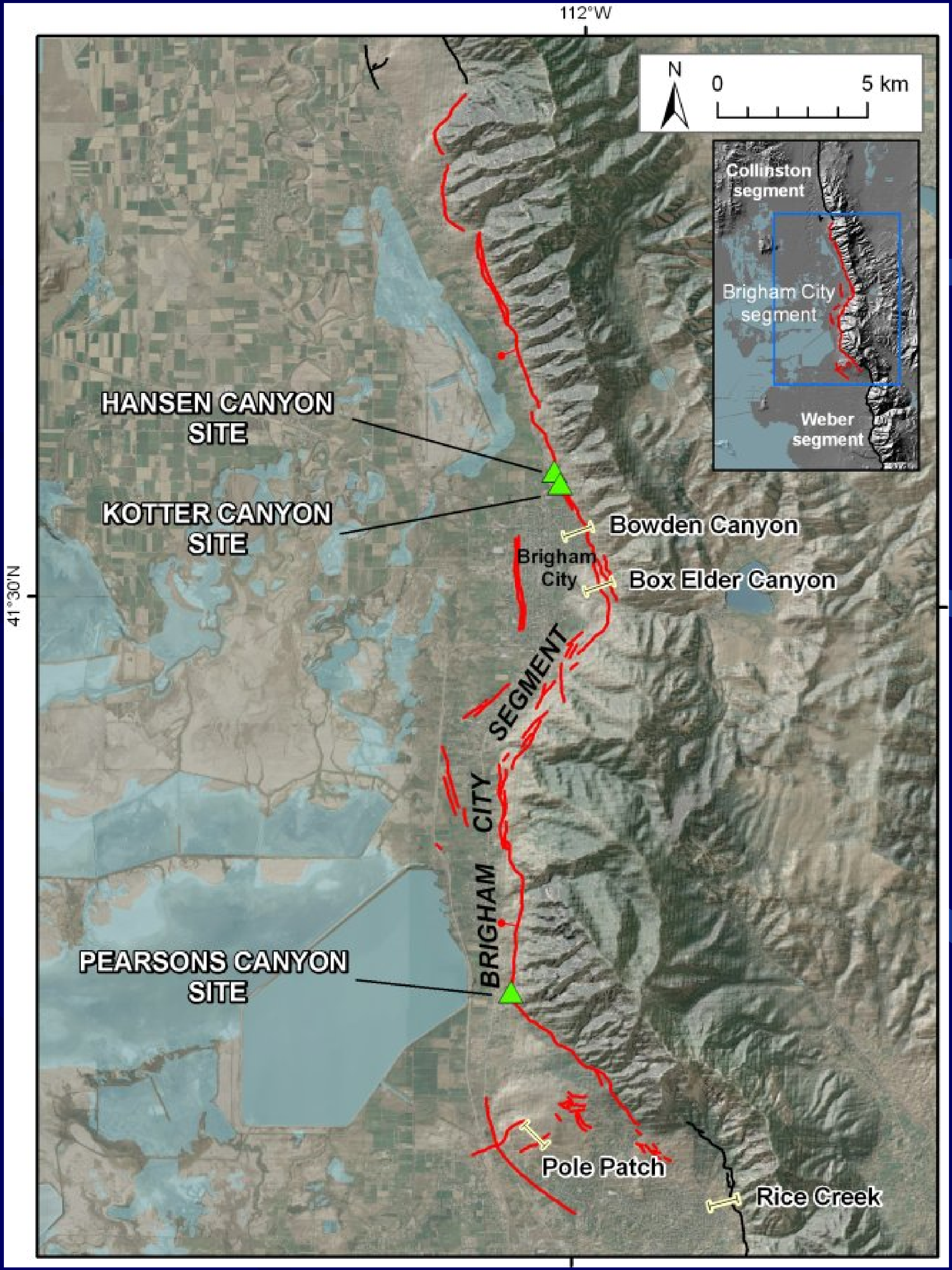
- 5 completed, but unpublished studies
  - Brigham City segment (3)
  - Provo segment (1)
  - Nephi segment (1)

- 2 upcoming studies
  - Salt Lake City/West Valley fault zone (1)
  - Nephi (1)

Brigham City segment

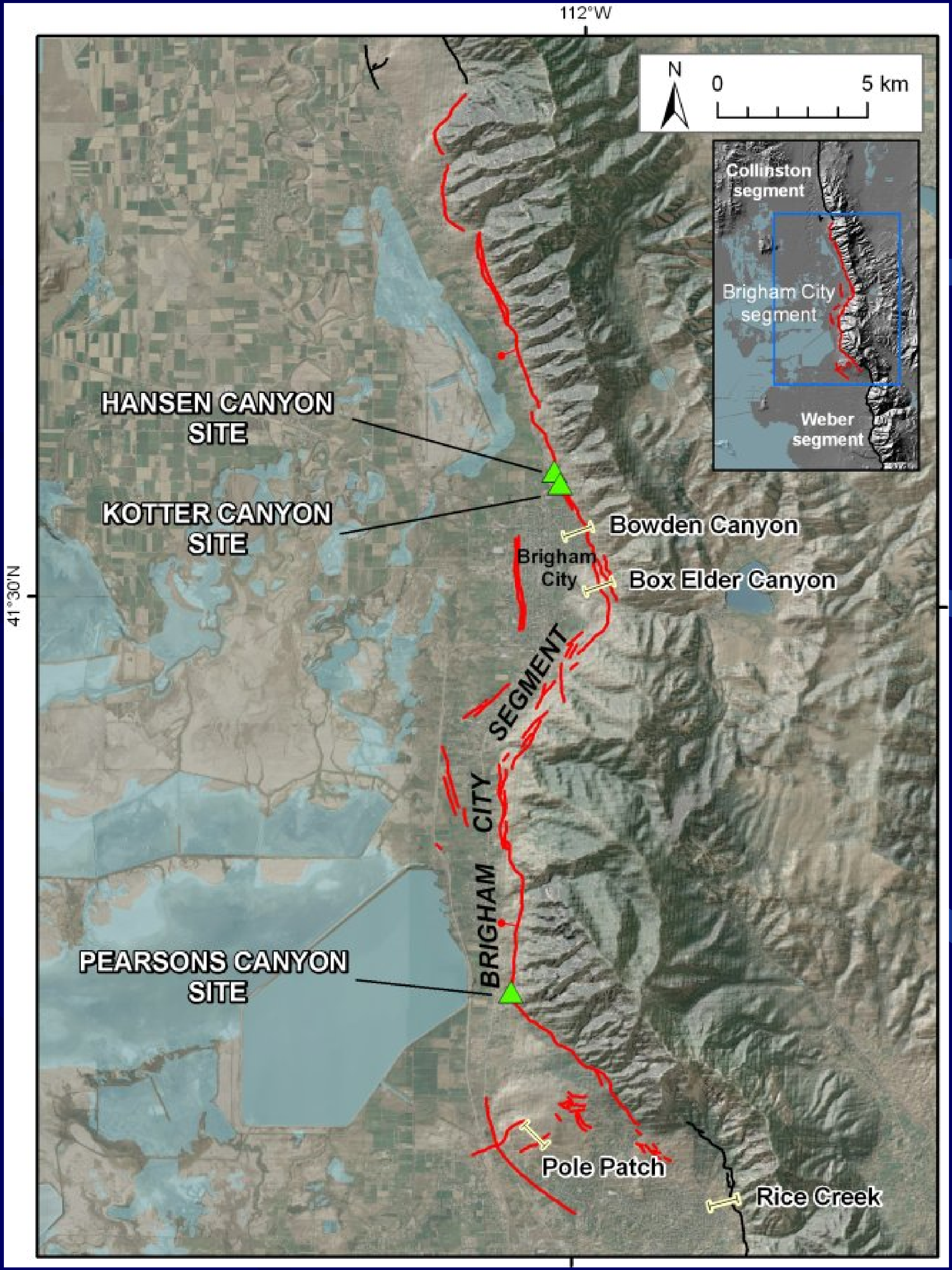
Brigham City segment

- Length
  - 36 km (straight line)
  - 40 km (trace length)
- Segment boundaries (Personius, 1990)
  - North: range-front reentrant
  - South: 1.5 km left step with Weber segment, Pleasant View salient



Paleoseismic Studies

- Paleoseismic studies (north to south)
  - Hansen Canyon (DuRoss et al., in prep [2008])
  - Kotter Canyon (DuRoss et al., in prep [2008])
  - Bowden Canyon (Personius, 1991)
  - Box Elder Canyon (McCalpin & Forman, 2002
  - Pearsons Canyon (DuRoss et al., in prep [2008])
  - Pole Patch (Personius, 1991)



Paleoseismic data (~2004)

- Earthquake timing & recurrence
  - MRE: 2.1 ka (Box Elder Canyon only)
  - Six Holocene earthquakes; average recurrence: 1.3 ky
- Displacement and slip rate
  - 1.7 ± 0.8 m (1σ) / event (5 observations)
  - Interval slip rates: average 0.8–1.9 mm/yr (BC5–BC2)
  - Average slip rates:
    - 0.2–1.4 mm/yr (post-Provo [<14 ka])
    - 1.5–1.6 mm/yr (post Bonneville [<17 ka])

UQFPWG (Lund, 2005)

- BC1 2.1 ± 0.8 ka
- BC2 3.45 ± 0.3 ka
- BC3 4.65 ± 0.5 ka
- BC4 5.95 ± 0.25 ka
- BC5 7.5 ± 1.0 ka
- BC6 8.5 ± 1.5 ka
- BC7 >14.8 ± 1.2, <17 ka
- Holocene recurrence: 0.5–1.3–2.8 ky
- Holocene slip rate: 0.6–1.4–4.5 mm/yr

Paleoseismic data (2008)

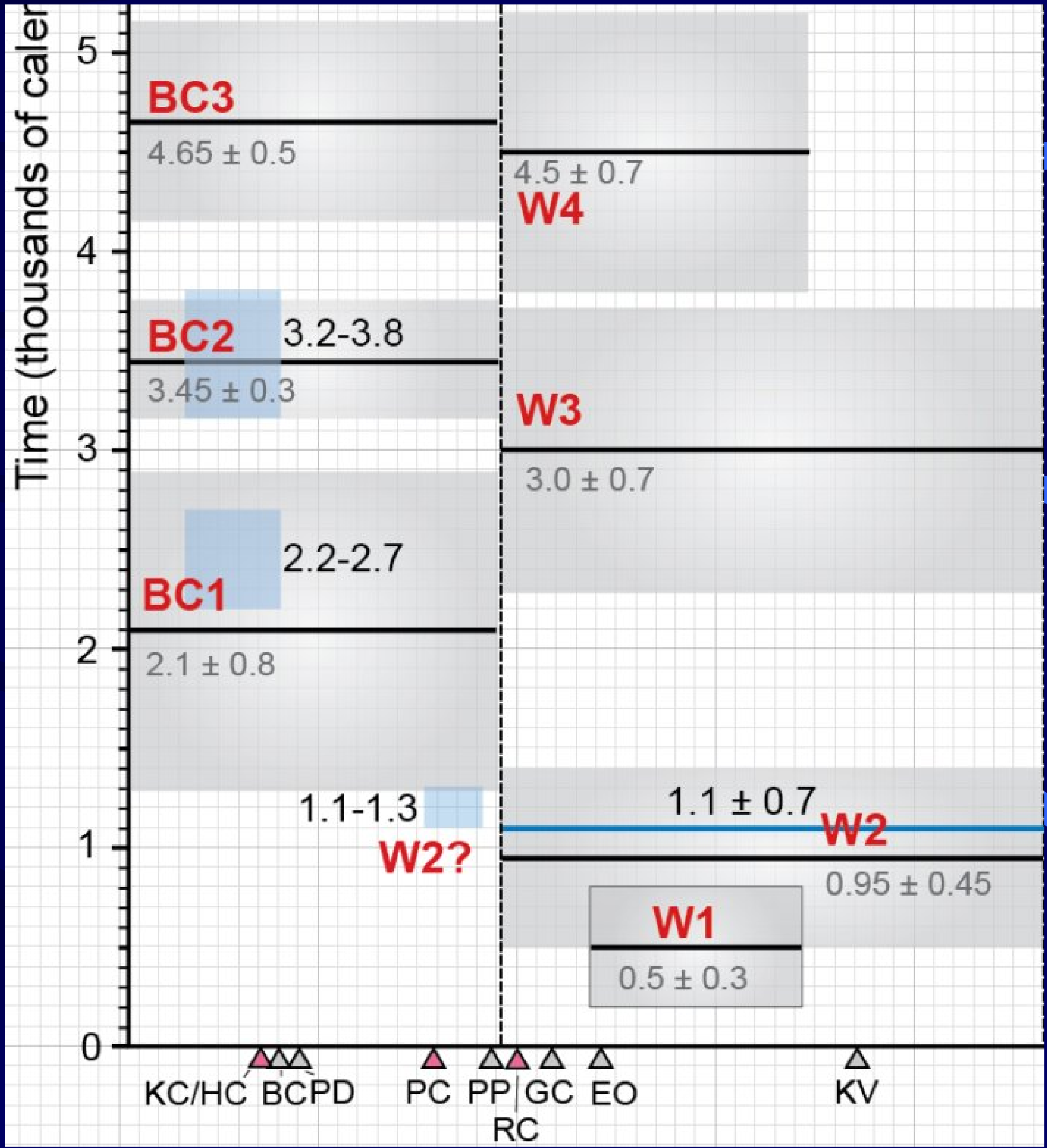
- Hansen Canyon
  - MRE: 1.9–4.8 ka
  - Displacement: 0.6–2.5 m

- Kotter Canyon
  - MRE: 2.2–2.7 ka (2σ--OxCal)
  - 2nd event: 3.2–3.8 ka (2σ--OxCal)
  - Displacement: 0.7–1.9 m / event

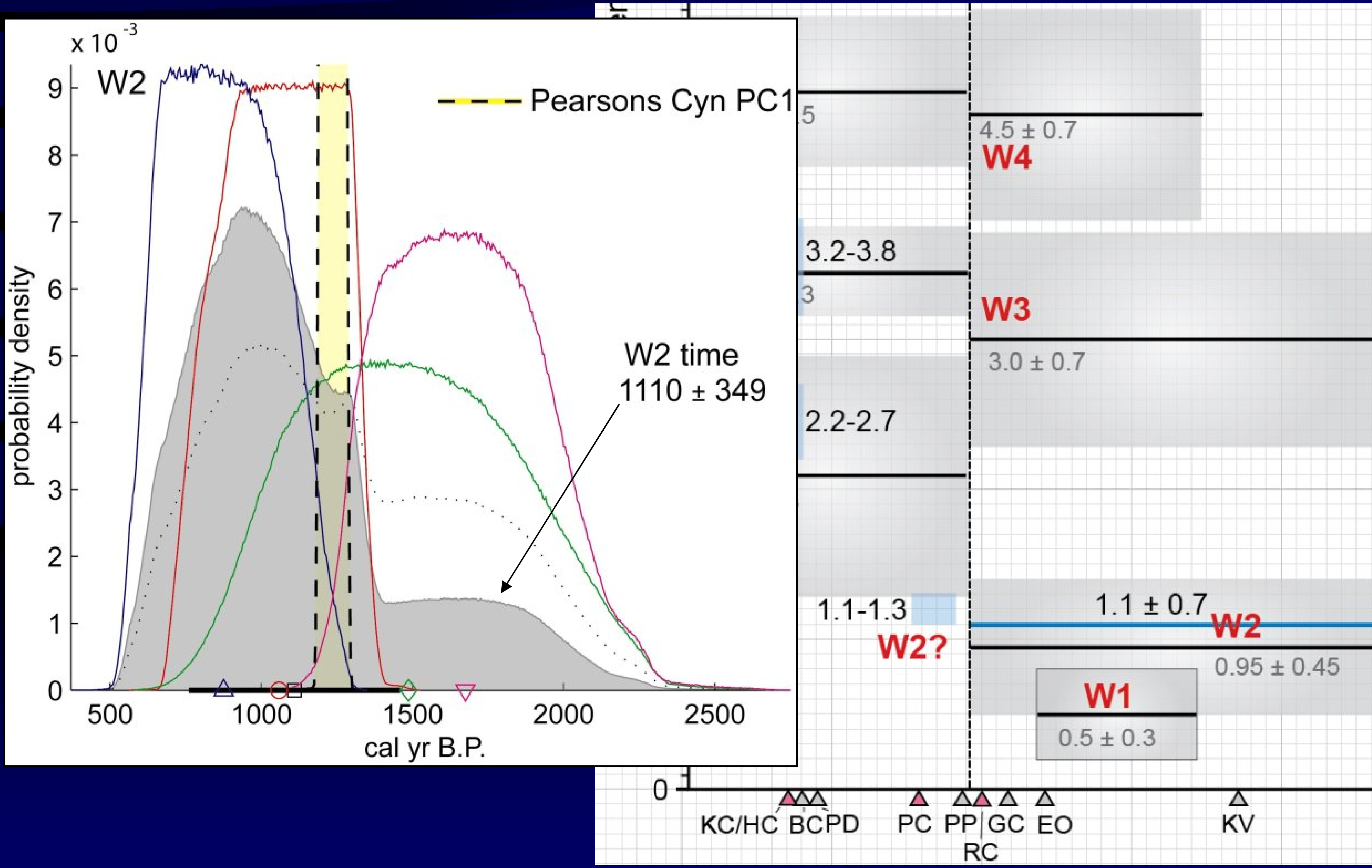
- Pearsons Canyon
  - MRE: 1.1–1.3 ka (~2σ--OxCal)
  - Displacement: 0.1–0.8 m

Comparison with previous data

- Time since MRE:
  - ~2 ka on the northern segment (Hansen, Kotter, & Box Elder Canyons)
  - 1.1–1.3 ka on the southern segment (Pearsons Canyon)
- Extent of 1.1–1.3-ka rupture? Spillover from Weber segment earthquake W2?



Comparison with previous data



Segmentation

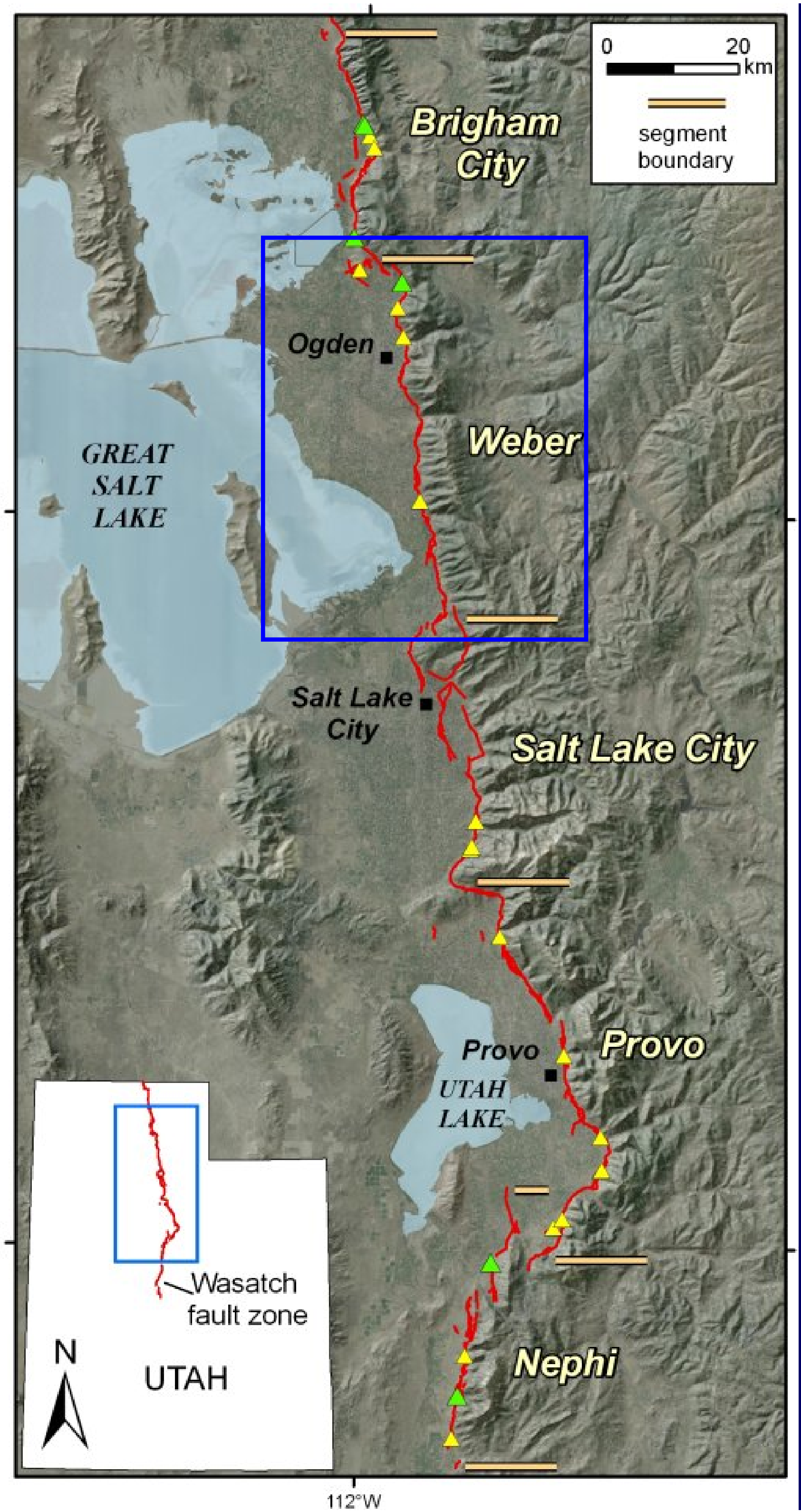
- Southern 6–9 km of Brigham City segment rupture in Weber segment earthquake W2 (1.1 ± 0.4 ka)?

Oblique view to the northeast

Brigham City summary

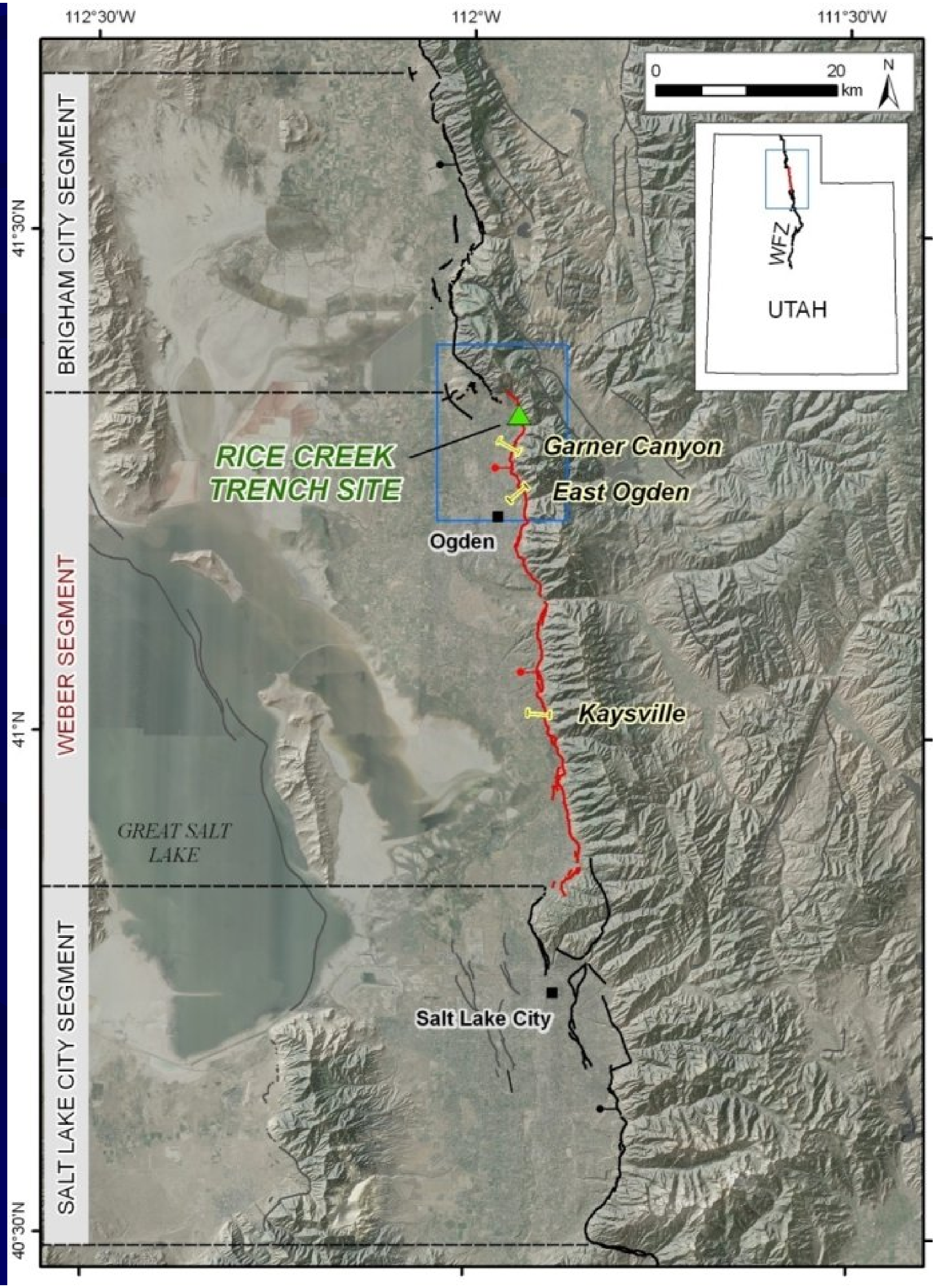
- Early Holocene record (BC7–BC5) from Box Elder Canyon
- Fairly consistent mid-late Holocene record (BC4–BC2) from Kotter, Box Elder, and Pole Patch
- 2008 data support MRE at ~2 ka on northern part of segment
- 1.1–1.3-ka earthquake on southern segment – partial rupture related to Weber segment earthquake?

Weber segment



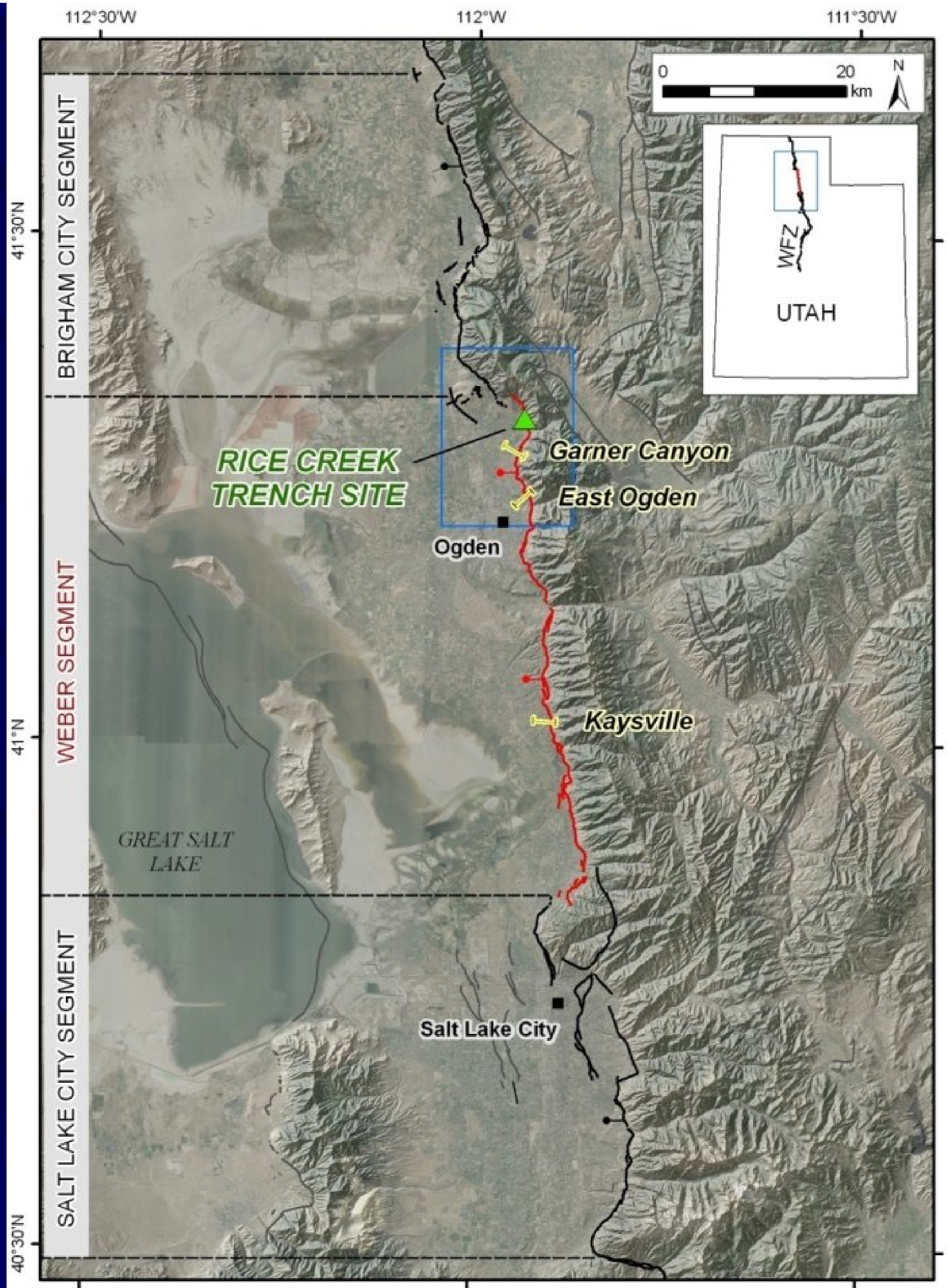
Weber segment

- Length
  - 56 km (straight line)
  - 61 km (surface trace)
- Segment Boundaries (Nelson and Personius, 1993)
  - North: Pleasant View salient
  - South: 2 km right step with Warms Springs fault (Salt Lake City salient)



Weber segment

- Paleoseismic studies
  - Rice Creek (DuRoss et al., 2009)
  - Garner Canyon (Nelson et al., 2006)
  - East Ogden (Nelson et al., 2006)
  - Kaysville (Swan et al., 1980; McCalpin et al., 1994)



Paleoseismic data (~2004)

- Earthquake timing and recurrence
  - MRE: ~0.5 ka (partial rupture?)
  - 3–4 Holocene earthquakes per site
  - Multiple earthquake-correlation possibilities
  - Poorly constrained recurrence (~1.1–1.6 ky depending on event W1)

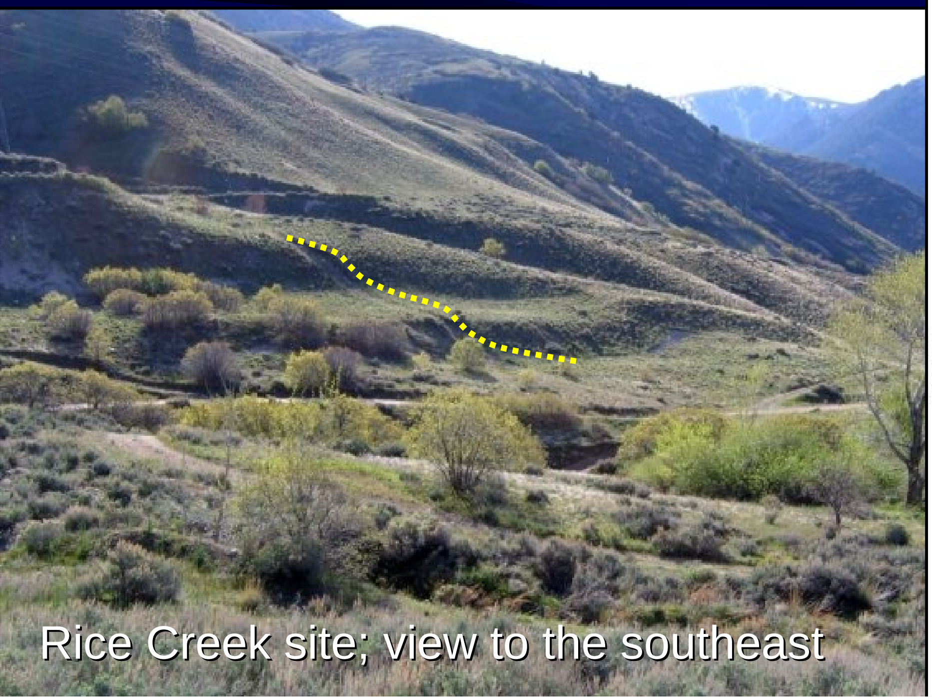
UQFPWG (Lund, 2005)

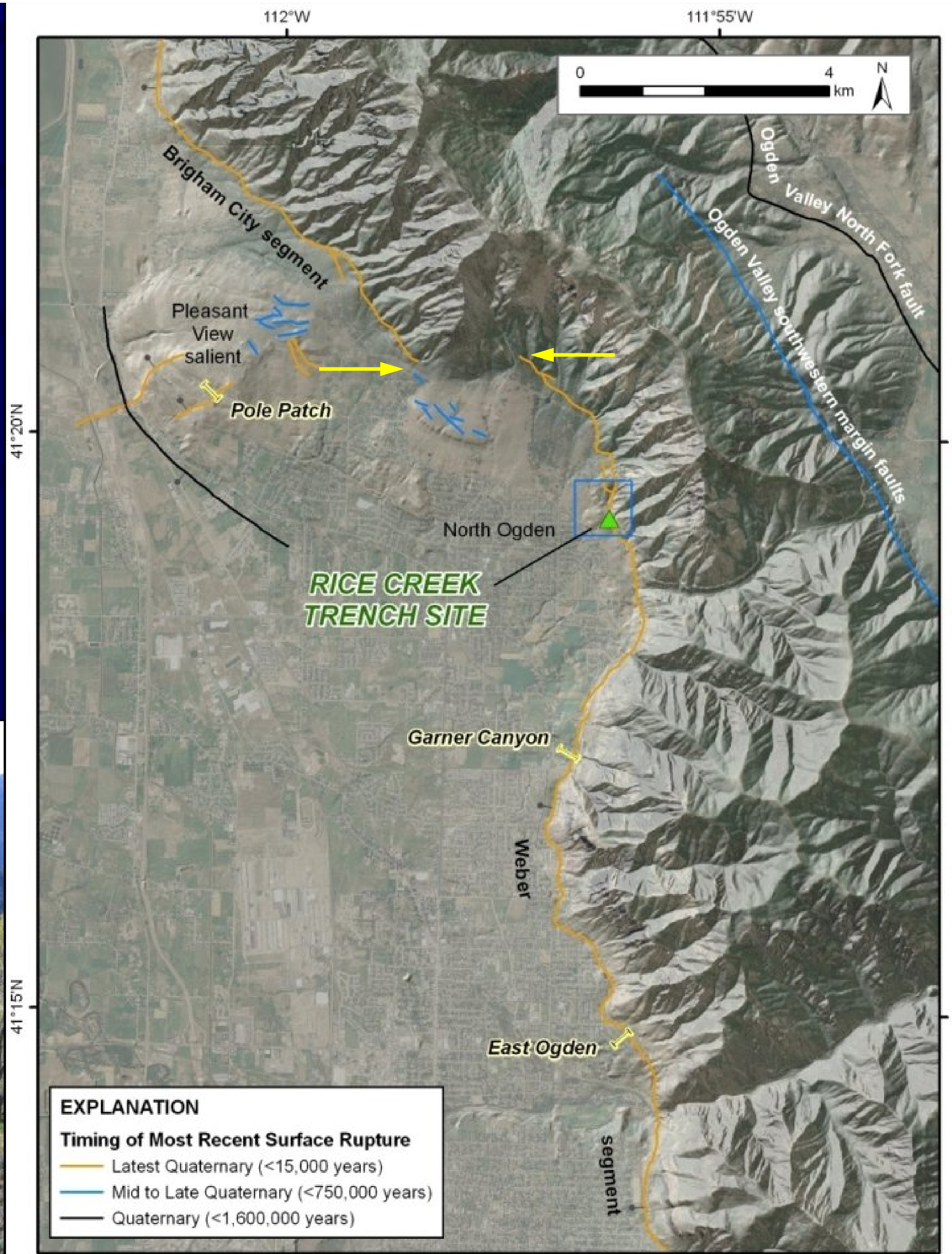
- W1 0.5 ± 0.3 ka (?)
- W2 0.95 ± 0.45 ka
- W3 3.0 ± 0.7 ka
- W4 4.5 ± 0.7 ka
- W5 6.1 ± 0.7 ka
- Holocene recurrence: 0.5–1.4–2.4 ky
- Holocene slip rate: 0.6–1.2–4.3 mm/yr

- Displacement and slip rate
  - 2.1 ± 1.3 m (1σ) / event (10 observations; max: 4.2 m)
  - Average interval slip rates: 0.9–1.9 mm/yr (W5–W2; Kaysville):
  - Longer-term slip rates: 1–3 mm/yr (post-mid-Holocene), 0.8–1.7 mm/yr (post-Provo)

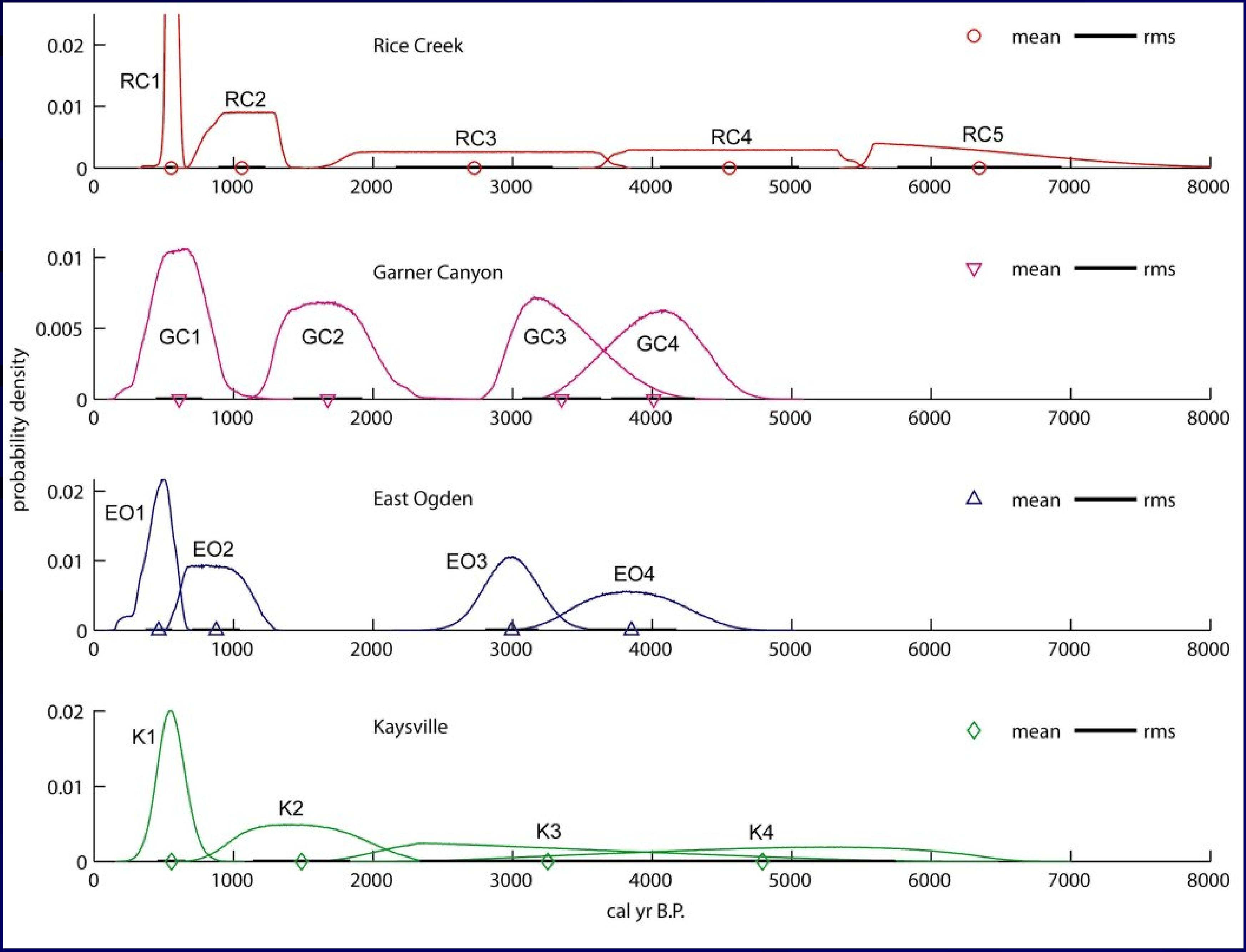
Rice Creek (2007)

- 6 Holocene earthquakes (DuRoss et al., 2009)
  - RC1: 0.5–0.6 ka (2σ)
  - RC2: 0.8–1.4 ka
  - RC3: 1.8–3.7 ka
  - RC4: 3.7–5.4 ka
  - RC5: 5.5–7.5 ka
  - RC6: >8–10 ka

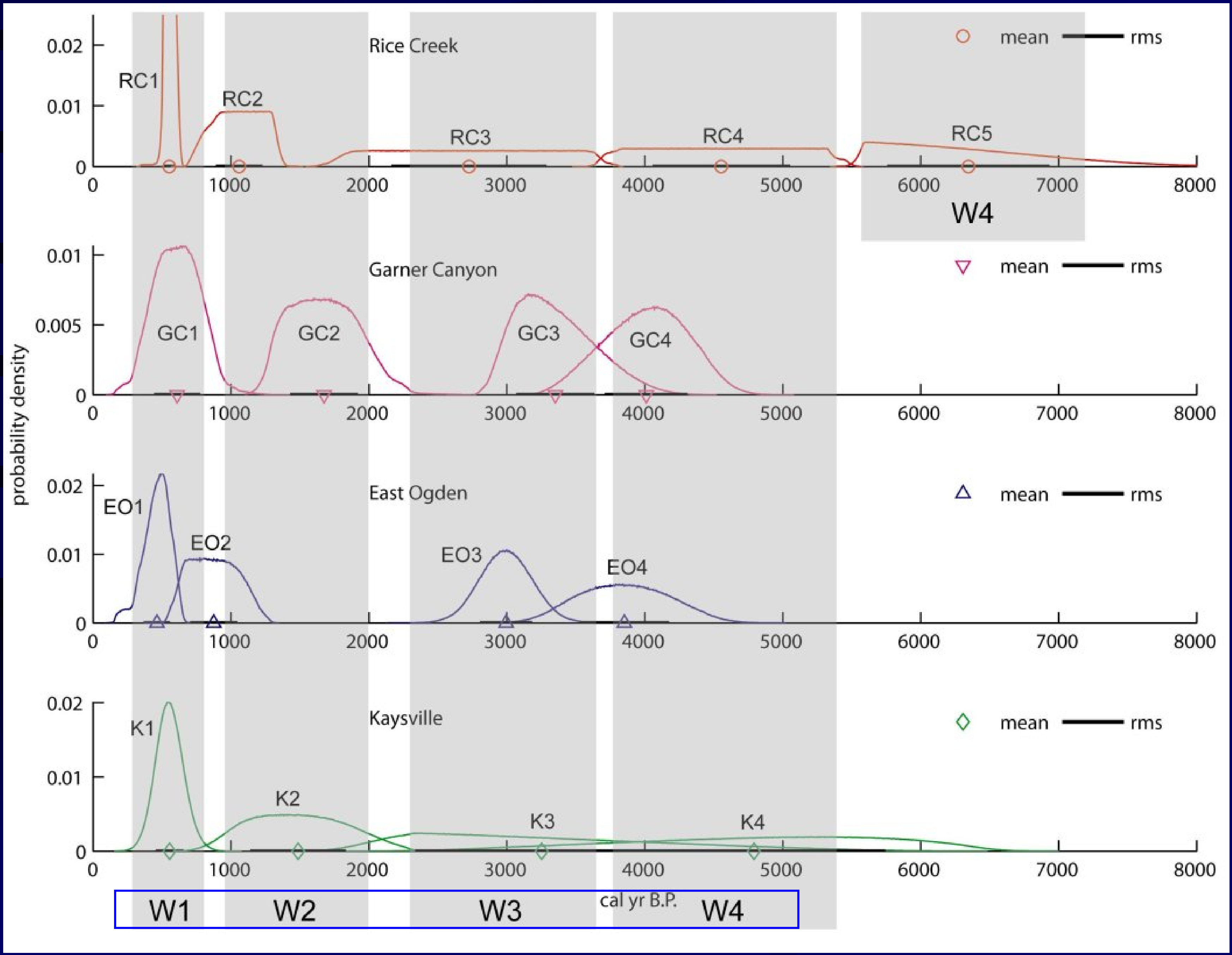

Rice Creek site; view to the southeast



Integrating Weber segment paleoseismic data



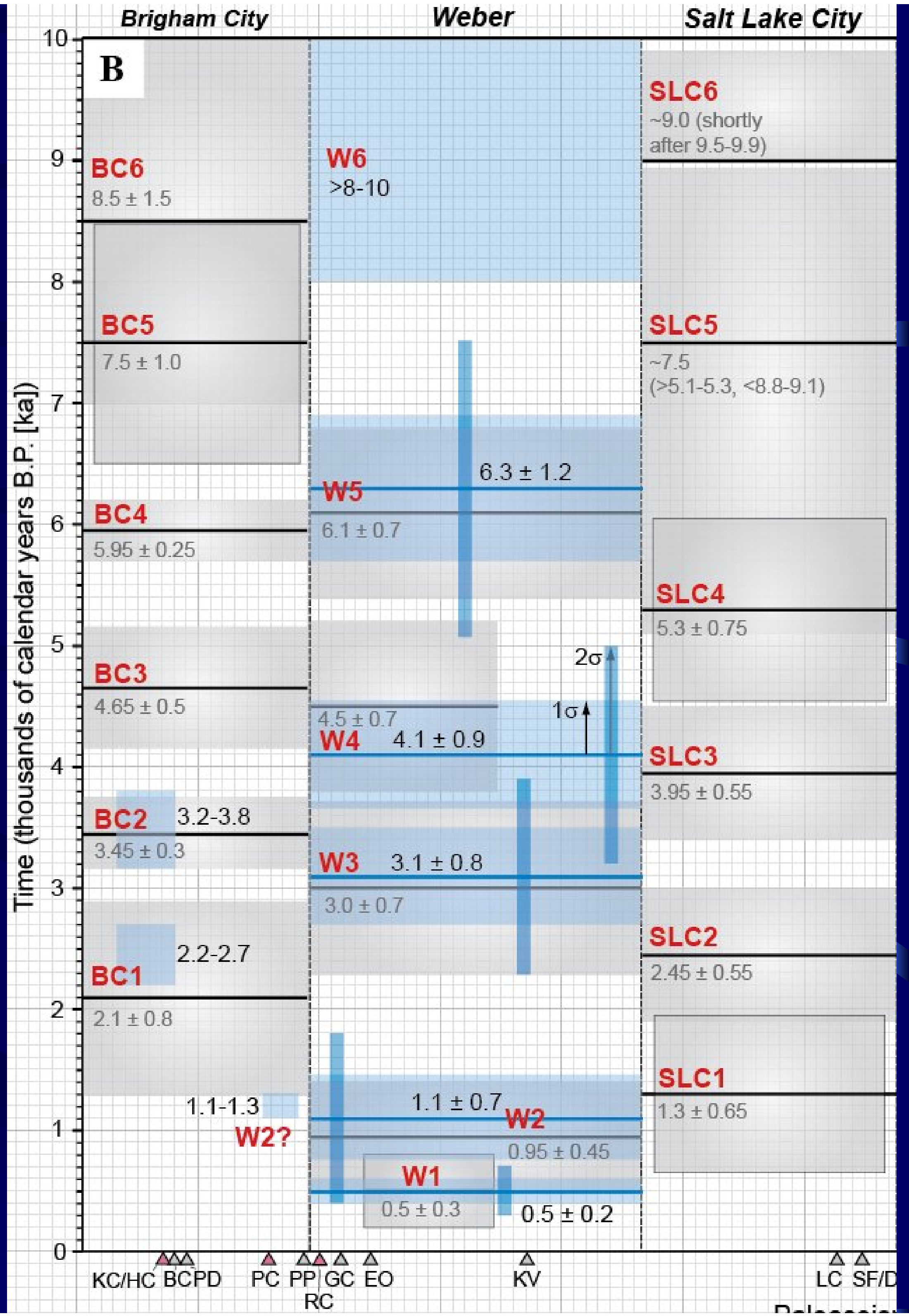
Correlation of site pdfs



Weber segment results

- DuRoss et al., in prep
  - W1 0.5 ± 0.2 ka (2σ)
  - W2 1.1 ± 0.7 ka
  - W3 3.1 ± 0.8 ka
  - W4 4.1 ± 0.9 ka
  - W5 6.3 ± 1.2 ka
  - Recurrence: **1.5 ± 0.9** ky (1σ) (0–3.3 ky--2σ)
  - Slip rate: **2.0 ± 1.3** mm/yr (1σ) (0–4.6 mm/yr--2σ)

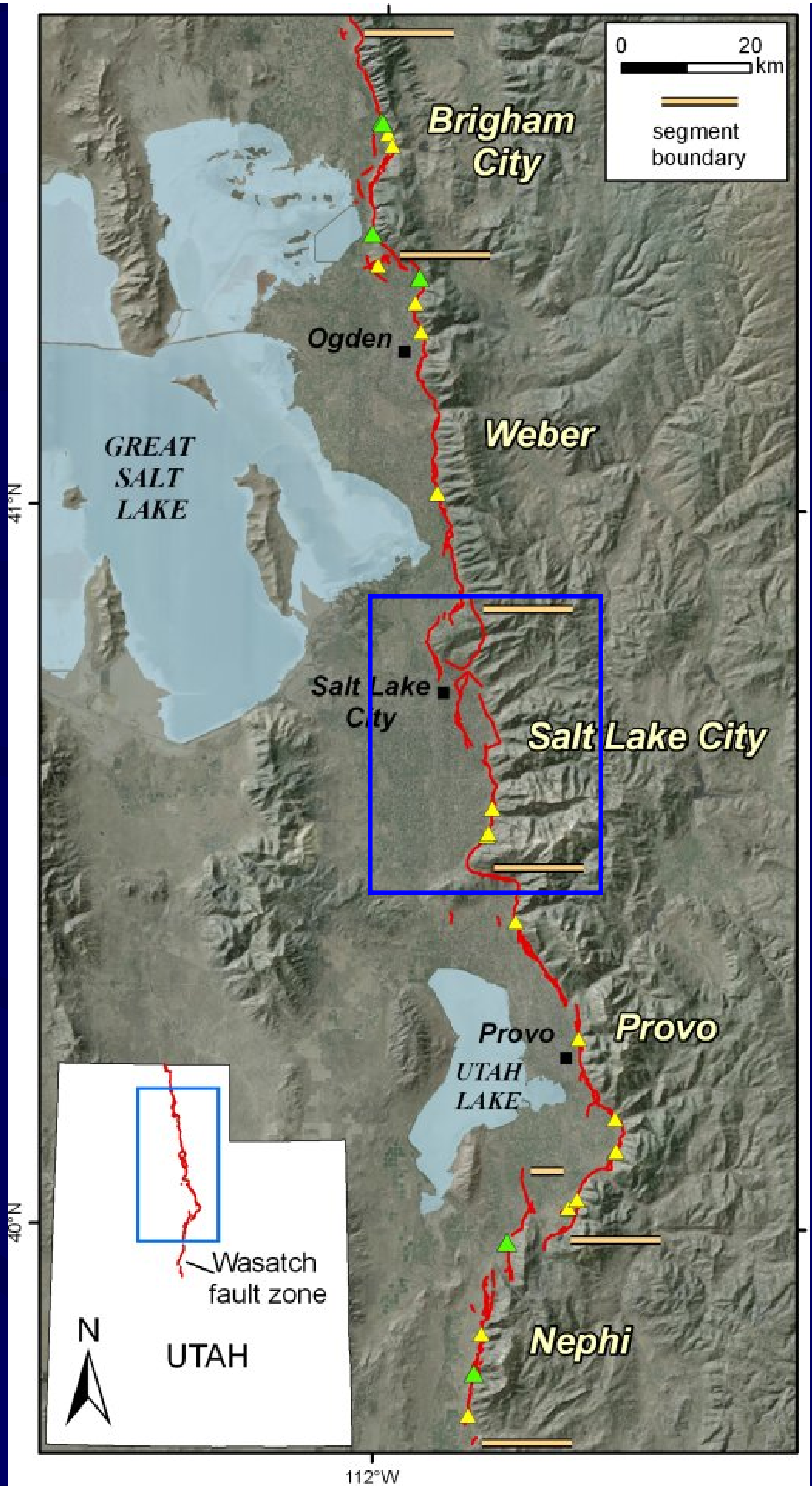
- UQFPWG
  - Recurrence: **1.4** ky (0.5–2.4--2σ)
  - Slip rate: **1.2** mm/yr (0.6–4.3--2σ)



Weber segment summary

- New method to integrate Weber segment paleoseismic data
- Revised paleoearthquake parameters
  - MRE: 500-yr; older earthquake times similar to UQFPWG
  - Recurrence is poorly constrained (1.5 ± 0.9 ky--1σ):
    - Short (~0.5–1 ky) intervals between W2–W1 & W4–W3
    - longer (~2 ky) intervals between W3–W2 & W5–W4
  - Mean interval slip rate is 2.0 ± 1.3 mm/yr (1σ) – consistent with site estimates (~1–3 mm/yr).
- Only single trench site for southern ~45 km of segment

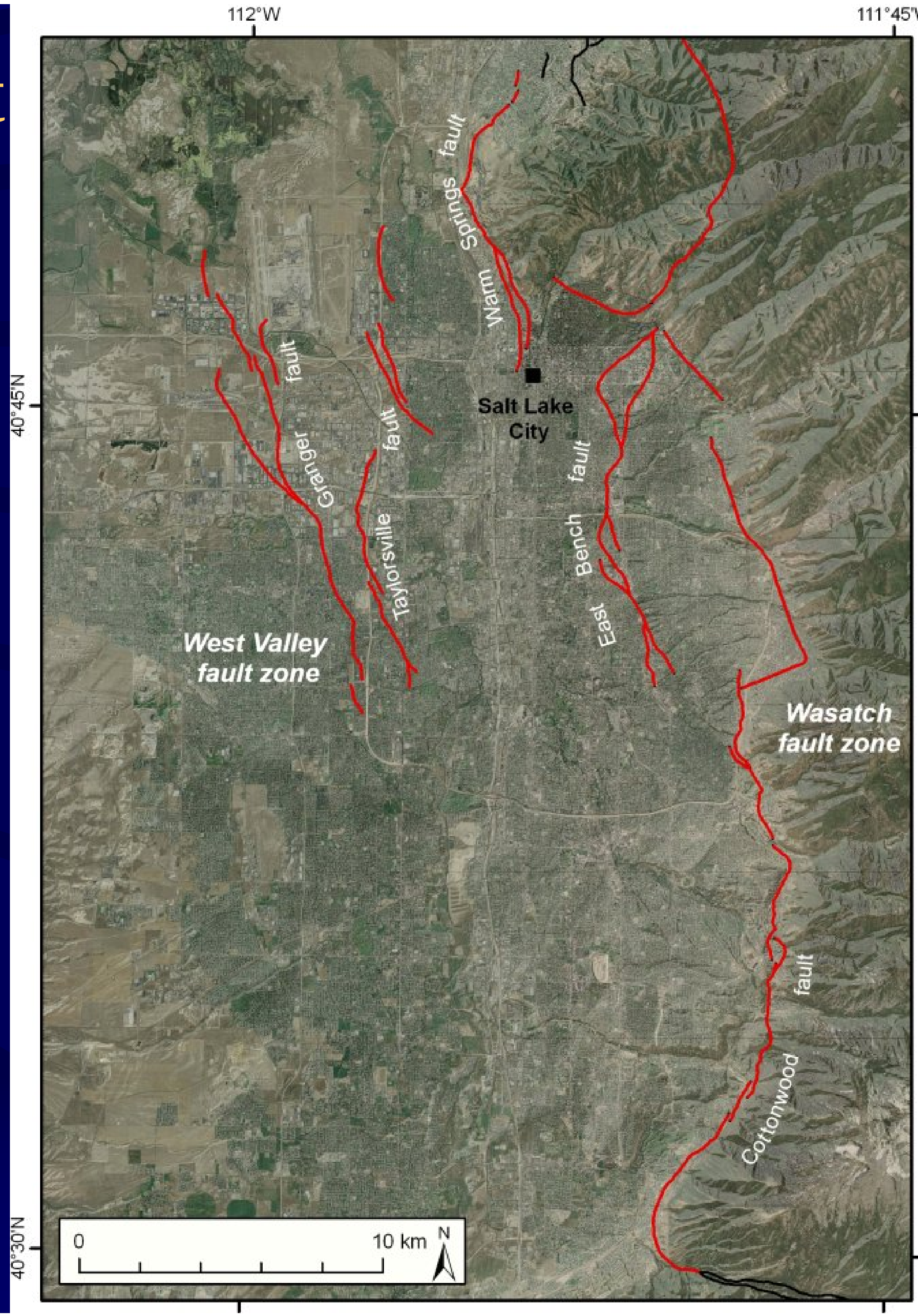
Salt Lake City segment



Salt Lake City segment

- Length
  - 39 km (straight line)
  - 46 km (surface trace)

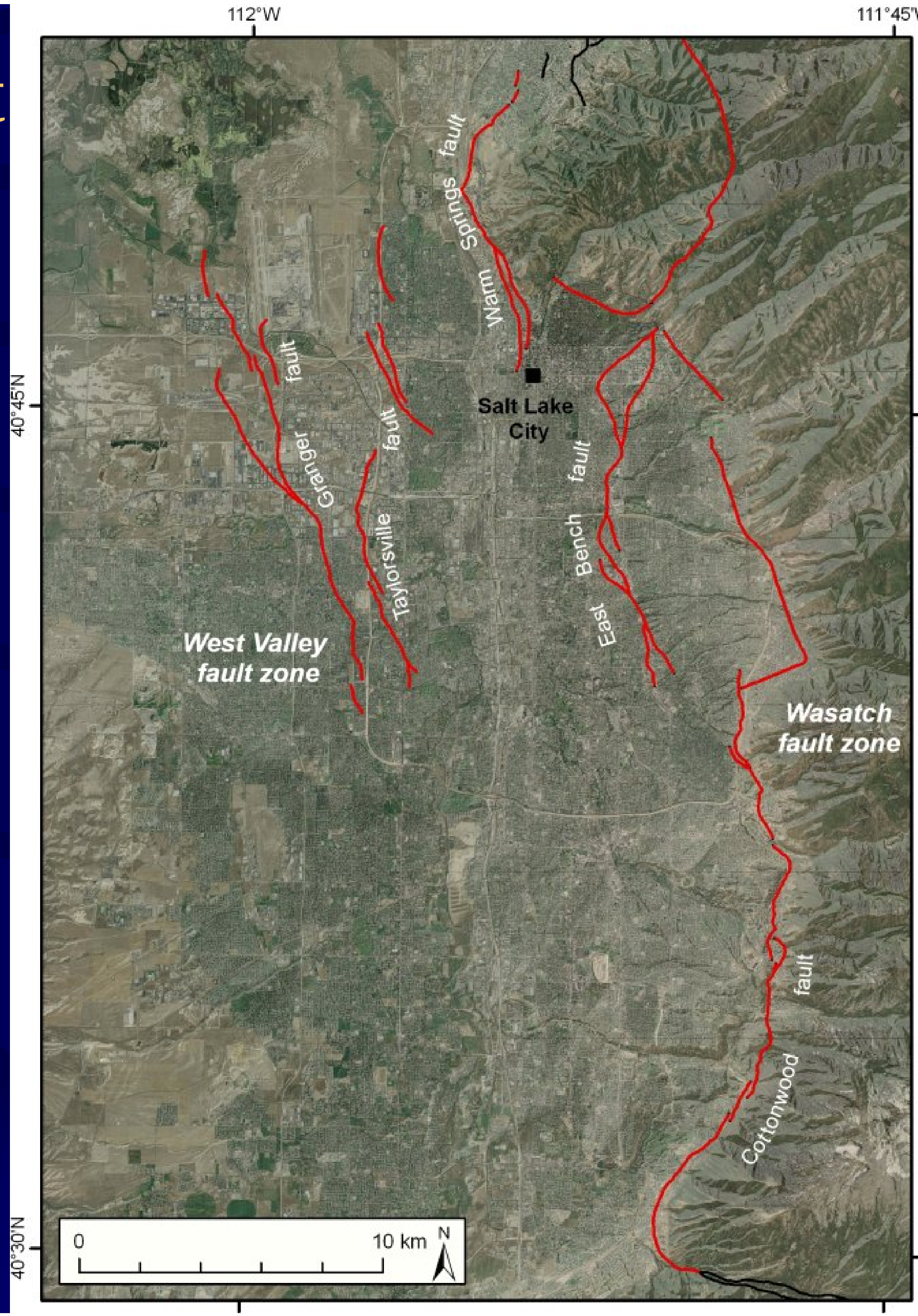
- Segment Boundaries (Personius and Scott, 1992)
  - North: Salt Lake City salient
  - South: change in fault strike east of Traverse Mountain



Salt Lake City segment

- Subsections
  - Warm Springs fault (7–10 km)
  - East Bench fault (12 km)
  - Cottonwood fault (20 km)

- West Valley fault zone (WFVZ)
  - Granger fault
  - Taylorsville fault
  - Zone of faulting: 16 km by 1–6 km



Salt Lake City segment

- Paleoseismic studies

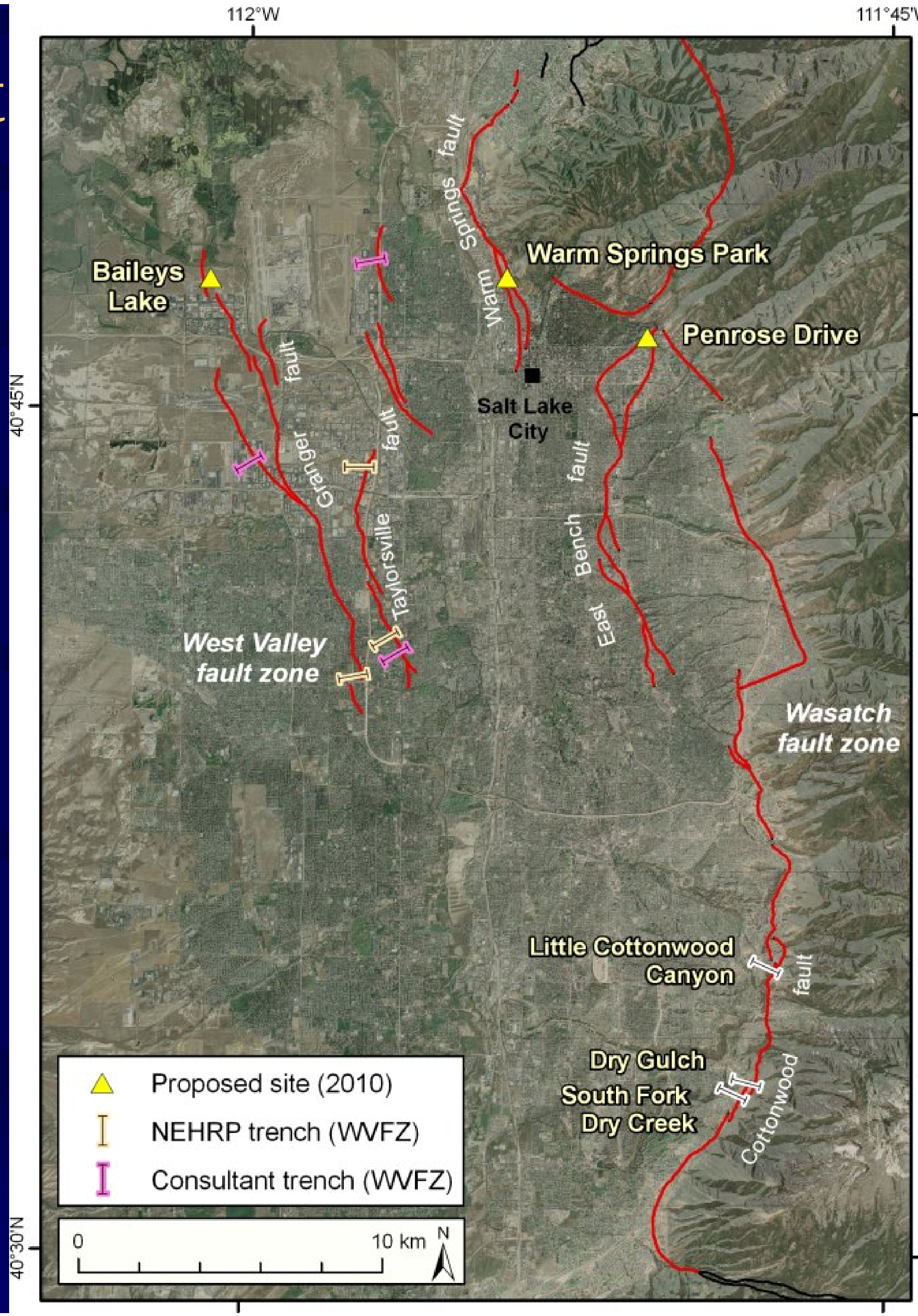
<u>SLCS</u>

  - Dry Gulch/South Fork Dry Creek (Black et al., 1996)
  - Little Cottonwood Canyon megatrench (McCalpin, 2002)

<u>WVFZ</u>

  - Trenches & borehole studies (Keaton and others, 1987; Keaton and Currey, 1989)
  - Geotechnical studies

- Proposed sites (UGS/USGS)



Paleoseismic data (SLCS)

- Earthquake timing and recurrence
  - MRE: ~1.3 ka
  - Post-mid-Holocene recurrence: 1.3 ± 0.4 ky (<5.3 ka)
  - Early Holocene/latest Pleistocene recurrence: ~2–8 ky (5–17 ka)
  - SLCS data limited to Cottonwood fault
- Displacement and slip rate
  - Per-event displacement: 1.5–2.5 m (single observation)
  - Interval slip rate: ~1–2 mm/yr (SLC3–SLC1)
  - Longer-term slip rate: 0.7–1.6 mm/yr (<15–17-ka; Bells Canyon moraine)

UQFPWG (Lund, 2005)

- SLC1 1.3 ± 0.65 ka
- SLC2 2.45 ± 0.55 ka
- SLC3 3.95 ± 0.55 ka
- SLC4 5.3 ± 0.75 ka
- SLC5 ~7.5 ka (<8.8–9.1 ka, but >5.1–5.3 ka)
- SLC6 ~9 ka (<9.5–9.9 ka)
- SLC7 ~17 ka
- SLC8(?) 17–20 ka
- Holocene recurrence: 0.5–1.3–2.4 ky
- Holocene slip rate: 0.6–1.2*–4.0 mm/yr

*Based on slip-rate data for the Weber and Provo segments

Paleoseismic data (WVFZ)

- Earthquake timing and recurrence
  - Timing data from geotechnical trench sites
    - MRE: shortly(?) after ~1.3–1.7 ka
    - 2nd event: shortly(?) after ~1.9–2.4 ka
  - Recurrence: 1.8–2.2 ky (fault zone)
    - 6–7 events in 13 ky
    - Timing of individual events unknown

UQFPWG (Lund, 2005)

- Holocene recurrence: insufficient data
- Holocene slip rate: 0.1–0.4–0.6 mm/yr

- Displacement and slip rate
  - Per-event displacement (Taylorsville fault): ~0.5–1.5 m
  - Average slip rate: 0.5–0.6 mm/yr (fault zone) based on trench and borehole studies

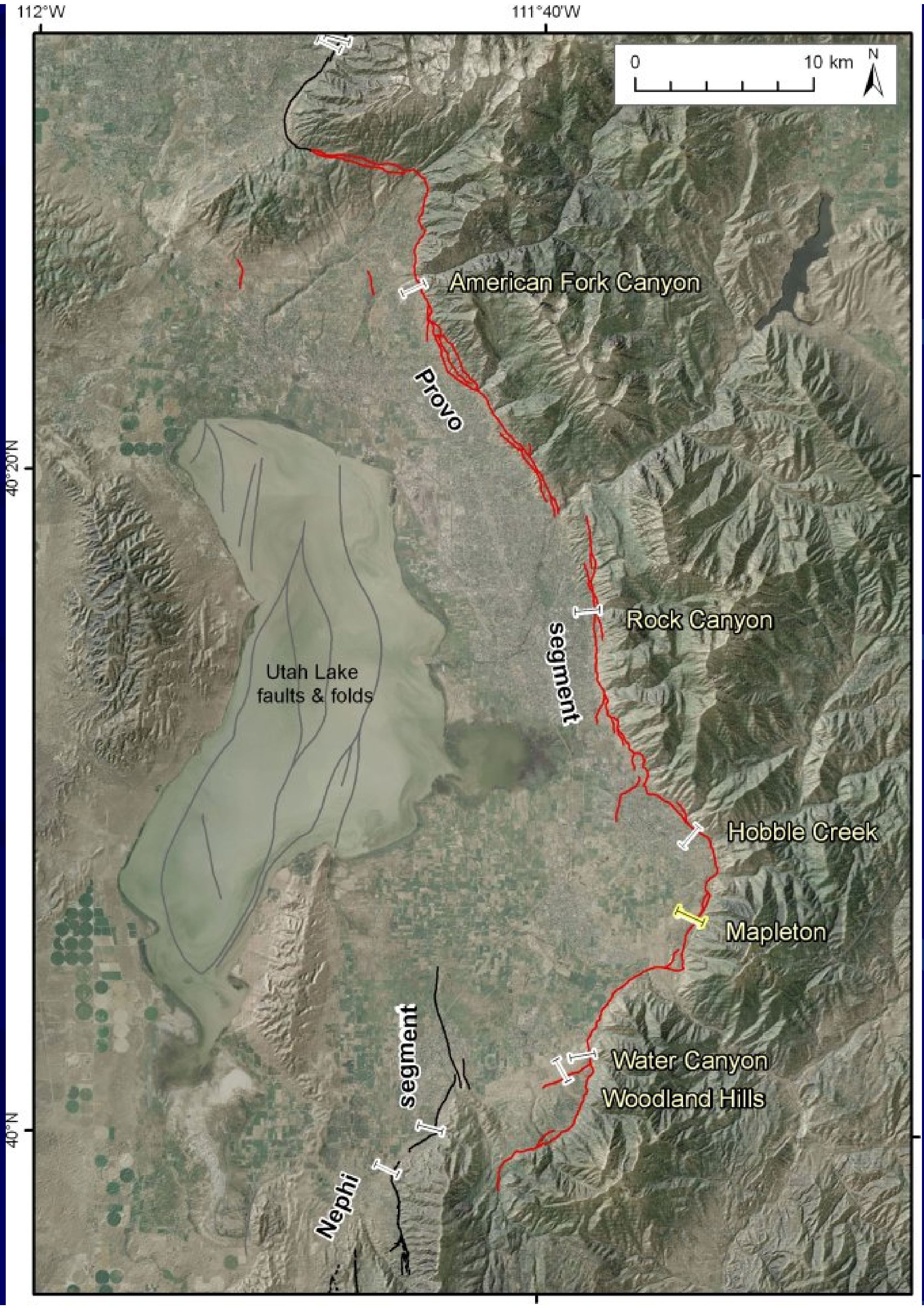
Salt Lake City segment summary

- SLCS – no earthquake-timing data for East Bench or Warm Springs faults
  - Single (poor quality) per-event displacement estimate
  - Limited Holocene slip-rate data
  - Long recurrence intervals in early Holocene/latest Pleistocene?
  - Step-over zones between these subsections?
- WVFZ – Holocene surface faulting, but independent source?
  - Timing data from geotechnical studies
  - Recurrence between earthquakes?
  - Relation to SLCS generally unknown
- 2010 trenching (UGS and USGS)

Provo segment

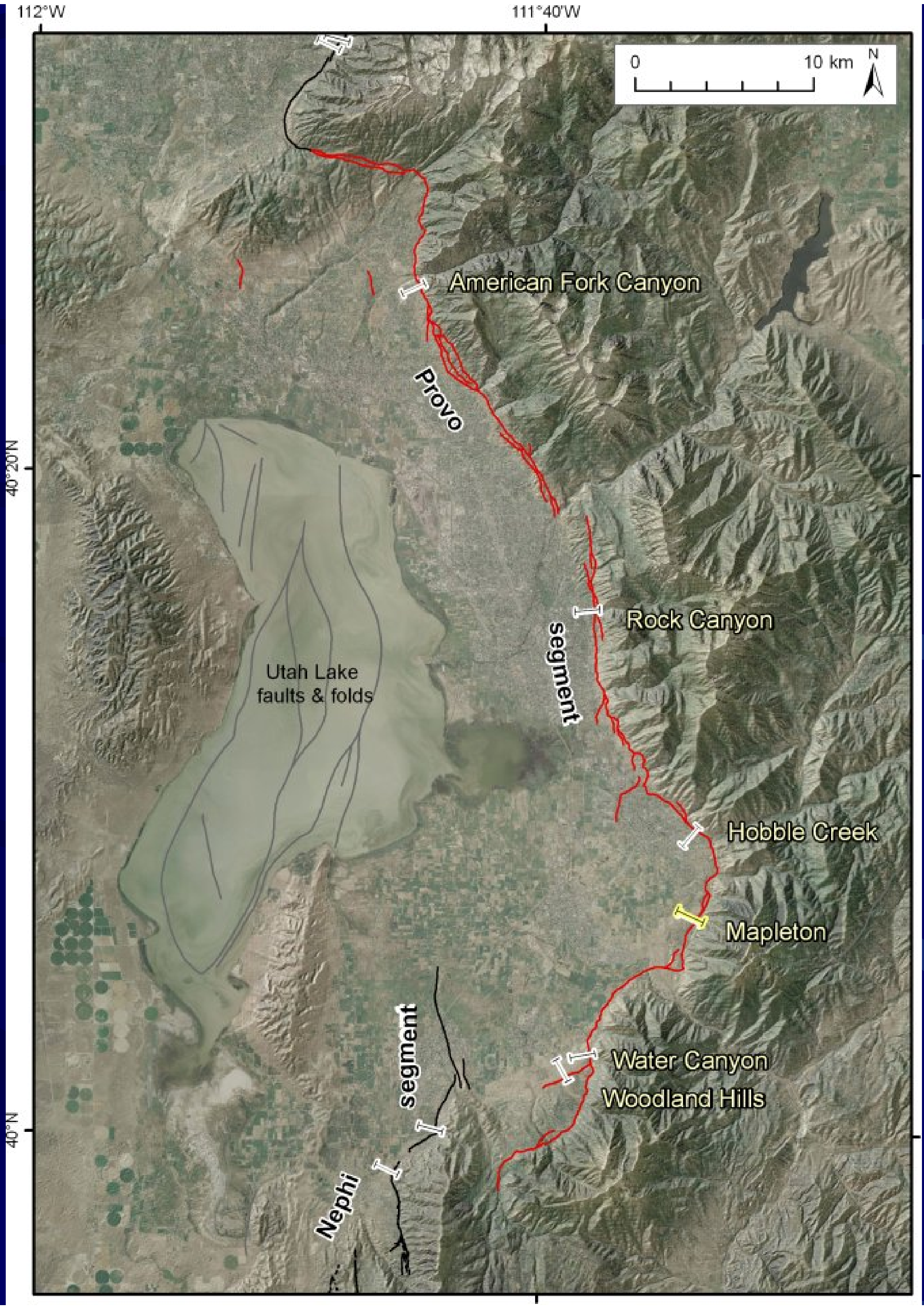
Provo segment

- Length
  - 59 km (straight line)
  - 70 km (surface trace)
- Segment Boundaries (Machette, 1992)
  - North: Traverse Mountain/Fort Canyon
  - South: overlapping, ~5–10-km wide right step with Nephi segment



Provo segment

- Paleoseismic studies
  - American Fork (Machette, 1988; Machette et al., 1992)
  - Rock Canyon (Lund and Black, 1998)
  - Hobble Creek (Swan et al., 1980)
  - Mapleton (Lund et al., 1991)
  - Mapleton megatrench (Olig et al., in progress)
  - Water Cyn/Woodland Hills (Ostenaa, 1990 [abs])



Paleoseismic data (~2004)

- Earthquake timing and recurrence
  - MRE well constrained to ~0.6 ka
  - Recurrence estimate: 2.4 ± 0.3 ky (P3–P1)
- Displacement and slip rate
  - 2.9 ± 0.9 m (1σ) / event (8 observations; max: ~3–5 m at Mapleton megatrench)
  - Interval slip rates?
  - Avg. Holocene slip rate: 0.5–1.4 mm/yr
  - Longer-term slip rate: 0.2–0.8 mm/yr (post Provo), 0.8–2.7 mm/yr (post Bonneville)

UQFPWG (Lund, 2005)

- P1 0.6 ± 0.35 ka
- P2 2.85 ± 0.65 ka
- P3 5.3 ± 0.3 ka
- Holocene recurrence: 1.2–2.4–3.2 ky
- Holocene slip rate: 0.6–1.2–3.0 mm/yr

Paleoseismic data (Mapleton megatrench)

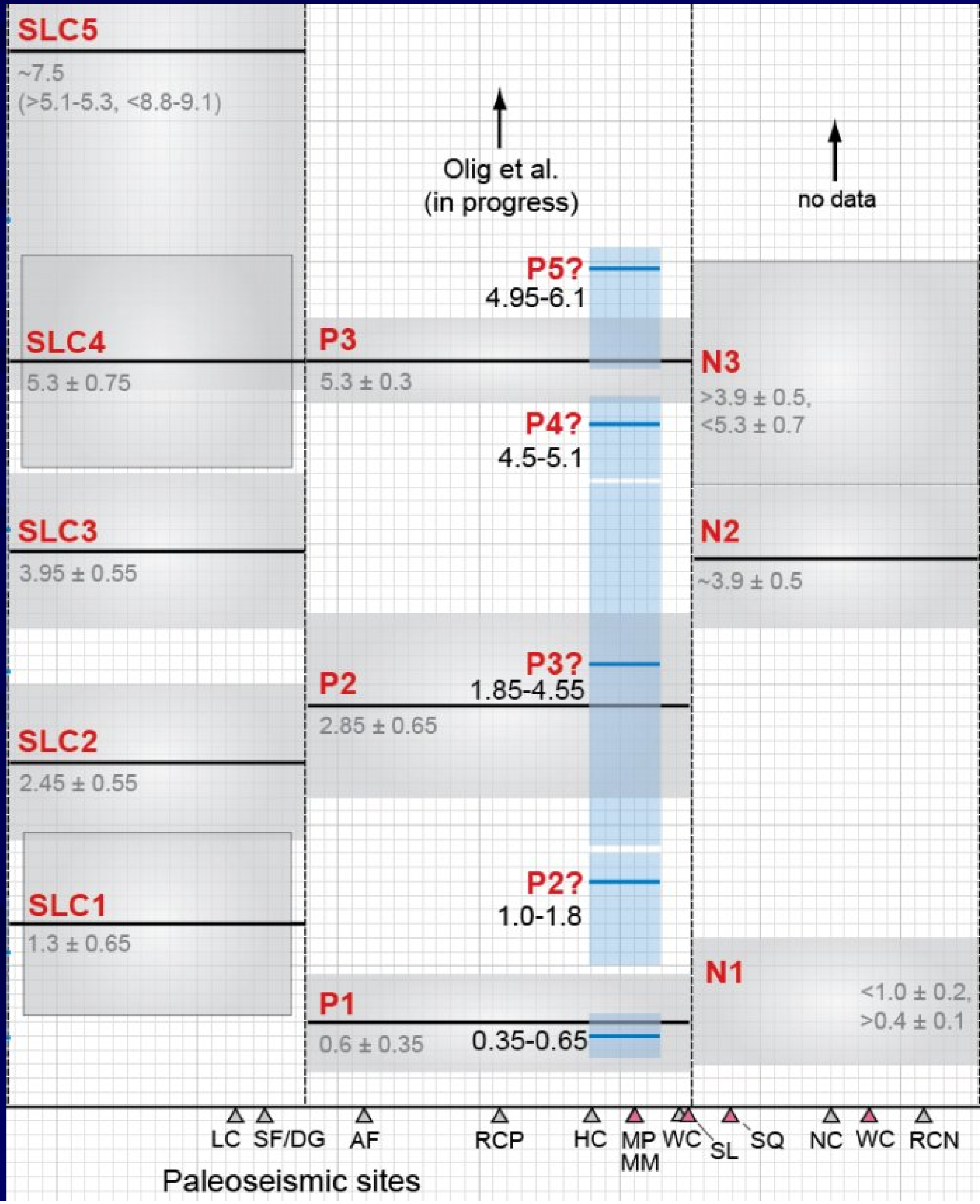
- Earthquake timing
  - 4–5 earthquakes after ~6 ka
    - MRE: 0.5 ± 0.15 ka
    - Second event at ~1.6 not identified in previous studies
  - 7–10 (possibly 11+) earthquakes <13 ka

- Earthquake recurrence
  - Average mid-late Holocene: 1.45 ± 0.25 ky
  - Average Holocene (<13 ka): 1.4–2.1 ky
  - UQFPWG consensus recurrence interval: 2.4 (+0.8, -1.2) ky

Mapleton megatrench; view to the east

Comparison with previous data/summary

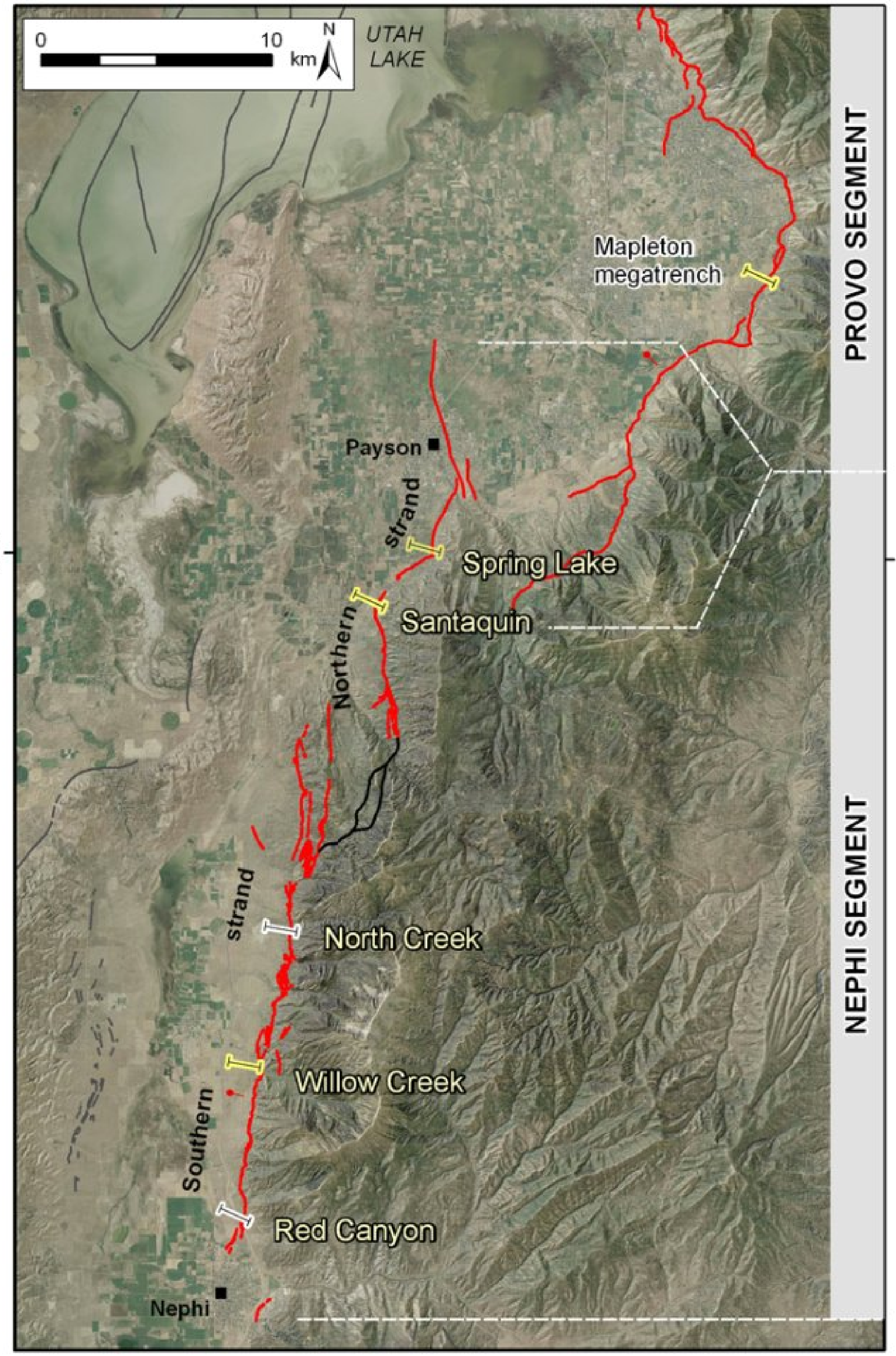
- Post-mid-Holocene record well constrained
  - P1 ~0.5–0.6 ka
  - P3 ~3 ka
  - P5 ~5.3–6.1 ka
- Extent of second event (~1.6 ka)?
- No significant change in average recurrence over the Holocene



Nephi segment

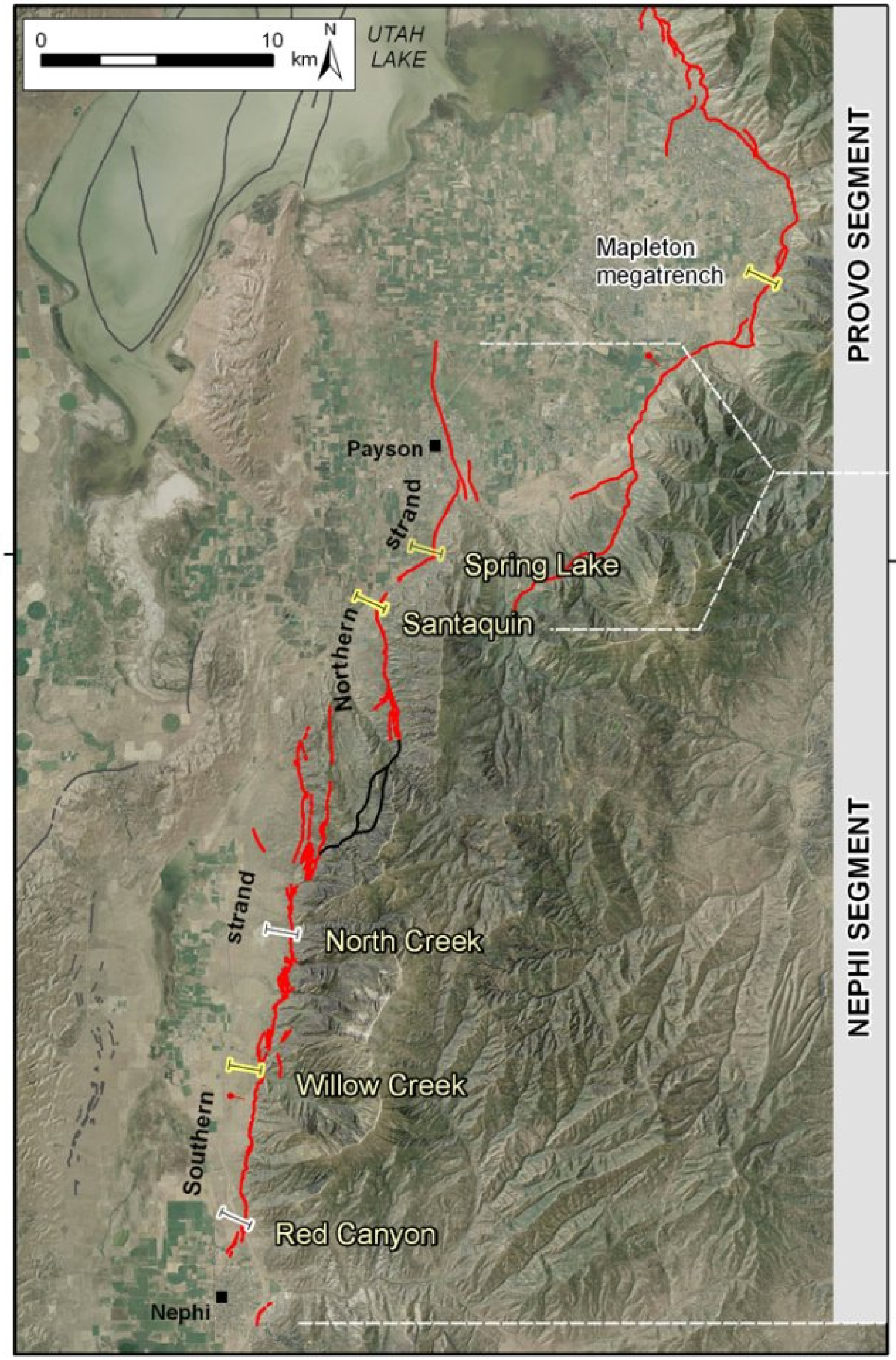
Nephi segment

- Length
  - 38 km (straight line)
  - 43 km (surface trace)
- Segment boundaries (Machette, 1992; Harty et al., 1997)
  - North: right step with Provo segment
  - South: 15 km gap in Holocene surface faulting (5 km gap in Quaternary surface faulting)
- Subsections
  - Northern strand (12 km)
  - Southern strand (25 km)



Nephi segment

- Paleoseismic studies
  - Spring Lake
    (Danny Horns, in prep [2007])
  - Santaquin
    (DuRoss et al., 2008)
  - North Creek
    (Hansen and others, 1981)
  - Willow Creek
    (Machette et al., 2007)
  - Red Canyon
    (Jackson, 1991)



Paleoseismic data (~2004)

- Earthquake timing and recurrence
  - Poorly constrained earthquake times:
    - N1 (MRE): <1.0 ka
    - N2: either ~1.3–1.7 ka or ~4 ka
    - N3: <5 ka (indirect evidence / age control)
  - Recurrence: poorly constrained (0–4 ky)
  - Data limited to southern strand

- Displacement and slip rate
  - 2.0 ± 0.6 m (1σ) / event (6 observations)
  - Avg. Holocene slip rate: 0.5–1.2 mm/yr

UQFPWG (Lund, 2005)

- N1 <1.0 ± 0.4 ka,
  possibly 0.4 ± 0.1 ka
- N2 ~3.9 ± 0.5 ka
- N3 >3.9 ± 0.5 ka,
  <5.3 ± 0.7 ka
- Holocene recurrence:
  1.2–2.5–4.8 ky
- Holocene slip rate:
  0.5–1.1–3.0 mm/yr

Nephi segment (Northern strand [2005-2007])

- <u>Santaquin</u>
  (DuRoss et al., 2008)
  - MRE: 0.35–0.6 ka (2σ)
  - Displacement: 2.8–3.2 m
  - Slip rate: 0.5 mm/yr (<17 ka)

- <u>Spring Lake</u>
  (Horns et al., in progress)
  - MRE: <2.5–2.7 ka
  - 2nd event: <3.5–3.6 ka
  - Displacement: ~2–3 m

Nephi segment (Northern strand [2005])

Willow Creek (Machette et al., 2007)

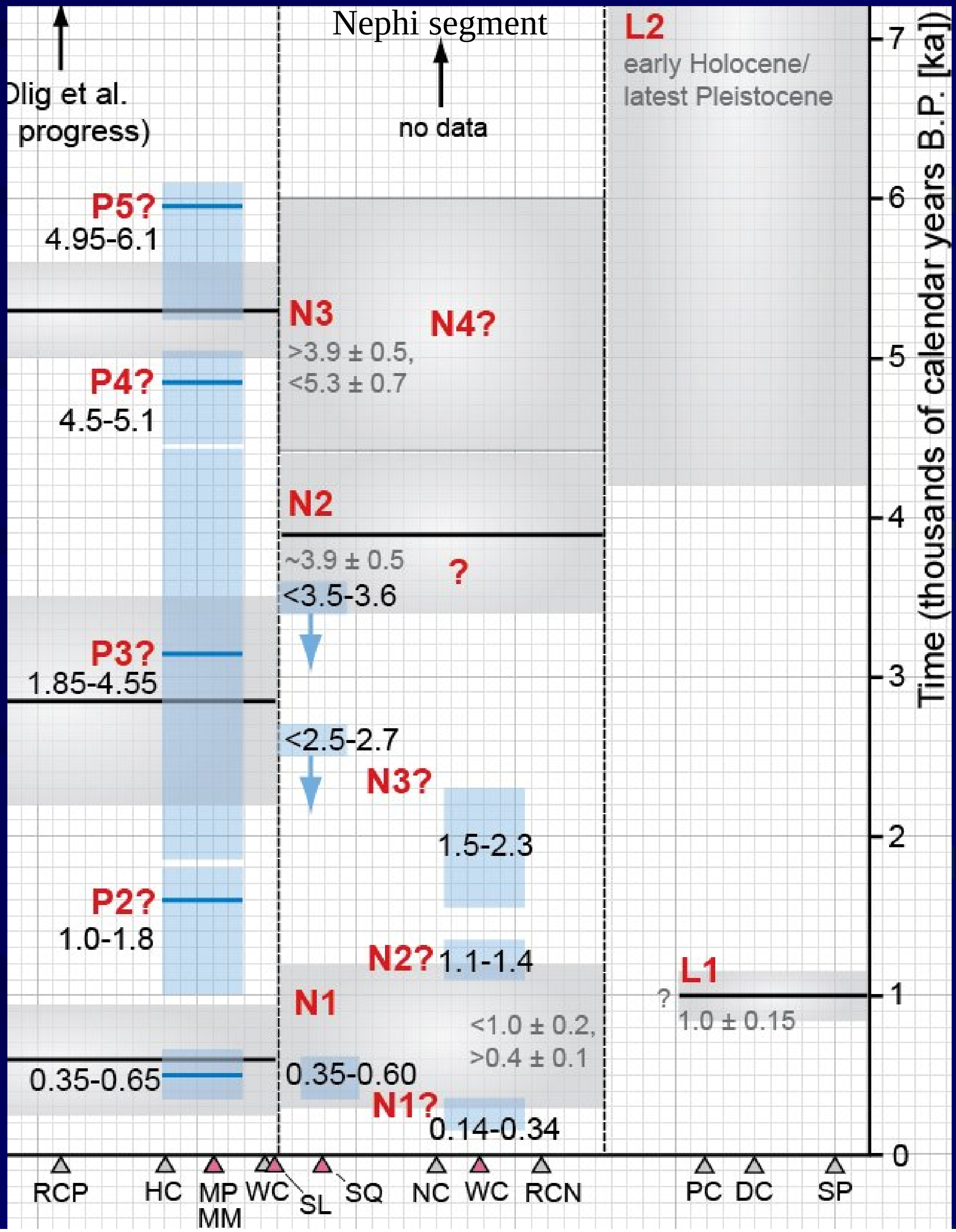
- Three earthquakes in <2.5 ka
  - P1: 0.14–0.34 ka
  - P2: 1.1–1.4 ka
  - P3: 1.5–2.3 ka

- Recurrence & slip rate
  - Average recurrence ~0.8–1.2 ky
  - Slip rate: 2.6 mm/yr (6 m / 2.3 ky)

Willow Creek site; view to the east

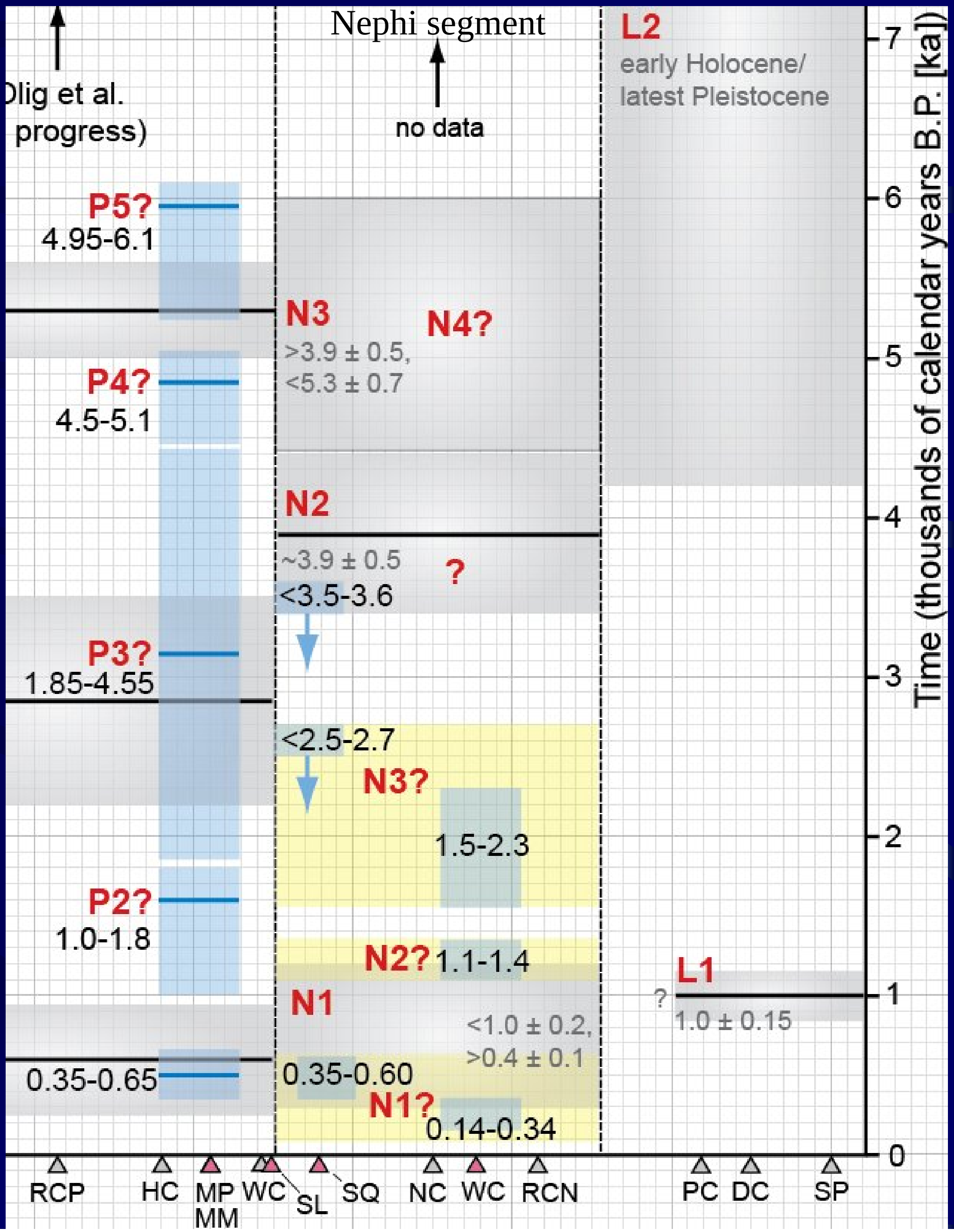
Comparison with previous data

- Three earthquakes in 2.5 ky (previously ~5 ky)
- Correlation of events?



Comparison with previous data

- Three earthquakes in 2.5 ky (previously ~5 ky)
- Correlation of events?
  - Northern and Southern strand MREs <u>(N1? ~0.3–0.5 ka)</u>
  - Spring Lake MRE and and Willow Creek 3rd event <u>(N3? ~1.5–2.5 ka)</u>
  - Northern strand and Provo MREs? <u>(~0.5–0.6 ka)</u>



Nephi segment summary

- Recent (2005–2007) studies improved late Holocene earthquake history

- Remaining questions
  - Correlation of most recent earthquakes across segment?
  - Most recent earthquakes clustered in late Holocene?
  - Early-mid Holocene record?

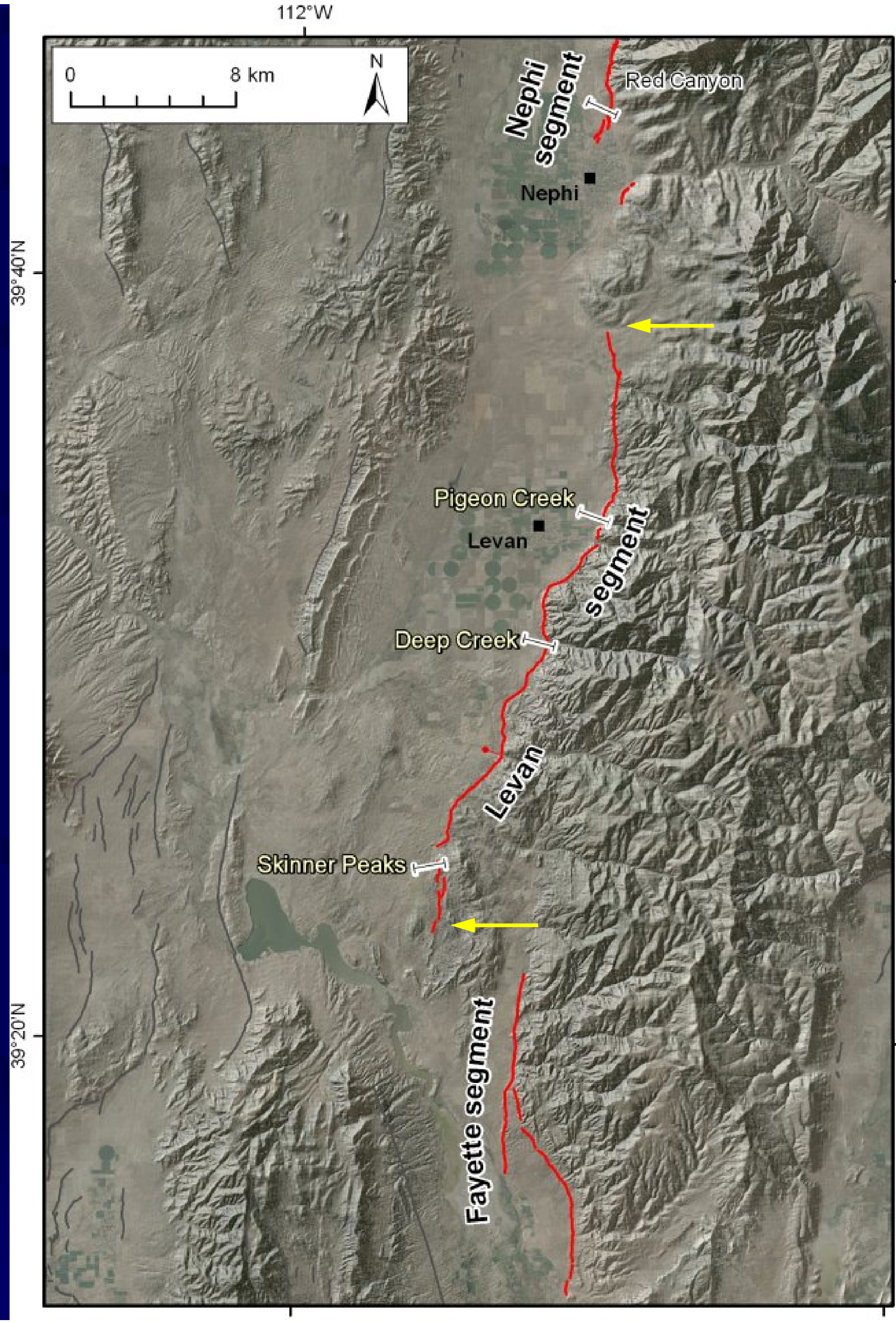
- Upcoming study: Danny Horns (Utah Valley Univ.) – trench ~1 km north of Spring Lake site (summer, 2010)

Southern segments

Levan segment

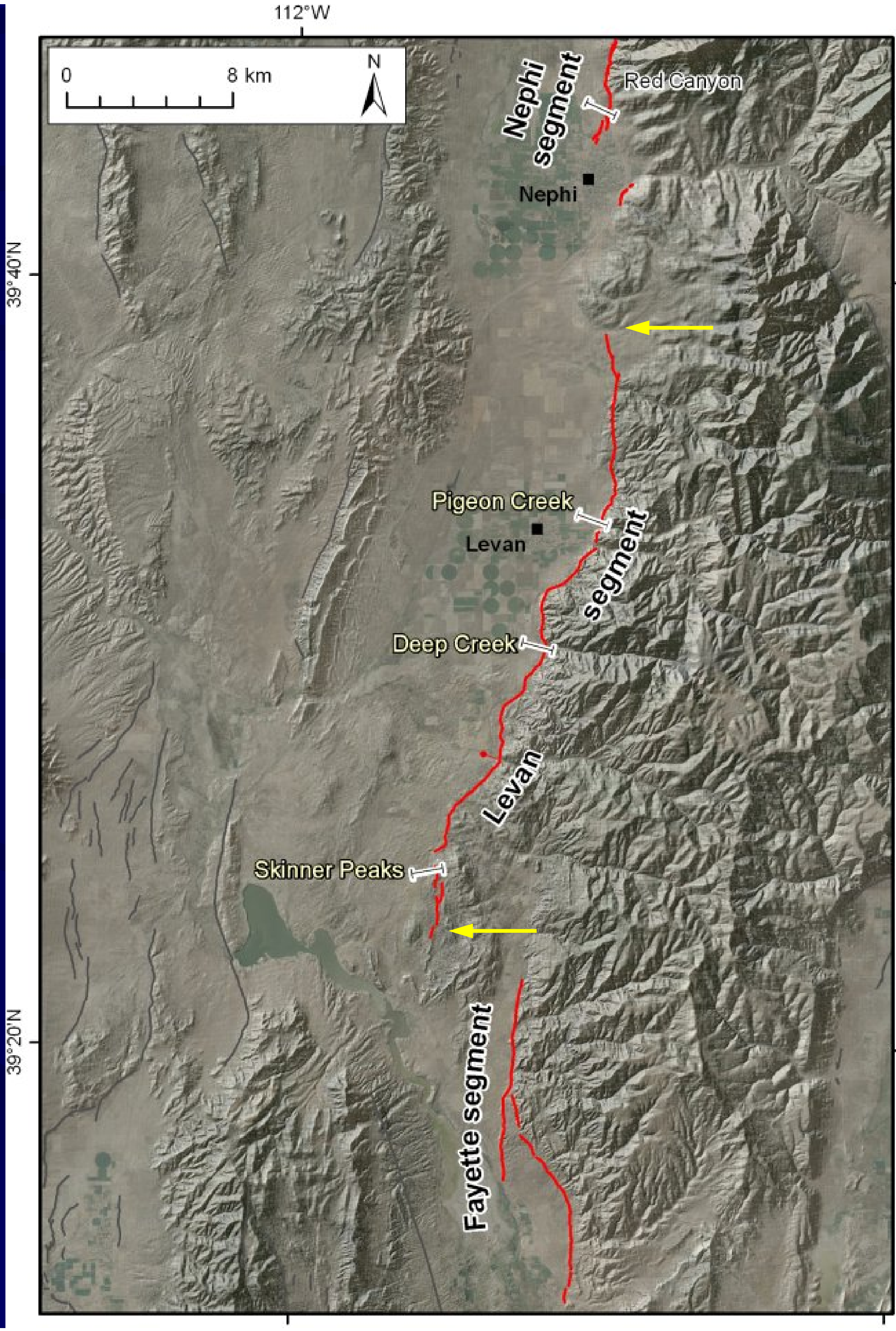
- Length
  - 30 km (straight line)
  - 32 km (surface trace)

- Segment boundaries (Hylland and Machette, 2008)
  - North: gap in surface faulting
  - South: 5-km-wide left step with Fayette segment



Levan segment

- Paleoseismic studies:
  - Pigeon Creek (Crone, 1983; Schwartz and Coppersmith, 1984)
  - Deep Creek (natural exposure) (Schwartz and Coppersmith, 1984; Jackson, 1991)
  - Skinner Peaks (Jackson, 1991)



Paleoseismic data

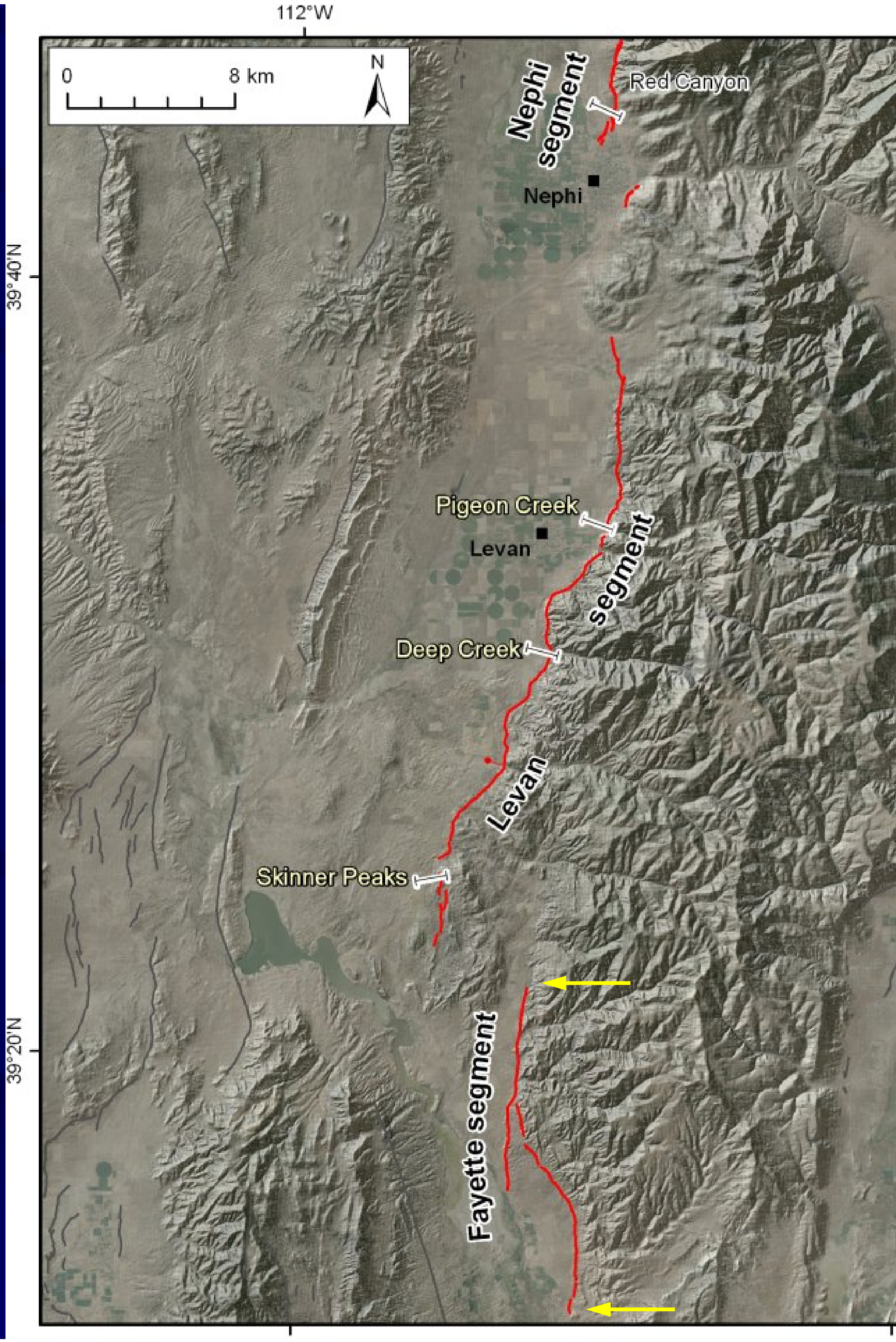
- Earthquake timing & recurrence
  - MRE (L1): close(?) maximum of ~1.0 ka
  - L2: older than 6–11 ka (7300 ^{14}CyrBP for charcoal from debris flow that post dates second event)
  - Hylland and Machette (2004): scarp-profile evidence for two surface-faulting earthquakes on southern 15 km of segment
- Displacement and slip rate
  - Displacement per event: ~1.5–2.2 m
  - Slip rate: Deep Creek <0.2–0.4 mm/yr
  - Scarp-diffusion-based slip rate: 0.3–0.5 mm/yr for southern segment

UQFPWG (Lund, 2005)

- L1 shortly after 1.0 ± 0.15 ka
- L2 unknown but likely early Holocene to latest Pleistocene (partial segment rupture)
- Holocene recurrence: >3 and <12 ky
- Holocene slip rate: 0.1–0.6 mm/yr

Fayette segment

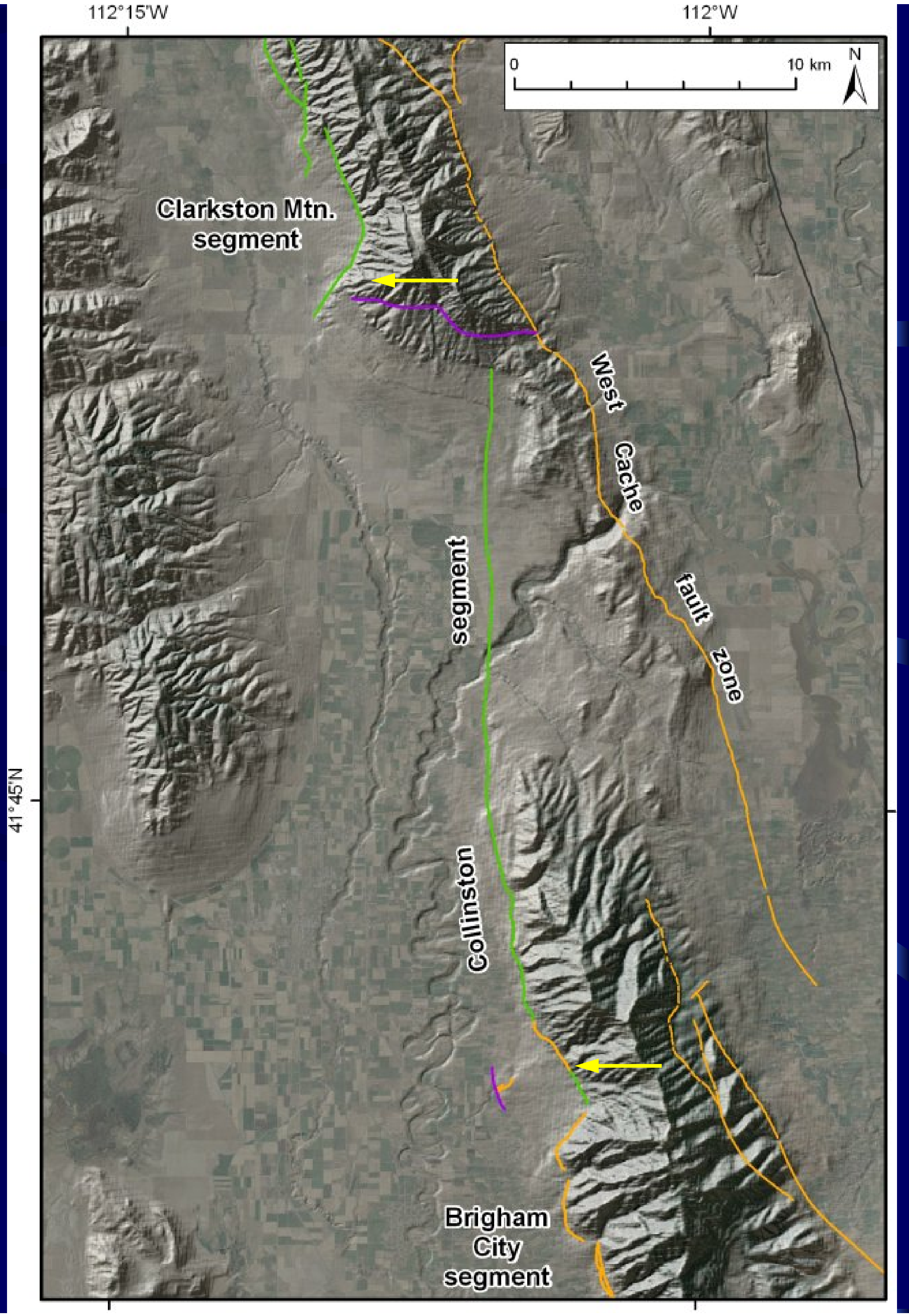
- Length
  - 18 km (straight line)
- Surface faulting (Hylland and Machette, 2008)
  - Pleistocene(?) (northern strand)
  - Latest Pleistocene (southeastern strand)
  - Holocene (southwestern strand)
- Slip rate: <0.1 mm/yr (<100-250 ka) (Hylland and Machette, 2008)



Northern segments

Collinston segment

- Length
  - 25–30 km (straight line)
  - 30–37 km (surface trace)
- Surface faulting
  - Faulting predates transgressive phase of Lake Bonneville? (~30 ka)
- Segment boundary
  - North: 7 km left step in late Pleistocene faulting at east-west “Short Divide” fault
  - South: range-front reentrant; overlap Brigham City segment



Clarkston Mountain segment

- Length
  - 17 km (straight line)
  - 19 km (surface trace)
- Surface faulting
  - No post-Bonneville surface faulting
  - Slip rate: <0.1 mm/yr (<18 ky) (Hylland 2007)
- Segment boundary
  - North: bedrock spur near Woodruff
  - South: 7 km left step

Malad City segment

- Length
  - 17–40 km (straight line) (Machette et al., 1992; USGS Fault and Fold Database)
- Surface faulting
  - No post-Bonneville (<17 ka) surface faulting
  - Scarps on late Pleistocene(?) alluvium
- Segment boundary
  - South: bedrock spur near Woodruff

Overview of Forecast Model Inputs

Working Group on Utah Earthquake Probabilities

Ivan G. Wong
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URS Corporation
Oakland, CA 94612

Salt Lake City, UT
10 February 2010

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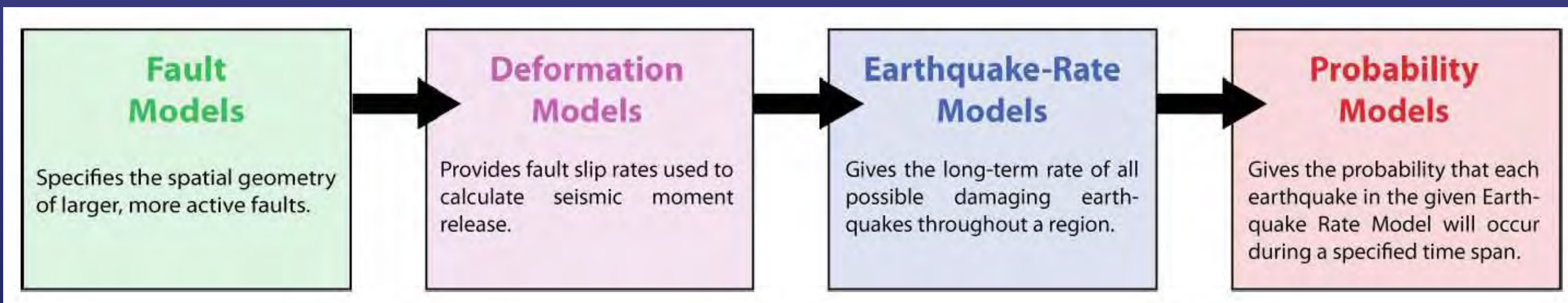
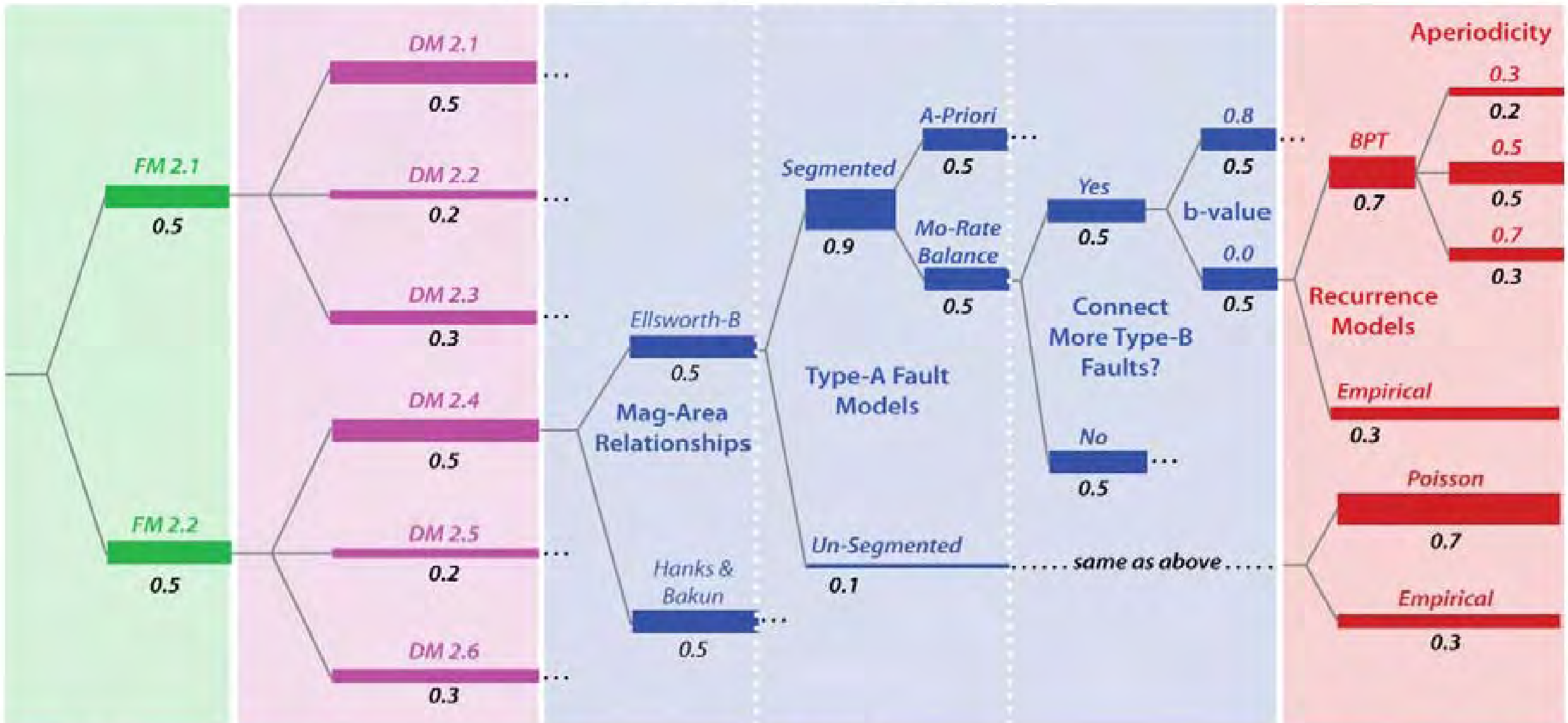
Four Basic Component of the UCERF 2 Model



Branches of the UCERF Logic Tree

Components of the Uniform California Earthquake Rupture Forecast 2
(abbreviated logic tree of 480 branches)



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

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

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

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

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Fault Model

- Ruptures on known active faults (Type-A and Type-B sources)
- Earthquakes in zones of distributed shear (Type-C sources)
- Earthquakes distributed to account for unknown faults (background sources)

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Fault Model

- Section name
- Fault trace
- Average dip
- Average upper seismogenic depth
- Average lower seismogenic depth
- Average long-term slip rate
- Average aseismic slip factor
- Average rake

Deformation Models

- The deformation models were derived primarily from geologically-estimated fault slip rates.
- In some cases, geodetically-constrained slip rates were considered.
- Geodetic data were also used to constrain the strain rates for the crustal shear zones that contained the Type-C earthquake sources.

Earthquake Rate Models

- The data and model analysis require conversion of seismic moment release M_0 to earthquake magnitude M (for comparisons between observed and model earthquakes) and to fault area A and average fault slip D (for comparisons with geologic and geodetic slip rates).

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Earthquake Rate Models

- The earthquake rate model is a combination of the following seismic sources:
  - earthquake rates
  - earthquake rates from crustal shear zones
  - a grid of background earthquake rate values

Reduction of Moment Rate on Faults

- In addition to the average aseismic slip factor, the WGCEP (2007) considered two additional variables that could act to reduce the moment rate, or seismic slip rate, on all faults in the deformation model
    - the seismic coupling coefficient, and
    - the percentage of moment accommodated by small events and aftershocks.

Moment Balancing

- A moment-balanced version of the model, which modifies the earthquake rate to match the observed long-term slip-rate data, was also calculated. The resulting rates were constrained to fall within the ranges derived from paleoseismic observations.

WGCEP (2003) Probability Models

- WGCEP (2003) applied five types of probability models:
  1. the Poisson model
  2. the Brownian Passage Time (BPT) model, also know as the inverse Gaussian model
  3. a "BPT-Step" model that accounted for Coulomb stress change effects of a previous earthquake
  4. a "Time-Predictable" model
  5. an "Empirical" model (Reasenberg et al., 2003) based on historic changes in seismicity rates

WGCEP (2003) Probability Models

- The Poisson model computes the probability of one or more events as $1-e^{-R\Delta T}$, where ΔT is the forecast duration and R is the long-term rate of the earthquake rupture.
- The BPT models and the Time-Predictable models are stress-renewal models that involve computing the probability each segment will rupture, conditioned on the date of last event, and then mapping these probabilities onto the various possible ruptures according to the relative frequency of each (from the long-term rate model) and the probability that each segment will nucleate each event.

OVERVIEW OF THE UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP MODEL

DETERMINING CONSENSUS RECURRENCE-INTERVAL AND VERTICAL SLIP-RATE ESTIMATES FOR UTAH'S QUATERNARY FAULTS

UTAH QUATERNARY FAULT PARAMETER WORKING GROUP

- Funded by NEHRP/UGS
- Convened and administered by the Utah Geological Survey
- Patterned after seismic-hazard-evaluation initiatives in California (Working Group on California Probabilities, 1988, 1990, 1999)
- Working Group members were subject-matter experts who served in a volunteer capacity

WORKING GROUP GOALS

- Critically evaluate Utah's Quaternary fault paleoseismic <u>trenching</u> data.
- Establish consensus recurrence-interval and/or vertical slip-rate estimates with appropriate uncertainty limits for faults where the data are permissive.
- Identify critical gaps in Utah's paleoseismic database and recommend/prioritize faults requiring further study to ensure Utah's earthquake hazard is adequately characterized.
- Make Working Group results available to user communities and the general public.

NEED FOR CONSENSUS VALUES

Consensus recurrence-interval and vertical slip-rate estimates are critical in four areas directly related to reducing losses from earthquakes in Utah.

1. **Updating the National Seismic Hazard Maps for the Utah region**
2. **Characterizing seismic sources**
3. **Performing probabilistic seismic-hazard analyses**
4. **Providing peer-reviewed consensus data for other fault-related research/applications**

ORIGINAL WORKING GROUP MEMBERS

GROUP 1

Suzanne Hecker – USGS

Michael Hylland – UGS

William Lund – UGS

Michael Machette – USGS

James McCalpin – GEO-HAZ Consulting

Alan Nelson – USGS

Susan Olig – URS Corp.

Dean Ostenaa – USBR

Stephen Personius – USGS

David Schwartz – USGS

GROUP 2

Craig dePolo – NBMG

Kathleen Haller – USGS

Philip Pearthree – AZGS

James Pechmann – UUGG

Mark Peterson – USGS

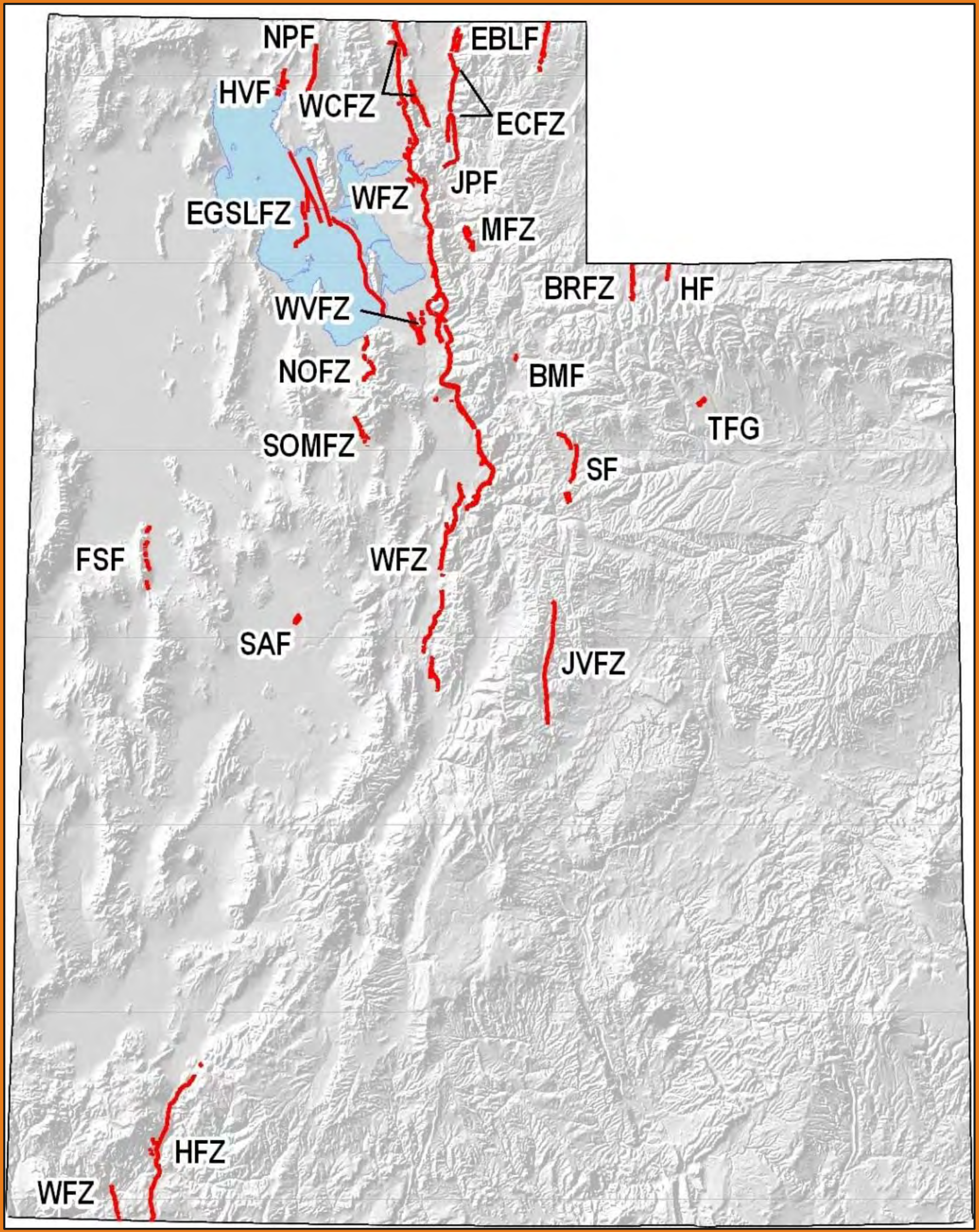
Robert Smith – UUGG

Ivan Wong – URS Corp.

UTAH'S PALEOSEISMIC TRENCHING DATABASE

- 212 Quaternary faults or fault sections identified in Utah (Hecker, 1993; Black and others, 2003).
- 33 (16%) had some or all of the following paleoseismic trenching data: earthquake timing, mean repeat time, displacement per event, cumulative displacement, vertical slip rate.
- Available paleoseismic source documents included more than 60 published papers, abstracts, government studies, and geotechnical reports representing the work of more than 40 investigators over a period of more than 30 years.

Utah Q Faults with Paleoseismic Trenching Data



Bald Mountain fault
Bear River fault zone
East Bear Lake fault
East Cache fault zone
East Great Salt Lake fault zone
Fish Springs fault
Hansel Valley fault
Hogsback fault
Hurricane fault zone
James Peak fault
Joes Valley fault zone
Morgan fault zone
Northern Oquirrh fault zone
North Promontory fault
Southern Oquirrh Mountains fault zone
Strawberry fault
Sugarville area faults
Towanta Flat graben
Wasatch fault zone
- Brigham City segment
- Weber segment
- Salt Lake City segment
- Provo segment
- Nephi segment
- Levan segment

Washington fault zone
West Cache fault zone
West Valley fault zone

ORIGINAL UQFPWG PROCESS

- Working Group Coordinator reviewed the paleoseismic source documents and prepared a summary data form for each fault/fault section.
- Working Group members reviewed the summarized data.
- Three meetings were held to jointly evaluate the trenching data and establish consensus vertical slip-rate and recurrence-interval estimates.
- Prepared a final technical report for the USGS, released a UGS publication presenting working group results, and presented working group results to professional groups and societies.

DATA ISSUES

- Data adequacy
  - Wasatch fault zone
  - Other Quaternary faults
- Sources of uncertainty
  - Numerical ages; >300 ^{14}C and luminescence ages
  - Relative ages; Lake Bonneville chronology and soils
  - Earthquake timing and uncertainty limits
  - Net-slip measurements
  - Investigation limitations; trench depth, completeness
  - Incomplete documentation

CONSENSUS PARAMETER VALUES

- Utah's paleoseismic trenching data generally are not sufficient to permit rigorous statistical analysis, or to constrain uncertainty ($\pm$) within rigidly quantifiable bounds.
- The Working Group relied upon the expertise and collective judgment of its members to arrive at consensus fault parameter estimates.
- The Working Group "kept in mind" ~ two sigma (5^{th} and 95^{th} percentile) error limits when assigning upper and lower limits for their preferred recurrence-interval and slip-rate estimates.

WASATCH FAULT CONSENSUS VALUES

Parameter	Brigham City	Weber	Salt Lake City	Provo	Nephi	Levan
Earthquake Timing (cal yr B.P.)	Z 2100±800 Y 3450±300 X 4650±500 W 5950±250 V 7500±1000 U 8500±1500 T >14,800, <17,000	Za 0.5±0.3 ka Zb 1000±450 Y 3050±800 X 4400±700 W 6150±700	Z 1300±650 Y 2450±550 X 3950±550 W 5300±750 V ~7.5 ka U ~9 ka T ~ 17 ka S 17–20 ka (?)	Z 600±350 Y 2850±650 X 5300±300	Z <1±0.2 ka Y ~3.9±0.5 ka X >3.9±0.5, <5.3±0.7 ka	Z 1.0±0.2 ka
Preferred Recurrence Interval (yr)	2800 1300 500	2500 1400 500	2400 1300 500	3200 2400 1200	4800 2500 1200	12 ky 3ky
Preferred Vertical Slip Rate (mm/yr)	4.5 1.4 0.6	4.3 1.2 0.6	4.0 1.2 0.6	3.0 1.2 0.6	3.0 1.1 0.5	0.6 0.1

EXAMPLE CONSENSUS FAULT PARAMETERS

Parameter	Eastern Bear Lake FZ	Bear River FZ	Hurricane FZ	Joes Valley FZ
Earthquake Timing	Z >0.6±0.08, <2.1+0.2 ka Y >5.0±0.5 ka, but just greater X >15.2±0.8, <31±6 ka W >31±6, <39±3 ka V >31±6, <39±3 ka U >39±3 ka, but just greater	Z 2370 ±1050 yr B.P. Y 4620±690 yr B.P.	Z 5-10 ka Y >5-10, <25-50 ka X >25-50 ka?	Minimum of 4 earthquakes in 250 kyr and 2 earthquakes in the past ~30 kyr
Preferred Recurrence Interval	3-8-15 kyr	1-100 kyr	5-50 kyr	5-10-50 kyr
Preferred Vertical Slip Rate	0.2-0.6-1.6	0.05-1.5-2. 5	0.05-0.2-0.4	JVFZ forms a graben, which exhibits no net slip

FAULTS IDENTIFIED FOR ADDITIONAL PALEOSEISMIC INVESTIGATION

Cedar City/Parowan monocline
Clarkston fault, West Cache fault zone
Collinston & Clarkston segments WFZ
Eastern Bear Lake fault
East Cache fault zone
East Great Salt Lake fault zone
Enoch graben/Red Hills faults
Faults beneath Bear Lake
Faults beneath Utah Lake
Gunnison fault
Hurricane fault zone
Levan segment WFZ
Nephi segment WFZ
Scipio Valley faults
Sevier/Toroweap fault
Wasatch Range back-valley fault
Washington fault zone
Weber segment WFZ
Weber segment “megatrench”
West Valley fault zone

RESULTS OF INITIAL UQFPWG PROCESS

- **Paleoseismic-trenching data are only available for 16% of Utah's Quaternary faults.**
- **Earthquake timing and recurrence for the central segments of the WFZ were considered comparatively well understood to the middle Holocene – less so for older earthquakes; data for the remaining Quaternary faults were limited and often poorly constrained.**
- **Limited data precluded rigorous statistical analysis and required use of a "Consensus Process" that employed expert opinion to establish preferred fault parameters and ~ two sigma ranges.**
- **The new consensus parameters now represent the "best available" data for Utah, but as one Working Group member commented: "Consensus data are a lot like sausages, tasty, but you really don't want to know how they are made."**

So, by 2004 Utah had established consensus slip-rate and recurrence-interval values using chiefly expert opinion and "best available data" for those Quaternary faults with paleoseismic trenching data. We also had established a list of Quaternary faults that required further study to do "a minimally acceptable job of characterizing earthquake hazard in the state."

UQFPWG MODEL TODAY

- One of three (now four) UGS earthquake-hazard standing committees that helps set and coordinate Utah's earthquake-hazard research agenda.
- Remains broadly based with representation from state and federal government, academia, and private industry.
- Meets annually (since 2005) to review ongoing paleoseismic research in Utah, and to update the Utah consensus slip-rate and recurrence-interval database as necessary.
- Provides advice/insight regarding technical issues related to fault behavior in Utah.
- Reviews and prioritizes Utah Quaternary faults that require further paleoseismic study.

UQFPWG QUATERNARY FAULT STUDY PRIORITY LIST

Fault/Fault Segment	Original UQFPWG Priority (2005)
Nephi segment WFZ	1
West Valley fault zone	2
Weber segment WFZ – most recent event	3
Weber segment WFZ – multiple events	4
Utah Lake faults and folds	5
Great Salt Lake fault zone	6
Collinston & Clarkston Mountain segments WFZ	7
Sevier/Toroweap fault	8
Washington fault	9
Cedar City-Parowan monocline/ Paragonah fault*	10
Enoch graben	11
East Cache fault zone	12
Clarkston fault*	13
Wasatch Range back-valley faults	14
Hurricane fault	15
Levan segment WFZ	16
Gunnison fault	17
Scipio Valley faults	18
Faults beneath Bear Lake	19
Eastern Bear Lake fault	20
Bear River fault zone	Added 2007
Brigham City segment WFZ – most recent event	Added 2007
Carrington fault (Great Salt Lake)	Added 2007
Provo segment WFZ – penultimate event	Added 2007
Rozelle section – Great Salt Lake Fault	Added 2007
Northern Salt Lake City segment WFZ	Added 2009

*Included on Utah NSHM

Added to the priority list since 2005

2010 HIGHEST PRIORITY FAULTS/FAULT SEGMENTS FOR STUDY

Fault/Fault Section	Priority	Investigation Status	Investigating Institution
Northern Salt Lake City segment WFZ	1	Study funded (NEHRP)	UGS/USGS
West Valley fault zone	2	Study funded (NEHRP)	UGS/USGS
Penultimate event Provo segment WFZ	3	Trench site reconnaissance	UGS
Washington fault zone	4	Two trenching studies ongoing	UGS/Simon•Bymaster
Rozelle section, Great Salt Lake fault	5	No activity	

OTHER PRIORITY FAULTS/FAULT SEGMENTS REQUIRING FURTHER STUDY

Fault/Fault Section	Original UQFPWG Priority	Investigation Status	Investigating Institution
Cedar City-Parowan monocline/ Paragonah fault	10	No activity	
Enoch graben	11	Earth fissure study	UGS
Clarkston fault	13	No activity	
Gunnison fault	17	No activity	
Scipio Valley faults	18	No activity	
Faults beneath Bear Lake	19	No activity	
Eastern Bear Lake fault	20	No activity	
Bear River fault zone	2007	Trenching study	USGS

FAULTS/FAULT SEGMENT STUDIES COMPLETE OR ONGOING

Fault/Fault Section	Original UQFPWG Priority	Investigation Status	Investigating Institution
Nephi segment WFZ	1	UGS Special Study 124/USGS Map 2966/ ongoing UVU study	UGS/USGS/UVU
Weber segment WFZ – most recent event	3	UGS Special Study 130	UGS/USGS
Weber segment WFZ – multiple events	4	UGS Special Study 130	UGS/USGS
Utah Lake faults and folds	5	Ongoing	UUGG
Great Salt Lake fault zone	6	Ongoing	UUGG
Collinston and Clarkston Mountain segments WFZ	7	UGS Special Study 121	UGS
Sevier/Toroweap fault	8	UGS Special Study 122	UGS
East Cache fault zone	12	Ongoing	USU
Wasatch Range back-valley faults	14	Ongoing	USBR
Hurricane fault zone	15	UGS Special Study 119	UGS
Levan segment WFZ	16	UGS Map 229	UGS
Brigham City segment WFZ – most recent event	2007	Ongoing	UGS/USGS

QUESTIONS?

Time-Dependent Earthquake Recurrence Studies Along the Wasatch Front, Utah

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URS Corporation
1333 Broadway, Suite 800
Oakland, CA 94612

WGUEP Meeting, Salt Lake City, UT

9 February 2010

Questions to Consider

- Does the past ≈ 6 ky of paleoseismic data provide an adequate baseline for understanding large earthquake recurrence along the WFZ? (record complete and accurate enough?)
- Do surface-faulting earthquakes occur randomly in space and time on individual fault segments or is their recurrence modulated by some type of cyclic behavior?
- What models will best fit observed fault recurrence behavior?
- Are surface faulting earthquakes clustered in space or time?
- Is there contagion behavior between segments?
- Are there multisegment or partial multisegment ruptures?
- What is our time period of interest?

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Input Needed to Calculate Time-Dependent Recurrence Intervals or Earthquake Probabilities

- **Mean Recurrence**
- **Elapsed Time (time since the most recent event)**
- **Coefficient of Variation (measure of periodicity)**

$$\textbf{COV} = \frac{\sigma}{\mu}$$

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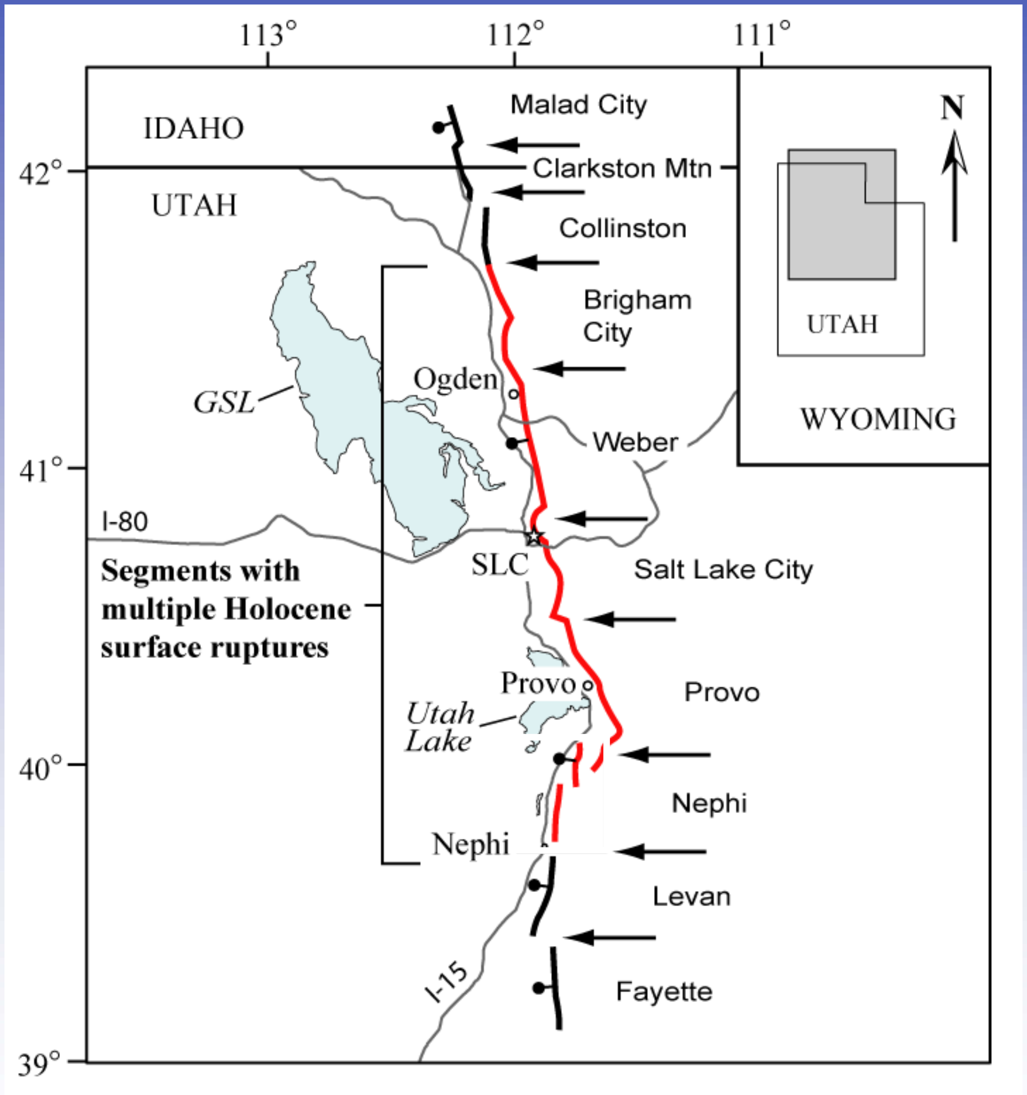
Previous Time-Dependent Studies

- **Cluff et al. (1980)**
- **McCalpin and Nishenko (1996); McCalpin (2002)**
- **Olig et al. (1999); Wong et al (2002); Olig et al. (2005); Wong et al. (2009)**

Wasatch Fault Zone



After Machette et al., 1992

- Cluff et al. (1980)
  - Weber Segment (Kaysville)
  - Provo Segment (Hobble Creek)
- McCalpin and Nishenko (1996)
  - All central segments
- McCalpin (2002)
  - SLC Segment (Megatrench)
- Olig/Wong et al. (1999-2009)
  - BC, SLC, and Provo Segments

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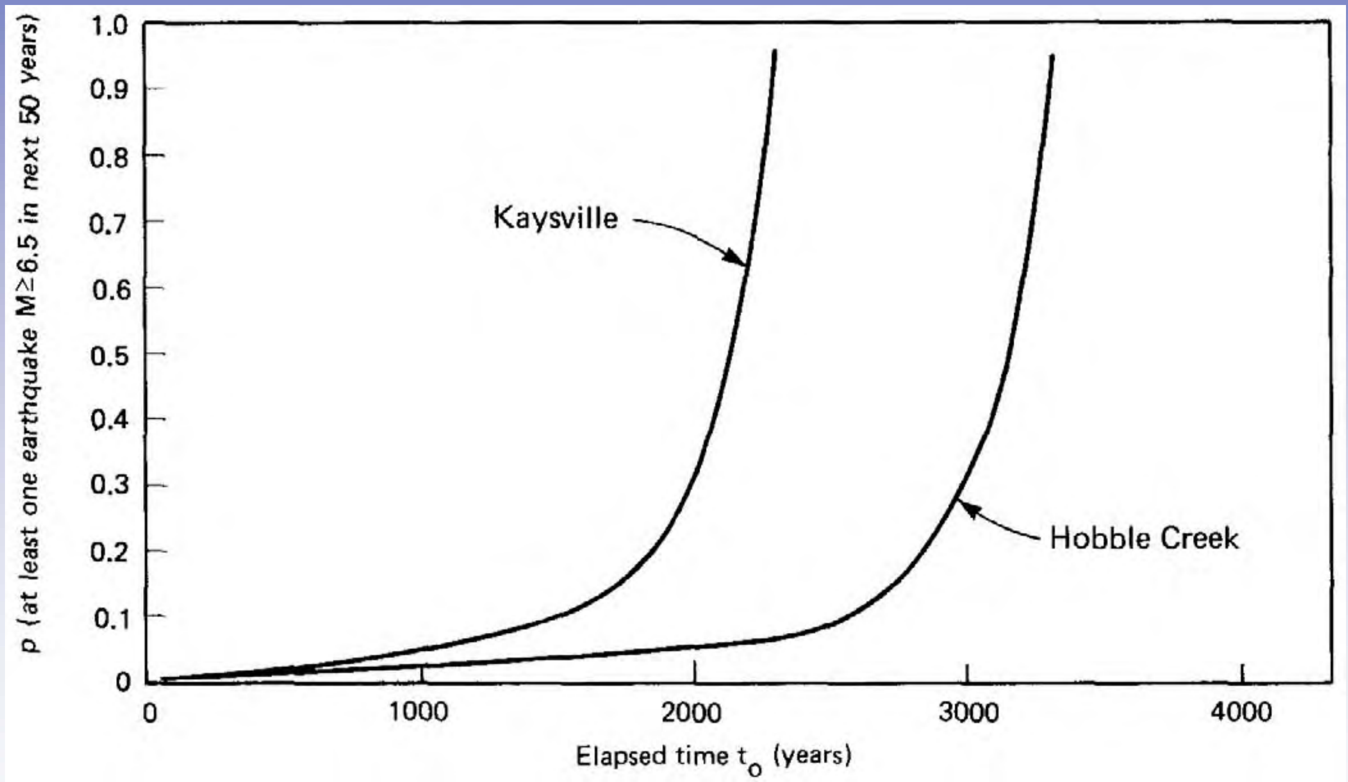
Cluff et al (1980) – Highlights

- Used Semi-Markov model
- Earthquake probabilities function of:
  - time period of interest (50 yrs)
  - elapsed time
  - holding time (based on seismological and geologic rates)
  - size of most recent earthquake (M ≥ 6.5)

URS

Cluff et al. (1980) – Lessons Learned

Results are sensitive to average holding times
(Kaysville – 1,100 yrs; Hobble Creek – 2,100 yrs)



Cluff et al (1980) – Lessons Learned (cont.)

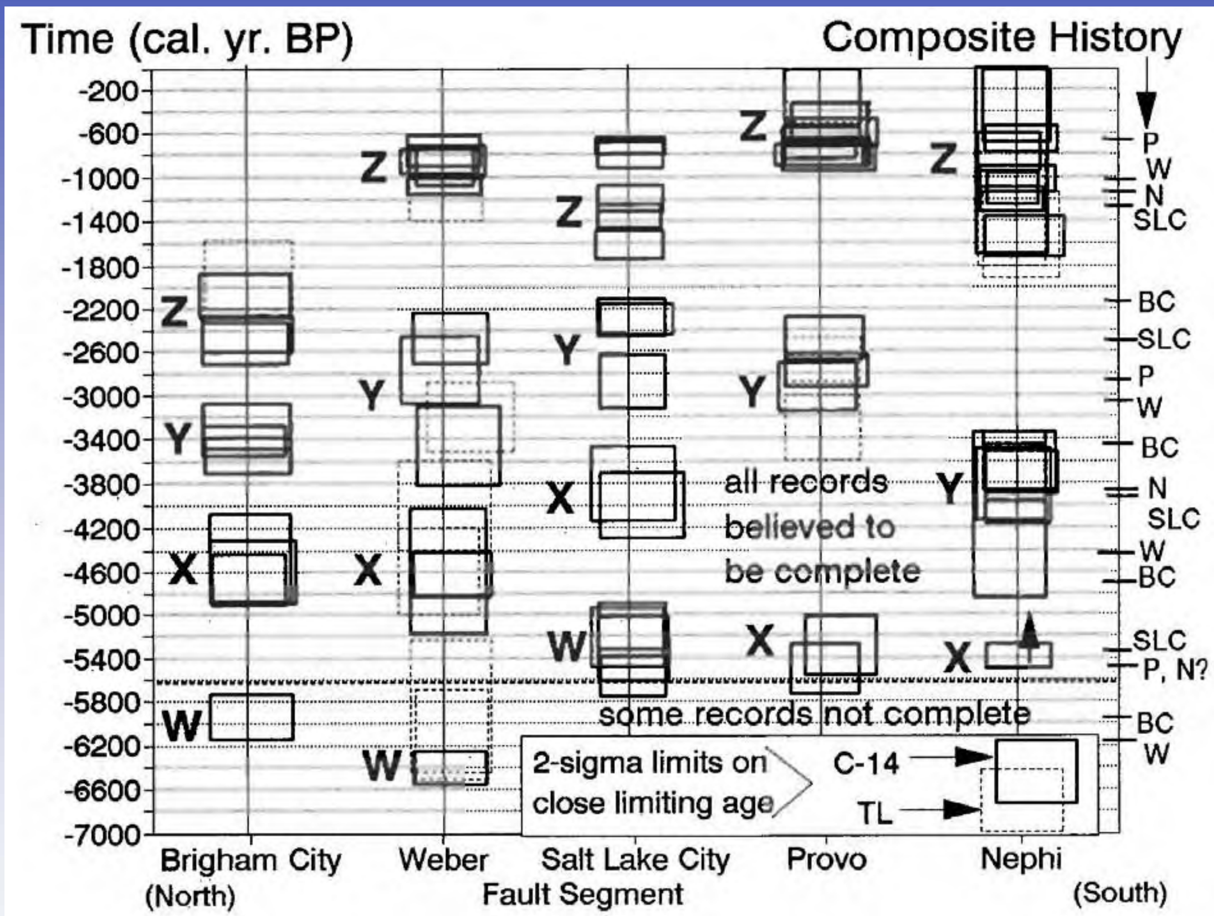
Results are very sensitive to elapsed time

All 7 segments **500 yrs**	→	**20% of** M $\geq$ **6** **in next 50 yrs**
2 segments 2,000 yrs **Rest 500 yrs**	→	**80% of** M $\geq$ **6** **in next 50 yrs**

Longer elapsed time yields higher probabilities

URS

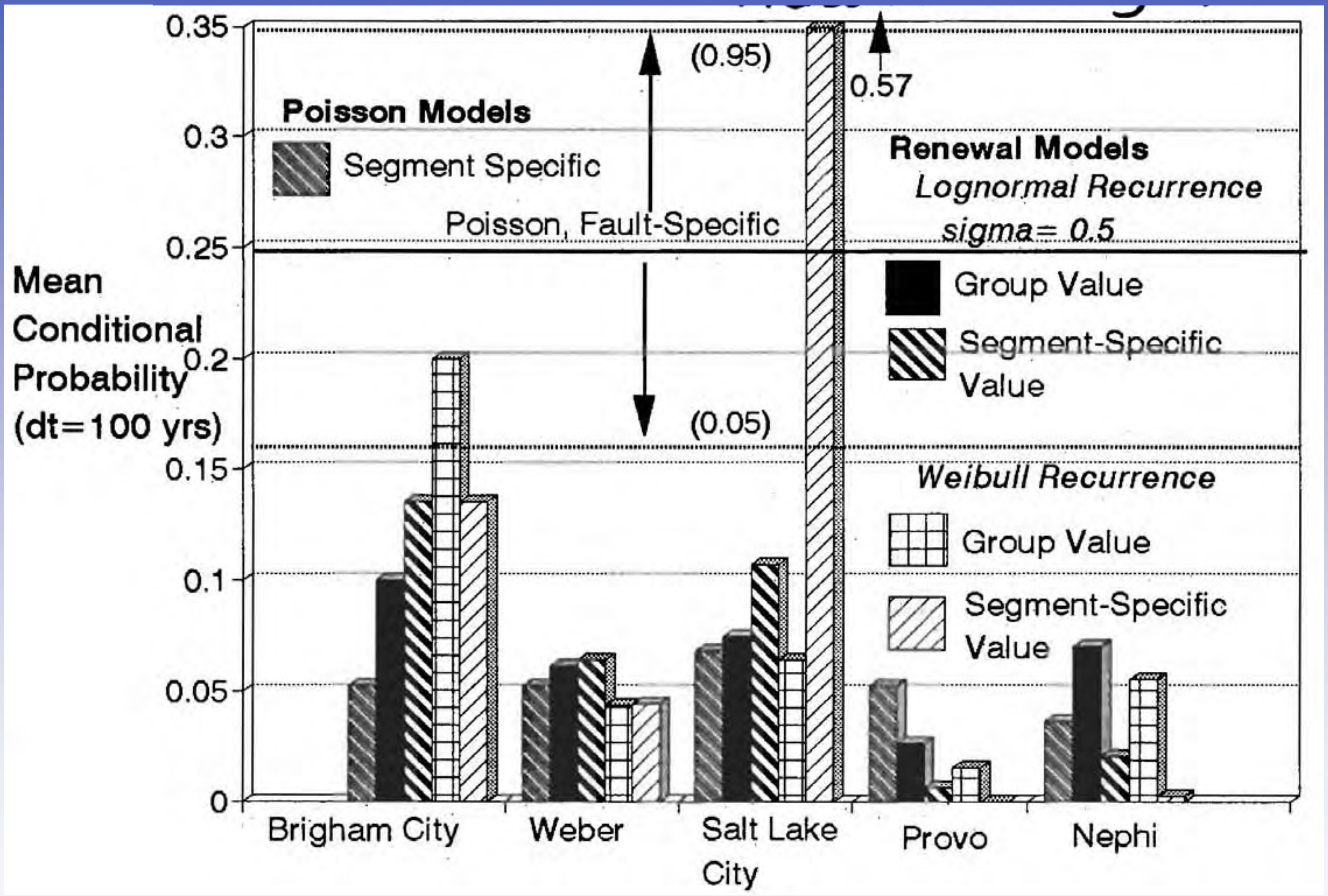
McCalpin and Nishenko (1996)



- **16 surface-faulting earthquakes on 5 central segments (avg. repeat time ≈350 yrs; COV=0.66)**
- **Considered the record complete for past 5.6 ky**
- **Conducted group and segment specific analyses**
- **Compared Poisson, Lognormal, and Weibull probabilities**

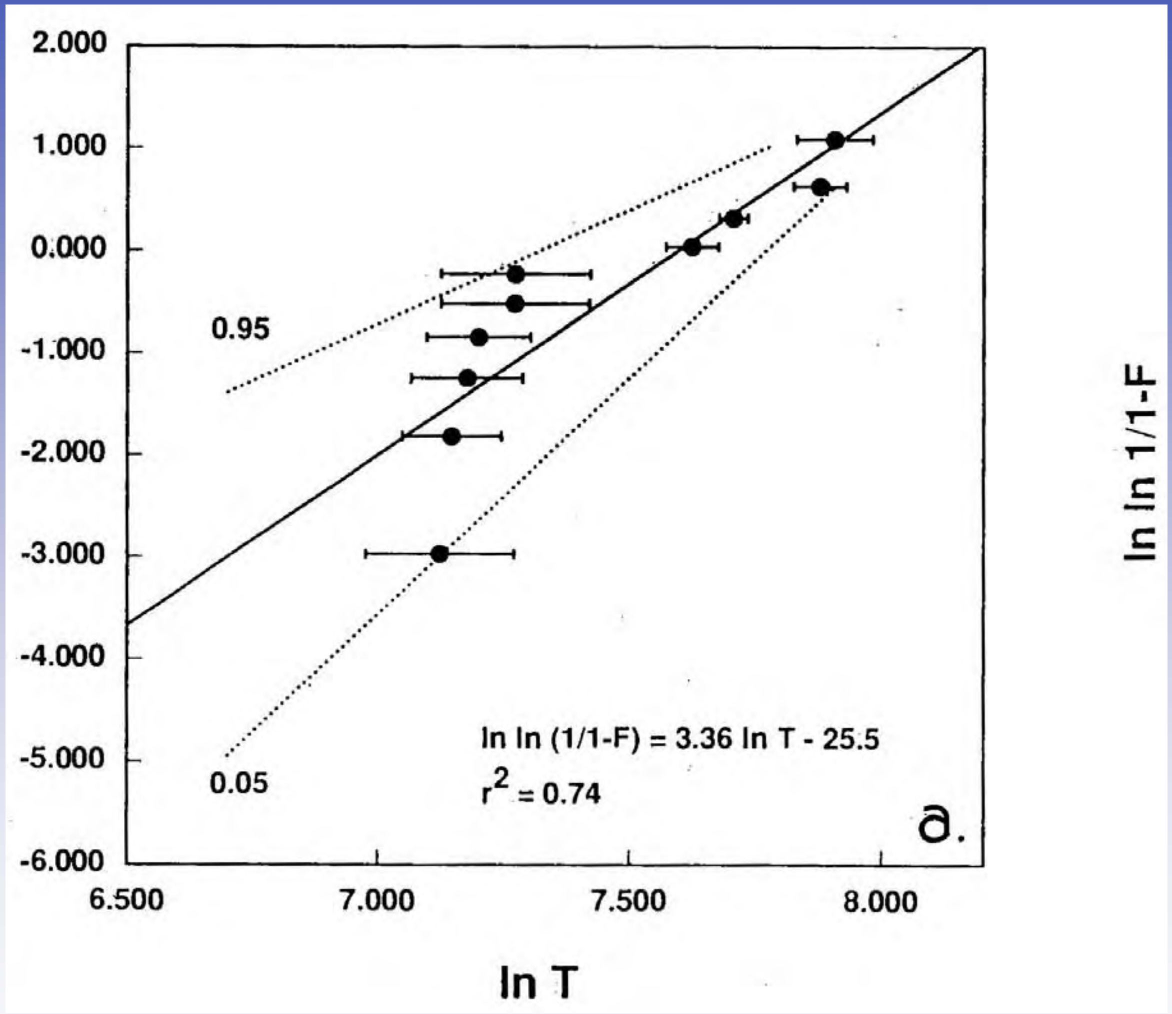
URS

Comparison of Conditional Probability Estimates Along Central WFZ Segments



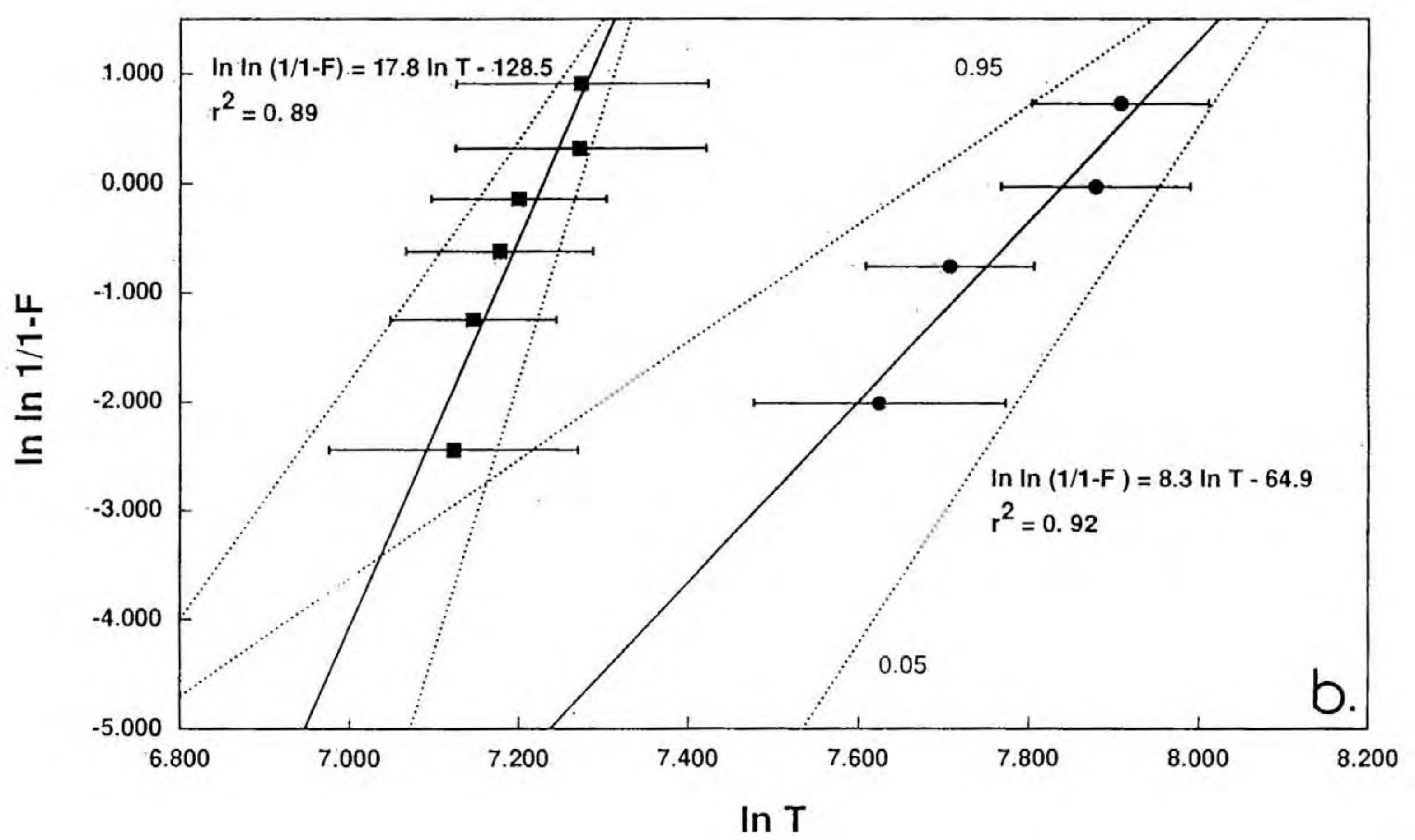
(From McCalpin and Nishenko (1996)

Cumulative Weibull Plot for Central WFZ Group Analysis for Past 5.6 ky



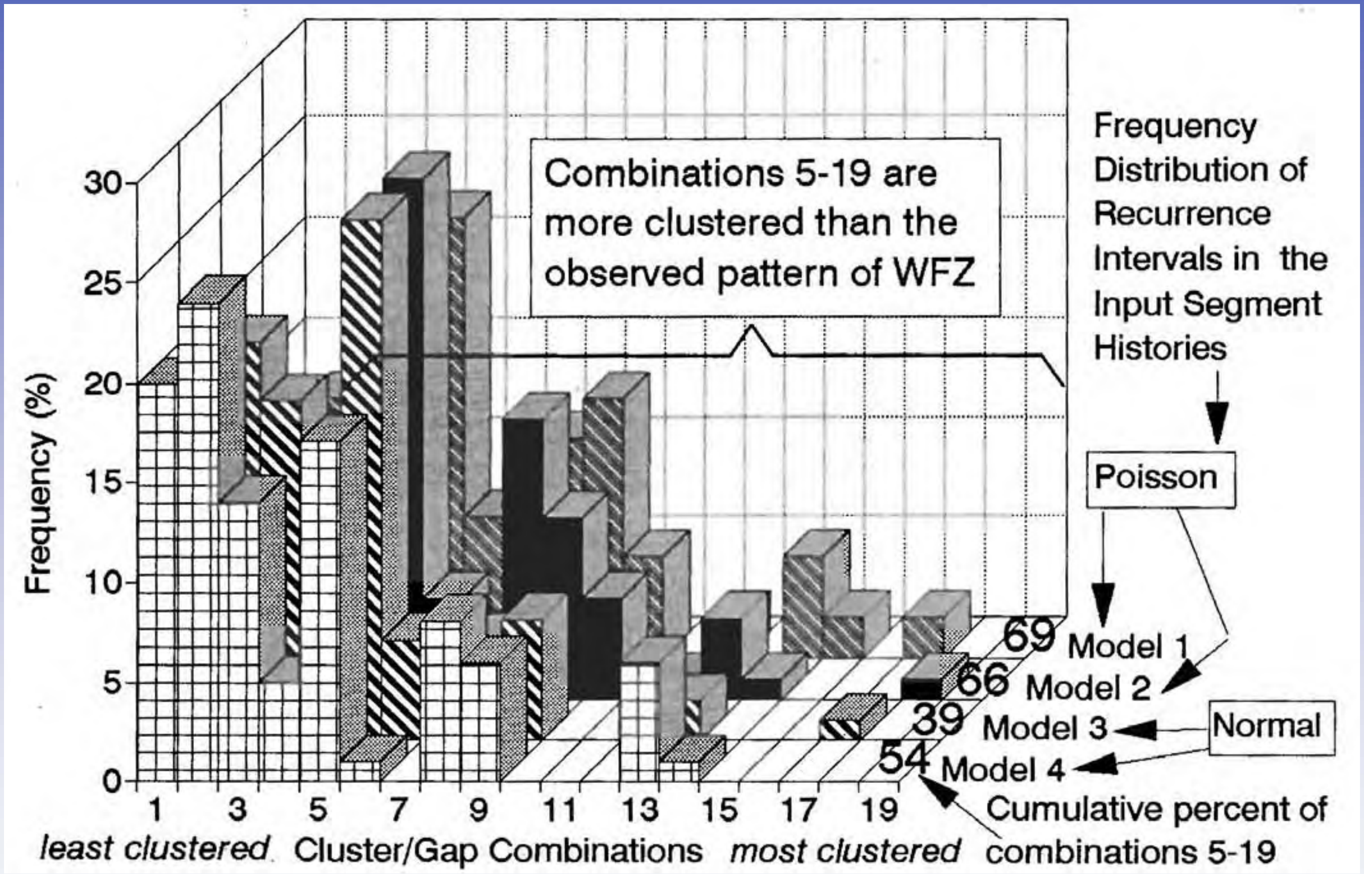
(From McCalpin and Nishenko (1996)

Cumulative Weibull Plot for Central WFZ Comparison of Two Subgroups (Bimodal Behavior)



(From McCalpin and Nishenko (1996)

Analysis of Synthetic Paleoseismic Records Generated With WFZ Parameters



Apparent temporal clustering could easily be produced by chance patterns

(From McCalpin and Nishenko (1996)

McCalpin (2002)
Salt Lake City Segment

- Concluded more reliable to use shorter paleoseismic record for time- dependent probability estimates (more representative of future behavior)

- Best estimate for COV ≈ 0.36 (McCalpin and Slemmons, 1998)

- Estimated ≈ 17% chance of surface-faulting earthquake occurring on the SLC segment in the next 100 years

URS

Olig et al. (1999) - Wong et al. (2009) –Approach Similar to 1999 Working Group on California Earthquake Probabilities

- Lognormal renewal model
- Time period of interest - **50 years**
- Calculated conditional probabilities and equivalent Poisson recurrence intervals (or Time-dependent recurrence intervals)

URS

Olig et al. (1999) - Wong et al. (2009) - Highlights

- **Calculated time-dependent recurrence intervals (or equivalent Poisson recurrence intervals) and conditional probabilities**

- **Interplay of Average Recurrence, Elapsed Time and COV as to sensitivity of time-dependent-earthquake probabilities**

- **Time- dependent recurrence intervals much shorter for BCS and SLCS and longer for PS**

- **Shorter term paleoseismic record preferred for estimating average recurrence (more reliable, complete, representative of behavior, and has better constrained ages), and it does support periodic behavior (best estimate COV 0.4)**

Olig et al. (1999); Wong et al. (2002)

PALEOSEISMIC DATA

Brigham City Segment		Salt Lake City Segment	
EVENT	Age ± 2 σ (cal yr BP)	EVENT	Age ± 2 σ (cal yr BP)
Z (most recent)	2,130 ± 800	Z (most recent)	1,300 ± 650
Y	3,450 ± 300	Y	2,450 ± 550
X	4,650 ± 500	X	3,950 ± 550
W	5,950 ± 250	W	5,300 ± 750
V	7,500 ± 1,000	V	~7,500
U(?)	8,500 ± 1,500	U	9,300 ± 500
T	~16,500	T	~17,000
		S (?)	17,000 to 20,000

Data Sources:
McCalpin and Nishenko (1996), Black et al. (1996), McCalpin (2002), McCalpin and Forman (2002), UQFPWG-Lund et al. (2004)

(vs Olig et al., 2005 and Wong et al., 2008 used UQFPWG consensus values with updates for Provo segment)

COV Values

- Ellsworth et al. (1998)
  Worldwide data: 0.5 ± 0.2

- McCalpin and Slemmons (1998)
  All faults: 0.36
  Normal faults: 0.35

- McCalpin and Nishenko (1996): 0.66 (WFZ analysis) but used 0.21 – 0.5

- Wong et al. (2002): 0.16 – 1.0 (WFZ analysis) but used 0.5 ± 0.2

- Wong et al. (2008): 0.42
  Monte Carlo analysis of UQFPWG values + Provo segment data (used preferred 0.4, 0.3 – 0.7)

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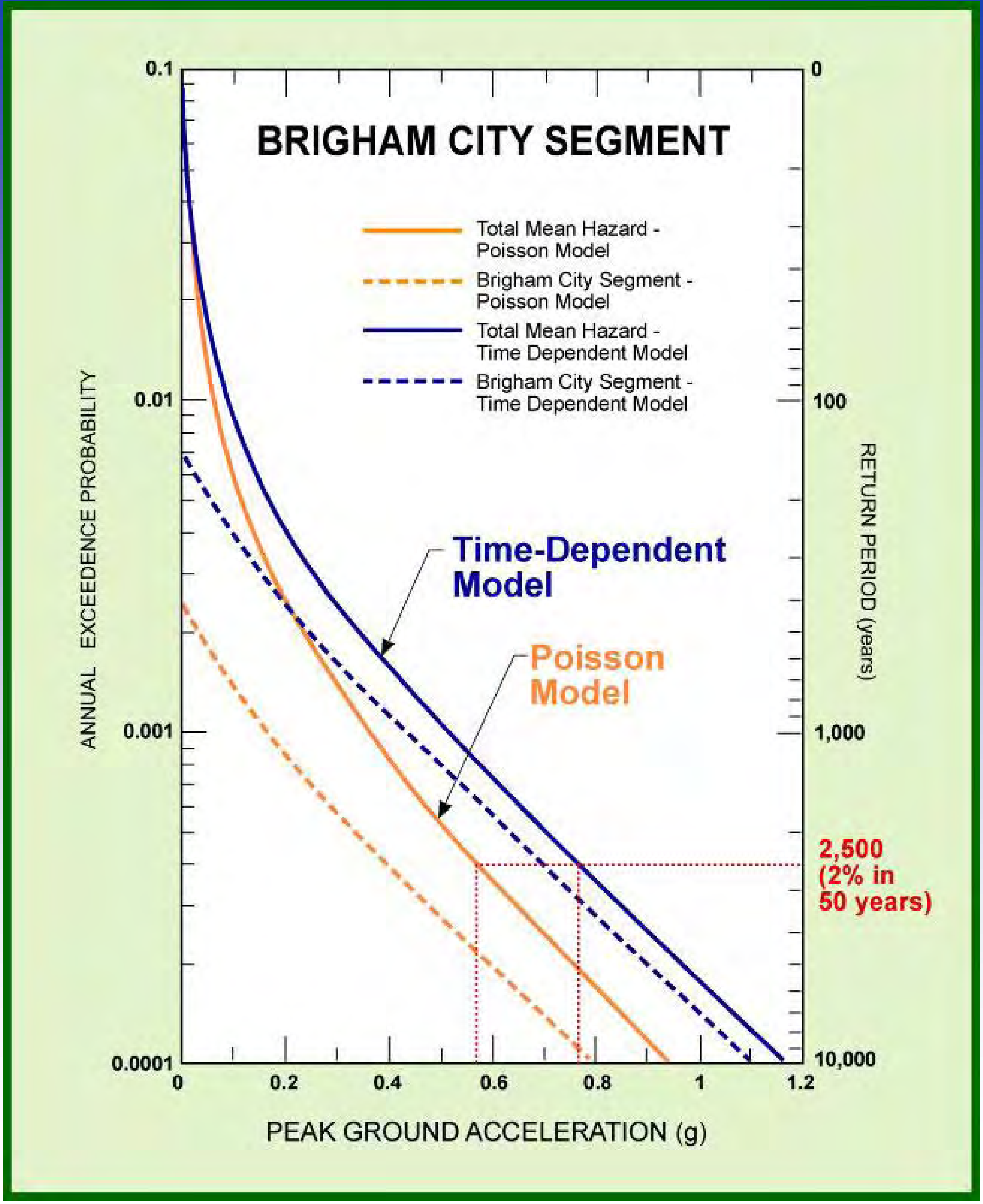
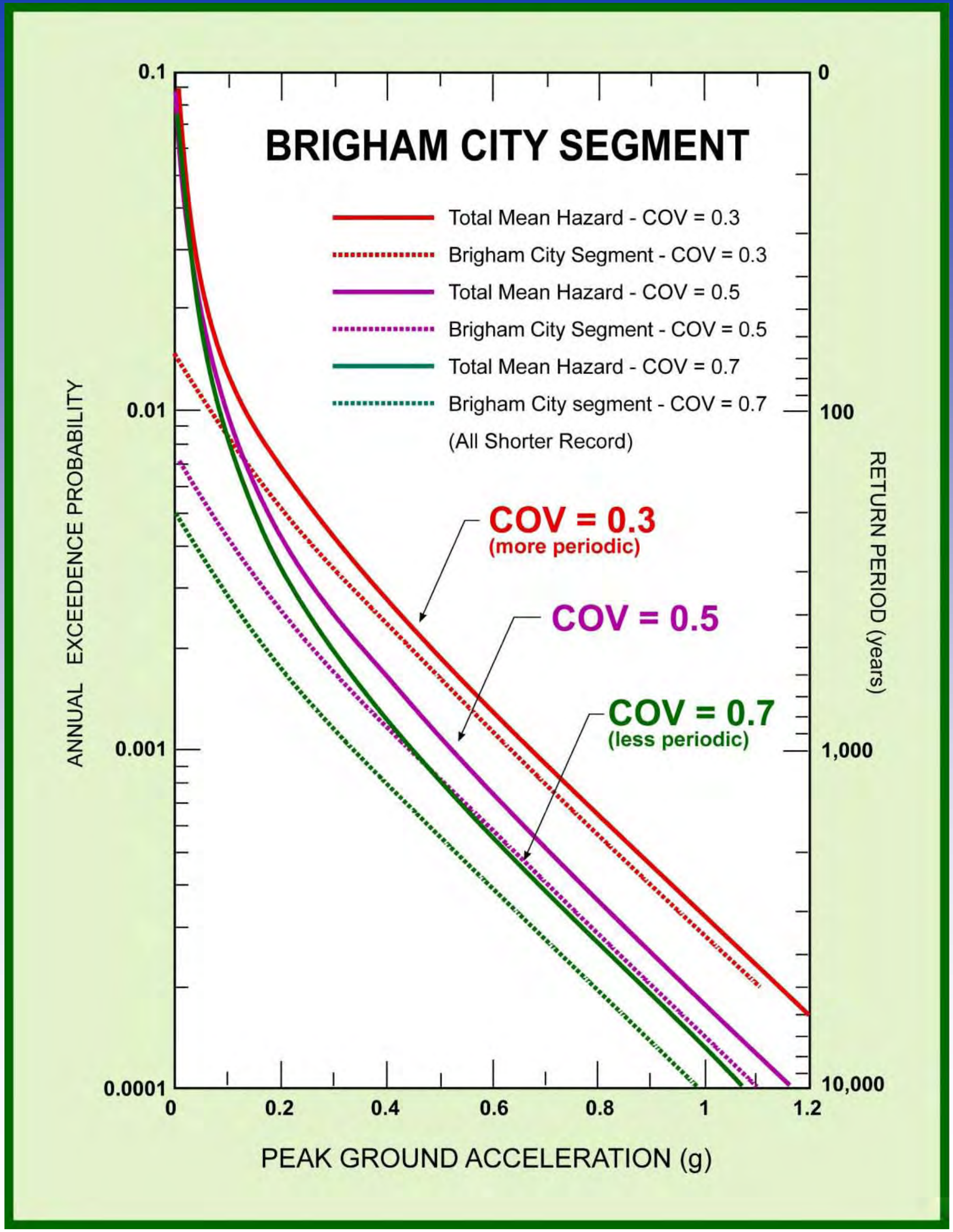
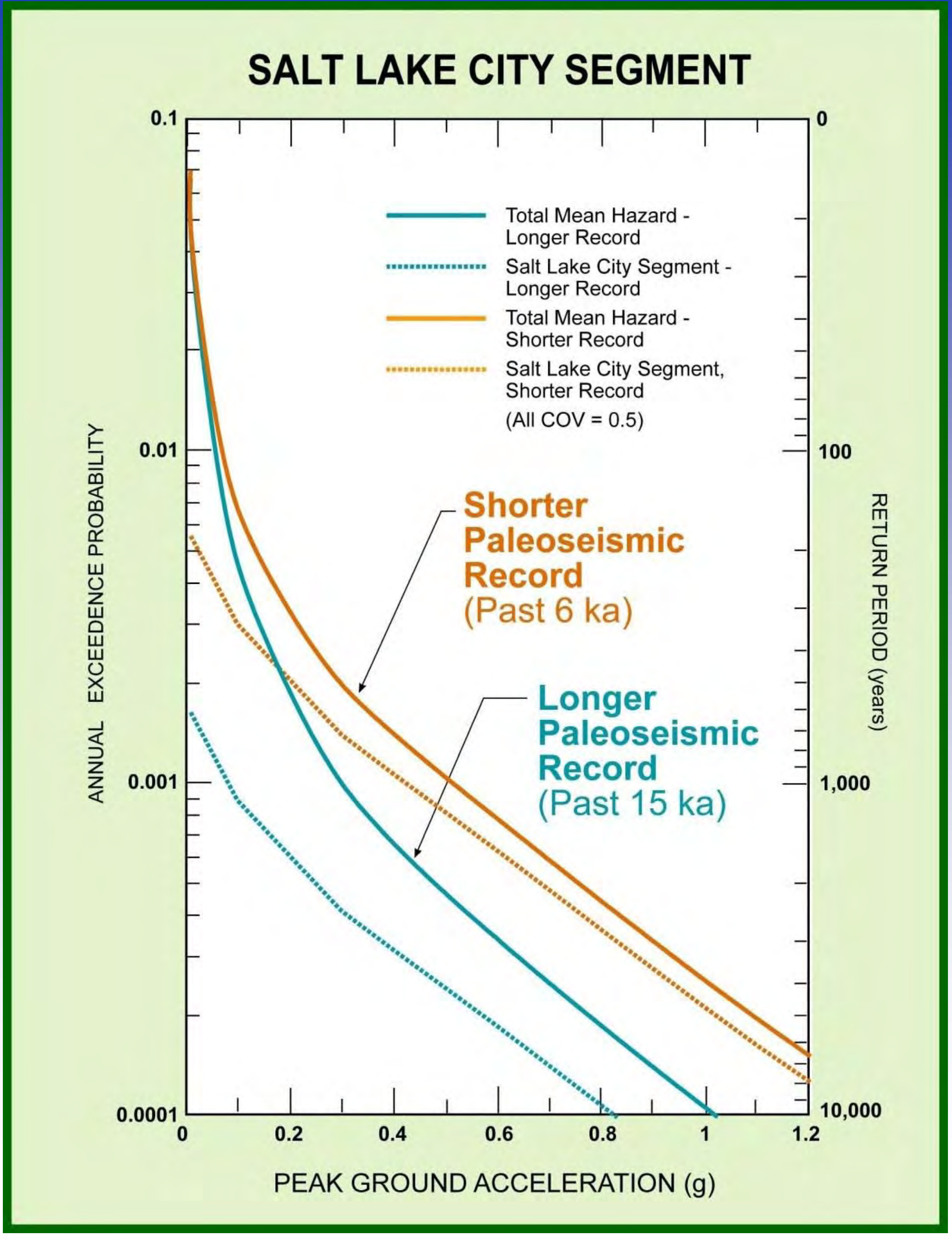
Time-Dependent Recurrence Parameters

	Salt Lake City Segment:						Brigham City Segment:					
	Shorter Record (past 6 ka)			Longer Record (past 17 ka)			Shorter Record (past 9 ka)			Longer Record (past 17 ka)		
Mean Recurrence	1,333 years			2,617 years			1,279 years			2,396 years		
Elapsed Time	1,300 years			1,300 years			2,125 years			2,125 years		
Coefficient of Variation	0.3	0.5	0.7	0.3	0.5	0.7	0.3	0.5	0.7	0.3	0.5	0.7
Conditional Probabilities (%)	11	7	6	< 1	< 2	2	16	9	6	5	4	3
Time-Dependent (Equivalent Poisson) Recurrence Intervals	450 yrs	650 yrs	850 yrs	9,600 yrs	2,900 yrs	2,200 yrs	300 yrs	550 yrs	800 yrs	950 yrs	1,250 yrs	1,500 yrs
UQFPWG Recurrence Interval Distribution	1,350 (500 – 2,400) yrs						1,300 (500 – 2,800) yrs					


BRIGHAM CITY SEGMENT
Total Mean Hazard - Poisson Model
Brigham City Segment - Poisson Model
Total Mean Hazard - Time Dependent Model
Brigham City Segment - Time Dependent Model
Time-Dependent Model
Poisson Model
2,500 (2% in 50 years)
ANNUAL EXCEEDENCE PROBABILITY
0.1
0.01
0.001
0.0001
RETURN PERIOD (years)
0
100
1,000
10,000
PEAK GROUND ACCELERATION (g)
0
0.2
0.4
0.6
0.8
1
1.2



BRIGHAM CITY SEGMENT
Total Mean Hazard - COV = 0.3
Brigham City Segment - COV = 0.3
Total Mean Hazard - COV = 0.5
Brigham City Segment - COV = 0.5
Total Mean Hazard - COV = 0.7
Brigham City segment - COV = 0.7
(All Shorter Record)
COV = 0.3
(more periodic)
COV = 0.5
COV = 0.7
(less periodic)
ANNUAL EXCEEDENCE PROBABILITY
0.1
0.01
0.001
0.0001
RETURN PERIOD (years)
0
100
1,000
10,000
0
0.2
0.4
0.6
0.8
1
1.2
PEAK GROUND ACCELERATION (g)



SALT LAKE CITY SEGMENT
Total Mean Hazard - Longer Record
Salt Lake City Segment - Longer Record
Total Mean Hazard - Shorter Record
Salt Lake City Segment, Shorter Record
(All COV = 0.5)
Shorter Paleoseismic Record
(Past 6 ka)
Longer Paleoseismic Record
(Past 15 ka)
ANNUAL EXCEEDENCE PROBABILITY
0.1
0.01
0.001
0.0001
RETURN PERIOD (years)
0
100
1,000
10,000
0
0.2
0.4
0.6
0.8
1
1.2
PEAK GROUND ACCELERATION (g)

Time Dependent Recurrence Intervals for the Brigham City Segment

	Preferred (weighted 0.6)	Maximum (weighted 0.2)	Minimum (weighted 0.2)
Elapsed time (yrs)[1]	2100	2100	2100
Mean recurrence (yrs)[1]	1300	2800	500
COV[2]	0.4	0.7	0.3
Time-dependent (or equivalent-Poisson) recurrence interval (yrs)[3]	430	1850	120

(From Wong et al. 2006)

1 From Lund (2005)

2 Range from WGCEP (1999) but the preferred value is based on a COV of 0.42 calculated for this study using Wasatch fault data (see text for discussion).

3 As per recommendations of the UQFPWG, these values were rounded to the nearest half century for our probabilistic analysis.

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Time Dependent Recurrence Intervals for the Salt Lake City Segment

	Preferred (weighted 0.6)	Maximum (weighted 0.2)	Minimum (weighted 0.2)
Elapsed time (yrs)[1]	1300	1875	1300
Mean recurrence (yrs)[1]	1300	2400	500
COV[2]	0.4	0.7	0.3
Time-dependent (or equivalent-Poisson) recurrence interval (yrs)[3]	555	1875	107

(From Wong et al. 2006)

1 From Lund (2005)

2 Range from WGCEP (1999) but the preferred value is based on a COV of 0.42 calculated for this study using Wasatch fault data (see text for discussion).

3 As per recommendations of the UQFPWG, these values were rounded to the nearest half century for our probabilistic analysis.

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Time Dependent Recurrence Intervals for the Provo Segment

	Preferred (weighted 0.6)	Maximum (weighted 0.2)	Minimum (weighted 0.2)
Elapsed time (yrs)[1]	550	550	550
Mean recurrence (yrs)[1]	1450	2800	500
COV[2]	0.4	0.7	0.3
Time-dependent (or equivalent-Poisson) recurrence interval (yrs)[3]	5080	10,160	140

(From Wong et al. 2006)

1 From Lund (2005)

2 Range from WGCEP (1999) but the preferred value is based on a COV of 0.42 calculated for this study using Wasatch fault data (see text for discussion).

3 As per recommendations of the UQFPWG, these values were rounded to the nearest half century for our probabilistic analysis

Summary of Lessons Learned From Previous Time- Dependent Studies

- Time-dependent models can significant impact earthquake probability (and hazard) estimates
- Probabilities are very sensitive to elapsed time, COV and mean recurrence
- Shorter (6 to 8 ka) paleoseismic record are more reliable for estimating mean recurrence (more representative of future behavior and more complete)
- COV appear to be stabilizing at ≈ 0.4
- May want to consider models that incorporate earthquake size, multisegment ruptures, contagion or clustered behavior

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Discussion of Questions to Consider

- Does the past ≈ 6 ky of paleoseismic data provide an adequate baseline for understanding large earthquake recurrence along the WFZ? (record complete and accurate enough?)
- Do surface-faulting earthquakes occur randomly in space and time on individual fault segments or is their occurrence modulated by some type of cyclic behavior?
- What models will best fit observed fault recurrence behavior?
- Are surface faulting earthquakes clustered in space or time?
- Is there contagion behavior between segments?
- Are there multisegment or partial multisegment ruptures?
- What is our time period of interest?

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Coefficient of Variation (COV)

- **Important factor that measures the periodicity of earthquake occurrence**
- **COV** $= \dfrac{\sigma}{\mu}$
- **Small COV (< 0.3) → very periodic behavior (recurrence intervals are relatively consistent)**

versus

Large COV (> 1.0) → not periodic behavior (recurrence intervals vary considerably)

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Hazard Results

Site (Elapsed time of dominant fault segment)	Peak Horizontal Ground Accelerations (PGA) for 2,500-year Return Period						
	Poisson Model	Time-Dependent Model	COV 0.3 (shorter record)	COV 0.5 (shorter record)	COV 0.7 (shorter record)	Shorter Paleoseismic Record (COV = 0.5)	Longer Paleoseismic Record (COV = 0.5)
Brigham City (~2,360 yrs)	0.57 g	0.76 g	0.93 g	0.77 g	0.69 g	0.77 g	0.69 g
Salt Lake City (~1,230 yrs)	0.65 g	0.68 g	0.94 g	0.84 g	0.78 g	0.84 g	0.55 g
Provo (~620 yrs)	0.54 g	0.36 g	0.34 g	0.35 g	0.44 g	NA	NA

(From Olig et al. 2001)

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Overview of Seismicity, Background Earthquakes, and Modeling Earthquake Rates in Utah

Walter Arabasz

UNIVERSITY OF UTAH
SEISMOGRAPH STATIONS
THE UNIVERSITY OF UTAH

Working Group on
Utah Earthquake Probabilities
February 11, 2010

Outline

I. **Excerpts from Arabasz & Burlacu 2009 GSA talk: *Overview of Seismicity in Utah Relevant to Seismotectonics and Earthquake Hazards***

II. **Excerpts from Arabasz 2006 BREWPG talk: *Observed Seismicity and Recurrence Modeling on the Wasatch Fault***

III. **Starting point for WGUEP (towards a Background Seismicity Rate Model)**

Part I . . .

Overview of Seismicity in Utah Relevant to Seismotectonics and Earthquake Hazards

Walter Arabasz and Relu Burlacu

UNIVERSITY OF UTAH SEISMOGRAPH STATIONS
THE UNIVERSITY OF UTAH

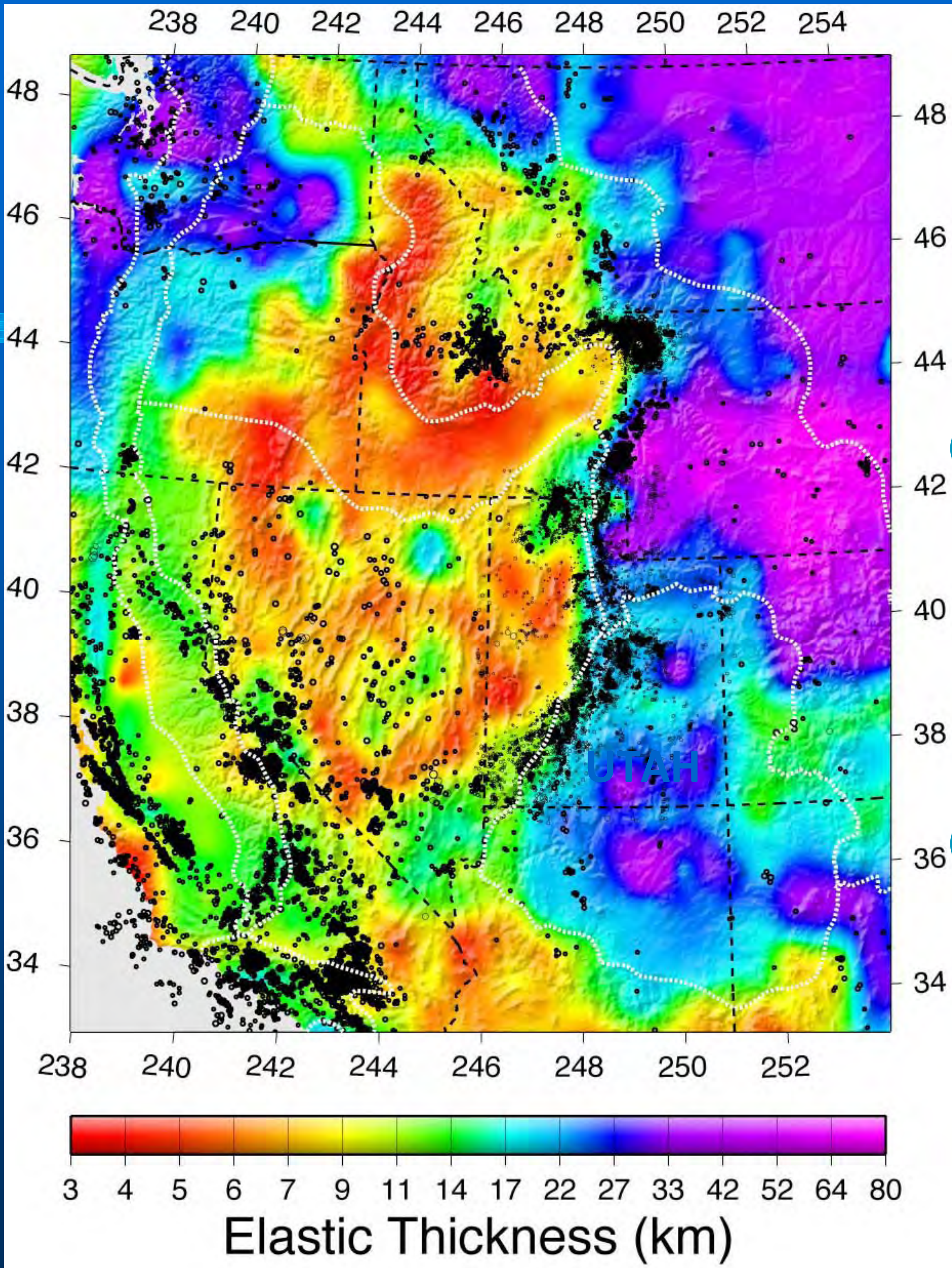
Rocky Mountain Section, GSA
Orem, Utah
May 12, 2009

Some Key Points

- Although there have been major advances in Utah's seismic network, fine-scale correlation of seismicity with geologic structure (notably in 3D) remains a challenge
- Handicaps: limited station density outside the Wasatch Front area; no earthquakes of $M \geq 5$ since 1992; complex superposition of normal faulting upon older thrustbelt structure

Some Key Points (cont’d)

- Only 12% of natural earthquakes in the UU catalog since 1981 have well-constrained focal depths; these show evident variations in maximum focal depths (15–30 km) across the BR-CP transition in central Utah and east of the Wasatch fault in northern Utah



Big Picture

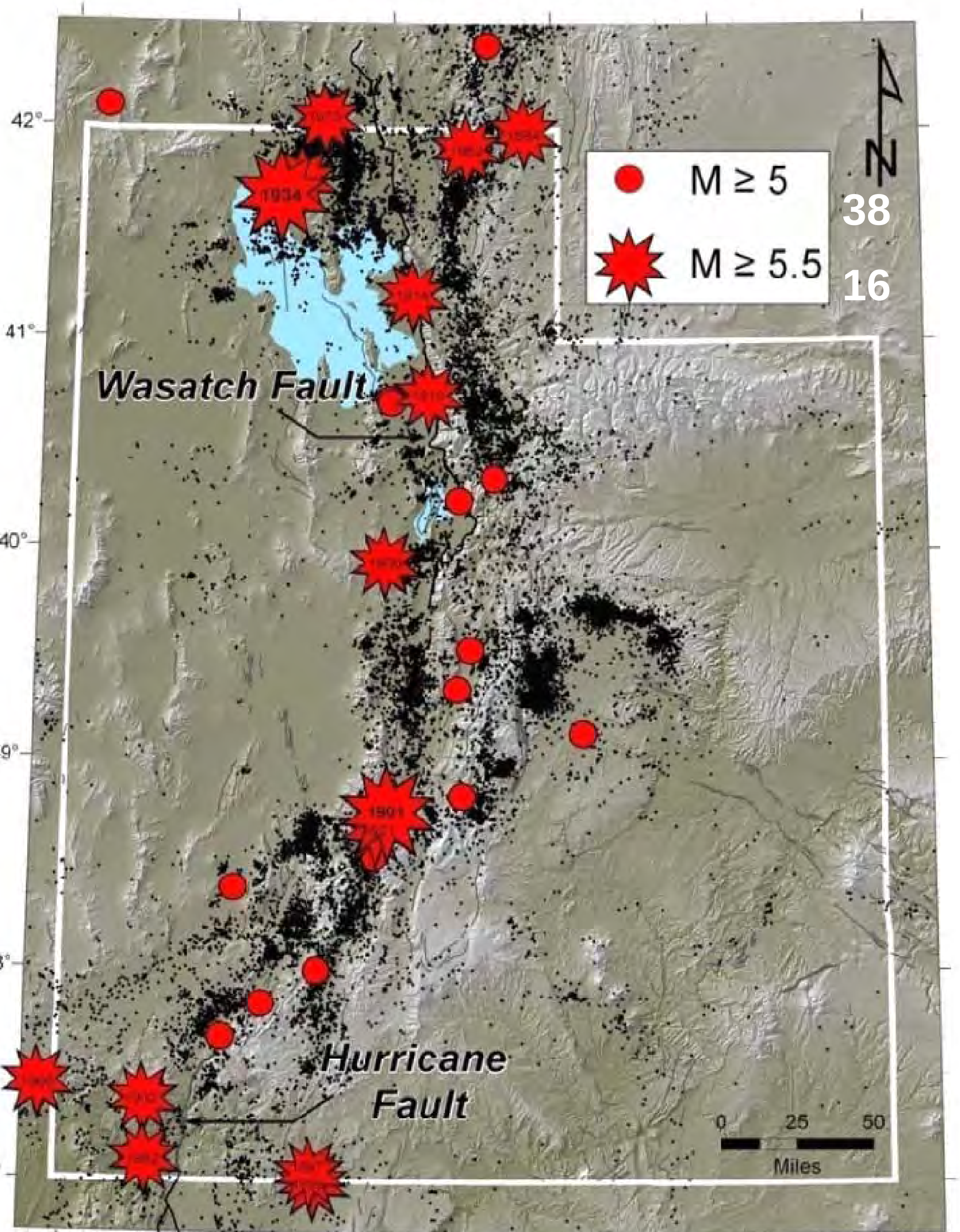
"Thickness" here is a proxy for depth of ductile flow

Seismicity correlates with large gradients in lithospheric strength

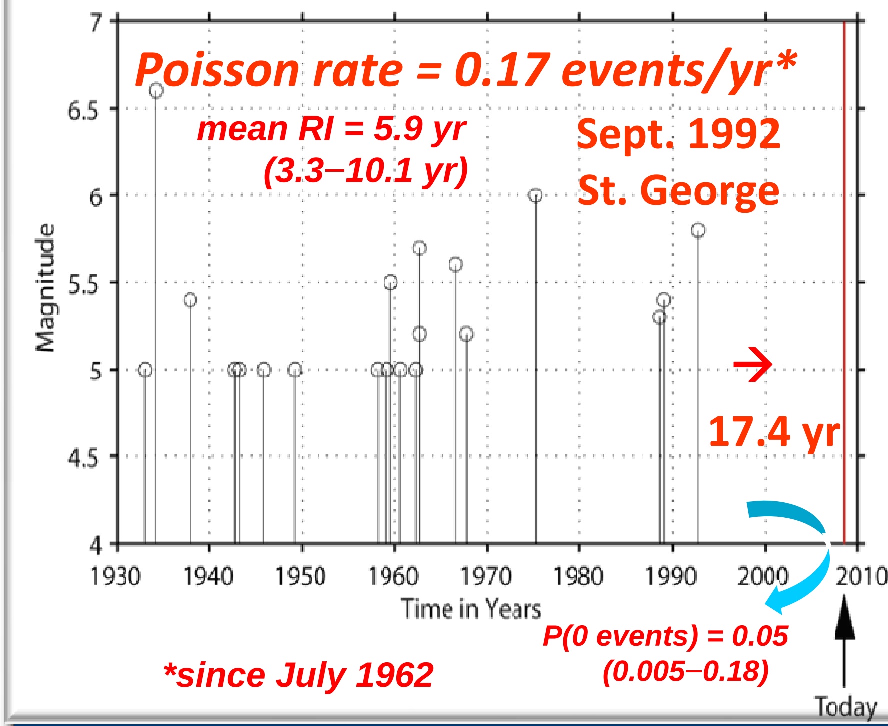
Lowry et al. (2000, JGR)

Historical Seismicity

HISTORICAL & INSTRUMENTAL SEISMICITY
IN THE UTAH REGION (1850-2008)

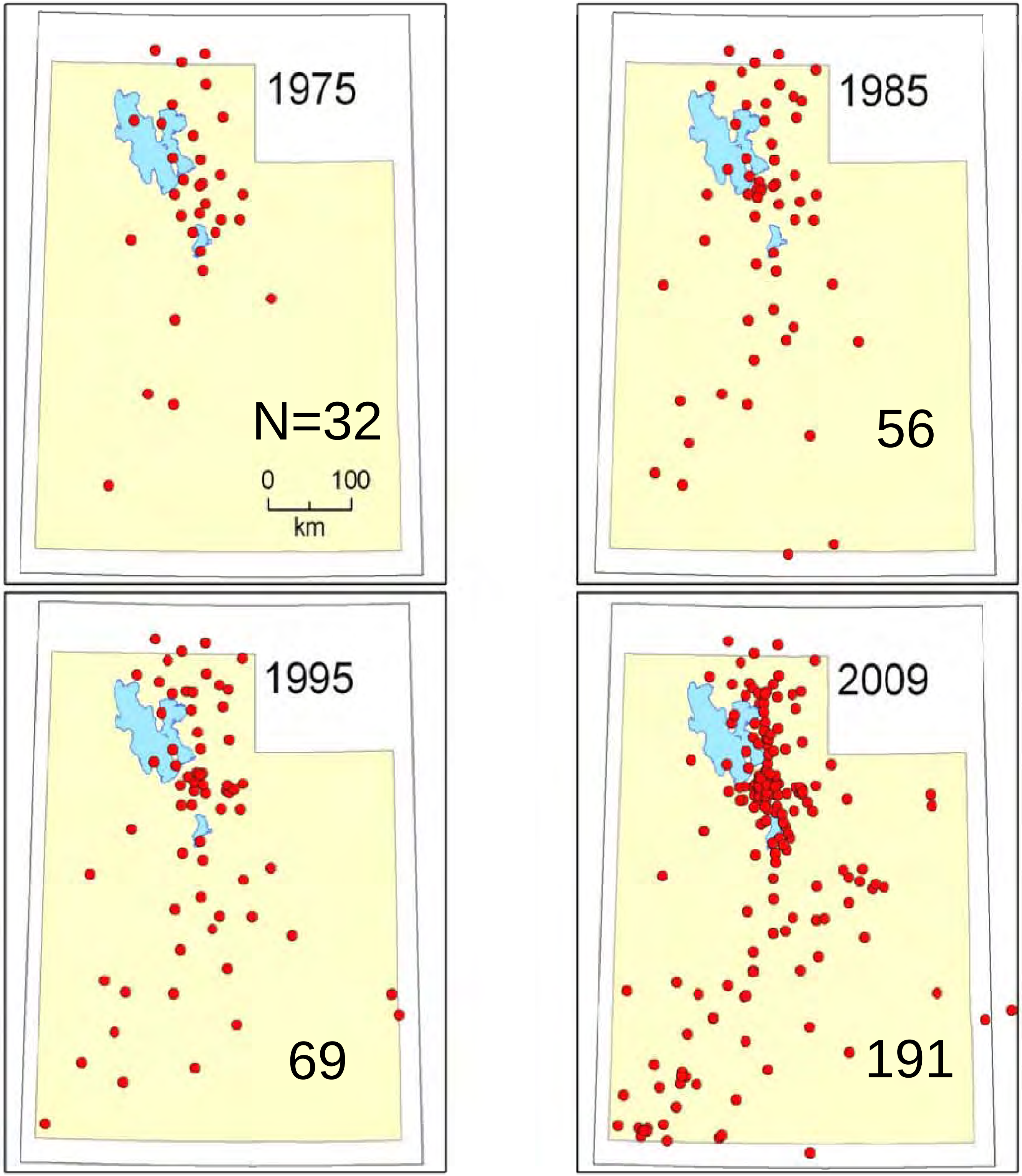


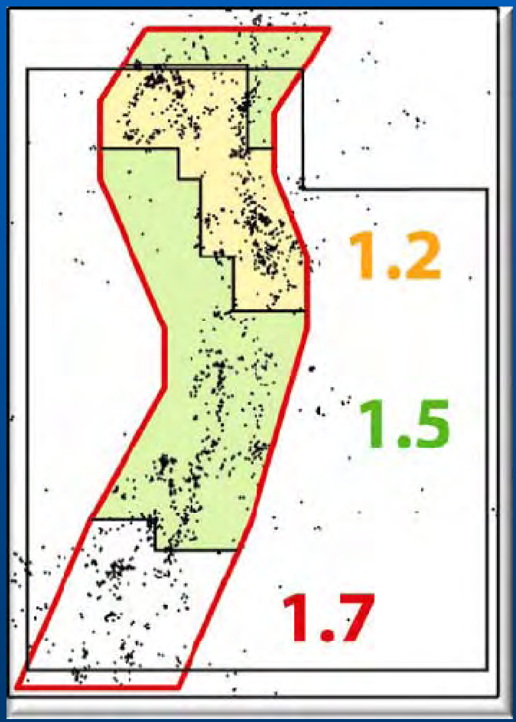
*Source: University of Utah Seismograph Stations earthquake catalog
(number of earthquakes = 44,634)



Mainshocks of M ≥ 5
Since 1930

Seismographic Coverage





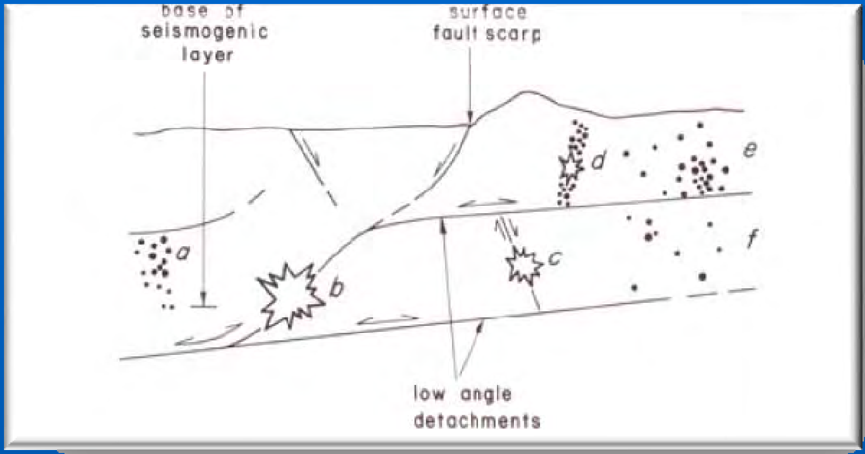
Magnitude of completeness 2000– 2003

Wasatch Front Region

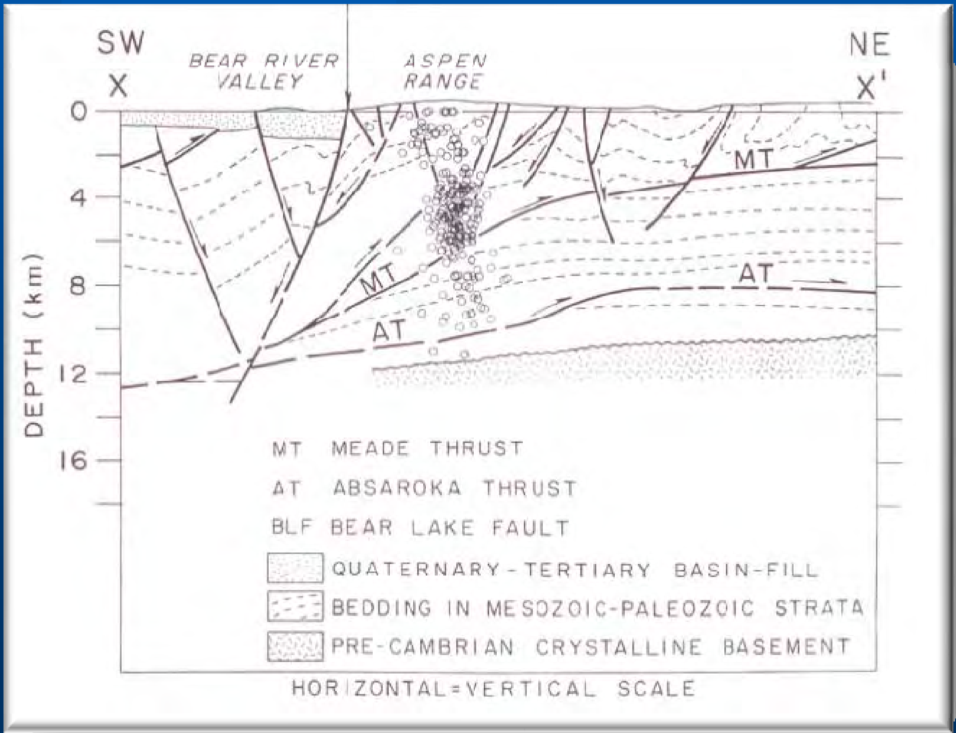
Magnitude Range	Completeness Period
$2.0 \leq M_L \leq 2.5$	Jan 1981 –
$2.5 \leq M_L \leq 3.0$	Jan 1981 –
$3.0 \leq M_L \leq 3.5$	July 1962 –
$3.5 \leq M_L \leq 4.0$	July 1962 –
$4.0 \leq M_L$	July 1962 –
$4.7 \leq M_L$	Jan 1950 –**?**
$5.3 \leq M_L$	Jan 1938 –
$6.0 \leq M_L$	Jan 1900 –

Correlating Seismicity and Geologic Structure

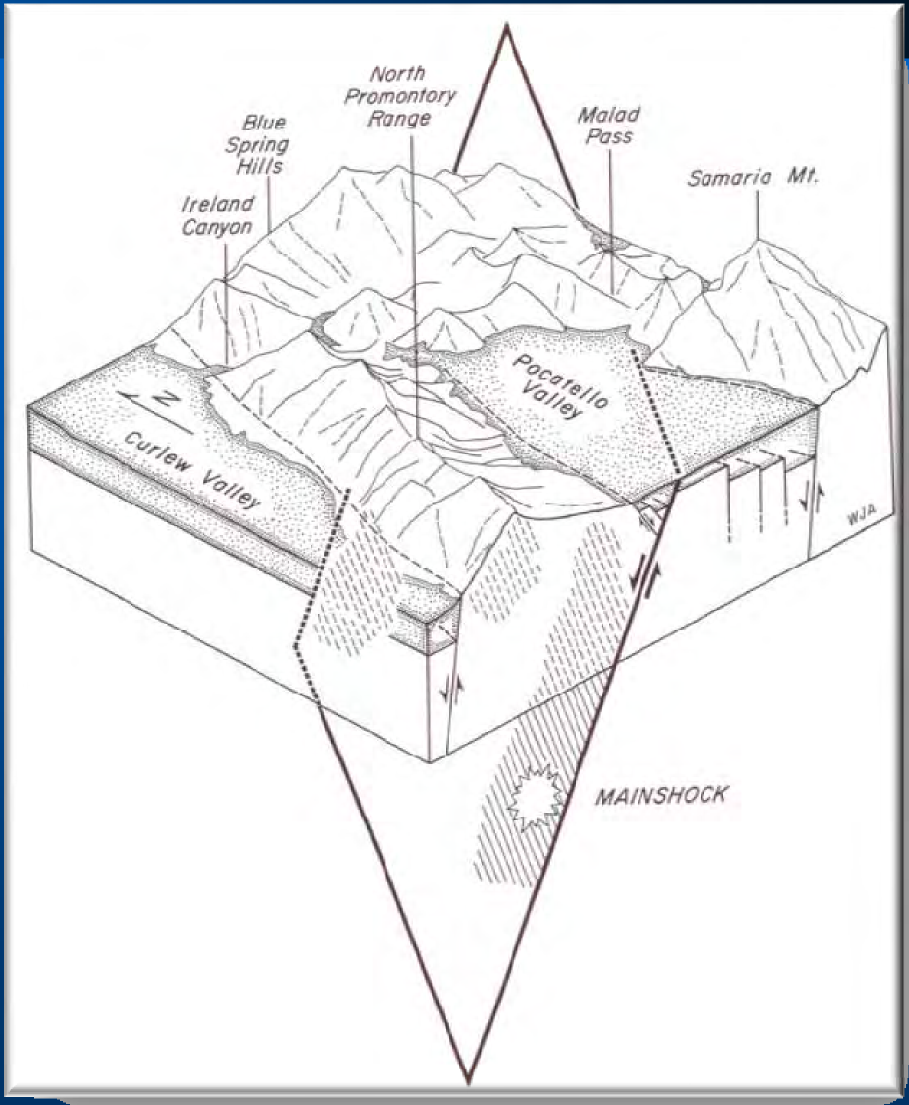
. . . 20 to 30 years ago



Arabasz & Julander (1986)

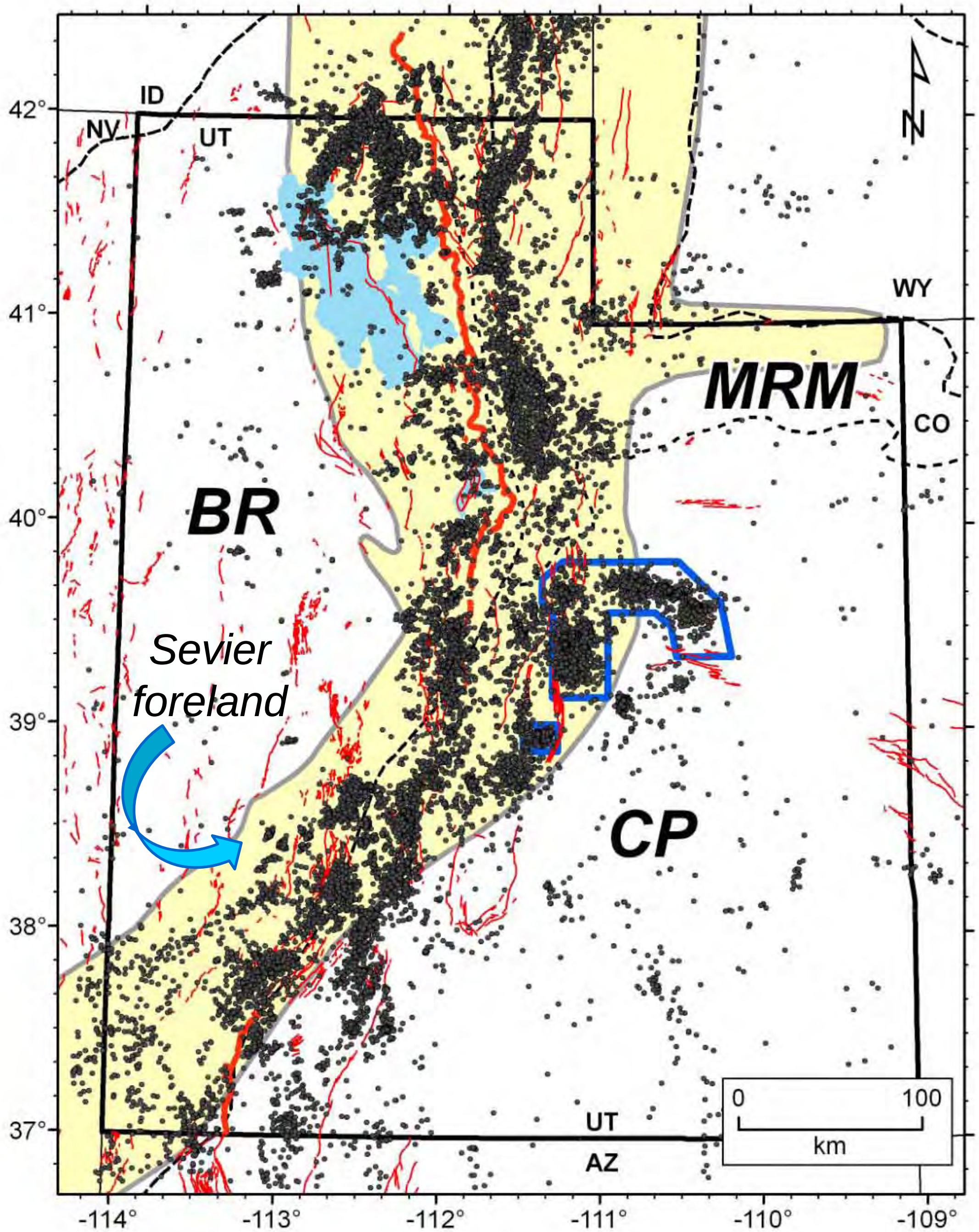


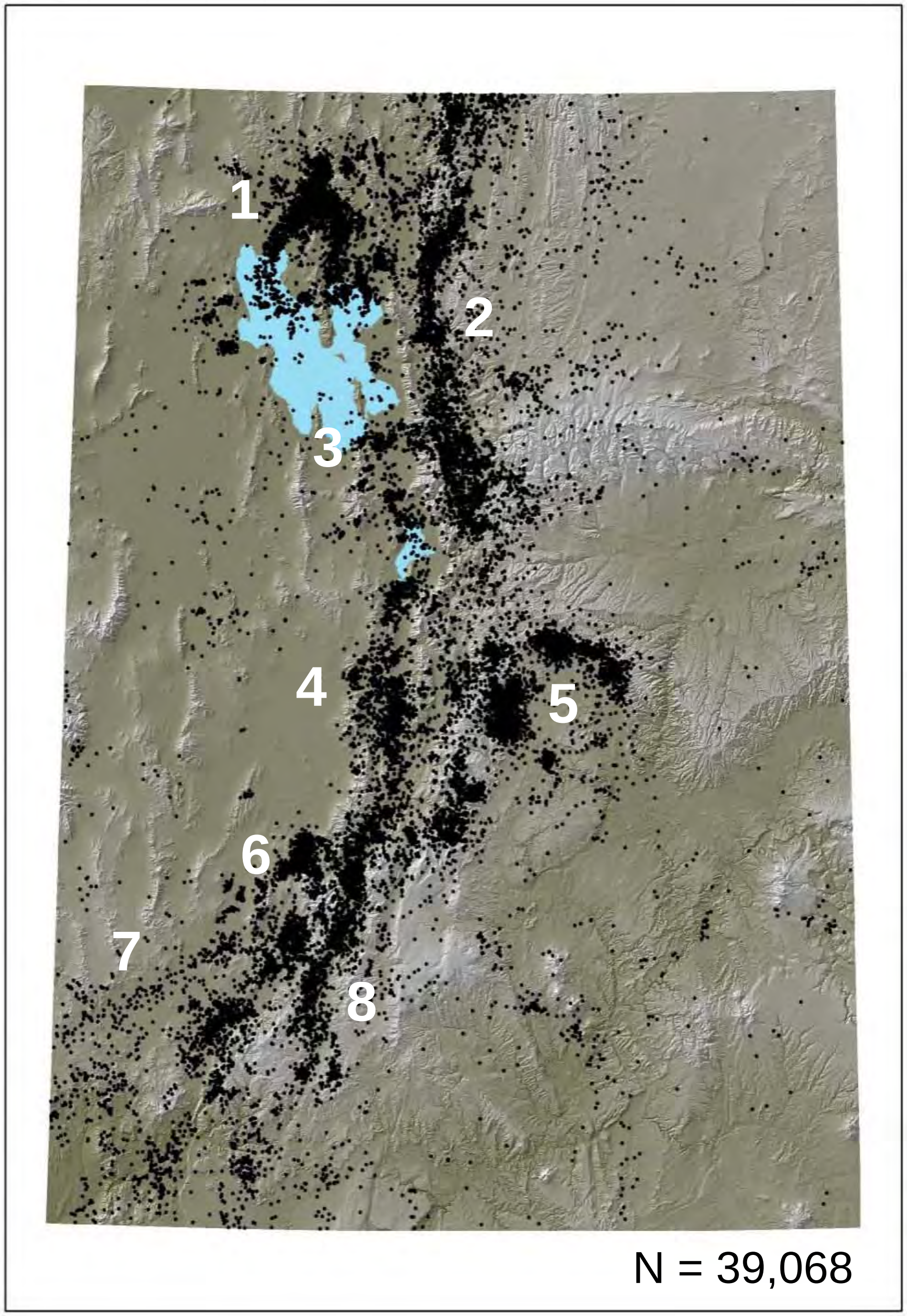
Richins et al. (1983)



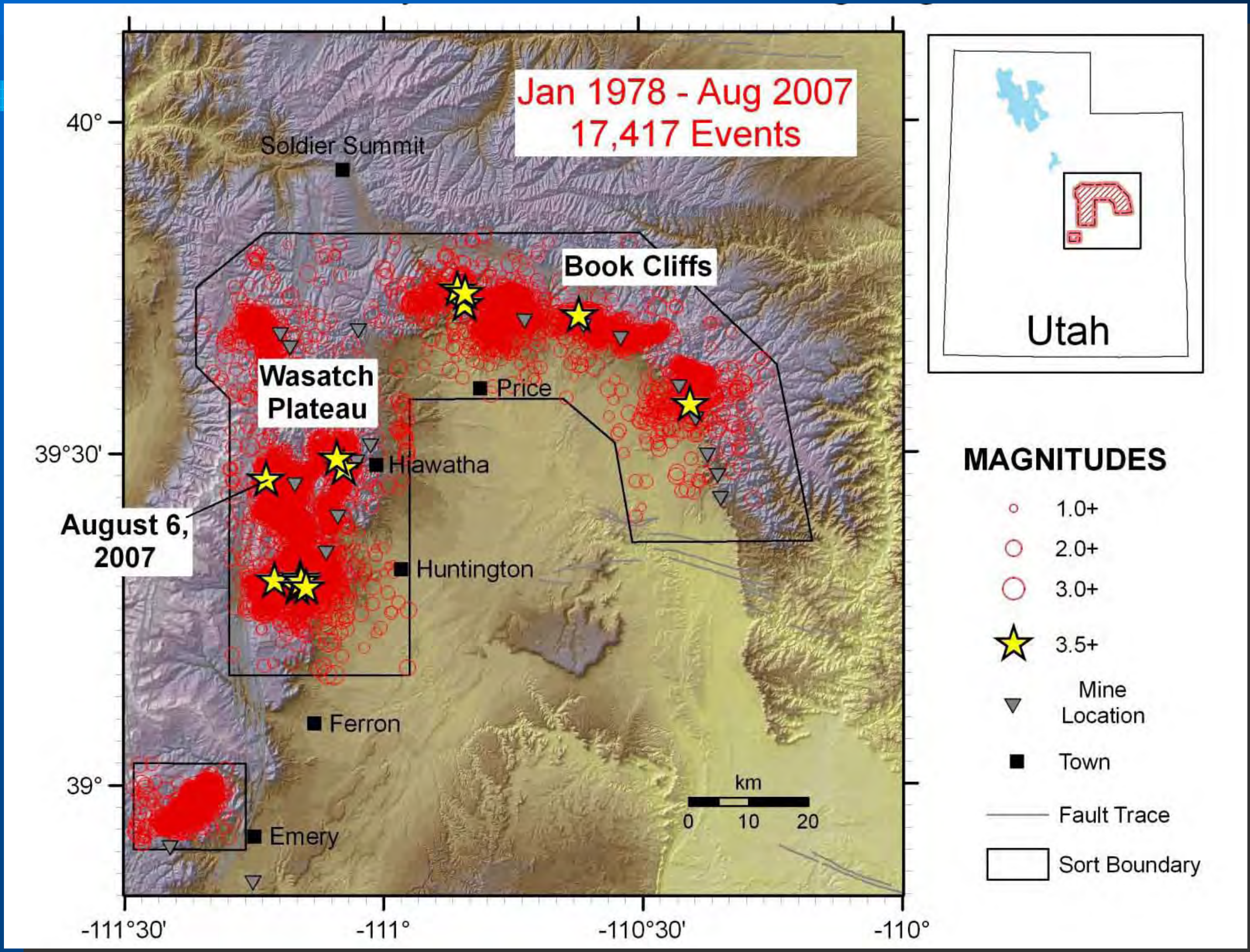
Arabasz et al. (1981)

Seismicity of the Utah Region, 1981–2008





Coal-mining-induced seismicity in the Wasatch Plateau-Book Cliffs region



Pechmann et al. (2008)

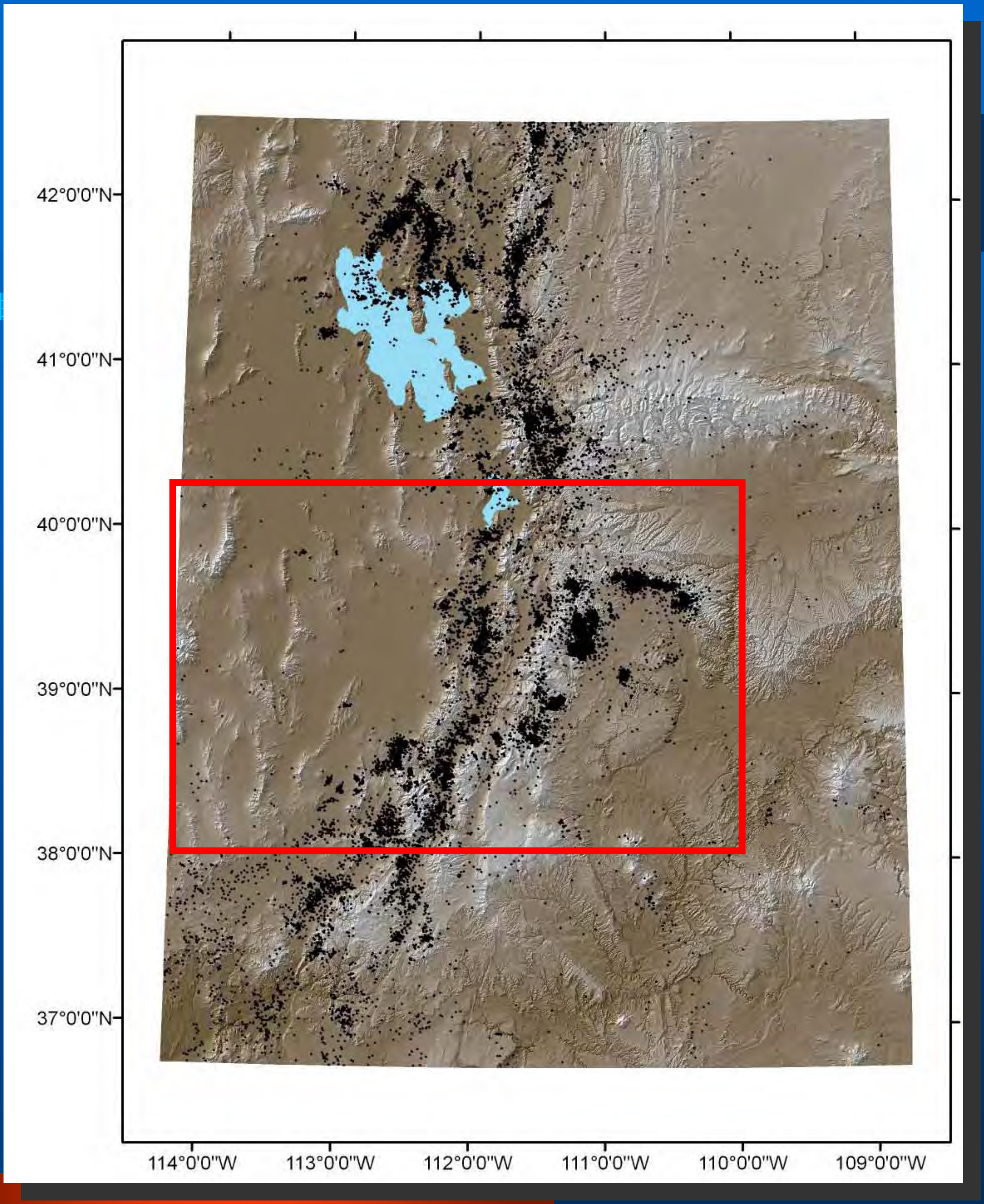
Within these polygons, nearly all seismic events are mining-related.
In test studies, we have found < 2% of events that arguably might be tectonic.

Focal-Depth Resolution 1981–2008 Utah Region Catalog*

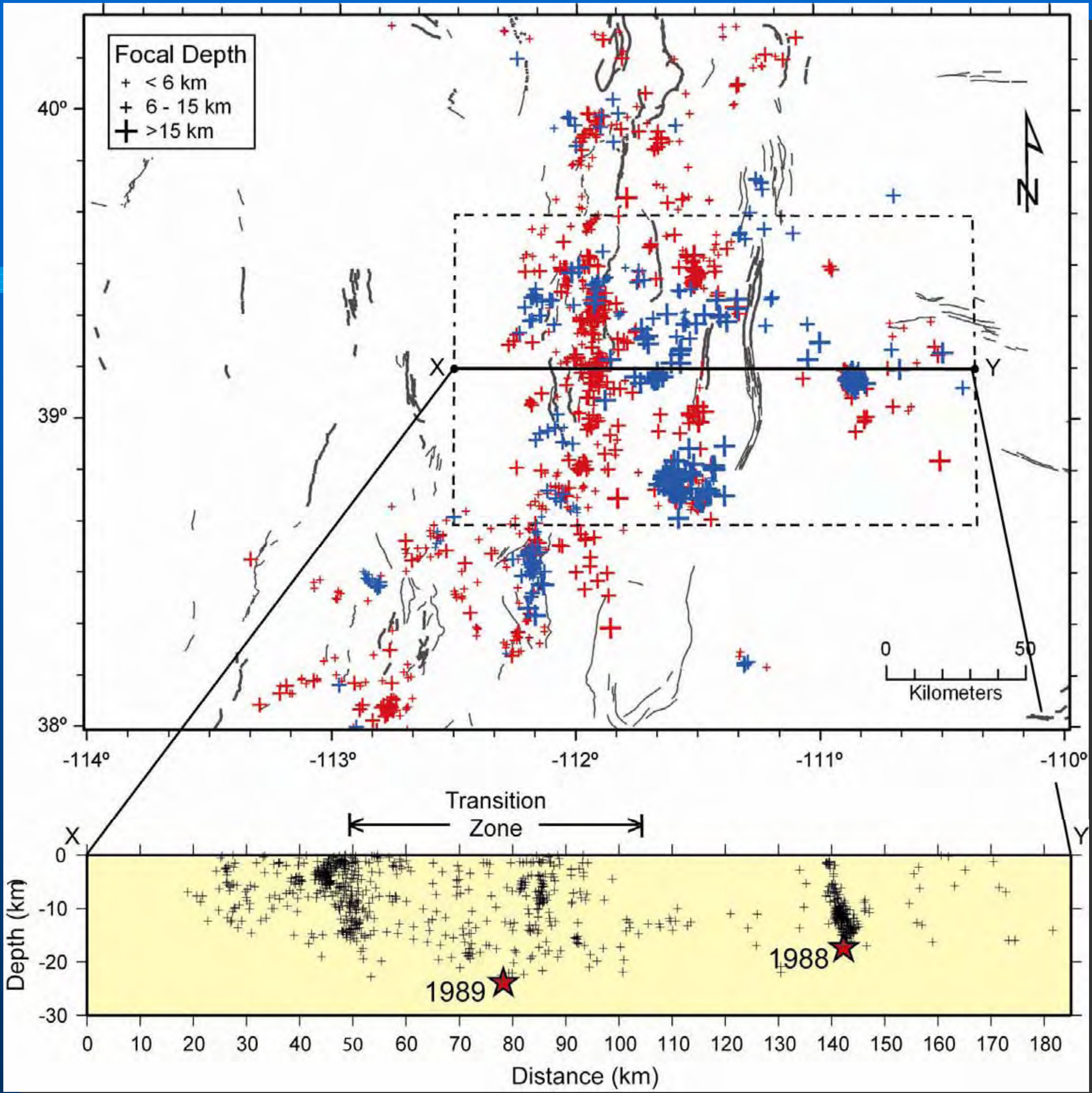
"Well-constrained": N = 2,334 (12%)
(DMIN ≤ focal depth OR 5.0 km
AND ERZ ≤ 2.0 km)

"Fair": N = 3,465 (18%)
(DMIN ≤ 2 x focal depth OR 30.0 km
AND ERZ ≤ 2.0 km)

**** N = 19,730 (excluding mining-induced seismicity)***



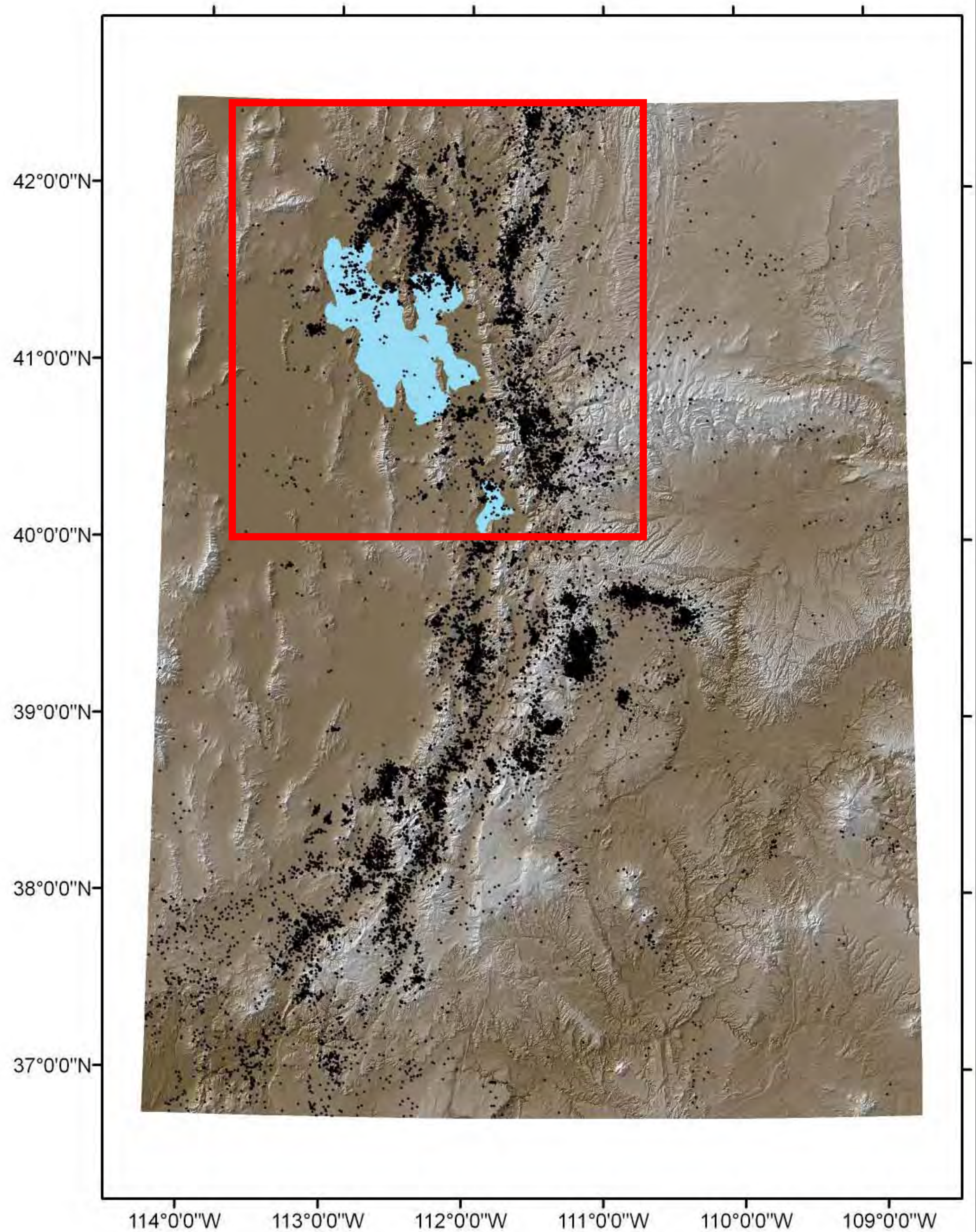
Central Utah



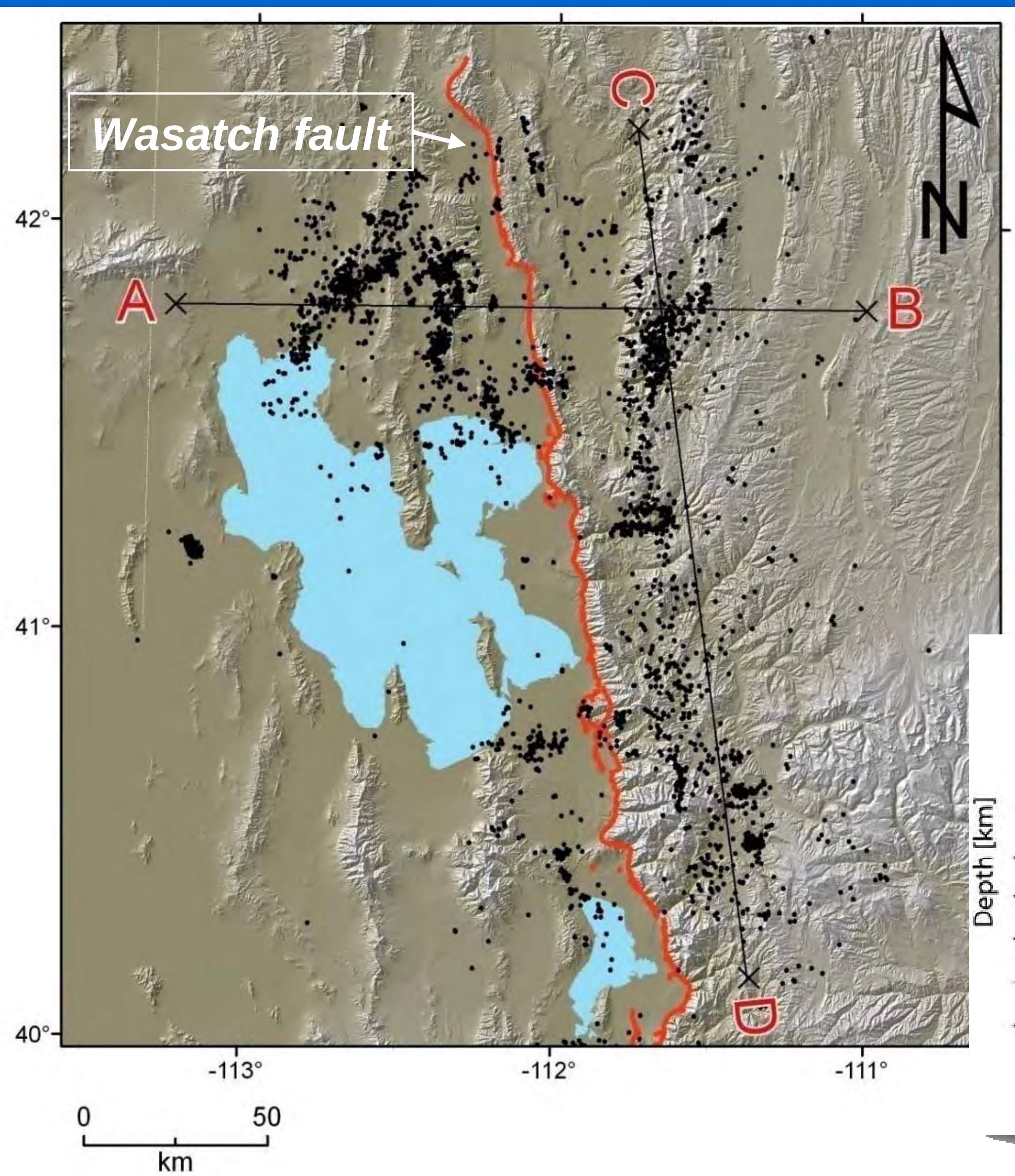
BLUE = "Well-constrained"

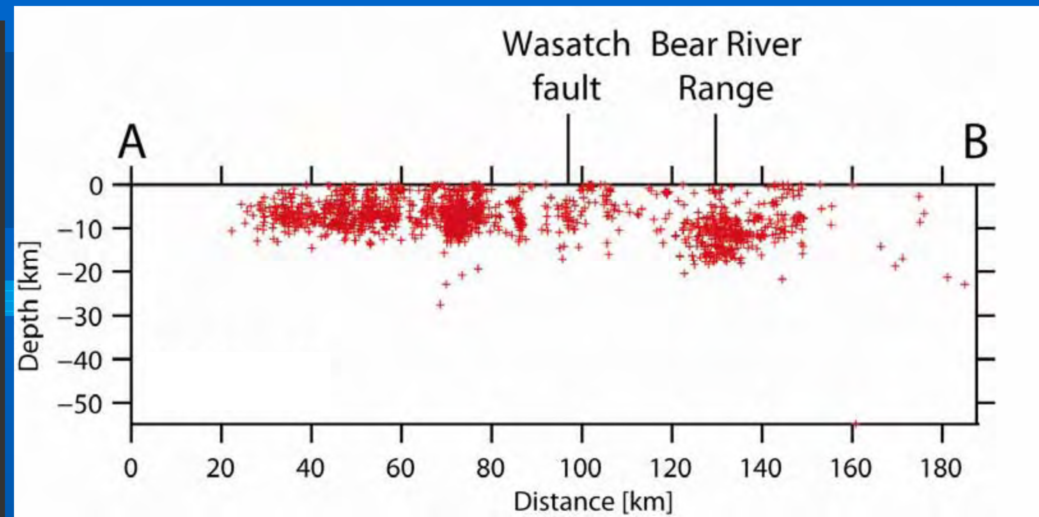
RED = "Fair"

Arabasz et al. (2007, UGA 36)

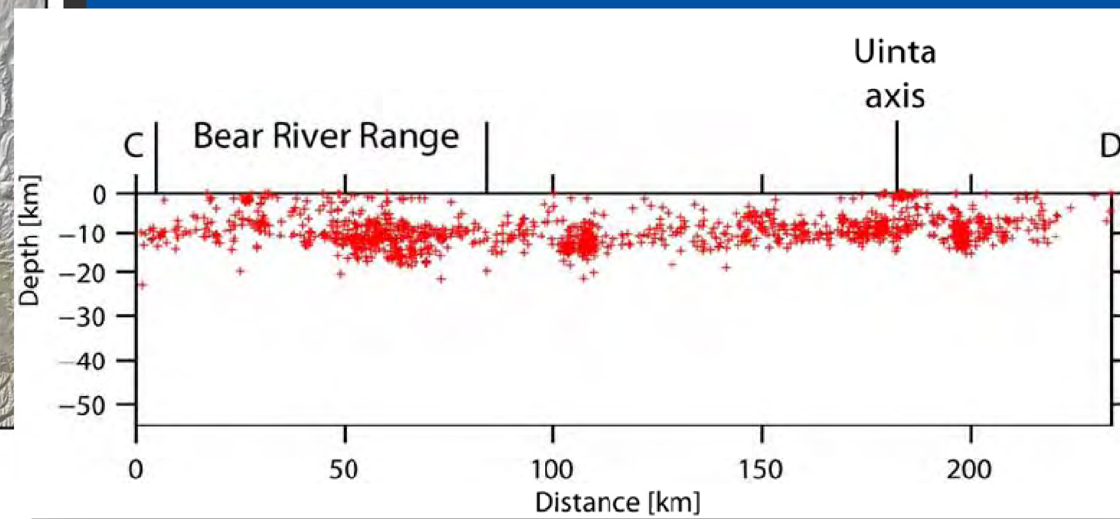


Northern Utah



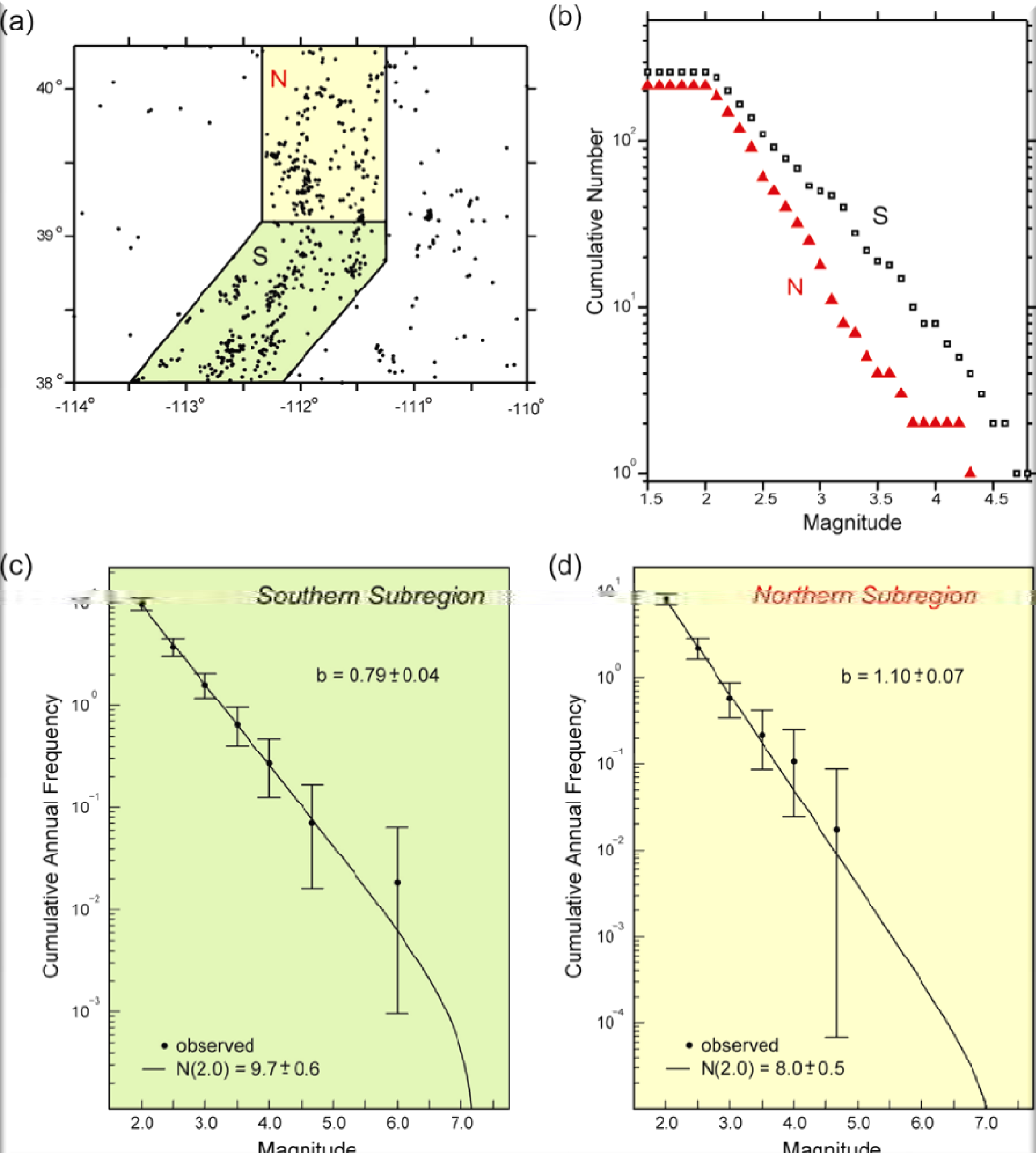


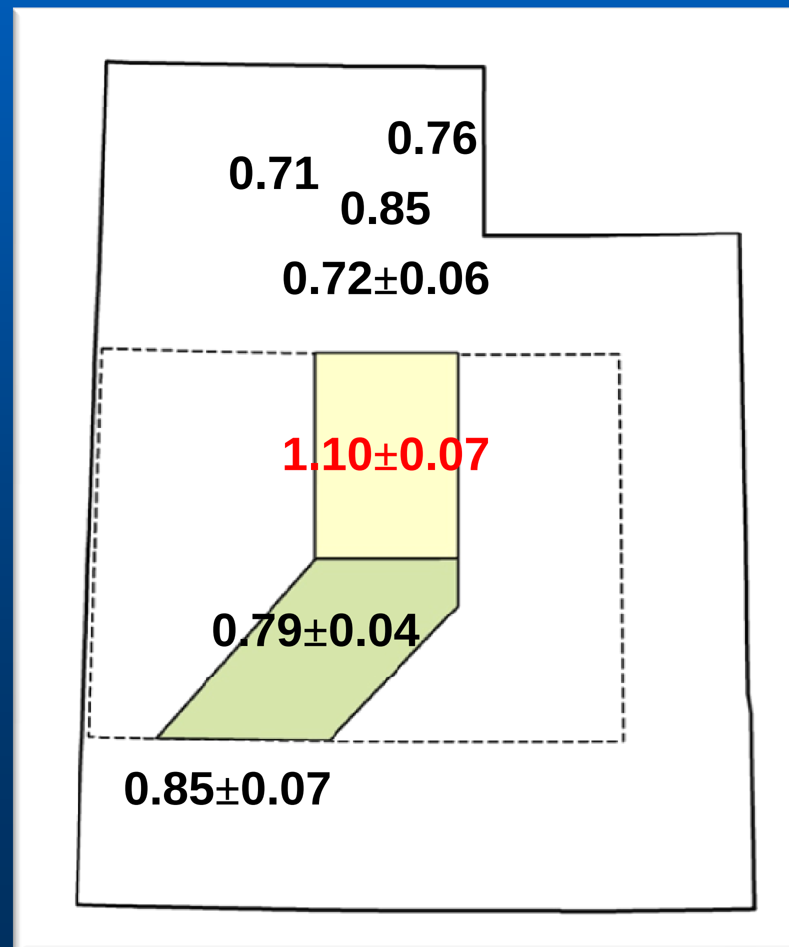
horizontal = vertical scales



Earthquakes with well-constrained and fair focal depths only

Recurrence Modeling and b-values





Arabasz et al. (2007, UGA 36)

Part II . . .

Observed Seismicity and Recurrence Modeling on the Wasatch Fault

Walter Arabasz

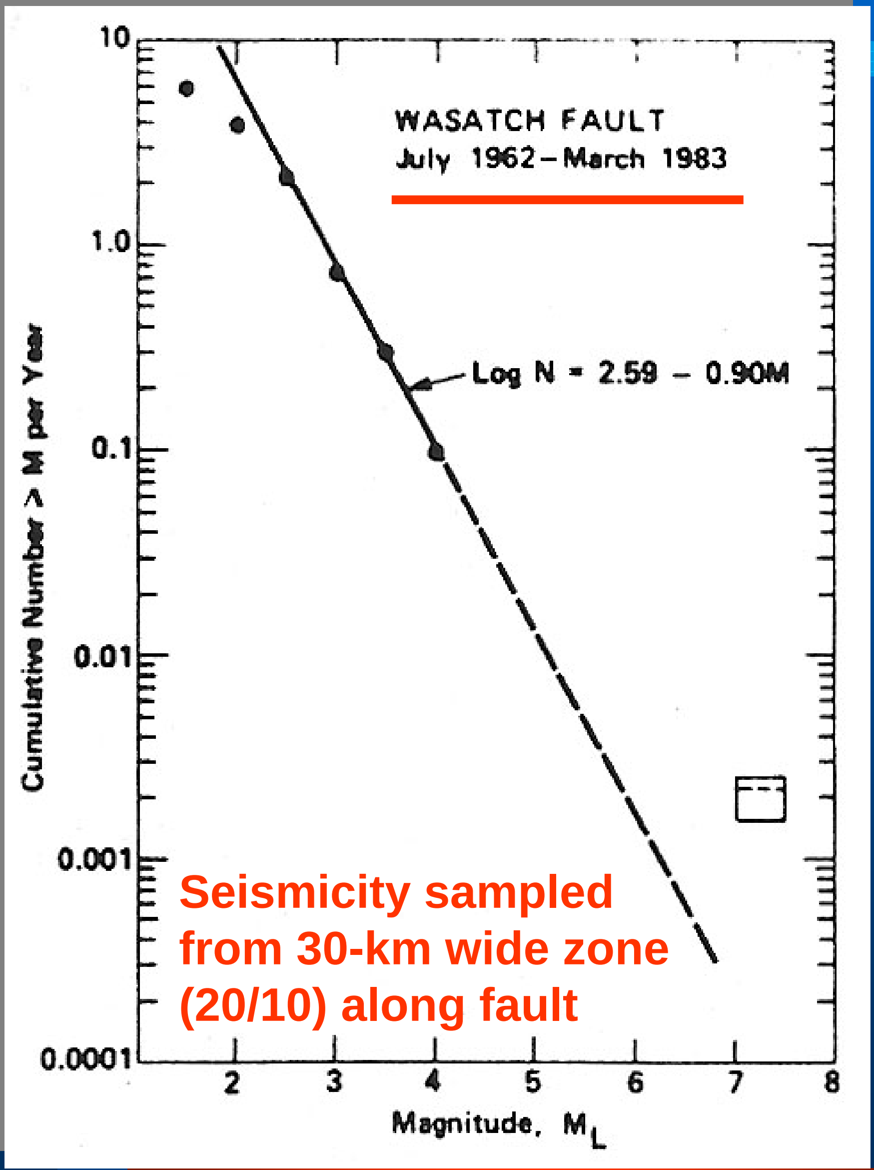
UUSS
university of utah
seismograph stations

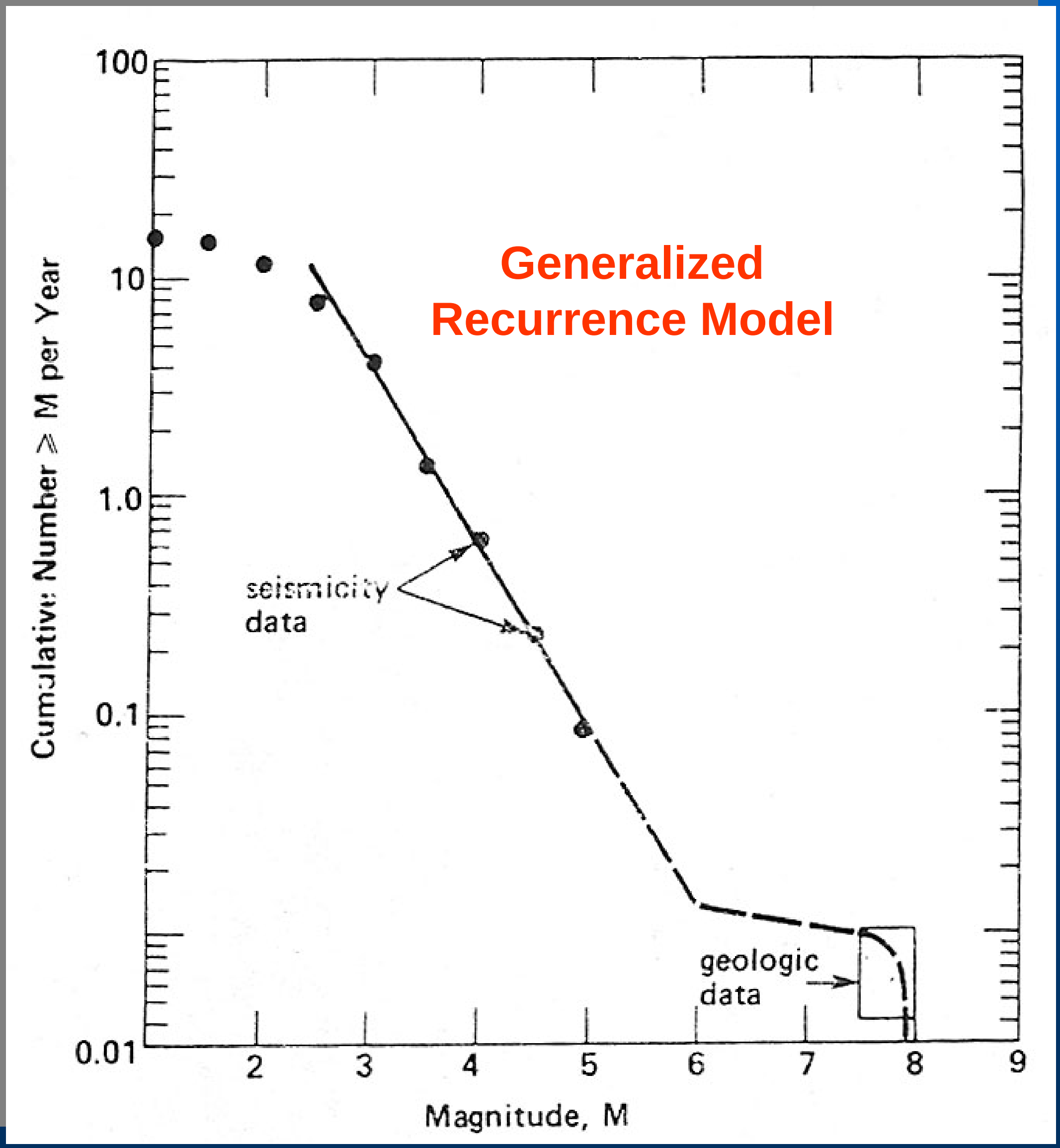
March 8, 2006

Towards Weighting Recurrence Models for the Wasatch Fault

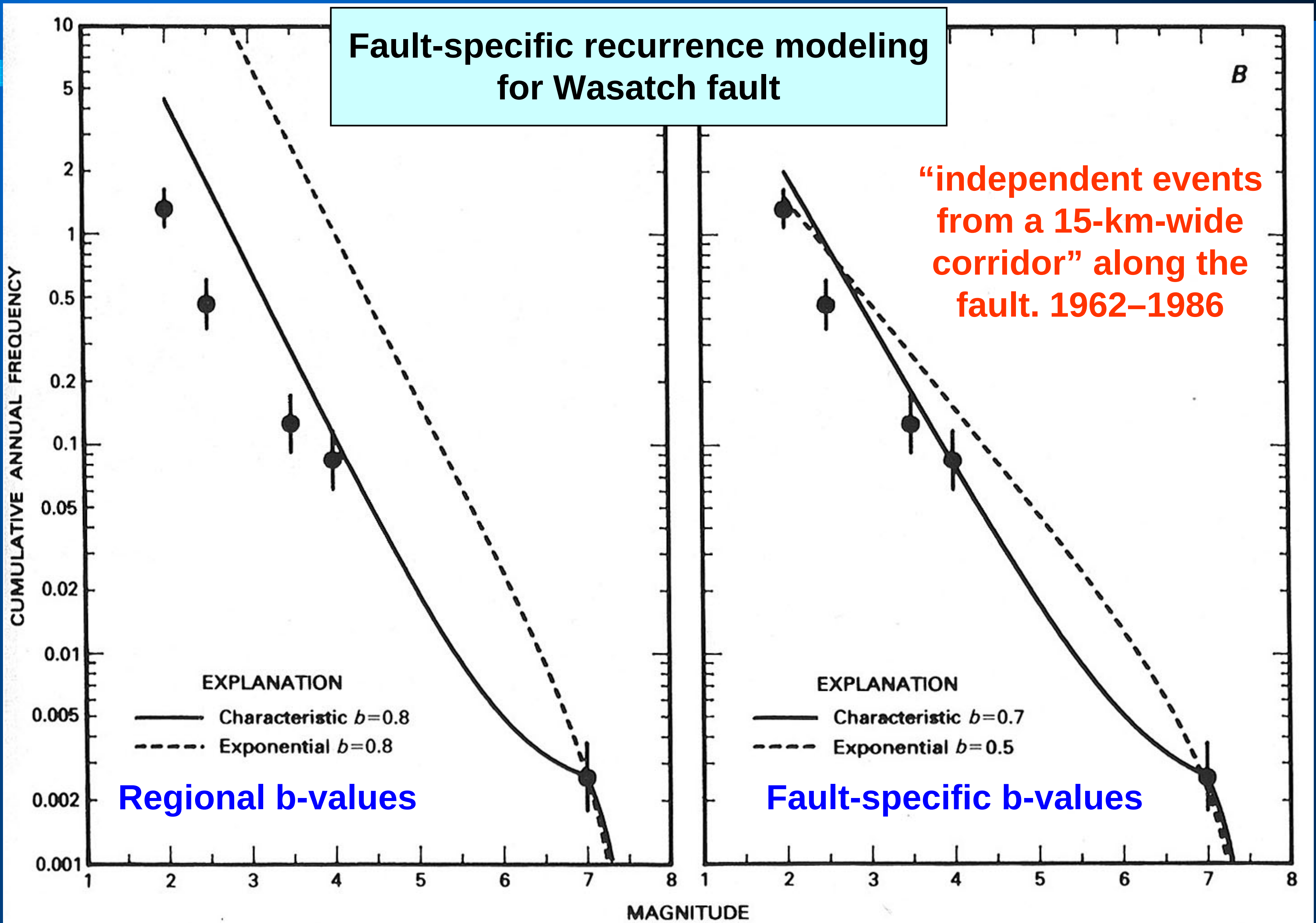
- What can we say from observational seismology?
- Keeping an eye on lack-of-knowledge uncertainty
- If we don't really know the magnitude distribution, we at least know we can't double count

Schwartz & Coppersmith (1984)

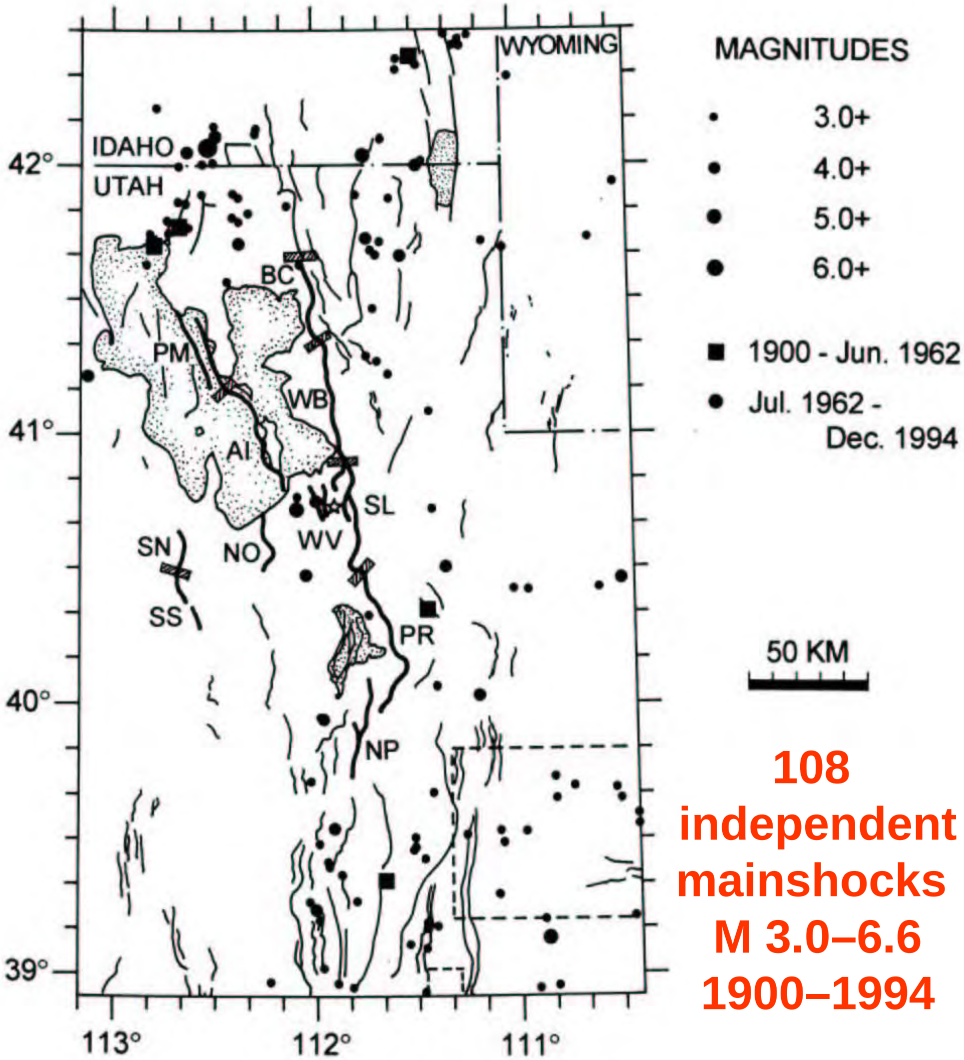




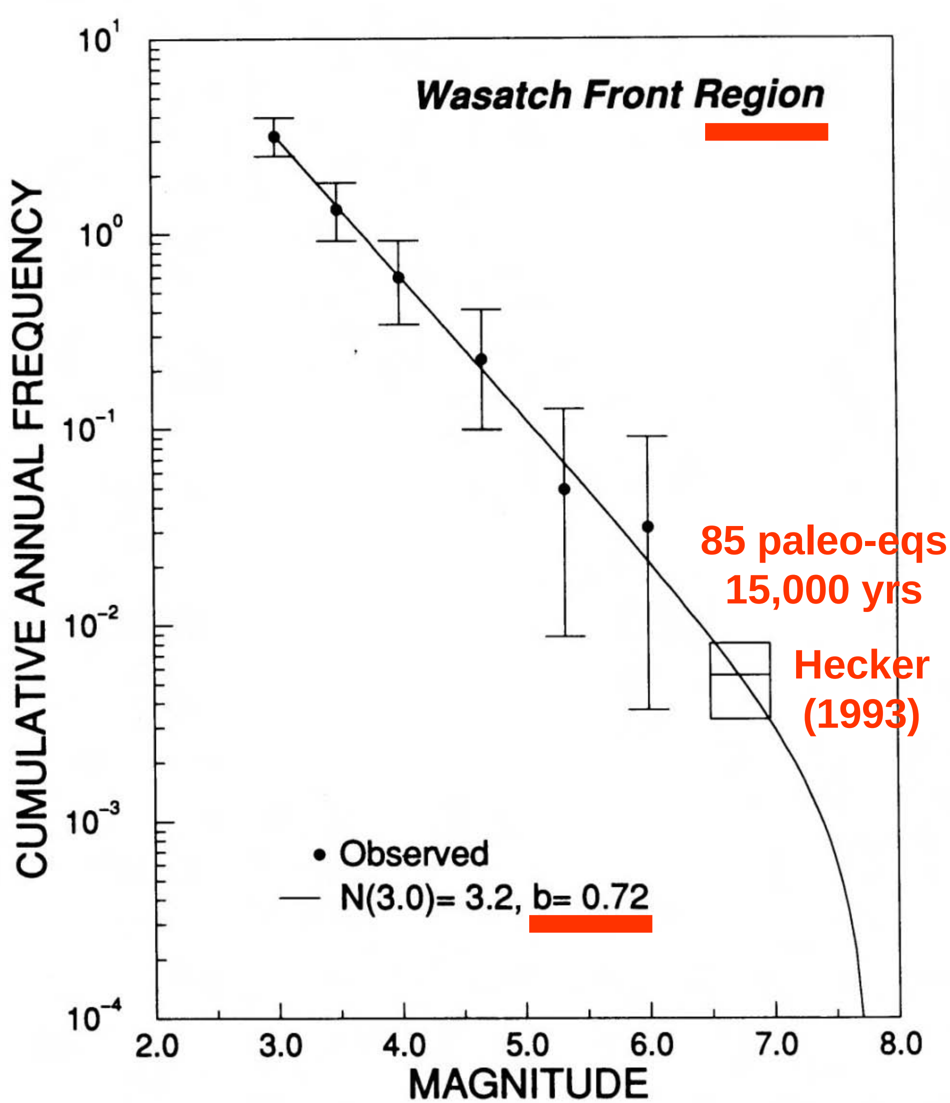
Youngs et al. (1987, 2000)



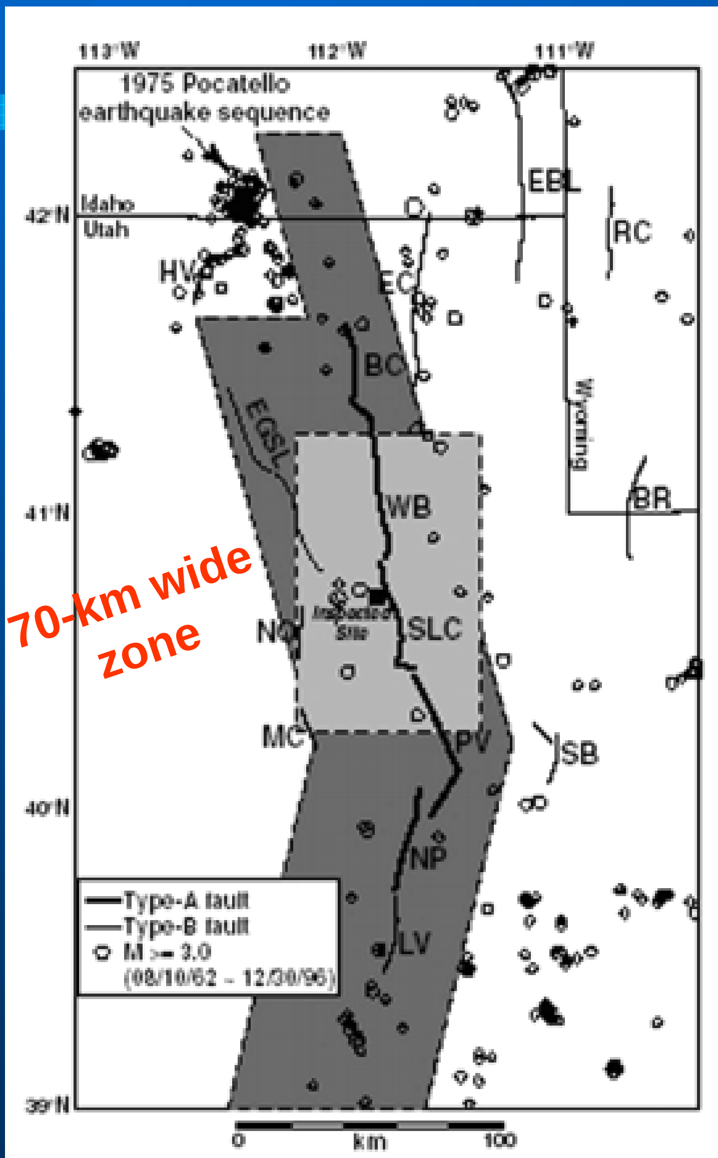
Pechmann & Arabasz (1995)

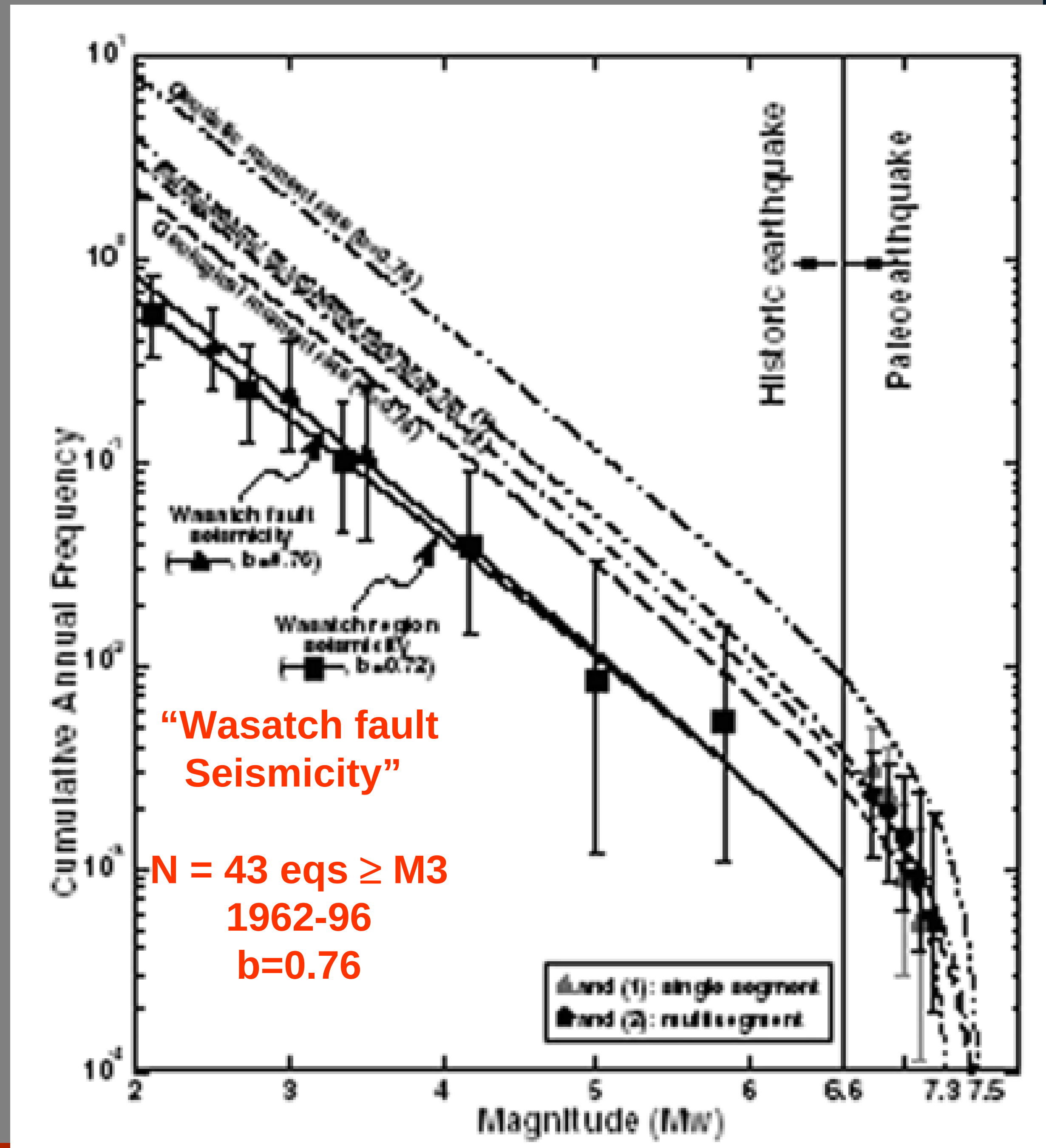


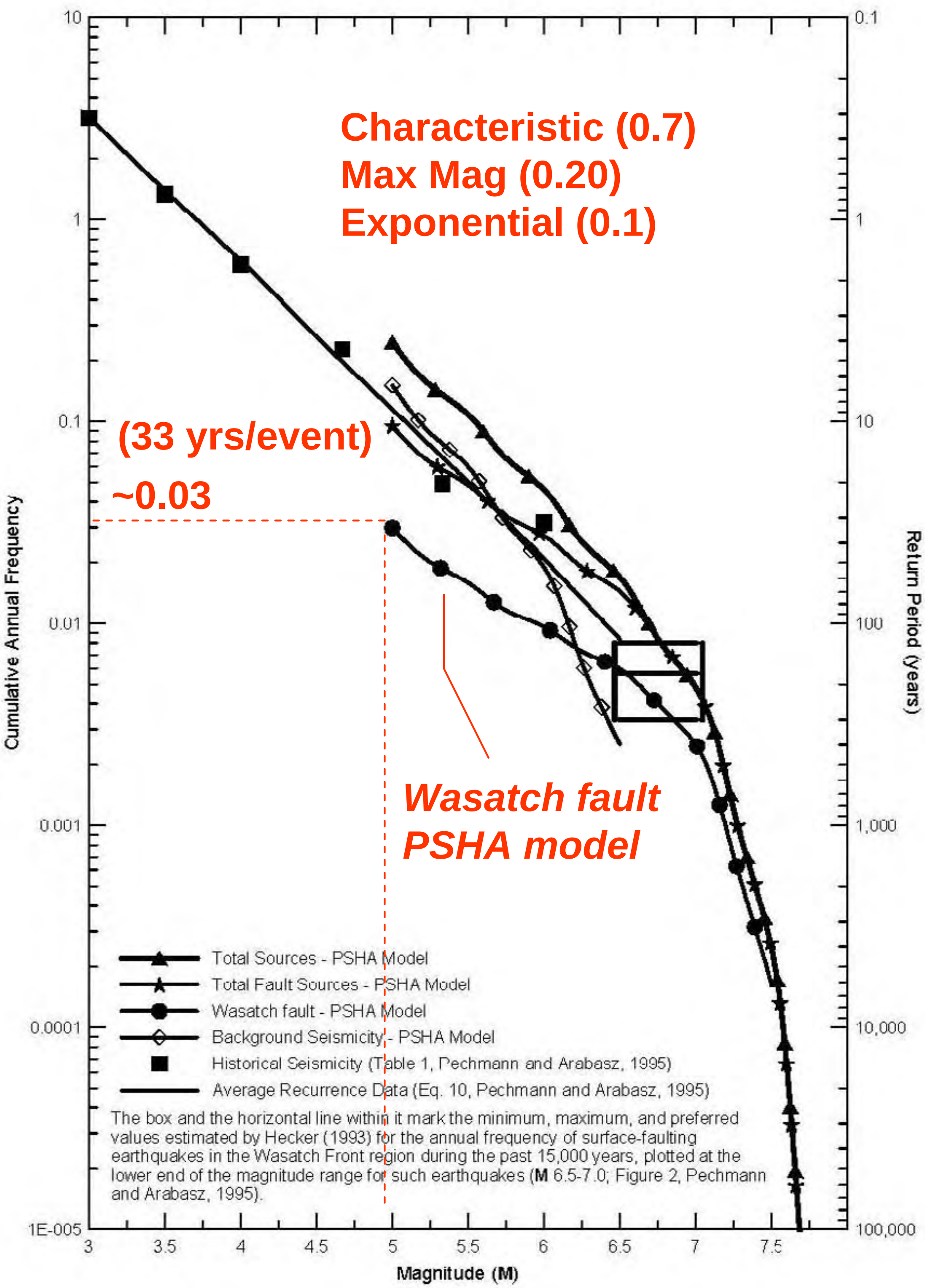
108 independent mainshocks M 3.0–6.6 1900–1994



Chang & Smith (2002)



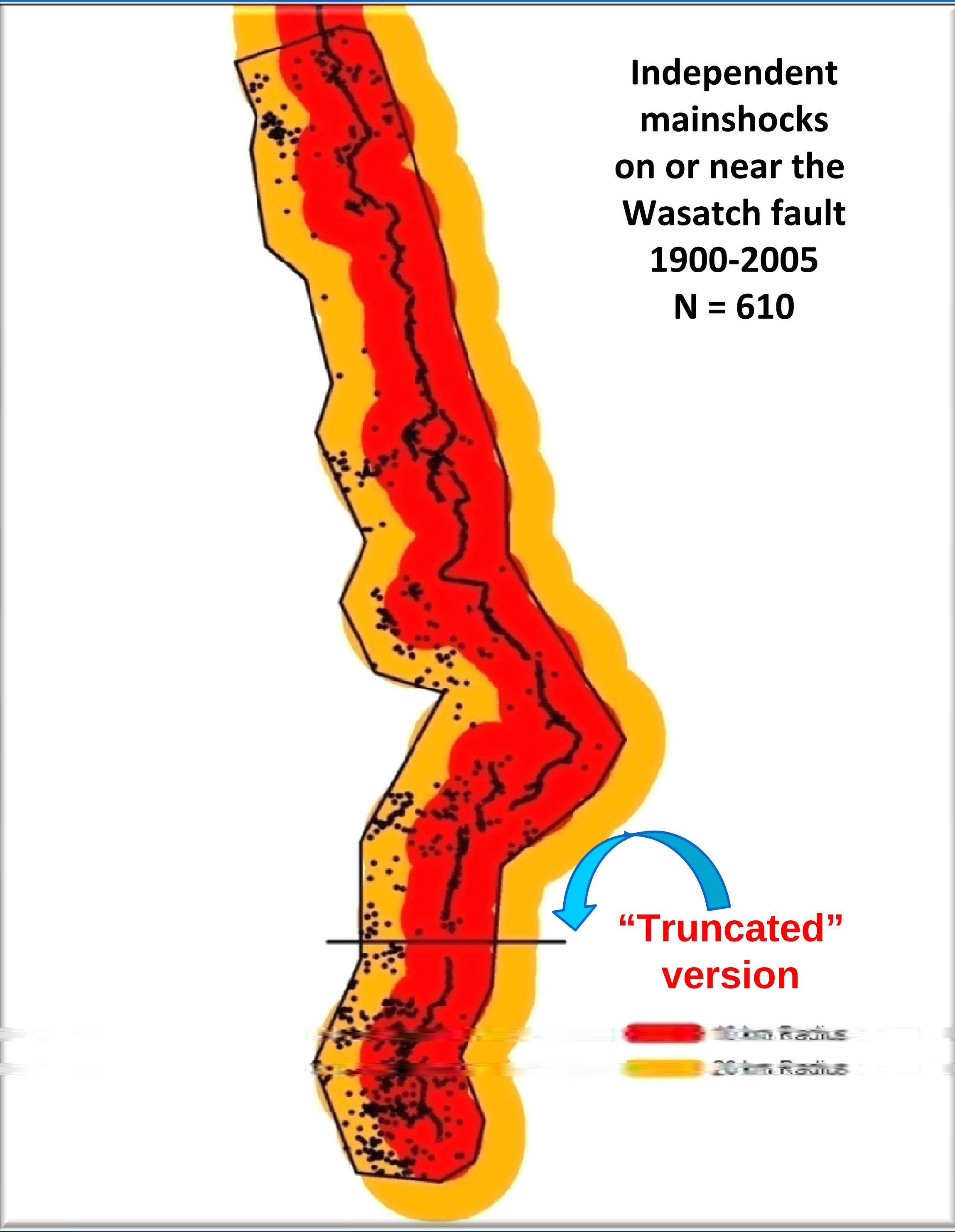




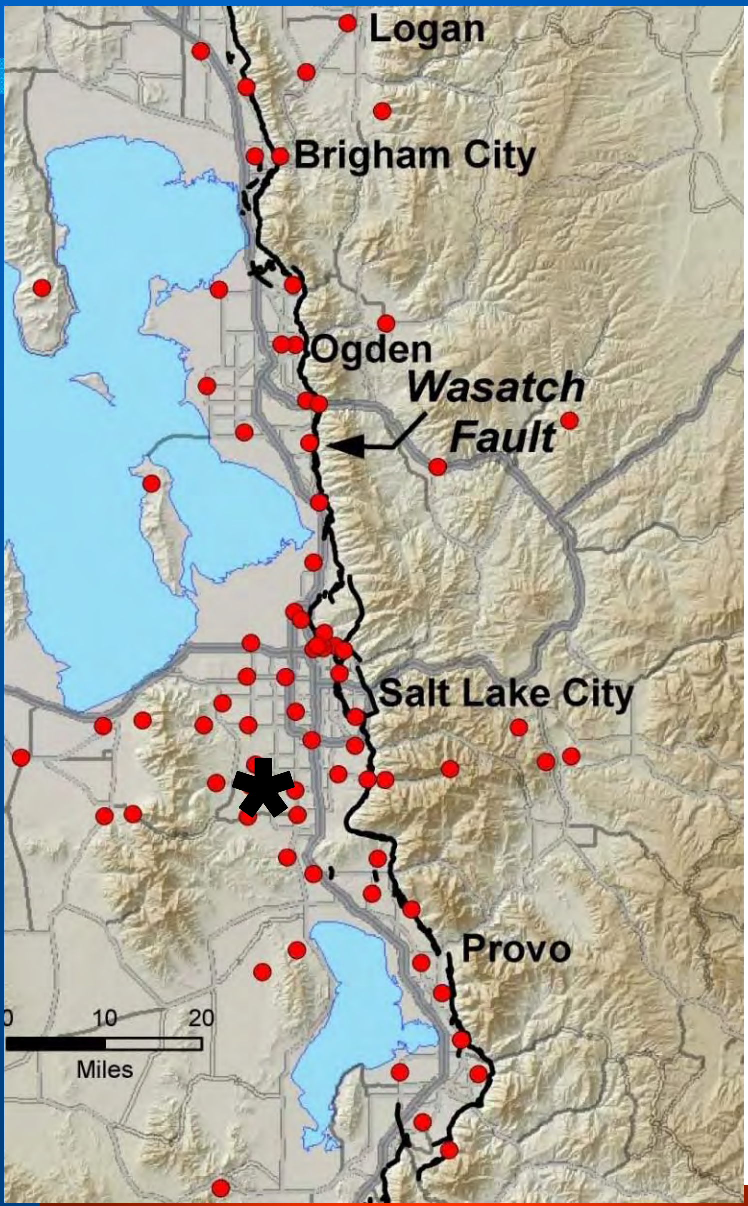
Wong et al. (2002)

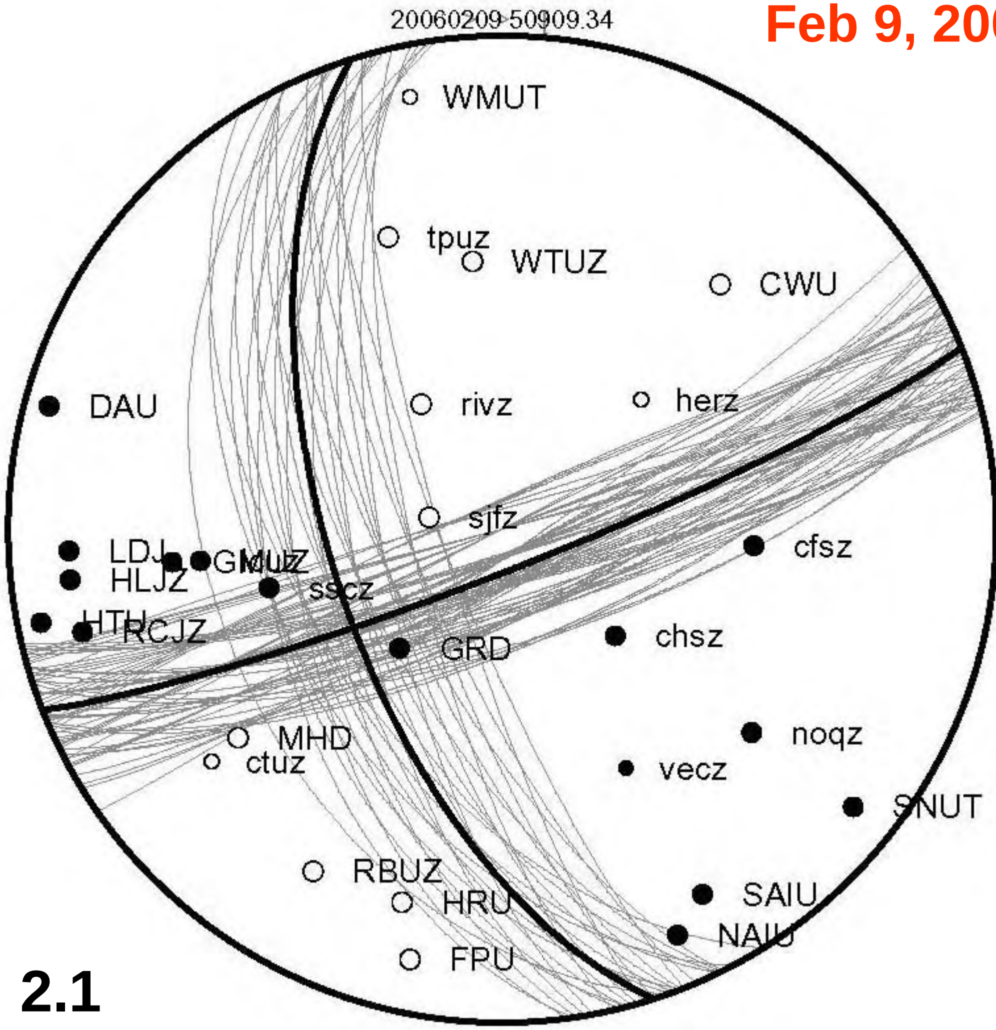
Recurrence modeling on the Wasatch fault

Arabasz (2006)



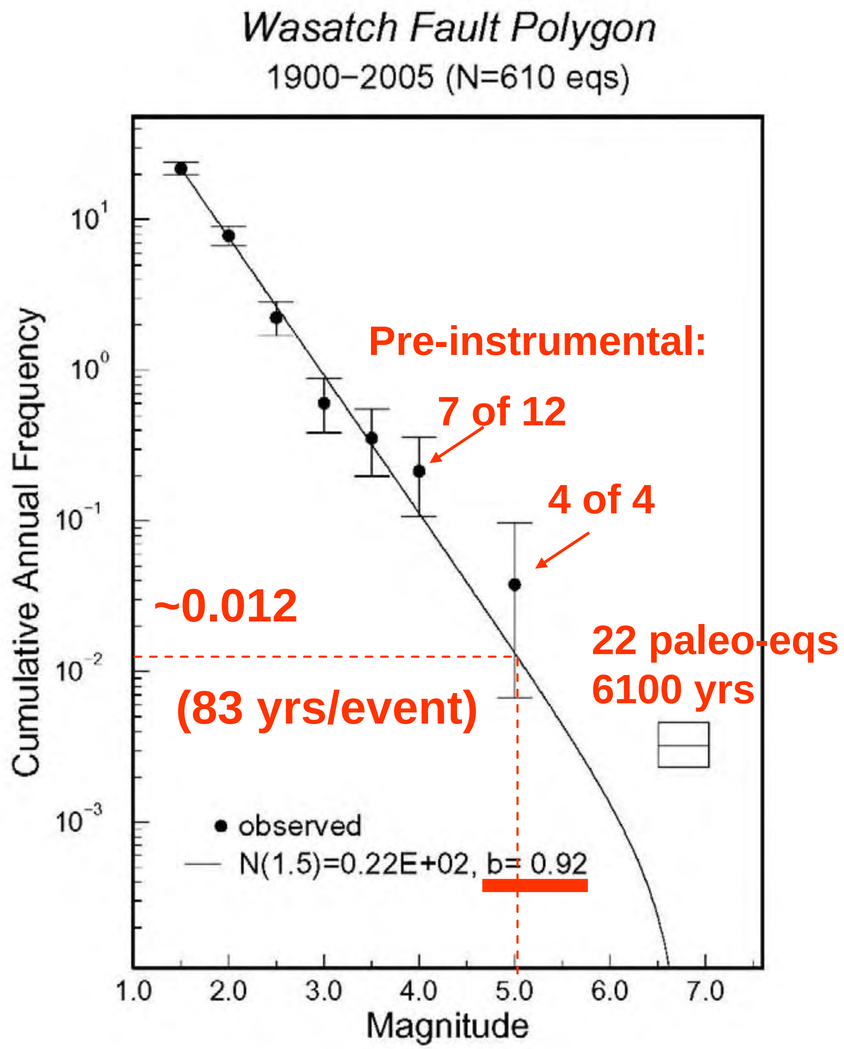
Problematic spatial correlation
One example...

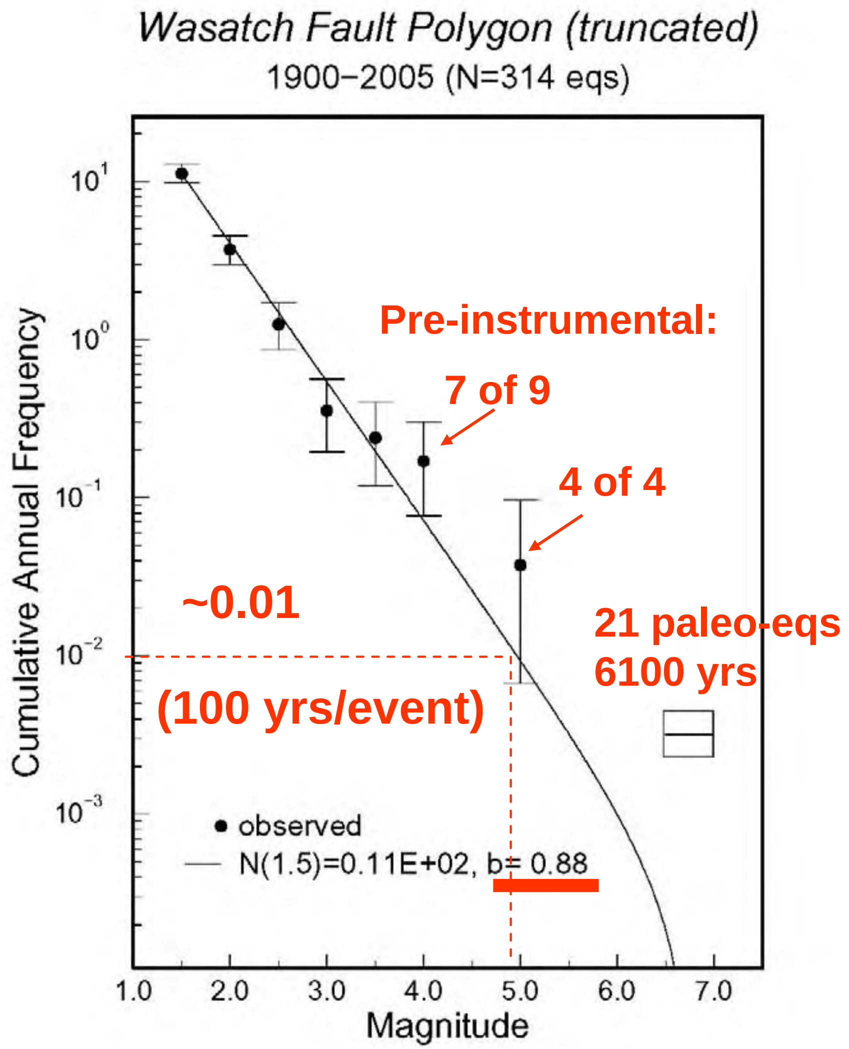


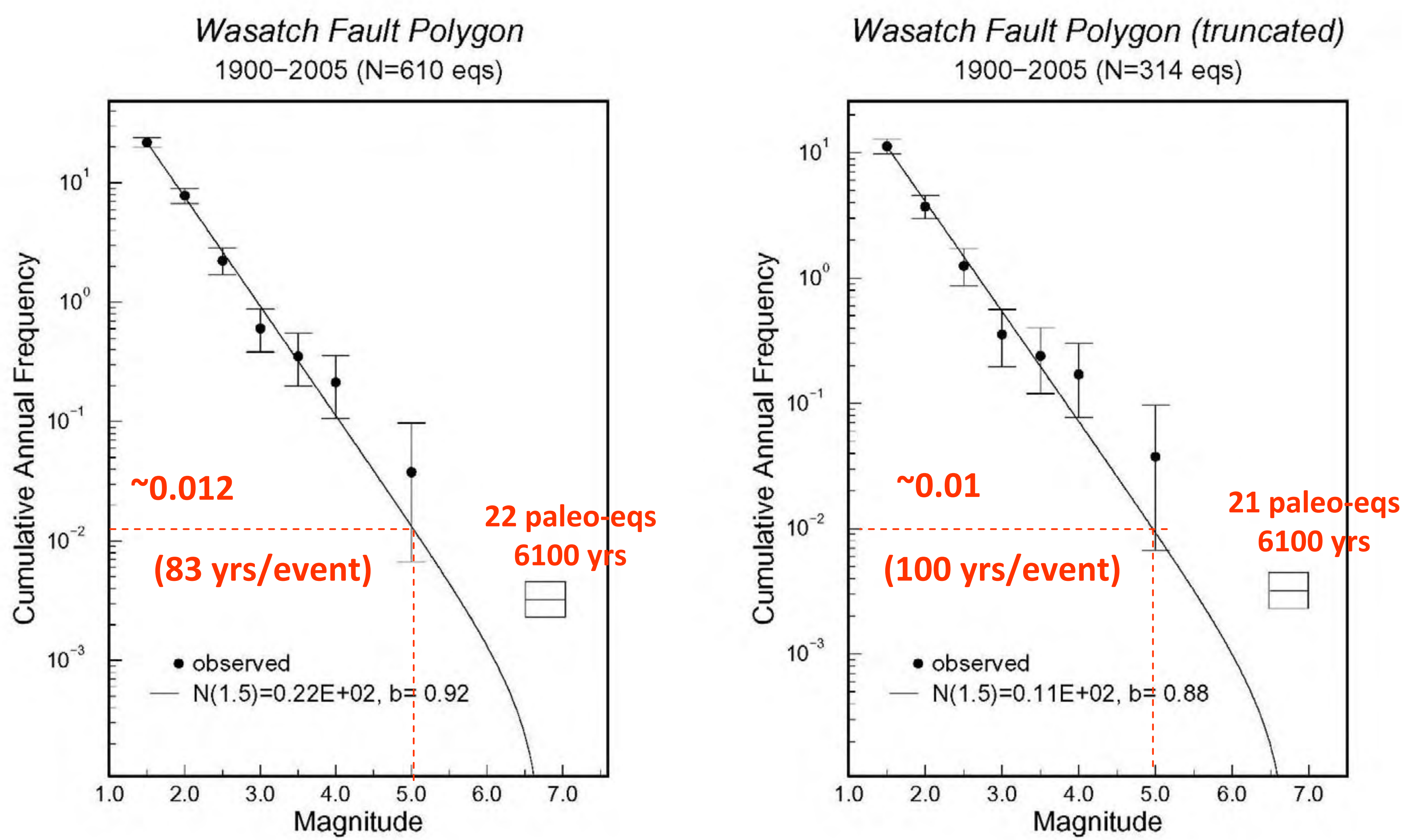


Feb 9, 2006

M 2.1
depth = 12.3 km


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

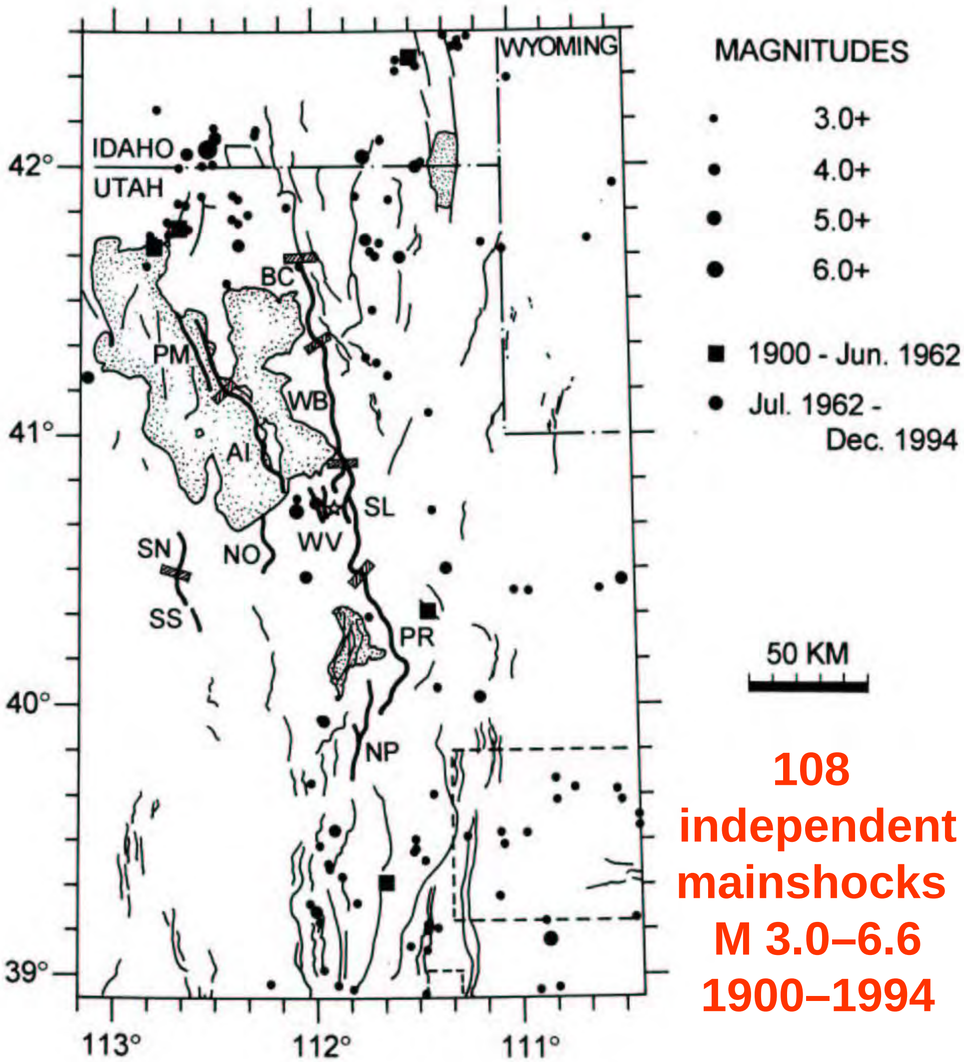


- **Observed seismicity is consistent with the characteristic model — BUT association of sampled seismicity with the Wasatch fault is uncertain**
- **Maximum magnitude model is viable IF smaller earthquakes are part of a background seismic zone and not on the Wasatch fault**

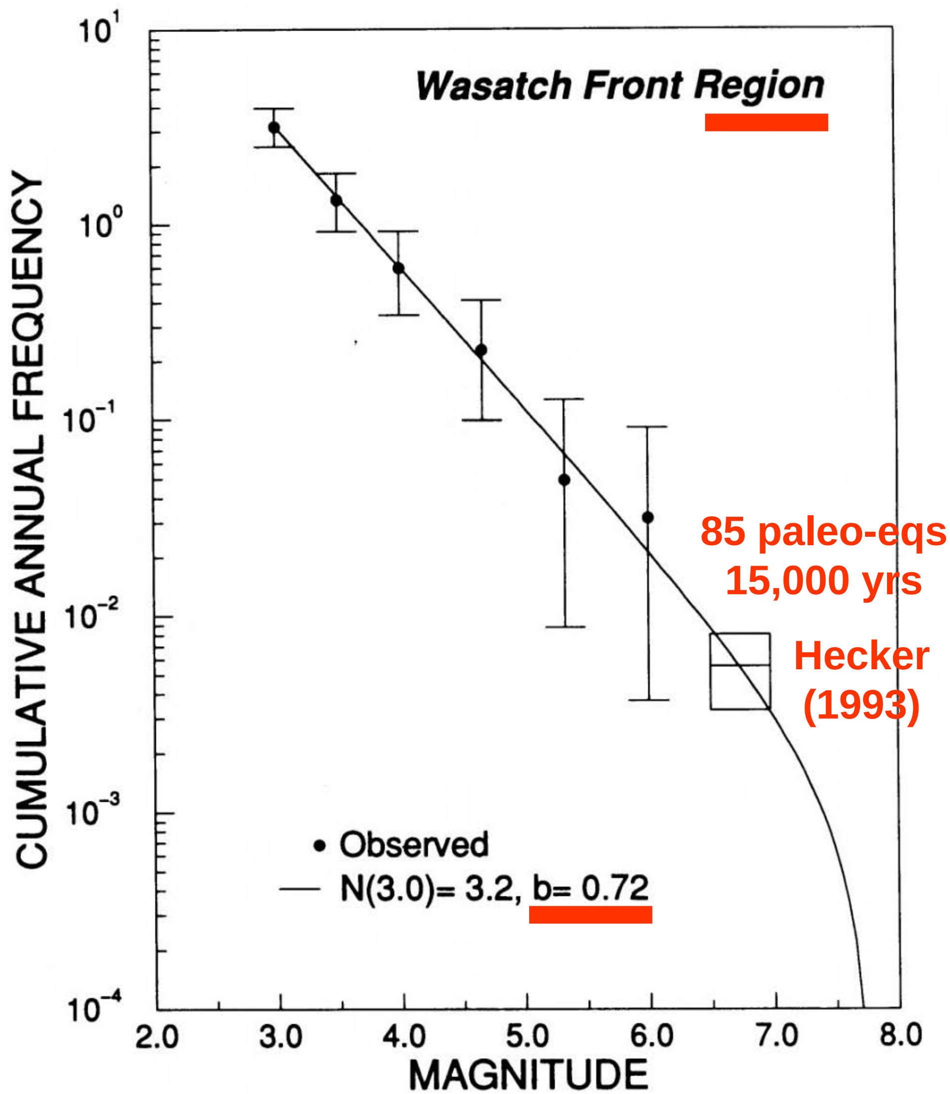
Part III . . .

Starting Point for WGUEP (towards a Background Seismicity Rate Model)

Pechmann & Arabasz (1995)

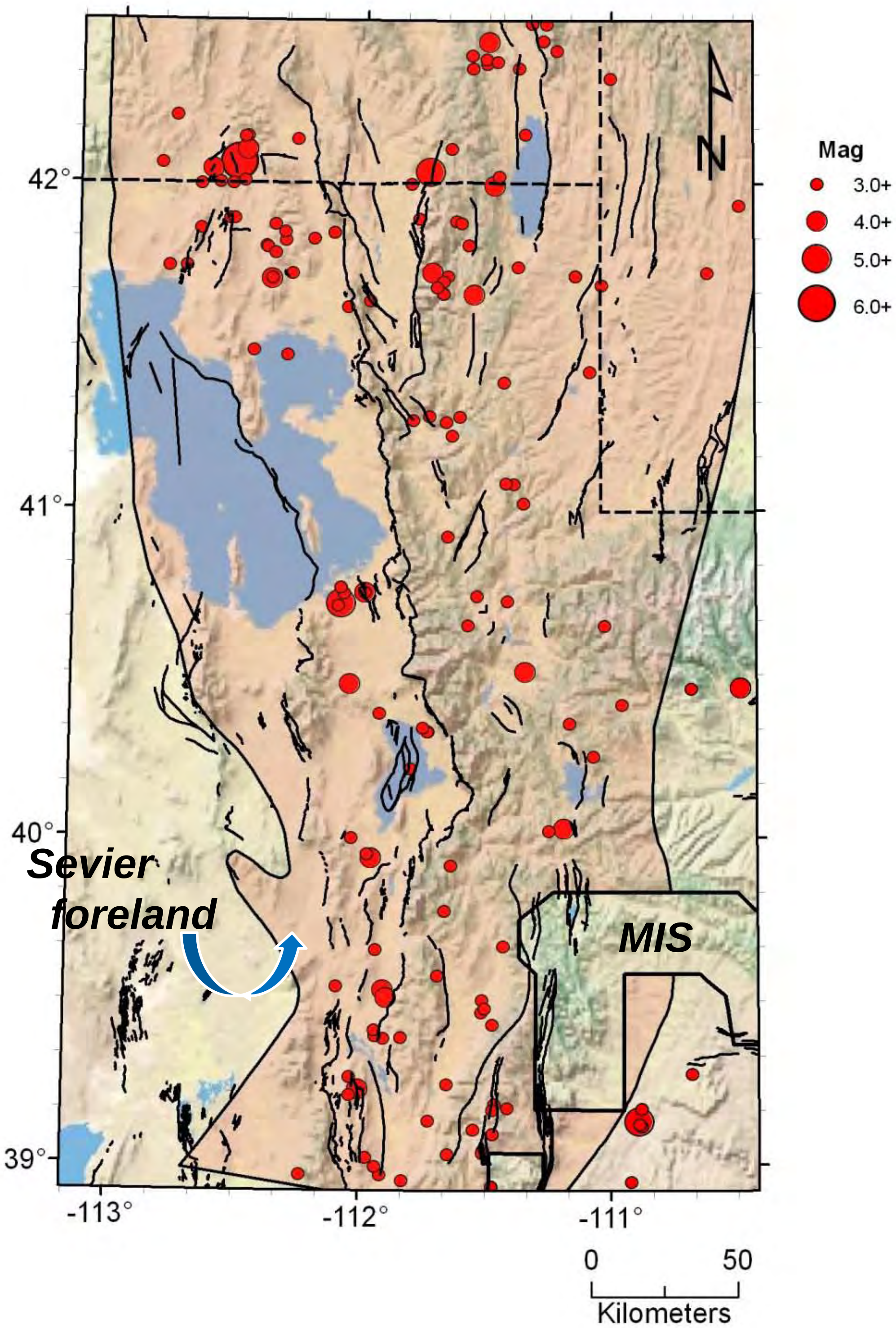


108 independent mainshocks M 3.0–6.6 1900–1994



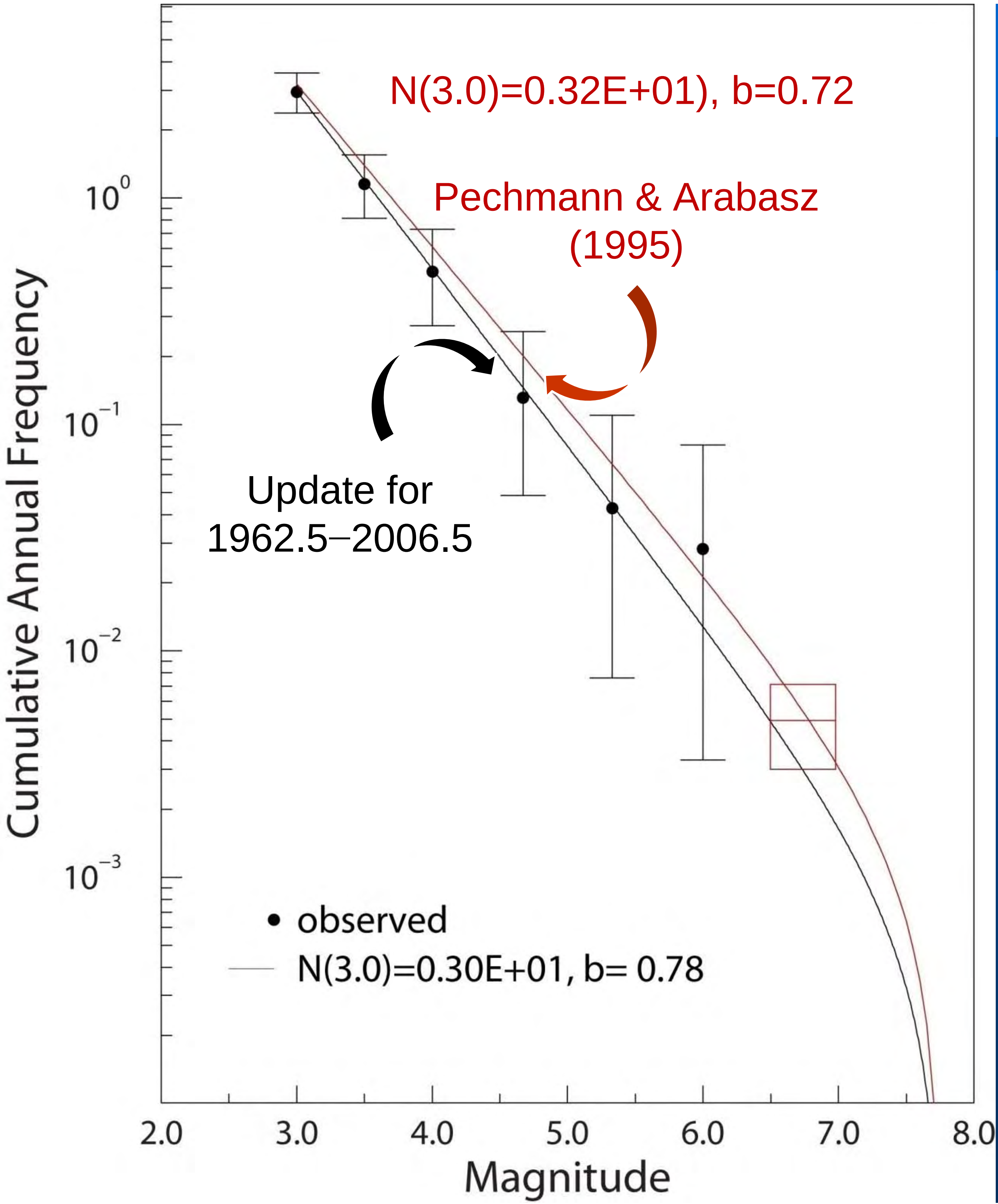
85 paleo-eqs 15,000 yrs

Hecker (1993)



Revisiting Pechmann and Arabasz (1995)

Independent mainshocks
M ≥ 3.0
(1962.5–2006.5)
N = 128



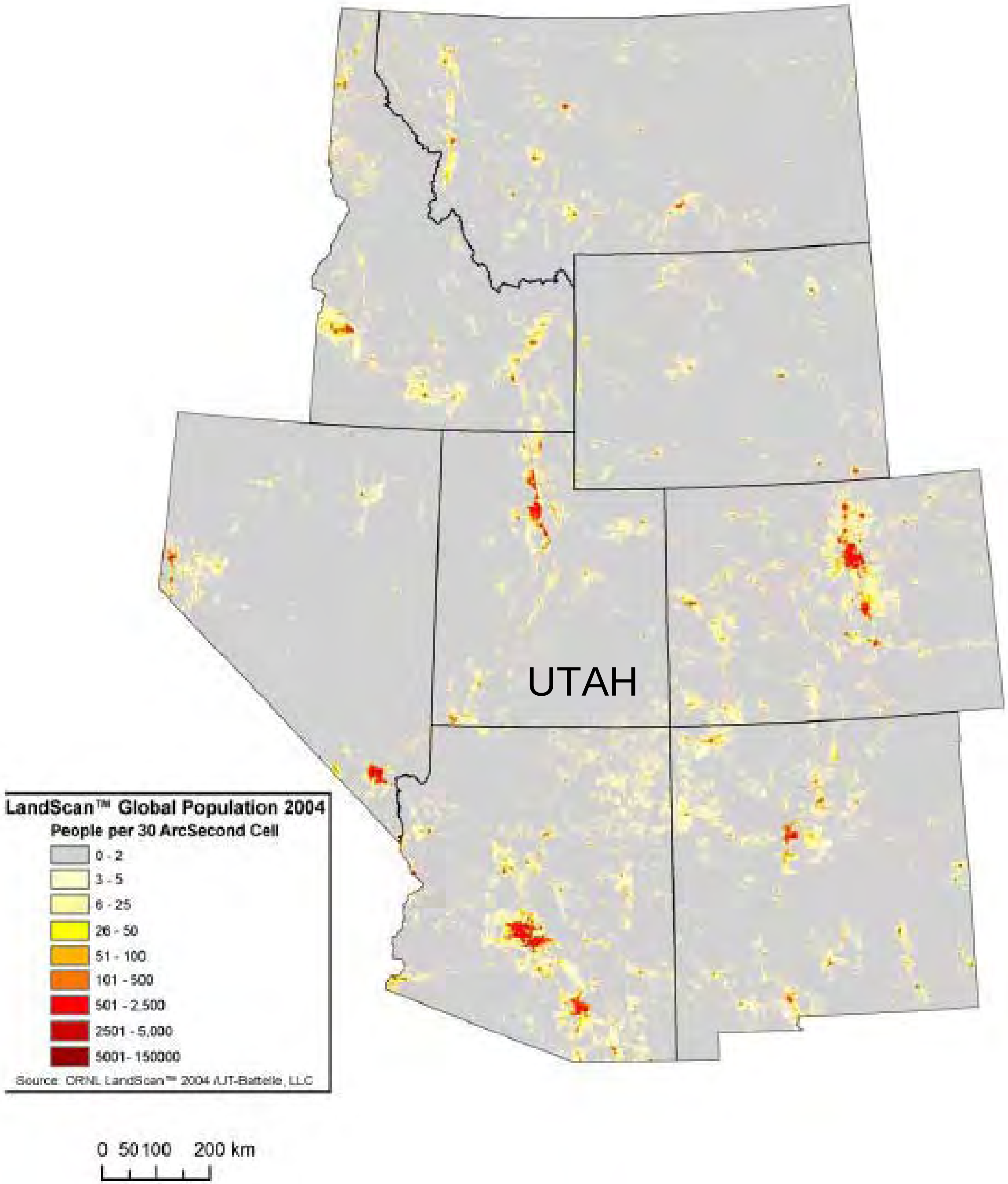
Revisiting Pechmann and Arabasz (1995)

(continued)

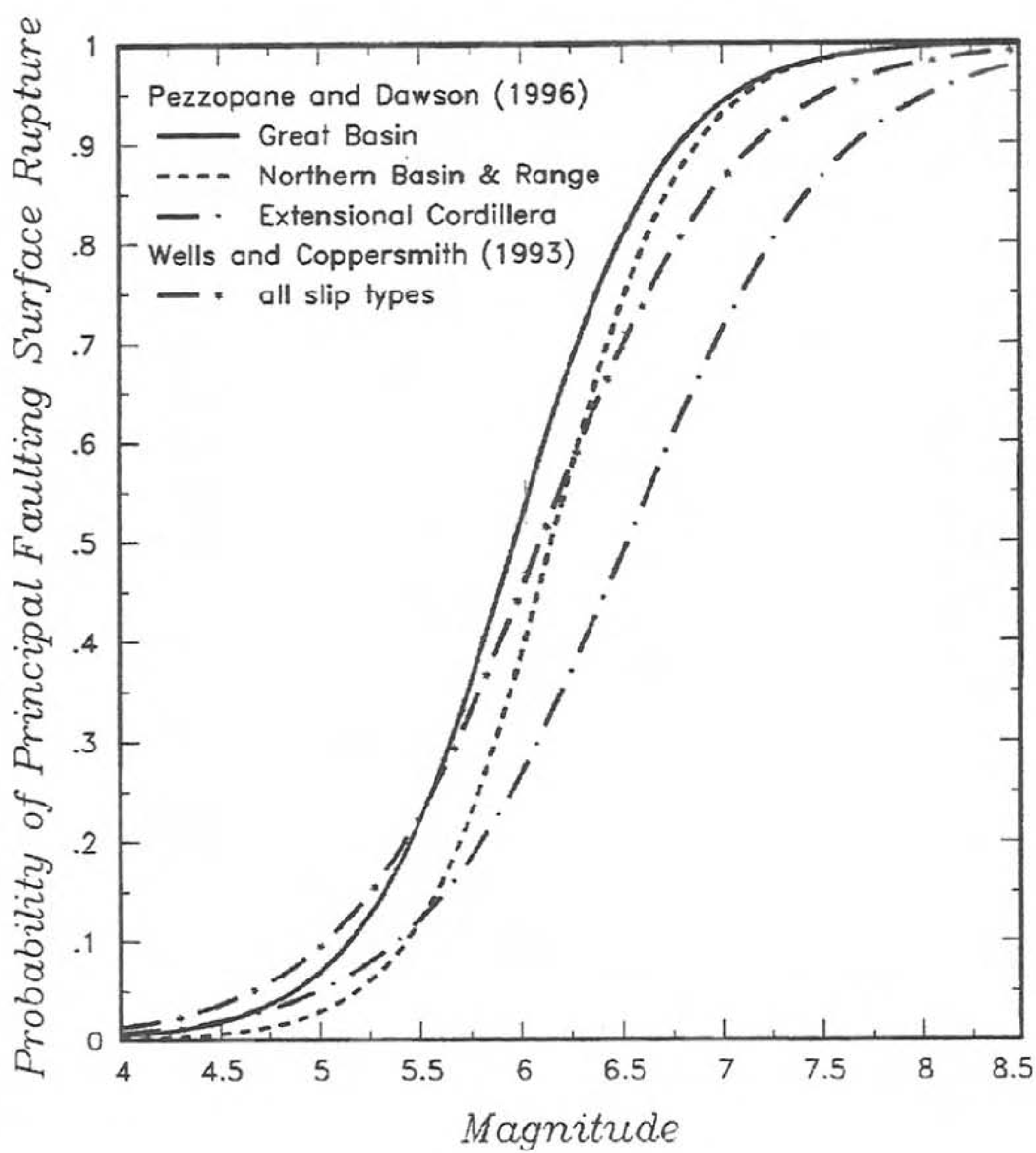
Average Recurrence Interval (yr) for Wasatch Front Region

	Pechmann and Arabasz (1995)	Update for 1962.5–2006.5
M ≥ 5.0	8.7	12
M ≥ 5.5	20	30
M ≥ 6.0	48	76
M ≥ 6.5	120	200

Population Distribution



Probability of Surface Rupture



Youngs et al. (2003)

Overview of the University of Utah Earthquake Catalog

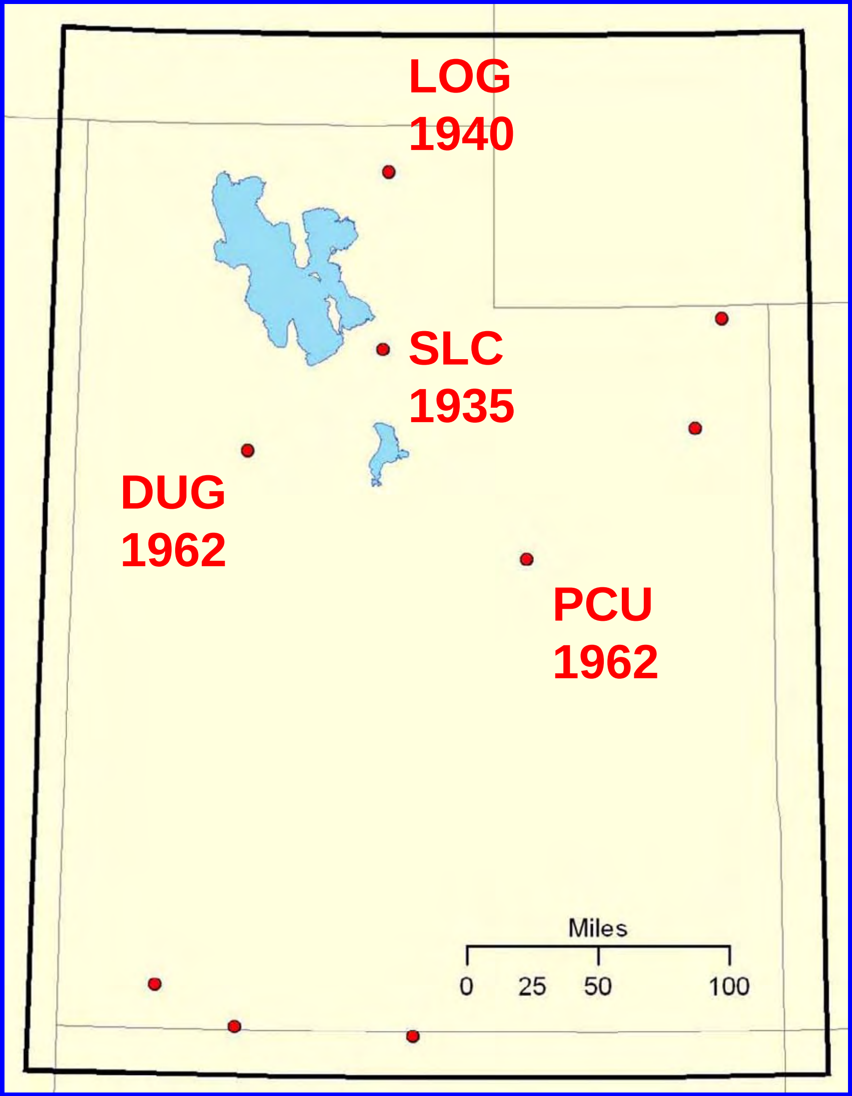
by

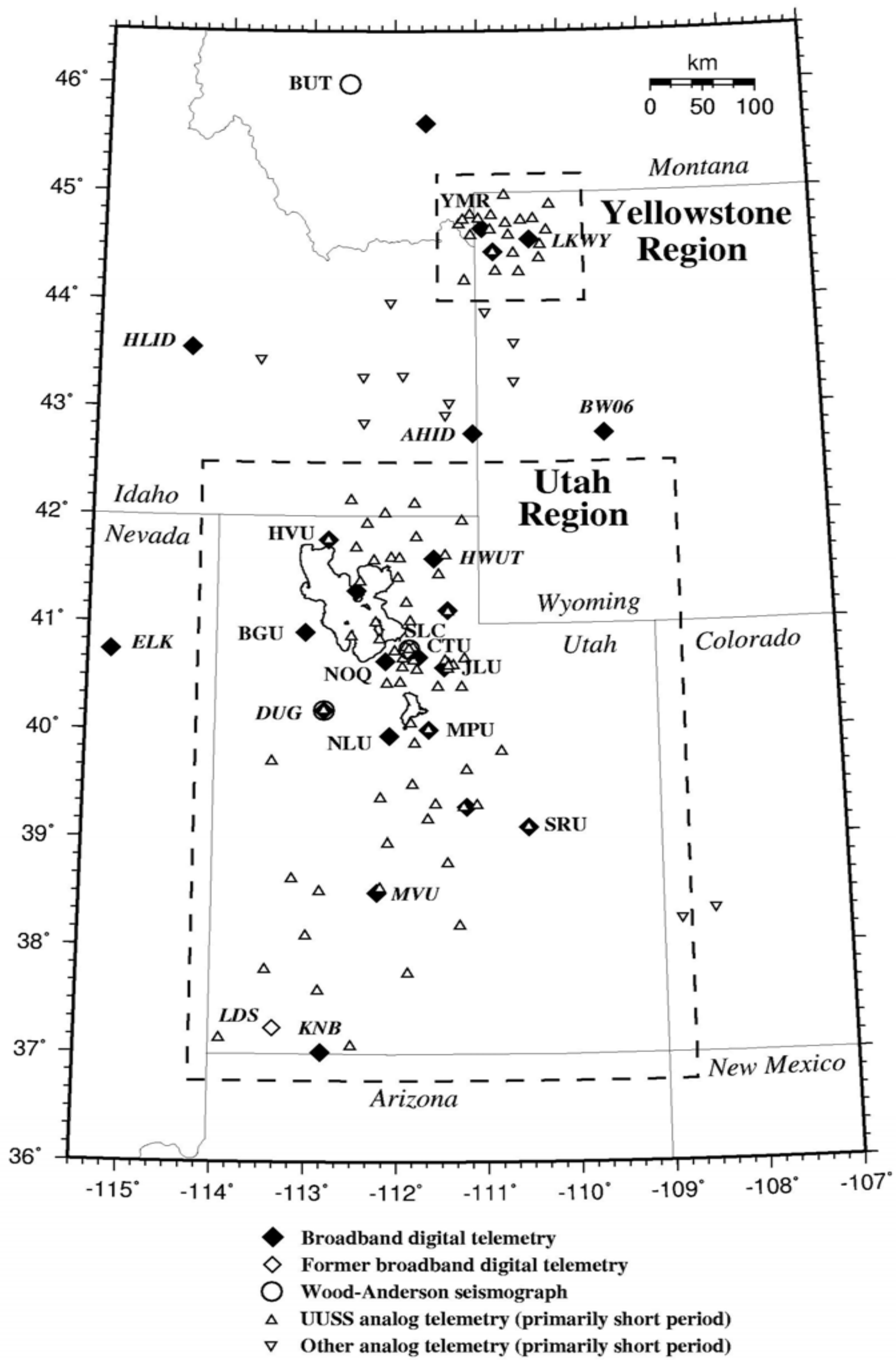
James C. Pechmann and Walter J. Arabasz
University of Utah, Salt Lake City, Utah

Evolution of EQ Recording in Utah

- 1907: First seismographs on University of Utah campus
- 1939 to 1950s: Stations at University of Utah and Utah State University
- 1960s: Skeletal statewide network of five stations
- 1974: Regional telemetered net (~50 stations in 1978)
- 1981: Digital recording
- 1997: First UUSS broadband digital telemetry station
- 2000: Real-time earthquake information system, including urban strong-motion network
- 2009: 236-station regional/urban network (176 in Utah), 194 operated by UUSS

Seismic Stations in Utah Region: 1966





UUSS Network December 2001

University of Utah Seismograph Stations (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 film): July 1962 -1980**
  - **—From digital records: 1981 - present**

Magnitudes in the UUSS Earthquake Catalog

- **Historical Catalog: 1850 - June 1962**
  - —**Most magnitudes (M) estimated from maximum Modified Mercalli Intensity (INT) using**

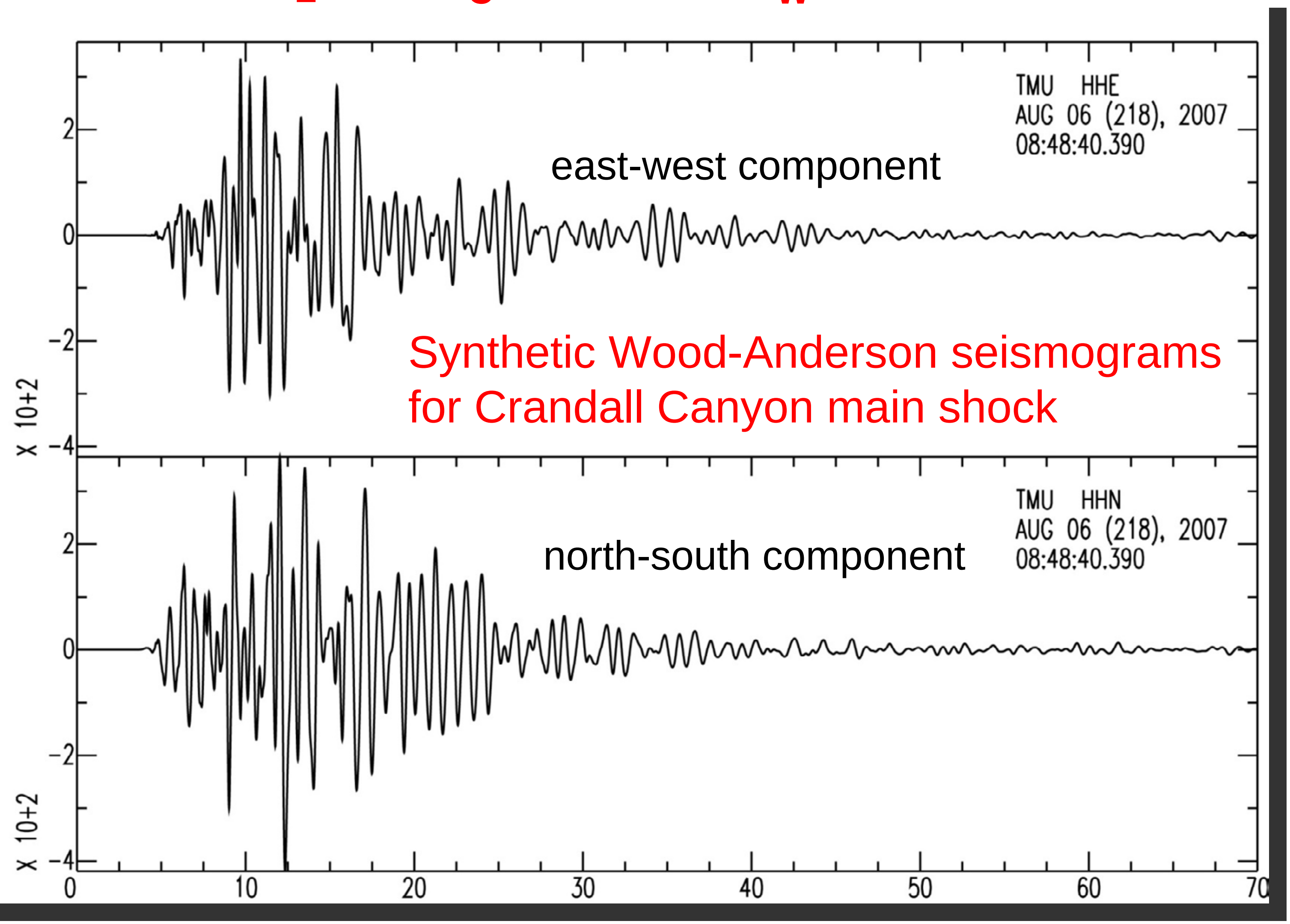
    $M = (2/3)\ INT + 1$ (Gutenberg and Richter, 1956)

- **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**

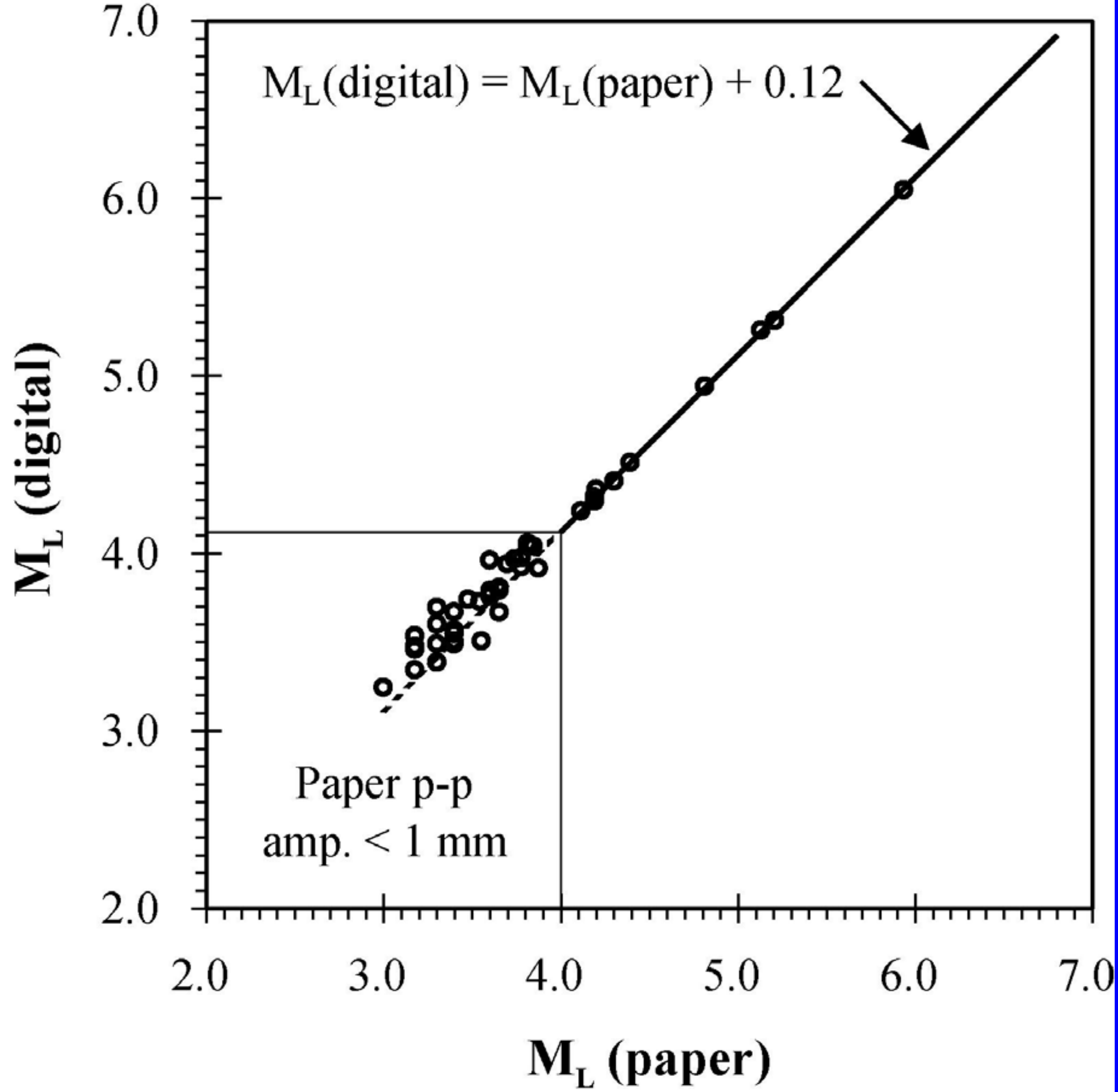
Measuring size

(Richter, coda, and moment magnitudes)

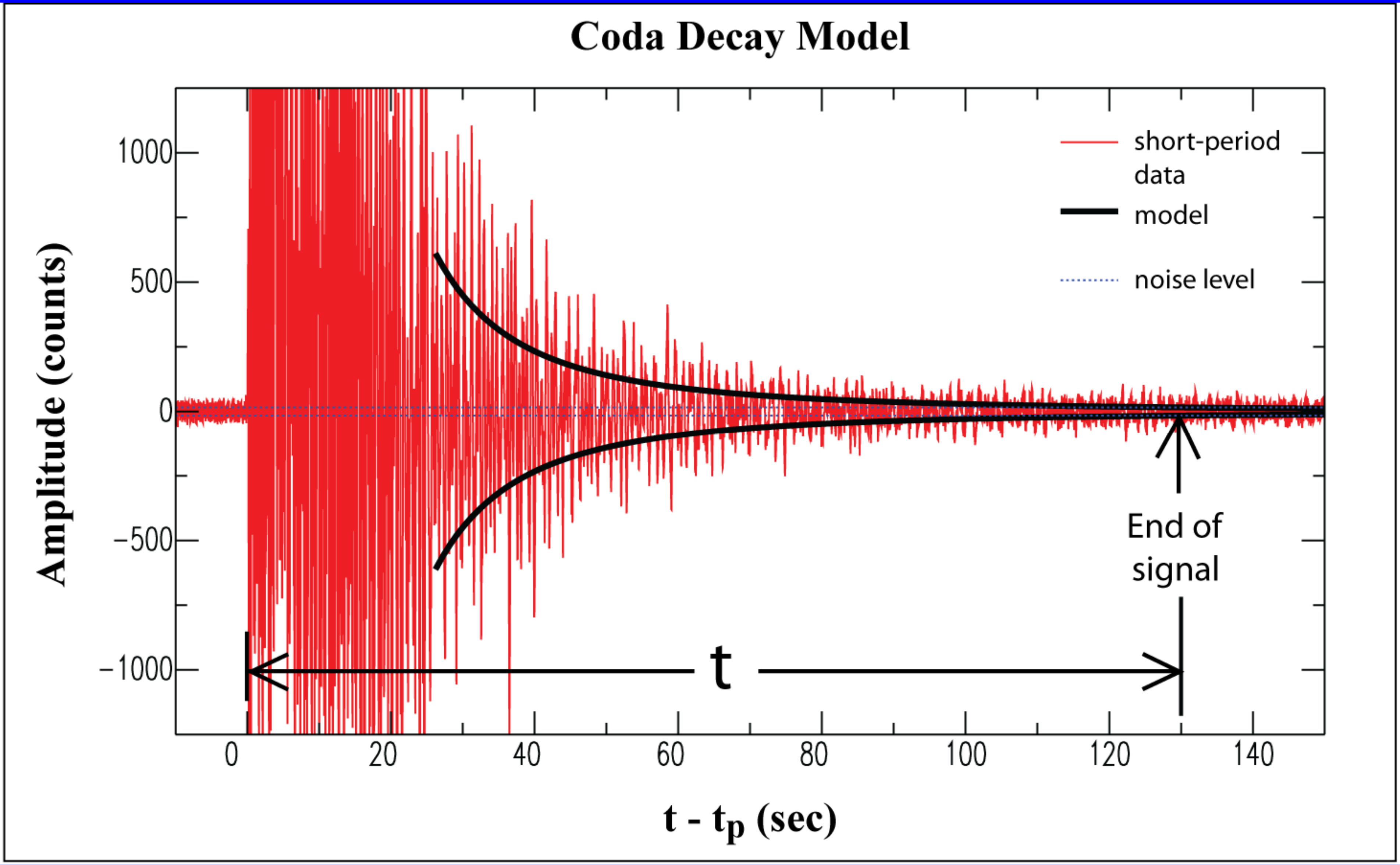
M_L M_C M_W



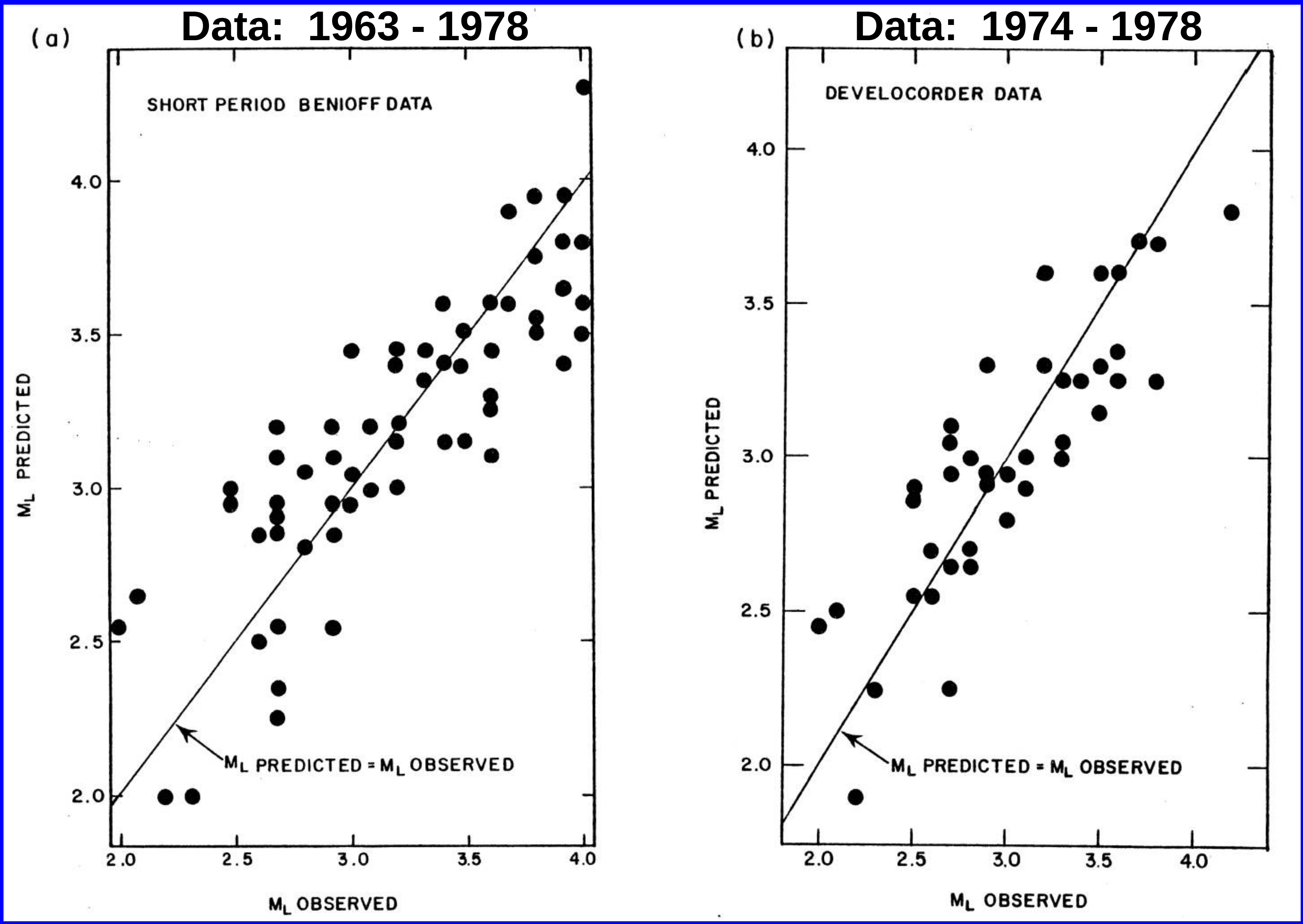
Comparison of M_L from DUG Digital and Paper Records



Short-Period Vertical-Component Record
Station MLI, ML 3.8 Utah Earthquake, 6/28/1990



M_C Calibrations

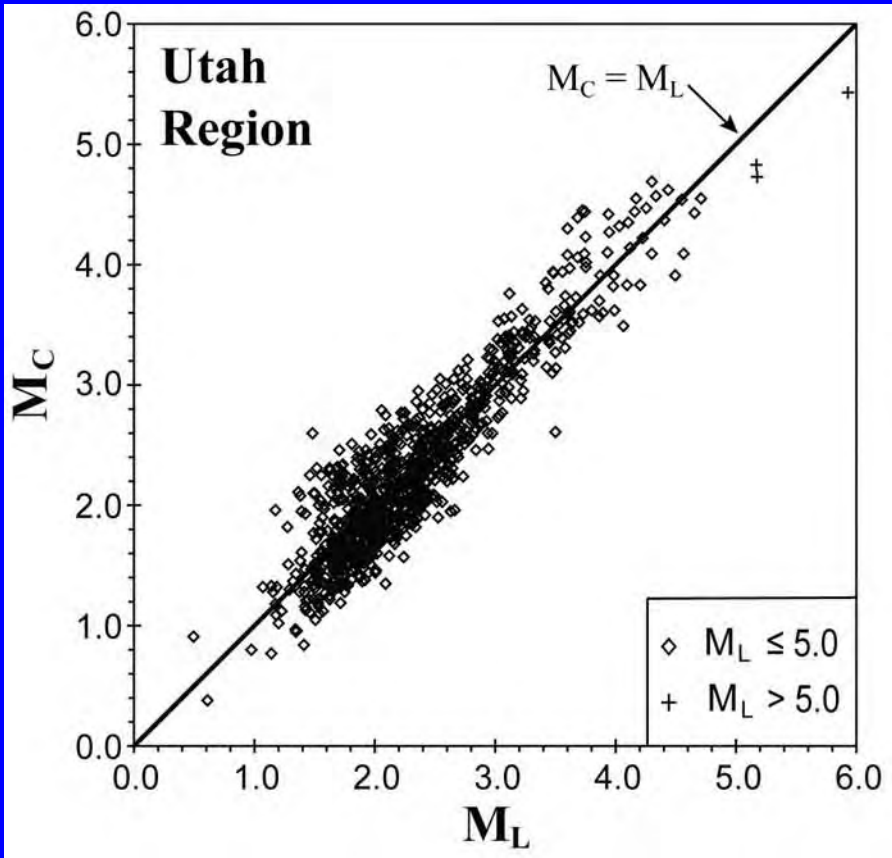


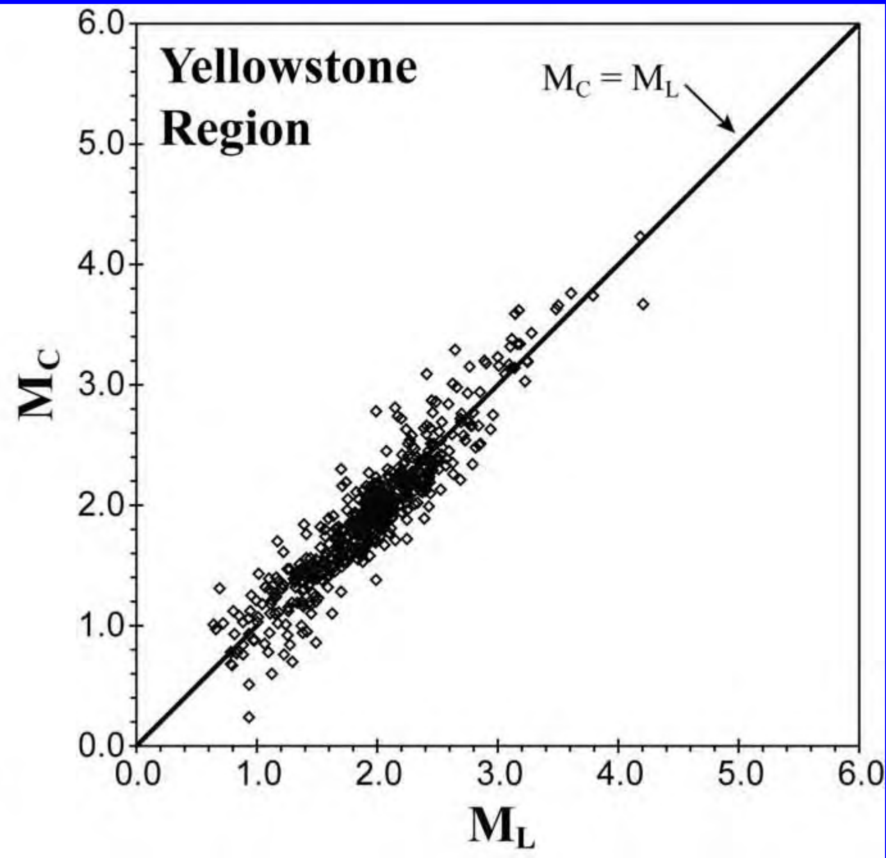
From Griscom and Arabasz, 1979

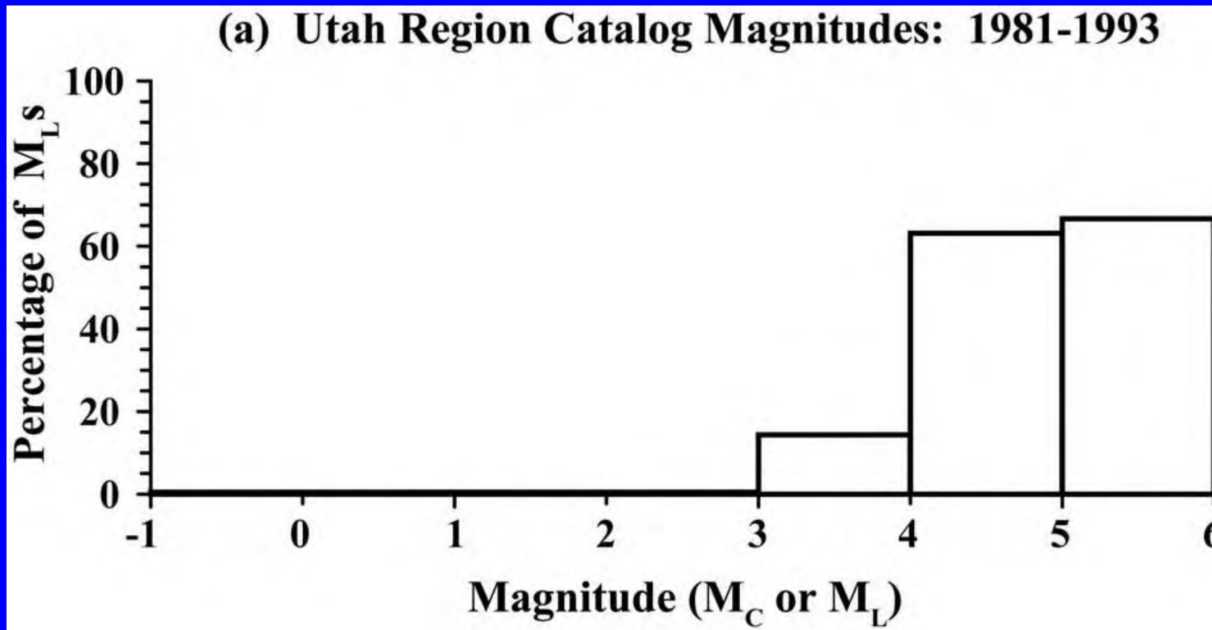
M_C Calibrations

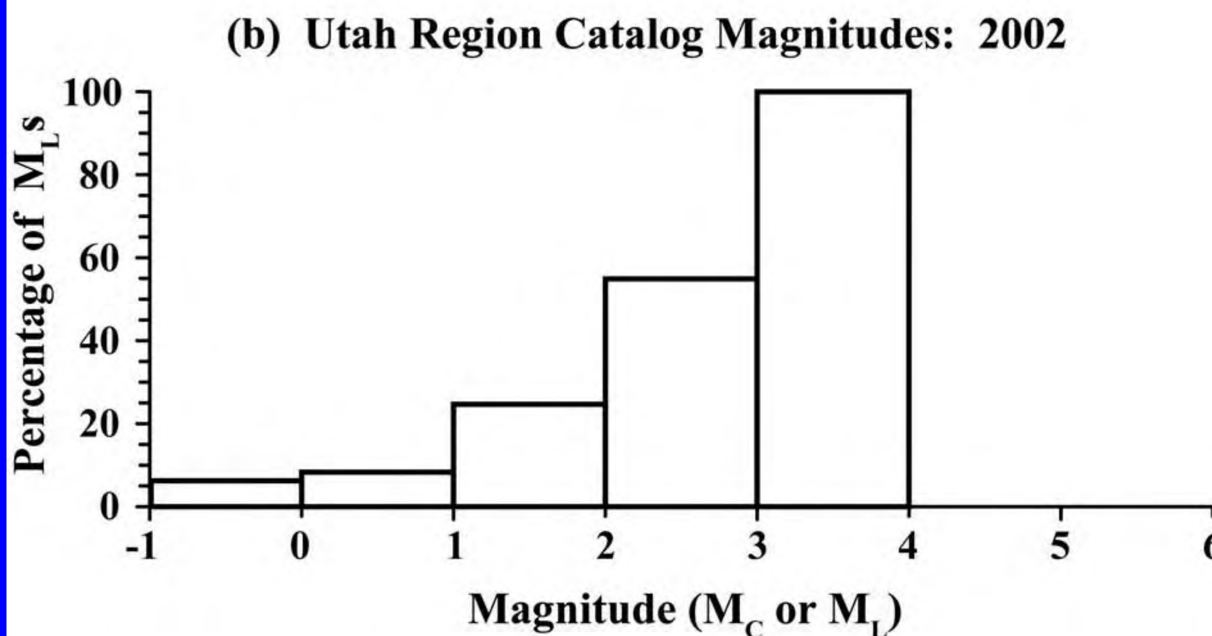
Data: 1981 - 2001

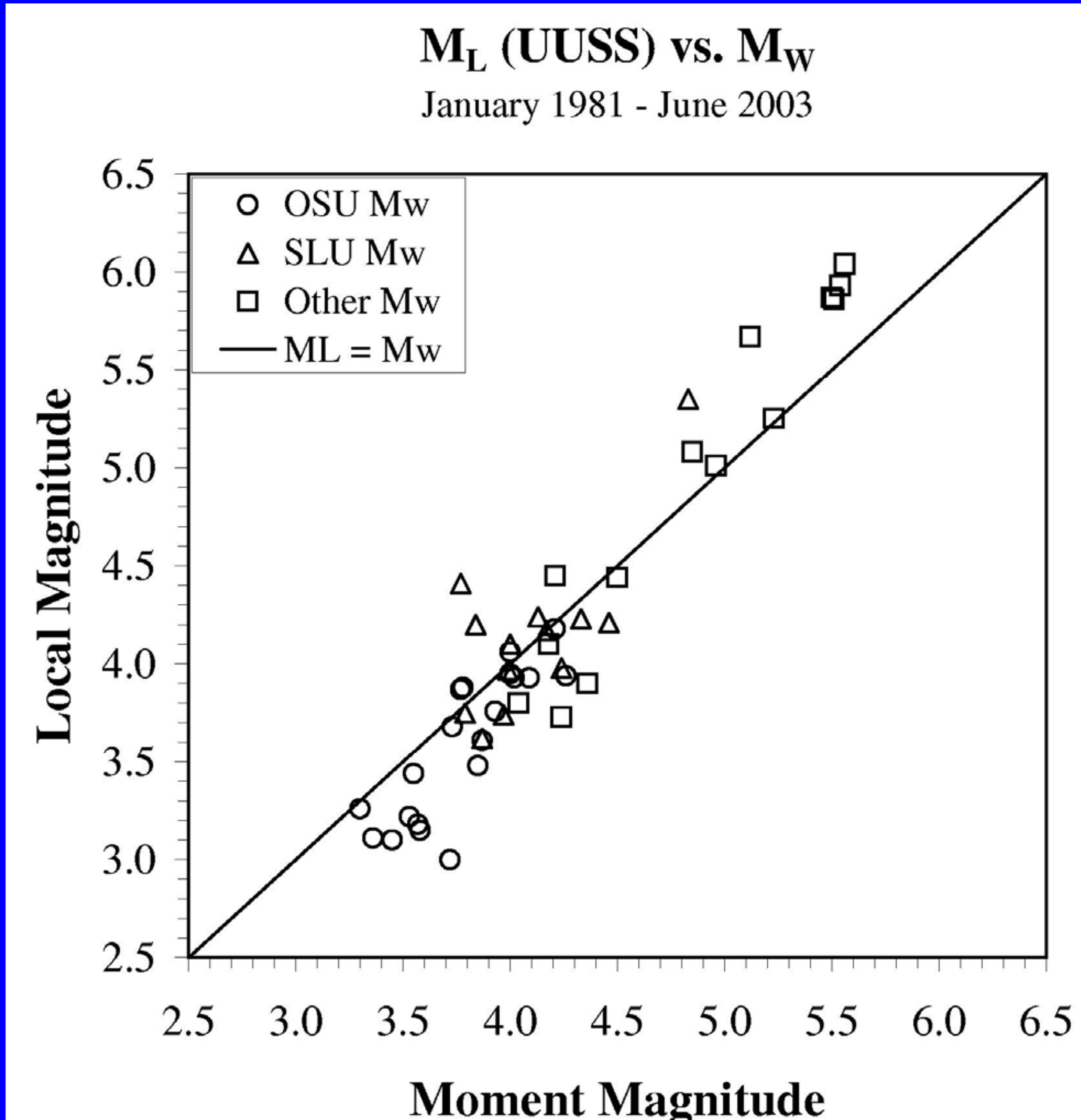
Data: 1995 - 2001






(a) Utah Region Catalog Magnitudes: 1981-1993
Percentage of M_Ls
100
80
60
40
20
0
-1
0
1
2
3
4
5
6
Magnitude (M_C or M_L)

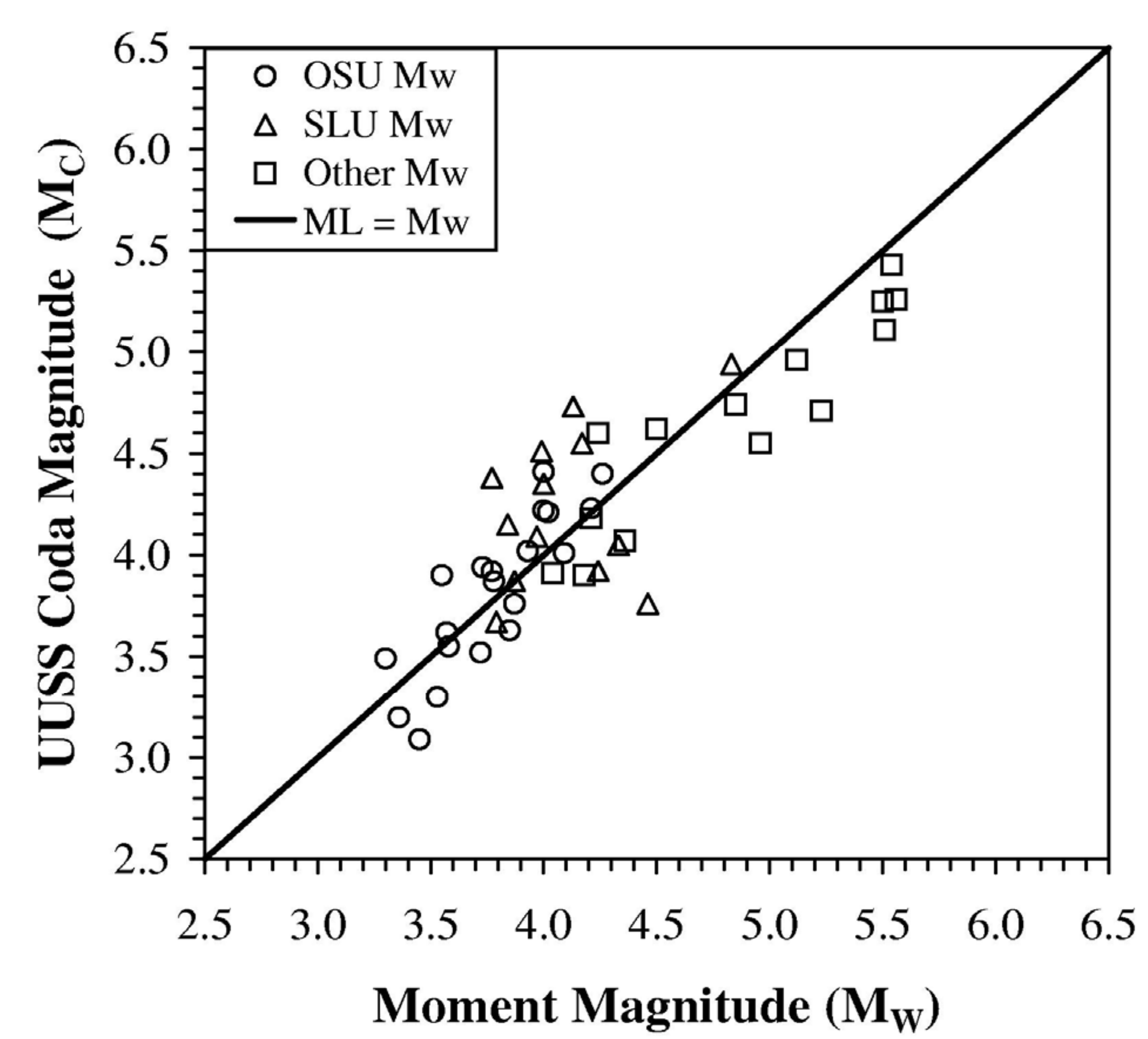

(b) Utah Region Catalog Magnitudes: 2002
Percentage of M_Ls
100
80
60
40
20
0
-1
0
1
2
3
4
5
6
Magnitude (M_C or M_L)



M_L (UUSS) vs. M_W
January 1981 - June 2003
OSU Mw
SLU Mw
Other Mw
ML = Mw
Local Magnitude
Moment Magnitude
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5

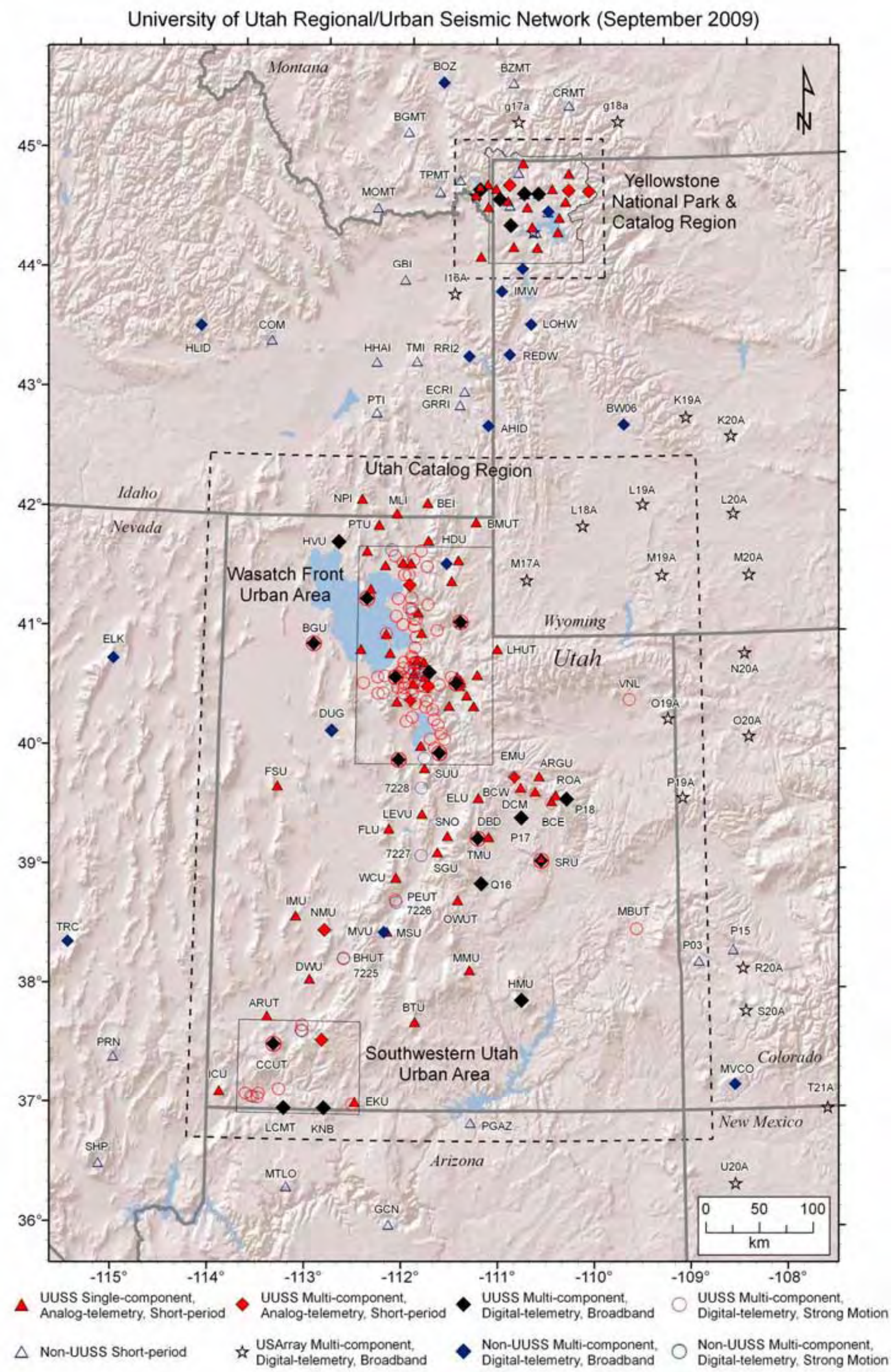
M_C (UUSS) vs. M_W

January 1981 - June 2003



Conclusions (Part 1)

- **The magnitudes in the UUSS historical catalog, 1850- June 1962, are mostly calculated from maximum intensities and therefore have relatively large uncertainties.**
- **The UUSS instrumental earthquake catalog is expected to have a certain amount of heterogeneity (like most catalogs) due to changes in station distribution and instrumentation.**
- **We consider the magnitudes in the instrumental catalog, July 1962 - present, to be generally quite reliable—especially since 1981.**
- **The UUSS local and coda magnitudes are in reasonably good agreement with moment magnitudes determined by others.**



UUSS Network September 2009

GPS Studies of the Wasatch Fault, Utah, with Implications for Normal Fault Behavior and Earthquake Hazards

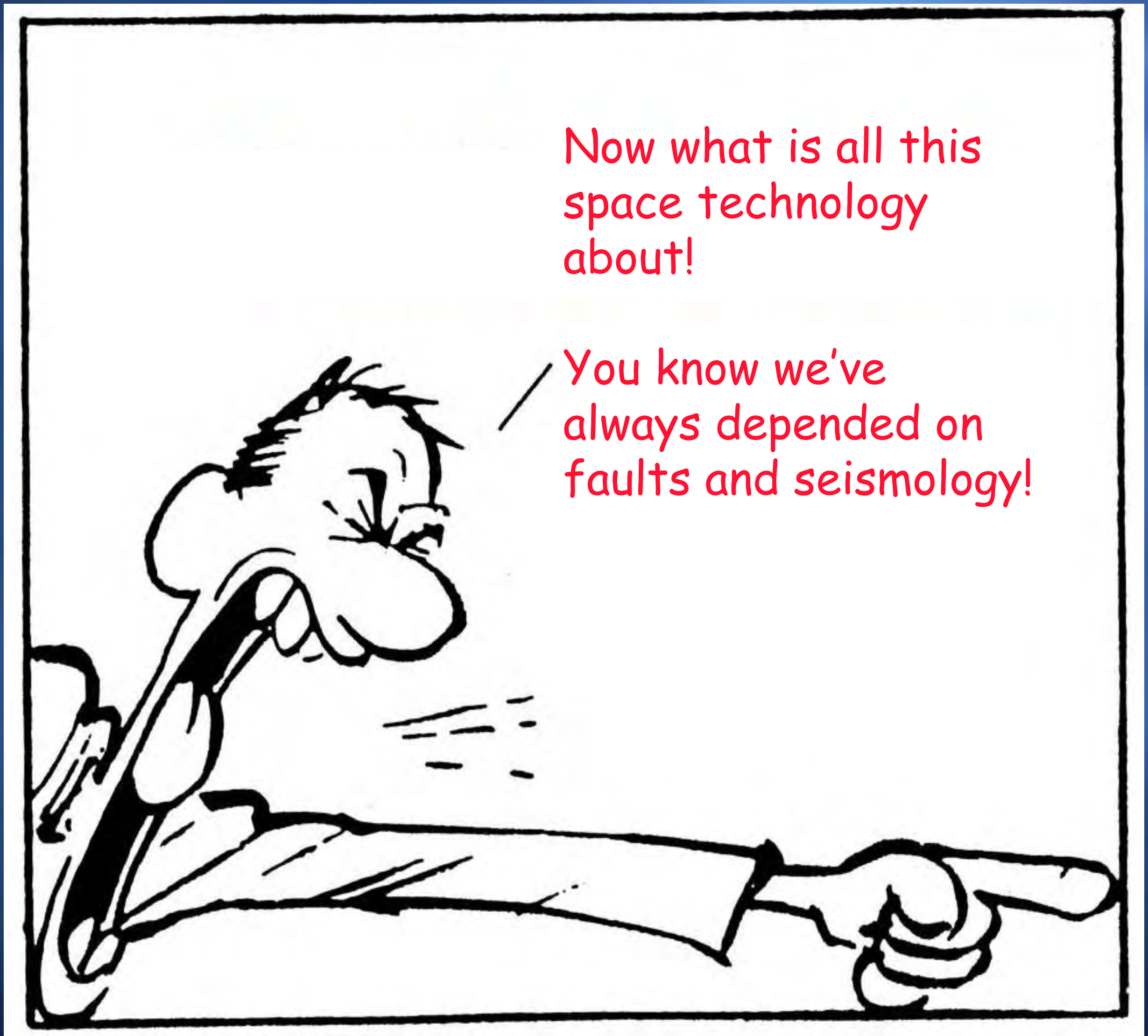
- *Update on the Wasatch GPS network*
- *GPS measurements of the velocity and strain rate*
- *Wasatch fault behavior in a western U.S. framework*
- *Implications for earthquake hazard*

Robert B. Smith, Christine M. Puskas, and Wu-Lung Chang
Department of Geology and Geophysics
University of Utah

THE UNIVERSITY OF UTAH

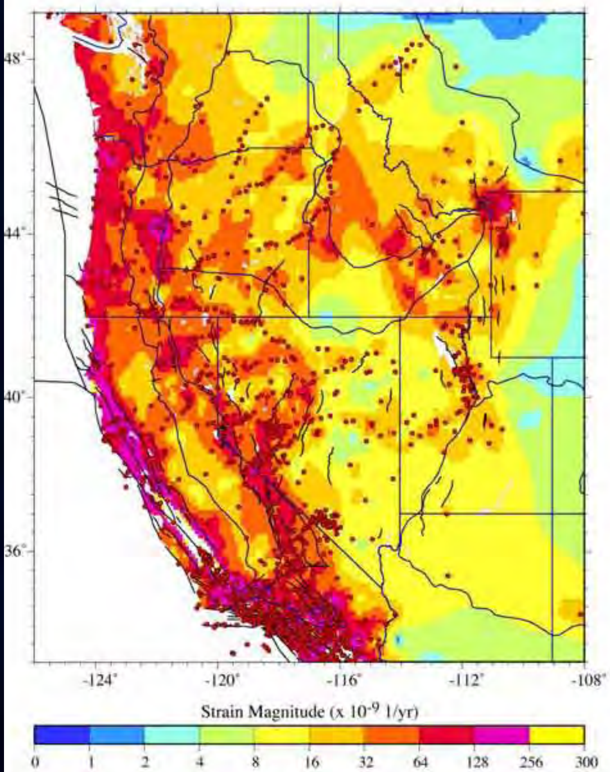
Seismology Research Group

Supported by the USGS NEHRP UGS, multiple universities, and EarthScope NSF Programs

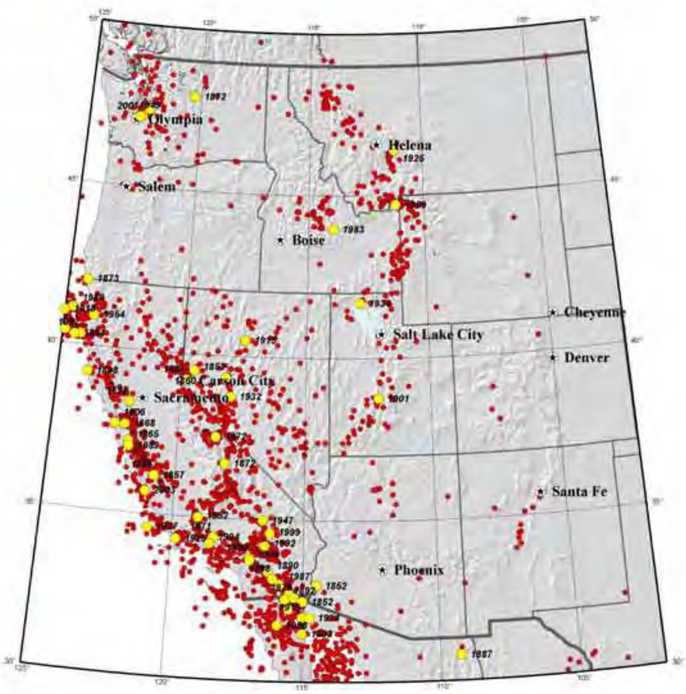

Now what is all this space technology about!
You know we've always depended on faults and seismology!

GPS Deformation Correlates With Earthquake Hazards

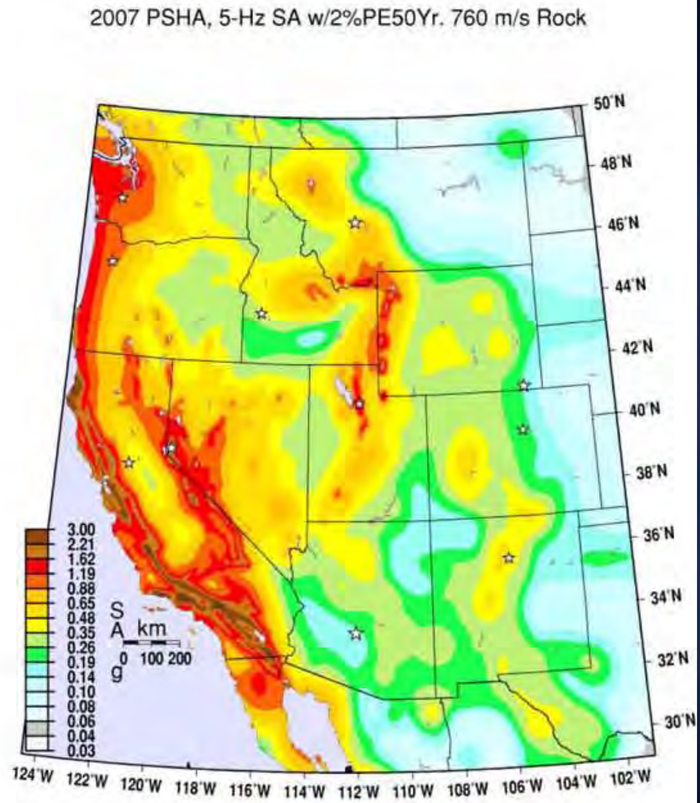
GPS derived
strain rate



Earthquakes
in the Western US



Spectral Acceleration
2% Probability of Exceedance
in 50 Years



High deformation rates correlate with
- Seismically active areas
- Regions of increased seismic hazard

Requires integration into hazard modeling
- Improving geodetic data set
- Deformation data available where paleoearthquake info. not well-known

The Wasatch fault fits into the kinematics of western U.S. (from ~2000 GPS observations)

Permanent GPS sites

Velocity vectors (interpolated)

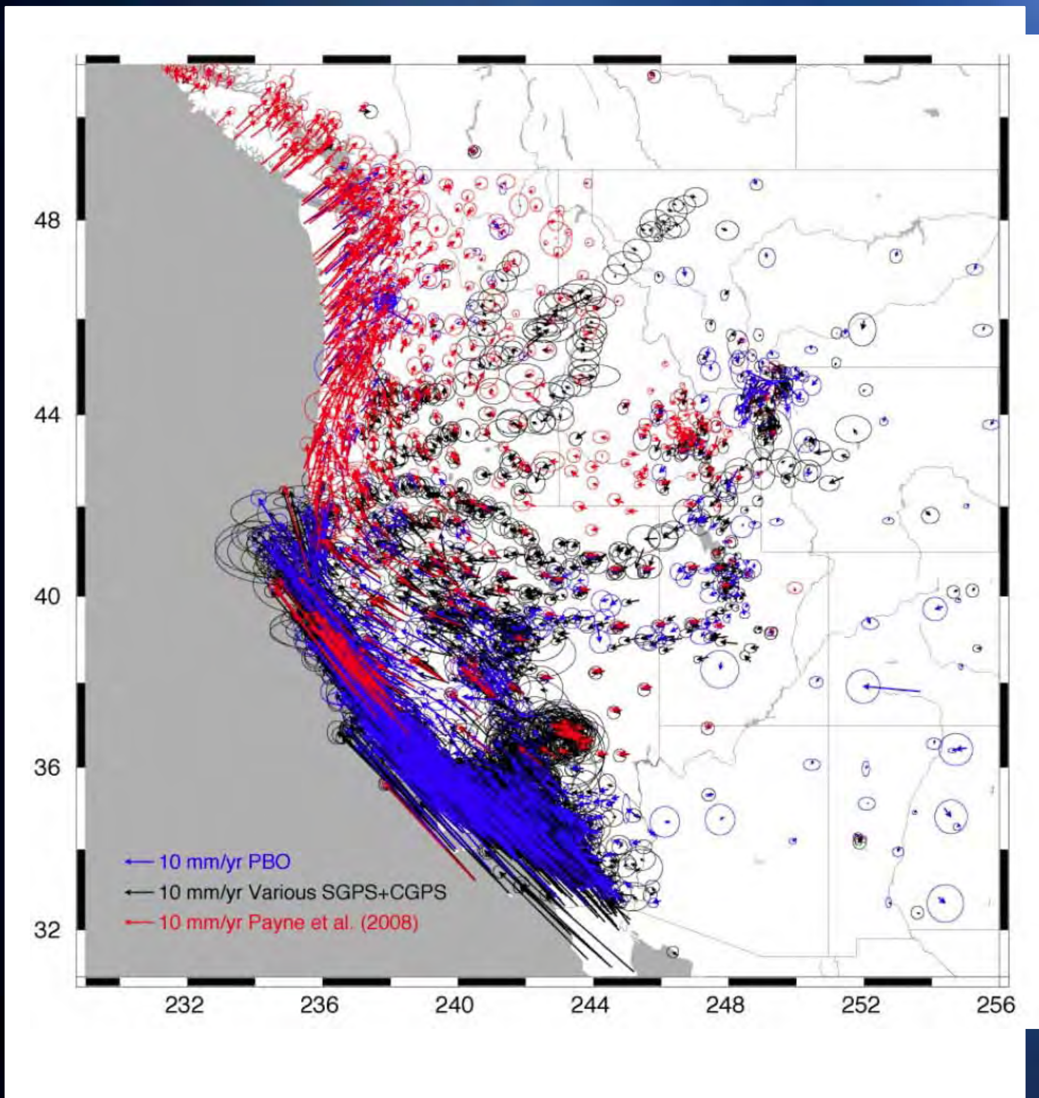
QuickTime™ and a
decompressor
are needed to see this picture.

(Puskas and Smith 2007, 2008)

The Wasatch fault fits into the kinematics of western U.S. (from ~2500 GPS observations)

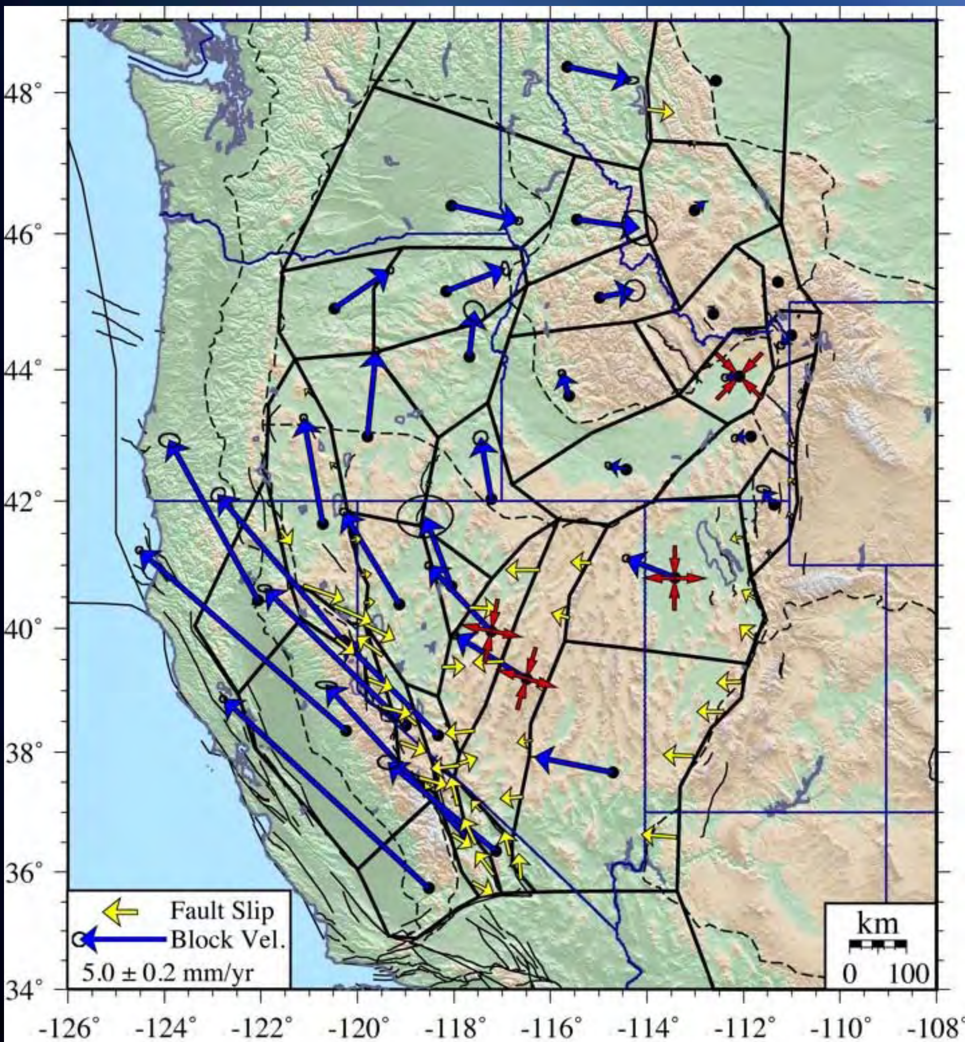
Permanent GPS sites

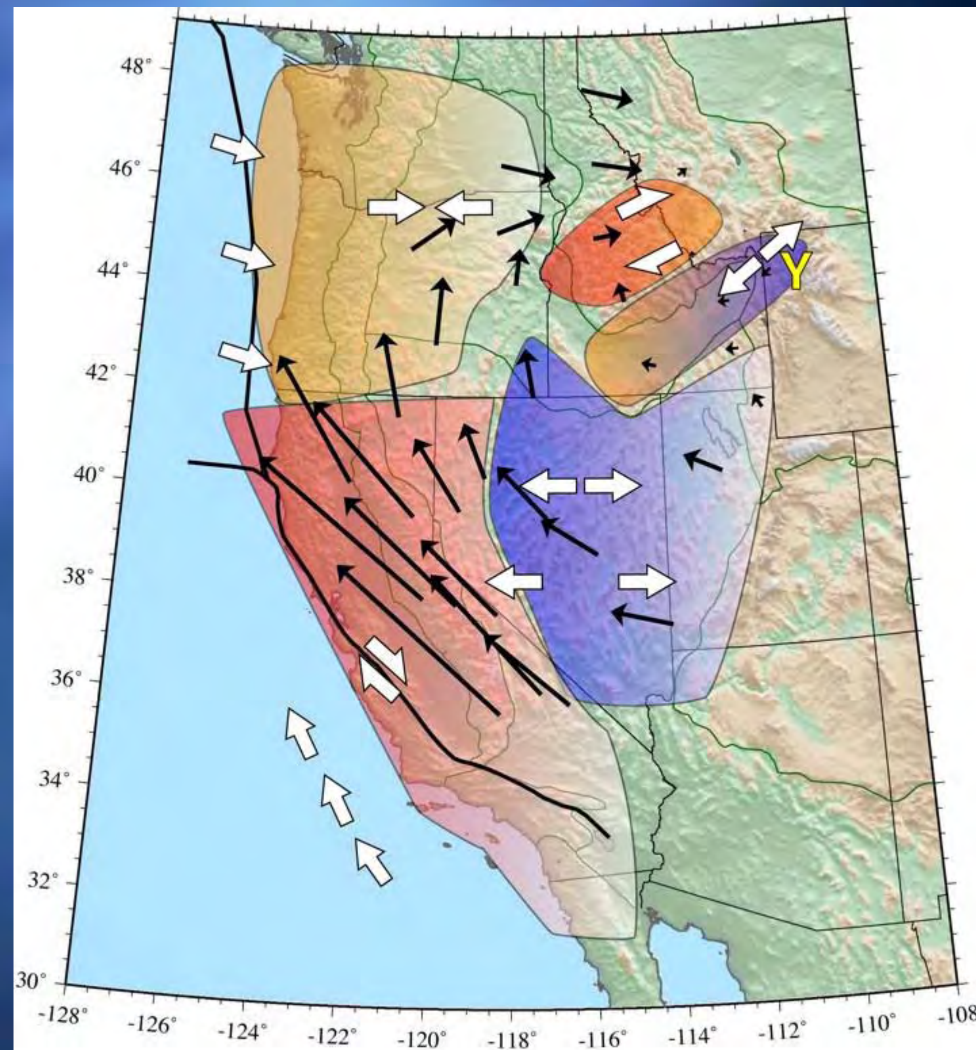
Velocity vectors. The Wasatch fault is loaded at the intraplate boundary



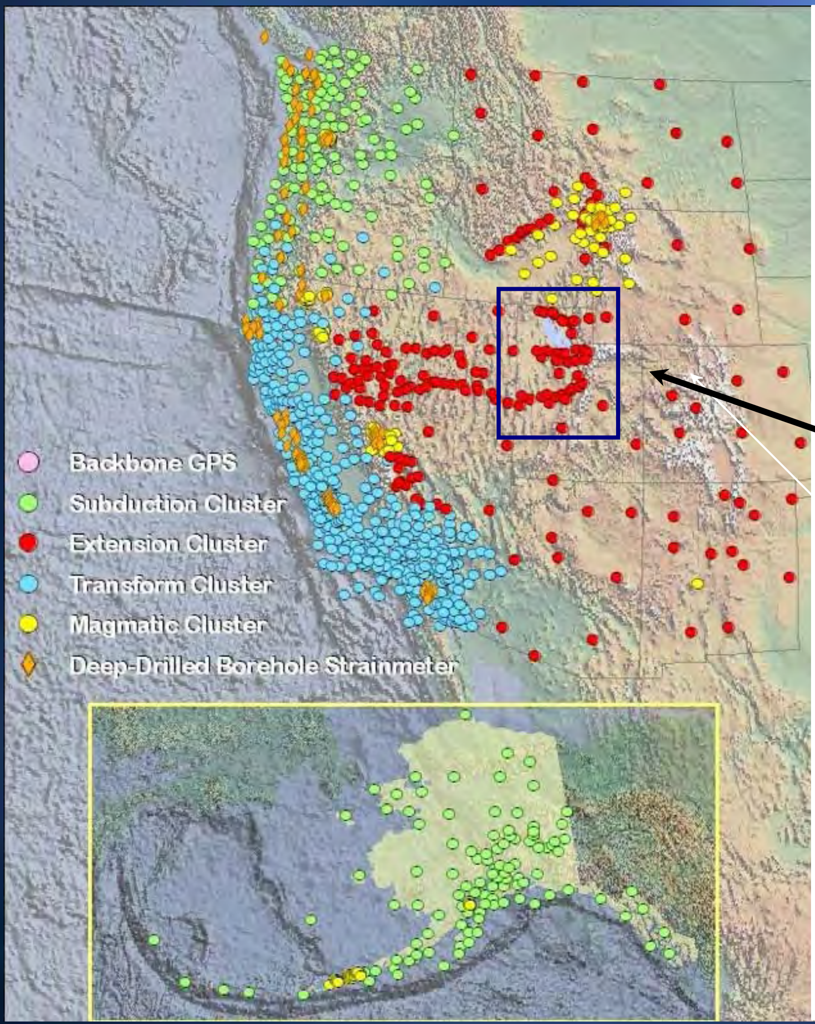
e™ and a
pressor
e this picture.

(Puskas and Smith 2007, 2008)


48°
46°
44°
42°
40°
38°
36°
34°
-126°
-124°
-122°
-120°
-118°
-116°
-114°
-112°
-110°
-108°
Fault Slip
Block Vel.
5.0 ± 0.2 mm/yr
km
0 100


48°
46°
44°
42°
40°
38°
36°
34°
32°
30°
-128°
-126°
-124°
-122°
-120°
-118°
-116°
-114°
-112°
-110°
-108°
Y

Western U.S. EarthScope PBO GPS Network (tectonic extensional regime)



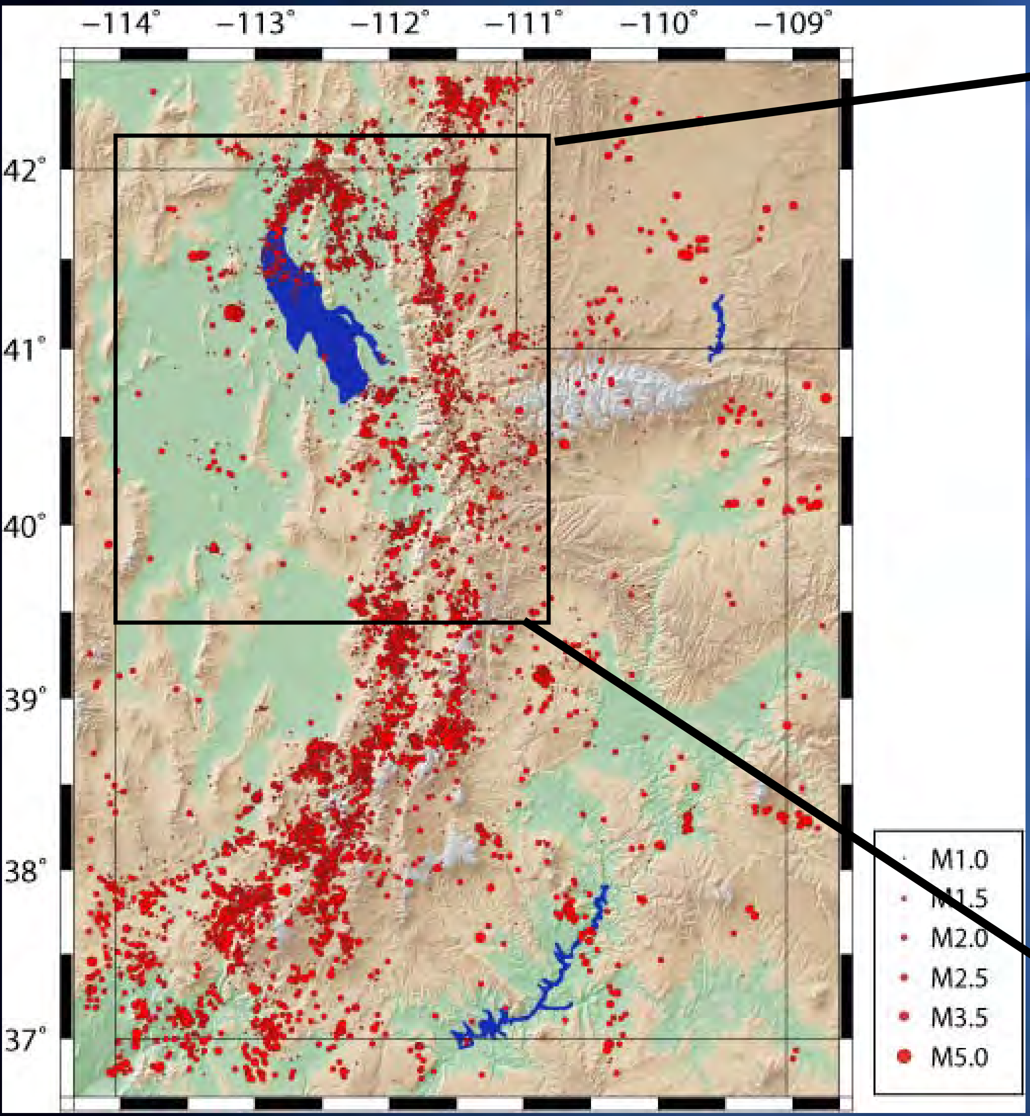
EarthScope extensional tectonics GPS stations in red

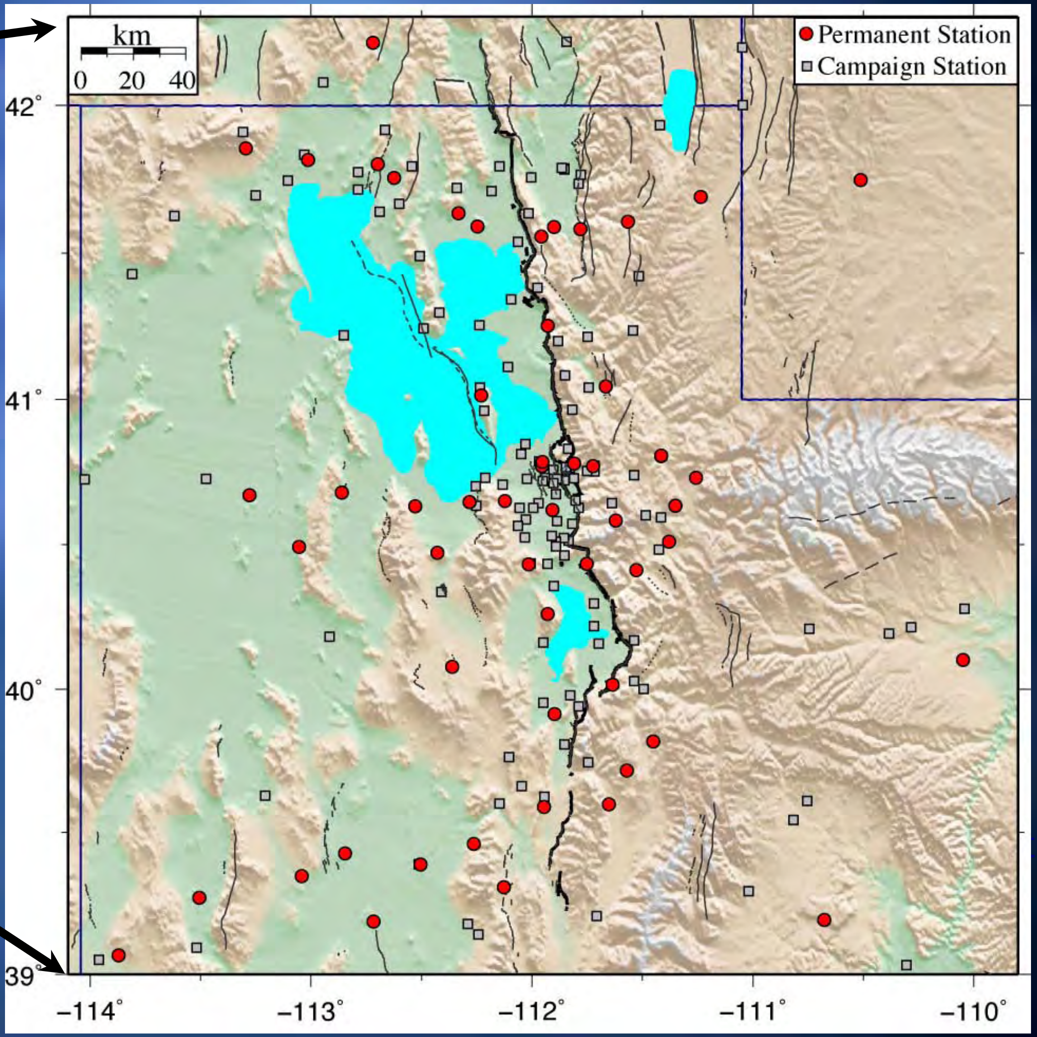
Wasatch fault zone,

- 40 PBO stations,
- 15 UU stations
- Value, ~$6Million

Utah seismicity and Wasatch GPS Network

Utah Seismicity





A new tool in earthquake science: GPS

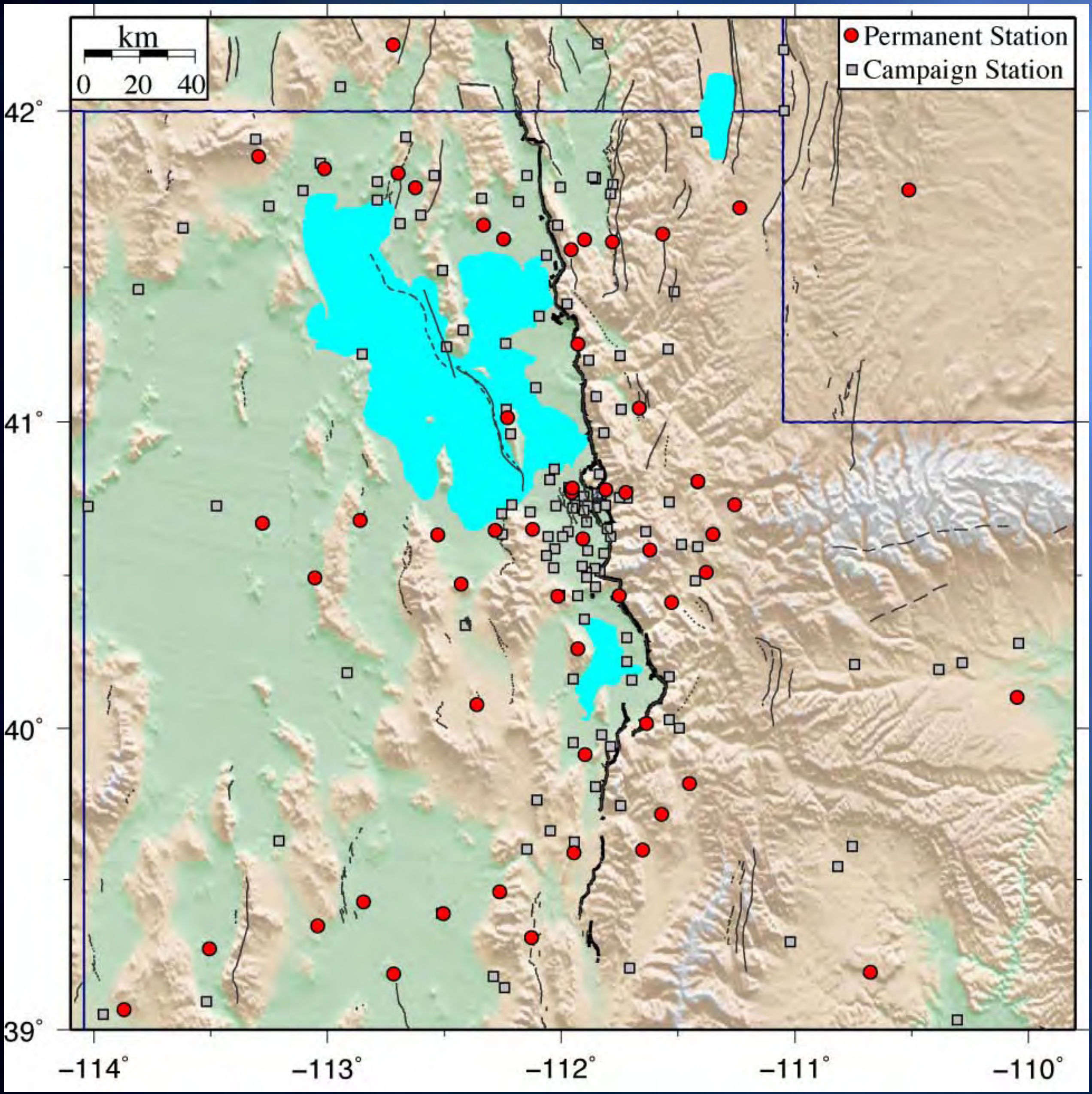
Alta, Utah

Lake Mountain, Utah County

Antelope Island

Orbiting GPS satellites provide
precise 3D locations on earth that can be tracked
with time, 4D, to an accuracy of a few mm/yr.

Wasatch Front GPS Seismic Network Parameters



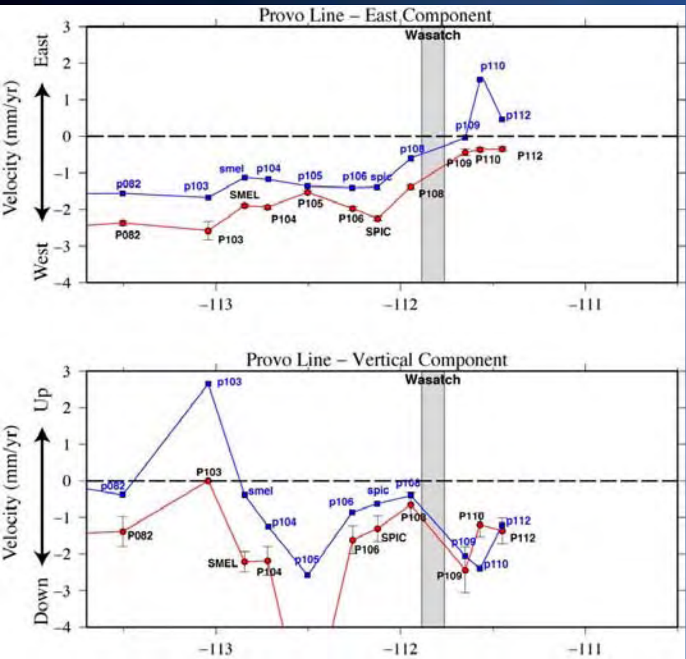
Data recorded and transmitted daily

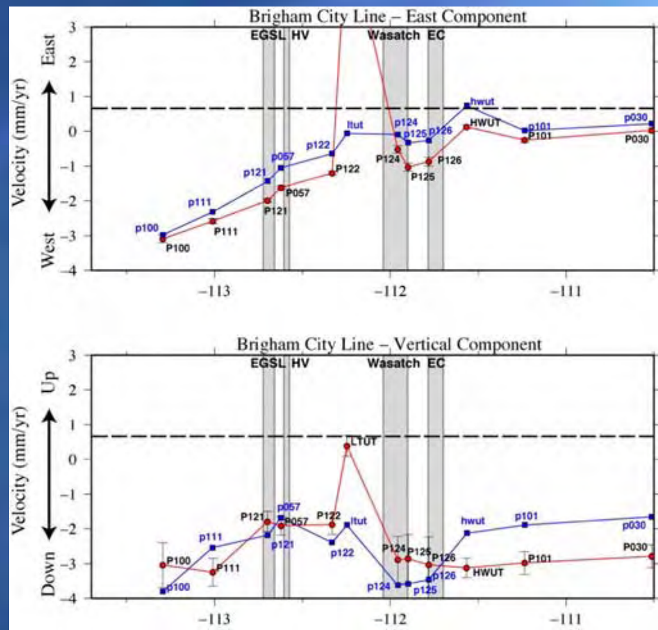
- 30-second recording rate
- 55 permanent stations (Univ of Utah and PBO)
- Installed as part of the "Tectonic extensional regime" EarthScope program
- Total resource ~$6M
- 90 campaign, temporary stations

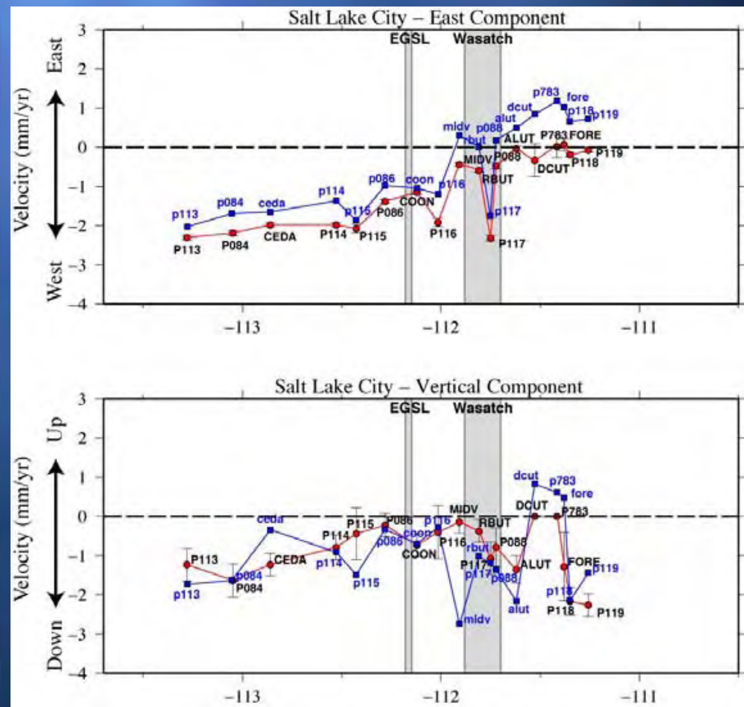
Processed data products

- Daily position solutions
- Site velocities

West-East GPS derived ground velocities, N to S

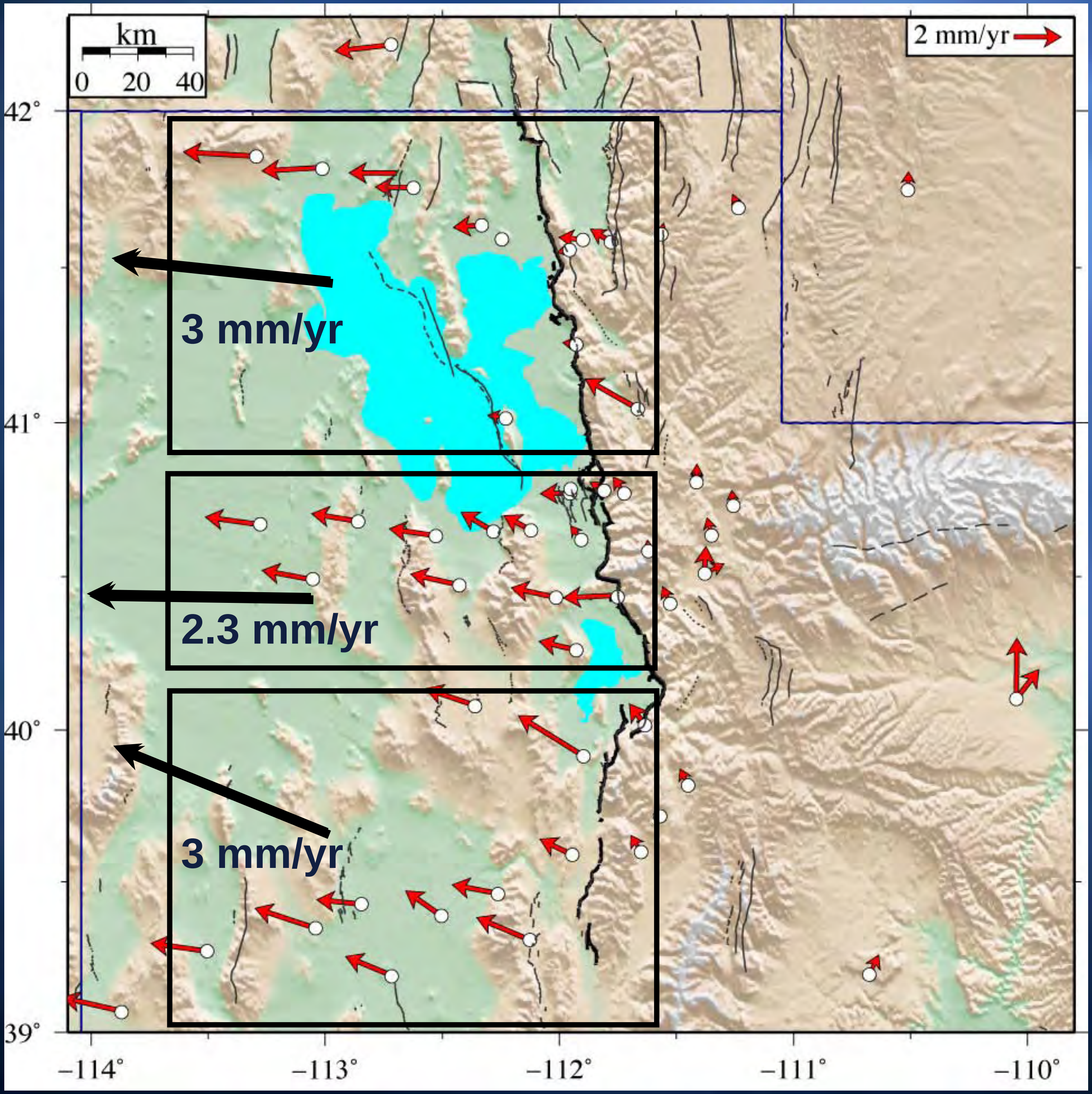




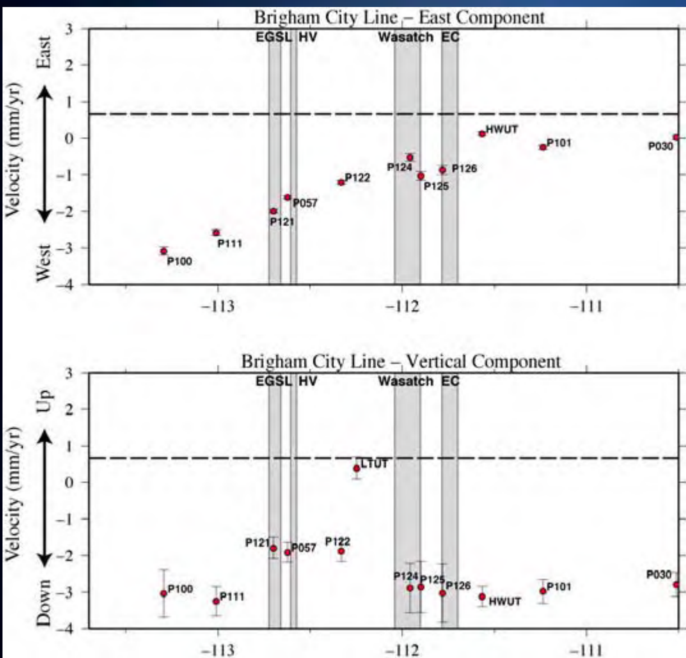


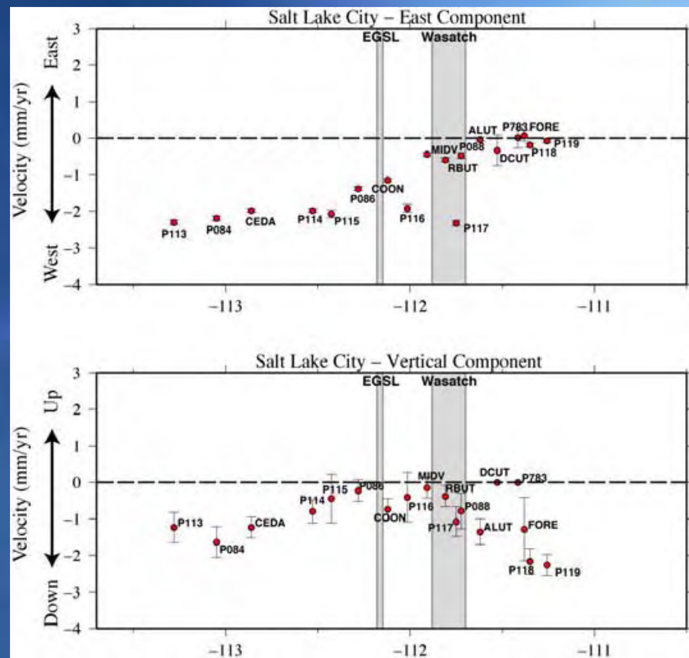
Note the rapid changes of rate at the faults

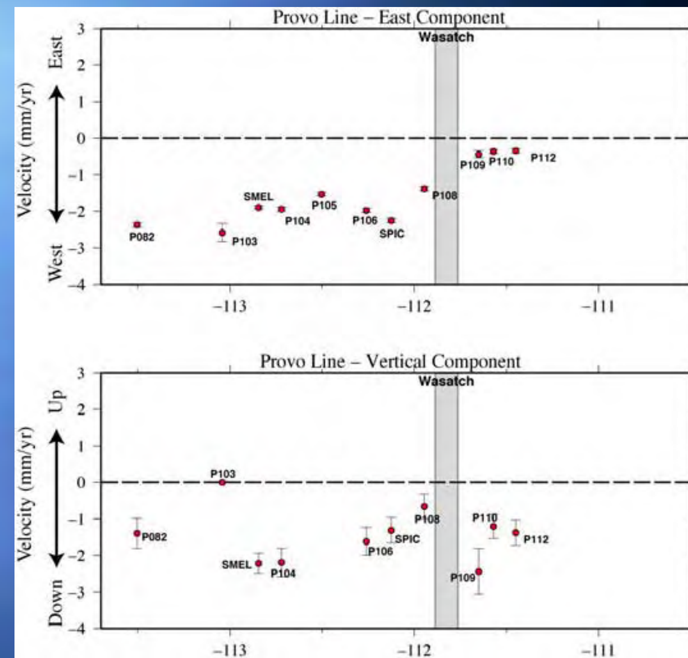
Wasatch Horizontal GPS Velocities

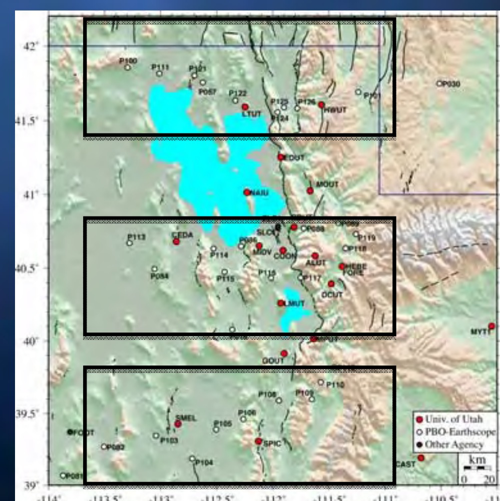


Wasatch fault GPS velocity profiles

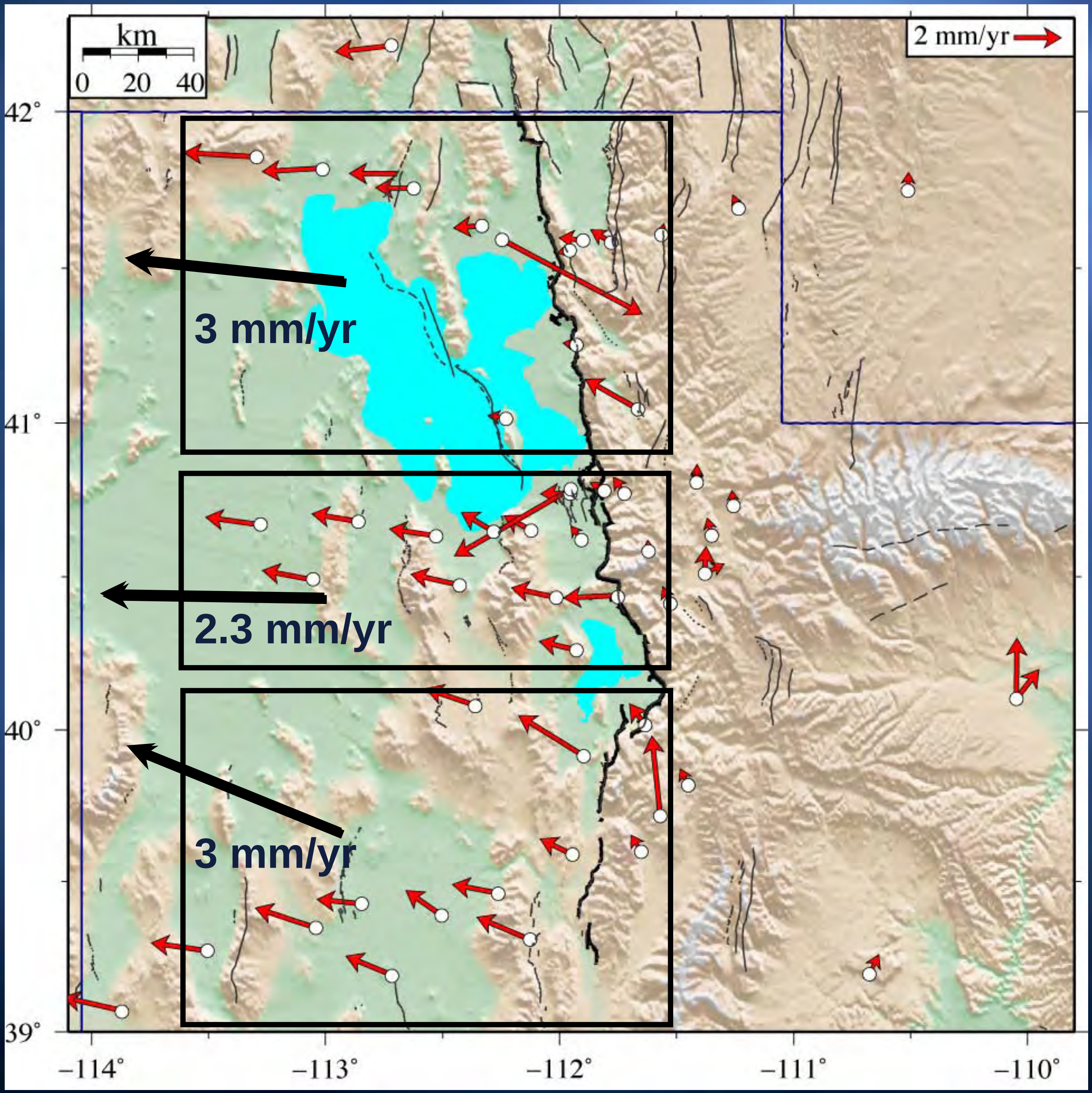




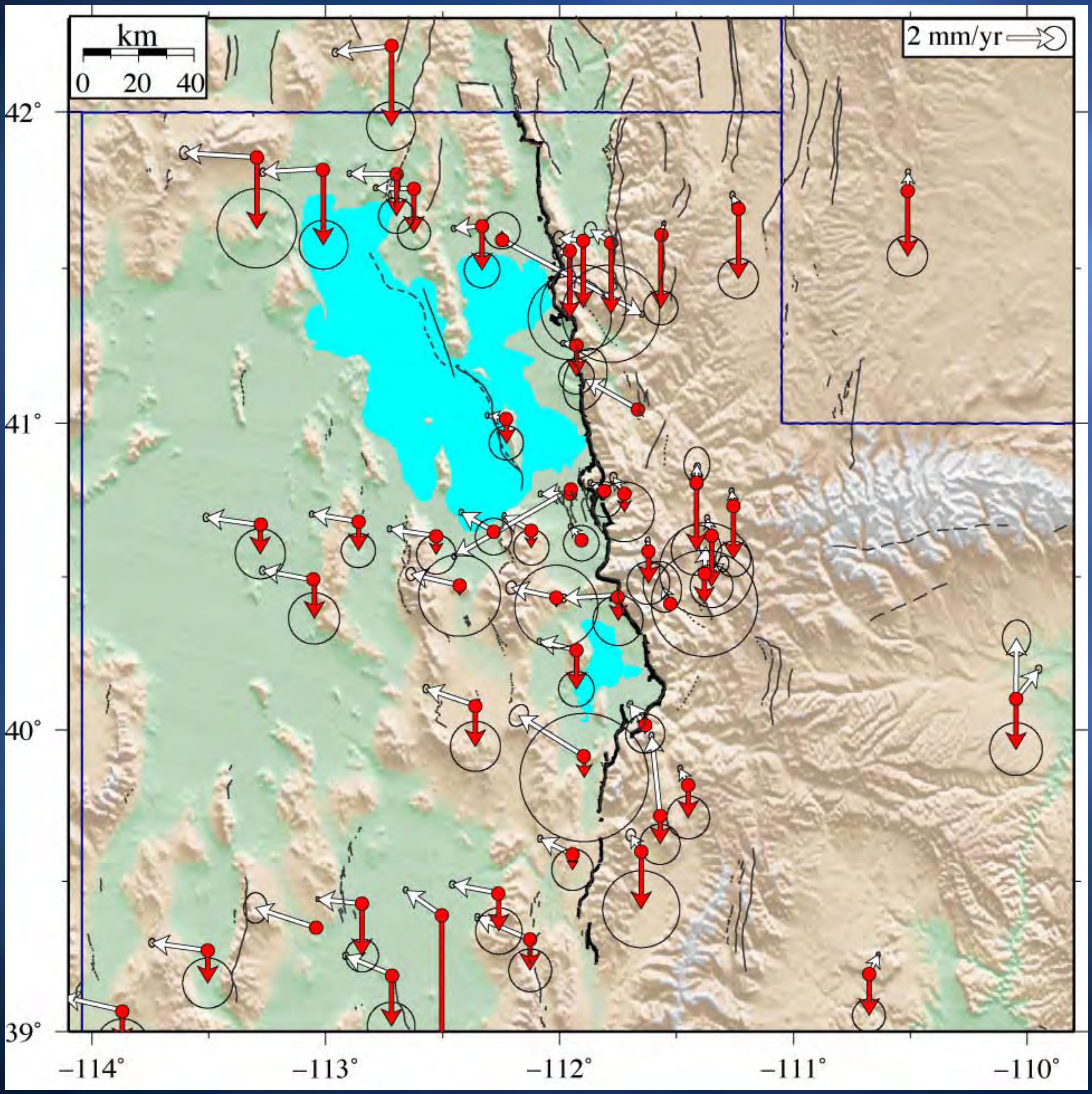




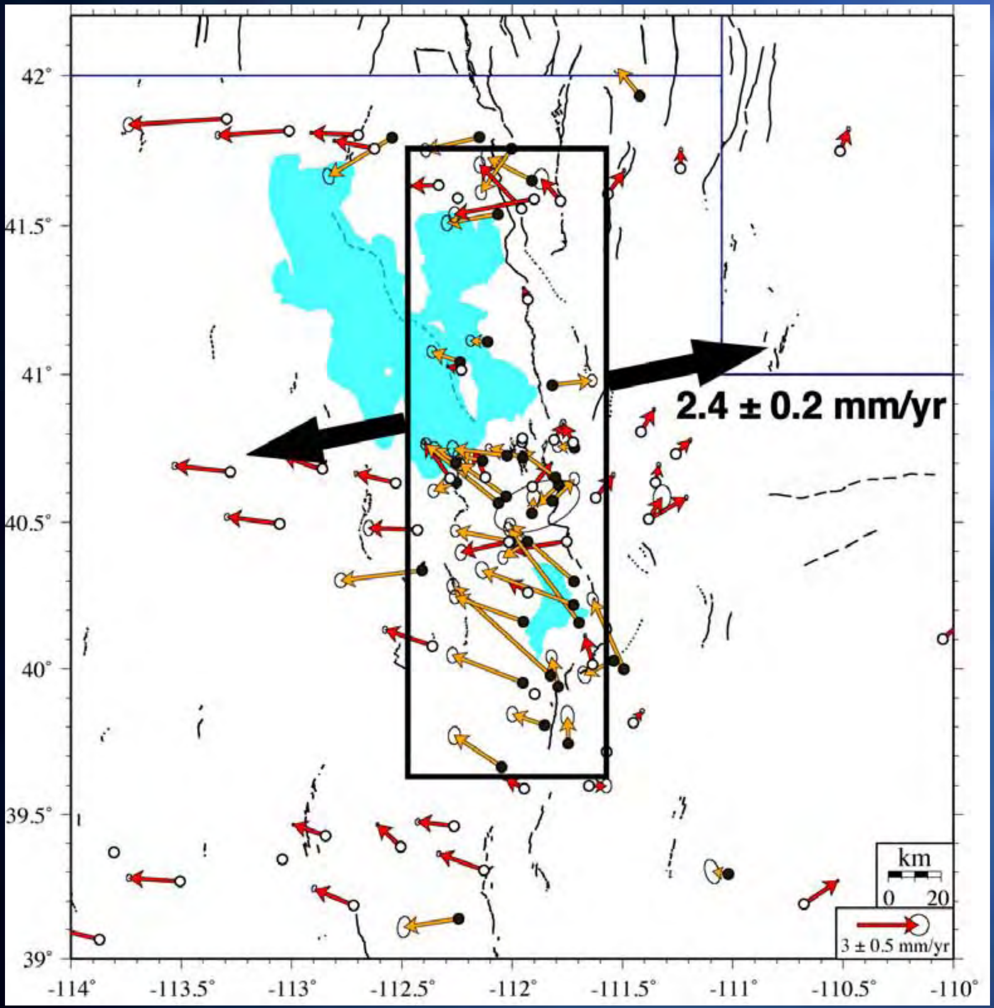
Wasatch Front Horizontal GPS Velocities



Horizontal and Vertical GPS Velocities



Deformation Rates across the Wasatch fault



Fault	Slip rate mm/yr
Wasatch-Brigham City	0.9
Wasatch-Weber	1.6
Wasatch-Salt Lake City	1.2
Wasatch-Provo	1.2
Wasatch-Nephi	1.7
E Great Salt Lake	0.6
E Cache	0.2
E Bear Lake	0.6
Bear River	2.0
Rock Creek	1.7
Stansbury	0.4
Wasatch Front GPS	**2.4 ± 0.2 mm/yr**

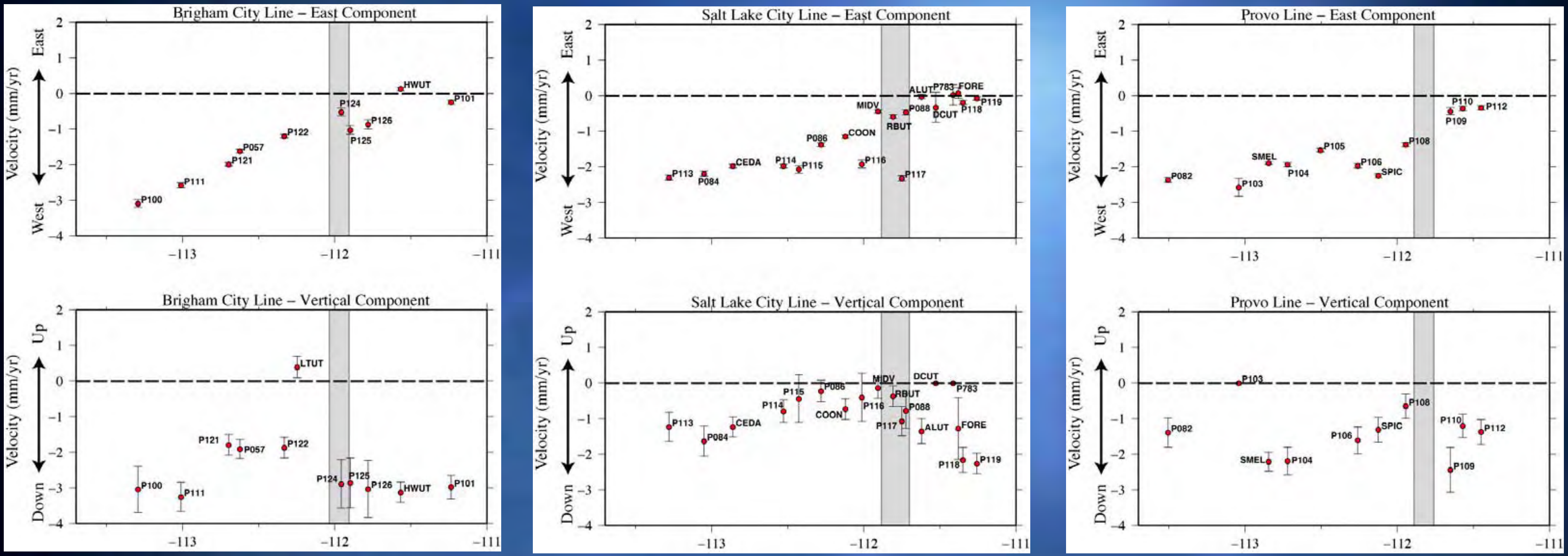
Average GPS rate for the 55-km wide Wasatch fault zone!

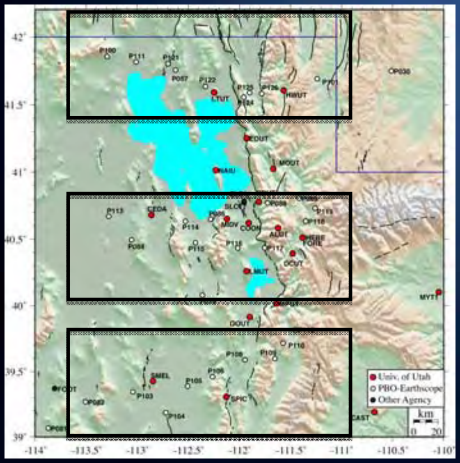
How is the USGS going to deal with this descrpancy!!

Monitoring of Wasatch fault

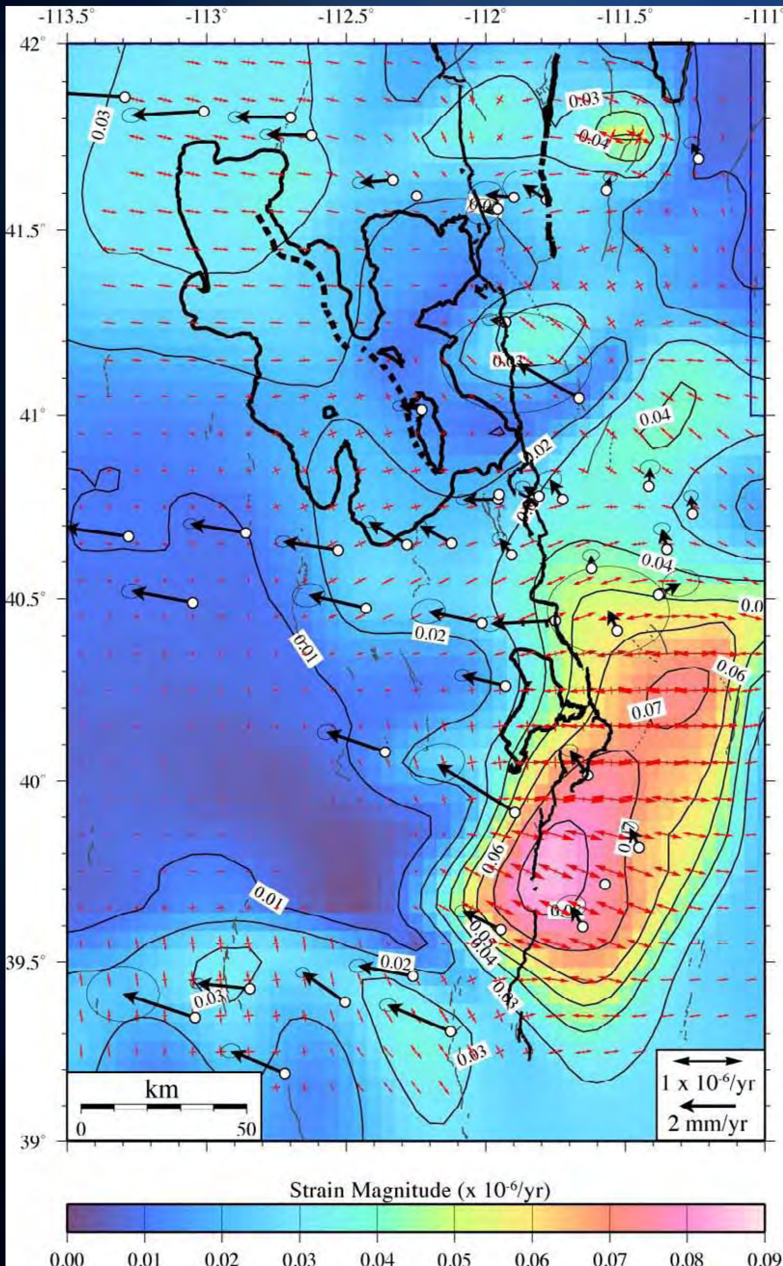
- Campaign GPS: 1992-2003
- Permanent GPS: 1996-2010

Wasatch fault velocity profiles

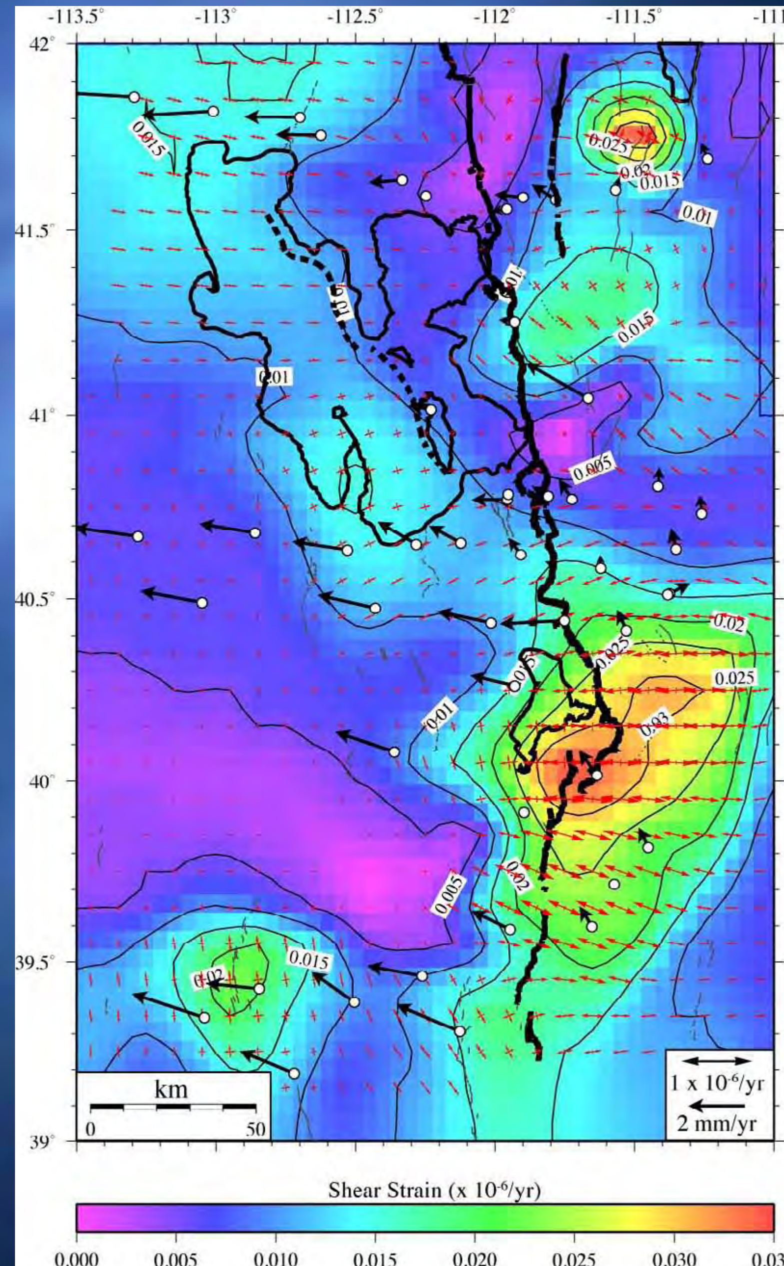




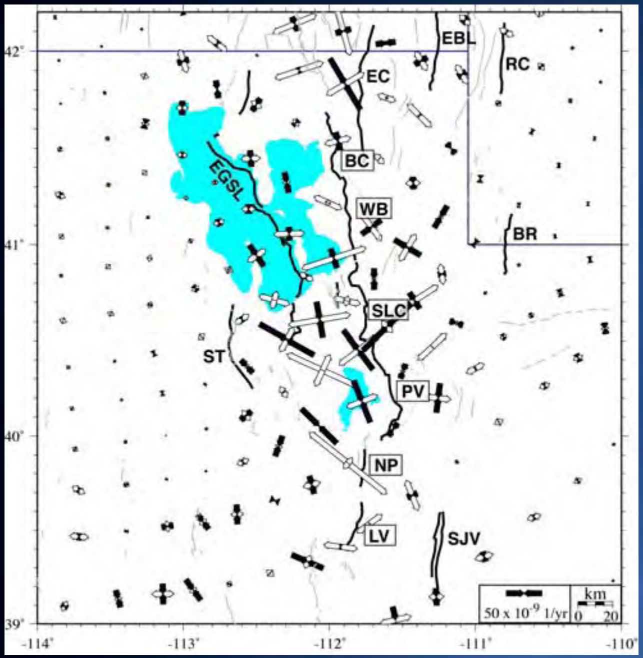
Wasatch GPS (black arrows), horizontal strain rates (red crosses), and strain magnitudes (background)



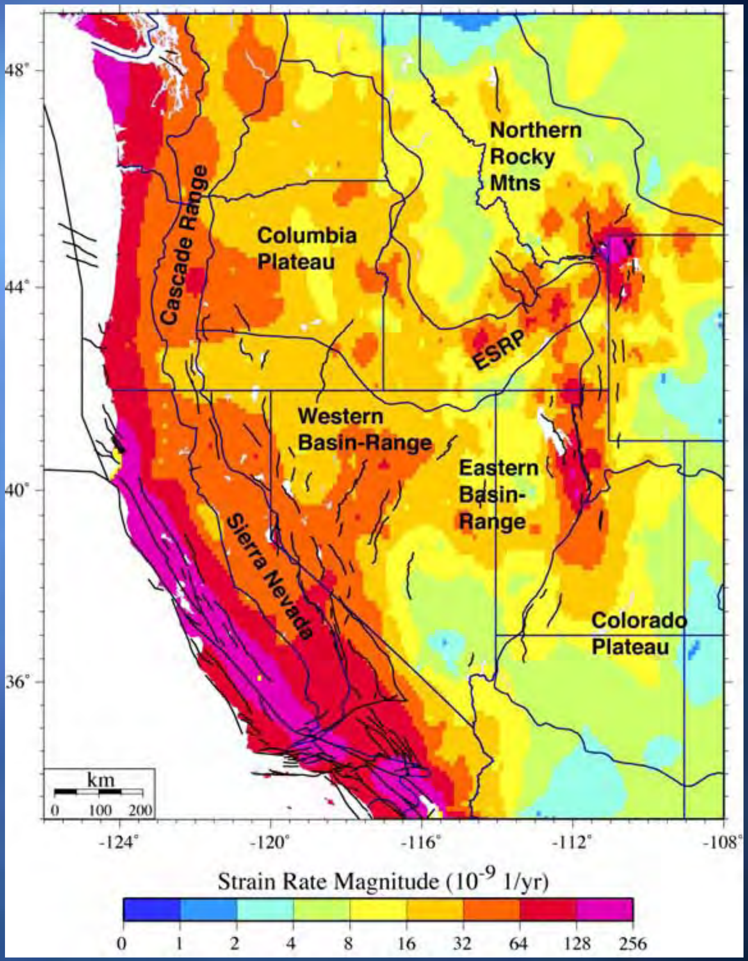
Wasatch GPS (black arrows), horizontal strain rates (red crosses), and shear strain (background)

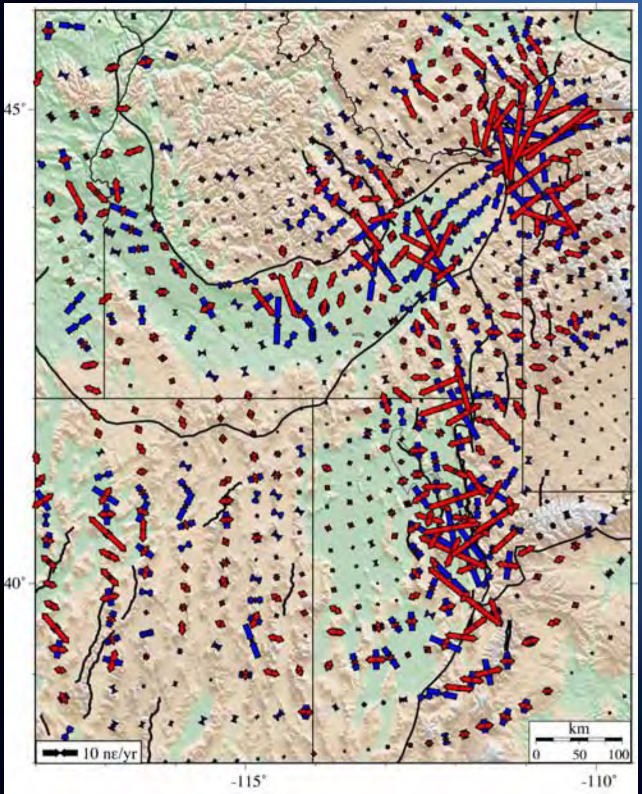


Distribution of Deformation



Region	Max Magnitude (x 10^{-9} 1/yr)
Yellowstone Plateau	240
Wasatch Front	210
Eastern Basin-Range	14
Northern Rockies	17

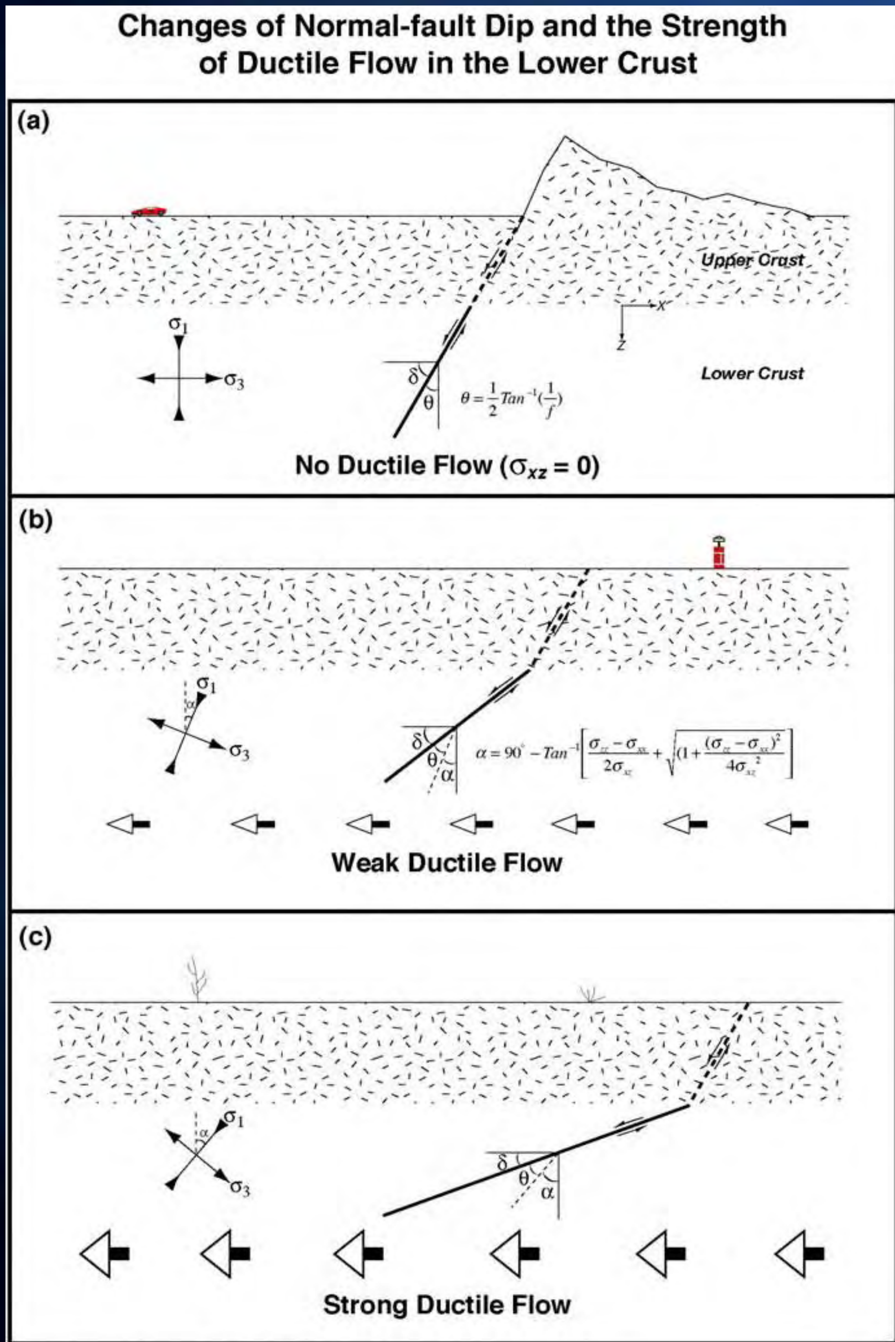




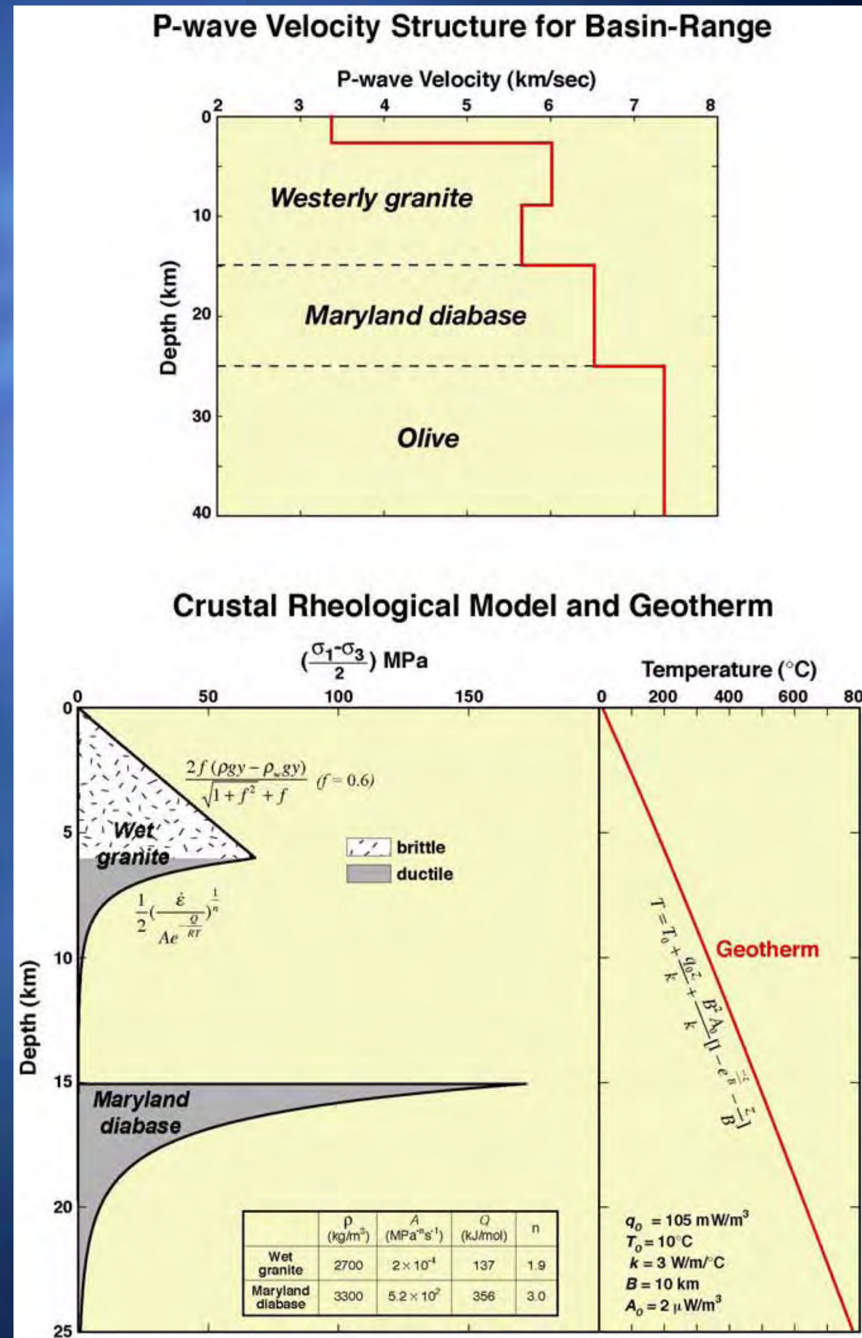
Continuum finite element deformation modeling

- Interpolate strain rate tensors and magnitudes
- Magnitudes reflect seismic belts, tectonic blocks
- Wasatch comparable to Yellowstone Plateau

Normal fault brittle-ductile flow models

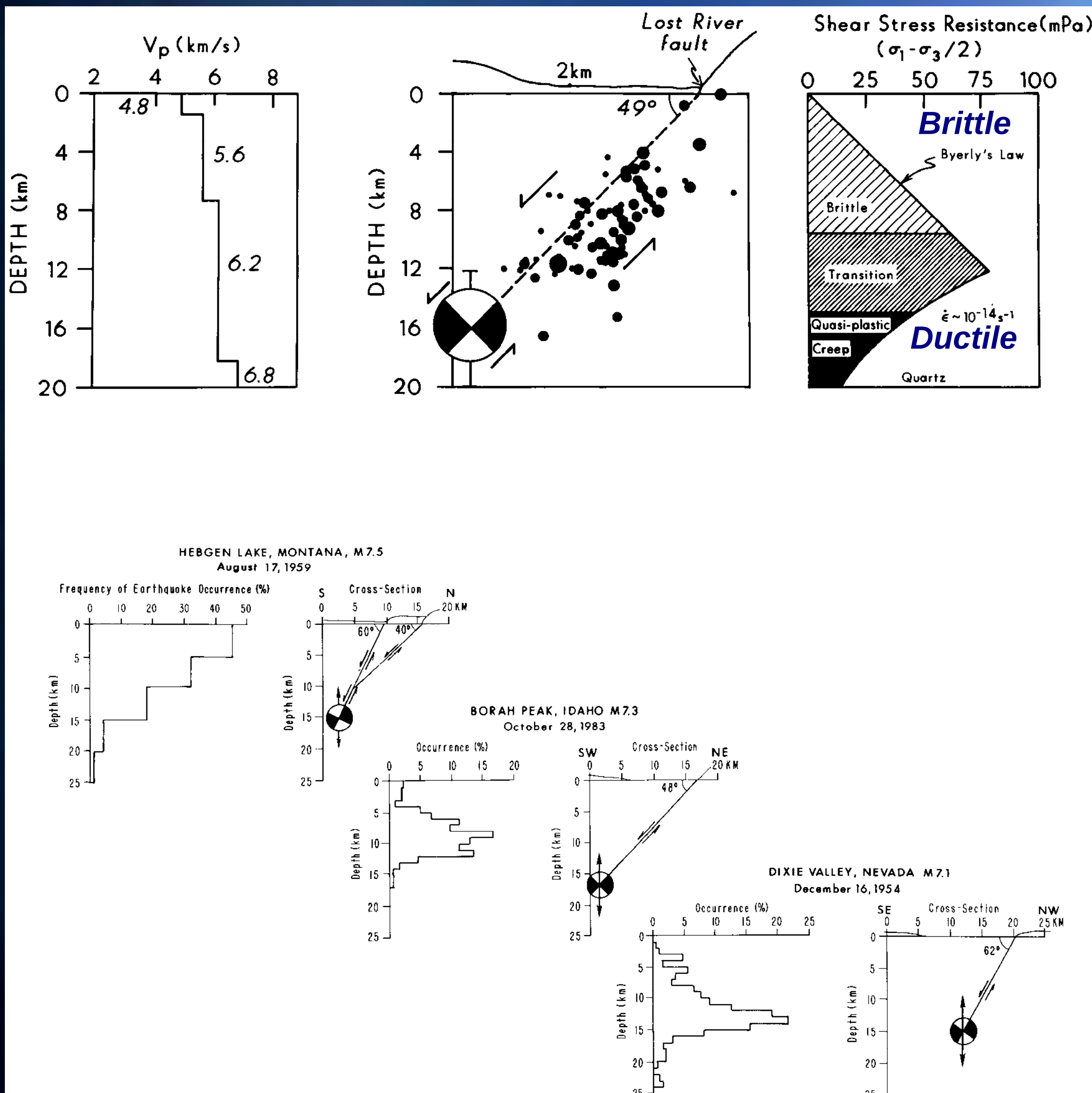


(after *Westaway* [1998])



after *Smith and Bruhn* [1984]

Working Model for A Normal-Faulting Earthquake



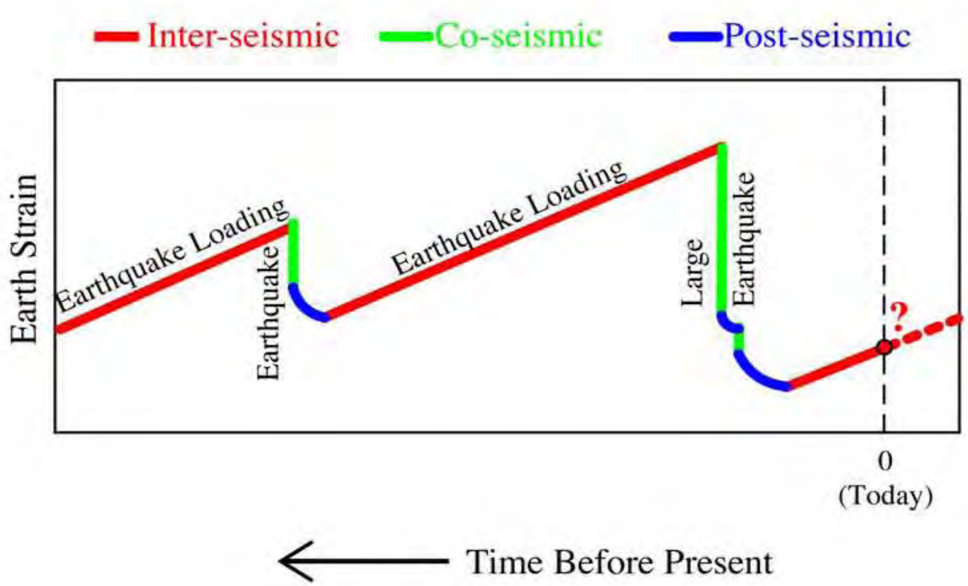
Properties:

Planar, 45 ° to 60° dipping fault nucleating at the mid crustal transition zone from brittle to ductile rheology .

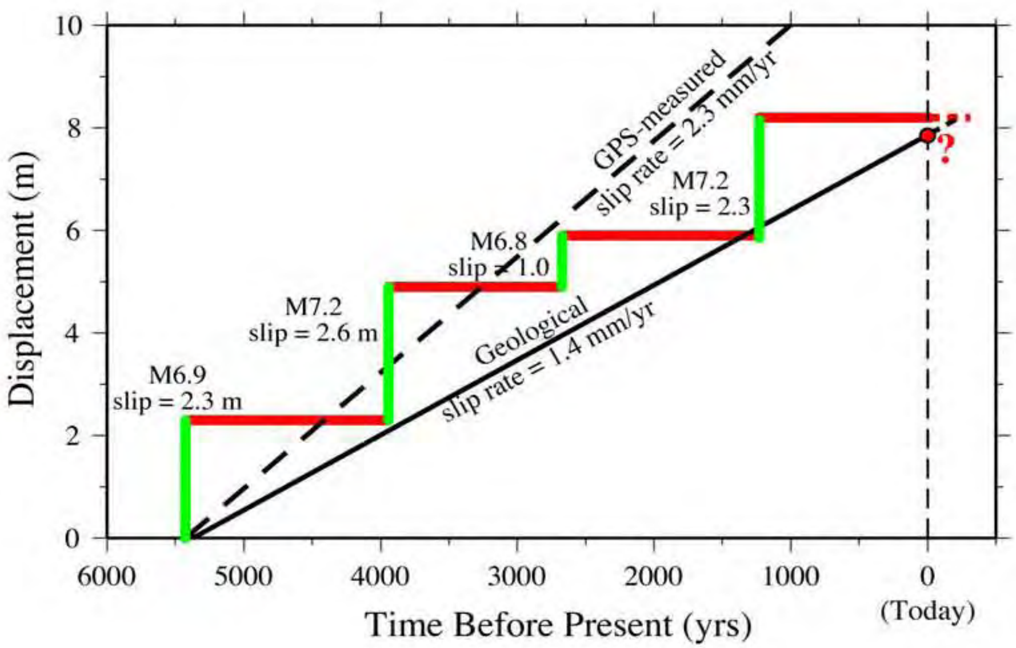
Smith and Arabasz, 1991

Earthquake Cycle

History of earthquakes
and earthquake loading

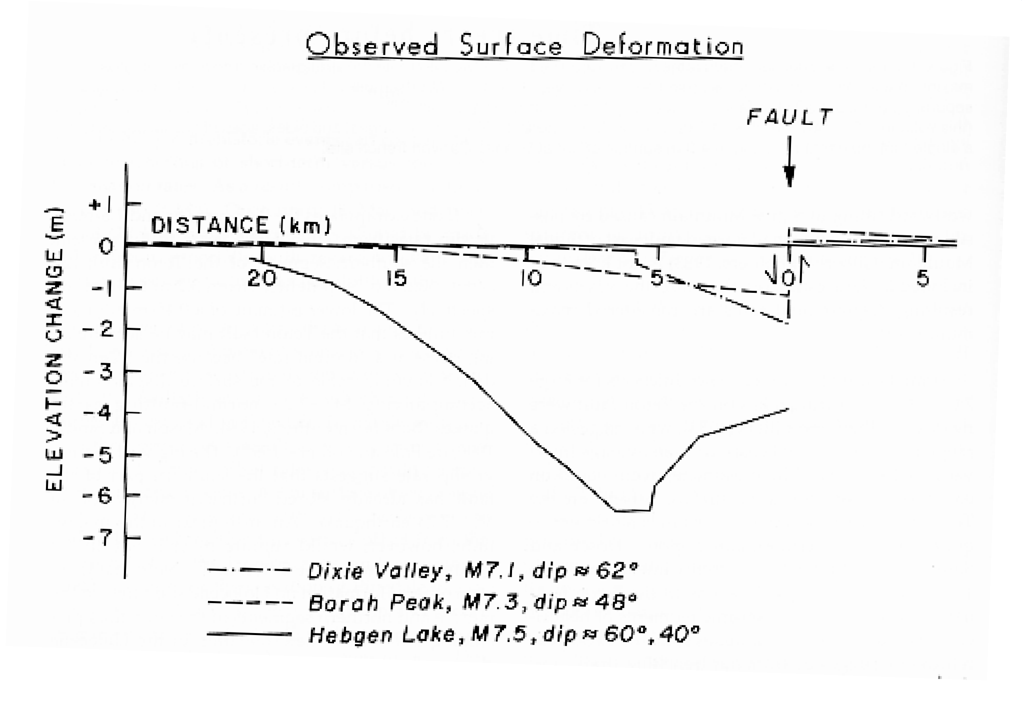


Wasatch fault earthquake history



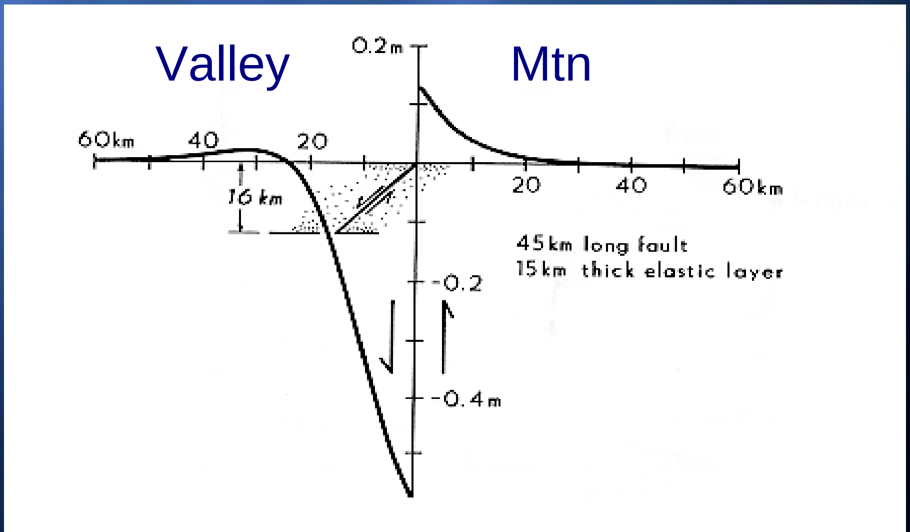
- GPS measures the co- and inter-seismic loading rates.
- A key topic is how the inter-seismic rate employed as a proxy for geologically determined fault-loading rate.
- And conversely how to convert the geologic rate to a finite strain deformation rate.

Ground deformation of normal-faulting earthquakes
is not normal!



Notably more hanging-wall subsidence than foot-wall uplift accompanying normal faulting earthquakes producing asymmetric deformation.

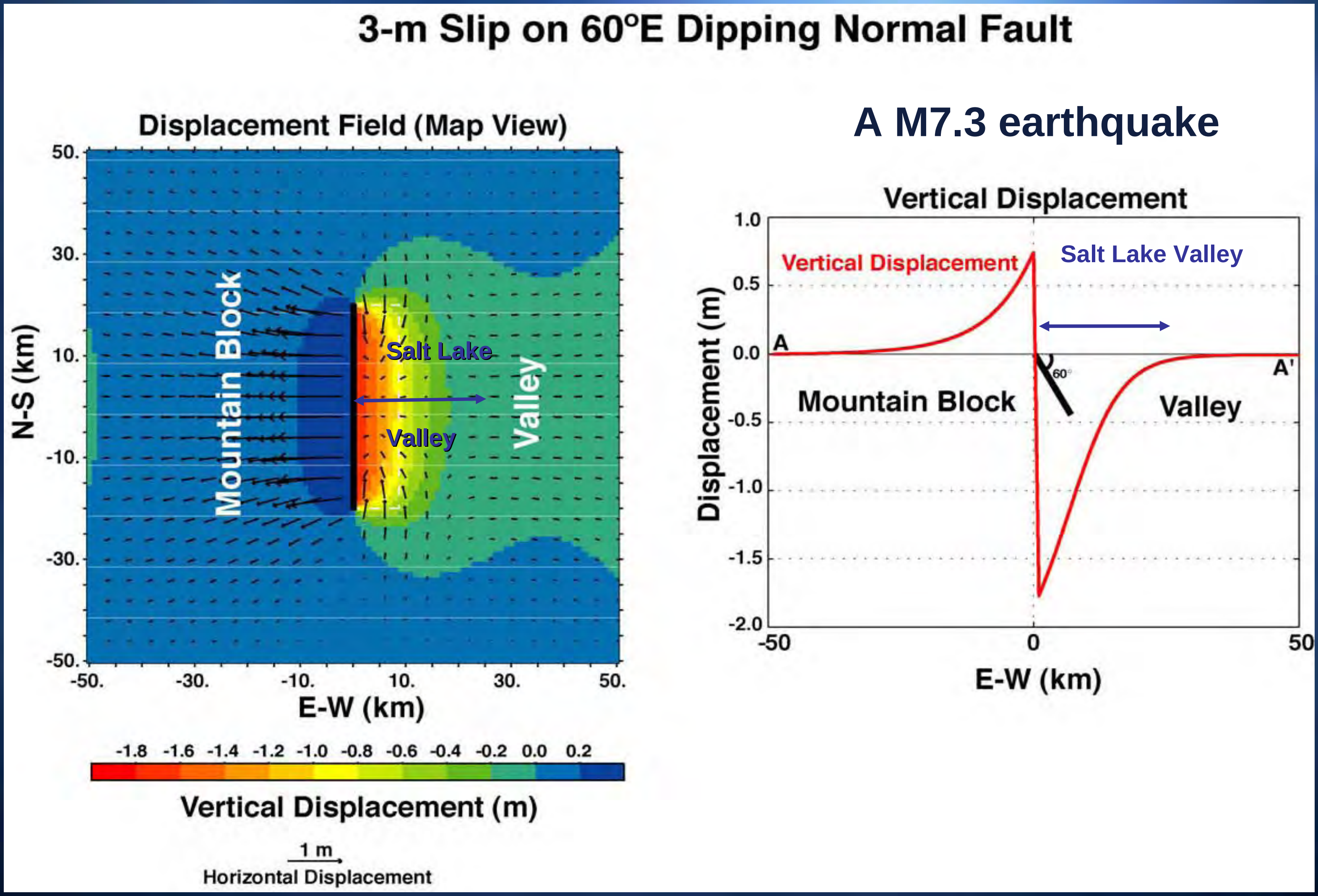
Elastic model reveals asymmetric deformation of valley subsidence and mountain uplift



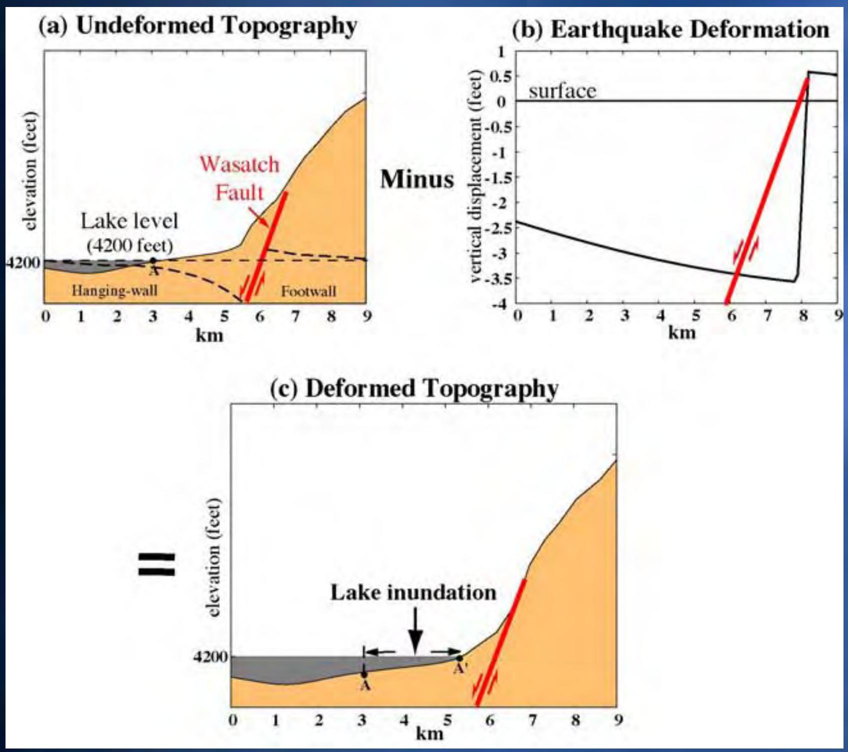
(Smith and Arabasz, 1991)

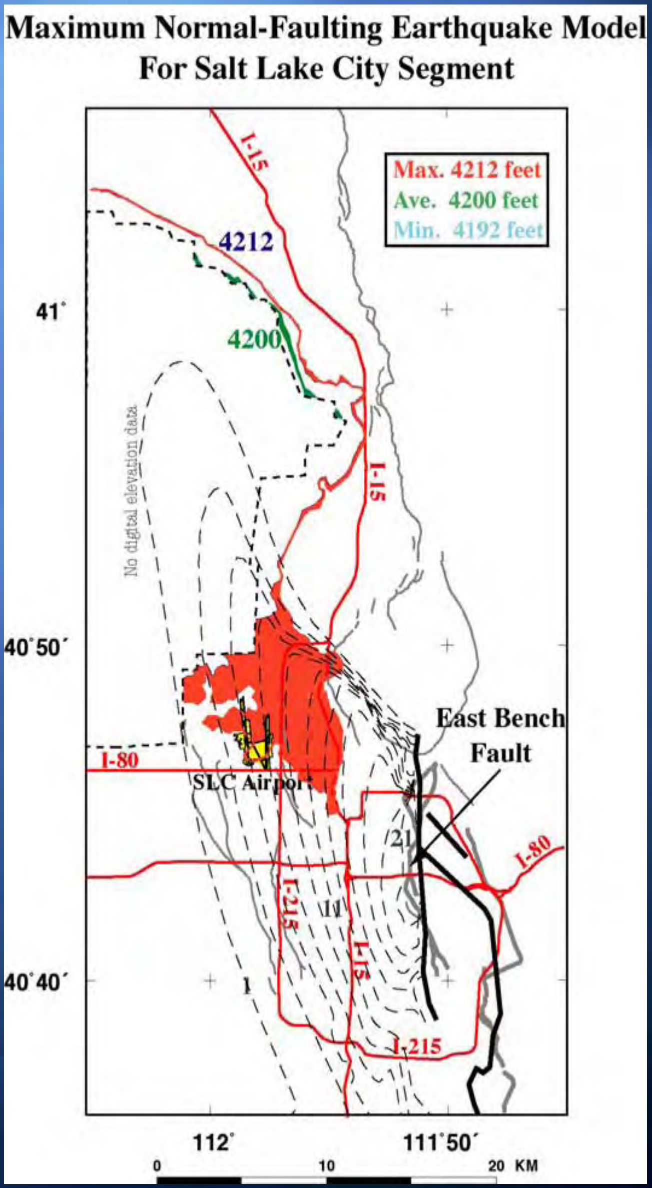
An Elastic Normal Fault Model

Valleys Go Down A Lot and the Mountains Go Up A Little



Consequences of normal faulting deformation: Induced flooding of the Great Salt Lake from a large earthquake on the Wasatch Fault





(Chang and Smith,1997)

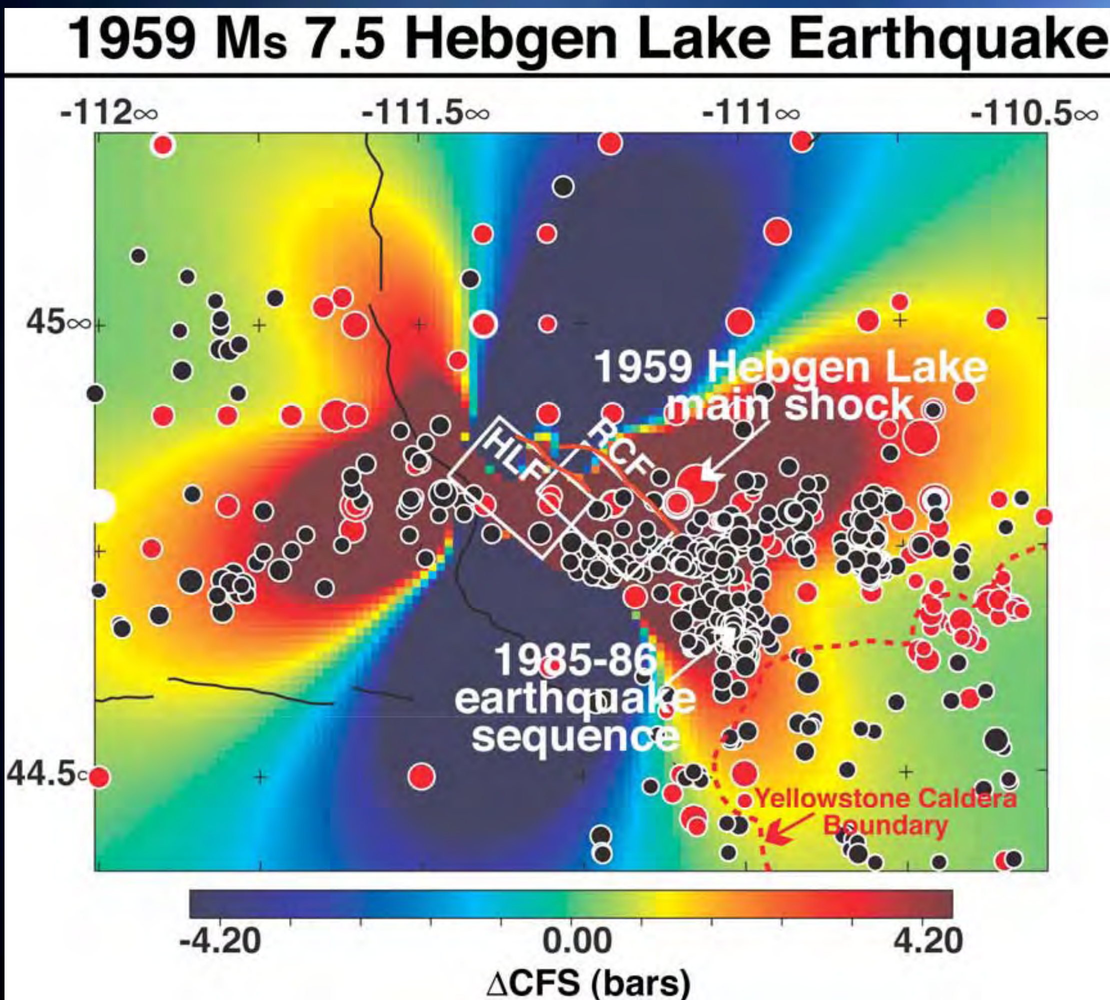
Big Intermountain earthquakes

1983 Borah Peak, ID earthquake

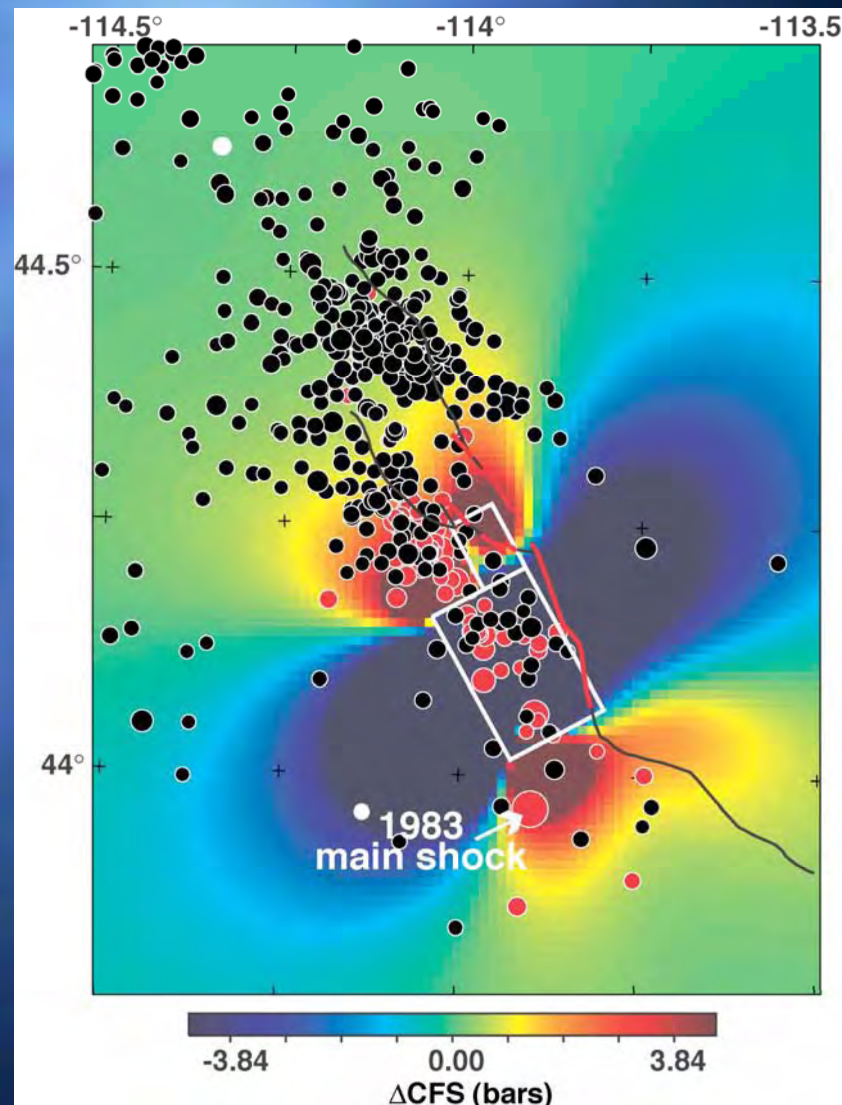
M = 7.5 1959, Hebgen Lake, Montana, Fault Scarp
Maximum displacement = 5.7 m

5.7 m offset, 1959 M7.5
Hebgen Lake Earthquake

Two largest and most recent Intermountain earthquakes exhibited strong stress contagion

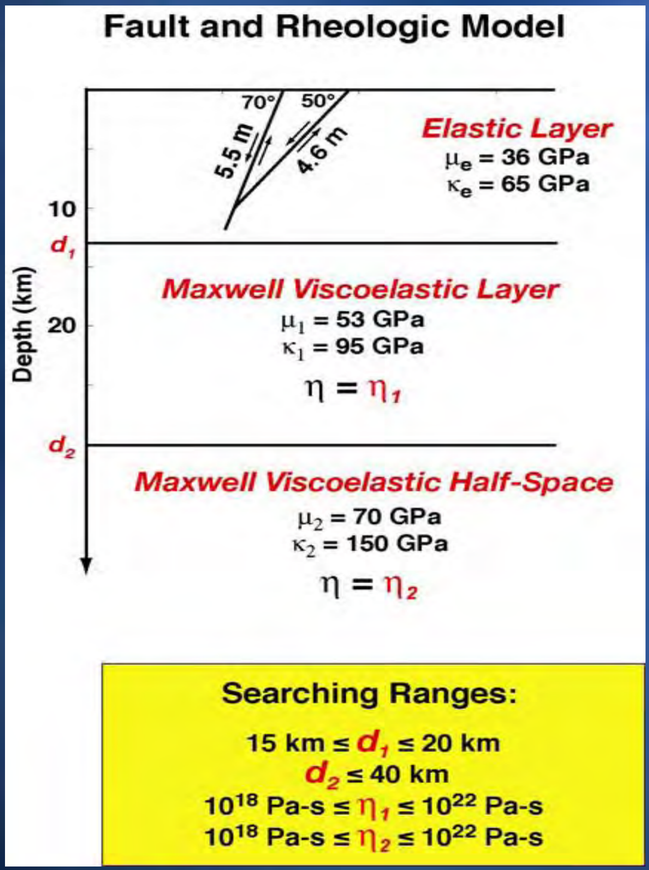


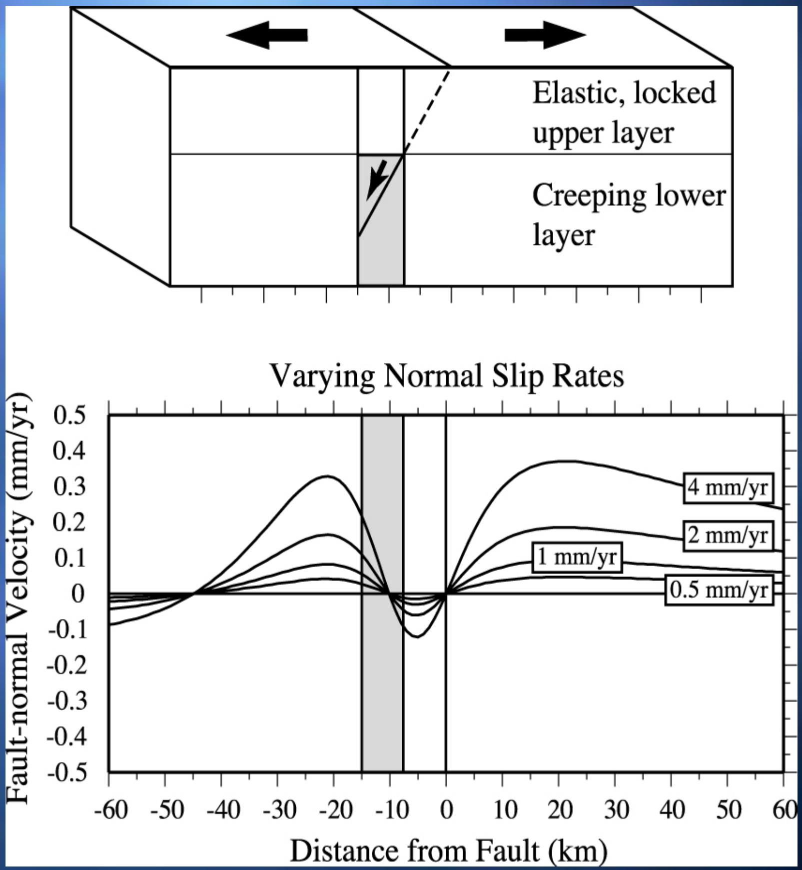
1983 Ms 7.3, Borah Peak, Earthquake



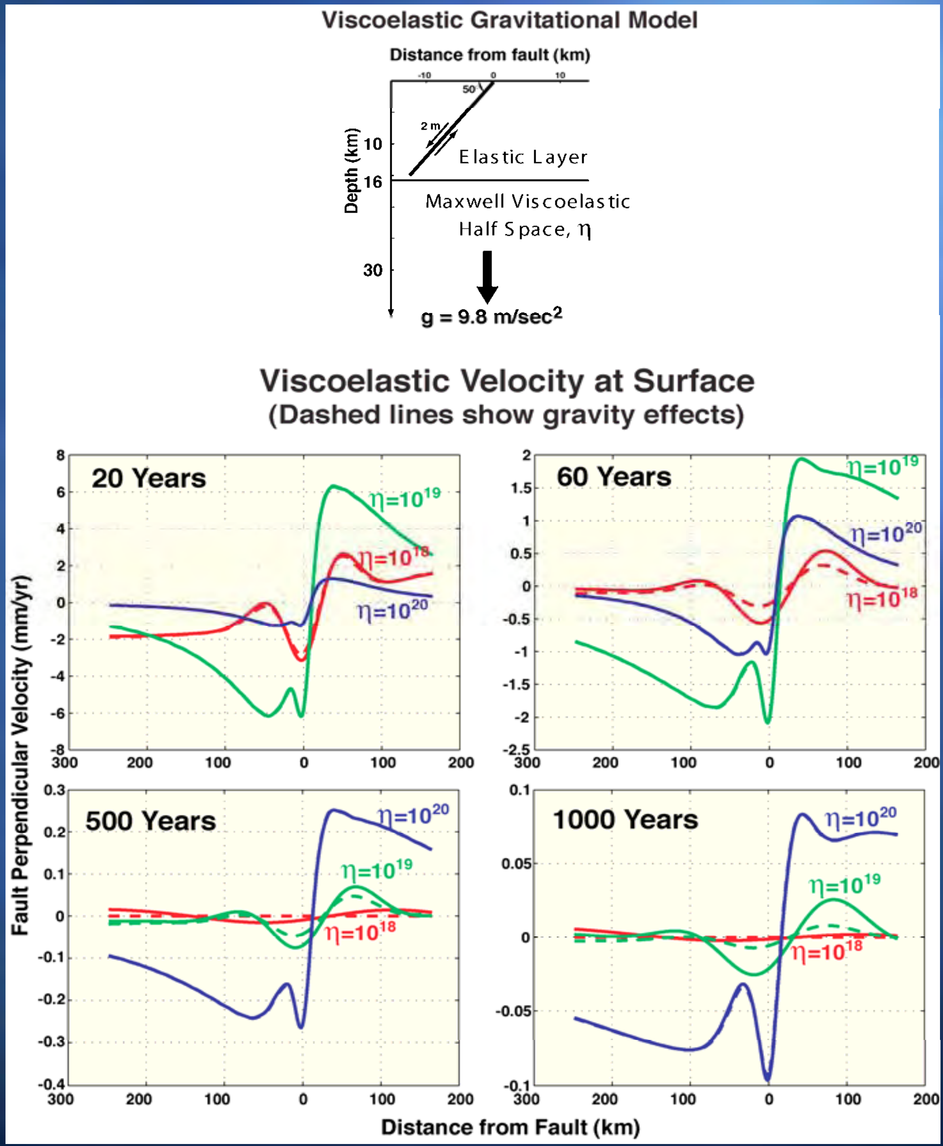
(Chang and Smith, 2002)

Basin-Range fault rheology model





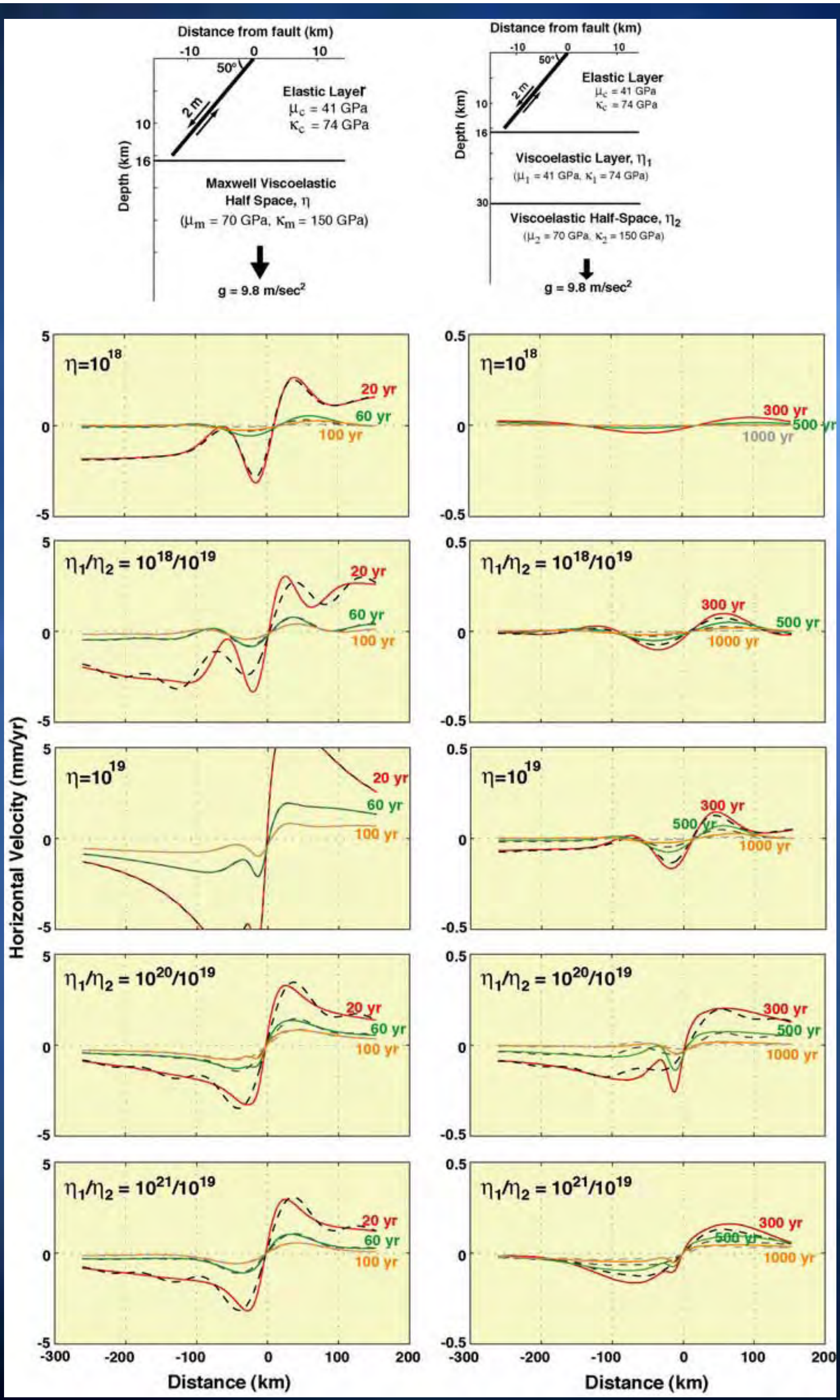
Faults never stop moving? because of viscoelastic flow of the lower crust



Wasatch fault measured motion

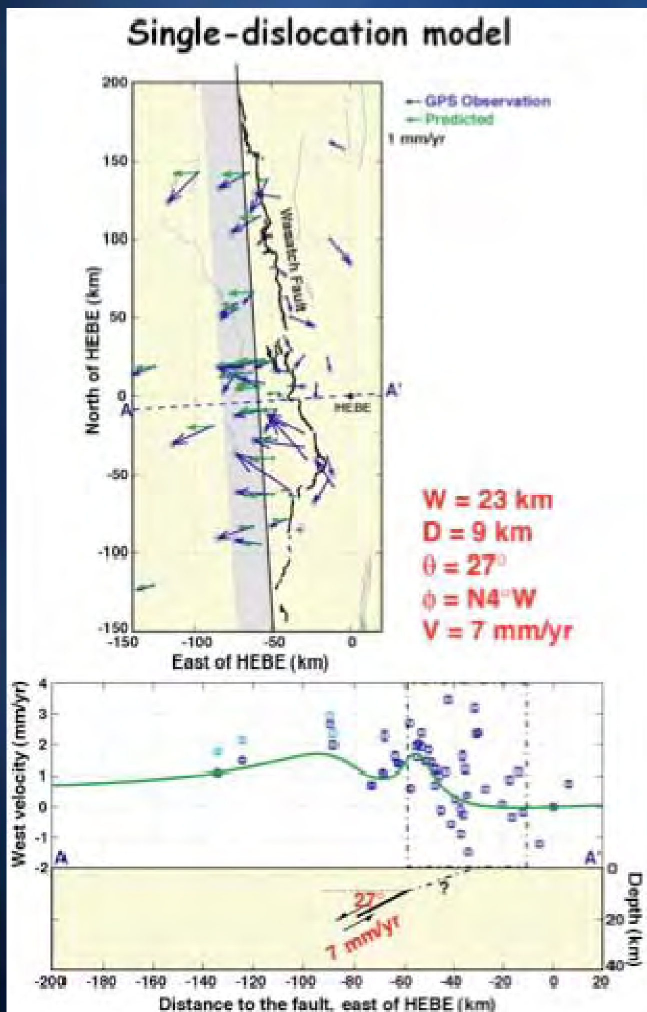
Best solution is for | = 10^{19} Pa-sec.

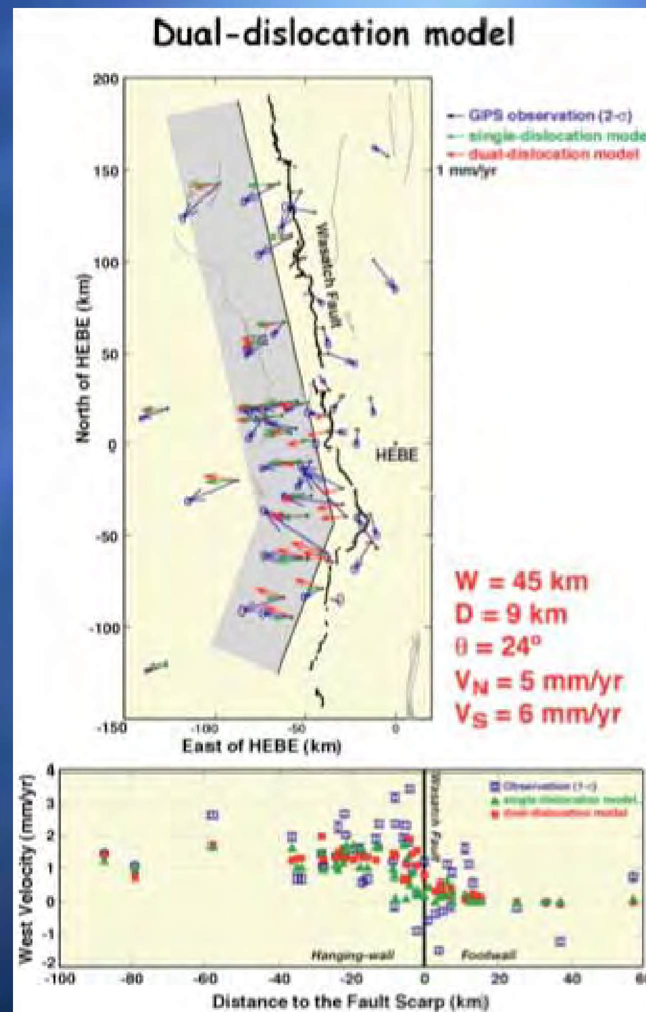
Time-dependent motion following a normal-faulting earthquake: interseismic loading



Distance from fault (km)
-10
0
10
50°
2 m
Elastic Layer
μ_c = 41 GPa
κ_c = 74 GPa
Depth (km)
10
16
Maxwell Viscoelastic
Half Space, η
(μ_m = 70 GPa, κ_m = 150 GPa)
g = 9.8 m/sec²
Distance from fault (km)
Elastic Layer
μ_c = 41 GPa
κ_c = 74 GPa
30
Viscoelastic Layer, η_1
(μ_1 = 41 GPa, κ_1 = 74 GPa)
Viscoelastic Half-Space, η_2
(μ_2 = 70 GPa, κ_2 = 150 GPa)
g = 9.8 m/sec²
Horizontal Velocity (mm/yr)
$\eta=10^{18}$
20 yr
60 yr
100 yr
$\eta_1/\eta_2 = 10^{18}/10^{19}$
$\eta=10^{19}$
$\eta_1/\eta_2 = 10^{20}/10^{19}$
$\eta_1/\eta_2 = 10^{21}/10^{19}$
300 yr
500 yr
1000 yr
Distance (km)
Distance (km)

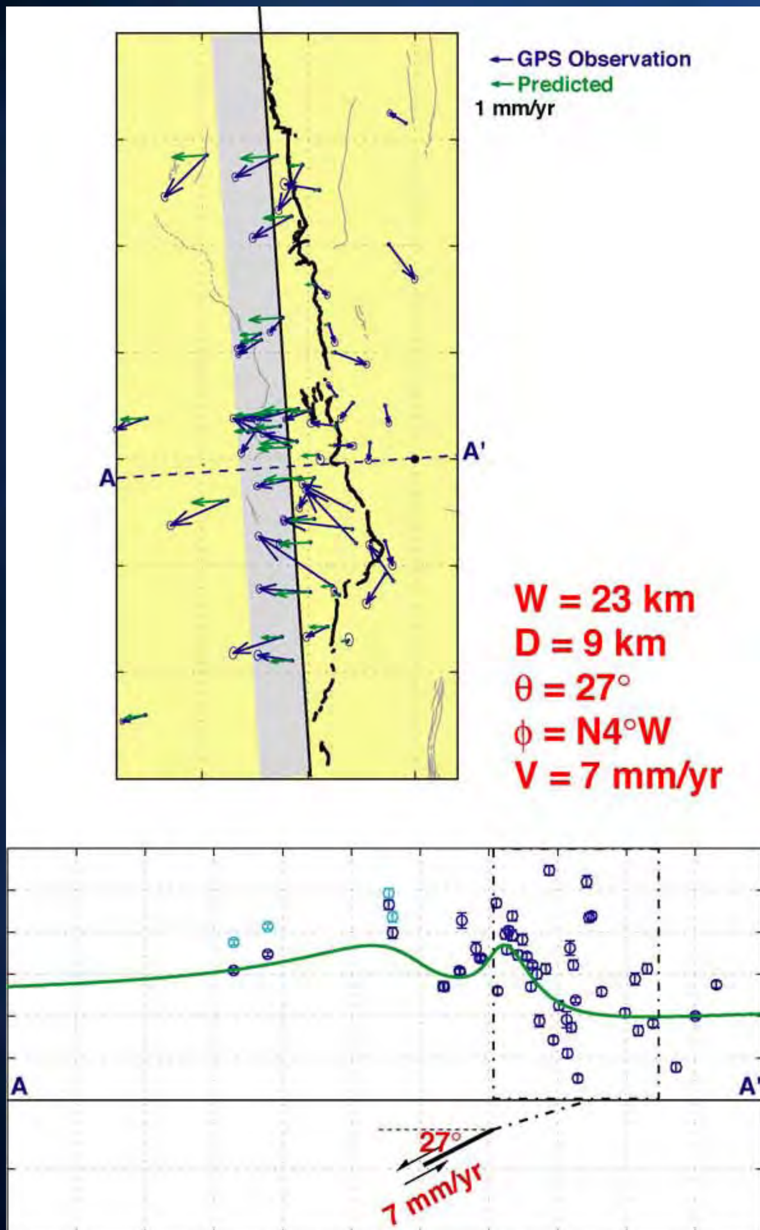
Models of Contemporary Wasatch fault deformation -- *loading of a ductile layer that in turns loads the seismogenic layer*

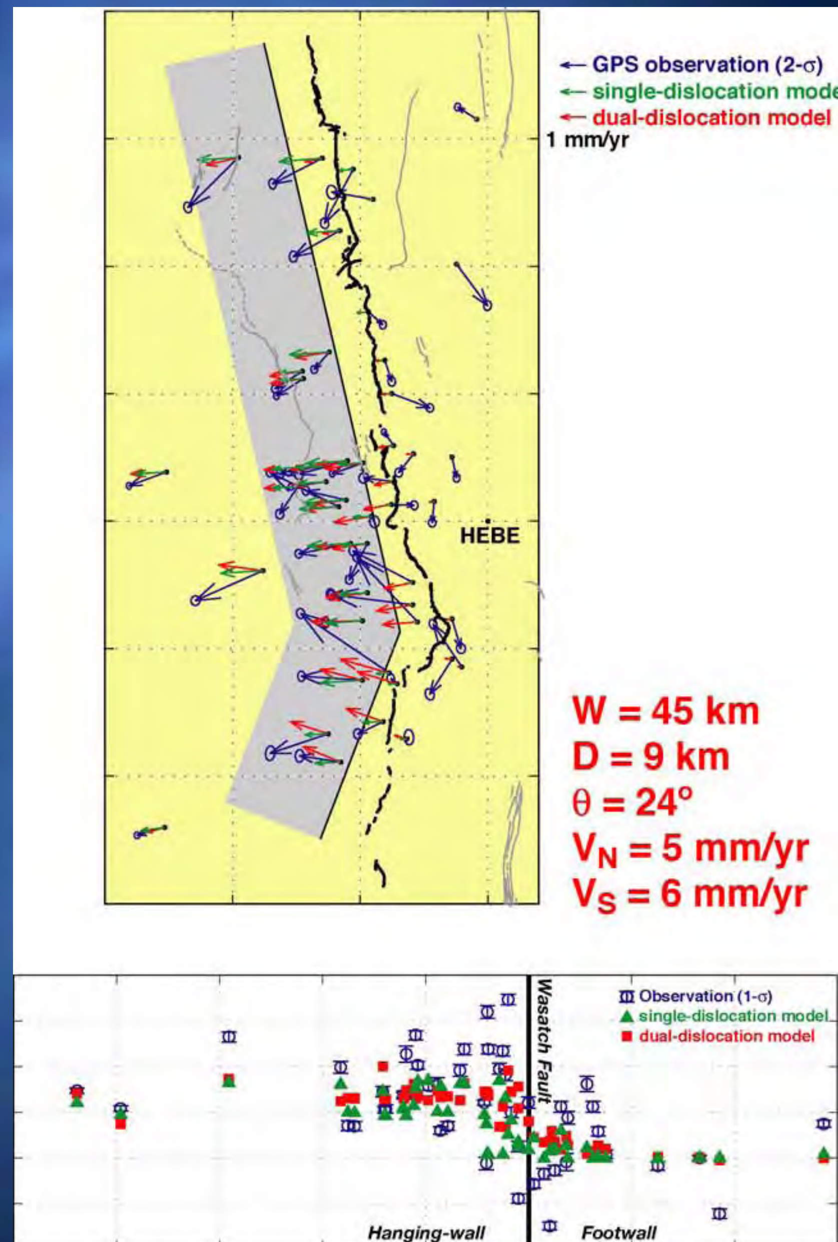




(after the methodlogy of Chang and Smith, 2002)

Inverting GPS Velocity for Inter-seismic Loading of the Wasatch Fault

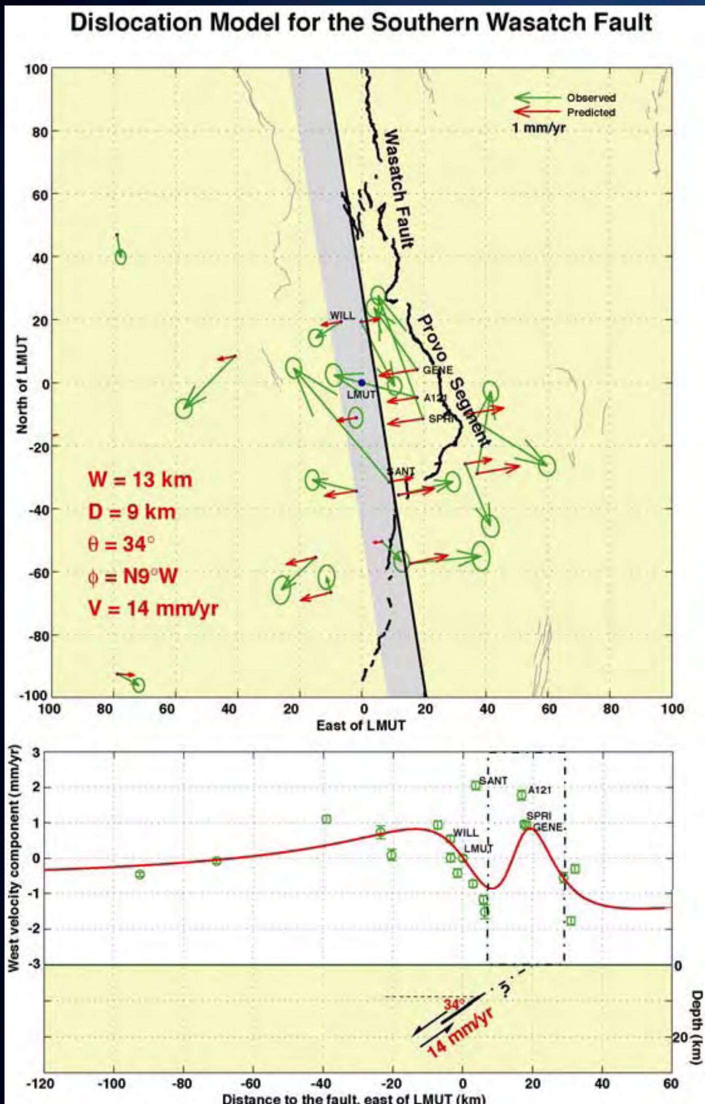


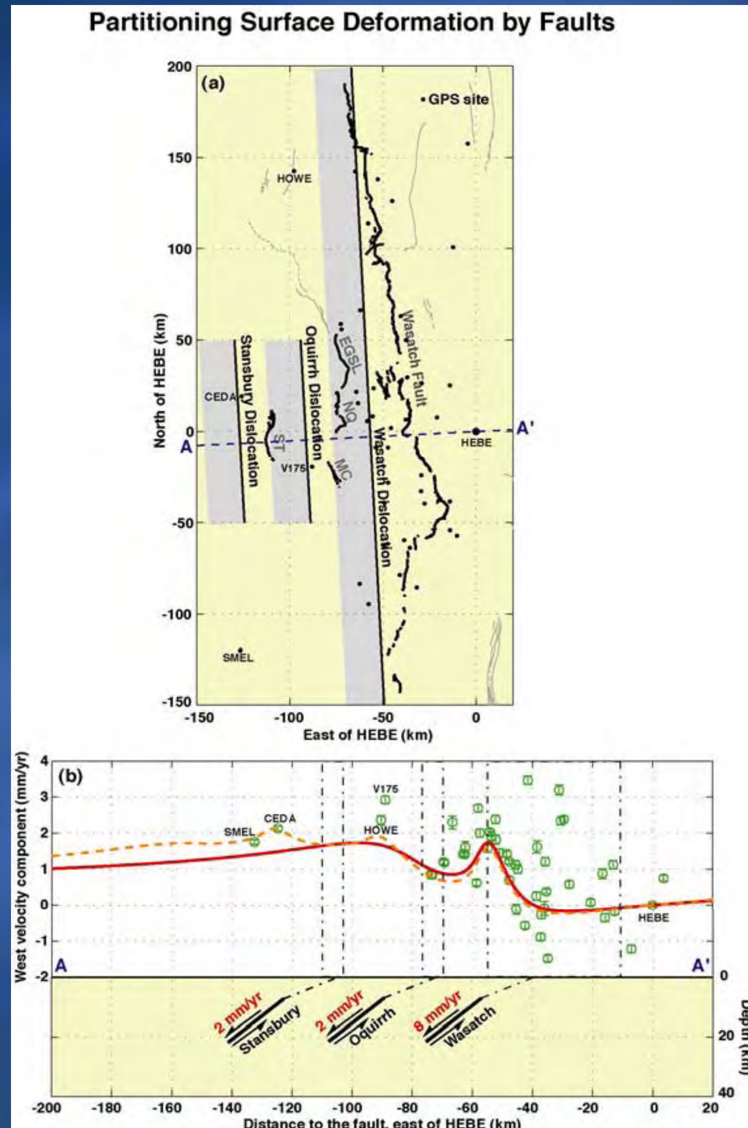


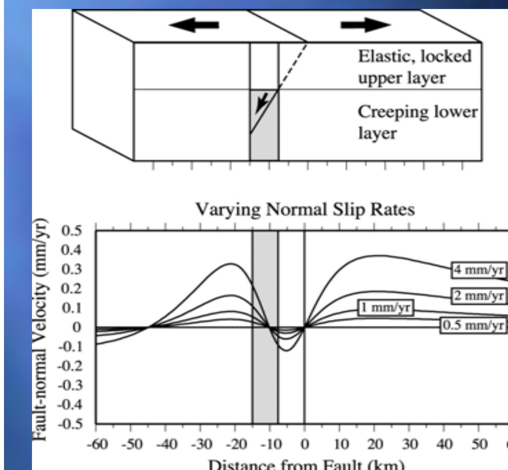
(Chang and Smith, 2002)

Chang et al. [2006, in preparation]

Fault Loading Models of Wasatch Fault GPS Motions

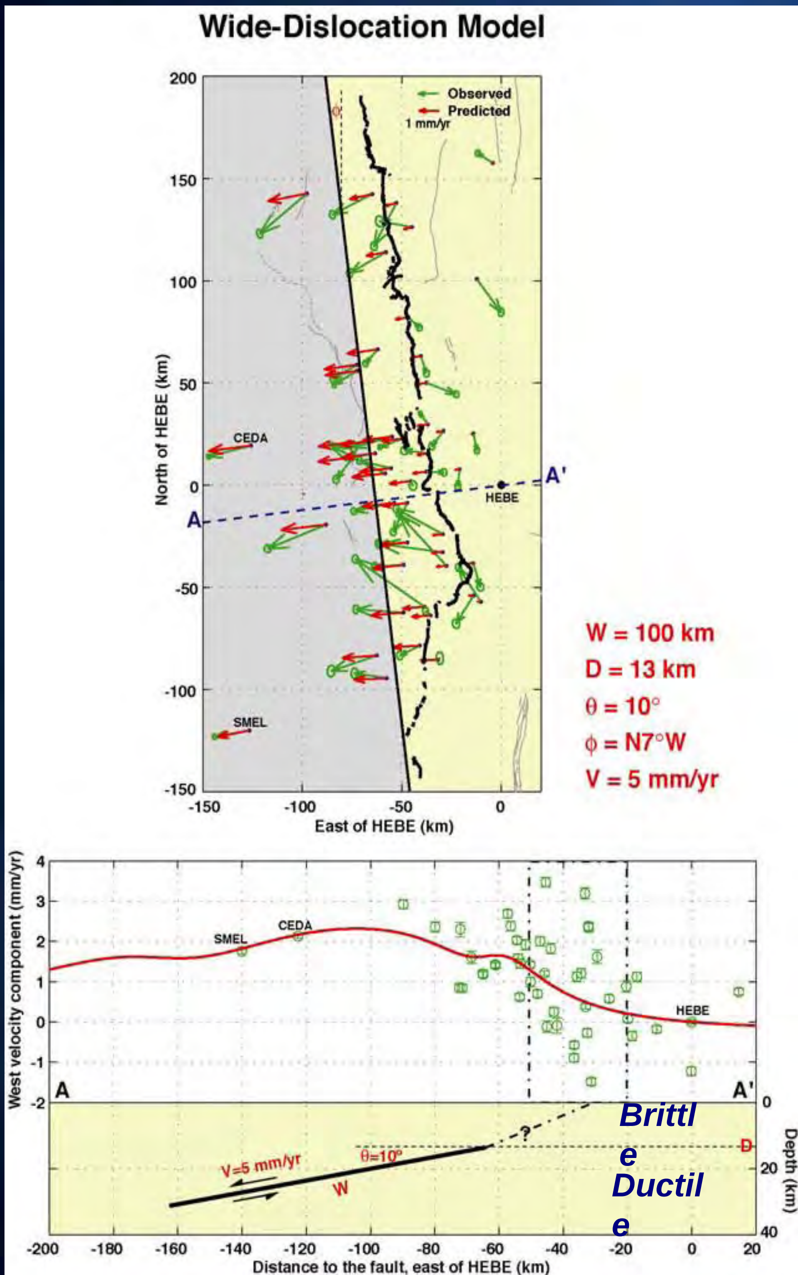


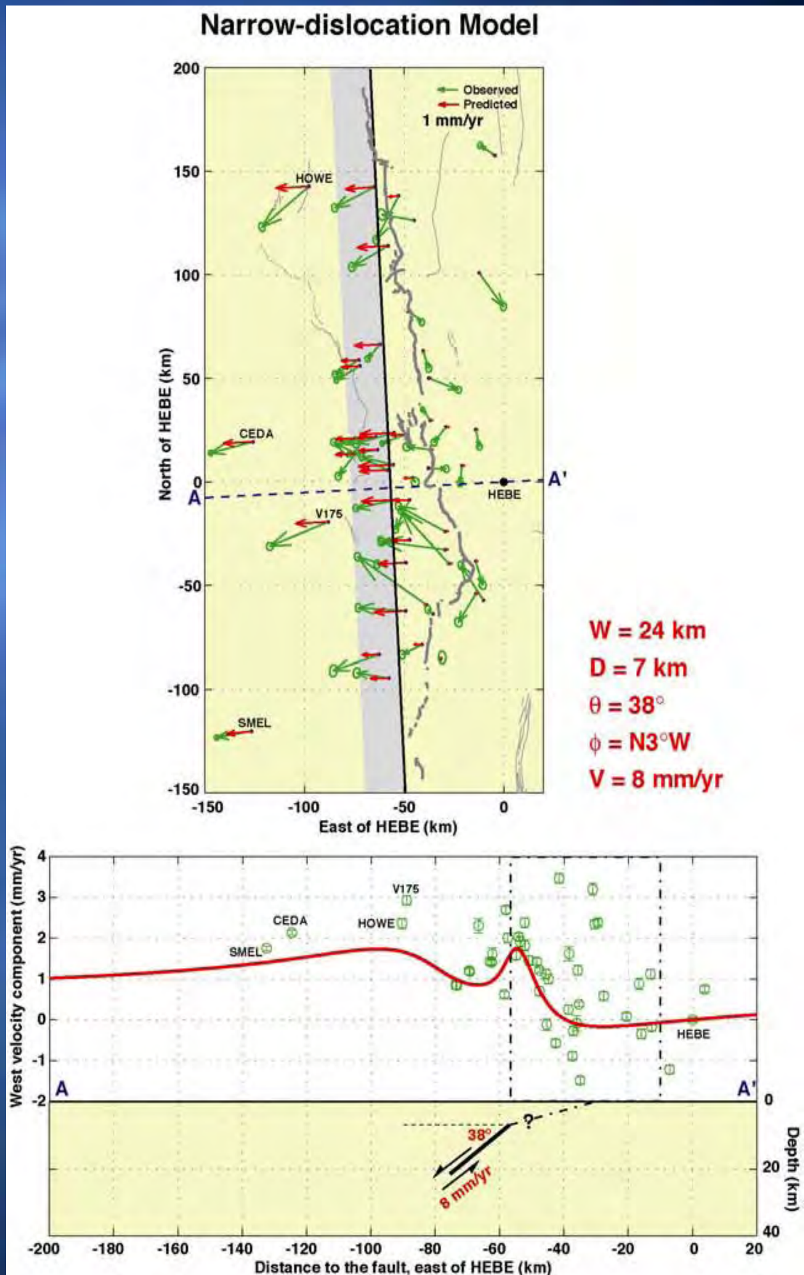




Fault loading models

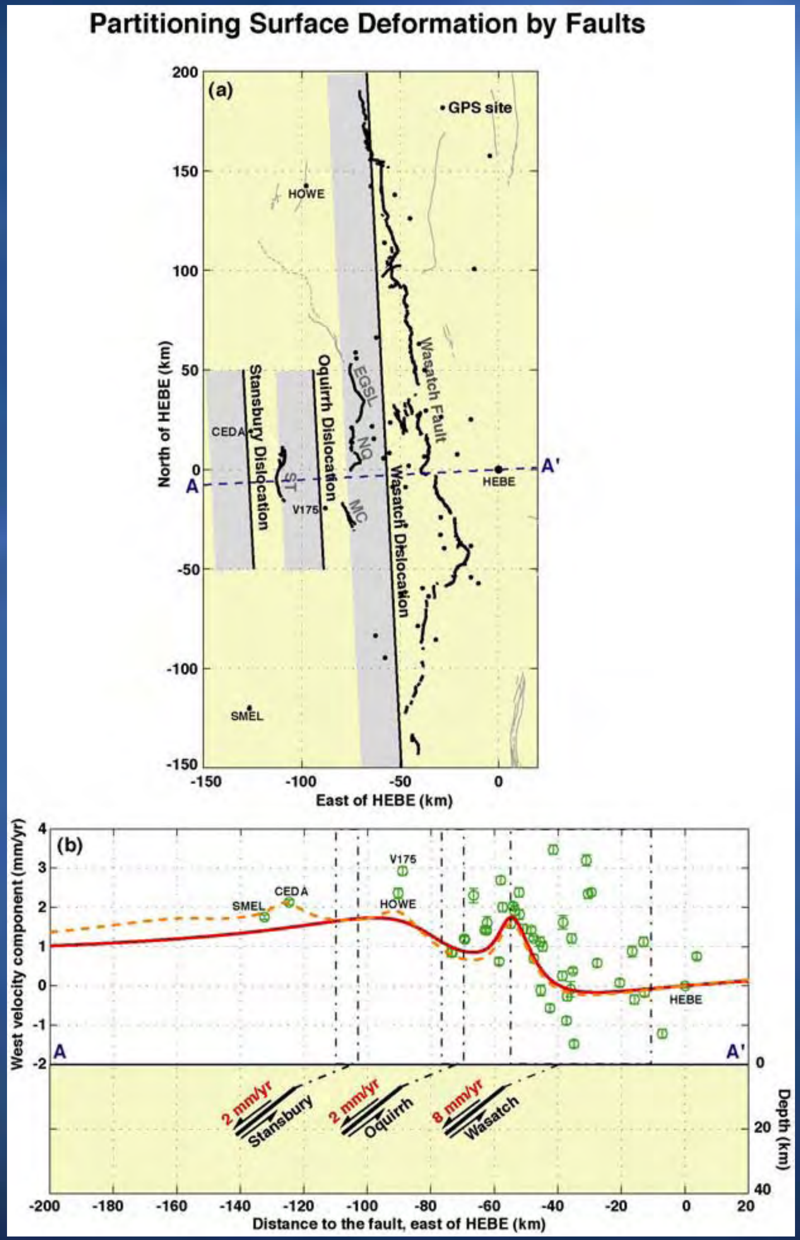
- Locked brittle layer
- Creeping ductile layer, loading the overlying brittle layer
- High rates on low angle creeping structure convert to lower rates on a vertical fault at surface.





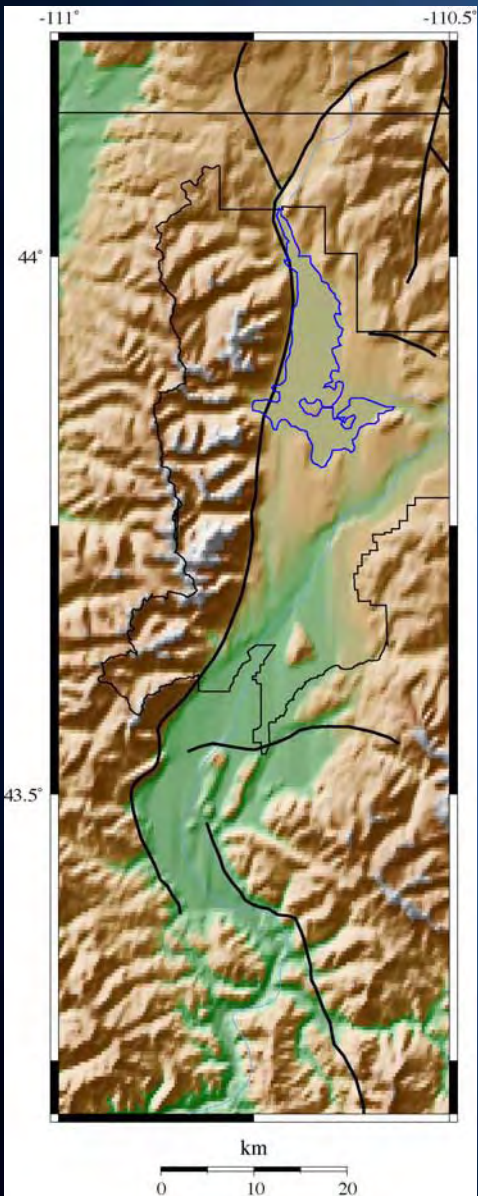
(after the methodlogy of Chang and Smith, 2002)

Distributed fault models



(after the methodlogy of Chang and Smith, 2002)

Building mountains with normal faulting earthquakes (elastic) and post seismic deformation (visco-elastic)

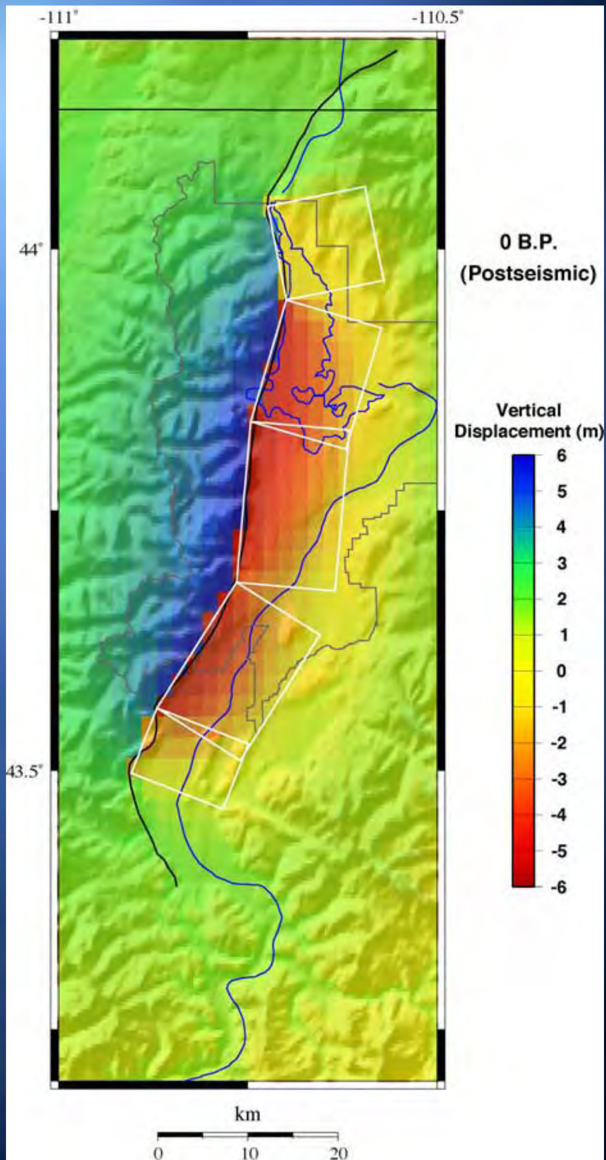


Scenario model of *co-seismic* (*few seconds of violent ground shaking*) and *post-seismic* ground motion (*hundreds of years of slow motion*) from the Teton fault, 14,000 years ago to present.

Consists of seven M7+ earthquakes producing 12 m of total offsets.

Note in the following sequence the rise of the mountains and drop of the valley *during* (co-seismic) and *between* earthquakes (*the interseismic phase*).

Total uplift and subsidence

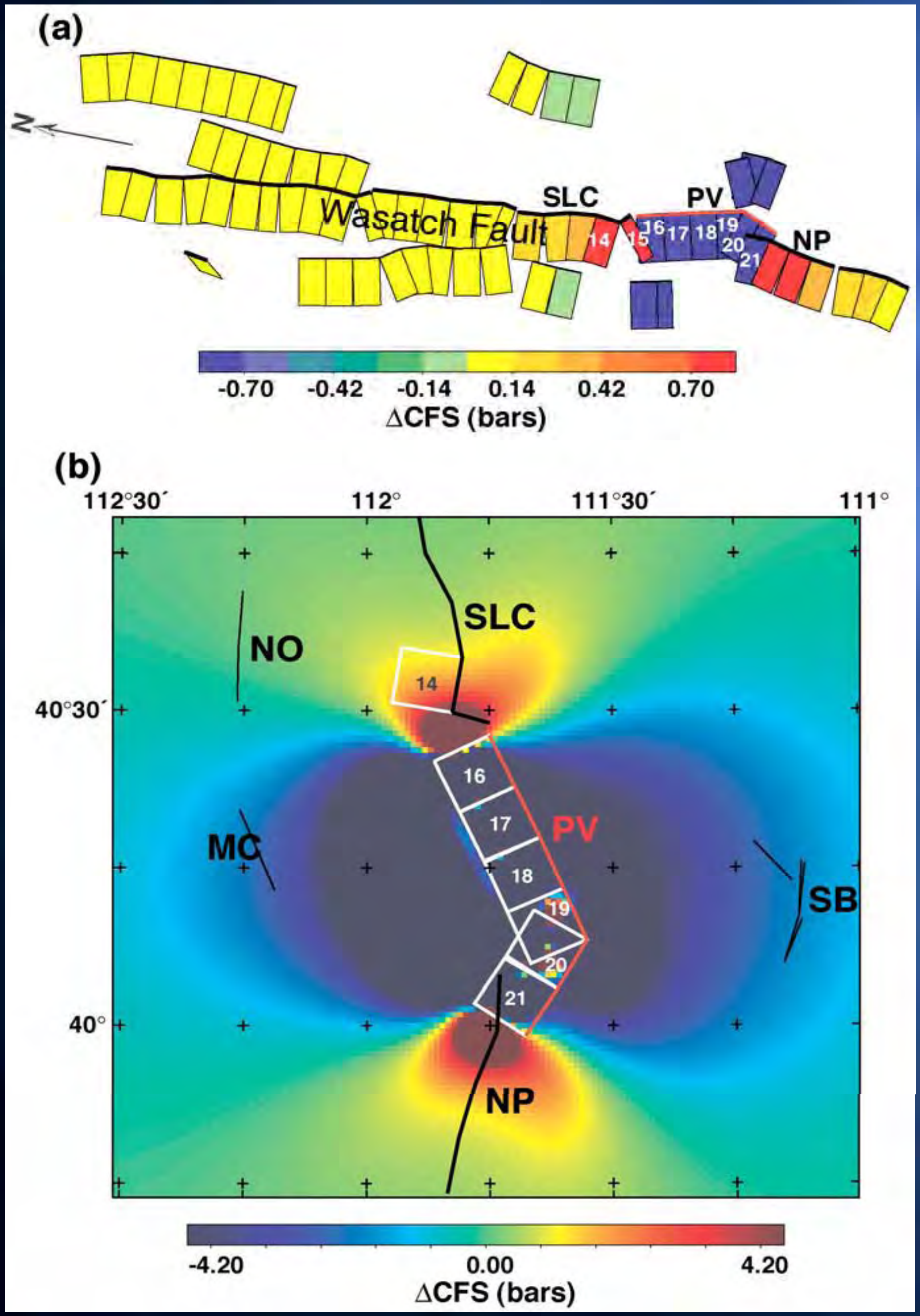


Modeled fault patches outlined

Growing mountains and dropping valleys

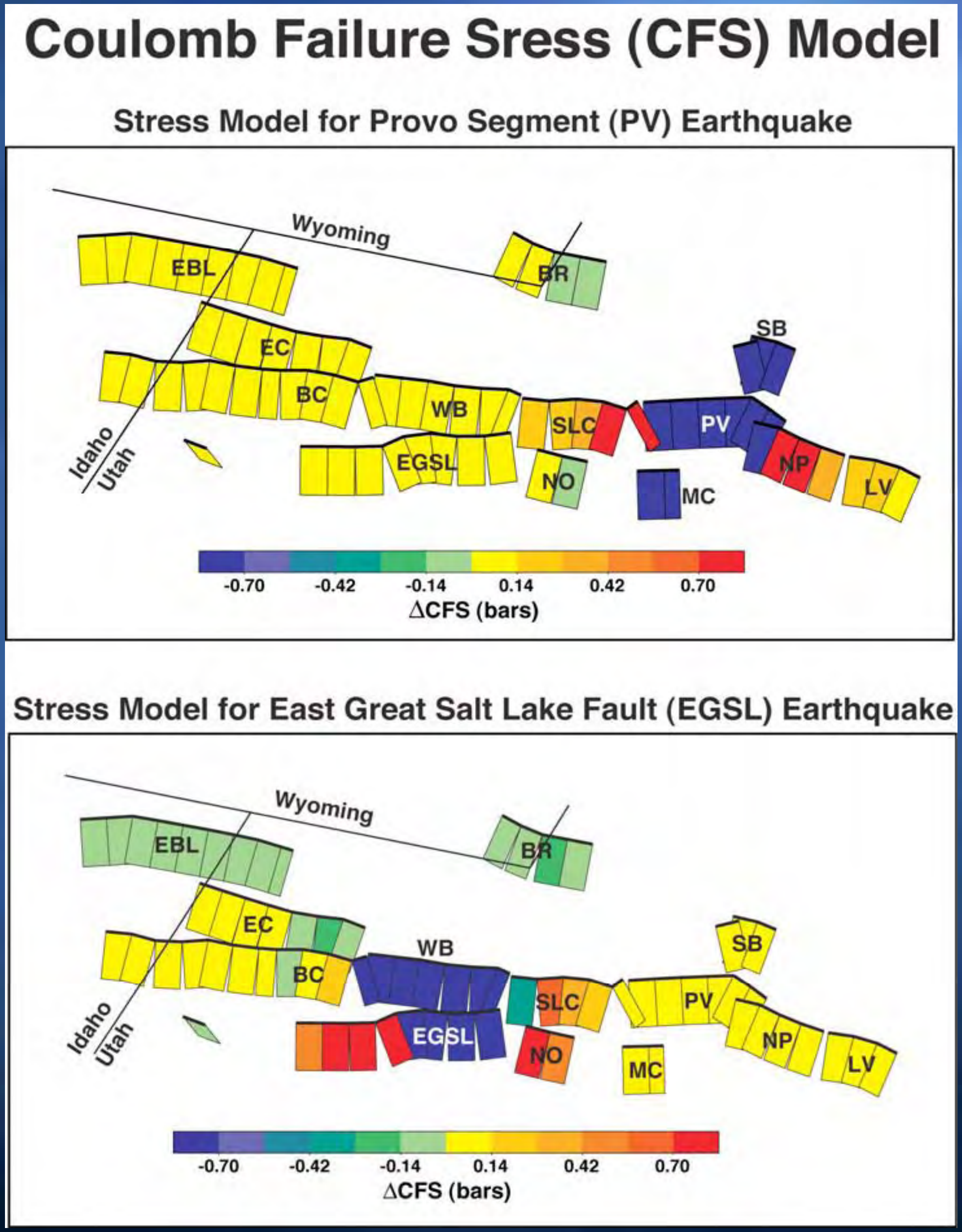
QuickTime™ and a
H.264 decompressor
are needed to see this picture.

Stress Modeling of Wasatch Fault Scenario Earthquake



DCFS induced by a scenario earthquake on the Provo segment (PV) of the Wasatch fault. The event ruptures 60 km with 2 m of slip (Ms 7.1 and Mw 7.1). DCFS is shown (a) at the center of each fault patch, and (b) as a map-view of 10-km depth. Results show that large earthquakes on the Provo segment can increase the failure stress of the Salt Lake City segment (SLC, ~1.2 bars on fault patch 14) and in turn trigger SLC to rupture.

Time dependent stress contagion on Wasatch fault



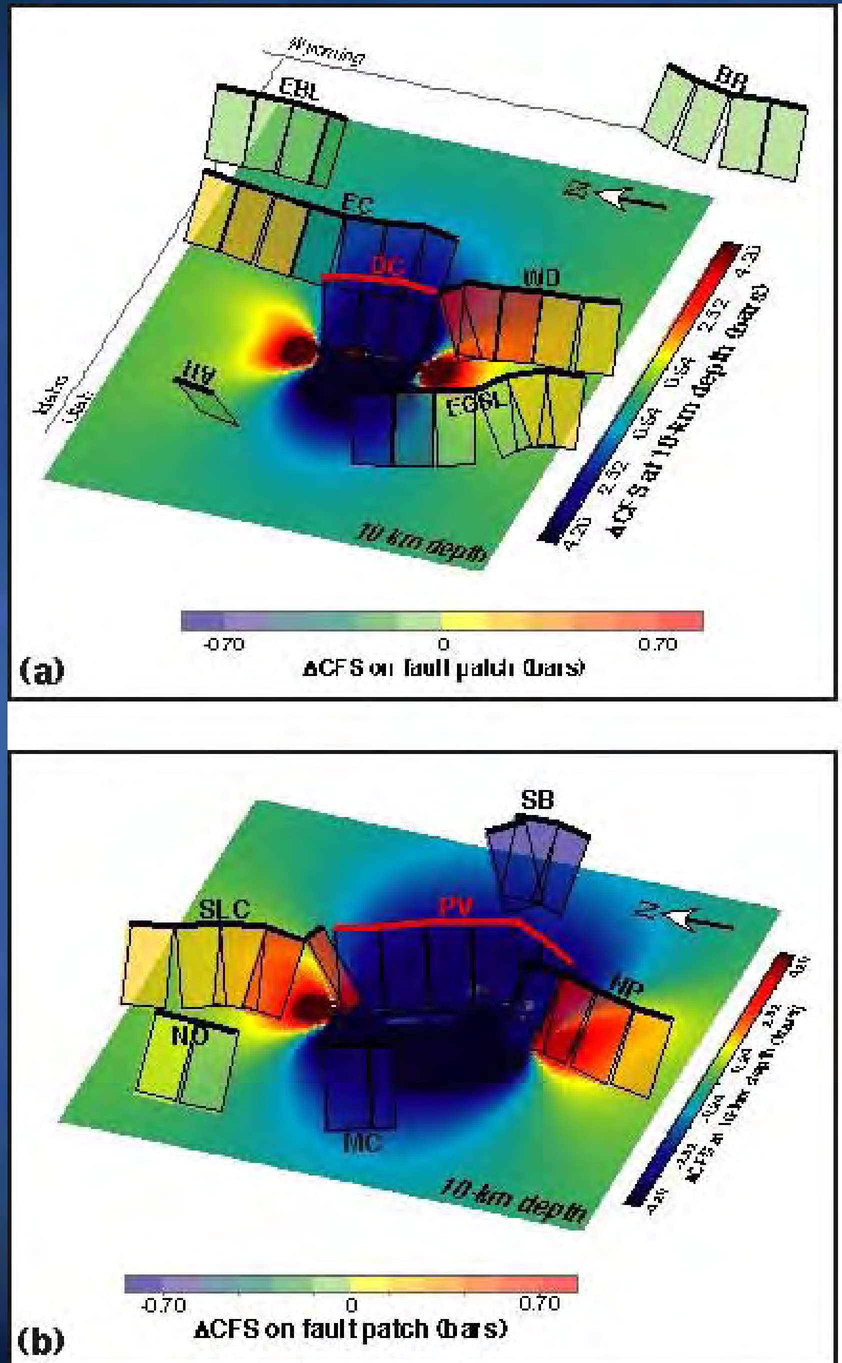
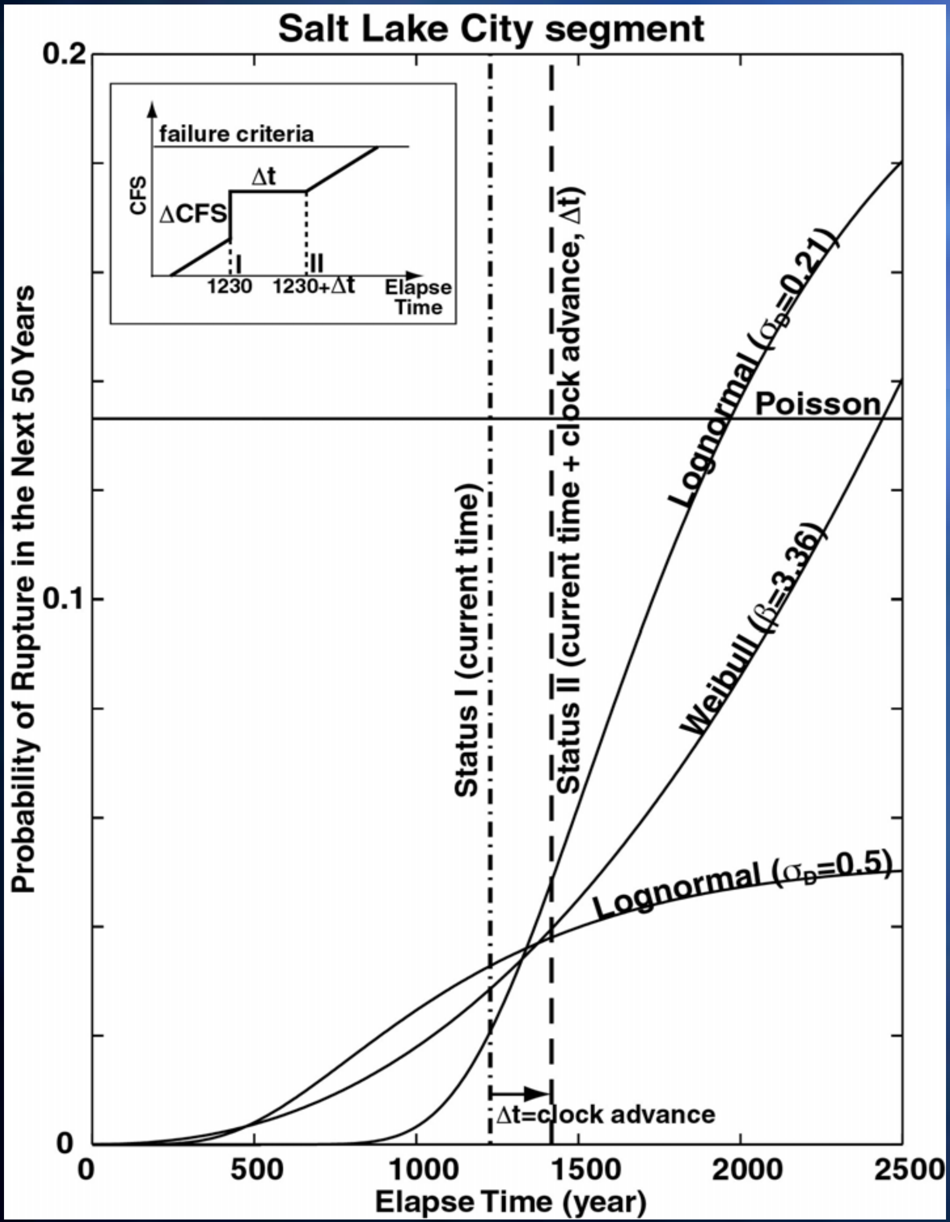

Wyoming
EBL
BB
EC
DC
WD
N
HY
EGBL
Idaho
Utah
ΔCFS at 10-km depth (bars)
10 km depth
-0.70
0
0.70
ΔCFS on fault patch (bars)
(a)
SB
SLC
PV
N
HP
NO
MC
10-km depth
-0.70
0
0.70
ΔCFS on fault patch (bars)
(b)

Figure 3

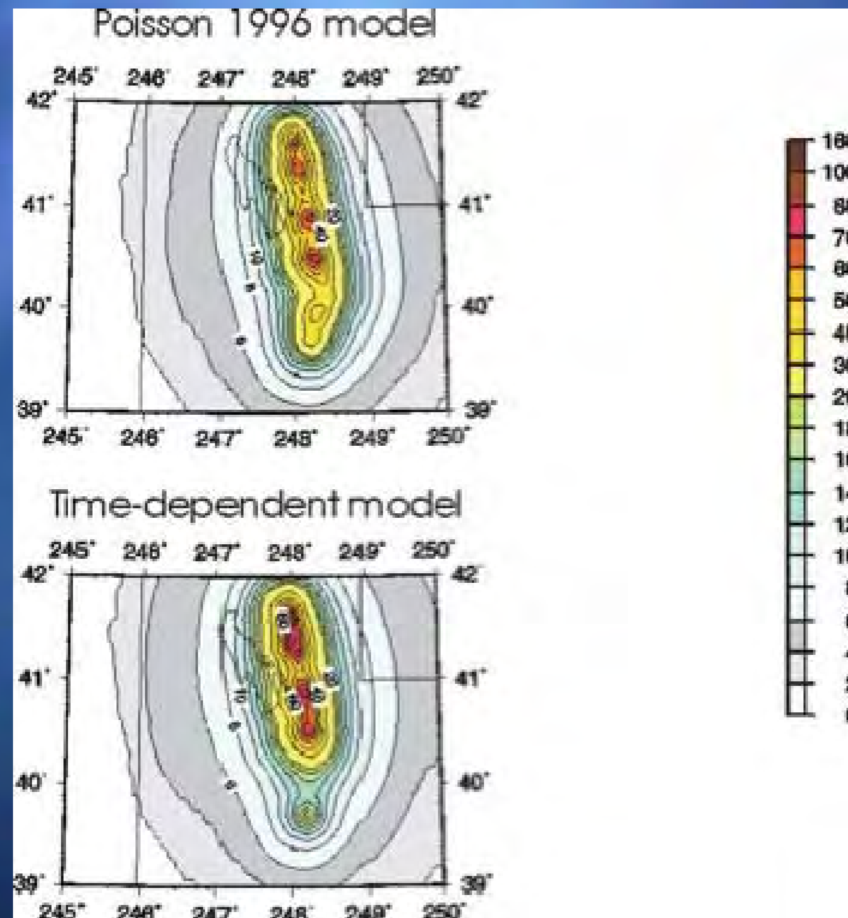
Time-Dependent Modeling of Wasatch Fault Rupture (advancement of rupture because of stress contagion)



Time-dependent (elastic) probabilistic earthquake risk, conditional on the elapsed times and the number of events of relevant fault segments (Chang and Smith, 2002).

Example of Wasatch Fault Time-Dependent Probabilistic Seismic Hazard Assessment from Mark Petersen (USGS)

	Med. Rec.	Elapsed time	50-year prob
Brigham City:	1230	2175	8%
Weber:	1674	1066	3%
Salt Lake:	1367	1280	6%
Provo:	2413	668	0.1%
Nephi:	2706	1198	0.8%



Incorporating seismic, fault and geodetic data into PSHA

Source type	Fault name	Recurrence Model
Type A	BC, WB, SLC, PV, NP	(1) From paleoearthquake recurrence rate: Lognormal distribution ($\sigma_D = 0.5$)* (2) Including geodetic earthquake moment rate:
Type B	LV, EC, HV, NO, SB, MC, PM, FI, AI, EBL, BR, RC.	(1) From geologic earthquake moment rate:

Type A, (2):

$$\dot{M}^{A}_{seismic} = \frac{\dot{M}_f + \mu L W_e V_g}{2}$$

$$N(6.6, m_u) = \frac{\dot{M}^{A}_{seismic}}{C_d(6.6, m_u)}$$

Type B, (1):

$$\dot{M}^{B}_{seismic} = \dot{M}_f$$

$$N(6.6, m_u) = \frac{\dot{M}^{B}_{seismic}}{C_d(6.6, m_u)}$$

$$N(3.0) = 3.2 \times 10^{-0.72(m-3.0)} - 1.2 \times 10^{-3}$$

$$N(6.6, 7.2) = \frac{\sum_{\text{all faults}} \dot{M}_f}{C_d(6.6, 7.2)}$$

$$N(6.6, 7.2) = 0.0020$$

$$N(3.0, 6.5) = \frac{\dot{M}_g - \sum_{\text{faults in geodetic area}} \dot{M}_f}{C_d(3.0, 6.5)}$$

$$N(6.6, 7.2) = \frac{\sum \dot{M}^{A}_{seismic}}{C_d(6.6, 7.2)}$$

All types — Geologic earthquake moment rate of each fault:

$$\dot{M}_f = \mu L W_f V_f$$

$$\dot{M}_g = 2\mu L W_e H_e \dot{\varepsilon}$$

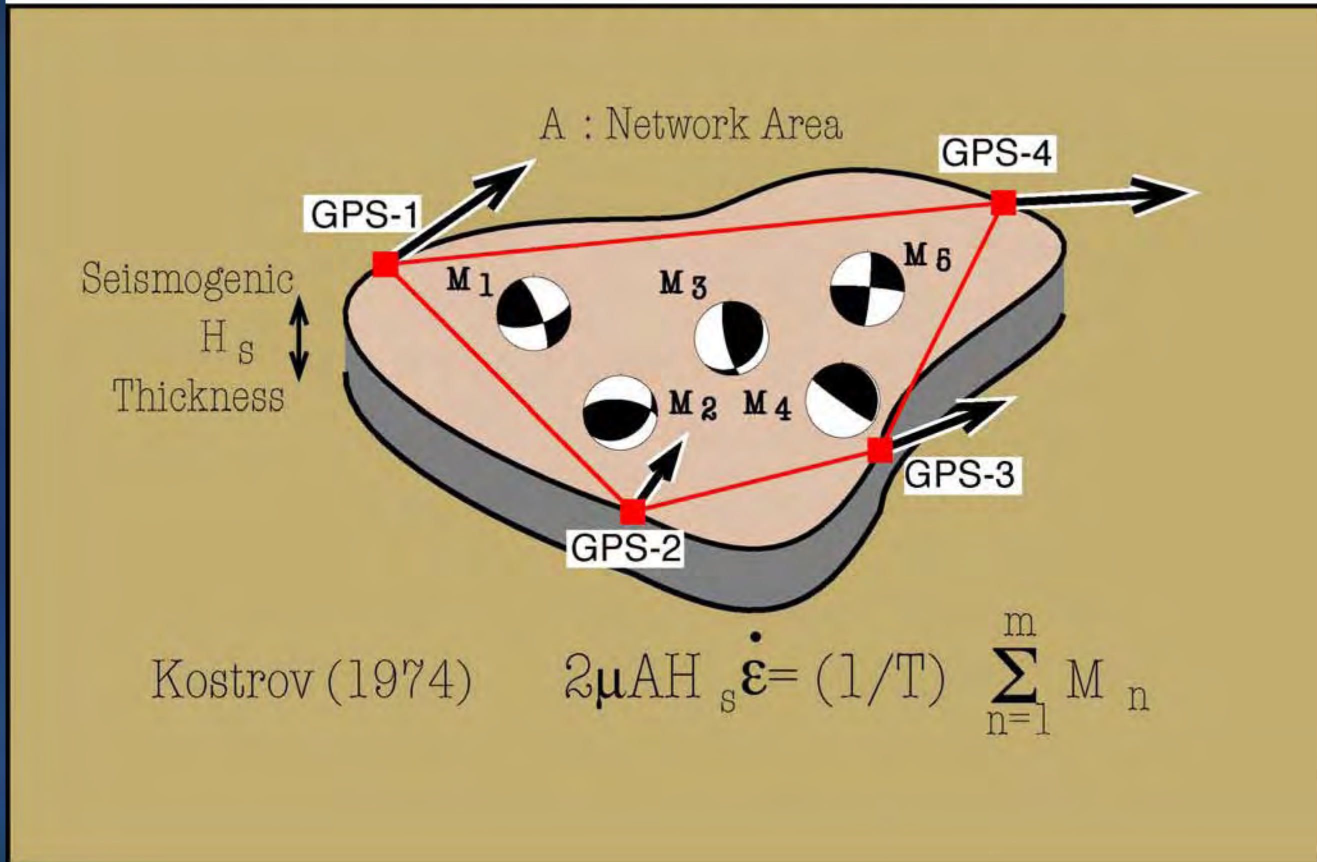
$$C_d(m_1, m_2) = \frac{\int_{m_1}^{m_2} 10^{a-bm} \cdot 10^{1.5m+9}\, dm}{\int_{m_1}^{m_2} 10^{a-bm}\, dm}$$

$$N(m) = 10^{a-bm}$$

$$N(m_1, m_2) = 10^{a}(10^{-bm_1} - 10^{-bm_2})$$

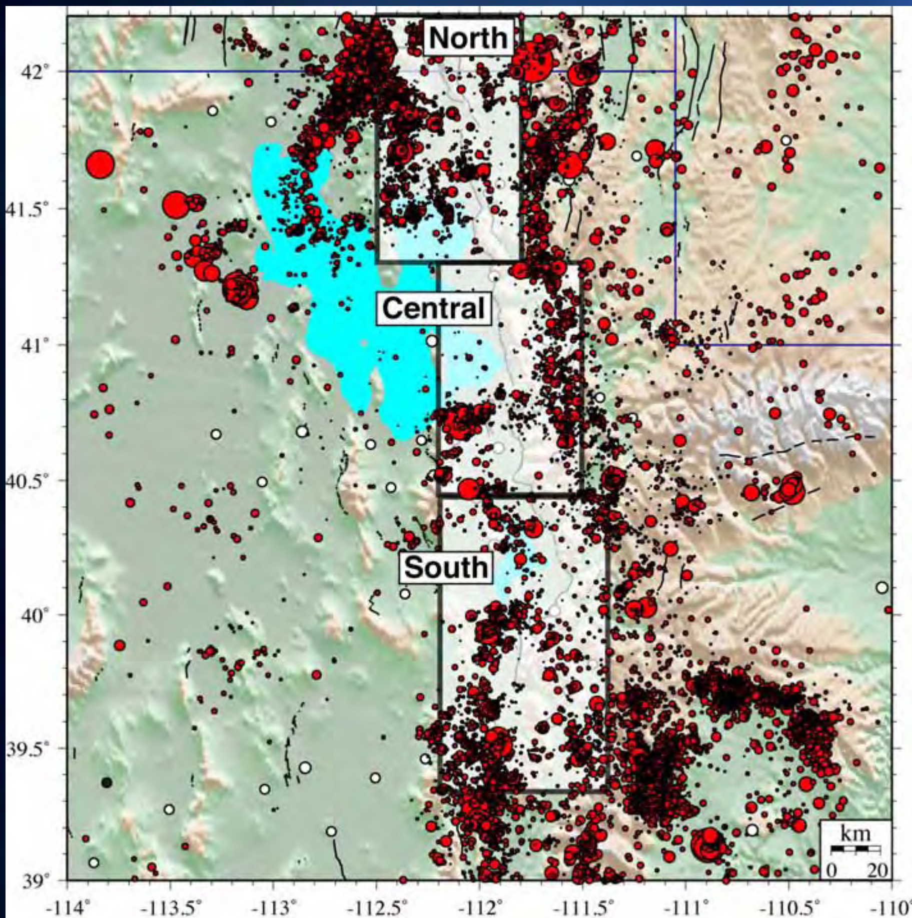
$$N(m) = 10^{a-bm} - N(m_u)$$

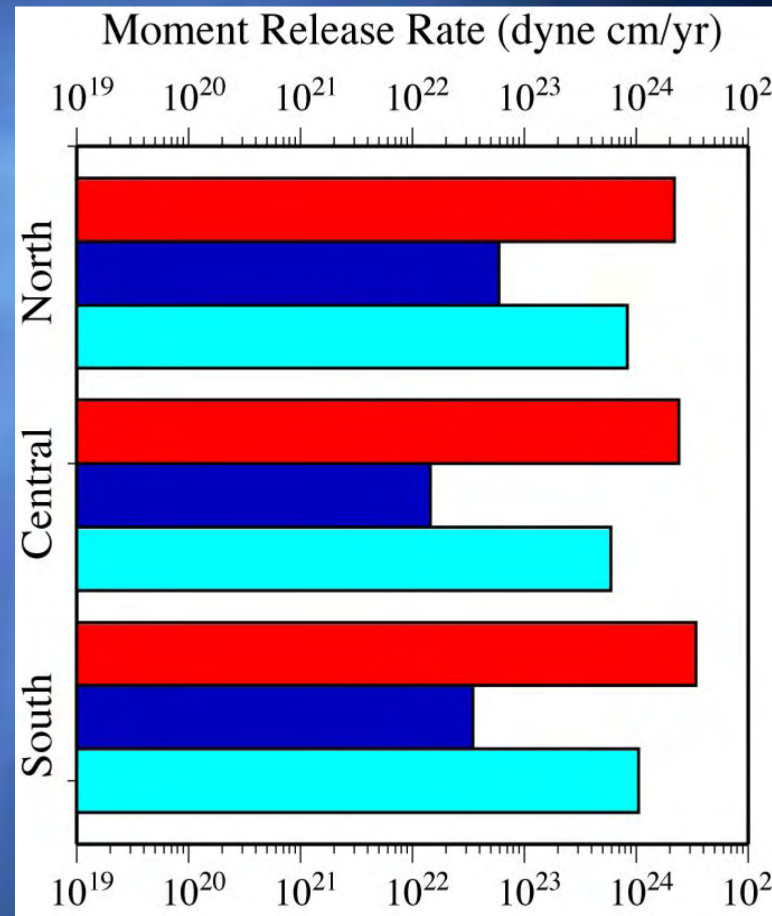
Geodetic Moment Rate from GPS



Strain rate from historic seismic moment rate ~ 1 to 4 nstrain/yr [*Eddington et al*., 1987]
GPS horizontal strain rate = 24 ± 6 nstrain/yr [*Chang et al*., 2006]

Comparitive Moment Release Rates





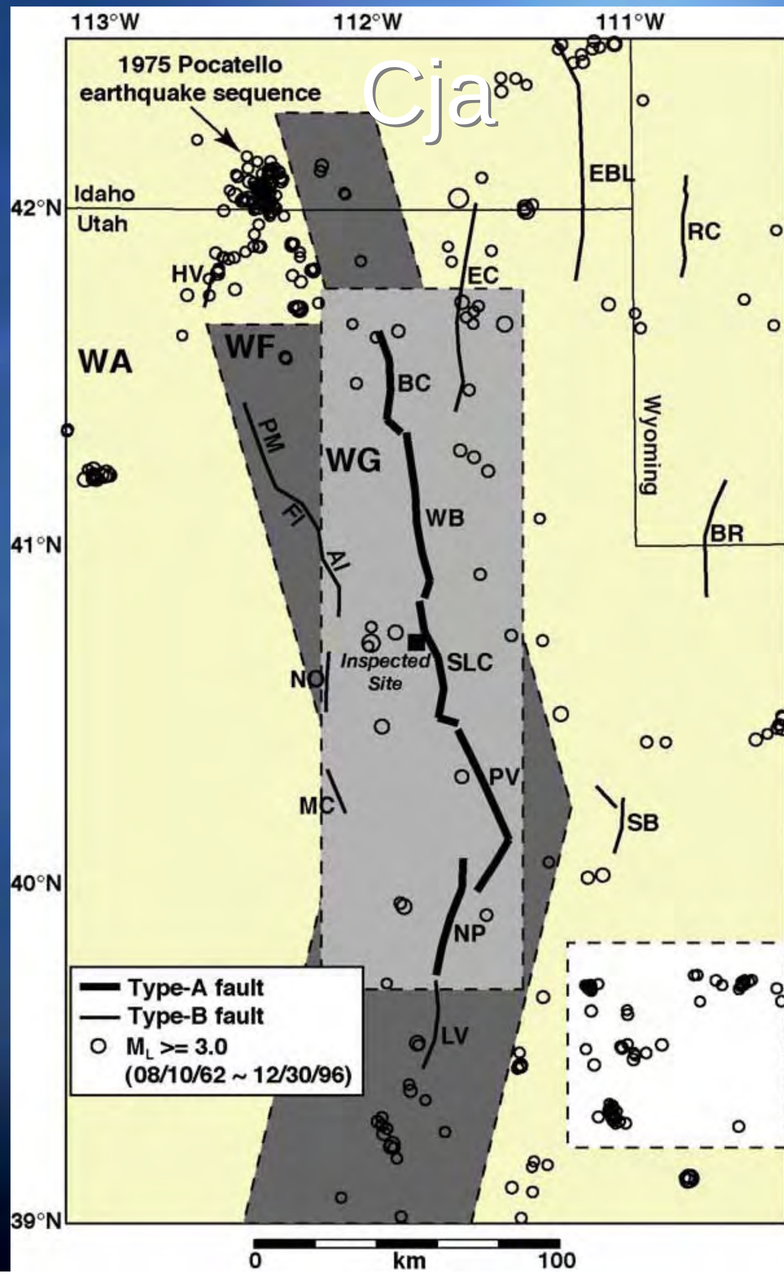
Section	Total (dyne cm/yr)	Seismic (dyne cm/yr)	Fault Slip (dyne cm/yr)
North	2.18×10^{24}	5.94×10^{22}	8.26×10^{23}
Central	2.39×10^{24}	1.44×10^{22}	5.91×10^{23}
South	3.42×10^{24}	3.45×10^{22}	1.04×10^{24}

Measure energy of deformation

- GPS: total moment release
- Historic earthquakes: earthquake recurrence rate
- Fault slip rates: fault slip rate from trenching

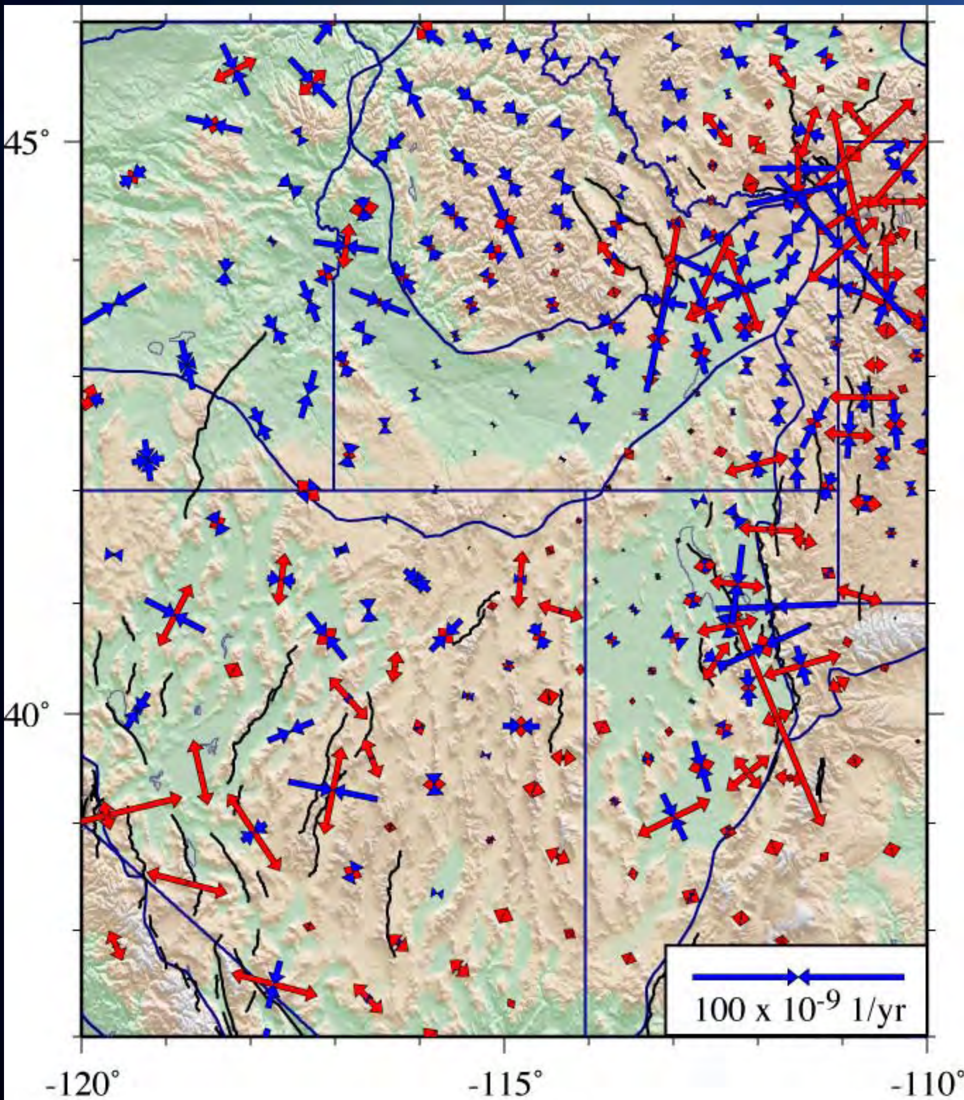
A Big Deficit!

in Chang and Smith, 2002

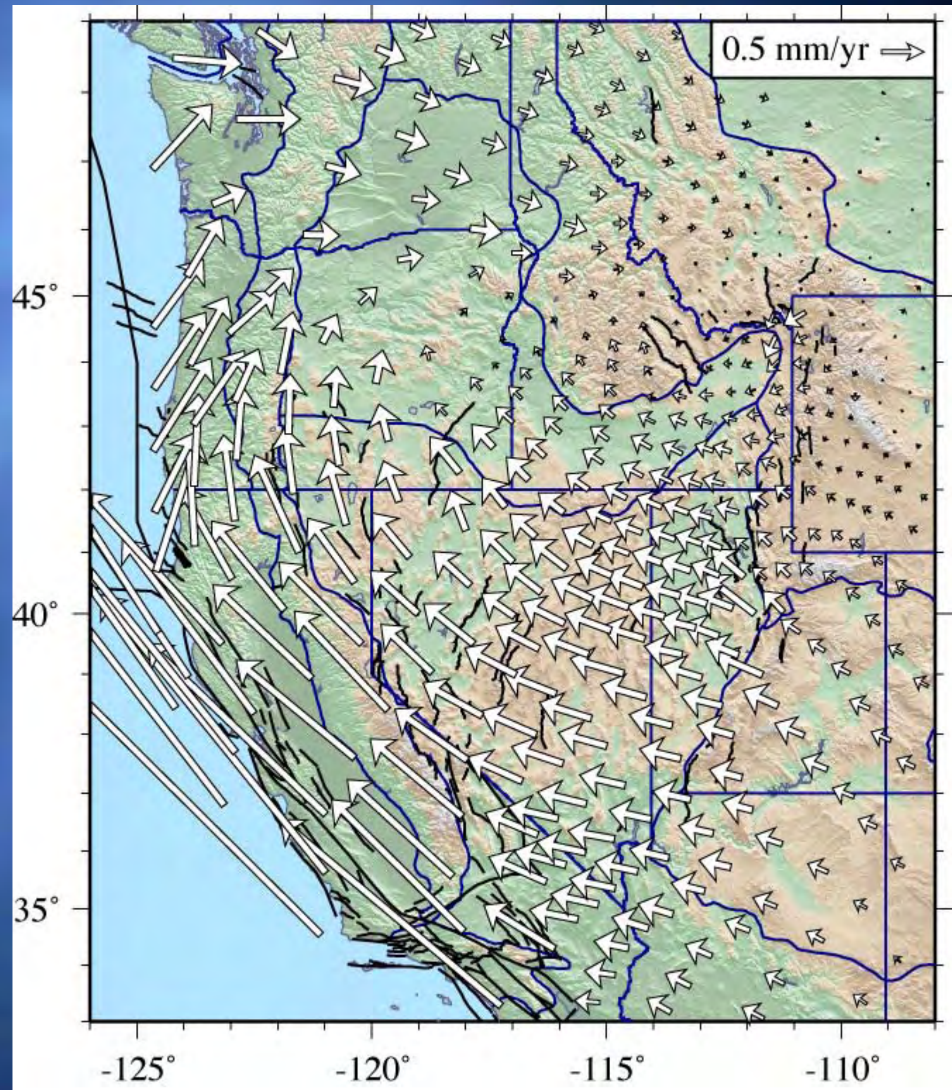


Kinematic Fields

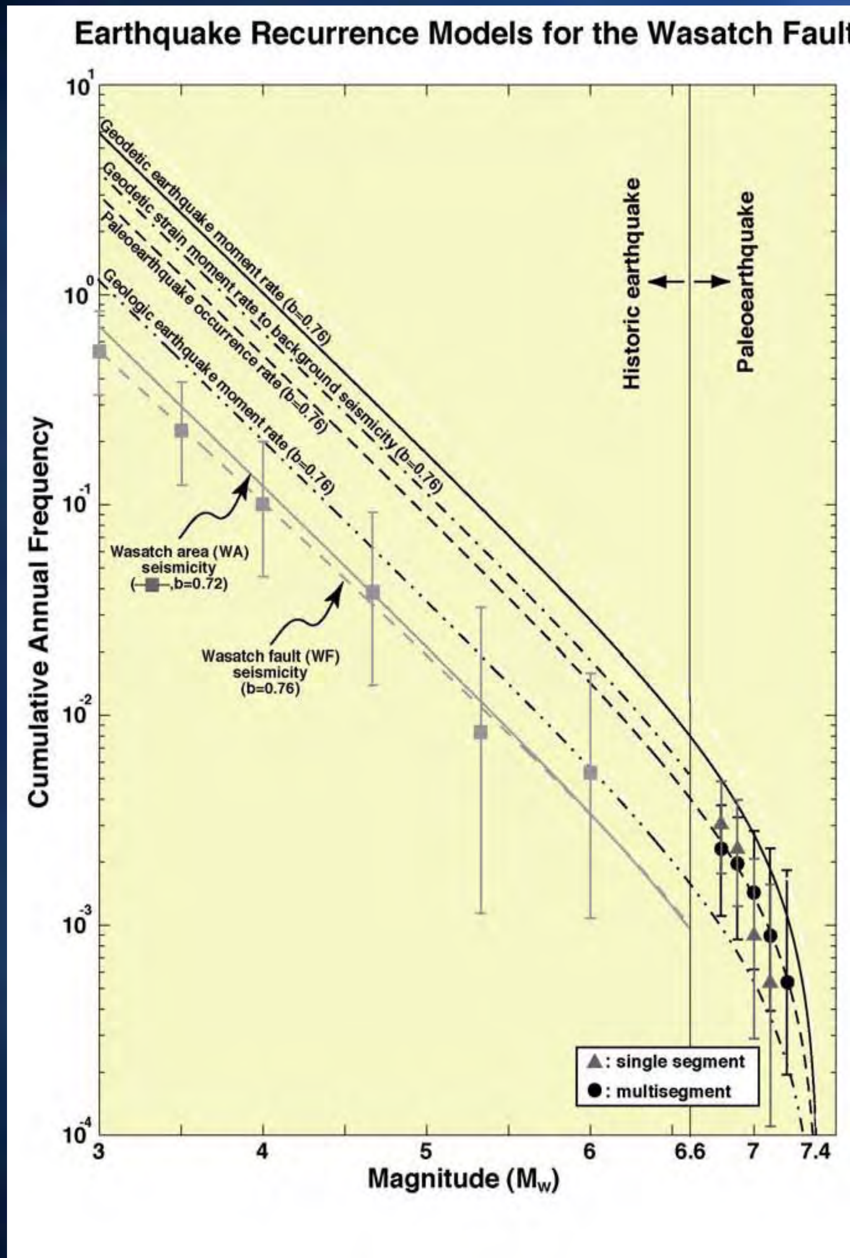
Strain Rate Field



Velocity Field



- Continuum model solves for strain rates and velocities on a grid
  - Obtain extension at Yellowstone Plateau and Basin-Range
  - Contraction+shear in Eastern Snake River Plain
  - Clockwise rotation of velocities



Geologic moment rate

$$\dot{M}_f = \mu L W_f V_f$$

Geodetic moment rate

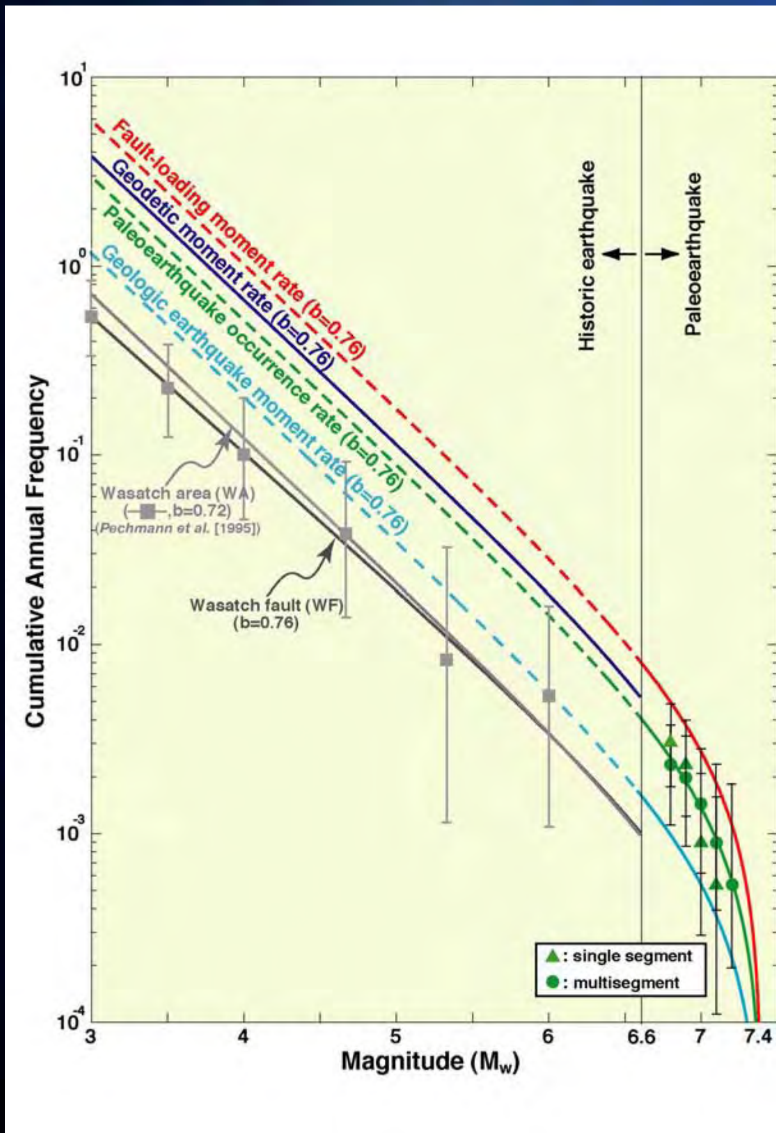
$$\dot{M}_g = 2\mu L W_e H_e \dot{\varepsilon}$$

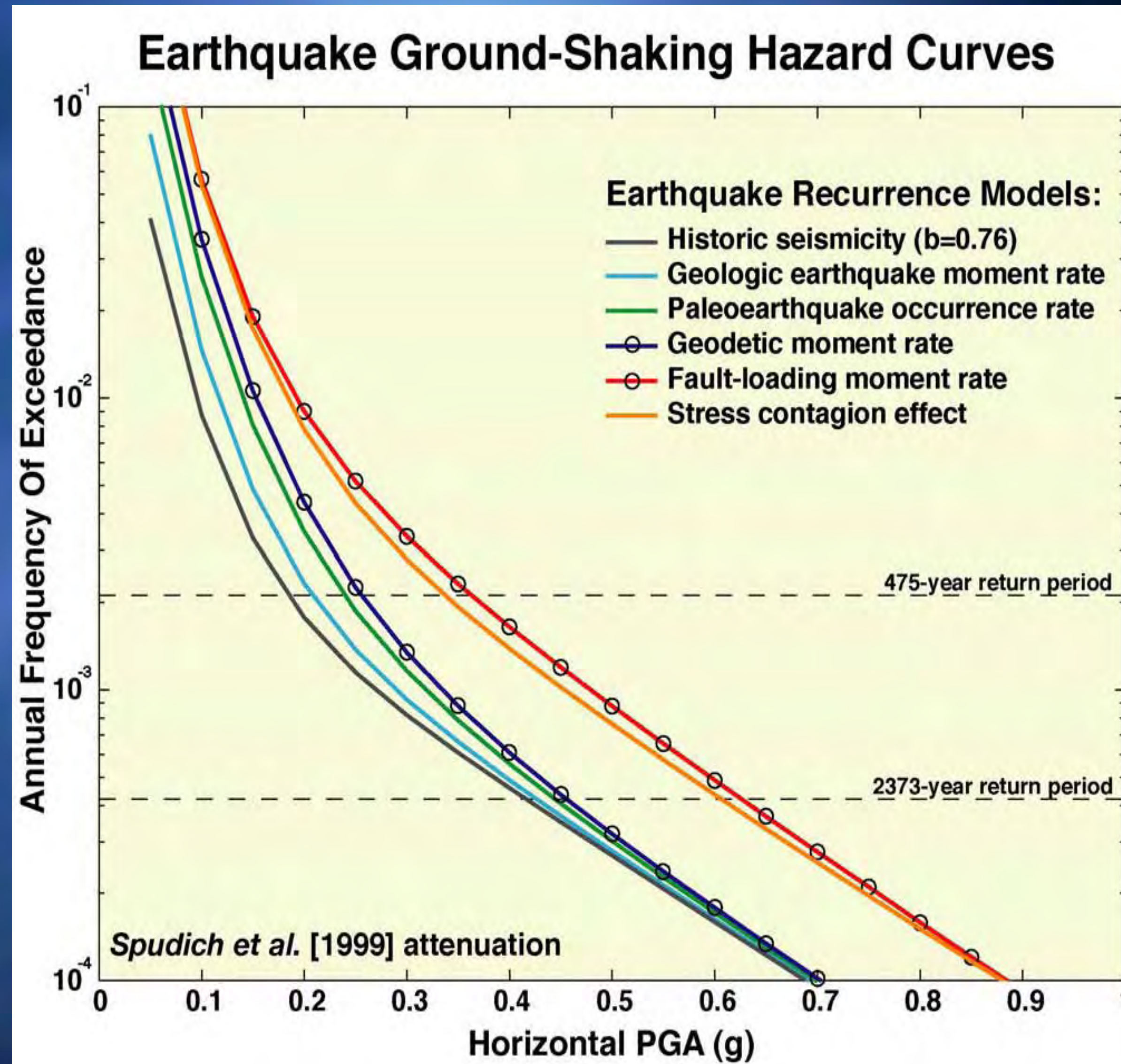
$$N(3.0,6.5) = \frac{\dot{M}_g - \sum\limits_{\substack{\text{faults in} \\ \text{geodetic area}}} \dot{M}_f}{C_d(3.0,6.5)}$$

$$\dot{M}^{A}_{seismic} = \frac{\dot{M}_f + \mu L W_e V_g}{2}$$

$$N(6.6,m_u) = \frac{\dot{M}^{A}_{seismic}}{C_d(6.6,m_u)}$$

Integrated Earthquake Probabilistic Seismic Hazard Assessment for the middle of Salt Lake Valley





Chang and Smith [2002]

Some key topics in new Utah PSHAs and other things

- The is no choice now but to include geodetic (GPS) data into any new Utah earthquake hazards assessments!

- Time-dependent hazard models must include visco-elastic models

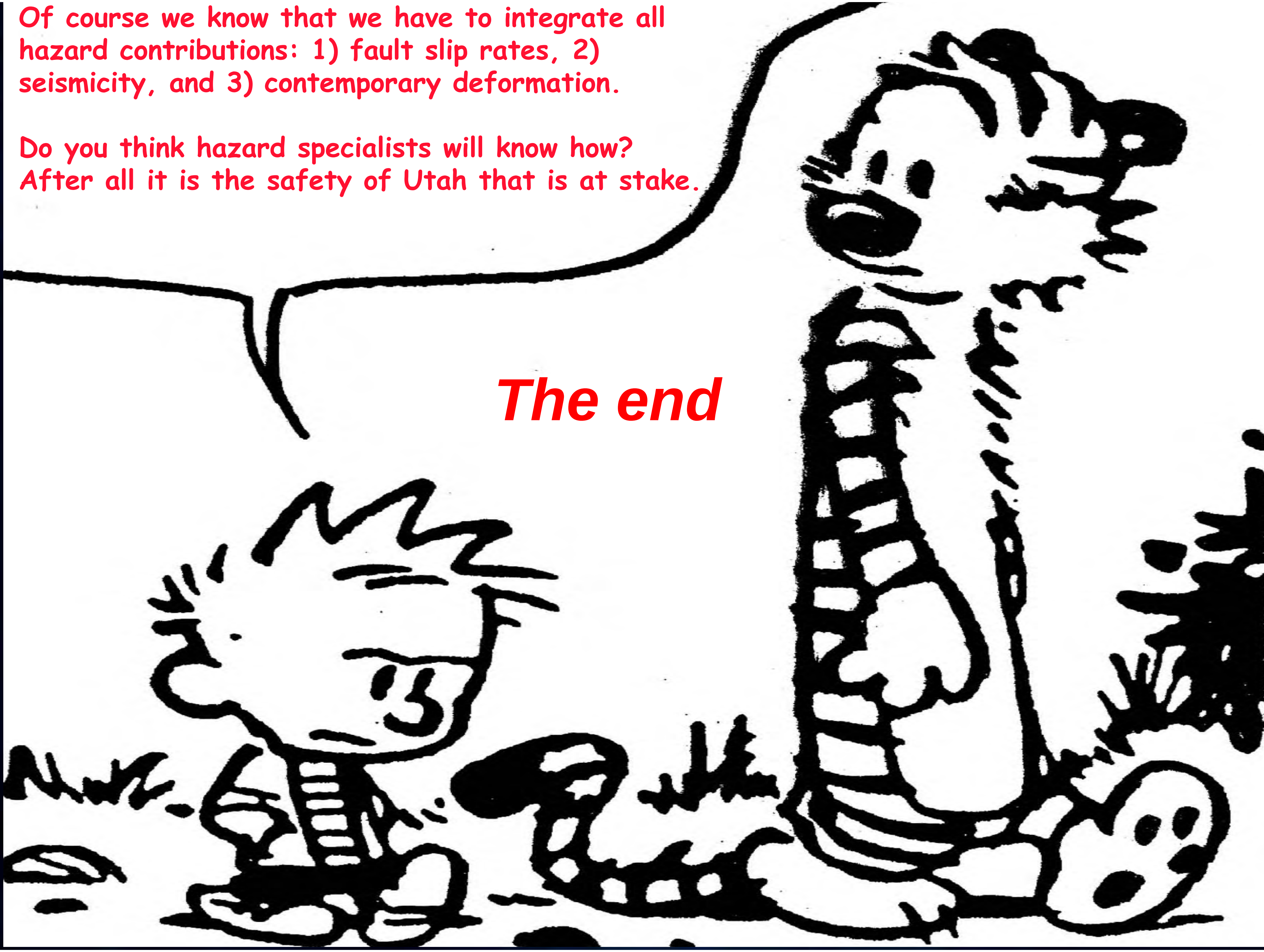
- Time-dependent inter-segment stress interaction must be included.

- Extreme ground motions for normal faults has to be incorporated in new PSHAs, both new from new and from dynamic stress models.

- Fault slip and GPS rate PSHA data must be evaluated probabilistically and PIs of all such data must give a complete error analysis that can be considered in the aleatoric uncertainty.

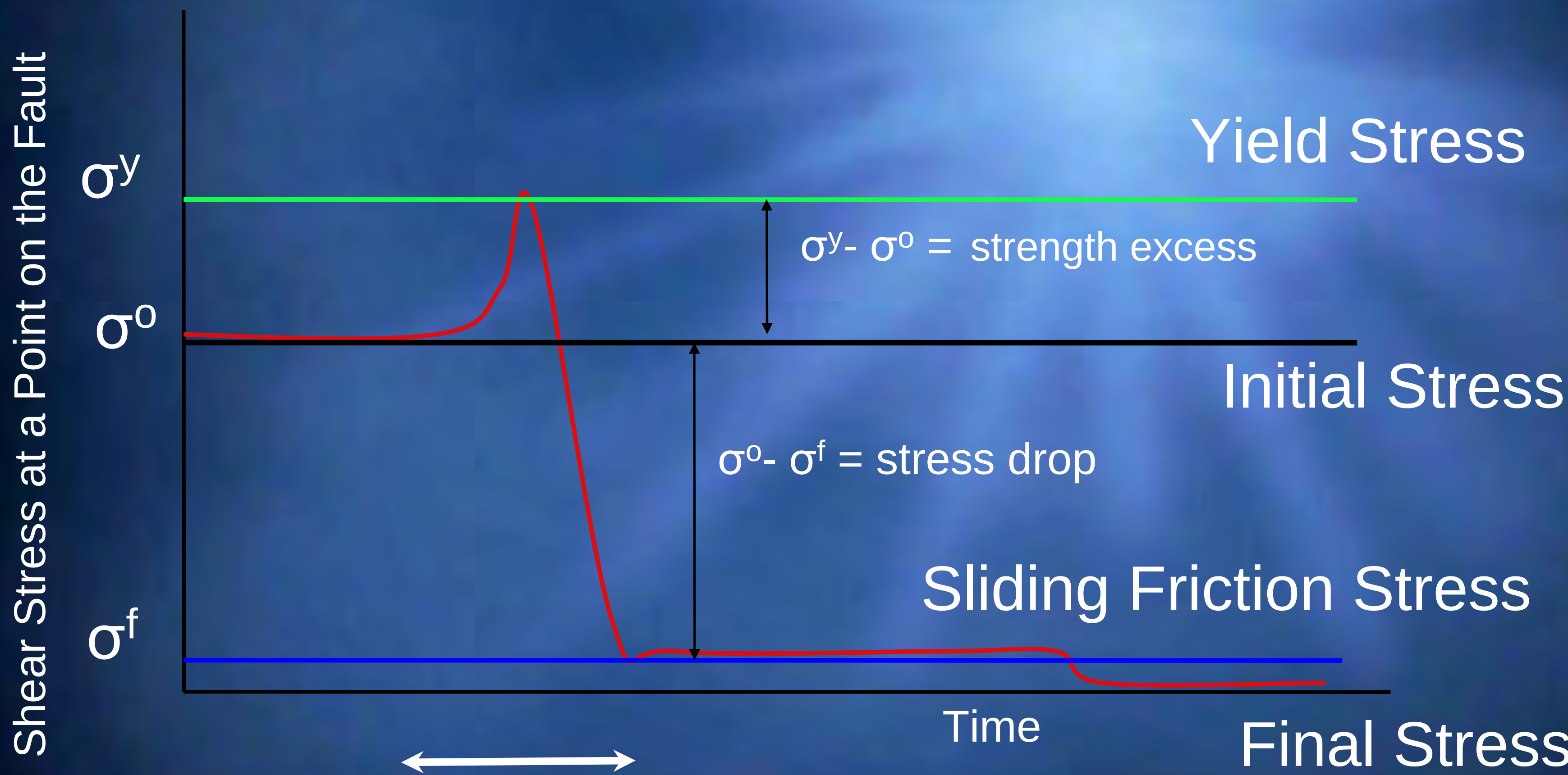
- A new USGS-SCEC report on extreme ground motions for normal faults will be completed in spring, 2010 and should be evaluated for application to Utah PSHAs.

- A new USGS report on SSHAC level 3 and 4 elicitation, May 2009, should be reviewed by the Utah hazard group.


Of course we know that we have to integrate all hazard contributions: 1) fault slip rates, 2) seismicity, and 3) contemporary deformation.
Do you think hazard specialists will know how? After all it is the safety of Utah that is at stake.
The end

Short explanation of dynamic and kinematic stress

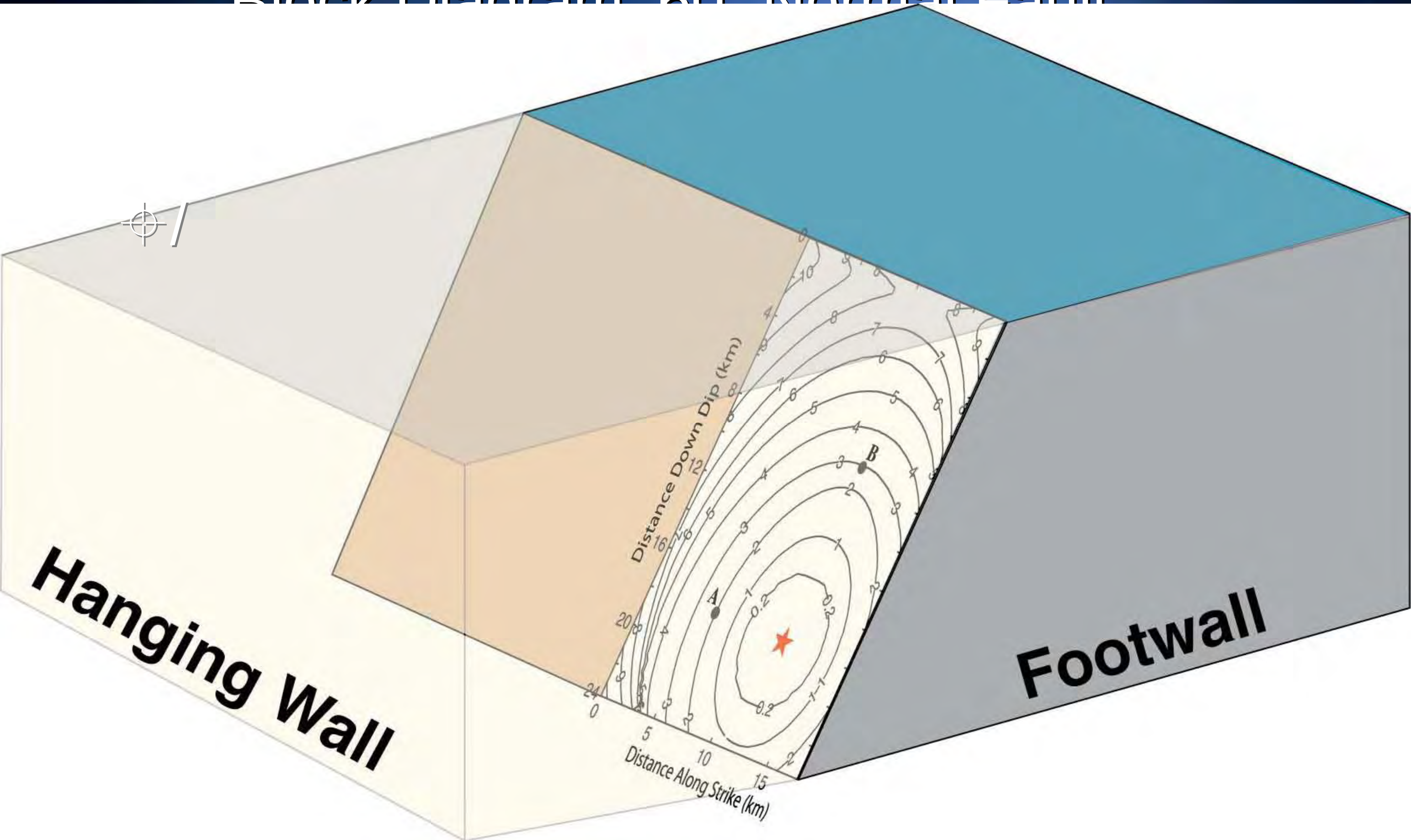
Behavior of Shear Stress at a Point on the Fault



Dynamic Stress Period of Extreme Ground Shaking, 5 to 20 sec

S = Strength Excess/Stress Drop

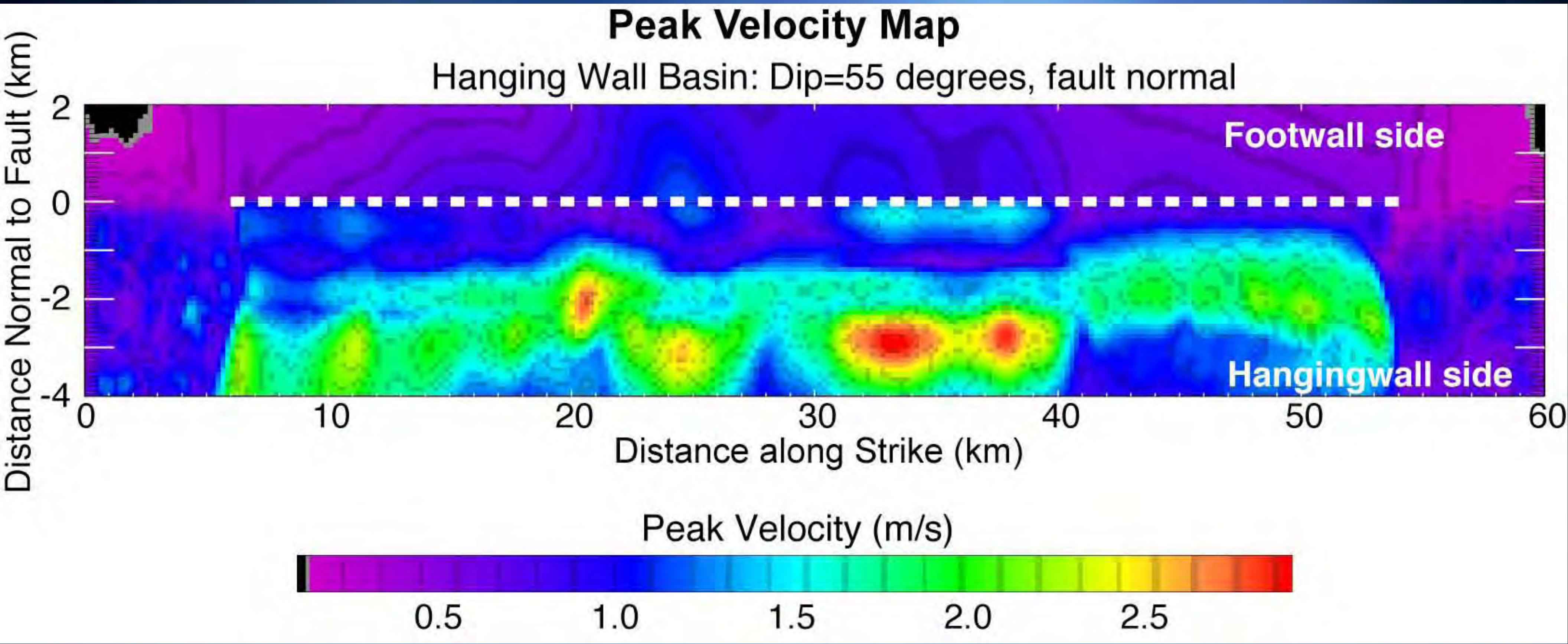
Block Diagram: 60° Normal Fault



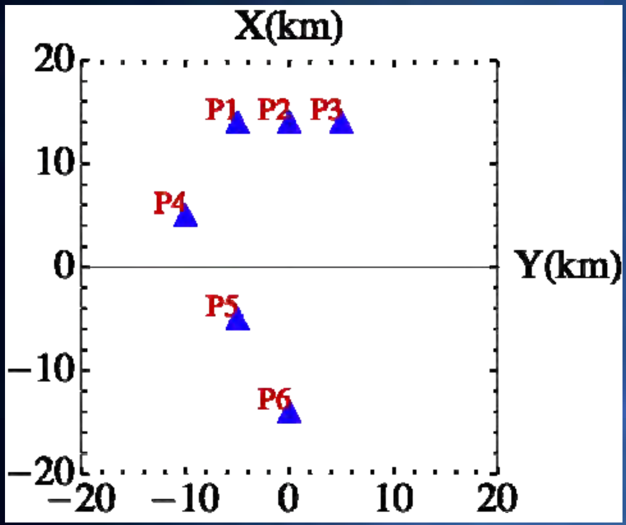
Movie: Slip Rate and Stress Change 60°

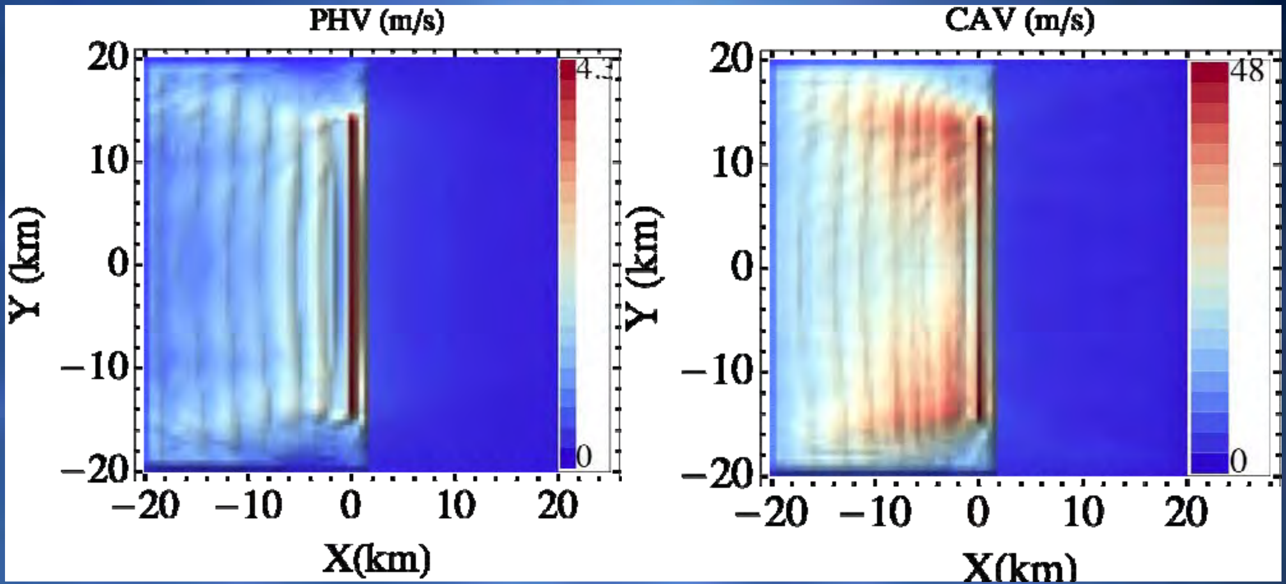
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

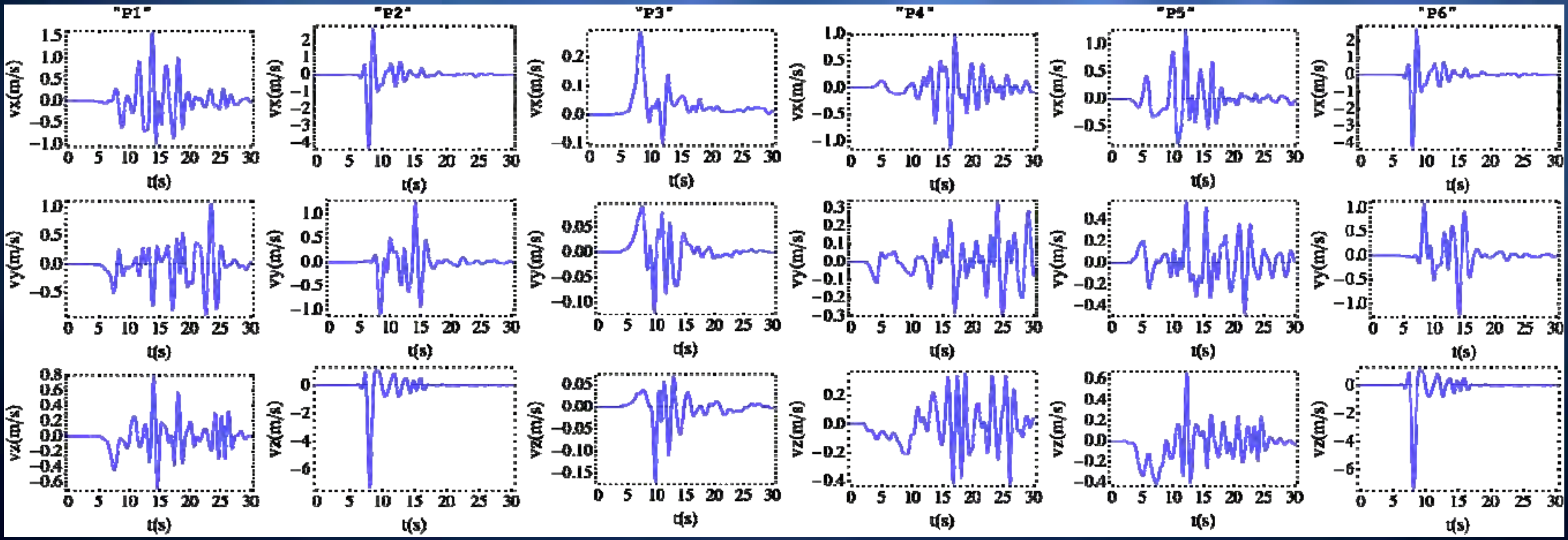
Map View: Surface Peak Velocity



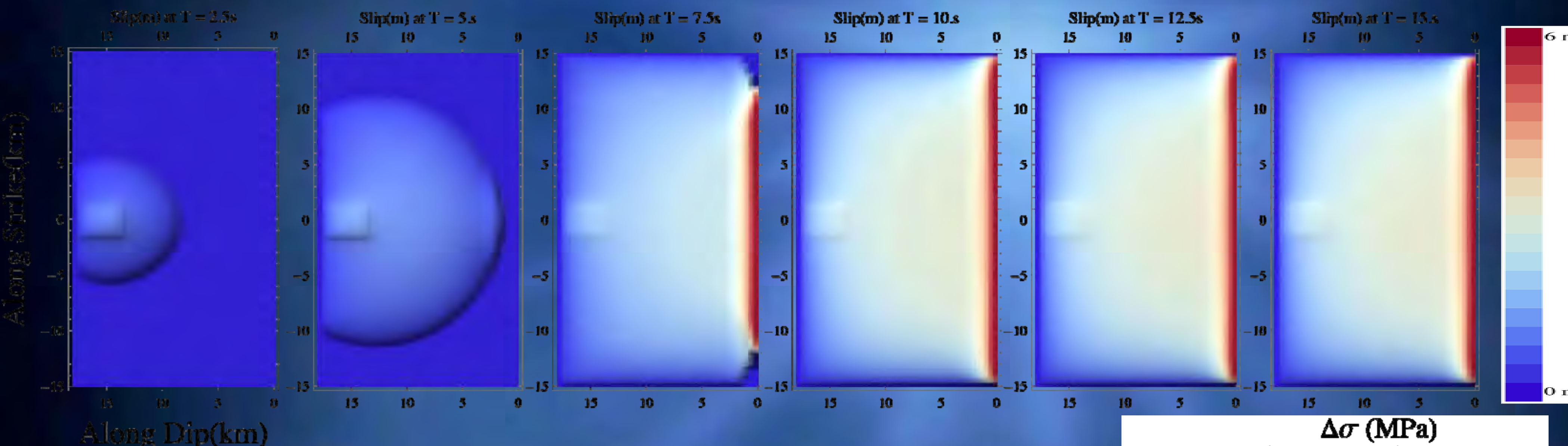
Case 2: Ground Motion



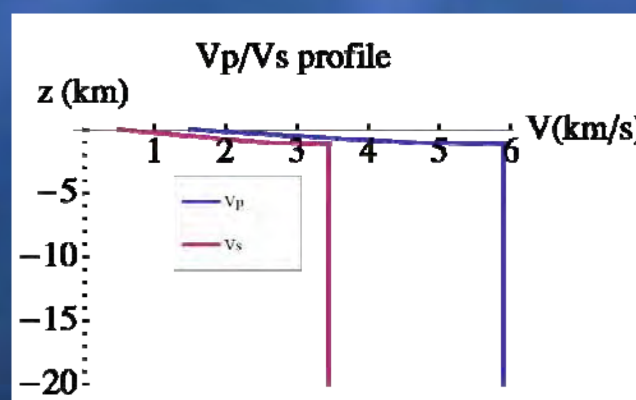


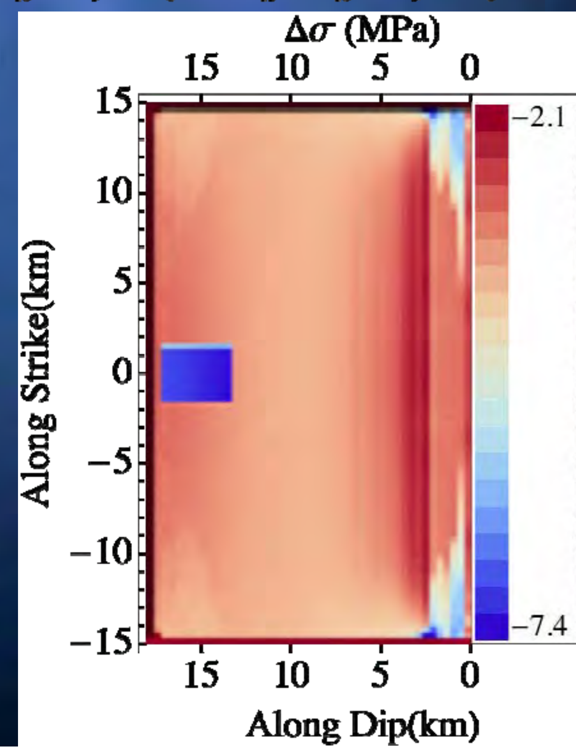


Case 2: Layered Model



Simulation result from Model C, simplified layered model (velocity increase from free surface to 1km depth on the hanging wall side), top column is the rupture snapshot.
Figure on the right is the shear stress drop due to the rupture.

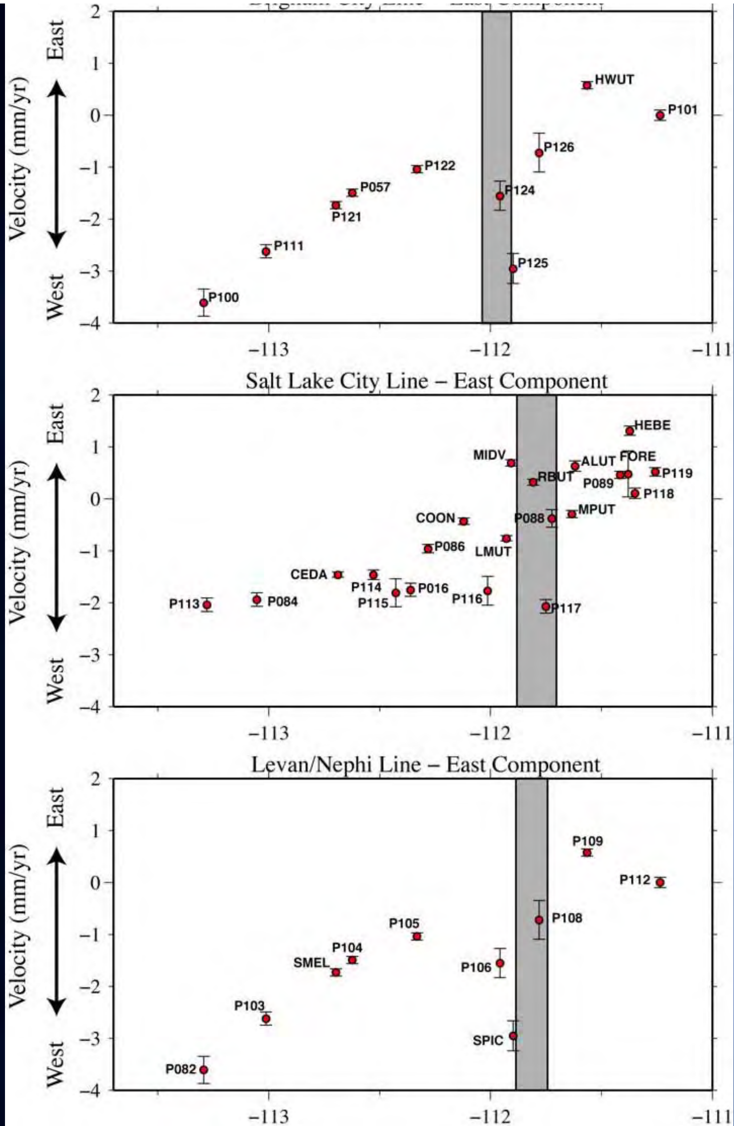




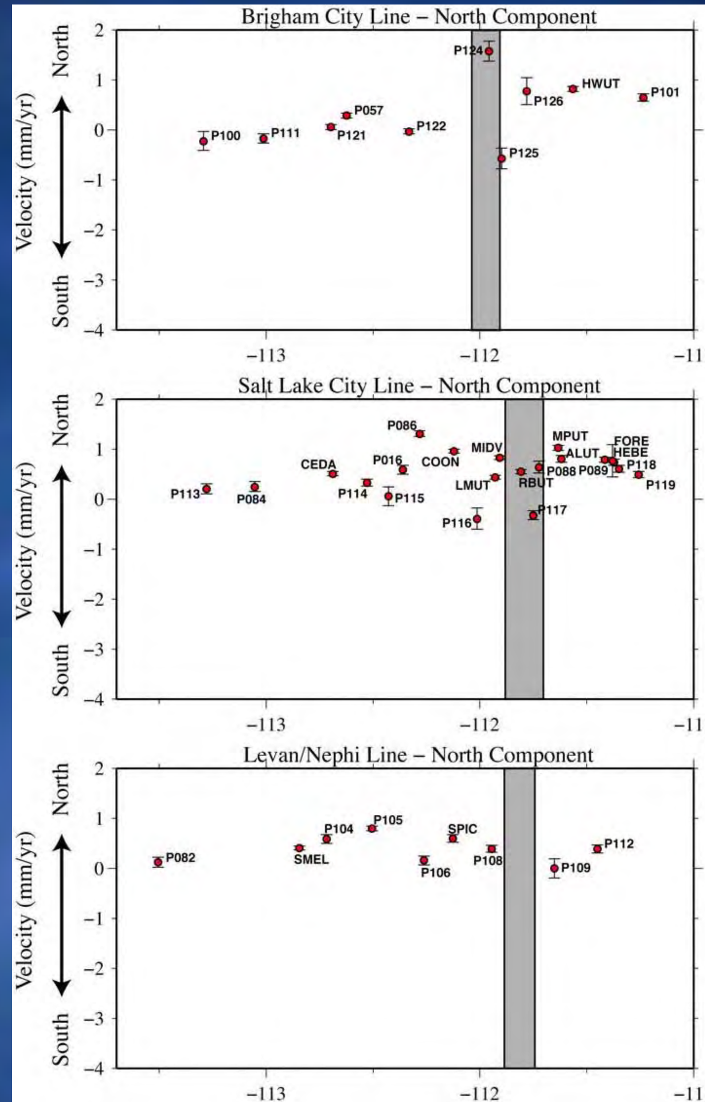
The Wasatch fault in our backyardwill experience 5 to 20 sec of exteme ground shaking due the dynamic stress propagtion producing 10s% to 100% larger ground velocities than those normally used in PSHA

G.K. Gilbert recognized the range front as a major active fault scarp.

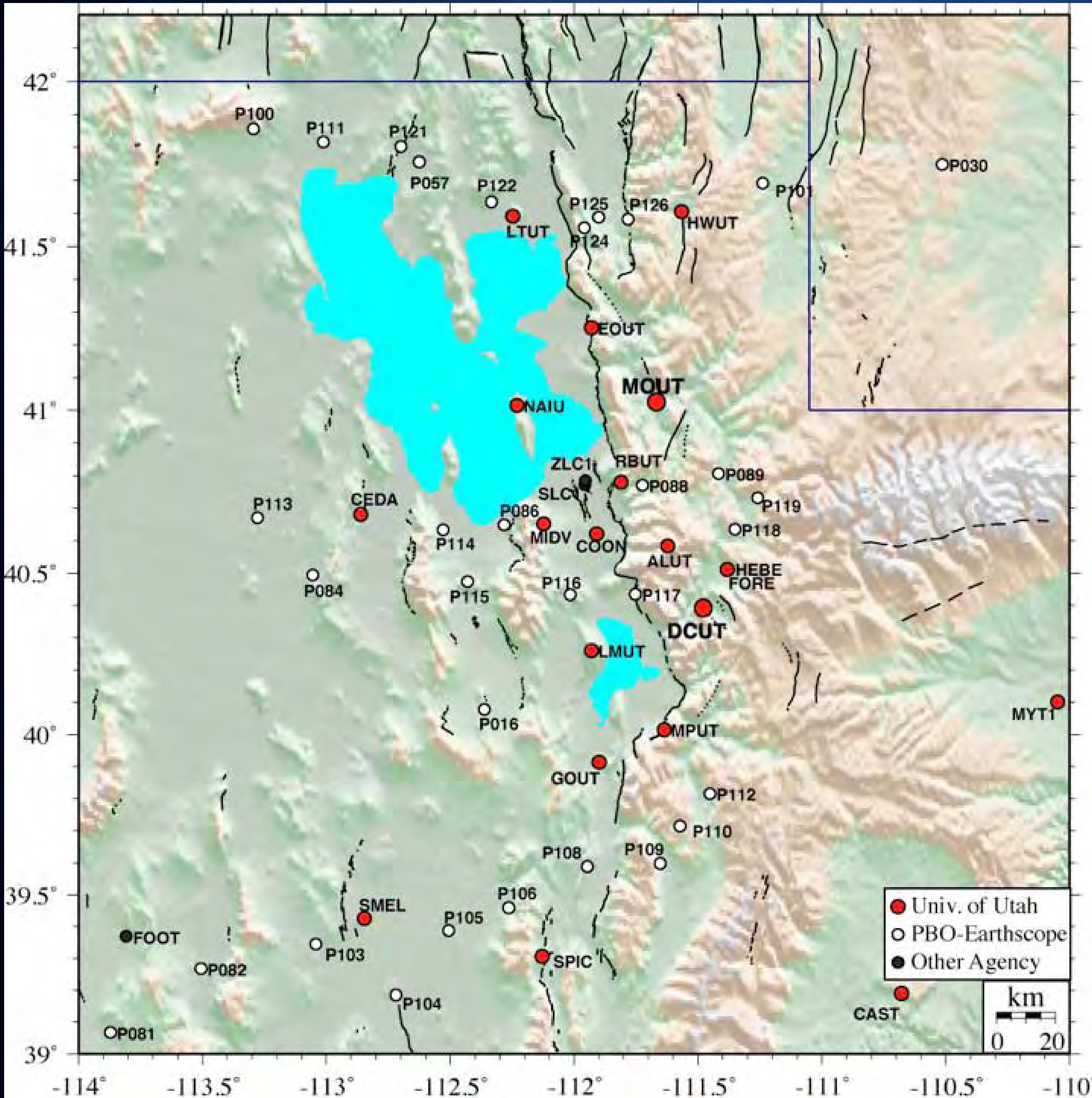
What have learned since and what will we do about it!



Velocity (mm/yr)
East
West
P100
P111
P121
P057
P122
P124
P125
P126
HWUT
P101
Salt Lake City Line – East Component
HEBE
MIDV
ALUT
FORE
RBUT
P089
P119
P118
COON
P088
MPUT
P086
LMUT
CEDA
P114
P115
P016
P116
P113
P084
P117
Levan/Nephi Line – East Component
P109
P112
P105
P108
P104
SMEL
P106
P103
SPIC
P082
−113
−112
−111



Brigham City Line – North Component
Velocity (mm/yr)
North
South
P124
P126
HWUT
P101
P100
P111
P057
P121
P122
P125
Salt Lake City Line – North Component
P086
CEDA
P016
COON
MIDV
MPUT
FORE
ALUT
HEBE
P088
P089
P118
P119
P113
P084
P114
P115
LMUT
RBUT
P116
P117
Levan/Nephi Line – North Component
P104
P105
SPIC
P112
P082
SMEL
P106
P108
P109
−113
−112
−111



All data are recorded and transmitted in realtime to the Univ of Utah and PBO
recording rate
processing
output as velocities

All GPS data are available at Univ of Utah
http://www.mines.utah.edu/~ggcmpsem/UUSATRG/

GPS time series are available at th
EarthScope website:
GPS/time_series.html
http://facility.unavco.org/data/data.html

Fault Slip: 60˚ Normal Fault in a Halfspace