BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP

WESTERN STATES SEISMIC POLICY COUNCIL
U.S. GEOLOGICAL SURVEY
UTAH GEOLOGICAL SURVEY

BRPEWG GOALS

- Bring together subject-matter experts to discuss evidence, evaluate issues, and define strategies for resolving issues.

- Establish consensus on issues wherever possible to advise the USGS regarding the next update of the National Seismic Hazard Maps.

- Where consensus is not possible, outline research programs to resolve outstanding technical issues that the USGS can use when setting research priorities.

BRPEWG SCHEDULE

- **BRPEWG Meeting March 8, 9, & 10, 2006, in Salt Lake City.**
- **Draft recommendations document ready for review and approval by WSSPC Board on April 17, 2006 in San Francisco.**
- **Present BRPEWG recommendations to the USGS at National Seismic Hazard Maps Intermountain West Regional Meeting in Reno, Nevada May 31 & June 1, 2006.**

BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP AGENDA MARCH 8, 9, & 10, 2006

Wednesday, March 8, 2006

8:00 am – 12:00 noon **Use and relative weighting of time dependent, Poisson, and clustering models in characterizing fault behavior, discussion leaders Susan Olig and John Anderson.**

1:00 pm – 5:00 pm **Proper magnitude frequency distributions (Gutenberg Richter versus characteristic earthquake models) for BRP faults, discussion leaders Ivan Wong and David Schwartz.**

Thursday, March 9, 2006

8:00 am – 12:00 noon **Use of length versus displacement relations to estimate earthquake magnitude, discussion leaders Mark Hemphill-Haley and Glenn Biasi.**

1:00 pm – 5:00 pm **Probabilities and magnitudes of multi-segment ruptures, discussion leaders Jim Pechmann and Craig dePolo.**

Friday, March 10, 2006

8:00 am – 12:00 noon **Resolving discrepancies between geodetic extension rates and geologic slip rates, discussion leaders Robert Smith and Wayne Thatcher.**

1:00 pm – 5:00 pm **Wrap up outstanding items from earlier discussions and discuss the format/preparation of the BRPEWG final report to the USGS.**

BRPEWG MEMBERS

1. **John Anderson*, University of Nevada Reno Seismological Laboratory**
2. **Walter Arabasz, University of Utah Seismograph Stations**
3. **Glenn Biasi* – University of Nevada Reno Seismological Laboratory**
4. **Tony Crone – USGS Denver**
5. **Craig dePolo*, Nevada Bureau of Mines & Geology**
6. **Chris DuRoss, Utah Geological Survey**
7. **Kathy Haller, USGS Denver**
8. **Bill Hammond, Nevada Bureau of Mines & Geology**
9. **Suzanne Hecker – USGS Menlo Park**
10. **Mark Hemphill-Haley*, Humboldt State University**
11. **David Love – New Mexico Bureau of Geology & Mineral Resources**
12. **William Lund, Utah Geological Survey**
13. **Vince Matthews, Colorado Geological Survey**
14. **Jim McCalpin, GeoHaz, Inc.**
15. **Susan Olig*, URS Corp.**
16. **Dean Ostenna – USBR, Denver**
17. **Phil Pearthree, Arizona Geological Survey**
18. **Jim Pechmann*, University of Utah Seismograph Stations**
19. **Mark Petersen, USGS Denver**
20. **Bill Phillips, Idaho Geological Survey**
21. **Dave Schwartz*, USGS Menlo Park**
22. **Burt Slemmons – University of Nevada Reno, emeritus**
23. **Robert Smith*, University of Utah**
24. **Mike Stickney, Montana Bureau of Mines & Geology**
25. **Wayne Thatcher*, USGS Menlo Park**
26. **Chris Wills – California Geological Survey**
27. **Ivan Wong*, URS Corp.**

**Issue discussion leader*

BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP

WESTERN STATES SEISMIC POLICY COUNCIL

UTAH GEOLOGICAL SURVEY

U.S. GEOLOGICAL SURVEY

WESTERN STATES SEISMIC POLICY COUNCIL

UTAH GEOLOGICAL SURVEY

USGS science for a changing world

WESTERN STATES SEISMIC POLICY COUNCIL POLICY RECOMMENDATION 04-5

WSSPC recommends convening a technical Basin and Range Province Earthquake Working Group (BRPEWG) to develop scientific consensus regarding fault behavior, ground-shaking and ground-failure modeling, and research priorities relevant to seismic policy and the USGS National Seismic Hazards Maps (NSHMs) in the Basin and Range Province (BRP). The BRPEWG will be convened under the auspices of the USGS NSHM project.

SEISMIC-POLICY ISSUES IDENTIFIED AT BRPSHSII

1. Use and relative weighting of time-dependent, Poisson, and clustering models to characterize BRP fault behavior.
2. Proper magnitude-frequency distributions (Gutenberg-Richter vs. characteristic earthquake models) for BRP faults.
3. Use of length vs. displacement relations to estimate earthquake magnitudes.
4. Probabilities and magnitudes of multi-segment ruptures on BRP faults.

SEISMIC-POLICY ISSUES IDENTIFIED AT BRPSHSII

5. Resolving discrepancies between horizontal geodetic extension rates and vertical geologic slip rates.

6. Appropriate attenuation relations, stress drops, and kappa in modeling ground motions, including evidence from precarious rock studies.

BRPEWG GOALS

- Bring together subject-matter experts to discuss evidence, evaluate issues, and define strategies for resolving issues.
- Establish consensus on issues wherever possible to advise the USGS regarding the next update of the NSHMs.
- Where consensus is not possible, outline research programs to resolve outstanding technical issues that the USGS can use when setting research priorities.

BRPEWG MEMBERS

1. John Anderson*, University of Nevada Reno Seismological Laboratory
2. Walter Arabasz, University of Utah Seismograph Stations
3. Glenn Biasi* – University of Nevada Reno Seismological Laboratory
4. Tony Crone – USGS Denver
5. Craig dePolo*, Nevada Bureau of Mines & Geology
6. Chris DuRoss, Utah Geological Survey
7. Kathy Haller, USGS Denver
8. Bill Hammond, Nevada Bureau of Mines & Geology
9. Suzanne Hecker – USGS Menlo Park
10. Mark Hemphill-Haley*, Humboldt State University
11. David Love – New Mexico Bureau of Geology & Mineral Resources
12. William Lund, Utah Geological Survey
13. Vince Matthews, Colorado Geological Survey
14. Jim McCalpin, GeoHaz, Inc.
15. Susan Olig*, URS Corp.
16. Dean Ostenna – USBR, Denver
17. Phil Pearthree, Arizona Geological Survey
18. Jim Pechmann*, University of Utah Seismograph Stations
19. Mark Petersen, USGS Denver
20. Bill Phillips, Idaho Geological Survey
21. Dave Schwartz*, USGS Menlo Park
22. Burt Slemmons – University of Nevada Reno, emeritus
23. Robert Smith*, University of Utah
24. Mike Stickney, Montana Bureau of Mines & Geology
25. Wayne Thatcher*, USGS Menlo Park
26. Chris Wills – California Geological Survey
27. Ivan Wong*, URS Corp.

**Issue discussion leader*

BRPEWG SCHEDULE

- BRPEWG Meeting March 8, 9, & 10, 2006, in Salt Lake City
- Draft recommendations document ready for review and approval by WSSPC Board on April 17, 2006 in San Francisco.
- Present BRPEWG recommendations to the USGS at their Intermountain West Regional Meeting in Reno, Nevada in May 2006.

Basin and Range Province Earthquake Working Group Workshop: Wednesday AM

John G. Anderson

Agenda

- **Wednesday, March 8, 2006**
- 7:15 am Continental breakfast
- 8:00 am – 12:00 noon* Use and relative weighting of time dependent, Poisson, and clustering models in characterizing fault behavior, discussion leaders Susan Olig and John Anderson.

Key Questions

- Are time-dependent models appropriate for Basin and Range Province (BRP) faults? If so, which faults have sufficient paleoseismic data?
  - Which earthquake renewal models (e.g., lognormal, Weibull, empirical, Brownian passage time) and what corresponding weights are appropriate?
  - What parameter values (coefficient of variation, exposure window) are suitable, and should earthquake clustering (i.e., the use of short- and long-term slip rates) be included?

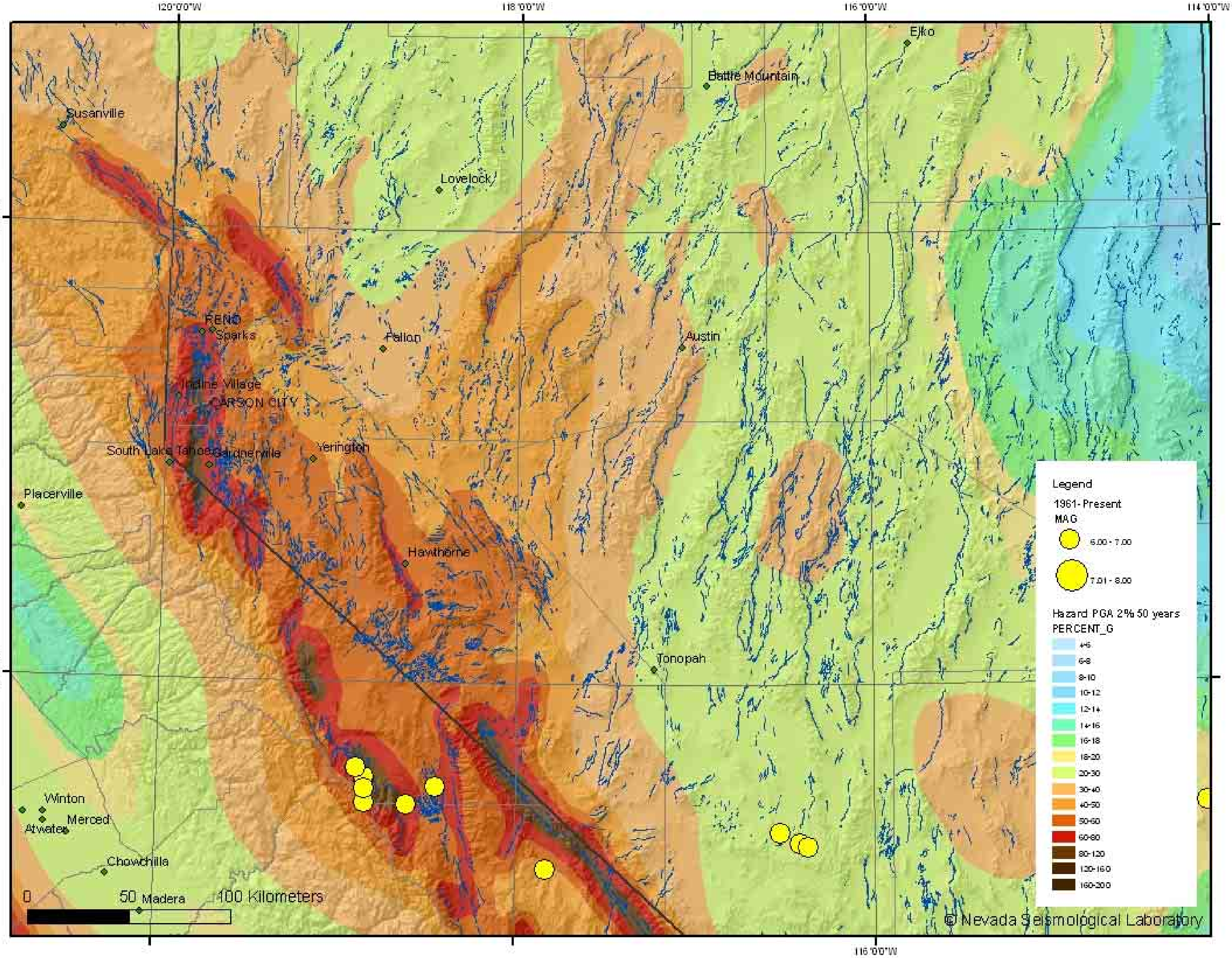
NEVADA Seismological Laboratory

ISSUES:

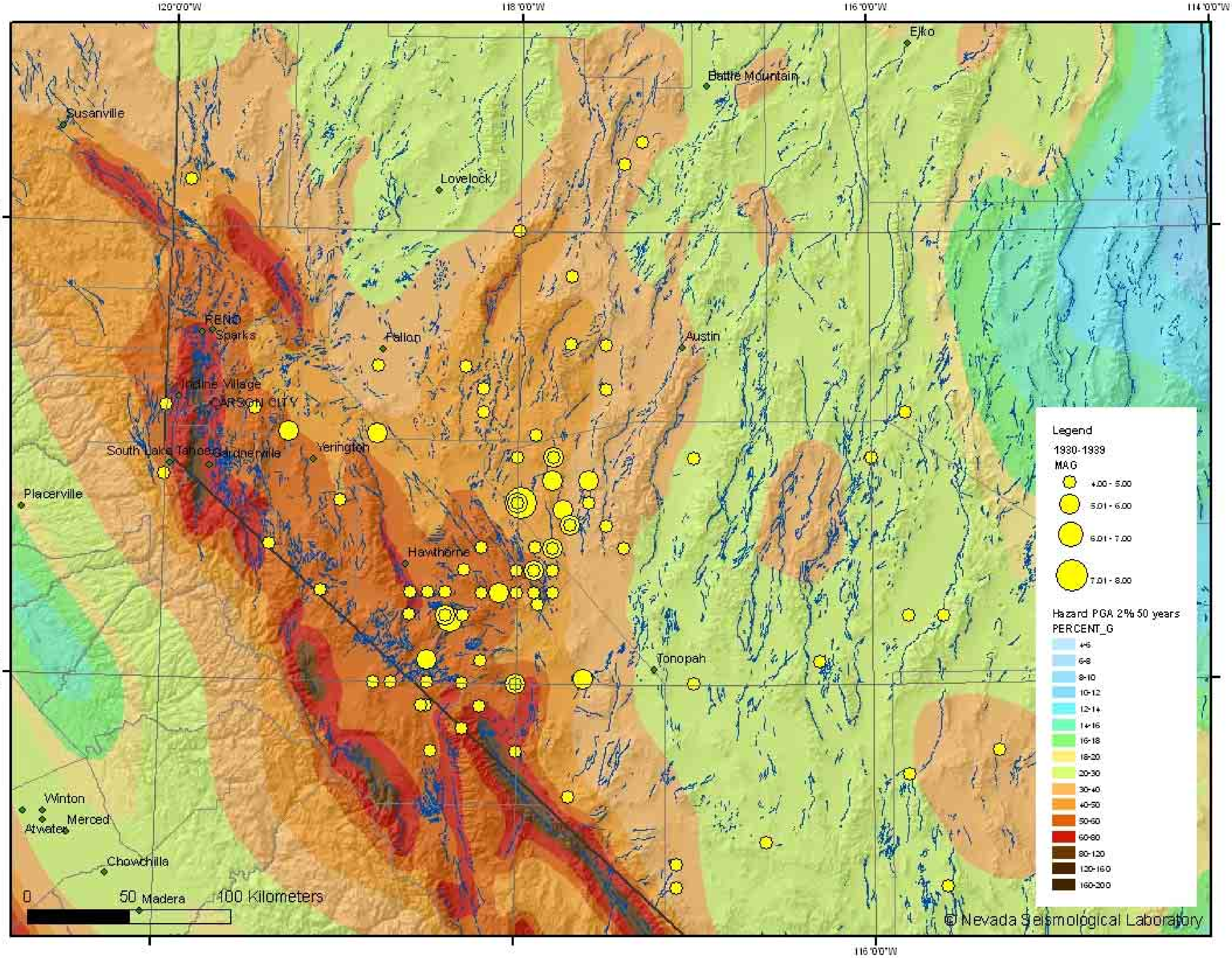
- Which time-dependent and -independent models are applicable to BRP faults?
- How incorporate error, expert opinion, and still have a useable result?
- Use of short- and long-term rates, background/floating earthquakes, and current seismicity/geodetic strain in characterizing fault behavior?
- Data limitations; minimum data necessary to characterize BRP faults?
- Model parameters (COV, alpha, magnitude, recurrence intervals)?

Reshaped Questions

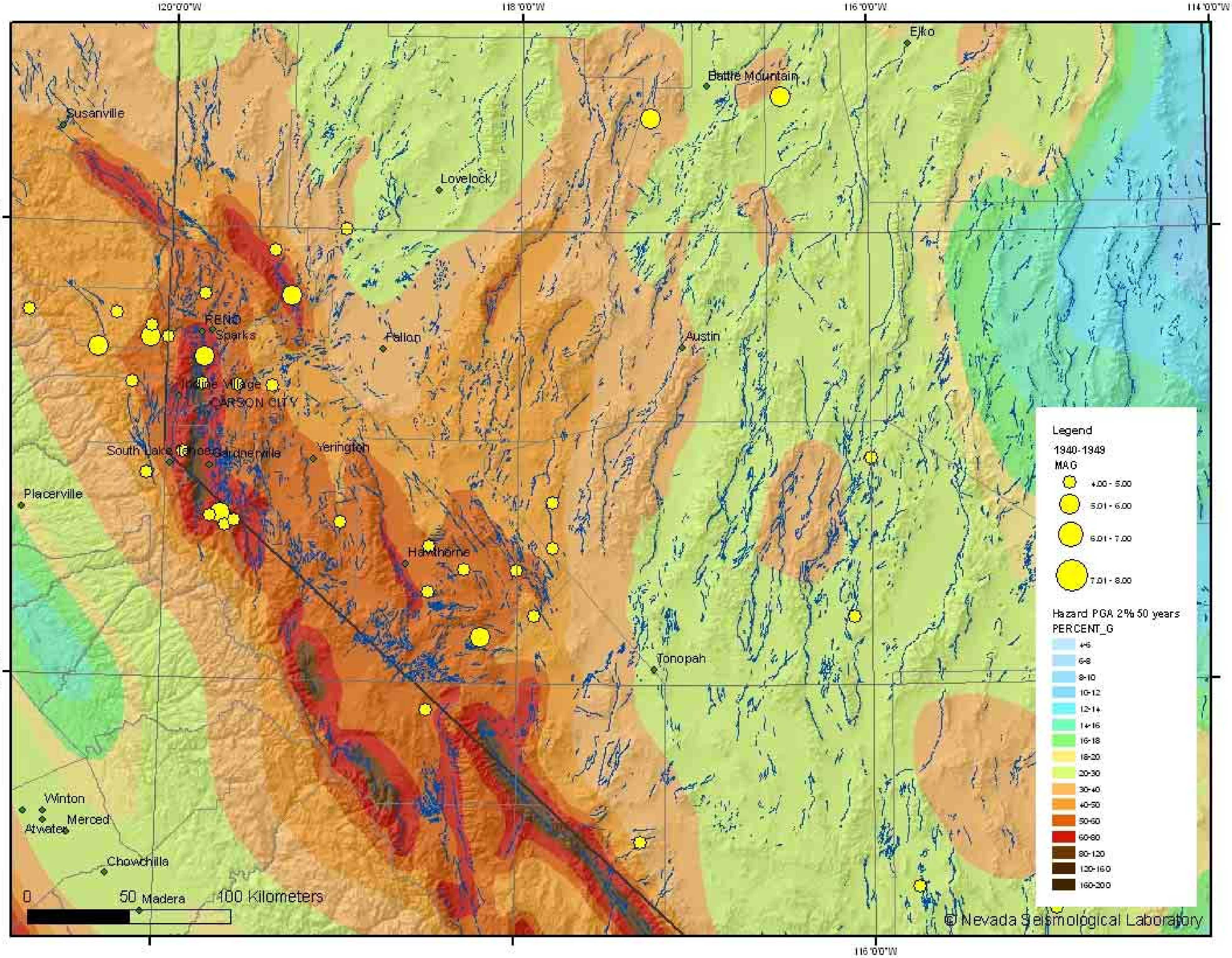
- 1a. For time-dependent seismic hazard analyses in the BRP, which individual or weighted combinations of renewal models should be used (lognormal, Weibull, Empirical, Brownian Passage Time, time-predictable) and what parameter values (coefficient of variation, exposure window) are applicable?
- 1b. For time-independent seismic hazard analyses, which individual or weighted combinations of earthquake recurrence models should be used (Gutenberg-Richter, characteristic, truncated exponential, maximum magnitude), and if applicable, should fault growth/age be considered when assigning the characteristic model weight?

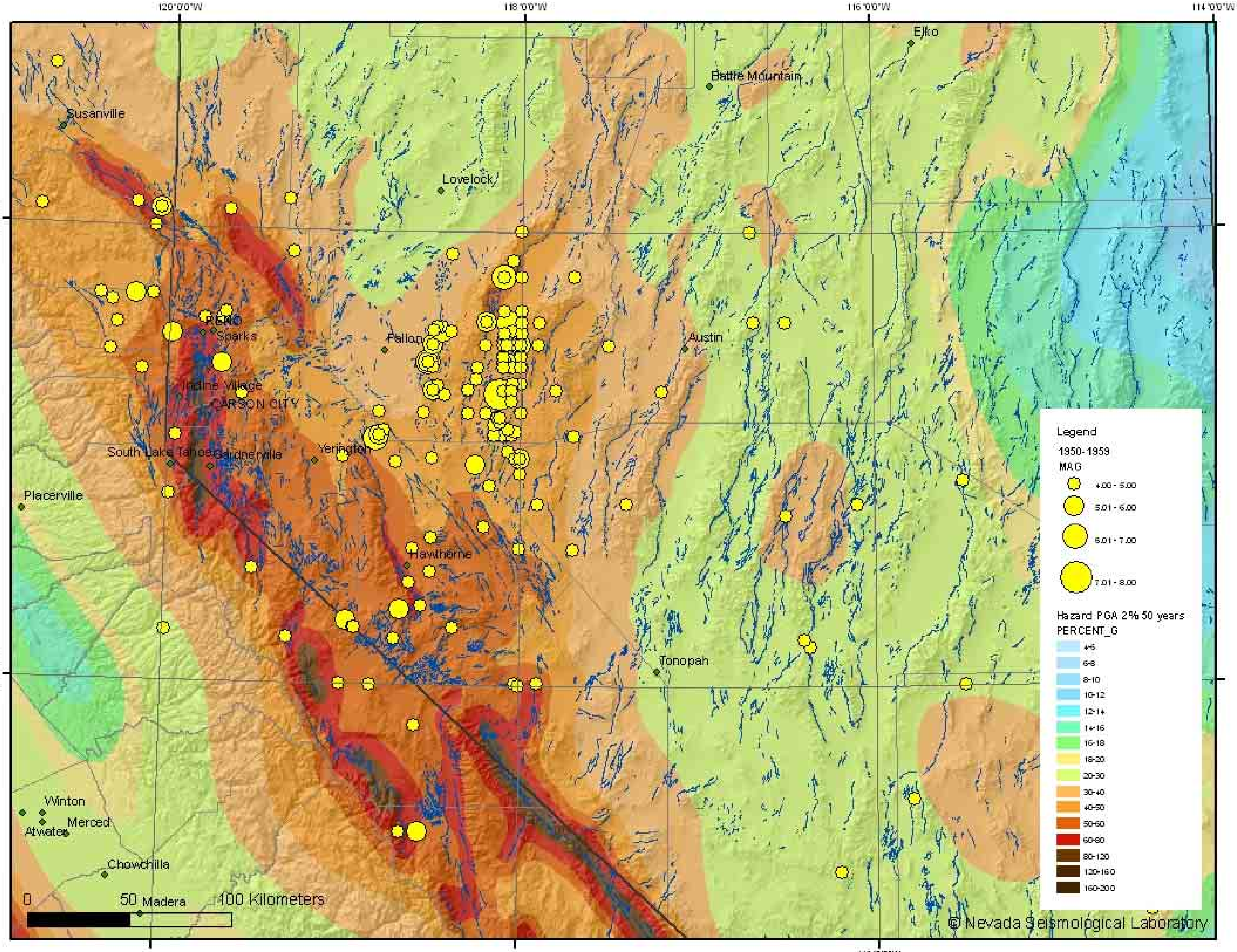


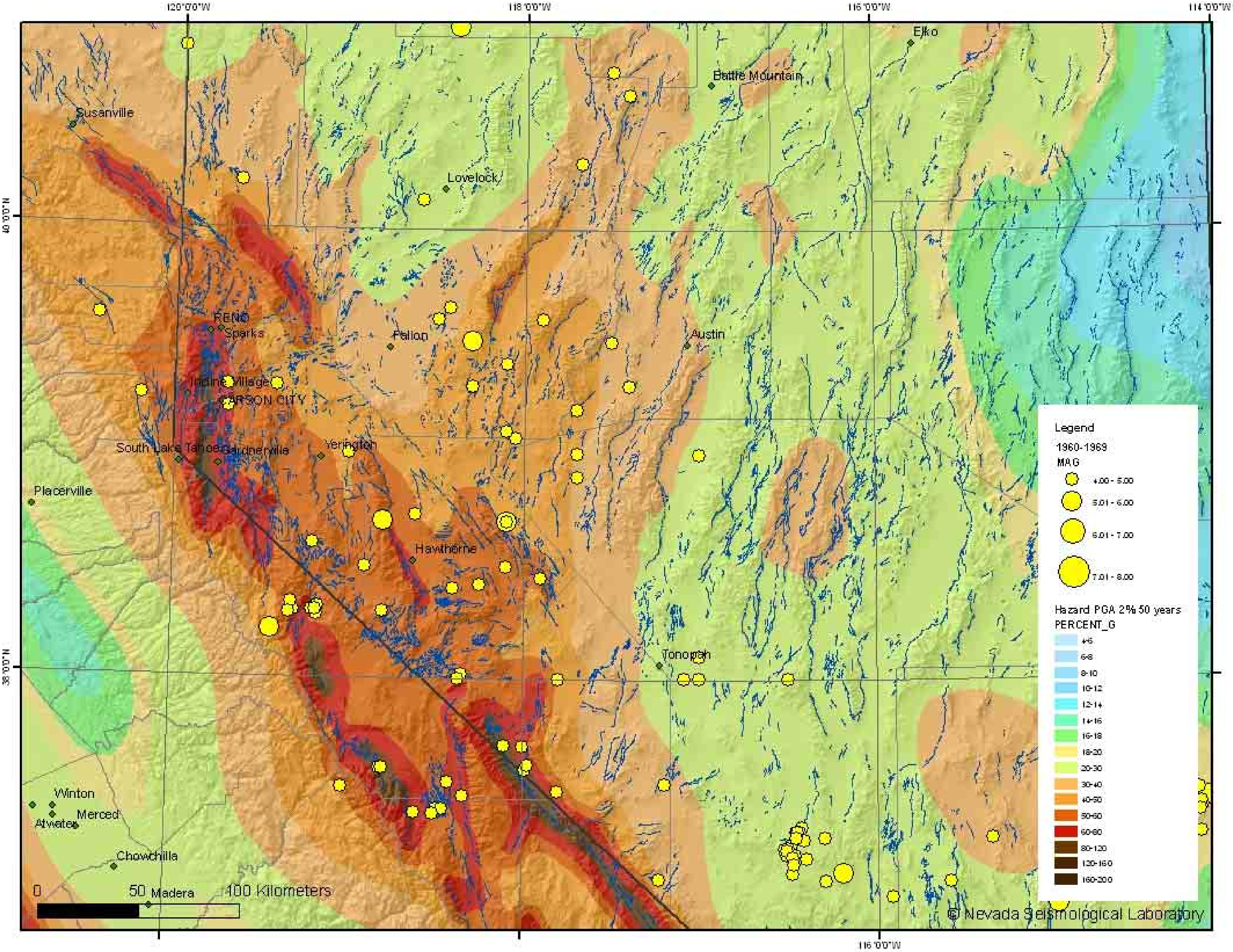
120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
1961- Present
MAG
6.00 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200

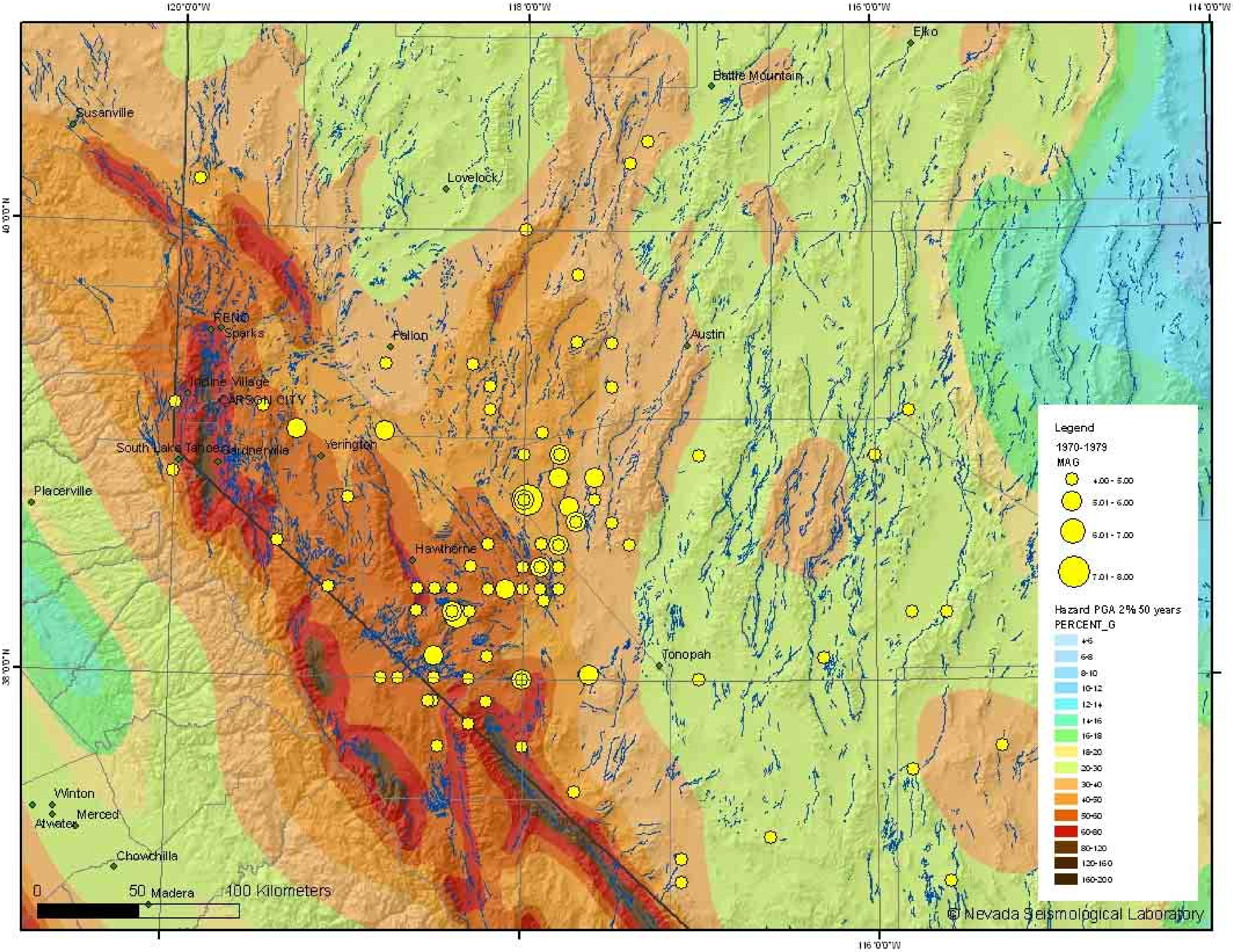


120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1930-1939
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory

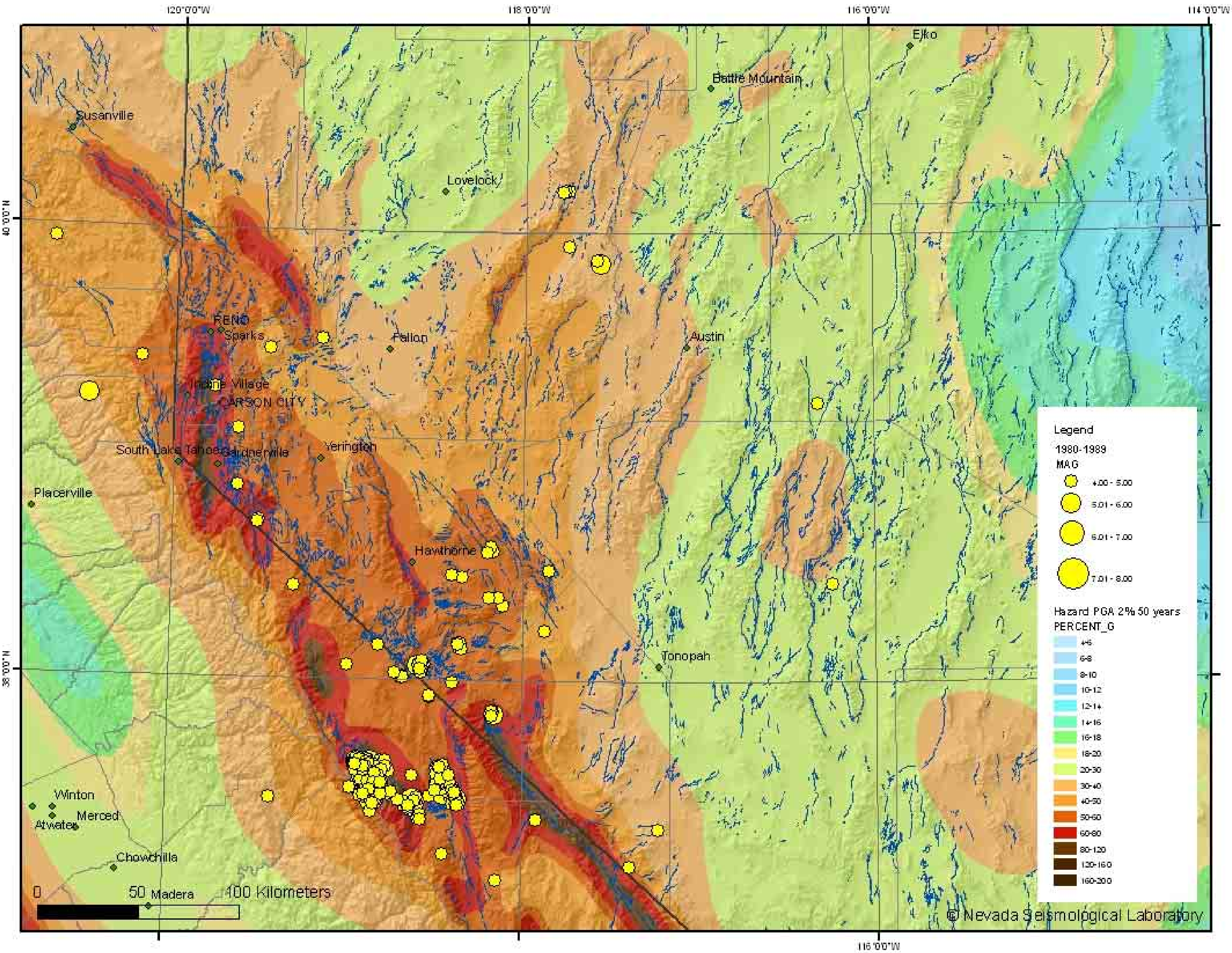

120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
1940-1949
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200


120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
1950-1959
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200

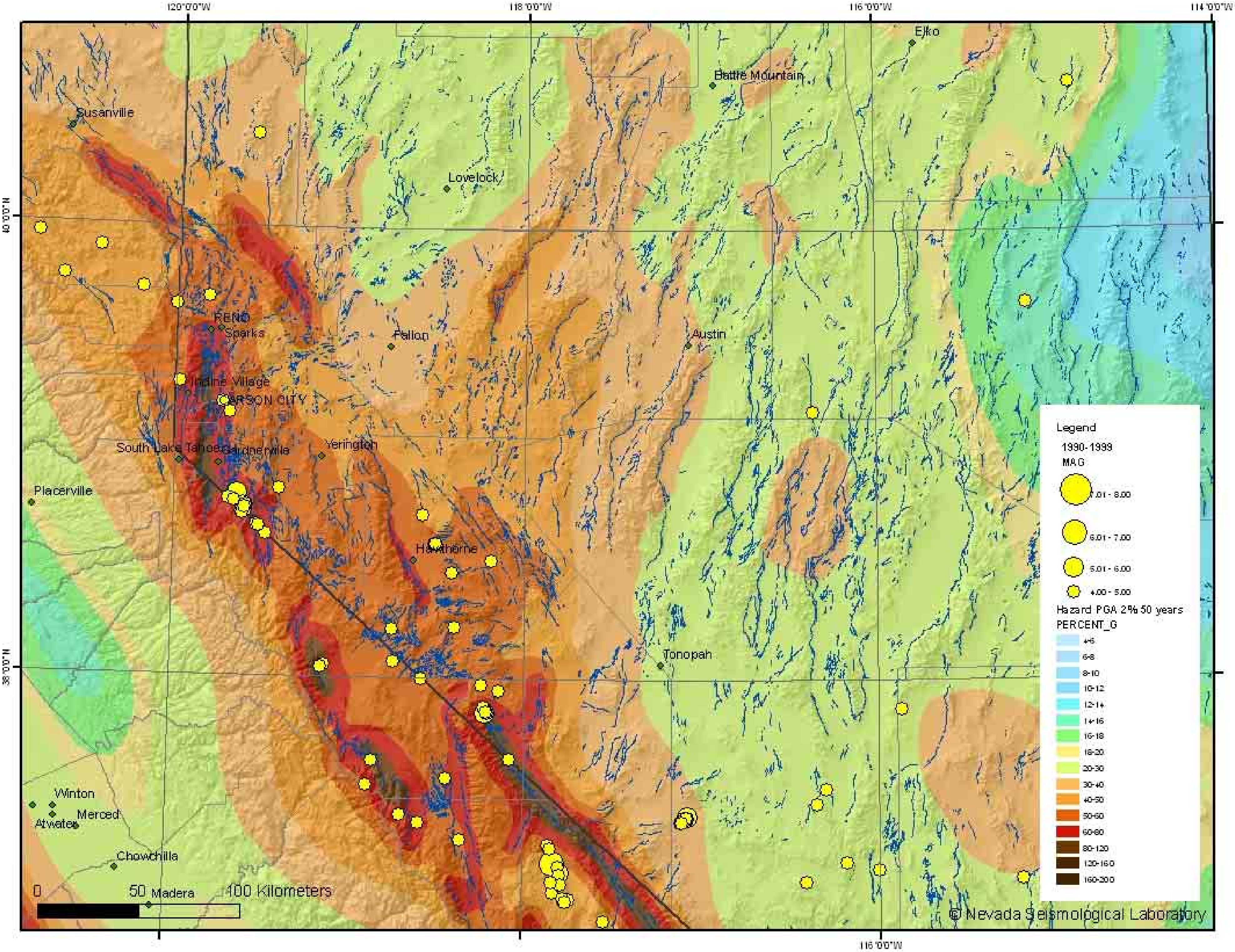

120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1960-1969
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory



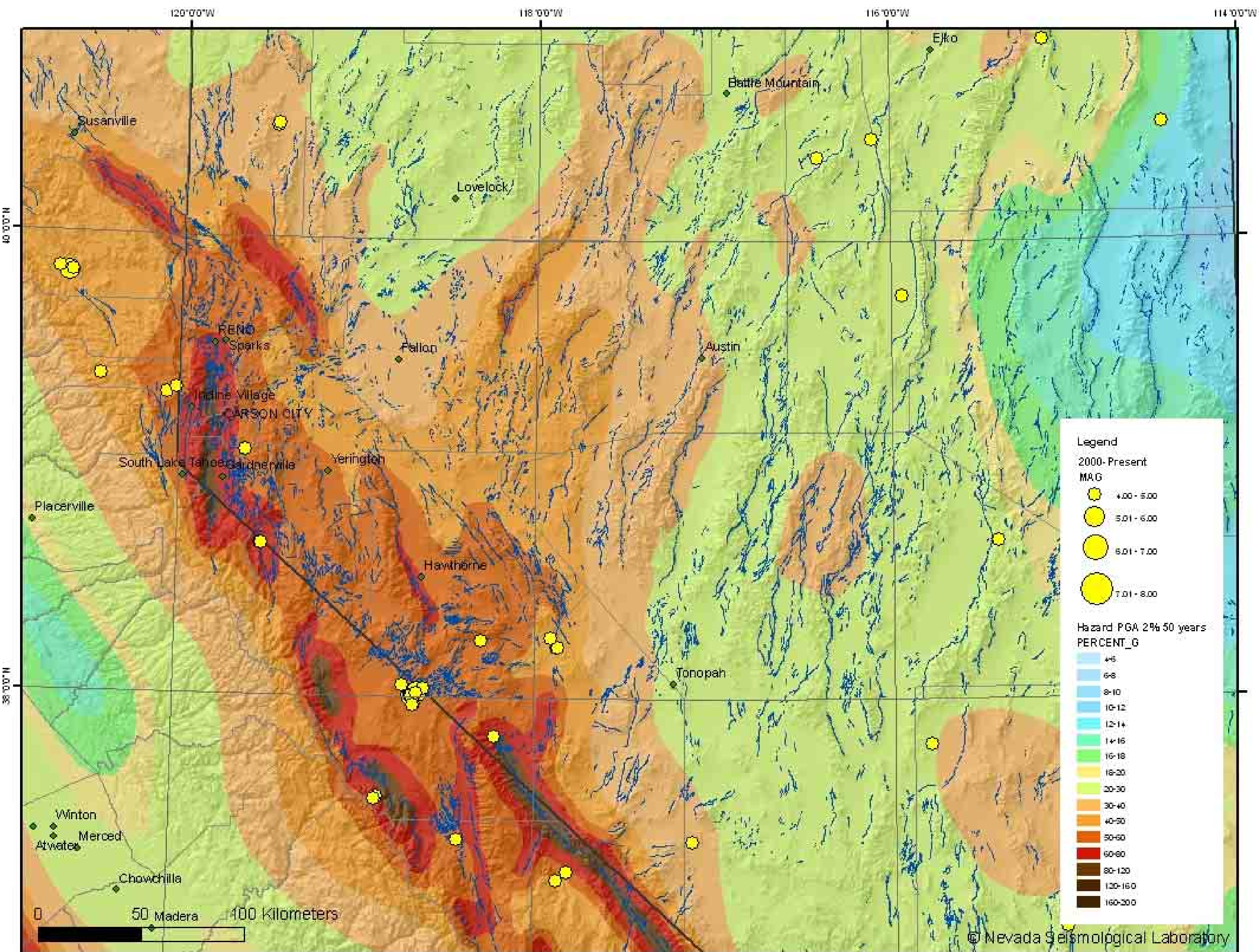
120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
1970-1979
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200



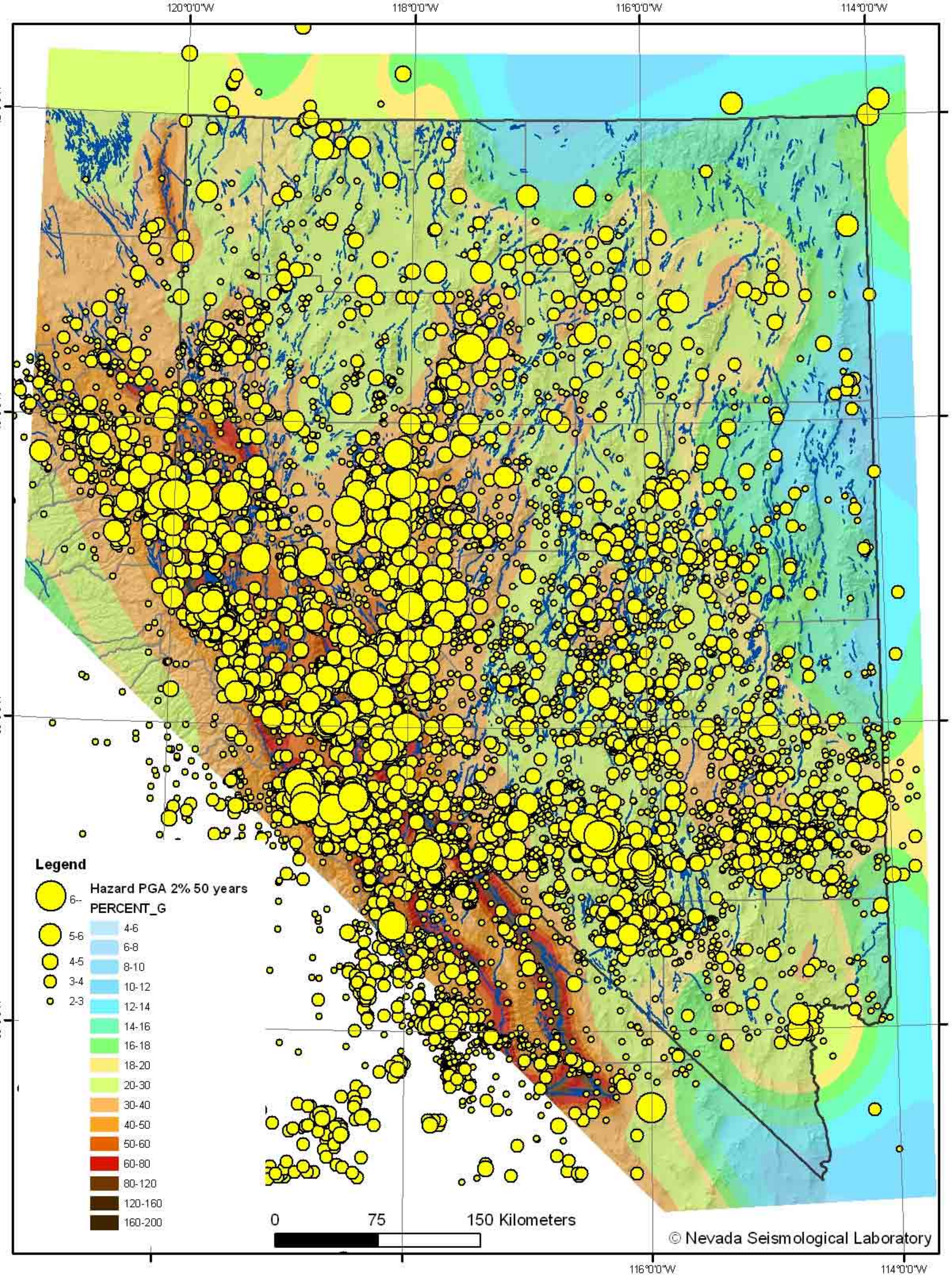
120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1980-1989
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory



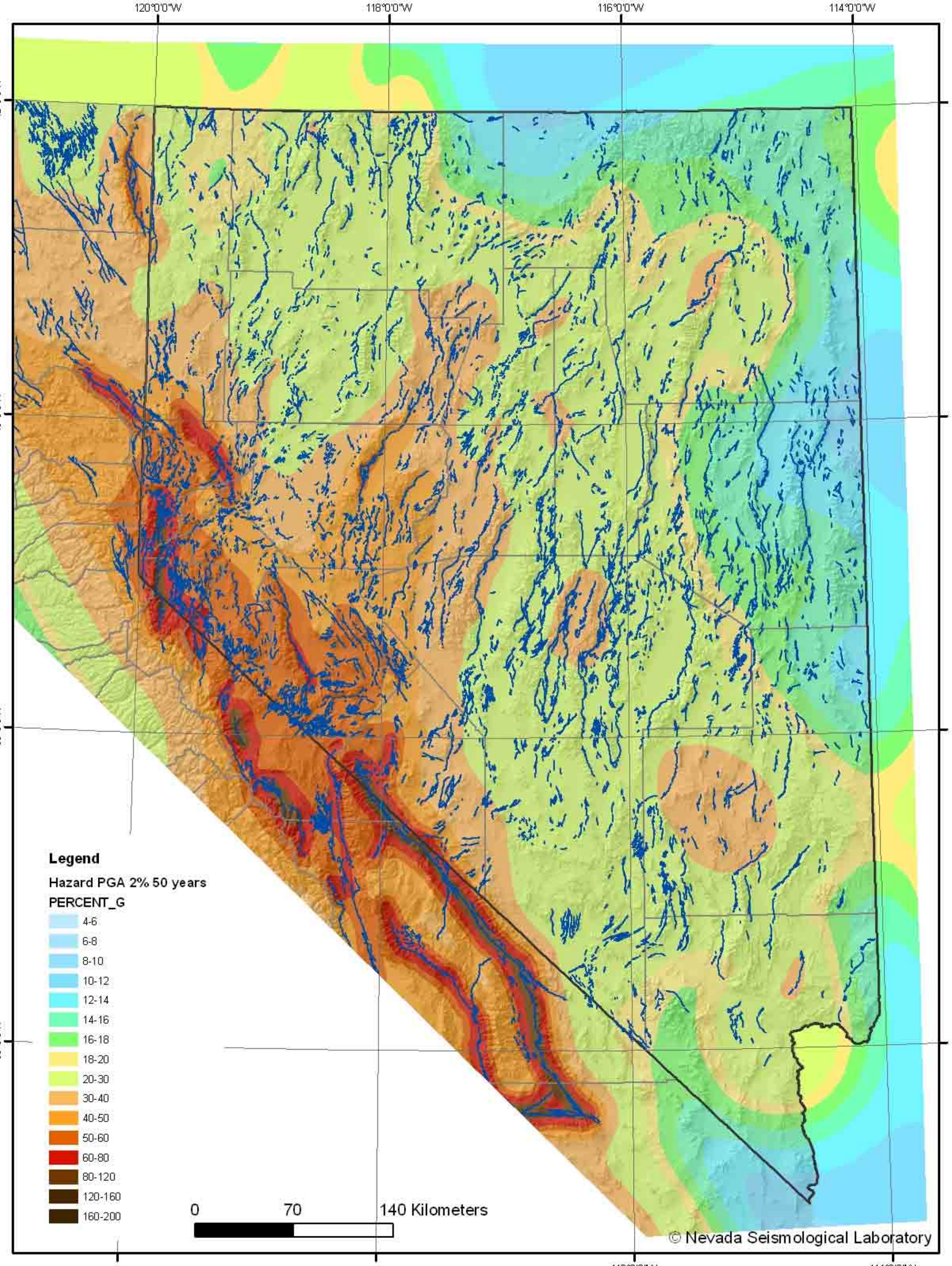
120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1990-1999
MAG
7.01 - 8.00
6.01 - 7.00
5.01 - 6.00
4.00 - 5.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory



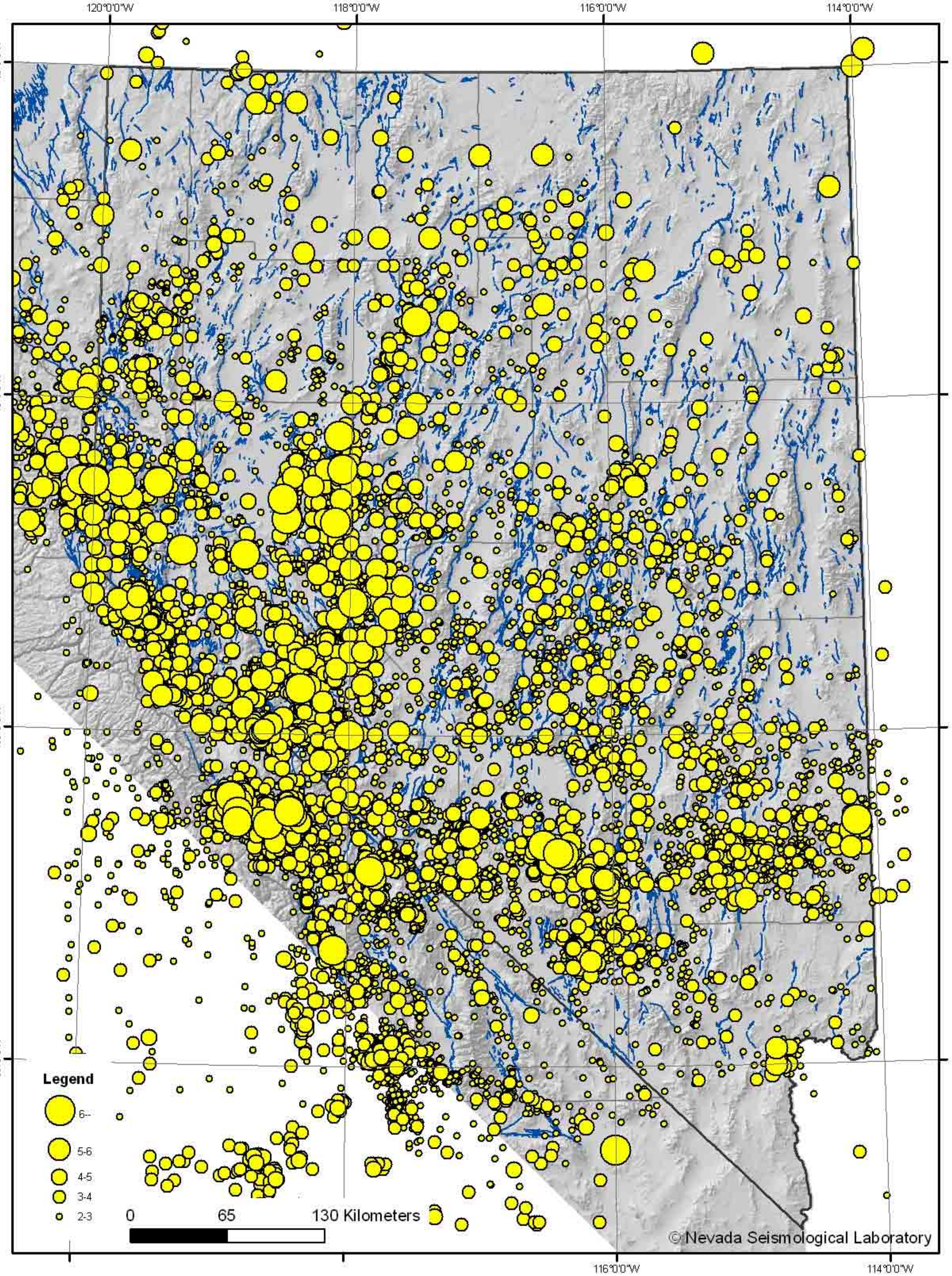
120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
2000-Present
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200



NEVADA Seismological Laboratory

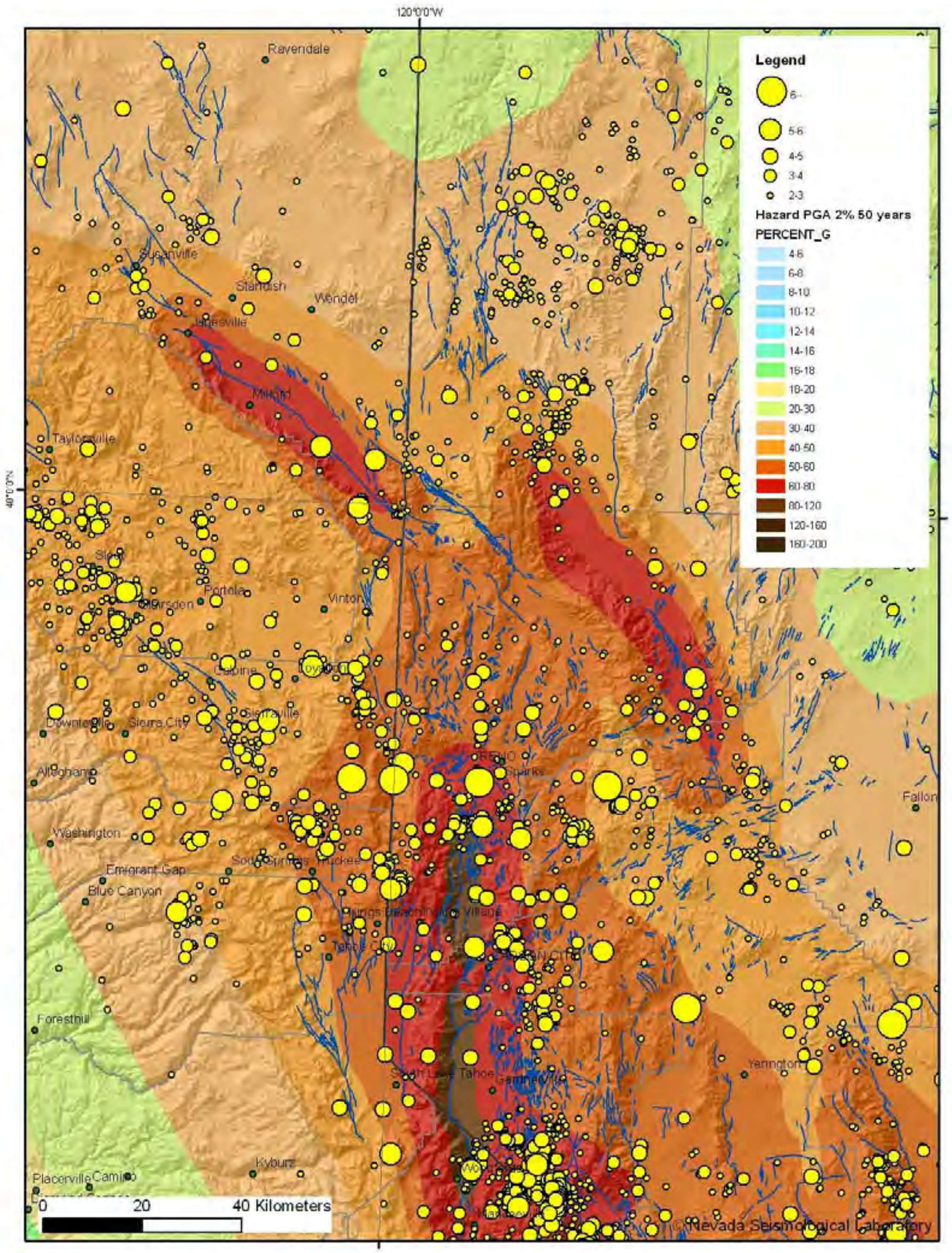


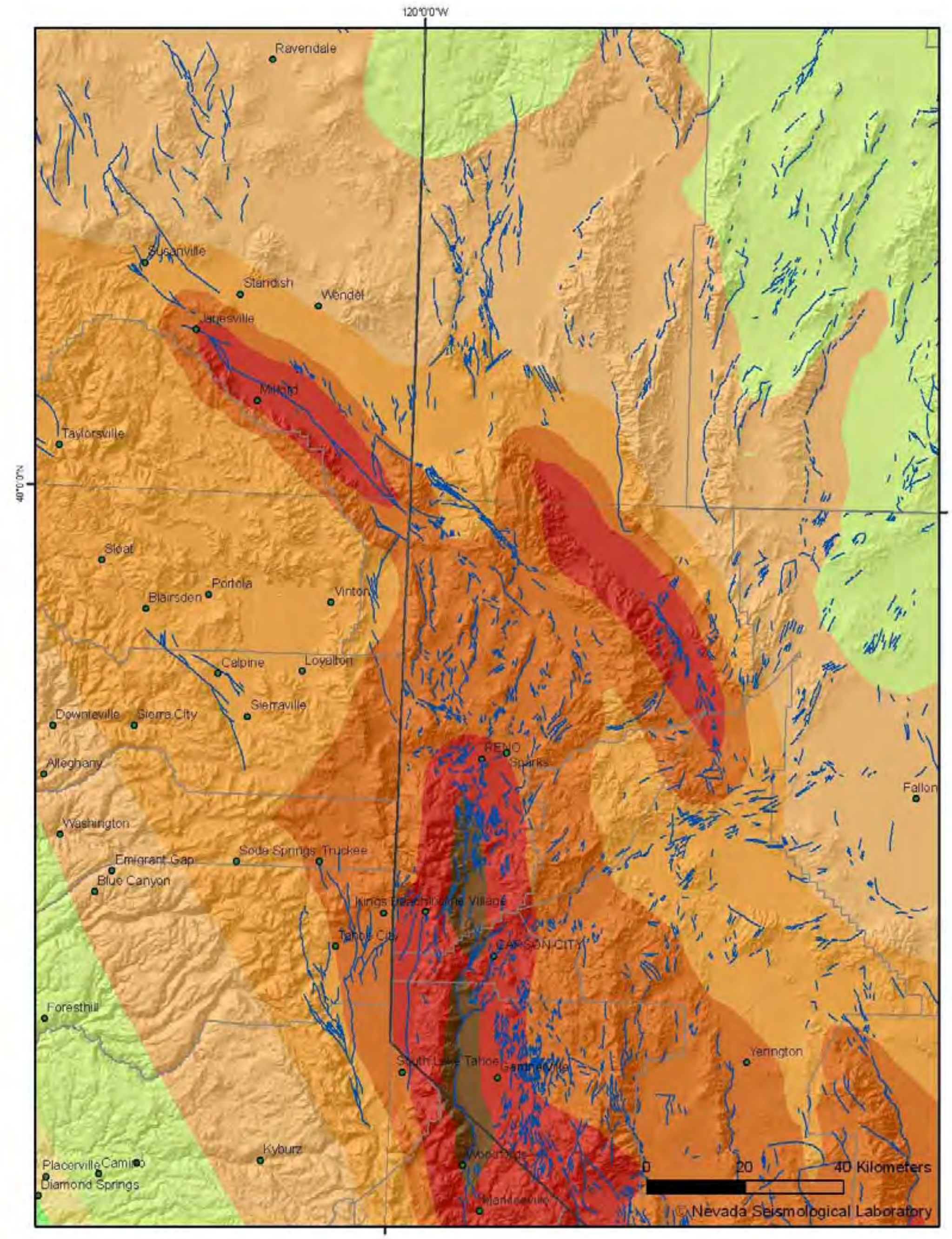
NEVADA Seismological Laboratory



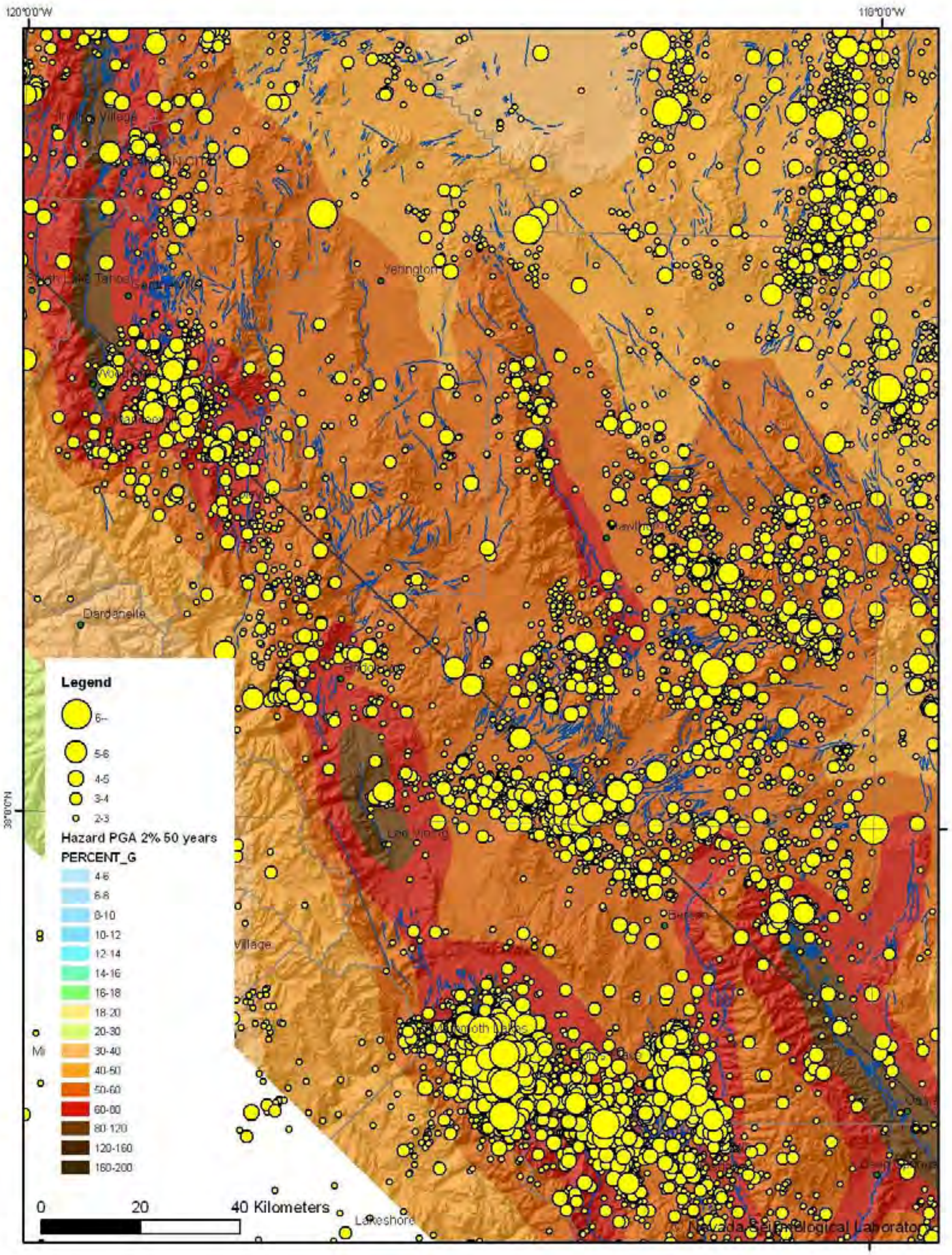
Nevada Seismological Laboratory

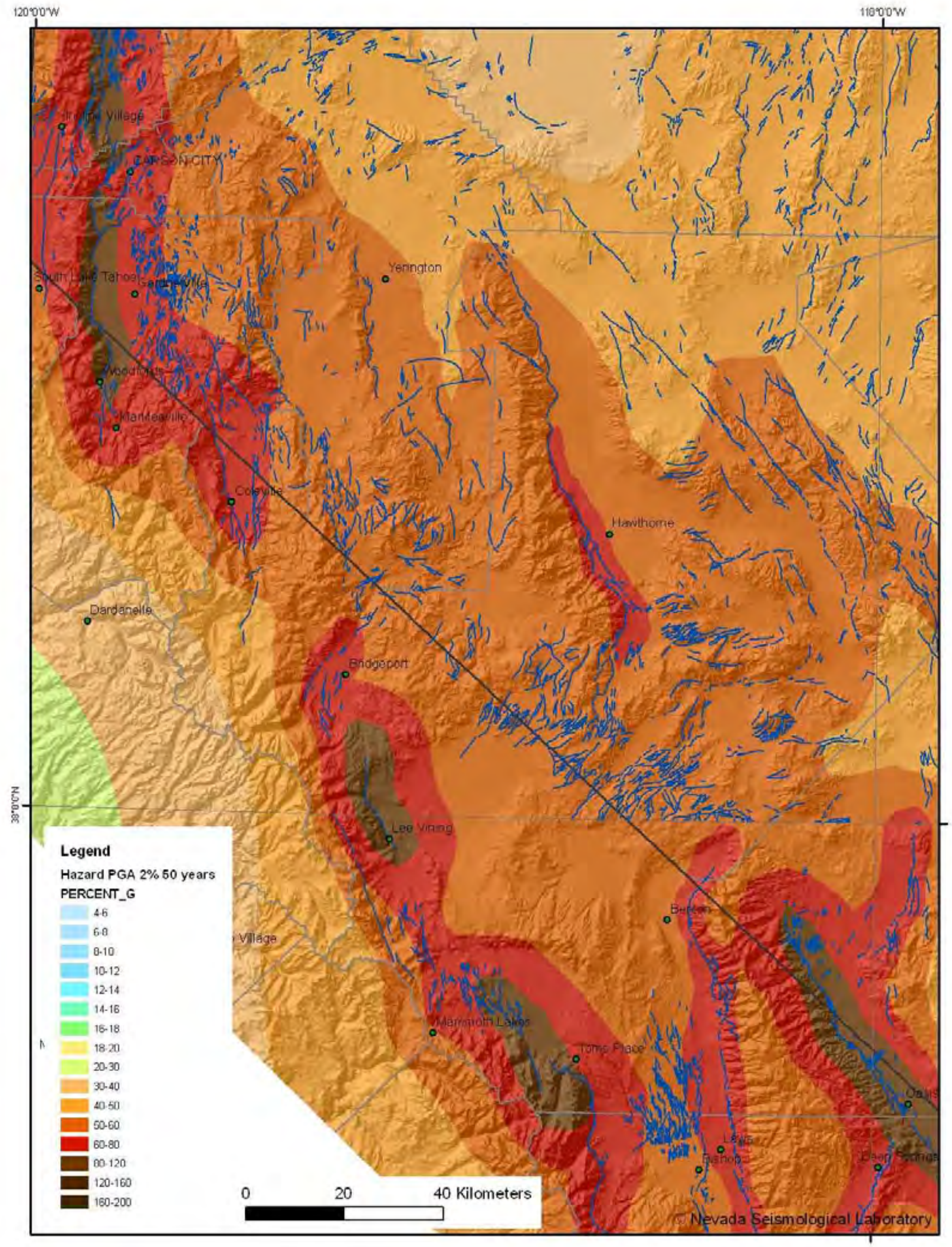
Susanville to Carson City

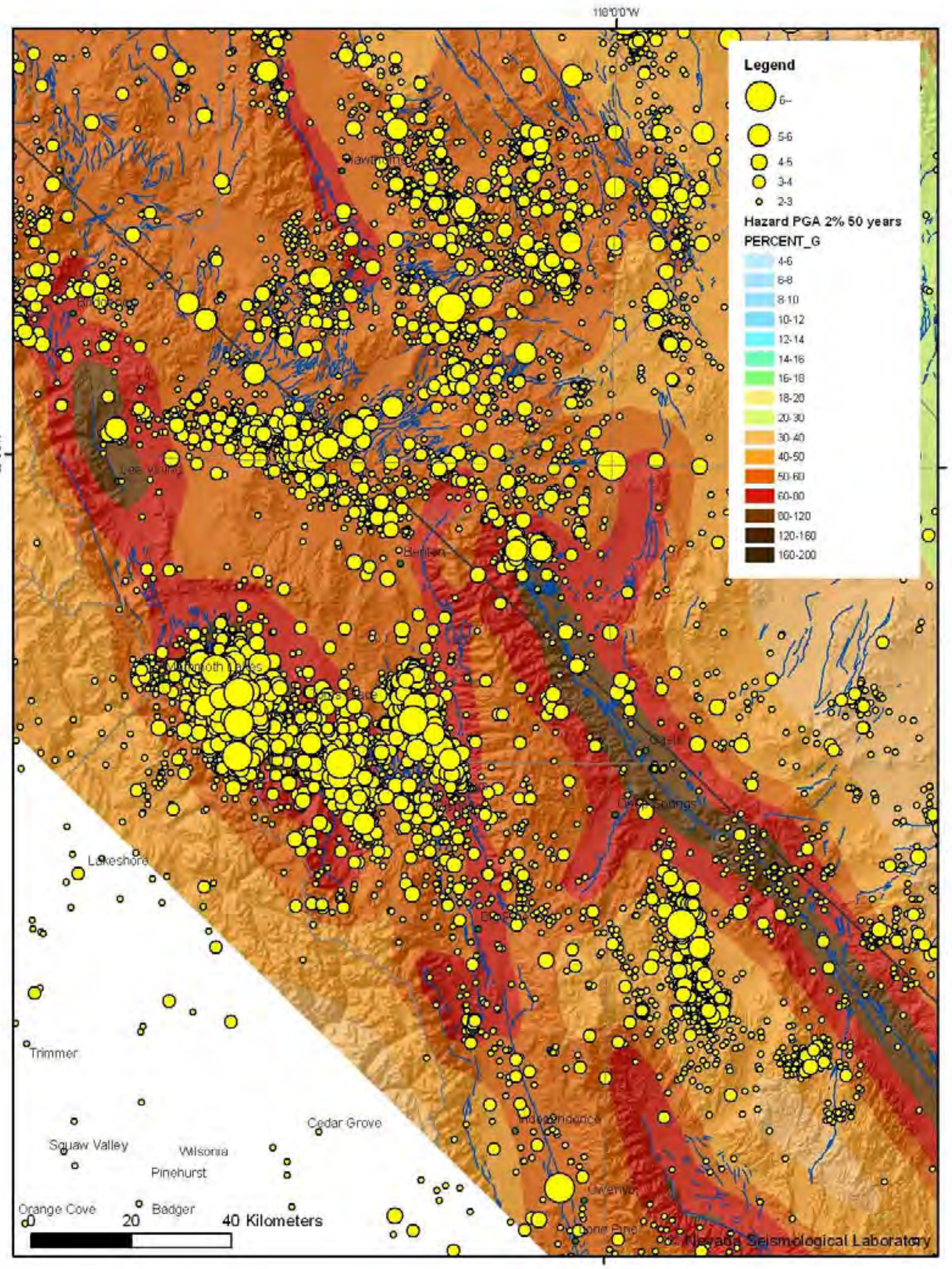




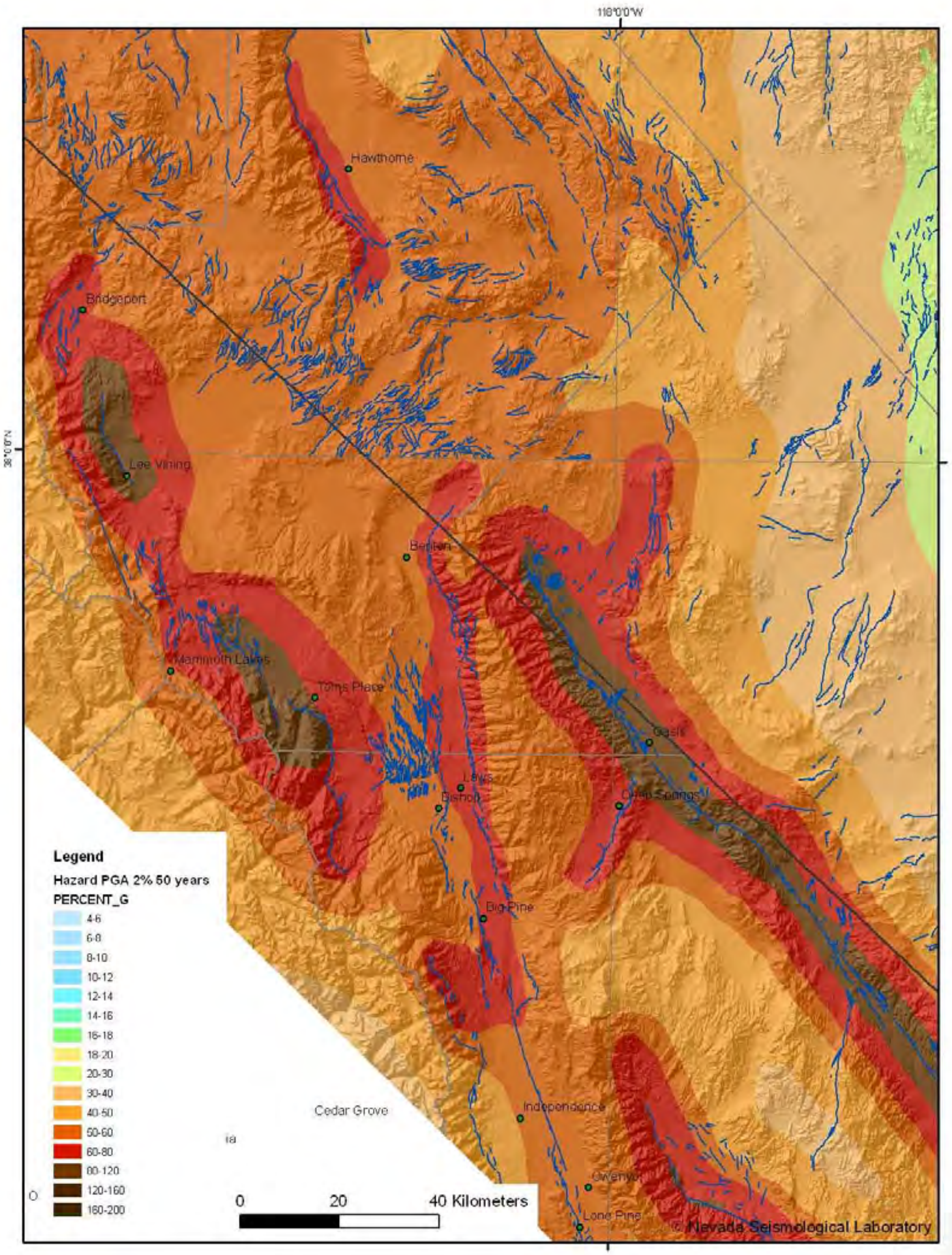
Carson City to Mammoth Lakes





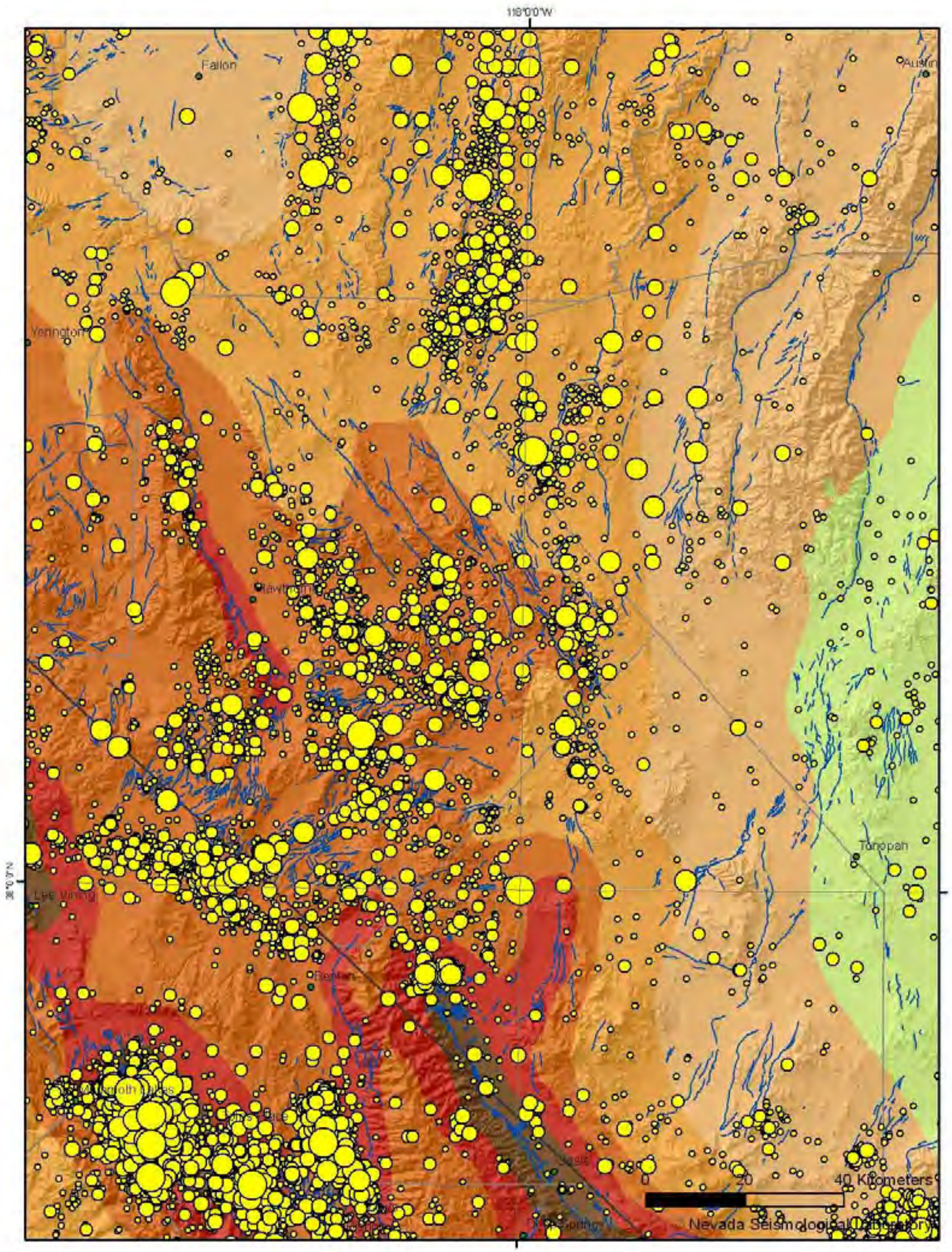


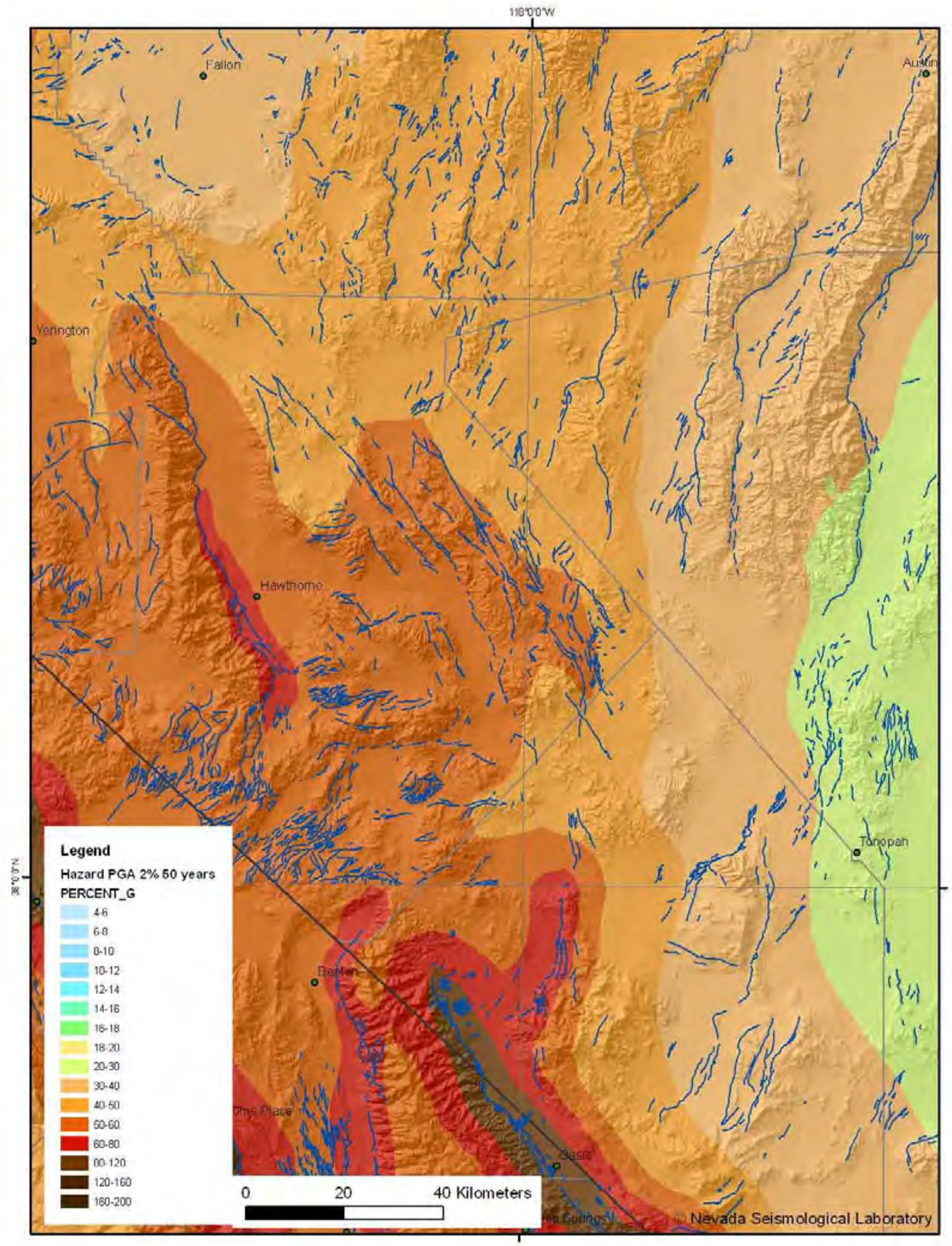
Legend
6--
5-6
4-5
3-4
2-3
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
Hawthorne
Bridgeport
Lee Vining
Benton
Mammoth Lakes
Oasis
Deep Springs
Lakeshore
Trimmer
Cedar Grove
Squaw Valley
Wilsonia
Pinehurst
Orange Cove
Badger
Independence
Owenyo
Lone Pine
0
20
40 Kilometers
© Nevada Seismological Laboratory



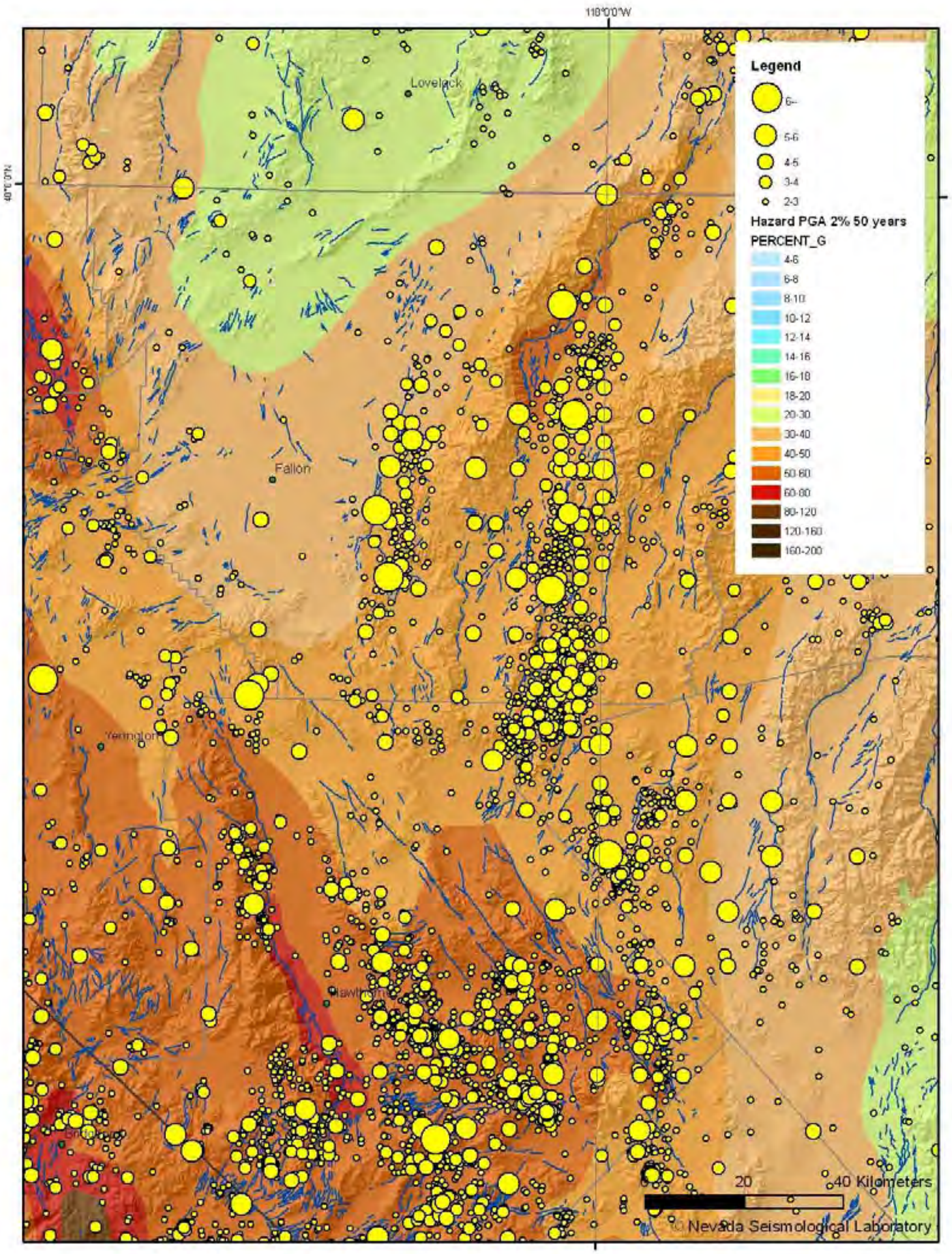
Hawthorne
Bridgeport
Lee Vining
Benton
Mammoth Lakes
Toms Place
Oasis
Laws
Bishop
Deep Springs
Big Pine
Independence
Cedar Grove
Owenyo
Lone Pine
Legend
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
0
20
40 Kilometers
© Nevada Seismological Laboratory

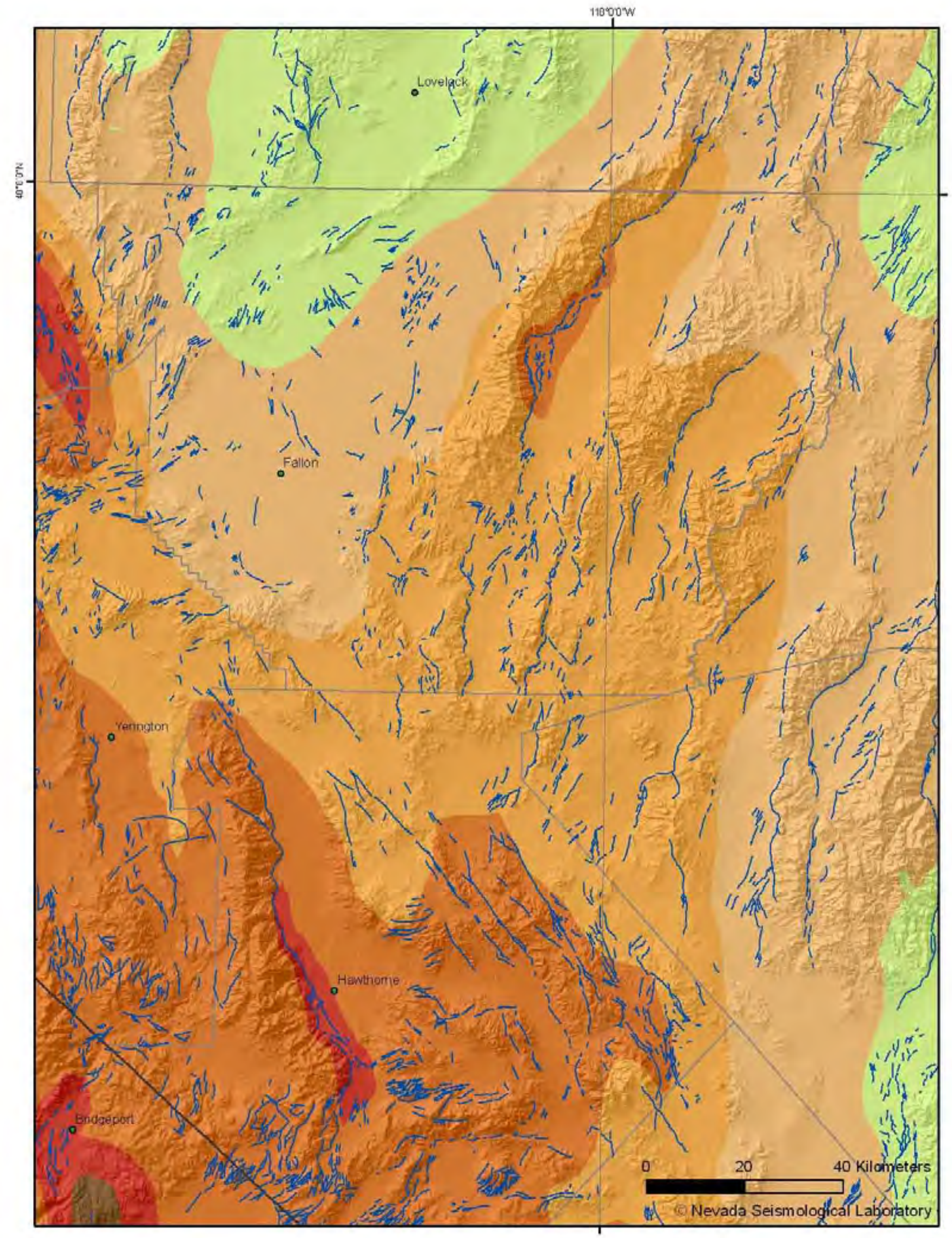
Southern CNSB



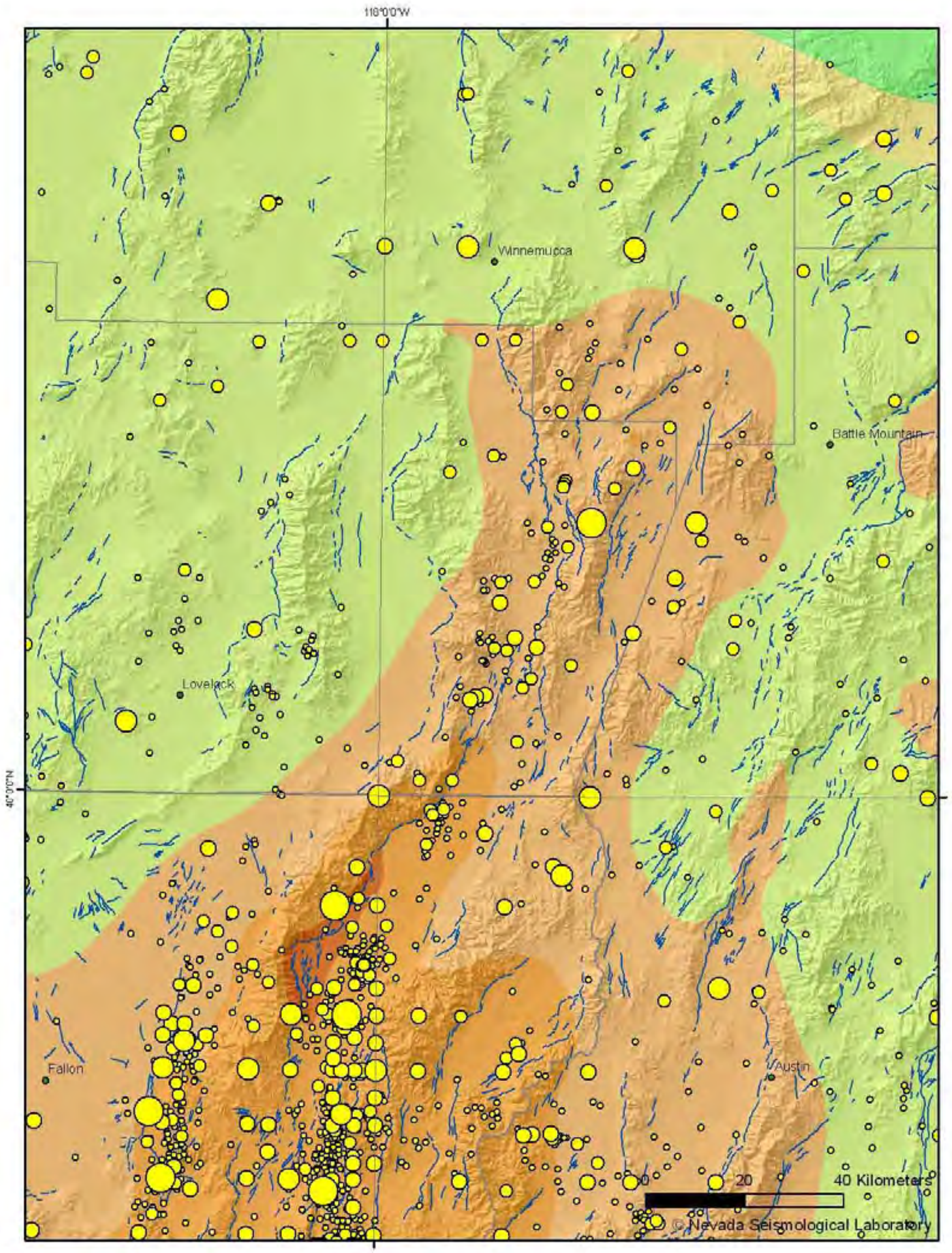


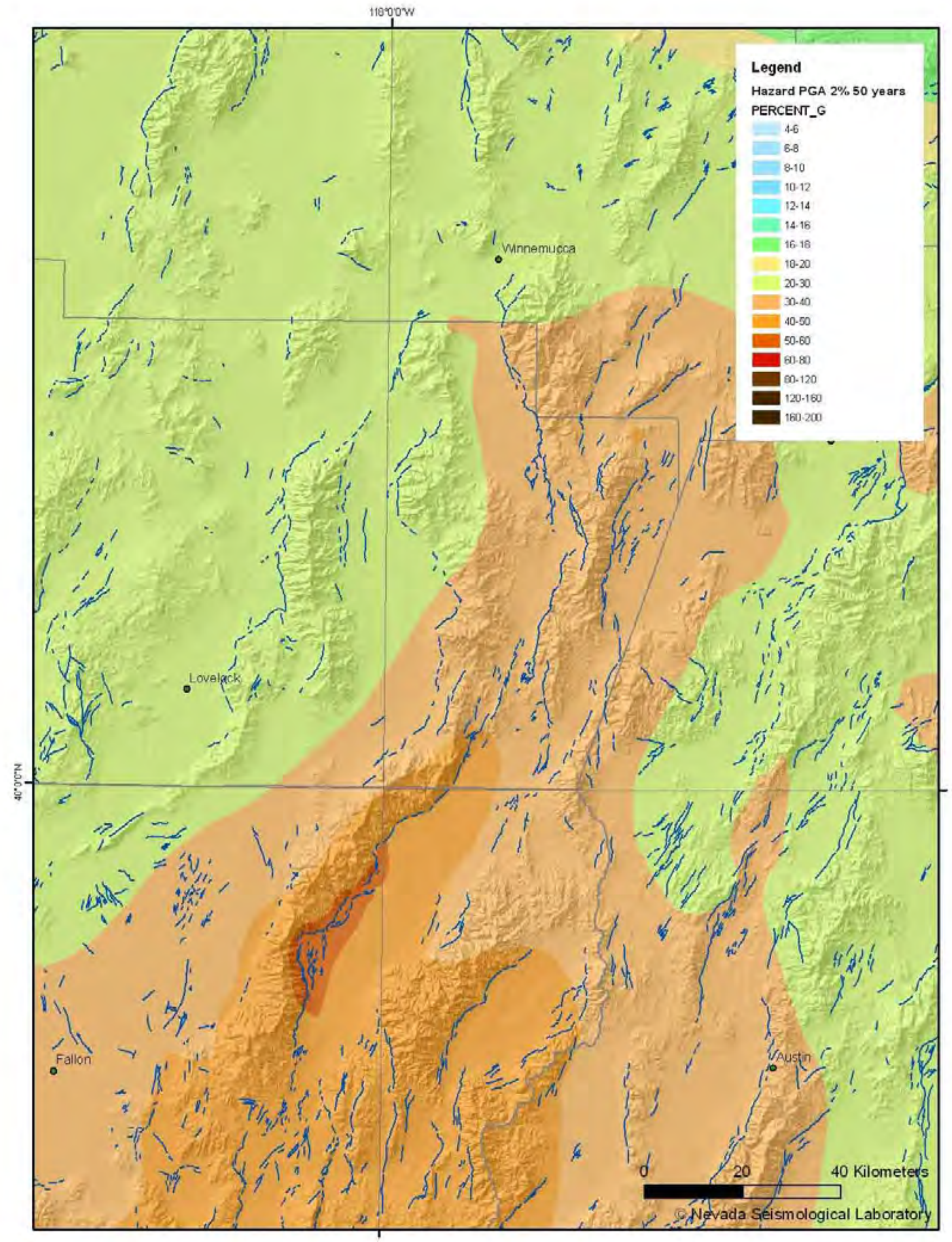
Central Nevada Seismic Belt

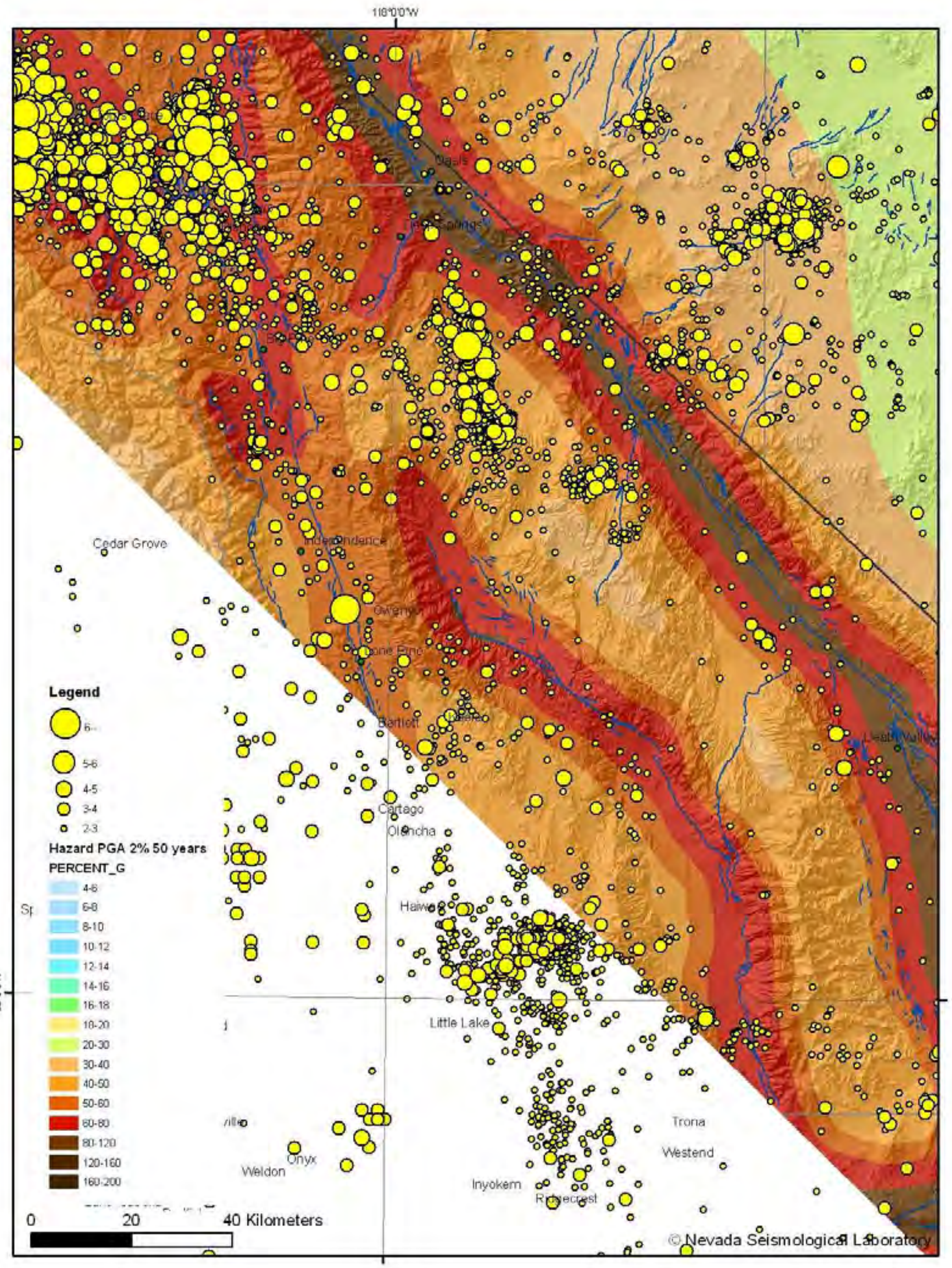


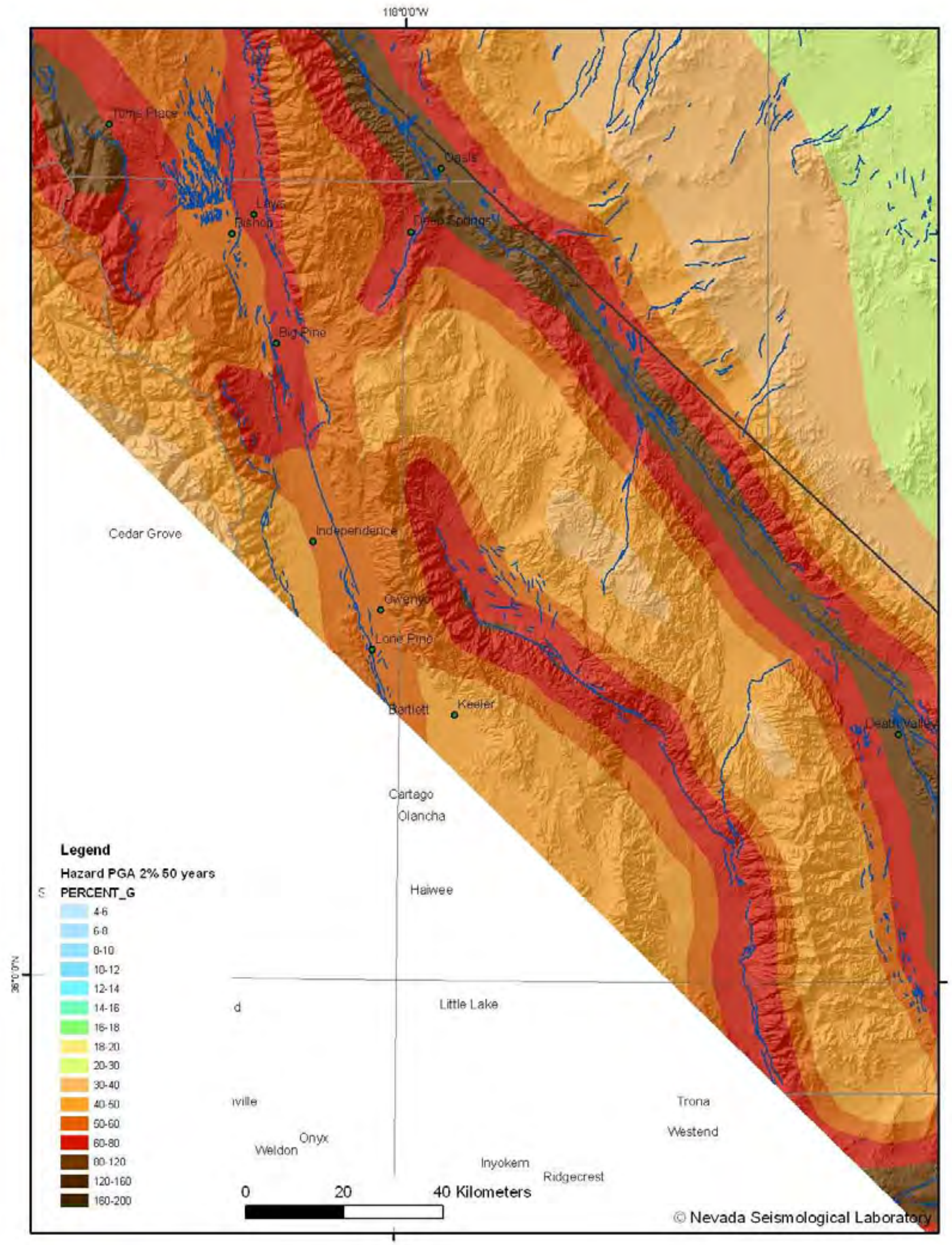


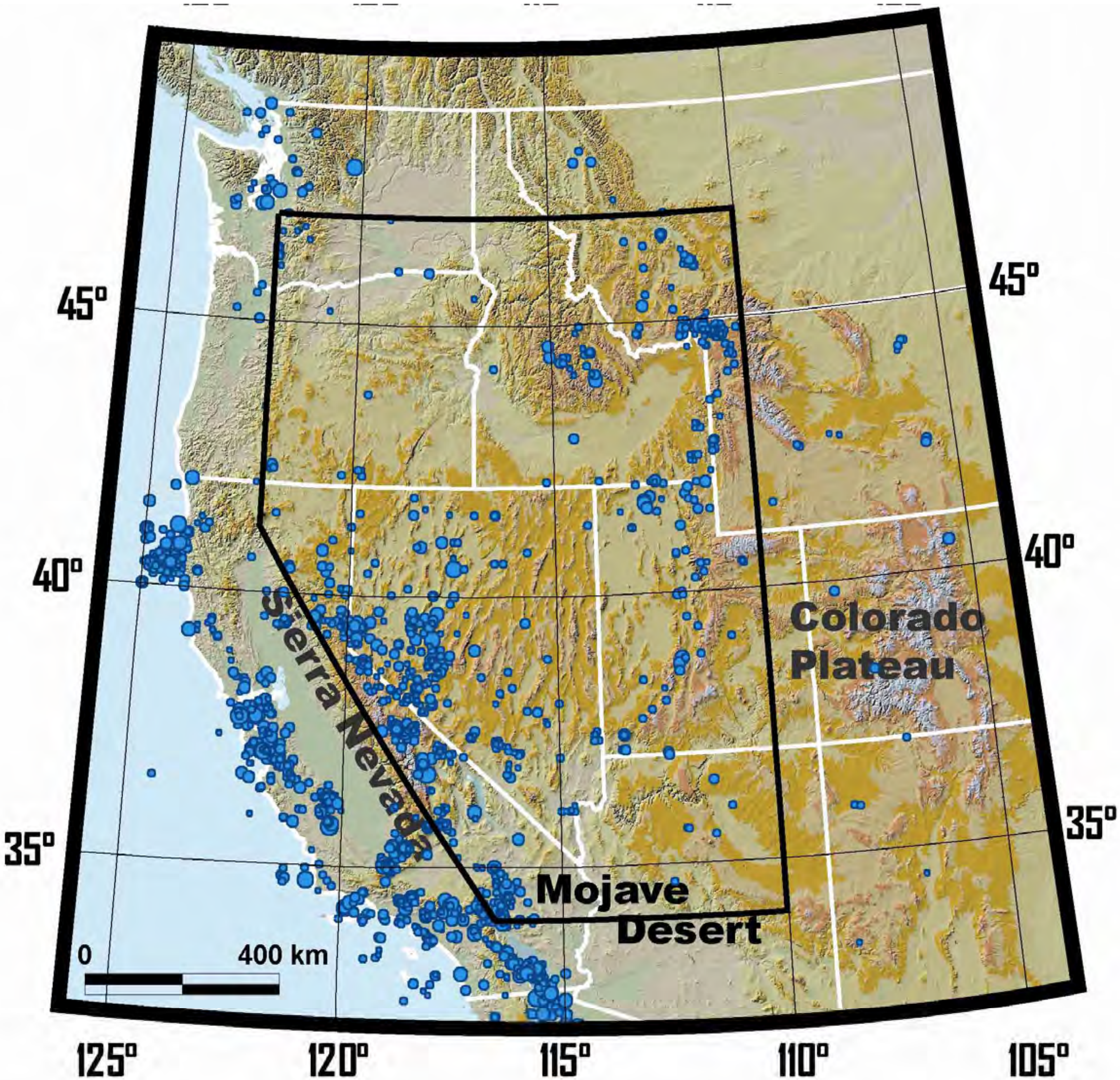
Northern CNSB



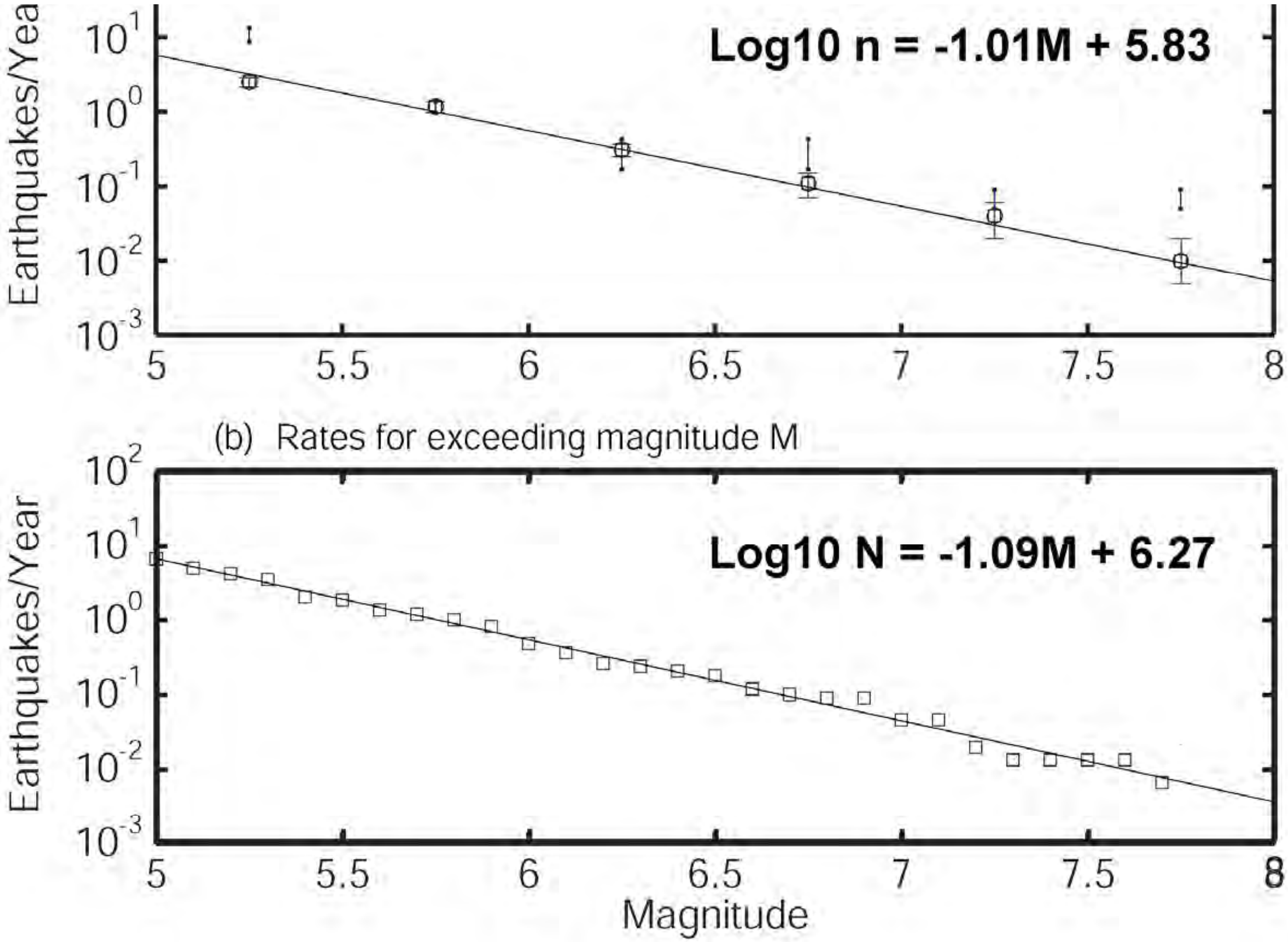



118°0'0"W
36°0'0"N
Cedar Grove
Independence
Owenyo
Lone Pine
Bartlett
Keeler
Death Valley
Cartago
Olancha
Haiwee
Little Lake
Trona
Westend
Weldon
Onyx
Inyokern
Ridgecrest
Legend
6-
5-6
4-5
3-4
2-3
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
0
20
40 Kilometers
© Nevada Seismological Laboratory


118°0'0"W
36°0'0"N
Toms Place
Laws
Bishop
Oasis
Deep Springs
Big Pine
Cedar Grove
Independence
Owenyo
Lone Pine
Bartlett
Keeler
Death Valley
Cartago
Olancha
Haiwee
Little Lake
Trona
Westend
Weldon
Onyx
Inyokern
Ridgecrest
Legend
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
0
20
40 Kilometers
© Nevada Seismological Laboratory

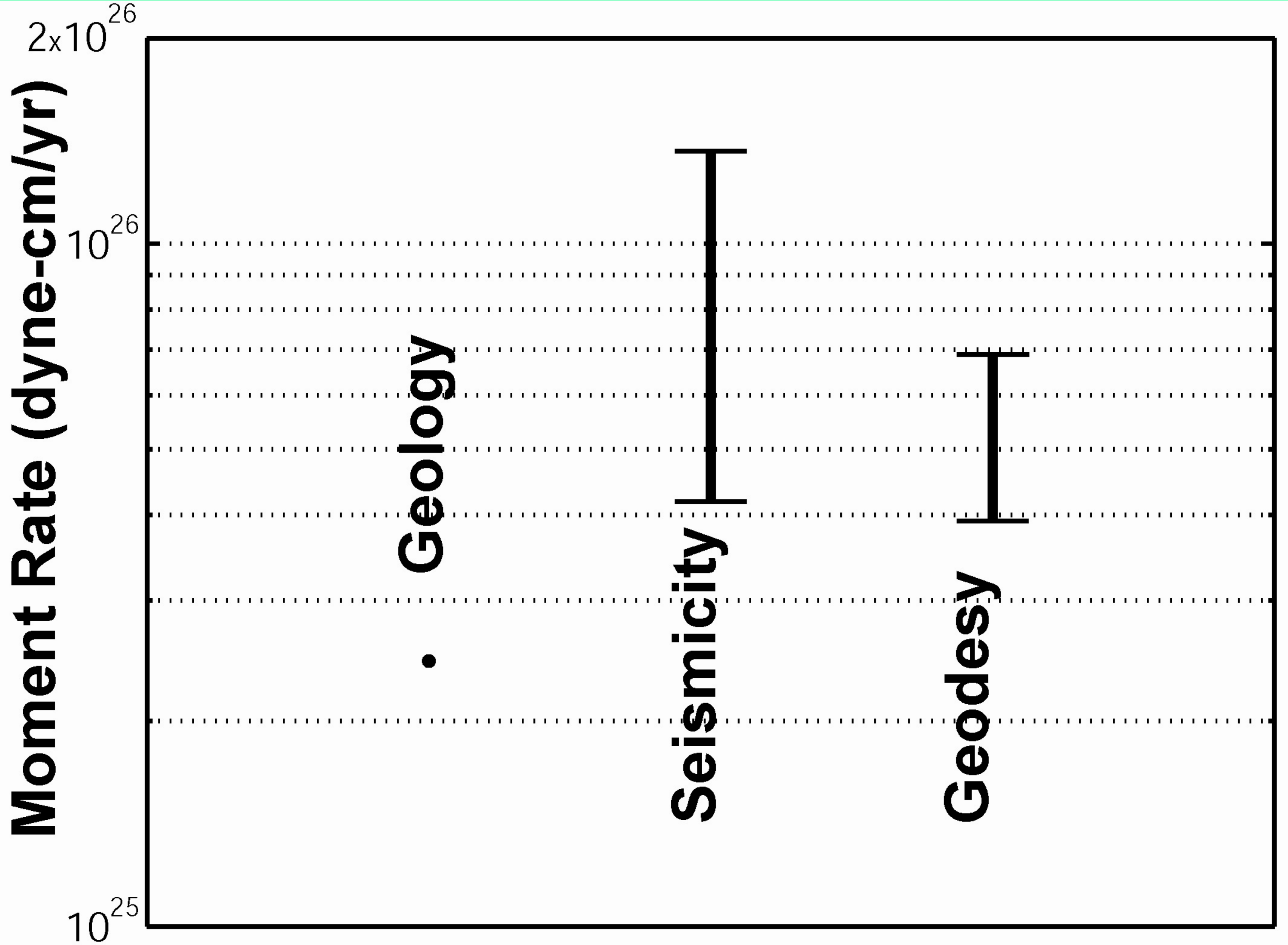


ological
atory



Earthquakes/Yea
Log10 n = -1.01M + 5.83
(b) Rates for exceeding magnitude M
Earthquakes/Year
Log10 N = -1.09M + 6.27
Magnitude

Figure 4



2x10^26
10^26
10^25
Moment Rate (dyne-cm/yr)
Geology
Seismicity
Geodesy

Figure 12

Seismological
Laboratory

Genoa fault

Paleoearthquake 1

1 sigma	500-600 cal B.P.
2 sigma	460-900 cal B.P.

Paleoearthquake 2

1 sigma	2,000-2,200 cal B.P.
2 sigma	1,770-2,700 cal B.P.

Genoa fault

Time since last event

1 sigma	500-600 yrs
2 sigma	460-900 yrs

PE1-PE2 interseismic interval

1 sigma	1,400-1,700 yrs
2 sigma	870-2,240 yrs

Monte Cristo fault zone
[1932 Cedar Mountain Eq.]

HE1	12/20/1932 10 p.m. (PST)	
PE1	930-1,678	cal B.P.
PE2	2,367-5,828	cal B.P.
PE3	5,622-10,324	cal B.P.
PE4	15,379-17,946	cal B.P.
PE5	17,720-21,359	cal B.P.

Note: all 1 sigma

Monte Cristo fault zone

Time since last event: 74 yrs

Interseismic intervals:

HE1-PE1	912	-	1,678	yrs
PE1-PE2	689	-	4,898	yrs
PE2-PE3	0	-	7,957	yrs
PE3-PE4	5,055	-	12,324	yrs
PE4-PE5	0	-	5,980	yrs

Warm Springs Valley fault system

Present	
	PE1 (smallest event)
	PE2
9-11 cal B.P.	
	PE3
14.5-16 cal B.P.	PE4
	PE5
	PE6
	PE7?
	PE8
17-25 y.b.p.	

Warm Springs Valley fault system

Average Earthquake Recurrence Intervals

~21,000 ybp to ~10,000 ybp

1.2 – 5 (1.7) ky

~10,000 ybp to present

3 – 11 (5) ky

Warm Springs Valley fault system

The last earthquake:

Probably within the last 2 kyrs (young).

But wimpy event (20 cm max. apparent vertical).

Partial stress release???

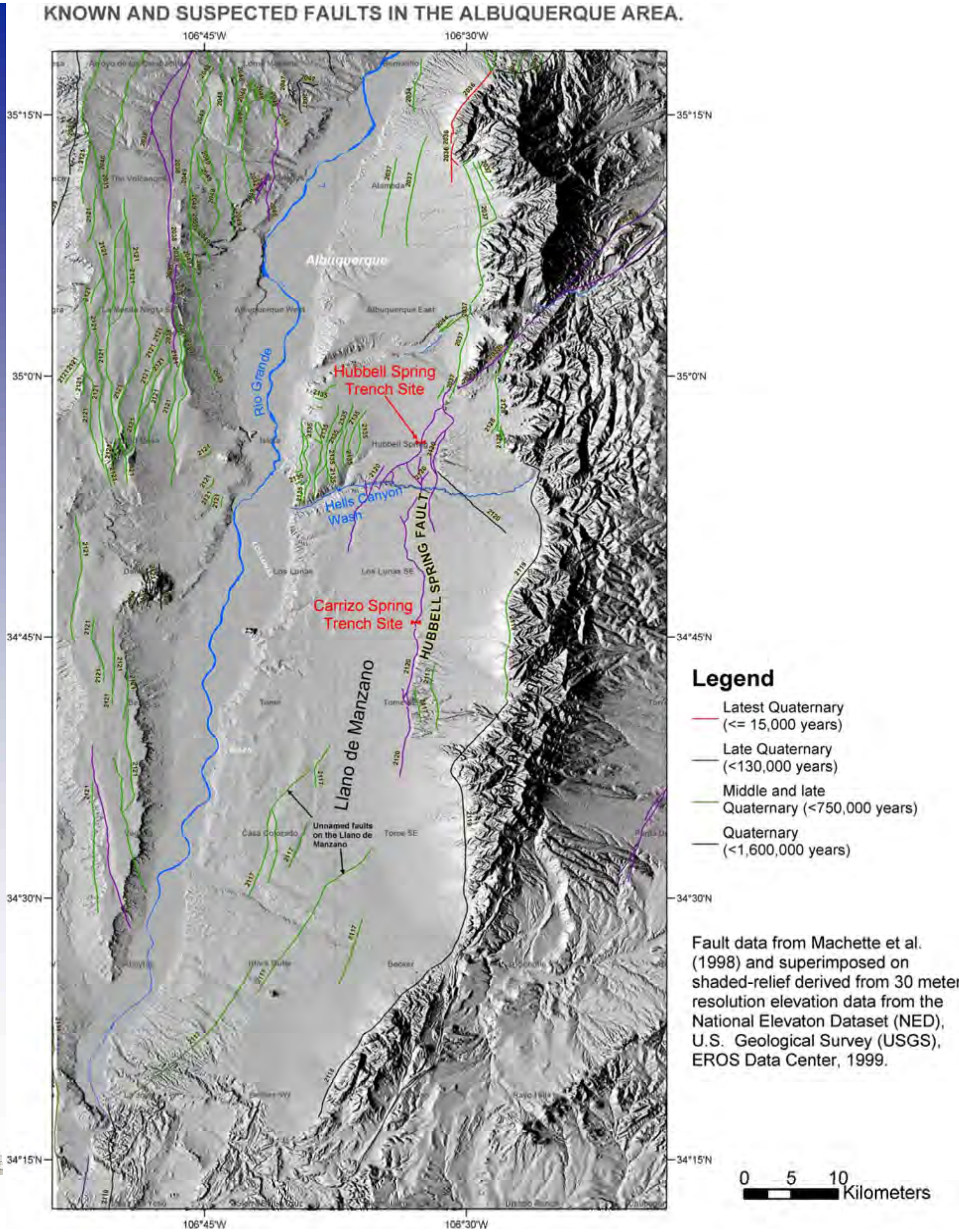
No worries? or primed to go?

Example of Non-characteristic Behavior in the Rio Grande Rift: Hubbell Spring Fault, NM

Susan Olig, Martha Eppes, Steven Forman, David Love, and Bruce Allen

NEHRP Award No. 99HQGR0089

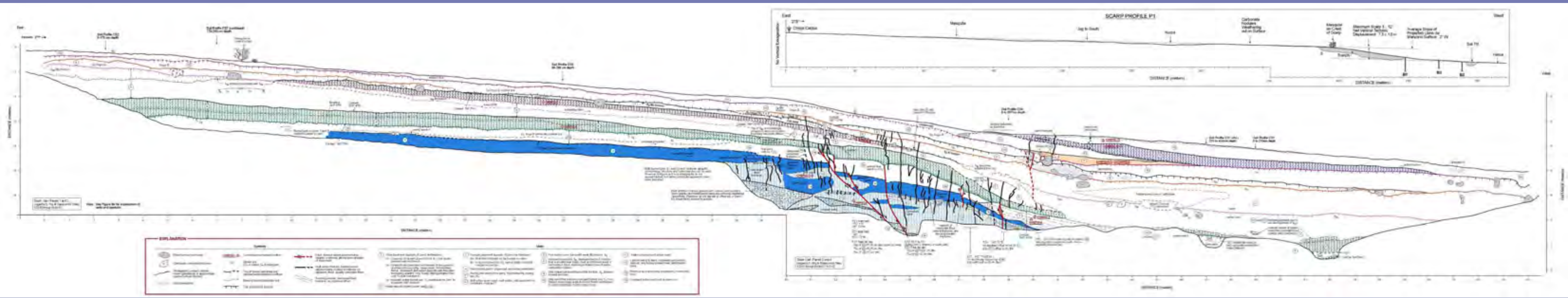
March 8, 2006



- **Intrabasin fault zone**
- **Multiple splays**
- **Complex geometry**
- **Active (late Quaternary) rift margin**

Carrizo Spring Trench Site

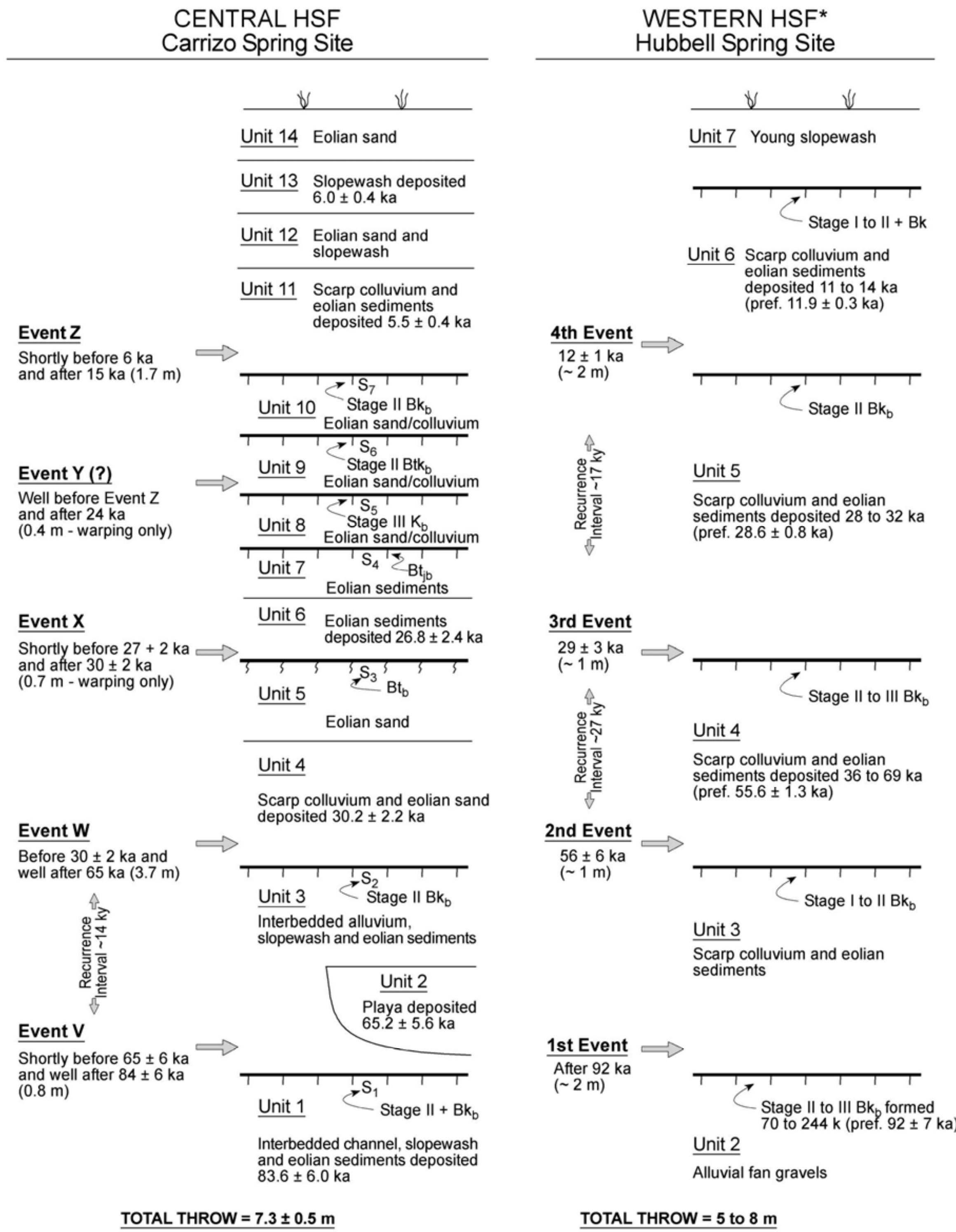
Carrizo Spring Trench Log



- At least 4, probably 5 earthquakes occurred since 84 ± 6 ka
- Throw per event is well-constrained

ESTIMATE OF DISPLACEMENTS PER EVENT ON THE CENTRAL HUBBELL SPRING FAULT*

SURFACE DEFORMATION EVENT	EVENT HORIZON	ESTIMATED NET VERTICAL TECTONIC DISPLACEMENT (m)	BASIS FOR ESTIMATE	STYLE OF DEFORMATION
Event Z	Top of **Buried Soil S_7** (on Unit 10)	**1.7** (1.4, 2.0)	Total apparent throw on top of S_7 (1.7± 0.3 m)	• Normal slip on FZ5 • Warping • Fracturing (?) • Backtilting (in FZ5 hanging wall)
Event Y (?)	Top of **Buried Soil S_5** (on Unit 8)	**0.4** (0, 1.2)	Differential offset between total apparent throw on top of S_5 (2.1 ± 0.5 m) and top of S_7	• Warping • Fracturing • Backtilting (?)
Event X	Top of **Buried Soil S_3** (on Unit 5)	**0.7** (> 0, 1.8)	Differential offset between total apparent throw on top of S_3 (2.8 ± 0.6 m) and top of S_5	• Warping • Fracturing
Event W	Top of **Buried Soil S_2** (on Unit 3)	**3.7** (2.6, 4.8)	Differential offset between total apparent throw on top of S_2 (6.5 ± 0.5 m) and top of S_3	• Normal slip on FZ1 through FZ4 (and buried faults west of Stn. 40m?) • Warping • Fracturing
Event V	Top of **Buried Soil S_1** (on Unit 1)	**0.8** (>0**, 1.6)	Differential offset between total apparent throw on top of S_1 (7.3 ± 0.3 m) and top of S_2	• Normal slip on FZ1, FZ2, and FZ3 (and buried faults west of Stn. 40m?) • Warping • Fracturing



* Data Sources: Personius *et al.*, 2001; and Personius and Mahan, 2003

Total Throw
<u>Per Event</u>

3.7 m

0.4 m

1.7 m

4.7 m

2.8 m

Hubbell Spring Fault Displacements (m)

Event	Central Splay	Western Splay	Total Throw
Z	1.7	2	3.7
Y (?)	0.4	0	0.4
X	0.7	~ 1	1.7
W	3.7	~ 1	4.7
V	0.8	~ 2	2.8

URS

Time-Dependent Probabilistic Seismic Hazard Analyses Along the Wasatch Front, Utah:

The Need for Longer Paleoseismic Records

Susan Olig, Patricia Thomas, and Ivan Wong

Seismic Hazards Group
URS Corporation
1333 Broadway, Suite 800
Oakland, CA 94612

18 May 2004

URS

Time-Dependent Probabilistic Seismic Hazard Analyses Along the Wasatch Front, Utah:

The Need for Longer Paleoseismic Records

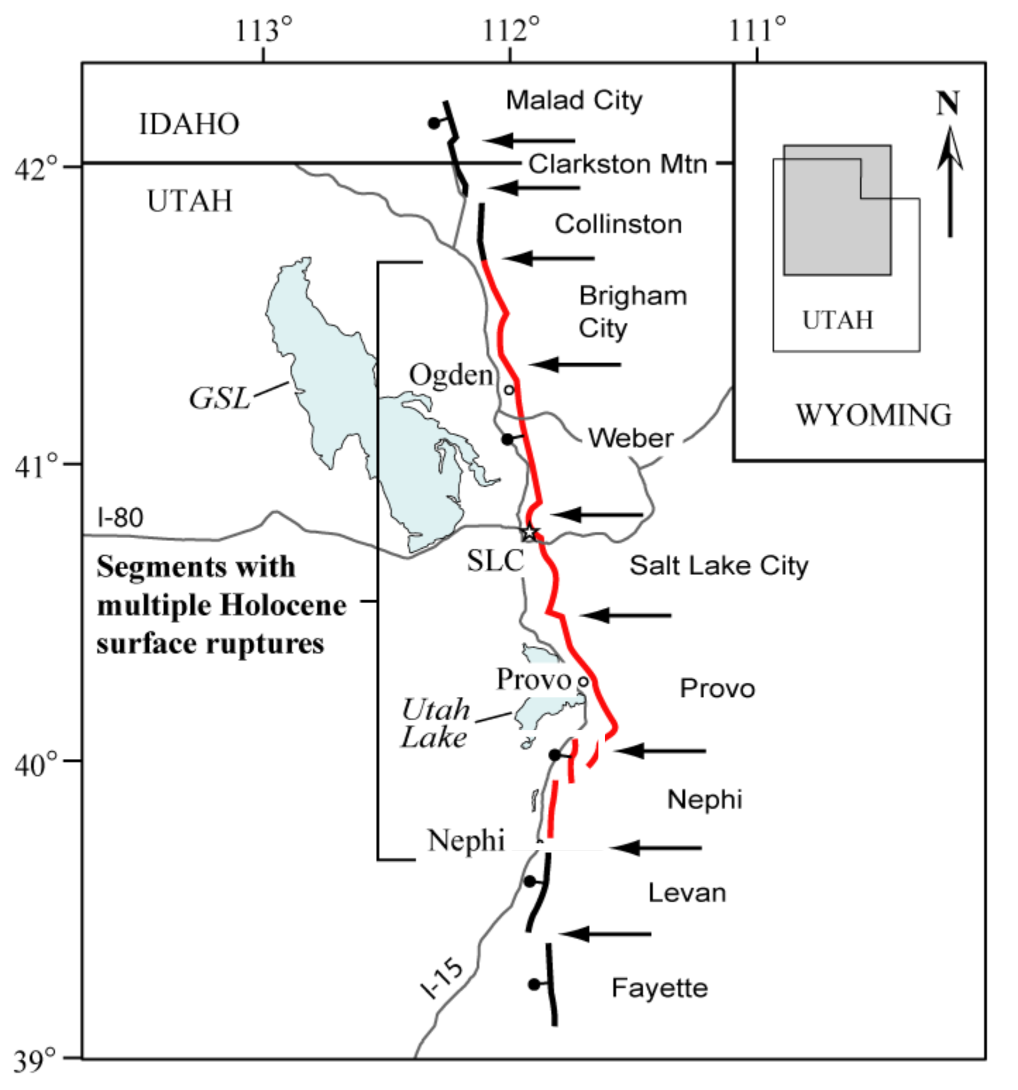
And More Complete

Susan Olig, Patricia Thomas, and Ivan Wong
Seismic Hazards Group
URS Corporation
1333 Broadway, Suite 800
Oakland, CA 94612

~~18 May 2004~~
8 March 2006

URS

Wasatch Fault Zone



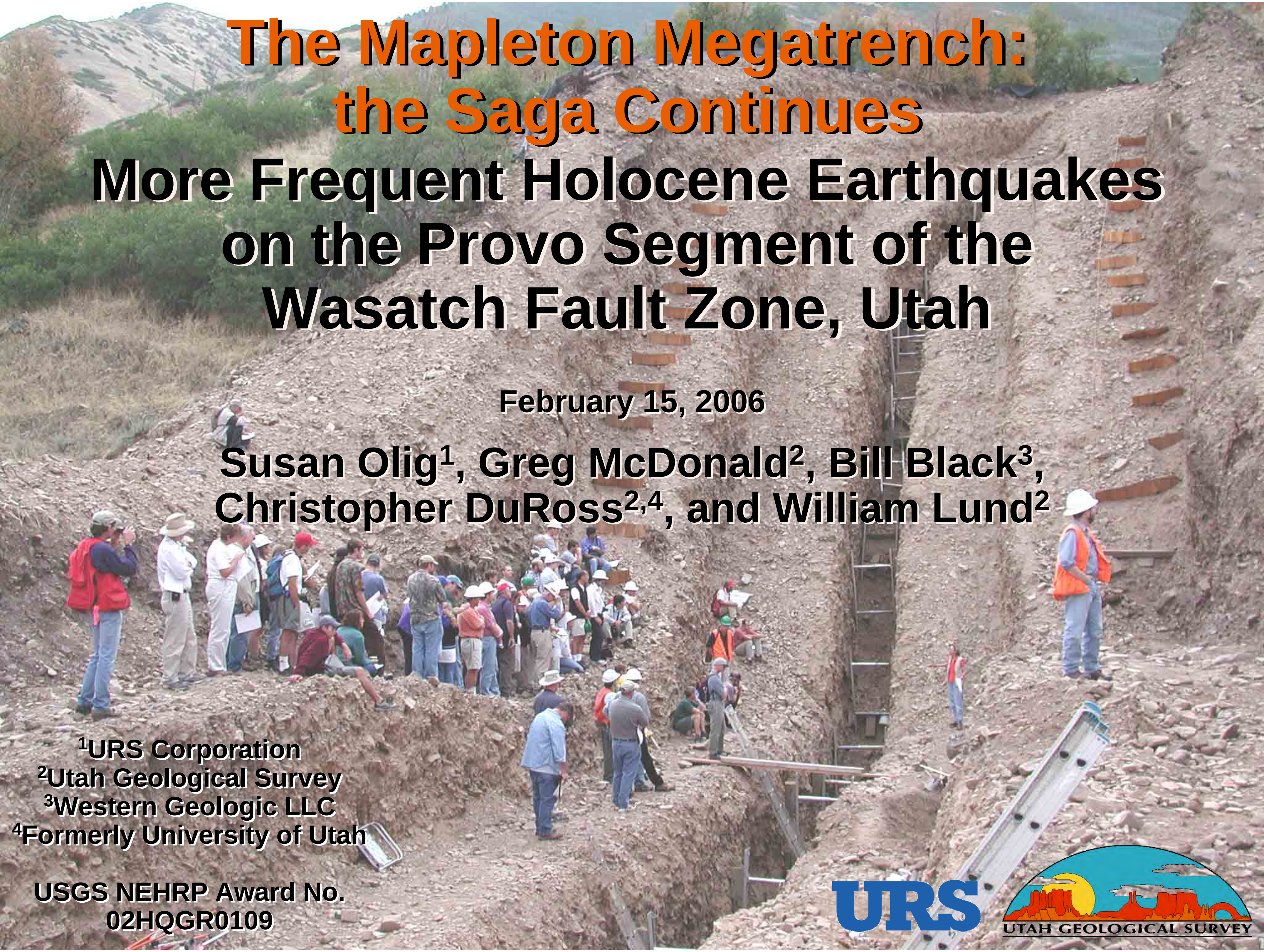
After Machette et al., 1992

- West-dipping normal fault
- ~370 km long
- 10 segments
- 5 central segments most active
- Extended paleoseismic records on:
  - Salt Lake City Segment
  - Brigham City Segment
  - Provo Segment (forthcoming)

Lesson Learned From Mapleton Megatrench on the Provo Segment:

More important to have a <u>complete</u> paleoseismic record than a long paleoseismic record for using time-dependent models in hazard analysis

URS



The Mapleton Megatrench: the Saga Continues

More Frequent Holocene Earthquakes on the Provo Segment of the Wasatch Fault Zone, Utah

February 15, 2006

Susan Olig[1], Greg McDonald[2], Bill Black[3], Christopher DuRoss[2,4], and William Lund[2]

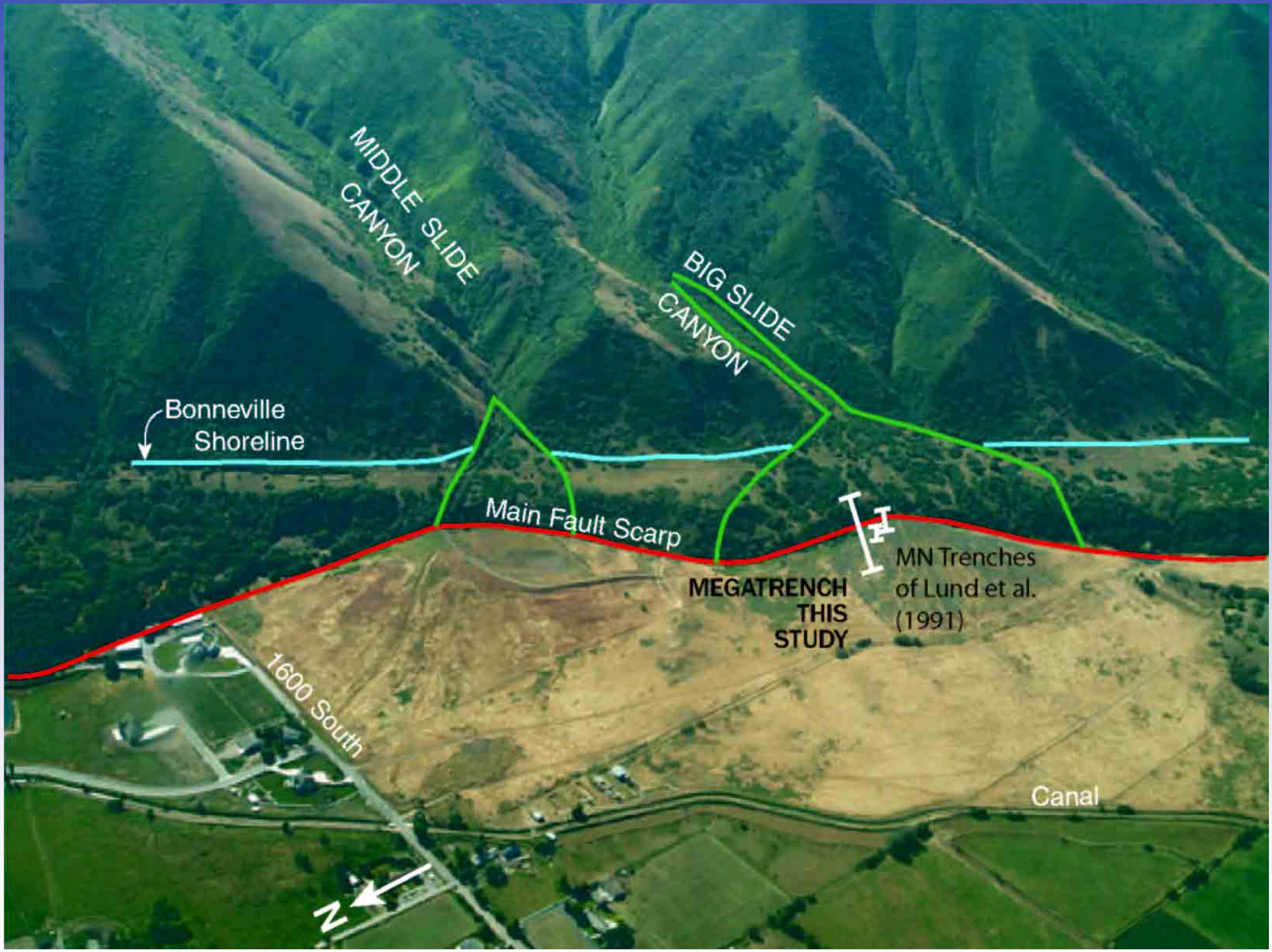
[1]URS Corporation
[2]Utah Geological Survey
[3]Western Geologic LLC
[4]Formerly University of Utah

USGS NEHRP Award No. 02HQGR0109

URS

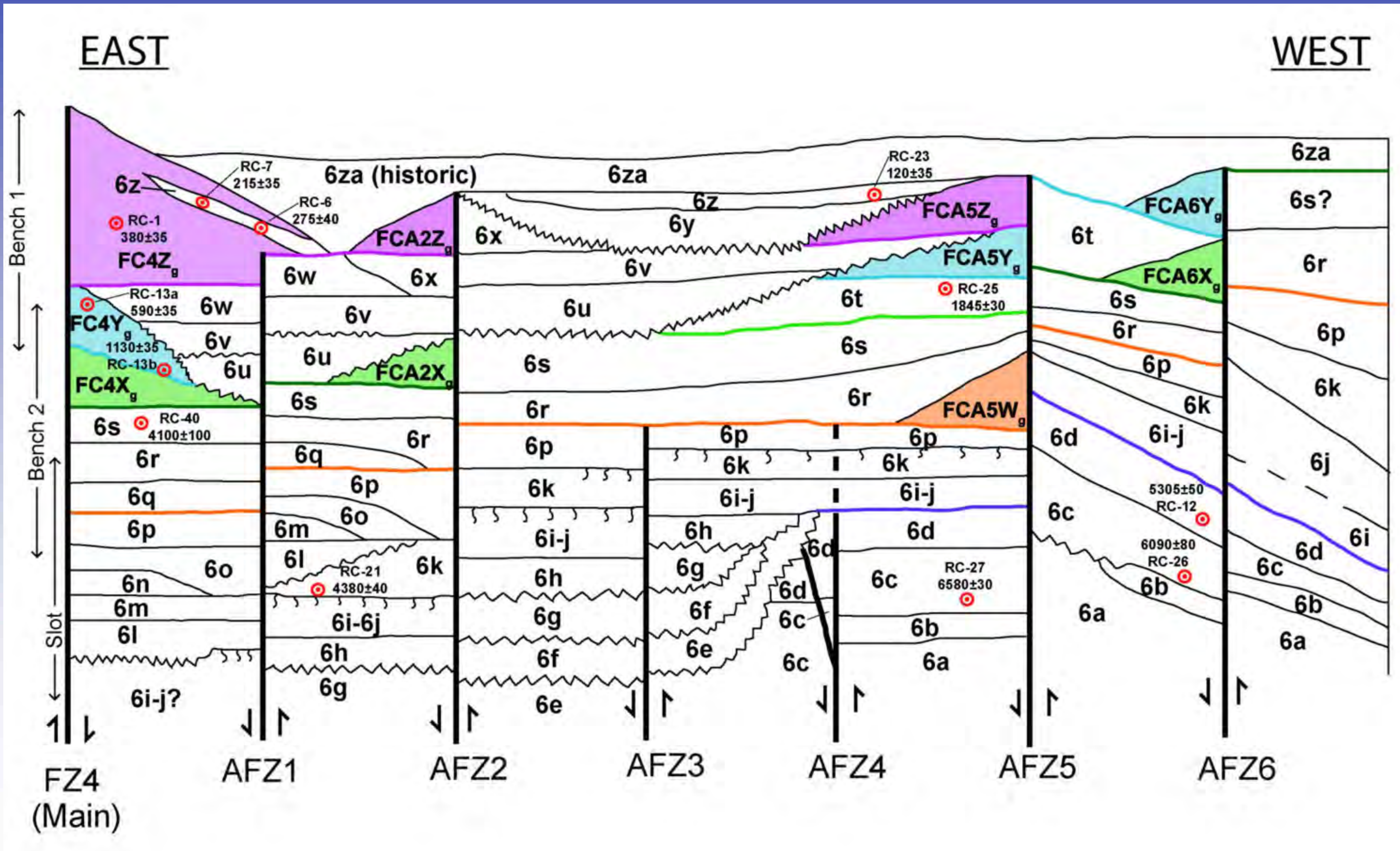
UTAH GEOLOGICAL SURVEY

Mapleton Megatrench Site



(Photo from R. Bruhn)

Graben Surface-Faulting Event Horizons
Events Z_g Through V_g (?)



URS

Graben Fault Summary

Surface Faulting Event and Age	FZ4	AFZ1	AFZ2	AFZ3	AFZ4	AFZ5	AFZ6
Z 600 (± 300) cal BP	- wedge - fault term. - buried free face - strat. offsets	- fault term. - strat. offsets	- wedge - fault term. - strat. offsets			- wedge - buried free face - strat. offsets	
Y 1,600 (+300, -600) cal BP	- wedge - fault term. - buried free face - strat. offsets	- diff. offsets - fault term.				- wedge on soil - buried free face - fault term. - diff. offsets	- wedge -buried free face - strat. offsets
X 3,100 (+1900, -1400) cal BP	- wedge/ fissure - strat. offsets - fault term.		- wedge - diff. offsets - fault term. - buried free face				- fissure/ wedge - diff. offsets - fault term. - buried free face
W 4,800 (± 400) cal BP	Not Active or Eroded	Not Active or Eroded		- diff. offsets - fault term. at soil		- wedge on soil - fault term. -diff. offsets	
V (?) 5,900 (+400, -1100) cal BP	Not Exposed	Not Exposed	Not Exposed	Not Exposed	- diff. Offset - fault term.		

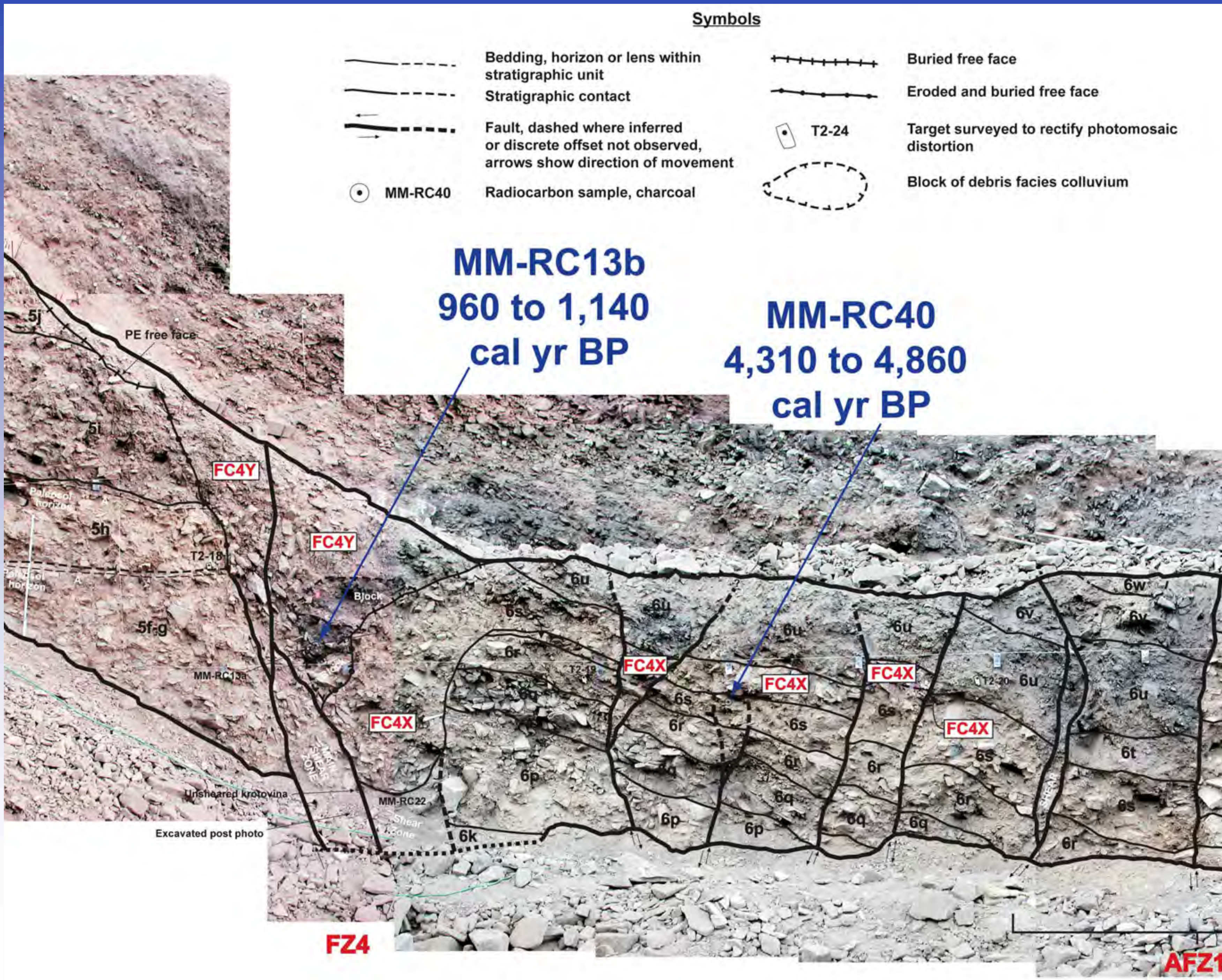
NOT ACTIVE

ACTIVE

<u>At least 4, Possibly 5 Separate Events</u>

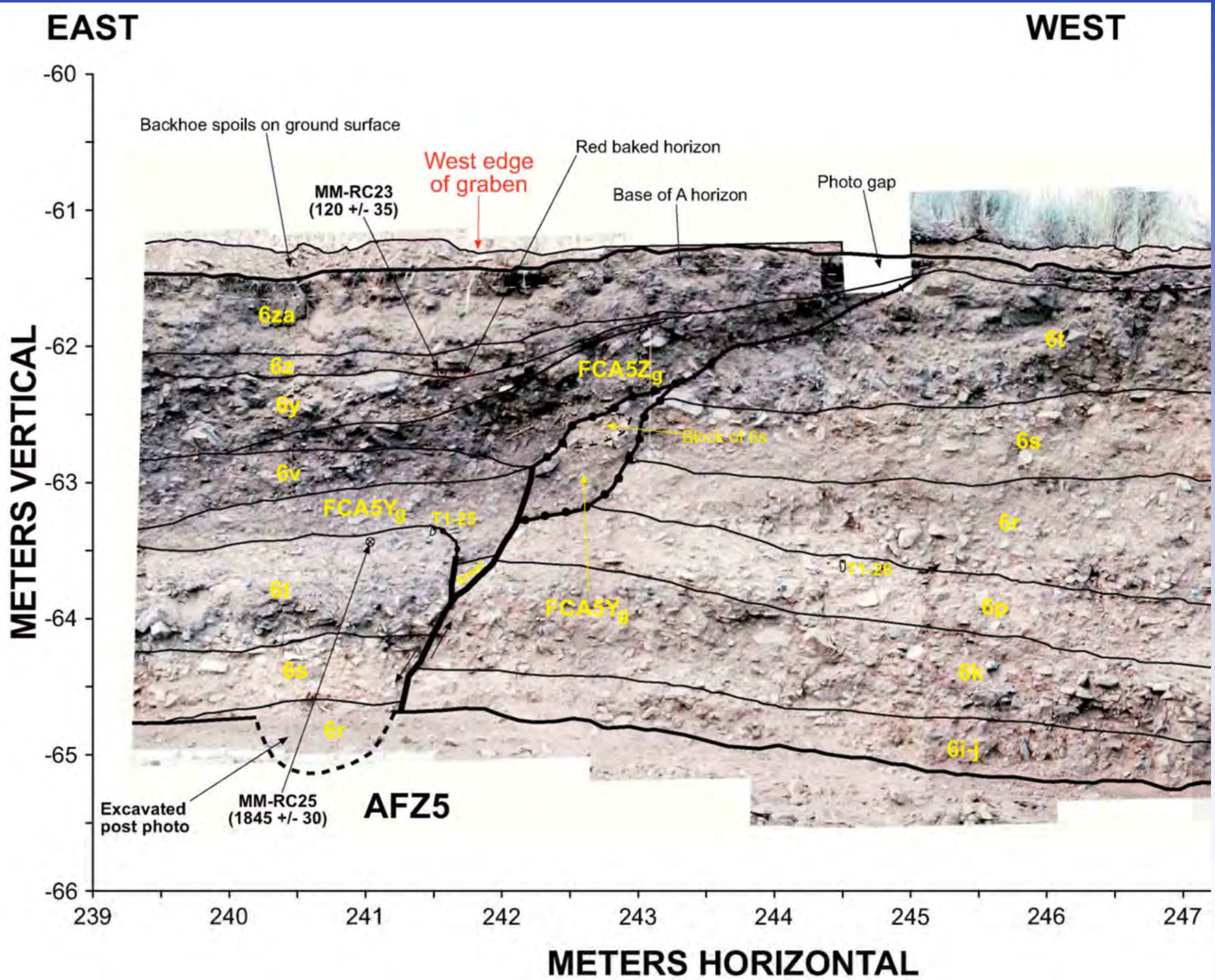
<u>Between ≈ 600 and 6,300 cal BP</u>

FZ4 Bench 2

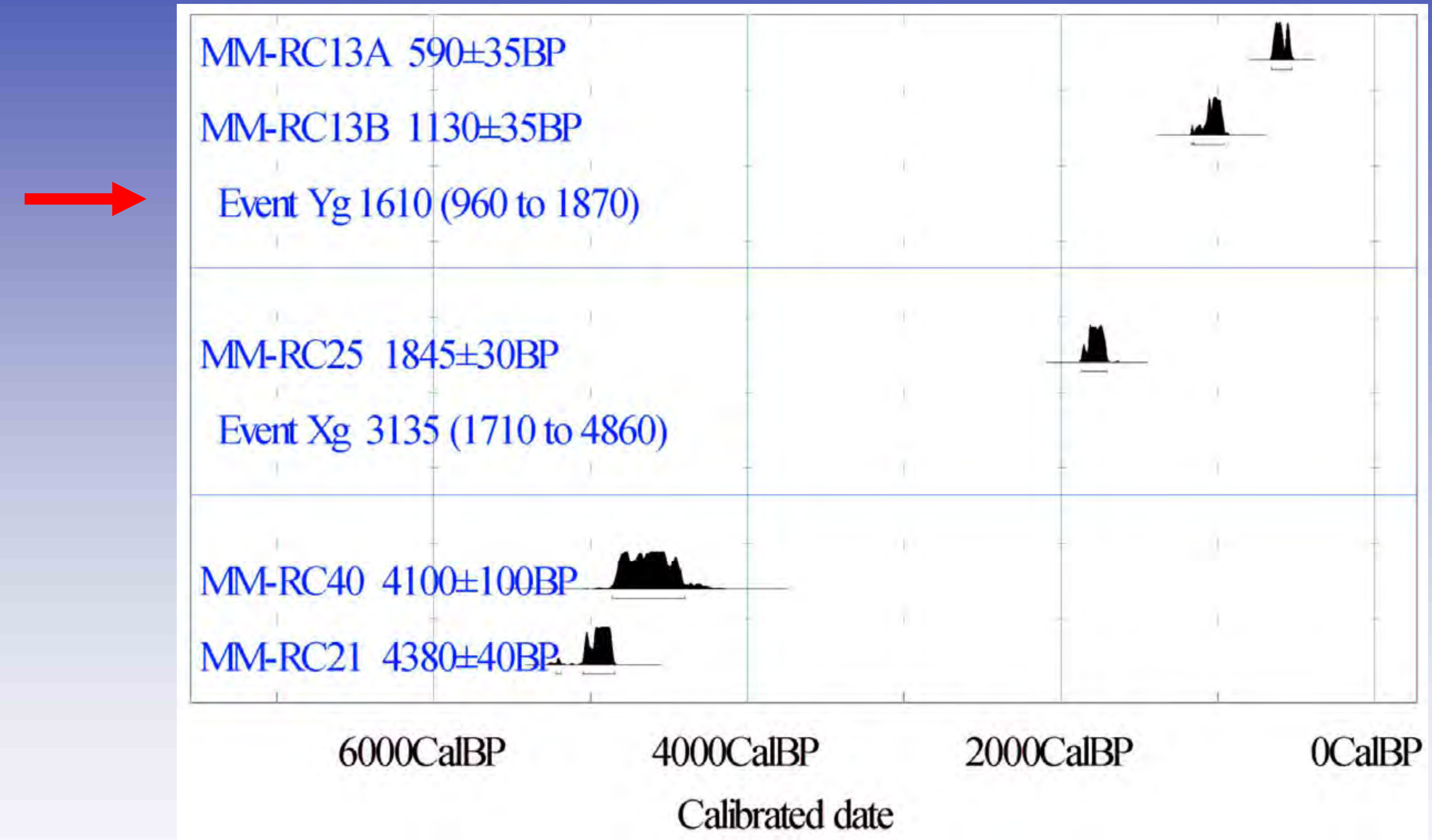


Symbols
Bedding, horizon or lens within stratigraphic unit
Stratigraphic contact
Fault, dashed where inferred or discrete offset not observed, arrows show direction of movement
MM-RC40
Radiocarbon sample, charcoal
Buried free face
Eroded and buried free face
T2-24
Target surveyed to rectify photomosaic distortion
Block of debris facies colluvium
MM-RC13b
960 to 1,140
cal yr BP
MM-RC40
4,310 to 4,860
cal yr BP
PE free face
FC4Y
FC4Y
FC4X
FC4X
FC4X
FC4X
FC4X
Block
Unsheared krotovina
Excavated post photo
MM-RC22
FZ4
AFZ1

AFZ5 Bench 1


EAST
WEST
Backhoe spoils on ground surface
West edge of graben
Red baked horizon
MM-RC23 (120 +/- 35)
Base of A horizon
Photo gap
6za
6z
6y
6v
FCA5Y$_g$
FCA5Z$_g$
Block of 6s
T1-25
6t
6s
6r
T1-26
6p
6k
6i-j
FCA5Y$_g$
Excavated post photo
MM-RC25 (1845 +/- 30)
AFZ5
METERS VERTICAL
METERS HORIZONTAL
-60
-61
-62
-63
-64
-65
-66
239
240
241
242
243
244
245
246
247

Event Y_g Occurred 1600 (+300, -600) cal BP



URS

Paleoseismic Summary Since Mid Holocene

EVENT	AGE (cal BP with ± 2 σ)	RECURRENCE INTERVAL
Z	600 (300 – 900)	
		1,000 (100 – 1,600)
Y	1,600 (1,000 – 1,900)	
		1,500 (100[a] – 4,000)
X	3,100 (1,700 – 5,000)	
		1,700 (50[b] – 3,500)
W	4,800 (4,400 – 5,200)	
		1,100 (200[c] – 1,900)
V(?)	5,900 (4,800 – 6,300)	

[a] Minimum estimate based on soil on Unit 6t

[b] Minimum estimate based on deposition of Units 6r and 6s

[c] Minimum estimate based on deposition of Units 6e to 6p with soils developed on Units 6i-j and 6k

Comparison With Previous Studies

Event	This Study MN	UQFPWG (Lund, 2005) Entire Segment	Lund et al. (1991) MN and MS	Machette et al. (1992) American Fork	Swan et al. (1980); Schwartz et al. (1983) Hobble Creek	Ostenaa (1990)[1] Water Canyon	
						WC1	WC2
						<540	
Z	600 (300 to 900)	600 ± 350	600 ± 80	500 ± 200	6 or 7 events since Provo delta formed (Provo Phase ended 13,700 to 14,000)	700 (500 to 900)	1,300 (500 to 2,000)
Y	1,600 (1,000 to 1,900)					Not Exposed	
X	3,100 (1,700 to 5,000)	2,850 ± 650	2,820 +150/-130	2,650 ± 250			3,500 (1,600 to 4,400)
W	4,800 (4,400 to 5,200)	5,300 ± 300	Not Exposed	5,300 ± 300			4,700 (3,700 to 5,600)
V (?)	5,900 (4,800 to 6,300)			5.3 to 8.1 ka			

[1] Based on radiocarbon ages and relations provided by D. Ostenaa, USBR, pers. comm. (1/11/2006). Recalibrated using OxCal 3.10 (Bronk Ramsey, 1995; 2001) and IntCal04 calibration curve (Reimer et al., 2004)

URS

Summary and Implications for UQFPWG

- At least 4, possibly 5, events occurred since 6.3 ka (more events!)
- 4 events occurred between 600 (± 300) cal BP and 4,800 (± 400) cal BP
- This indicates shorter average mid to late Holocene recurrence intervals of 1,400 ± 250 years
- Preferred estimates of individual recurrence intervals range from 1,000 to 1,700 years
- Compared to previous consensus values of 2,400 (+800, -1200) years by UQFPWG (Lund, 2005)

URS

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)

Hazard on Provo Segment ↓ by ~33%

URS

Input Used to Calculate Time-Dependent Recurrence Intervals for Lognormal Model

- Mean Recurrence (2,400 years)
- Elapsed Time (620 years)
- Coefficient of Variation (or aperiodicity) (0.3 – 0.7)

Time-Dependent Recurrence Parameters for Provo Segment

	Old (2001)	New (2006)
Mean Recurrence	2,400 yrs	1,400 yrs
Elapsed Time	620 yrs	600 yrs
COV	0.5	0.5
Time-Dependent Recurrence Interval	22,950 yrs	2,050 yrs

URS

Session 1: Earthquake Clustering and Time Dependent Models

BRPEWG 2006

John Anderson and Susan Olig

March 8, 2006

THE UNIVERSITY OF NEVADA RENO

URS

Issue

"Use and relative weighting of time-dependent, Poisson, and clustering models in characterizing fault behavior"

THE UNIVERSITY OF NEVADA RENO

URS

Examples of Temporal Clustering

- Canyon Ferry Fault, MT
- Lost River Fault, ID
- Pajarito Fault System, NM

Canyon Ferry Fault, MT

From Anderson *et al.* (2005)

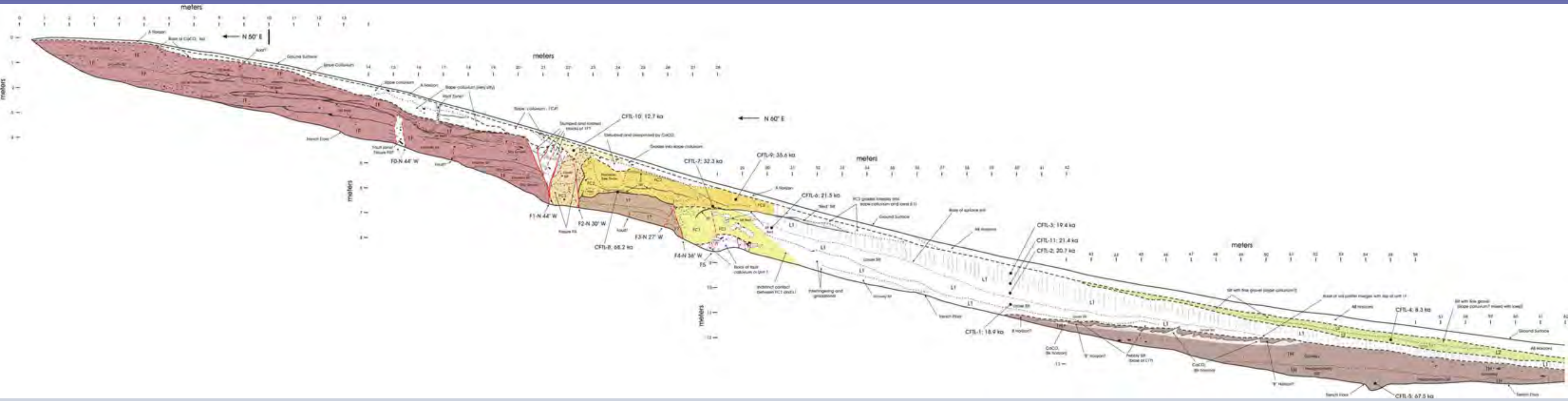
G/T Ranch Trench Site – Canyon Ferry Fault

Photo by L. Anderson

Average late Quaternary slip rate:
9 ± 1 m / 68 ± 4 ky = 0.13 mm/yr

URS

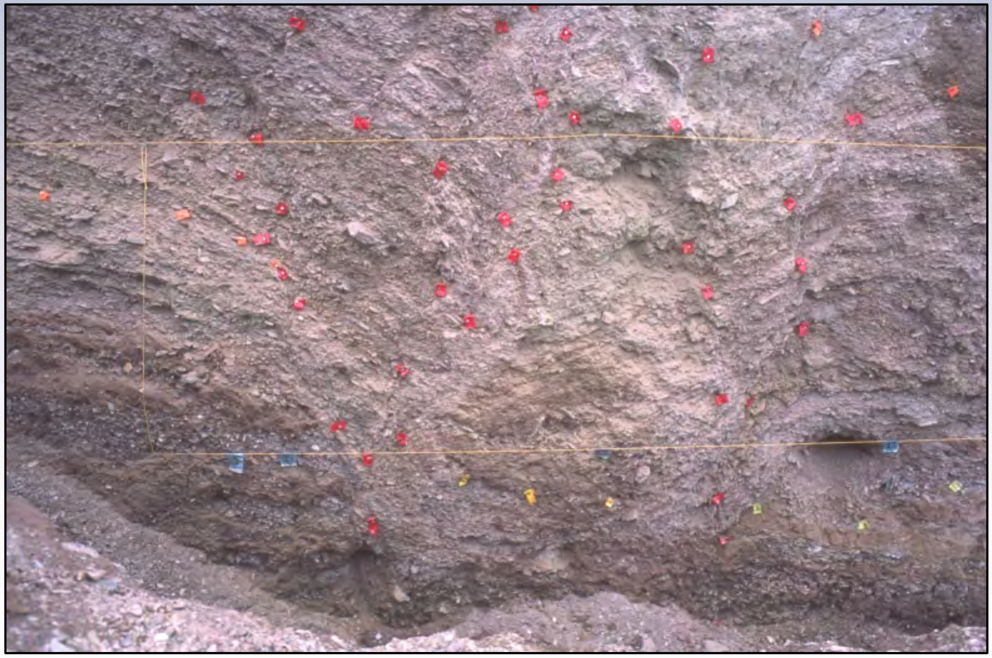
G/T Ranch Trench Log



From Anderson *et al.* (2005)

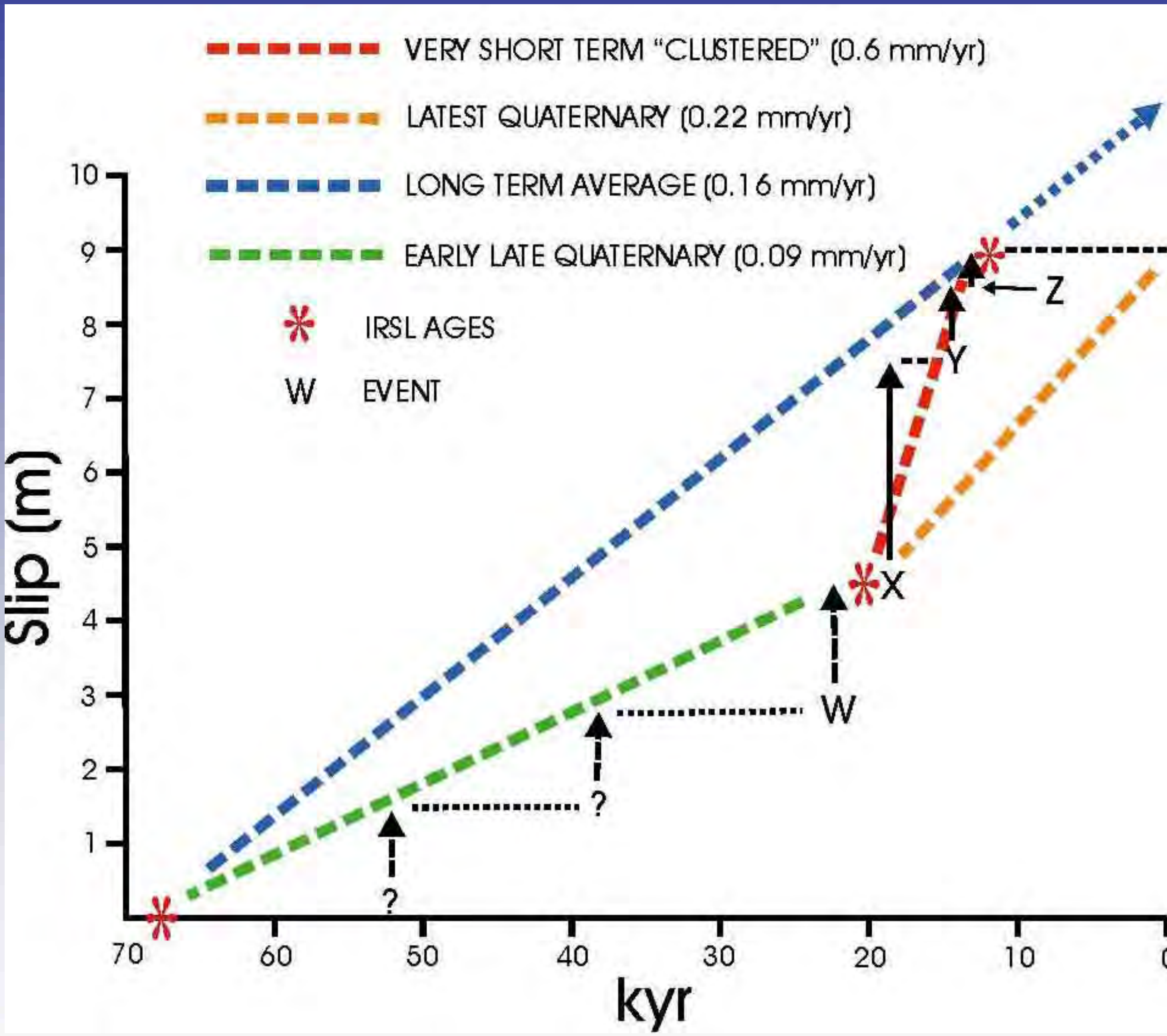
Cluster of at least 2, possibly 3, earthquakes that occurred between 13 and 21 ka and resulted in 5 m of dip slip

North Wall G/T Ranch Trench Fault Zone F1 and Fissure Fill



URS

Canyon Ferry Fault Slip Rates Over Time



From Anderson *et al.* (2005)

Slip Rates Used in Wong *et al*. (2005):

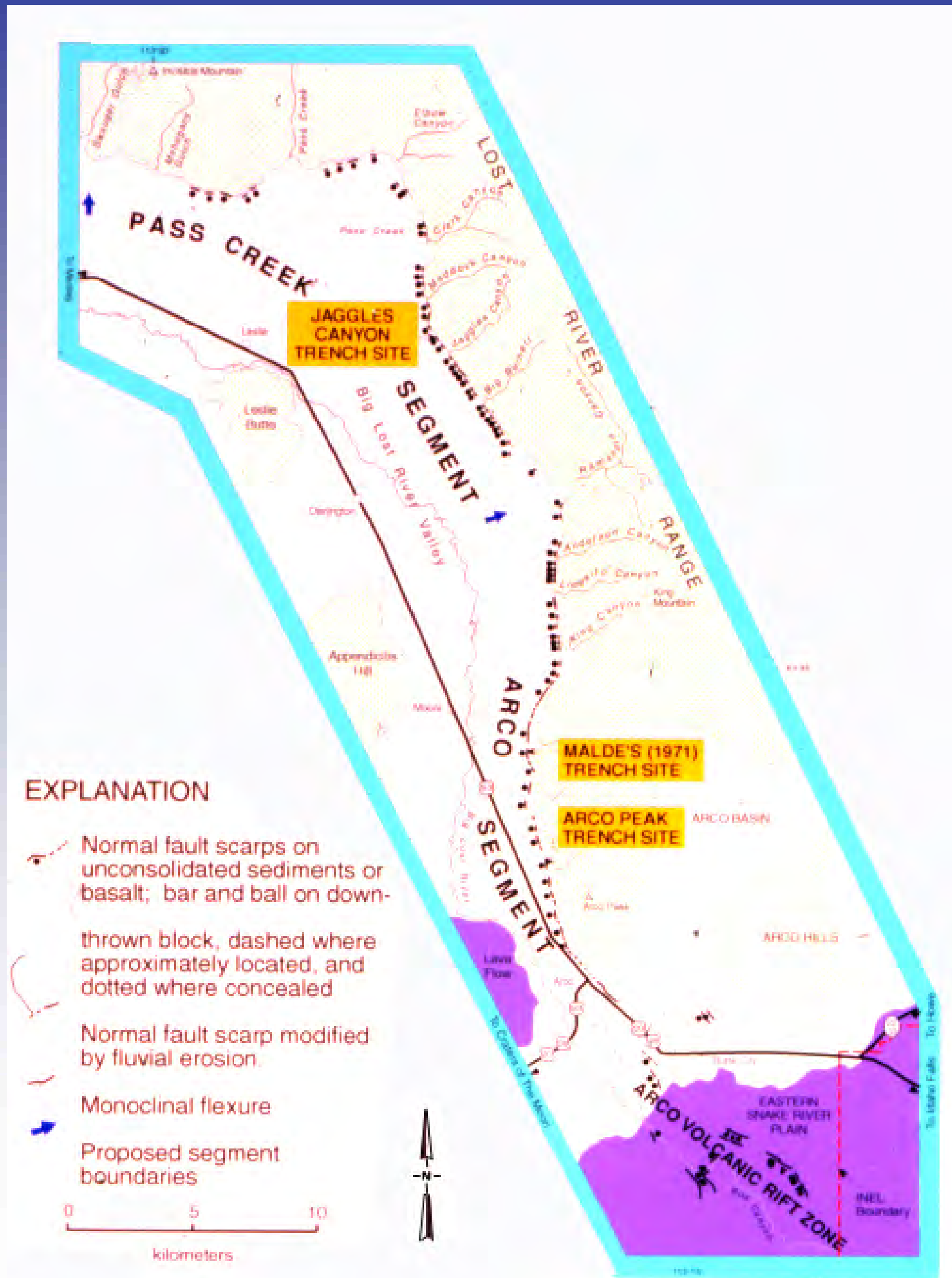
0.1 mm/yr (0.2)
0.16 mm/yr (0.3)
0.66 mm/yr (0.3)
1.0 mm/yr (0.2)
WM: 0.5 mm/yr

Slip Rate Used in Frankel *et al*. (2002):

0.15 mm/yr

Temporal Clustering of Earthquakes Results in Highly Variable Rates

Southern Lost River Fault Zone

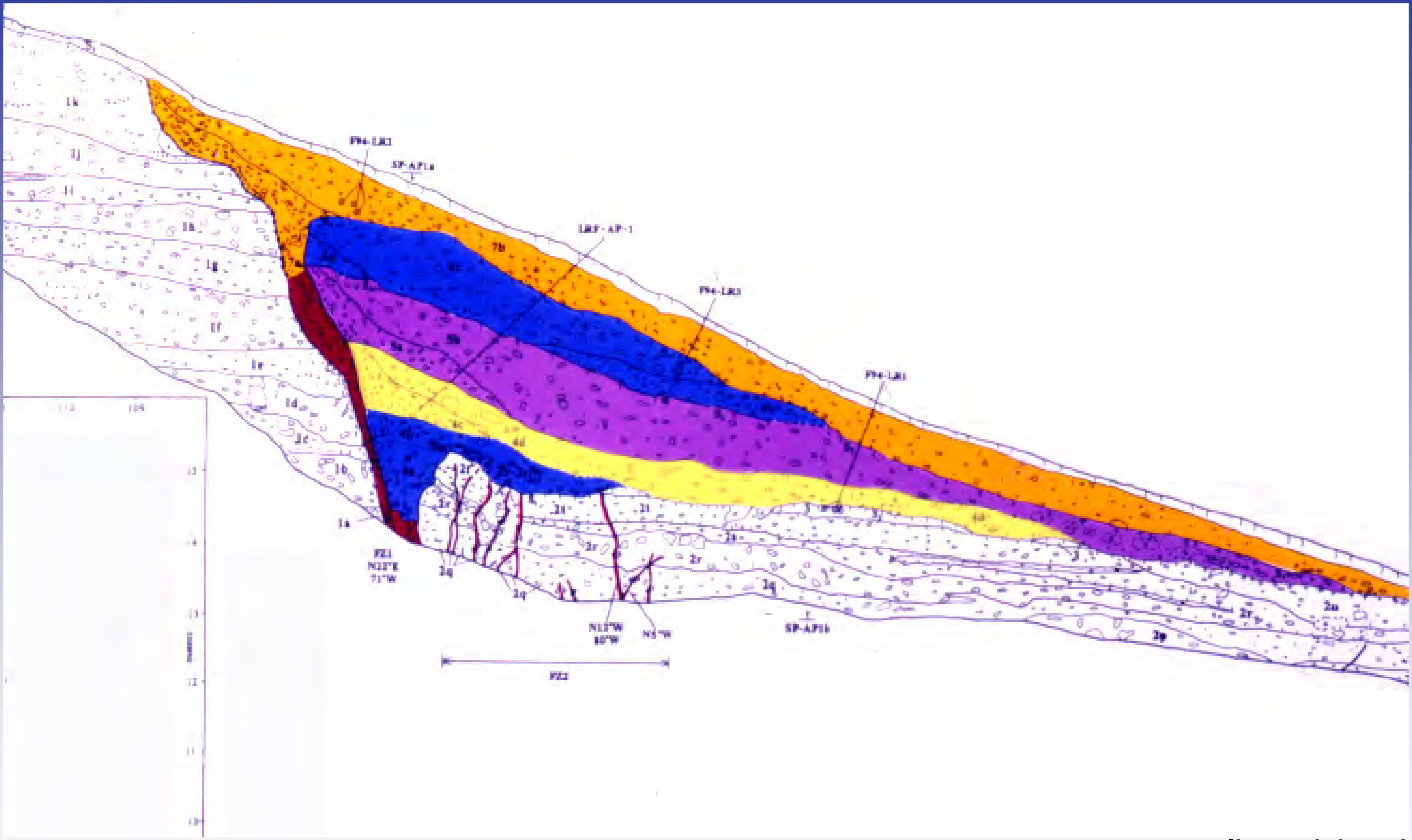


From Olig *et al.* (1995)

Arco Peak Trench Site

Average late Quaternary slip rate:
6 ± 0.5 m / 100 to 130 ka
= 0.05 ± 0.01 mm/yr

Arco Peak Trench



From Olig *et al.* (1995)

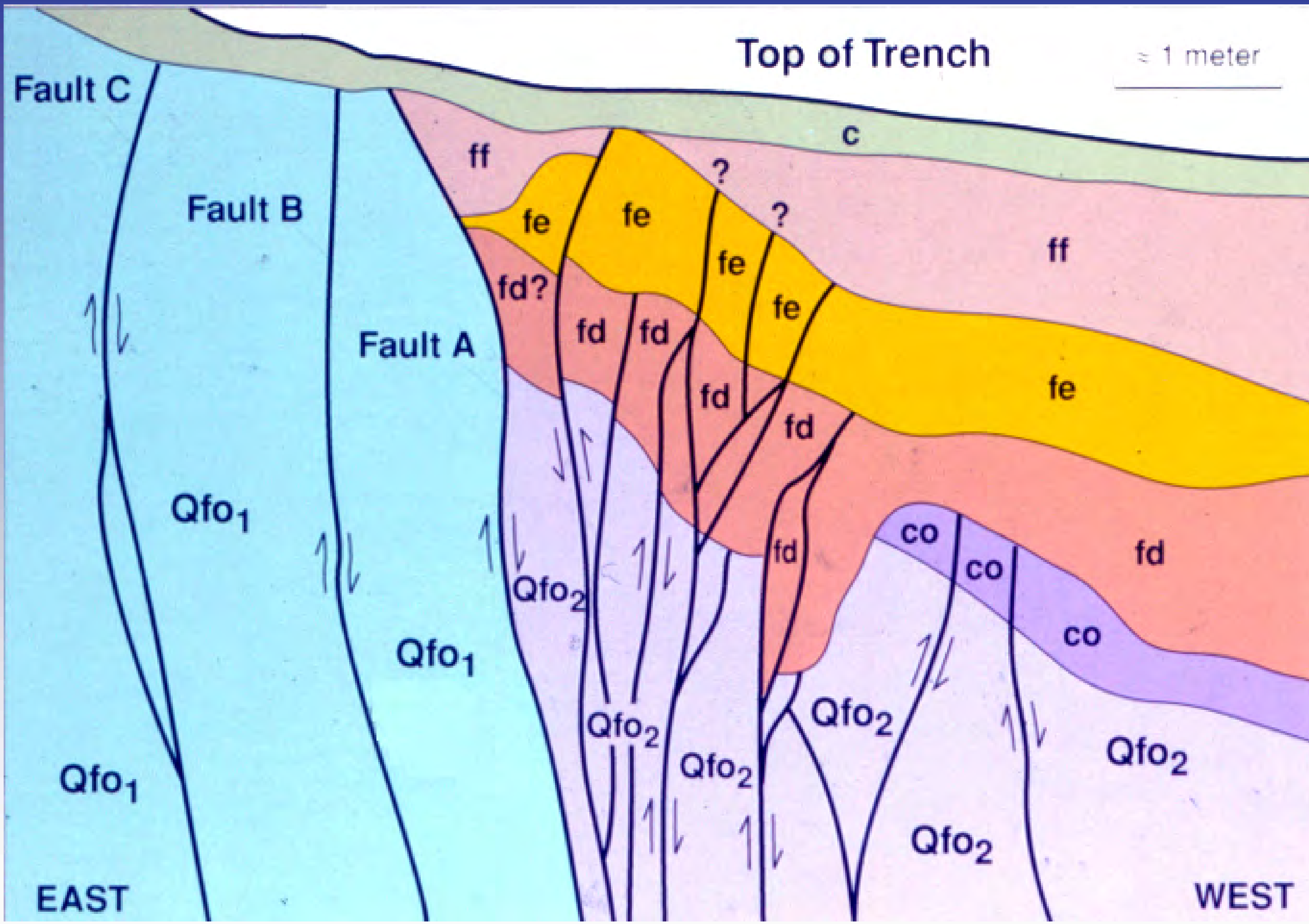
4 to 5 earthquakes occurred since 100 ka

1.2 (0.5 to 2.5) m of slip per event

2 clusters: 2 to 3 earthquakes after 60 ka

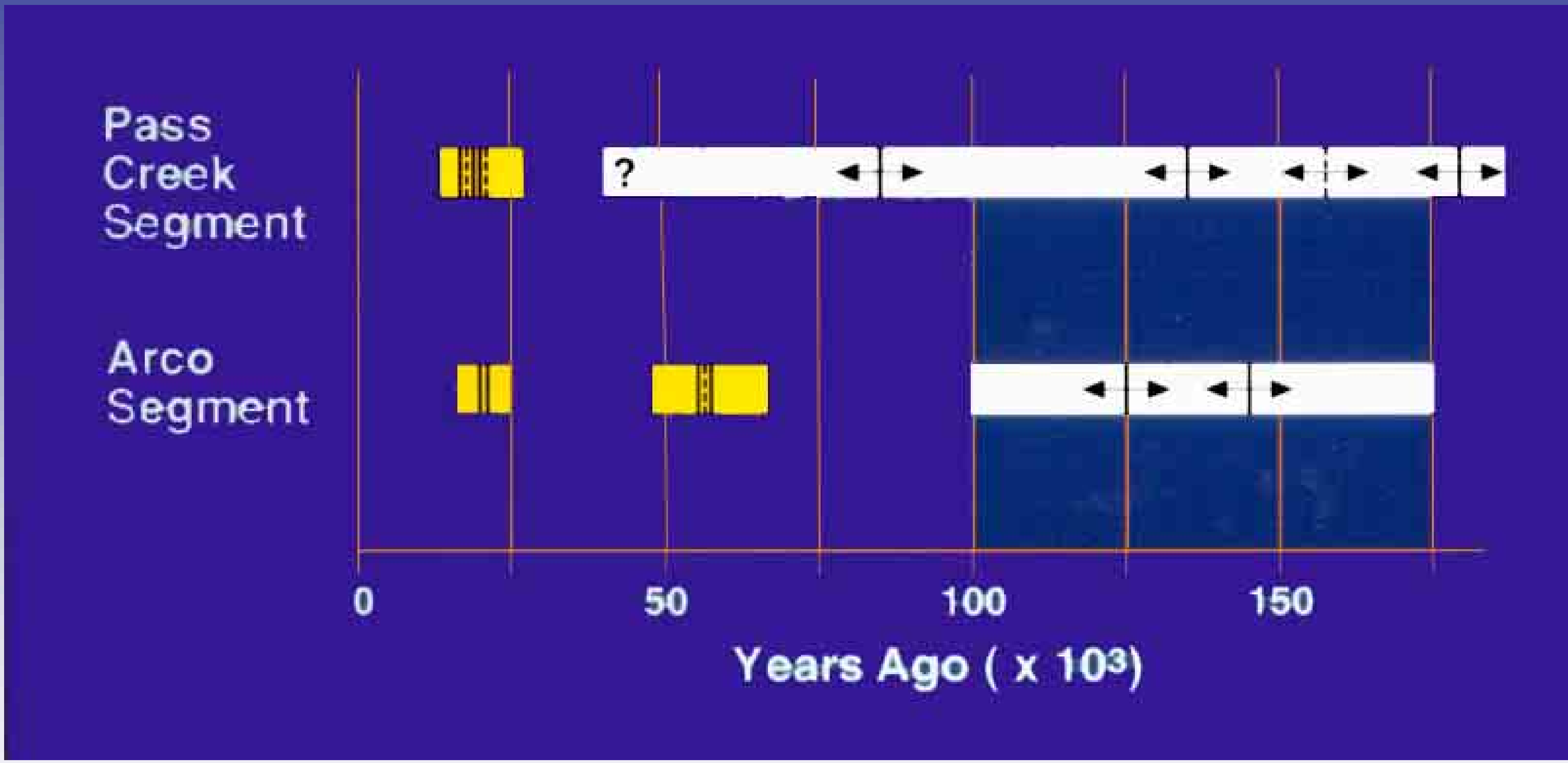
2 earthquakes between 21 ± 4 and 20 ± 4 ka

Schematic Reinterpretation of Maldes (1971) Trench



From Olig *et al.* (1995)

Surface-Faulting Earthquakes Southern Lost River Fault



From Olig *et al.* (1995)

- Observations of 2 clusters of earthquakes separated by long periods of quiescence
- Slip rates varied from < 0.05 to > 1 mm/yr

Southern Lost River Fault

Slip rates (mm/yr) used in Wong *et al.* (2005):

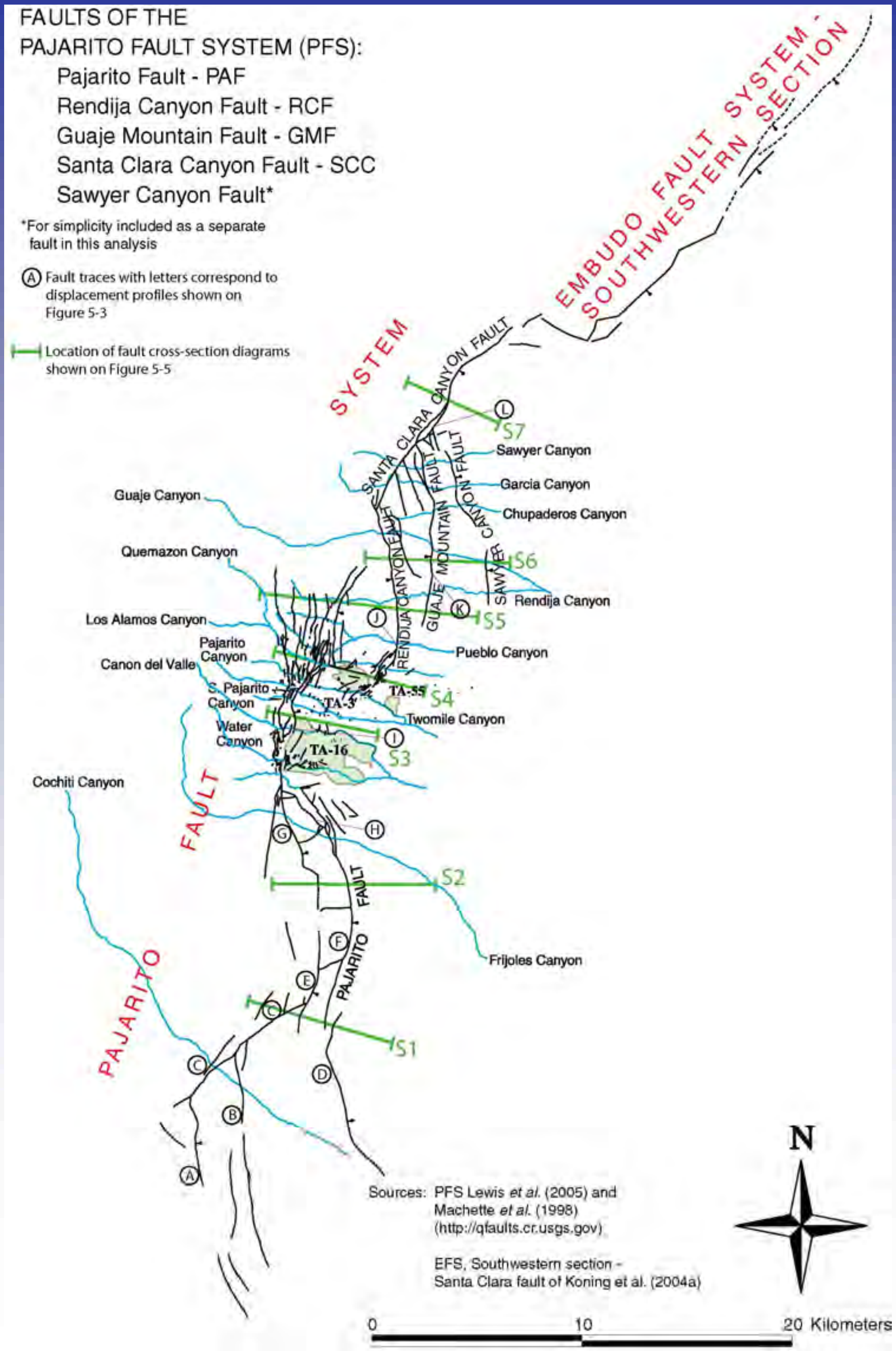
0.05 (0.2)
0.2 (0.6)
1.0 (0.2)

Weighted Mean: 0.3

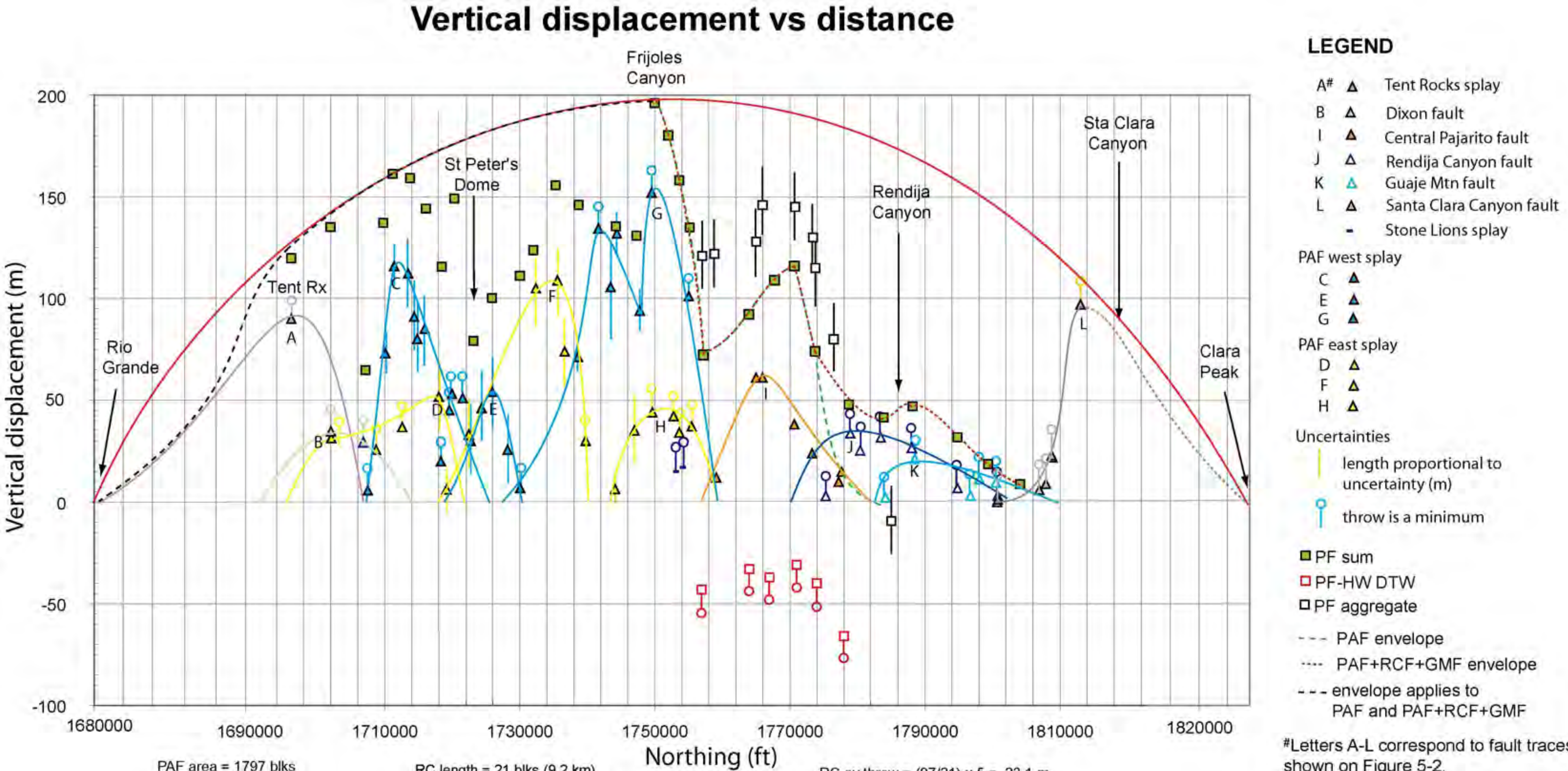
Slip rate (mm/yr) used in Frankel *et al.* (2002):

0.15

Pajarito Fault System



From Lewis *et al.* (2005)



PAF area = 1797 blks
RC area = 97 blks
GM area = 47 blks
SCC area = 200 blks

RC length = 21 blks (9.2 km)
GM length = 19 blks (8.6 km)
SCC length = 25 blks (11.5 km)
RS-a: PAF length = 78.5 blks (36.1 km)*
RS-b: PAF+RC length = 84.6 blks (38.9 km)
RS-c: PAF+GM length = 92.2 blks (42.4 km)
RS-d: PAF+RC+GM+SCC length = 108.3 blks (49.8 km)
RS-e: PAF+RC+GM+SCC+E length = 132.4 blks (60.9 km)
RS-f: PAF+RC+SCC length = 108.3 blks (49.8 km)
RS-g: PAF+GM+SCC length = 108.3 blks (49.8 km)

RC av throw = (97/21) x 5 = 23.1 m
GM av throw = (47/19) x 5 = 12.4 m
SCC av throw = (200/25) x 5 = 40.0 m
RS-a: PAF av throw = (1797/78.5) x 5 = 114.5 m; rate = 0.10 mm/yr
RS-b: PAF+RC av throw = (1797+97)/84.6 x 5 = 111.9 m; rate = 0.09 mm/yr
RS-c: PAF+GM av throw = (1797+47)/92.2 x 5 = 100.0 m; rate = 0.08 mm/yr
RS-d: PAF+RC+GM+SCC av throw = (1797+97+47+200)/108.3 x 5 = 98.8 m; rate = 0.08 mm/yr
RS-e: PAF+RC+GM+SCC+E av throw = (1797+97+47+200)/132.4 x 5 = 80.9 m; rate = 0.07 mm/yr; BUT use 0.08 mm/yr
RS-f: PAF+RC+SCC av throw = (1797+97+200)/108.3 x 5 = 96.7 m; rate = 0.08 mm/yr
RS-g: PAF+GM+SCC av throw = (1797+47+200)/108.3 x 5 = 94.4 m; rate = 0.08 mm/yr

*These are straight-line, N-S lengths.

Modified from Lewis *et al.* (2005)

Average Quaternary slip rate:
94 to 115 m / 1.2 Ma 4 = 0.09 ± 0.01 mm/yr

PFS Paleoseismic Record
(16 sites, numerous investigators)

Event	Fault and Trench Site[2]																						
	PAF																			GM			RC
	97-3[3]	97-3[4,5]	97-4[3]	97-4[4,6]	97-5[4]	97-6[4]	97-7[3]	97-7[4]	97-7a[3]	97-7a[4]	EOC-2[3,11]	WETF-2c[3,20]	98-4[3]	98-4[4]	98-5[3]	98-6[3]	98-6[22]	Pajarito Canyon[7,8]	Water Tanks[7,8]	Cabra Cyn[3,15]	Sportsmen's Club[7,8,21]	Chupaderos Cyn[3,15]	Guaje Pines[7,9,10]
P1		1.3 2.2		<2.3 (<4.5)			1.4 2.2	1.4 4	1.2[12] 2.2	~1.4		1.3 7.3											
P2	2.2 20		2.1 19								5.5 8.6				3 12	2.4 7.0	2.4 16			4.2 6.5	age?	3.4 10	
P3								>2.2			8.6 10.5	9 10.9	10 21	10 18		2.7 24							>8.6
P4	20 45	~20	age?	age?	3 or 4 events since 177 to 184 (Possibly 7 events since 492)	At least 2 events since 25 to 132 (Possibly 8 events between 4 and 445)						>14.1	<31[17]	14 60	11 44		41 58				age?	38.8 40.4	age?
P5	36 97	≤81	age?	age?				45 63[13]										age?	50[18] 61				60 75
P6 (?)																		age?	50[18] 63				
P7		81 106		age?													78 <1,220						
P8		~100[19]																					age?
P9		~110[19] (97-117)						2 events between 61 and 1,220			At least 5 events >43					At least 1 event between 58 and 1,220							
P10		age?																>137	Possibly 5 events between 57 and 1,220		>144[16] 300		
P11																		age?					
P12		1,100 1,220																Possibly 3 events between 137 and 1,220					>140 <1,220
P13																							
P14																							

- At least 2, probably 3 Holocene earthquakes (between 1.4 and 9-10 ka)
- At least 6, possibly 9 earthquakes since ~ 110 ka

URS

Pajarito Fault System

Slip rate (mm/yr) used in Frankel *et al.* (2002):

0.068

Slip rates (mm/yr) used in Wong *et al.* (2004):

0.01 (0.1)
0.05 (0.2)
0.09 (0.4)
0.2 (0.2)
0.95 (0.1)

(Weighted Mean: 0.18)

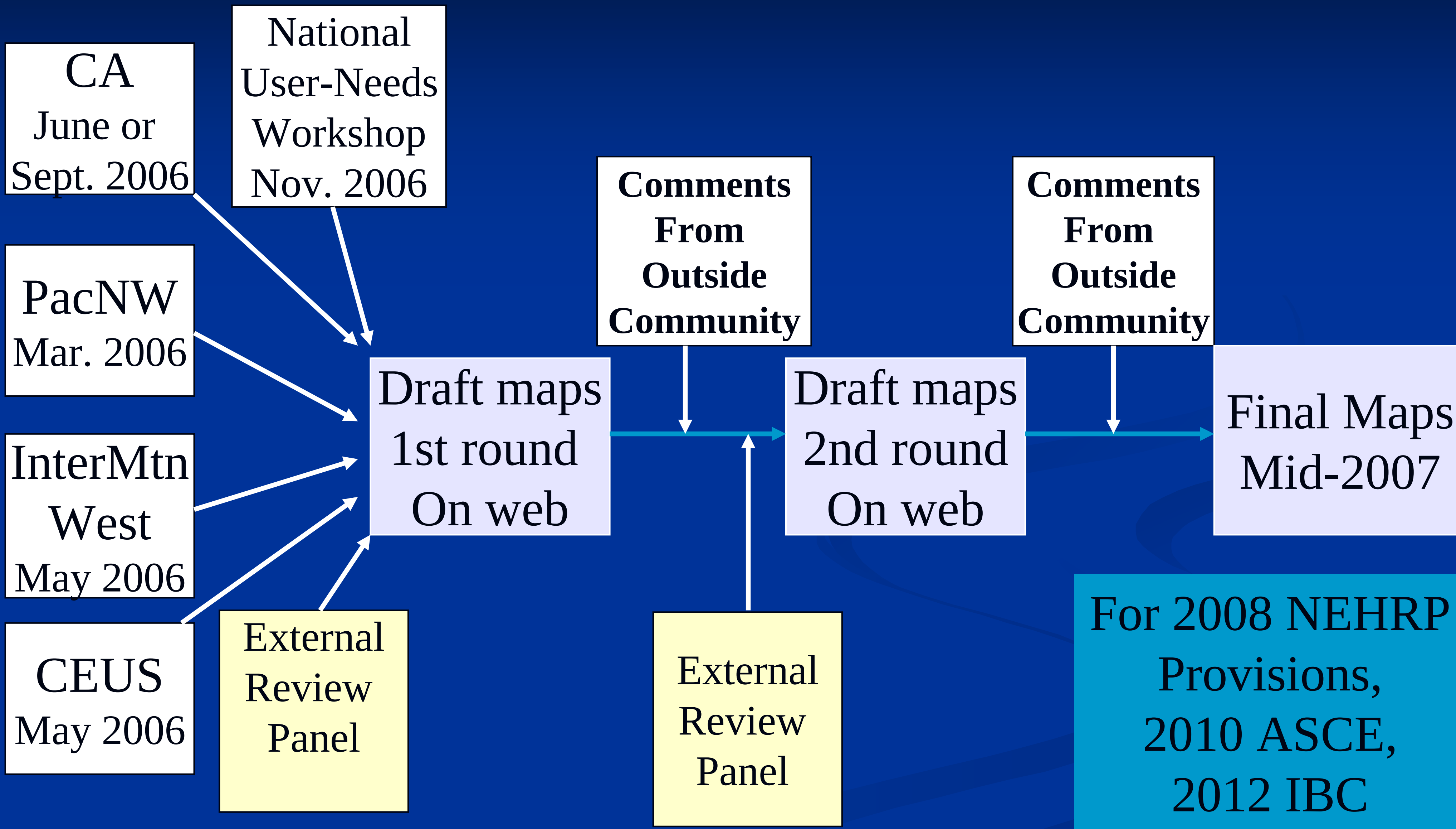
Preliminary values for LANL PSHA Update:

0.02 (0.1)
0.06 (0.24)
0.11 (0.32)
0.23 (0.24)
1.0 (0.1)

(Weighted Mean: 0.21)

URS

Process for 2007 Maps



eqhazmaps.usgs.gov

Time-dependent hazard analysis

- Use and relative weighting of time-dependent, Poisson, and clustering models in characterizing fault behavior:
  - USGS has produced preliminary time-dependent maps for Alaska, California, Utah, and New Madrid region. These models are combinations of time-dependent and Poisson recurrence.
  - Currently, the USGS considers these maps as research products.
  - These products will be posted at our website.
  - For 2007 building codes the USGS will continue to use the Poisson maps.
- Working Group 1999-2002 used five recurrence models
  - Poisson
  - Time-predictable
  - BPT
  - BPT+step
  - Empirical

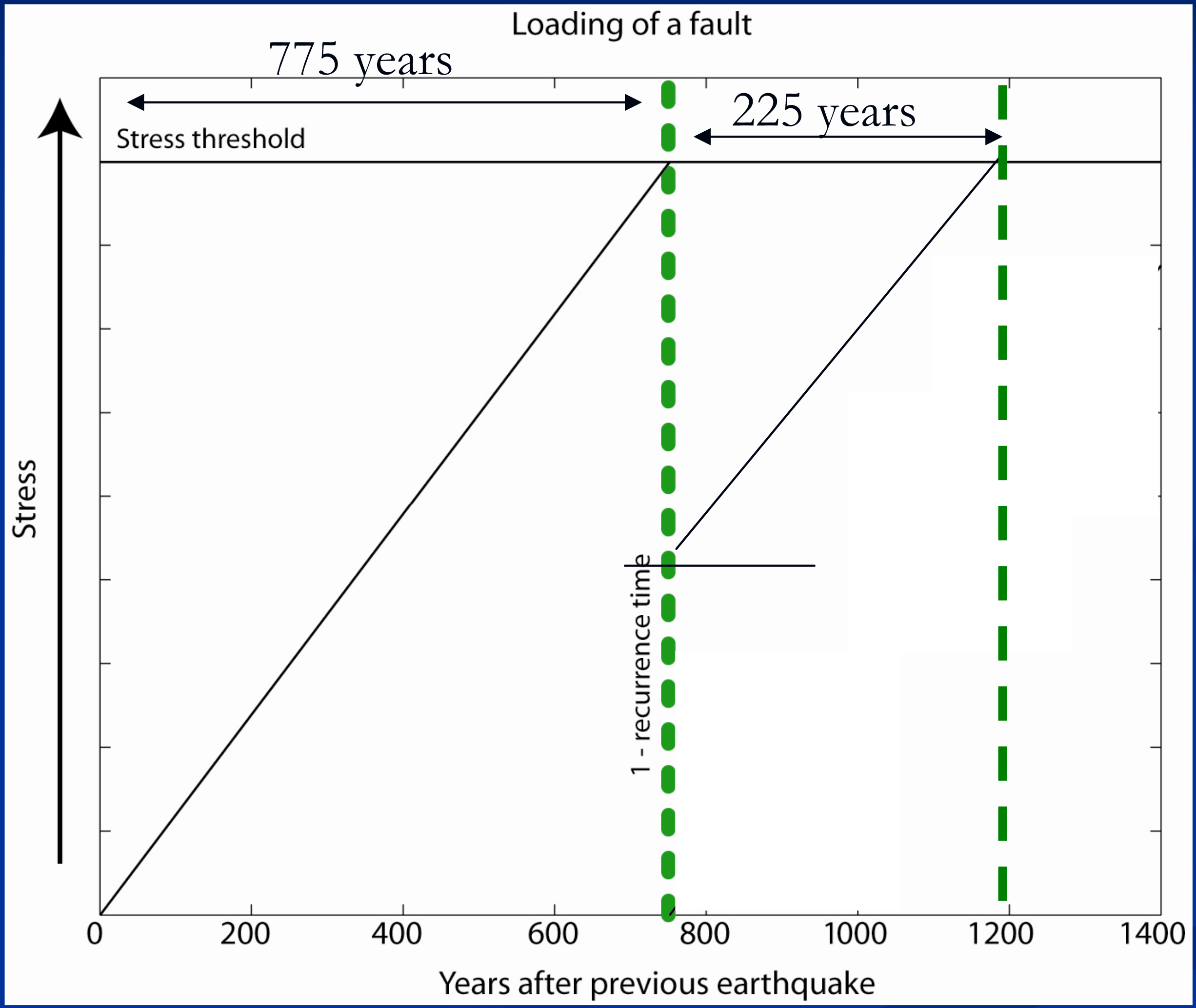
  - The largest contribution of uncertainty in the 2002 report was due to the recurrence model used.

Poisson Process

- $P(N>0)=1-e^{(-\text{annual rate}*t)}$ expresses the probability of no events occurring in a fixed time (e.g., t=50 years) if these events occur with a known average rate, and are independent of the time since the last event.
- Simple model, only one parameter needed (annual rate)

Time-predictable model

- Linear loading
- Time-predictable model: size (slip) in last event and strain accumulation rate predicts the time of next event.

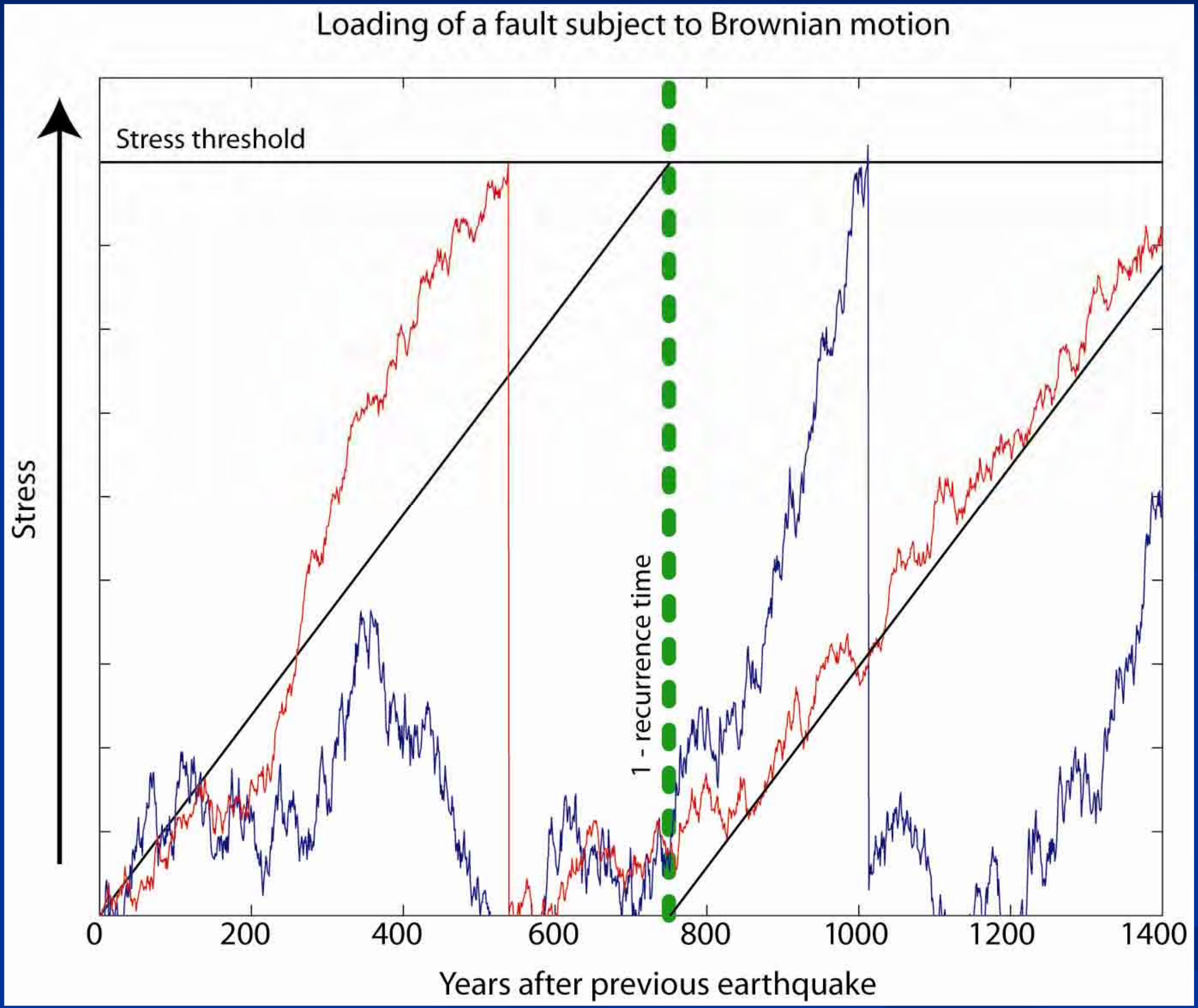


Shimazaki and Nakata (1980), Murray and Segall (2002)

Oliver Boyd

Brownian Passage Time

- Linear loading with Brownian motion with superimposed stress fluctuations.

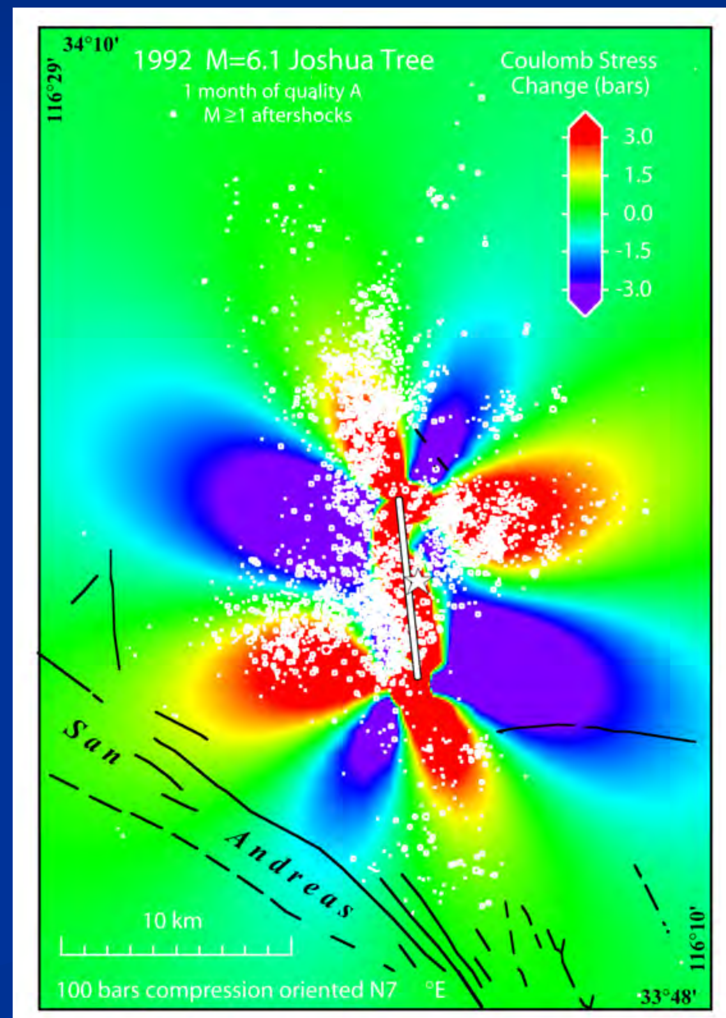


Oliver Boyd

How do stress changes influence time-dependent earthquake probabilities?

- *Southern California*: Coulomb stress change for optimally oriented faults

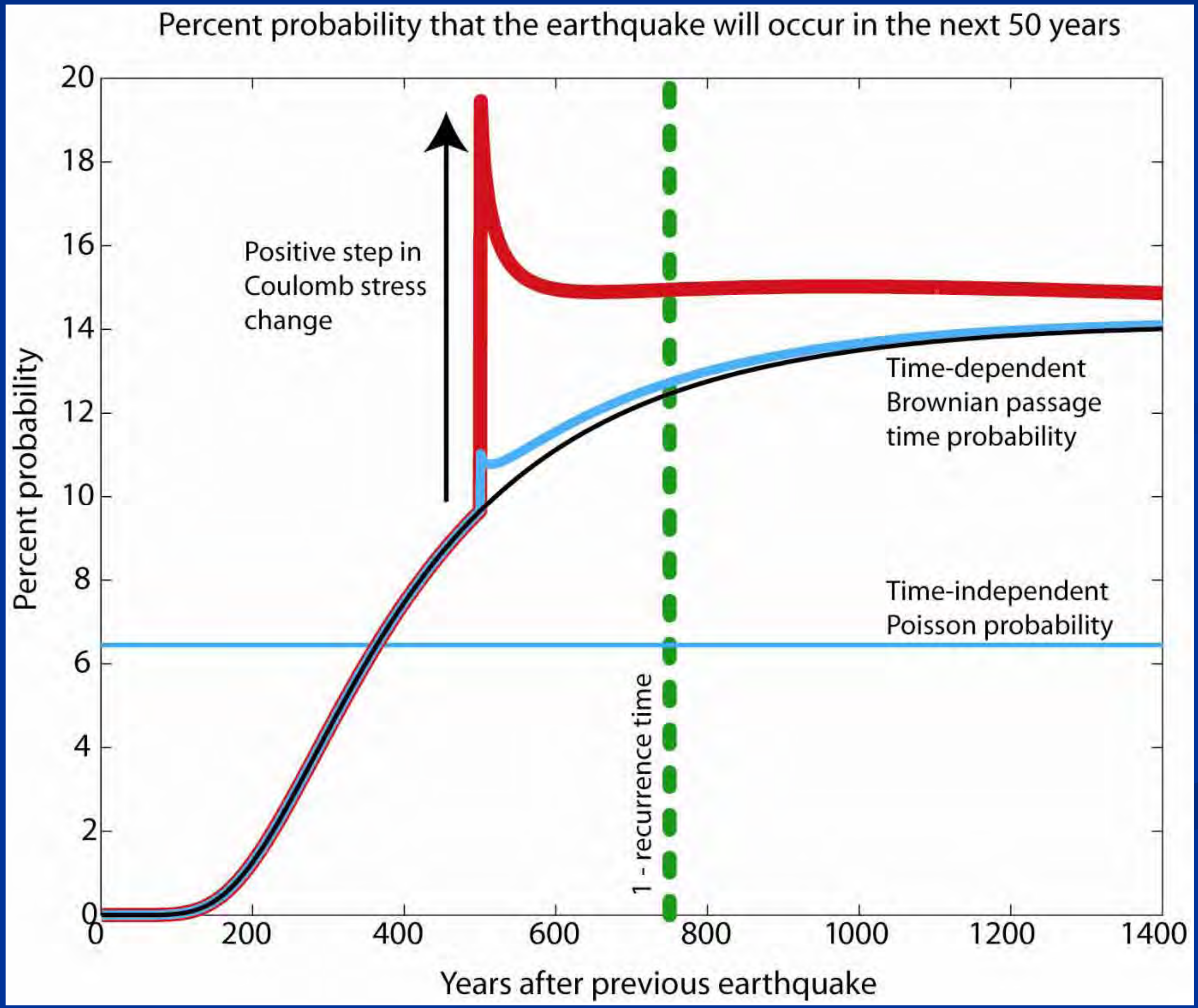
$$\Delta CS = \sigma_S + \mu' \sigma_N$$



King et al., BSSA 1994

How do stress changes influence time-dependent earthquake probabilities?

- Time-dependent conditional probability *with stress changes*



Empirical model

- To account for stress shadow following the 1906 earthquake
- Uses observed seismicity rates since 1906 as proxy for stress shadow
- Scales rates by factor (0.4, 0.5, 0.7) and then computes Poisson probabilities using these updated rates

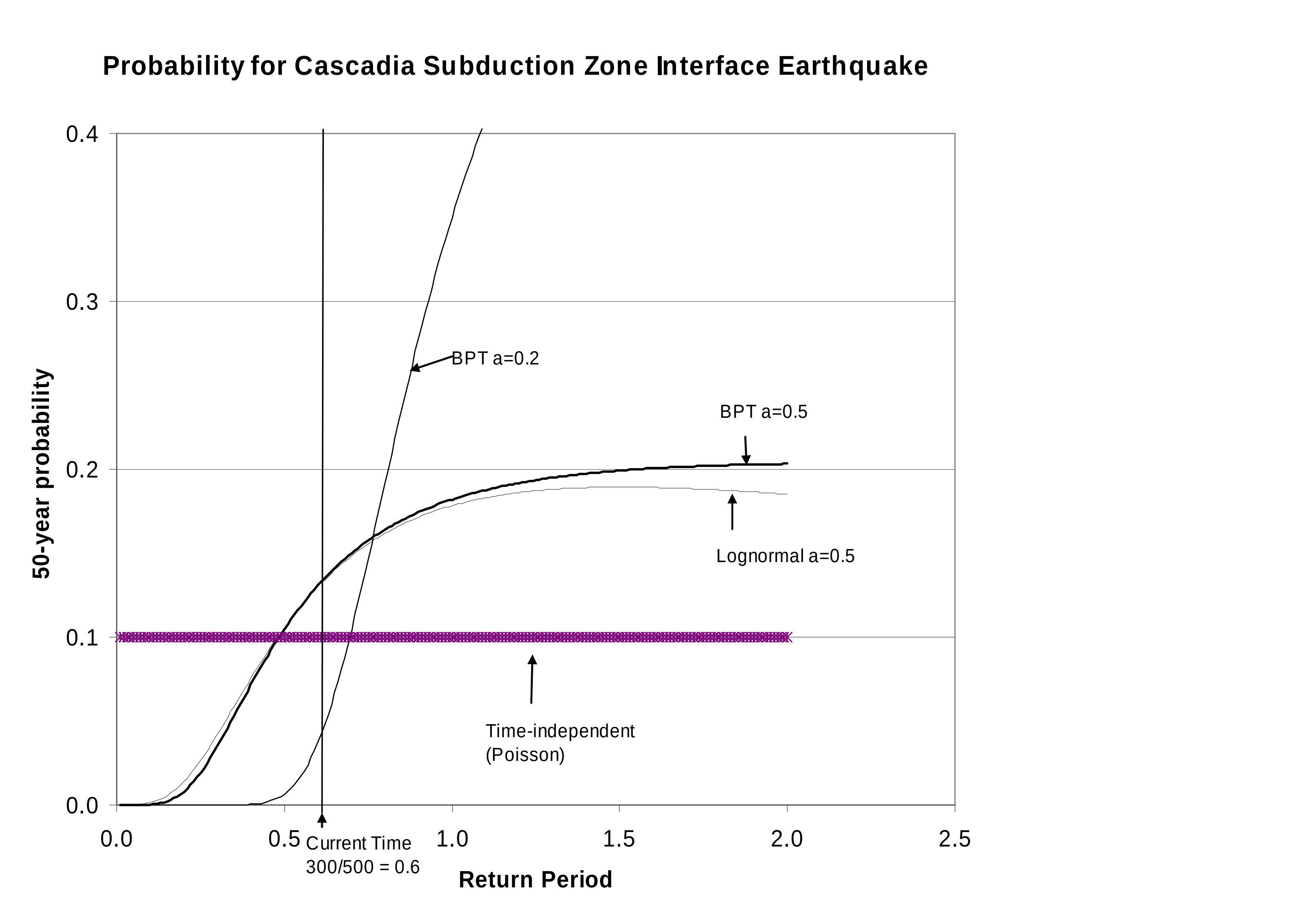
Lognormal density function: defined by sigma and mu-hat which is The median recurrence.

$$f_T(t) = \frac{1}{t\sigma_{\ln T_i}\sqrt{2\pi}} \exp\left\{\frac{-[\ln(t/\hat{\mu})]^2}{2\sigma^2_{\ln T_i}}\right\}$$

,

$$P(t_e \le T \le t_e + \Delta t \,|\, T > t_e) = \frac{P(t_e \le T \le t_e + \Delta t)}{P(t_e \le T \le \infty)}$$

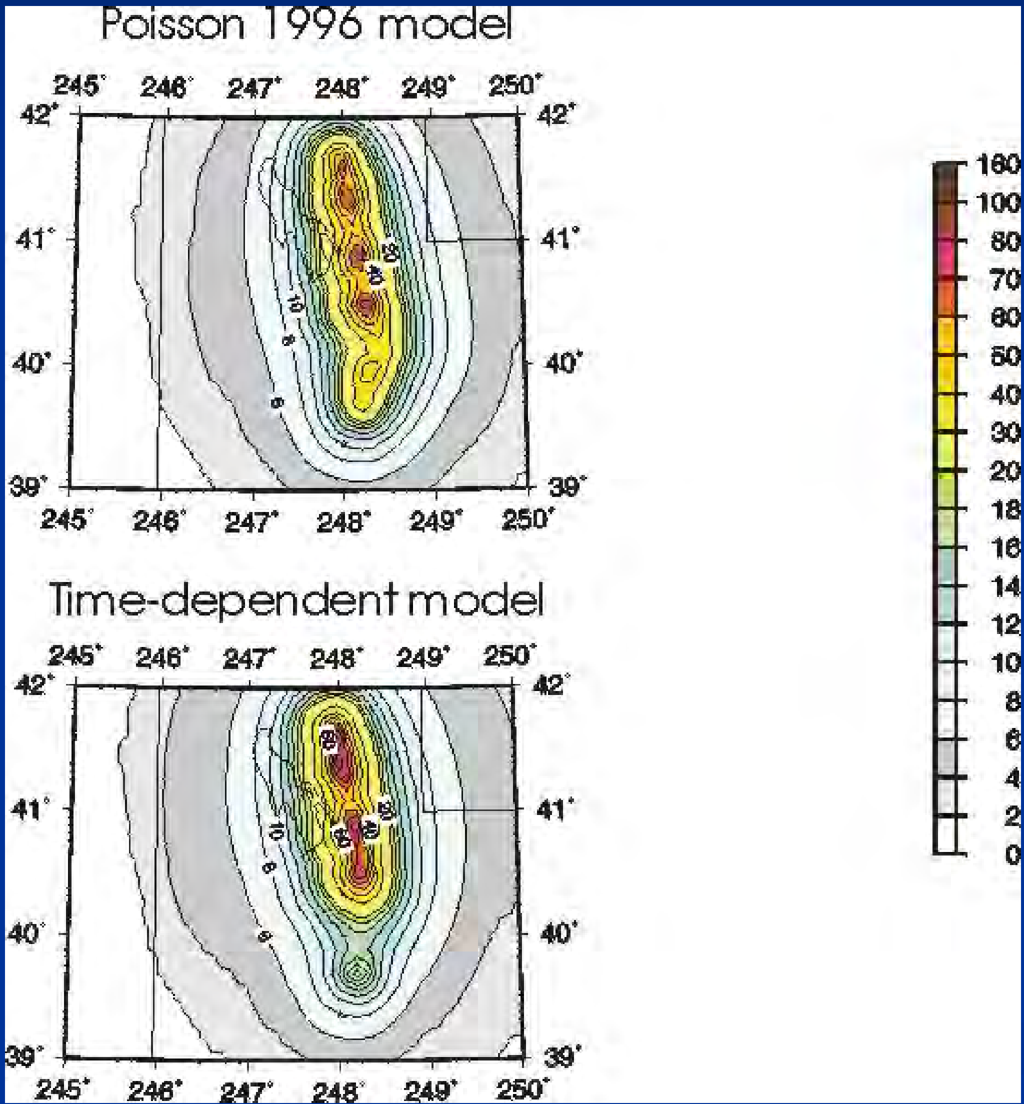
Time-dependent hazard maps

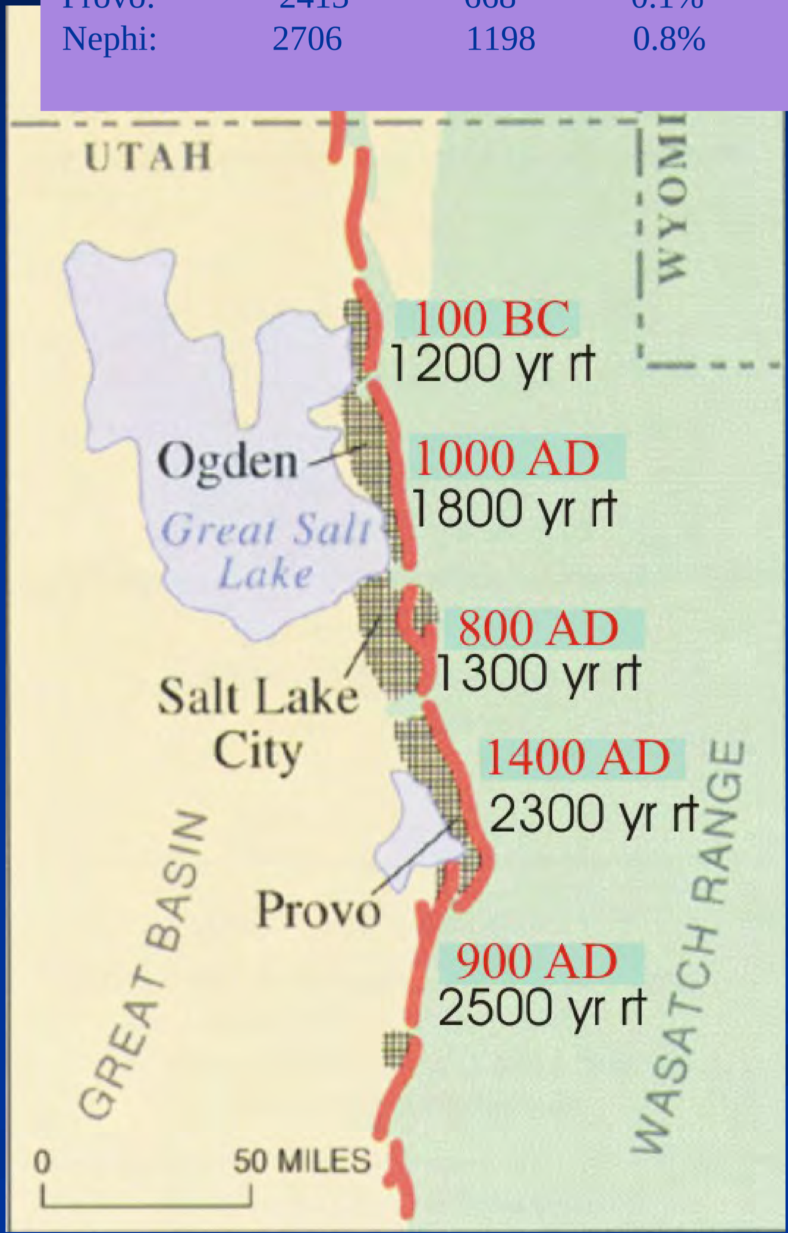


Source characterization

Time-dependent models

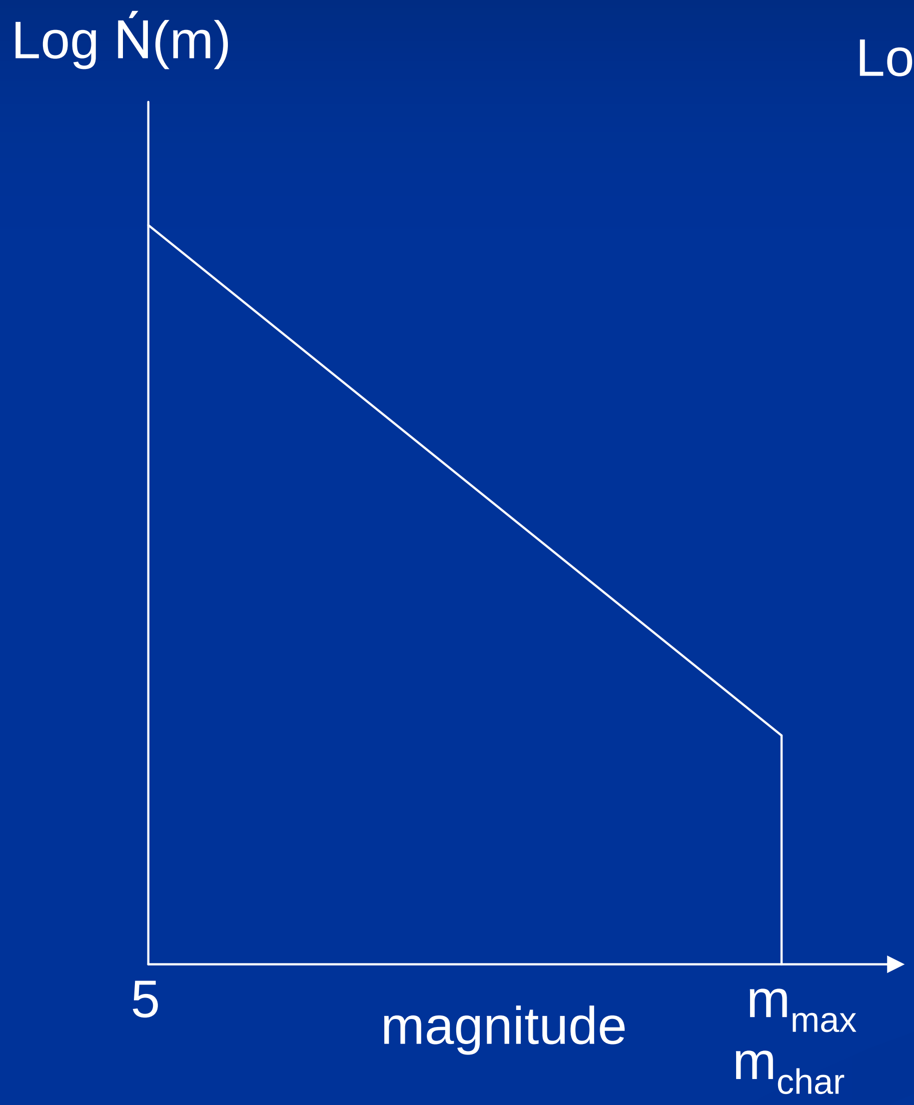
	Med. Rec.	Elapsed time	50-year prob
Brigham City:	1230	2175	8%
Weber:	1674	1066	3%
Salt Lake:	1367	1280	6%
Provo:	2413	668	0.1%
Nephi:	2706	1198	0.8%

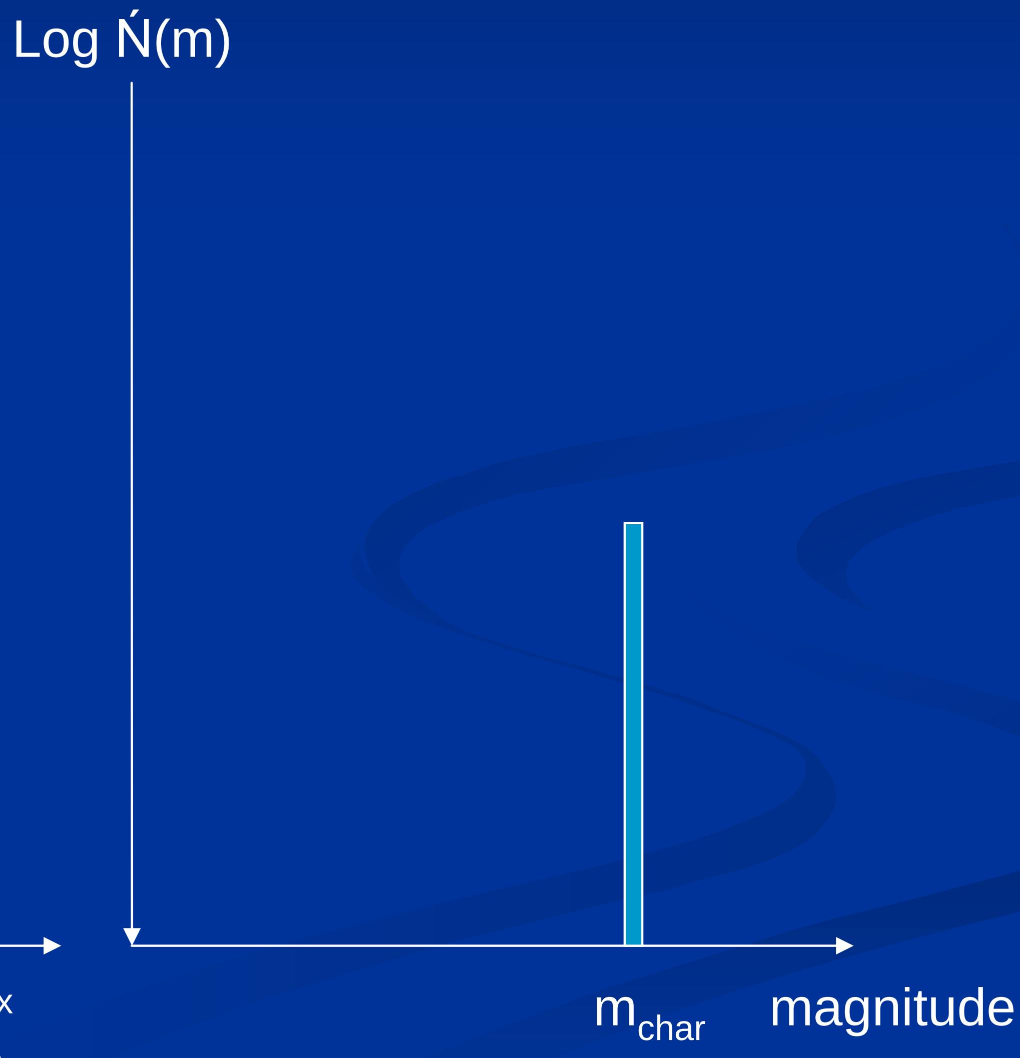




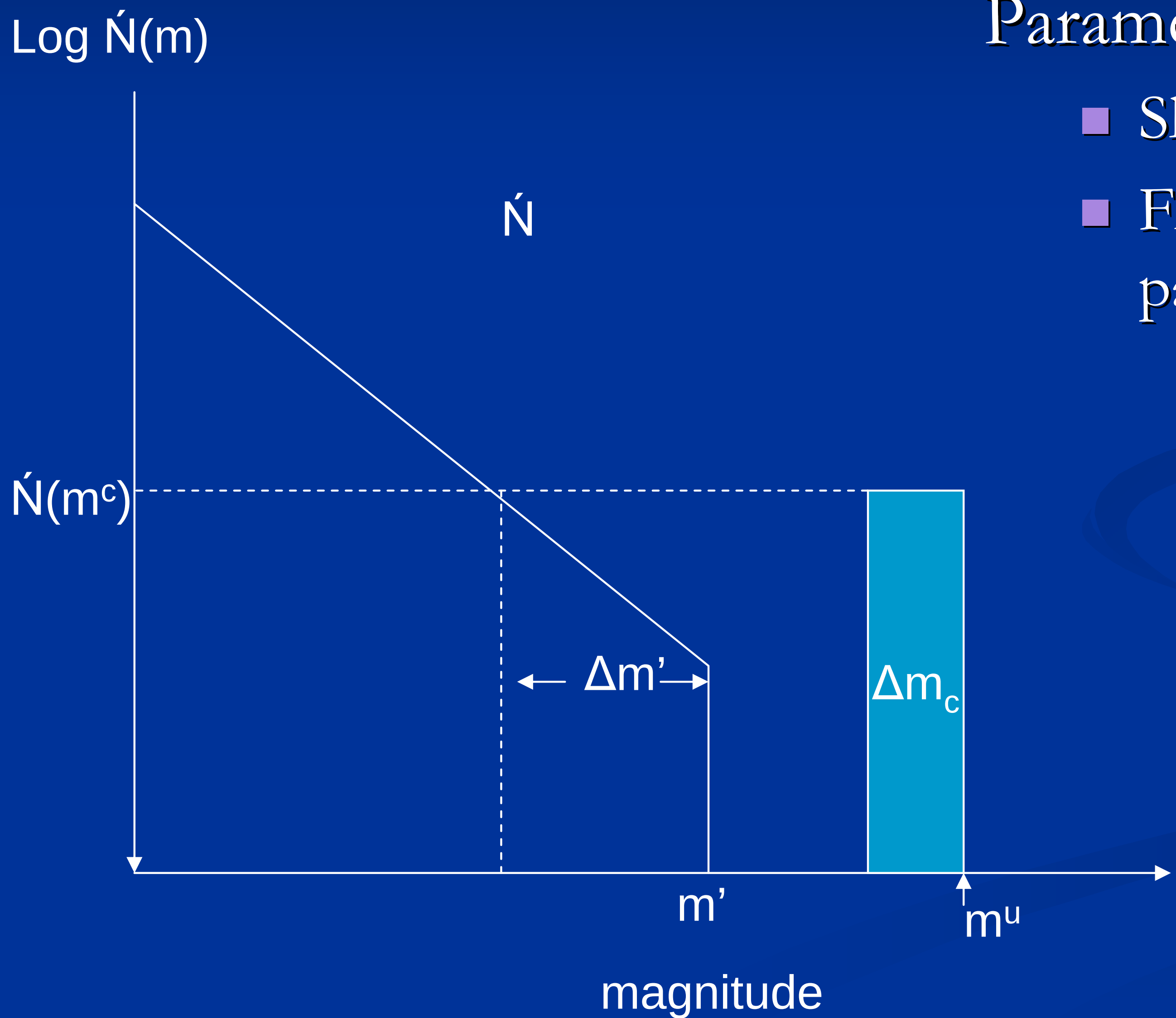
Magnitude-frequency distribution used in NSHMP

Characteristic and GR to describe M-f distribution on a fault





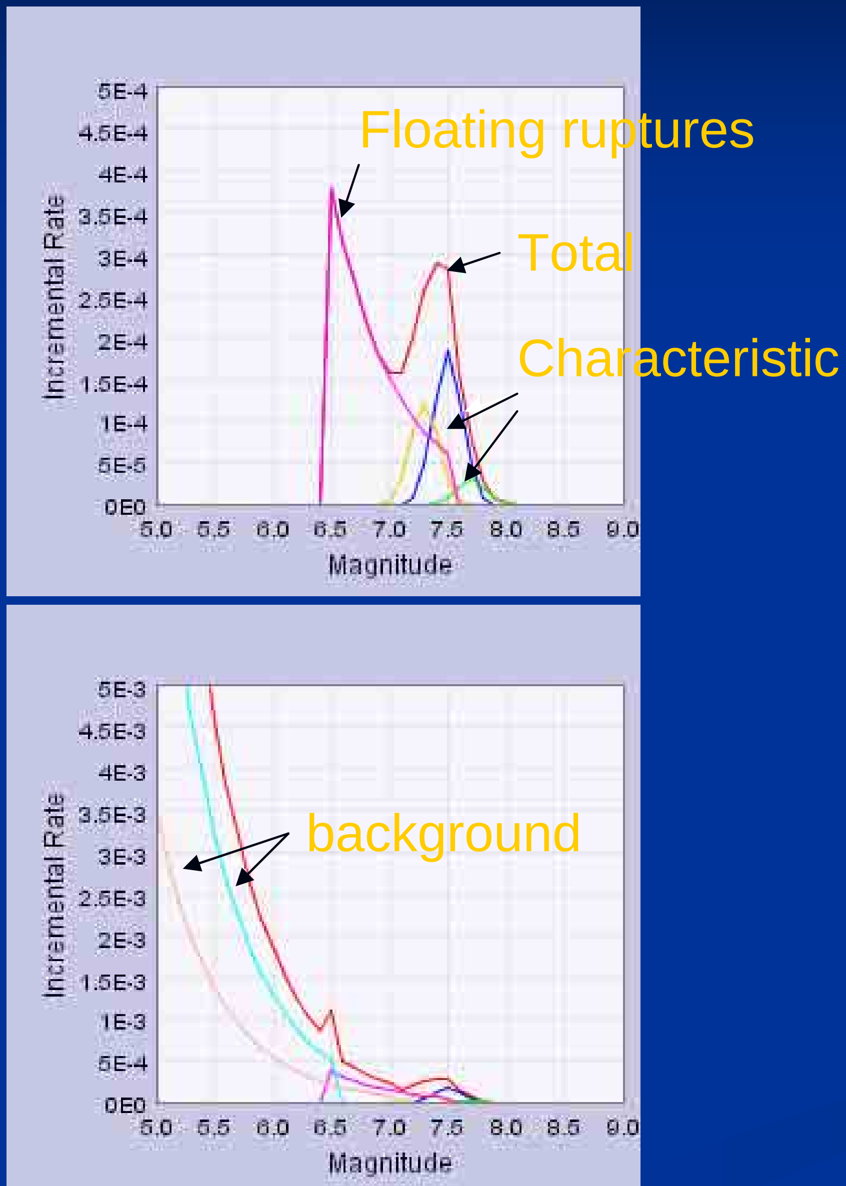
Youngs and Coppersmith (1985) Magnitude-frequency distribution



Parameters

- Slip rate
- Five of the following six parameters
  - $\acute{N}(M_0)$
  - b
  - m'
  - m^u
  - Δm_c
  - $\acute{N}(m^c)$

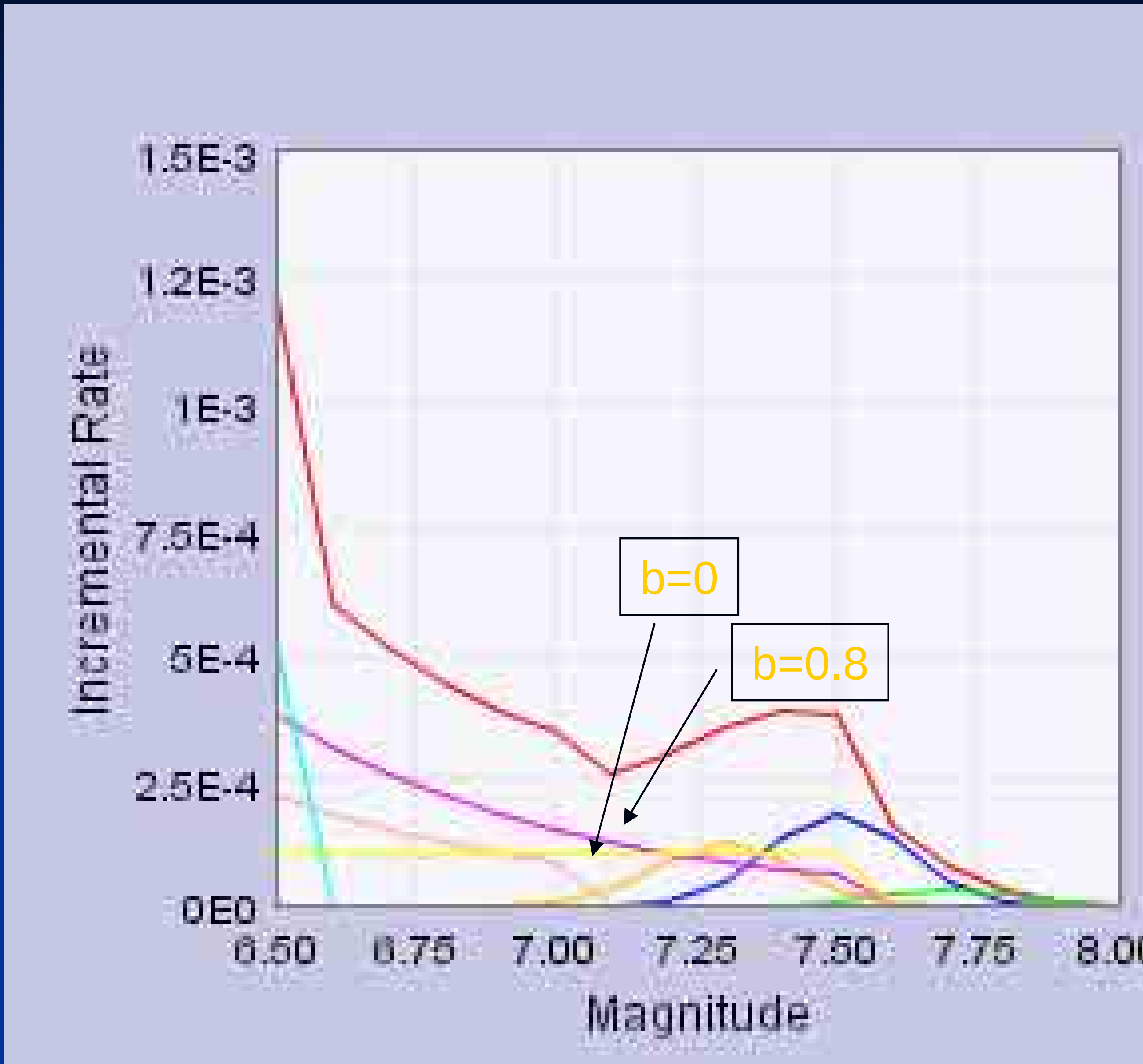
USGS Magnitude-frequency model



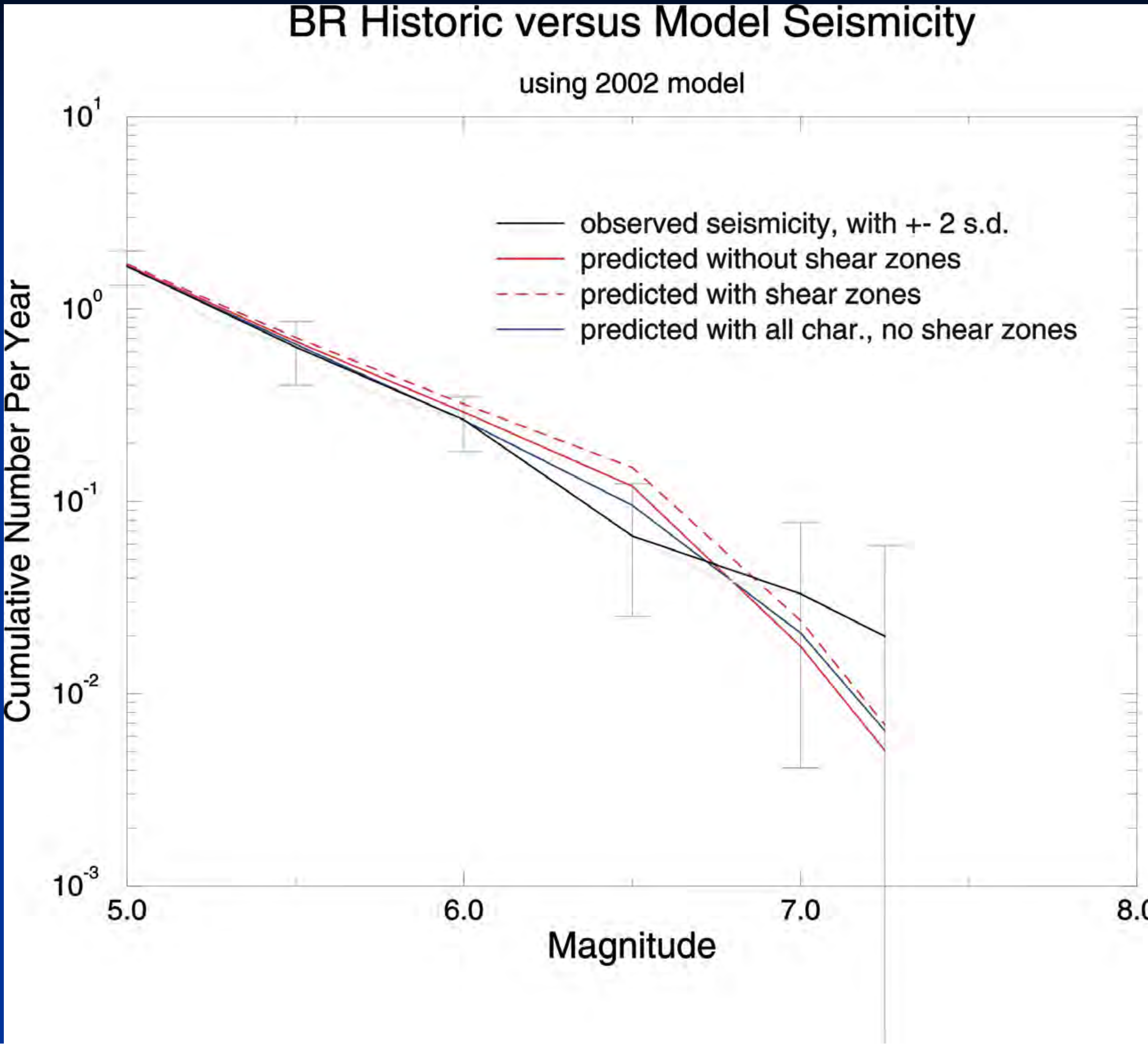
Parameters

- Slip rate
- Characteristic or maximum magnitude
- Epistemic and aleatory uncertainty
- Ratio of Characteristic to Floating Rupture moment rate
- Minimum magnitude
- b-value

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

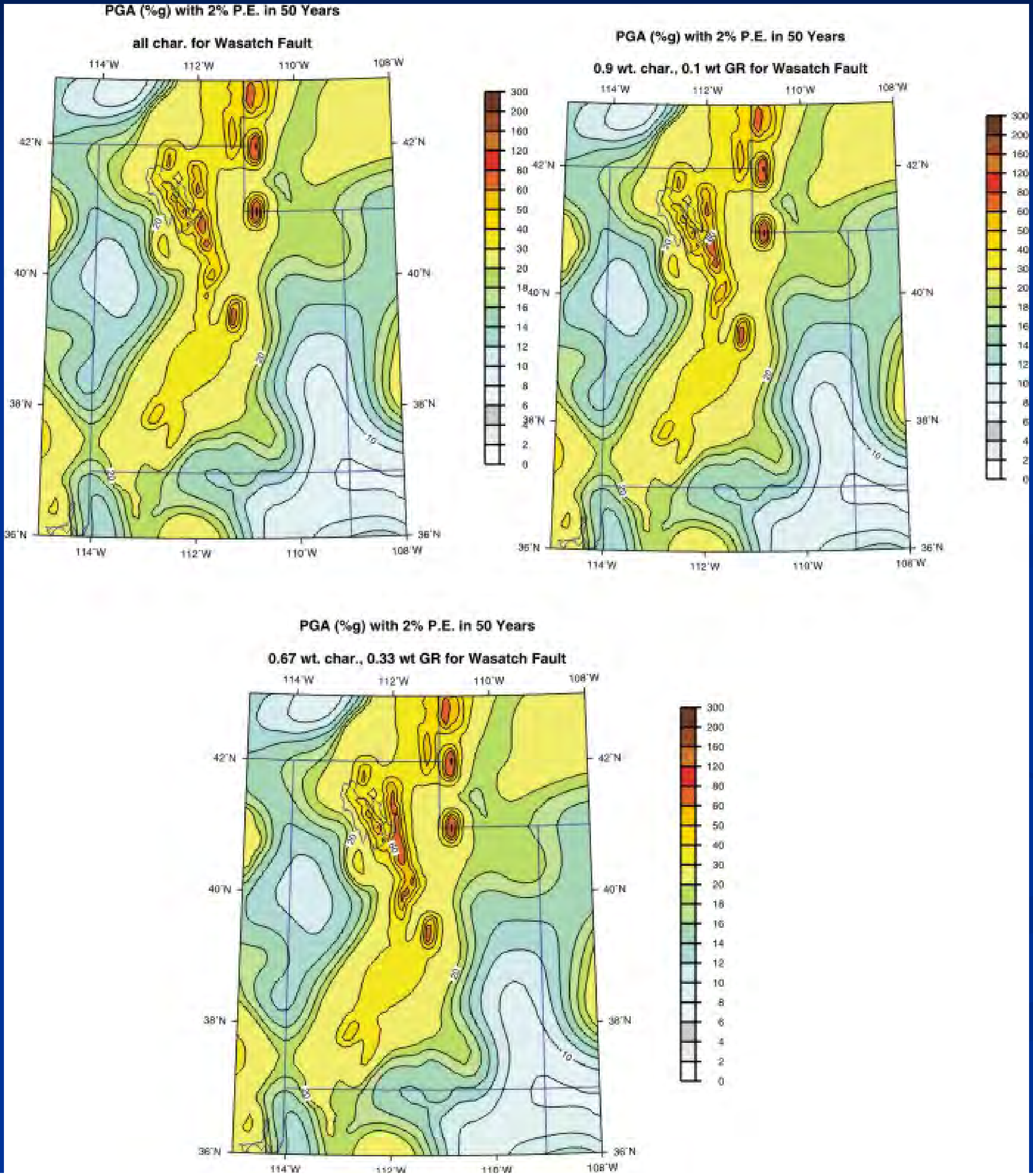


1.5E-3
1.2E-3
1E-3
7.5E-4
5E-4
2.5E-4
0E0
Incremental Rate
6.50
6.75
7.00
7.25
7.50
7.75
8.00
Magnitude
b=0
b=0.8


BR Historic versus Model Seismicity
using 2002 model
observed seismicity, with +- 2 s.d.
predicted without shear zones
predicted with shear zones
predicted with all char., no shear zones
Cumulative Number Per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
5.0
6.0
7.0
8.0
Magnitude

Source characterization

Magnitude-frequency distributions

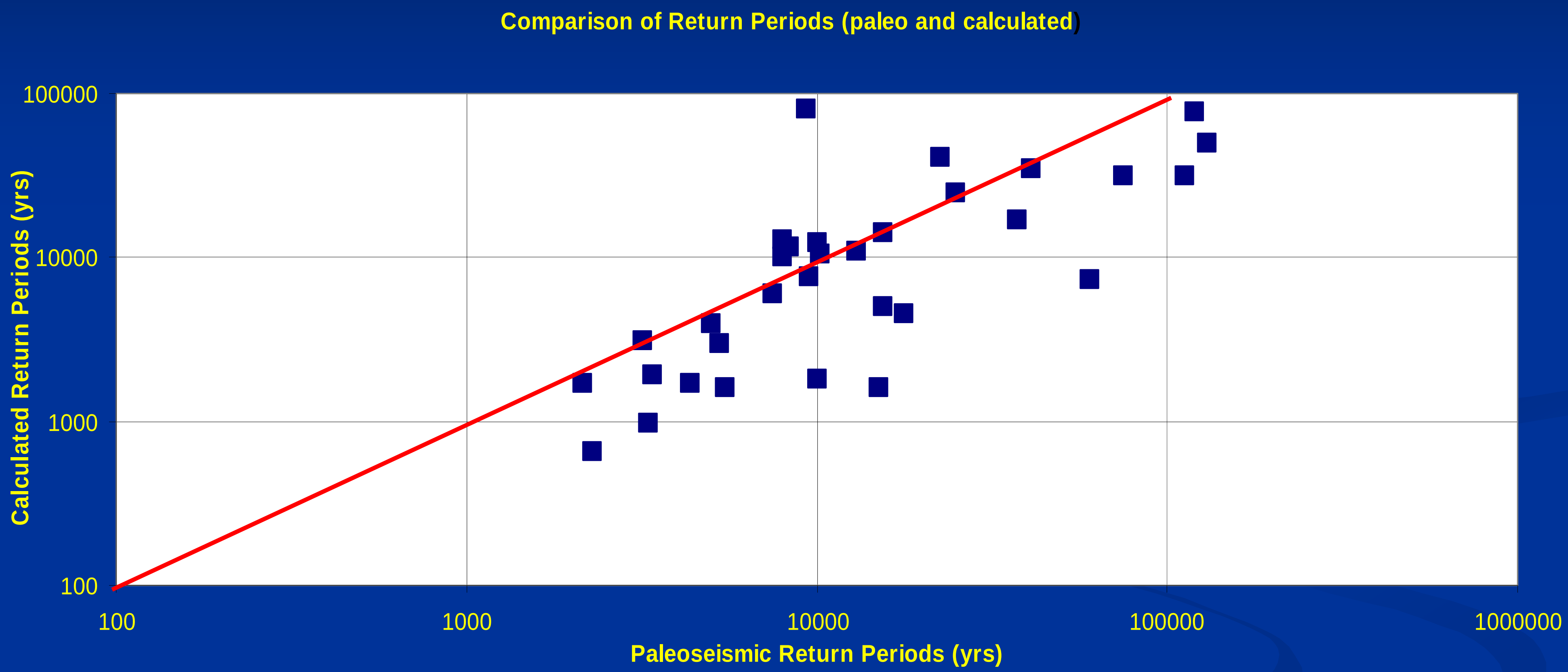


Characterization of magnitudes for Intermountain West region

- Used magnitude-length relations (all fault types), no data available for fault area.
- Assumed 60 degree dip for normal faults
- Assumed 15 km depth of rupture
- Constrained large magnitudes to 7.5

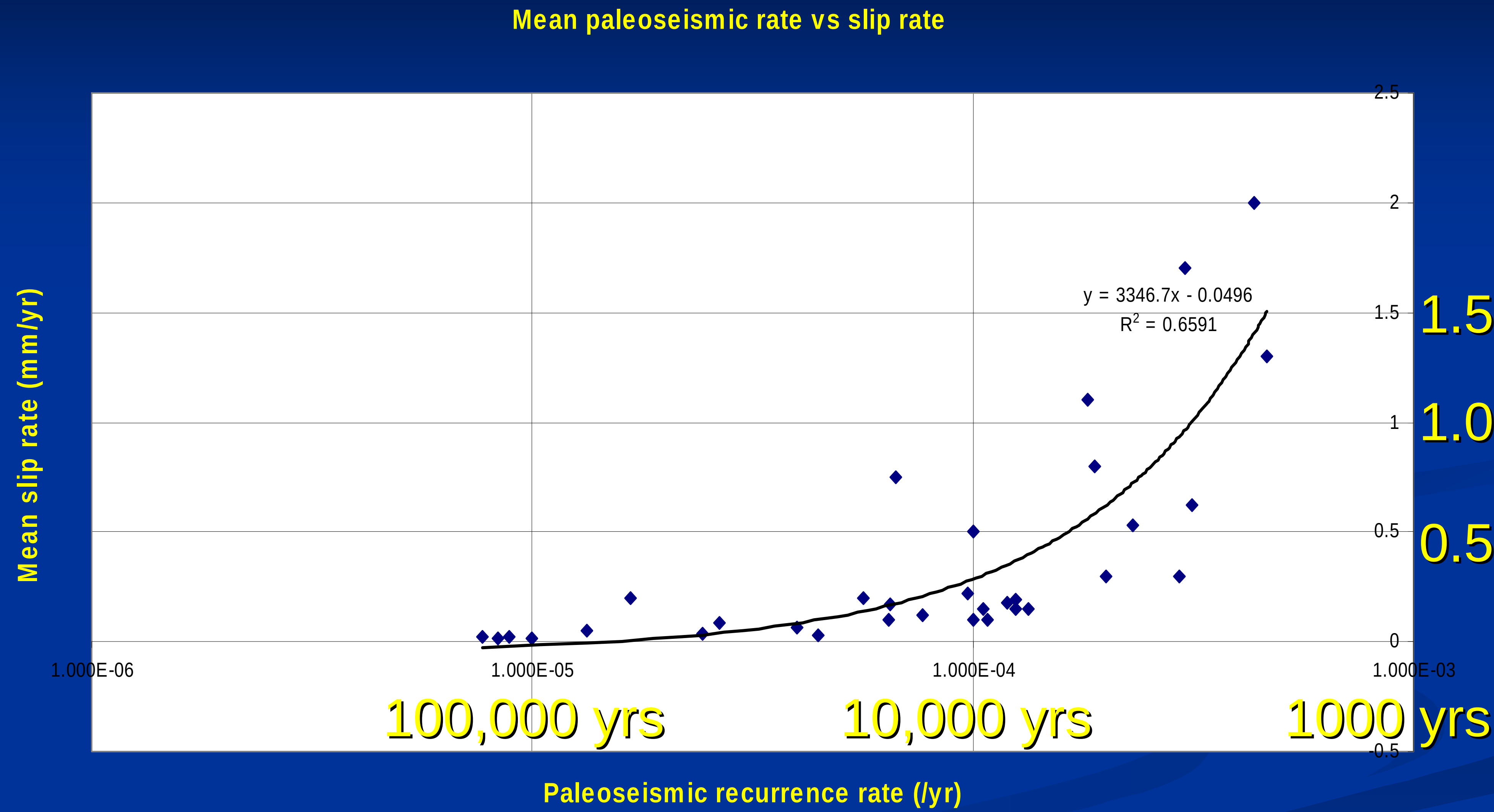
Source characterization

Estimating Return Period of Earthquake



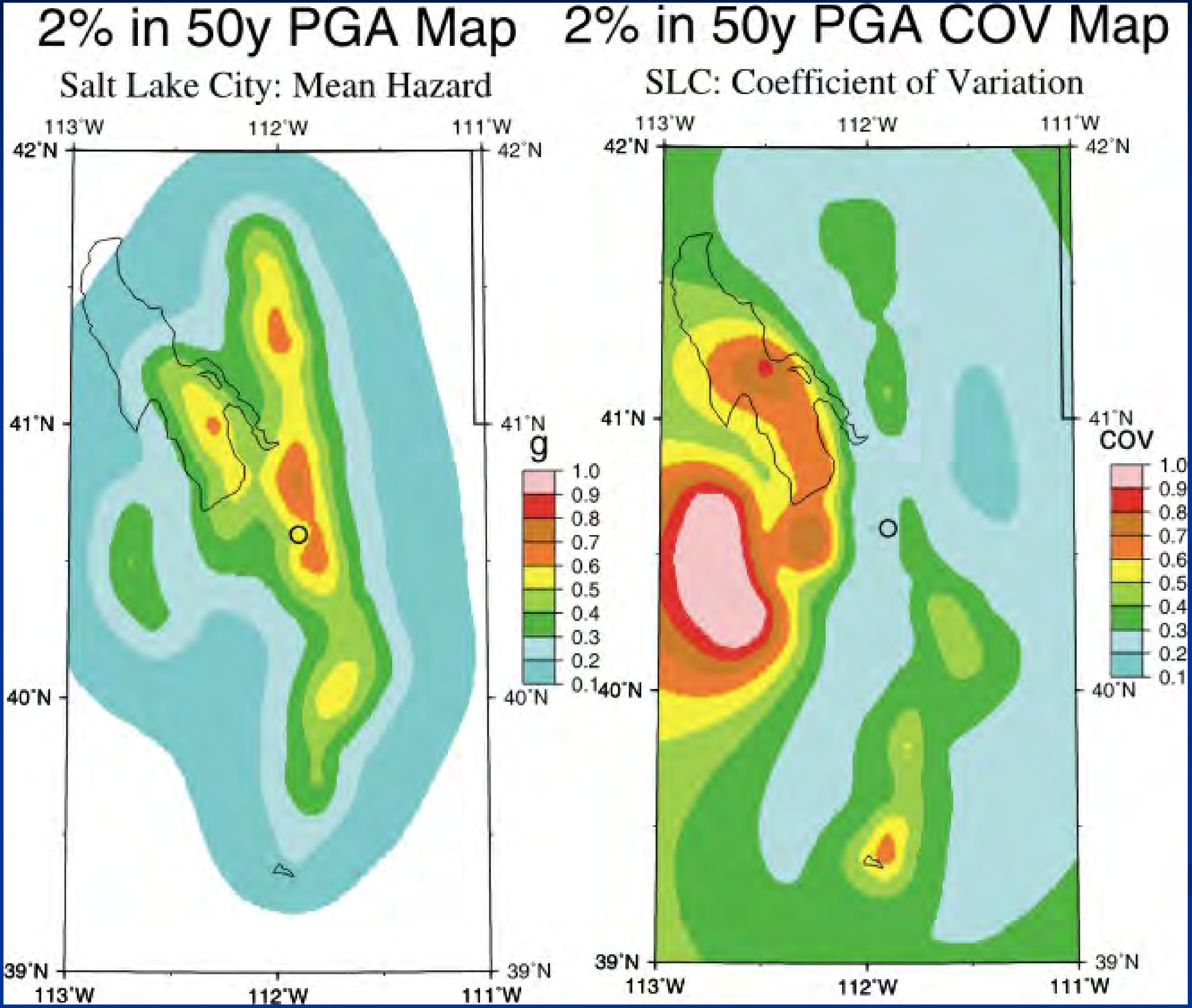
USGS
science for a changing world

Correlation between slip rate and recurrence



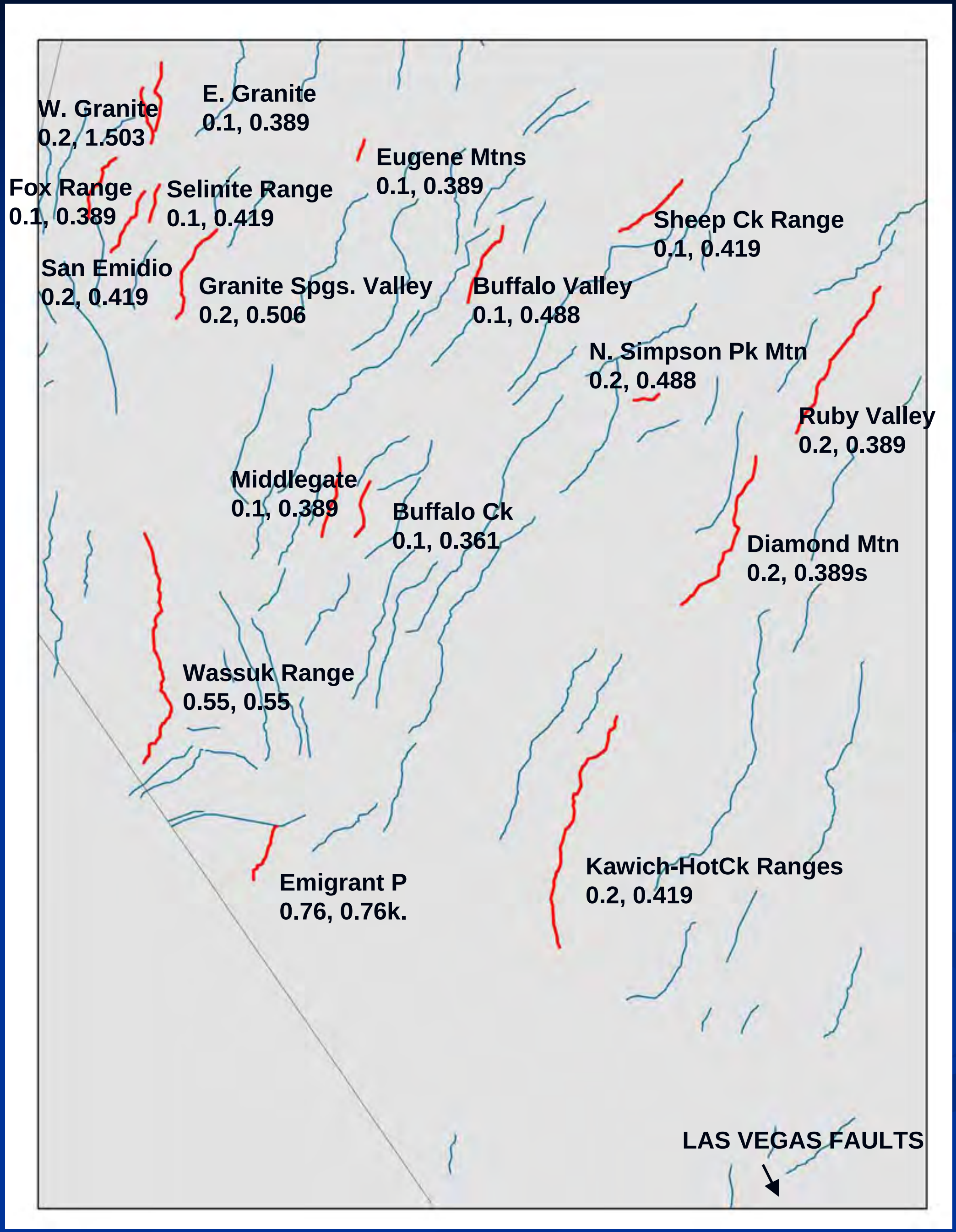
Testing and UncertaintyAnalysis

UNCERTAINTY ANALYSIS

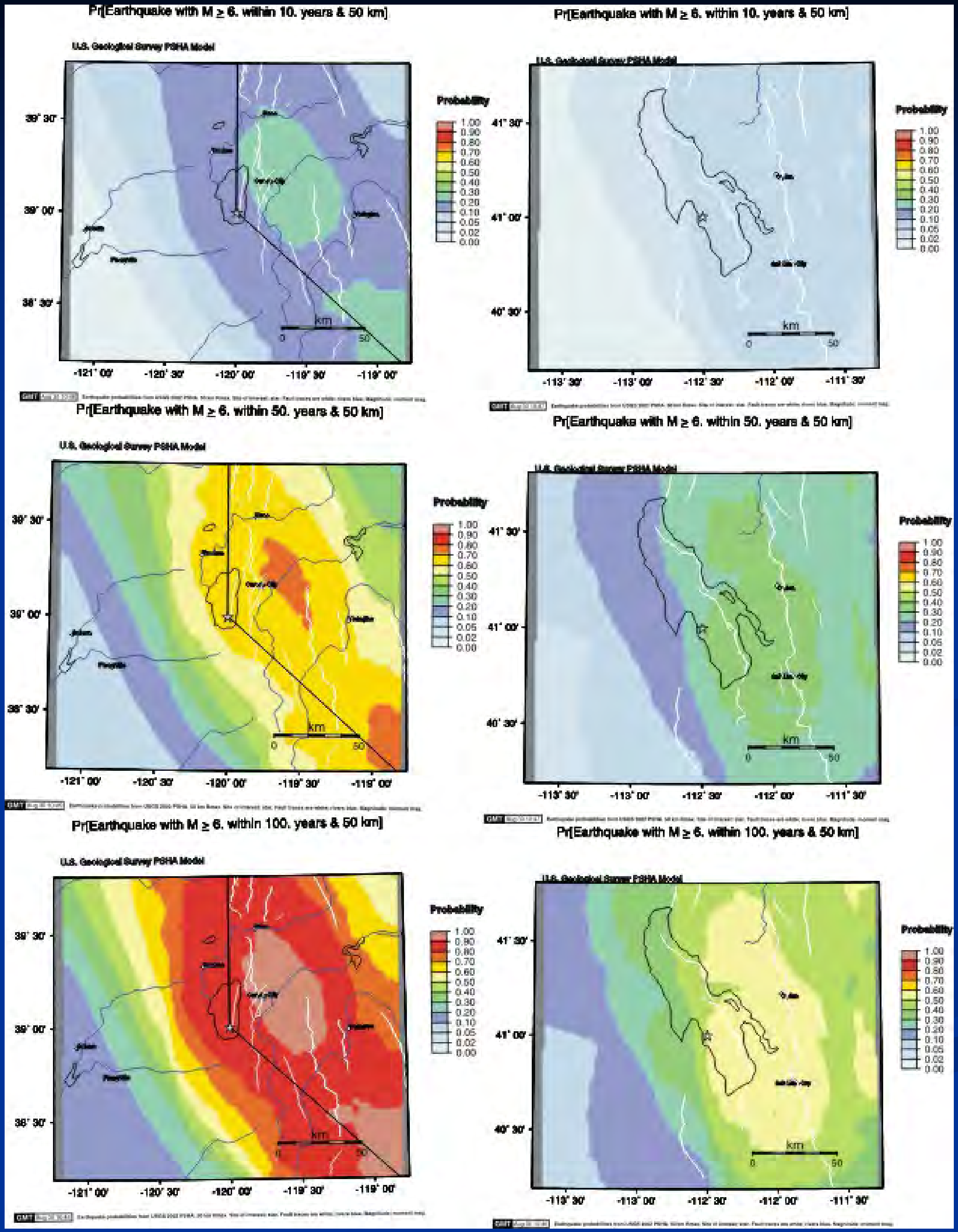


Source characterization

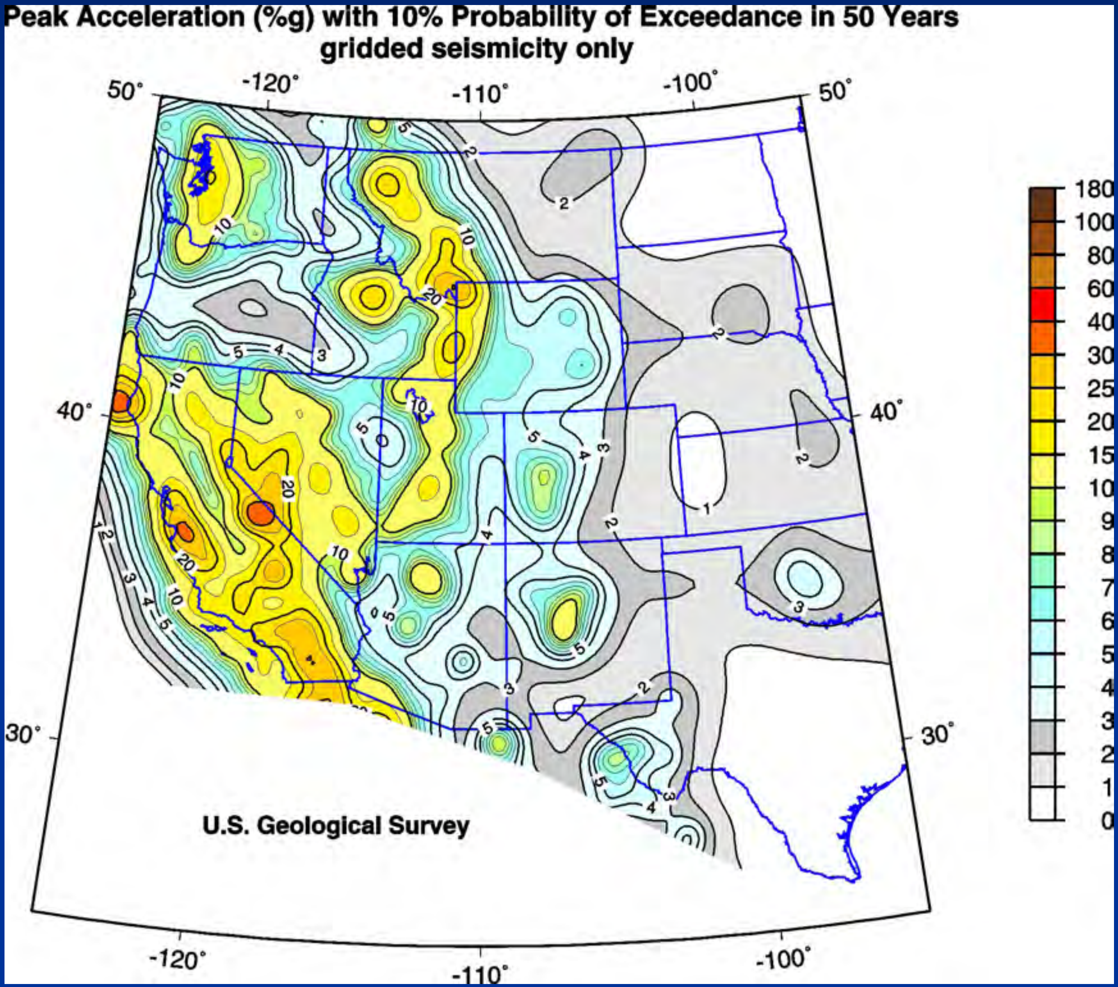
Slip rates:

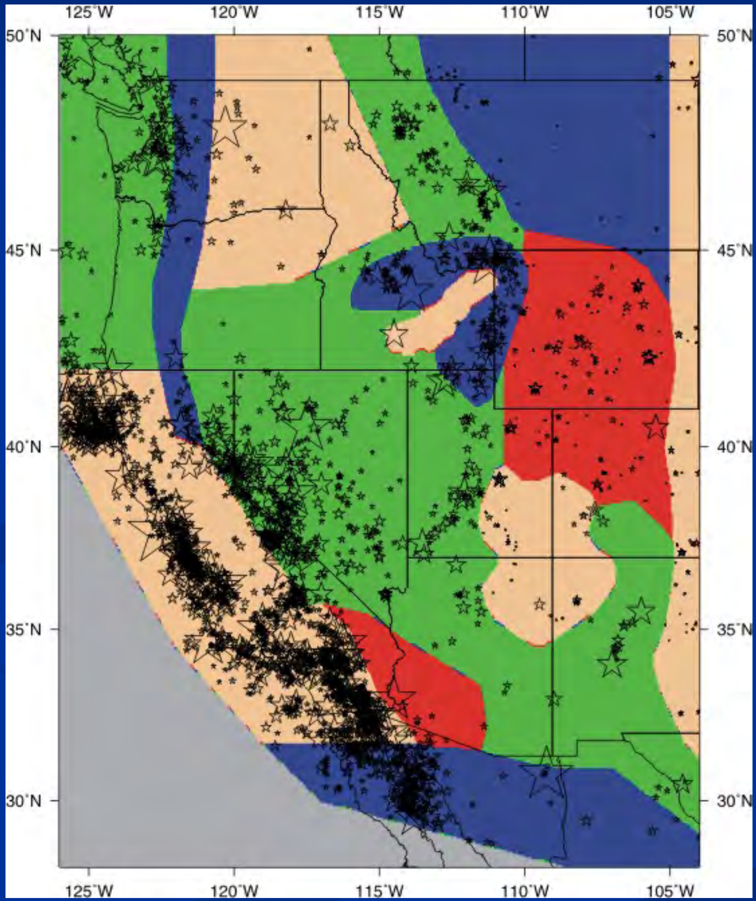


Probability maps

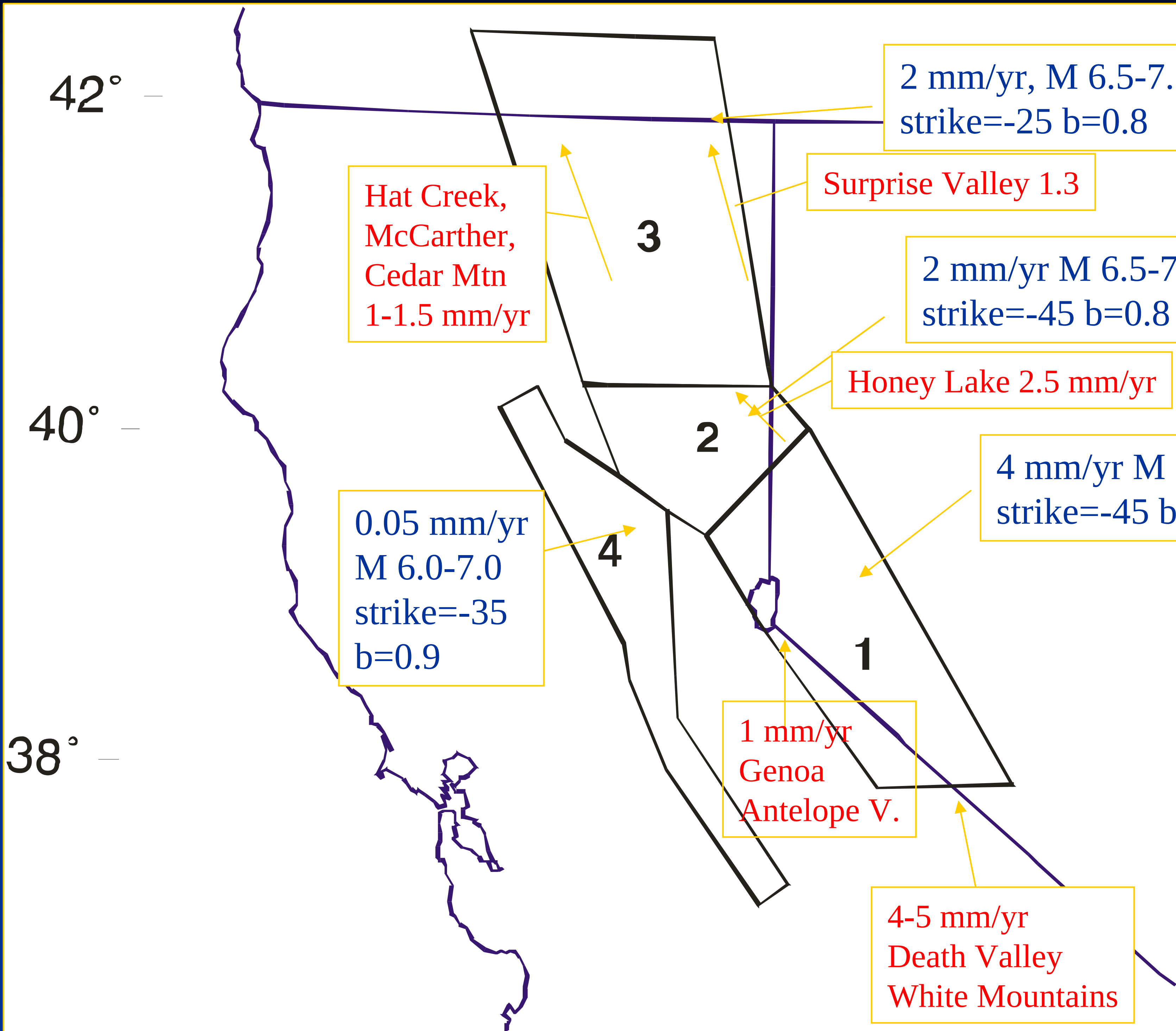


Background random earthquakes



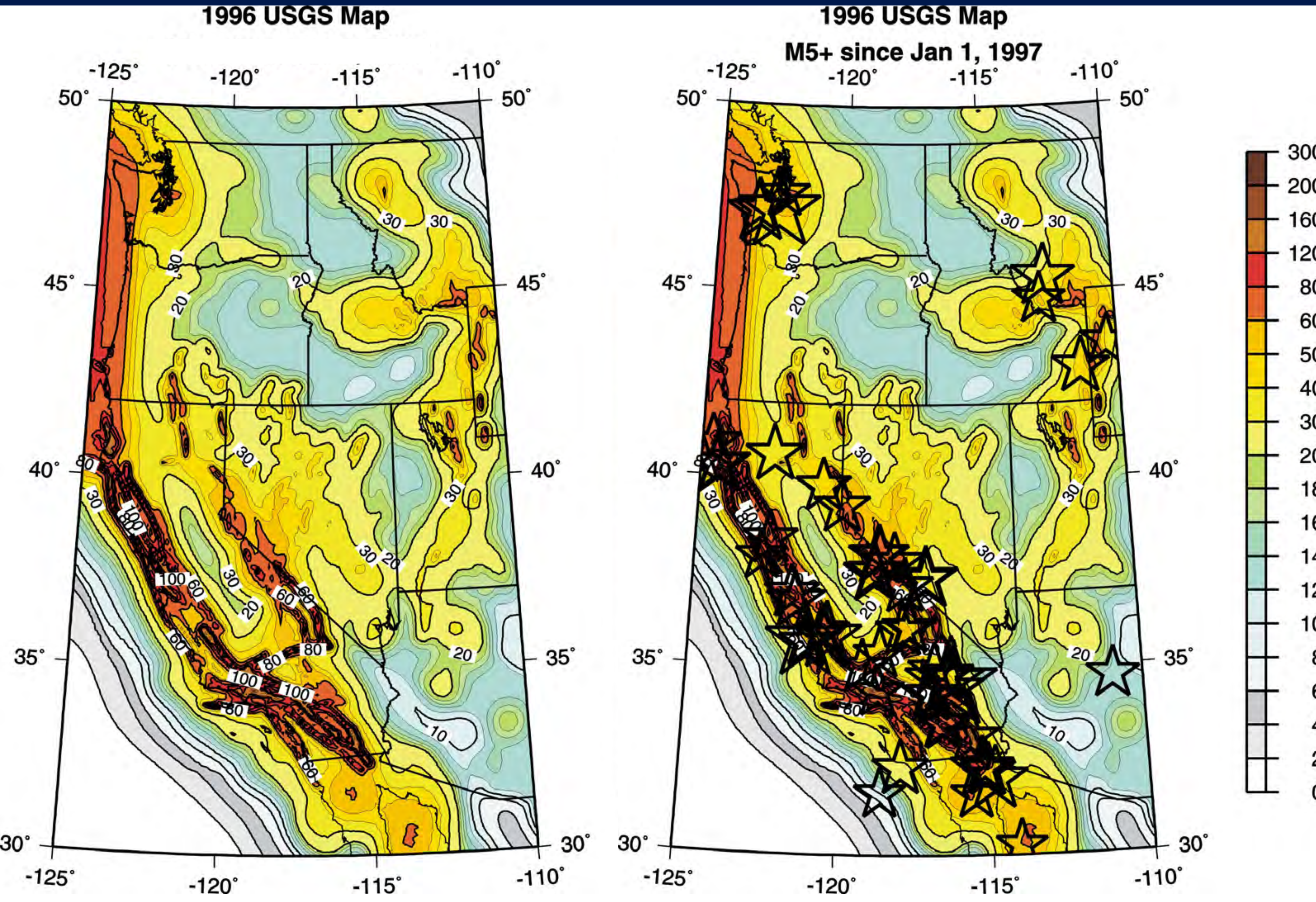


Geodetic based source zones

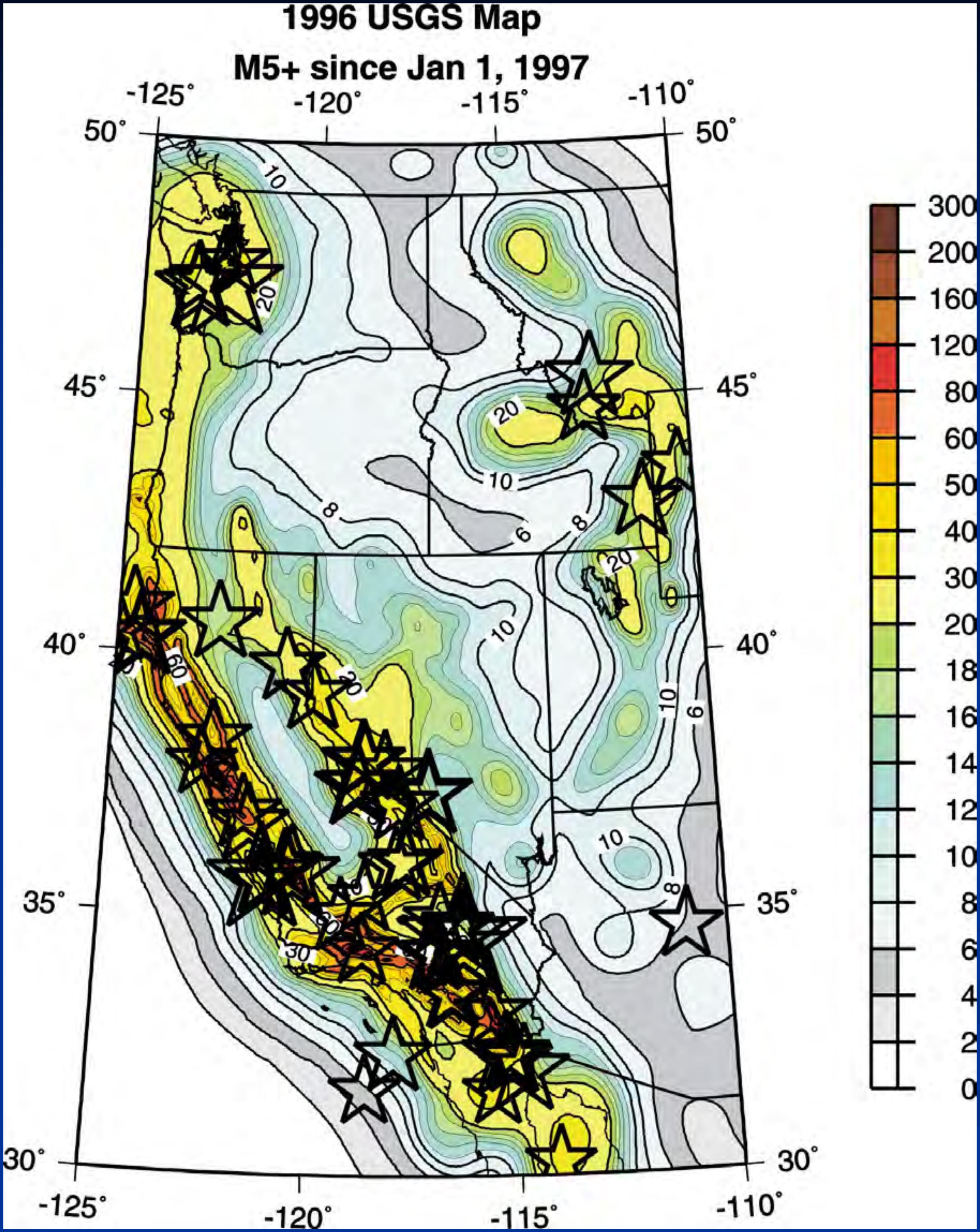


PGA (%g) with
2% PE in 50 yr

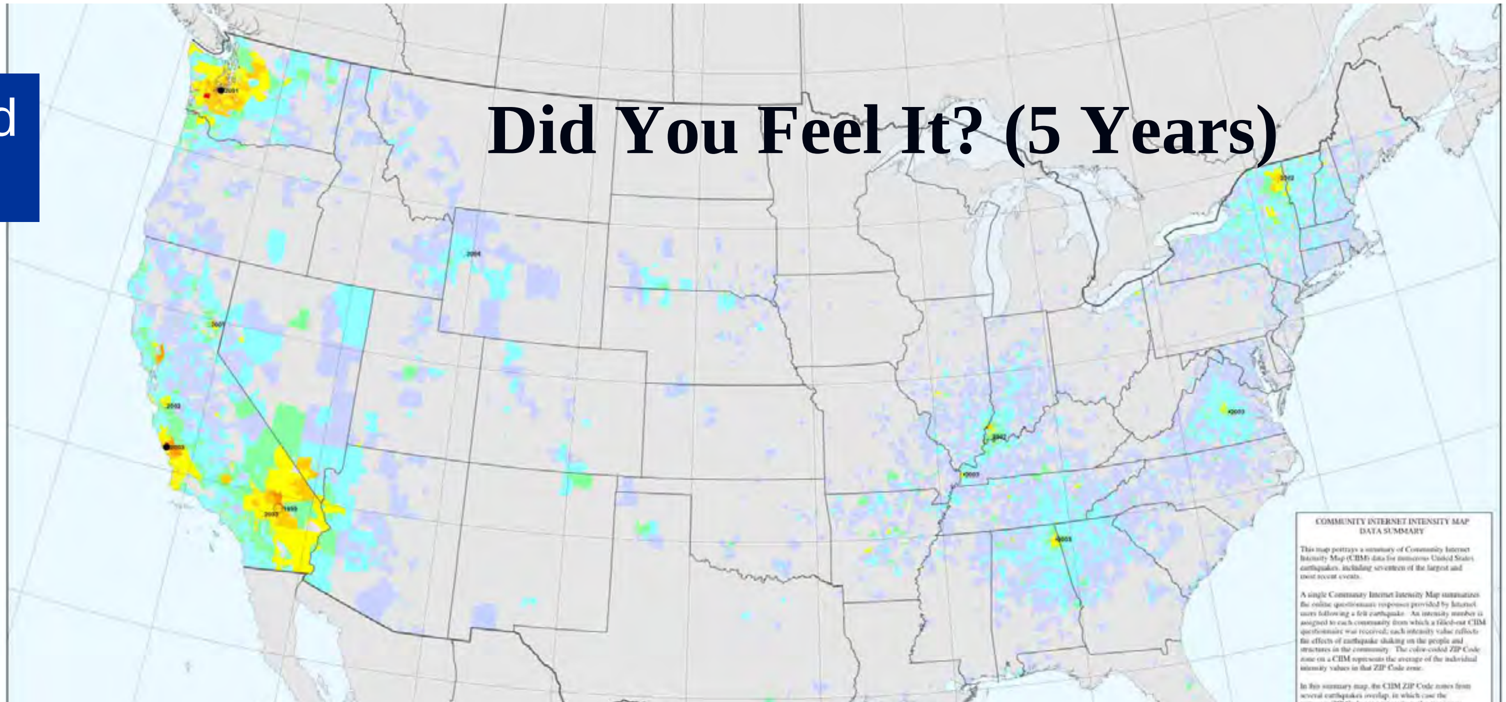
62 events

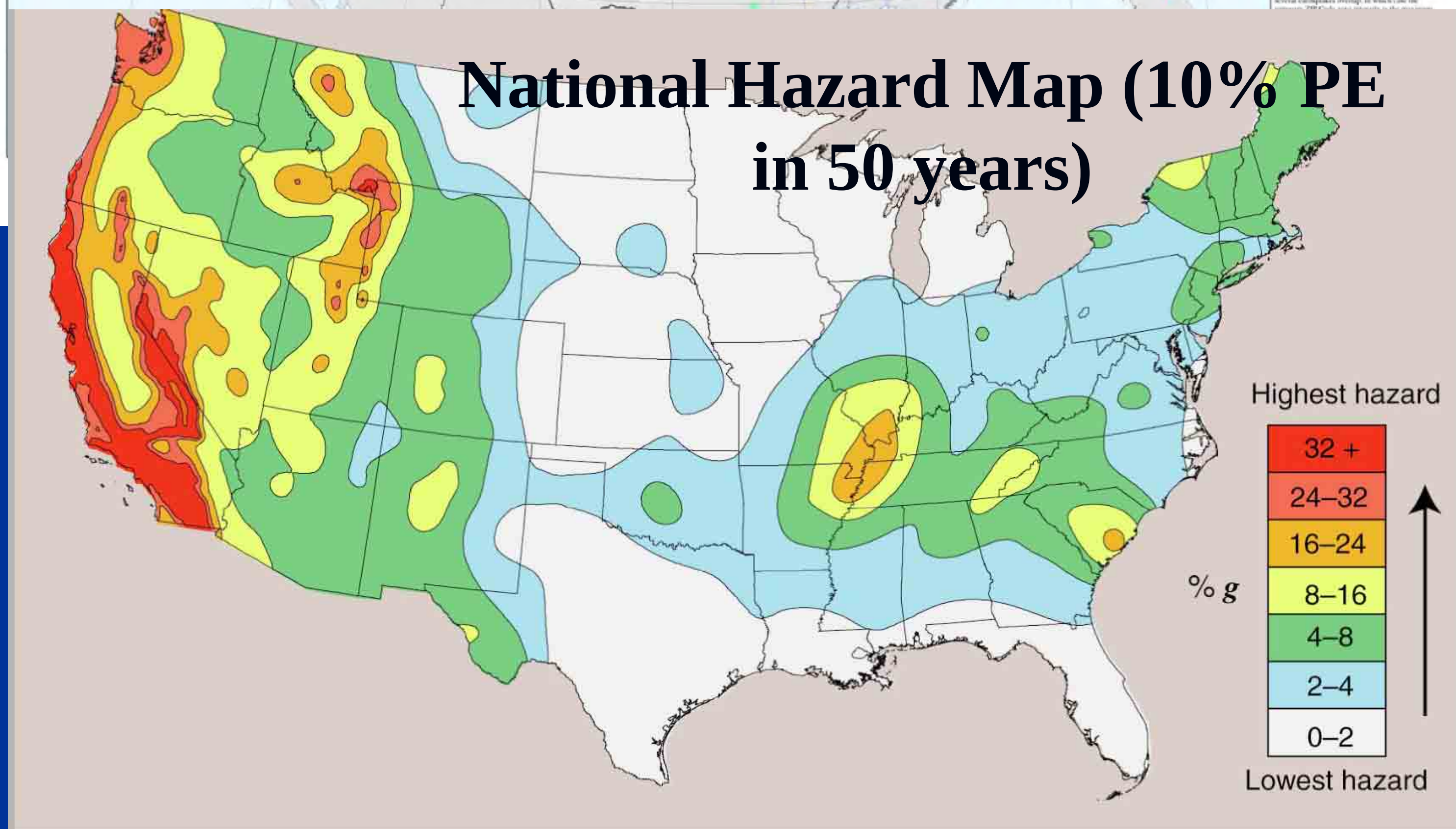


PGA (%g)
With 10% PE
In 50 years



Slide composed by D. Wald

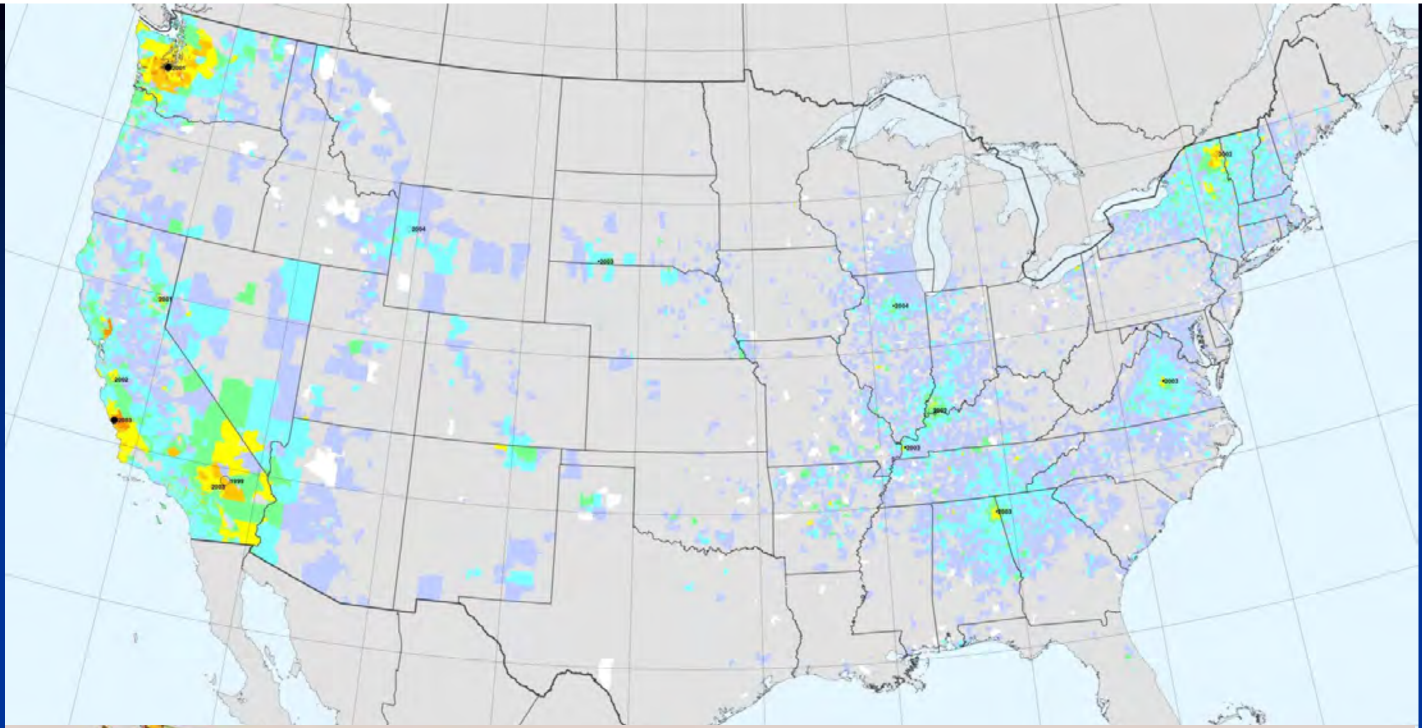




USGS science for a changing world

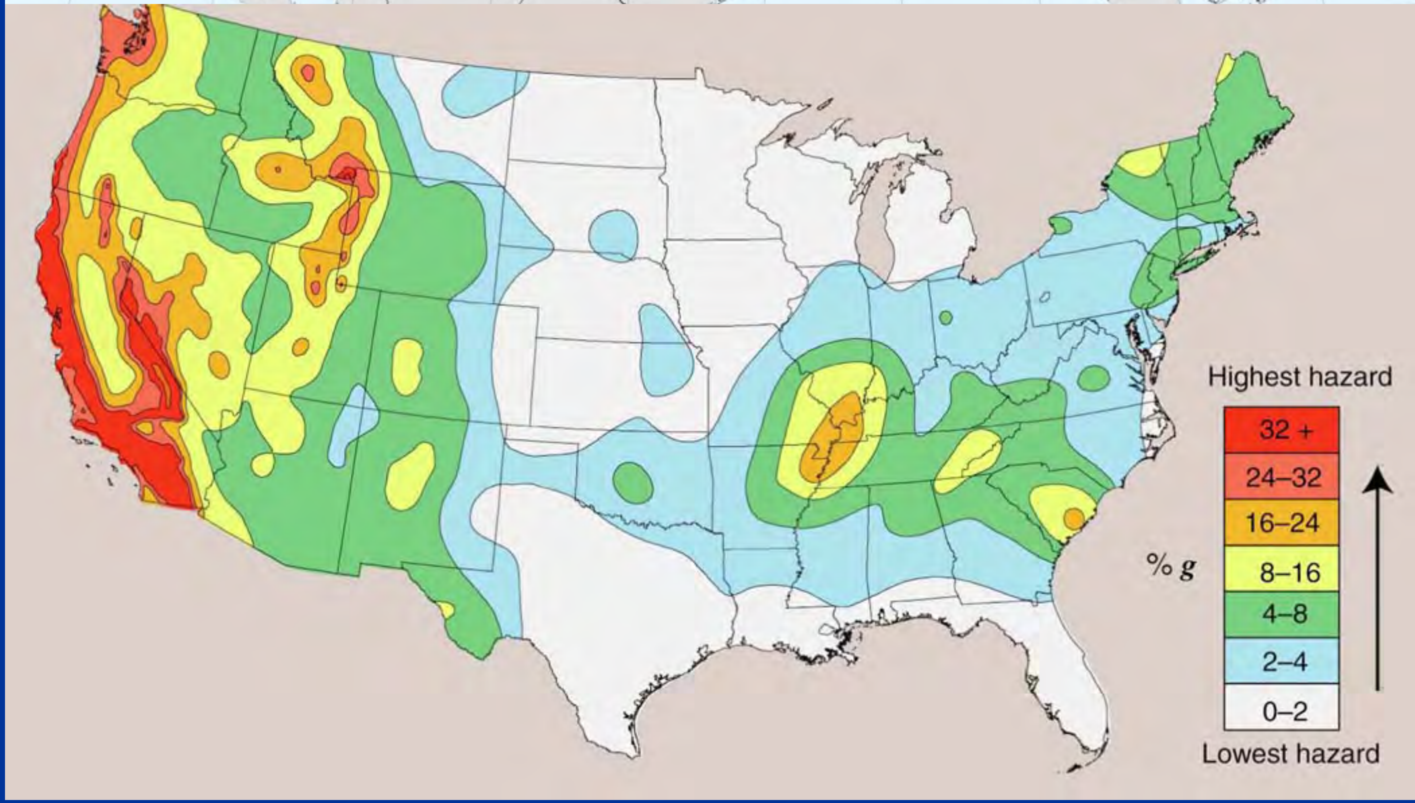
DID YOU FEEL IT?

5 Years



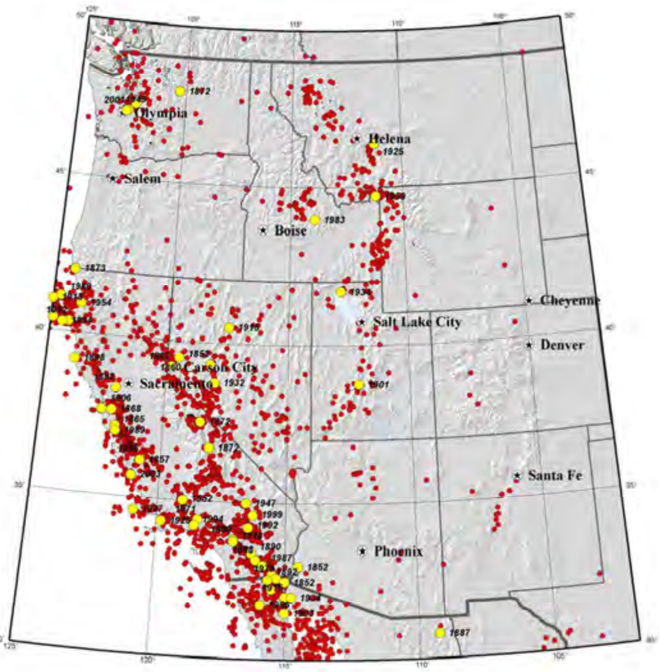
USGS HAZARD MAP

10% probability
Of exceedance in
50 years

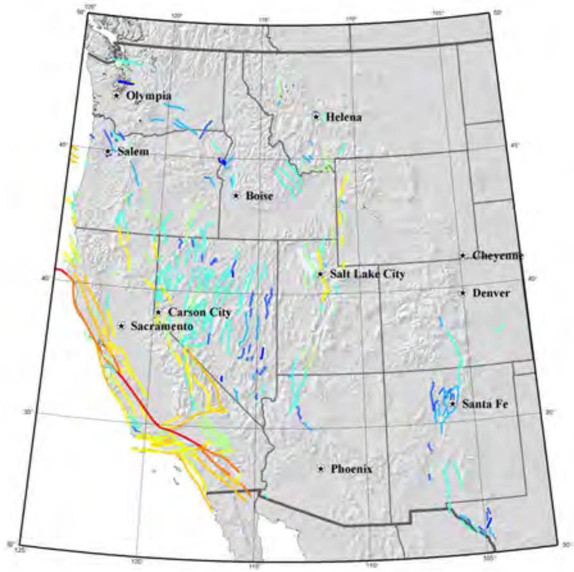


DATA FOR DEVELOPING MAPS:

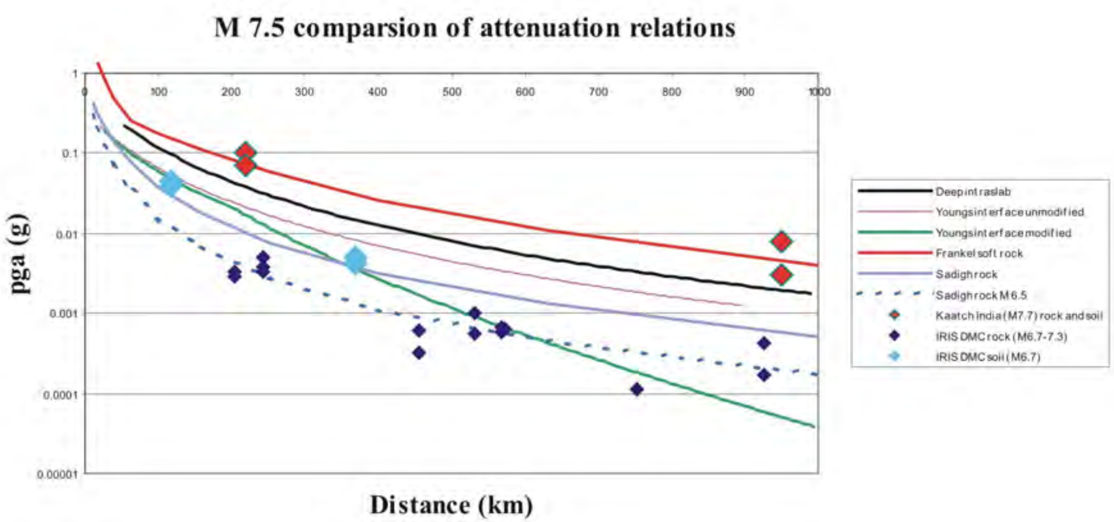
EARTHQUAKES



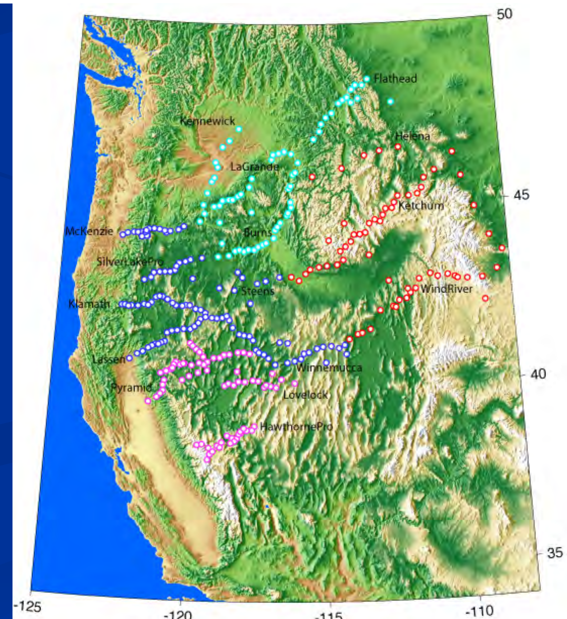
QUATERNARY FAULTS



ATTENUATION RELATIONS

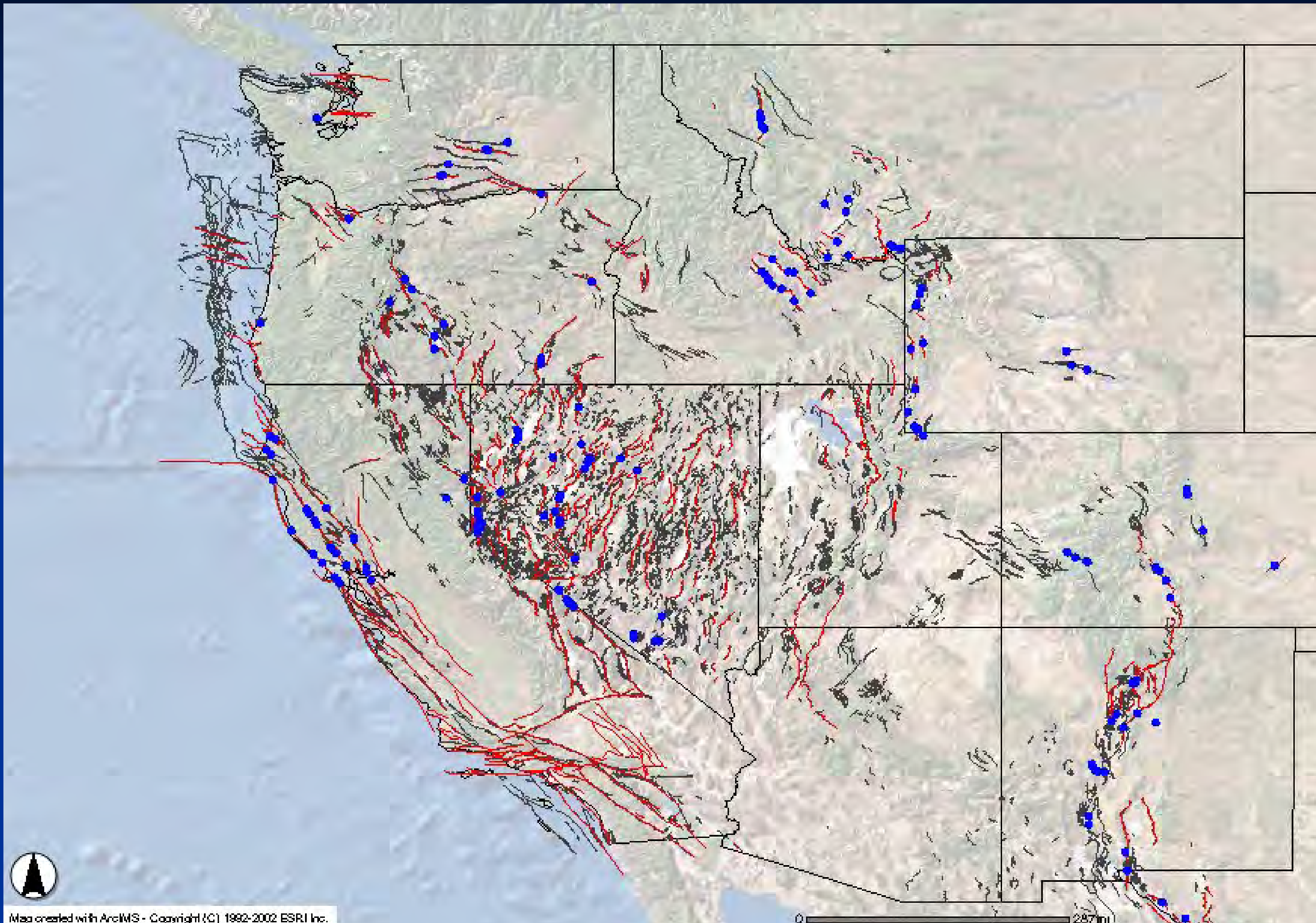


GEODETIC DATA



Blue sites surveyed once in 1999 and will be surveyed again June 2003.
Cyan sites surveyed once in 2001, expecting resurvey in 2005
Magenta sites surveyed once in 2000, expecting resurvey in 2004
Red sites have been described and sited, expecting first survey in September 2003.

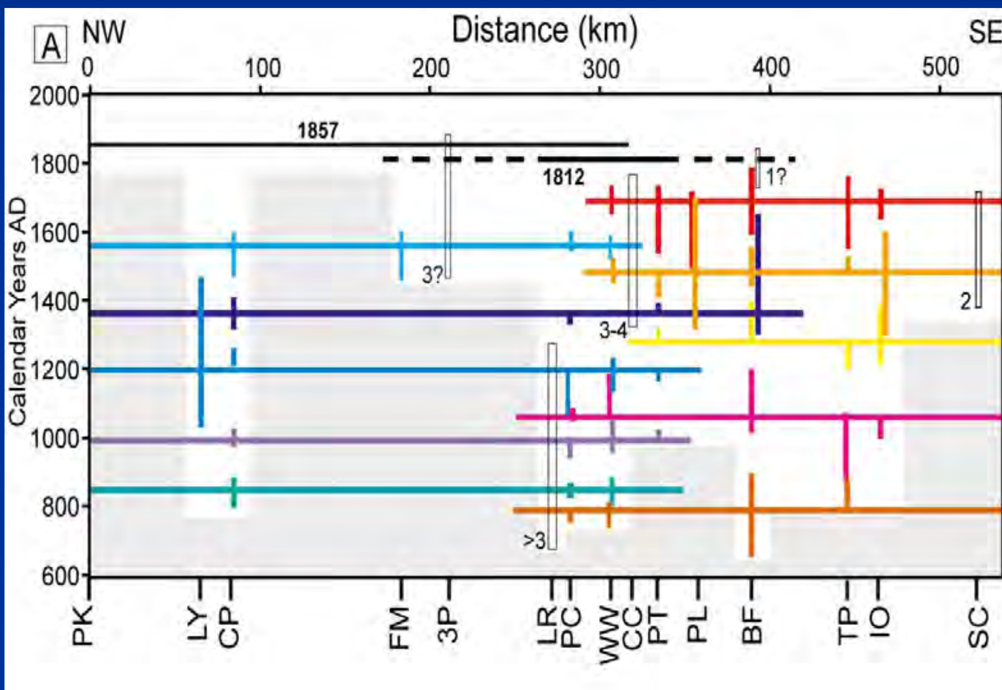
Quaternary Fault – Consensus Fault Database /ARCIMS interface

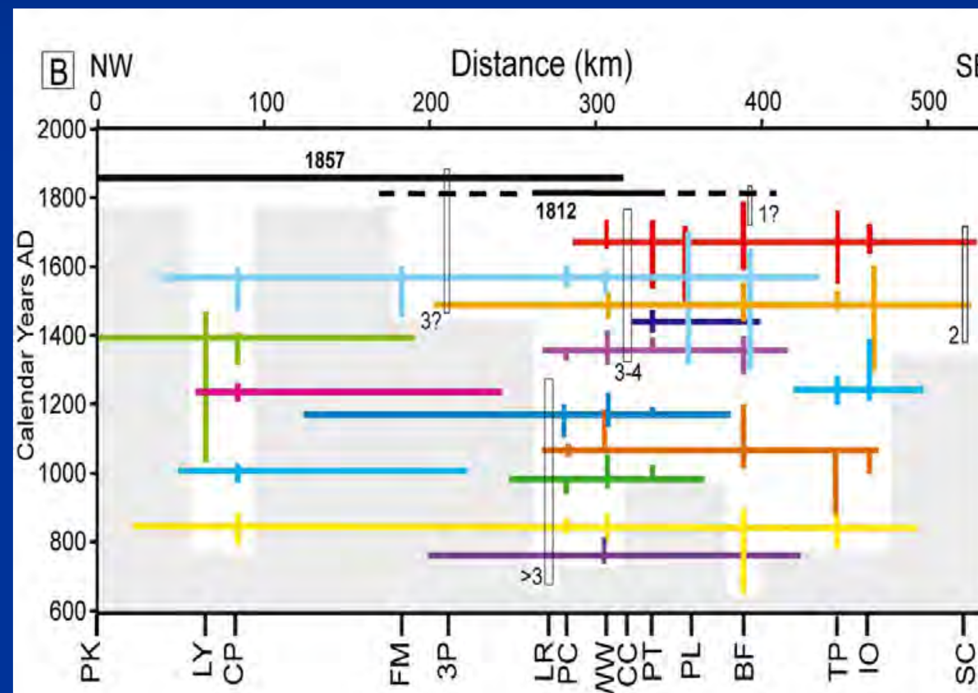


GEOLOGIC DATA

Two multi segment rupture models based on Weldon et al. 2002

From Weldon et al.:



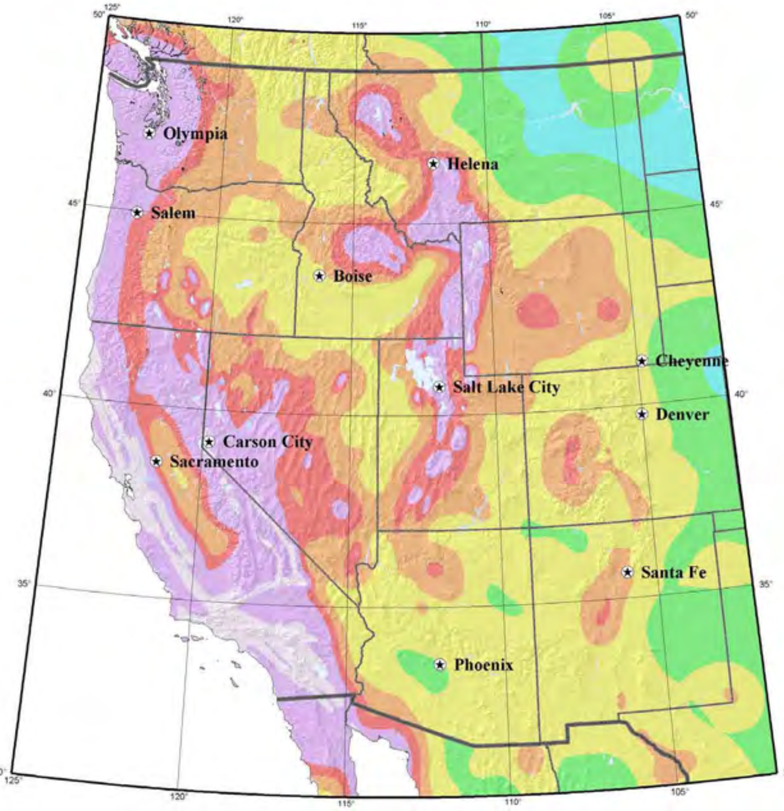


Rupture scenarios for the Southern San Andreas fault. Vertical bars represent the age range of paleoseismic events recognized to date, and horizontal bars represent possible ruptures. Gray shows regions/times without data. In (A) all events seen on the northern 2/3 of the fault are constrained to be as much like the 1857 AD rupture as possible, and all other sites are grouped to produce ruptures that span the southern ½ of the fault; this model is referred to the North Bend/South Bend scenario. In (B) ruptures are constructed to be as varied as possible, while still satisfy the existing age data.

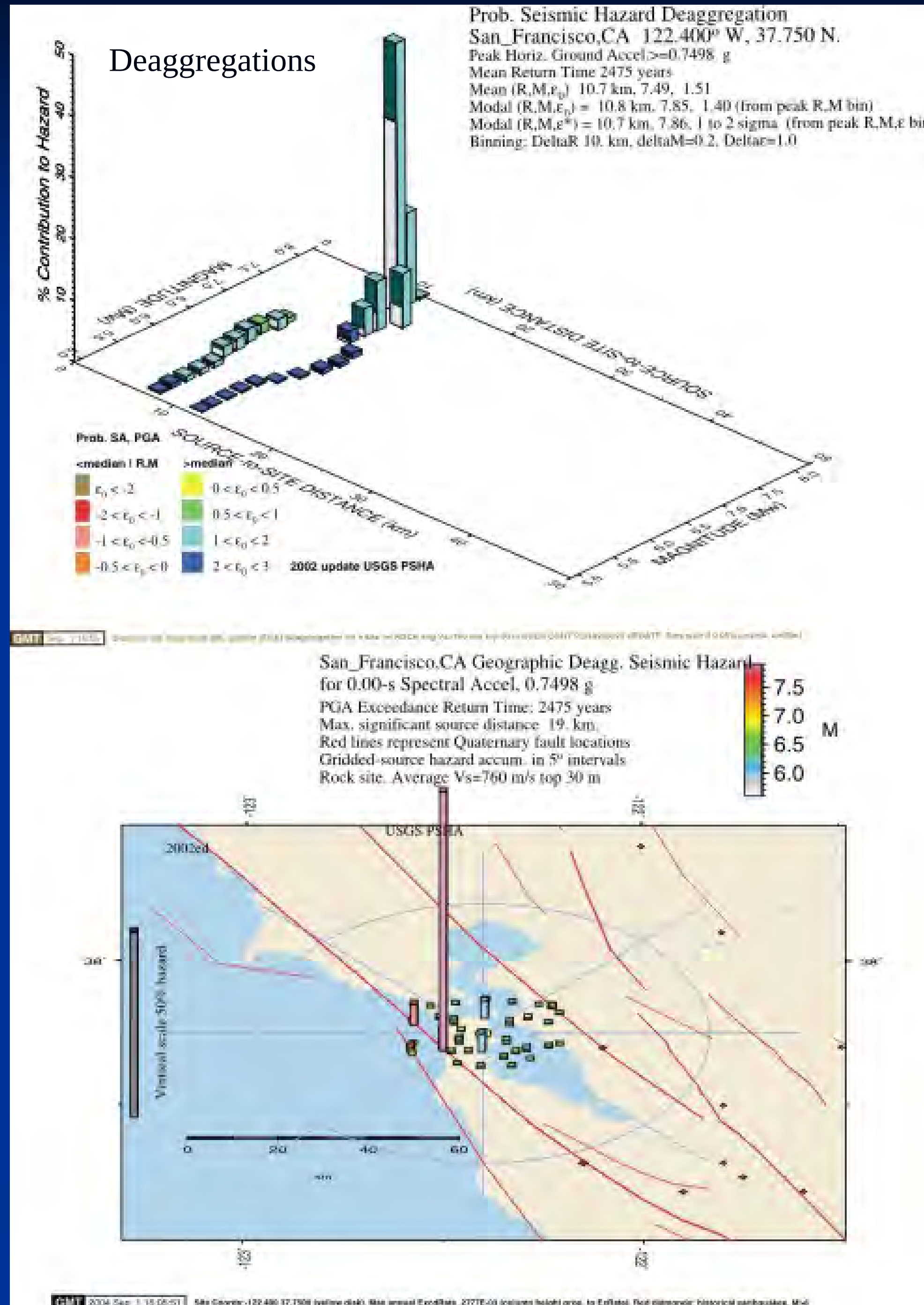
HAZARD PRODUCTS

http://eqhazmaps.usgs.gov

2002 Hazard Maps - PGA-rock
2% probability of exceedance in 50-years

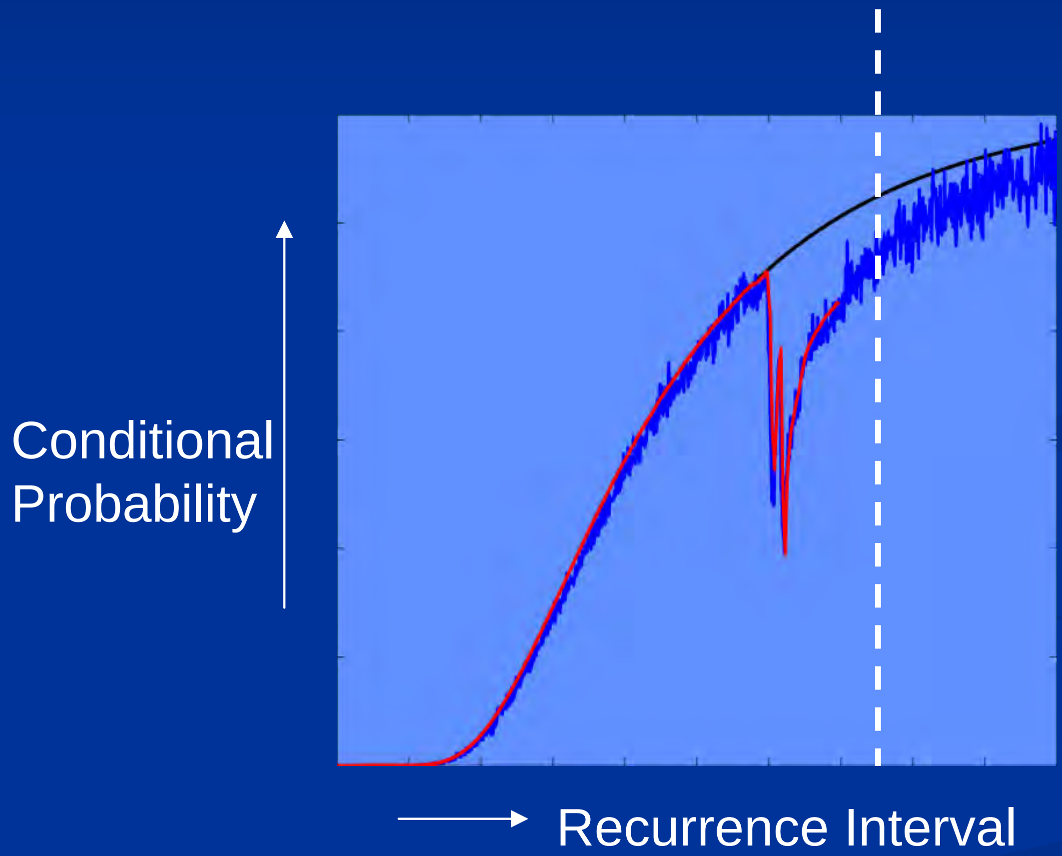


Purple-0.3g and greater
Yellow -0.1g and greater



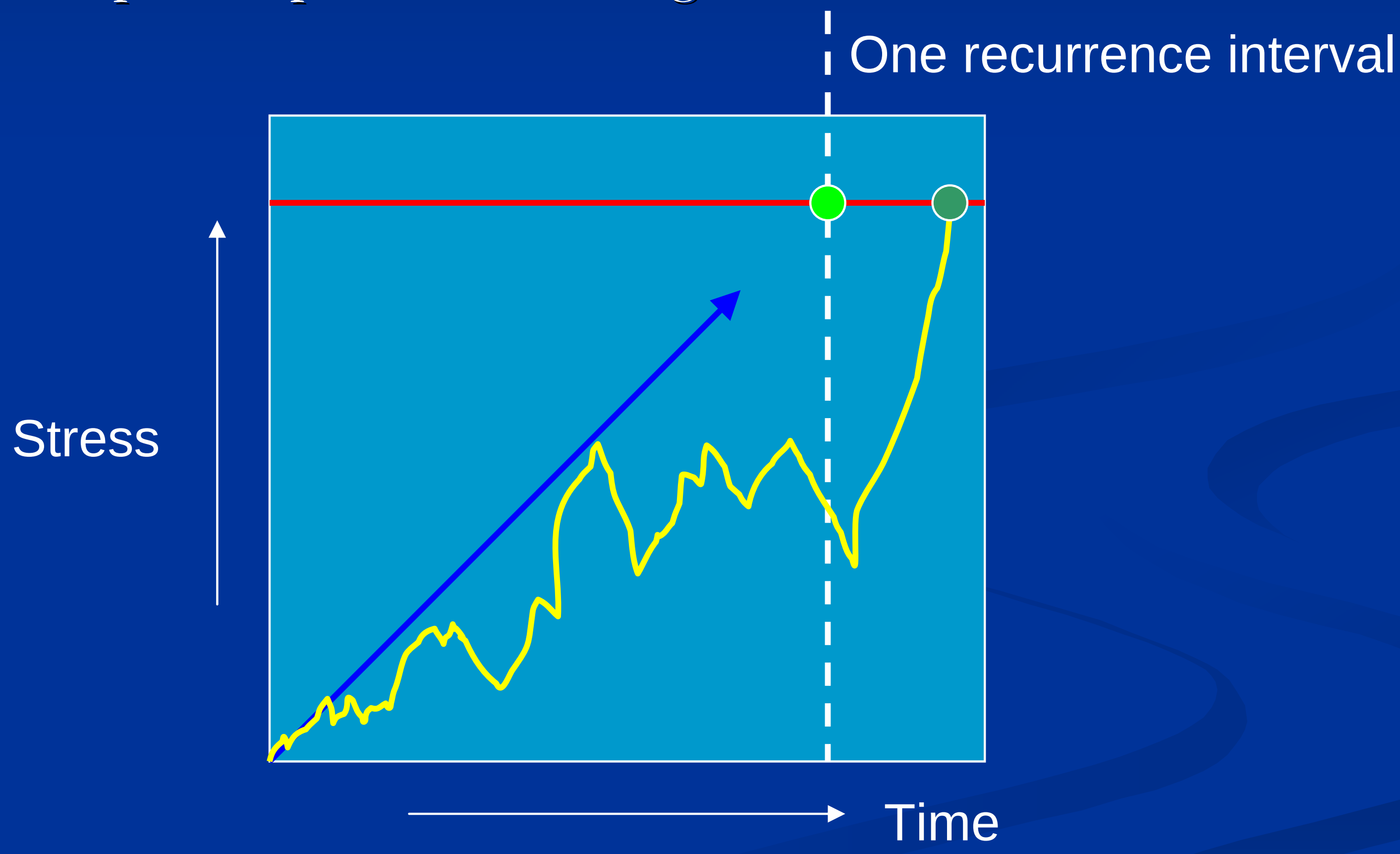
Brownian Passage Time

- Conditional probability and steps in stress during the seismic cycle.



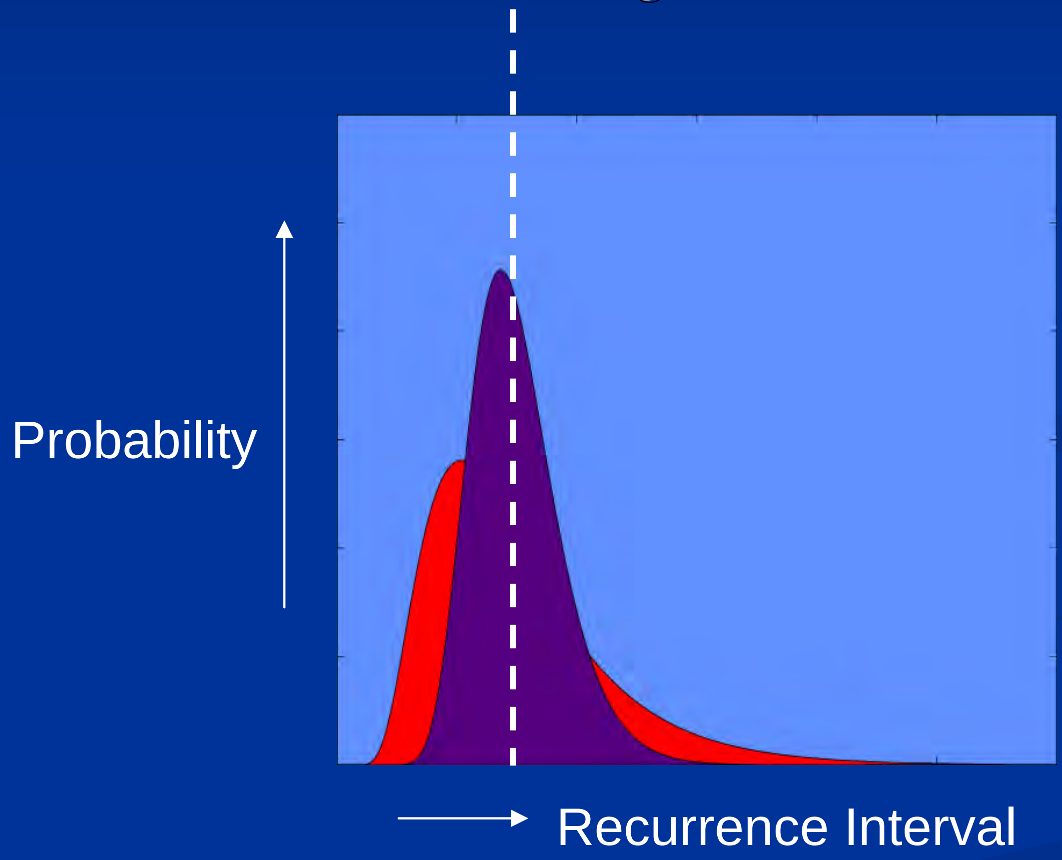
Brownian Passage Time

- Brownian passage time (BPT) loading on a fault – random fluctuations of stress superimposed upon linear loading of a fault.



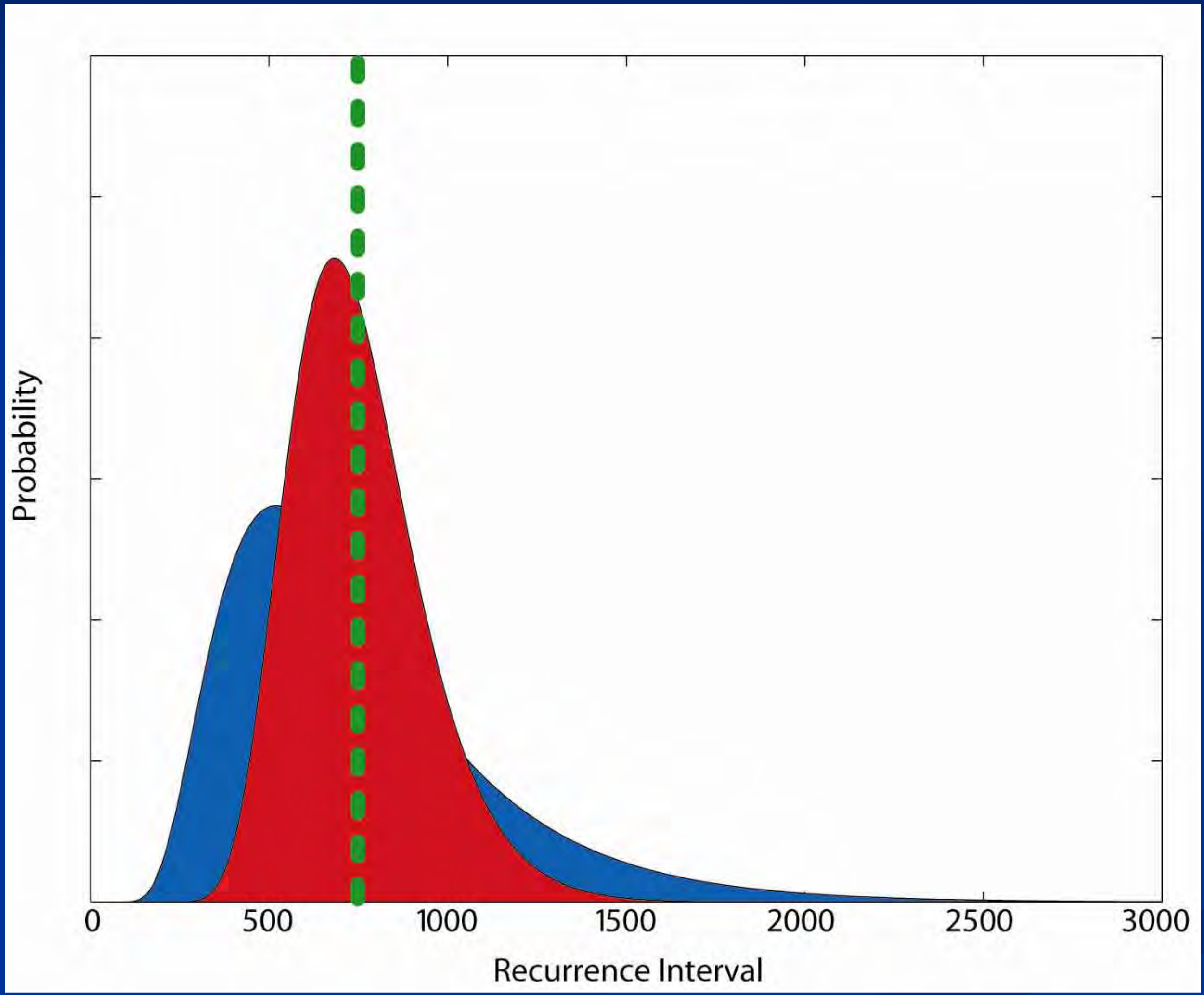
Brownian Passage Time

- The shape of this curve is dependent on the magnitude of random fluctuations versus the linear increase in loading.



What are time-dependent earthquake probabilities?

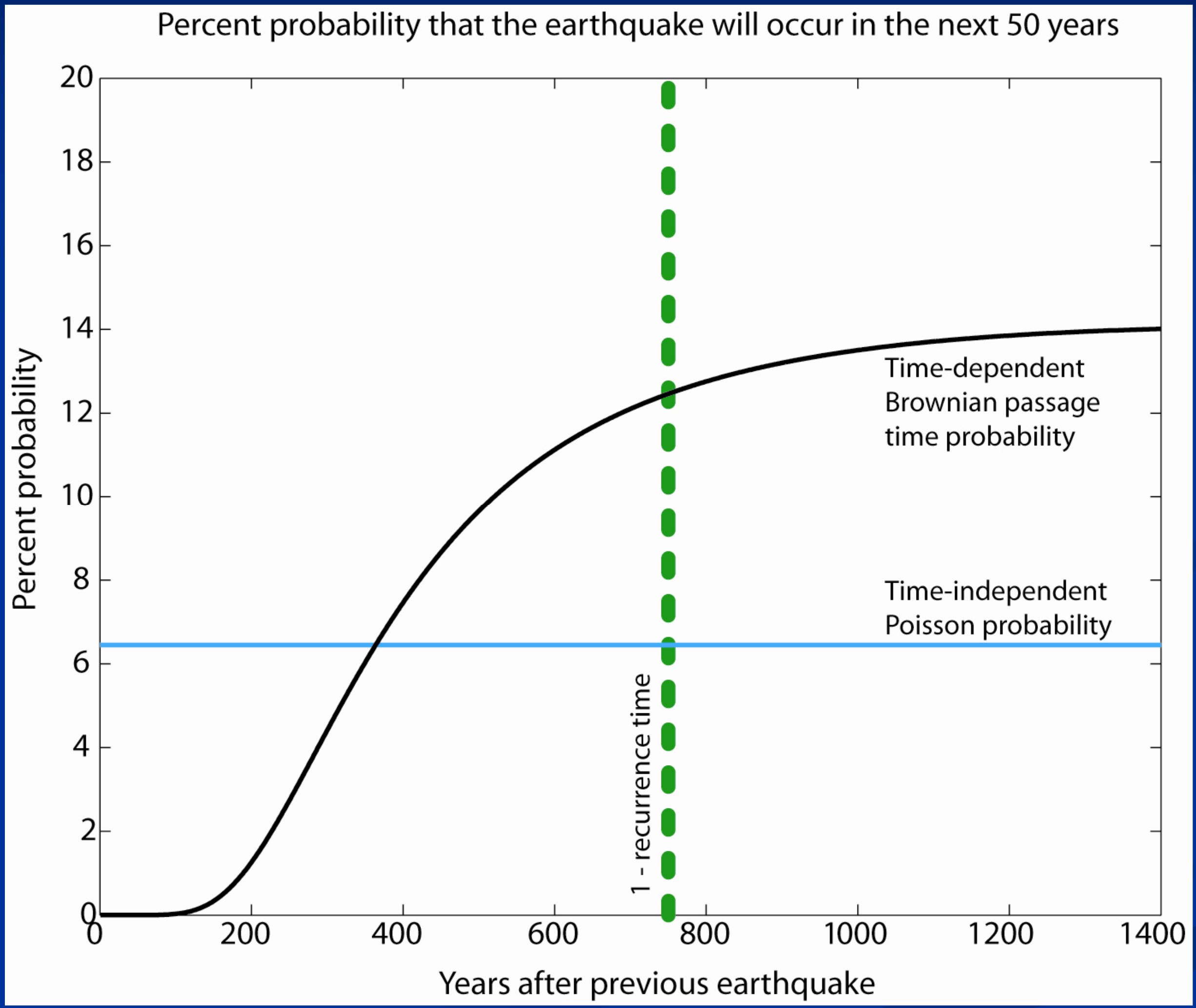
- Linear loading with Brownian motion



Oliver Boyd

What are time-dependent earthquake probabilities?

- Time-dependent conditional probability



Oliver Boyd

Basin and Range Province Earthquake Working Group Workshop: Wednesday AM

John G. Anderson

Recommendation 1

- For the 2007 iteration of the National Hazard Map, USGS should incorporate uncertainties in slip rates for the more significant faults.
  - Most studies giving slip rates identify range of uncertainties.
  - In Utah, use the slip rate / recurrence interval distributions developed by Utah Quaternary Fault Parameters Working Group.

Recommendation 2

- In the longer term, regional working groups are needed to develop consensus slip-rate and/or recurrence interval distributions for significant faults.
  - These rate distributions would represent temporal variation of the rates, if any, and other uncertainties.
  - A high-level working group needs to recommend the guidelines for establishing these distributions
  - Each regional group needs a "champion" who will take "ownership".
  - Regions will not necessarily be by state. Some organization (e.g. USGS or WSSPC) needs to take responsibility to assure complete geographic coverage.

Recommendation 3

- USGS should continue to develop time-dependent maps as a research product.
  - Only a few faults have been studied well enough for time-dependence to be applied.
  - In general, research needs to focus more on the timing of the most recent earthquake, average recurrence and determining coefficients of variation for recurrence.
  - One special case is faults with historical ruptures, where the recurrence time has practically no impact on the conclusion that the chance of a repeat rupture in the next 50 years.
  - Time dependence should theoretically raise the probabilities of earthquakes on some faults.

Agenda

- **Wednesday, March 8, 2006**
- 7:15 am Continental breakfast
- 8:00 am – 12:00 noon* Use and relative weighting of time dependent, Poisson, and clustering models in characterizing fault behavior, discussion leaders Susan Olig and John Anderson.

Key Questions

- Are time-dependent models appropriate for Basin and Range Province (BRP) faults? If so, which faults have sufficient paleoseismic data?
  - Which earthquake renewal models (e.g., lognormal, Weibull, empirical, Brownian passage time) and what corresponding weights are appropriate?
  - What parameter values (coefficient of variation, exposure window) are suitable, and should earthquake clustering (i.e., the use of short- and long-term slip rates) be included?

NEVADA Seismological Laboratory

ISSUES:

- Which time-dependent and -independent models are applicable to BRP faults?
- How incorporate error, expert opinion, and still have a useable result?
- Use of short- and long-term rates, background/floating earthquakes, and current seismicity/geodetic strain in characterizing fault behavior?
- Data limitations; minimum data necessary to characterize BRP faults?
- Model parameters (COV, alpha, magnitude, recurrence intervals)?

Reshaped Questions

- 1a. For time-dependent seismic hazard analyses in the BRP, which individual or weighted combinations of renewal models should be used (lognormal, Weibull, Empirical, Brownian Passage Time, time-predictable) and what parameter values (coefficient of variation, exposure window) are applicable?
- 1b. For time-independent seismic hazard analyses, which individual or weighted combinations of earthquake recurrence models should be used (Gutenberg-Richter, characteristic, truncated exponential, maximum magnitude), and if applicable, should fault growth/age be considered when assigning the characteristic model weight?

NEVADA Seismological Laboratory

RECOMMENDATION #1

The use of the USGS' "floating exponential" model needs to be validated to the extent possible or at least made consistent with the paleoseismic and historical earthquake record in the Basin and Range Province. The model should also be compared with the traditional models used in state-of-the-practice PSHAs.

RECOMMENDATION #2

- The USGS should use the same recurrence models and weights for all Basin and Range faults unless there is a technical basis for deviating from this characterization.

RECOMMENDATION #3

- The weights assigned to the maximum magnitude and “floating exponential” models should be the same weights as those in California unless there is a technical basis for different weights.

RECOMMENDATION #4

- To avoid double-counting earthquakes in the range of M 6. 5 to the characteristic magnitude, zones surrounding Basin and Range Province faults should be removed from the areas included in the Gaussian smoothing of background seismicity.

RECOMMENDATION #5

- For the National Seismic Hazard Maps, the methodology must be fully transparent. The USGS should be urged to publish, if only as a short note, the methodology used for recurrence modeling, especially for fault-specific sources.

Observed Seismicity and Recurrence Modeling on the Wasatch Fault

Walter Arabasz

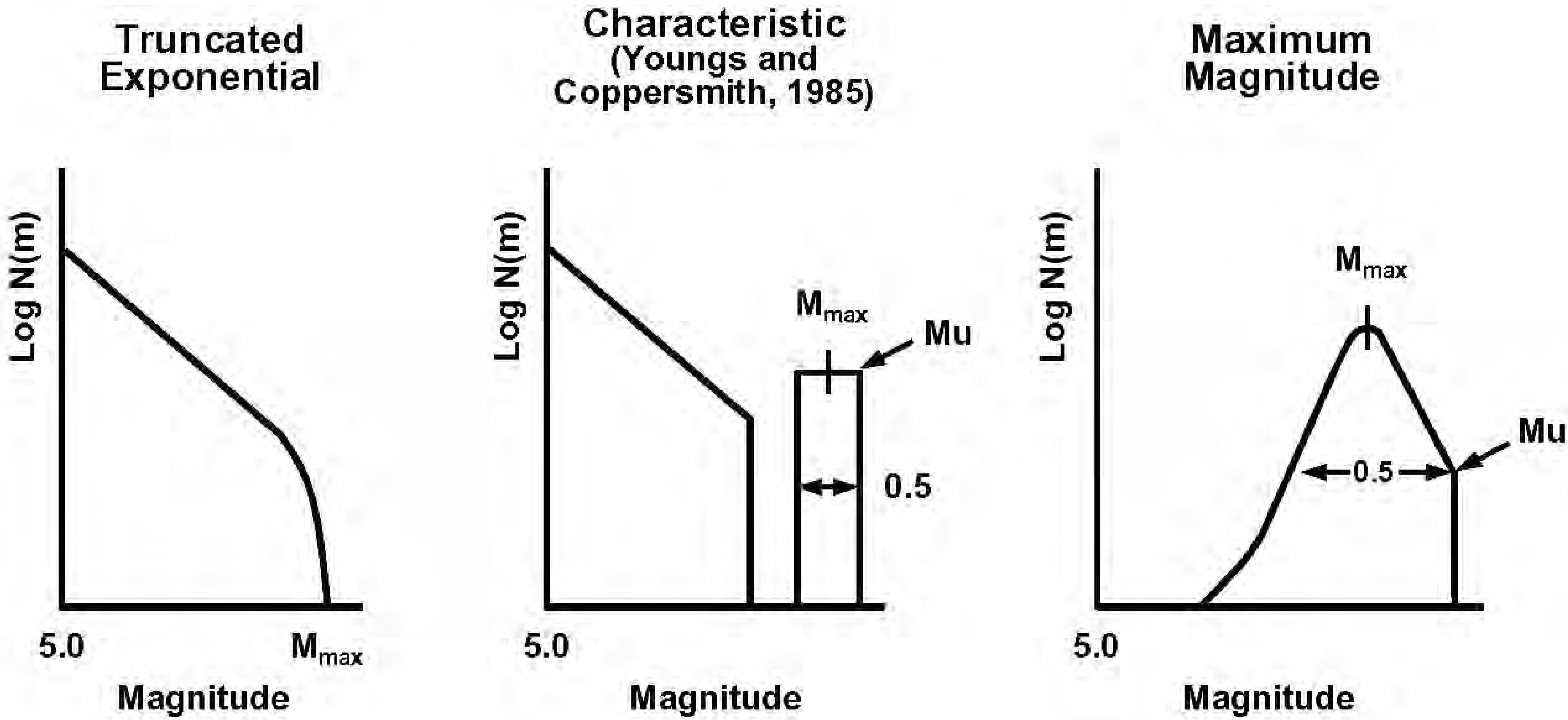
UUSS
university of utah
seismograph stations

March 8, 2006

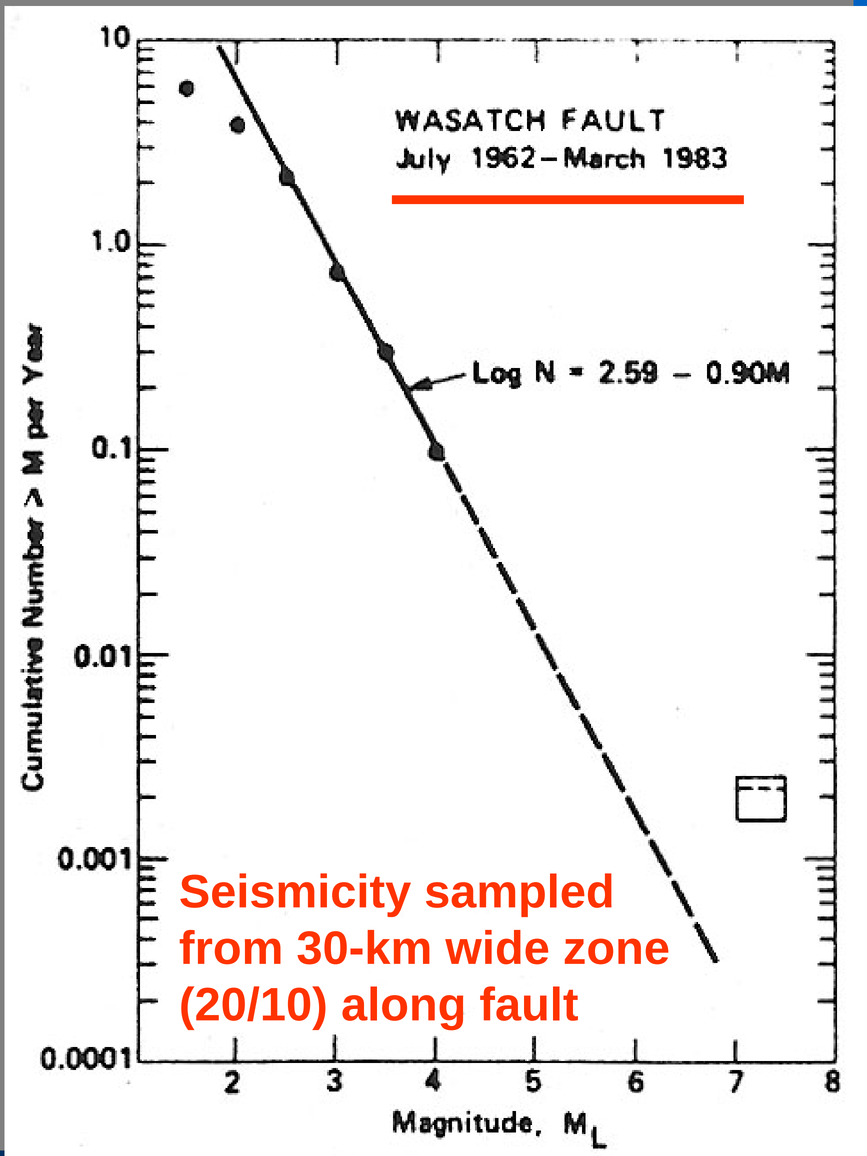
Towards Weighting Recurrence Models for the Wasatch Fault

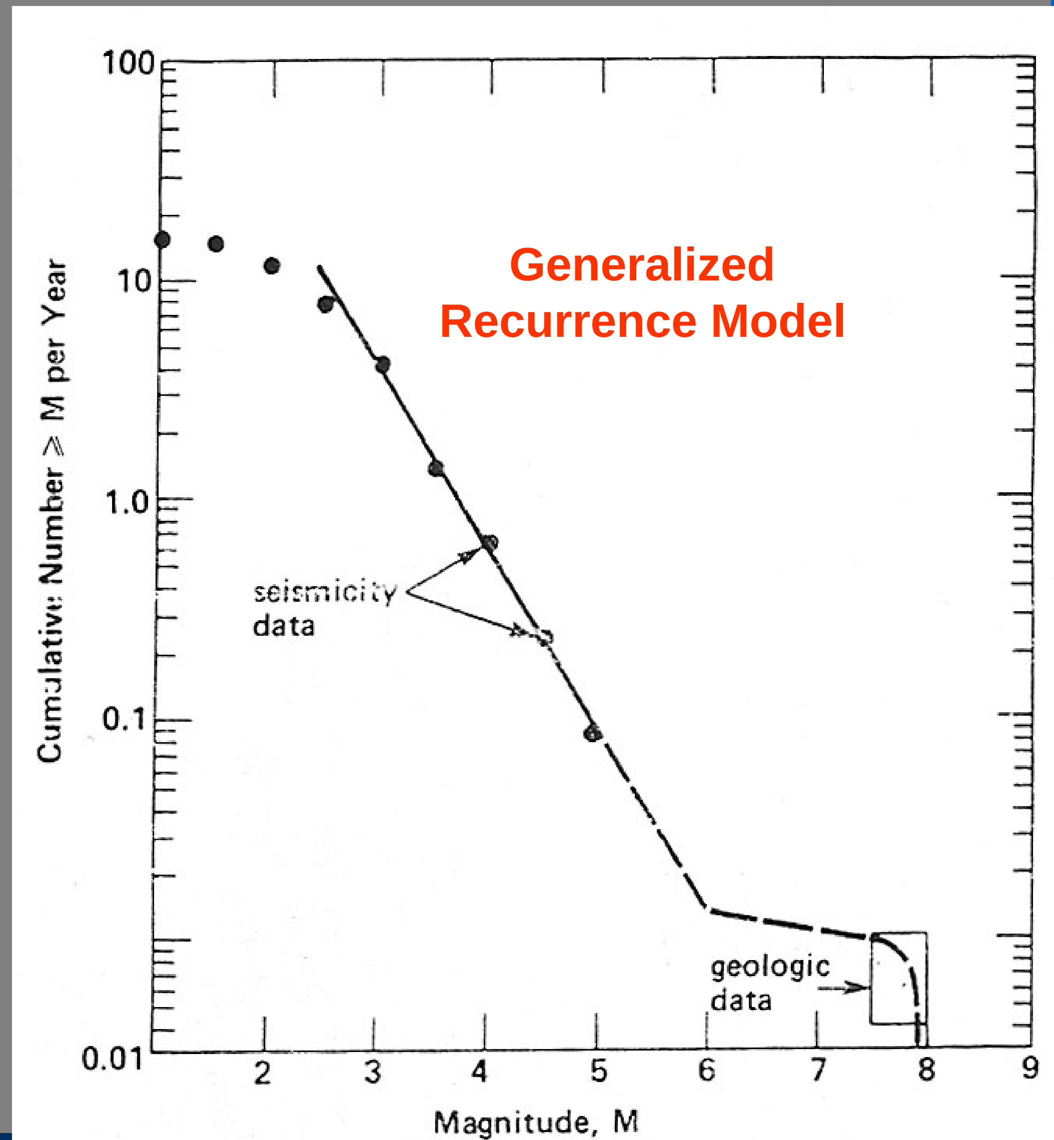
- What can we say from observational seismology?
- Keeping an eye on lack-of-knowledge uncertainty
- If we don’t really know the magnitude distribution, we at least know we can’t double count

RECURRENCE MODELS

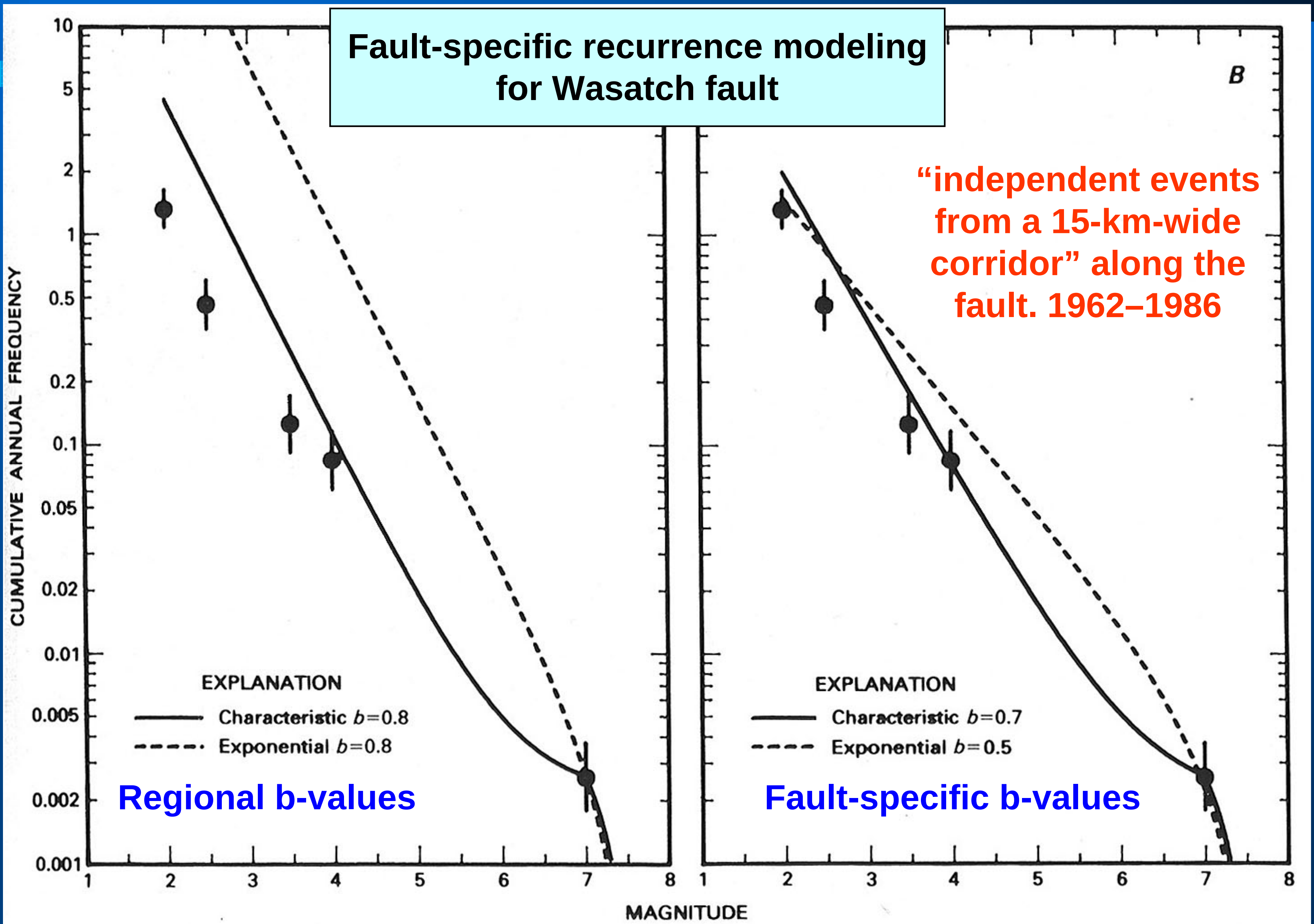


Schwartz & Coppersmith (1984)

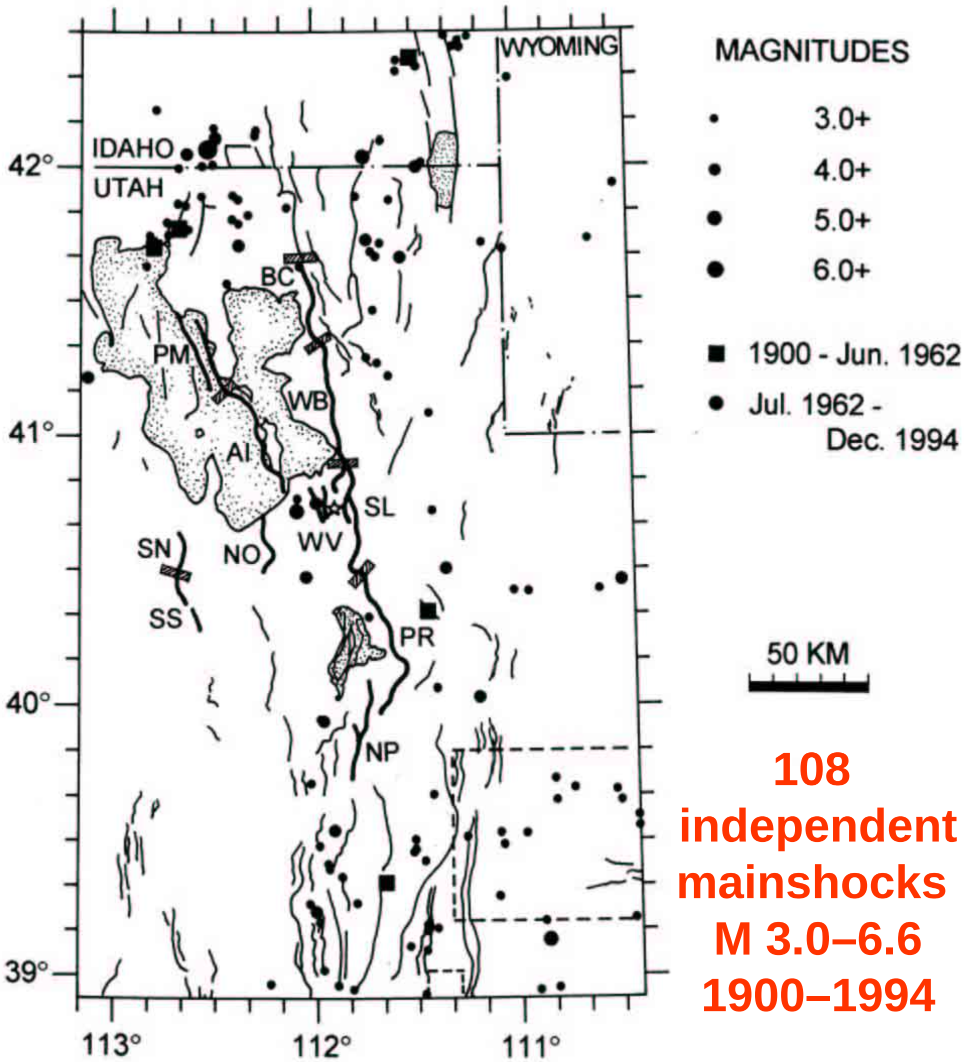




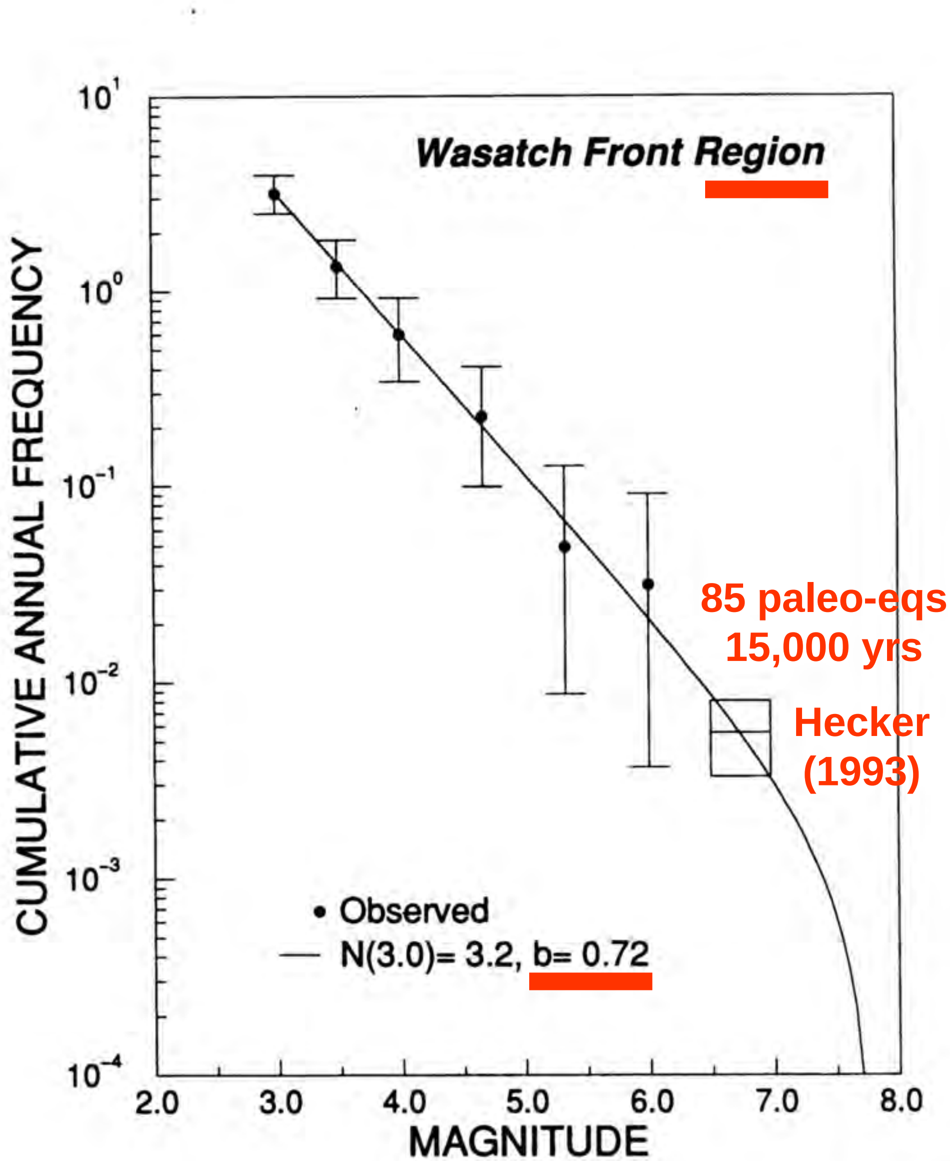
Youngs et al. (1987, 2000)



Pechmann & Arabasz (1995)



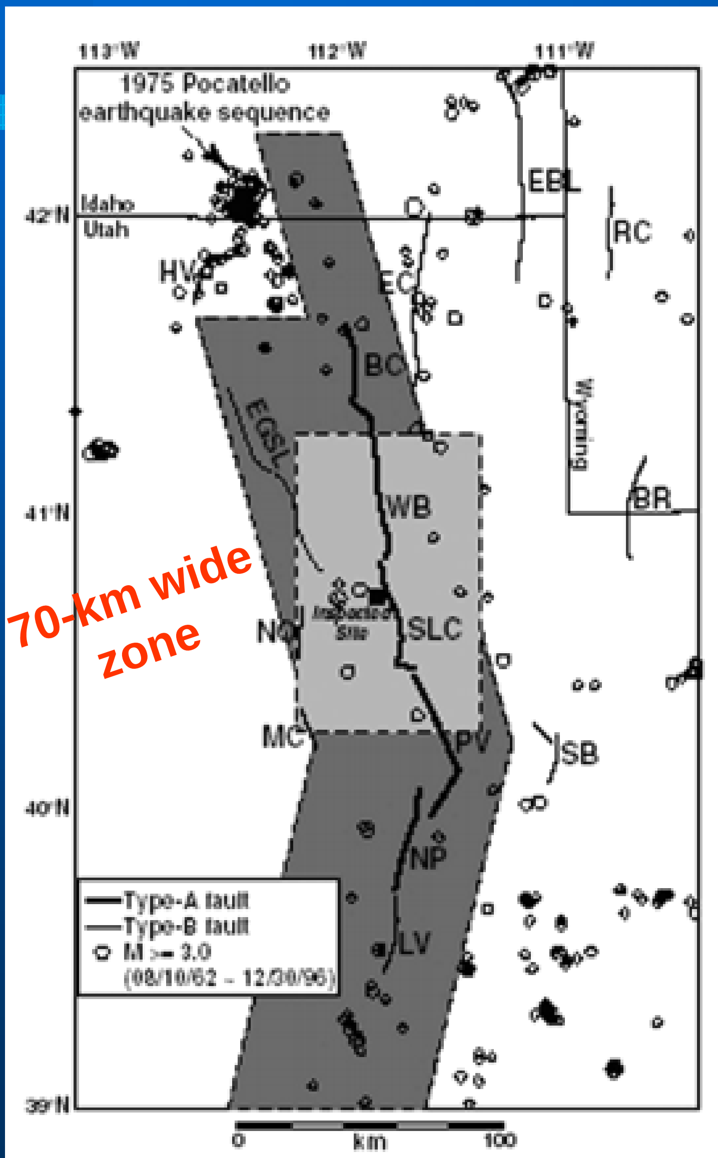
108
independent
mainshocks
M 3.0–6.6
1900–1994

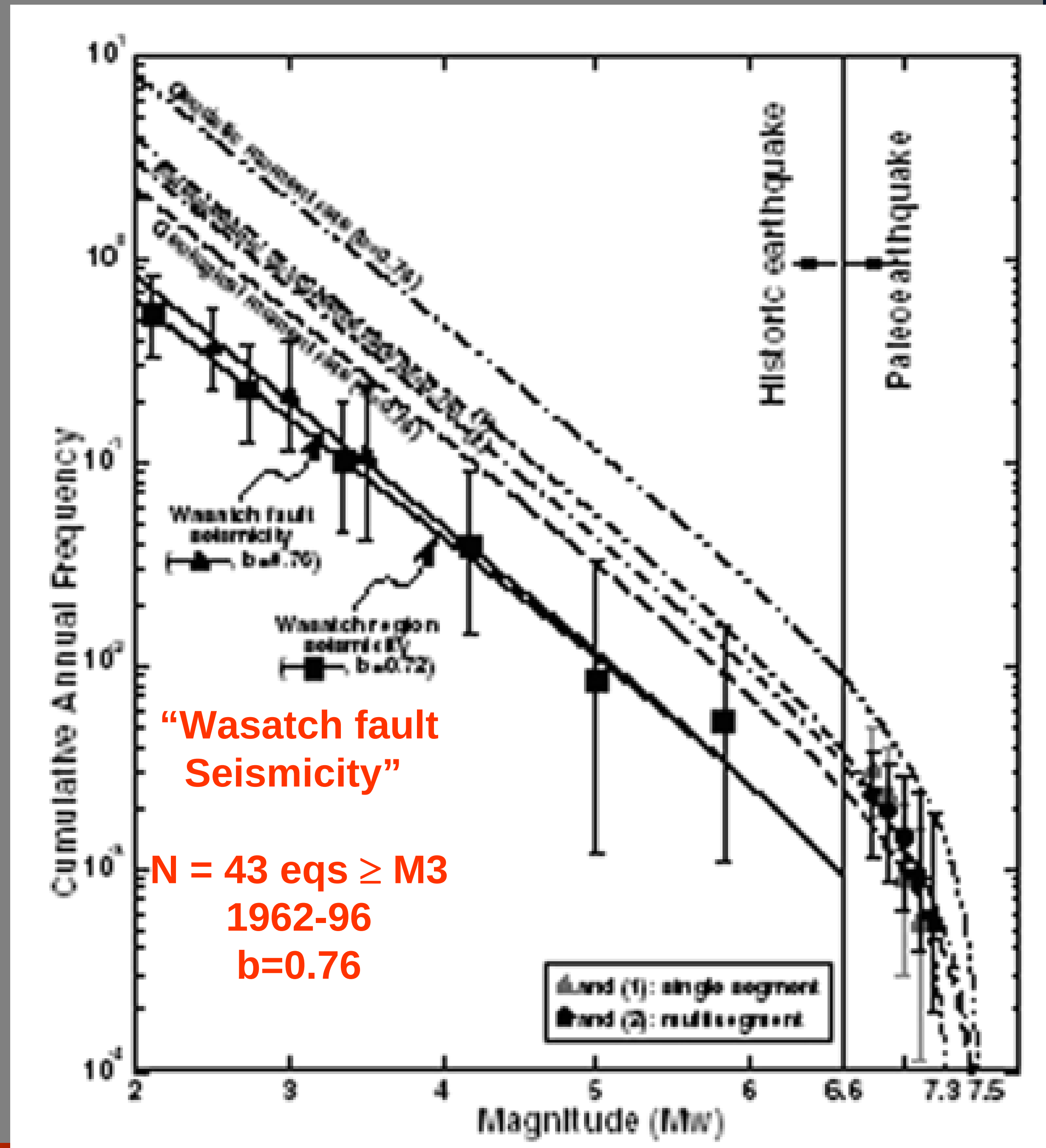


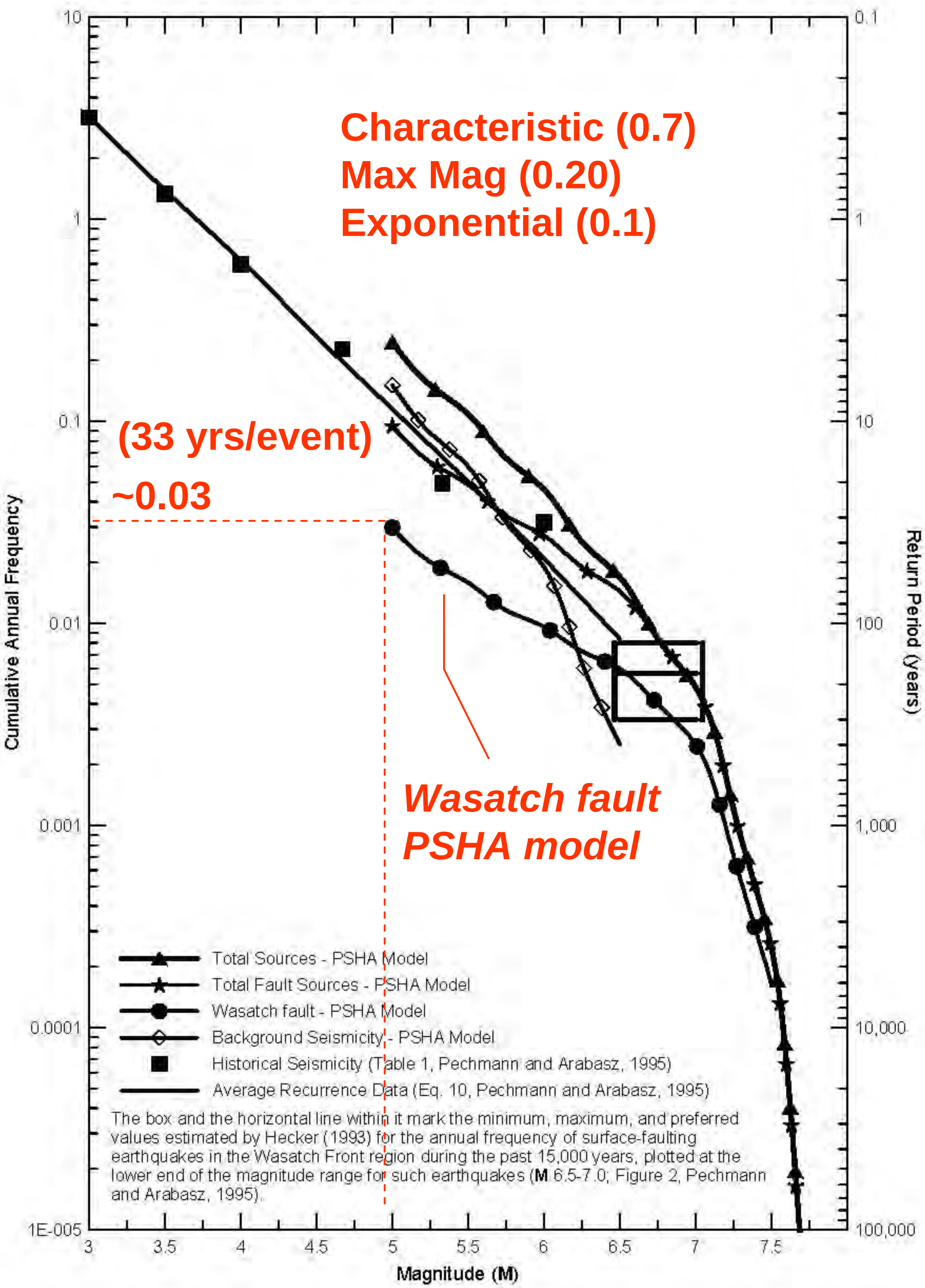
85 paleo-eqs
15,000 yrs

Hecker
(1993)

Chang & Smith (2002)

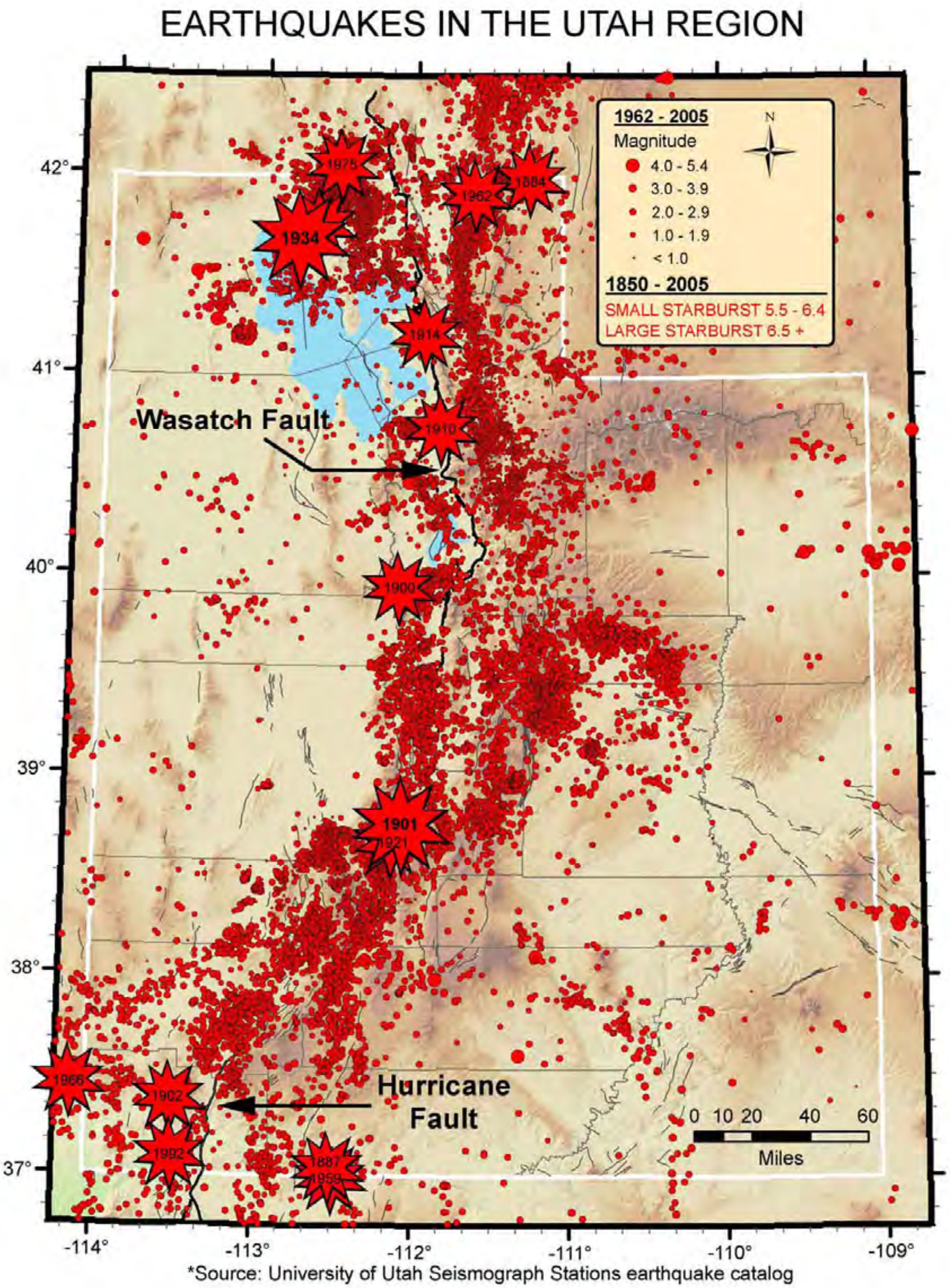


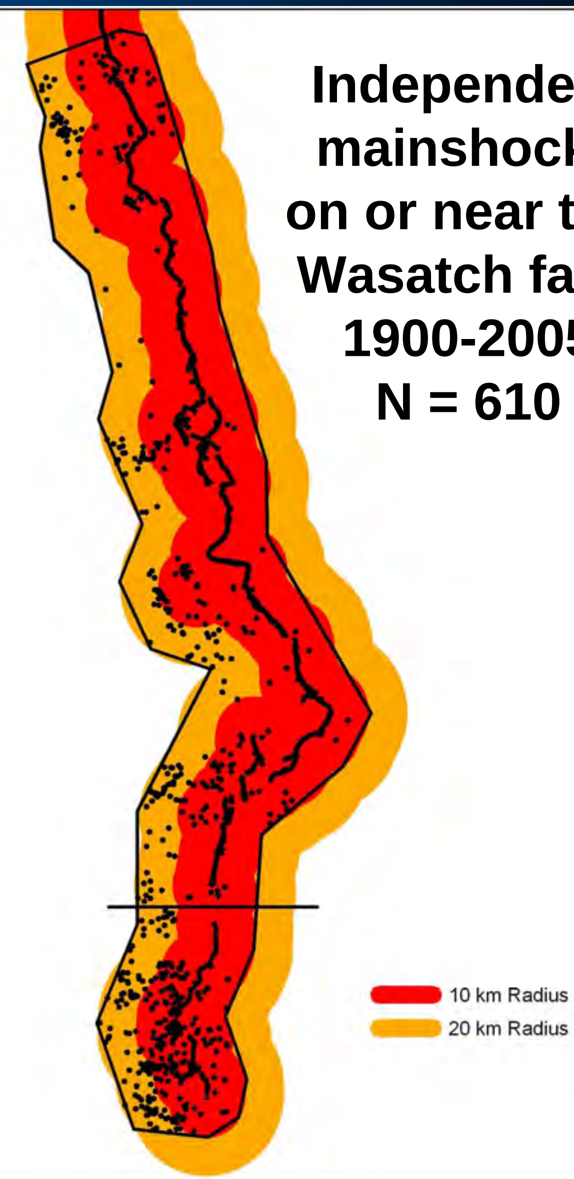




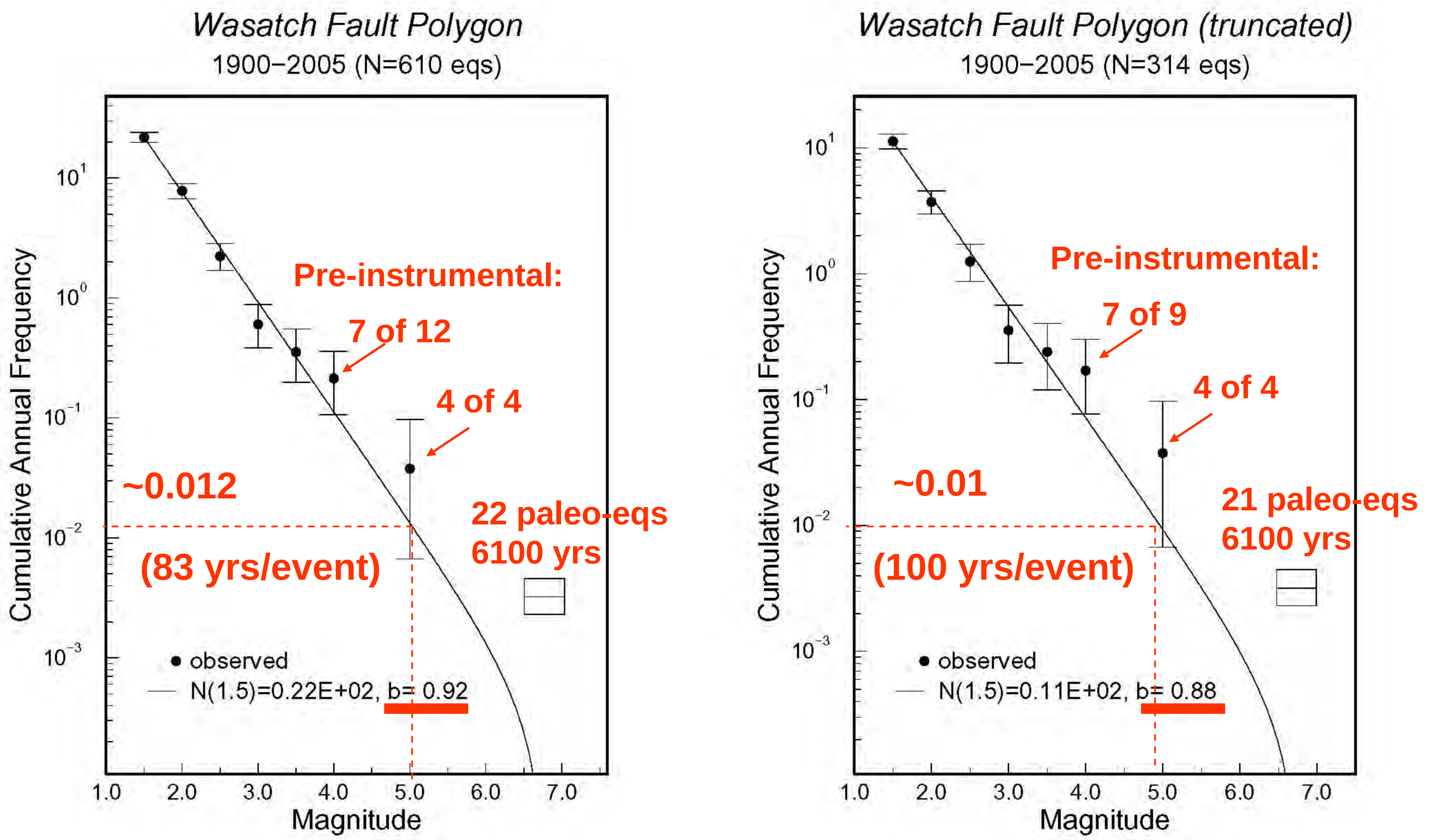
Wong et al. (2002)

A closer look...



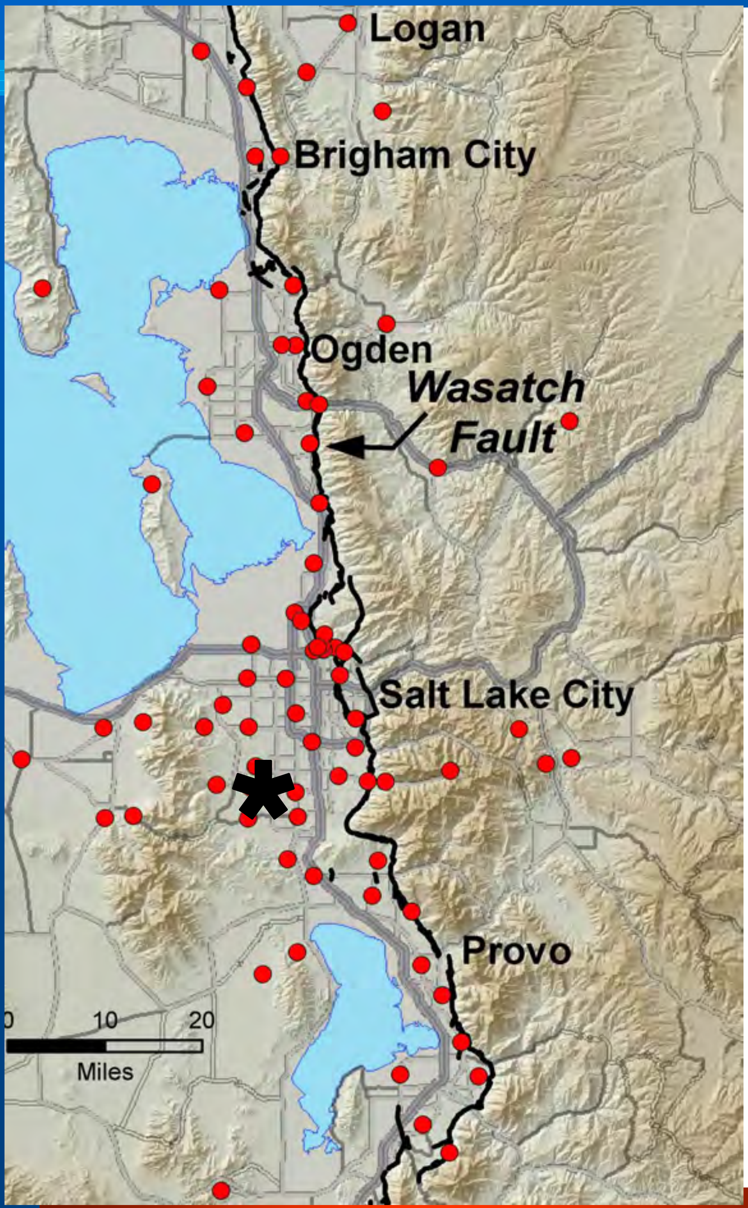


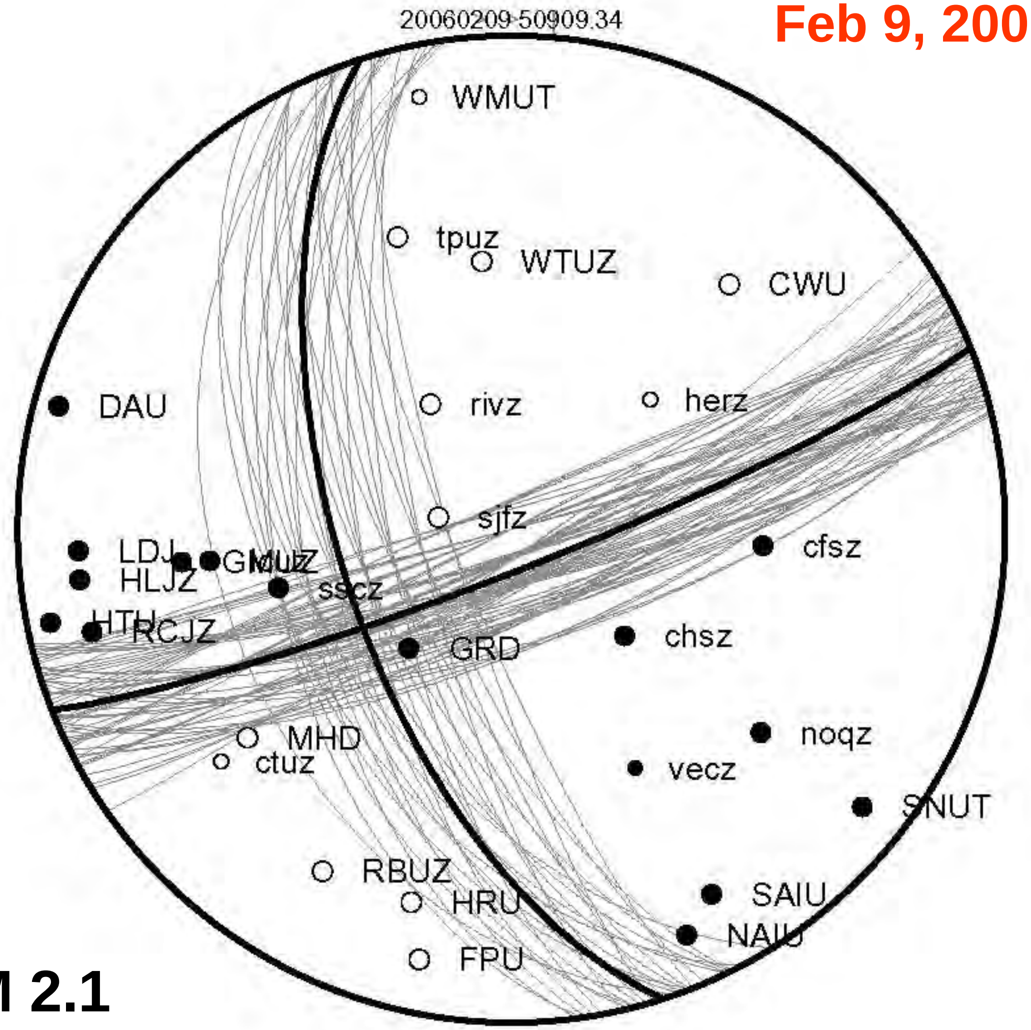
Independent mainshocks on or near the Wasatch fault 1900-2005
N = 610



Wasatch Fault Polygon
1900–2005 (N=610 eqs)
Cumulative Annual Frequency
Magnitude
Pre-instrumental:
7 of 12
4 of 4
~0.012
(83 yrs/event)
22 paleo-eqs
6100 yrs
observed
N(1.5)=0.22E+02, b= 0.92
Wasatch Fault Polygon (truncated)
1900–2005 (N=314 eqs)
Cumulative Annual Frequency
Magnitude
Pre-instrumental:
7 of 9
4 of 4
~0.01
(100 yrs/event)
21 paleo-eqs
6100 yrs
observed
N(1.5)=0.11E+02, b= 0.88

Addressing spatial correlation
One recent example...



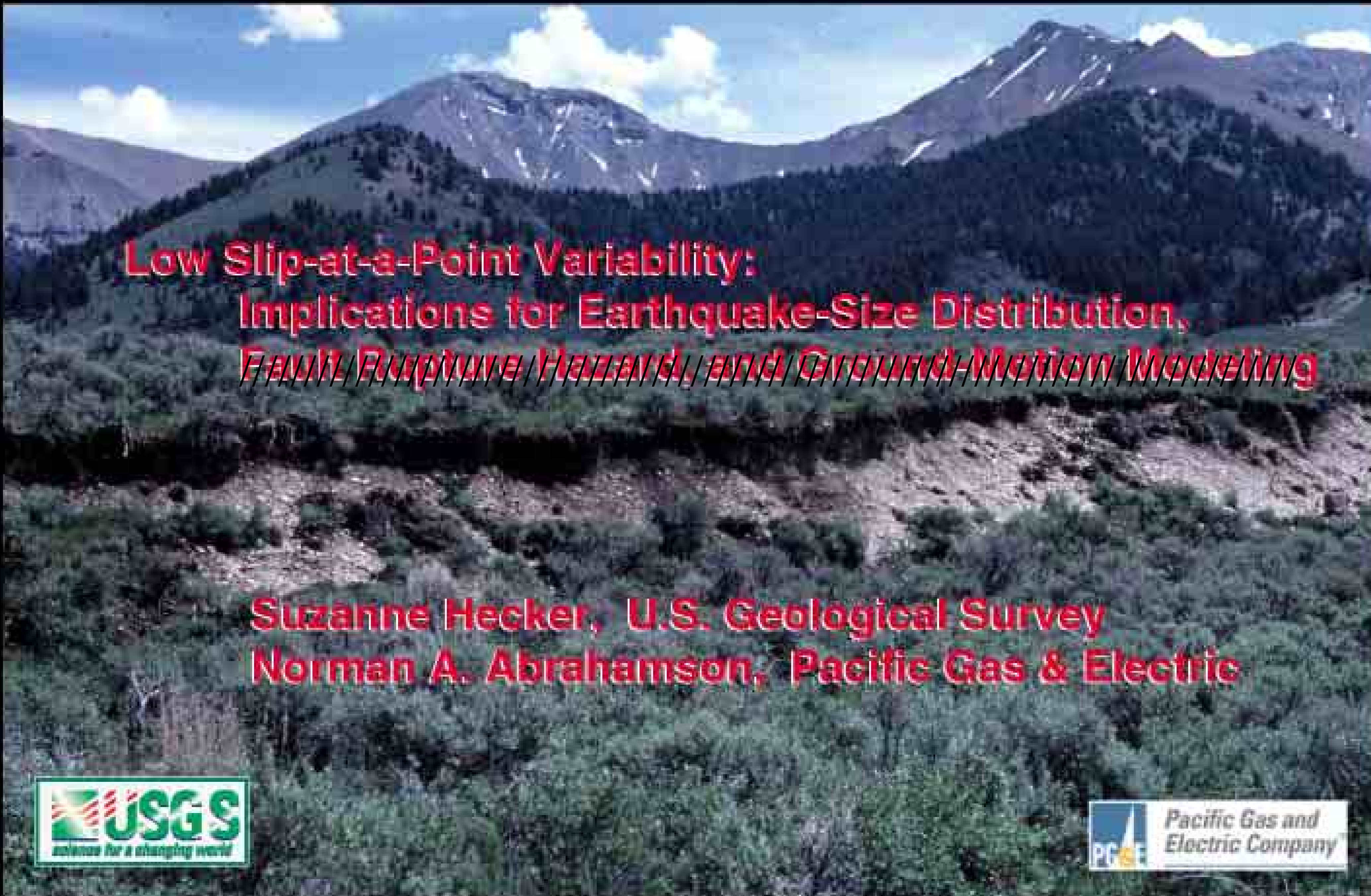


Feb 9, 2006

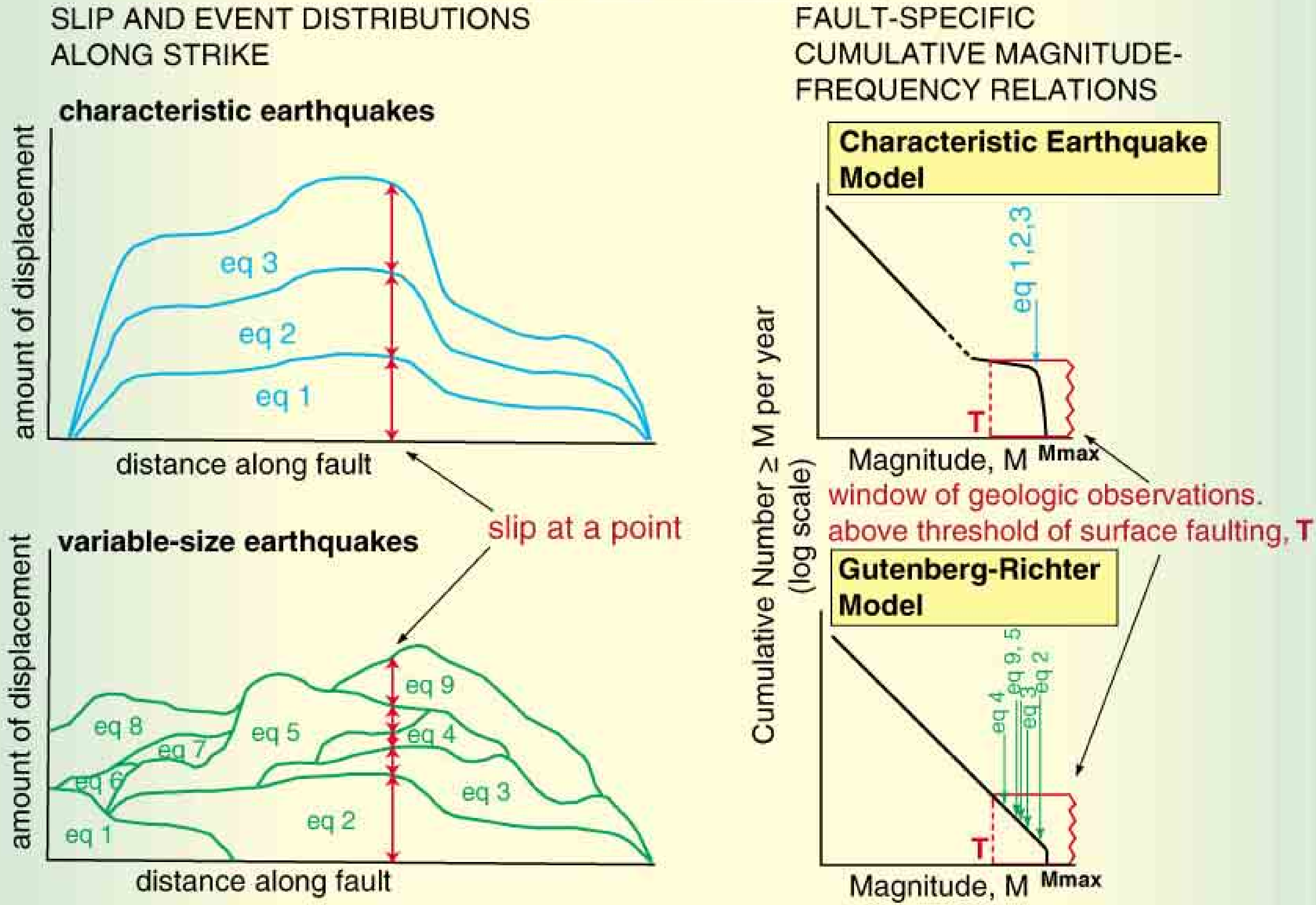
M 2.1
depth = 12.3 km

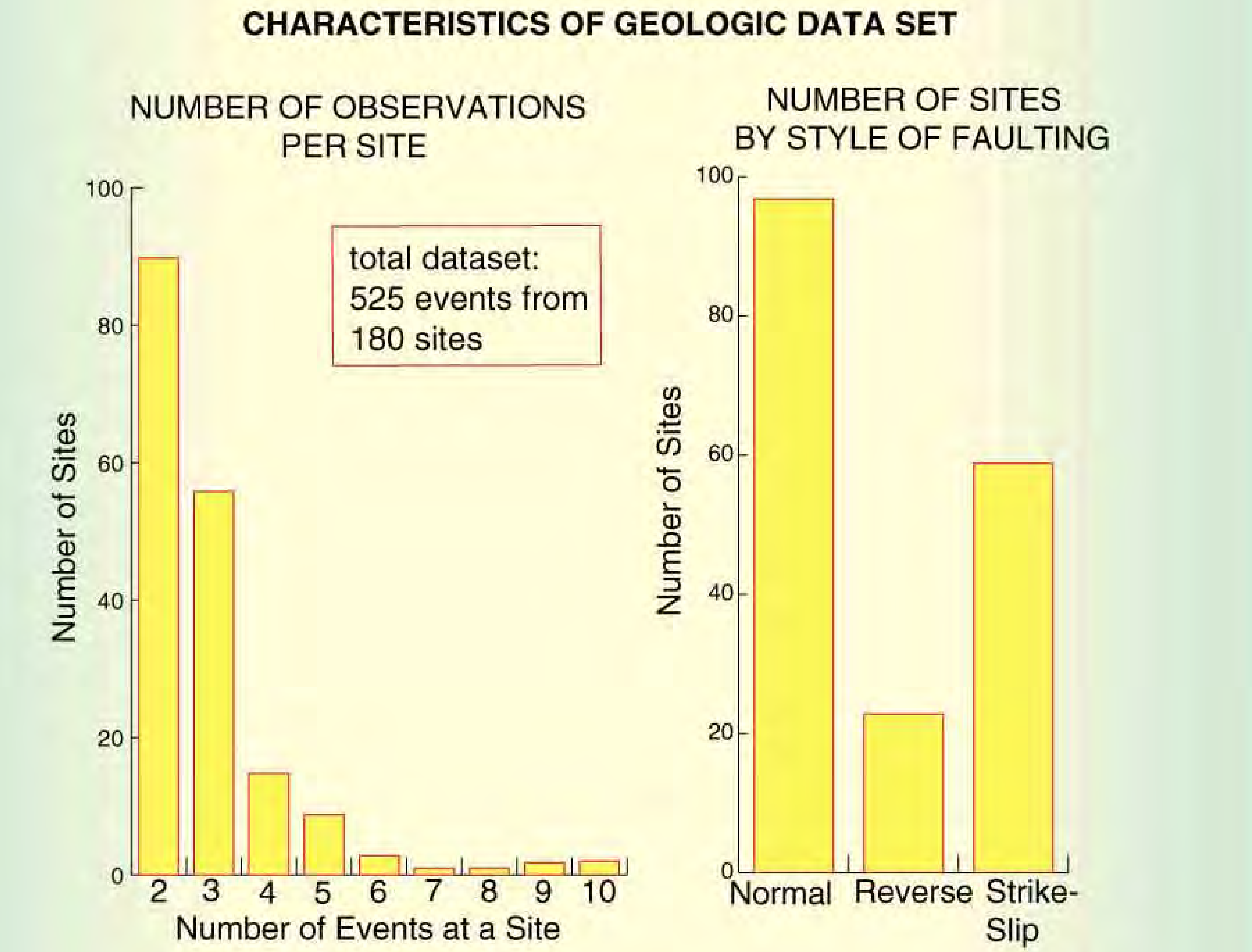
So what does this all mean for a fault-specific model for the Wasatch?

- Data don’t favor exponential model
- 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 the smaller earthquakes are part of a background seismic zone and not on the Wasatch fault


Low Slip-at-a-Point Variability:
Implications for Earthquake-Size Distribution,
~~Fault Rupture Hazard, and Ground-Motion Modelling~~
Suzanne Hecker, U.S. Geological Survey
Norman A. Abrahamson, Pacific Gas & Electric
USGS
science for a changing world
PG&E
Pacific Gas and Electric Company

FAULT BEHAVIOR MODELS





CHARACTERISTICS OF GEOLOGIC DATA SET
NUMBER OF OBSERVATIONS PER SITE
total dataset:
525 events from
180 sites
Number of Sites
Number of Events at a Site
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
NUMBER OF SITES BY STYLE OF FAULTING
Number of Sites
Normal
Reverse
Strike-Slip

Coefficient of Variation (CV)

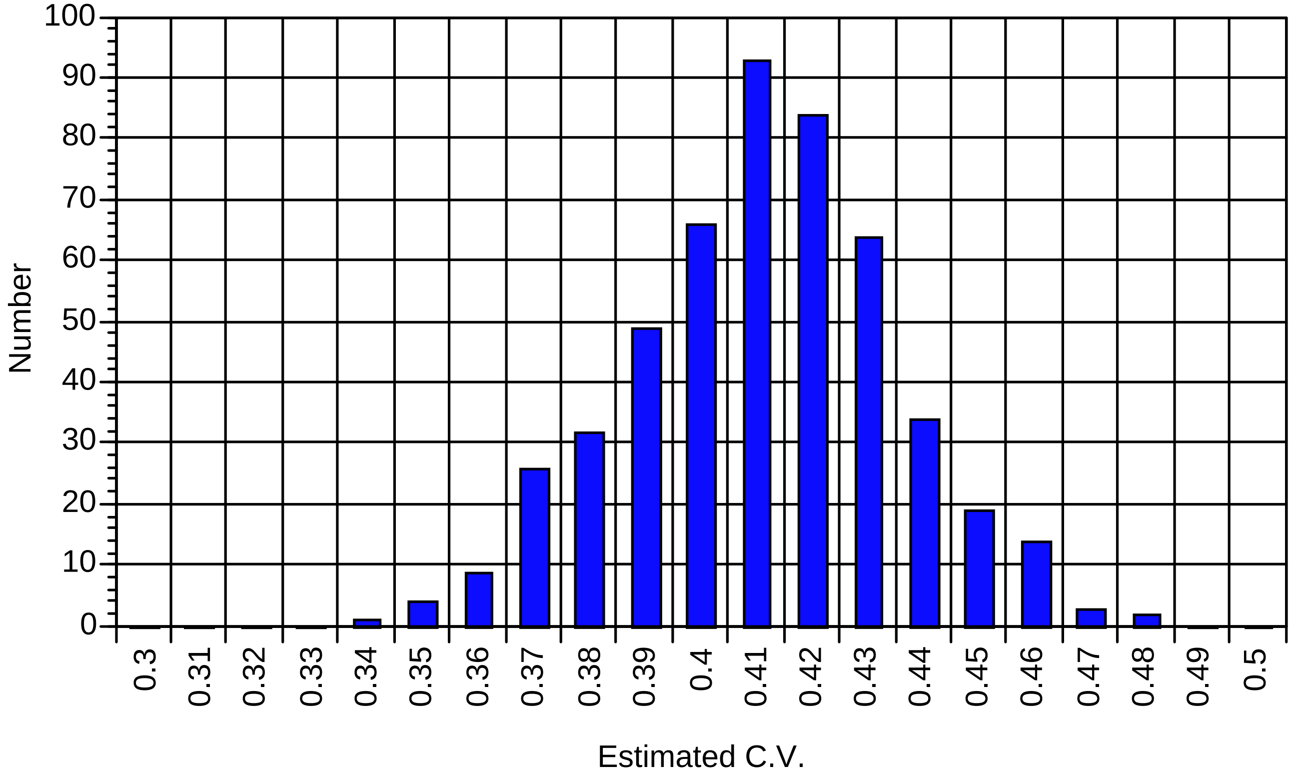
$$C.V. = \frac{\sigma_i}{\overline{D}_i} = \alpha$$

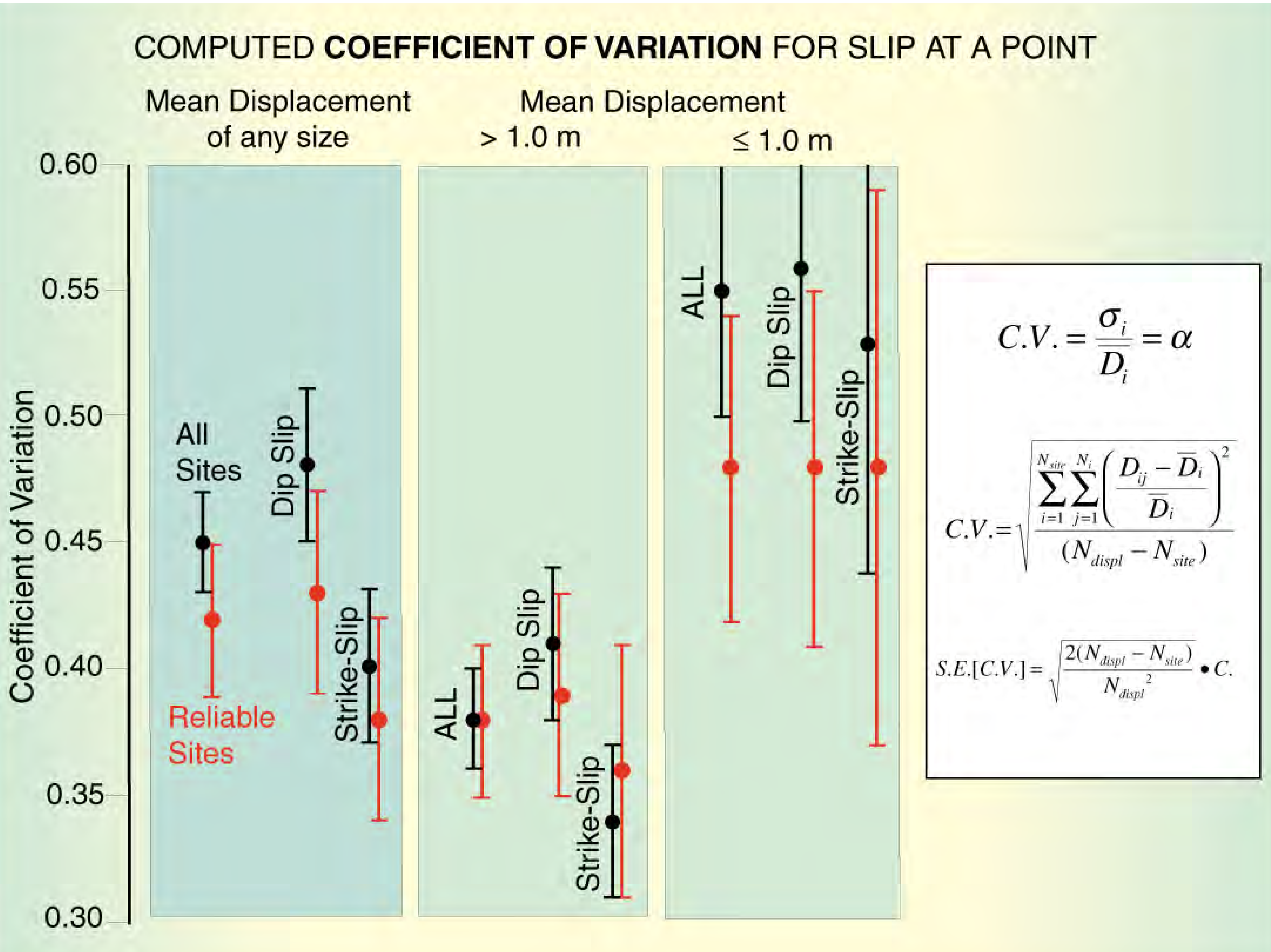
$$C.V. = \sqrt{\frac{\sum_{i=1}^{N_{site}} \sum_{j=1}^{N_i} \left(\frac{D_{ij} - \overline{D}_i}{\overline{D}_i} \right)^2}{(N_{displ} - N_{site})}}$$

$$S.E.[C.V.] = \sqrt{\frac{2(N_{displ} - N_{site})}{N_{displ}^{\ 2}}} \bullet C.$$

Effect of Small Number of Events per Site

- Use Monte Carlo
  - Population C.V.=0.4
  - Same sampling as in data set
- Result:
  - Average C.V.=0.41 (small bias toward larger CV)



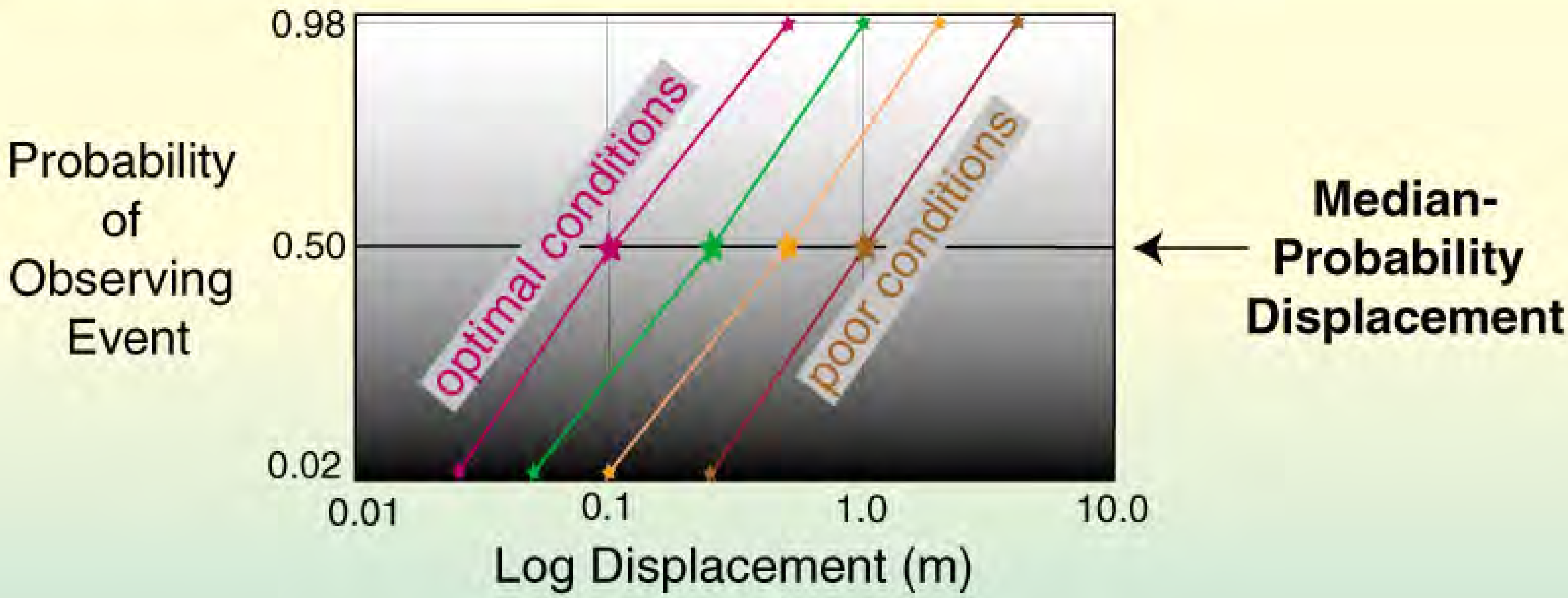

COMPUTED COEFFICIENT OF VARIATION FOR SLIP AT A POINT
Mean Displacement of any size
Mean Displacement > 1.0 m
≤ 1.0 m
Coefficient of Variation
0.60
0.55
0.50
0.45
0.40
0.35
0.30
All Sites
Reliable Sites
Dip Slip
Strike-Slip
ALL
Dip Slip
Strike-Slip
ALL
Dip Slip
Strike-Slip
$C.V. = \frac{\sigma_i}{\overline{D}_i} = \alpha$
$C.V. = \sqrt{\frac{\sum_{i=1}^{N_{site}} \sum_{j=1}^{N_i} \left(\frac{D_{ij} - \overline{D}_i}{\overline{D}_i} \right)^2}{(N_{displ} - N_{site})}}$
$S.E.[C.V.] = \sqrt{\frac{2(N_{displ} - N_{site})}{N_{displ}^{2}}} \bullet C.$

Threshold of Event Detection

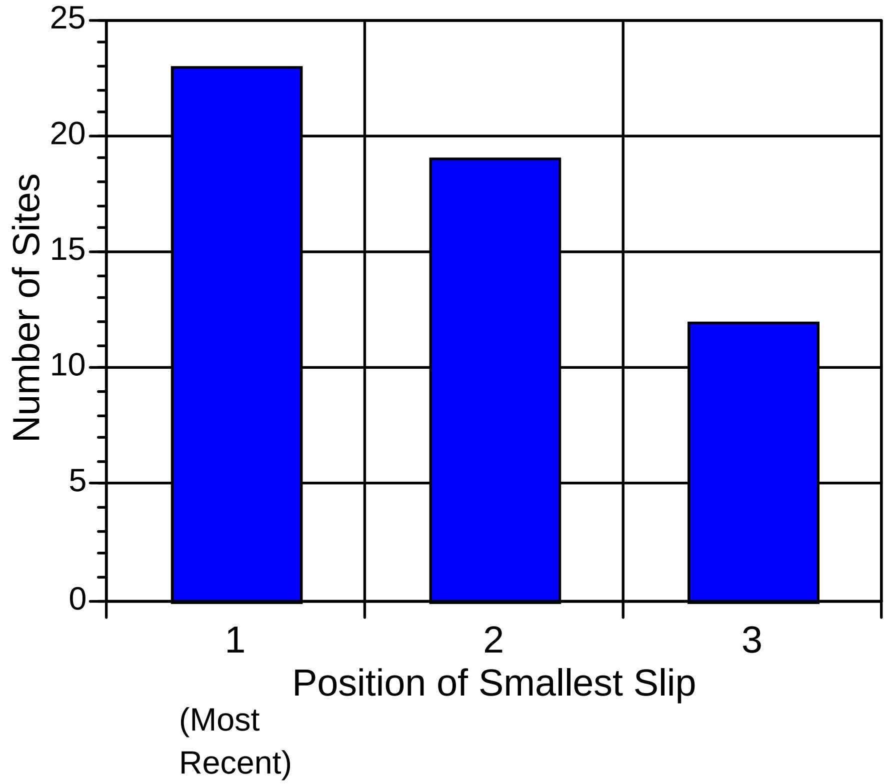
Model based on General Field Conditions

Median-Probability Displacement

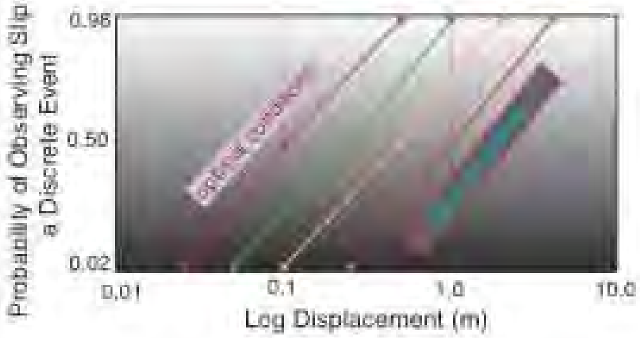
Median-Probability Displacement	Field conditions
0.1 m	▪ Historical record of earthquakes
0.25 m	▪ Well-bedded stratigraphy and individual event horizons (deposition ≥ events)
0.5 m	▪ Poorly or complexly bedded stratigraphy ▪ Compound colluvial wedges/ superimposed event horizons (deposition < events) ▪ Progressive lateral offset of closely-spaced features
1.0 m	▪ Massive, poorly exposed, or poorly preserved compound colluvial wedges ▪ Progressive displacement of geomorphic surfaces with age ▪ Progressive lateral offset of features separated along strike ▪ Faceted compound fault scarps



Event Position of Smallest Slip



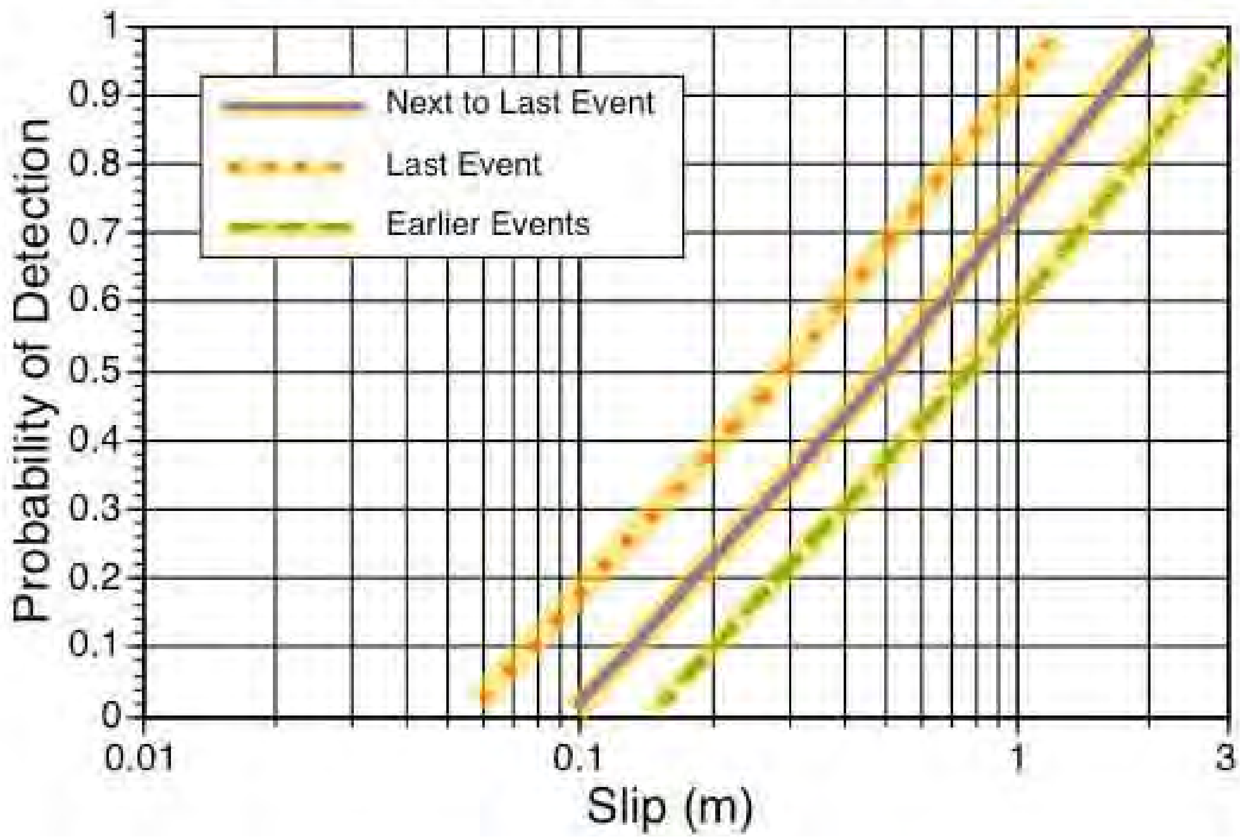
- Smallest slip is more often the most recent event
- Accommodate effect by varying the probability of detection by event position
- Calibrate using observed frequencies



Probability of Detection Model

Example: 50% at 0.5m for next to last event

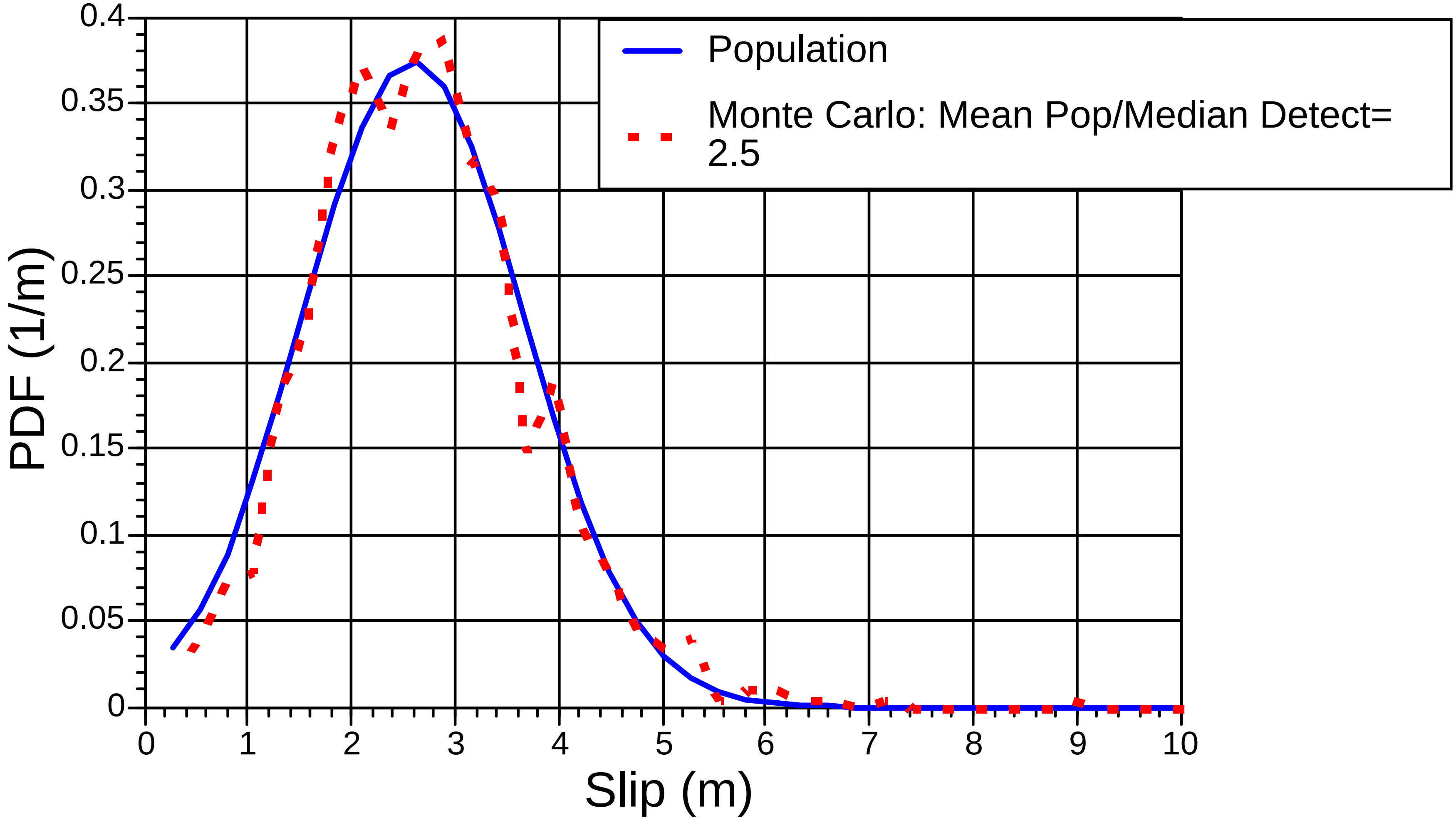
This leads to observed rates of position of smallest slip



Effect of Probability of Detection

Example: mean slip is 2.5 times detection threshold

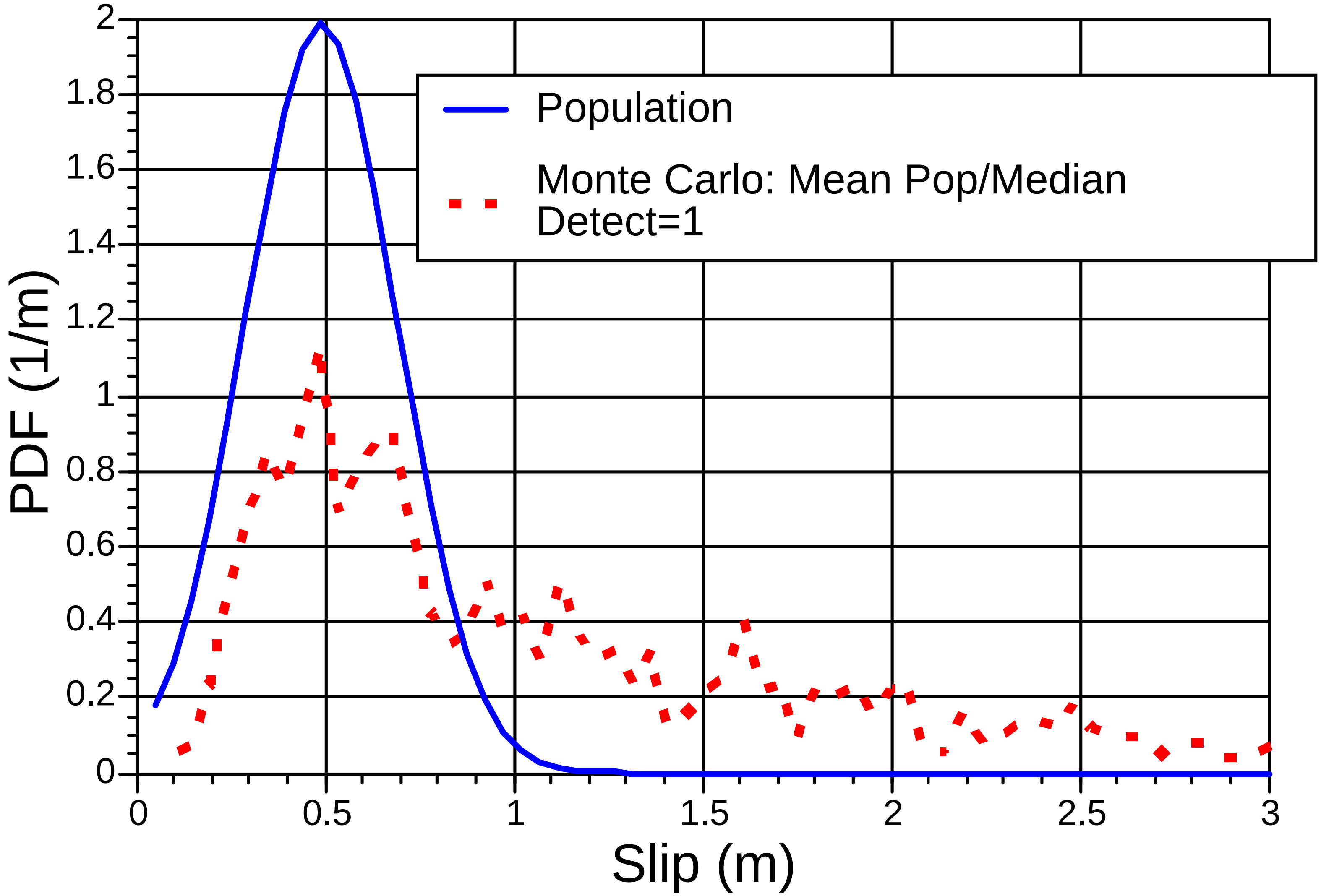
Result: Similar C.V.



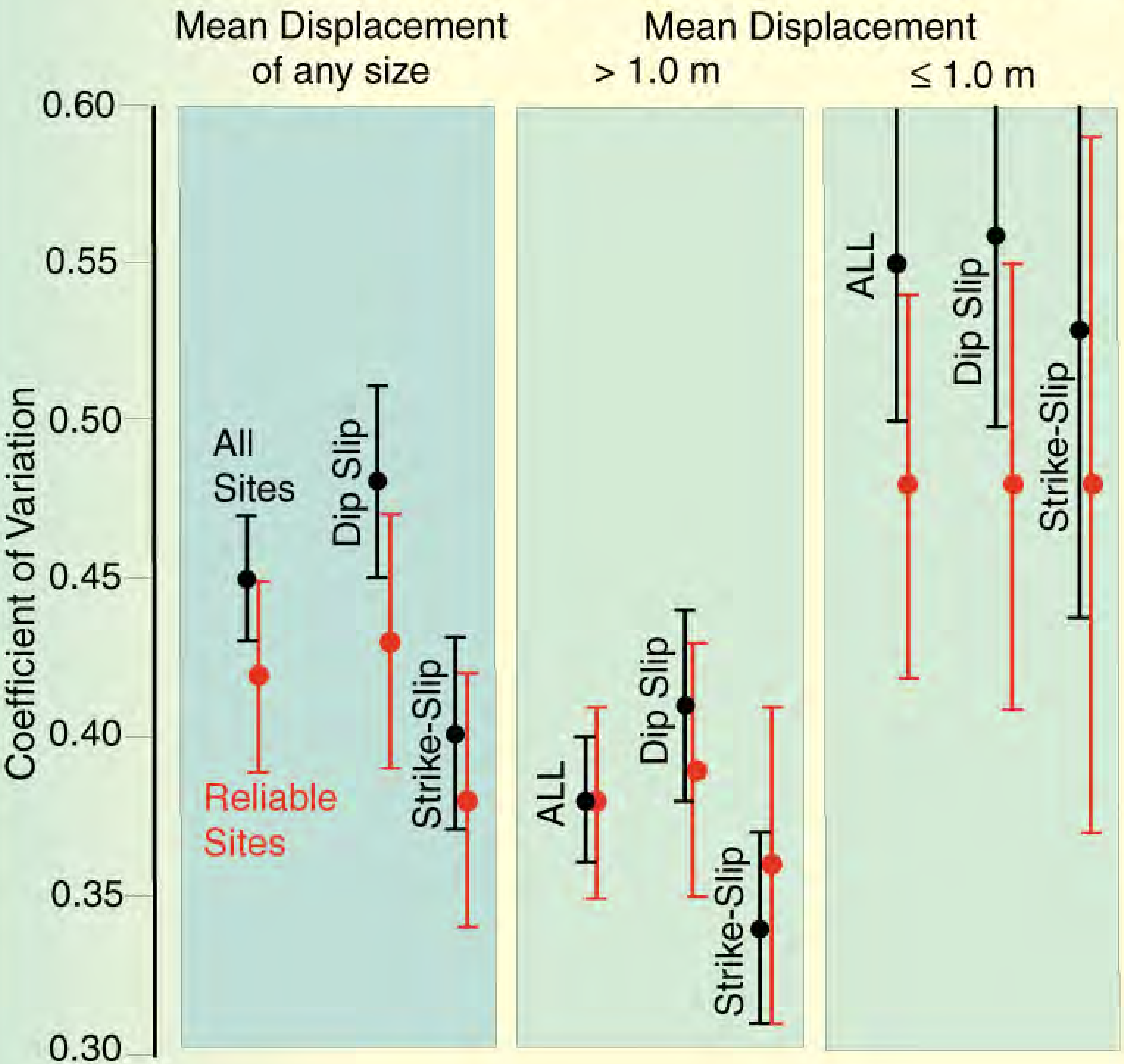
Effect of Probability of Detection

Example: mean slip is close to detection threshold

result: Increase in C.V.



COMPUTED **COEFFICIENT OF VARIATION** FOR SLIP AT A POINT



$$C.V. = \frac{\sigma_i}{\overline{D}_i} = \alpha$$

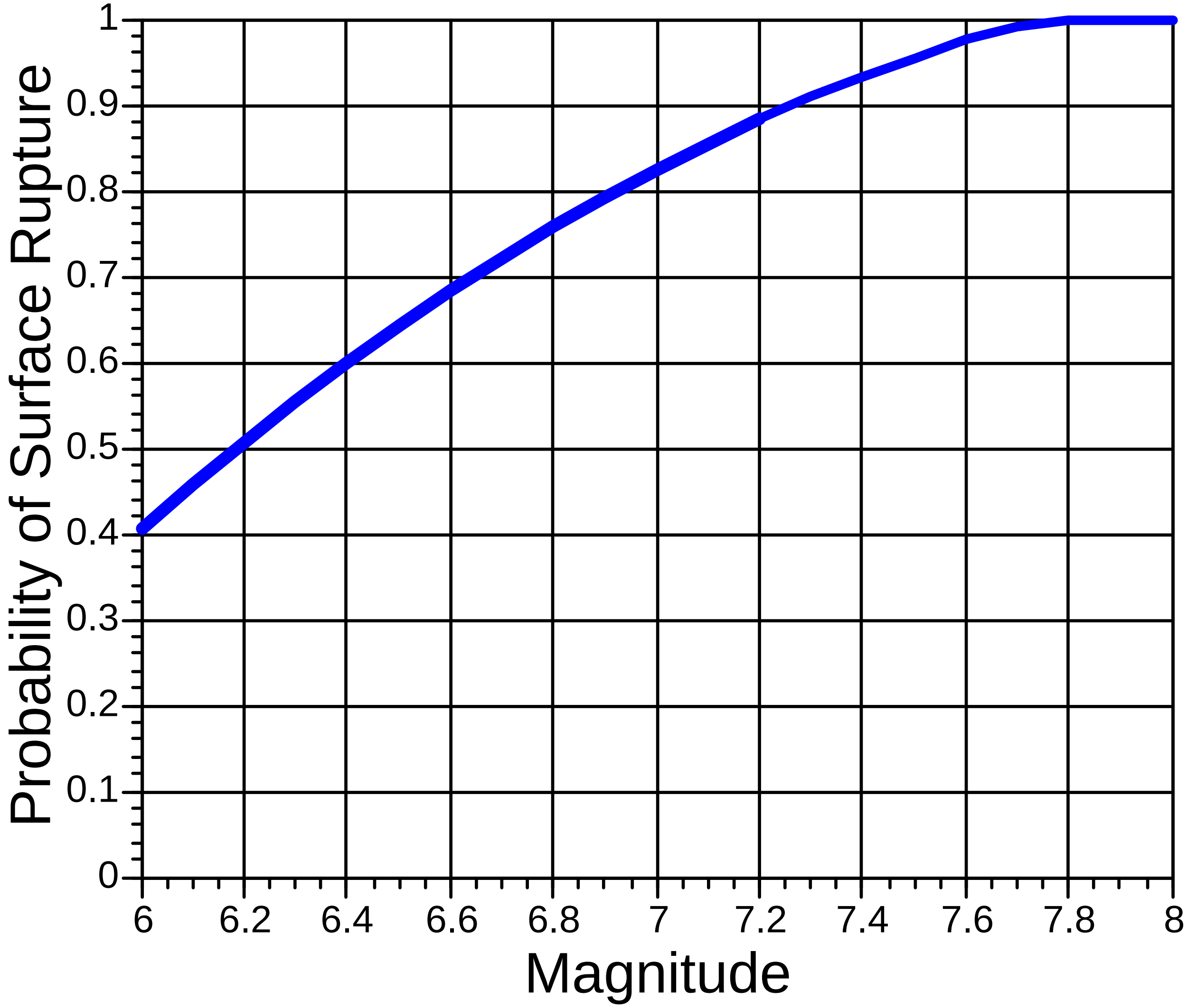
$$C.V. = \sqrt{\frac{\sum_{i=1}^{N_{site}} \sum_{j=1}^{N_i} \left(\frac{D_{ij} - \overline{D}_i}{\overline{D}_i} \right)^2}{(N_{displ} - N_{site})}}$$

$$S.E.[C.V.] = \sqrt{\frac{2(N_{displ} - N_{site})}{N_{displ}^{\;2}}} \bullet C.$$

Testing of Magnitude Recurrence Models Using C.V.

- Forward Modeling of expected observations of slip at a point
  - Prob (M) (from mag recurrence model)
  - Prob (rupture to surface given M)
  - Prob (rupture past site given Rup Length(M))
  - Prob (amount of surface slip given M)
  - Prob (detection) including effect of adding slip from non-detected events to the detected events
- Magnitude recurrence models
  - Truncated exponential
  - Youngs & Coppersmith Characteristic
  - Max Mag = 7.5, MinMag = 6.0

Probability of Surface Rupture (modified from IGNS, 2003)



Amount of Surface Slip

- Average Displacement
  - Use Wells and Coppersmith for all fault types
  - $\log(AD) = -4.8 + 0.69M \pm 0.36$ (± 0.82 ln units)
- Variation in Displacement along Strike
  - Use results from (Hemphill-Haley and Weldon, 1999)
  - Sigma along strike approx 0.7 natural log units
- Total standard deviation of slip-at-a-point
  - $\text{Sqrt}(0.82^2+0.70^2)= 1.07$

C. V. from Modeling Results

Case 1: Using full Slip Variability for given M

Slip with 50% chance of detection in next to last event	Truncated Exponential C.V.	Y&C Characteristic C.V.
0.1 m	1.55	1.33
0.25 m	1.39	1.26
0.5 m	1.17	1.14
1.0 m	0.94	0.98
2.0 m	0.86	0.87

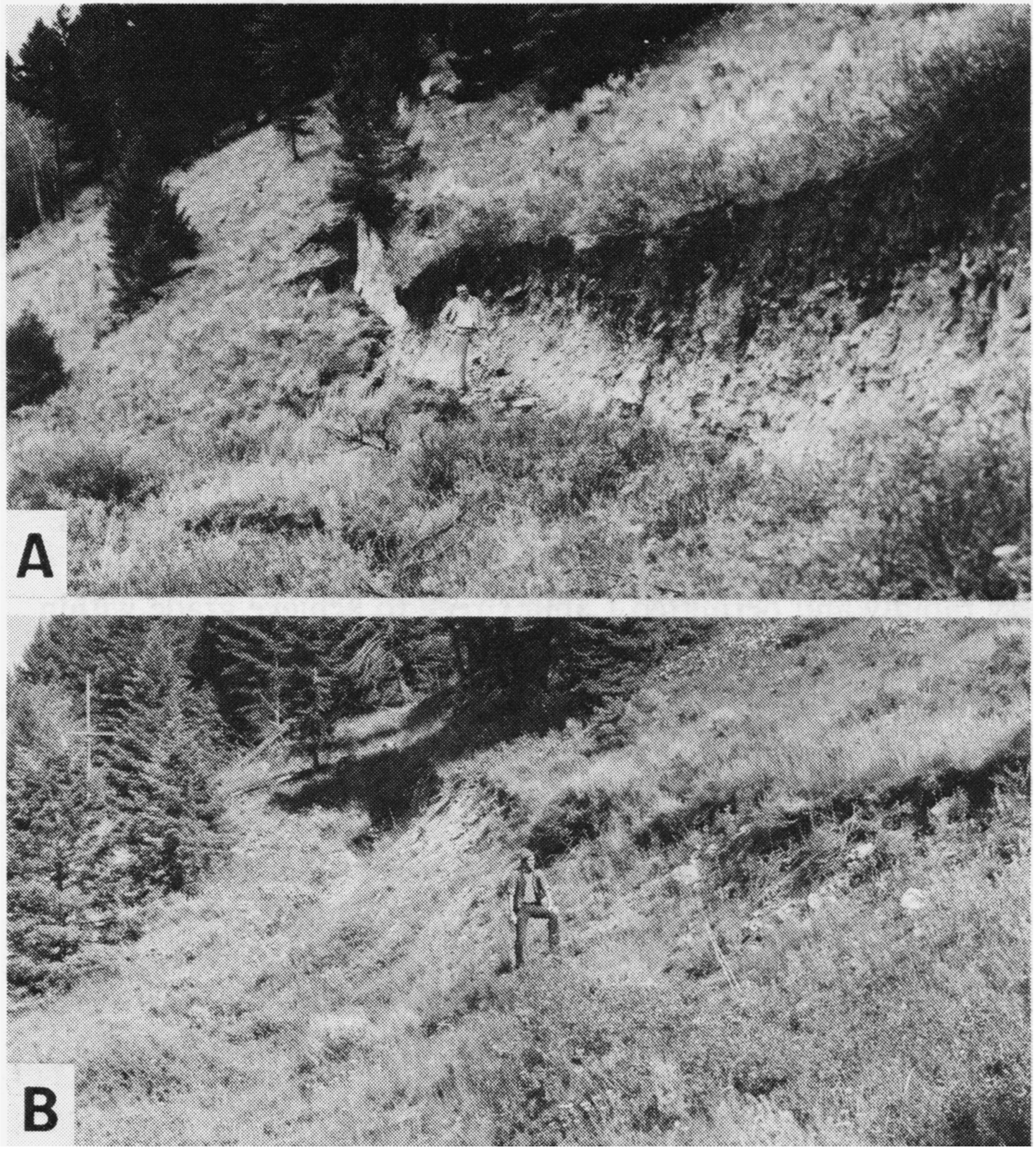
C. V. from Modeling Results

Case 2: Using reduced Variability for given M (reduced to 0.3 natural log units)

Slip with 50% chance of detection in next to last event	Truncated Exponential	Y&C Characteristic
0.1 m	0.71	0.44
0.25 m	0.64	0.42
0.5 m	0.68	0.48
1.0 m	1.06	0.78
2.0 m	1.13	0.98

Conclusions from Forward Modeling

- Variability of slip at a point must be much smaller than expected using global models
- The Y&C mag recurrence model can give C.V. values similar to observed values if small variability in slip for given mag is used.
- The truncated exponential mag recurrence model gives much larger C.V. values than observed even with reduced variability in slip given mag.
  - The truncated exponential model is not consistent with the observed C.V. values.

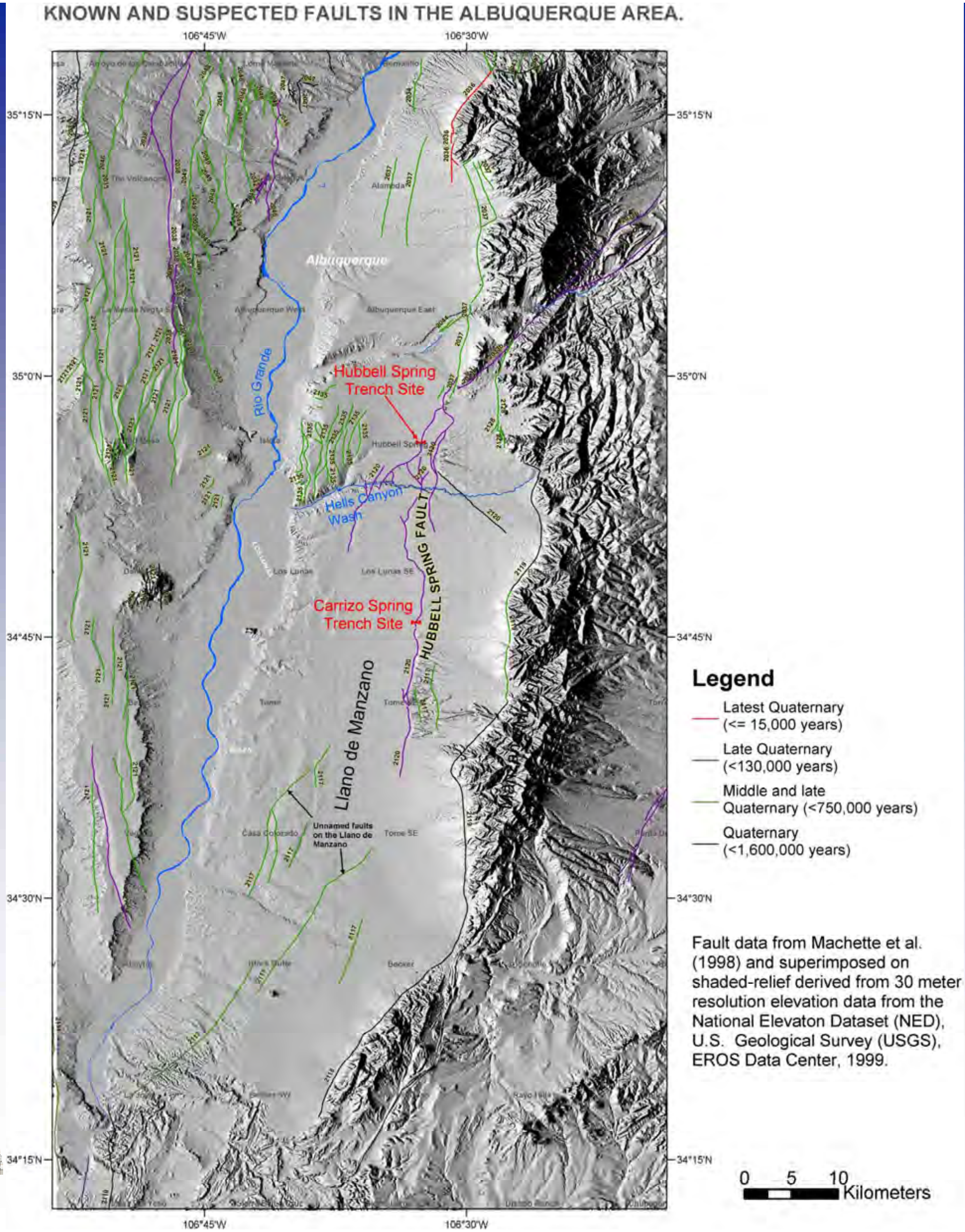

A
B

Example of Non-characteristic Behavior in the Rio Grande Rift: Hubbell Spring Fault, NM

Susan Olig, Martha Eppes, Steven Forman, David Love, and Bruce Allen

NEHRP Award No. 99HQGR0089

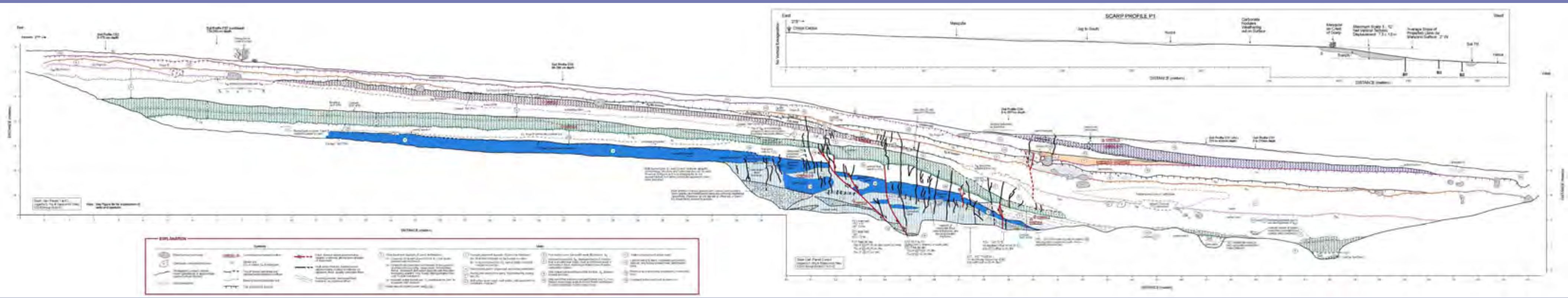
March 8, 2006



- **Intrabasin fault zone**
- **Multiple splays**
- **Complex geometry**
- **Active (late Quaternary) rift margin**

Carrizo Spring Trench Site

Carrizo Spring Trench Log



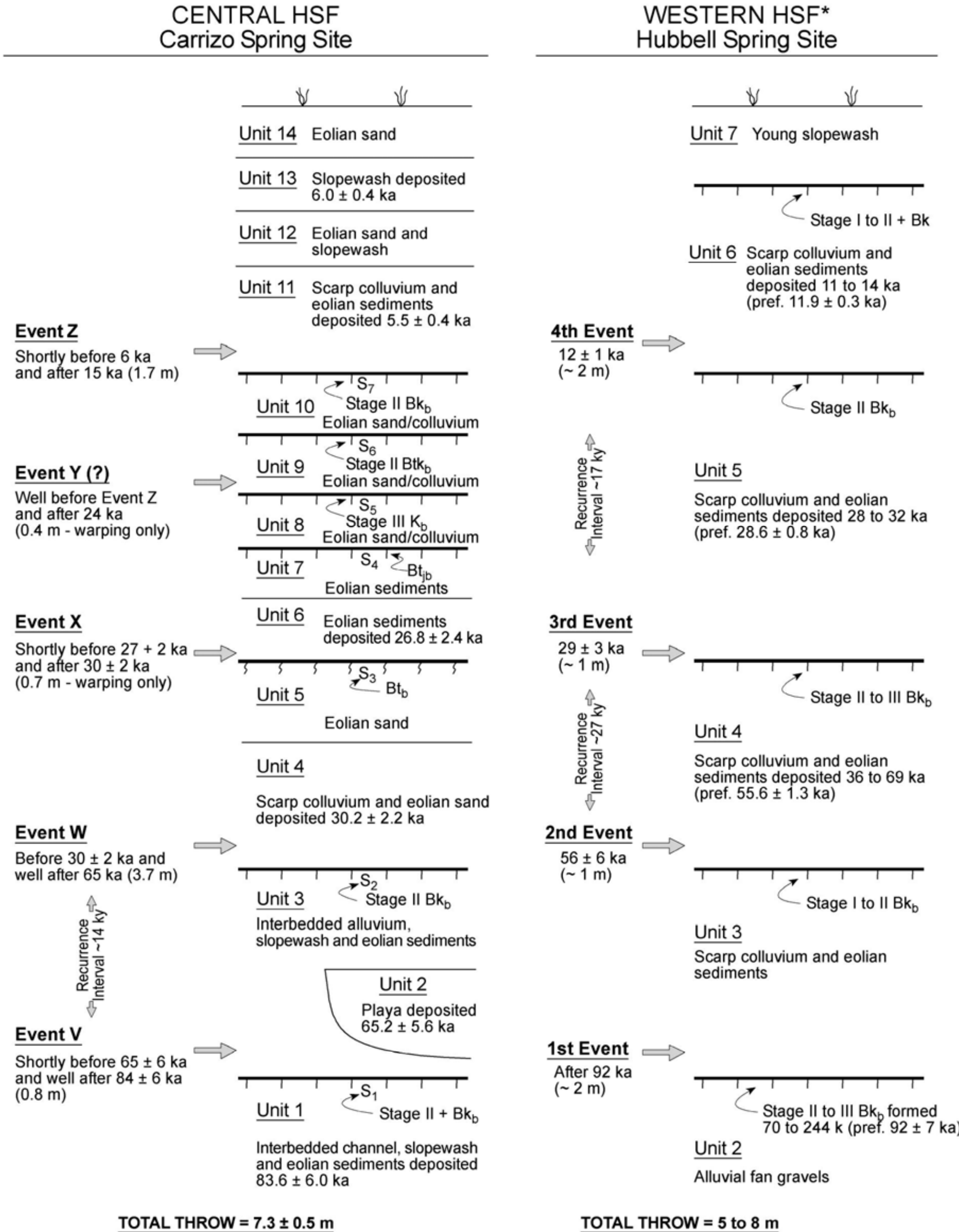
- At least 4, probably 5 earthquakes occurred since 84 ± 6 ka
- Throw per event is well-constrained

ESTIMATE OF DISPLACEMENTS PER EVENT ON THE CENTRAL HUBBELL SPRING FAULT*

SURFACE DEFORMATION EVENT	EVENT HORIZON	ESTIMATED NET VERTICAL TECTONIC DISPLACEMENT (m)	BASIS FOR ESTIMATE	STYLE OF DEFORMATION
Event Z	Top of Buried Soil S_7 (on Unit 10)	1.7 (1.4, 2.0)	Total apparent throw on top of S_7 (1.7± 0.3 m)	• Normal slip on FZ5 • Warping • Fracturing (?) • Backtilting (in FZ5 hanging wall)
Event Y (?)	Top of Buried Soil S_5 (on Unit 8)	0.4 (0, 1.2)	Differential offset between total apparent throw on top of S_5 (2.1 ± 0.5 m) and top of S_7	• Warping • Fracturing • Backtilting (?)
Event X	Top of Buried Soil S_3 (on Unit 5)	0.7 (> 0, 1.8)	Differential offset between total apparent throw on top of S_3 (2.8 ± 0.6 m) and top of S_5	• Warping • Fracturing
Event W	Top of Buried Soil S_2 (on Unit 3)	3.7 (2.6, 4.8)	Differential offset between total apparent throw on top of S_2 (6.5 ± 0.5 m) and top of S_3	• Normal slip on FZ1 through FZ4 (and buried faults west of Stn. 40m?) • Warping • Fracturing
Event V	Top of Buried Soil S_1 (on Unit 1)	0.8 (>0**, 1.6)	Differential offset between total apparent throw on top of S_1 (7.3 ± 0.3 m) and top of S_2	• Normal slip on FZ1, FZ2, and FZ3 (and buried faults west of Stn. 40m?) • Warping • Fracturing

New Mexico Bureau of Geology and Mineral Resources — New Mexico Tech — Earth Science for the 21st Century

URS



* Data Sources: Personius *et al*., 2001; and Personius and Mahan, 2003

Total Throw
<u>Per Event</u>

3.7 m

0.4 m

1.7 m

4.7 m

2.8 m

Hubbell Spring Fault Displacements (m)

Event	Central Splay	Western Splay	Total Throw
Z	1.7	2	3.7
Y (?)	0.4	0	0.4
X	0.7	~ 1	1.7
W	3.7	~ 1	4.7
V	0.8	~ 2	2.8

Magnitude-Frequency Distributions for Basin and Range Province Faults

Ivan Wong
Seismic Hazards Group, URS Corporation, 1333 Broadway, Suite 800, Oakland, CA 94612
and
David Schwartz
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

BRPEWG Workshop

8 March 2006

Agenda

1:00 – 1:10	Introduction of Issue Specific Questions	Wong/Schwartz
1:10 – 1:30	Recurrence Models and Their Physical and Observational Basis – Characteristic – Maximum Magnitude – Truncated Exponential	Schwartz
1:30 – 1:45	Impact on Hazard	Wong
1:45 – 2:00	Models and Weights Used in USGS National Hazard Maps	Petersen
2:00 – 2:30	Analysis of Paleoseismic Displacements and Implications to Recurrence Models	Hecker
2:30 – 2:50	Paleoseismic Displacements from the Hubbell Springs Fault Zone	Olig
2:50 – 3:10	Break	
3:10 – 3:30	Analyses of Wasatch Front Historical Seismicity	Arabasz
3:30 – 3:45	Models and Their Weights Considered in Other PSHAs and Rationale	Wong
3:45 – 4:45	Discussion	All
4:45 – 5:00	Recommendations to USGS	All

Issues and Questions

- **Which recurrence models (characteristic, maximum magnitude or moment, and truncated-exponential) should be used in the National Hazard Maps and how should they be weighted?**

- **Note that the recurrence models used in the National Hazard Maps differ in nomenclature and somewhat in characteristics than the models as originally defined.**

- **What factors should be considered when assigning recurrence models? Paleoseismic displacements? Fault complexity or age? Historical seismicity?**

Issues and Questions (cont.)

- Should the models/weights apply to the entire BRP or vary by region or fault?
- Should unstudied BRP faults be considered as having characteristic behavior?
- Does fault behavior evolve from an exponential to characteristic (segmented) process?

Challenges

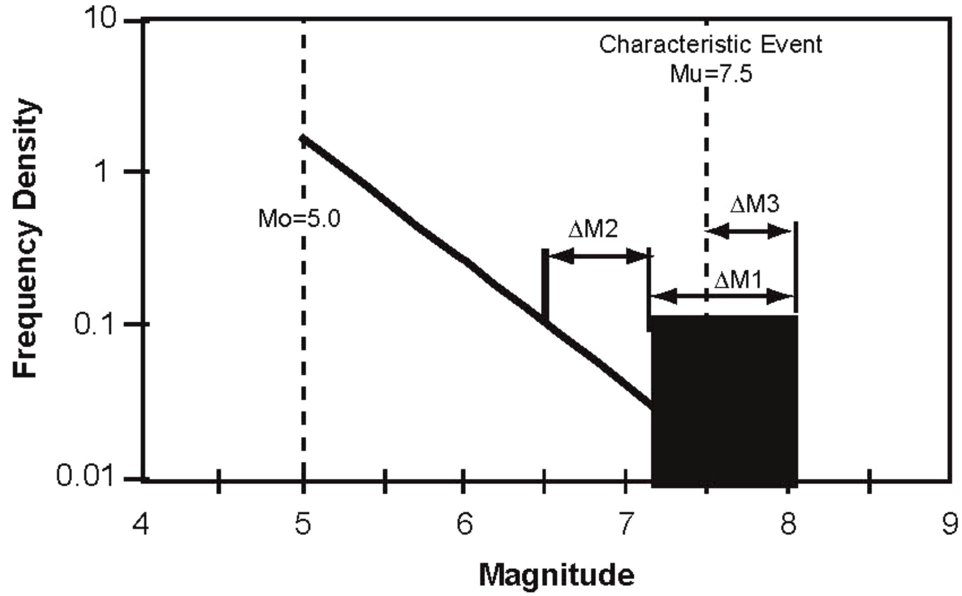
- Is there any empirical evidence that indicates that B&R faults behave other than “characteristically” (or maximum magnitude)?
- Difficulties in assessing magnitudes from paleoseismic displacements – large uncertainties.
- Minimum resolution of paleoseismic displacements is M 6 to 6½? (Yucca Mountain is one of the few places where small displacements have been looked at.)

Challenges (cont.)

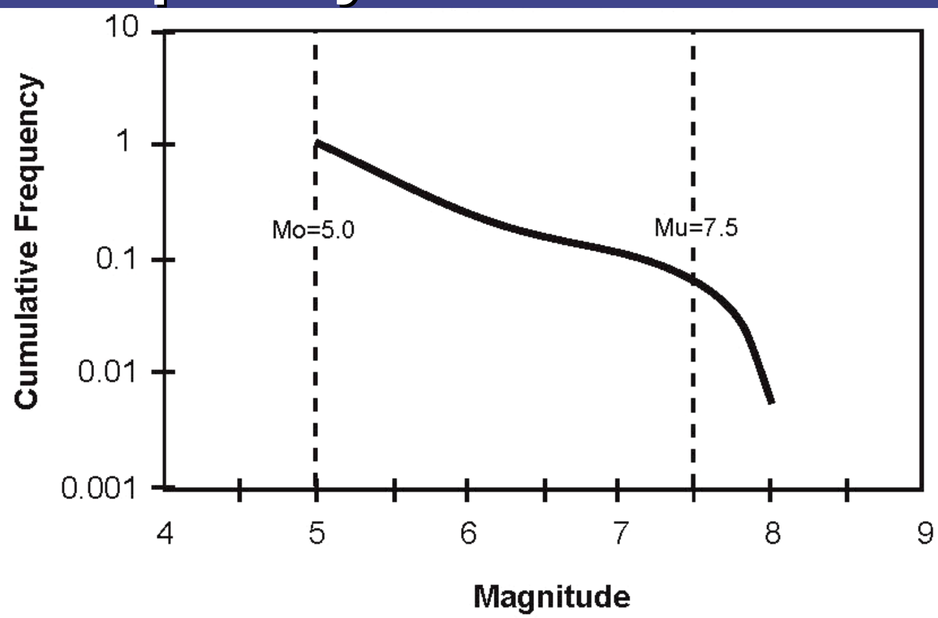
- Short and incomplete historical record and contemporary seismicity even at M < 3 levels shows no obvious association with B&R faults.
- The issue has been looked at more along strike-slip faults (e.g., California) than B&R normal faults. Do they behave differently?

Impact on Hazard from Choice of Recurrence Model

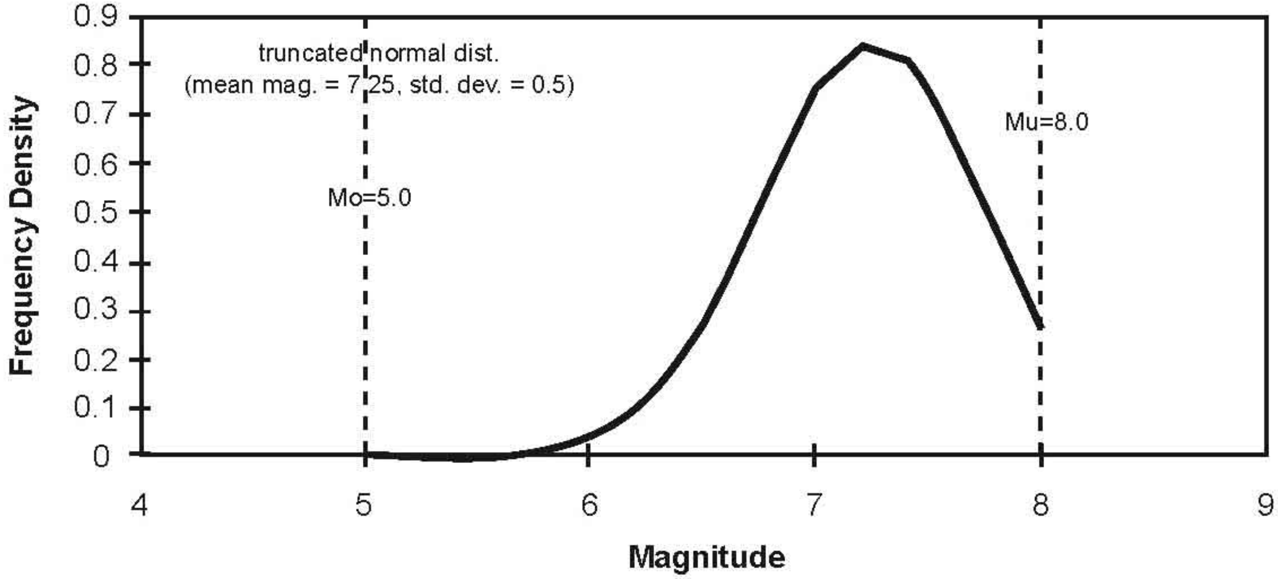
Frequency Density Function Characteristic Model



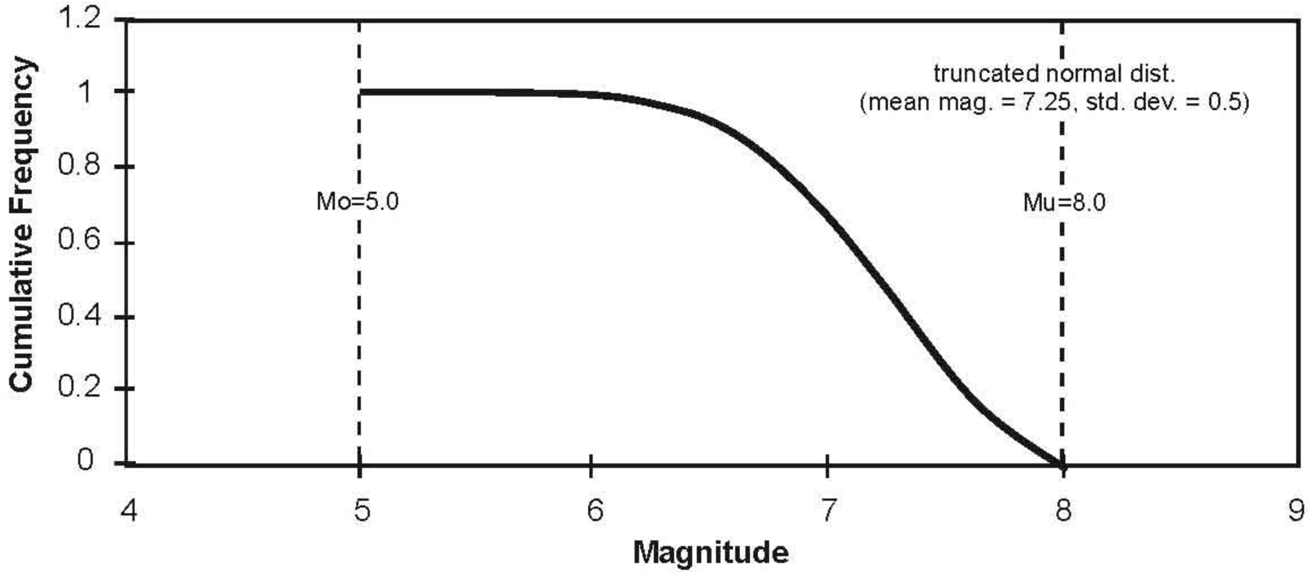
Cumulative Frequency Function Characteristic Model



Frequency Density Function Maximum Magnitude Model

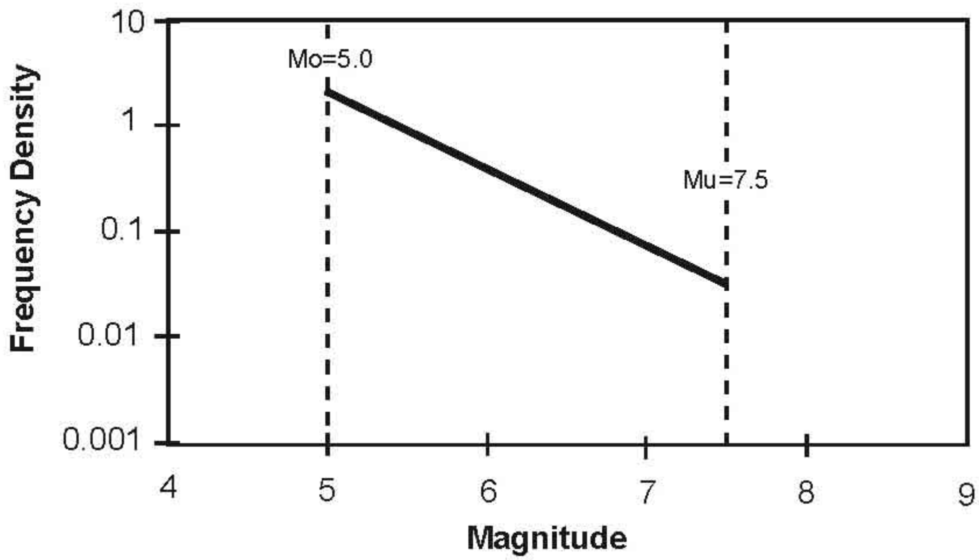


Cumulative Frequency Function Maximum Magnitude Model

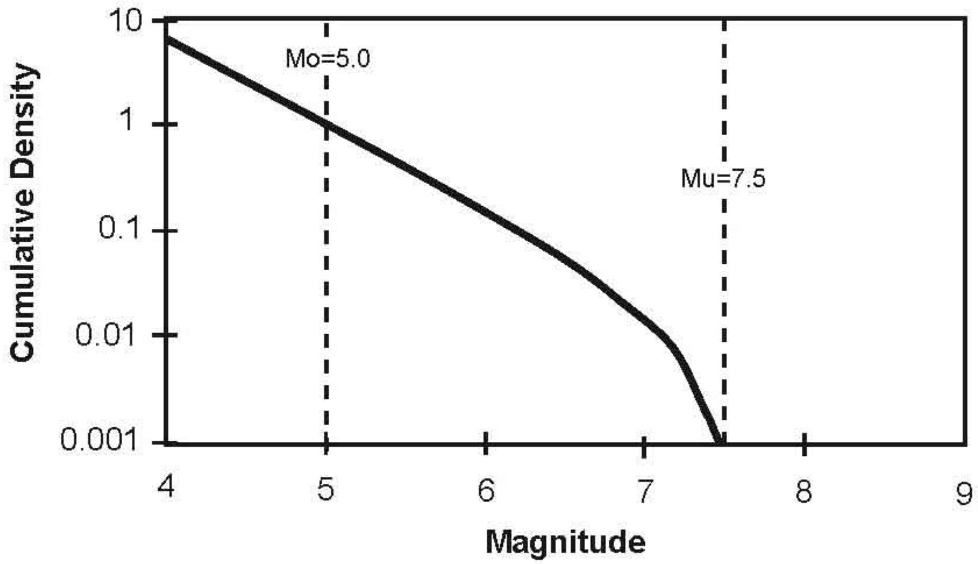


URS
SEISMIC HAZARDS

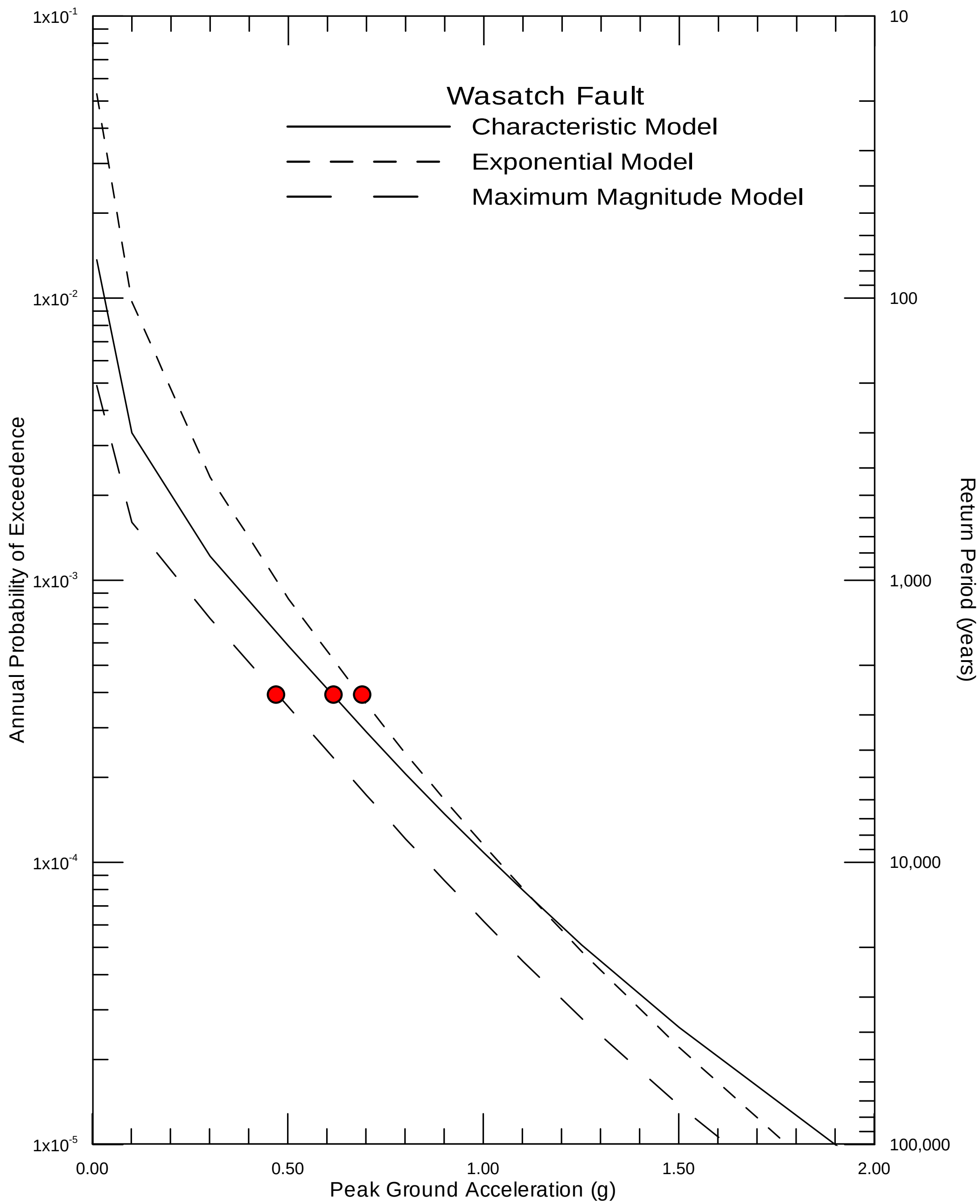
Frequency Density Function Truncated Exponential Model



Cumulative Frequency Function Truncated Exponential Model



Sensitivity to Recurrence Model



2,500 Years

Characteristic	**0.60 g**
Maximum magnitude	**0.46 g**
Truncated exponential	**0.68 g**

URS
SEISMIC HAZARDS

Recurrence Models and Their Weights Considered in Other PSHAs and Rationale

USGS Recurrence Models and Weights

Non-CA A-type faults (WFZ segments):

- **Characteristic (0.8)**
- **Truncated G-R (0.2)**

Non-CA B-type faults:

- **Characteristic (0.5) (really maximum magnitude, fault only ruptures entire segment length)**
- **G-R exponential (0.5) (only for M ≥ 6.5 to maximum rupture-length magnitude; b-value = 0.8 [non-CA])**

CA A-type faults:

- **Characteristic (1.0)**

CA B-type faults:

- **Characteristic (0.67)**
- **Truncated G-R (0.33)**

Recurrence Models and Weights Used in Other PSHAs

YUCCA MOUNTAIN

<u>Ake, Slemmons, & McCalpin</u>

Local faults:

- 0.7 Characteristic
- 0.2 Truncated exponential
- 0.1 Maximum magnitude

Regional faults:

- 0.8 Maximum magnitude
- 0.2 Characteristic

<u>Arabasz, Anderson, & Ramelli</u>

Local faults:

- 0.7 Characteristic
- 0.3 Truncated exponential

Regional faults:

- 0.7 Characteristic
- 0.3 Truncated exponential

<u>Except</u>

- 1.0 Characteristic (Death Valley-Furnace Creek)

Recurrence Models and Weights Used in Other PSHAs (cont.)

YUCCA MOUNTAIN

Smith, Bruhn, & Knuepfer *

Local faults:

- 0.3 – 0.6 Characteristic
- 0.4 – 0.7 Truncated exponential

Regional faults:

- 0.4 – 0.9 Characteristic
- 0.1 – 0.6 Truncated exponential

Doser, Fridrich, & Swan *

Local faults:

Distributed

- 0.6 Characteristic
- 0.2 Maximum magnitude
- 0.2 Truncated exponential

Independent

- 0.6 Characteristic
- 0.3 Maximum magnitude
- 0.1 Truncated exponential

Regional faults:

- 0.6 Characteristic
- 0.3 Maximum magnitude
- 0.1 Truncated exponential

Recurrence Models and Weights Used in Other PSHAs (cont.)

YUCCA MOUNTAIN

Rogers, Yount, & Anderson

Local faults:
- 0.9 Characteristic
- 0.1 Truncated exponential

Regional faults:
- 0.1 – 0.9 Characteristic
- 0.1 – 0.9 Truncated exponential

Smith, DePolo, & O'Leary

Local faults:
- 0.7 Characteristic
- 0.3 Truncated exponential

Regional faults:
- 0.7 Characteristic
- 0.3 Truncated exponential

SKULL VALLEY, UTAH

Geomatrix Consultants
- 0.65 Characteristic
- 0.13 Maximum magnitude
- 0.22 Truncated exponential

Recurrence Models and Weights Used in Other PSHAs (cont.)

BASIN AND RANGE

<u>Wong and Olig</u>

Long segmented faults:

- Characteristic (0.7)
- Maximum magnitude (0.2)
- Truncated exponential (0.1)

Short independent faults:

- Characteristic (0.6)
- Maximum magnitude (0.2)
- Truncated exponential (0.2)

Zones of faults:

- Truncated exponential (0.5)
- Characteristic (0.5)

Famous Quotes

Stirling, Wesnousky, and Shimazaki (1996)

Magnitude-frequency distributions from a data set of 22 strike-slip faults from around the world are generally consistent with the characteristic earthquake model, whereby geological estimates of the recurrence rate of the largest earthquakes are orders of magnitude more frequent than rates predicted from interpretation of earthquake statistics.

Stirling, Wesnousky, and Shimazaki (1996) (cont.)

We observe that fault-trace complexity is a decreasing function of cumulative slip, a smoothing process that would allow for longer rupture lengths and a more homogenous stress field along the fault, therefore increasing the size of the largest earthquakes and reducing the number of small earthquakes. Regardless of a physical basis for the characteristic earthquake model, the model is more appropriate than the Gutenburg-Richter relationship in describing the seismicity of strike-slip faults for seismic hazard analysis.

Wesnousky (1994)

When combining geological and instrumental data bearing on the size and repeat time of earthquakes along the major strike-slip fault zones of southern California to place limits on the shape of the magnitude-frequency distribution, seismicity along the Newport-Inglewood, Elsinore, Garlock, and San Andreas faults is consistent with the characteristic earthquake model of fault behavior, whereas seismicity along the San Jacinto fault zone appears suitably described by the Gutenberg-Richter relationship.

However, if attention is limited to segments of the san Jacinto that are separated by distinct steps in fault trace or the rupture zones of large historical earthquakes, the observed distribution along each segment may be explained by the characteristic earthquake model.

Wesnousky (1994) (cont.)

The term characteristic earthquake model has often been used to suggest that faults are characterized by the repeated occurrence of identical earthquakes. That extreme interpretation is not being argued here or in W94. Rather, the term characteristic earthquake model is only being used to encompass fault behavior whereby extrapolation of statistic historical earthquakes of small to moderate size will underestimate the occurrence of the largest-expected earthquakes along a particular fault zone. The largest-expected earthquakes do not need to be identical in size nor repeat in the exact same locations through time.

Wesnousky (1994) (cont.)

It also is not my contention that all faults necessarily behave according to the characteristic earthquake distribution. To the contrary, it seems naive to expect that all faults behave exactly according to either the characteristic earthquake or the Gutenberg-Richter model. The data for the San Jacinto fault are a possible case in point.

More likely there is a continuum of behaviors, a continuum that may reflect the structural complexity of faults (e.g., Wesnousky, 1988, 1990). A study similar to W94, but much more extensive in scope, is consistent with the idea that faults characterized by complex traces tend to exhibit magnitude-frequency distributions more consistent with the Gutenberg-Richter distribution, whereas faults characterized by relatively smooth fault traces exhibit distributions more consistent with the characteristic earthquake model (Stirling *et al.*, 1995).

Hazard Maps

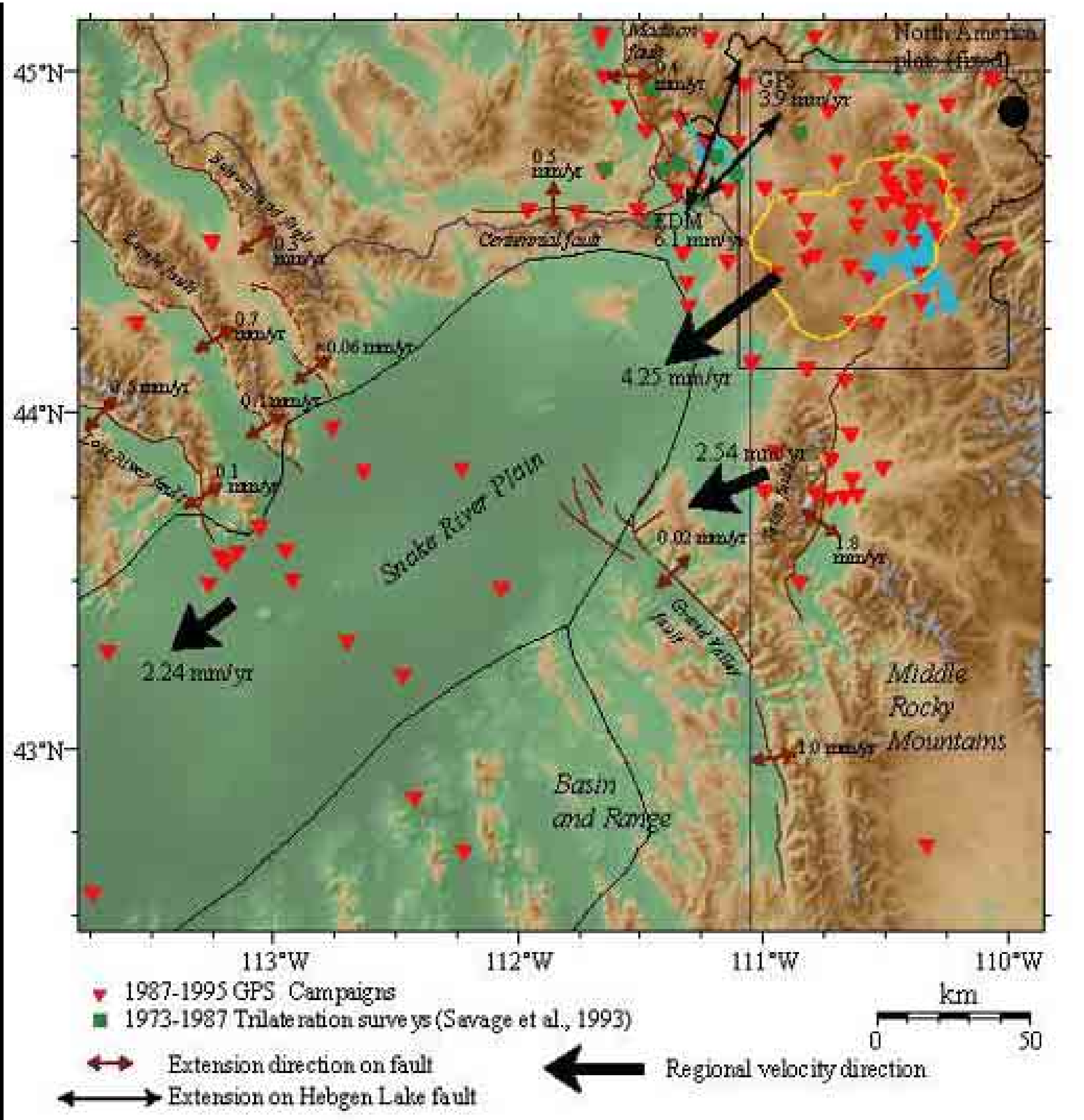
probabilistic ground motions

Source Characteristics
Location
Recurrence
Magnitude

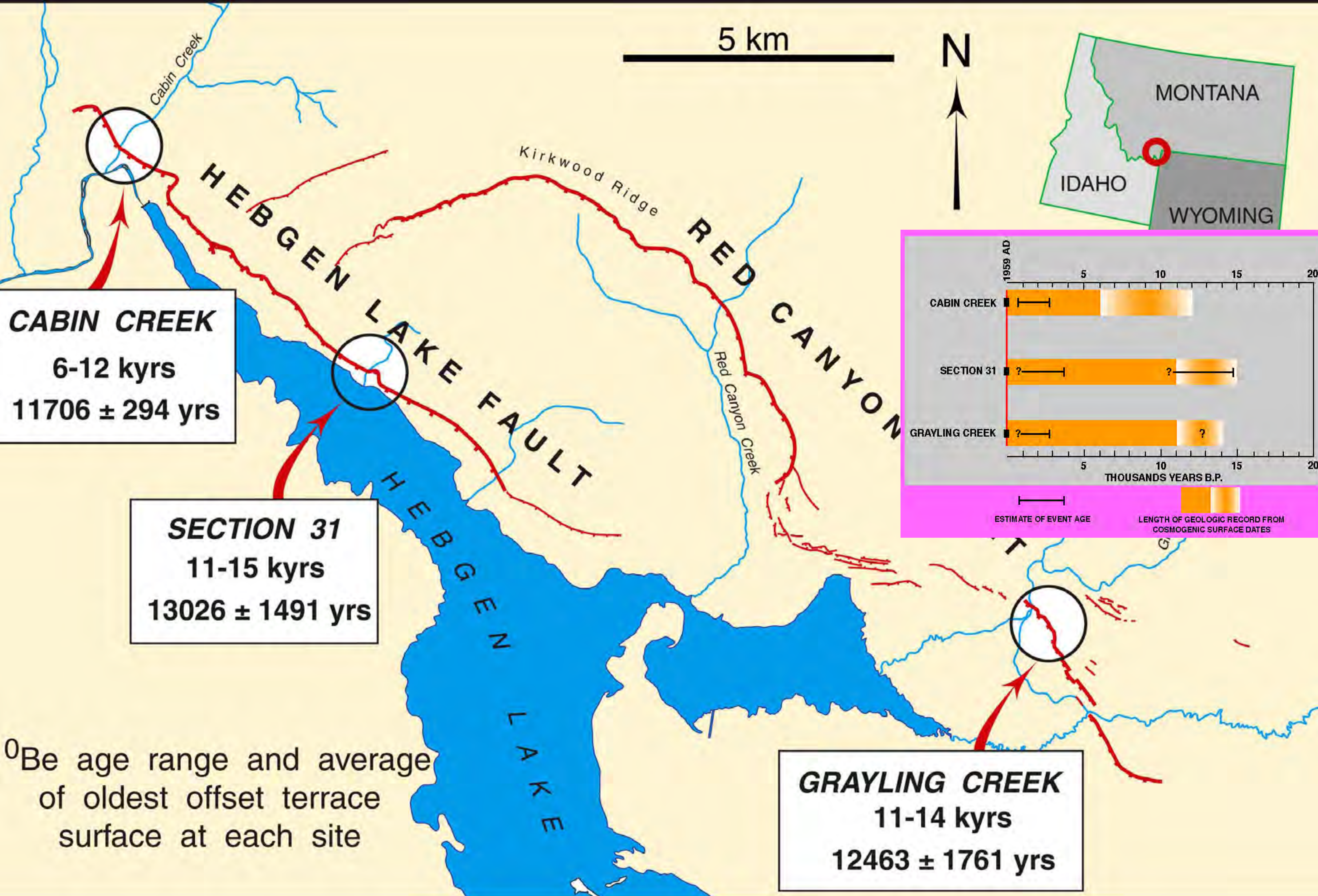
building codes

Segmentation ← Timing of events, slip/event, slip rate

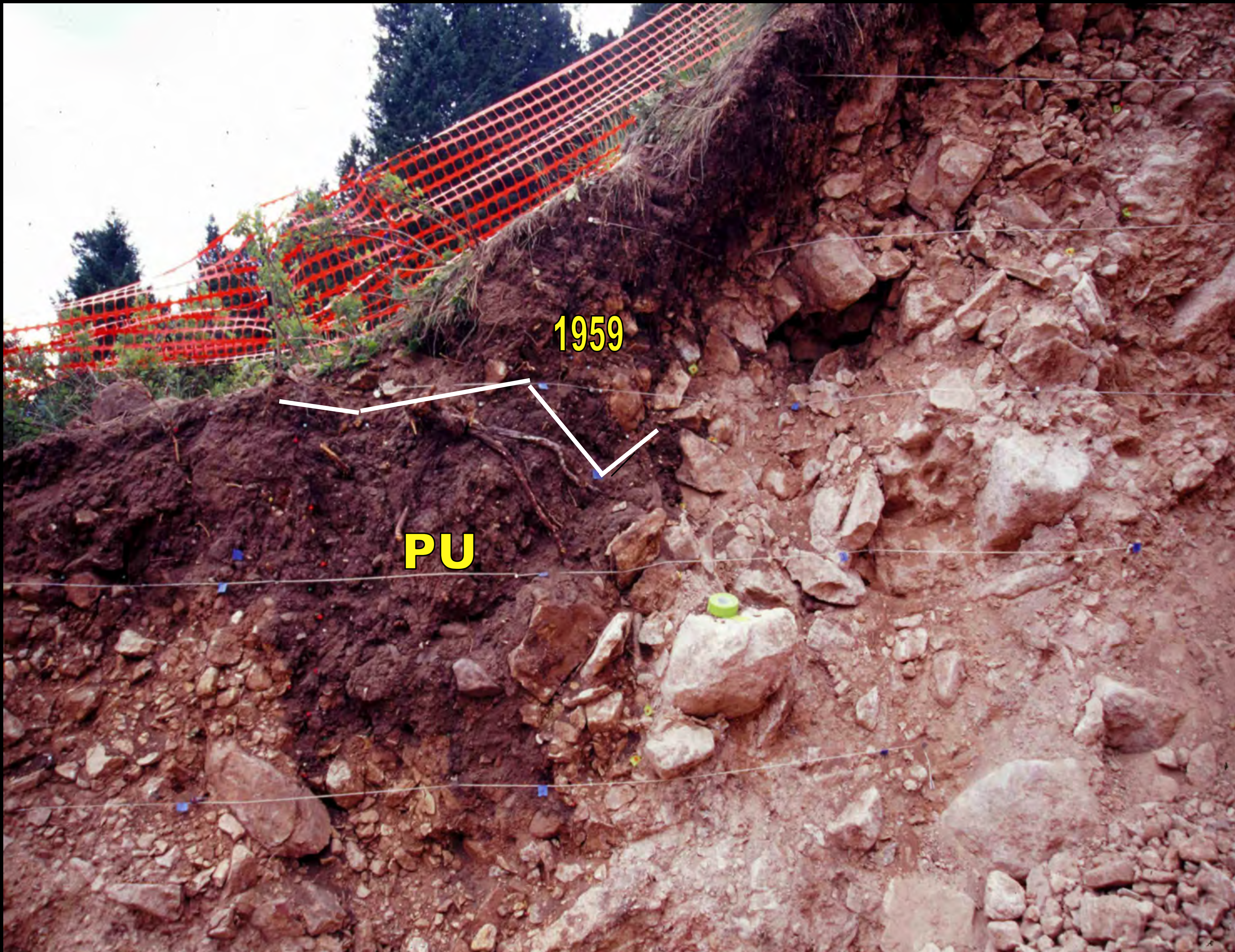
How do we improve the inputs to hazard maps that reflect more realistic earthquake behavior?

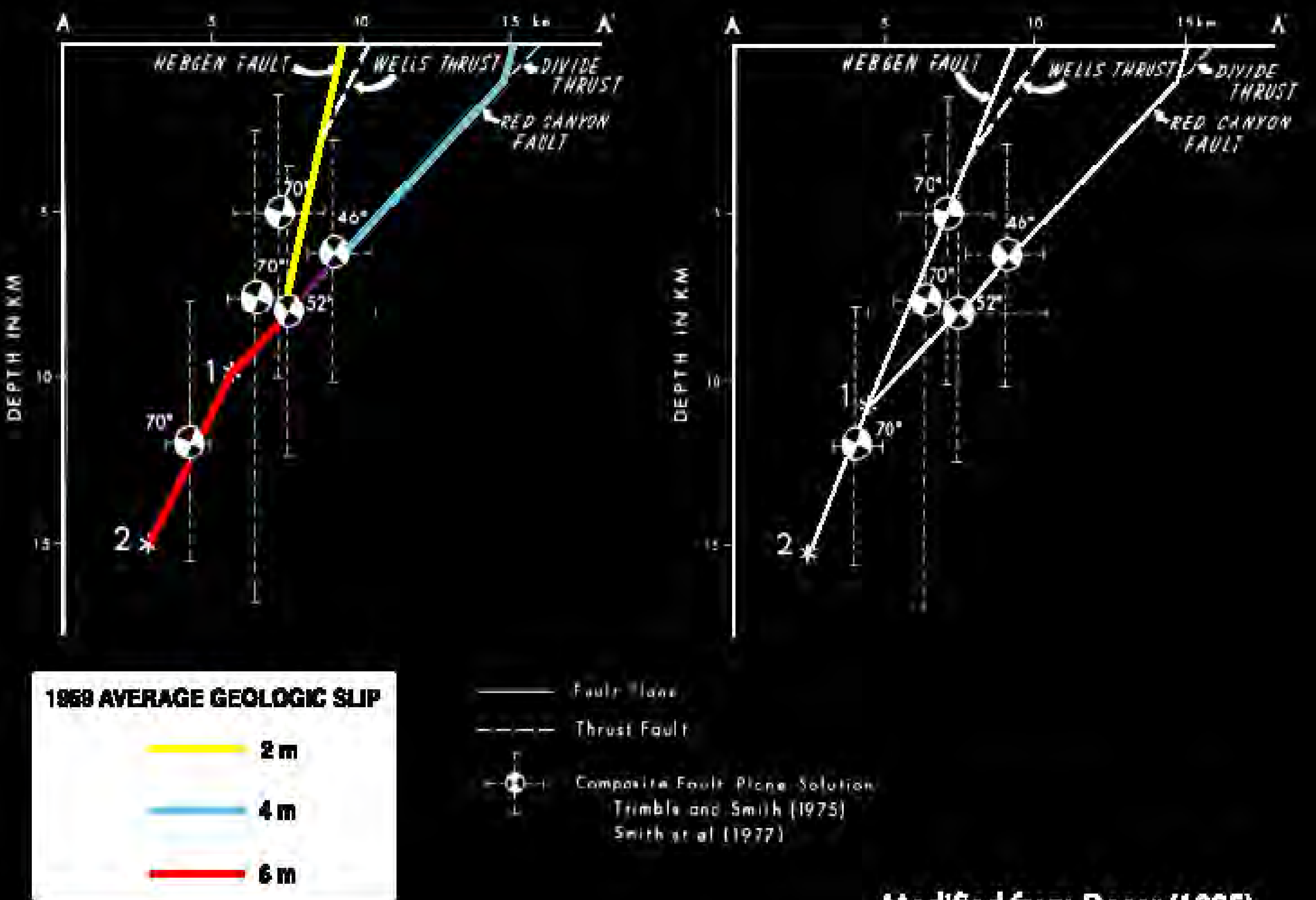


North America plate (fixed)
Madison fault
GPS 3.9 mm/yr
EDM 6.1 mm/yr
0.3 mm/yr
Centennial fault
Lemhi fault
Lost River fault
Snake River Plain
4.25 mm/yr
2.54 mm/yr
2.24 mm/yr
0.7 mm/yr
0.06 mm/yr
0.1 mm/yr
0.02 mm/yr
1.3 mm/yr
1.0 mm/yr
Grand Valley fault
Middle Rocky Mountains
Basin and Range
45°N
44°N
43°N
113°W
112°W
111°W
110°W
1987-1995 GPS Campaigns
1973-1987 Trilateration surveys (Savage et al., 1993)
Extension direction on fault
Extension on Hebgen Lake fault
Regional velocity direction
km
0
50

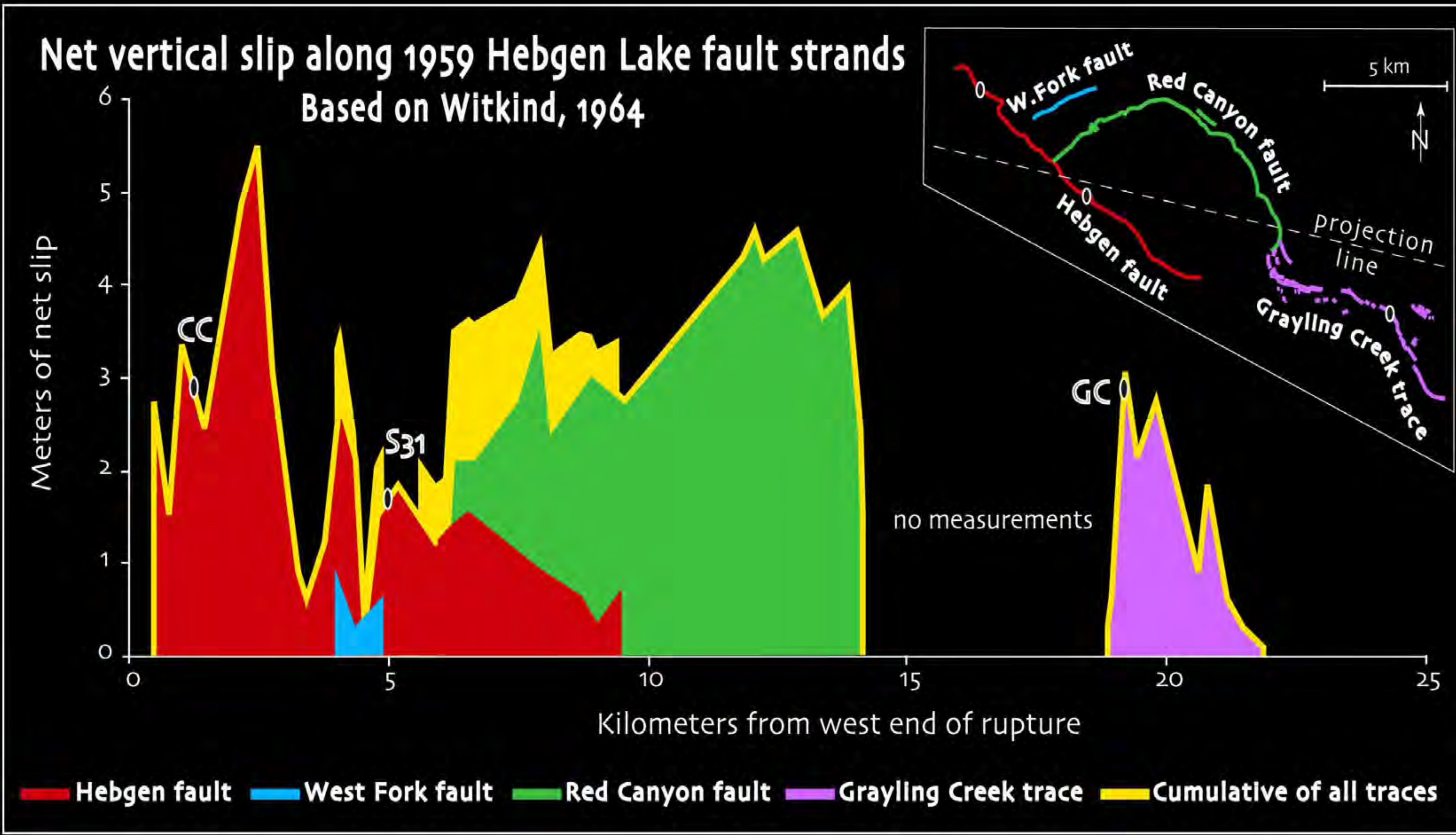


5 km
N
MONTANA
IDAHO
WYOMING
Cabin Creek
Kirkwood Ridge
HEBGEN LAKE FAULT
RED CANYON
Red Canyon Creek
HEBGEN LAKE
CABIN CREEK
6-12 kyrs
11706 ± 294 yrs
SECTION 31
11-15 kyrs
13026 ± 1491 yrs
GRAYLING CREEK
11-14 kyrs
12463 ± 1761 yrs
0Be age range and average of oldest offset terrace surface at each site
1959 AD
CABIN CREEK
SECTION 31
GRAYLING CREEK
THOUSANDS YEARS B.P.
ESTIMATE OF EVENT AGE
LENGTH OF GEOLOGIC RECORD FROM COSMOGENIC SURFACE DATES

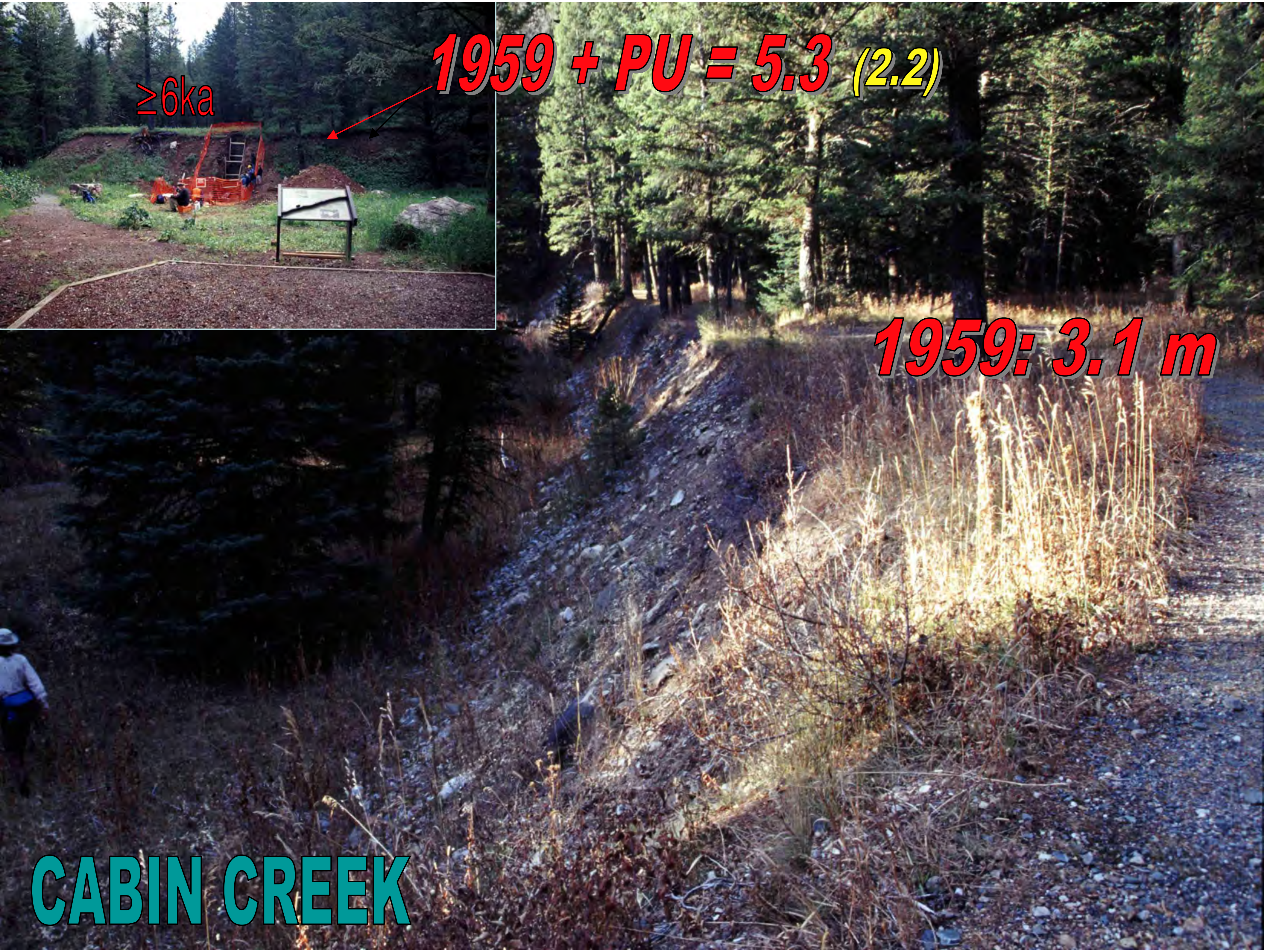

1959
PU

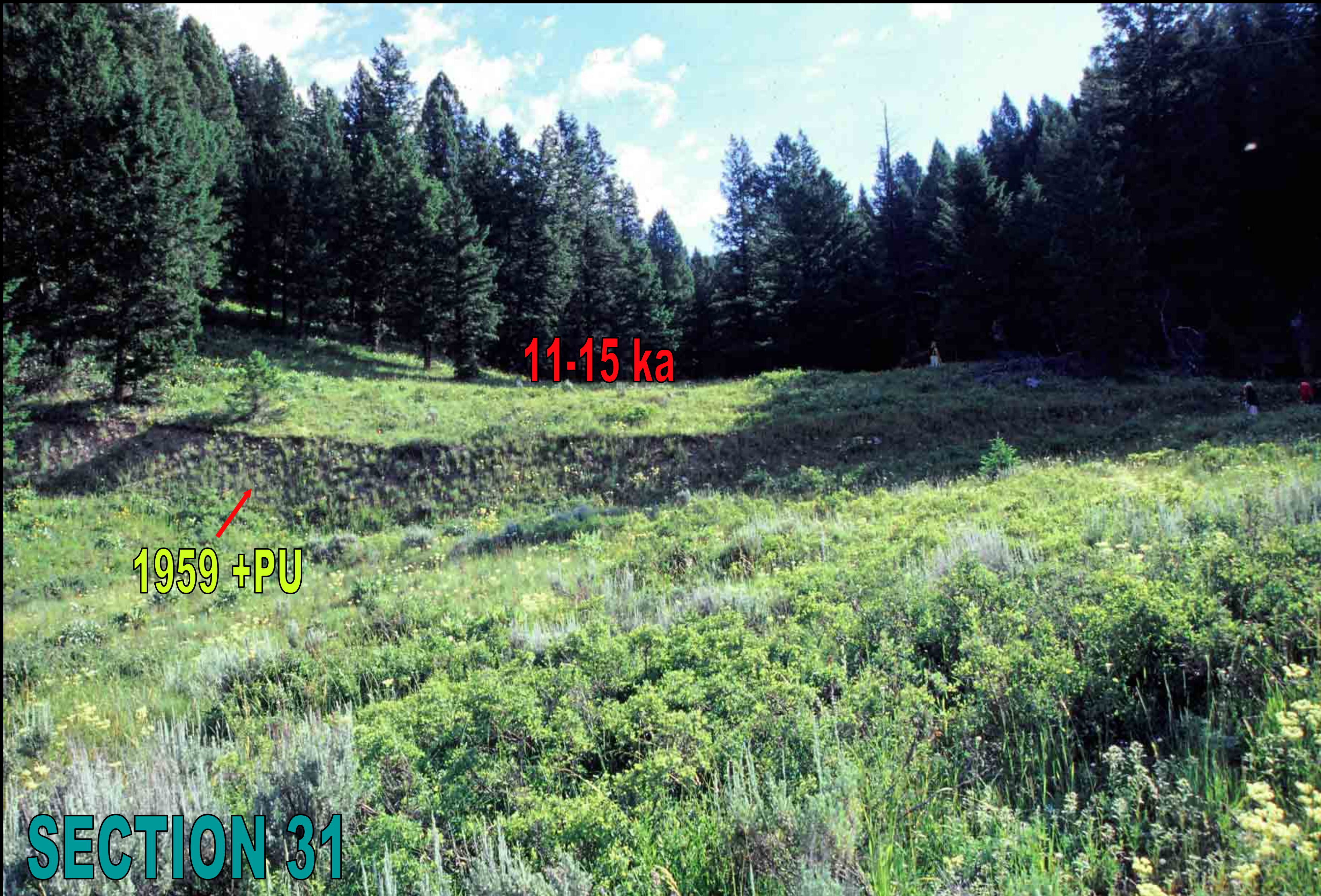


Modified from Doser (1985)



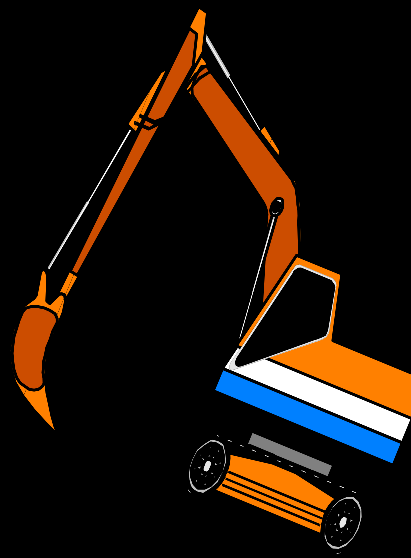
Net vertical slip along 1959 Hebgen Lake fault strands
Based on Witkind, 1964
Meters of net slip
0
1
2
3
4
5
6
CC
S31
GC
no measurements
0
5
10
15
20
25
Kilometers from west end of rupture
W.Fork fault
Red Canyon fault
5 km
N
projection line
Hebgen fault
Grayling Creek trace
Hebgen fault
West Fork fault
Red Canyon fault
Grayling Creek trace
Cumulative of all traces


1959 + PU = 5.3 (2.2)
≥6ka
1959: 3.1 m
CABIN CREEK

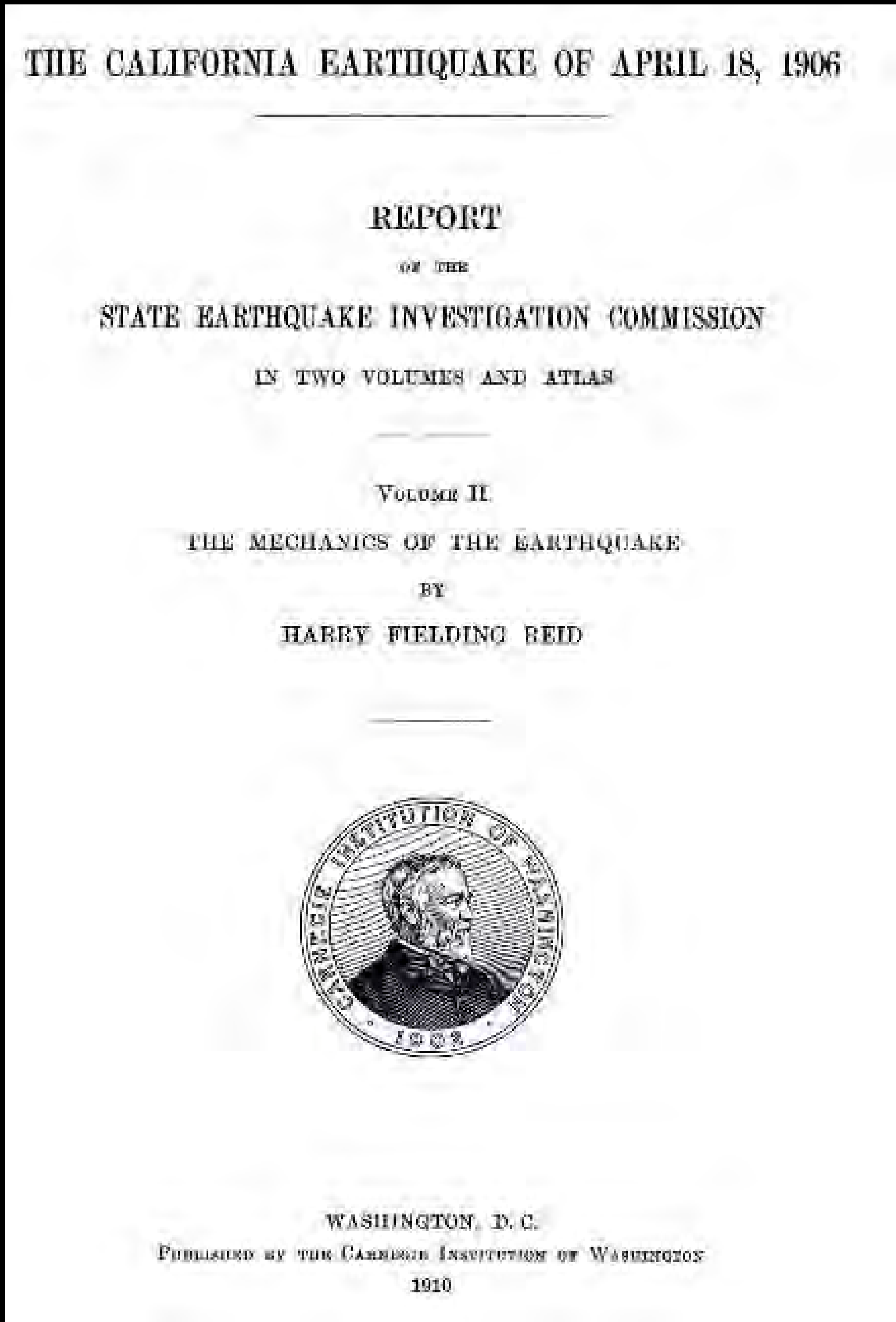

11-15 ka
1959 +PU
SECTION 31


1959 + PU = 2m
11-14 ka
GRAYLING CREEK

Hebgen Lake Slip/Event



	Hebgen	Red Canyon
CC	3.1 2.2	—
Sec 31	1.2 1.1 2.2-3.7	—
GC		1.0 1.0



THE CALIFORNIA EARTHQUAKE OF APRIL 18, 1906

REPORT

OF THE

STATE EARTHQUAKE INVESTIGATION COMMISSION

IN TWO VOLUMES AND ATLAS

VOLUME II

THE MECHANICS OF THE EARTHQUAKE

BY

HARRY FIELDING REID

WASHINGTON, D. C.

PUBLISHED BY THE CARNEGIE INSTITUTION OF WASHINGTON

1910

1910
ELASTIC REBOUND

Time Dependence

Static Stress Changes

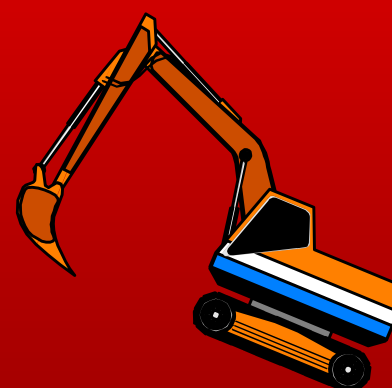
Time Dependence

It seems probable that a very long period will elapse before another important earthquake occurs along that part of the San Andreas rift which broke in 1906; for we have seen that the strains causing the slip were probably accumulating for 100 years. There have been no serious earthquakes reported along this part of the rift, except at its southern extremity, since the country has been occupied by white men, altho strong earthquakes have occurred in neighboring regions. It seems probable that more consistent results might be obtained regarding the periodicity of earthquakes if only the earthquakes occurring at exactly the same place were considered in the series. The Messina earthquake of December 28, 1908, seems to have resulted from a movement on the great fault passing thru the Straits of Messina. The last strong movement at the same place seems to have occurred in 1783; tho the Calabrian earthquake of 1905 may have been caused by a movement on another part of the same fault.

Time Dependence

HISTORICAL

EARTHQUAKE CYCLE

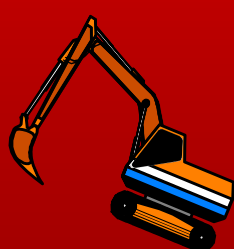


PALEOSEISMIC

Time Dependence

HISTORICAL

few repeat ruptures



PALEOSEISMIC

few very short recurrence intervals

Time Dependence

HISTORICAL

few repeat ruptures

<u>Wells and Coppersmith (1994)</u>

244 events (238 20th century)

M 5.5-8/0

Varied tectonic settings/slip rates

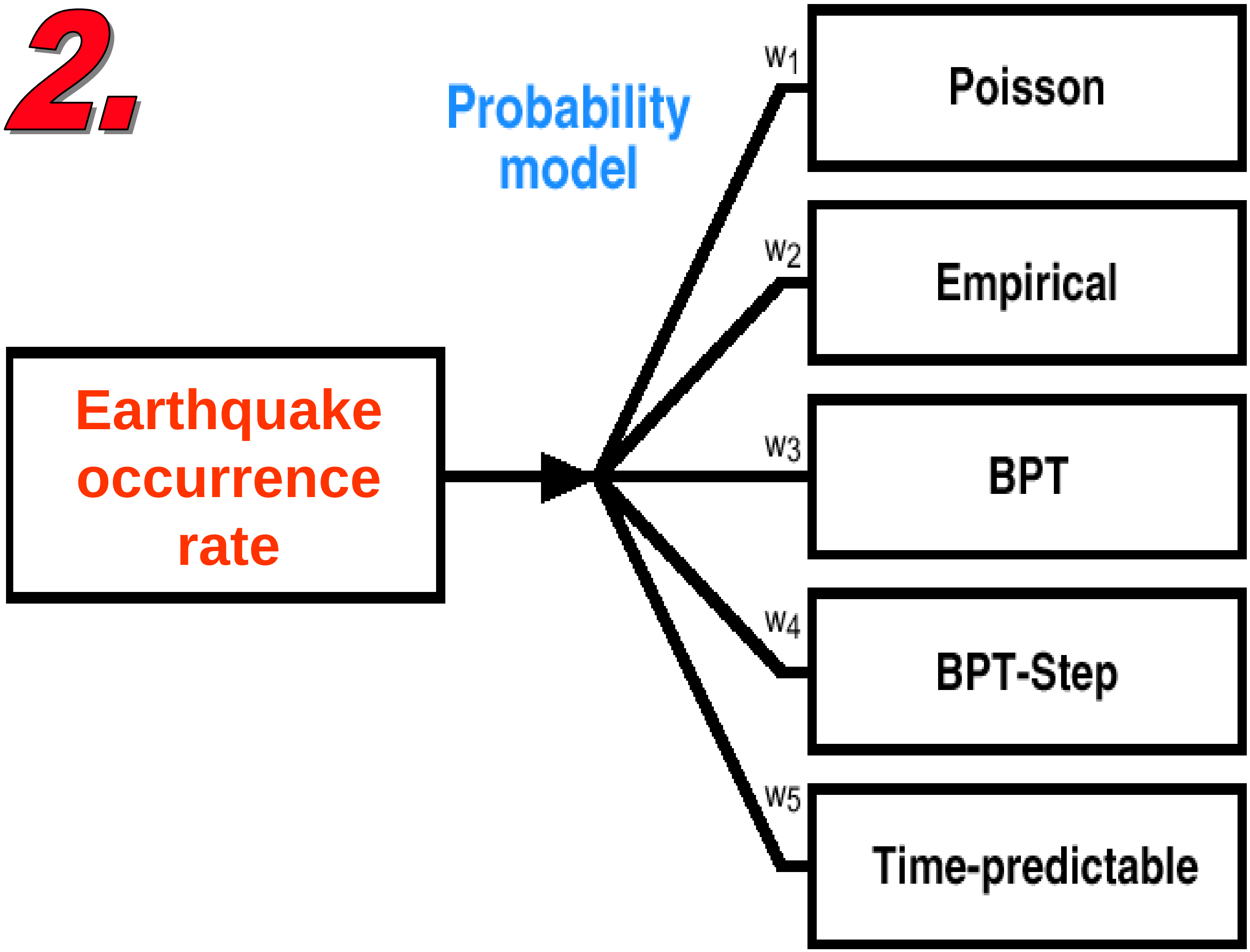
RIs 100s-1000s

San Andreas--Parkfield

Homestead Valley1979,1992

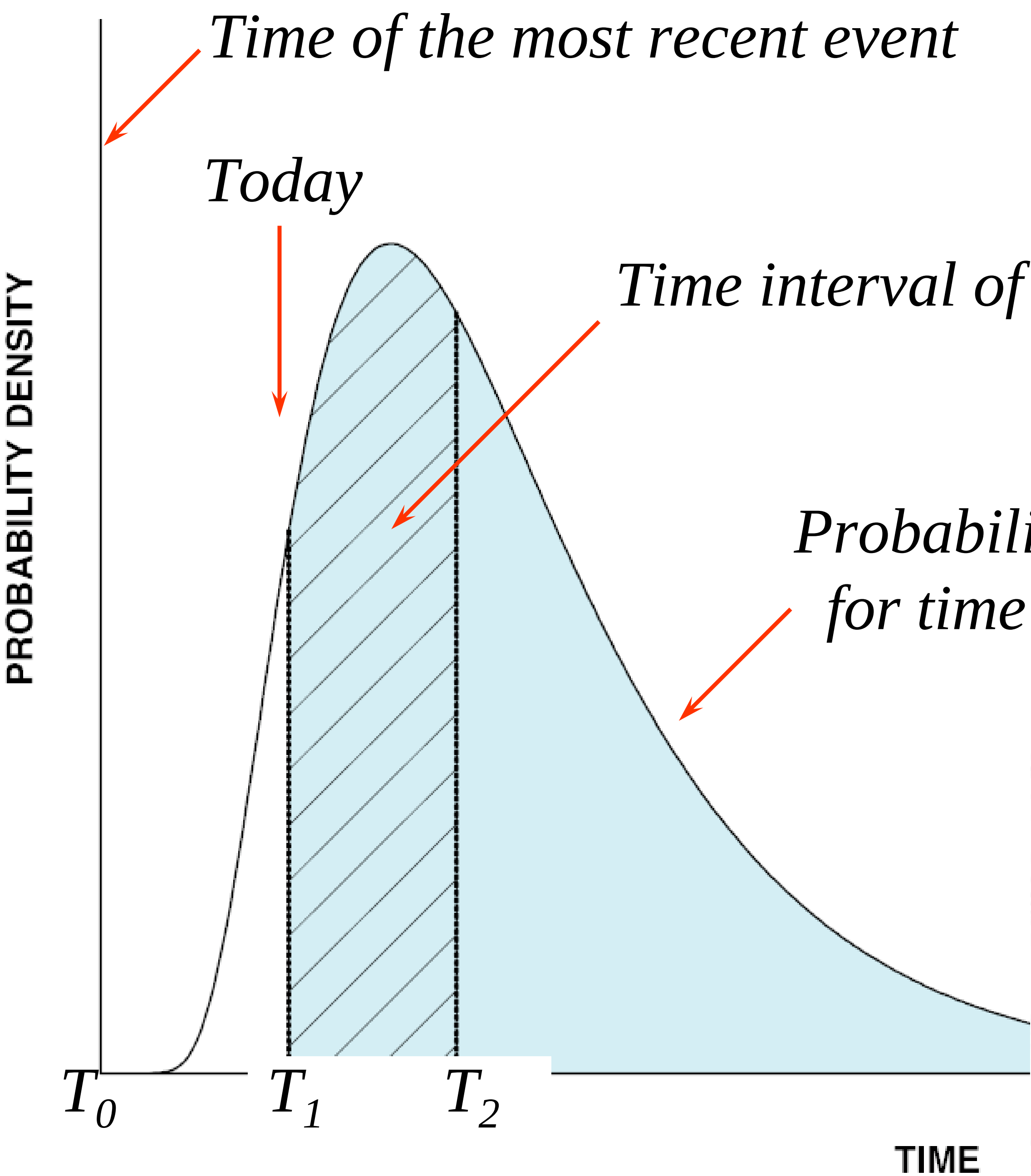
Oued Fodda 1954, 1980

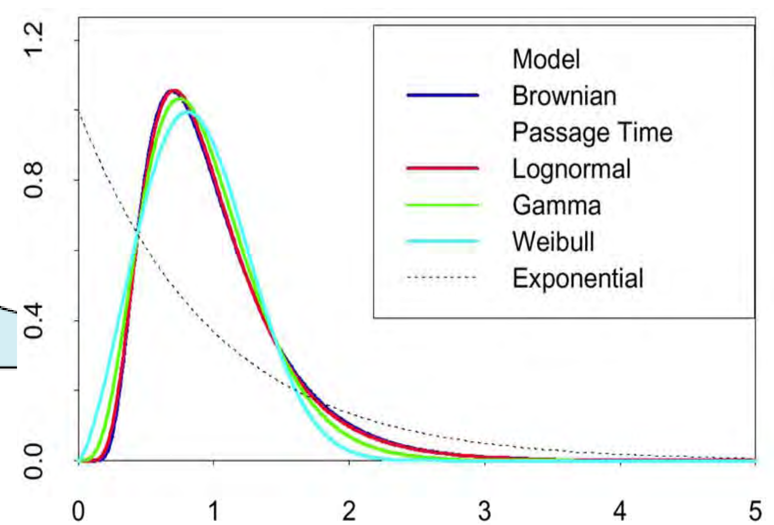
Imperial 1940, 1979


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

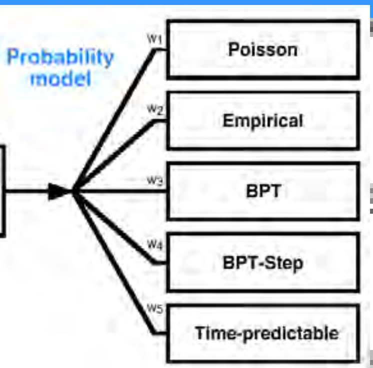
Probability of the Next Earthquake

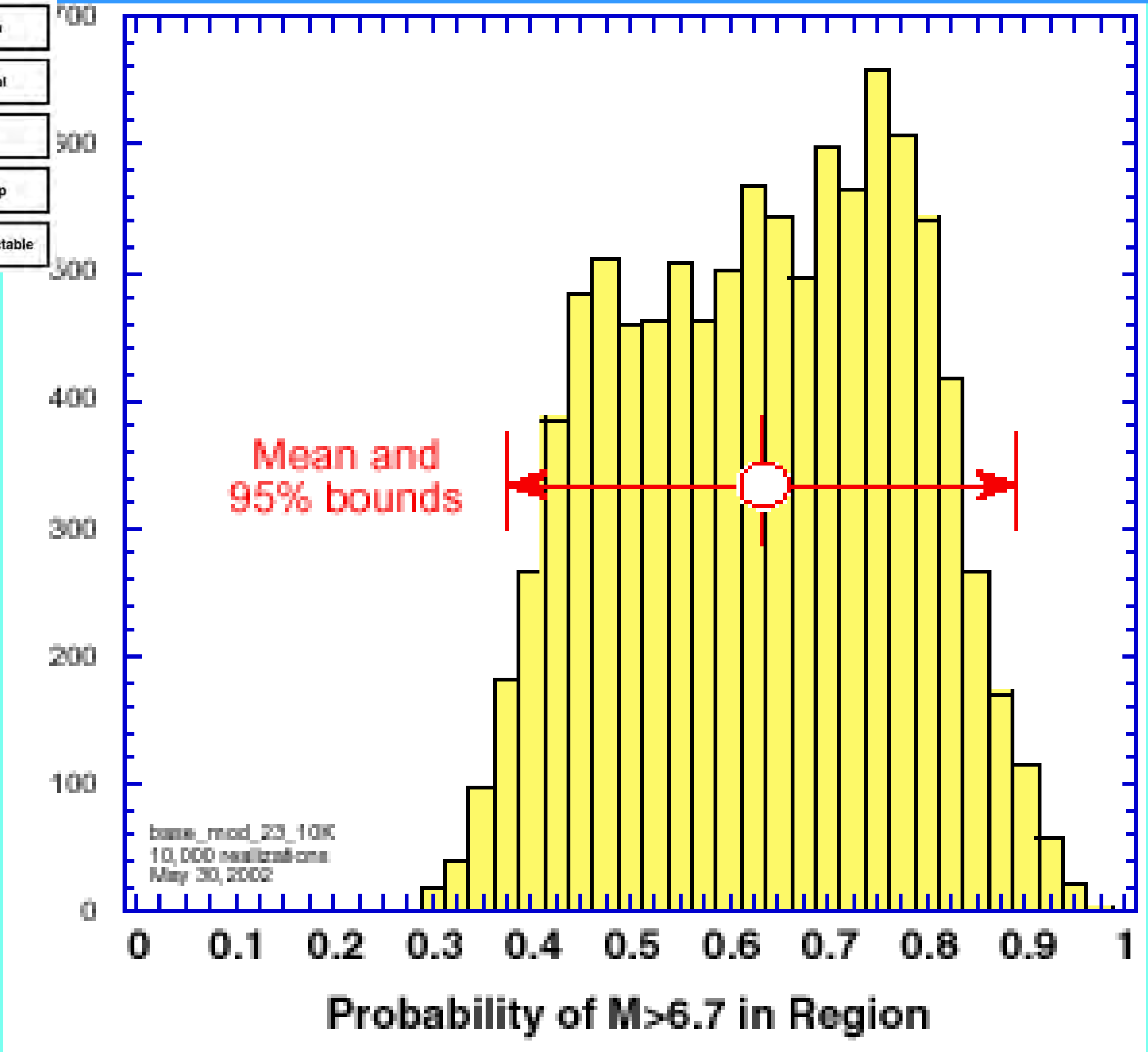
Recurrence interval
COV/aperiodcity
Elapsed time





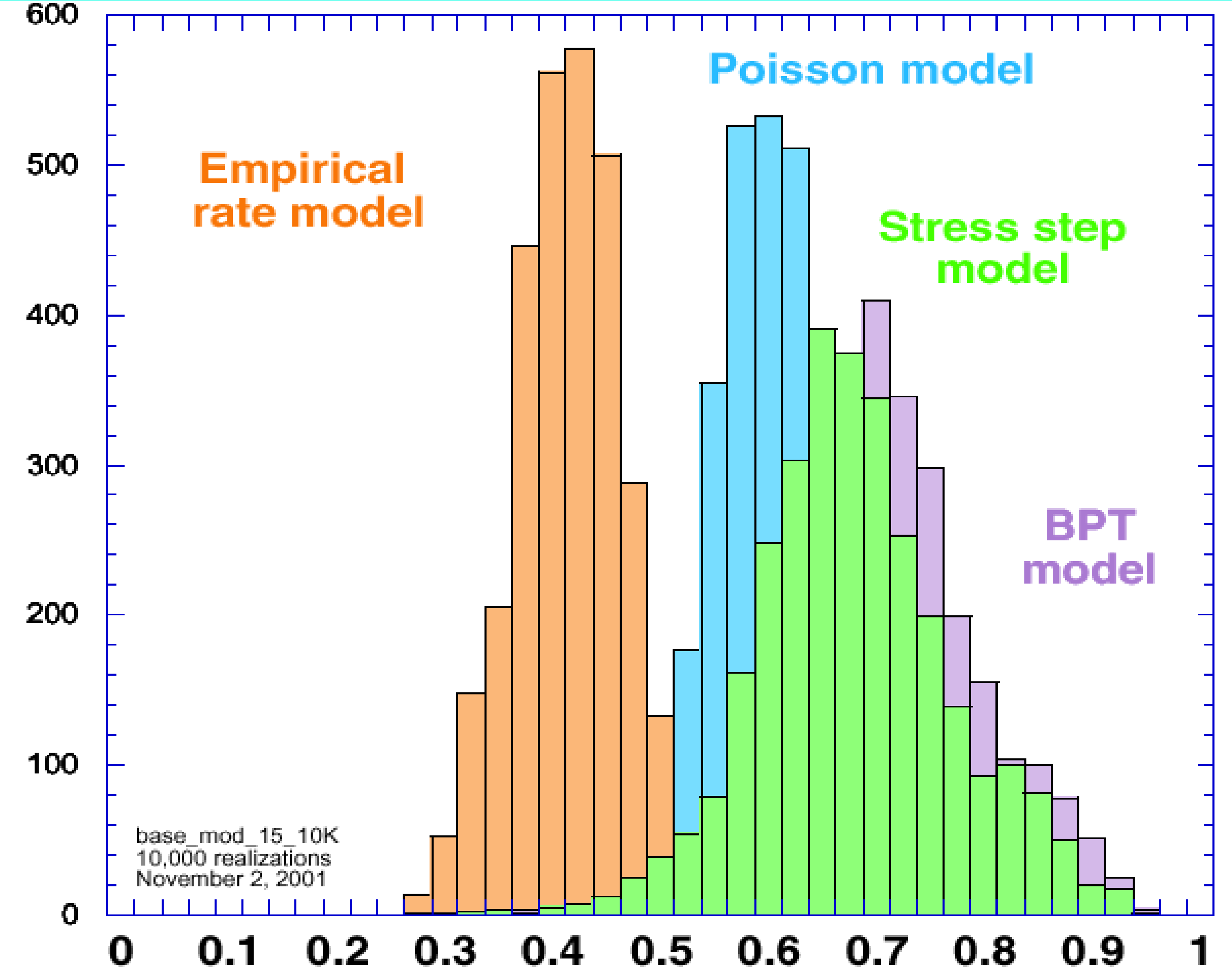
Combined Probability Models





Alternative Probability Models

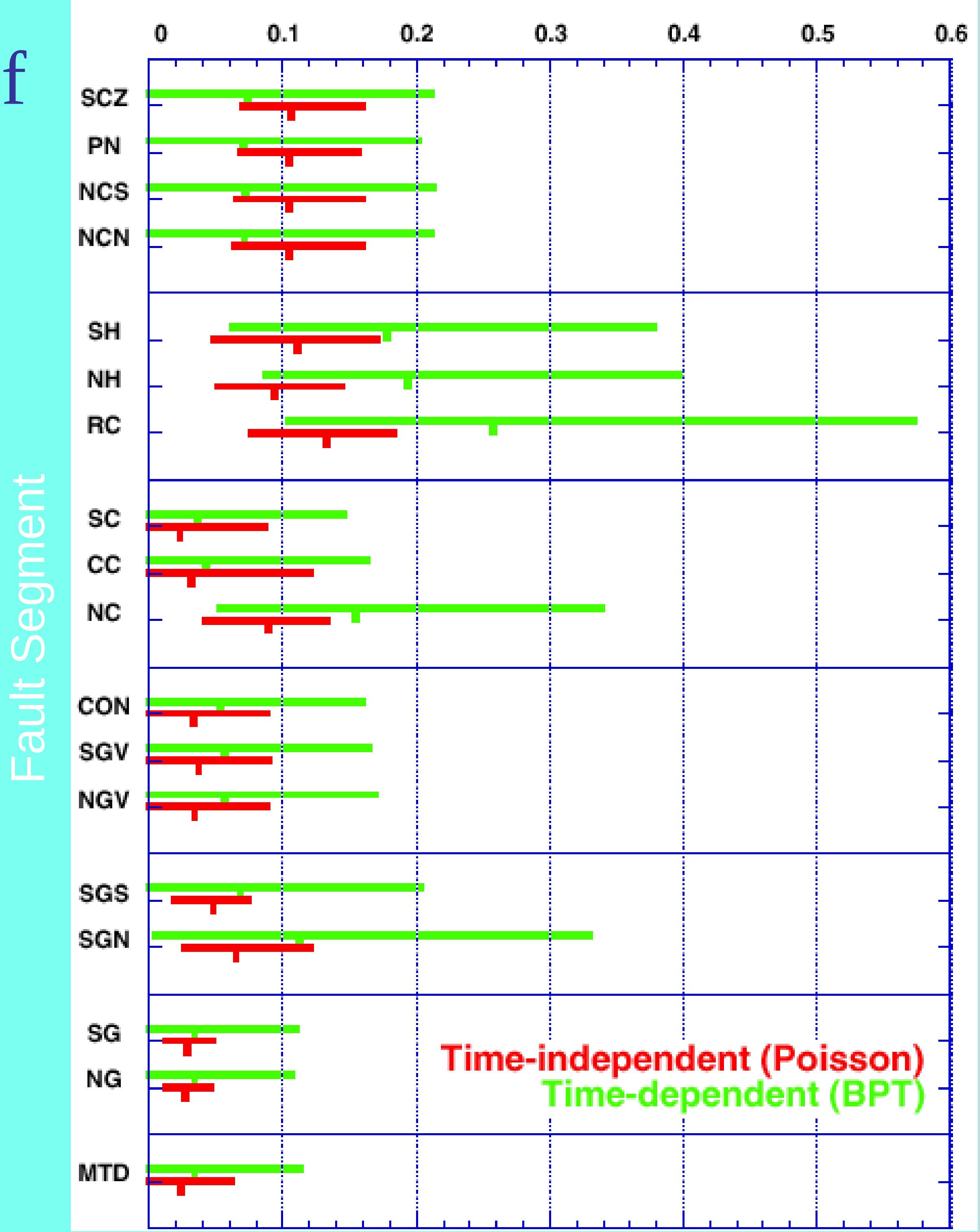
for M>6.7 in region, 2002-2031



30-year Probability of Rupture, M>6.7

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

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



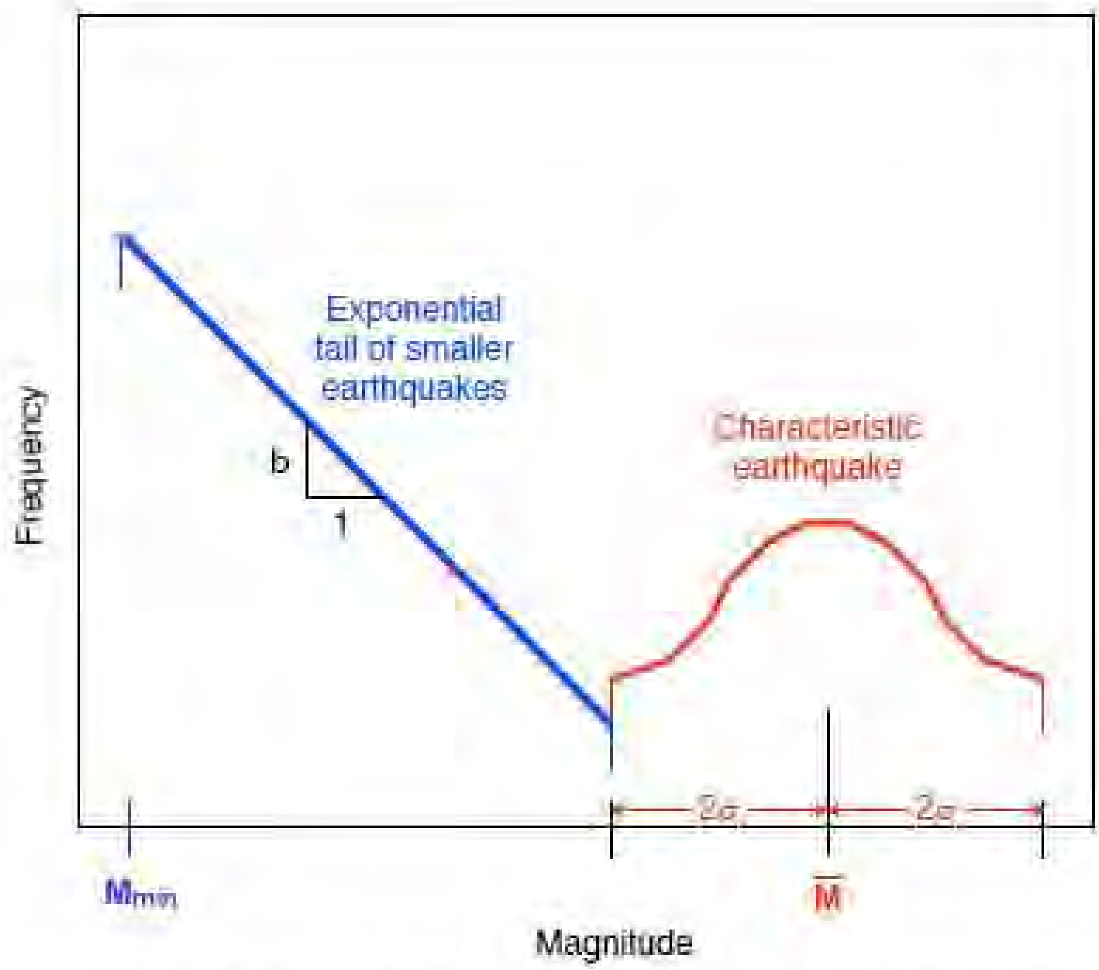
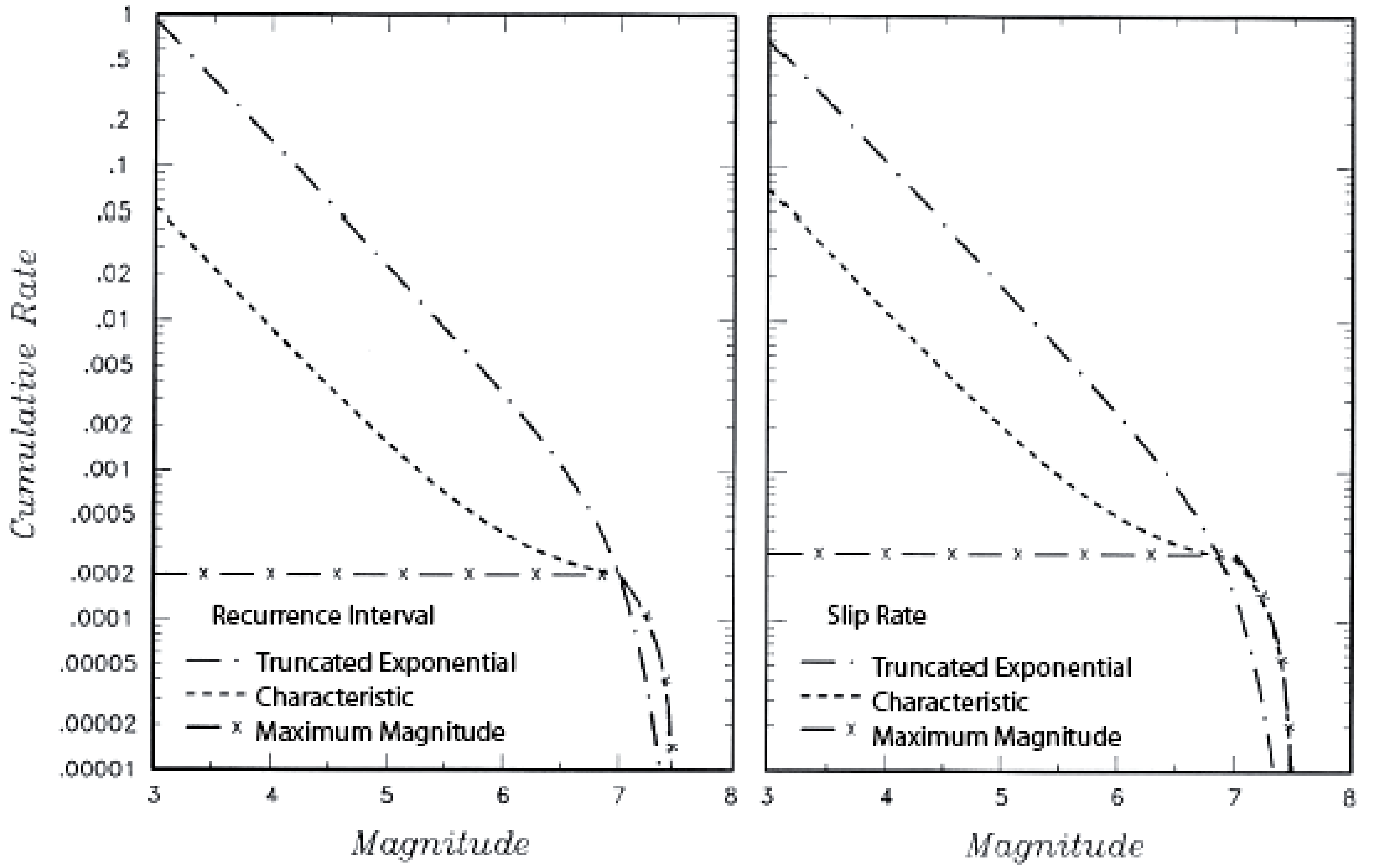
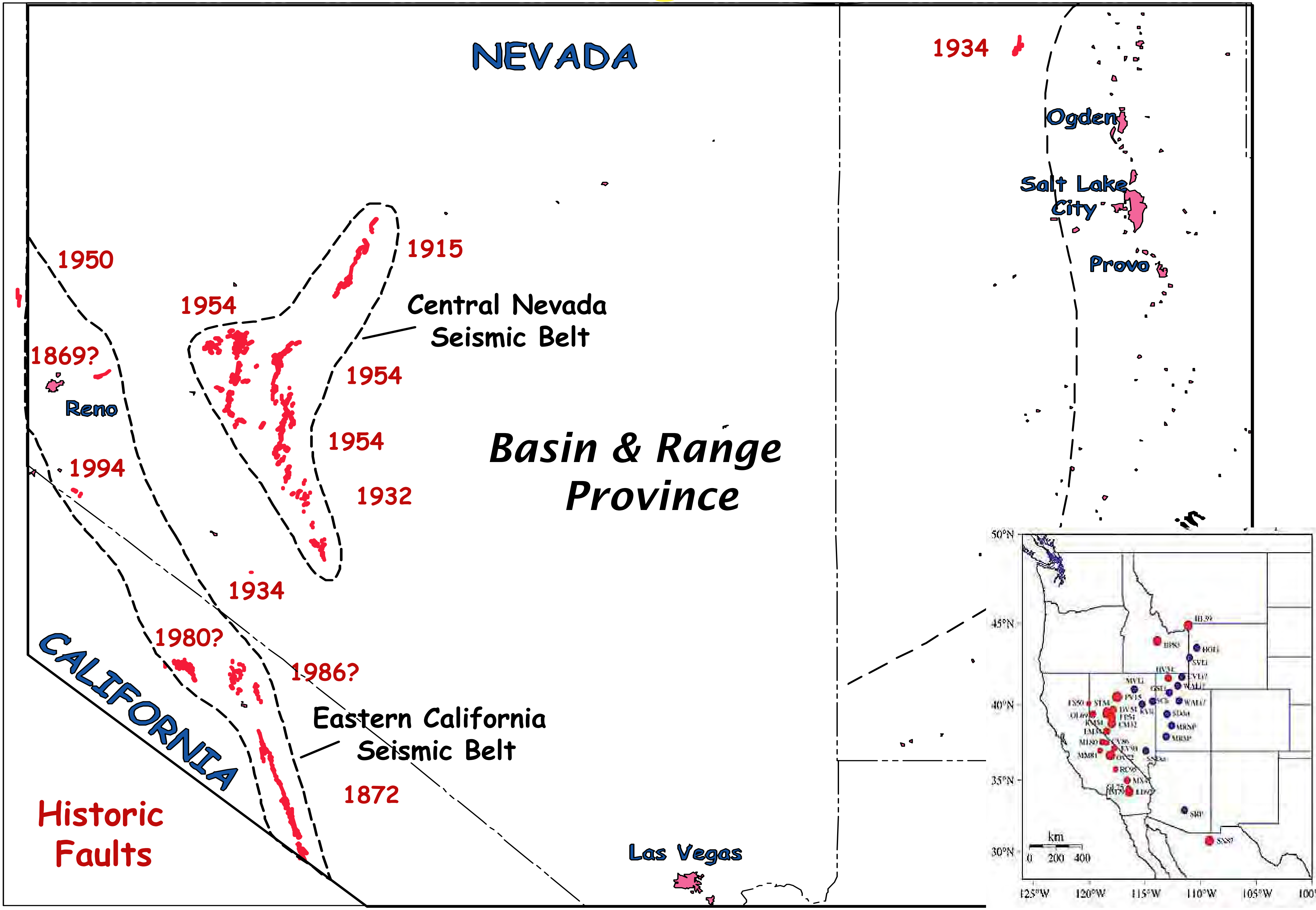


Figure 4.1. Illustration of a magnitude pdf (probability density function) for a WG99 fault containing a single rupture source. The characteristic rupture (which breaks the entire seismogenic area of the source) has a mean magnitude and a natural variability about that mean defined by +/- two standard 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.

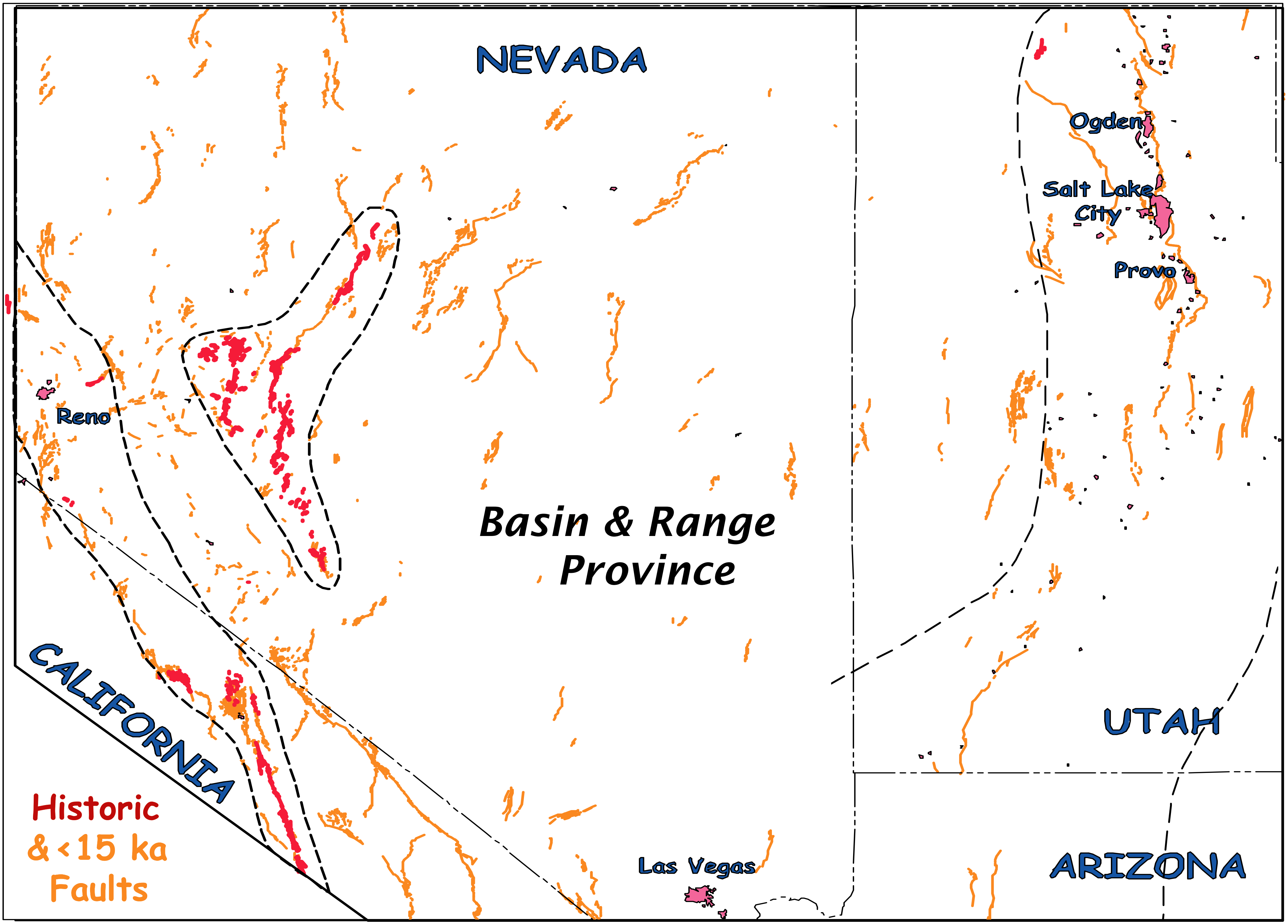


(Modified from R. Youngs, 1998)

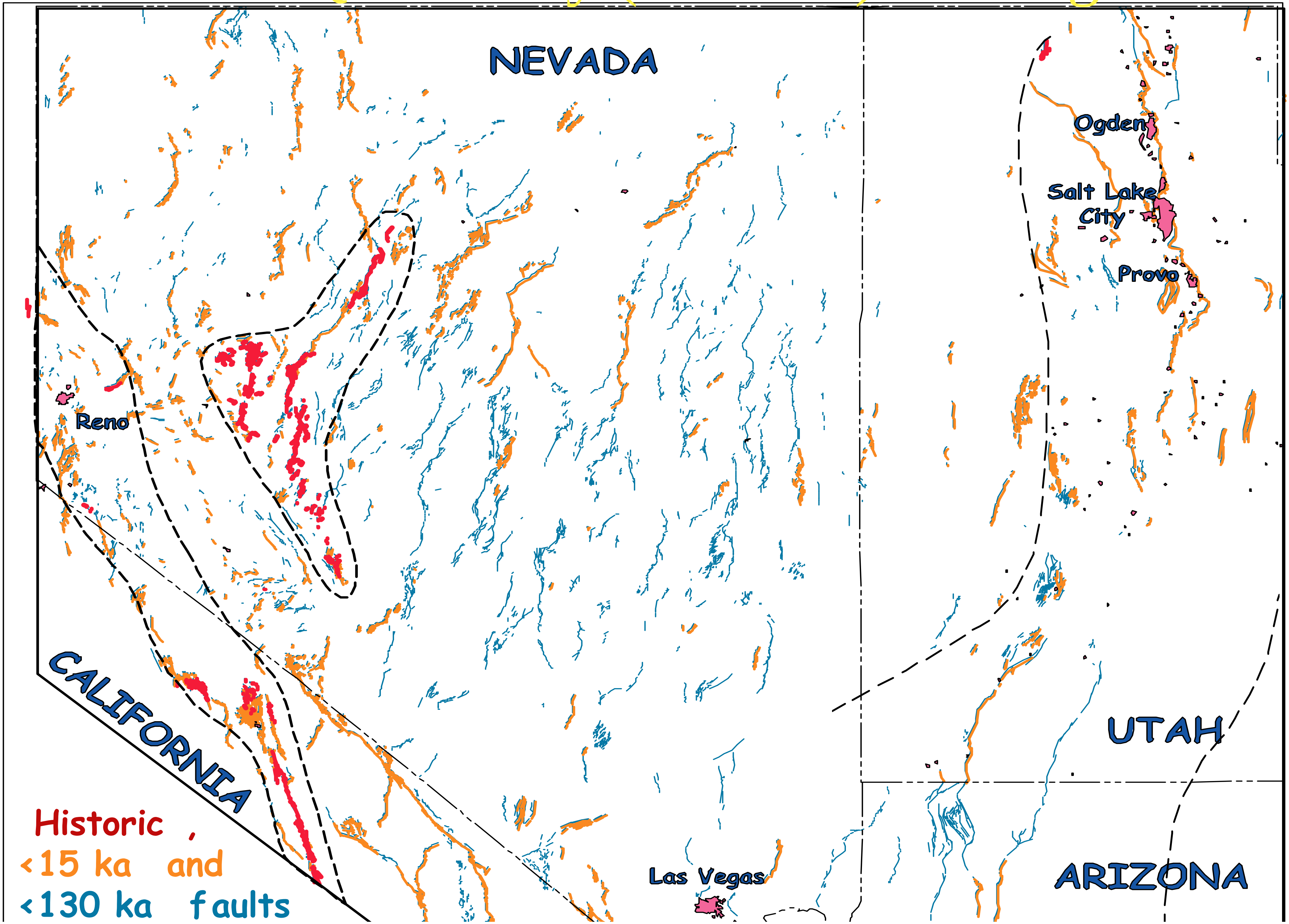
Historical faulting in Great Basin



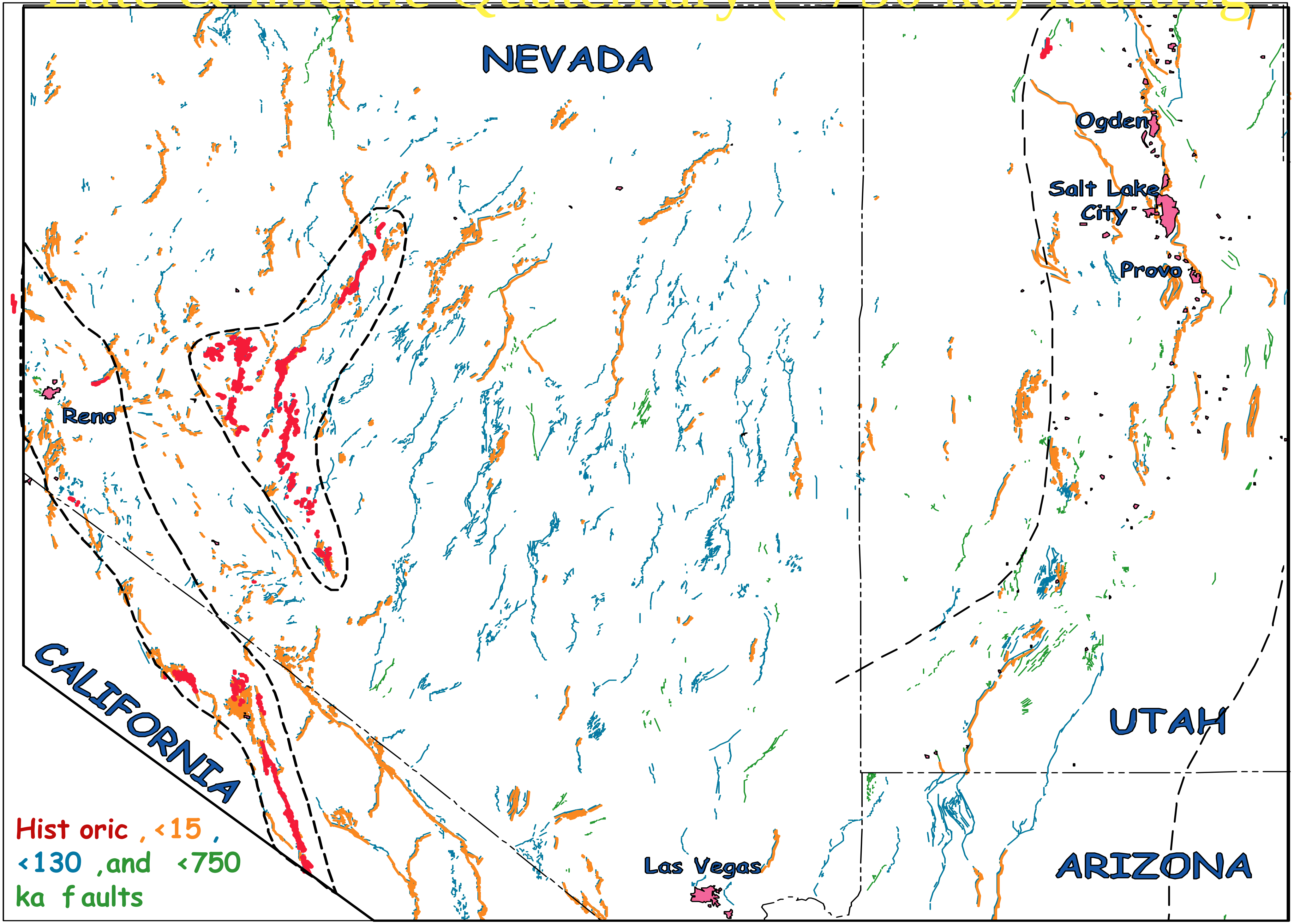
Latest Quaternary (<15 ka) faulting



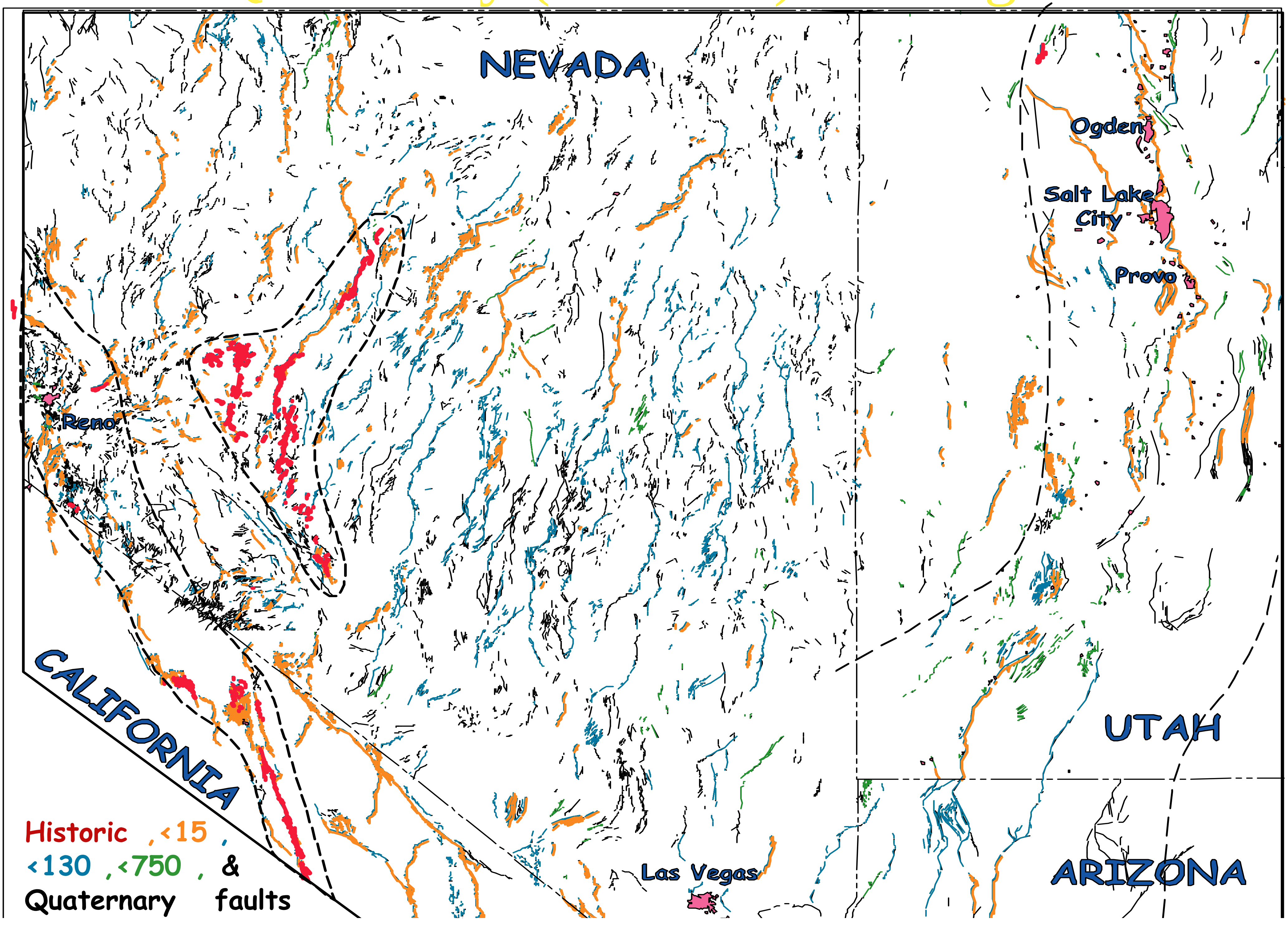
Late Quaternary (<130 ka) faulting



Late & middle Quaternary (<750 ka) faulting



Quaternary (<1.6 Ma) faulting



RECOMMENDATION #1

The use of the USGS' "floating exponential" model needs to be validated to the extent possible or at least made consistent with the paleoseismic and historical earthquake record in the Basin and Range Province. The model should also be compared with the traditional models used in state-of-the-practice PSHAs.

RECOMMENDATION #2

- The USGS should use the same recurrence models and weights for all Basin and Range faults unless there is a technical basis for deviating from this characterization.

RECOMMENDATION #3

- The weights assigned to the maximum magnitude and “floating exponential” models should be the same weights as those in California unless there is a technical basis for different weights.

RECOMMENDATION #4

- To avoid double-counting earthquakes in the range of M 6. 5 to the characteristic magnitude, zones surrounding Basin and Range Province faults should be removed from the areas included in the Gaussian smoothing of background seismicity.

RECOMMENDATION #5

- For the National Seismic Hazard Maps, the methodology must be fully transparent. The USGS should be urged to publish, if only as a short note, the methodology used for recurrence modeling, especially for fault-specific sources.

Probabilities of Magnitude and Surface Rupture Length from a Displacement Observation

Glenn Biasi[1] and Ray Weldon[2]

[1]University of Nevada Reno Seismological Laboratory, glenn@seismo.unr.edu

[2]University of Oregon, Eugene OR, ray@uoregon.edu

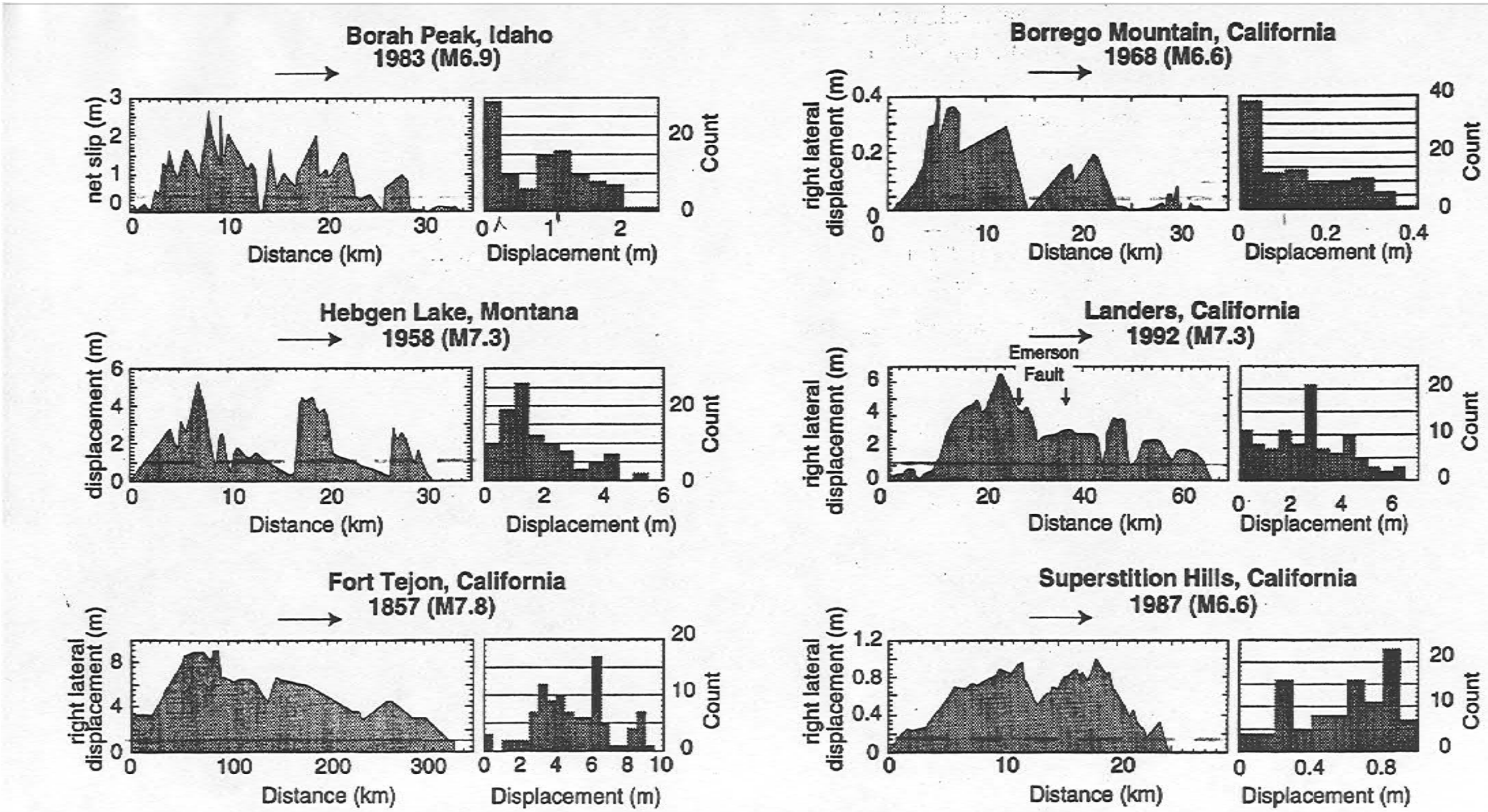
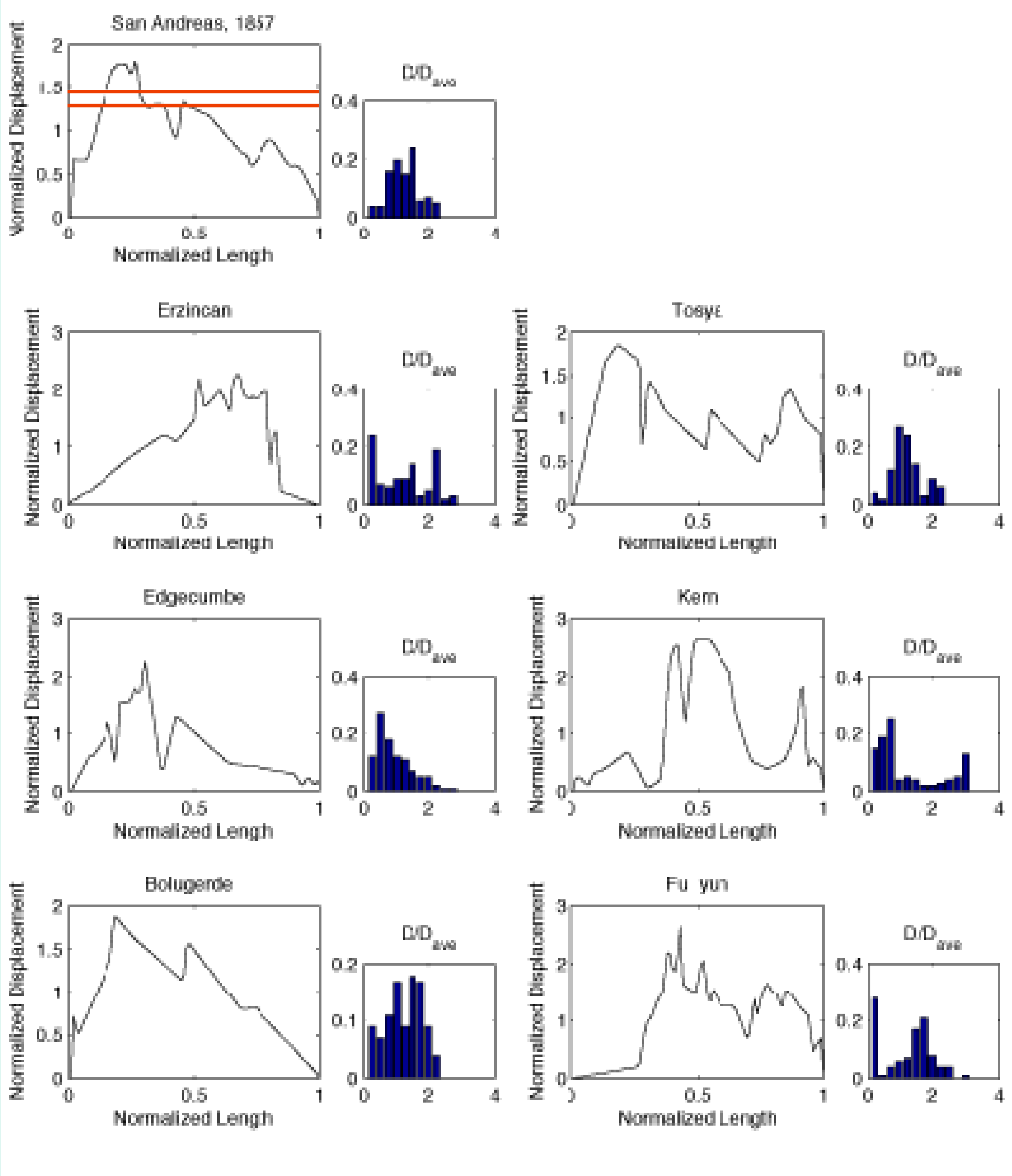


Figure 1. Example surface rupture profiles and histograms of displacements.

Histograms of displacement keep frequency of observations but discard the ordering. (from Hemphill-Haley and Weldon, 1999). Profiles are resampled at 1% intervals.

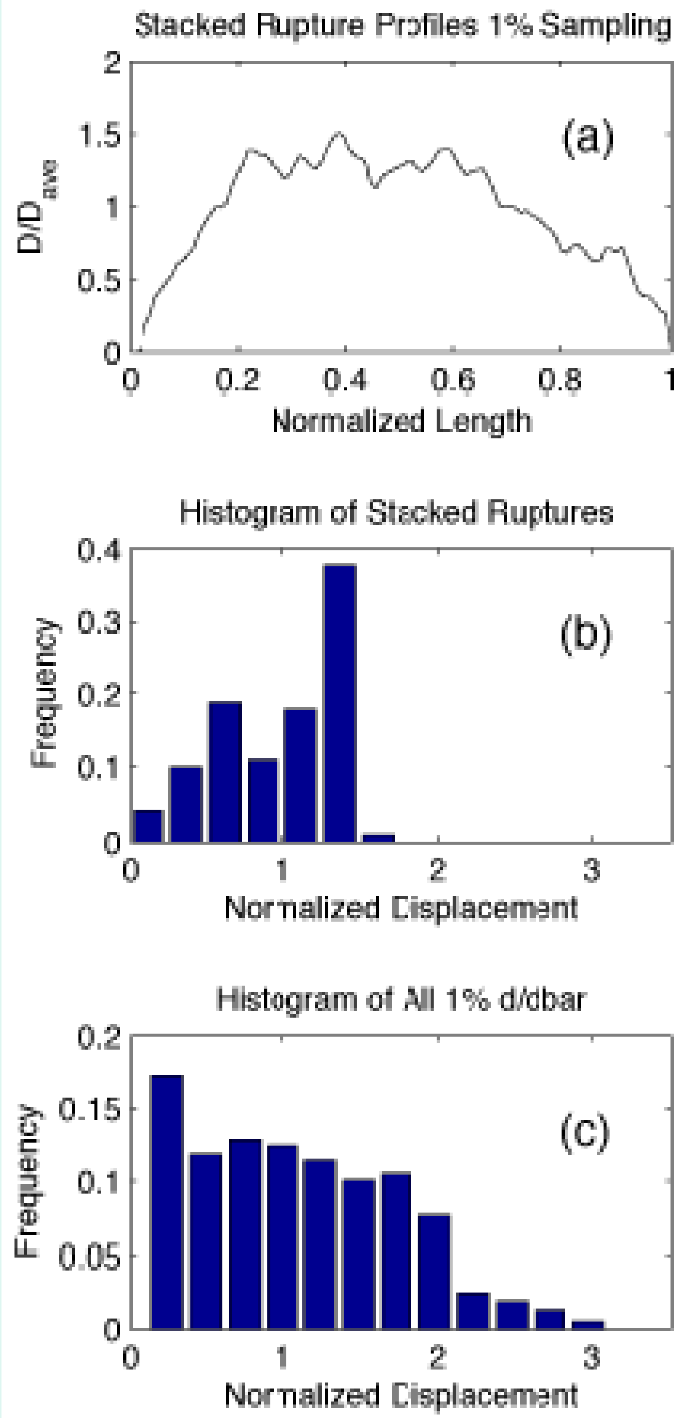


Normalize rupture profiles by length and mean displacement

Histograms become frequency of a given displacement compared to the average.

13 ruptures used here

- Averaging rupture profiles removes the variability.
- The combined histogram keeps extreme values, weighted by how often they occur.
  - E.g., $D/D_{ave} = 3$ is observed but only for a small fraction of total rupture length.
  - Interpret as a histogram of 1300 field displacement measurements cast in terms of D/D_{ave}.



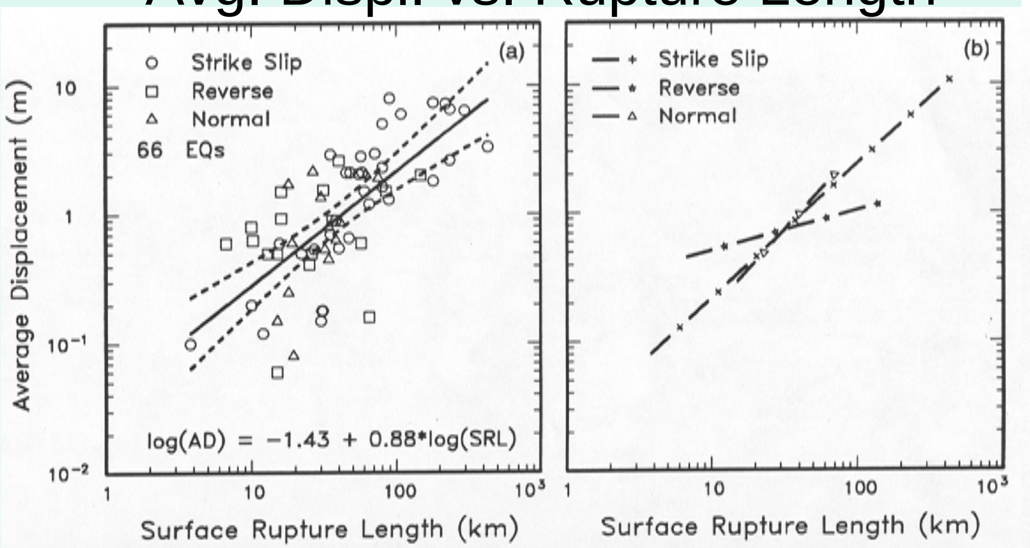
No

No

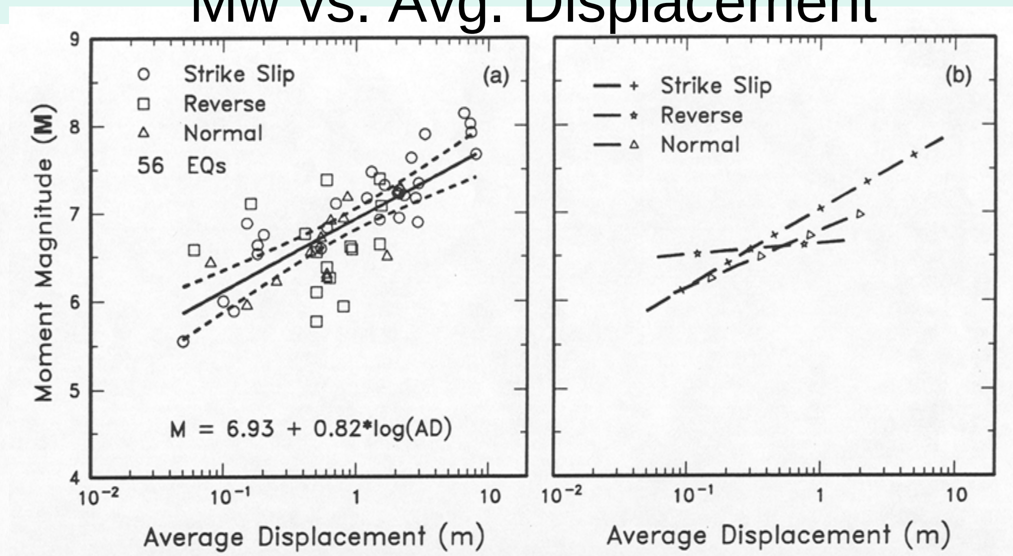
Yes

Magnitude, Length, and Average Displacement Regressions

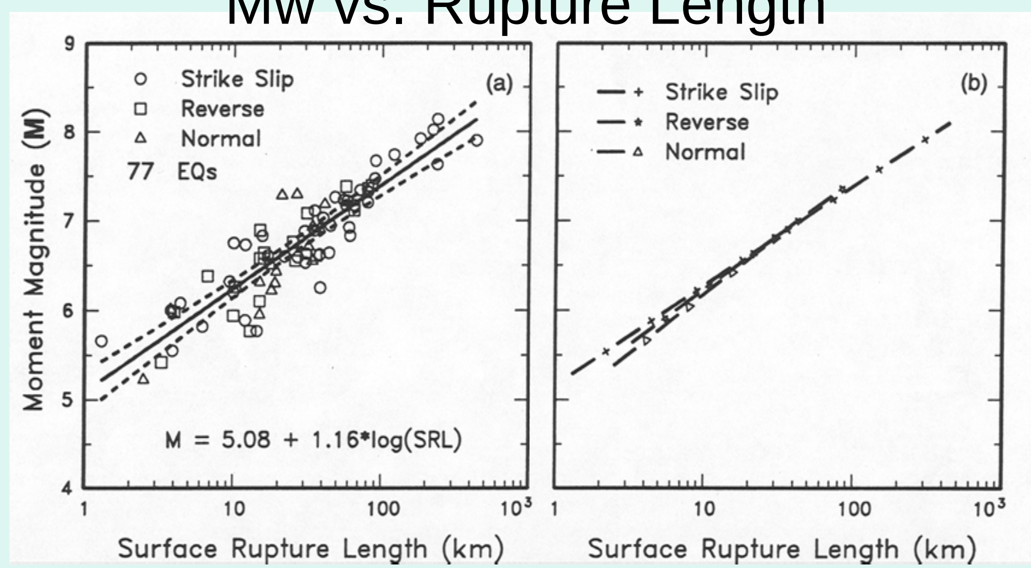
Avg. Displ. vs. Rupture Length



Mw vs. Avg. Displacement



Mw vs. Rupture Length



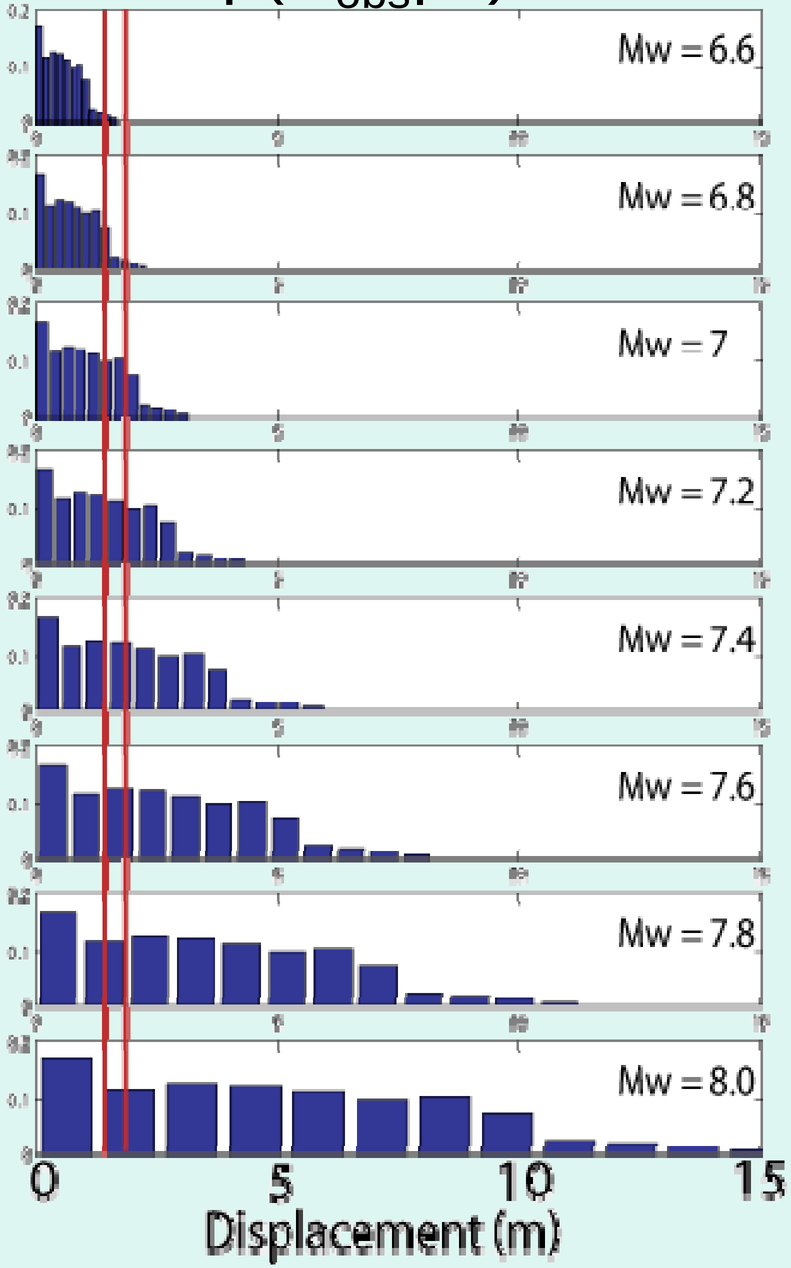
log(AD) = -1.43+0.88*log(SRL)

M = 6.93+0.82*log(AD)

M = 5.08+1.16*log(SRL)

- Scale variability with M<->AD relationship to get predicted displacement for a given magnitude: $p(D_{obs}|M)$
- Want the inverse: $p(M|D_{obs})$
- Red lines bound all the ways to get 2+-0.3 m observation. Fraction for each magnitude is $p(M|D_{obs}=2\text{ m})$. Sum over all magnitudes.

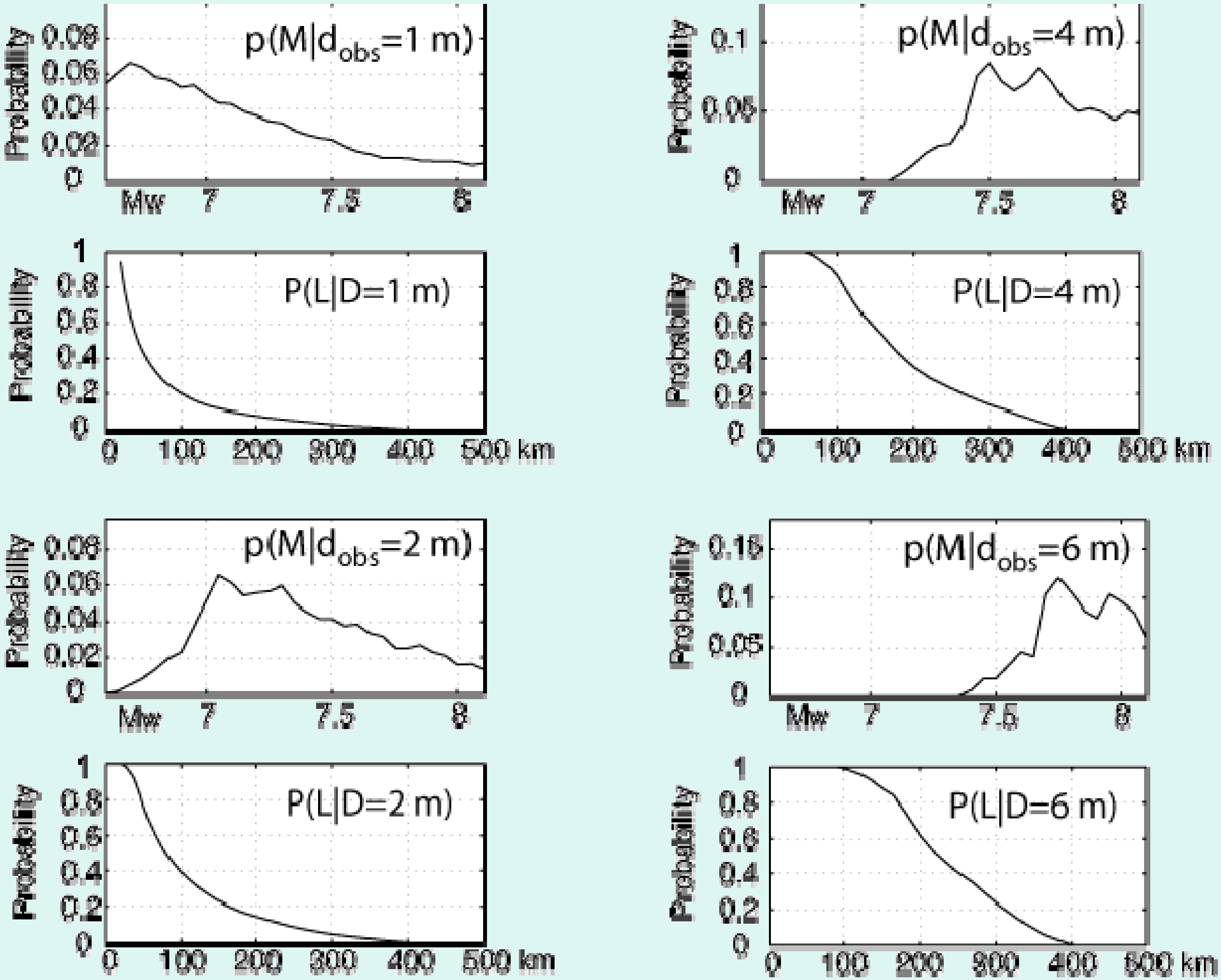
$p(D_{obs}|M)$



Bayesian inverse: $p(M|D_{obs})$ and $P(L|D_{obs})$

Inverse assuming any magnitude is as likely as any other within a range.

P(L|d) is the complimentary cumulative probability of p(M|d), rescaled by W&C M->L regression.

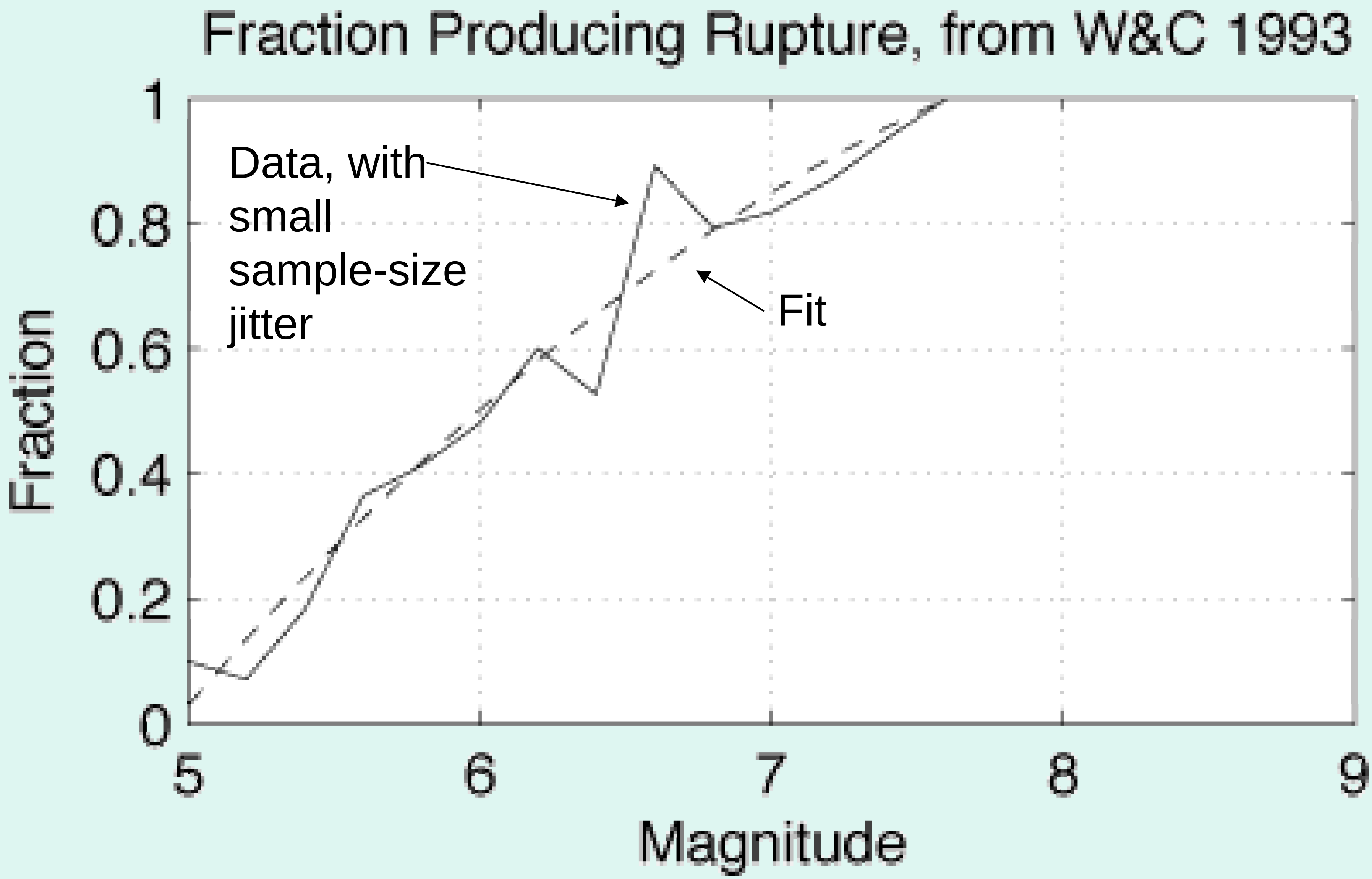


Bayesian inverse:

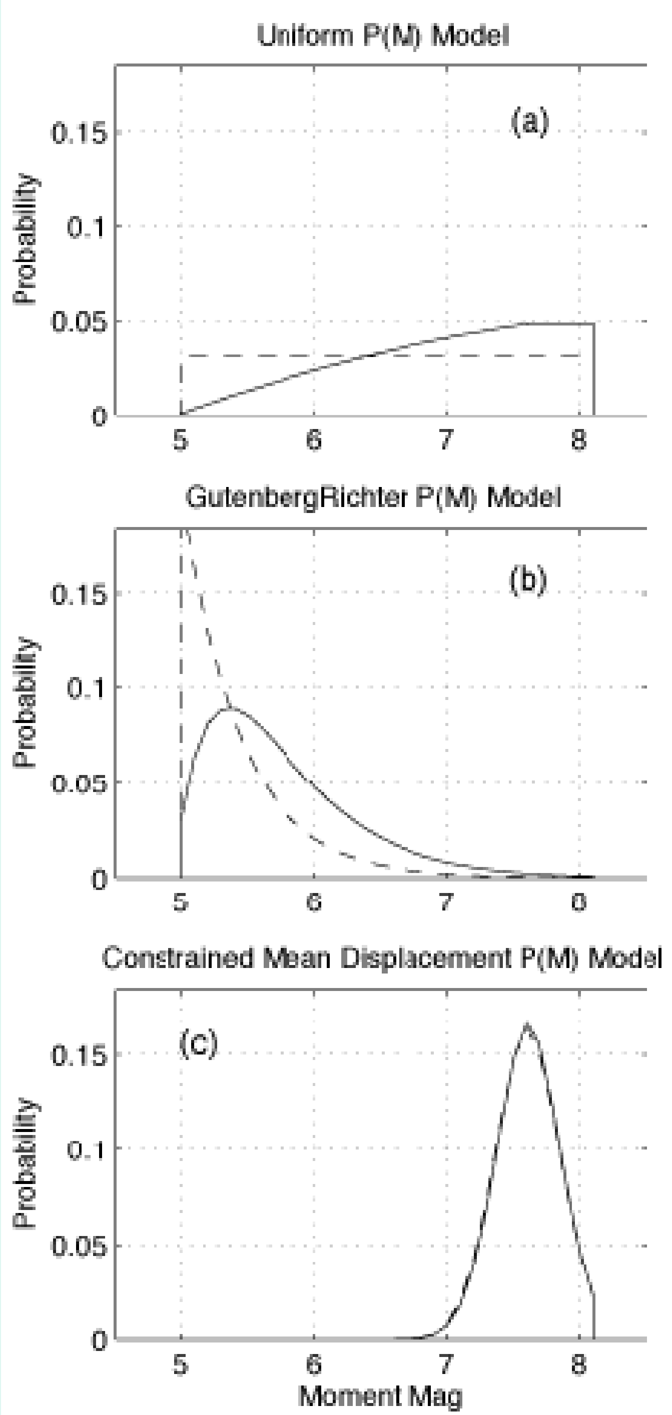
$P(M|D_{obs})$ = p(ground rupture|M)p(D_{obs}|M)p(M)/Constant

Magnitude-frequency model

Variability



Fraction Producing Rupture, from W&C 1993
Data, with small sample-size jitter
Fit
Fraction
Magnitude
1
0.8
0.6
0.4
0.2
0
5
6
7
8
9



Solid: p(ground rupture|M)*p(M)

Dashed: p(M)

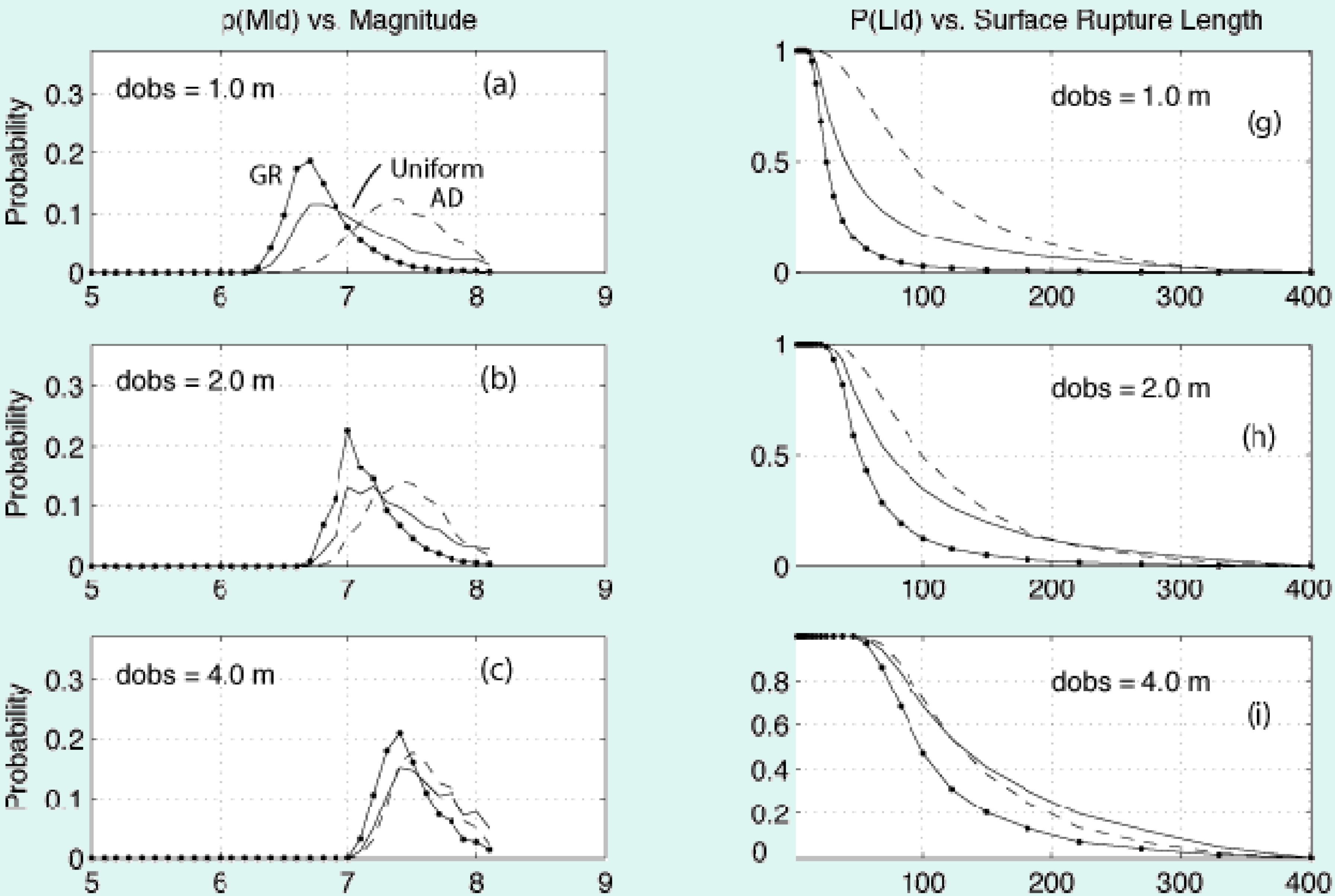
Uniform: equally likely on an interval

GR: exponential increase in frequency with decreasing M

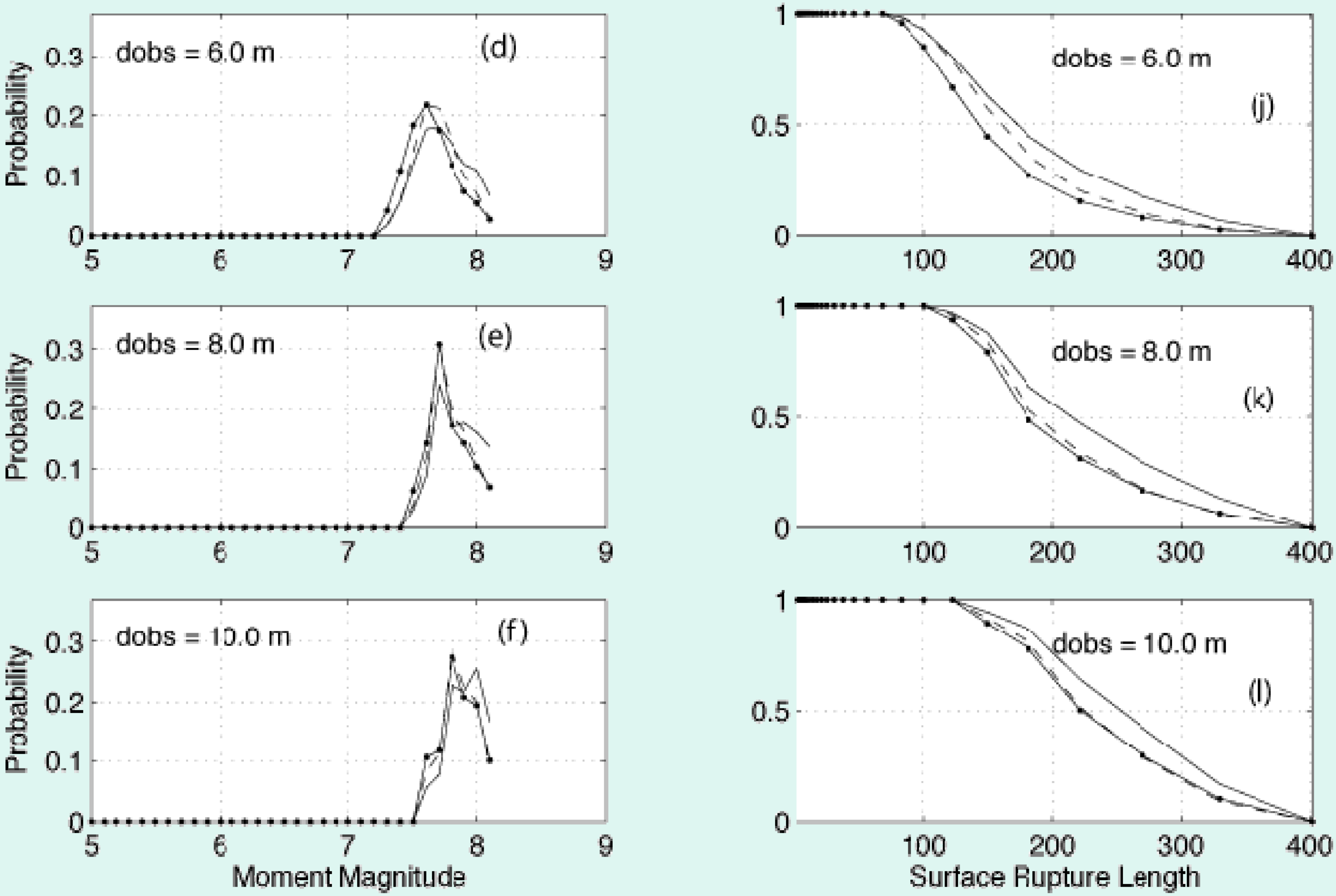
Constrained Mean: Accepts paleoseismic event count and total slip.

-- Model: 10 SAF earthquakes since 650 AD, ~44 meters, 4.4 m avg -> mid M 7

-- Event count and total displacement needed



p(M|d) vs. Magnitude
P(L|d) vs. Surface Rupture Length
Probability
dobs = 1.0 m
(a)
GR
Uniform
AD
dobs = 2.0 m
(b)
dobs = 4.0 m
(c)
(g)
(h)
(i)


dobs = 6.0 m
(d)
dobs = 8.0 m
(e)
dobs = 10.0 m
(f)
Probability
Moment Magnitude
dobs = 6.0 m
(j)
dobs = 8.0 m
(k)
dobs = 10.0 m
(l)
Surface Rupture Length

Method Reviewed

- Assume field observations can be combined after normalizing by average displacement (i.e., use all field experience)
- Scale D/Dave by magnitude using an AD vs. M regression
- Sample rupture at random location.
- Ask how likely it would be to find the displacement measurement as a function of magnitude, $p(M|d_{obs})$
- Choice of p(M) may matter.

Remaining Questions

- Ruptures of all types were used. What is the effect of using only normal fault ruptures?
- How sensitive are results to the M-AD and M-L regressions?
- What if the sample is not randomly located?

Fault Rupture Parameter Considerations with Respect to Magnitude - Recommendations

Two timeframes -

Short term - 2007 map

Long term - research/development goals

Biasi and Hemphill-Haley

Short-term, Estimating Displacement and Length:

- Include uncertainty in length and its consequences for magnitude.
- We recommend constraining the minimum magnitude assigned to ground-rupturing earthquakes to M 6.5 to be consistent with with the hazard set by background seismicity.

Short term (cont'd)

- Magnitude-displacement regressions may be used to improve magnitude estimates where the magnitude from fault-length appears inconsistent.

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

Long-term Research and Development Recommendations

<u>Regressions</u>

- Revisit the Wells and Coppersmith (1994) regressions to update the database and evaluate the need to censor short rupture lengths and small magnitudes.

- Develop a Mw vs. Surface Rupture Length*Displacement scaling as a tool for improving use of displacement.

Long-term (cont’d)

- Develop multi-variate regression for M given Length and Displacement, to improve M estimates on faults for which both are available.

- Invest in determining whether regional regressions materially improve ground motion predictions

Long-term (cont'd)

- For long strike-slip faults (western B&R) - consider using Hanks and Bakun (2002) Mw vs. Area regression relation.

- Short faults – consider whether Wells and Coppersmith (1994) is appropriate considering the results of Stirling et al. (2002)?

- Evaluate whether an estimate of M based on Area (with an assumed Width) is more appropriate than M based on Length.

Long-term (cont'd)

Displacement

- There should be a concerted effort to assess the variability of displacement along rupture strike for historic surface ruptures for the entire range of M and whether the data support a division a to Basin and Range subset.

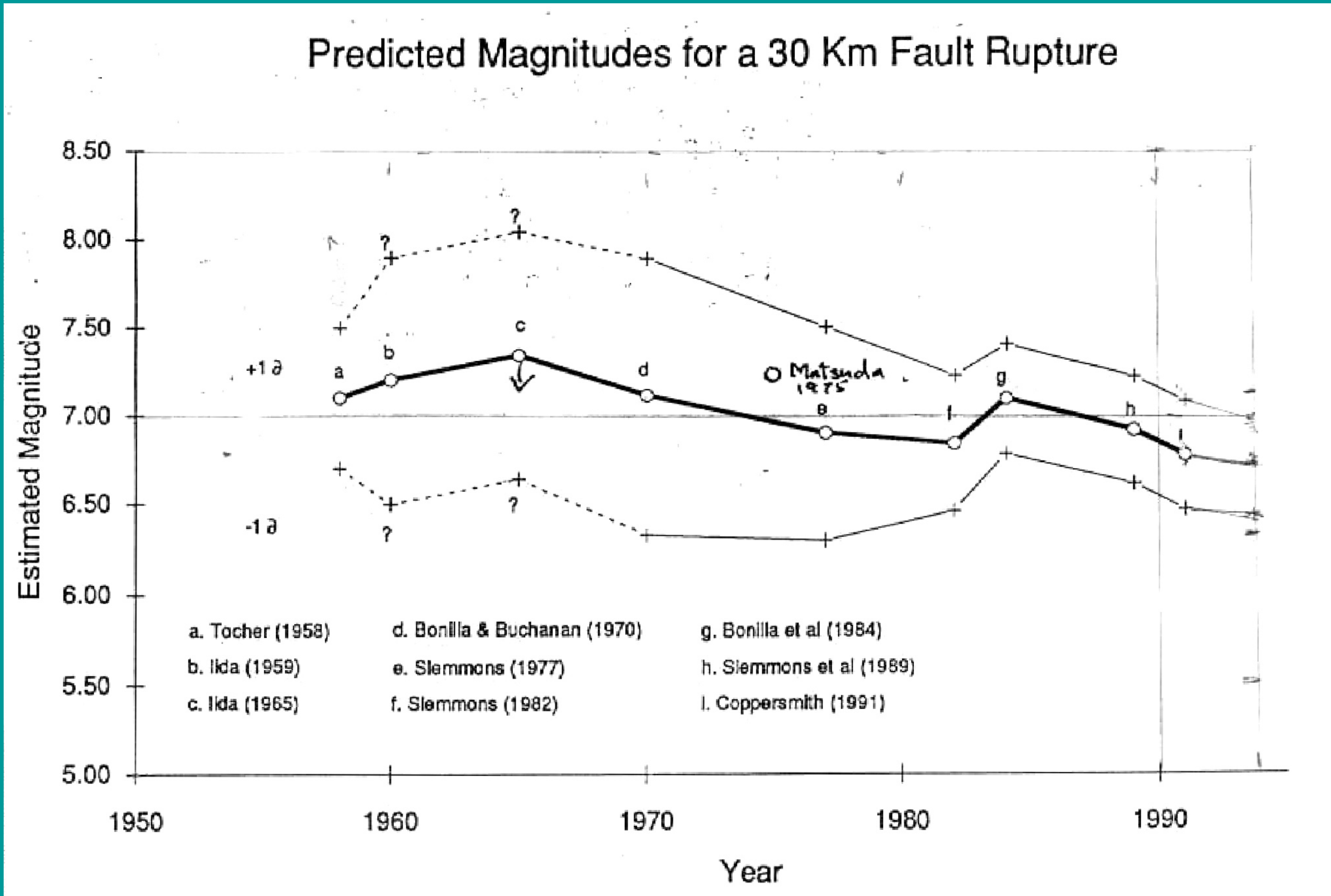
Burt Slemmons

BRPEWG Meeting

March 8-10,2006

Table 1 Linear regressions of magnitude, M, and surface rupture length for all fau
- A + B log L for rupture lengths in km, except * for length in m.

NO.	REFERENCE	REGION	EVENTS	A	B	M FOR 20 KM	M FOR 30 KM	STD DEV
1	Tocher, (1958)	W. U.S.	10	5.65	0.98	6.93	7.10	0.7
2	Iida (1959)	Worldwide	34	6.27	0.63	7.09	7.20	—
3	Iida (1965)	Worldwide	54	6.02	0.76	7.01	7.34	—
4	Bonilla and Buchanan (1970)	Worldwide	53	3.76*	0.76*	7.02	7.11	0.78
5	Slemmons (1977)	Worldwide	75	1.61*	1.18*	6.69	6.90	0.60
6	Slemmons (1982)	Worldwide	56	2.06*	1.07*	6.66	6.84	0.30
7	Bonilla and others (1984)	Worldwide	45	6.04	0.71	6.96	7.09	0.31
8	Slemmons and others (1989)	Worldwide	48	5.39	1.03	6.73	6.91	0.30
9	Coppersmith (1991)	Worldwide	60	5.00	1.20	6.56	6.77	0.30
10	Wells and Coppersmith (1994)	Worldwide	68	5.03	1.19	6.57	6.78	0.28

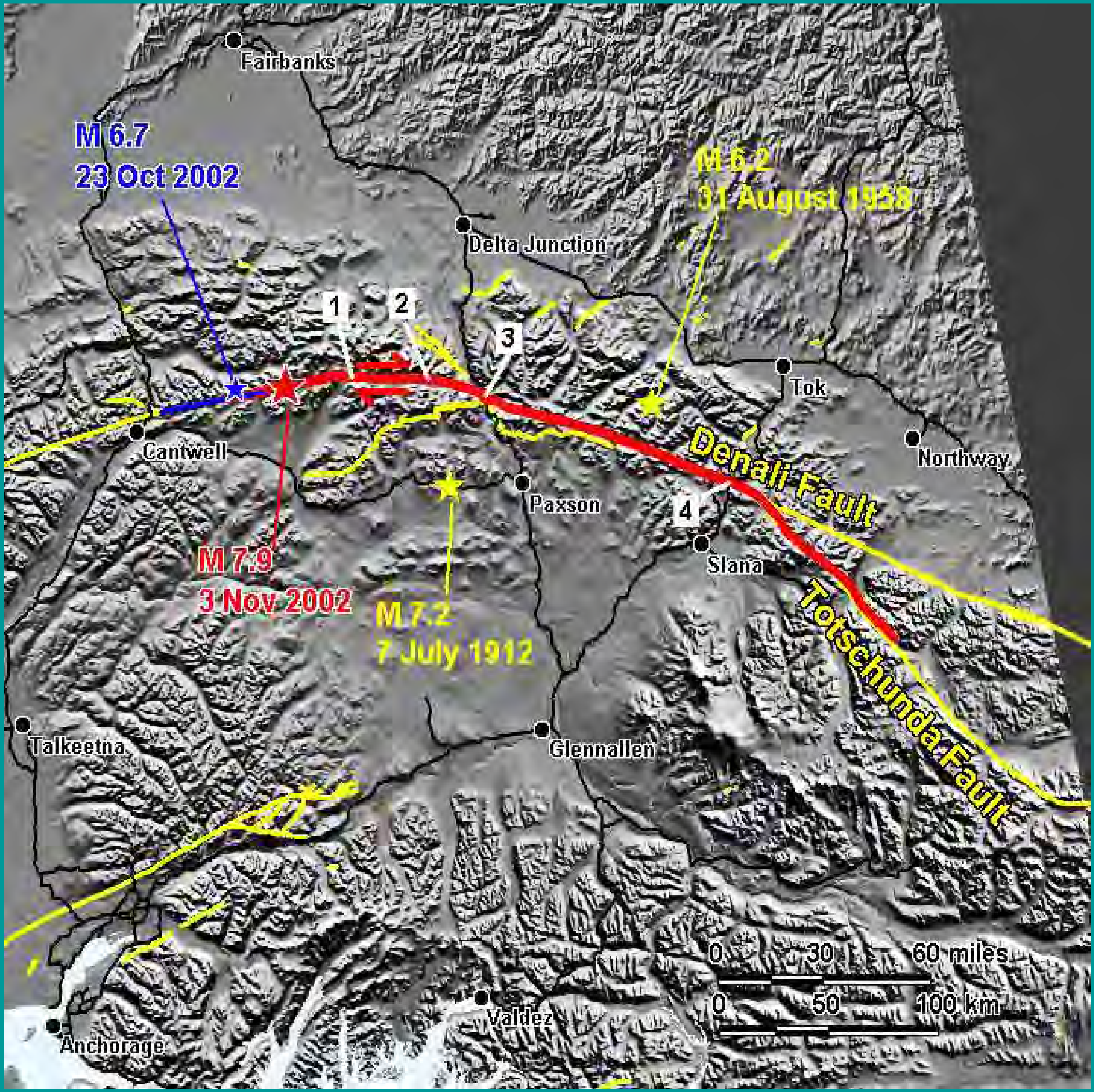

Predicted Magnitudes for a 30 Km Fault Rupture
Estimated Magnitude
8.50
8.00
7.50
7.00
6.50
6.00
5.50
5.00
1950
1960
1970
1980
1990
Year
+1 ∂
-1 ∂
O Matsuda 1975
a. Tocher (1958)
b. Iida (1959)
c. Iida (1965)
d. Bonilla & Buchanan (1970)
e. Slemmons (1977)
f. Slemmons (1982)
g. Bonilla et al (1984)
h. Slemmons et al (1989)
i. Coppersmith (1991)

Earthquake Location:

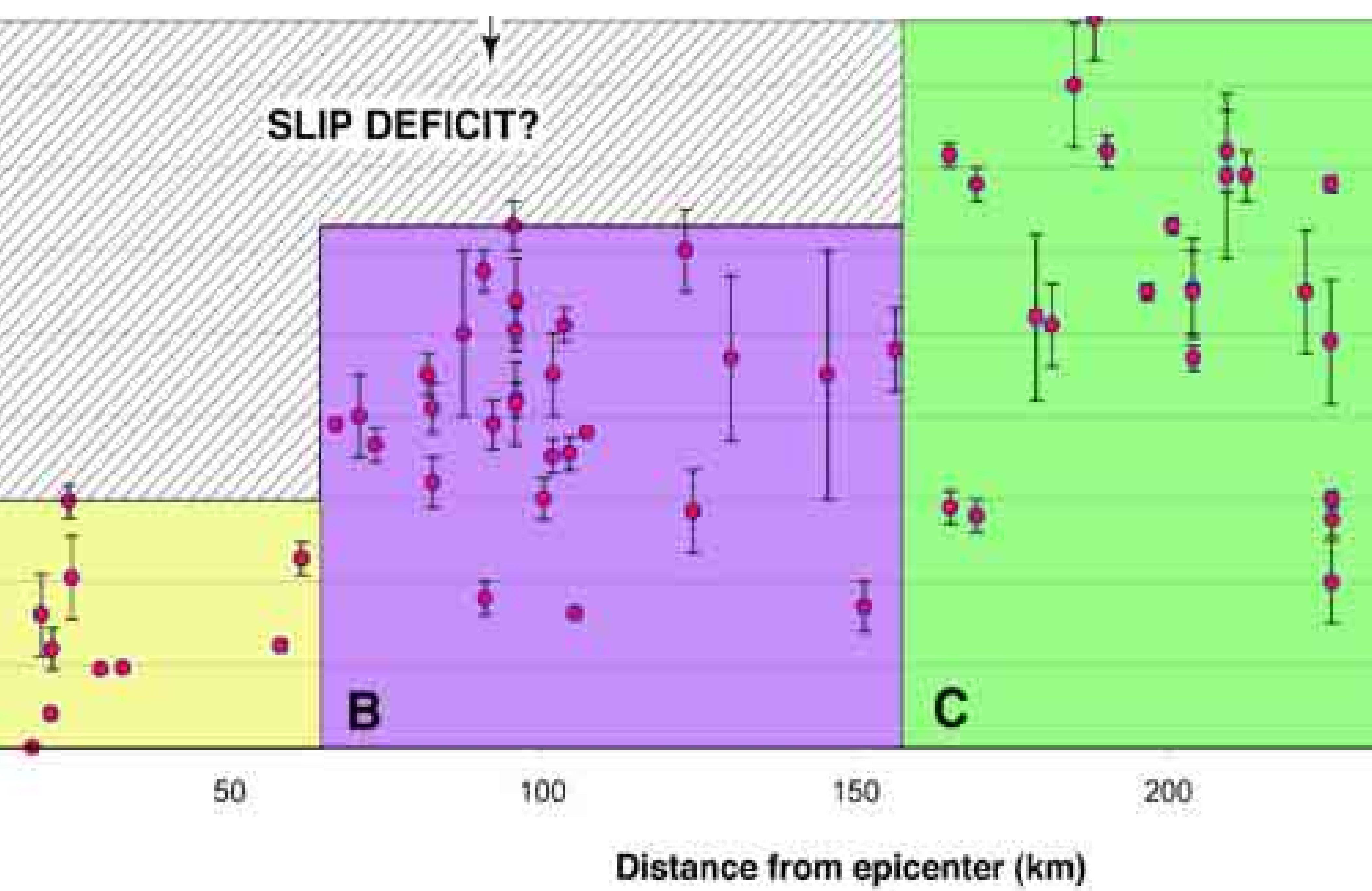
Denali Fault Alaska

Magnitude 7.9 11/3/2002

Rupture Length 354 km



Alaska DGGS Website



SLIP DEFICIT?
B
C
50
100
150
200
Distance from epicenter (km)

TAPS
Pipeline

View to North

Sleepers are 60 ft Apart

Denali Fault Crossing

And

Richardson Highway

Bucky Tart

Denali fault-crossing design parameters

Horizontal, 20 feet
Vertical, 5 feet

Most likely location

Right slip will cause pipeline to experience axial compression

November 3, 2002 rupture

- *Horizontal, 19 feet*
- *Vertical, 3.5 feet*
- *Axial compression, 11 feet*

Pipeline performed as designed, without spilling one drop of oil

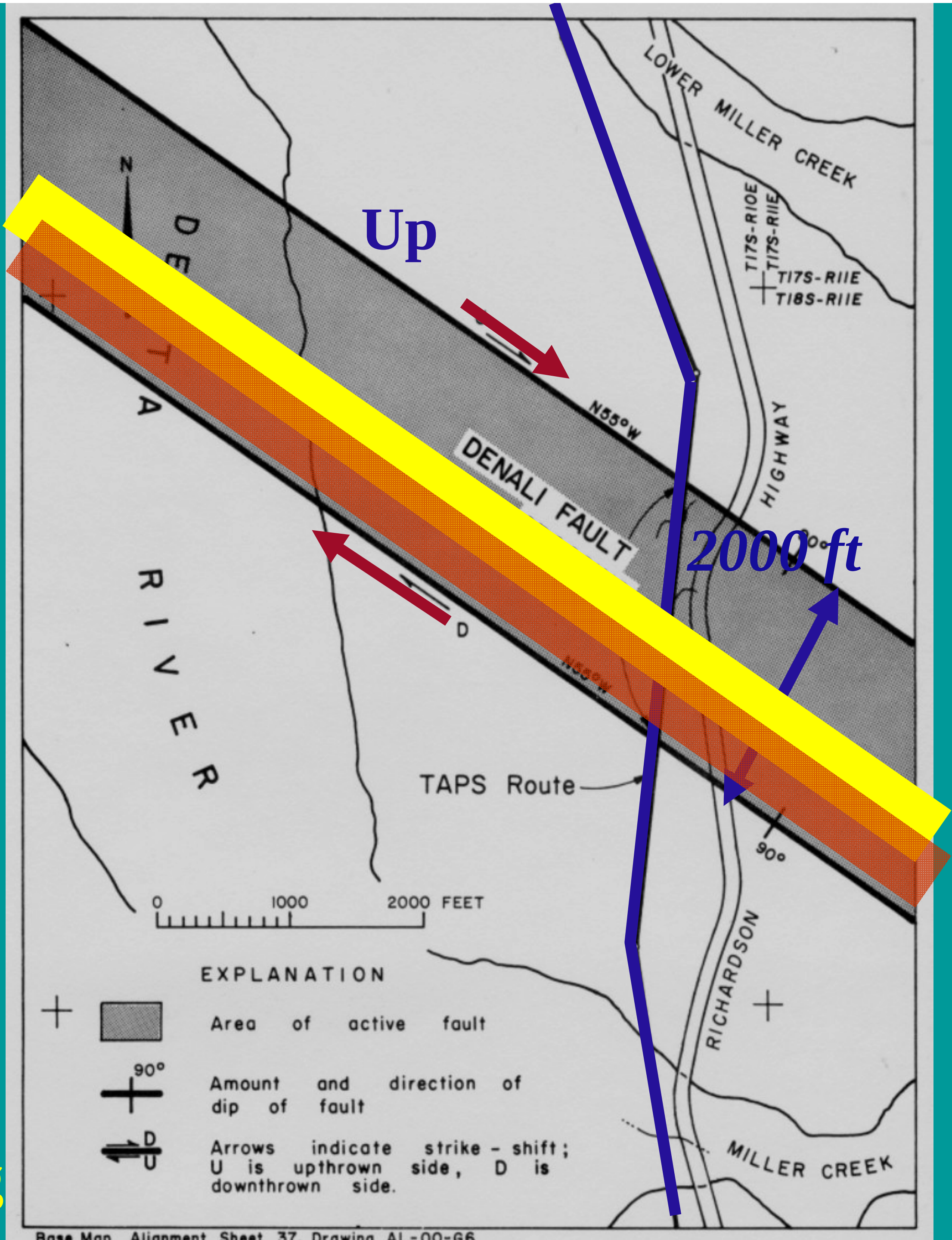
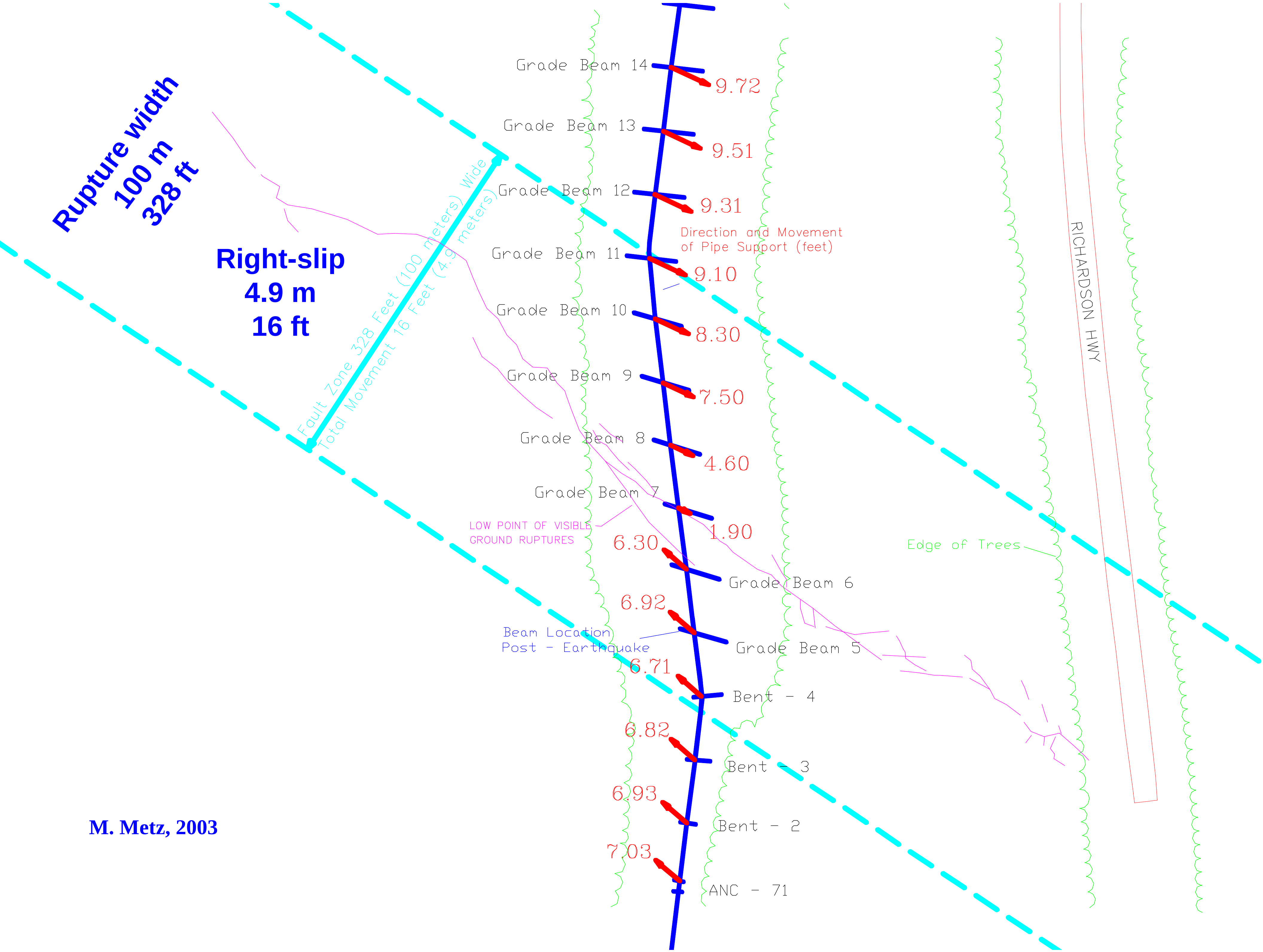
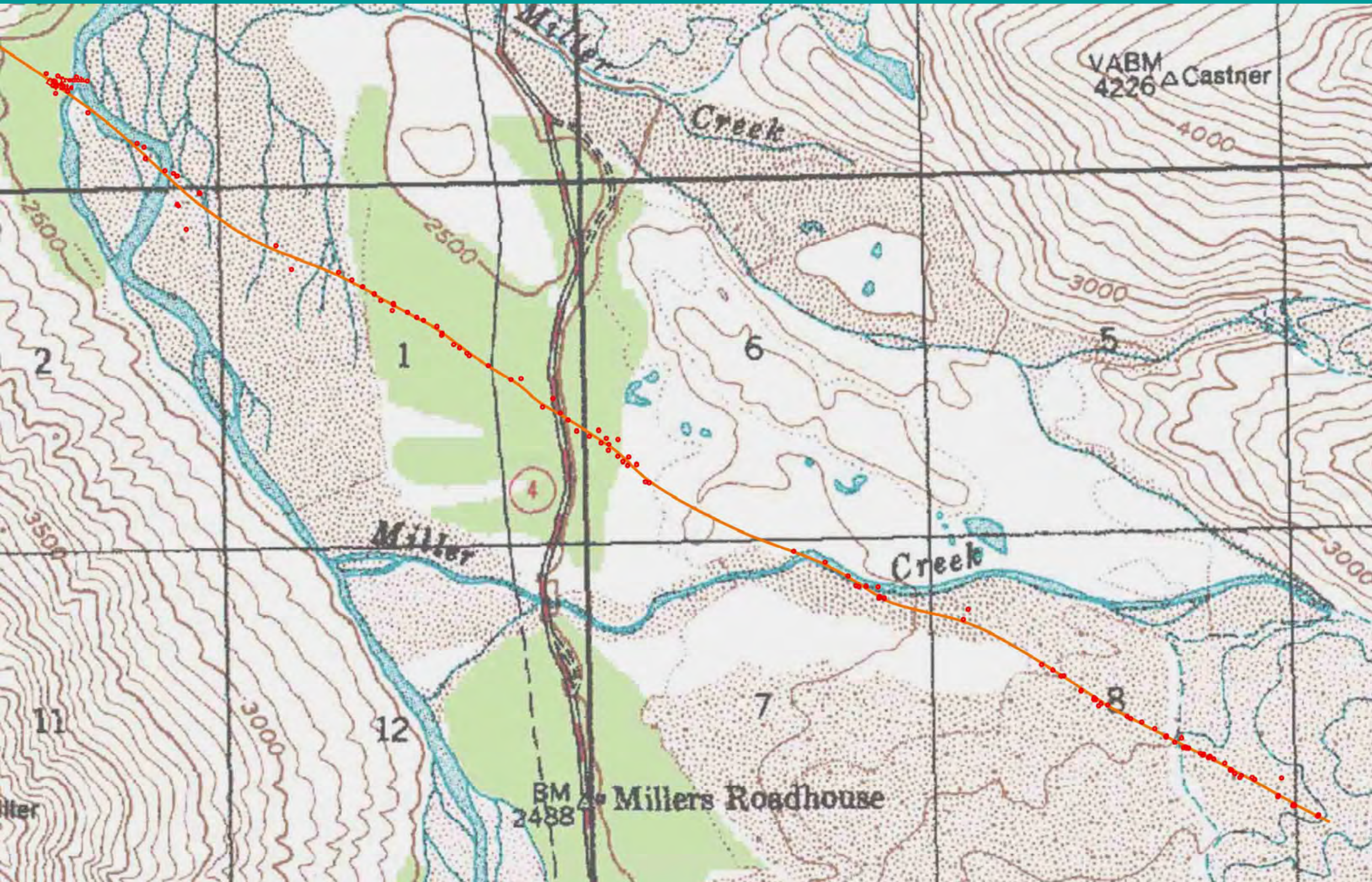


Figure 48. Map showing the location of the Denali fault crossing along the TAPS route.



Rupture width
100 m
328 ft
Right-slip
4.9 m
16 ft
Fault Zone 328 Feet (100 meters) Wide
Total Movement 16 Feet (4.9 meters)
Grade Beam 14
9.72
Grade Beam 13
9.51
Grade Beam 12
9.31
Direction and Movement
of Pipe Support (feet)
Grade Beam 11
9.10
Grade Beam 10
8.30
Grade Beam 9
7.50
Grade Beam 8
4.60
Grade Beam 7
1.90
LOW POINT OF VISIBLE
GROUND RUPTURES
6.30
Grade Beam 6
6.92
Beam Location
Post - Earthquake
Grade Beam 5
6.71
Bent - 4
6.82
Bent - 3
6.93
Bent - 2
7.03
ANC - 71
Edge of Trees
RICHARDSON HWY
M. Metz, 2003



Miller
Creek
VABM
4226
Castner
4000
2500
2500
3000
6
5
2
1
4
3500
Miller
Creek
3000
7
8
11
3000
12
BM
2488
Millers Roadhouse

- Denali fault zone well defined by paleoseismic methods.
- The mean Denali fault zone width was estimated in 1974 from 75 locations having widths of ~8 m (~25 ft) to ~178 m (~580 ft).
- Deformation from the November 3, 2002 EQ at TAPS was in a zone ~200 m wide with most slip was in a zone less than 18 m (~61 ft) wide.
- 2002 rupture combined subordinate brittle failure with plastic deformation in outwash and moraine deposits.
- Slip rate estimates reported in 1974 report were 0.5 to 3.5 cm/yr), and our new studies give ~1.0 to 1-1/2 cm/yr.
- Recurrence Interval from a Delta River pit ~346 to 416 yrs.
- GPS locations provide a much improved rupture path, and aid in discriminating between the ratios between fault rupture and distortion.
- The GPA data at 60 foot intervals along the pipeline gives an unusually good picture of the style and amount of deformation, and may be useful for interpreting many Walker Lane strike-slip faults.

Average Displacement Estimation in “Integrated Hazard Analysis of the Wasatch Front, Utah”

Chang and Smith

BSSA 92, 1904-1922

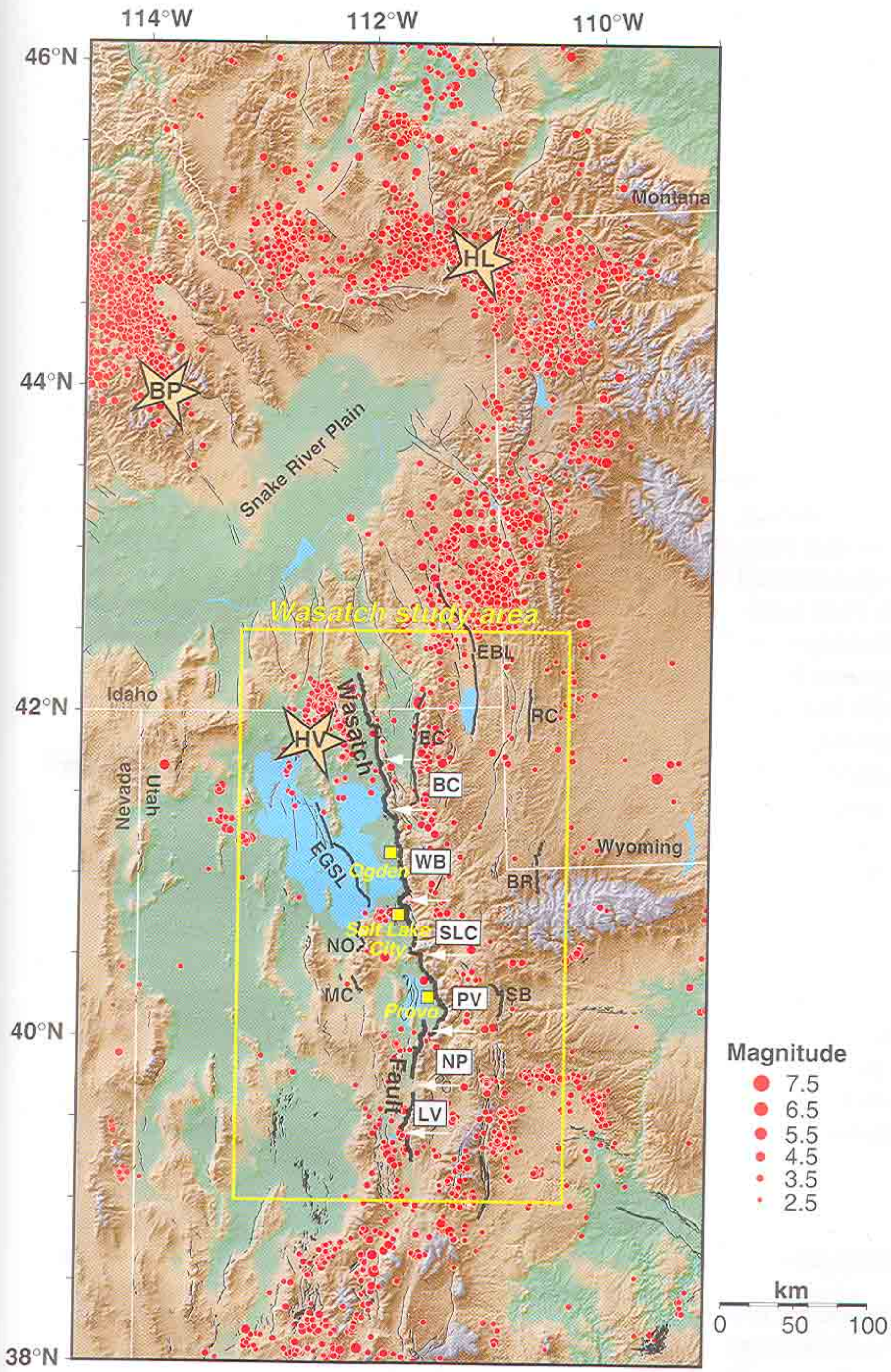


Figure 1. Earthquakes of the central and southern ISB (1962–1996). Three historical surface-faulting earthquakes are shown: HV, M_s 6.6, 1934 Hansel Valley, Utah; HL, M_s 7.5, 1959 Hebgen Lake, Montana; BP, M_s 7.3, 1983 Borah Peak, Idaho. Yellow rectangles indicate cities in the Wasatch Front, Utah, study area (yellow box). Thin, black lines mark late-Quaternary faults, and thick, black lines highlight those studied in this article. The six Holocene-active segments of the Wasatch fault are: BC, Brigham City; WB, Weber; SLC, Salt Lake City; PV, Provo; NP, Nephi; and LV, Levan; other studied faults are (from north to south): EBL, East Bear Lake Fault; RC, Rock Creek Fault; HV, Hansel Valley Fault; EC, East Cache Fault; EGSL, East Great Salt Lake Fault; BR, Bear River Fault; NO, North Oquirrh Fault; MC, Mercur fault; and SB, Strawberry Fault. Earthquake data from compilations of the University of Utah Seismograph Stations for the southern intermountain region and the Idaho National Engineering and Environmental Laboratory by URS Griener Consultants for the central and northern intermountain region (Wong, personnel communication, 1999).

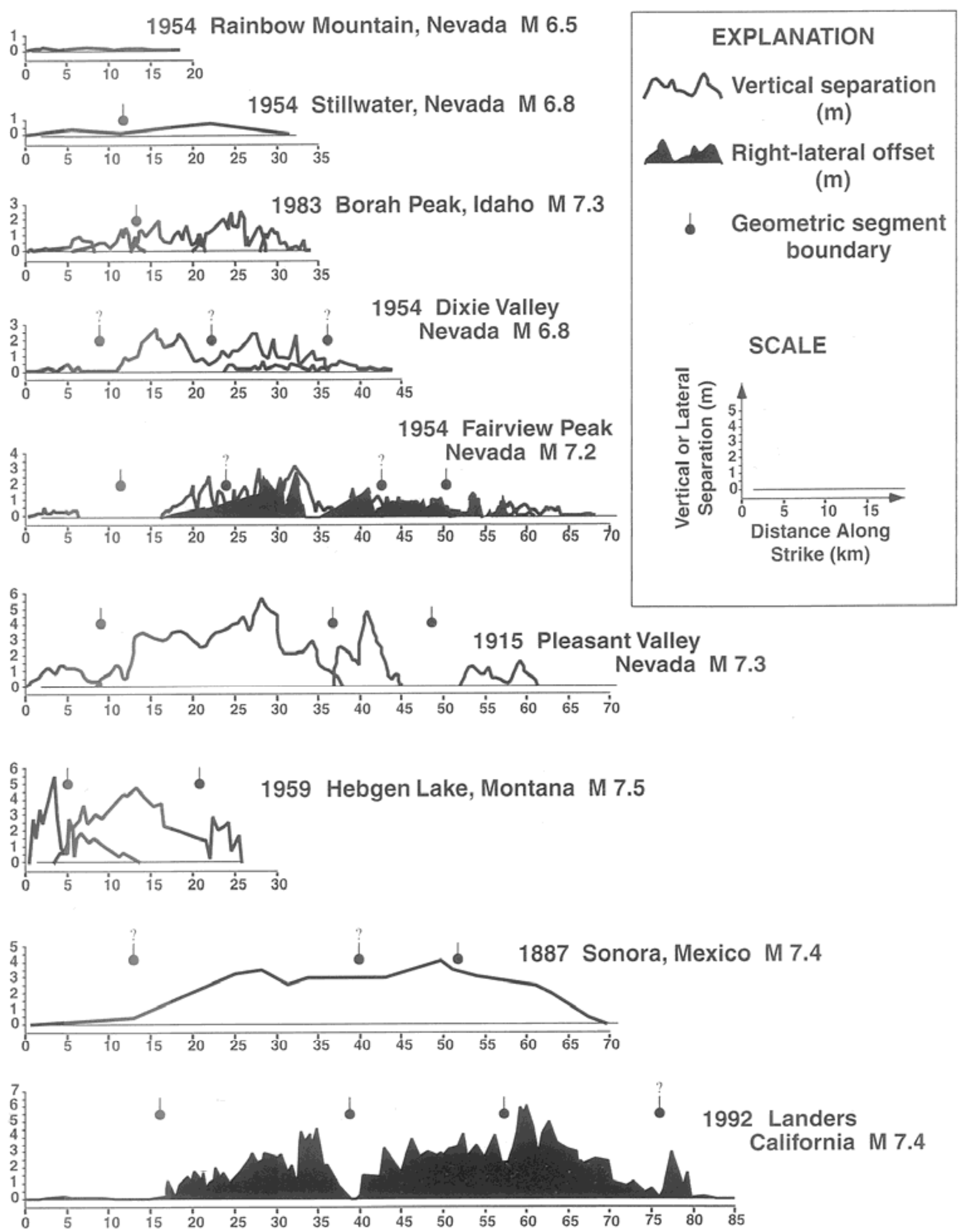


Figure 4. Along-strike fault displacements and segments of scarp-forming Basin–Range earthquakes (taken from Pezzopane and Dawson, 1996). Note that essentially all of these earthquakes experienced multisegment ruptures (except for the 1954 Rainbow Mountain, Nevada, earthquake). The observations corroborate the use of an elliptical distribution as a first-order approximation for the along-strike fault displacement.

Basin and Range rupture profiles are modeled as semi-ellipses.

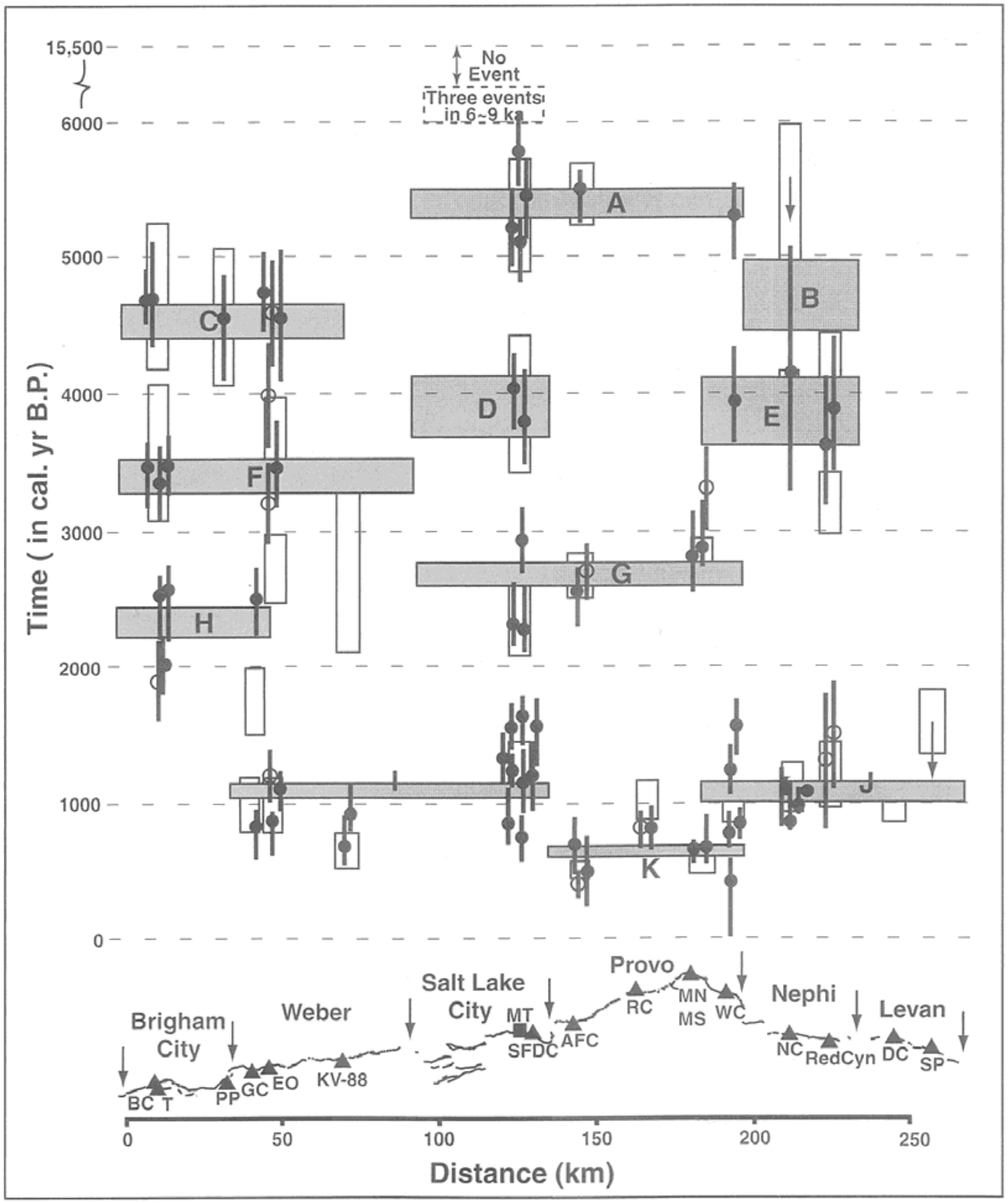


Figure 5. Space–time distribution of multisegment paleoearthquakes on the Wasatch Fault assumed by this study. There are as many as eight dual-segment ruptures (events A, C, E, F, G, H, I, J). Trench sites listed in Table 1 are shown by triangles. Black bars represent numerical ages from McCalpin and Nishenko (1996), with averages shown by dots (C^{14} dating) and circles (thermoluminescence dating). Hollow boxes represent paleoearthquakes determined from trenching (see Table 1). Each lettered gray box indicates a multisegment rupture. Notice that a newly excavated megatrench (MT, shown by a square; McCalpin and Nelson, 2001) on the Salt Lake City segment revealed a 6–7-ka period of tectonic quiescence between 9 and 15.5 ka ago (dashed box).

Event dates are available at 15 paleoseismic sites.

Dates among several events overlap in time, allowing multi-segment ruptures to be considered.

Average Displacement Estimation Strategy

- Assume segment boundaries as the rupture length (L).
- Estimate height of ellipse based on displacement from trenching. Least-squares fit with multiple displacement estimates.
- Calculate average displacement from ellipse (D).

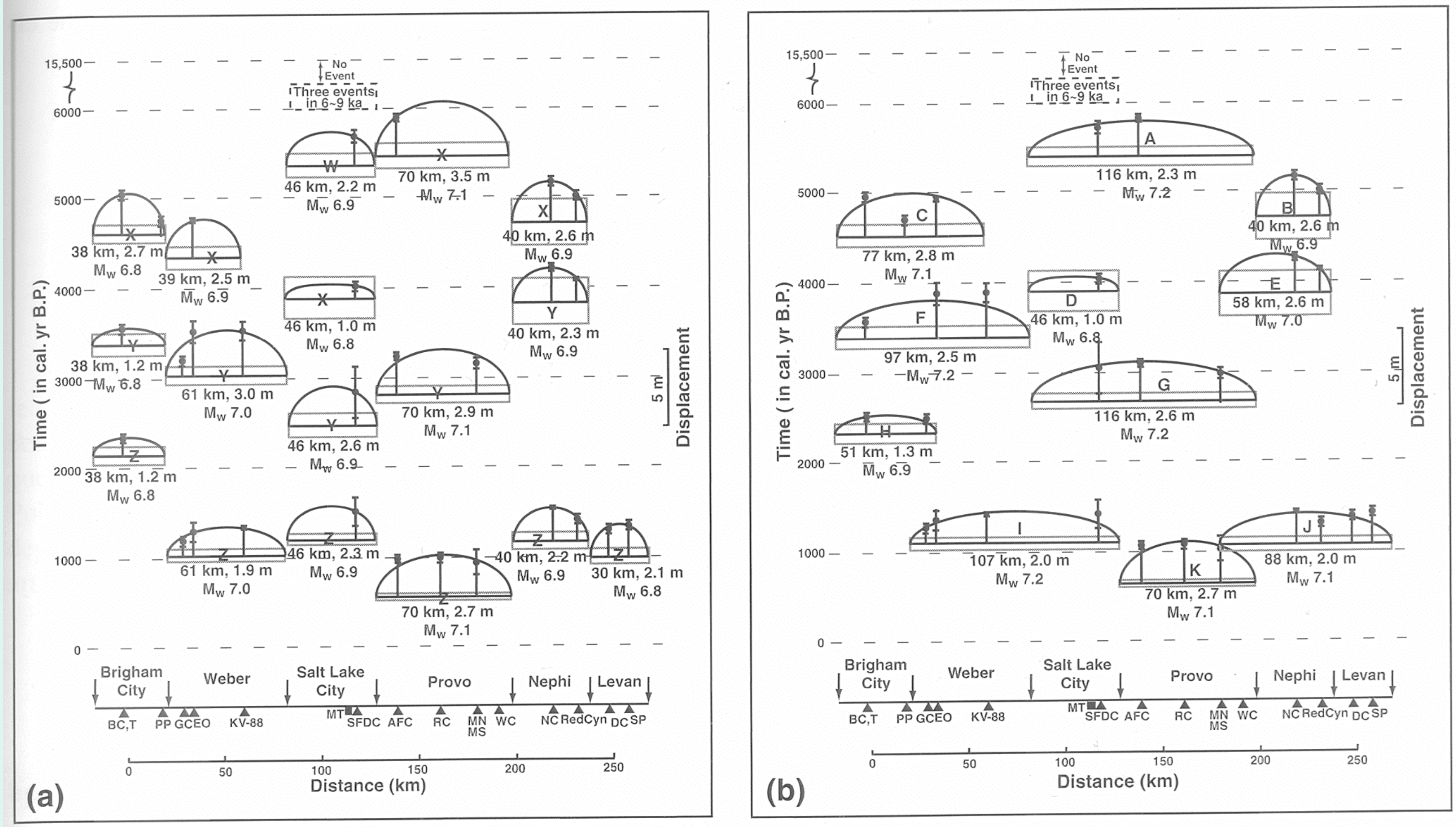


Figure 6. Modeled distributions of fault slip based on (a) single-segment and (b) multi-segment paleoearthquakes of the Wasatch Fault. Vertical black lines show averages (dots) and errors (between tics) of fault-slip data measured from trenches (see Table 1). For each event, fault displacements are fitted by a semi-elliptical envelope (see text for discussions). The rupture length, maximum displacement, and moment magnitude, shown for each event, are scaled from Wells and Coppersmith (1994) and Mason (1996).

Results

- Model magnitude estimates for single segment ruptures range from M 6.8 to 7.1
- Average magnitude for multi-segment ruptures 0.1 magnitude units greater than single-segments.
- Unexpected: Average and maximum displacements for multi-segment ruptures can be greater than those of the individual segments. Examples:
  - Provo(X) D=3.5 m; Provo(X)+SLC(W): 2.3 m
  - Weber(Y) D=3.0 m; Weber(Y)+Brigham(Y) 2.5 m

Bilinear Source Scaling

Hanks and Bakun

BSSA 92, p. 1841-1846

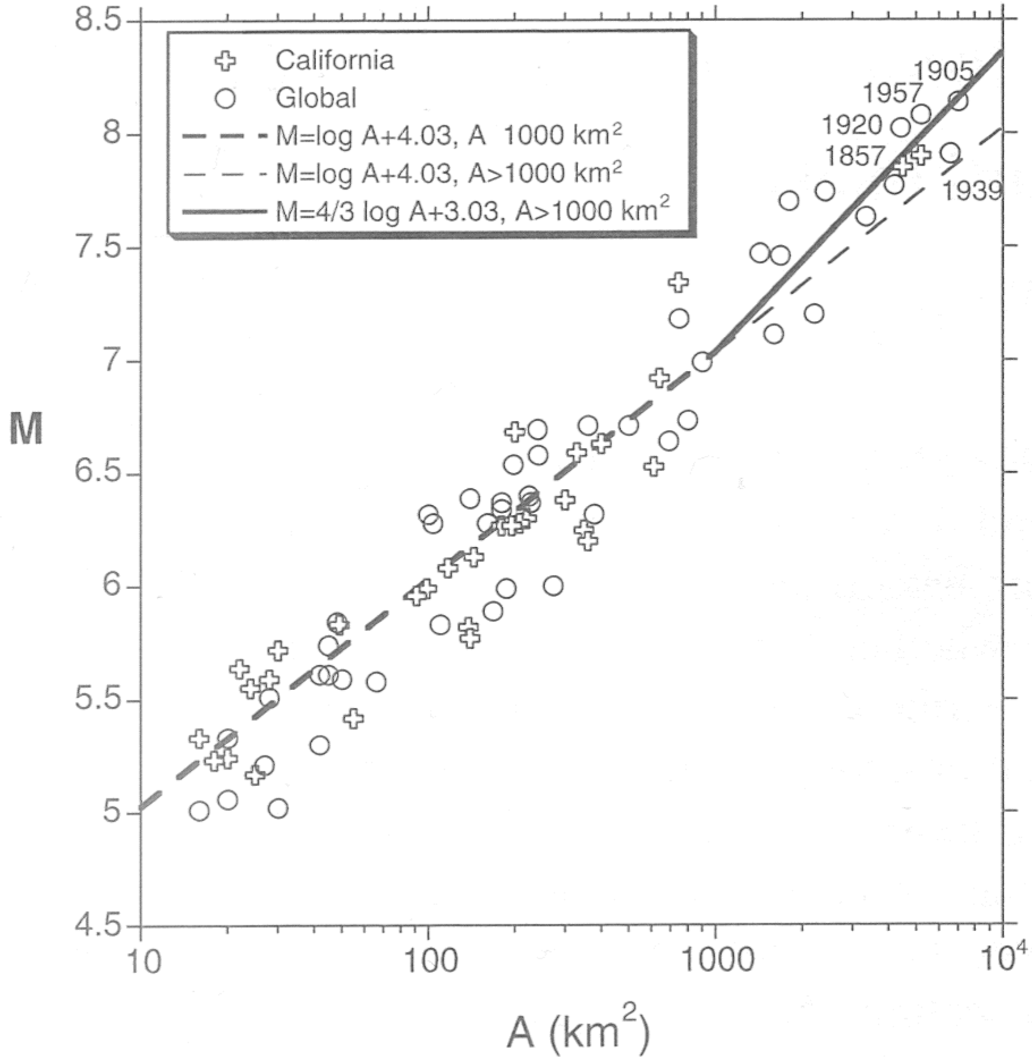


Figure 1. Model equations (7) and (13) and WC94 **M**–log *A* data for continental strike-slip earthquakes. Unlabeled symbols denote 75 **M** ≥5.0 continental, strike-slip earthquakes that qualified for the WC94 regression analysis (see text). The labeled (by year of occurrence) symbols denote five additional **M** ≥7.5, continental, strike-slip earthquakes with **M**–log *A* data given in Table 1.

Focus on strike-slip earthquakes in continental crust.

Motivated by W&C under-prediction of Mw above M~7.

W&C: Mw=1.02*logA+3.98

H&B:

Mw = logA + 3.98, Area <=537 km^2.

Mw=(4/3)*logA + 3.07 A>537

Stirling EA (all styles of faults)

Mw = 0.73*log(A) + 5.09, 6.1<=Mw<=8.1, 50<A<7000 km^2

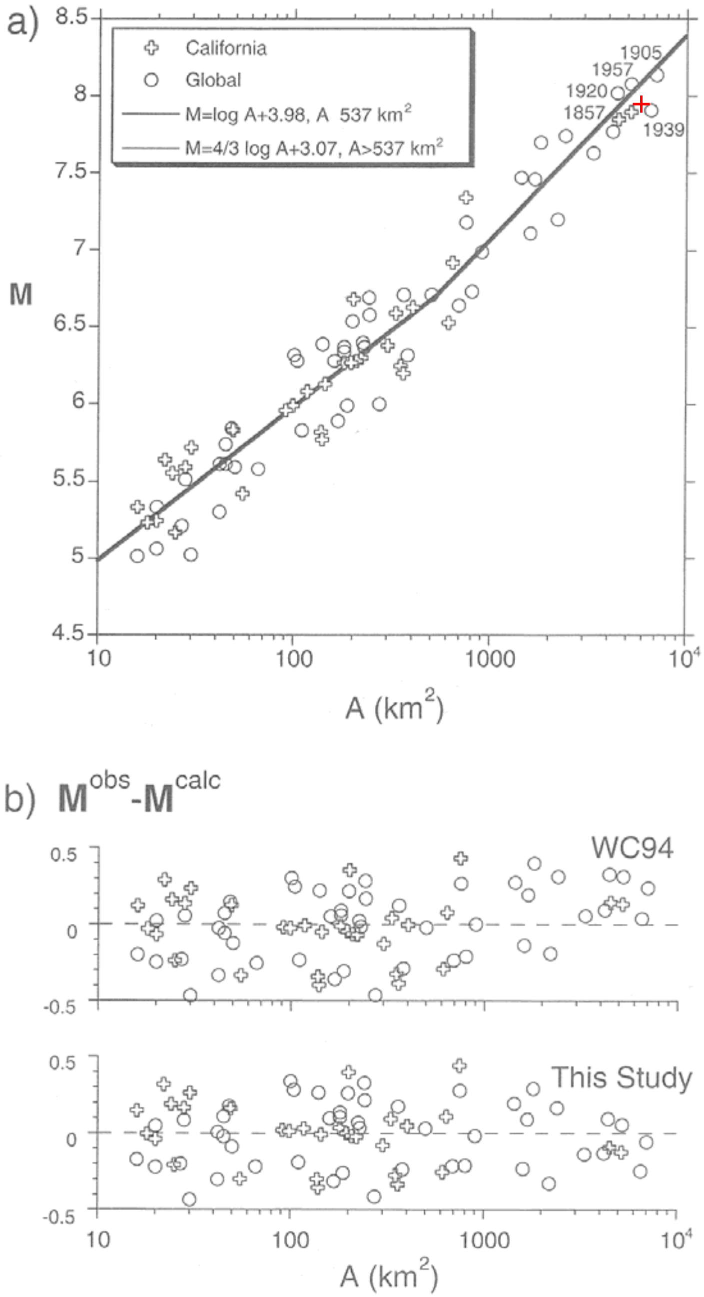


Figure 2. (a) Prediction equations (7a) and (13a), with data as in Fig. 1. (b) Magnitude residuals for the Wells and Coppersmith (1994) relation (equation 2) and the bilinear prediction equations proposed in this study (equations 7a and 13a).

Bilinear fit resolves asymmetry in misfit of WC94.

Applicability for BRP unclear.

Length and Displacement Inferences About Magnitude

$$M_o = \mu d l w$$

So, we will discuss d and l and w

Empirical Relations to Estimate Magnitude (M)

- Fault Area (length x downdip width)
- Length (surface or subsurface)
- Displacement (average or maximum)
- Slip Rate (average)

A little historical note:

M was once estimated by

1) measuring fault length from a geologic map
2) using *L/2*
3) Applying this to L vs. M relations ala Slemmons, 1977 or Bonilla et al., 1984
4) uncertainties…oh, say 1/4 M…maybe

…M7.25 implied we had done more work than we really had

Little history (cont’d)

- Then came Schwartz and Coppersmith, 1984
  - Every fault became a multi-segment fault and the word segment was misused repeatedly.
- Then came Wells and Coppersmith, 1994
  - Much plug and play began
- Some reevaluation of the fault parameter relations WRT M has been happening

Reasons current practice uses SRL to estimate M:

- Most data for historic ruptures include L
- Estimates for M reliably correlate to L in historic data sets
- Estimates of L available from geologic maps, air photos and seismicity (be vewy, vewy careful)
- segmentation schemes can be developed for large faults

Problems with using SRL for prehistoric earthquake magnitude estimates

- based on identification of subtle, fragile geomorphic features that are easily buried or eroded, especially on long-recurrence faults

- rupture can integrate faults that are not obviously related

- assessing single-event rupture segmentation can be difficult, even for short-recurrence, high slip-rate faults

- segmentation schemes difficult to quantify (logic trees)

- small D values (for example at the tails

1983 Borah Peak Earthquake

SRL = 36 km, M_W 6.9
Nearly 1/3 of length had displacements < 30 cm

Slide from S. Olig, URS

Advantages of using D to estimate M for prehistoric events?

- paleoseismic techniques better at measuring amount of D than SRL

- where D low, erosion or deposition rates high, fault obscured in bedrock or in playa settings, there is increased chance for missing SRL

- commonly, only a portion of scarp preserved but that bit of scarp retains D info
  - D can provide info about L, such as whether the apparent L is underestimated

- Can be used to estimate uncertainties

Problems with using D to estimate M

- D at a point could be the product of multiple events relatively closely spaced in time
- D_{max} may be anomalous and thus not reliable for estimate of M
- How many estimates of D are required to estimate M with acceptable uncertainty?
- Obtaining estimates of D can be expensive

D Anomalies

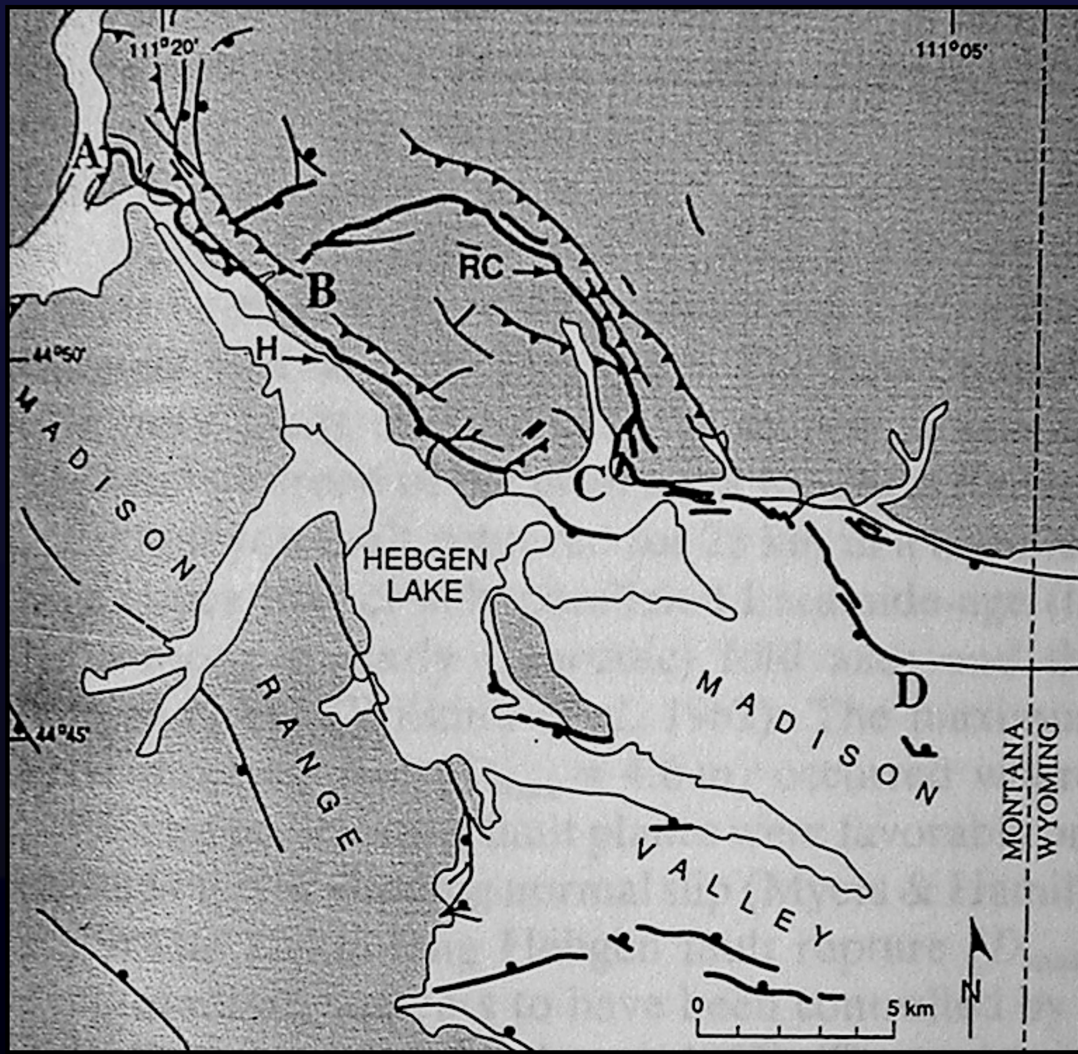
Anomalously Large D v M

- 1979 Stevens Pass earthquake - Modoc M4+ event produced surface rupture for ~2 km
- Holocene scarps on the Hat Creek fault - Modoc - in excess of 10 m/event
- 1850 Fort Sage Mountains? - M_L 5.6 - produced 9.5 km-long-scarp - Dmax on discrete rupture = 20 cm, if include warping 60 cm

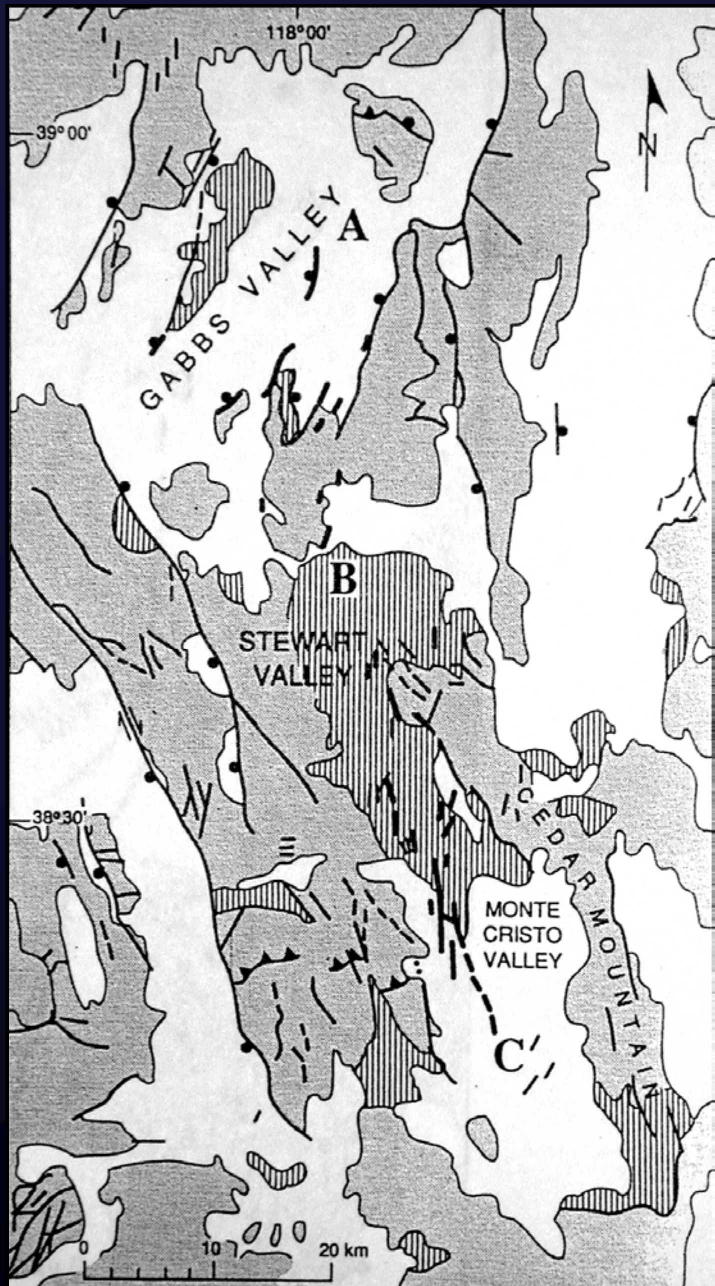
Anomalously Small D v M

- 1989 Loma Prieta, M 7.1 - no primary surface rupture - perhaps thrown into the “blind thrust” category?
- 1986 M 6.5 Chalfont Valley, NV - no discernable primary surface rupture

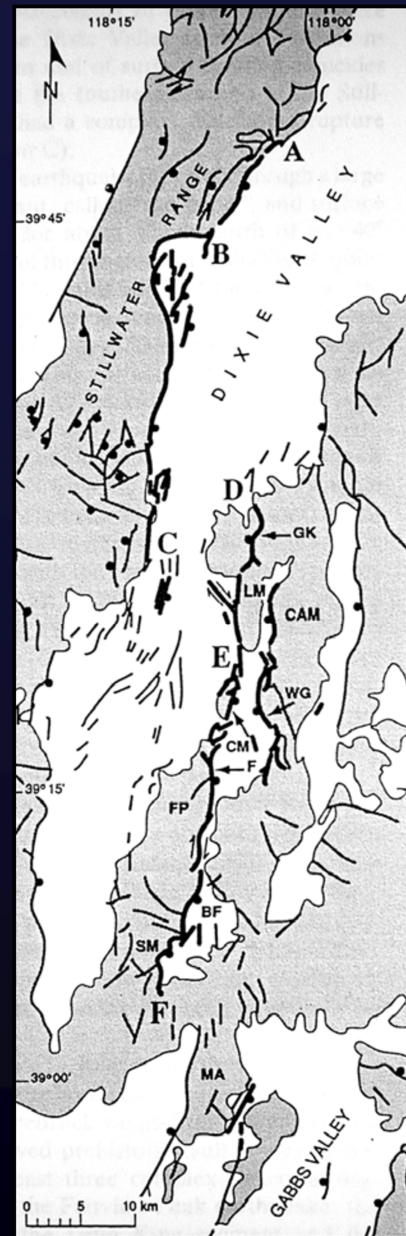
Surface Rupture Length concerns



1959 M_s 7.5 Hebgen Lake

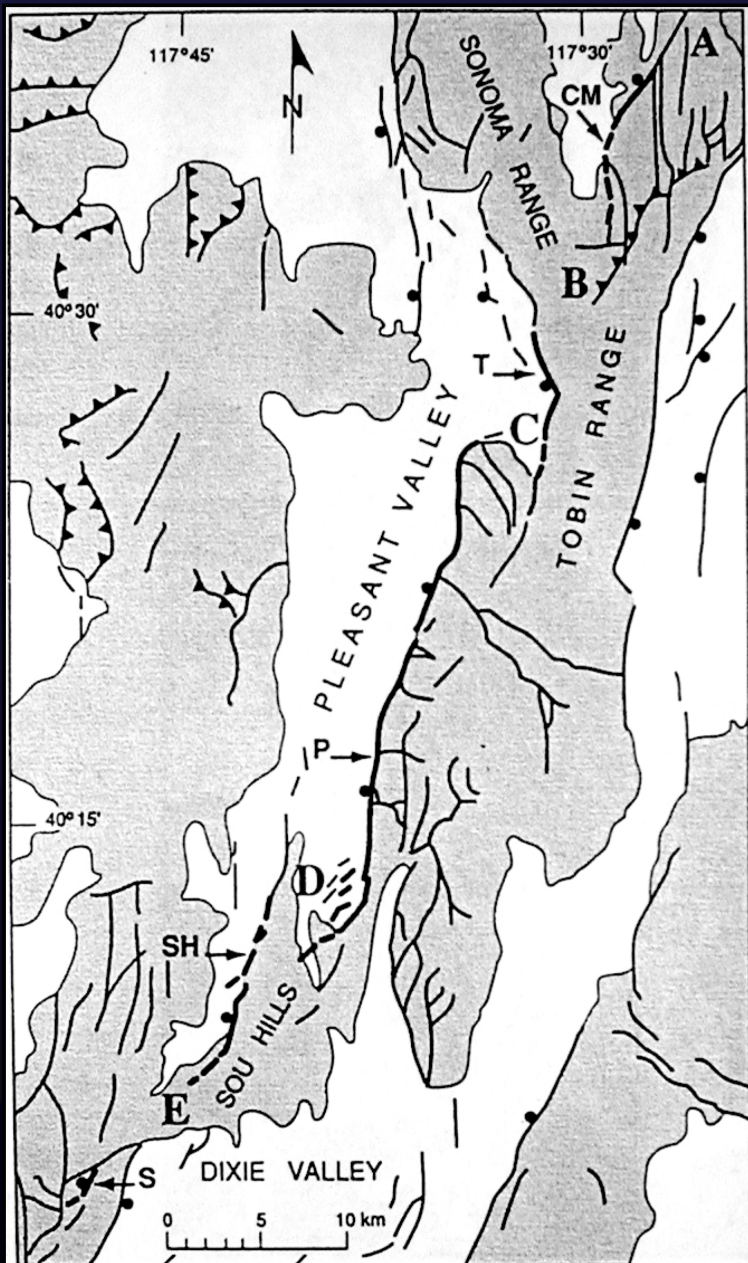


1932 M_s 7.2 Cedar Mtn

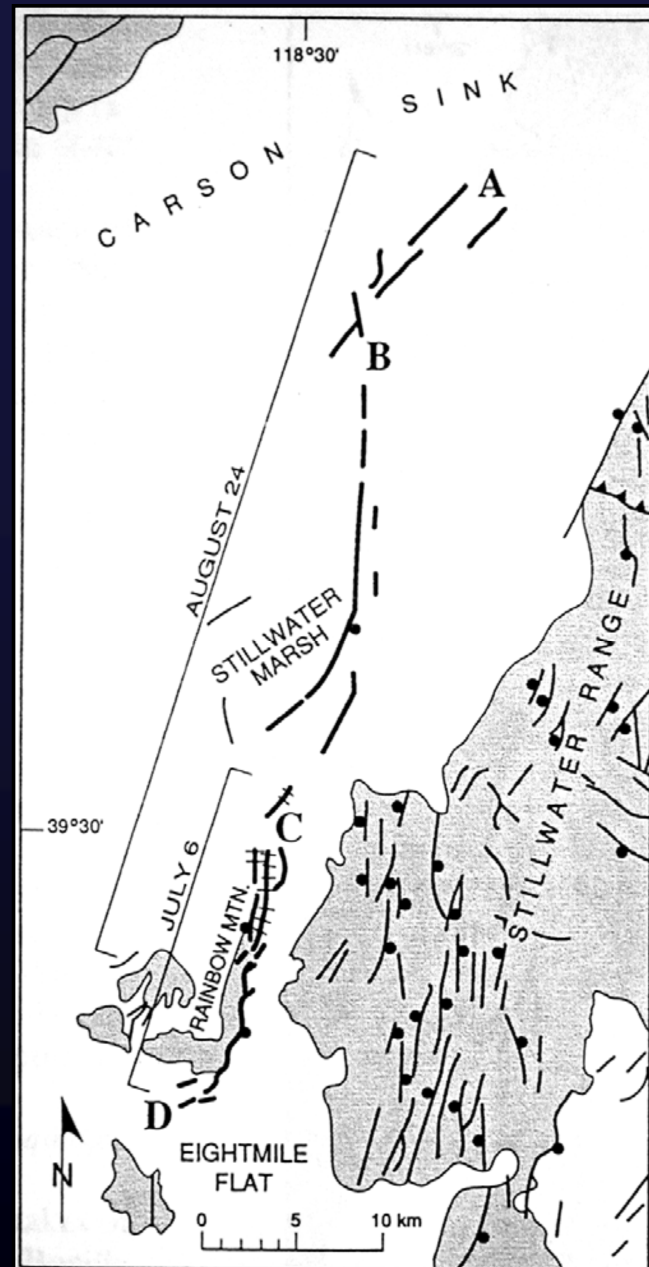


1954 M_s 7.2 Fairview Peak and M_s 6.8 Dixie Valley

Total SRL = 123 km implies M_W 7.5

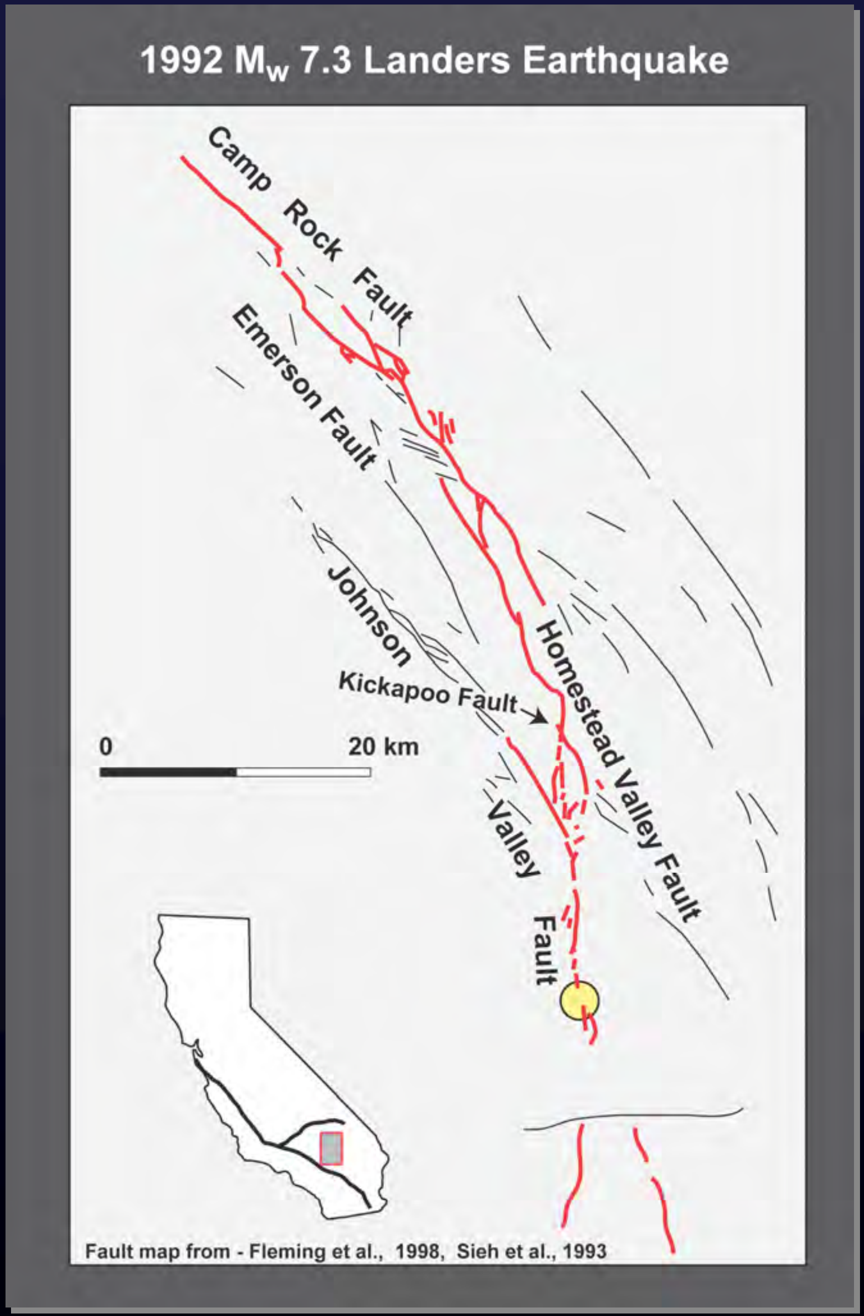


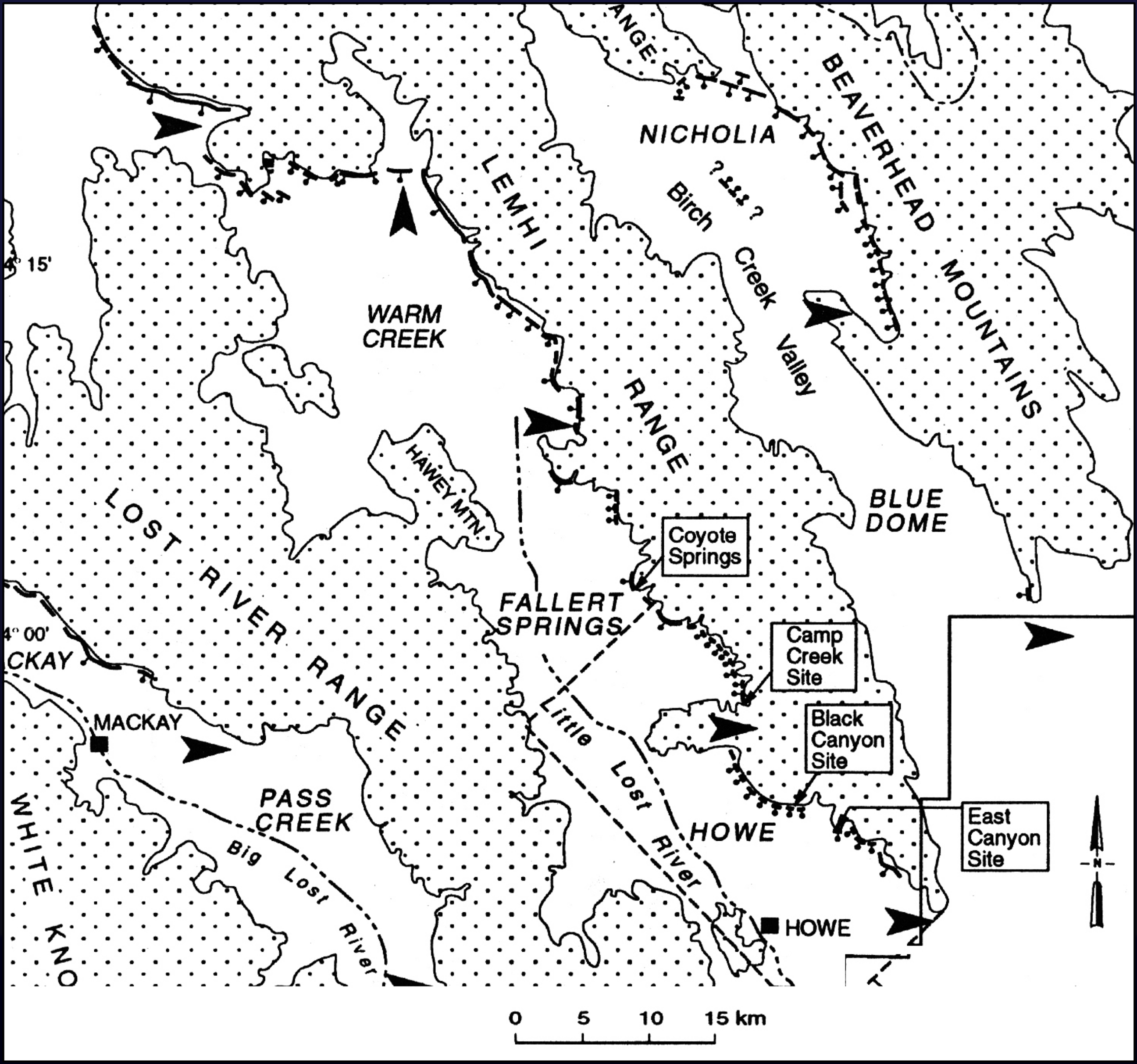
1915 M_s 7.6 Pleasant Valley



1954 M_s 6.3 Rainbow Mountain and M_s 7 Stillwater

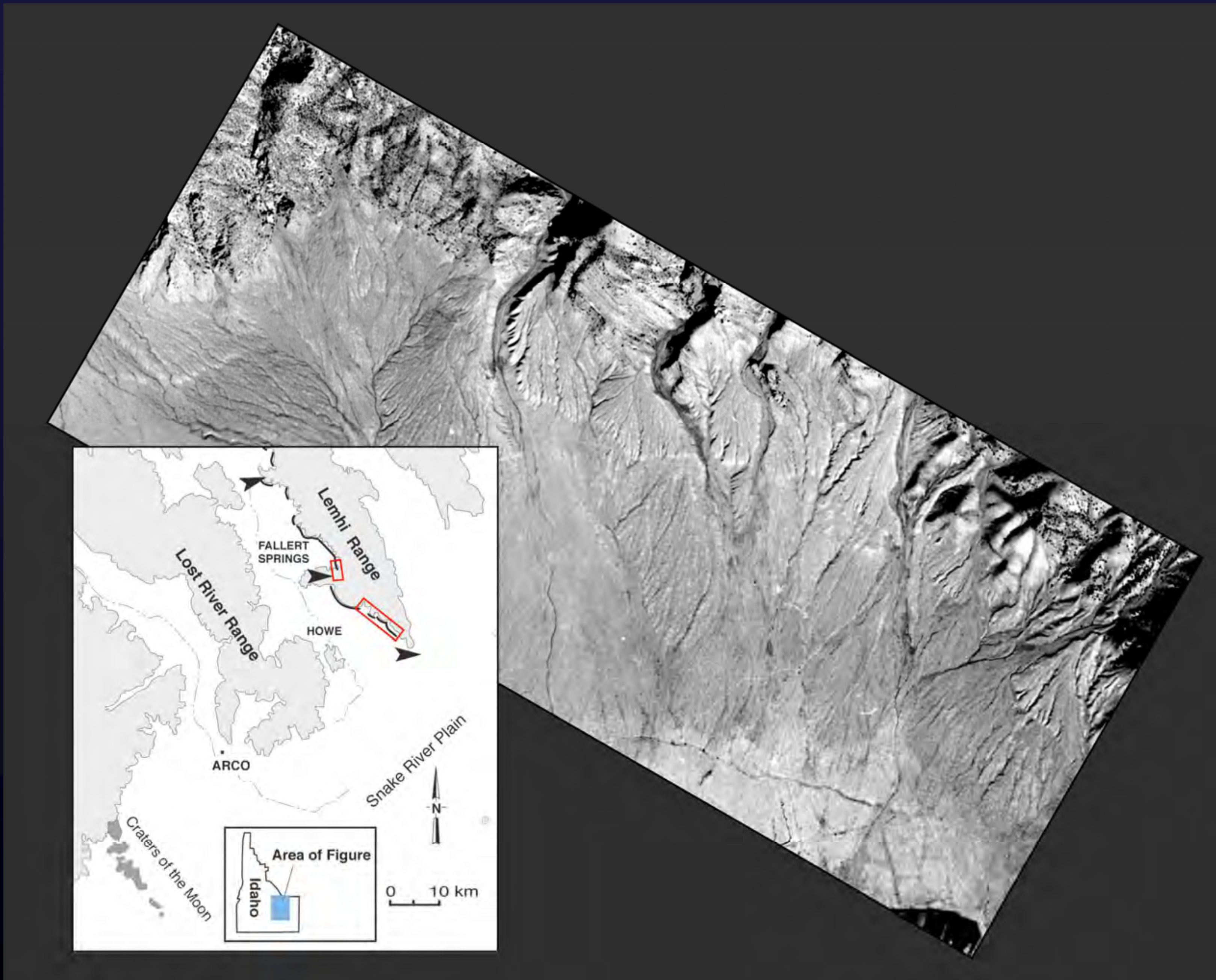
Landers example



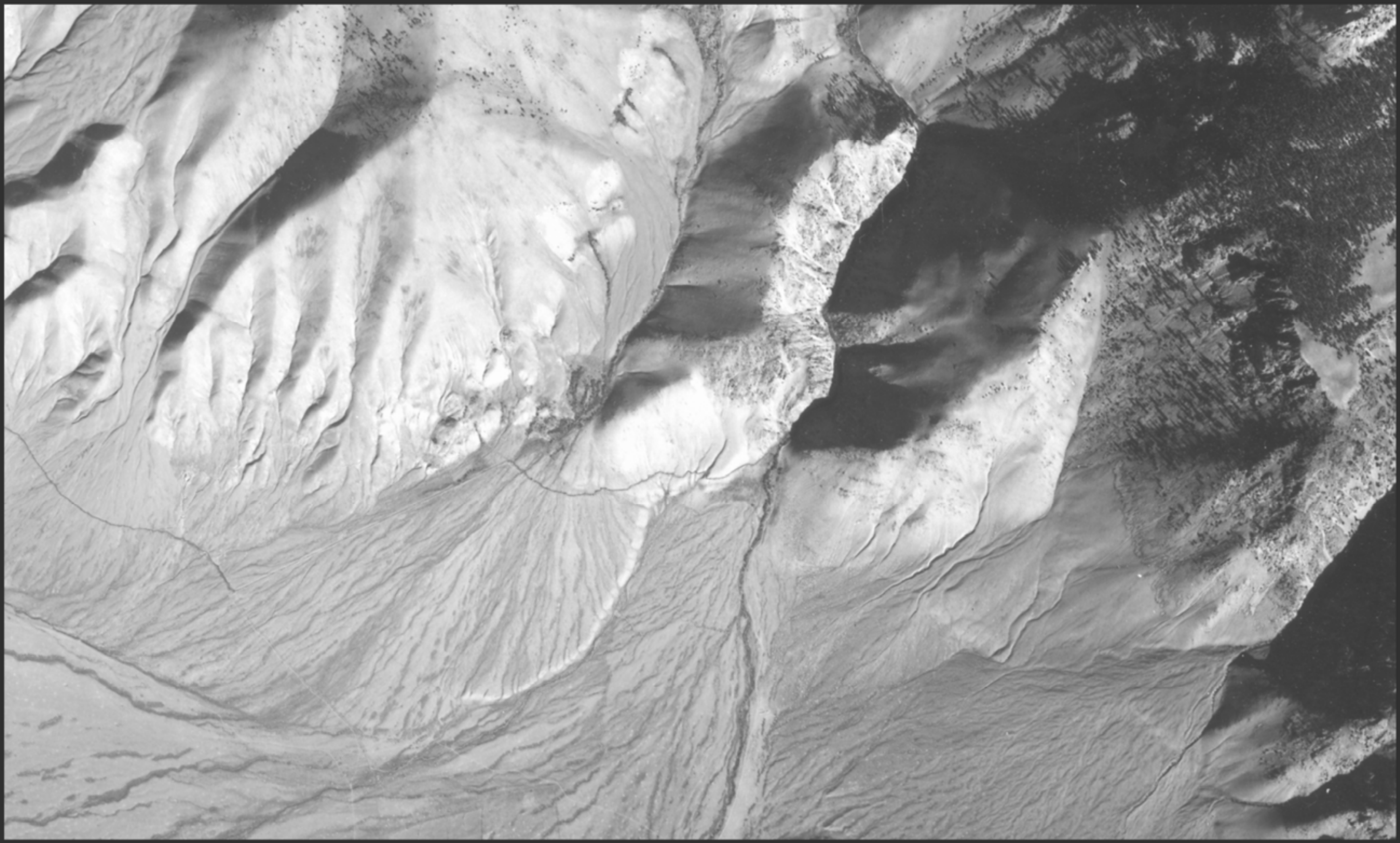


From Woodward-Clyde, 1992

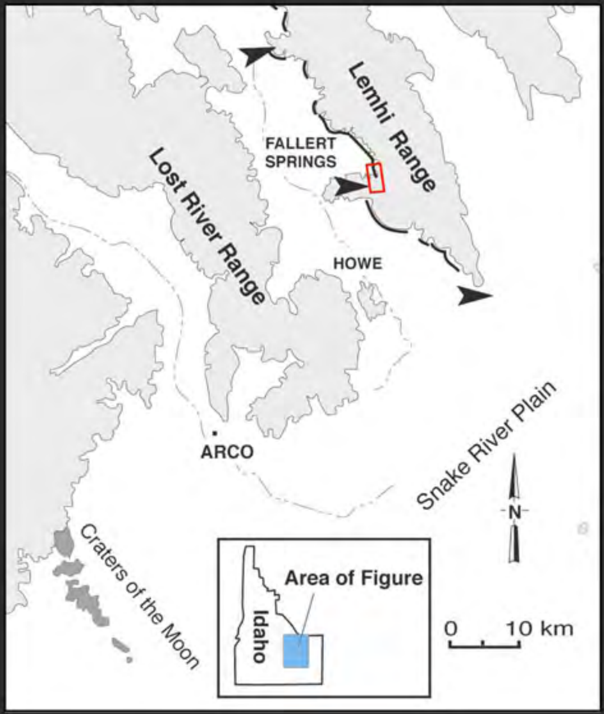
Lemhi range, southeastern Idaho

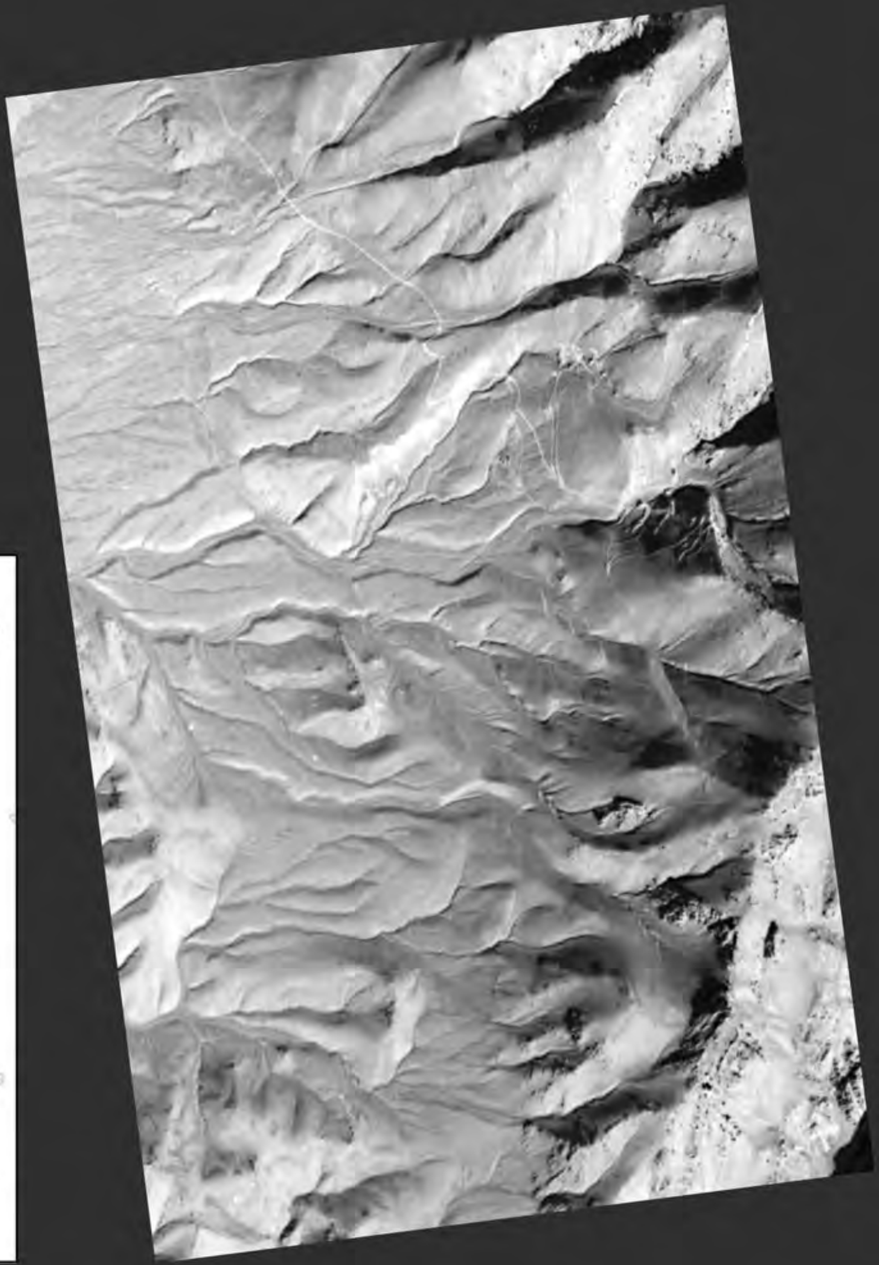


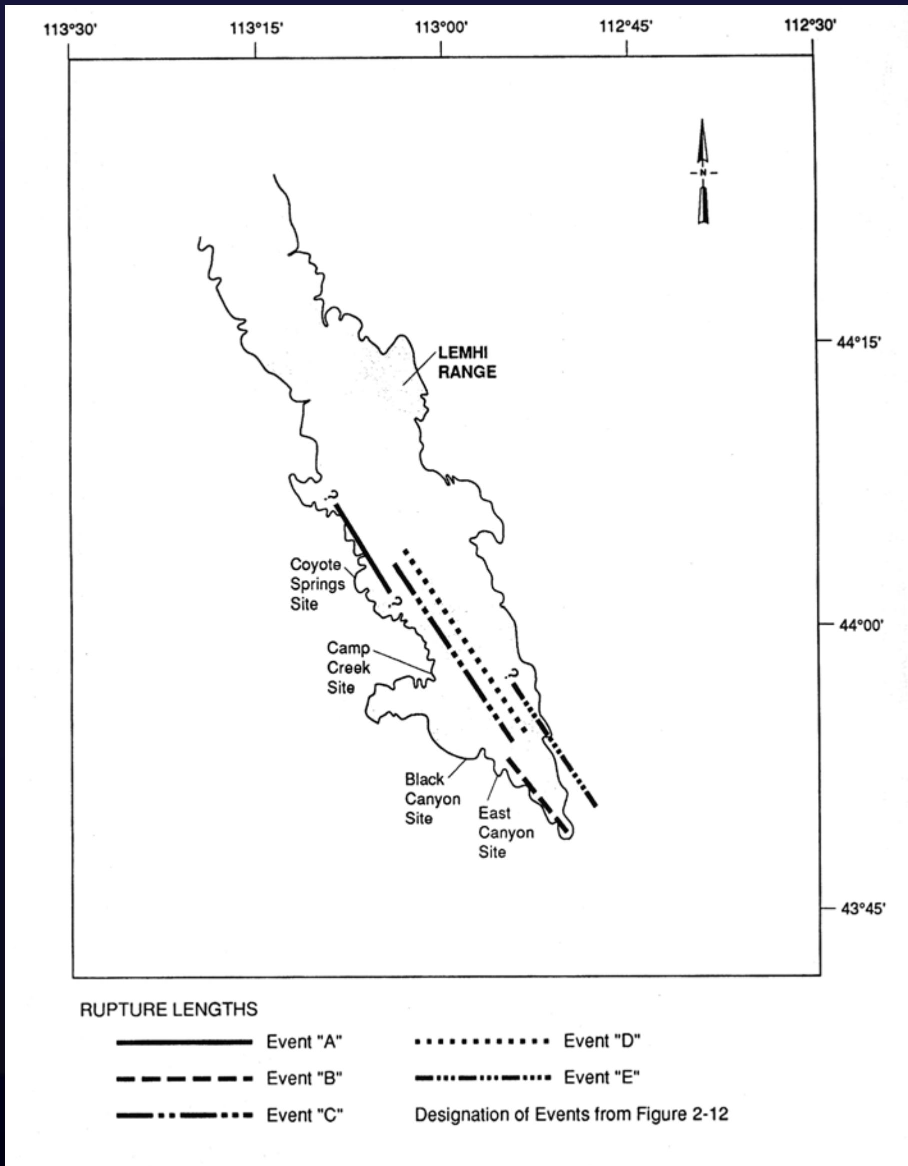
Lemhi range, alluvial and bedrock scarps

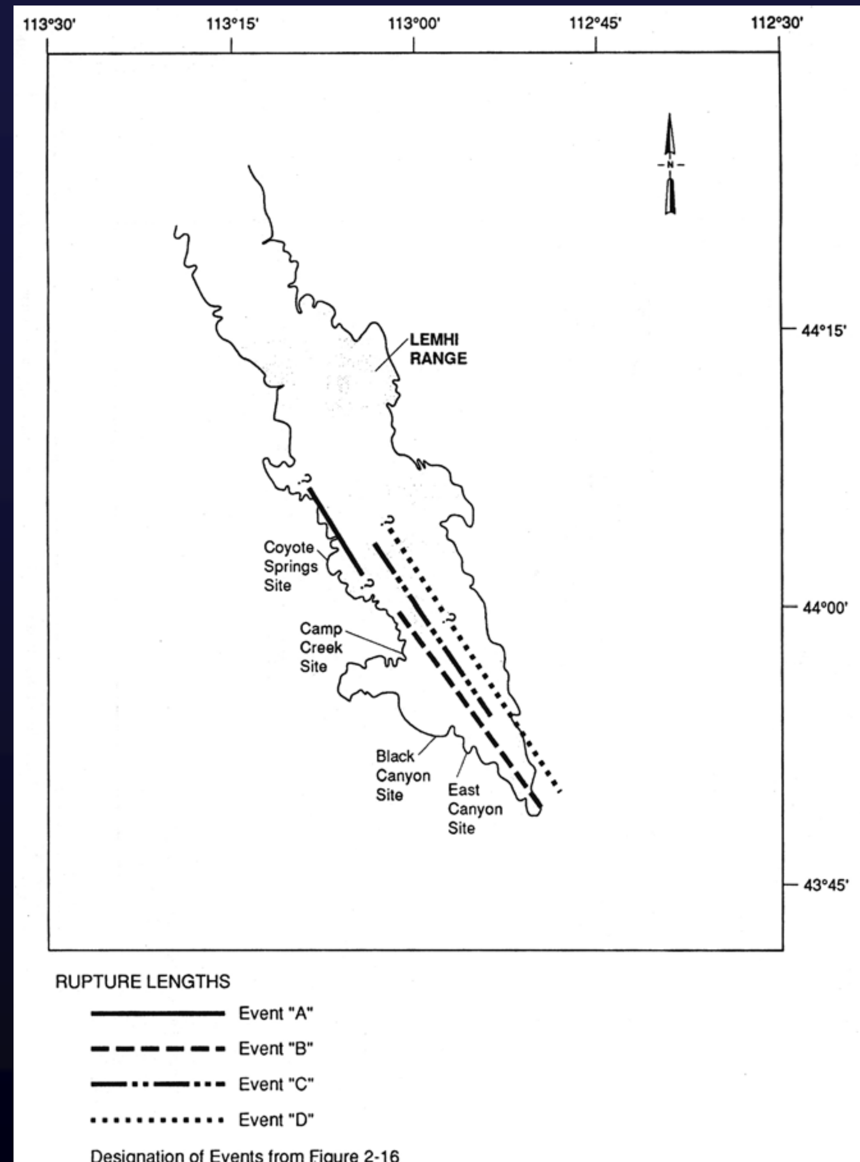


Lemhi range, segment boundary

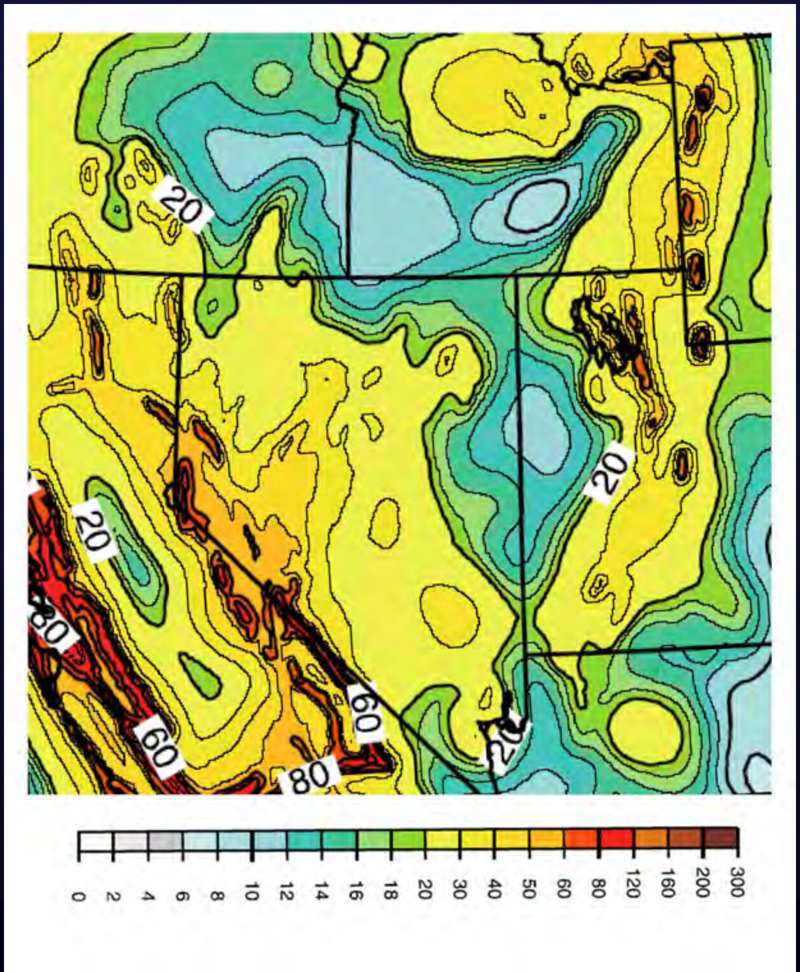




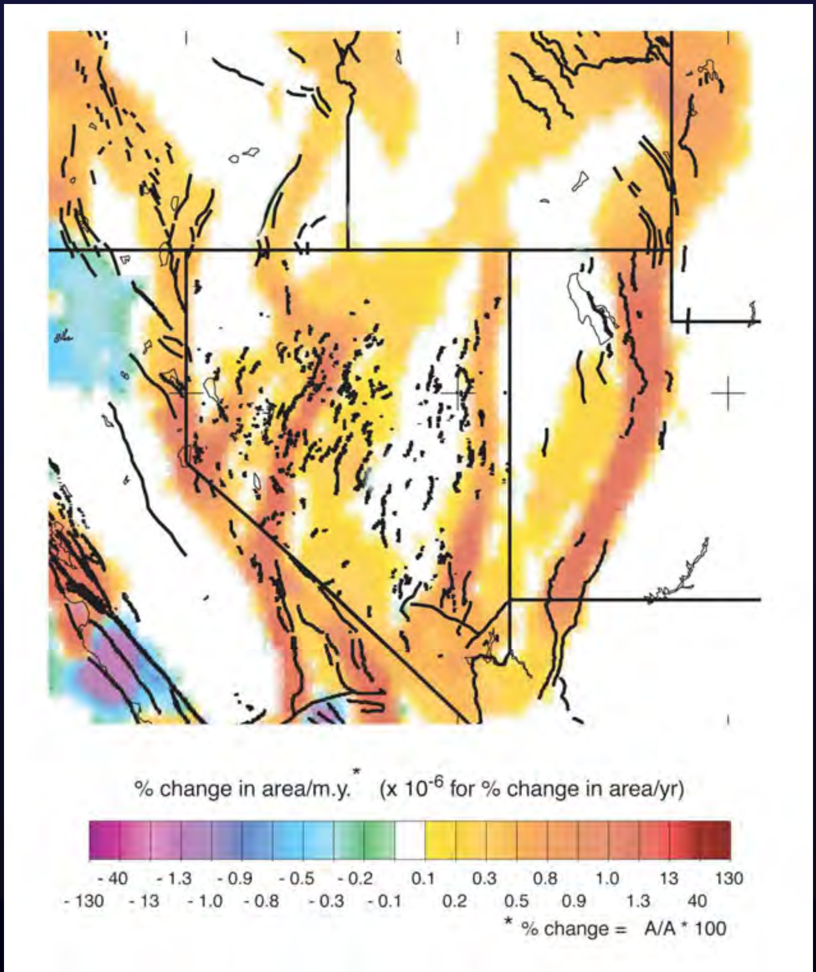

113°30'
113°15'
113°00'
112°45'
112°30'
44°15'
44°00'
43°45'
N
LEMHI RANGE
Coyote Springs Site
Camp Creek Site
Black Canyon Site
East Canyon Site
RUPTURE LENGTHS
Event "A"
Event "B"
Event "C"
Event "D"
Event "E"
Designation of Events from Figure 2-12


113°30'
113°15'
113°00'
112°45'
112°30'
44°15'
44°00'
43°45'
N
LEMHI RANGE
Coyote Springs Site
Camp Creek Site
Black Canyon Site
East Canyon Site
RUPTURE LENGTHS
Event "A"
Event "B"
Event "C"
Event "D"
Designation of Events from Figure 2-16

How internally diverse is the B&R province?



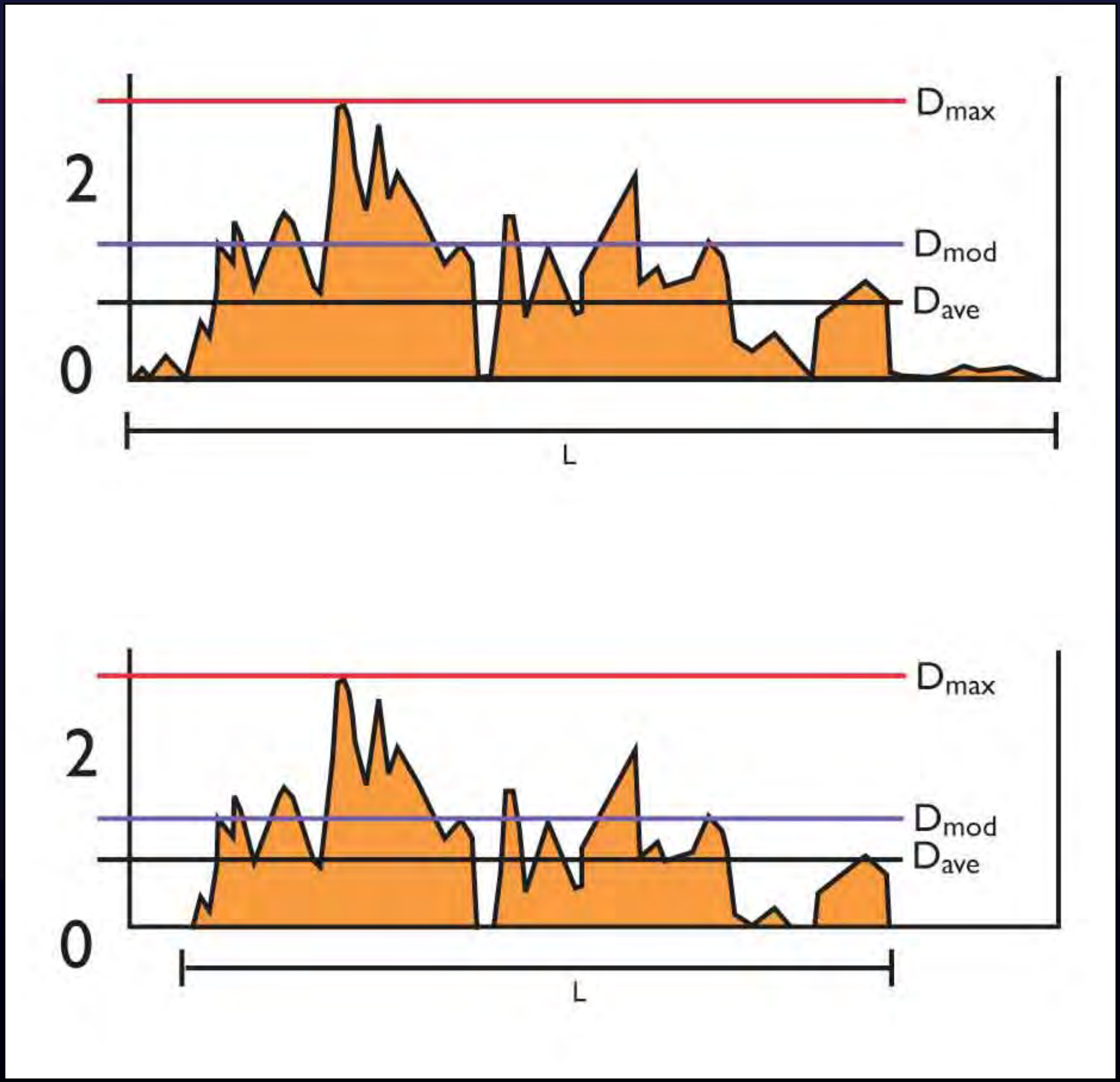
From Peterson et al., (2004) -2002 hazard map peak horizontal acceleration on firm rock site condition (2% probability of exceedance in 50 years).



From Hemphill-Haley, 1999 - Isotropic strain estimated from FEM

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

http://earthquake.usgs.gov/regional/imw/images/imw_home_fig2.jpg


2
0
Dmax
Dmod
Dave
L
2
0
Dmax
Dmod
Dave
L

Using Prehistoric Coseismic Surface Displacements to Estimate Earthquake Magnitude

Hemphill-Haley and Weldon, 1999

Considerations when estimating paleoearthquake magnitude

Must relate two data sets:

- measurements of paleoearthquake D
- D associated with modern events of known M

Must also understand the variability of D for modern events in order to evaluate paleoevents

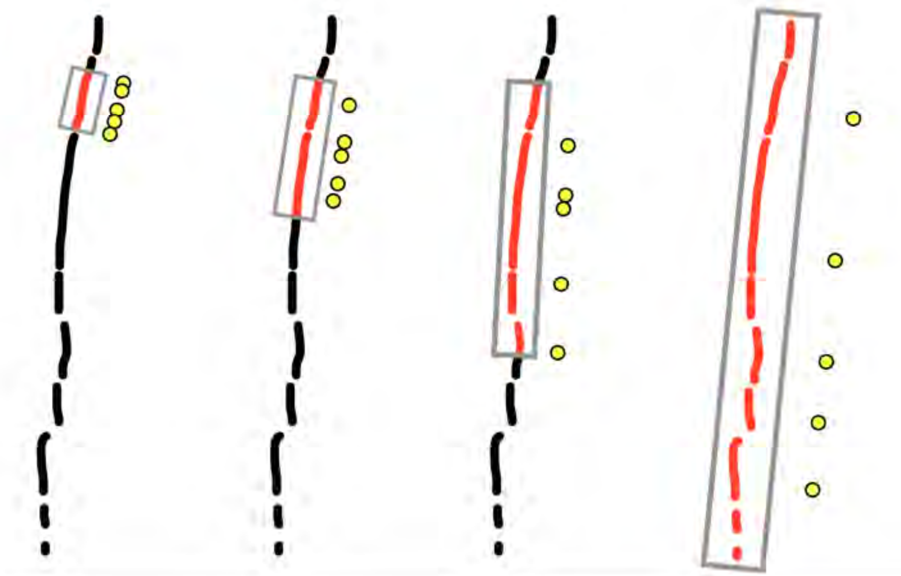
Considerations (cont’d)

Must understand how sampling the fault affects the statistics of the displacement
(wrt mean and uncertainty)

<u>Two parameters</u>

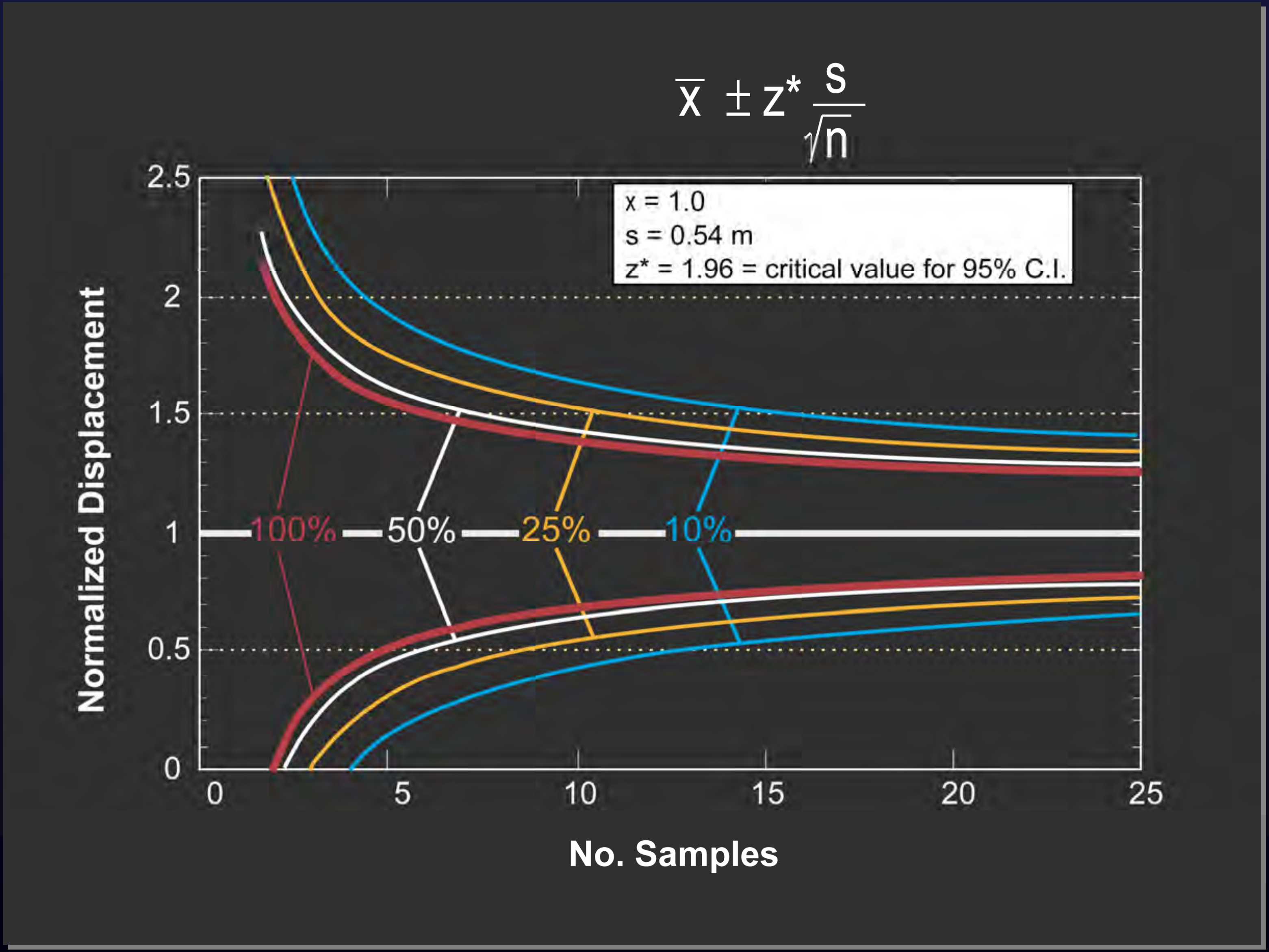
- number of measurements collected
- amount of surface rupture evaluated

Model sampling scheme



10%	25%	50%	100%	amount sampled
5	5	5	5	# samples

Ideal sampling model

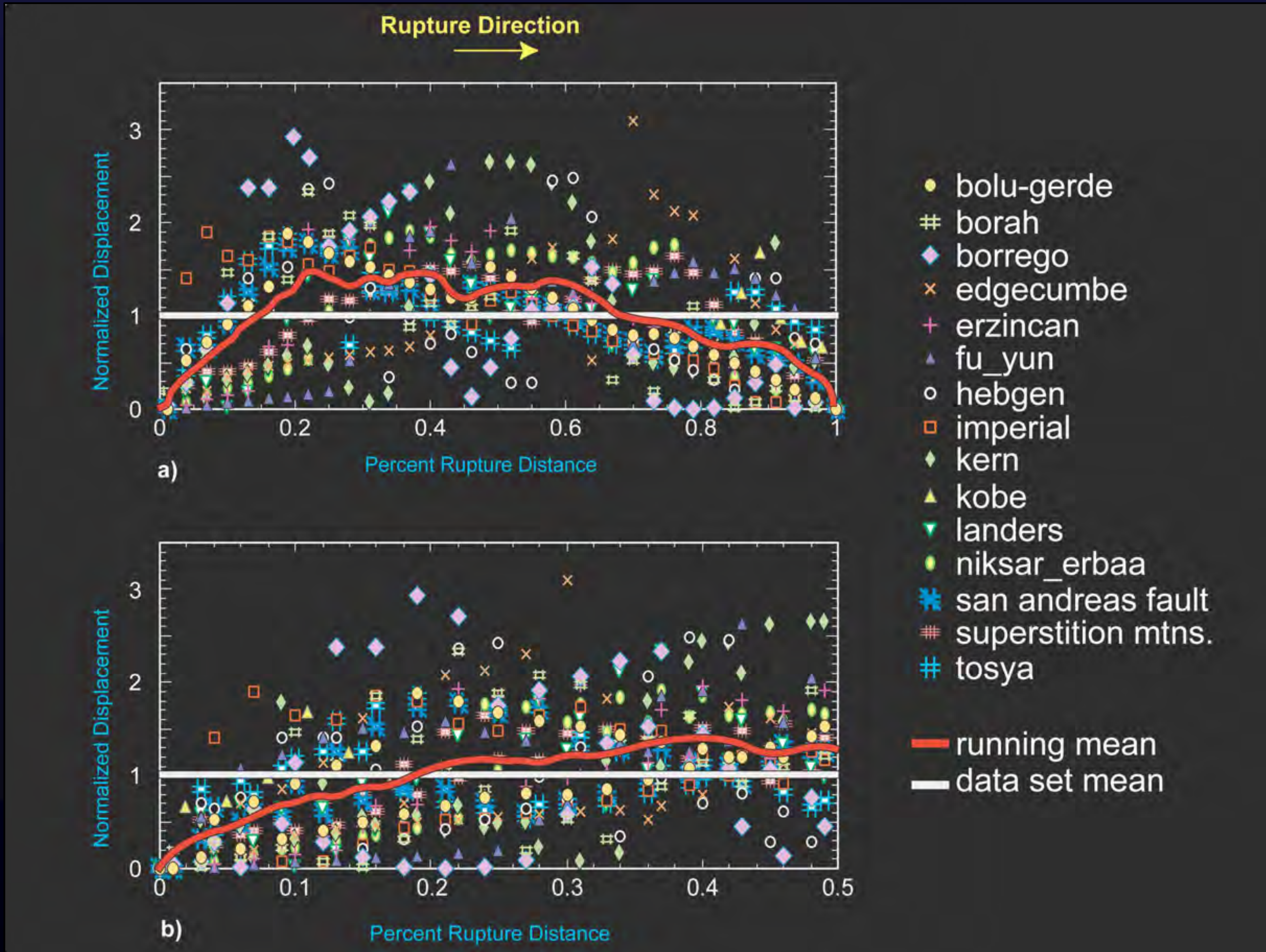


Analytically-derived statistics
for 95% confidence limits

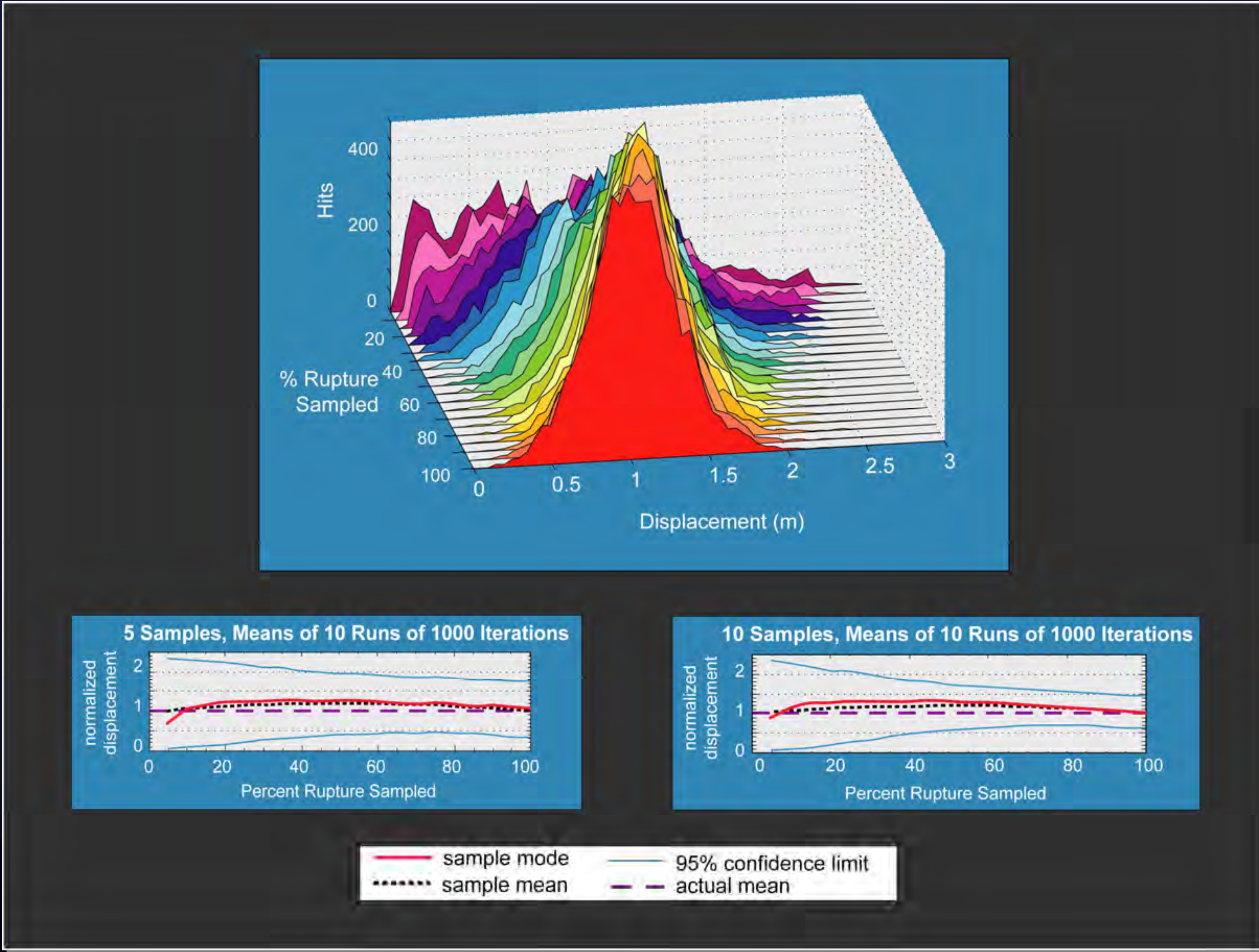
Creating stats from the historic data

- use a large iteration Monte-Carlo sampling algorithm
- one of the 14 historic rupture distributions is chosen at random
- a “window” of prescribed length randomly “drops” onto the rupture distribution and randomly selects sampling locations
- 10,000 iterations per 5% increment in fault length
- sample mean, mode, and 95% confidence limits collected

Combined Historic Rupture Distributions



Combined Historic Rupture Sampling Stats



5 and 10 sample stats

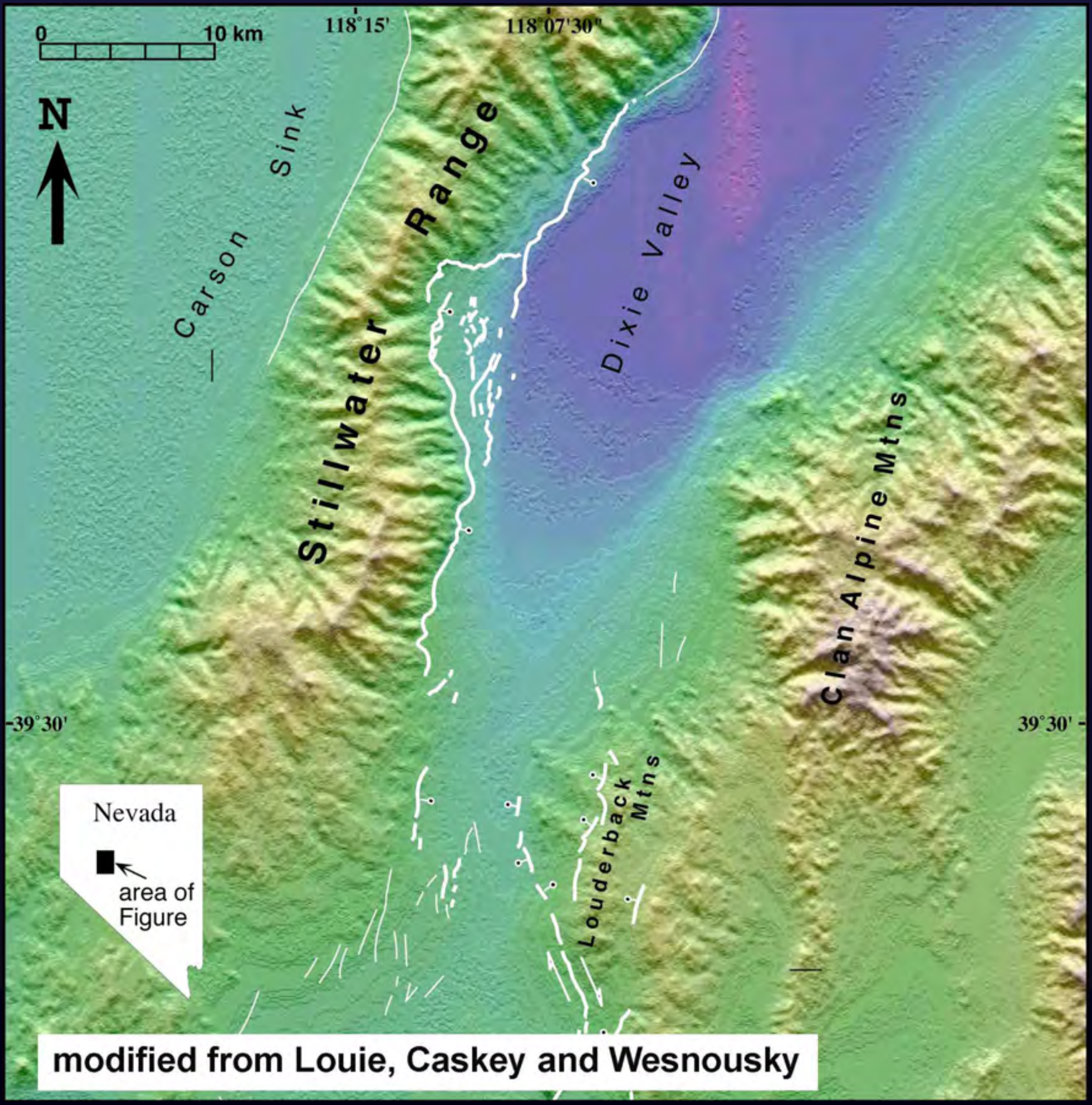
Statistical Parameters for use with Empirical Relations (D_{ave} v M_w)

Number of samples	Percent fault sampled	Upper Value factor	Mean Value factor	Lower Value factor
	10	0.09	0.97	2.31
	25	0.23	0.78	2.17
5	50	0.45	0.74	1.95
	75	0.5	0.81	1.86
	100	0.36	0.97	1.73

Apply statistical factors to established relations for mean displacement (D_{ave}) v. M_w (Wells and Coppersmith, 1994)

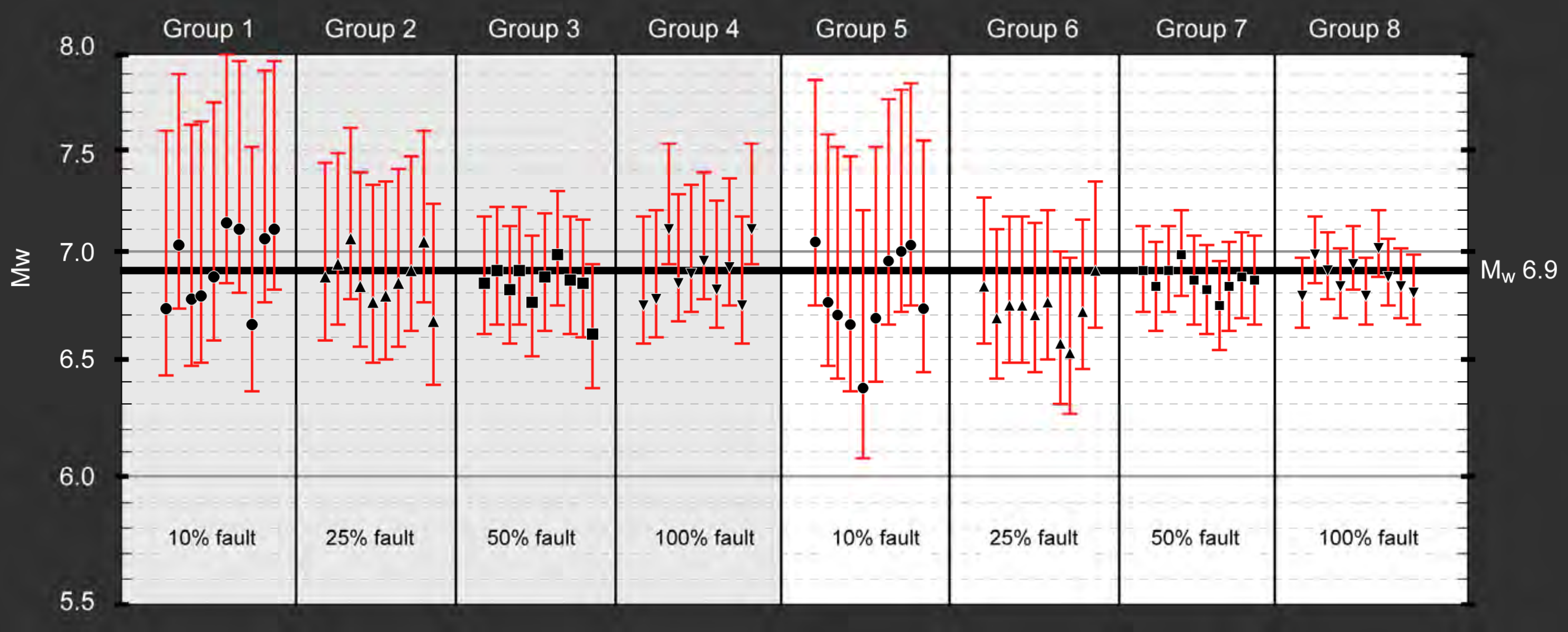
$$M_w = 6.93 + 0.82 \bullet \log (D_{ave} \bullet MVF)$$

Dixie Valley example



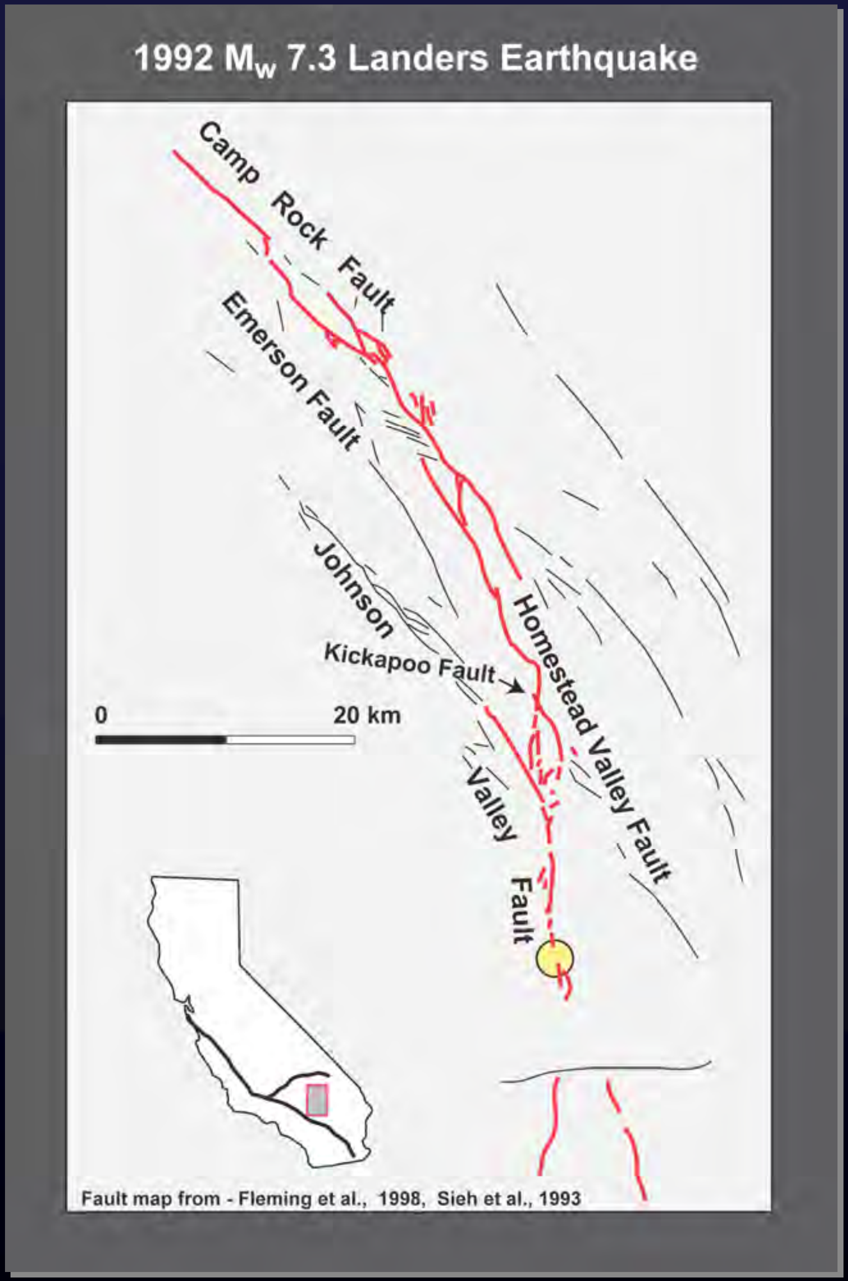
1954 M_w6.9 Dixie Valley earthquake

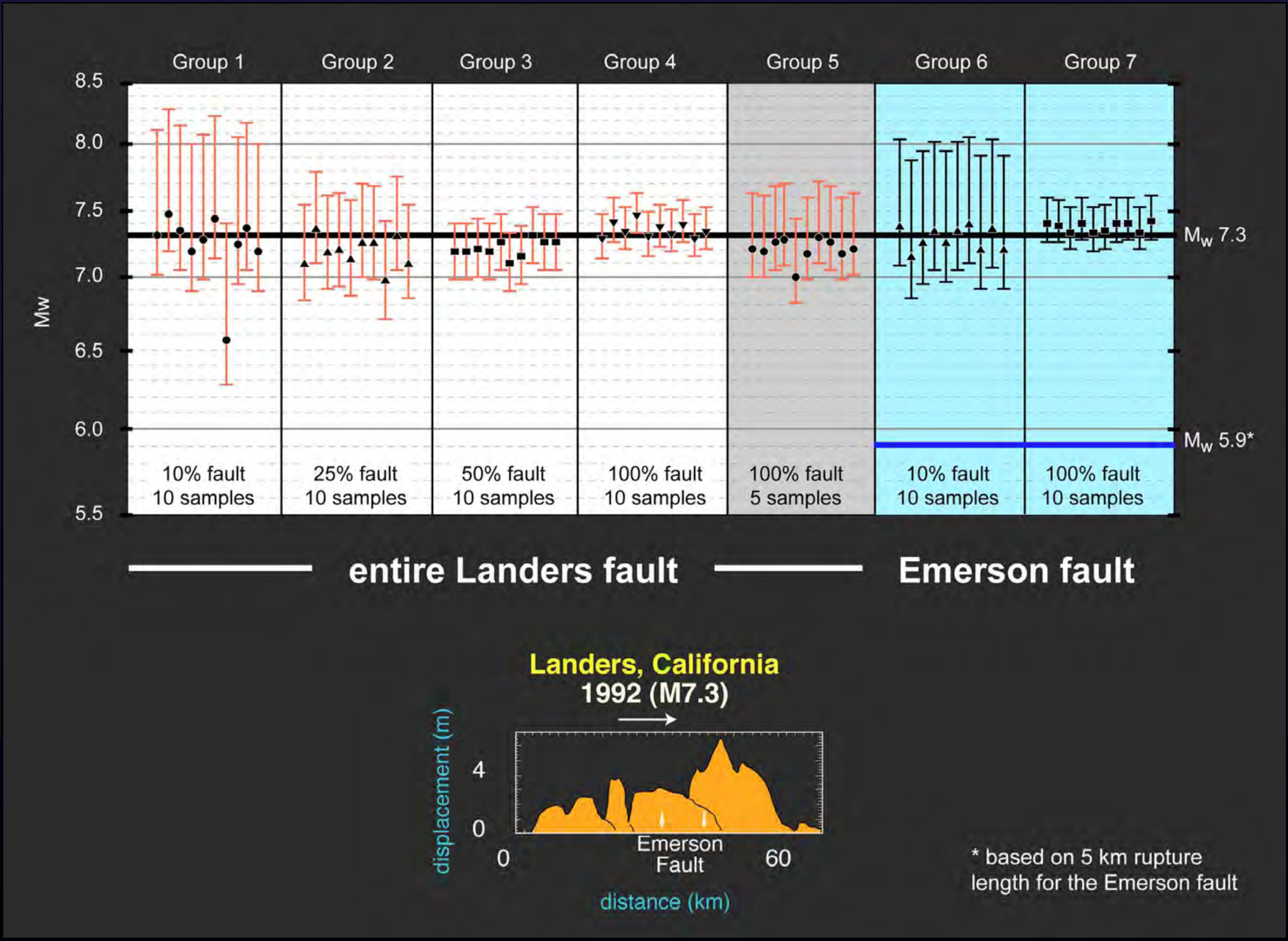
Dixie Valley magnitude estimates



5 Samples **10 Samples**

Landers example





Group 1
Group 2
Group 3
Group 4
Group 5
Group 6
Group 7
Mw
8.5
8.0
7.5
7.0
6.5
6.0
5.5
Mw 7.3
Mw 5.9*
10% fault
10 samples
25% fault
10 samples
50% fault
10 samples
100% fault
10 samples
100% fault
5 samples
10% fault
10 samples
100% fault
10 samples
entire Landers fault
Emerson fault
Landers, California
1992 (M7.3)
displacement (m)
4
0
0
Emerson
Fault
60
distance (km)
* based on 5 km rupture
length for the Emerson fault

Conclusions

- paleoearthquake magnitude estimates are difficult to obtain using SRL estimates because of large uncertainties (burial, erosion, rupture overlap…)

- a few judiciously collected samples of displacement, combined with large-iteration sampling statistics, applied to established D v. M relations (i.e., Wells and Coppersmith, 1994) may be more suitable

- provides a means for quantifying uncertainties (not available using SRL v. M)

- not cheap (trenches are expensive)

- relies upon carefully collected data

Issues

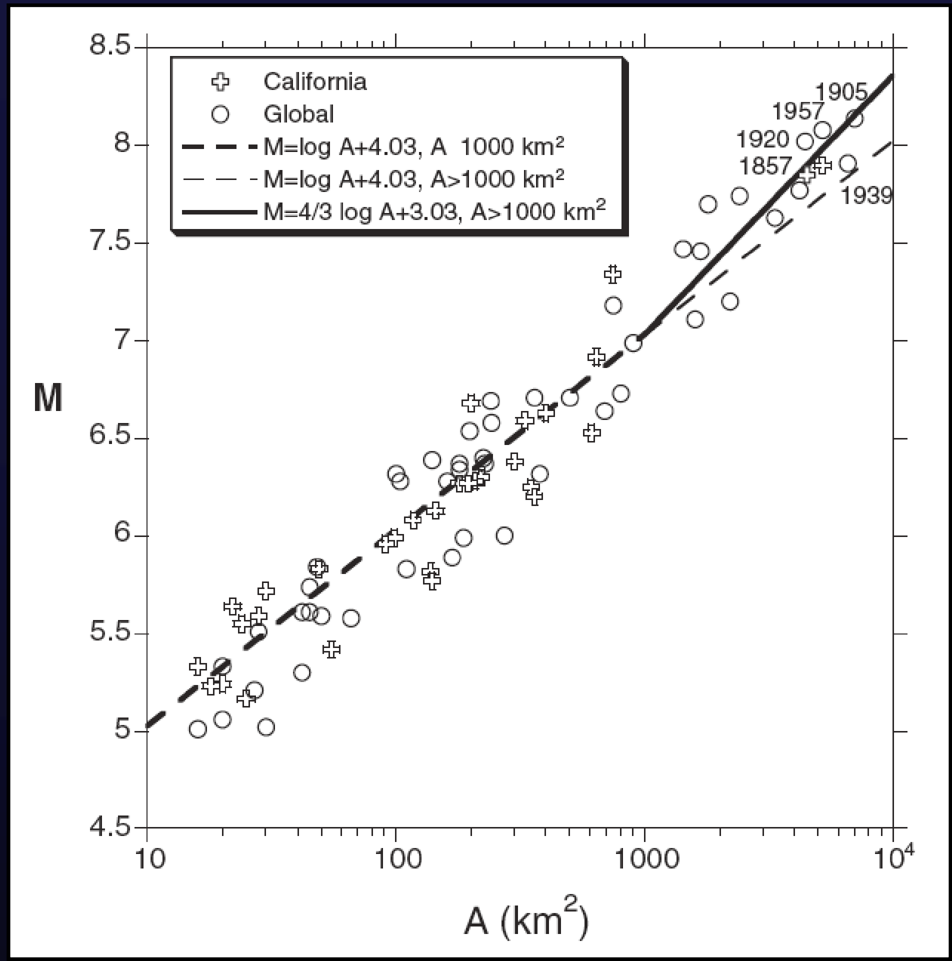
- Incorporate all estimates into weighted range of estimates
- Poor characterization of magnitudes for large events?
- Updated earthquake catalogs; regional vs. local catalogs
- Limitations of data (min/max magnitude, fault length, displacement)
- Issues with fault parameter data: displacement (limited number, single event?), surface rupture length (concealed trace, multi-segment

Other approaches to M

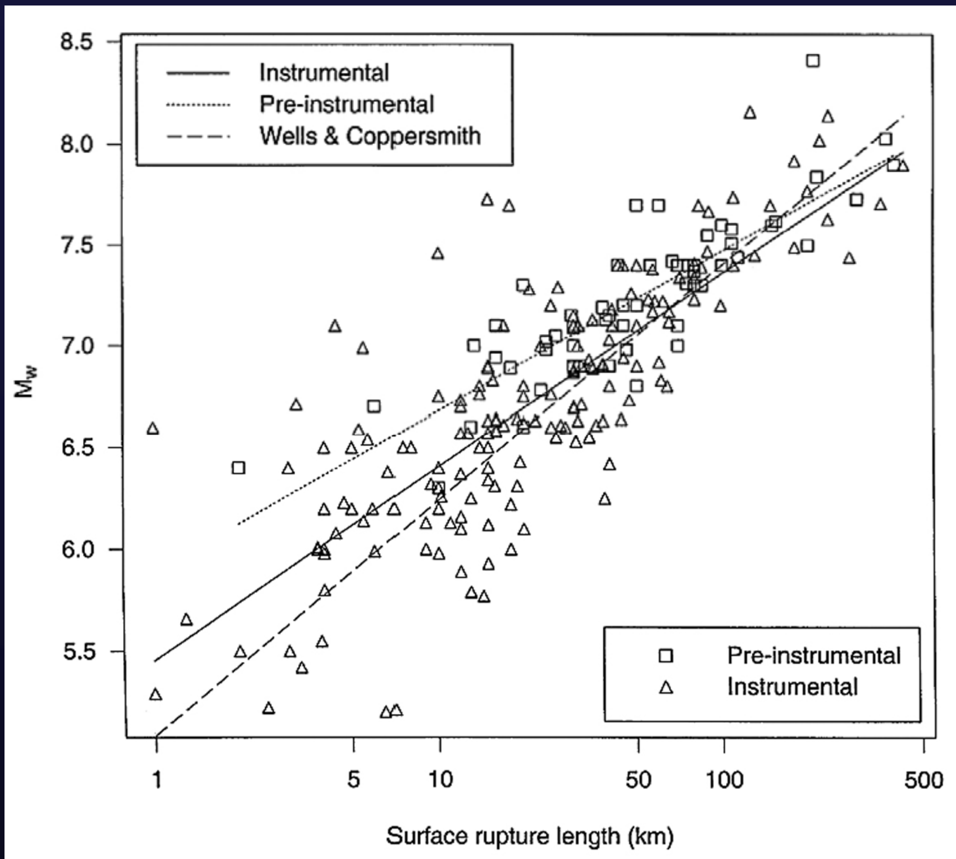
- Chang and Smith, 2002 - looking at D and considering individual vs. multi-segment ruptures of the Wasatch fault
- Anderson et al., 1996 - considering fault slip rate to estimate M

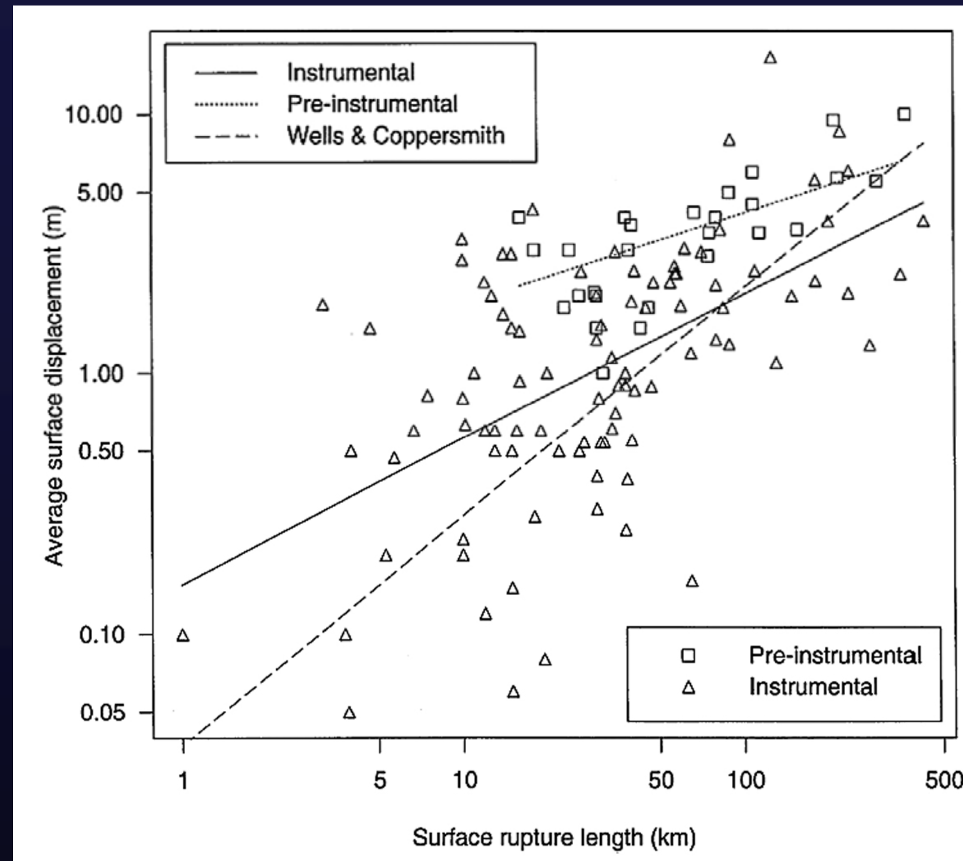
Regressions

- Wells and Coppersmith, 1994
- Hanks and Bakun, 2002 - suggest that regression M vs A is bilinear at about M7 events
- Stirling et al., 2002 - considered the idea that smaller surface rupture events are censored from W and C and thus bias the regression
- Dowrick and Rhoades, 2004 - consider the regional differences that may occur

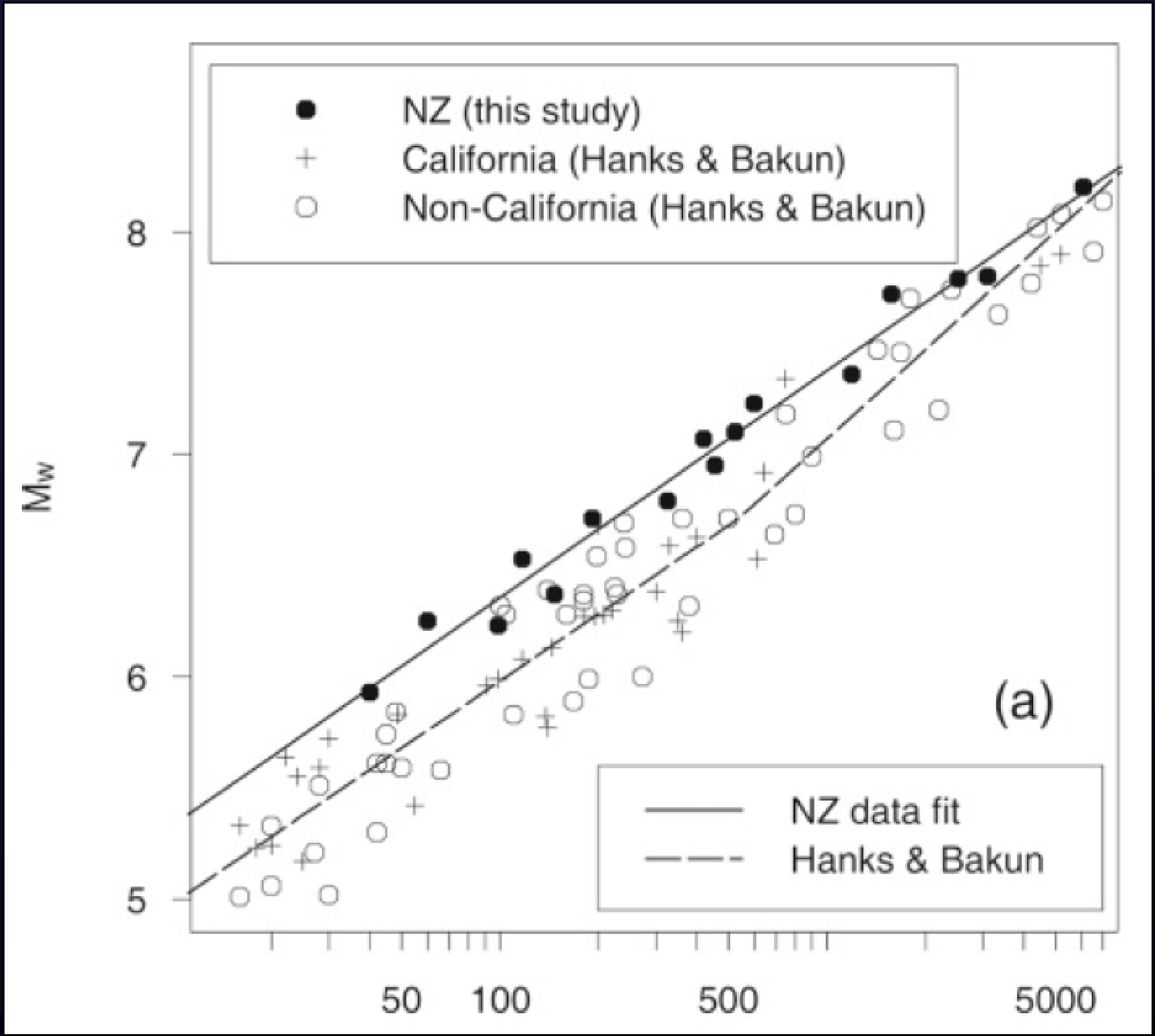


Hanks and Bakun, 2002





From Stirling et al., 2002



From Dowrick and Rhoades, 2004

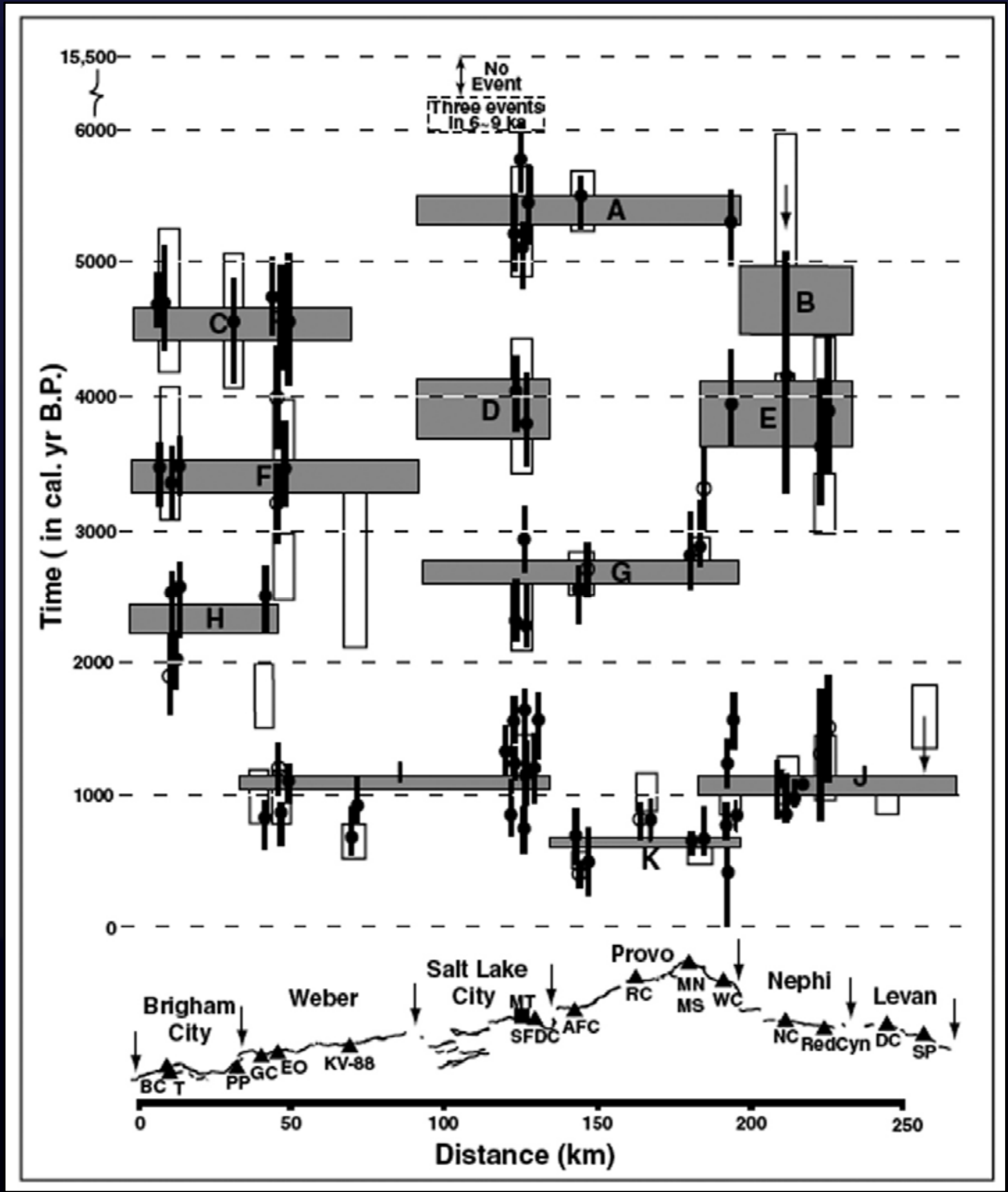
Which individual or weighted combination of magnitude regressions (local, regional, global, normal-fault specific, or “all” fault types) are applicable to BRP faults?

Which fault parameter is preferred (e.g., surface-rupture length, displacement, slip rate)?

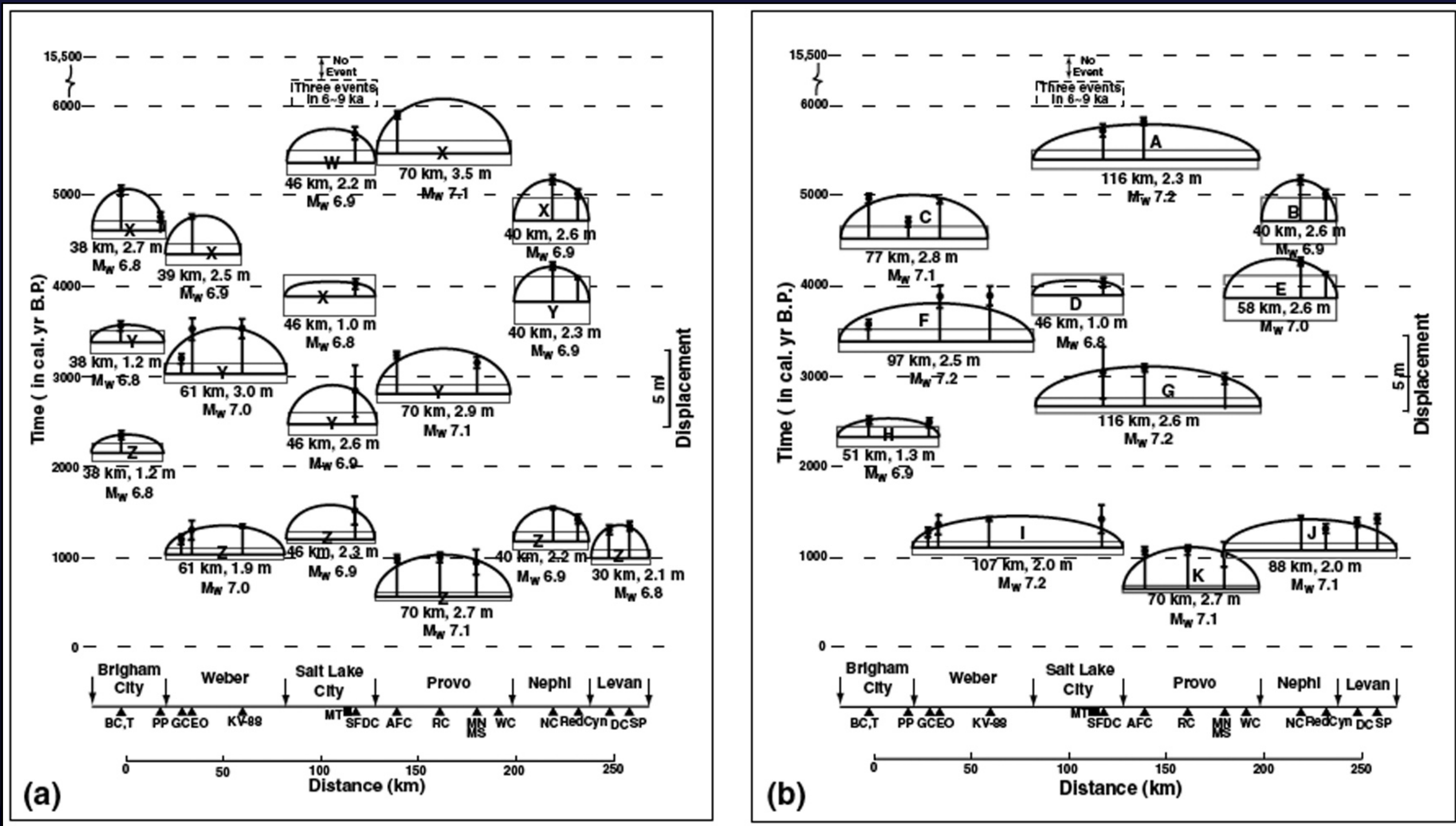
Which individual or weighted combination of magnitude regressions (local, regional, global, normal-fault specific, or “all” fault types) are applicable to BRP faults?

Which fault parameter is preferred (e.g., surface-rupture length, displacement, slip rate)?

Paleoseismic suggestions of multi-segment ruptures on the Wasatch fault

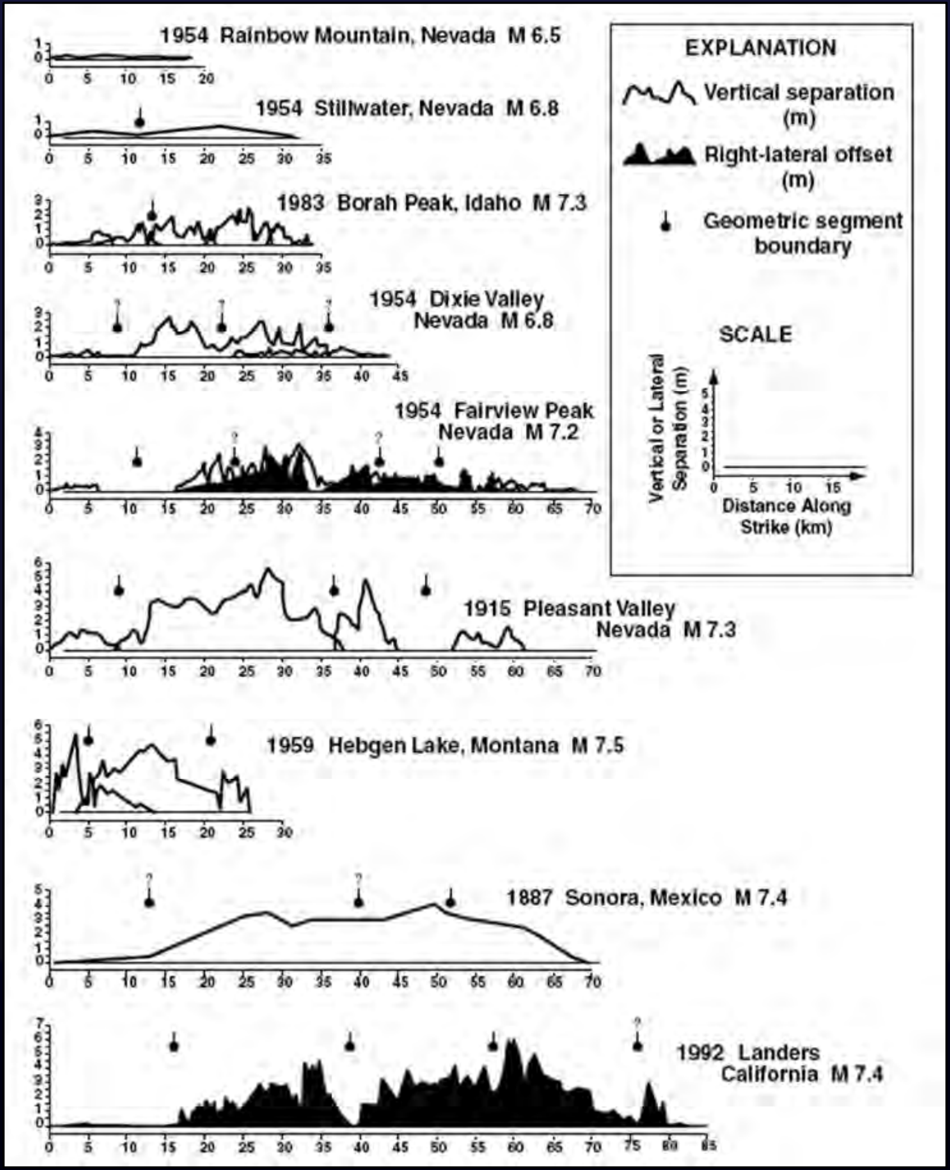


From Chang and Smith, 2002



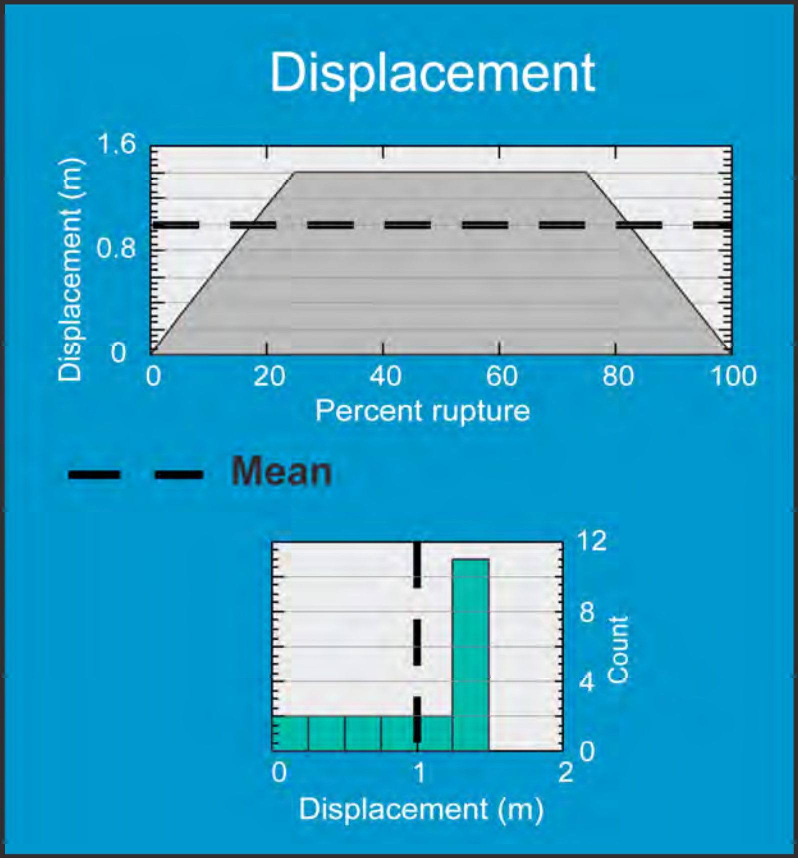
From Chang and Smith, 2002

Numerous examples of multi-segment rupture in B&R and ISB



From Pezzopane and Dawson, 1996 via Chang and Smith, 2002

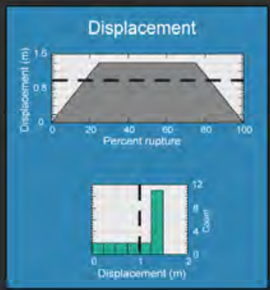
Synthetic rupture model

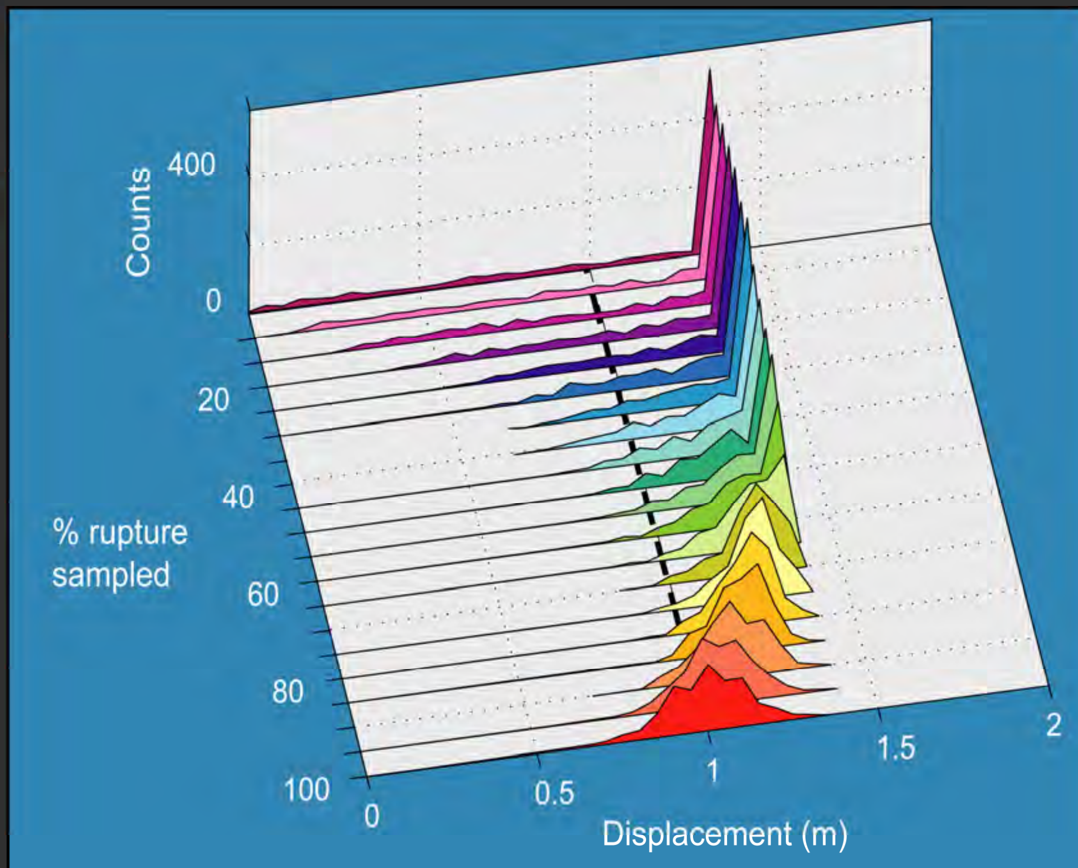


Creating stats from the synthetic data

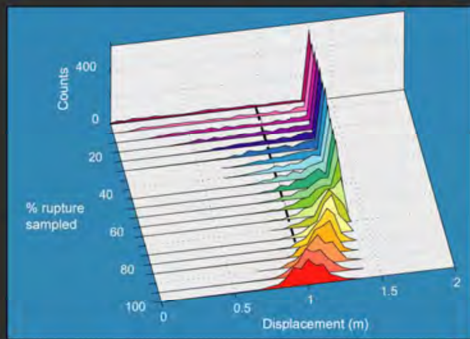
- use a large iteration Monte-Carlo sampling algorithm
- a “window” of prescribed length randomly “drops” onto the rupture distribution and randomly selects sampling locations
- 1000 iterations per 5% increment in fault length
- sample mean, mode, and 95% confidence limits collected

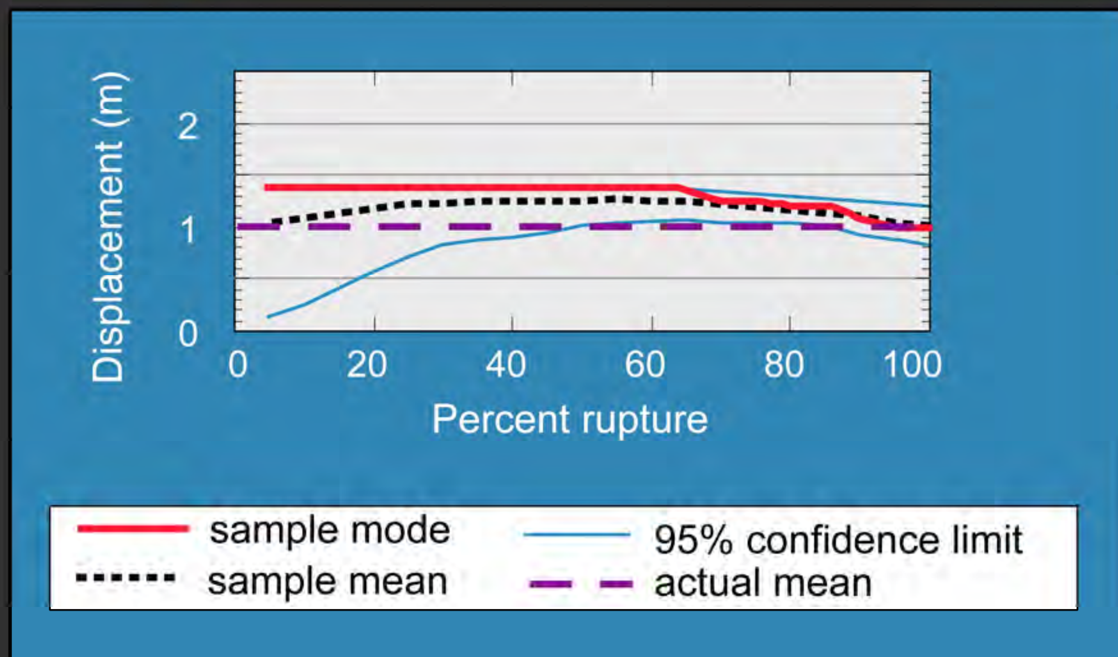
Synthetic model sampling distribution

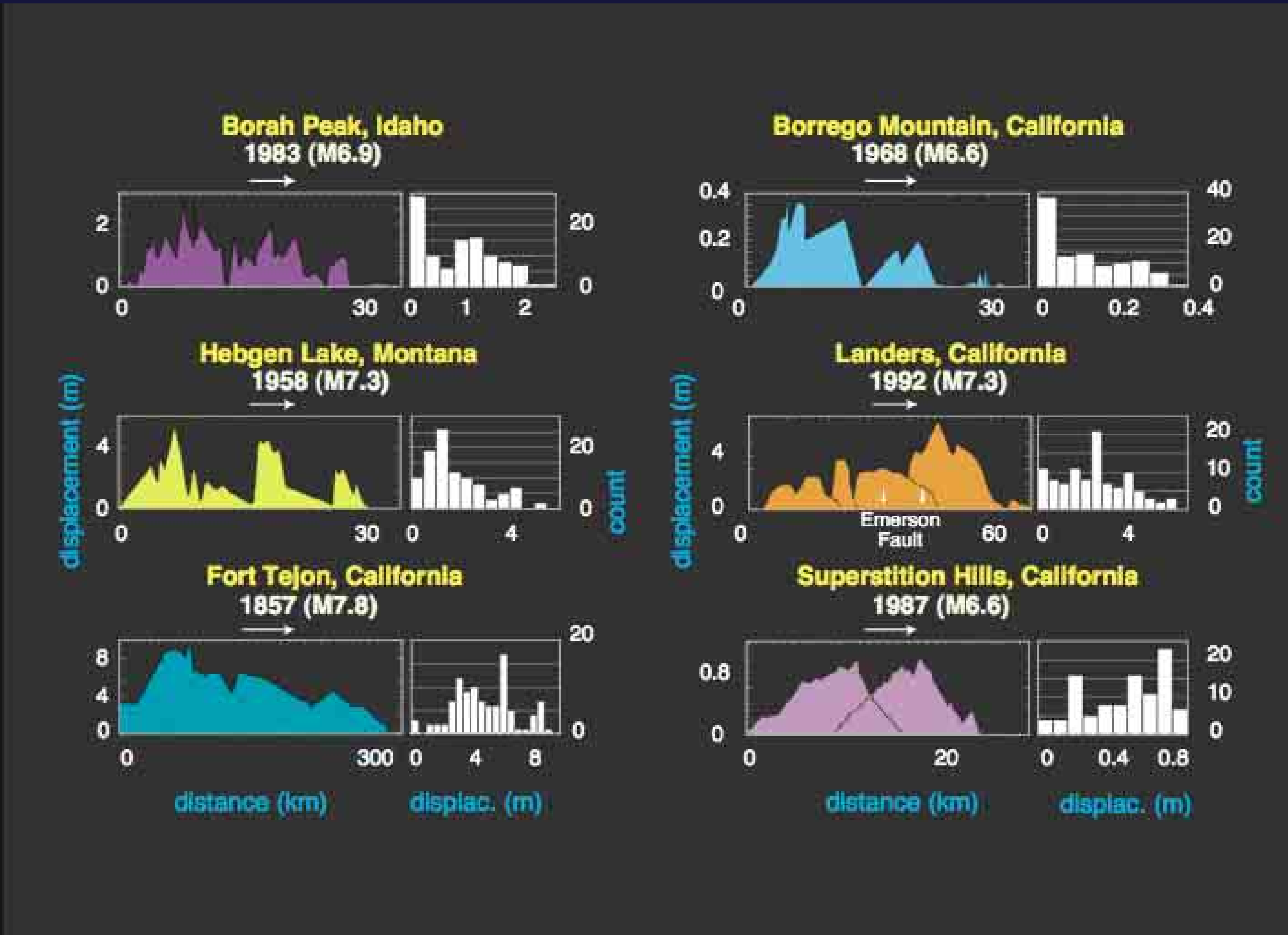




Synthetic model sampling stats







Borah Peak, Idaho
1983 (M6.9)
Borrego Mountain, California
1968 (M6.6)
Hebgen Lake, Montana
1958 (M7.3)
Landers, California
1992 (M7.3)
Emerson Fault
Fort Tejon, California
1857 (M7.8)
Superstition Hills, California
1987 (M6.6)
displacement (m)
count
distance (km)
displac. (m)

Instrumental vs. Preinstrumental Earthquake Scaling Relations

Stirling, Rhoades, and Berryman

BSSA 92, 812-830

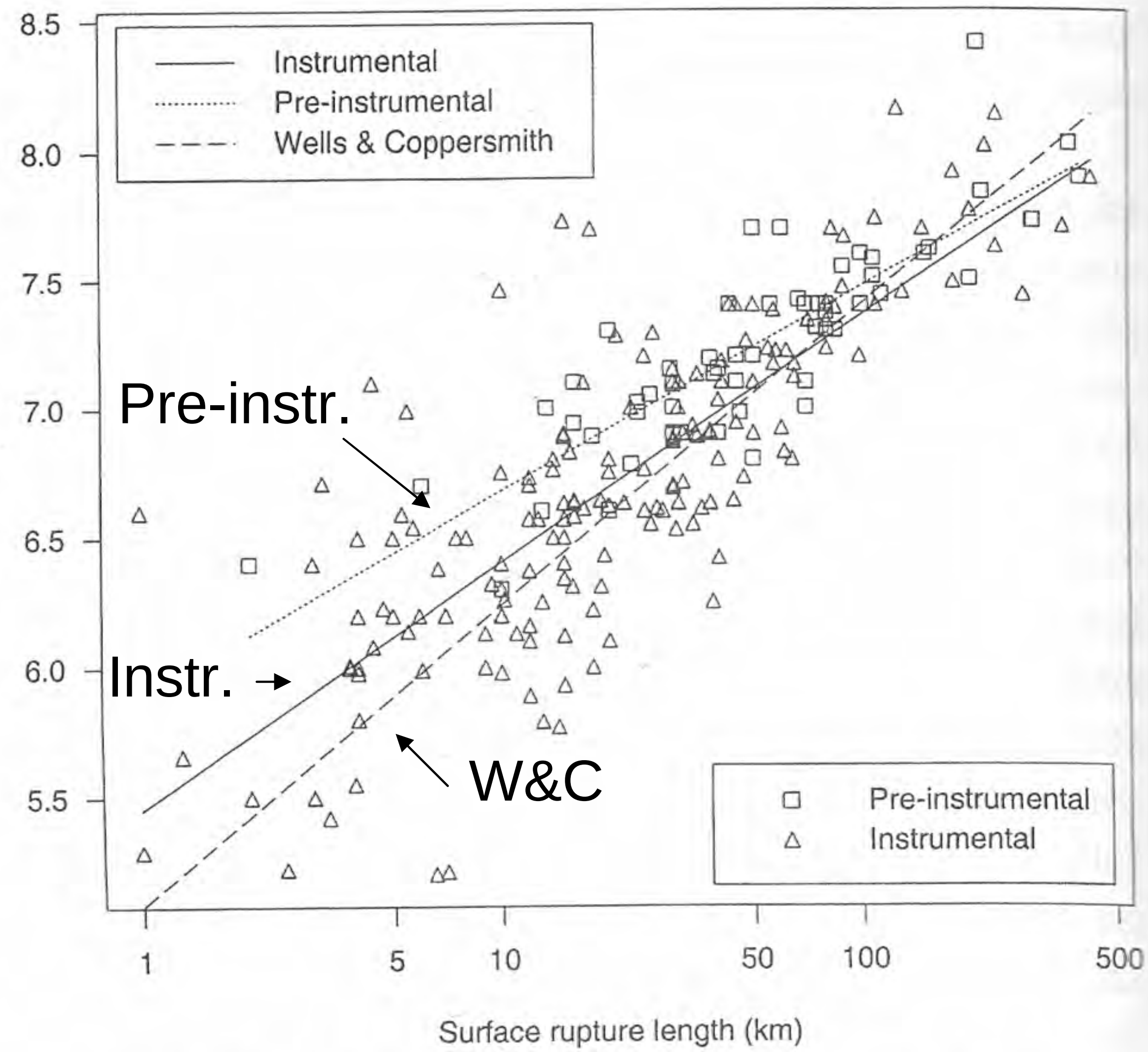


Figure 1. Regressions of magnitude versus surface rupture length for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters *a* and *b* for each of the regressions.

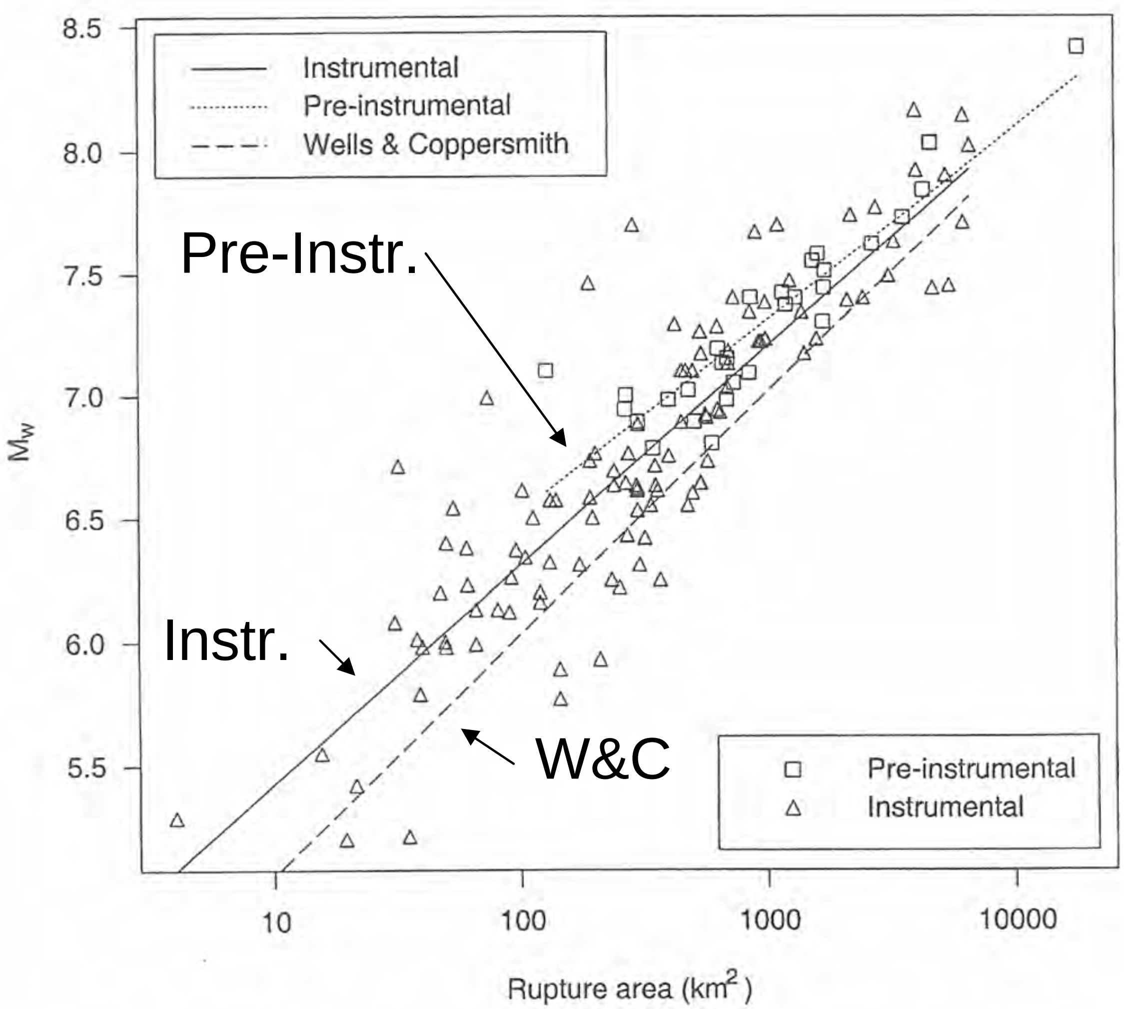


Figure 2. Regressions of magnitude versus an approximation of rupture area (i.e., derived from surface rupture length × rupture width) for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters *a* and *b* for each of the regressions.

Magnitude vs. Area - Pre-instrumental vs. instrumental

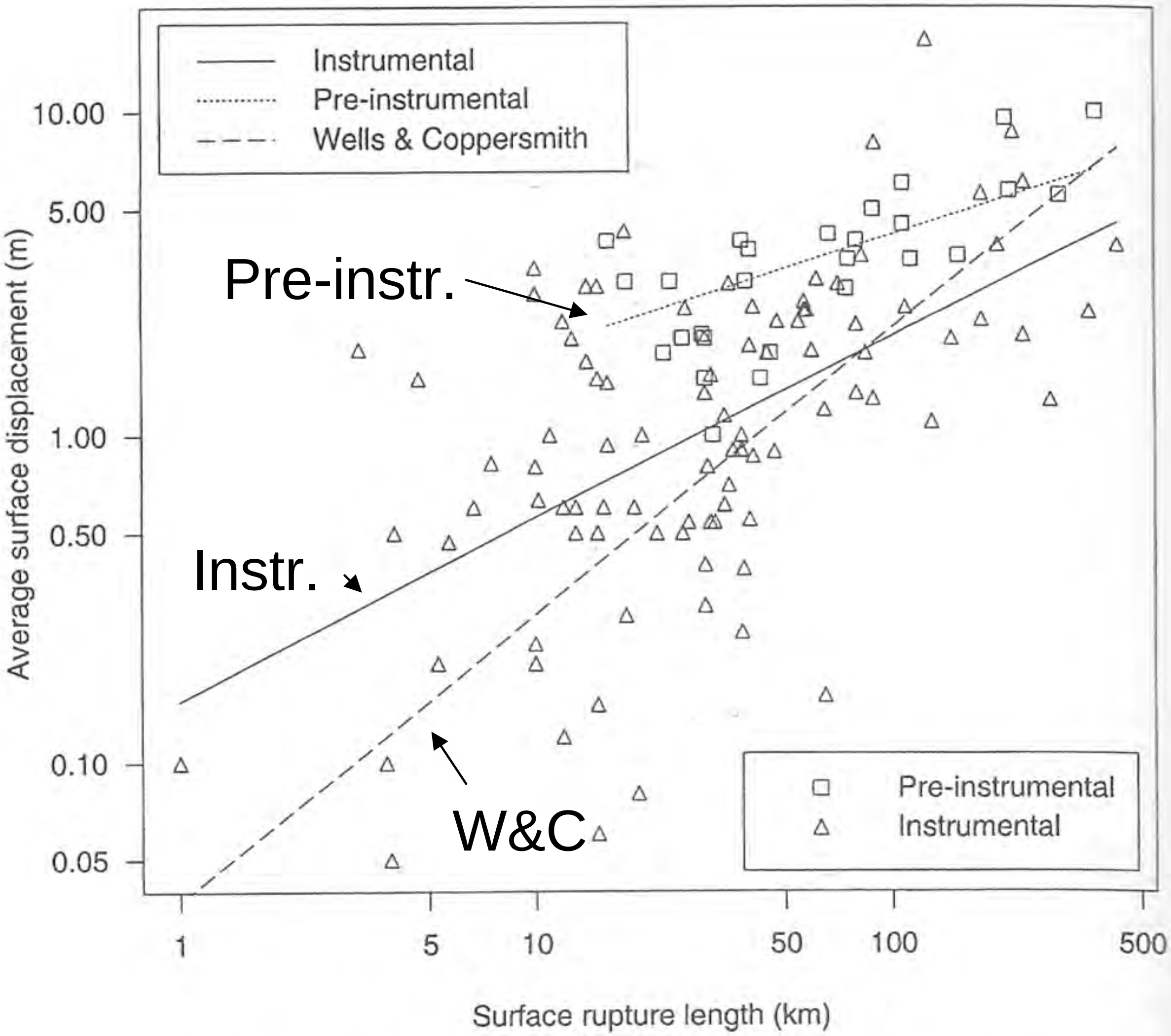


Figure 3. Regressions of average surface rupture displacement versus surface rupture length for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters *a* and *b* for each of the regressions.

AD vs. SRL

Scatter in AD for ruptures shorter than 50 km is huge.

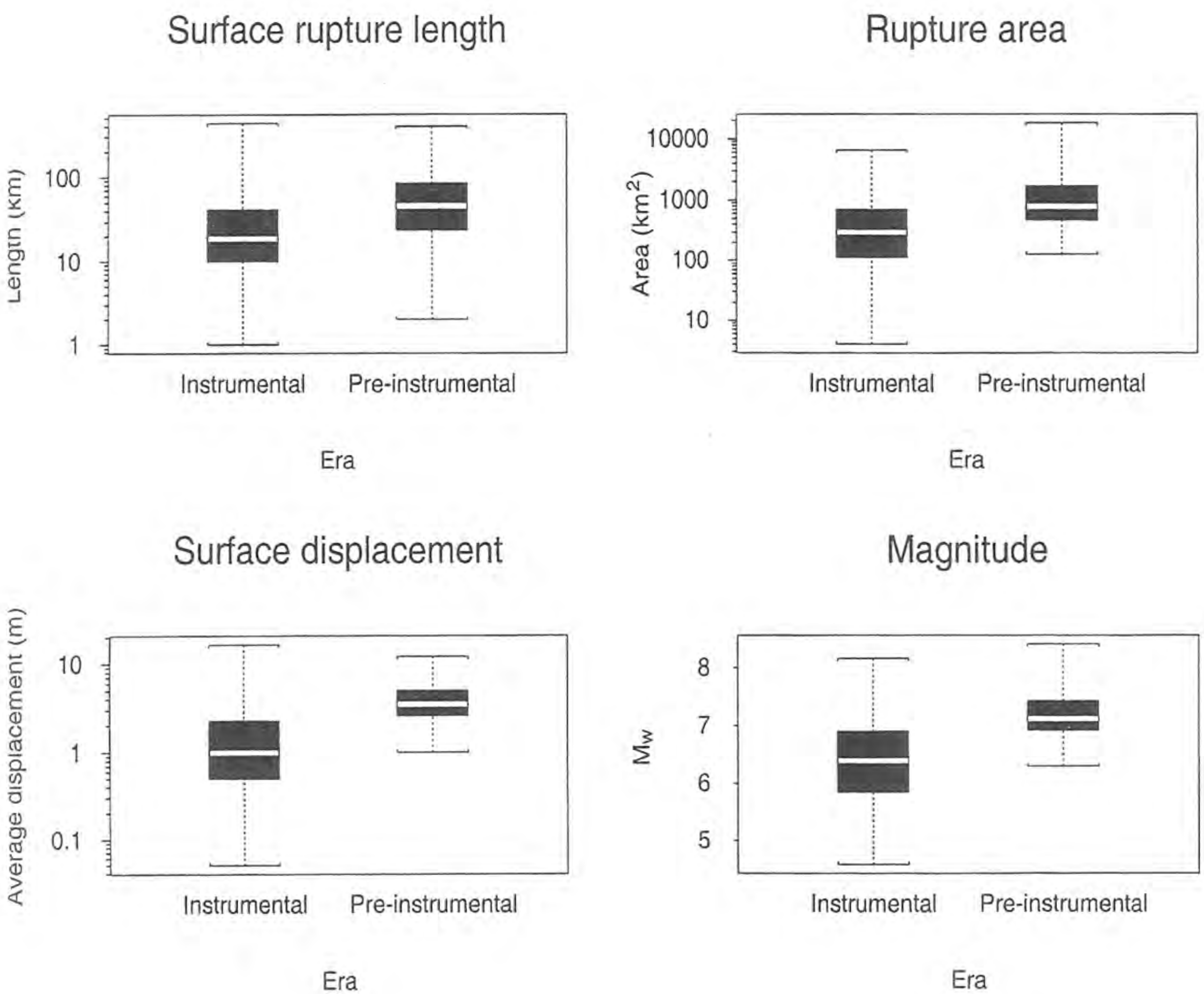


Figure 4. Box plots of the instrumental and preinstrumental data. The plots show the distributions of surface rupture length, rupture area, surface displacement, and magnitude for earthquakes in the two main subsets of our database. For each plot the box defines the interquartile range and the whiskers extend to the extremes of the data. The median is also indicated.

As a dataset the pre-instrumental earthquakes are larger, longer, and have larger average displacements.

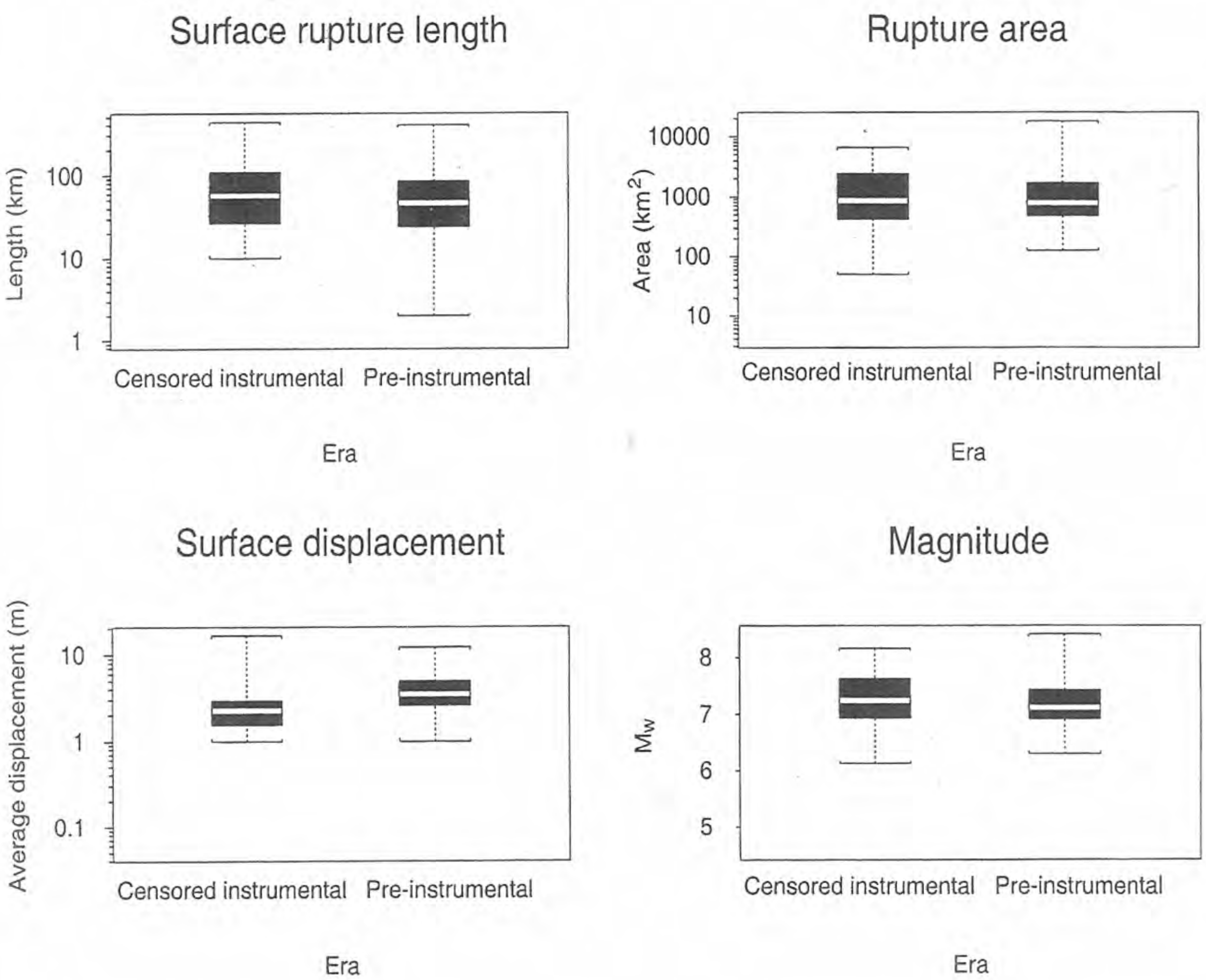


Figure 5. Box plots of the instrumental (censored, i.e., excluding all events with rupture lengths less than 10 km, rupture areas less than 200 km^2, average surface displacements less than 2 m, and $M_w < 6.5$) and preinstrumental earthquakes (cf. Fig. 4).

Instrumental data censored for L<10 km, A<200 km^2, AD < 2 m, & Mw < 6.5. Equivalence shows that larger events of the preinstrumental era track with modern equivalents.

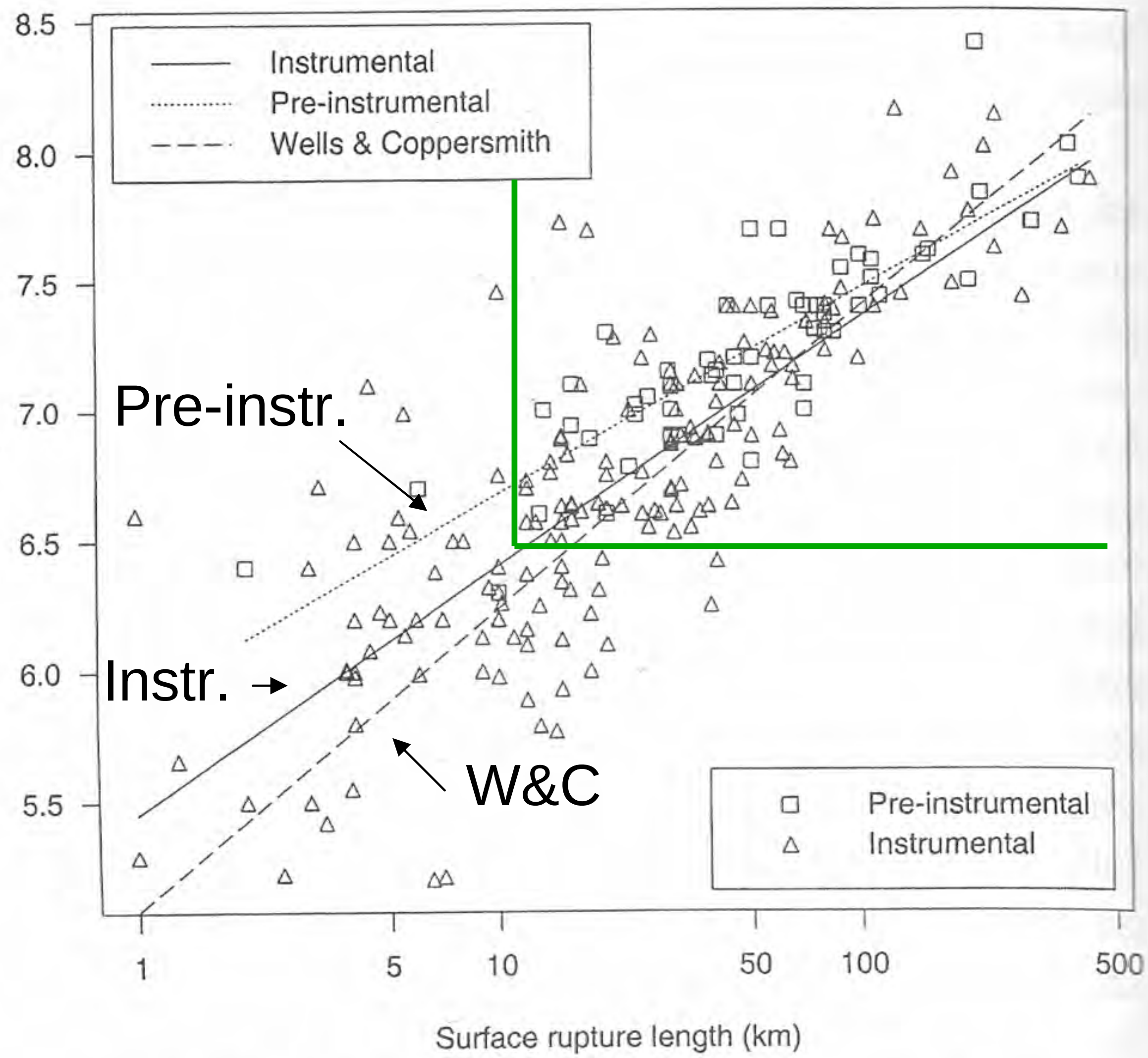
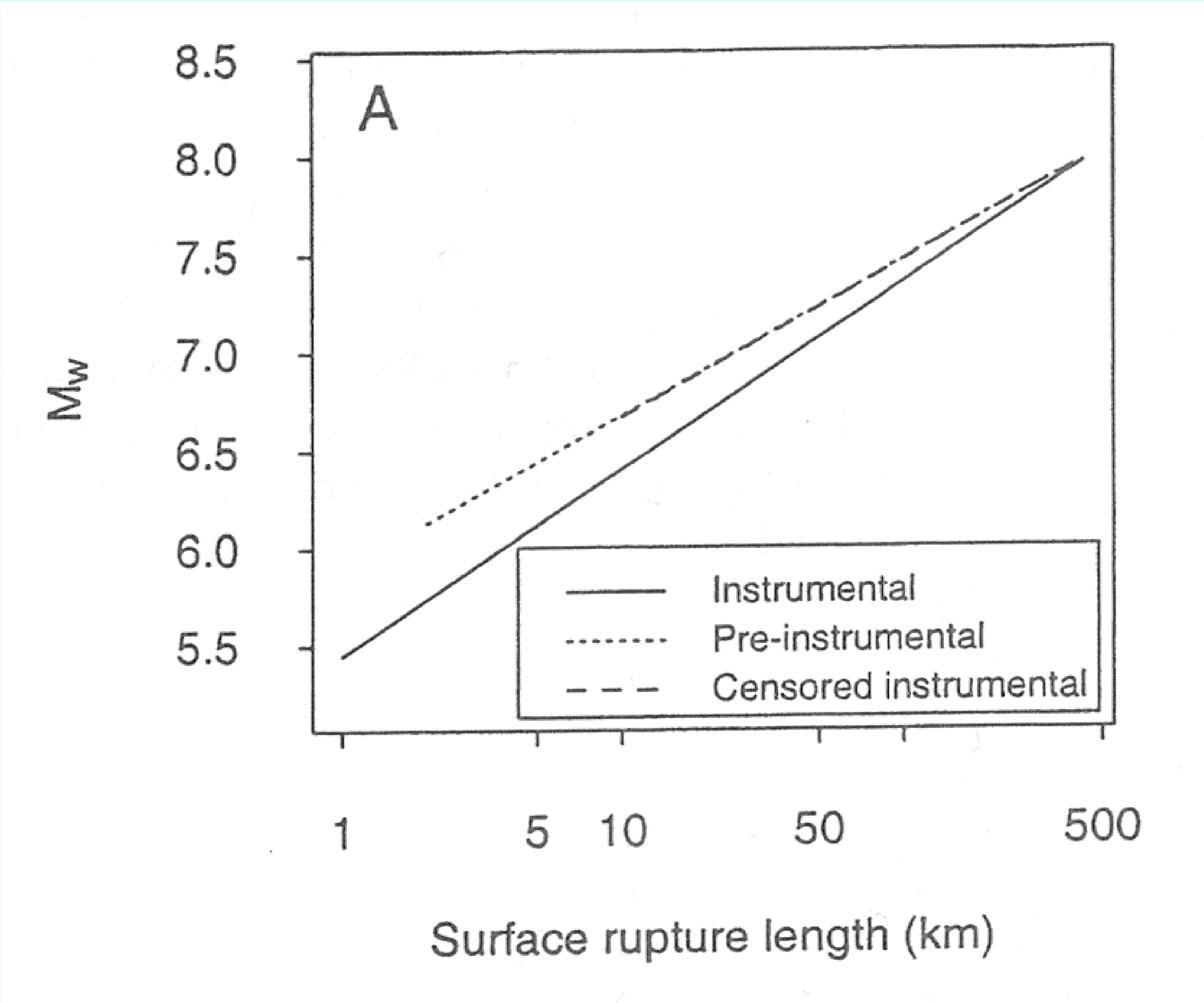


Figure 1. Regressions of magnitude versus surface rupture length for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters *a* and *b* for each of the regressions.



Mw vs SRL

Instrumental as a whole is drawn down by long ruptures of low M6 events.

Magnitude vs. Area - Pre-instrumental vs. instrumental

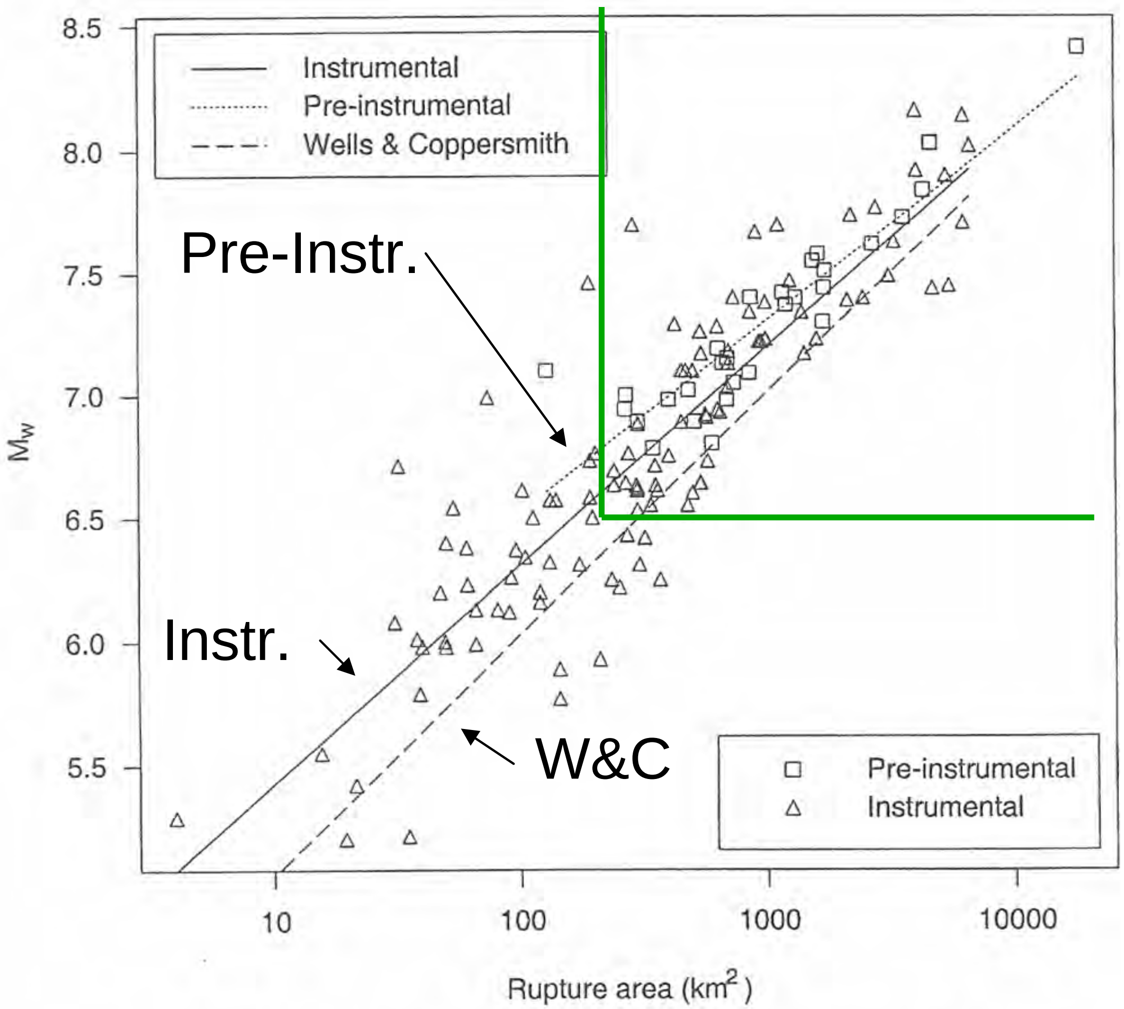
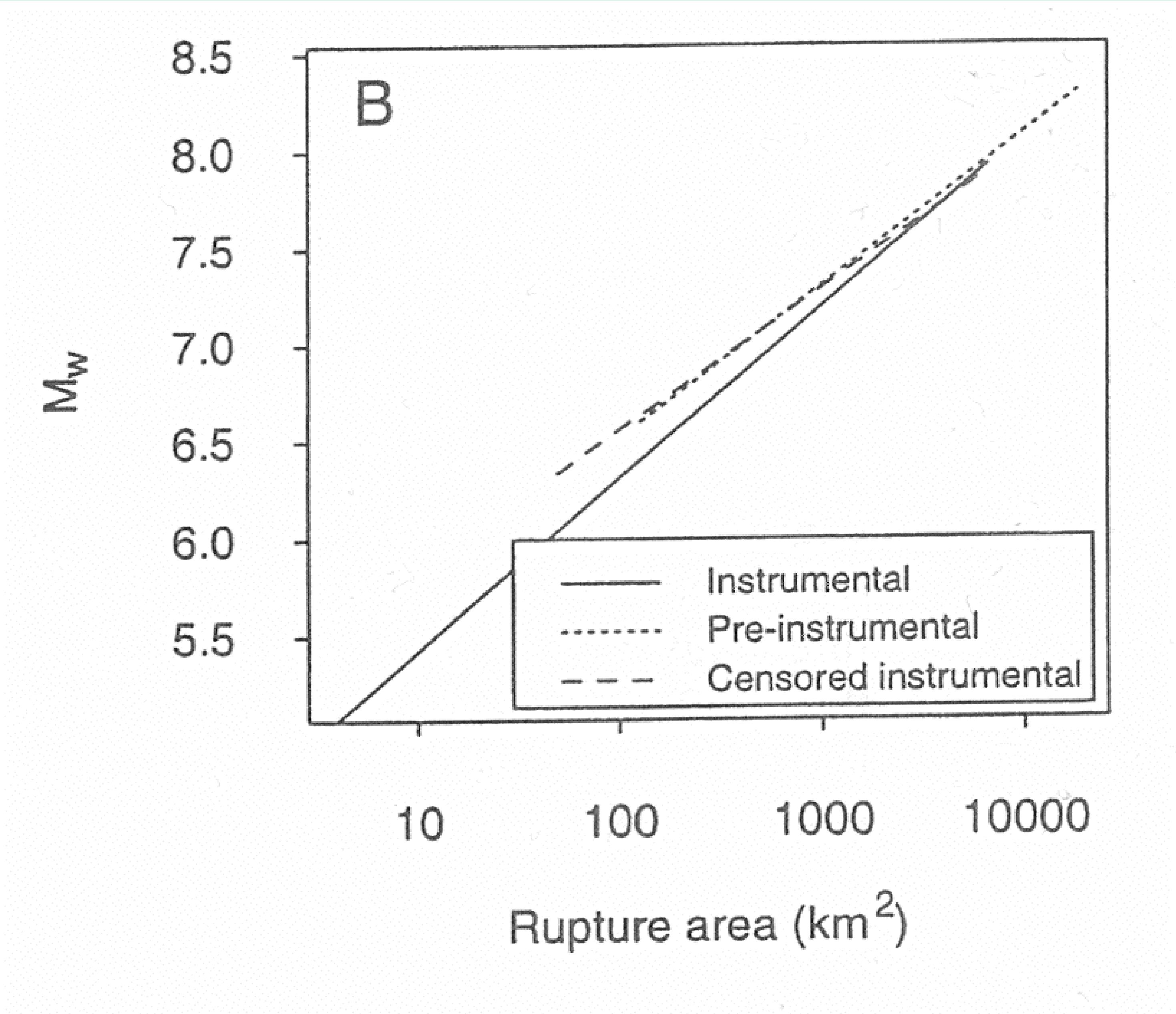


Figure 2. Regressions of magnitude versus an approximation of rupture area (i.e., derived from surface rupture length × rupture width) for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters *a* and *b* for each of the regressions.

Mw vs. Rupture Area



Mw = 0.73*log(A) + 5.09, 6.1<=Mw<=8.1, 50<A<7000 km^2

AD vs. SRL

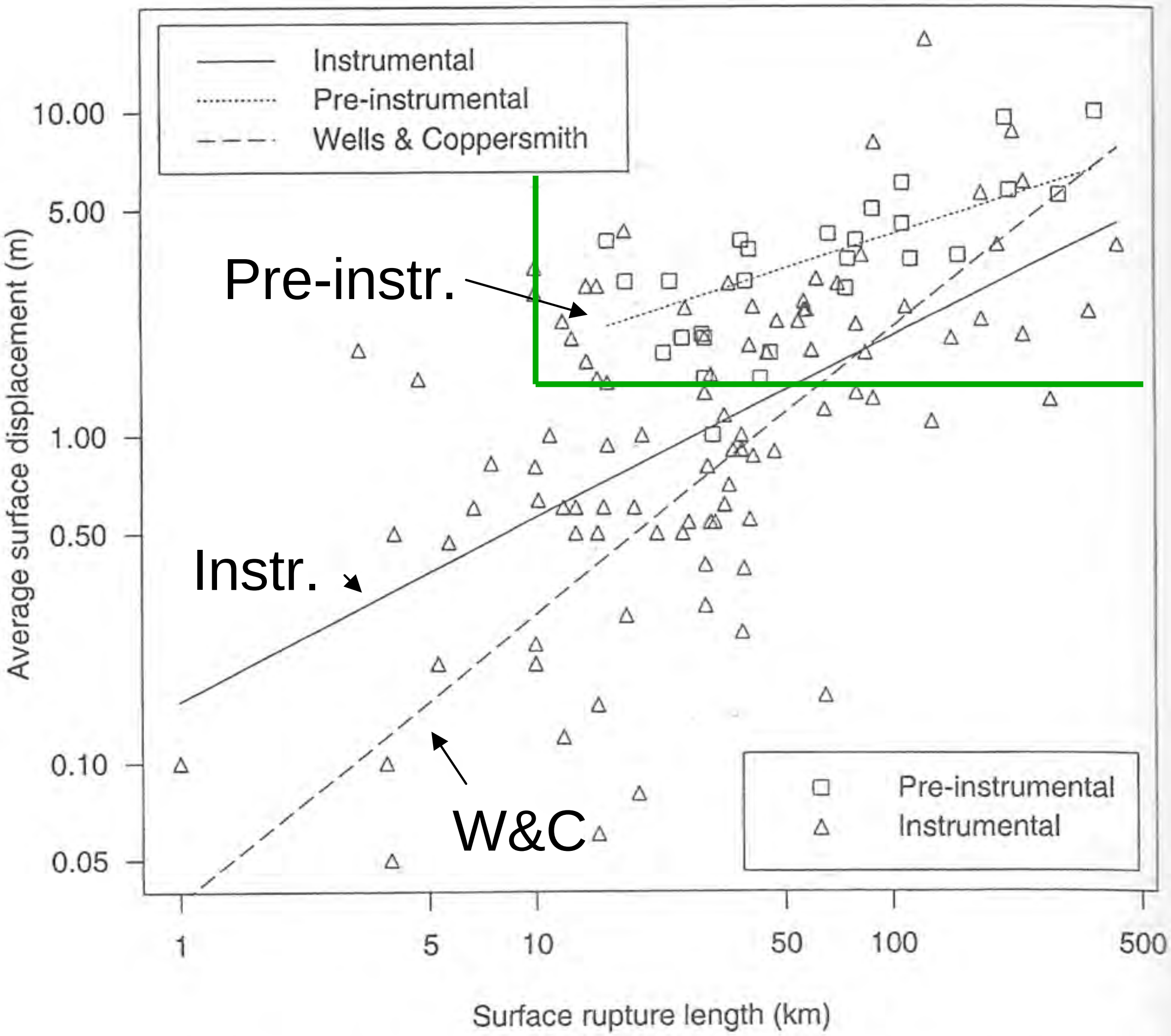


Figure 3. Regressions of average surface rupture displacement versus surface rupture length for our worldwide instrumental dataset, the worldwide pre-1900 preinstrumental dataset, and the original regressions of Wells and Coppersmith. See Table 1 for parameters *a* and *b* for each of the regressions.

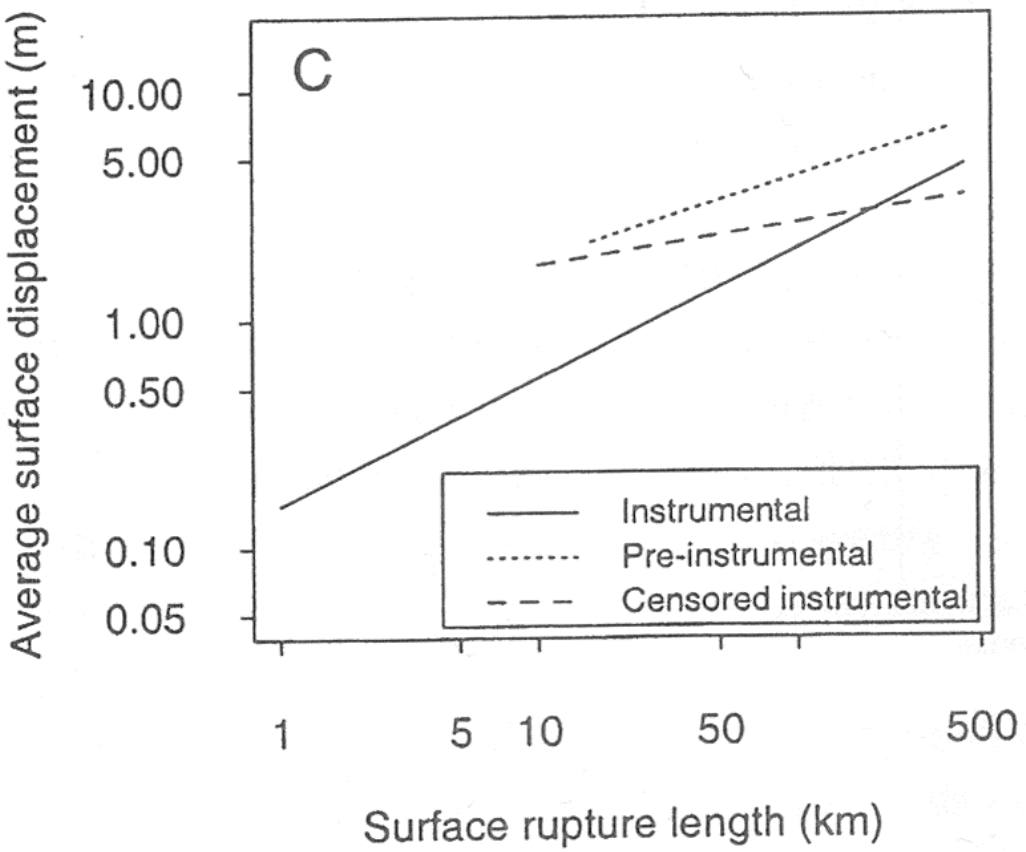


Figure 6. Regression lines compared for the instrumental, preinstrumental, and instrumental censored data: (A) magnitude on surface rupture length, (B) magnitude on rupture area, (C) average surface displacement on surface rupture length.

Average Surface Displacement vs. SRL.

-- AD is a weak predictor of SRL

-- SRL predictions strongly sensitive to AD

Conclusions

- W&C regression estimates of Mw and average surface displacement are significantly low.
- Difference can be explained by censoring by natural geologic processes including scarp degradation.
- Opportunity, value in improved correlations for M 6.5 events?

Magnitude vs. Mw

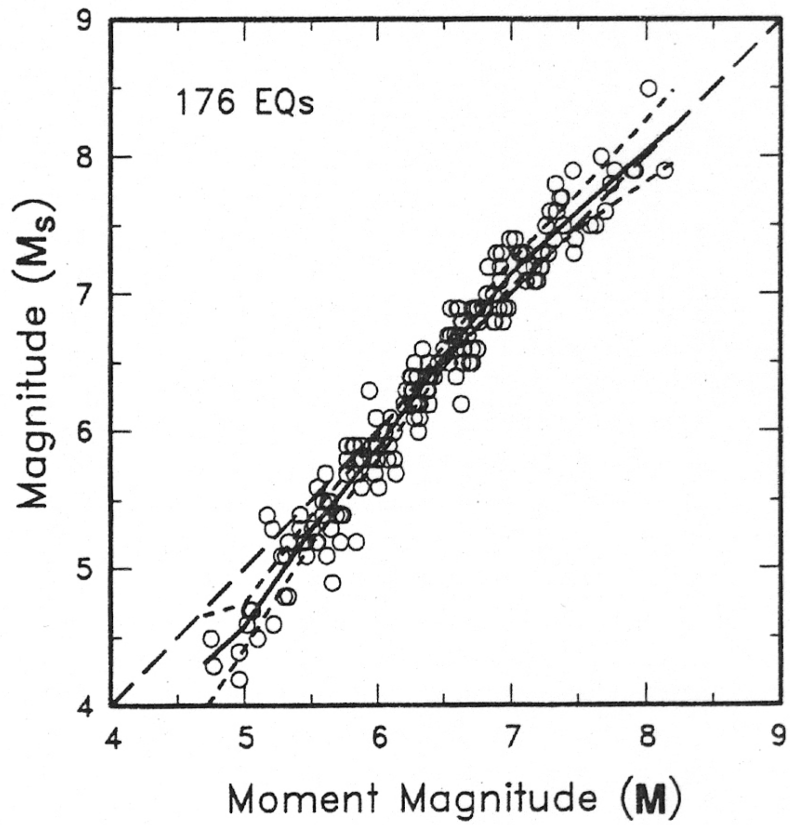


Figure 1. Surface-wave magnitude (M_S) versus moment magnitude (**M**) for historical continental earthquakes. Segmented linear regression shown as solid line, with segment boundaries at **M** 4.7, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, and 8.2. Short dashed lines indicate 95% confidence interval of regression line. Long dashed line indicates equal magnitudes (1 to 1 slope).

SRL vs. Subsurface Rupture Length

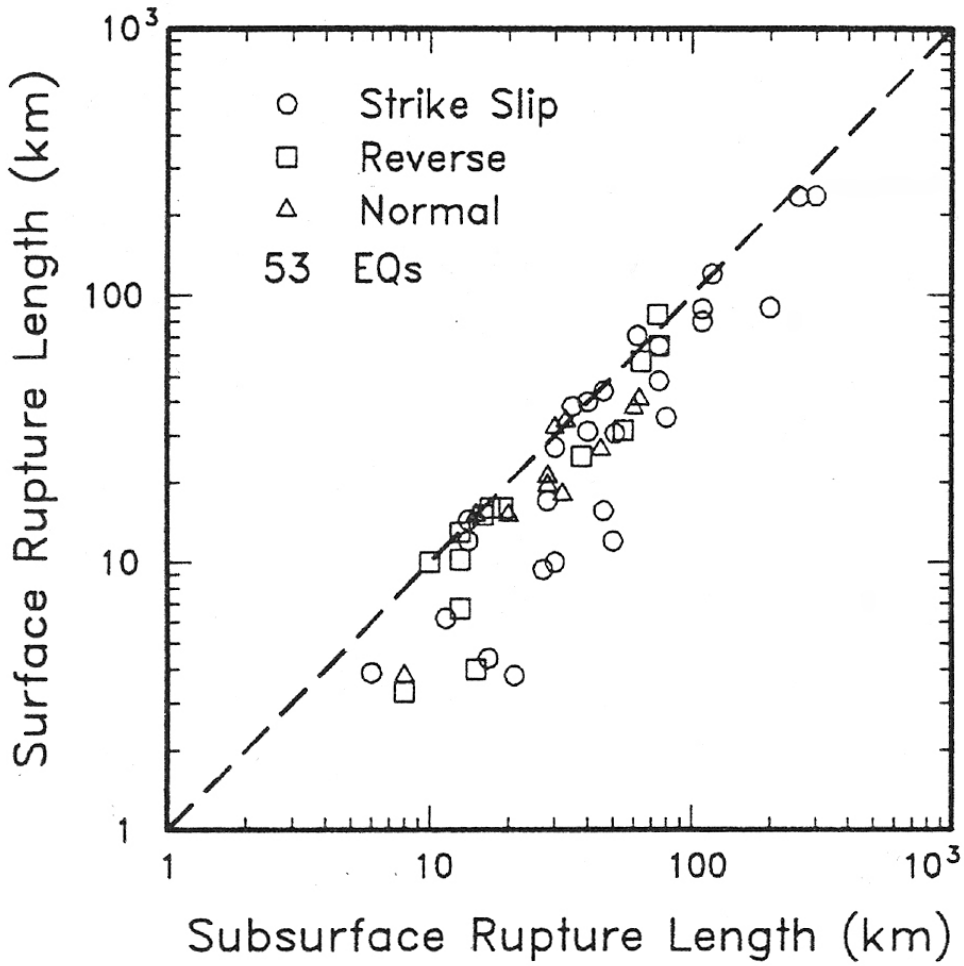


Figure 2. Surface rupture length versus subsurface rupture length estimated from the distribution of early aftershocks of historical continental earthquakes.

Surface/Subsurface Length vs. Magnitude

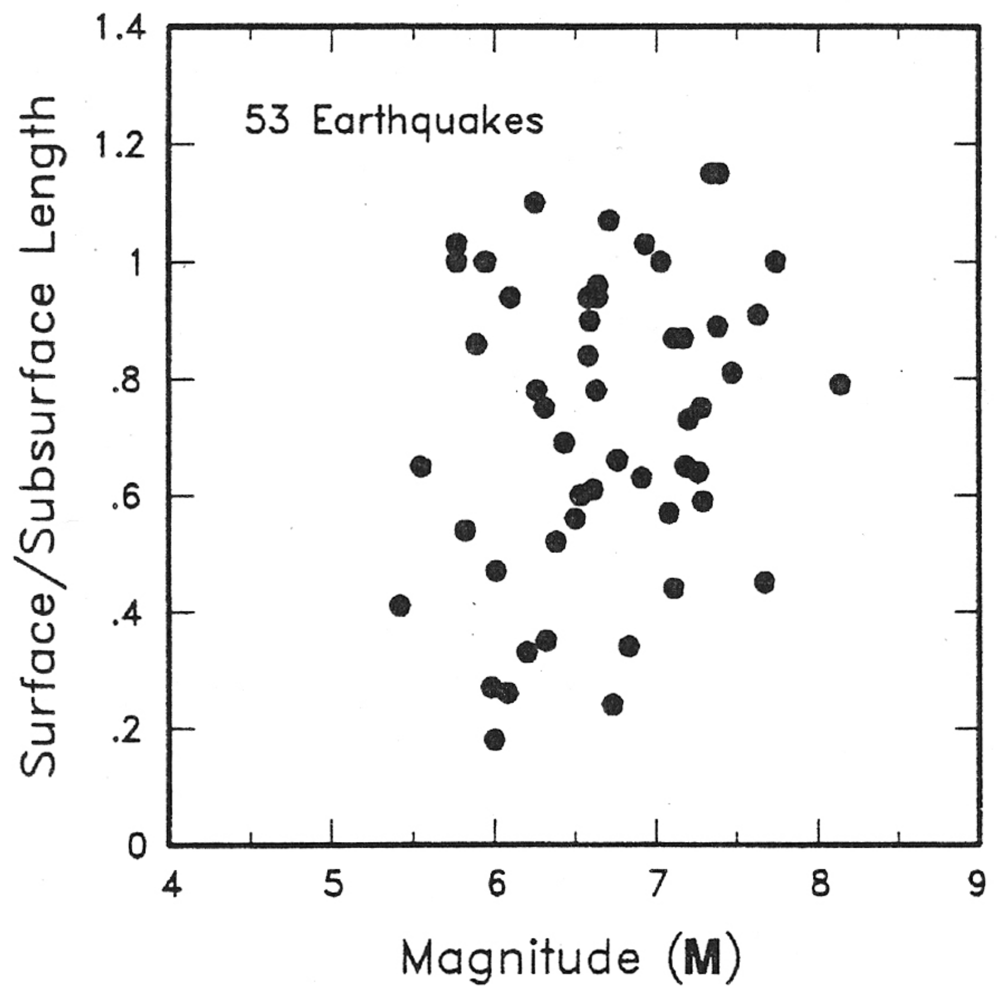


Figure 3. Ratio of surface to subsurface rupture length versus magnitude.

Avg/Max Displacement vs. Magnitude

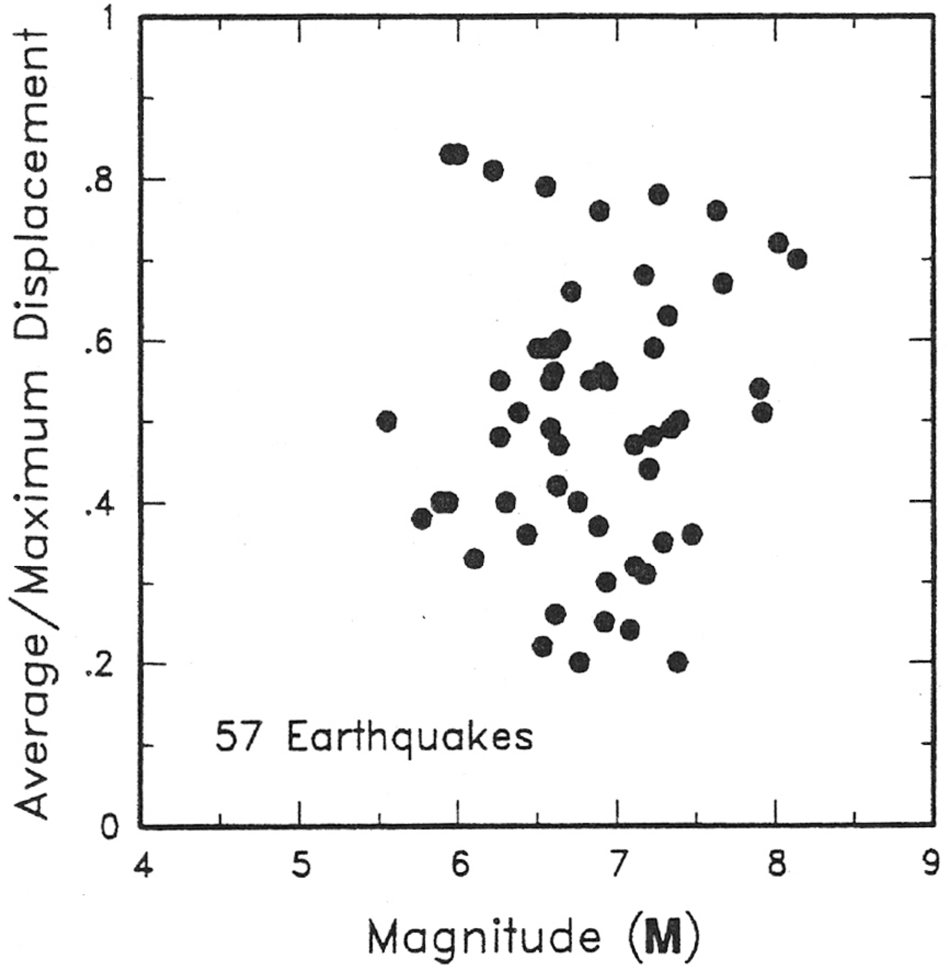


Figure 5. Ratio of average surface to maximum surface displacement versus magnitude.

Magnitude vs. Avg. Subsurface/Max, Avg Surface Displacement

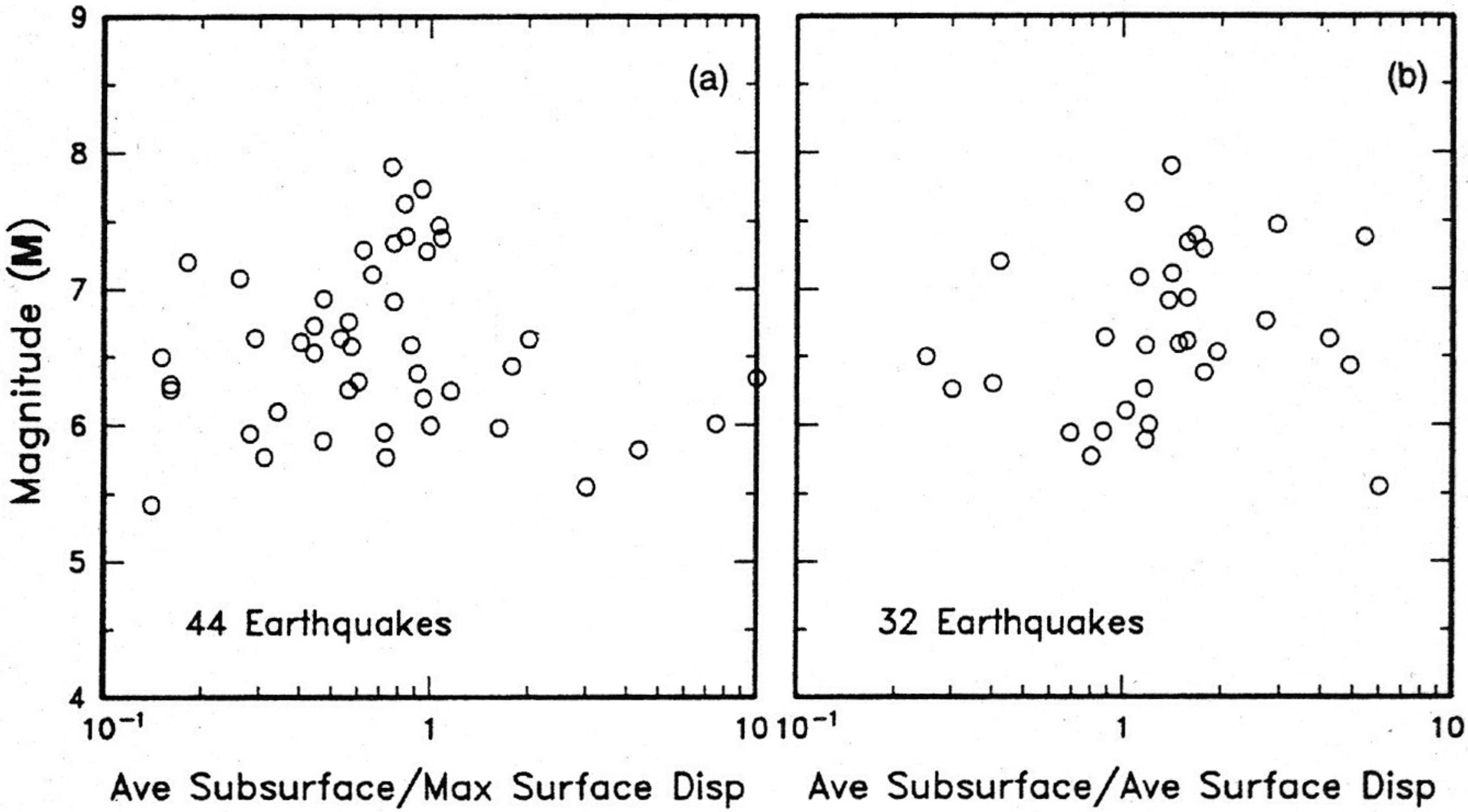


Figure 6. (a) Ratio of average subsurface to maximum surface displacement versus magnitude. (b) Ratio of average subsurface to average surface displacement versus magnitude. Average subsurface displacement is calculated from the seismic moment and the rupture area.

Average Subsurface vs. Max and Avg Surface Displacement

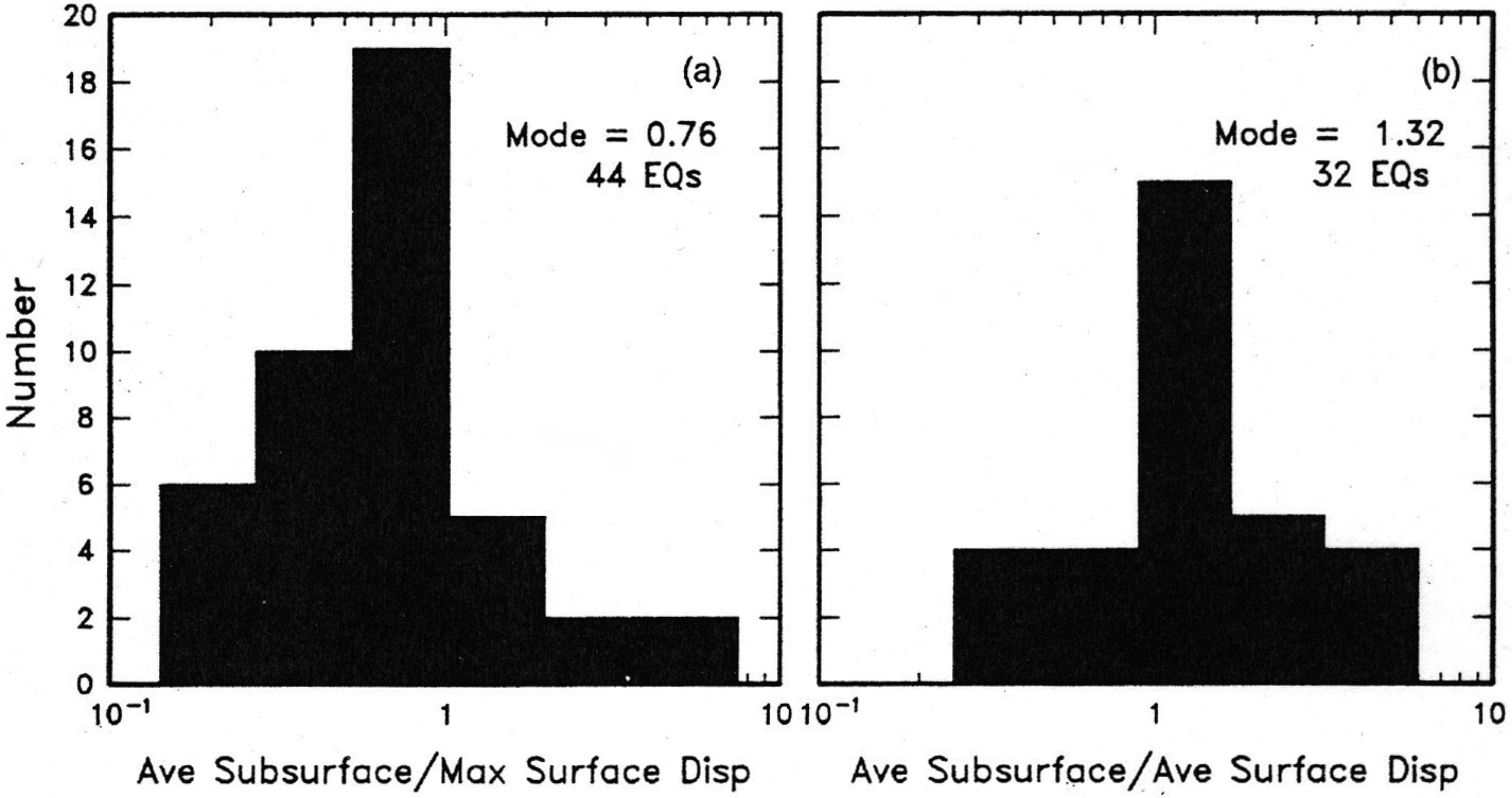


Figure 7. (a) Histogram of the logarithm of the ratio of average subsurface to maximum surface displacement. (b) Histogram of the logarithm of the ratio of average subsurface to average surface displacement. Average subsurface displacement is calculated from the seismic moment and the rupture area.

Residuals vs. SRL and Rupture Area

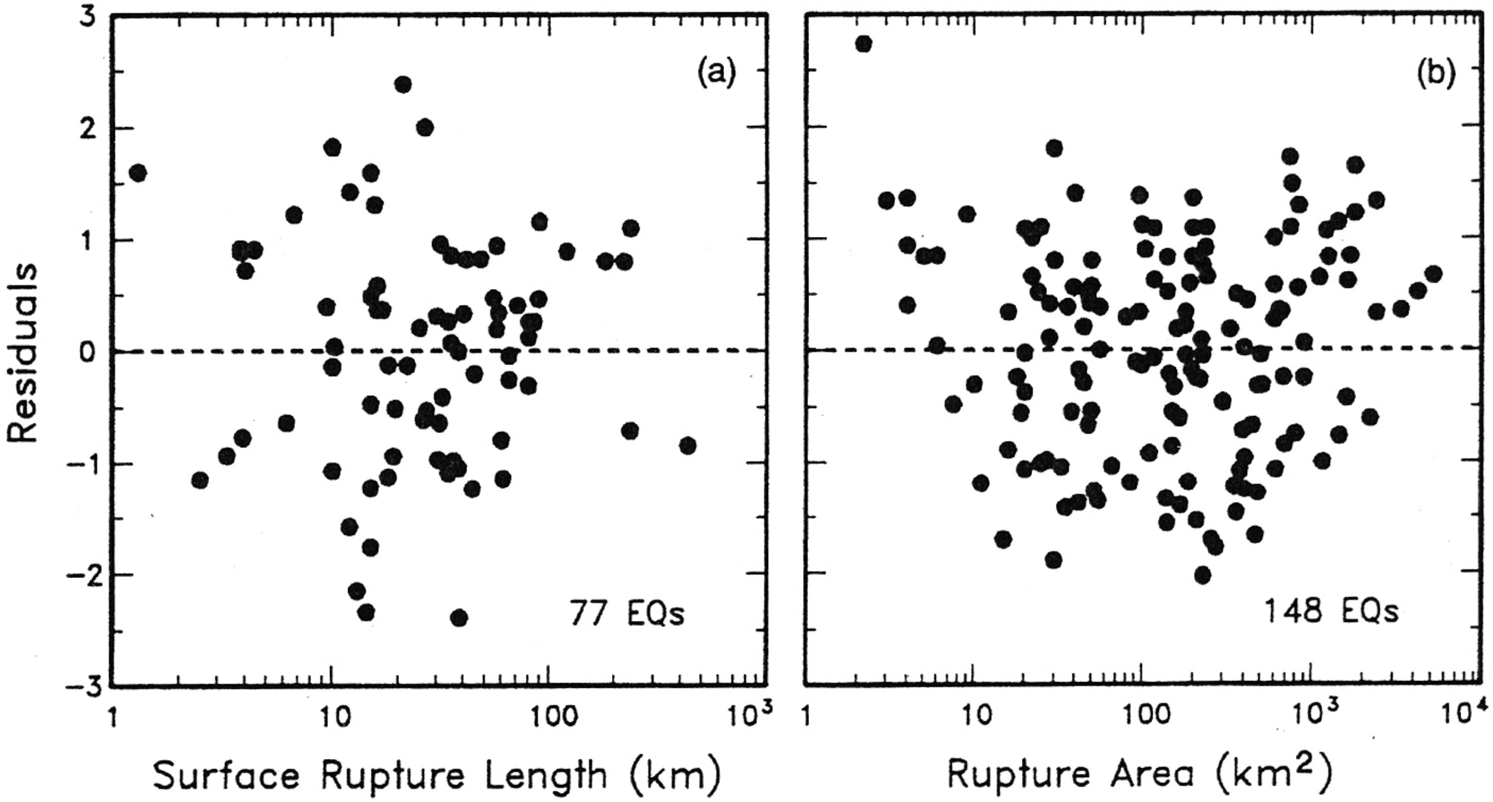


Figure 8. (a) Residuals for surface rupture length regression versus observed surface rupture length. (b) Residuals for rupture area regression versus observed rupture area.

Mw vs. SRL

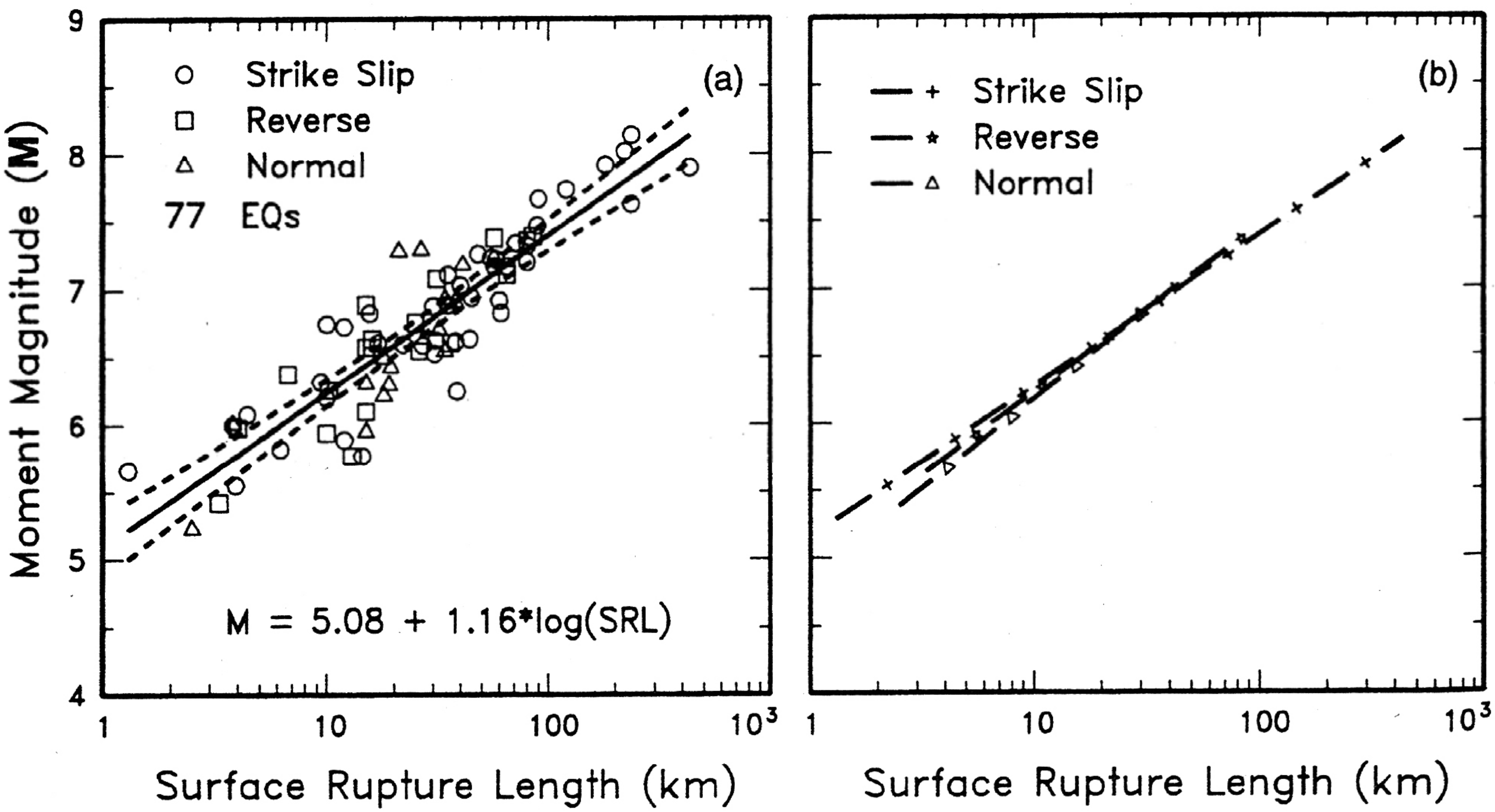


Figure 9. (a) Regression of surface rupture length on magnitude (**M**). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Mw vs. Maximum Displacement

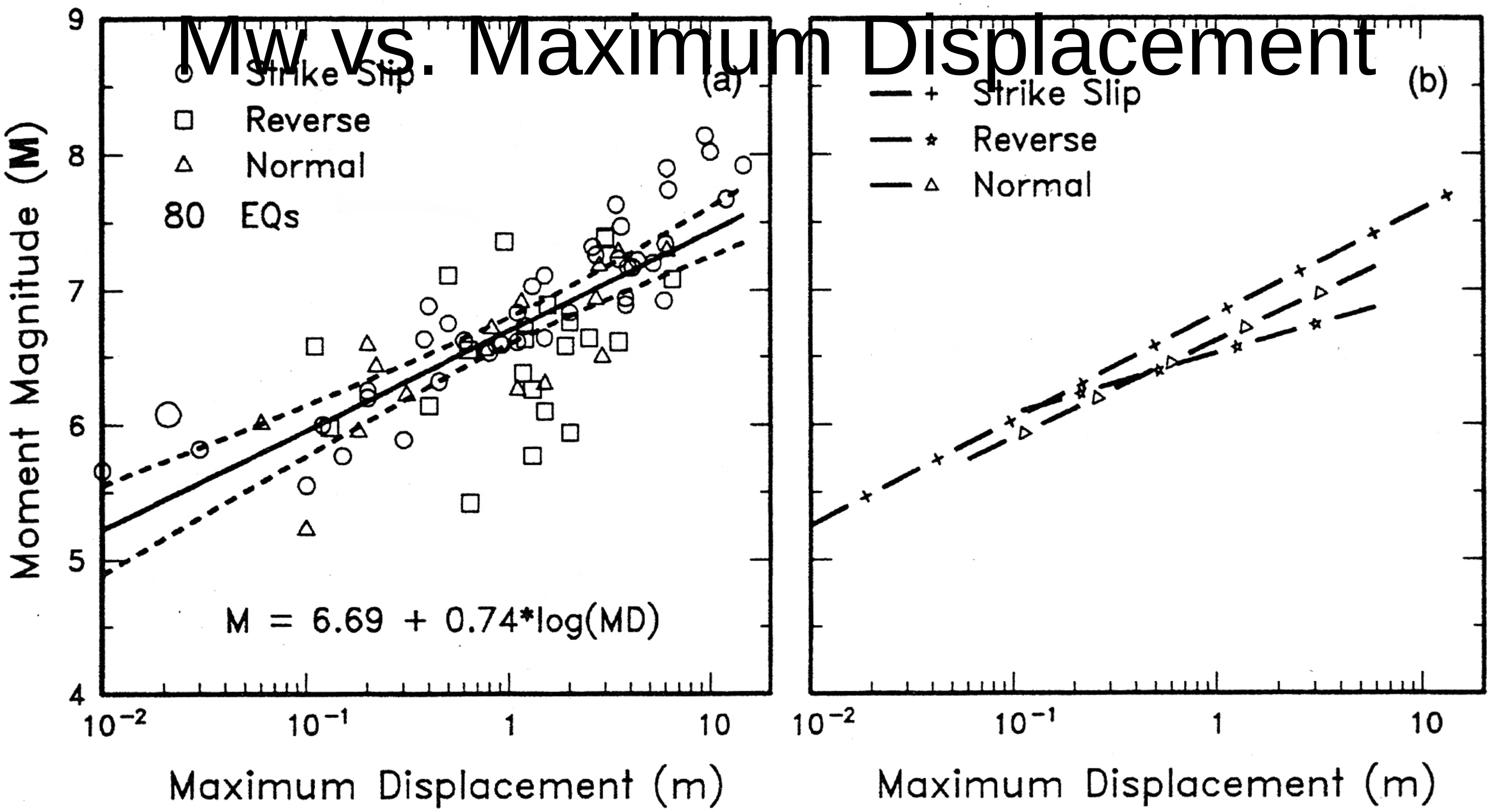


Figure 10. (a) Regression of maximum surface displacement on magnitude (**M**). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Mw vs. Average Displacement

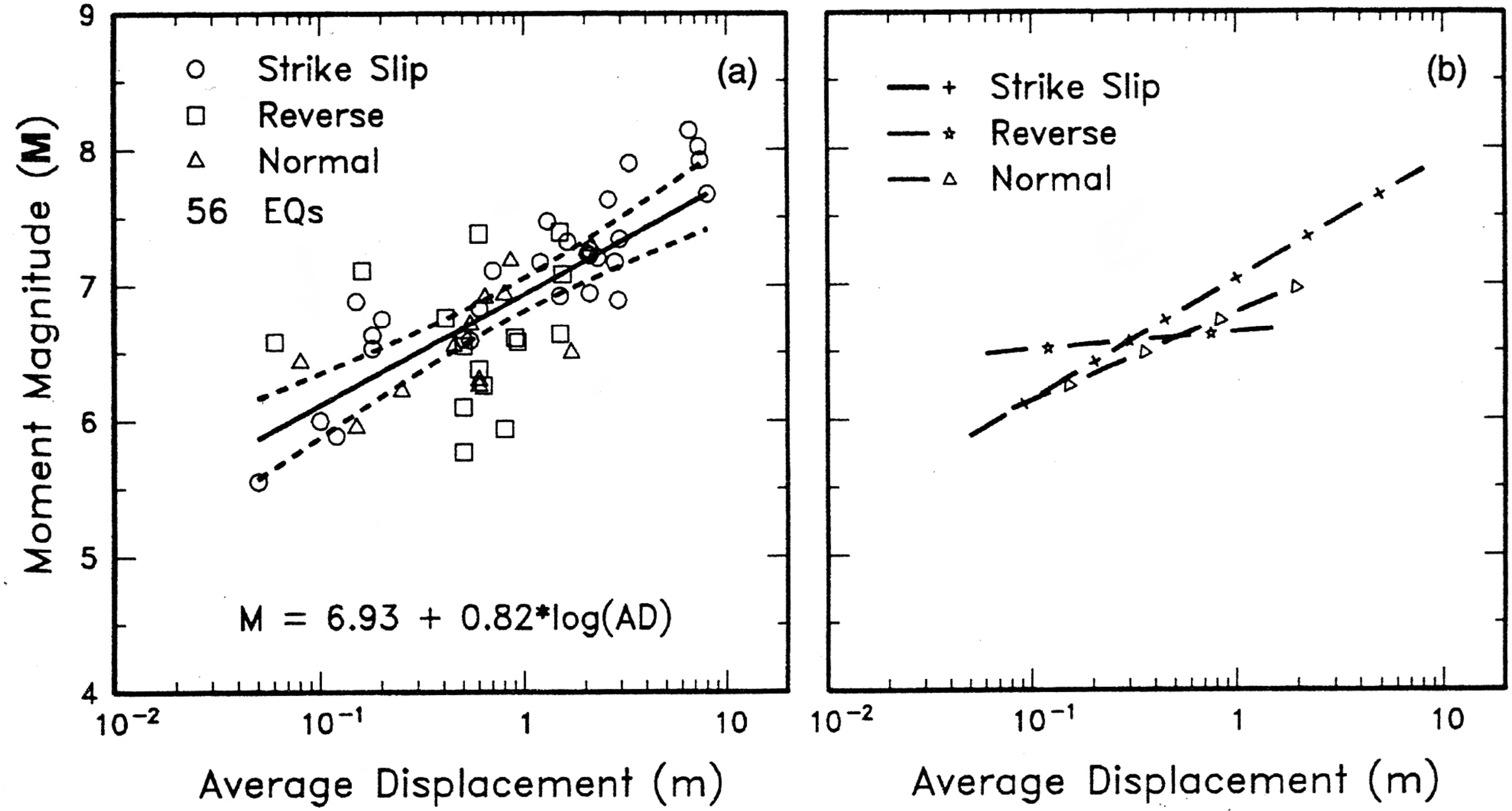


Figure 11. (a) Regression of average surface displacement on magnitude (**M**). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Maximum Displacement vs. SRL

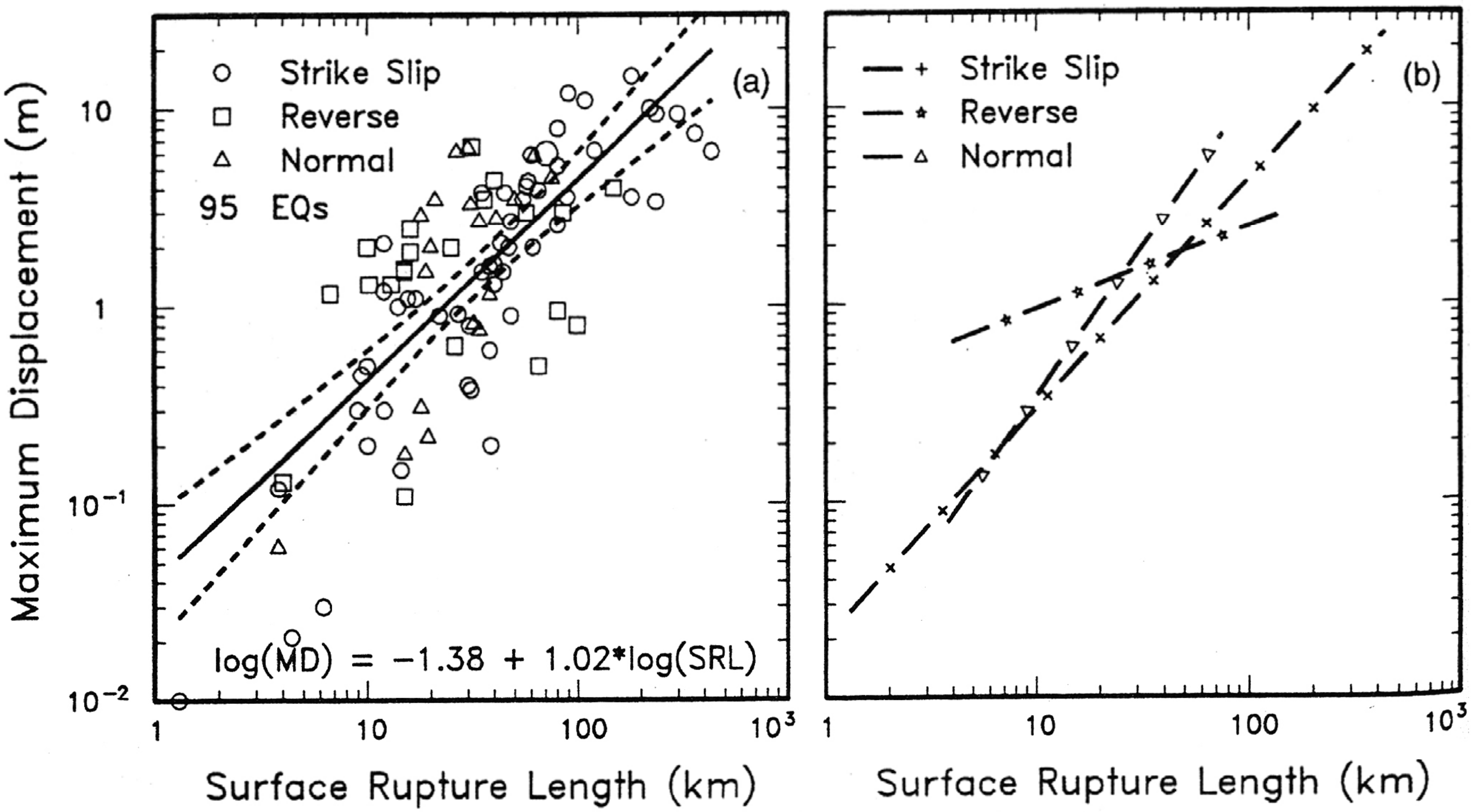


Figure 12. (a) Regression of surface rupture length on maximum displacement. Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Average Displacement vs. SRL

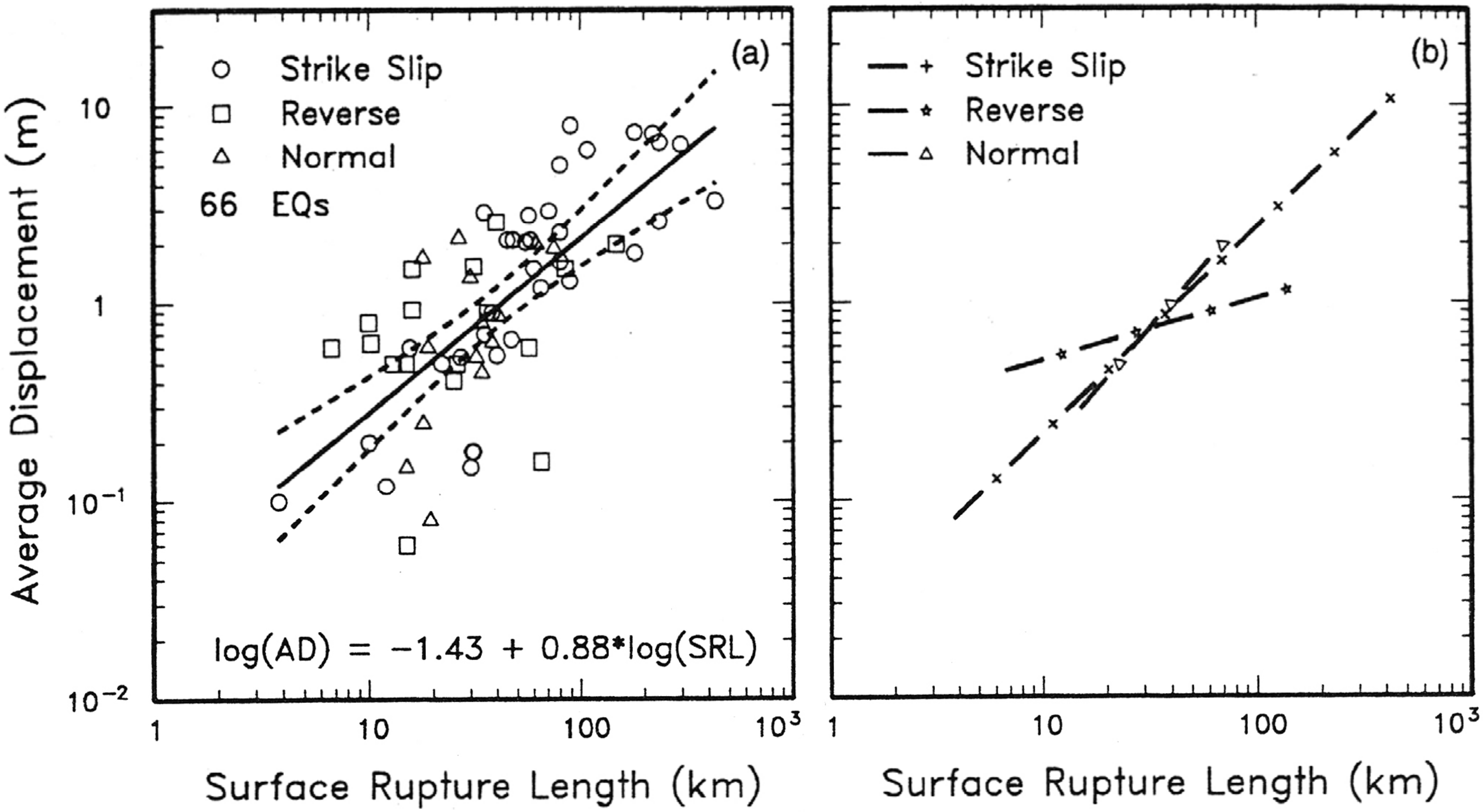


Figure 13. (a) Regression of surface rupture length on average displacement. Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Mw vs. SRL

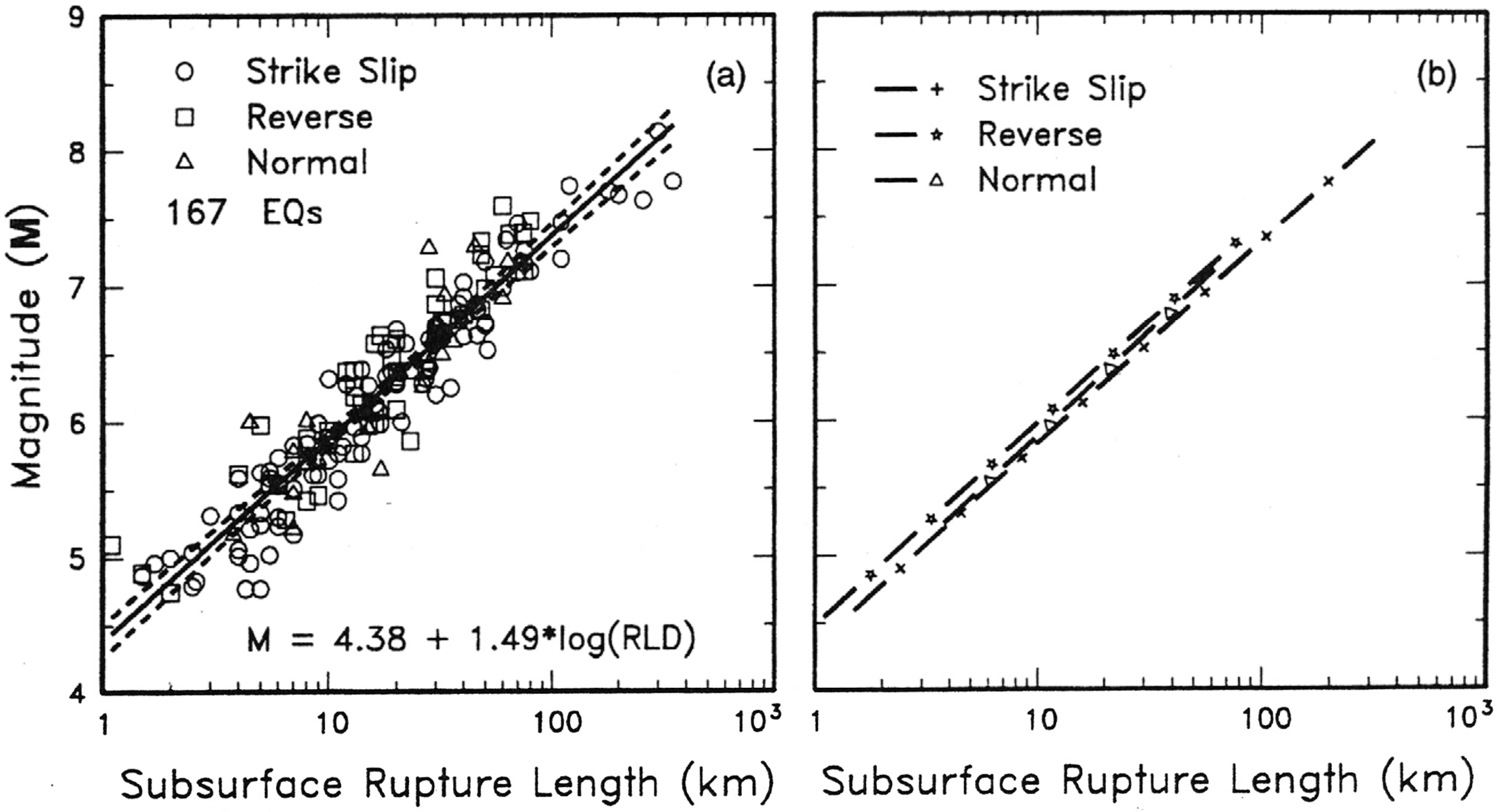


Figure 14. (a) Regression of subsurface rupture length on magnitude (**M**). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Mw vs. Subsurface Rupture Width

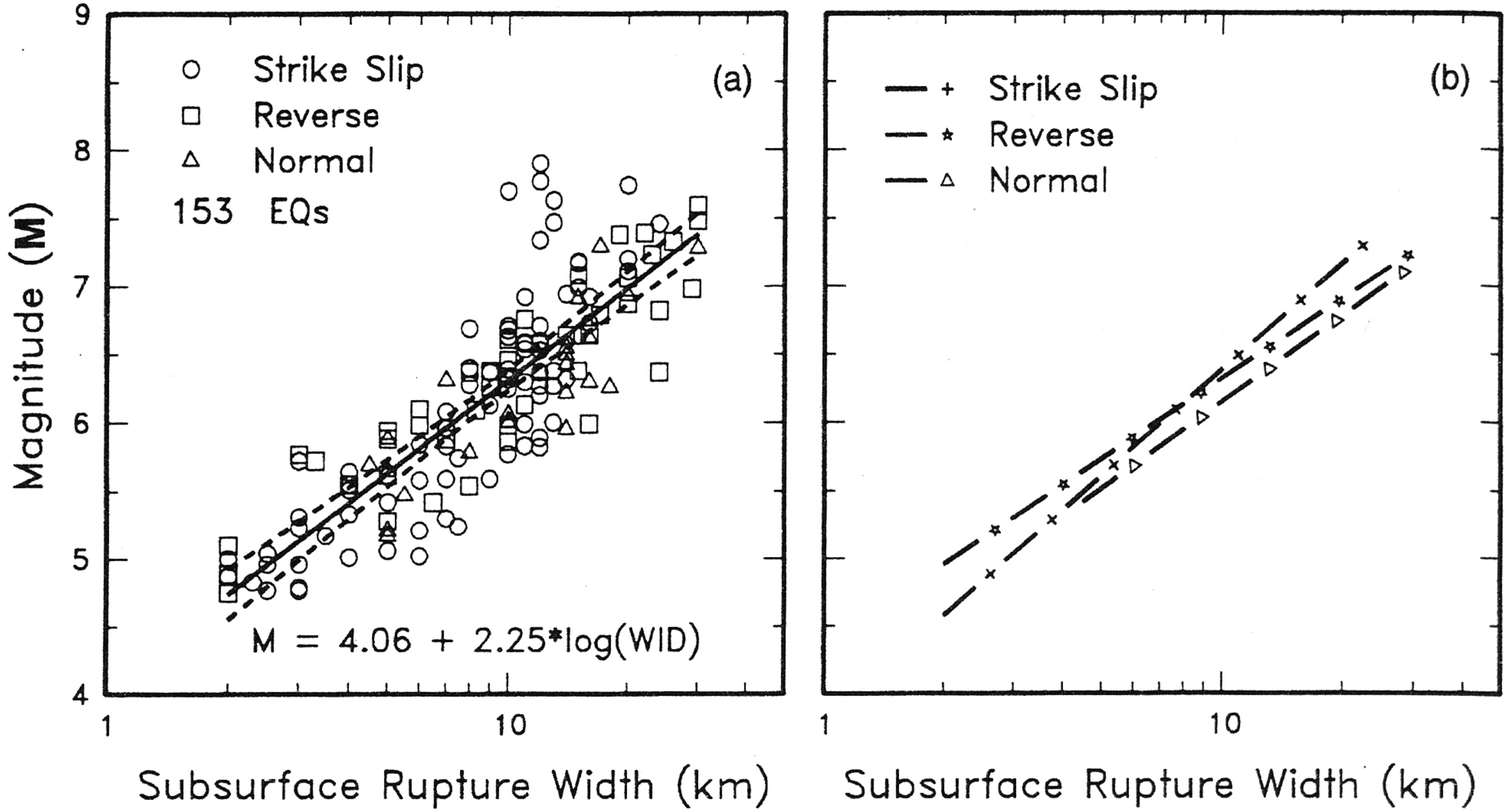


Figure 15. (a) Regression of downdip rupture width on magnitude (**M**). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Magnitude vs. Rupture Area

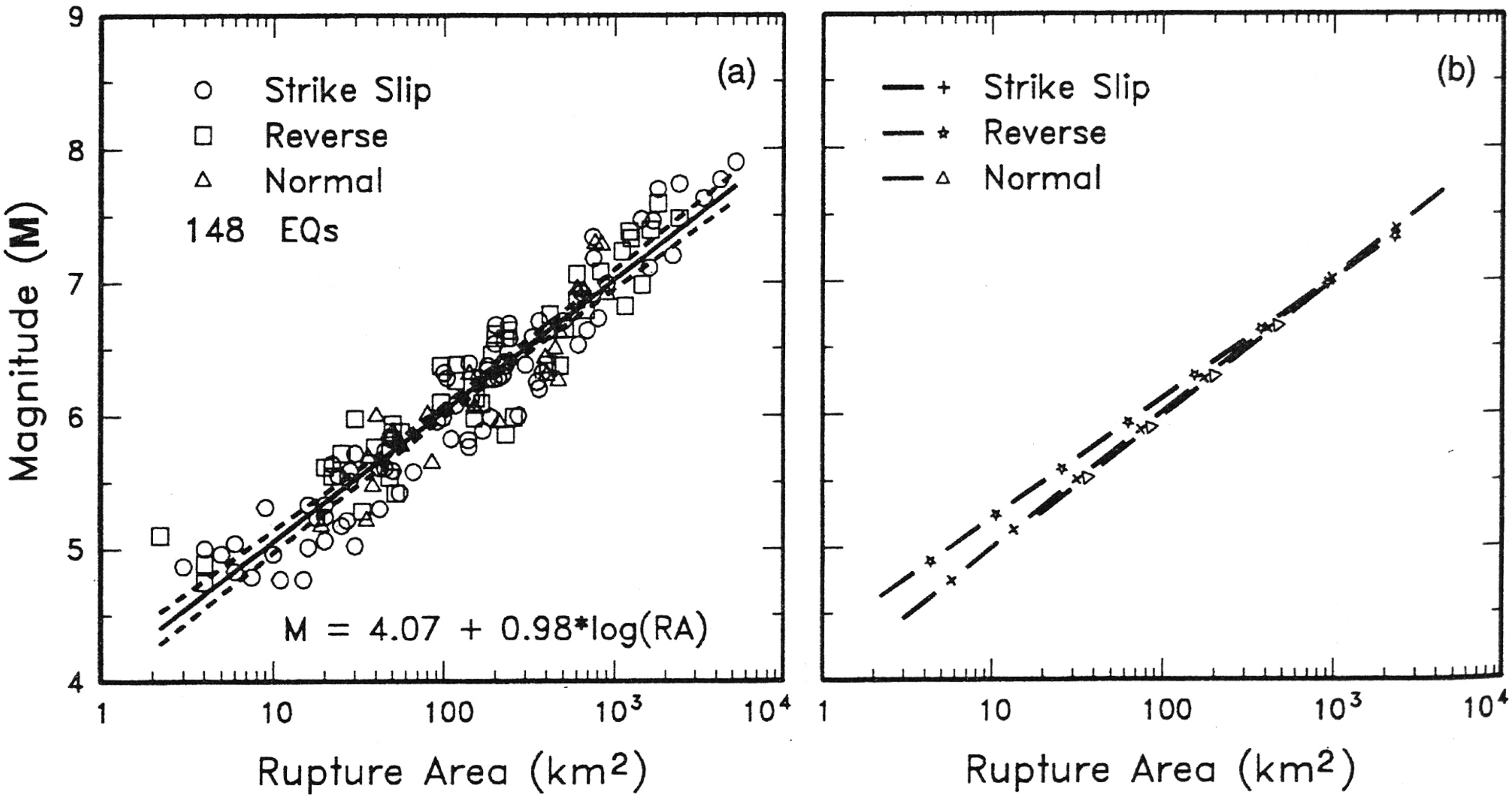


Figure 16. (a) Regression of rupture area on magnitude (**M**). Regression line shown for all-slip-type relationship. Short dashed line indicates 95% confidence interval. (b) Regression lines for strike-slip, reverse, and normal-slip relationships. See Table 2 for regression coefficients. Length of regression lines shows the range of data for each relationship.

Mw vs. Rupture Areas

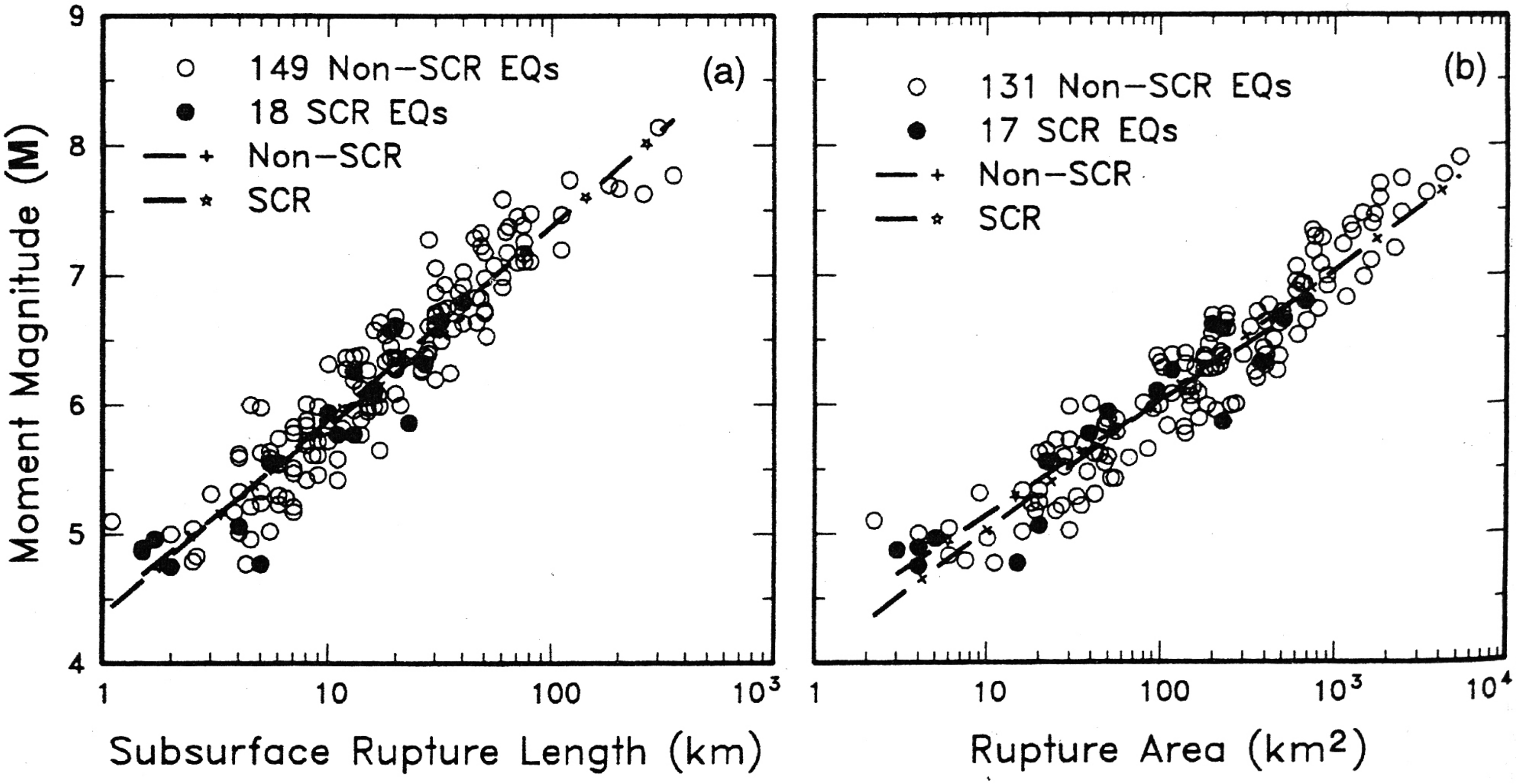


Figure 17. Regression lines for stable continental region (SCR) earthquakes and non-SCR continental earthquakes. (a) Regression of surface rupture length on magnitude (**M**). (b) Regression of rupture area on magnitude (**M**).

Probabilities and Magnitudes of Multi-Segment Ruptures: Specific Questions

The 2002 National Seismic Hazard Maps (NSHMs) use multi-segment rupture models for the San Andreas and Hayward faults in California.

1. **Should the NSHMs use multi-segment rupture models for Basin and Range faults?**

2. **If so, what general types of models should be used and how should it be weighted relative to single-segment rupture models?**

3. **Should rupture “spill-over” and triggered earthquakes be considered as well?**

Agenda

1:00 - 1:05	**Introduction: Specific Questions and Agenda (Jim Pechmann, UU)**
1:05 - 1:30	**Fault Segmentation Models in Probabilistic Seismic Hazard Analyses and an Example for the Wasatch fault (Kathy Haller, USGS)**
1:30 - 2:00	**The Fault Segmentation Model and Maximum Earthquake Magnitudes for the Basin and Range Province (Craig dePolo, UNR)**
2:00 - 2:30	**Addressing the Potential for Multi-segment Rupture on the Wasatch Fault (Chris DuRoss, UGS)**
2:30 - 2:40	**Use of Multi-segment Rupture Models in the National Seismic Hazard Maps: Options and Effects (Jim Pechmann, UU)**

Agenda (continued)

2:40 – 3:00 **Break**

3:00 - 4:30 **Discussion (All)**

4:30 - 5:00 **Recommendations to the USGS (All)**

Models for Multi-segment Fault Rupture

1. **Unsegmented model with maximum rupture length greater than average segment length**
   (e.g., Youngs et al., 1987; Wong et al., 2002)
   Subjective weighting generally applied to segmented and unsegmented (floating rupture) models

2. **Multi-segment rupture scenarios, weighted based on point estimates of earthquake frequencies**
   (e.g., 2002 NSHMs)
   Single-segment earthquake frequencies estimated from paleoseismic data: earthquake dates or fault slip rates

Models for Multi-segment Fault Rupture (con.)

3. **String of pearls: Rupture scenarios constructed probabilistically from paleoearthquake dates and displacements, with no *apriori* segmentation assumptions, and weighted based on estimated earthquake frequencies** (Biasi and Weldon, under development)
   Scenarios determined objectively, but generally non-unique.

Models for Multi-segment Fault Rupture (con.)

Cascade Models—Consider all possible single- and multi segment rupture scenarios

4. **Cascade model #1: Scenario frequencies selected to give a regional exponential frequency-magnitude relation**
   (WGCEP, 1995; Andrews and Schwerer, 2000)
   Underdetermined problem.

5. **Cascade model #2: Scenario frequencies calculated uniquely by assuming a constant probability that rupture on one segment will trigger a neighboring segment and conserving the moment rate on each segment**
   (Field et al., 1999. They used a triggering probability of 0.5 on most faults, but probabilities of 0.15 to 0.33 on others)

Effects of Multi-segment Rupture Models on Seismic Hazard Analyses

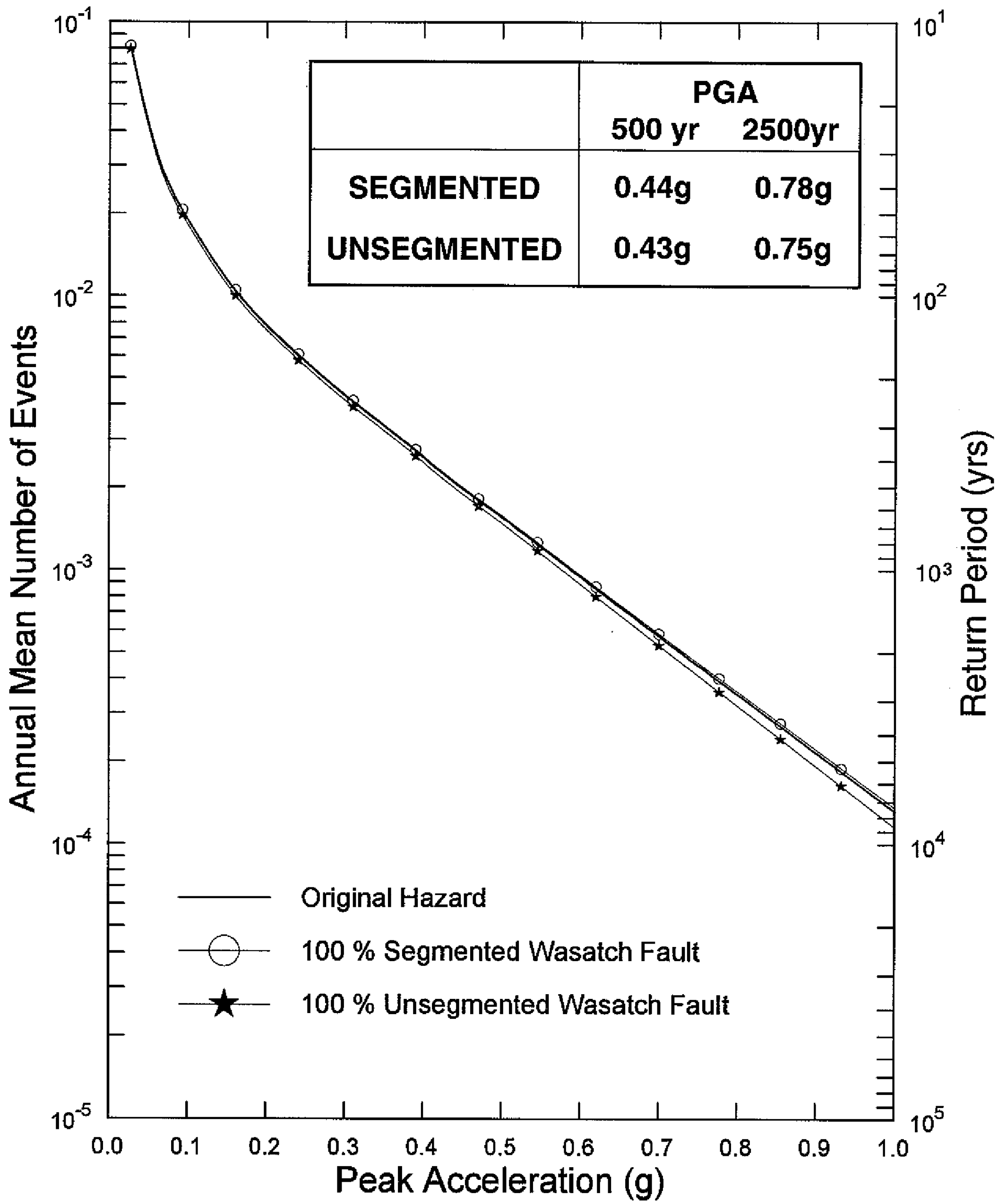
- Overall, multi-segment rupture models give **lower** probabilistic seismic hazard than single-segment models **if** the models are moment balanced (i.e, the slip rate is the same in both). Why? larger events → longer recurrence intervals → lower hazard

- Kathy Haller's Wasatch fault 2-segment rupture model:

  (a) Gives generally higher hazard than 1-segment rupture model because the models are not moment balanced, **but**

  (b) the differences are small (-4% g to +7% g)

- Multisegment rupture scenarios, if credible, are important for emergency planning purposes



SENSITIVITY TO SEGMENTATION MODEL

Site: Salt Palace
Salt Lake City, Utah

Rock Ground Motions

Unsegmented Model (with multisegment ruptures):
Max rupture length = 68 km
(twice average segment length)
$M_{max} = 7.2 \pm 0.3$

Segmented Model:
Based on Wong et al. (2002)

Figure courtesy of Ivan Wong
URS Corp.

“A thorough seismic hazard or risk study takes substantial energy and resources, and the analyst must concentrate on the issues that are most influential for the problem at hand.”

Robin K. McGuire, 2004
Seismic Hazard and Risk Analysis (EERI Monograph)

Probabilities and Magnitudes of Multi-Segment Ruptures: Specific Questions

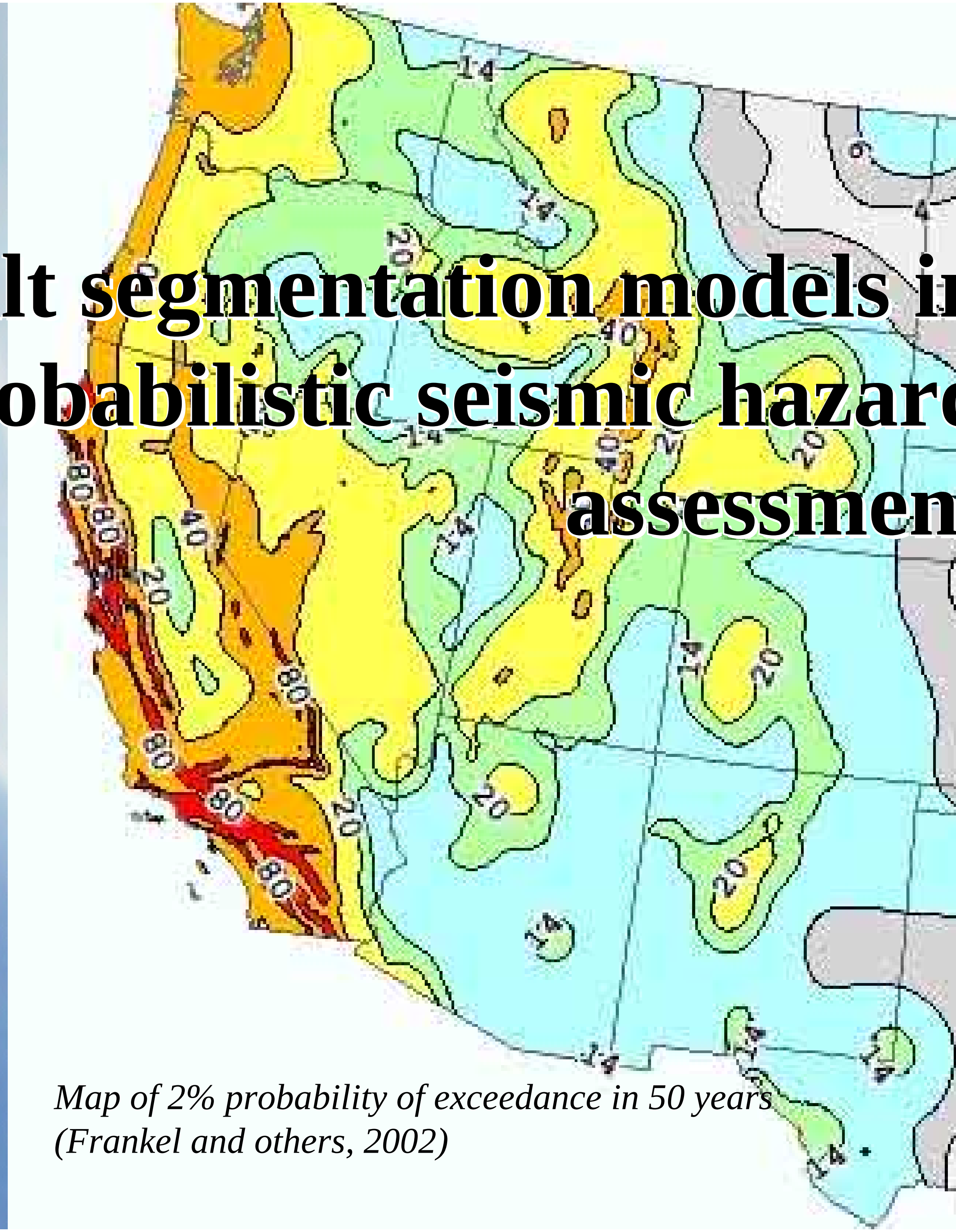
The 2002 National Seismic Hazard Maps (NSHMs) use multi-segment rupture models for the San Andreas and Hayward faults in California.

1. **Should the NSHMs use multi-segment rupture models for Basin and Range faults?**

2. **If so, what general types of models should be used and how should it be weighted relative to single-segment rupture models?**

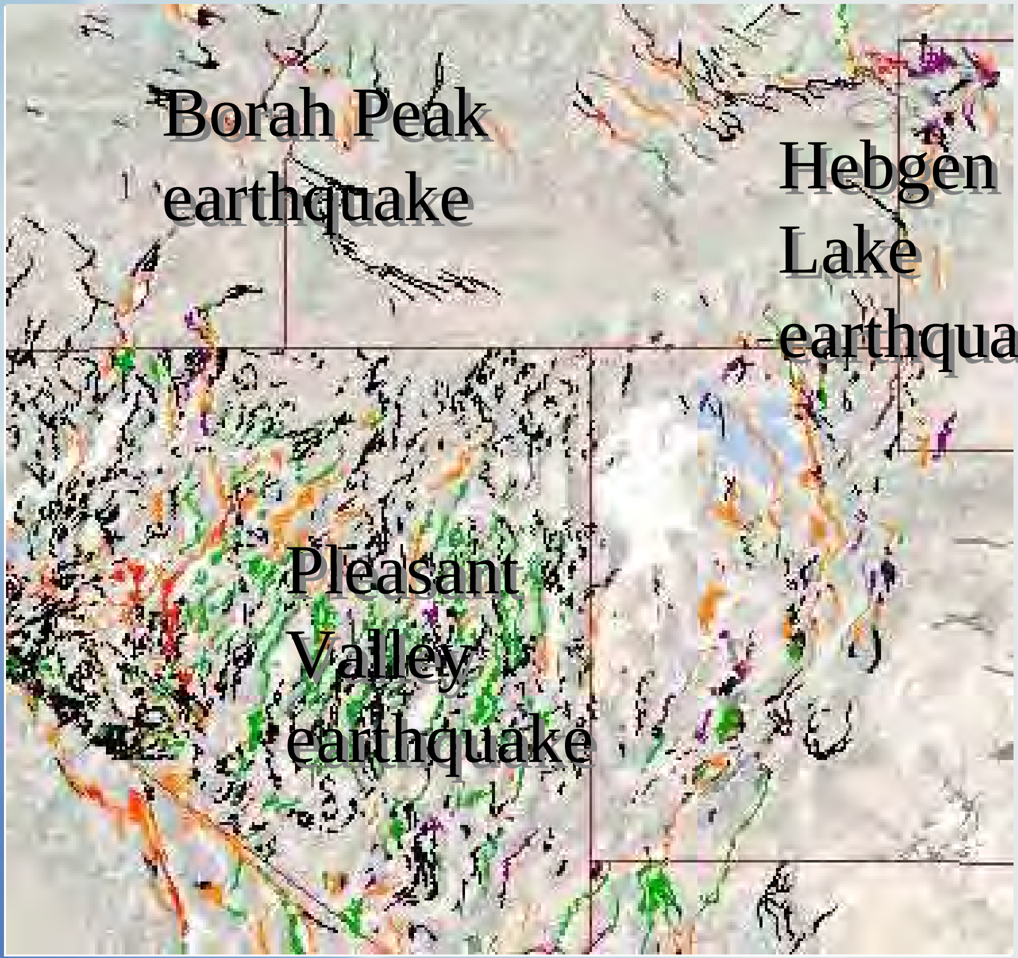
3. **Should rupture "spill-over" and triggered earthquakes be considered as well?**

Fault segmentation models in probabilistic seismic hazard assessment



Map of 2% probability of exceedance in 50 years (Frankel and others, 2002)

Historic Basin and Range surface ruptures



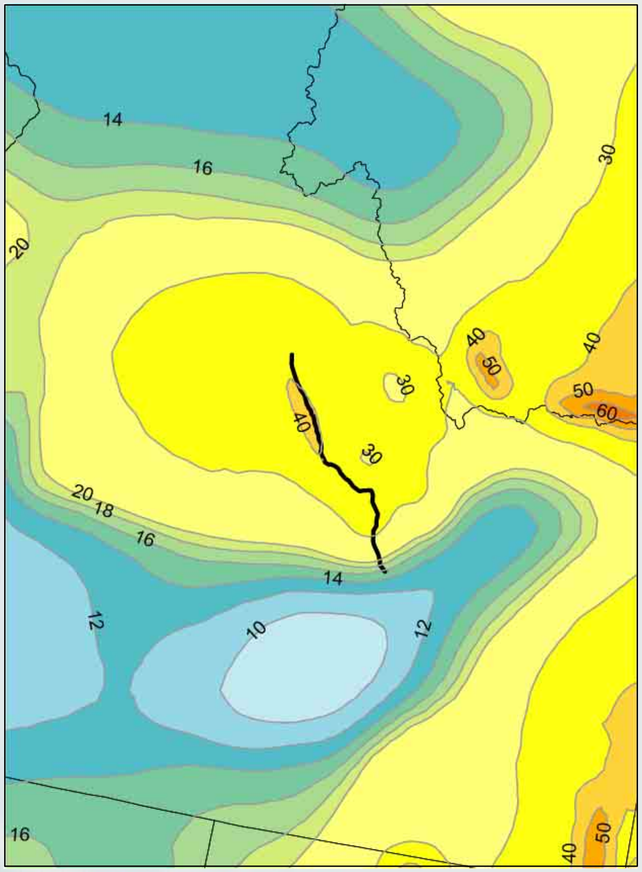
Fault segmentation

- Part of long faults rupture during an earthquake
- Segments have independent to quasi-independent histories
- Acceptance of models

1983 Borah Peak, Idaho, earthquake

Lost River fault, Idaho

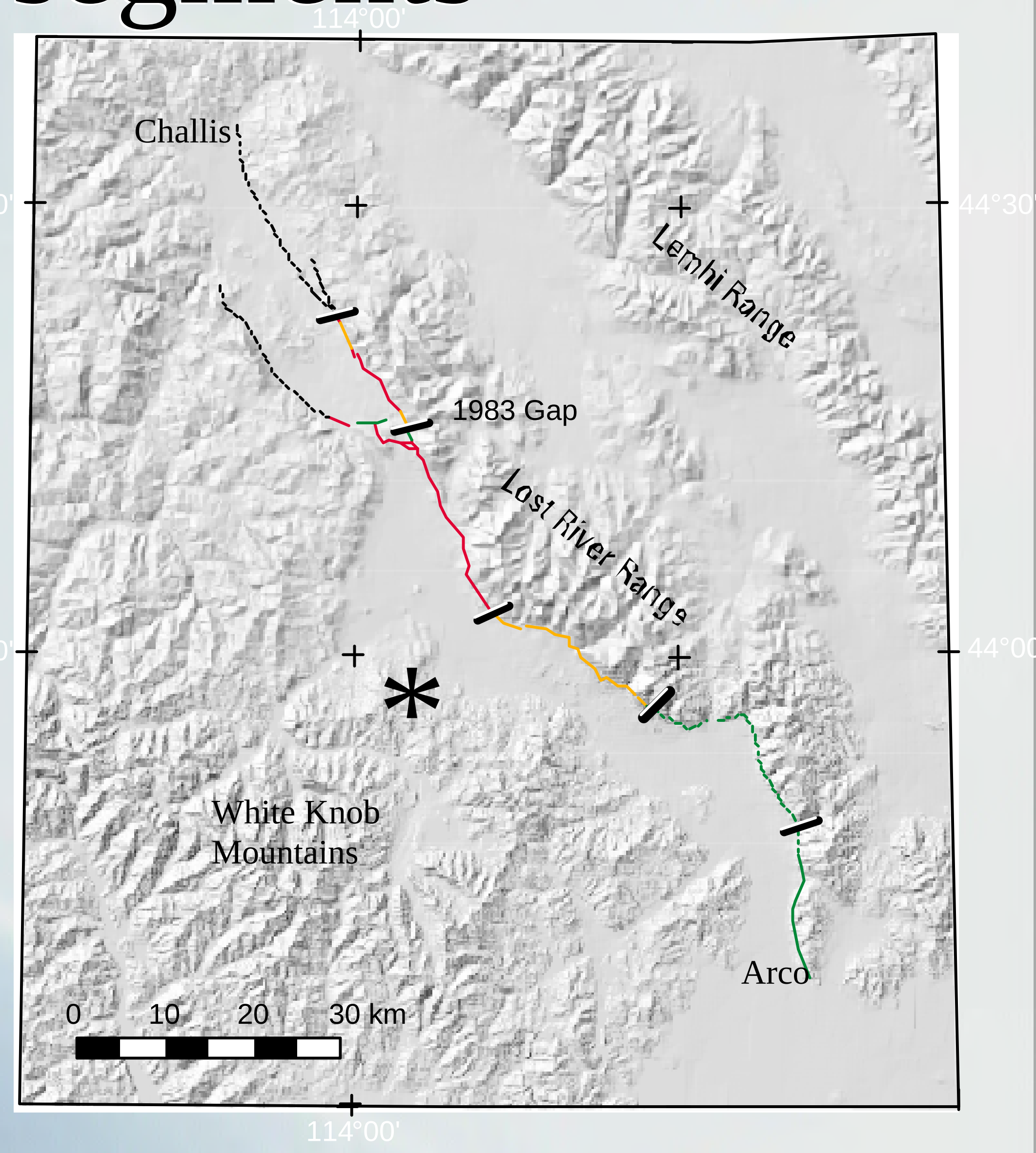
- Slip rate 0.15 mm/yr
- Magnitude fixed at 7, based on Borah Peak earthquake
- Maximum PGA 40% g for 2% in 50 yr
- Recurrence rate 0.000060384
  1650 yr
- 4 surface faulting events in 12 k.y.



Map of 2% probability of exceedance in 50 years (Frankel and others, 2002)

Defining segments

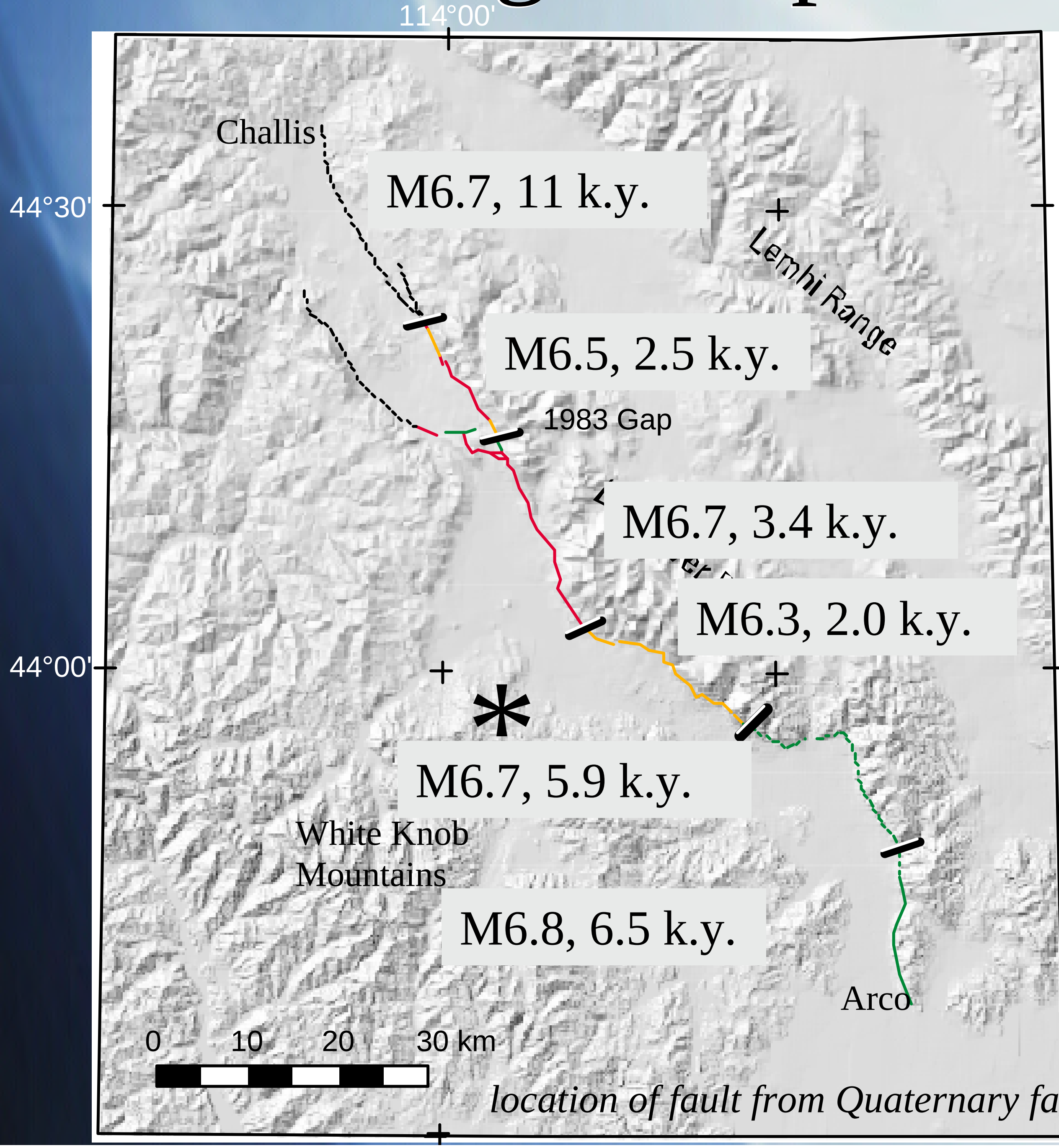
- Prominent changes in trend of range front
- Bedrock highs
- Change in timing of events along strike
- Echelon steps



Segment parameters

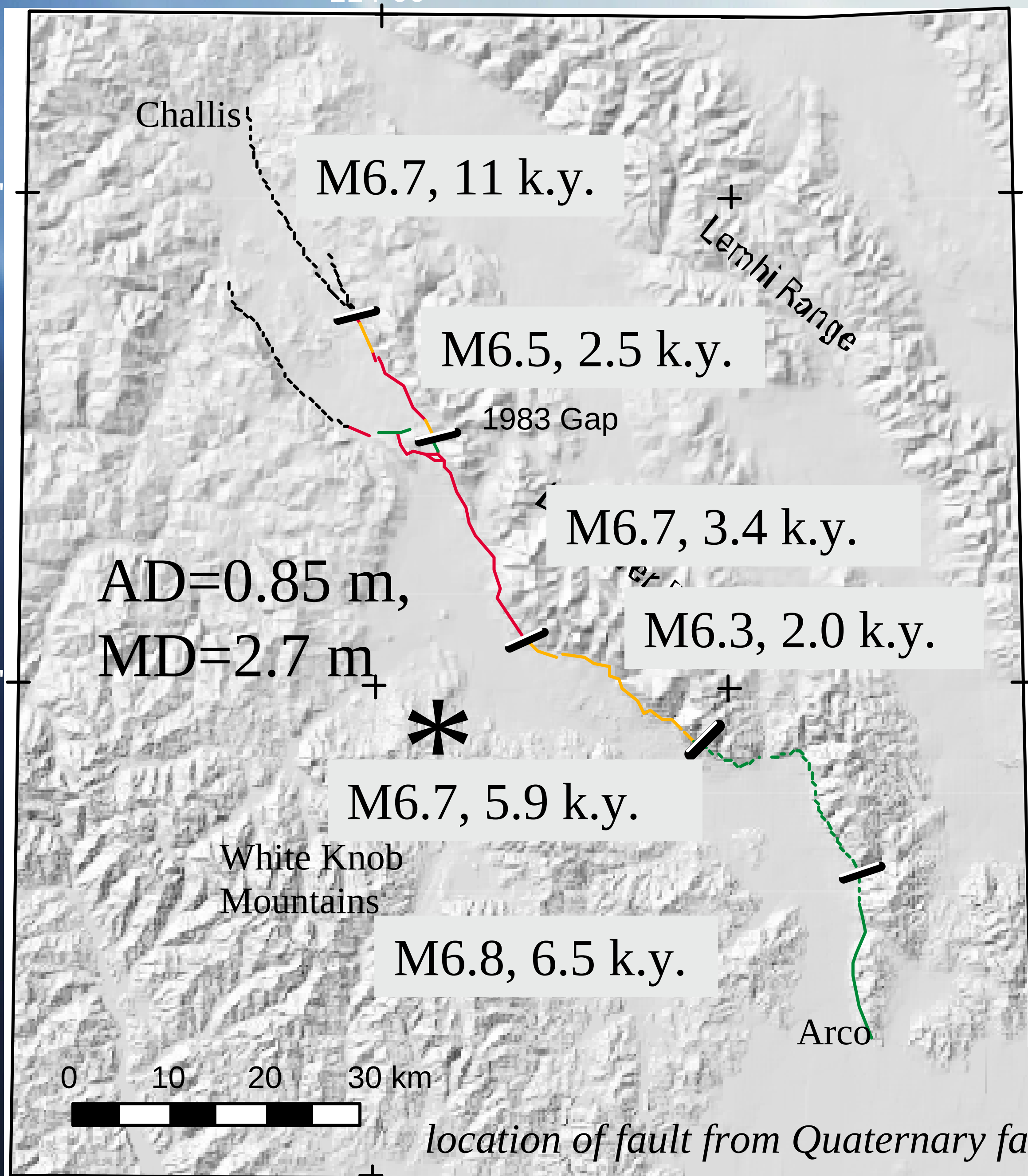
Segment	Assigned slip rate (mm/yr)	Length (km)	Char magnitude	Recurrence rate	Average repeat time (yr)
Challis	0.05	26	6.7	0.000091	11,000
Warm Spring	0.15	16	6.5	0.00040	2500
Thousand Springs	0.15	24	6.7	0.00029	3400
Mackay	0.15	12	6.3	0.00050	2000
Pass Creek	0.10	28	6.7	0.00017	5900
Arco	0.10	32	6.8	0.00015	6500

Segment parameters



location of fault from Quaternary fault and fold database of the United States

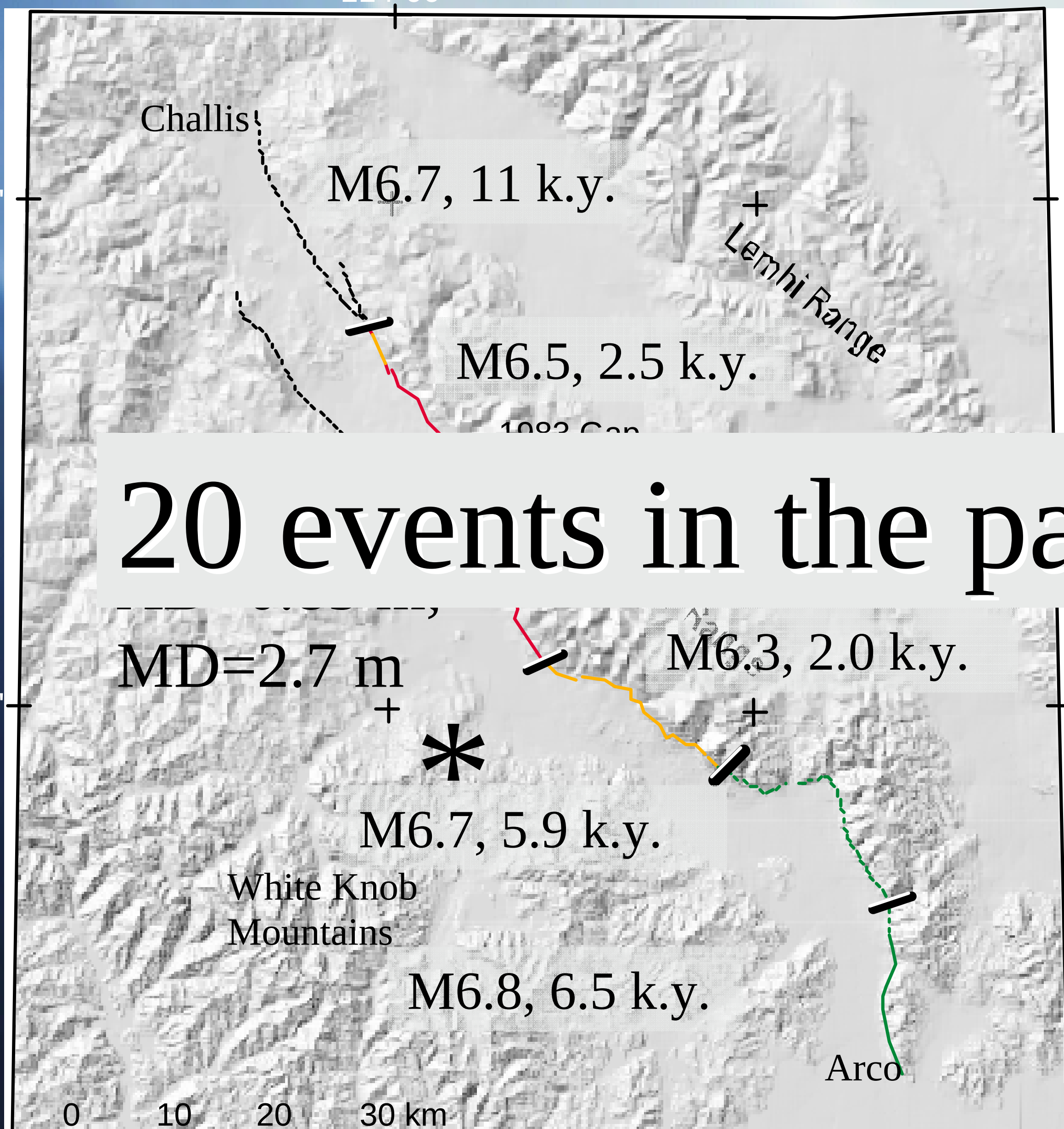
Segment parameters



Average	Maximum
0.63	1.1
0.11	0.7
0.60	1.0
0.34	0.55
0.67	1.2
0.75	1.3

location of fault from Quaternary fault and fold database of the United States

Segment parameters

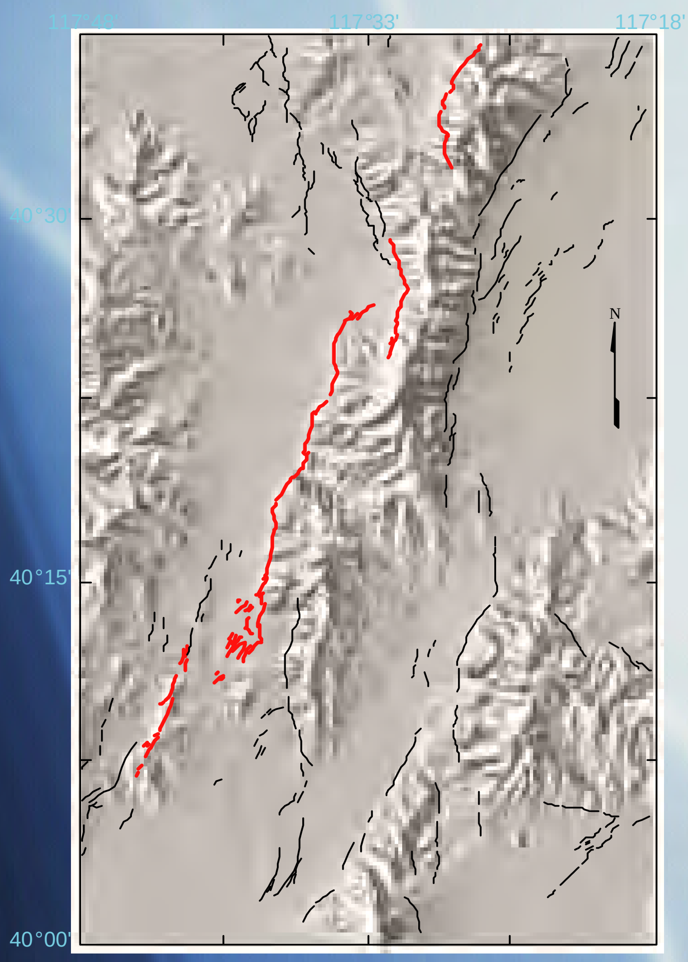


Average	Maximum
0.63	1.1
0.11	0.7
	1.0
0.34	0.55
0.67	1.2
0.75	1.3

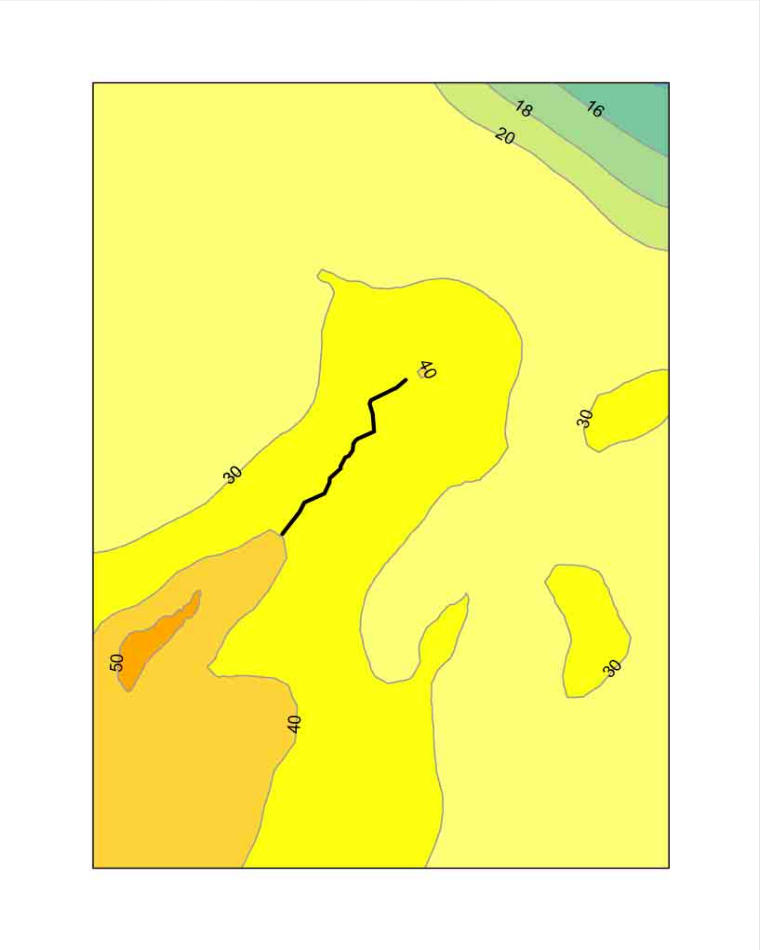
20 events in the past 12 k.y.

location of fault from Quaternary fault and fold database of the United States

Pleasant Valley earthquake, Nevada



location of fault from Quaternary fault and fold database of the United States



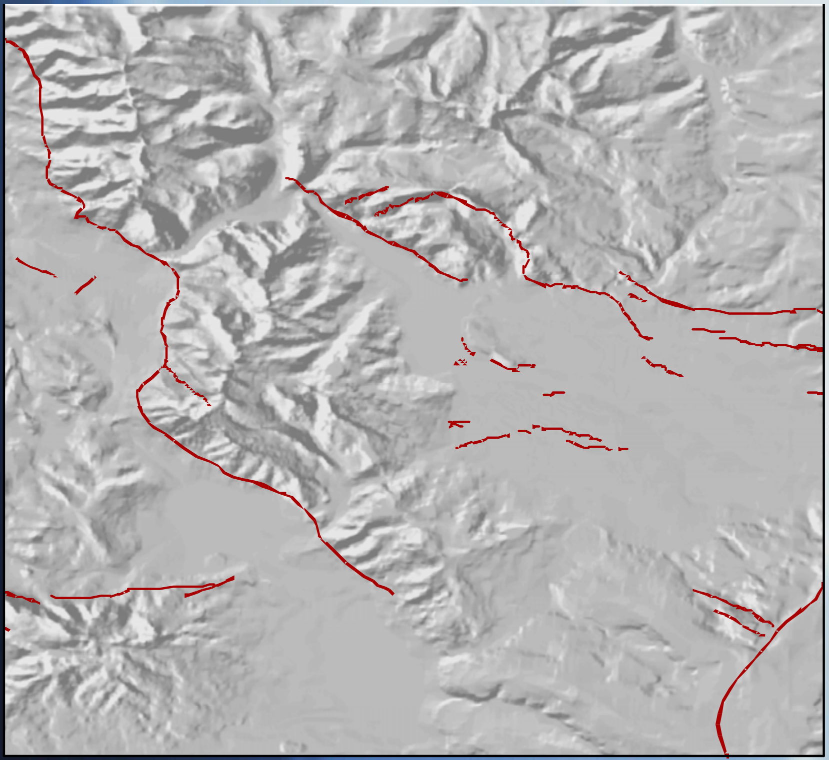
2% in 50 years

Hypothetical segment model

Segment	Assigned slip rate	Length (km)	Char Magnitude	Recurrence rate	Average repeat time
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pearce	0.1	31	6.80	0.00016	6300
Sou Hills	0.05	22	6.63	0.00010	9700

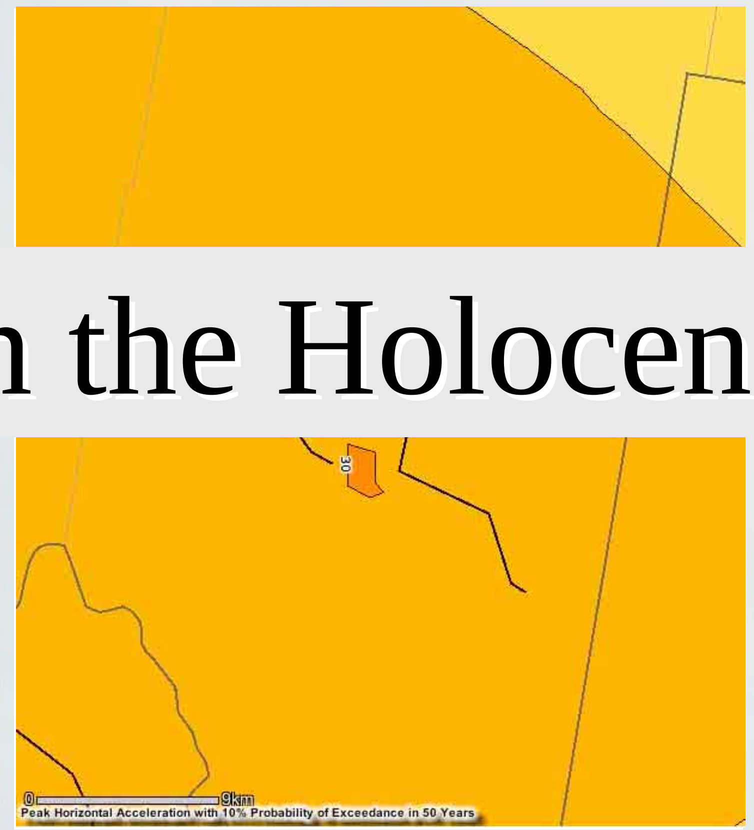
At least 6 events in the Holocene

Hebgen Lake earthquake, Montana



Hebgen Lake earthquake, Montana

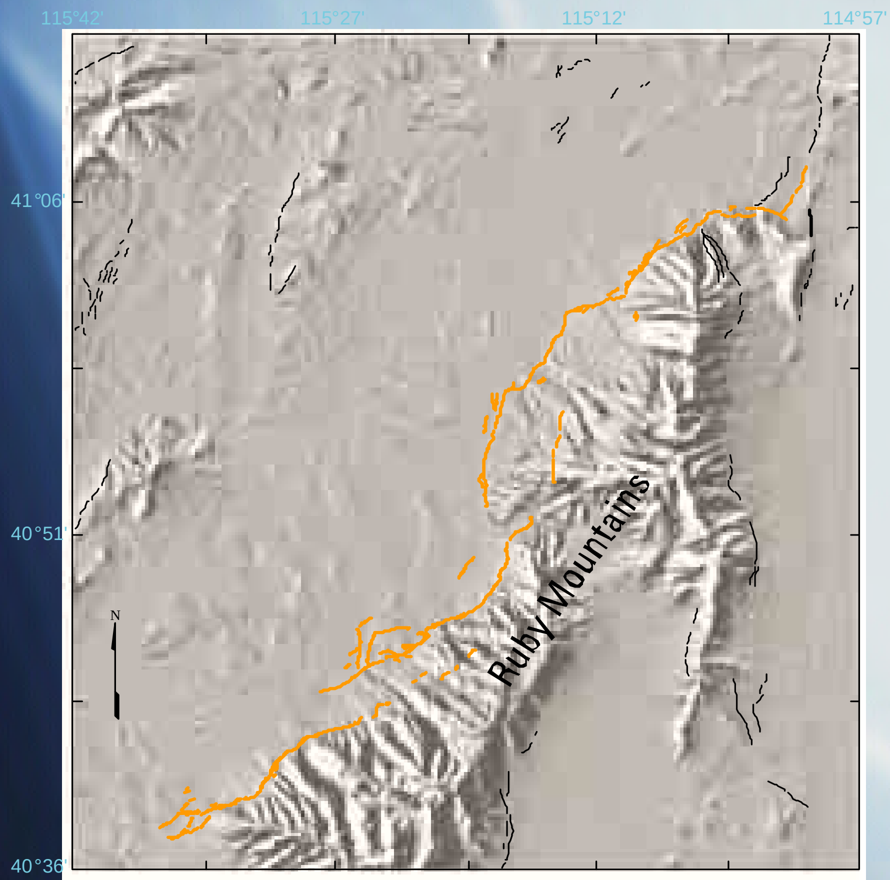
Red Canyon	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hebgen	0.5	13	7.3	0.00050	2000



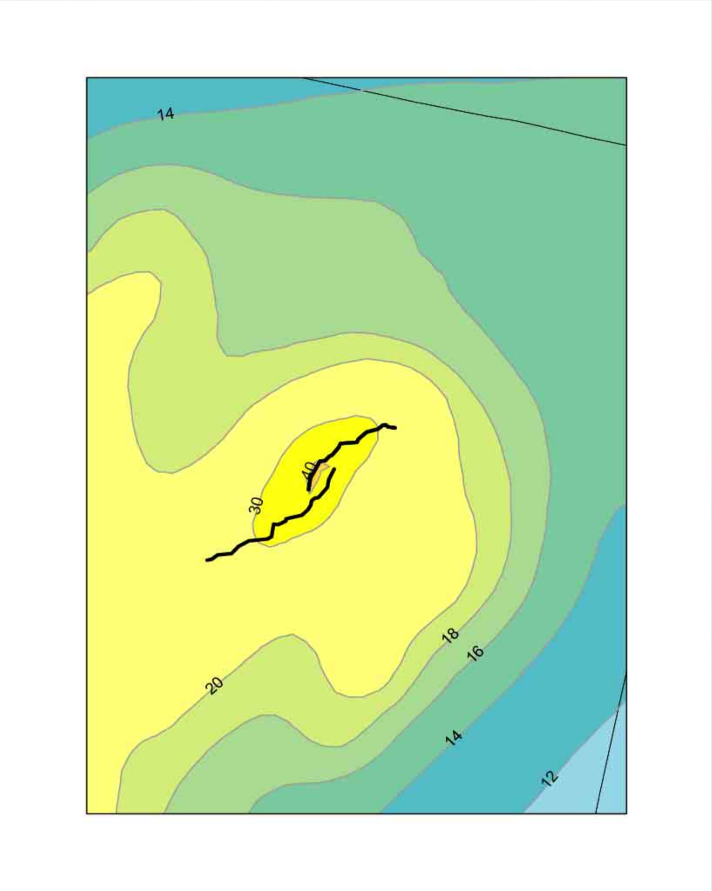
At least 12 events in the Holocene

Are these faults segmented?

Ruby Mountains fault, Nevada



location of fault from Quaternary fault and fold database of the United States



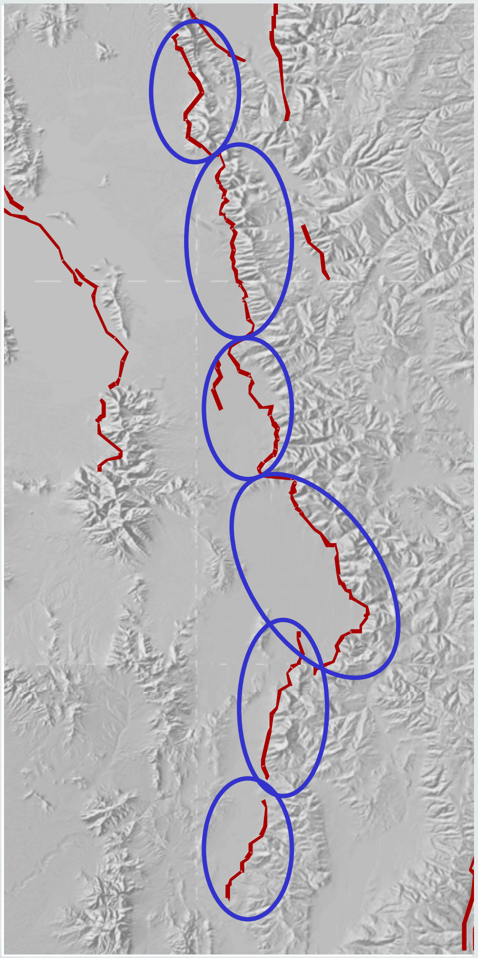
2% in 50 years

Segment parameters

Segment	Assigned slip rate (mm/yr)	Length (km)	Char Magnitude	Recurrence rate	Average repeat time (yr)
northern	0.28	37	6.9	0.0002492	4013
southern	0.28	53	7.1	0.0001789	5590

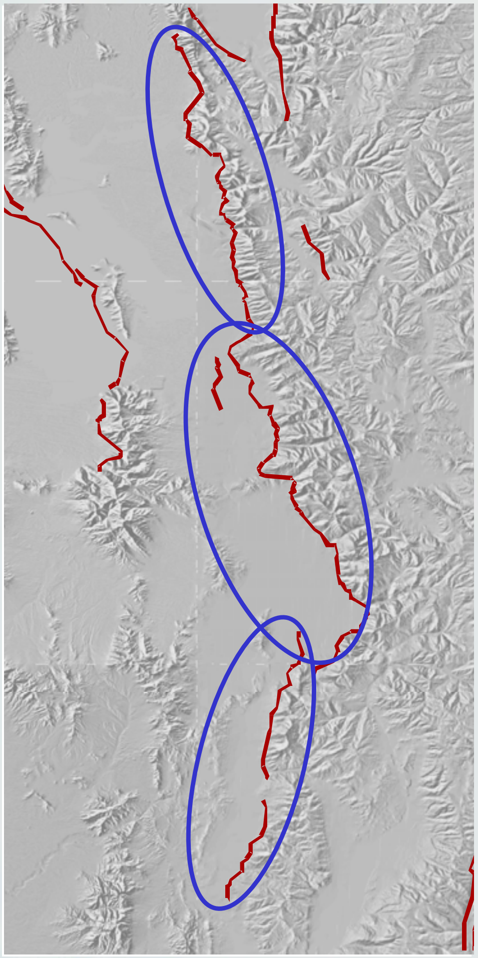
When do we model multi-segment ruptures

Segment	Length (km)	Magnitude	Average repeat time (yr)
Brigham City	41	6.8-7.2	1250
Weber	62	7.0-7.4	1790
Salt Lake City	48	6.9-7.3	1350
Provo	77	7.2-7.6	2290
Nephi	46	6.9-7.3	2500
Levan	32	6.7-7.1	4220

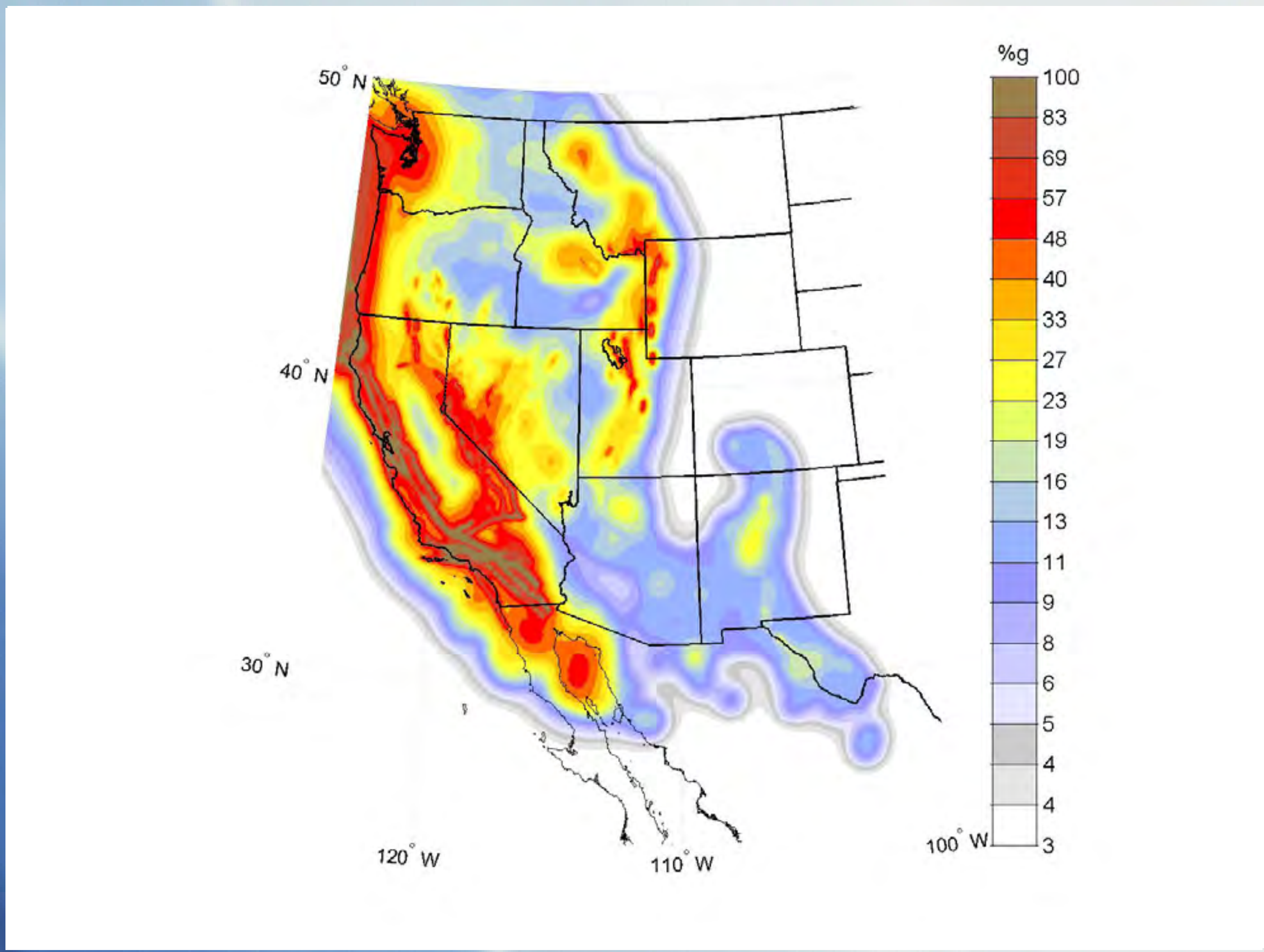


When do we model multi-segment ruptures

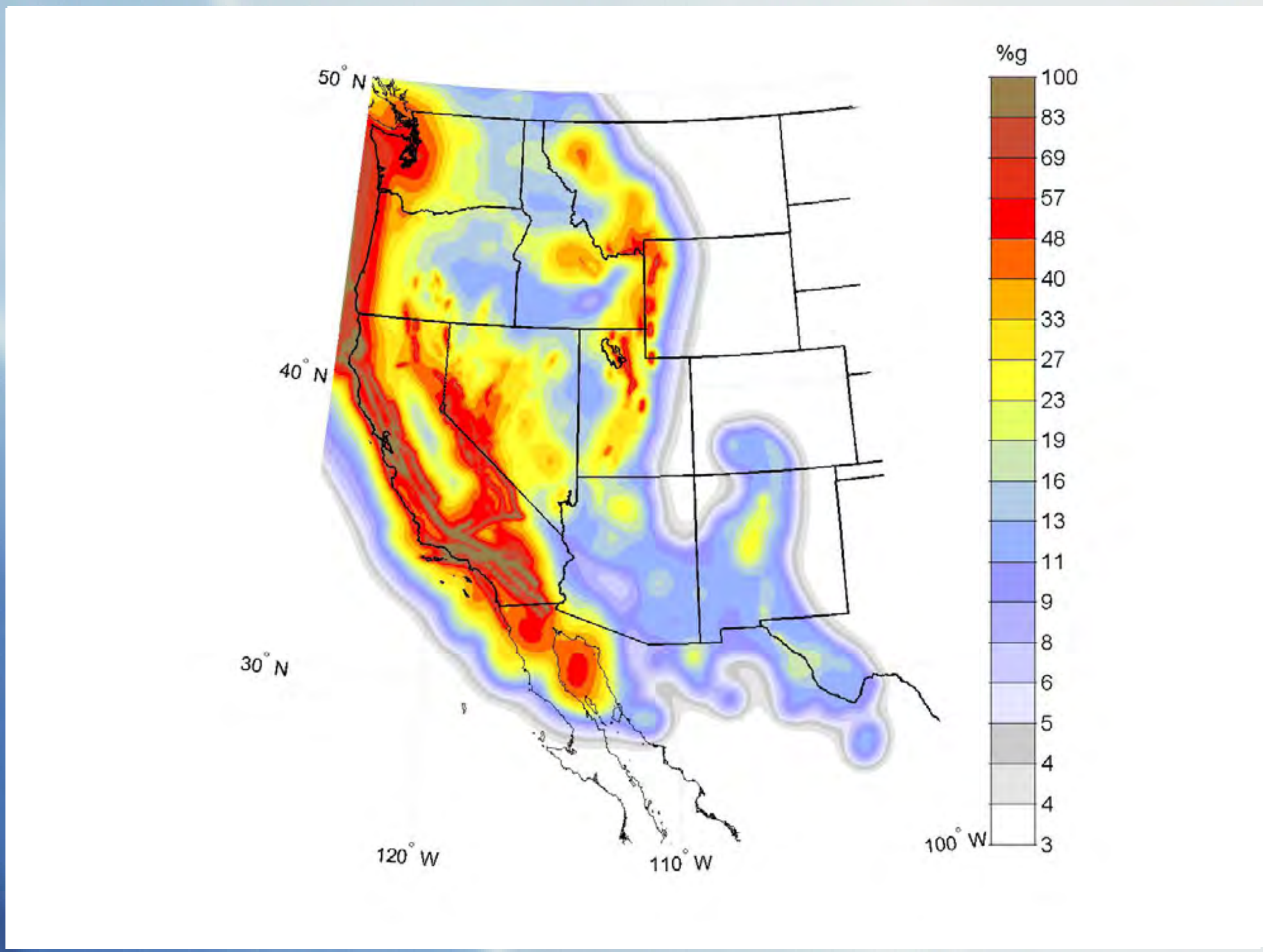
Segment	Length (km)	Magnitude	Average repeat time (yr)
Brigham City/Weber	91	7.2-7.6	1250
Salt Lake City/Provo	100	7.2-7.6	1350
Nephi/Levan	80	7.1-7.5	2500



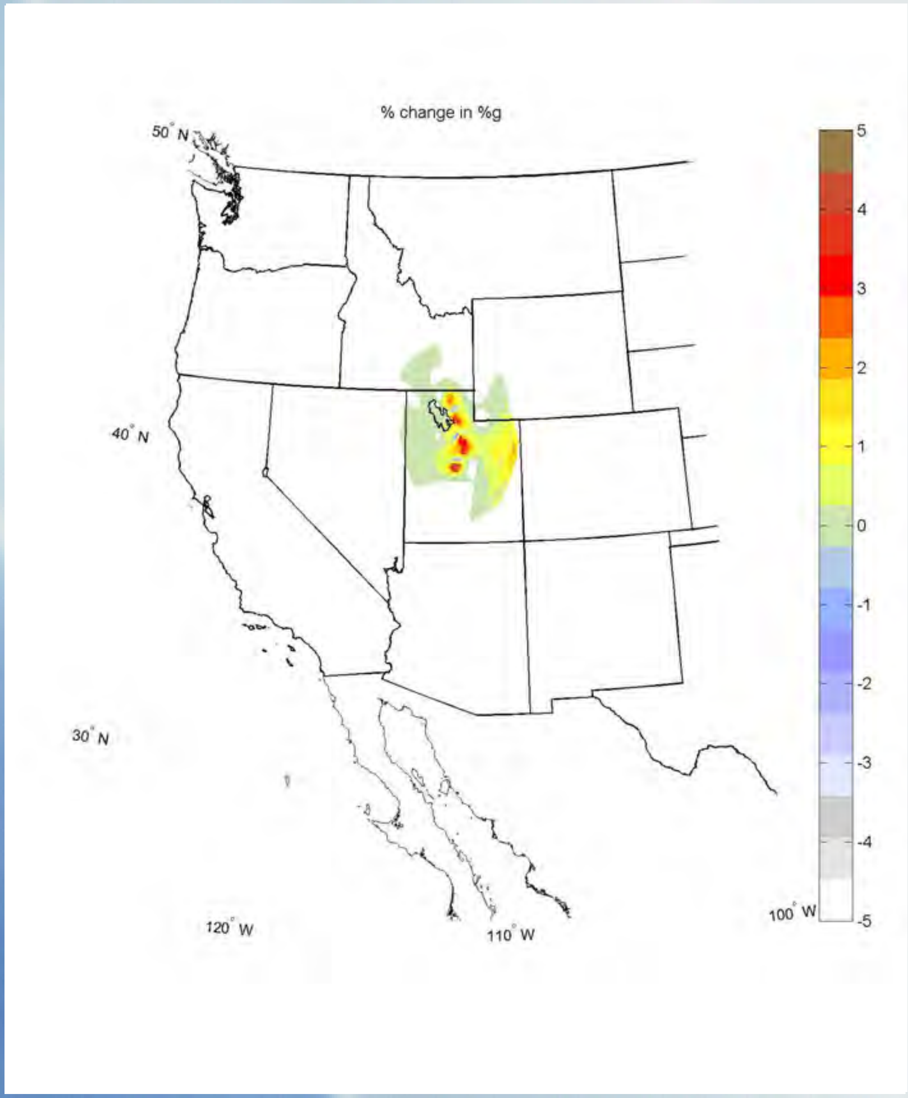
2% in 50 Western U.S.

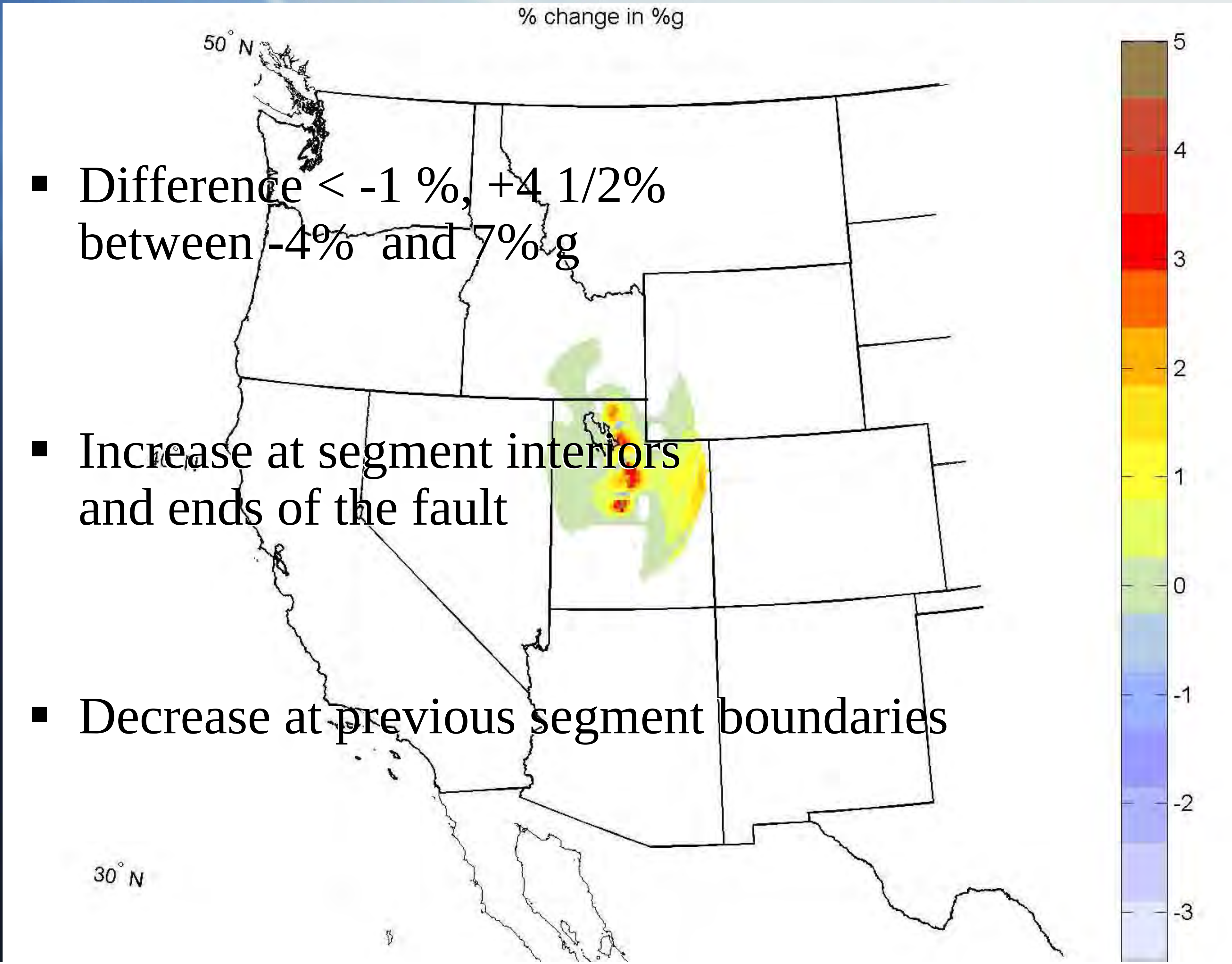


Multi-segment rupture scenario



Difference map





- Difference < -1 %, +4 1/2% between -4% and 7% g

- Increase at segment interiors and ends of the fault

- Decrease at previous segment boundaries

Lessons learned

- Evaluate quality (and quantity) of data
- Define a minimum standard for segmenting
- Be aware of outcome due to choice of model

Defining Fault Length for Determining Earthquake Size

- Total fault length
- Partial fault length

Partial Fault Length

- Half length
- Fractional fault length
- Earthquake segment length
- Statistical distribution

Earthquake Segmentation Technique

Use physical features of a fault, including historical earthquake and paleoseismic data, to define potential earthquake segments for approximating future earthquake ruptures.

Faults have several types of segments – we are interested in defining EARTHQUAKE SEGMENTS

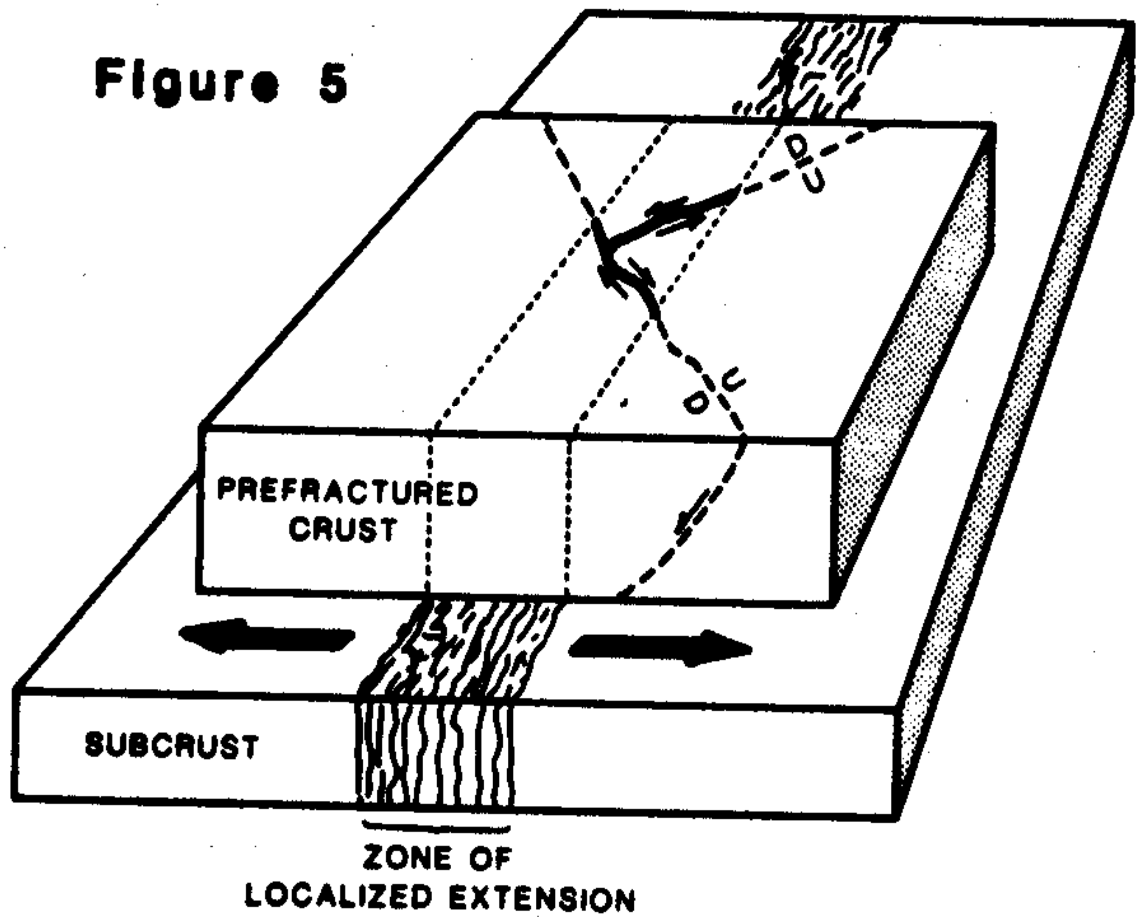
- Structural segments
- Geometric segments
- Behavioral segments
- Geologic segments

Multiple-Segment Ruptures

- Cascading failures of discontinuities along a fault.

- Subsurface rupture that is at an angle to the surface faults (Wallace model).

Figure 5



U
D
U
D
PREFRACTURED
CRUST
SUBCRUST
ZONE OF
LOCALIZED EXTENSION

The Earthquake Segmentation Model

1. Earthquake evidence
2. Segmentation Models

Earthquake Evidence
(for defining earthquake segments)

- Historical surface ruptures
- Trenching/event information
- Geomorphic signal (young fault scarps)

Segmentation Models

- General Fault Characteristics
- Fault Discontinuity Characteristics
- Earthquake Segment Characteristics

General Fault Characteristics

- Total displacement/fault maturity
- Sense of displacement
- Fault activity/slip rate

Fault Discontinuity Characteristics

- Discontinuity type (geometric, structural)
- Discontinuity size
- Dilational versus compressional
- Degree of nonconservative slip
- Linkage type (faults vs. distributed deformation)
- Combinations of characteristics

Earthquake Segment Characteristics

- Differences in material properties
- Variations in stress
- Rupture direction
- Mechanics of cascading ruptures
- Segment characteristics (length)
- Evidence of continuity (geodetic)

Historical Basin and Range Province Earthquakes

1872 Owens Valley	7.6	110	3G	ss
1887 Sonora	7.4	101	3-4G	n
1915 Pleasant V.	7.2-7.5	62	4G,S	n
1959 Hebgen Lake	7.0-7.3	28	2-3G,S	n
1954 Fairview Pk.	7.1-7.3	67	3-4+S	no
1954 Dixie V.	6.9-7.3	46	2G	n
1932 Cedar Mtn.	6.8-7.1	60	>3G,S	ss
1983 Borah Pk.	6.8-7.1	36	2-3G	no
1954 Stillwater	6.5-6.9	34	2S	ss
1954 Rainbow Mtn.	6.2-6.6	18	1S	ss
1934 Hansel V.	6.6	6?	1S	ss
1950 Fort Sage Mtns.	5.6-6.3?	9.5	1S	n

Rupture Length vs. # of Segments

1 seg. common

<15-20< km

2 seg. common

<30-50< km

3 seg. common

<60-110< km

4 seg. common

Historical BRP Earthquakes

About half of the end-points of the historical ruptures were definable.

Maximum Magnitudes for the Basin and Range Province

- Historical Earthquakes

  Magnitude 7.5 to 7.6

M6.5-6.8		M7.1-7.5

<15-20 km < most faults < 60-110 km <

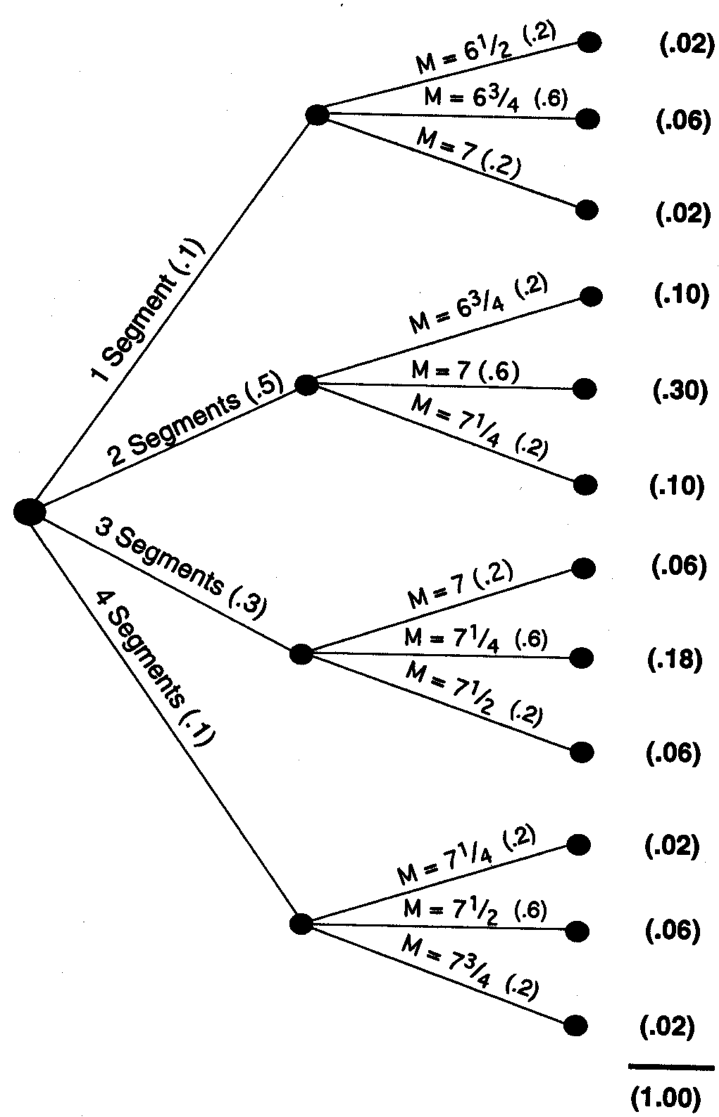
Single	poss. Mult.	Multiple
Eq.	Eq.	Eq.
Segs.	Segs.	Segs.

Threshold for considering a multi-segment model

- Historical earthquake
- Fault length >15-20 km
- Identifiable fault discontinuities
- Paleoseismic information of sufficient quality
  - Information exists
  - Data is of sufficient quality

Segmentation Models

- Segment or multi-segment model support (jibing displacement)
- Weighting of different models
- Statistical models
- Random models
- Fault Floating Earthquake


1 Segment (.1)
2 Segments (.5)
3 Segments (.3)
4 Segments (.1)
M = 6 1/2 (.2)
M = 6 3/4 (.6)
M = 7 (.2)
M = 6 3/4 (.2)
M = 7 (.6)
M = 7 1/4 (.2)
M = 7 (.2)
M = 7 1/4 (.6)
M = 7 1/2 (.2)
M = 7 1/4 (.2)
M = 7 1/2 (.6)
M = 7 3/4 (.2)
(.02)
(.06)
(.02)
(.10)
(.30)
(.10)
(.06)
(.18)
(.06)
(.02)
(.06)
(.02)
(1.00)

Division of long faults into earthquake segments makes physical sense and likely models future earthquakes, but the process of coming up with defensible segmentation models and likelihoods is difficult, especially lacking paleoearthquake data.

Why Segment Faults?

- Physically based
- Credibility issue
- Planning scenarios
- Help fault science progress

It is better to have segmented and lost,
than to have never have segmented at all.

Recommendations Regarding Single-Segment versus Multi-Segment Rupture Models for Basin and Range Province Faults

1. The hazard calculations for the National Seismic Hazard Maps (NSHM) should consider the possibility of multi-segment rupture on Basin and Range Province (BRP) faults (short-term)

2. For BRP faults for which single-segment rupture models are being used to compute the hazard, the 2007 maps should also use an unsegmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The unsegmented model should be given relatively low weight (short-term)

3. The two faults which ruptured in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the purpose of the 2007 NSHM hazard calculations (short term)

4. Displacement data should be used, where available, to provide a consistency check for segmentation models—especially to identify segments on which ruptures longer than the mapped length could occur (both short- and long-term)

\

5. Newly-developed methods for probabilistically constructing rupture scenarios from paleoearthquake dates and displacements should be applied to the Wasatch fault (long-term)

6. Research needs to be conducted in the BRP for segmentation modeling:

- How to recognize and characterize fault rupture segments.
- The quality and quantity of paleoseismic data needed to support a segmented earthquake model along a fault.
- Construction of earthquake segmentation models for important faults.

(long-term)

1. Segmented and Multisegmented Earthquakes for Faults in the BRP

2. The hazard calculations for the National Seismic Hazard Maps (NSHM) should consider the possibility of multi-segment rupture on Basin and Range Province (BRP) faults.

3. For BRP faults for which single-segment rupture models are being used to compute the hazard, the 2007 maps should also use an unsegmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The unsegmented model should be given relatively low weight.

4. The two faults which ruptured in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the purpose of the 2007 NSHM hazard calculations.

\

5. Newly-developed methods for probabilistically constructing rupture scenarios from paleoearthquake dates and displacements should be applied to the Wasatch fault.

6. Segmentation models need to be consistent with geological information about earthquakes along a given fault.

7. Displacement data should be used, where available, to provide a consistency check for segmentation models—especially to identify segments on which ruptures longer than the mapped length could occur.

8. Research needs to be conducted in the BRP for segmentation modeling:

- How to recognize and characterize fault rupture segments.
- The quality and quantity of paleoseismic data needed to support a segmented earthquake model along a fault.
- Construction of earthquake segmentation models for important faults.

Addressing the potential for multi-segment ruptures on the Wasatch fault

Chris DuRoss (Utah Geological Survey)

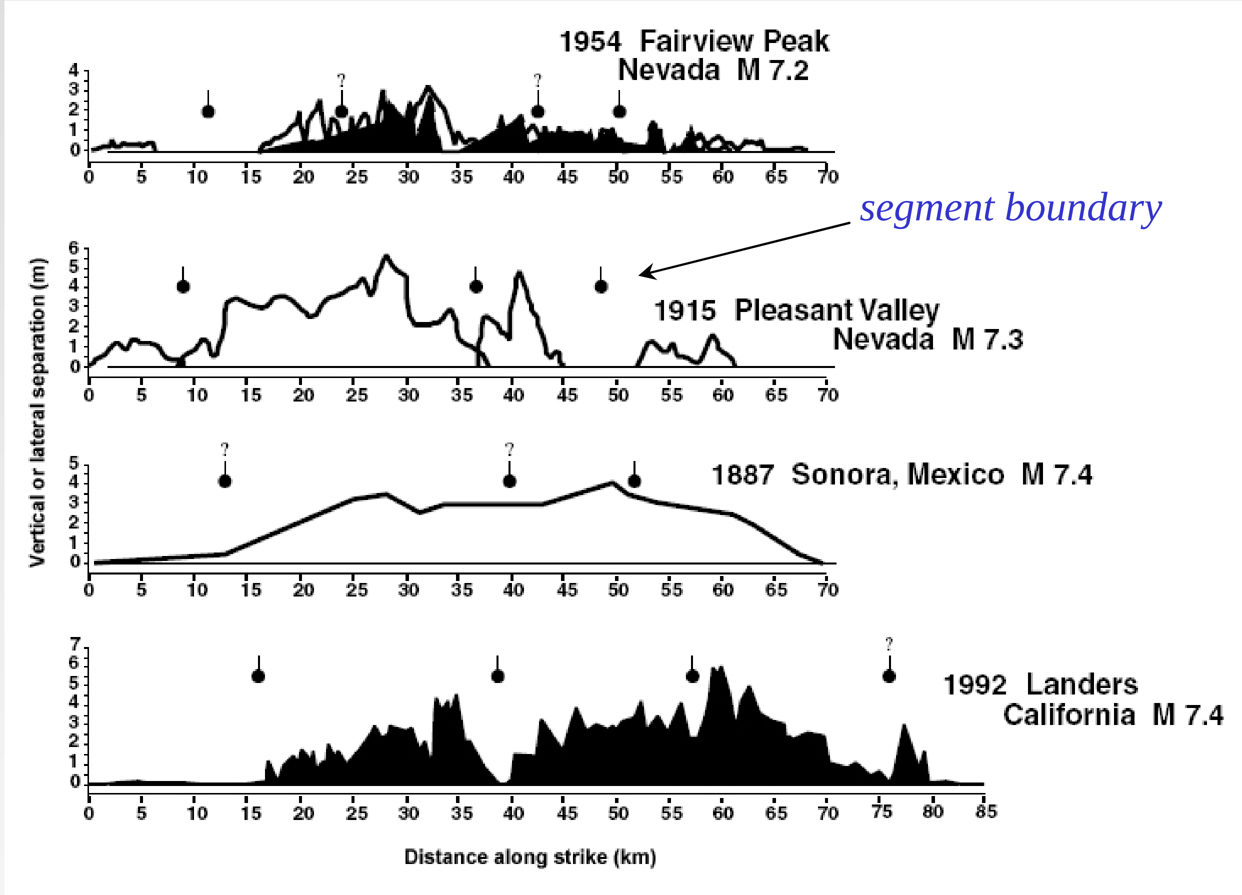
Basin and Range Province Earthquake Working Group
March 8-10, 2006

Multi-Segment Ruptures (MSRs)

MSRs - Why Bother?

1. Historical BRP surface faulting:

   complex and extensive – doesn't fit simple segmentation model (dePolo and others; 1991)



2. 2007 update of NSHMs

3. Directions for future WFZ paleoseismic research

Pezzopane and Dawson (1996)
Chang and Smith (2002)

MSR Analyses

Approaches

- ***Earthquake timing*** (paleoseismic studies: EQ time ranges, age distributions)
- ***Earthquake displacement*** (expected SRL given event slip)
- ***Segment boundary analysis*** (probability of rupture - SB characteristic, stress)
- ***Expert opinion*** (multiple working models)
- ***Some/all of the above,*** *or simple* ***time-independent model?***

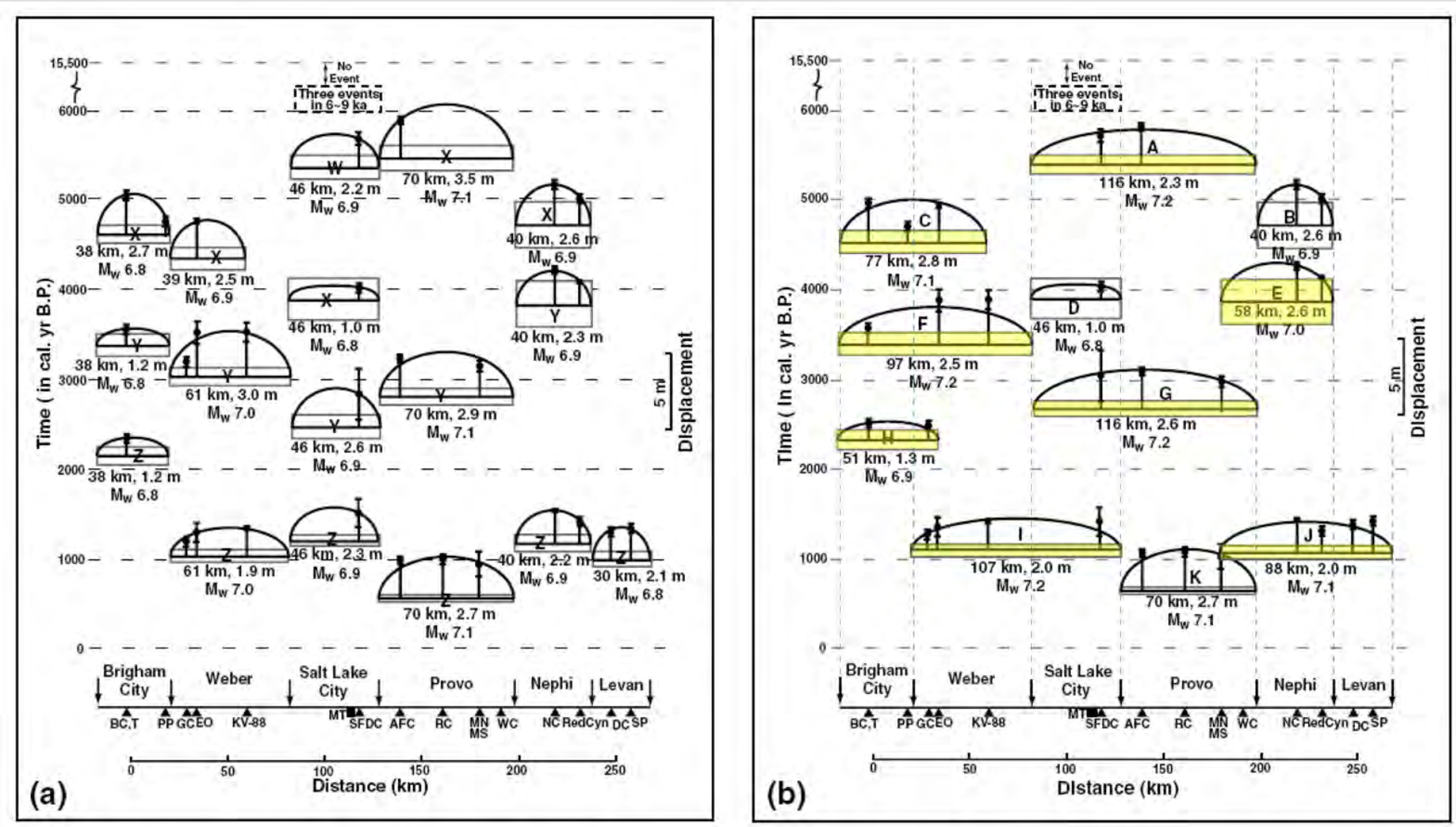
<u>In all cases need to:</u>

1. Honor geological information (e.g., timing, displacement)
2. Honor moment budget
3. Consider "*body and range of informed scientific opinion*" (Hanks, 1997)

MSR Analyses

Earthquake timing

Existing Wasatch fault zone (WFZ) MSR model:



Chang and Smith (2002); EQ timing: McCalpin and Nishenko (1996)

Wasatch Fault Zone (WFZ) MSR Analysis

WFZ multi-segment rupture model:

1. **Update and revise WFZ paleoearthquake space-time diagram** (UQFPWG; Lund, 2005)

2. **MSR rupture potential:**
   - compare UQFPWG preferred times

3. **Paleoseismic data confidence:**
   - number trench sites
   - number, style of limiting ages

4. **Generate multiple MSR models for the WFZ**

WFZ MSR Analysis

Preferred Method:

EQ Timing / Working Models (following WGCEP, 2003)

- ***Rupture model***: weighted combination of rupture scenarios, representing long-term behavior

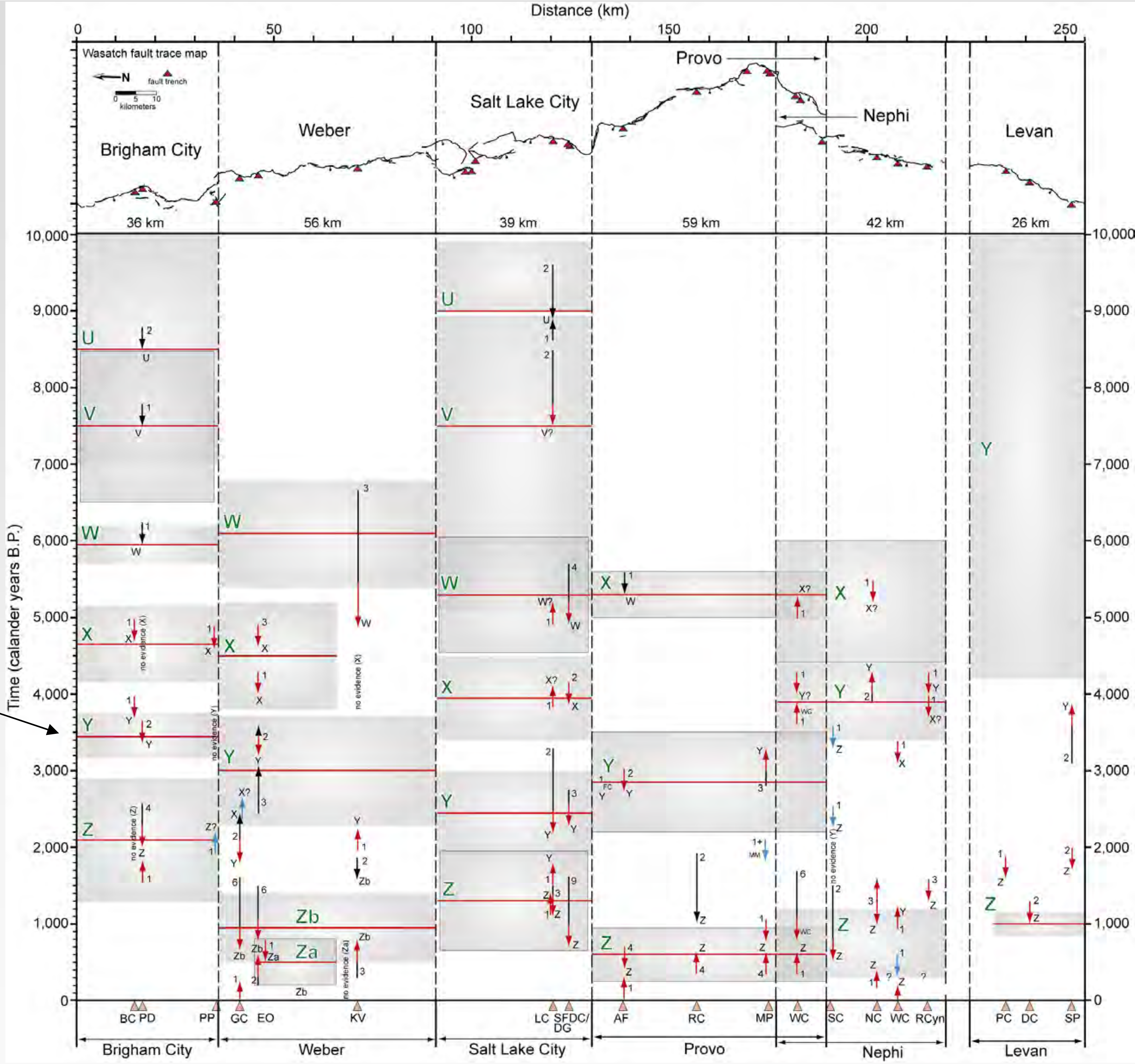
		MSR Models:	**A**	**B**	**C**
Rupture scenario	1.	BC, WB, SL, PV	1.0	0.8	0.2
	2.	BC+WB, SL, PV	0	0.05	0.2
	3.	BC, WB+SL, PV	0	0.05	0.2
	4.	BC, WB, SL+PV	0	0.05	0.2
	5.	BC+WB, SL+PV	0	0.05	0.2
			0.6	0.2	0.2

Rupture source

WFZ space-time

Earthquake timing UQFPWG (2005)

	<u>cal yr B.P.</u>
W	5950±250
X	4650±500
Y	3450±300
Z	2100±800



WFZ MSR Analysis

MSR Potential

MSR notation:

- BC+WB[W]; SLC[W]+PV[X]
- Multiple working models?

BC-WB			WB-SLC			SLC-PV			PV-NP		
BC[W]	WB[W]	5	WB[W]	SLC[W]	2	SLC[W]	PV[W]	0	PV[W]	NP[W]	5
	WB[X]	0		SLC[X]	0		PV[X]	5		NP[X]	0
BC[X]	WB[W]	0	WB[X]	SLC[W]	2	SLC[X]	PV[W]	0	PV[X]	NP[W]	0
	WB[X]	5		SLC[X]	3		PV[X]	0		NP[X]	0
	WB[Y]	0		SLC[Y]	0		PV[Y]	1		NP[Y]	0
BC[Y]	WB[X]	0	WB[Y]	SLC[X]	1	SLC[Y]	PV[X]	0	PV[Y]	NP[X]	4
	WB[Y]	3		SLC[Y]	3		PV[Y]	4		NP[Y]	0
	WB[Z]	0		SLC[Z]	0		PV[Z]	0		NP[Z]	0
BC[Z]	WB[Y]	2	WB[Z]	SLC[Y]	0	SLC[Z]	PV[Y]	0	PV[Z]	NP[Y]	1
	WB[Z]	1		SLC[Z]	4		PV[Z]	2		NP[Z]	4

*text colored gray due to unspecified Nephi and Provo events W

MSR Potential	
highest	5
	4
	3
	2
lowest	1
zero	0

WFZ MSR Analysis

Model C

- Only MSR potential: ***med-high***
- Relative weighting of scenarios
- 3/15 (20%) single-segment, 12/15 (80%) MSR earthquakes
- Limitation: no conflicting events (e.g., SLC[Y])

BC-WB			WB-SLC			SLC-PV		
BC[W]	**WB[W]**	**5**	WB[W]	SLC[W]	2.0	SLC[W]	PV[W]	0.0
BC[W]	WB[X]	0.0	WB[W]	SLC[X]	0.0	**SLC[W]**	**PV[X]**	**5**
BC[X]	WB[W]	0.0	WB[X]	SLC[W]	2.0	SLC[X]	PV[W]	0.0
BC[X]	**WB[X]**	**5.0**	WB[X]	SLC[X]	3.0	SLC[X]	PV[X]	0.0
BC[X]	WB[Y]	0.0	WB[X]	SLC[Y]	0.0	SLC[X]	PV[Y]	1.0
BC[Y]	WB[X]	0.0	WB[Y]	SLC[X]	1.0	SLC[Y]	PV[X]	0.0
BC[Y]	**WB[Y]**	**3**	WB[Y]	SLC[Y]	3.0	**SLC[Y]**	**PV[Y]**	**4**
BC[Y]	WB[Z]	0.0	WB[Y]	SLC[Z]	0.0	SLC[Y]	PV[Z]	0.0
BC[Z]	WB[Y]	2.0	WB[Z]	SLC[Y]	0.0	SLC[Z]	PV[Y]	0.0
BC[Z]	WB[Z]	1.0	**WB[Z]**	**SLC[Z]**	**4.0**	SLC[Z]	PV[Z]	2.0

Sum of highlighted: 34.5

Total weight for MSR scenarios (2-5): 80.0

		Relative weight:	Total weight
1)	BC, WB, SLC, PV		**20.0**
2)	BC+WB, SLC, PV	**0.38**	**30.1**
3)	BC, WB+SLC, PV	**0.12**	**9.3**
4)	BC, WB, SLC+PV	**0.26**	**20.9**
5)	BC+WB, SLC+PV	**0.25**	**19.7**
	sum:	1.0	*100.0*

WFZ MSR Analysis

Model D

- Identical to Model C, but including **paleoseismic data confidence**

Confidence multipliers:

high	1.00
medium-high	0.93
medium	0.85
medium-low	0.78
low	0.70

BC-WB			Conf mod:	WB-SLC			Conf mod:	SLC-PV			Conf mod:
BC[W]	**WB[W]**	5.0	3.50	WB[W]	SLC[W]	2.0		SLC[W]	PV[W]	0.0	
BC[W]	WB[X]	0.0		WB[W]	SLC[X]	0.0		**SLC[W]**	**PV[X]**	5.0	3.88
BC[X]	WB[W]	0.0		WB[X]	SLC[W]	2.0		SLC[X]	PV[W]	0.0	
BC[X]	**WB[X]**	5.0	3.88	WB[X]	SLC[X]	3.0		SLC[X]	PV[X]	0.0	
BC[X]	WB[Y]	0.0		WB[X]	SLC[Y]	0.0		SLC[X]	PV[Y]	1.0	
BC[Y]	WB[X]	0.0		WB[Y]	SLC[X]	1.0		SLC[Y]	PV[X]	0.0	
BC[Y]	**WB[Y]**	3.0	2.55	WB[Y]	SLC[Y]	3.0		**SLC[Y]**	**PV[Y]**	4.0	3.70
BC[Y]	WB[Z]	0.0		WB[Y]	SLC[Z]	0.0		SLC[Y]	PV[Z]	0.0	
BC[Z]	WB[Y]	2.0		WB[Z]	SLC[Y]	0.0		SLC[Z]	PV[Y]	0.0	
BC[Z]	WB[Z]	1.0		**WB[Z]**	**SLC[Z]**	4.0	4.00	SLC[Z]	PV[Z]	2.0	

um of confidence modified: 28.31

Total weight for MSR scenarios (2-5):

80.0

		Relative weight:	**Relative * total weight**
1)	BC, WB, SLC, PV		**20.0**
2)	BC+WB, SLC, PV	**0.35**	**28.0**
3)	BC, WB+SLC, PV	**0.14**	**11.3**
4)	BC, WB, SLC+PV	**0.27**	**21.4**
5)	BC+WB, SLC+PV	**0.24**	**19.2**
	sum:	*1.0*	*100.0*

WFZ MSR Analysis

Weighting the models

- Weighting for single-segment vs. MSR models? (**80/20?**)

Model A: single-segment earthquakes only, no MSRs
Model B: conflict OK, only MSR potential 3+
Model C: no conflict, only MSR potential 3+
Model D: no conflict, only MSR potential 3+, includes data confidence
Model E: Based on Chang and Smith (2002); relative weighting, conflict OK

MSR scenarios:	A	B	C	D	E	
1) BC, WB, SLC, PV	100	13.3	20.0	20.0	14.3	
2) BC+WB, SLC, PV	0	30.9	30.1	28.0	36.7	
3) BC, WB+SLC, PV	0	23.8	9.3	11.3	12.2	
4) BC, WB, SLC+PV	0	32.1	20.9	21.4	24.5	
5) BC+WB, SLC+PV	0	0.0	19.7	19.2	12.2	*sum*
Model weights (%):	**80**	**5**	**5**	**5**	**5**	*100*

Summary of relative scenario weights

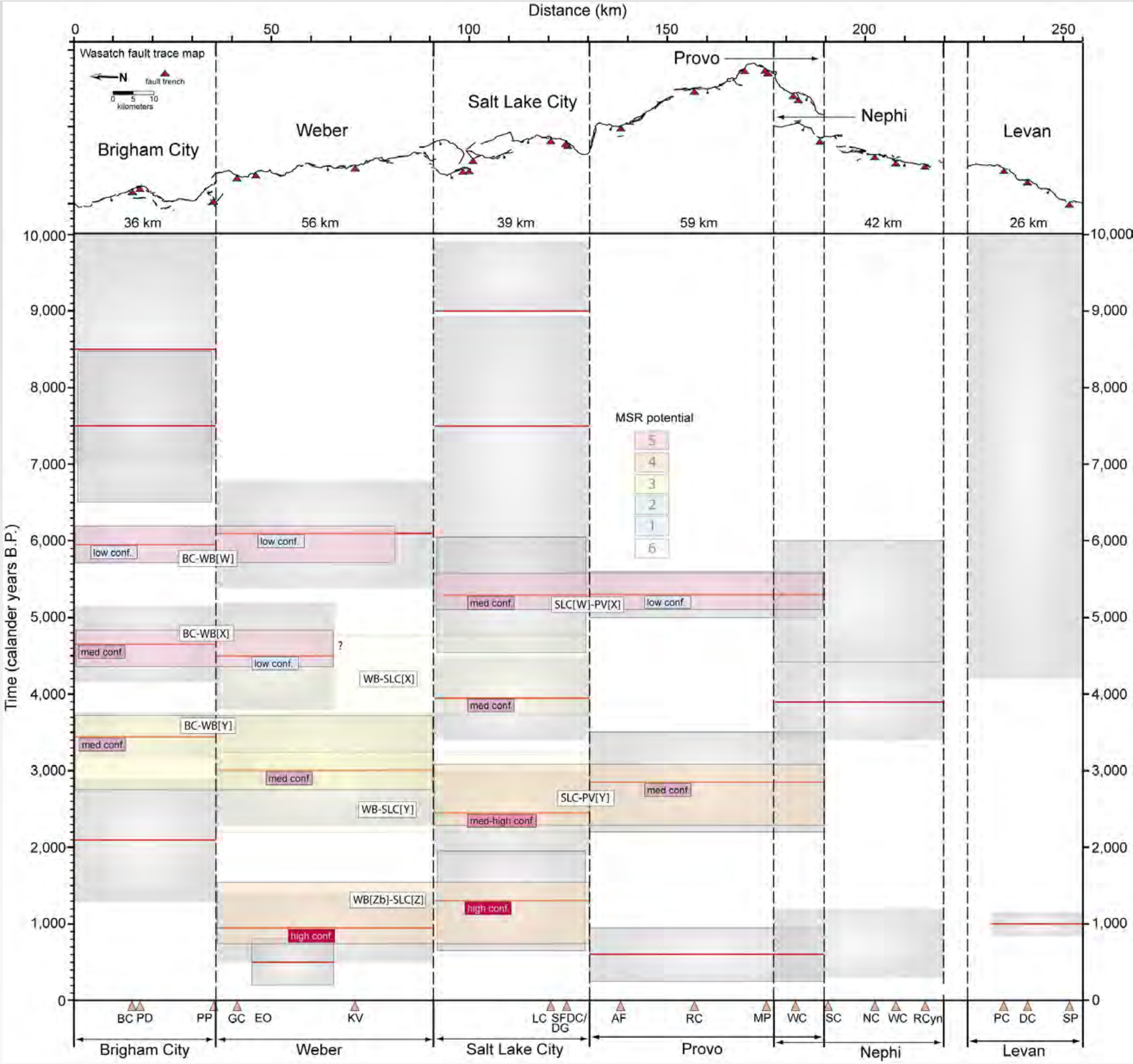
	A	B	C	D	E	
1) BC, WB, SLC, PV	80.0	0.7	1.0	1.0	0.7	**83.4**
2) BC+WB, SLC, PV	0.0	1.5	1.5	1.4	1.8	**6.3**
3) BC, WB+SLC, PV	0.0	1.2	0.5	0.6	0.6	**2.8**
4) BC, WB, SLC+PV	0.0	1.6	1.0	1.1	1.2	**4.9**
5) BC+WB, SLC+PV	0.0	0.0	1.0	1.0	0.6	**2.6**
					sum:	*100.0*

Preferred MSR Model

6-8 MSRs

2-3 single-segment EQs

Older events: ***low*** confidence; ***high*** MSR potential



Ongoing Work

Issues and recent advances

1. **EQ timing**
   - Estimated 95% time ranges?
   - Trench-site-specific data?

2. **Displacement data**
   - Large enough for MSRs?
   - Use to estimate SRL?
   - Moment balance?

3. **SAF rupture methods (using age distributions, displacement, moment balance) appropriate for WFZ/BRP?**
   - Possible Provo-Nephi segment MSR

1. EQ timing

EQ time distributions

Incorporating:

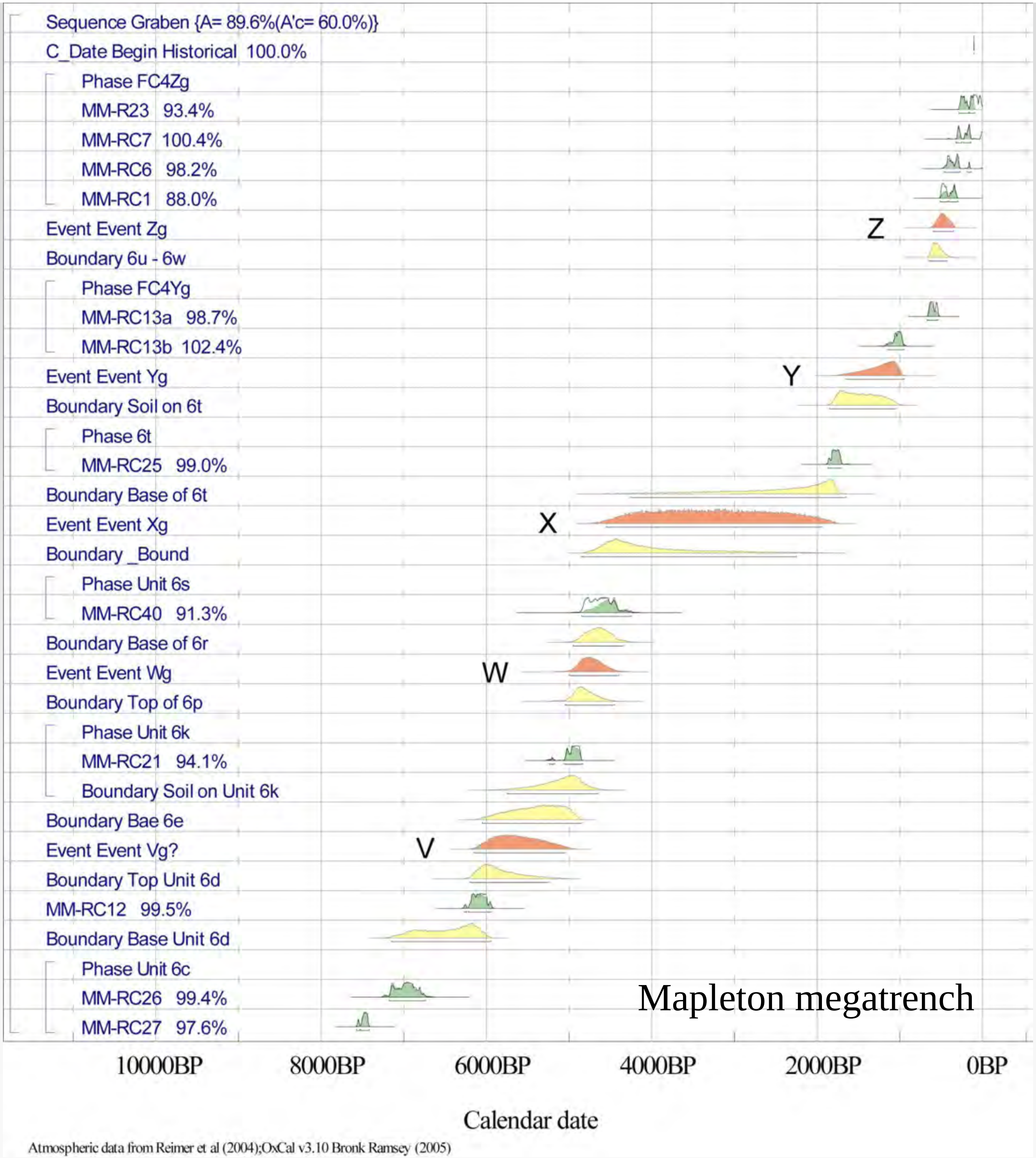
- layer ordering
- 14C ages
  (geological context)

To determine:

Age distributions for undated events

Compare events between sites

Biasi and others (2002)

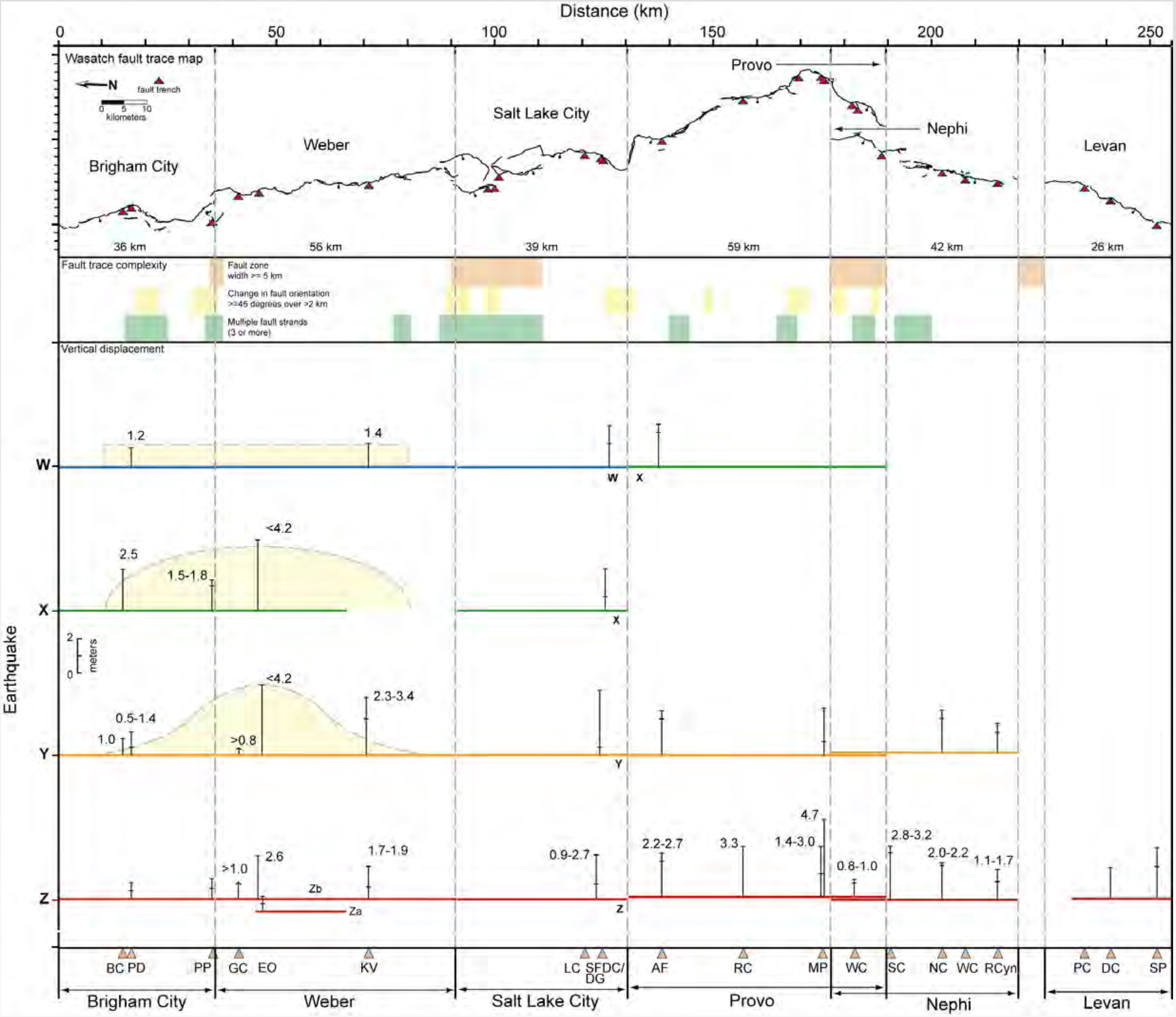


2. Displacement

WFZ Displacement per event

Displacement profile:

critical for moment balance



2. Displacement

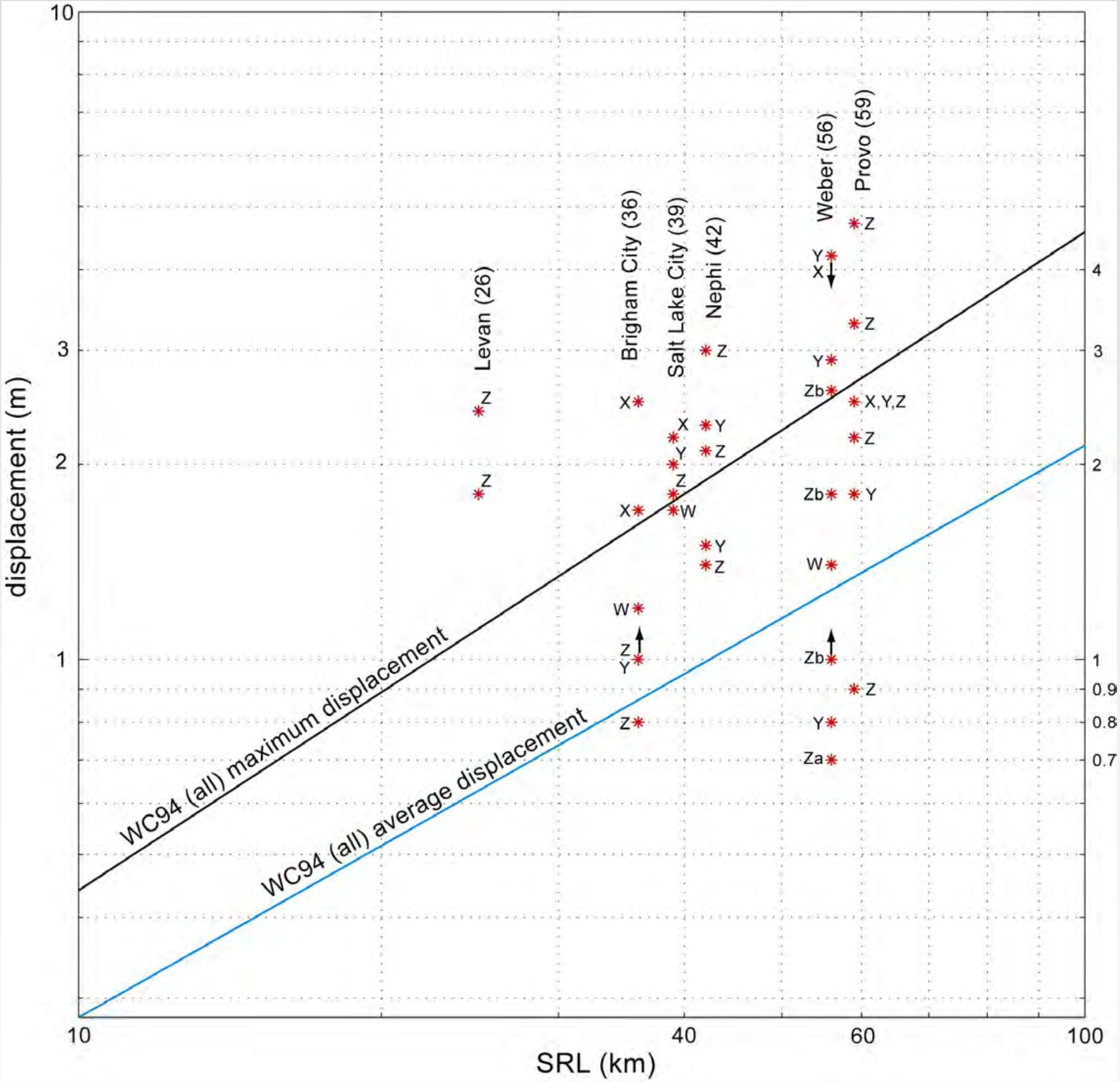
WFZ displacement-per-event data

(n=34)

47% - above max

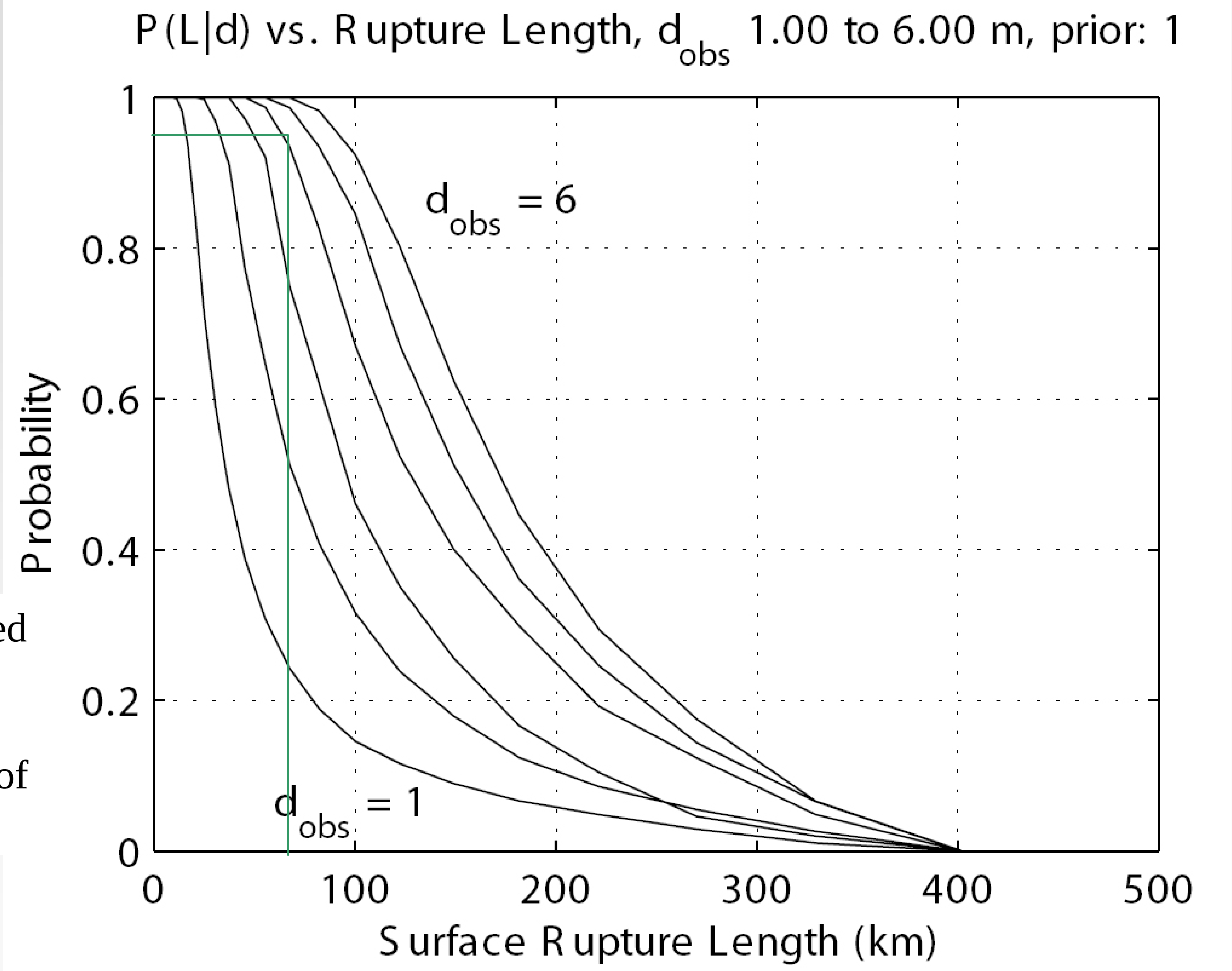
38% - between max and average

15% - below average



2. Displacement

Probability of SRL given displacement



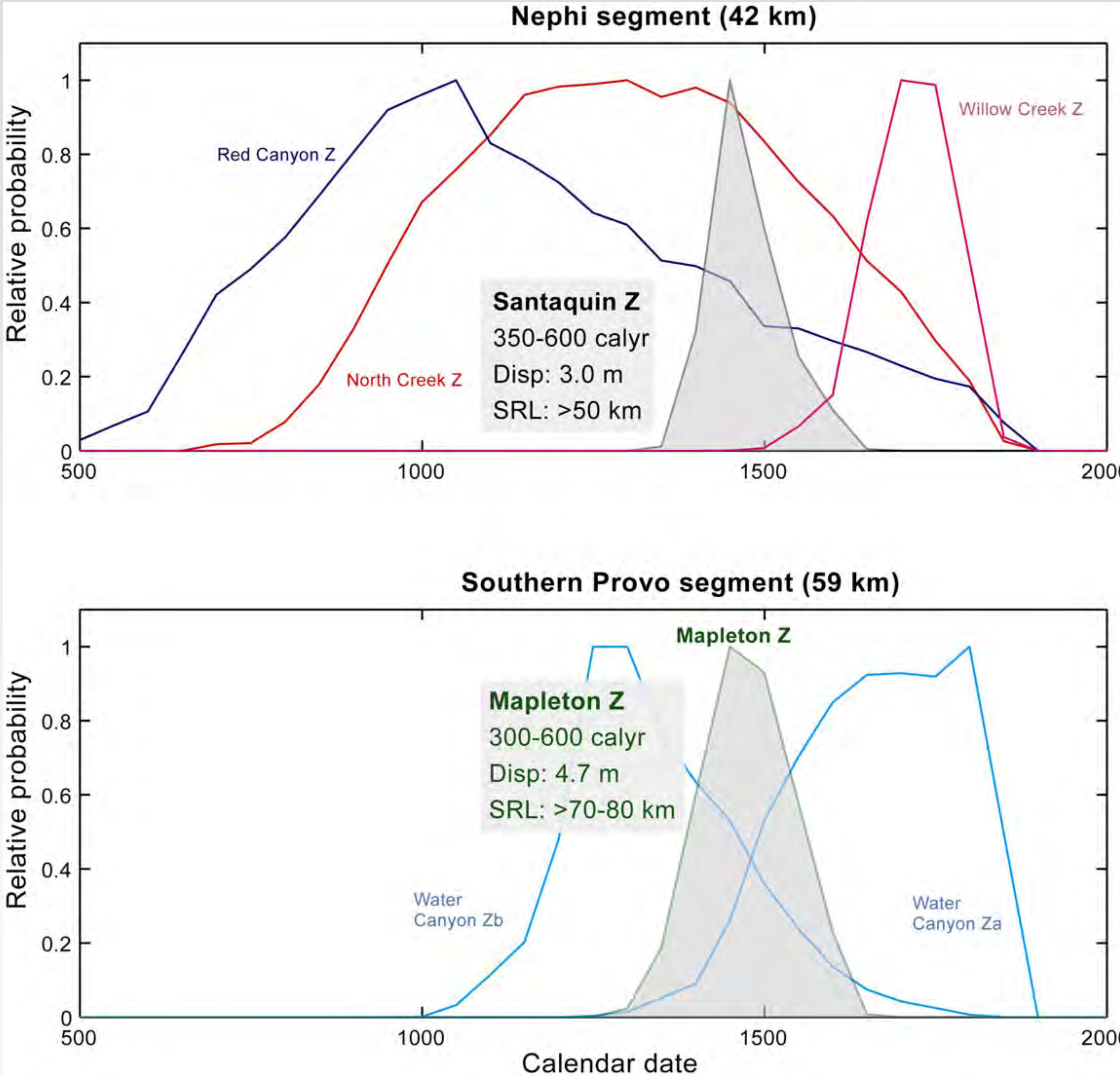
4-meter observed displacement: figure predicts a 95% likelihood of a **SRL ≥ 70 km**

Biasi and Weldon (BSSA, in press)

3. Example: Provo-Nephi MSR?

Integrate:

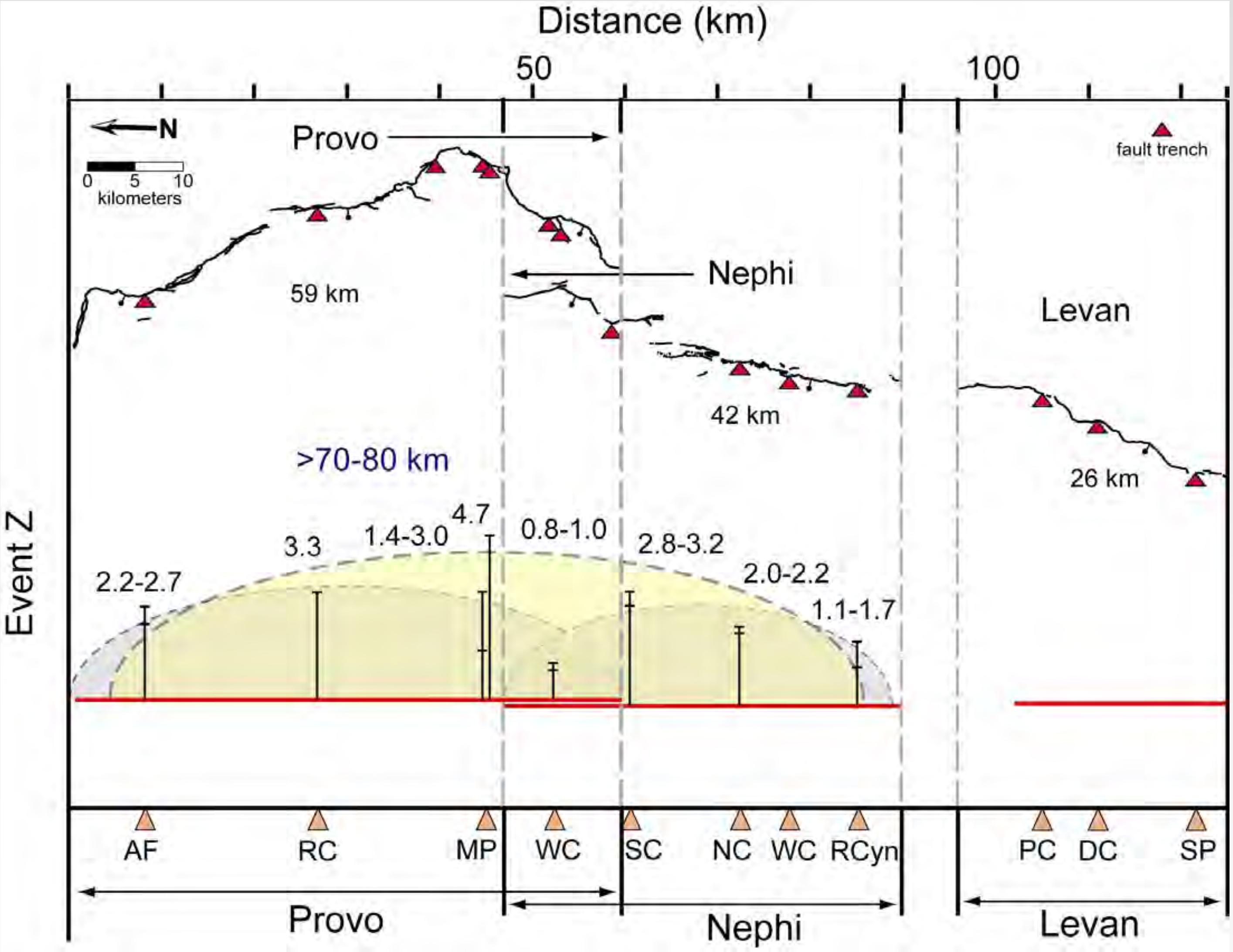
EQ time distribution, displacement and SRL information



3. Example: Provo-Nephi MSR?

Integrate:

EQ time distribution, displacement, and SRL information



WFZ & BRP MSRs

Discussion

1. So MSRs possible on WFZ (and other BRP faults?):
   - but, infrequent compared to single-segment ruptures?

2. MSRs accounted for in 2002 NSHM magnitude/length uncertainties?

PROBABILITIES AND MAGNITUDES OF MULTI-SEGMENT RUPTURES

Issue Discussion Leaders

Craig dePolo, Nevada Bureau of Mines and Geology, Reno, Nevada
James Pechmann, University of Utah Seismograph Stations, Salt Lake City, Utah

Presentations

BRPEWG afternoon session, March 9, 2006

Pechmann	Probabilities and Magnitudes of Multi-segment Ruptures: Specific Questions
Haller	Fault Segmentation Models in Probabilistic Seismic Hazard Analyses
dePolo	Defining Fault Length for Determining Earthquake Size
DuRoss	Addressing the Potential for Multi-segment Ruptures on the Wasatch Fault
Pechmann	Use of Multi-segment Rupture Models in the National Seismic Hazard Maps: Options and Effects

Session Summary

Jim Pechmann began the session by pointing out that the 2002 National Seismic Hazard Maps (NSHMs) use multi-segment rupture (MSR) models for the San Andreas and Hayward faults in California. He then posed three fundamental questions regarding the use of MSR models for Basin and Range Province (BRP) faults:

- Should the NSHMs use MSR models for BRP faults?
- If so, what general types of models should be used, and how should they be weighted relative to single-segment rupture (SSR) models?
- Should rupture "spill-over" and triggered earthquakes be considered in the models as well?

Kathy Haller stated that characteristic earthquake magnitudes for faults on the NSHMs are determined from surface rupture length only. She presented examples of three comparatively well-studied BRP faults (Lost River, Hebgen Lake, and Pleasant Valley) where application of segmentation (fault length) models results in a significant over estimation of the number of expected surface-faulting earthquakes compared to the paleoseismic record. Kathy noted that the two fault strands that ruptured together during the 1959 Hebgen Lake earthquake are modeled separately on the 2002 NSHMs. She then discussed the Ruby Mountain fault, which is one of only three segmented BRP faults on the NSHMs (the others being the Wasatch fault [WF] and the Hurricane fault). Using segment lengths to calculate the number of expected earthquakes for the Ruby Mountain fault works fairly well when compared to the paleoseismic record. However, the WF is modeled using average segment recurrence intervals, and consistently gives characteristic earthquake magnitudes that are too large for the segment lengths, thus supporting the possibility of MSRs. Examples of applying a MSR model to the WF showed only a small effect (between -4 and 7% g) on hazard. Lessons learned from Kathy's presentation include:

- The need to carefully evaluate both the quality and quantity of data supporting segmentation prior to segmenting a fault.

- The need to define a minimum data standard (type, quantity, and quality) for fault segmentation in the BRP.

- The need to be aware of possible outcomes when choosing a segmentation model.

Craig dePolo then discussed the history and present practice of defining fault segments on long faults. He defined earthquake segmentation as "Using physical features of a fault, including historical and paleoseismic data, to define potential earthquake segments for approximating future earthquake ruptures." The basis for earthquake segmentation includes (1) historical surface ruptures, (2) paleoseismic information (trenching data), and (3) tectonic geomorphology (chiefly young fault scarps). However, Craig noted that based on earthquake segmentation theory, only about half of the end points of historic BRP surface-faulting ruptures were definable. Regarding a threshold for MSRs, Craig believes that overall fault lengths must exceed 15-20 kilometers. Craig concluded by saying that the division of long faults into earthquake segments makes physical sense and likely does model future earthquakes; however, echoing Kathy, he stated that the process of determining defensible segmentation models and likelihoods is difficult, especially where good paleoearthquake data are lacking.

Chris DuRoss presented the results of his recent work on evaluating the potential for MSRs on the WF. To examine the that possibility, Chris updated and revised the WF paleoearthquake space-time diagram, evaluated paleoseismic data quality/confidence, and generated a variety of MSR models for the fault. His work is ongoing, but preliminary results indicate 6 to 8 MSRs are possible for the WF during the past 6000 years. Chris displayed a displacement versus rupture length diagram for the WF, which shows that 47% of the displacement data for WF segments is larger than the maximum displacement predicted by the Wells and Coppersmith (1994) regression equations, thus again indicating that MSRs are possible on the WF.

Jim Pechmann concluded the session presentations by reviewing the five principal types of MSR models presently in use, and the effects of MSR models on seismic-hazard analyses. He concluded that "Overall, MSR models give lower probabilistic seismic hazard than SSR models if the models are moment balanced (i.e., the slip rate is the same for both)." The hazard is lower because MSRs produce larger earthquakes, which result in longer recurrence intervals, which translate into fewer earthquakes over a given time period, and therefore, lower seismic hazard. Jim referred to Kathy Haller's two-segment rupture model for the WF, which showed only a small change in hazard compared to a SSR model. Jim finished by stating that while MSRs may only have a small effect on overall hazard, MSR scenarios, where credible, are important for emergency planning purposes.

Discussion following the presentations considered whether or not long faults on the NSHMs should be segmented, the Working Group consensus was yes, and whether or not current information for most BRP faults is sufficient to allow them to be segmented, the consensus was generally no. It was agreed that acquiring the new data necessary to permit fault segmentation would be a long-term undertaking. A suggestion was made to focus data-gathering activities on urban faults where the risk is greatest, but an objection was raised because most opportunities to study urban faults have been lost to development, while more remote faults are still largely available for study and may teach us important lessons. Discussion then moved on to whether or not an MSR model should be applied to BRP faults once they are segmented, and if so what kind of model should it be? The Working Group concluded that it is important to consider the effects of MSRs on the NSHMs, and that given our present understanding of fault segmentation in the BRP, that an un-segmented model with a maximum rupture length greater than the average segment length be applied to presently segmented BRP faults.

Recommendations

The Working Group reached consensus on six recommendations regarding SSR versus MSR models for BRP faults. Three are short-term recommendations and should be included in the 2007 NSHMs update. One recommendation is both short- and long-term, and the final two recommendations are long-term and are intended to guide future research.

Short-Term Recommendations

1. Hazard calculations for the NSHMs should consider the possibility of MSRs on BRP faults.

2, For BRP faults for which SSR models are being used to compute the hazard, the 2007 NSHMs should also use an un-segmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The un-segmented model should be given relatively low weight.

3. The two faults that ruptured together in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the purpose of the 2007 NSHM hazard calculations.

Short-Term/Long-Term Recommendation

4. Where available, displacement data should be used to provide a consistency check for segmentation models - especially to identify segments on which ruptures longer than the mapped length could occur.

Long-Term Recommendations

5. Newly-developed methods for probabilistically constructing rupture scenarios from paleoearthquake dates and displacements should be applied to the WF.

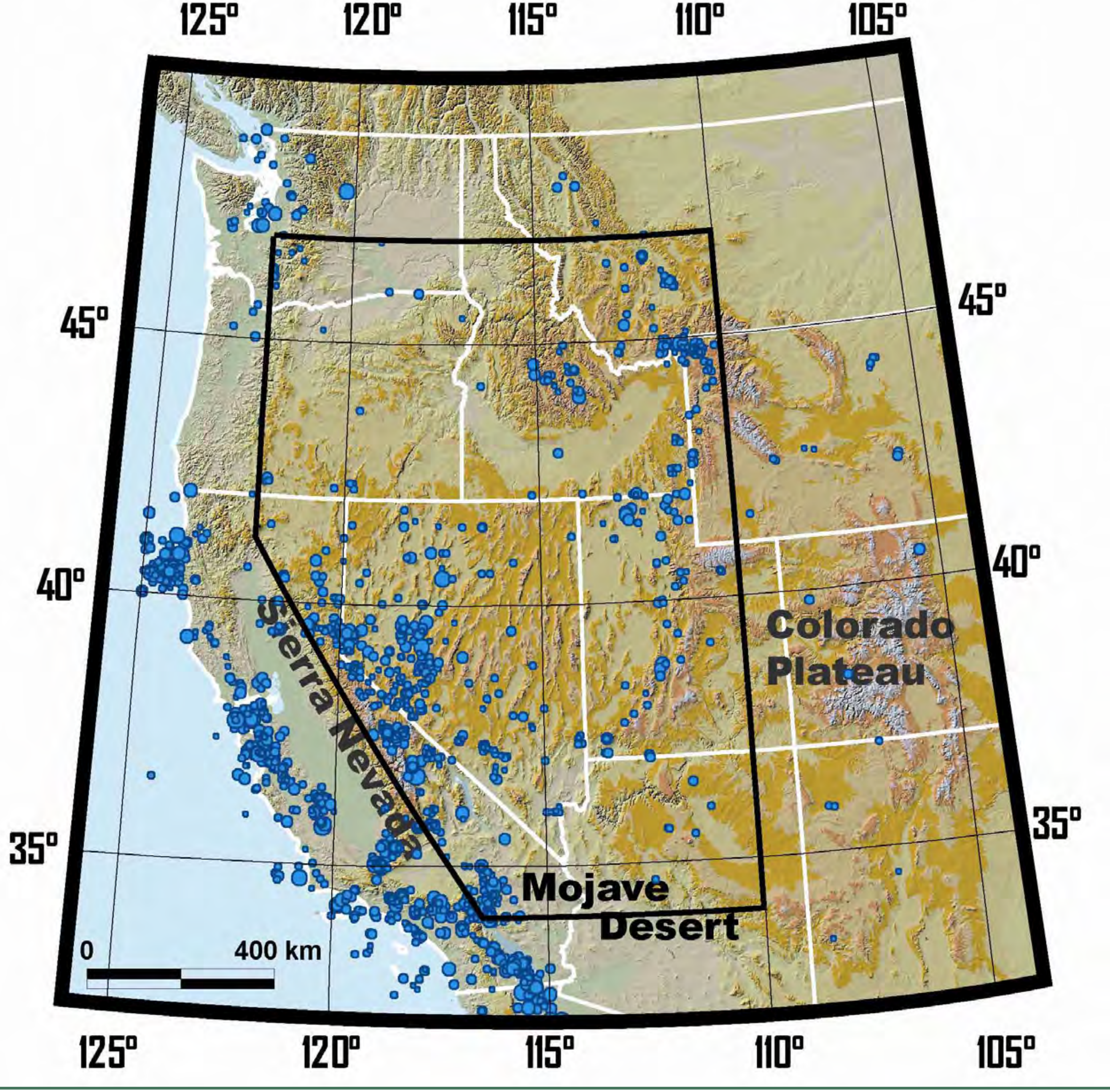
6. Research needs to be conducted in the BRP to facilitate segmentation modeling:

   (a) How to recognize and characterize fault-rupture segments.
   (b) Improve the quality and quantity of paleoseismic data needed to support segmented earthquake models along BRP faults.
   (c) Construct earthquake-segmentation models for important BRP faults.

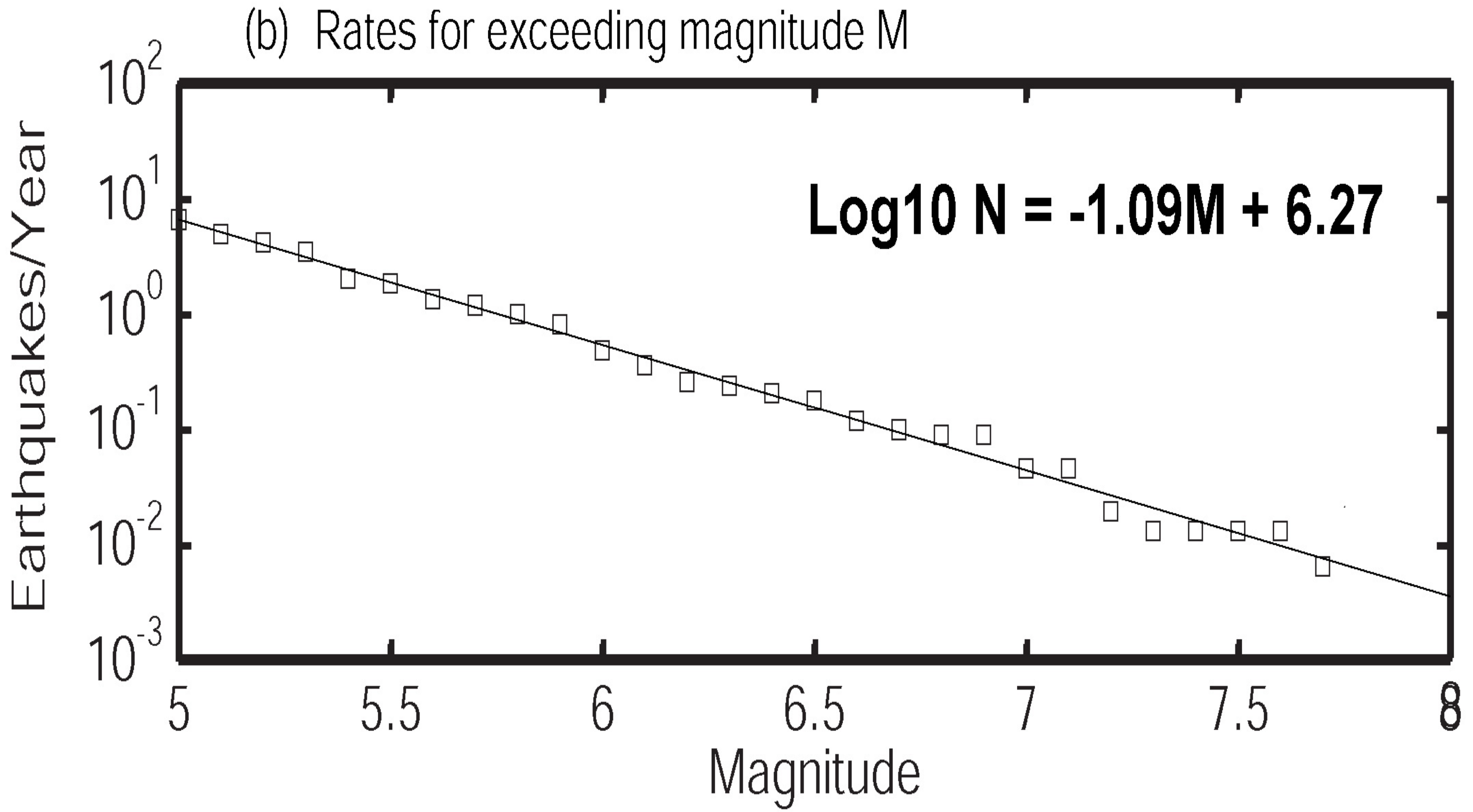
References

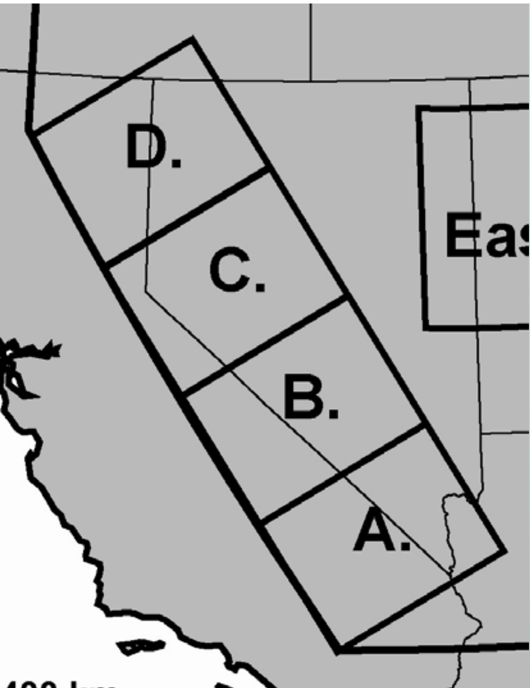
Basin and Range Province Earthquake Working Group Workshop: Friday AM

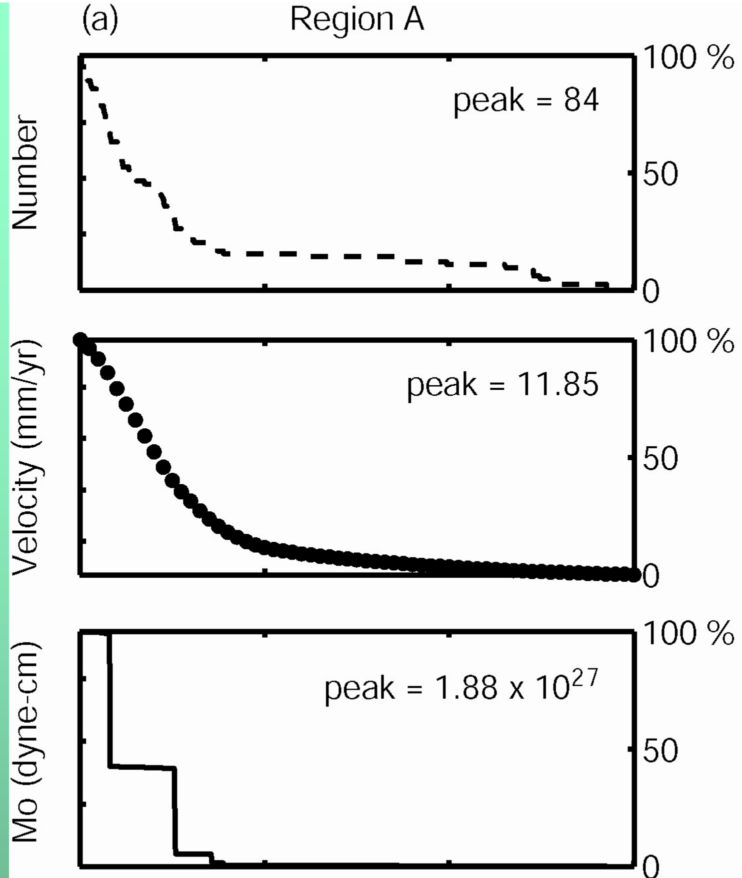
John G. Anderson

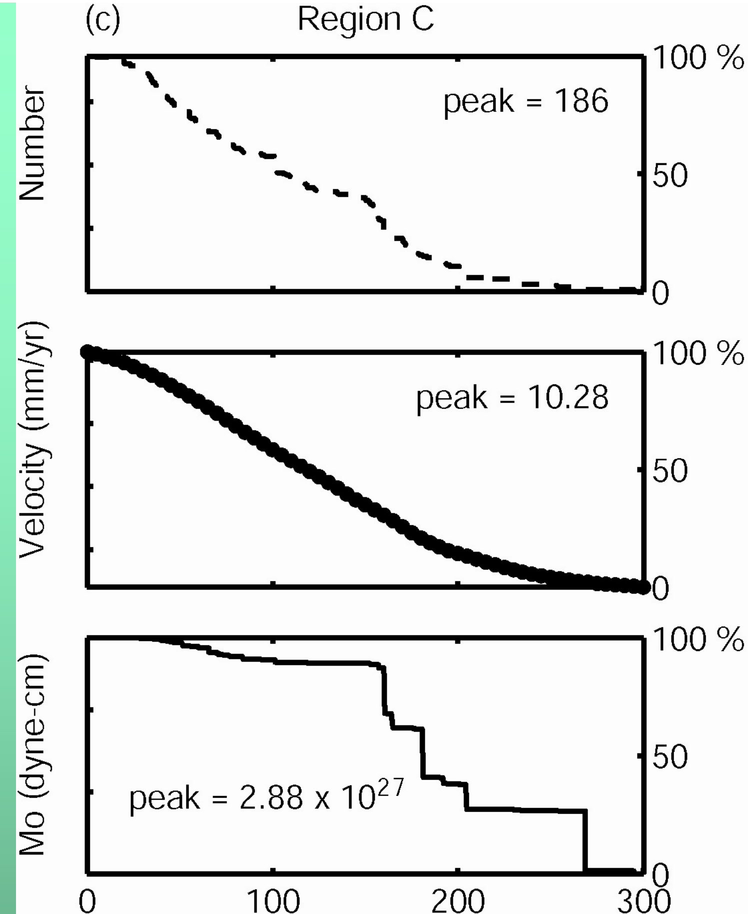


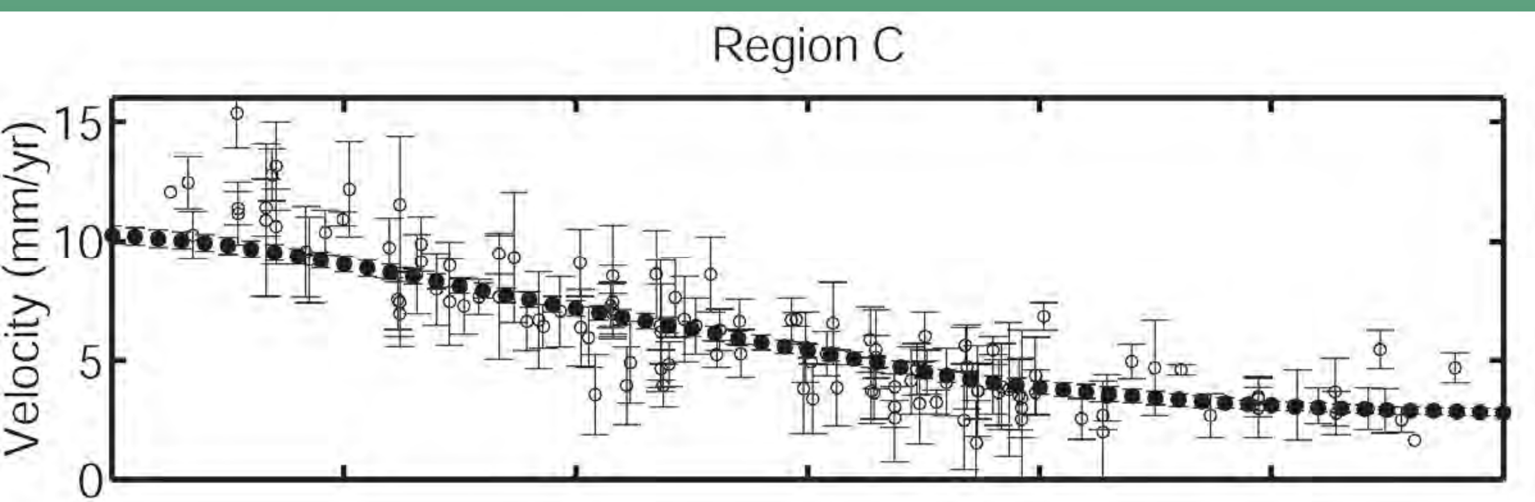
NEVADA Seismological Laboratory


(b) Rates for exceeding magnitude M
Log10 N = -1.09M + 6.27
Earthquakes/Year
10^2
10^1
10^0
10^-1
10^-2
10^-3
5
5.5
6
6.5
7
7.5
8
Magnitude



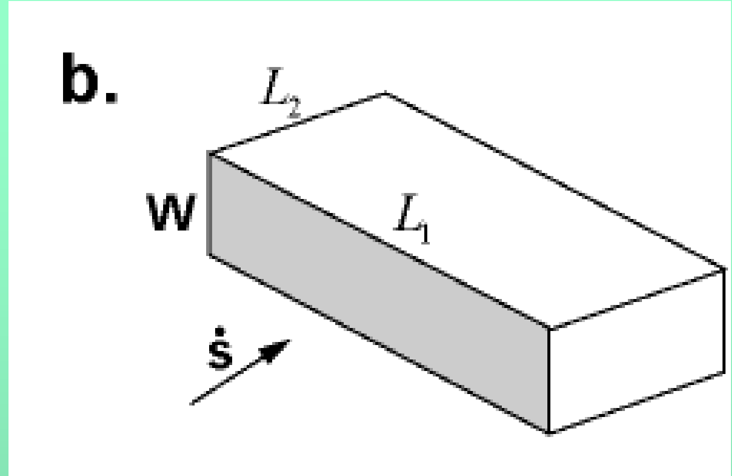




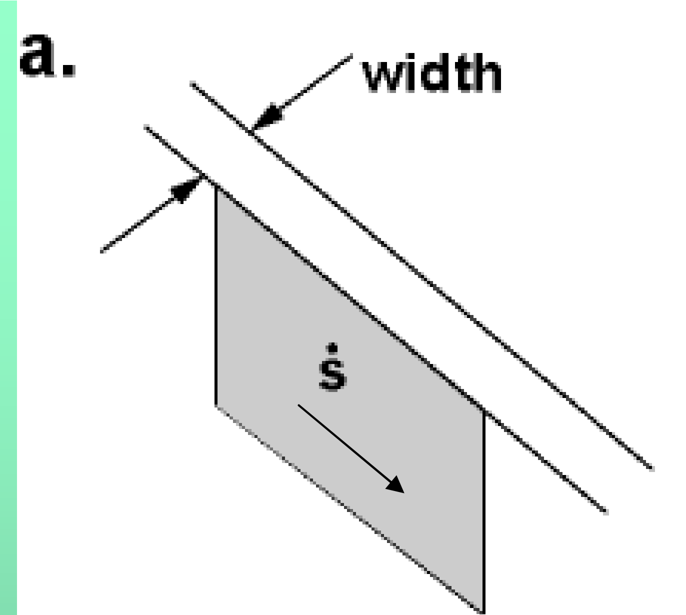


NEVADA Seismological Laboratory

Anderson (1979)

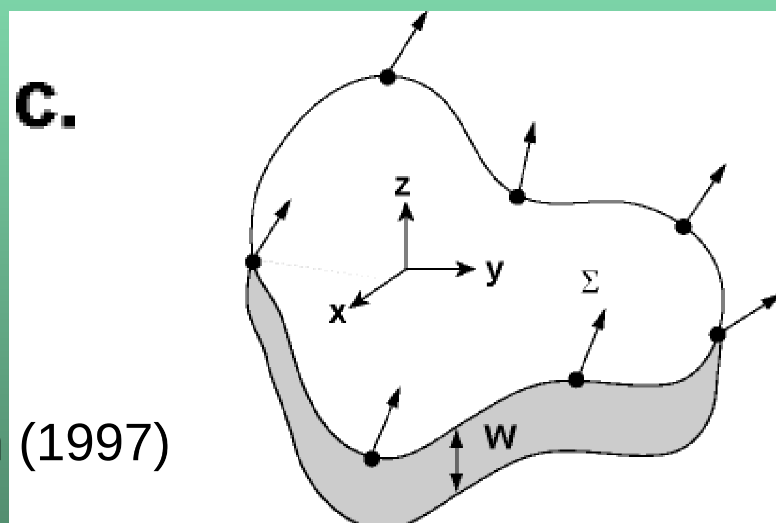


$$\dot{M}_o = 2\mu W L_1 L_2 \, \dot{\varepsilon}_2 / k \quad (k<1)$$

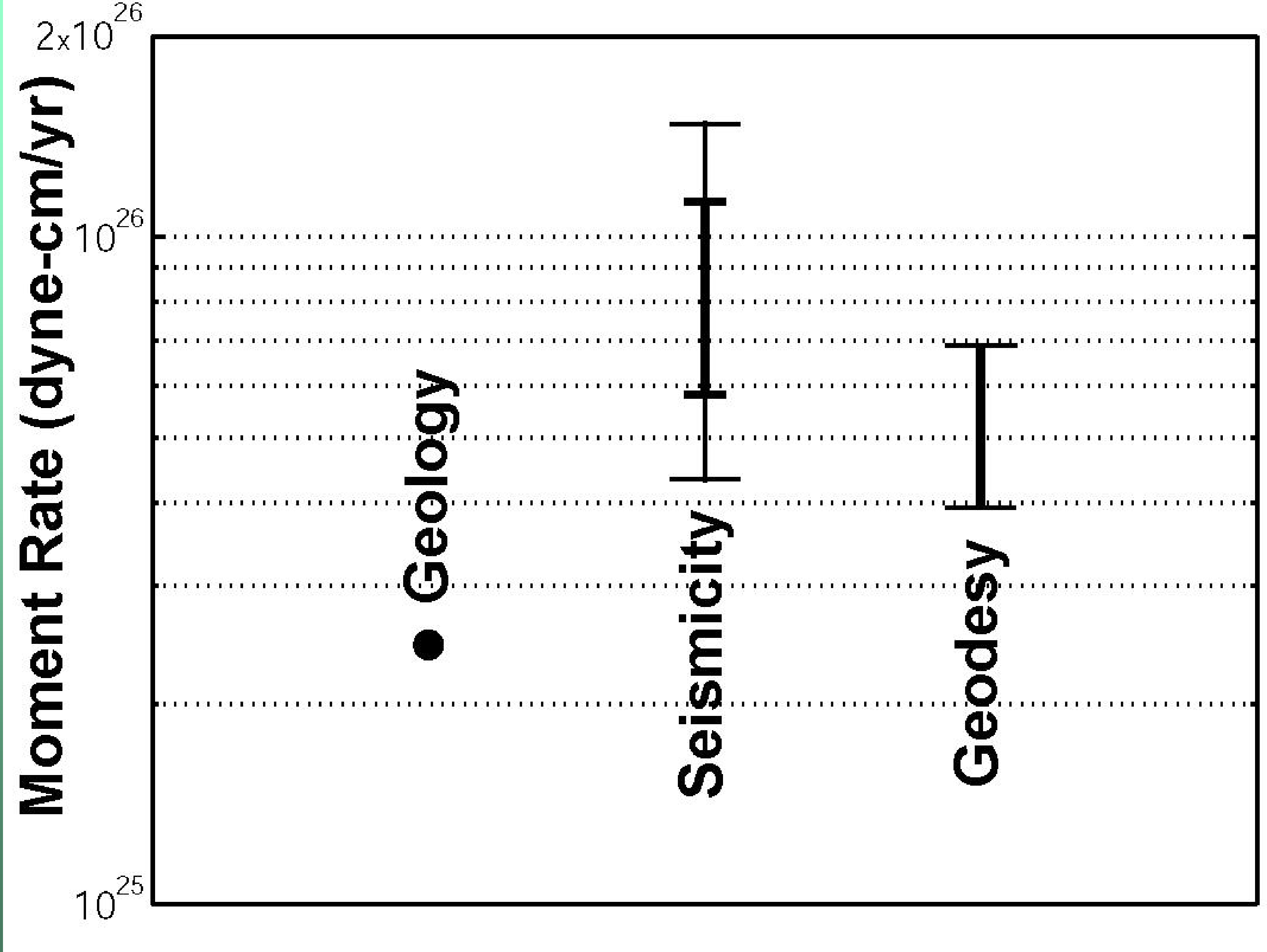


$$\dot{M}_o = \mu A \dot{s}$$

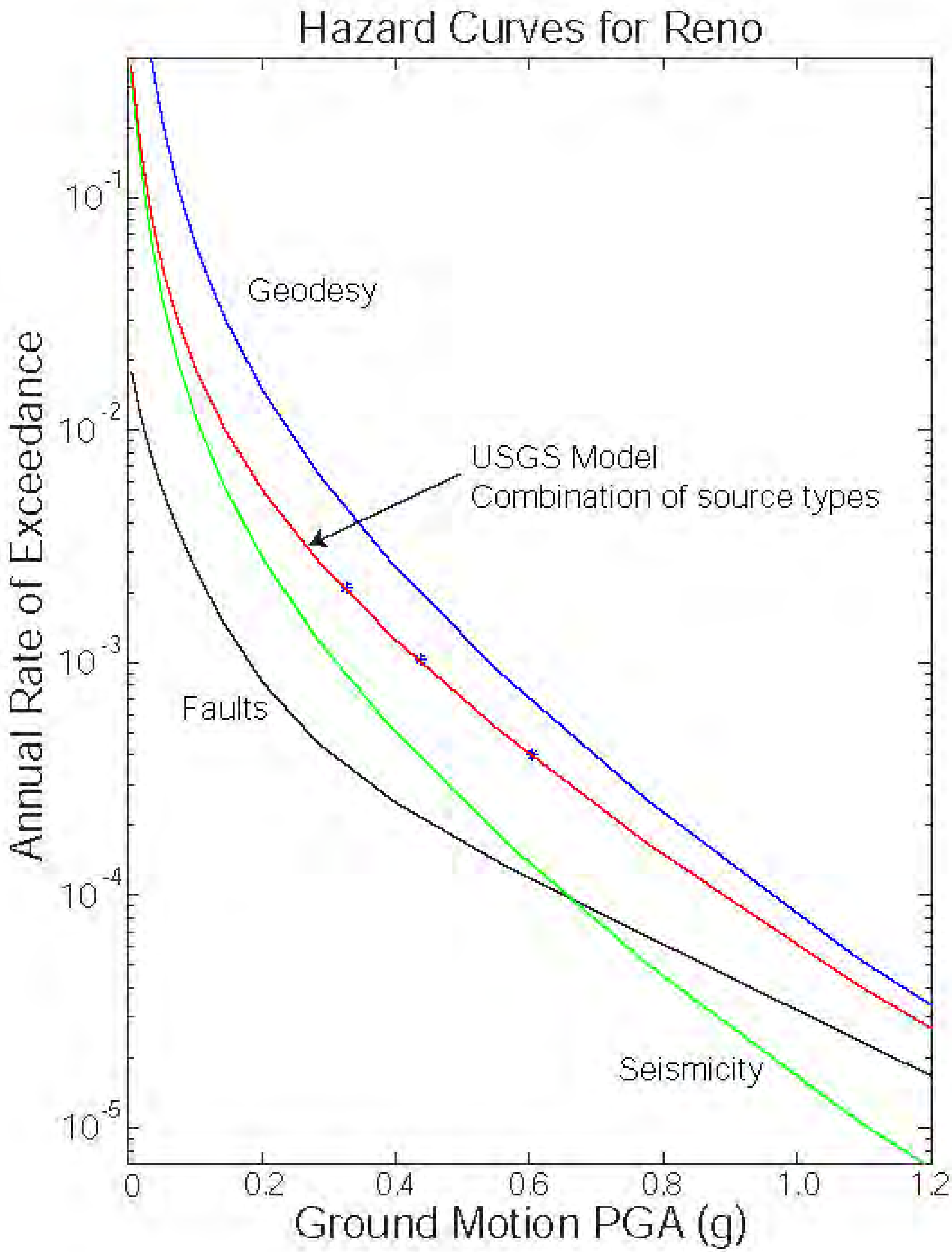
Savage and Simpson (1997)



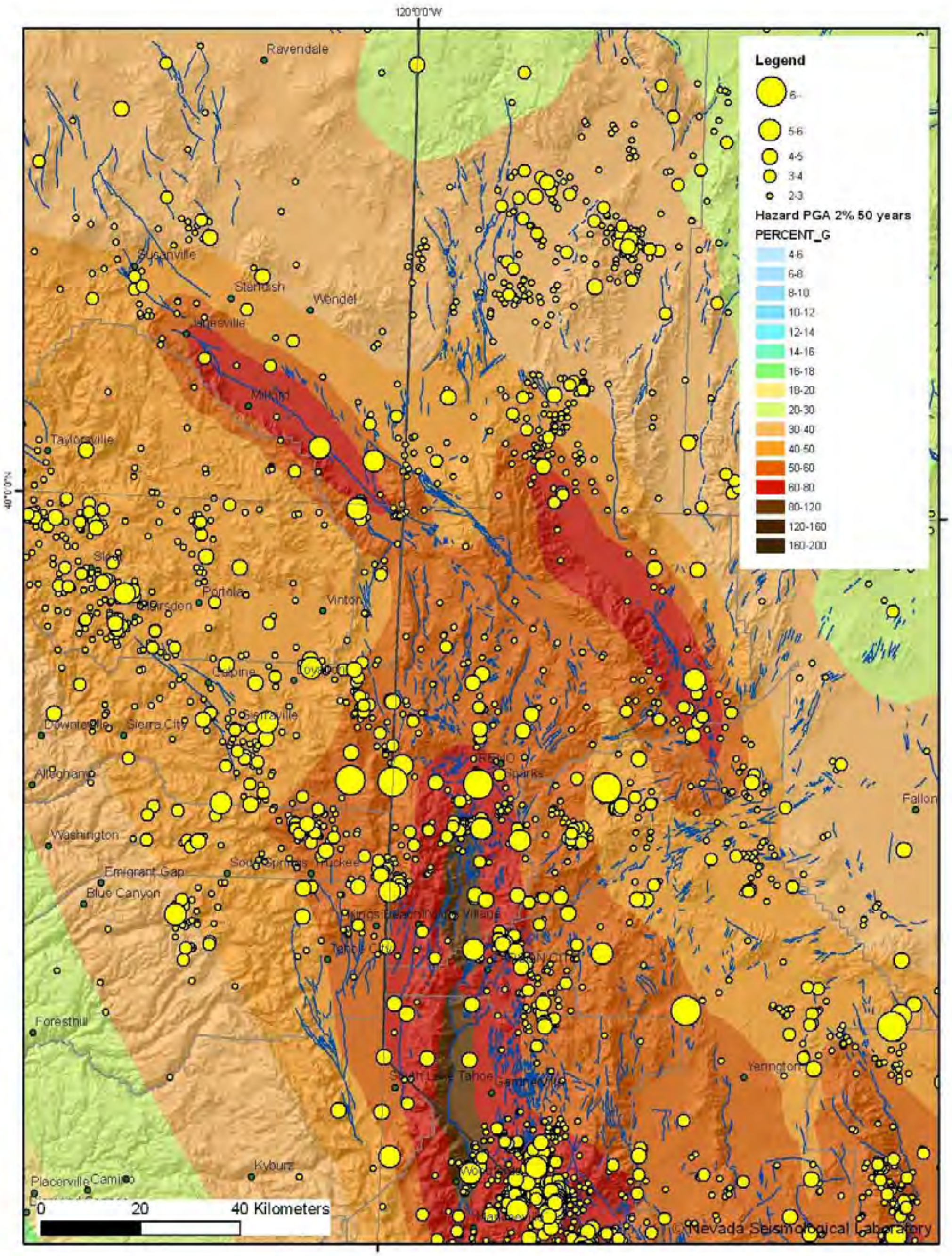
$$\dot{M}_o^{(\min)} = 2\mu W \Sigma Max\left(\left|\dot{\varepsilon}_1\right|, \left|\dot{\varepsilon}_2\right|, \left|\dot{\varepsilon}_1 + \dot{\varepsilon}_2\right|\right)$$

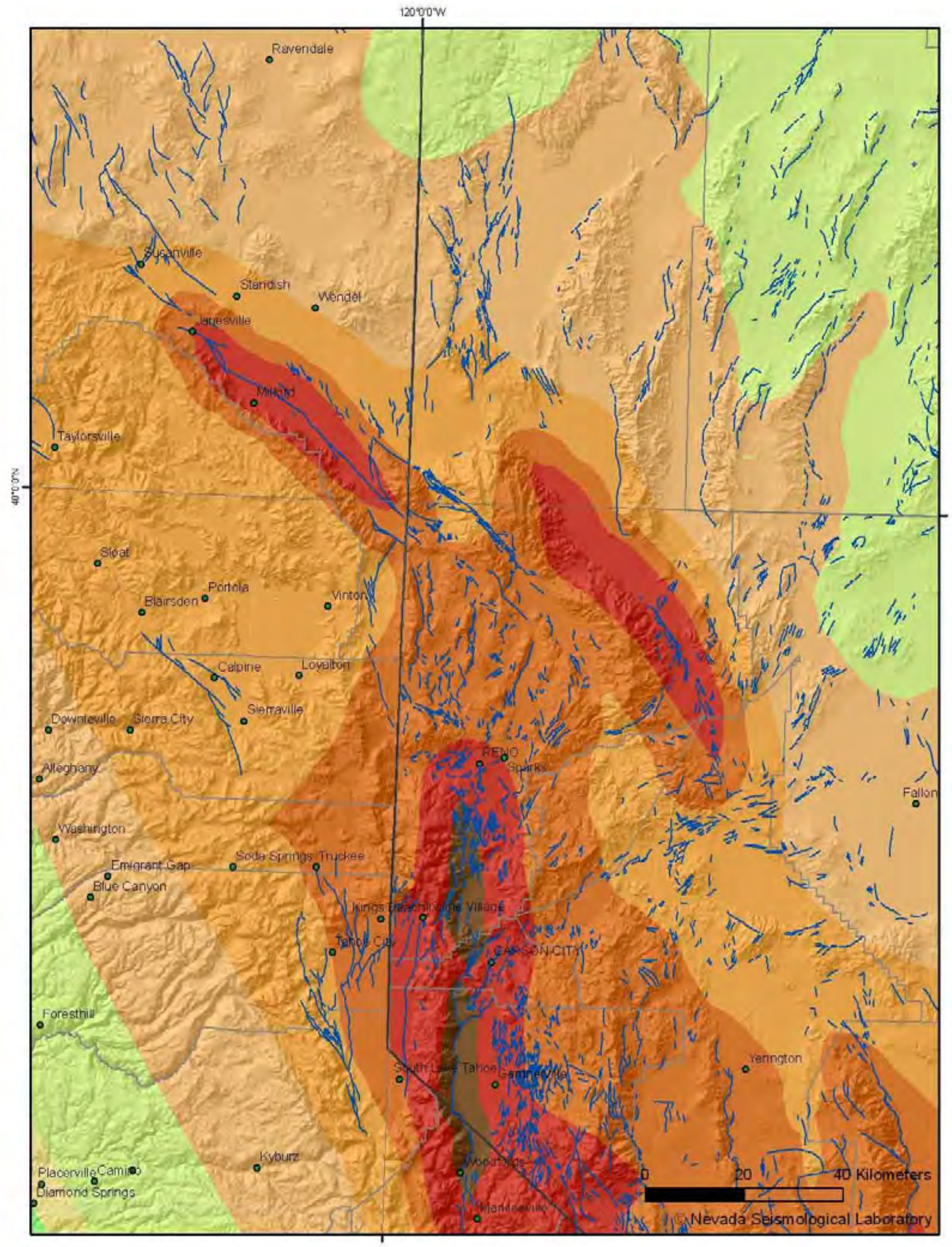


$2x10^{26}$
10^{26}
10^{25}
Moment Rate (dyne-cm/yr)
Geology
Seismicity
Geodesy

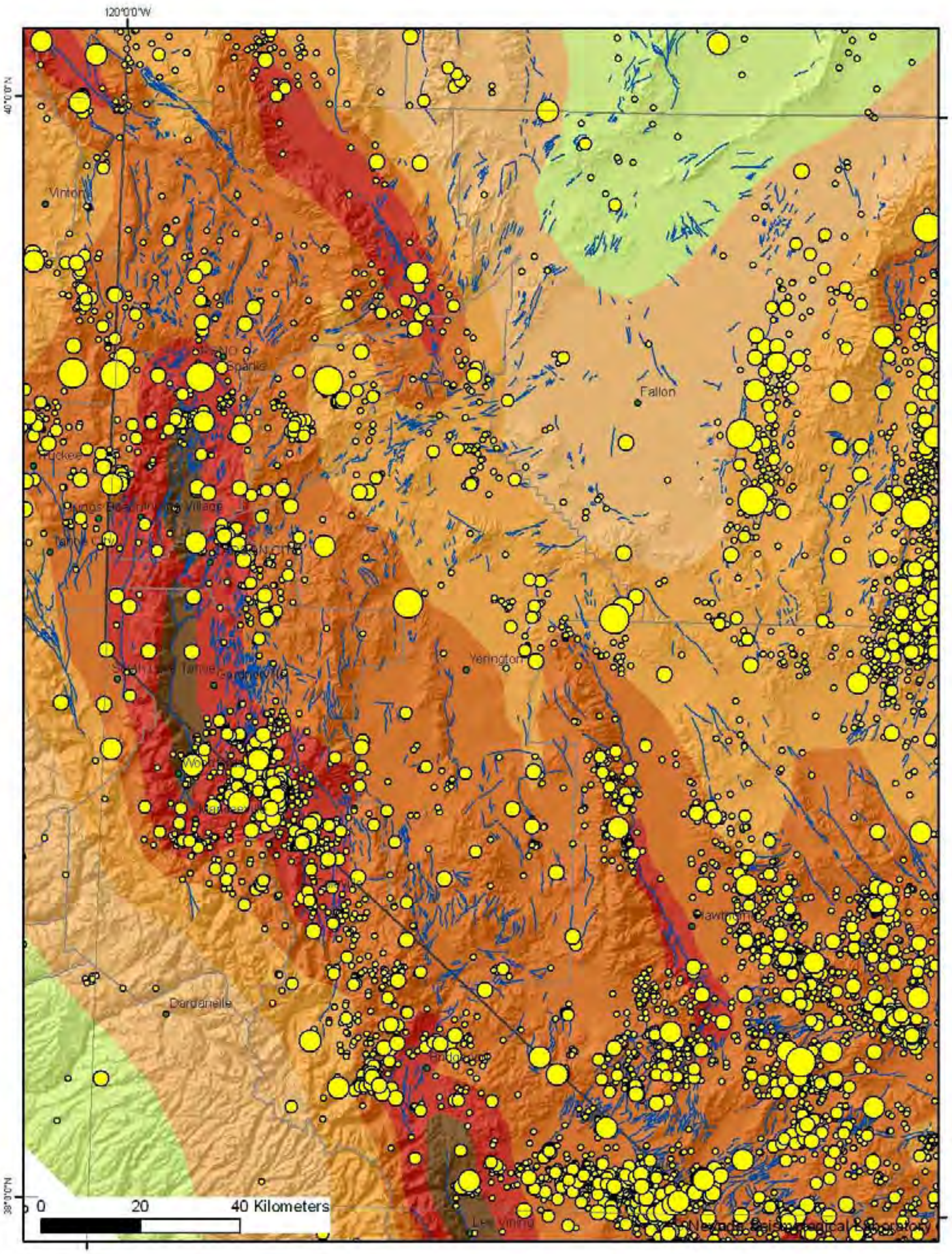

Hazard Curves for Reno
Annual Rate of Exceedance
Ground Motion PGA (g)
Geodesy
USGS Model
Combination of source types
Faults
Seismicity
10^-1
10^-2
10^-3
10^-4
10^-5
0
0.2
0.4
0.6
0.8
1.0
1.2

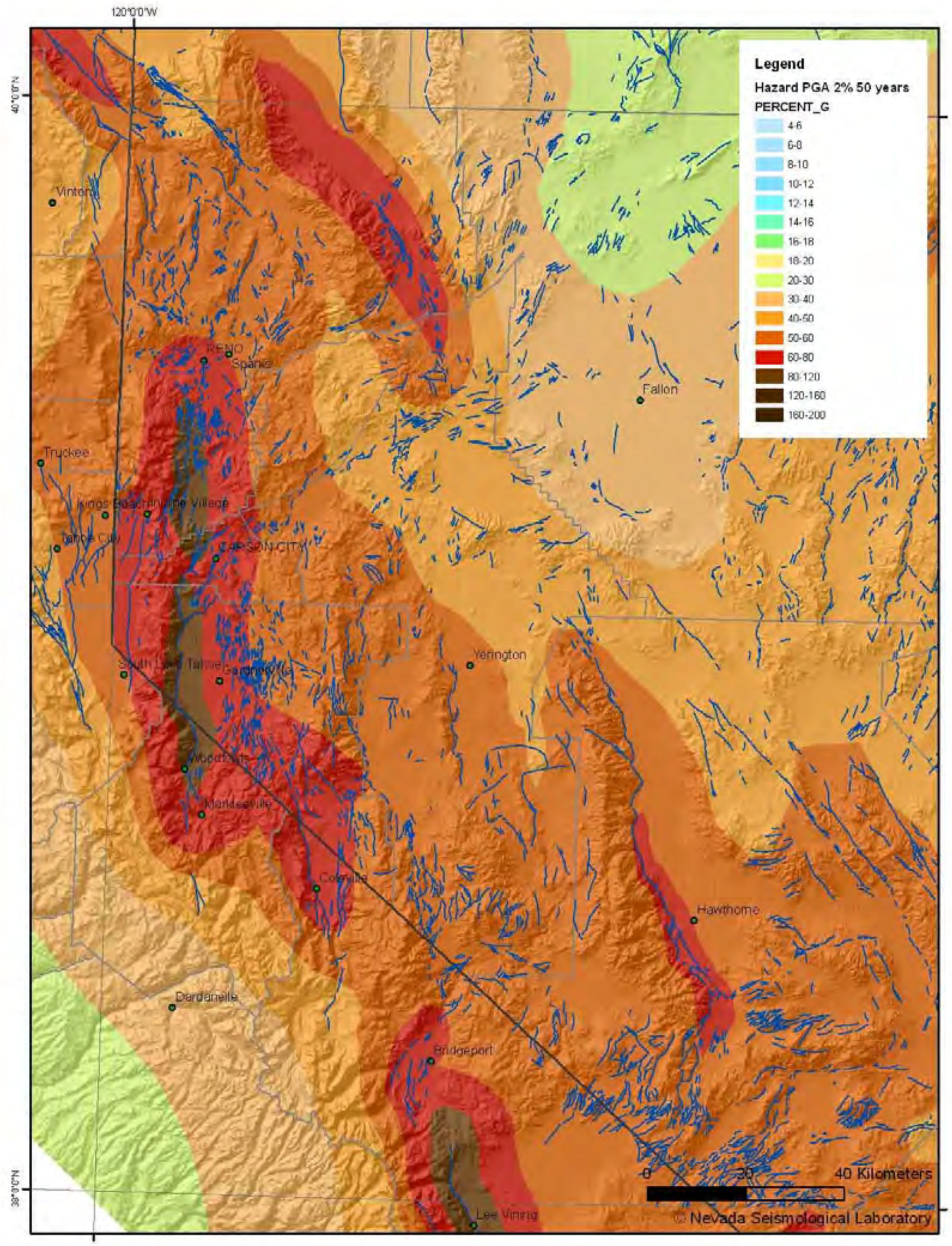
Susanville to Carson City



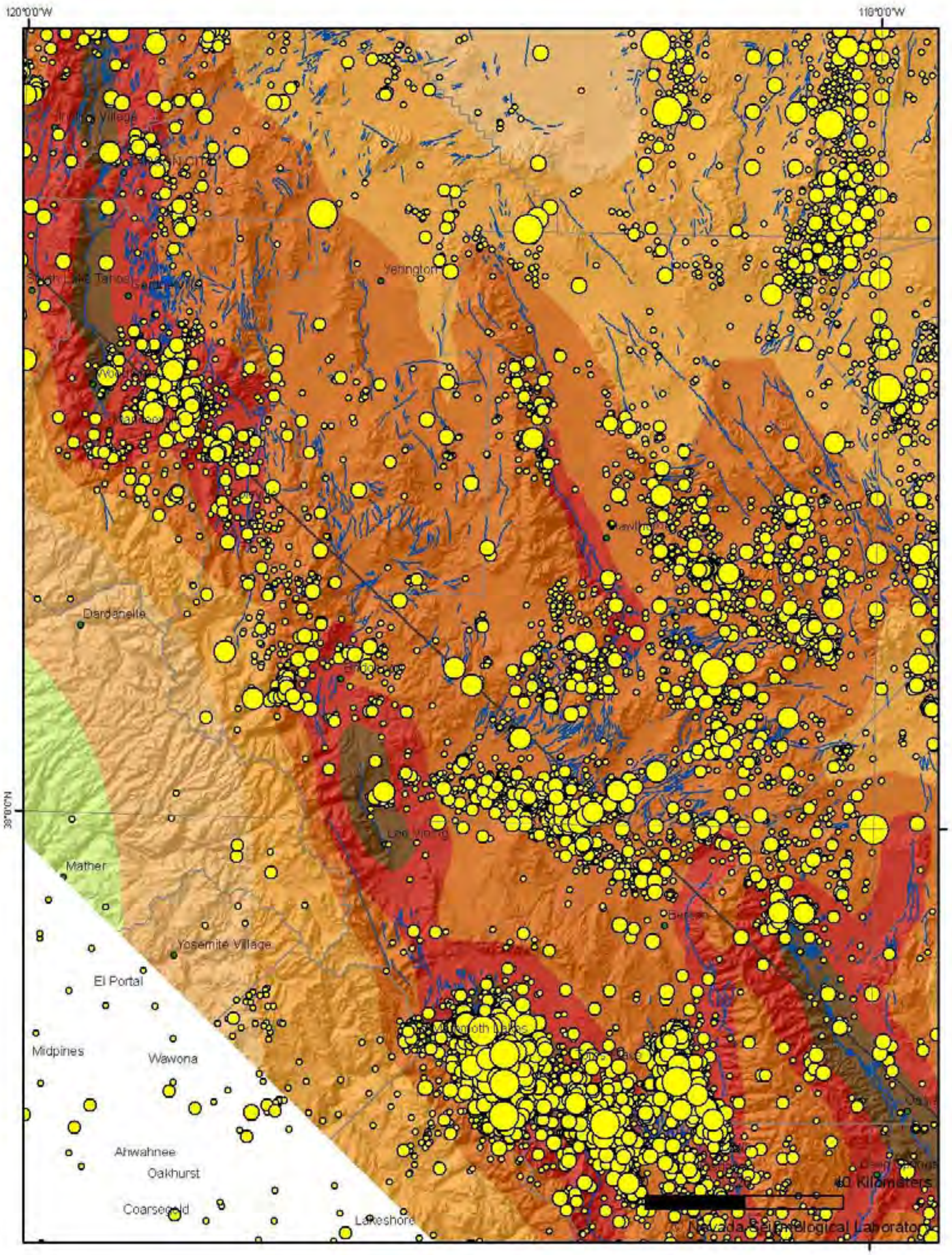


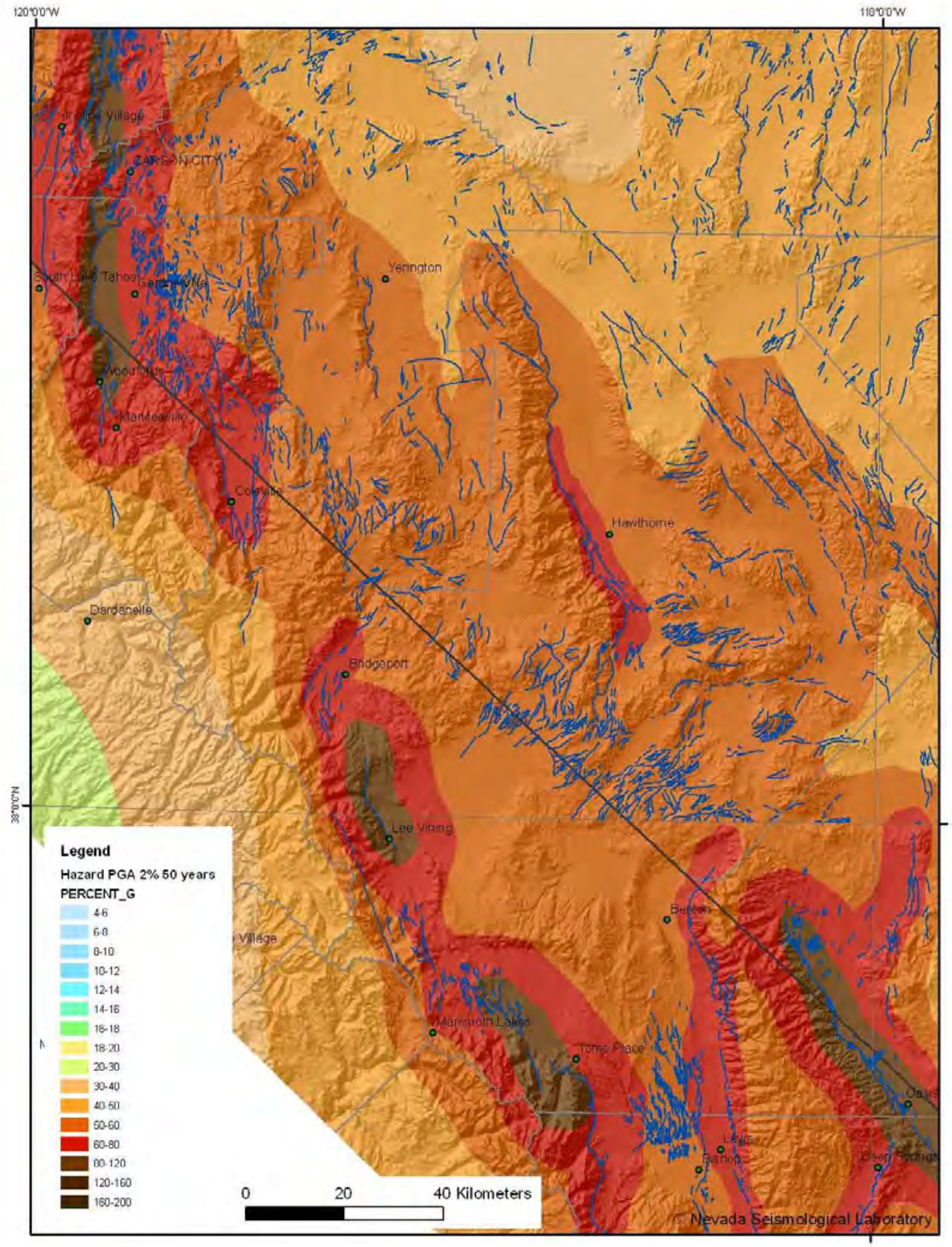
Reno – Carson City



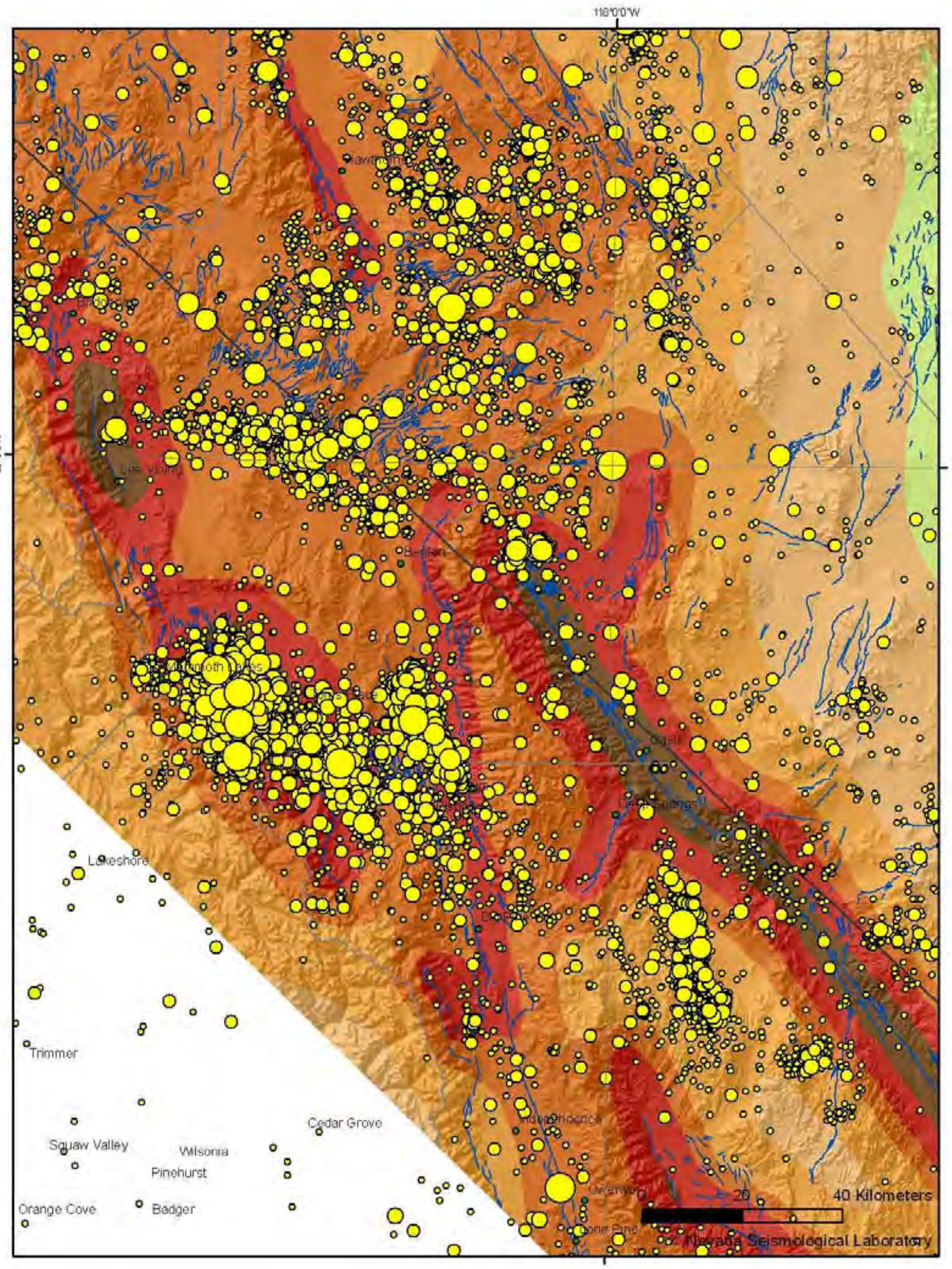


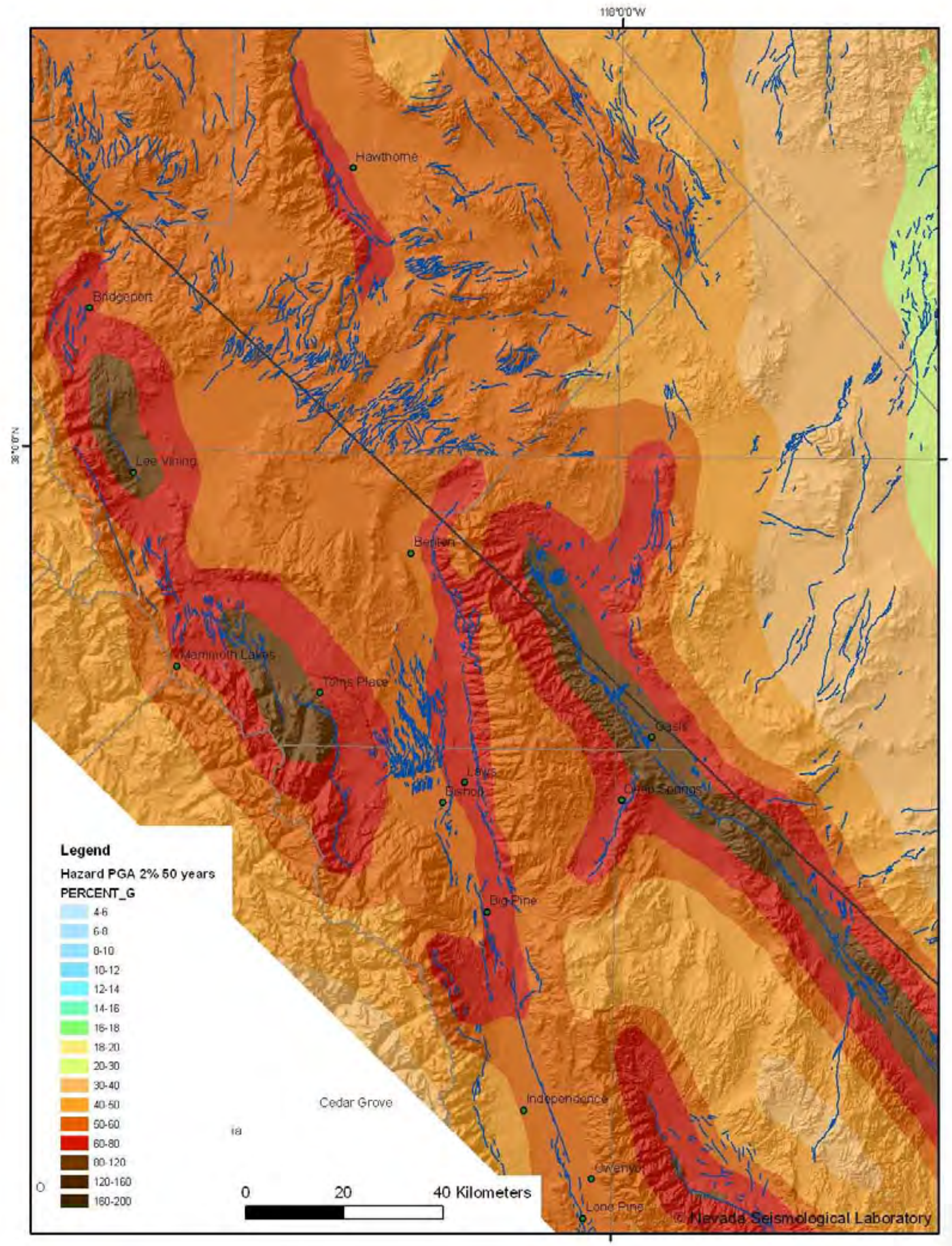
Carson City to Mammoth Lakes



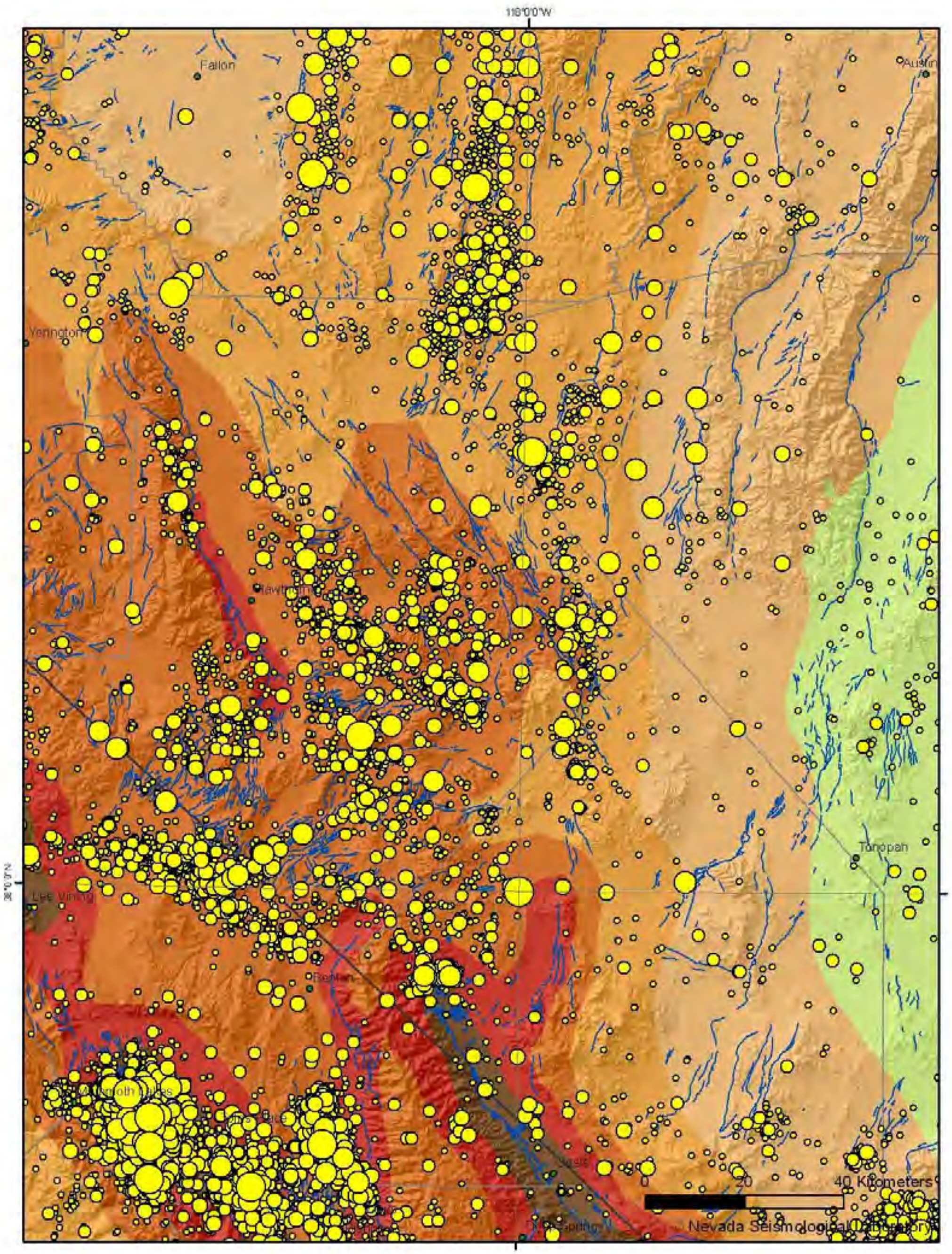


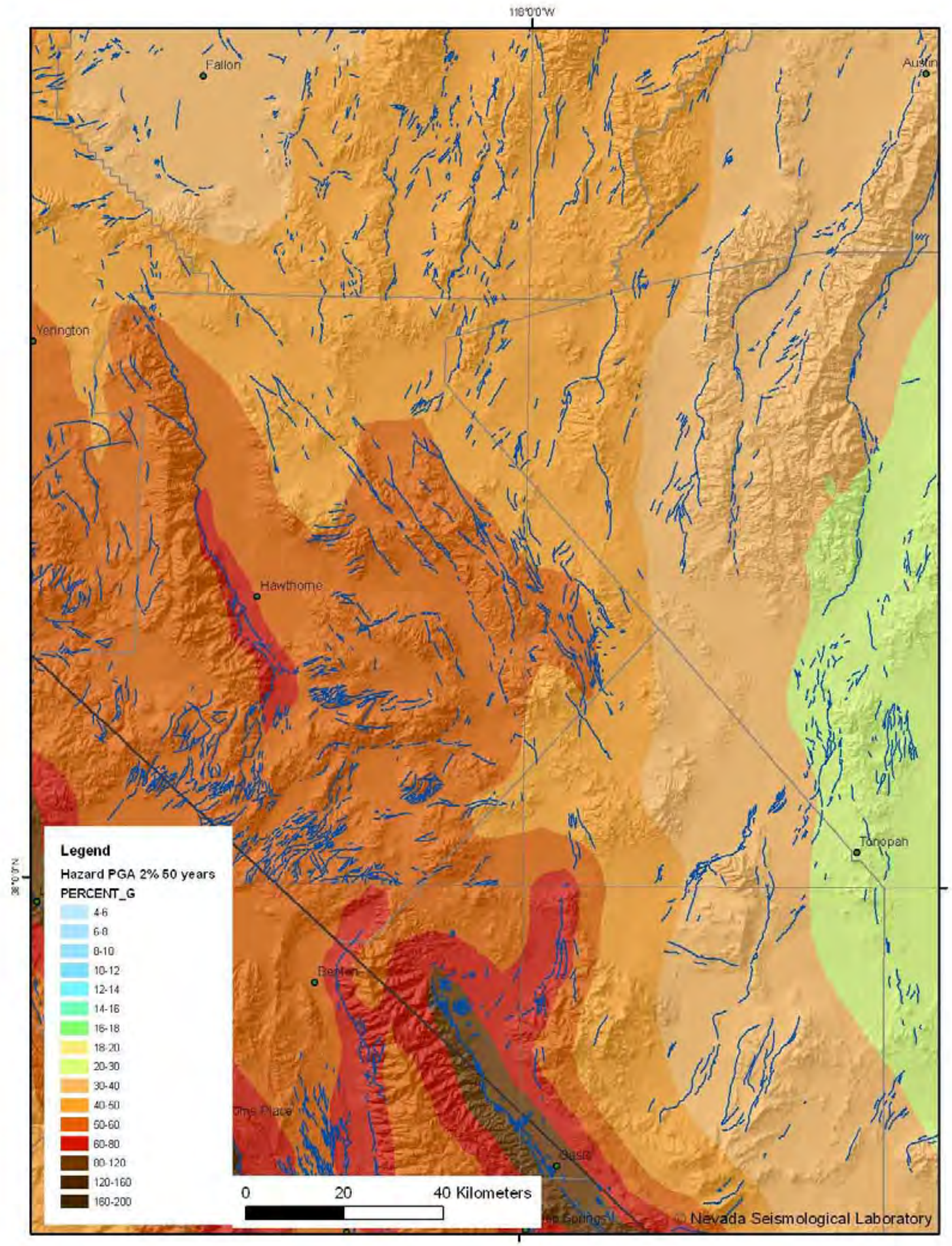
Mammoth Lakes



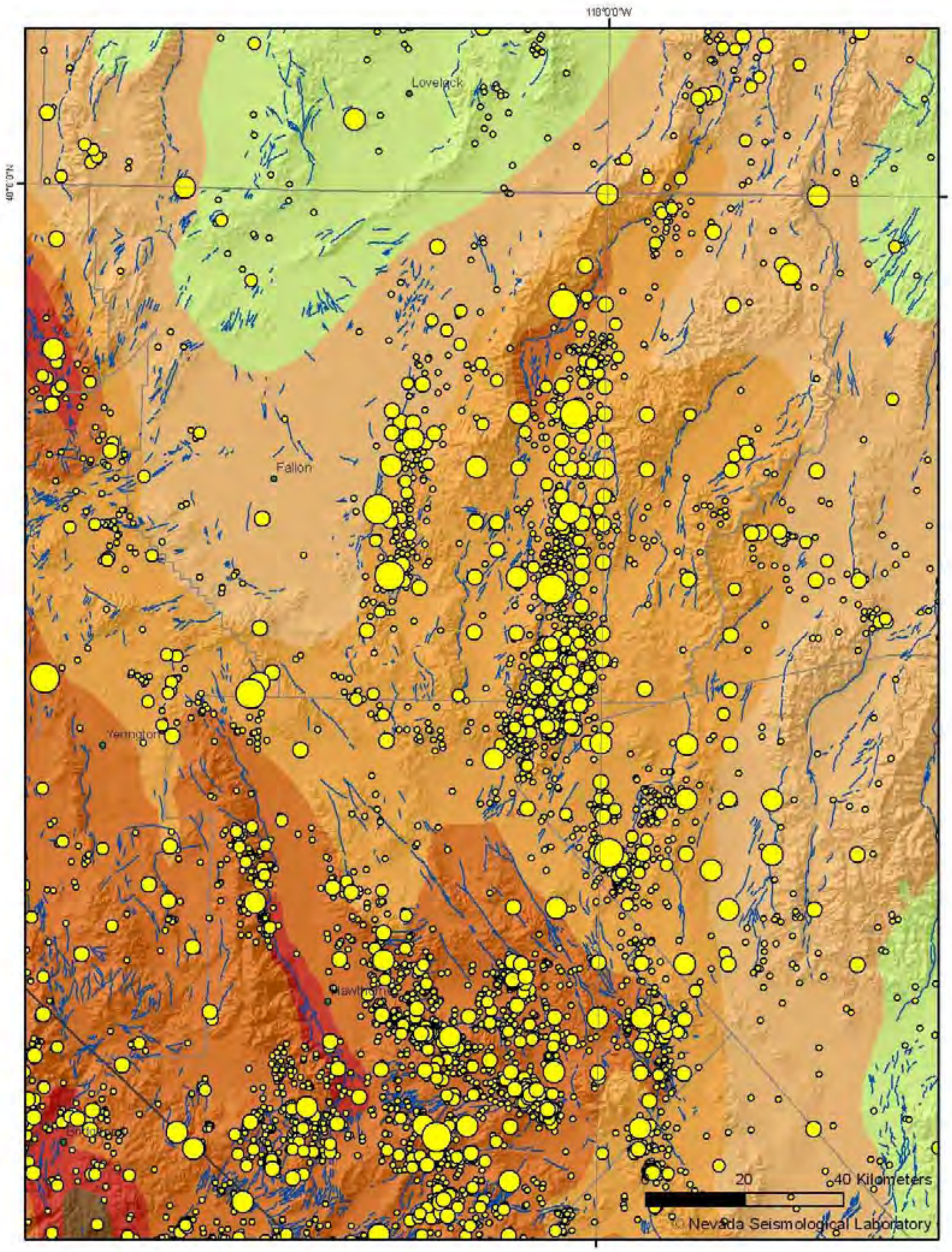


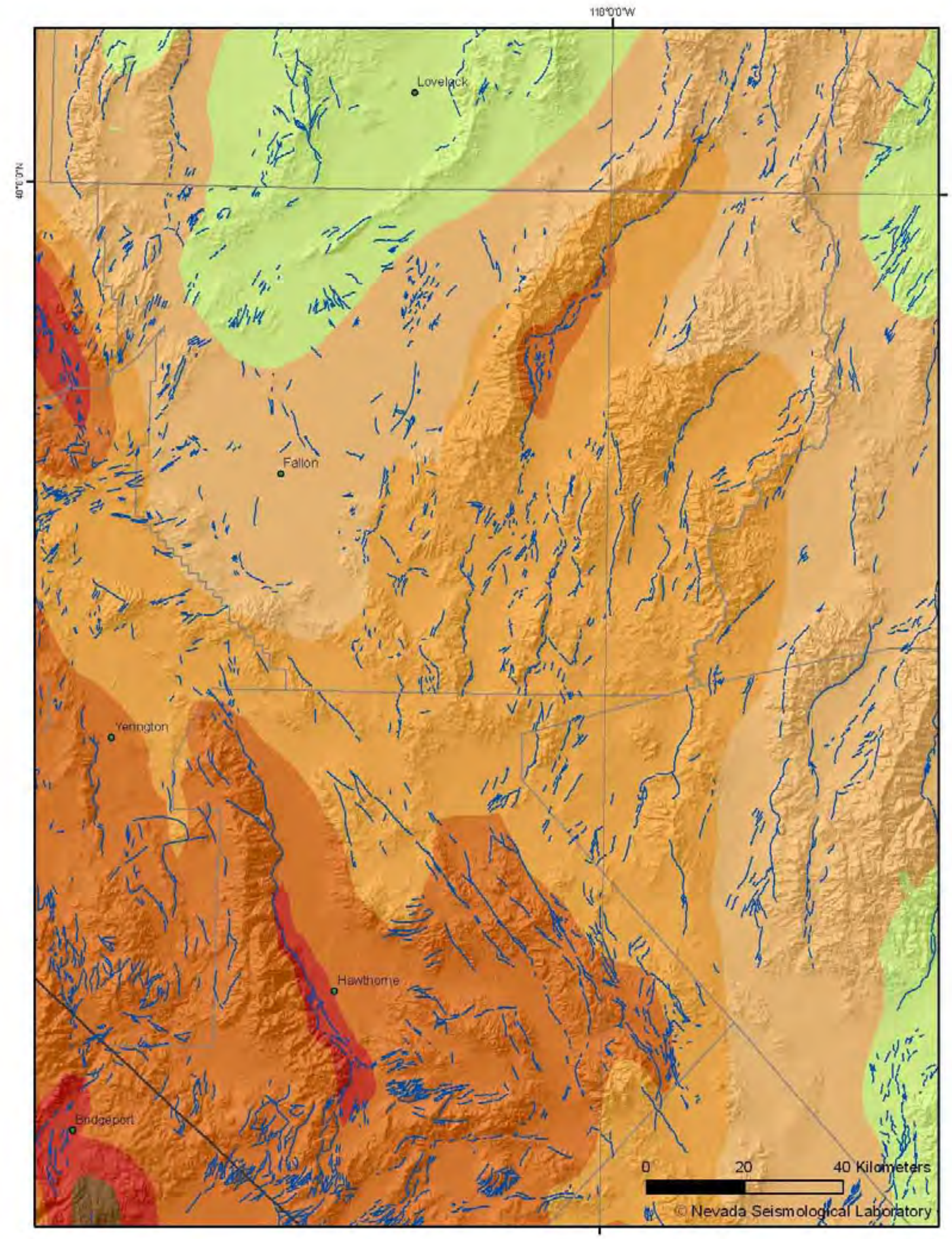
Southern CNSB



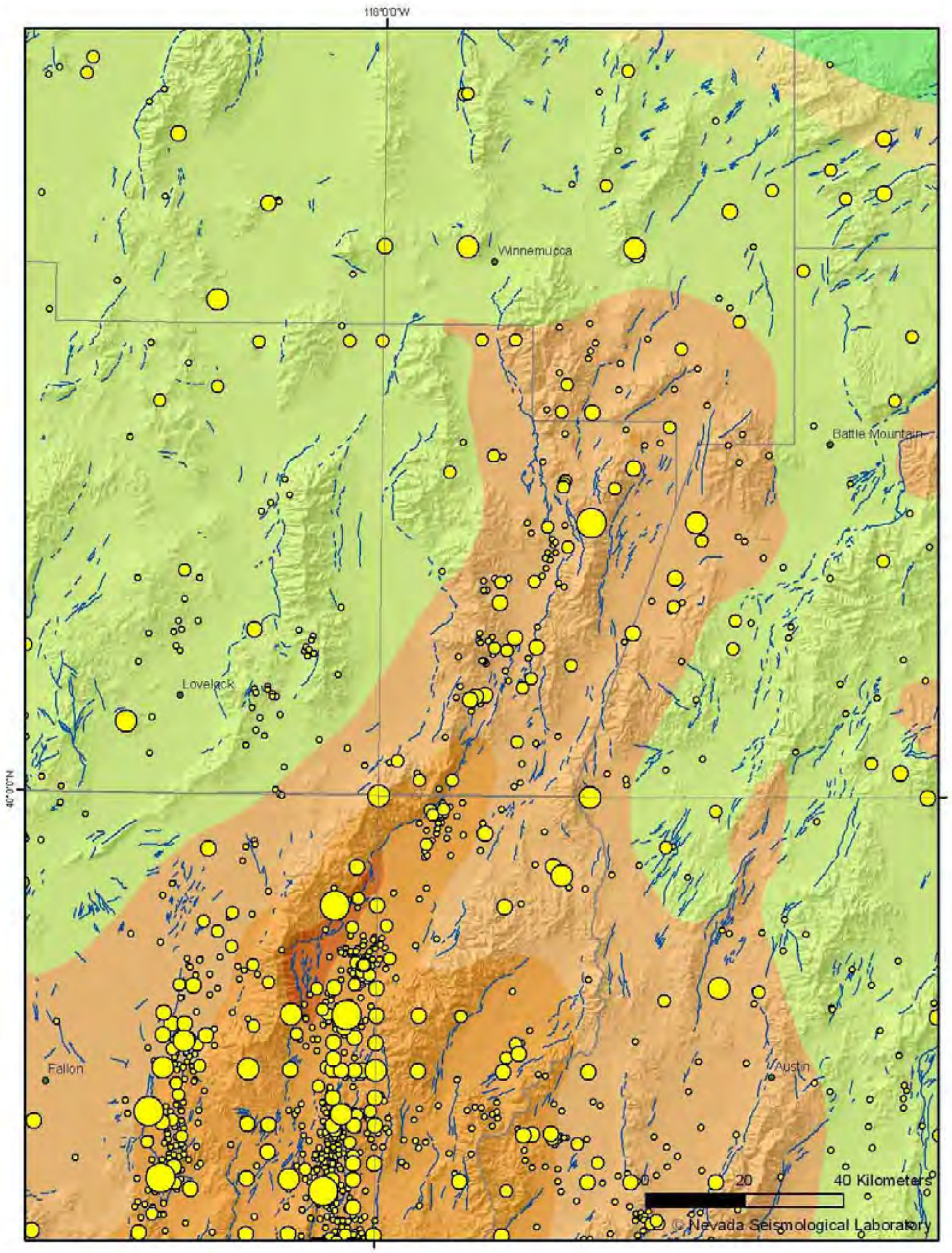


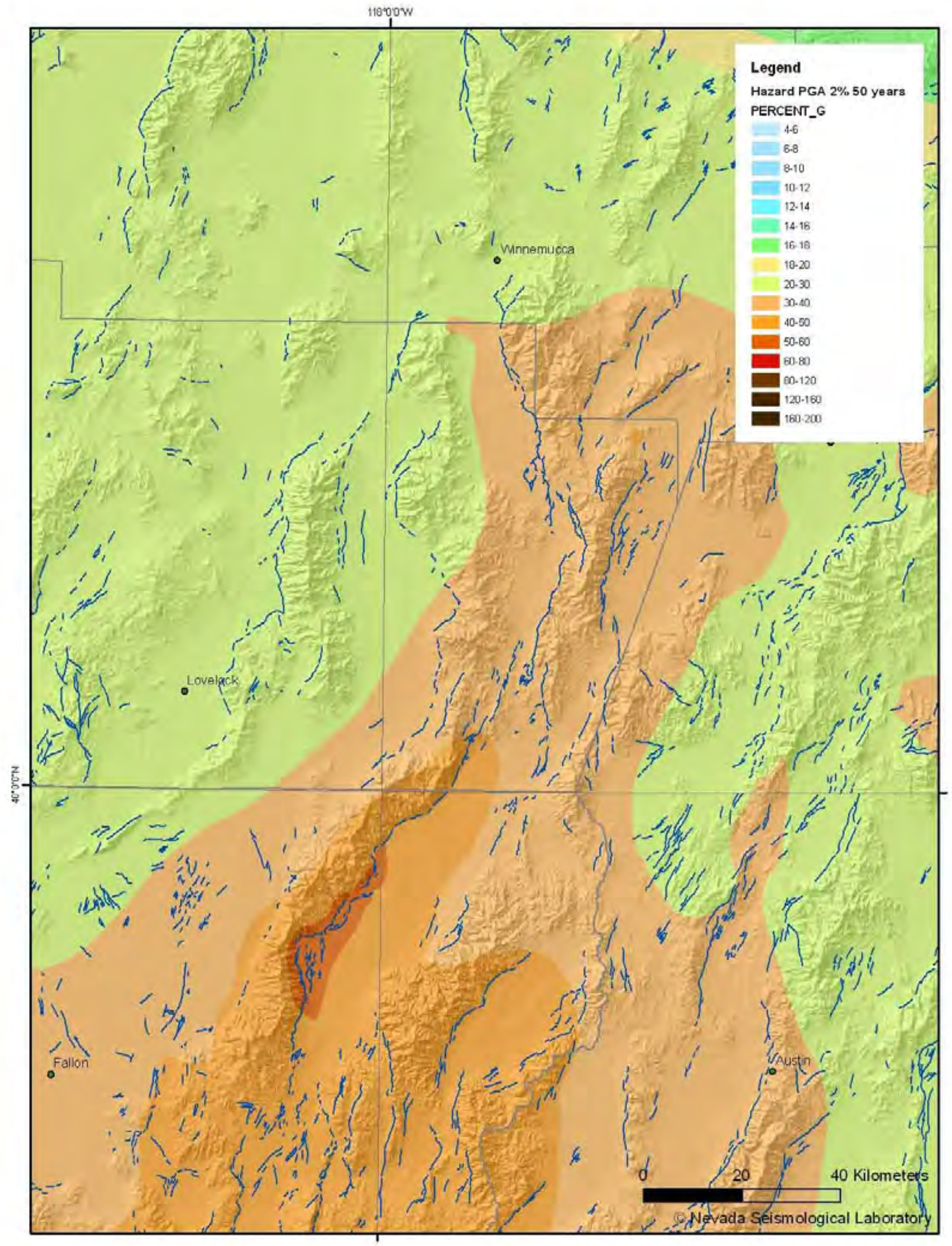
Central Nevada Seismic Belt

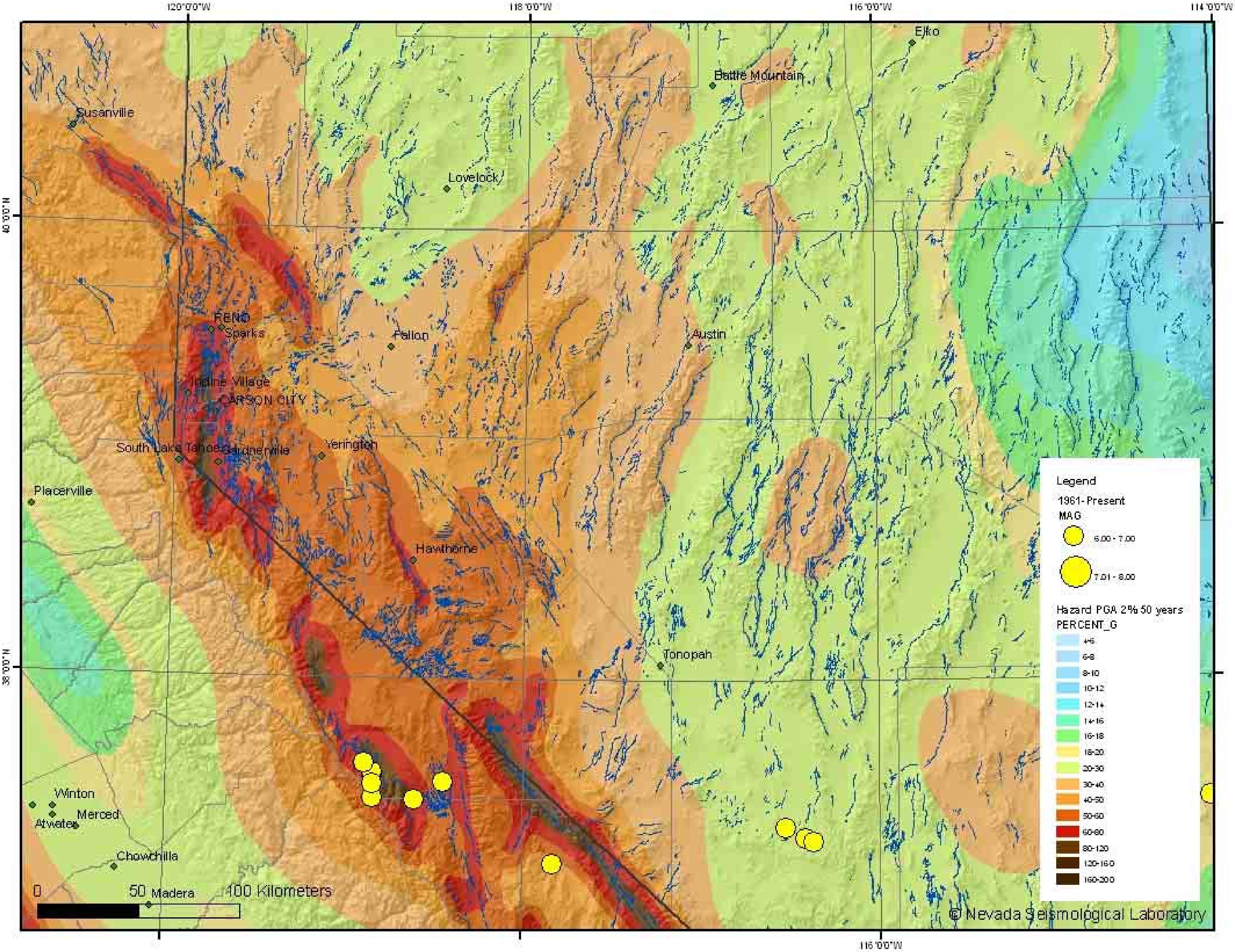


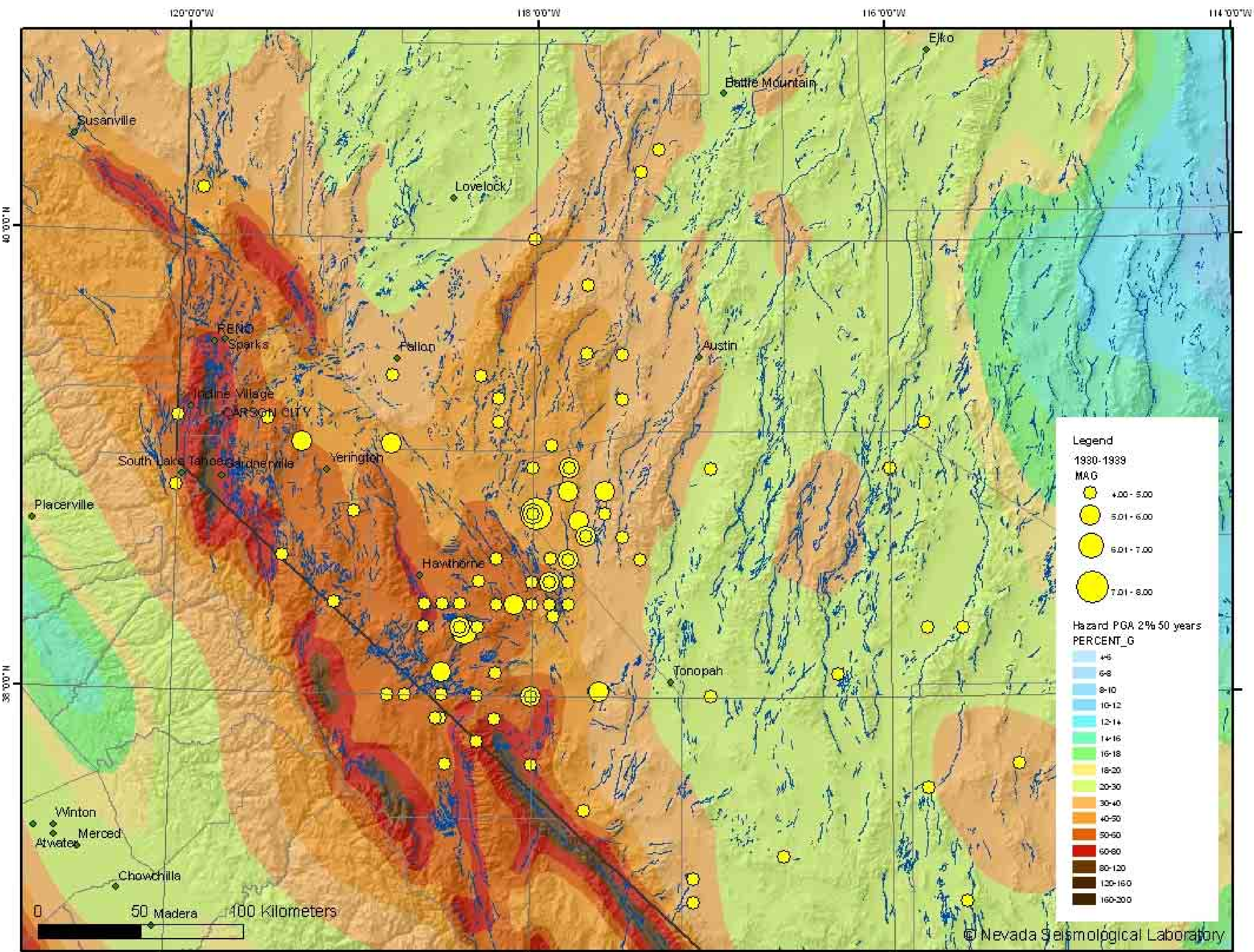


Northern CNSB

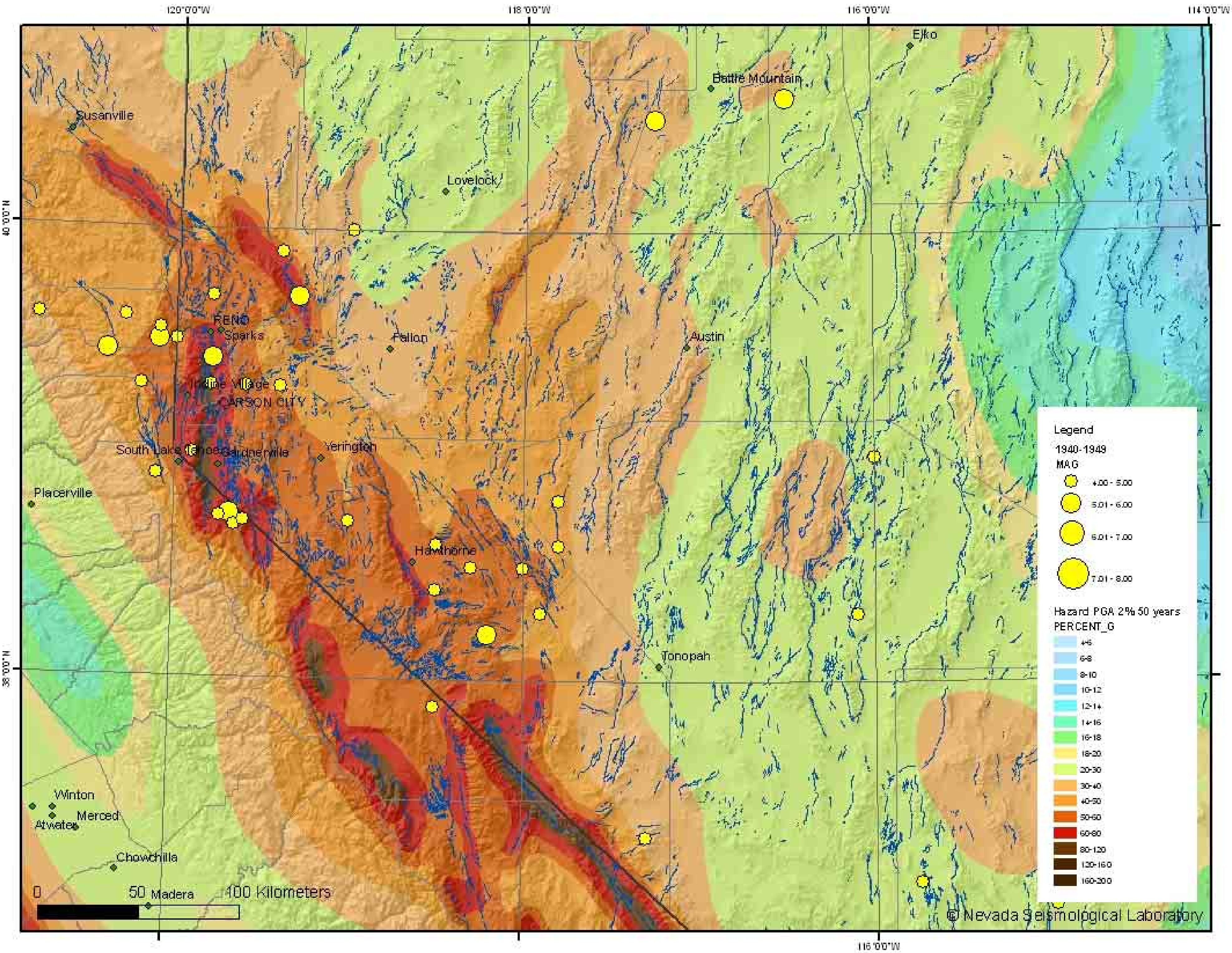




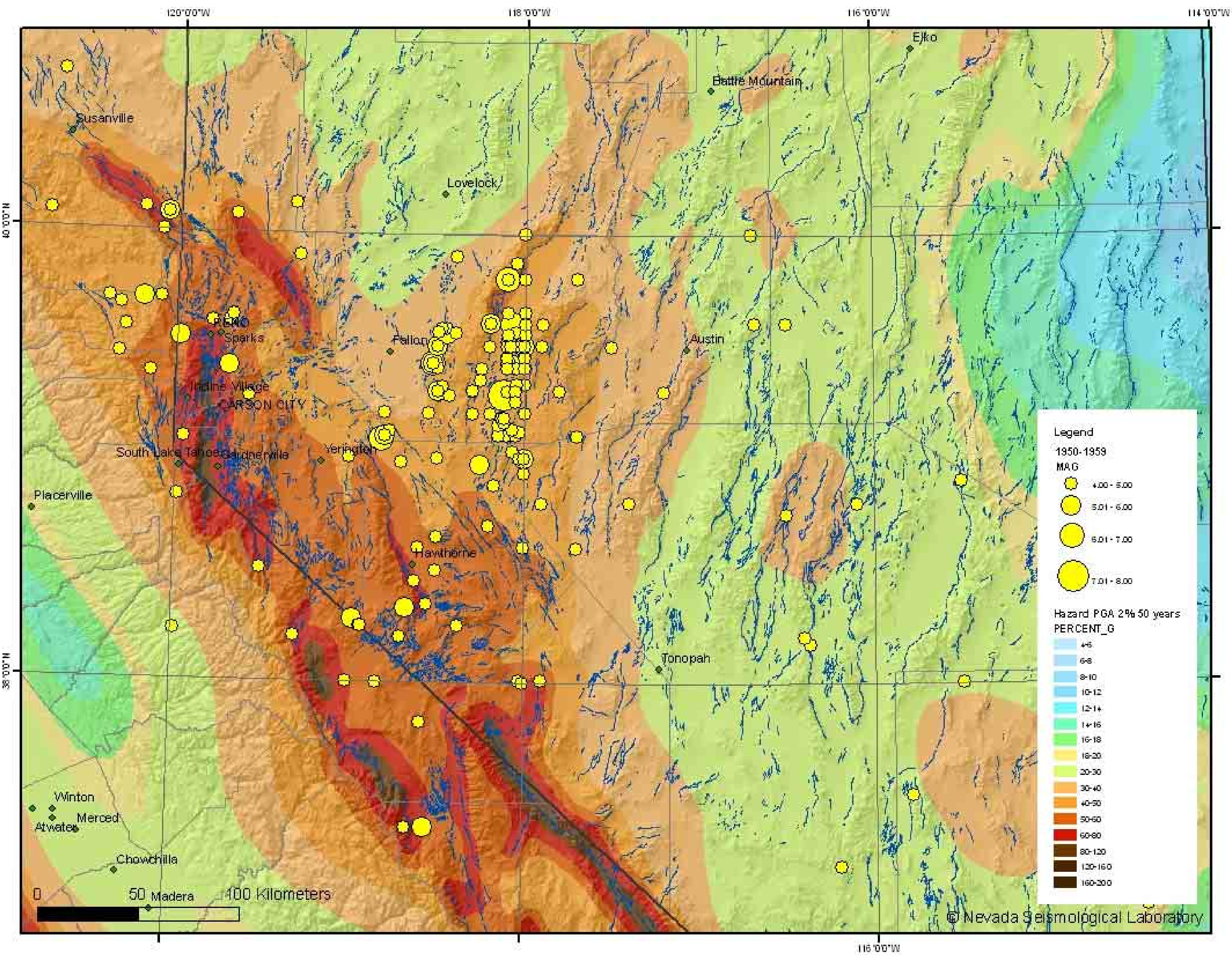

120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1961- Present
MAG
6.00 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory



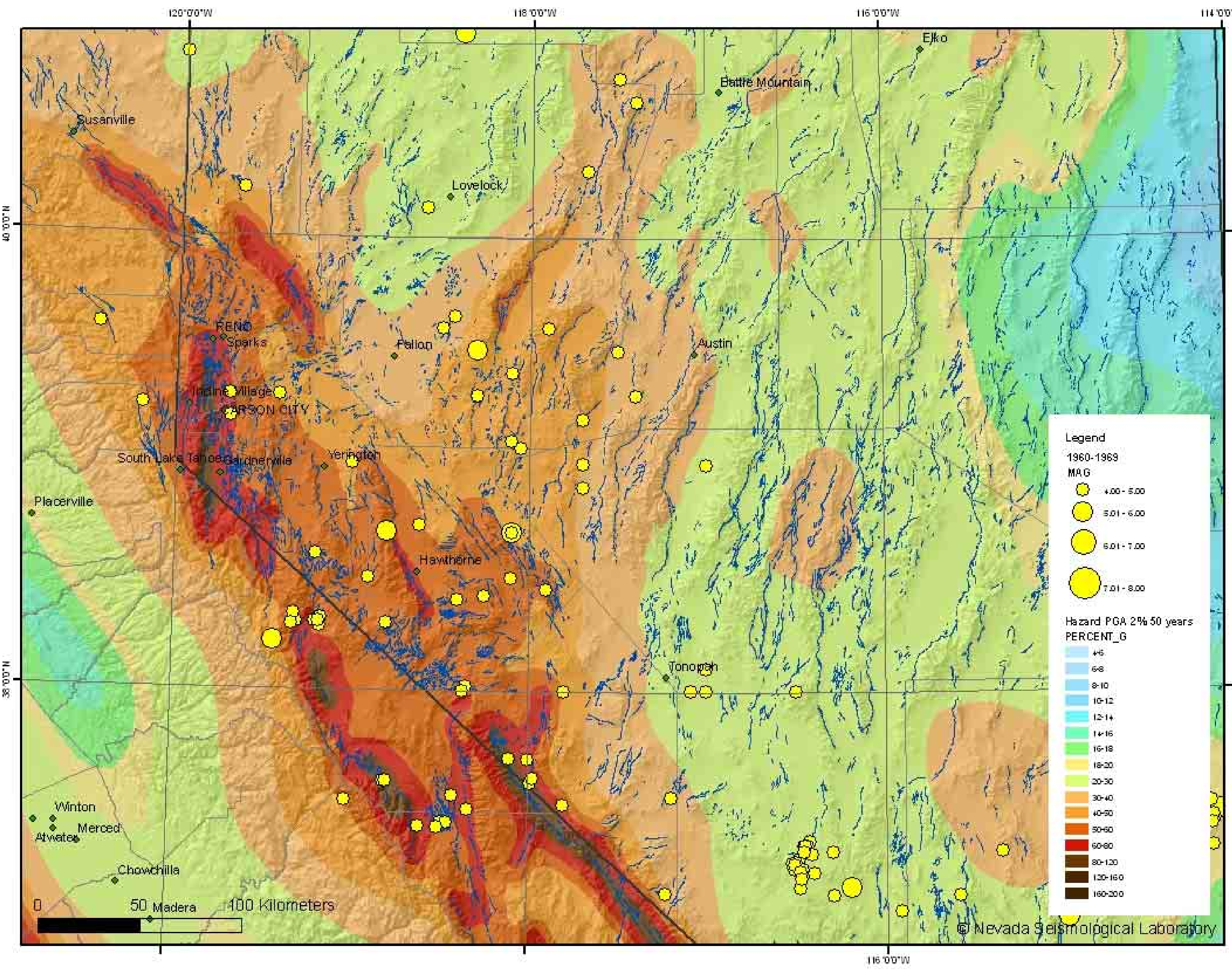
120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
1930-1939
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200

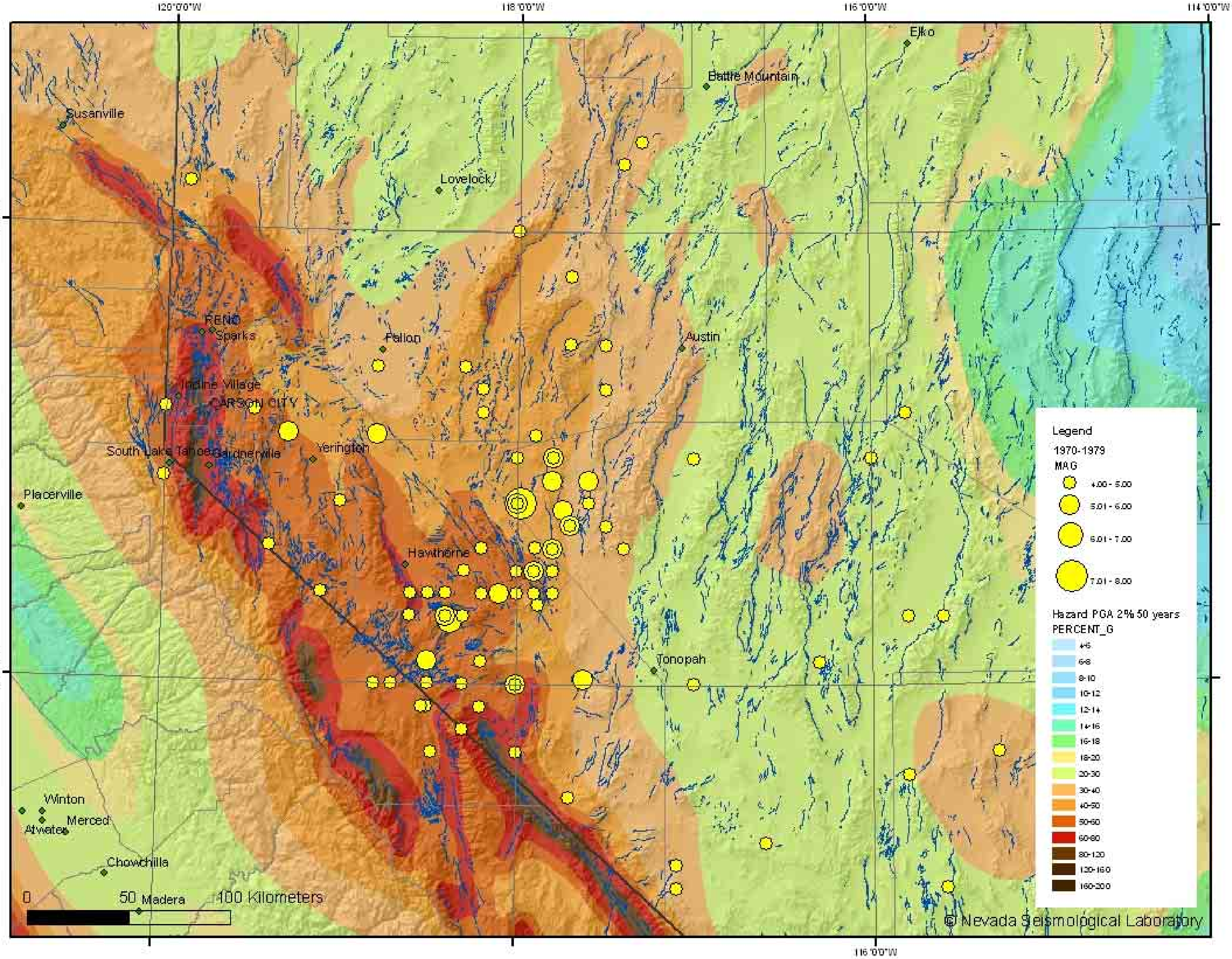


120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1940-1949
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory

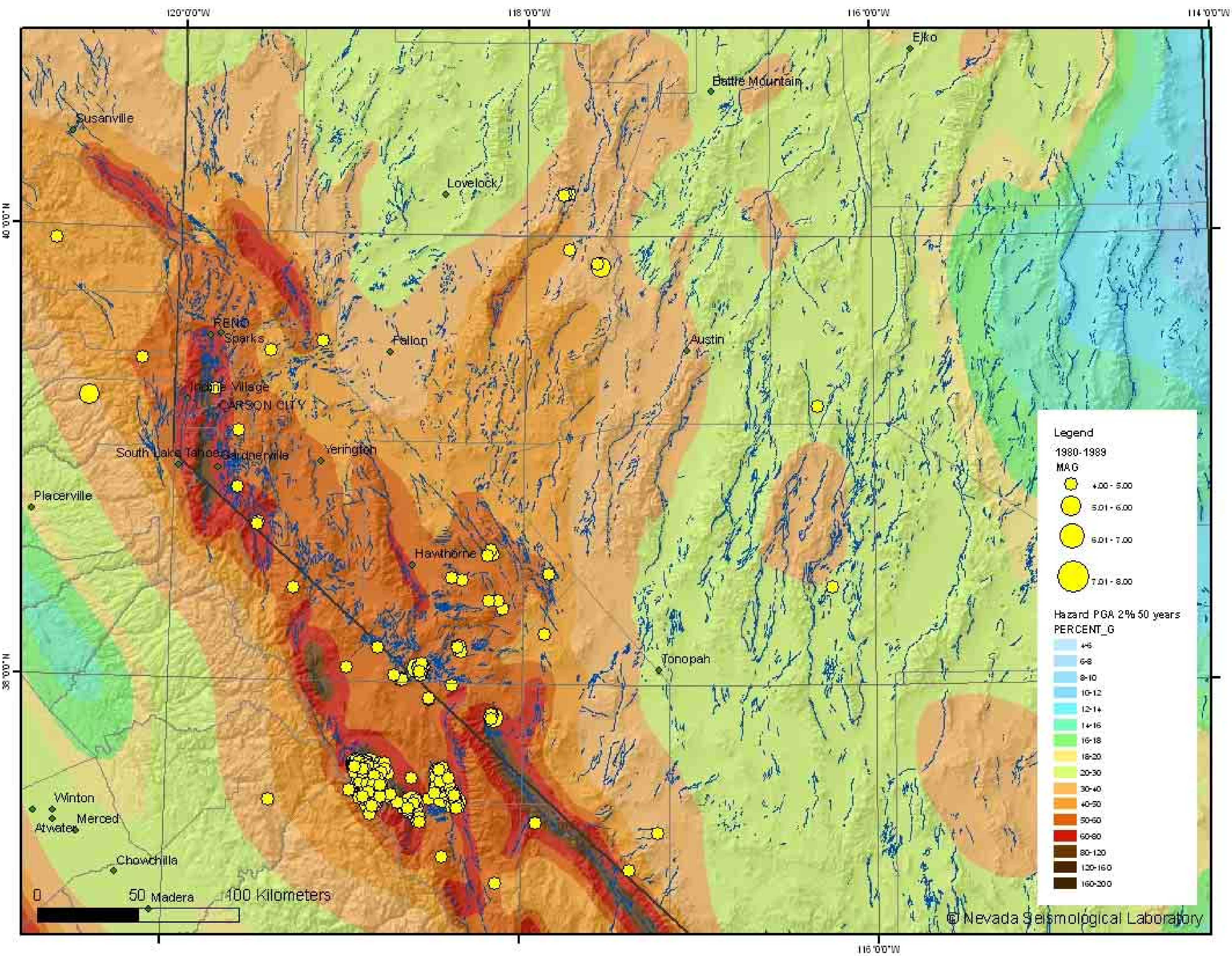


120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1950-1959
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory

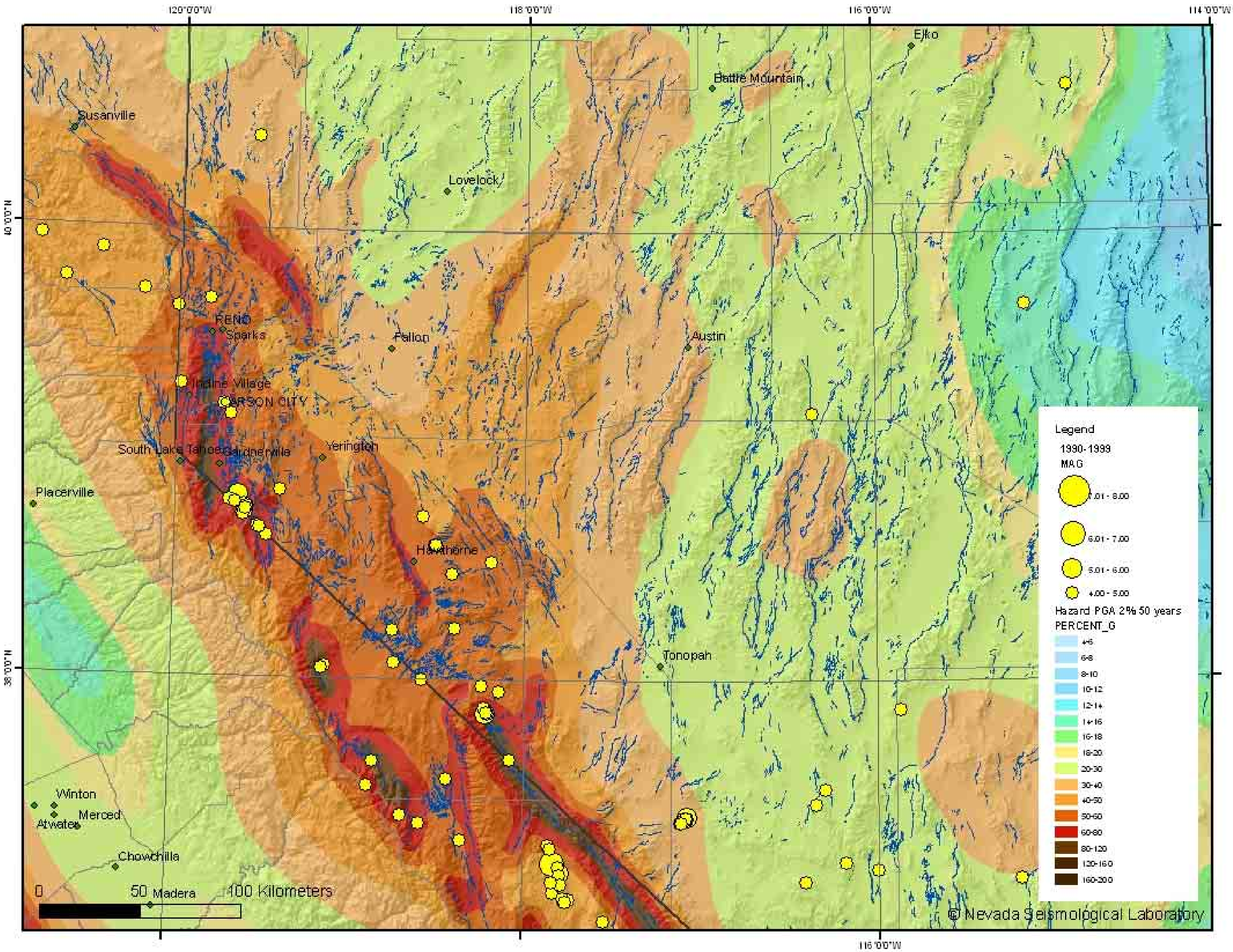

120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
1960-1969
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200

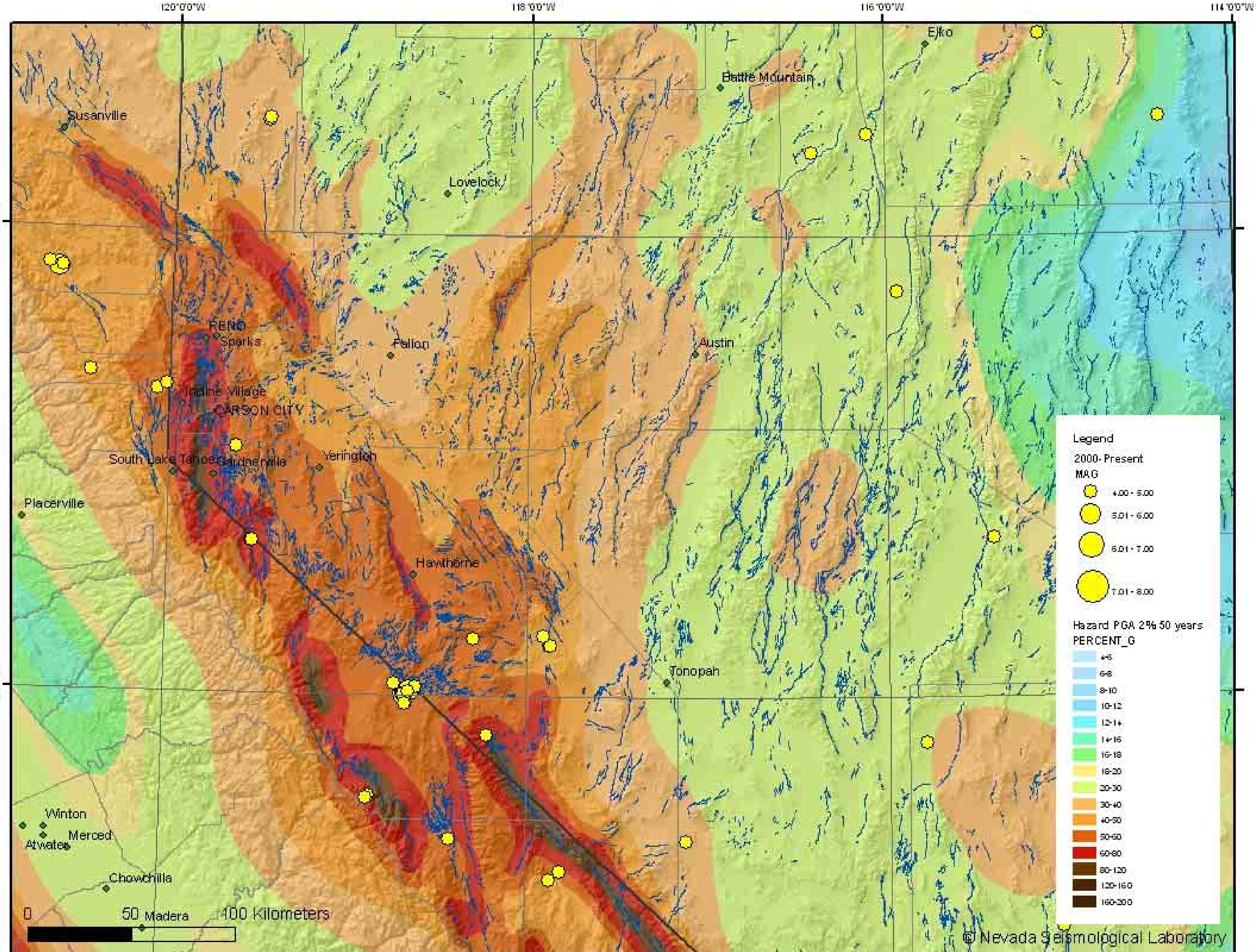


120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
1970-1979
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory

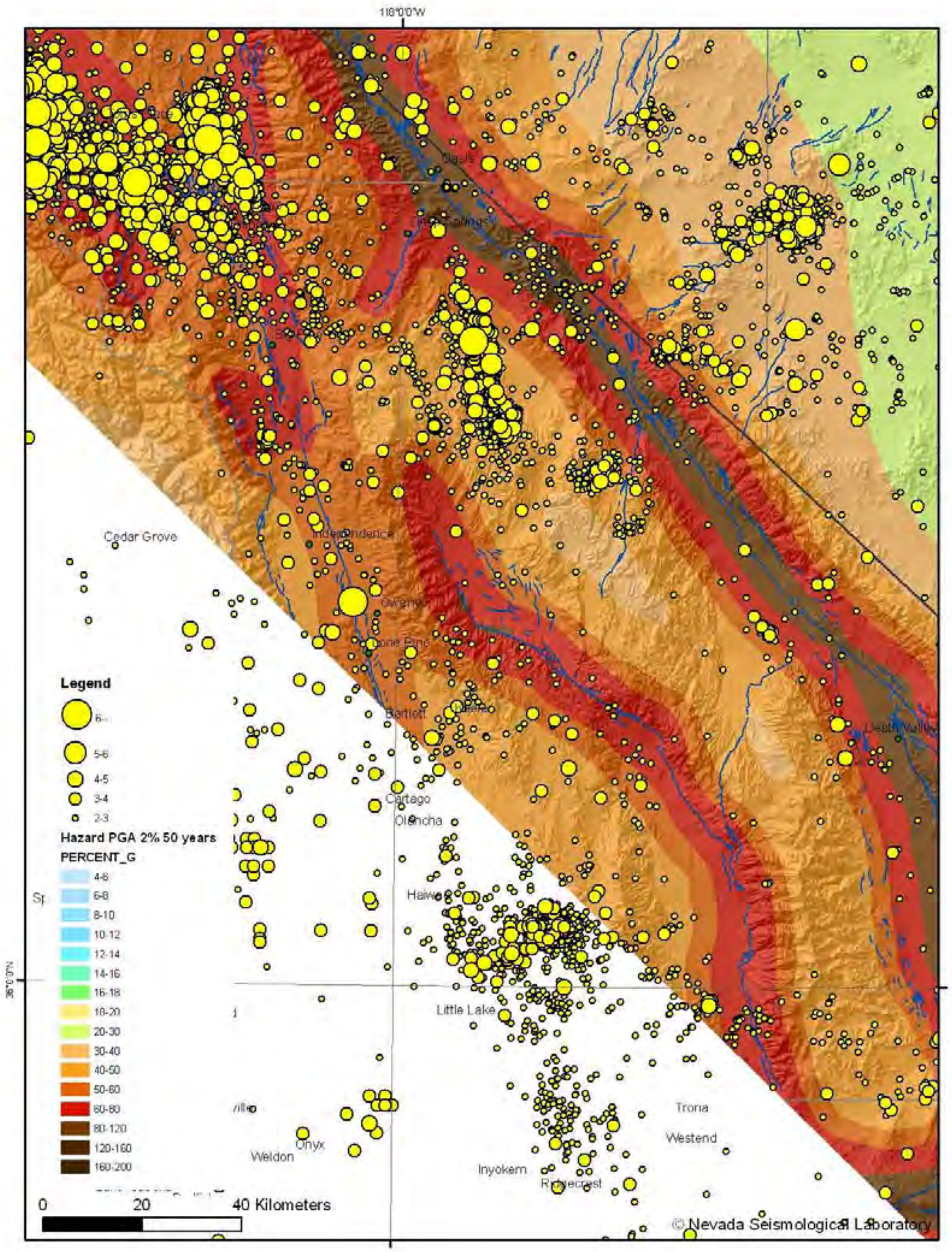


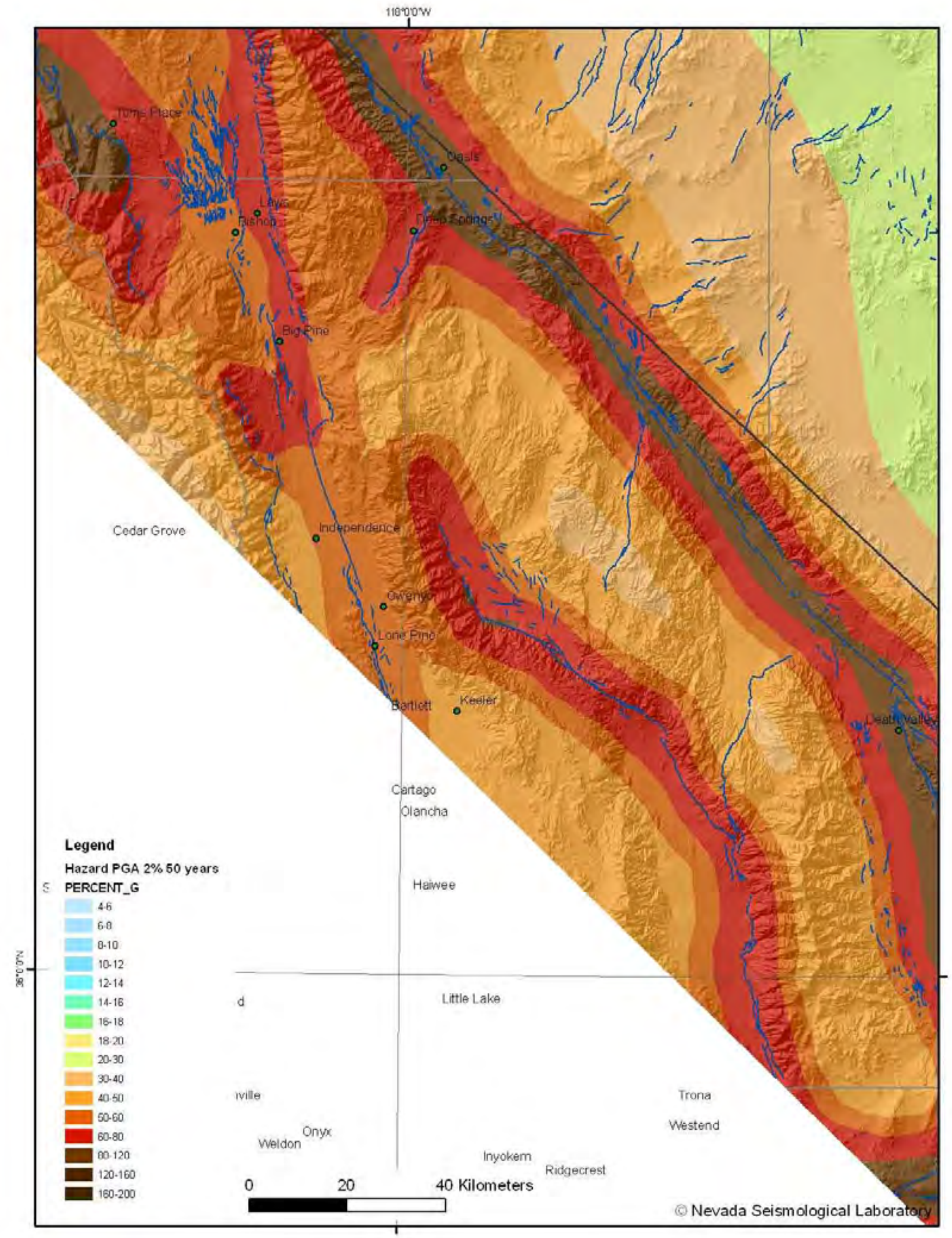
120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0 50 100 Kilometers
© Nevada Seismological Laboratory
Legend
1980-1989
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200


120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
© Nevada Seismological Laboratory
Legend
1990-1999
MAG
7.01 - 8.00
6.01 - 7.00
5.01 - 6.00
4.00 - 5.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200



120°0'0"W
118°0'0"W
116°0'0"W
114°0'0"W
40°0'0"N
38°0'0"N
Elko
Battle Mountain
Susanville
Lovelock
RENO
Sparks
Fallon
Austin
Incline Village
CARSON CITY
South Lake Tahoe
Gardnerville
Yerington
Placerville
Hawthorne
Tonopah
Winton
Merced
Atwater
Chowchilla
Madera
0
50
100 Kilometers
Legend
2000-Present
MAG
4.00 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
© Nevada Seismological Laboratory


118°0'0"W
36°0'0"N
Cedar Grove
Independence
Owenyo
Lone Pine
Bartlett
Keeler
Death Valley
Cartago
Olancha
Haiwee
Little Lake
Trona
Westend
Weldon
Onyx
Inyokern
Ridgecrest
Legend
6-
5-6
4-5
3-4
2-3
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
0
20
40 Kilometers
© Nevada Seismological Laboratory


118°0'0"W
36°0'0"N
Toms Place
Laws
Bishop
Oasis
Dyer
Big Pine
Cedar Grove
Independence
Owenyo
Lone Pine
Bartlett
Keeler
Death Valley
Cartago
Olancha
Haiwee
Little Lake
Trona
Westend
Weldon
Onyx
Inyokern
Ridgecrest
Legend
Hazard PGA 2% 50 years
PERCENT_G
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
20-30
30-40
40-50
50-60
60-80
80-120
120-160
160-200
0
20
40 Kilometers
© Nevada Seismological Laboratory

Agenda

- **Friday, March 10, 2006**
- 7:15 am Continental breakfast
- 8:00 am – 12:00 noon* Resolving discrepancies between geodetic extension rates and geologic slip rates, discussion leaders Robert Smith and Wayne Thatcher.

Key Questions

- Do we know enough about geodetic extension rates in the BRP to use them in the NSHMs?
  - If so, should the geodetic rates be used where geologic rates are lacking?
  - How should the discrepancy between geodetic and geologic rates be resolved?

ISSUES:

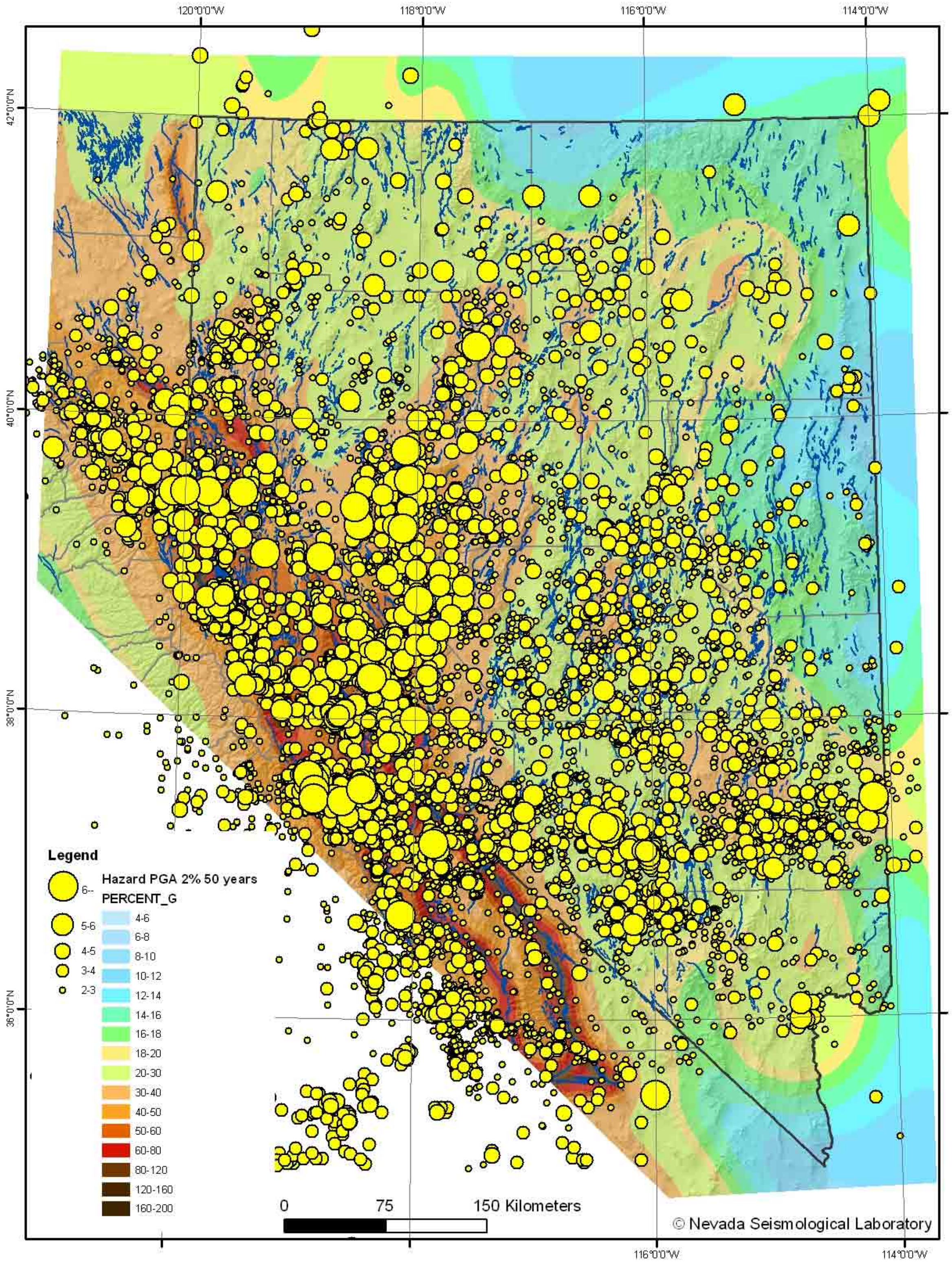
- Accounting for the discrepancy – change in rates, uncertainty, concealed faults?
- GPS rates be considered in BRP seismic hazard analyses?
- How resolve rate discrepancies (consensus)?
- How account for current discrepancy (Thatcher and others, 2000):
  - GPS results incorrect?
  - Geologic rates wrong?
  - GPS and geologic rates individually apply to a distinct, incompatible time interval?

NEVADA Seismological Laboratory

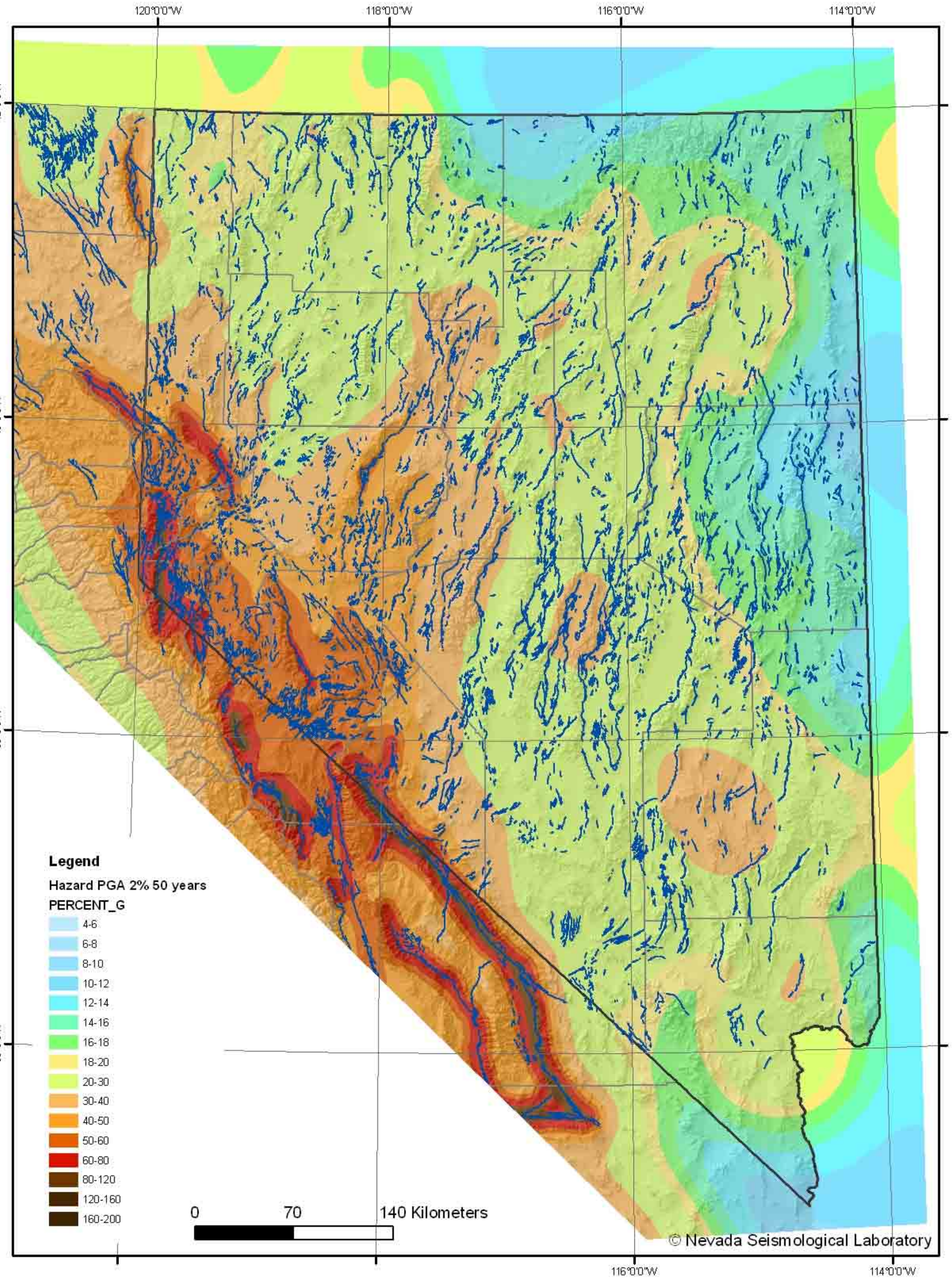
Reshaped Questions

- How should geodetically derived horizontal-extension rates be used in seismic hazard analyses: for Basin and Range Province regions with poor or no geologic or paleoseismic slip rates, should Global Positioning System extension rates be weighted heavily? What is the preferred method for converting vertical/horizontal motion?

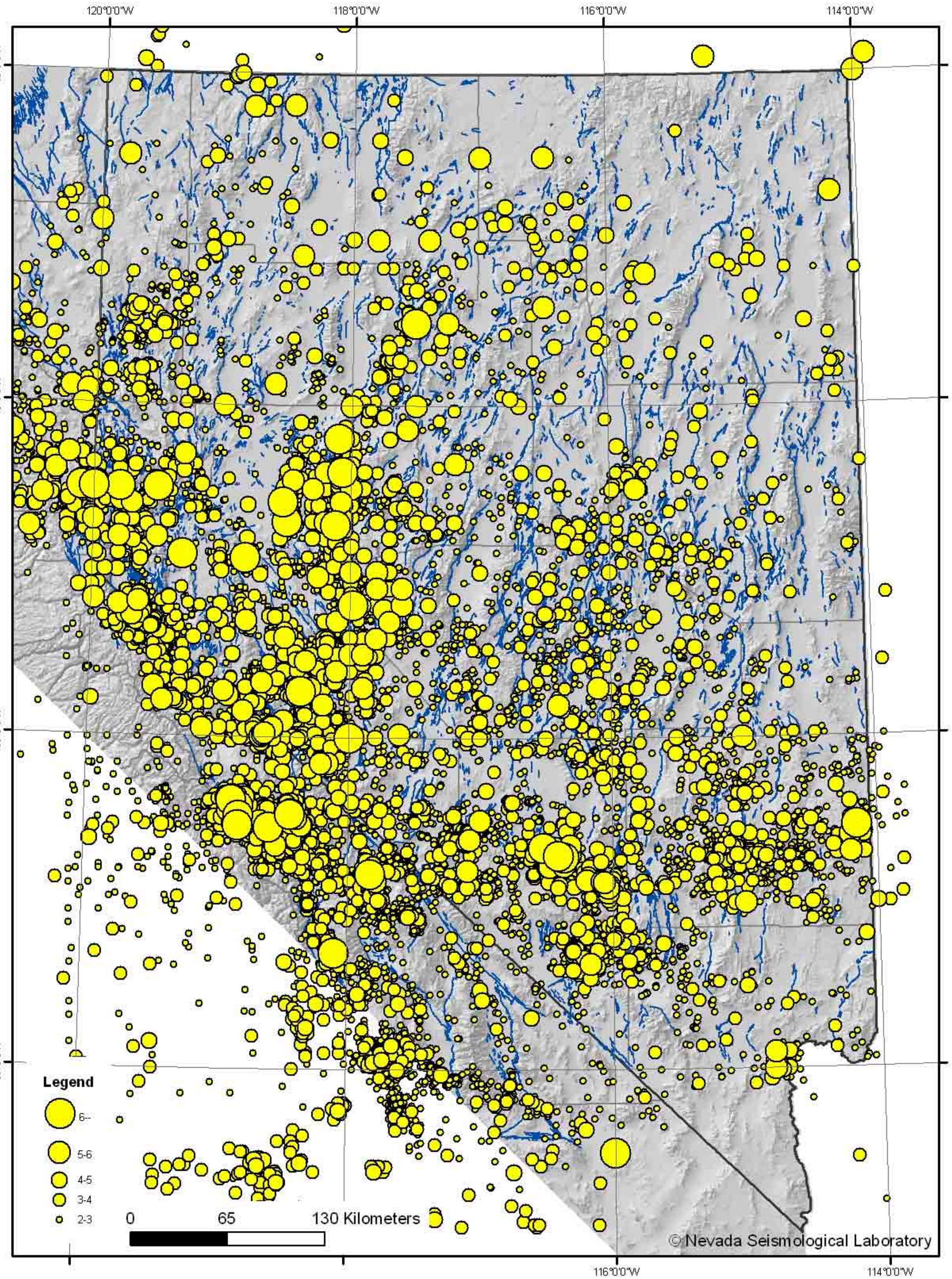
NEVADA Seismological Laboratory



NEVADA Seismological Laboratory



NEVADA Seismological Laboratory



NEVADA Seismological Laboratory

Key Questions

- 6. The 2002 NSHMs for the BRP use five equally weighted empirical attenuation relations: Boore and others (1997), Sadigh and others (1997), Abrahamson and Silva (1997), Spudich and others (1999), and Campbell and Bozorgnia (2003). Is this the most appropriate weighted combination of attenuation relations (for both strike-slip and normal-faulting regimes) for estimating BRP strong ground motion?
  - Should site effects (e.g., footwall/hanging-wall effects based on precarious rock studies) be incorporated? If so, how?
  - Should theoretical numerical models simulating strong ground motion in the BRP (e.g., Wong and others, 2002) be included? If so, how should the numerically derived relations be weighted (in comparison to empirical relations), and what are appropriate model parameter values and uncertainties (e.g., for stress drop and crustal and near-surface attenuation)?

NEVADA Seismological Laboratory

The Age and Distribution of Quaternary Faulting in the Basin & Range Province:

A Geological Perspective of Contemporary Deformation

USGS
science for a changing world

Objective

Provide a brief overview of:

- Spatial and temporal distribution of Quaternary faulting in the Basin and Range Province
  - ✓ Age of most recent surface-rupturing event
  - ✓ Fault slip rates (general proxy for probable recurrence rates)
- Offer thoughts for subsequent discussion

Information mainly derived from the USGS Quaternary fault and fold database (http://Qfaults.cr.usgs.gov/)

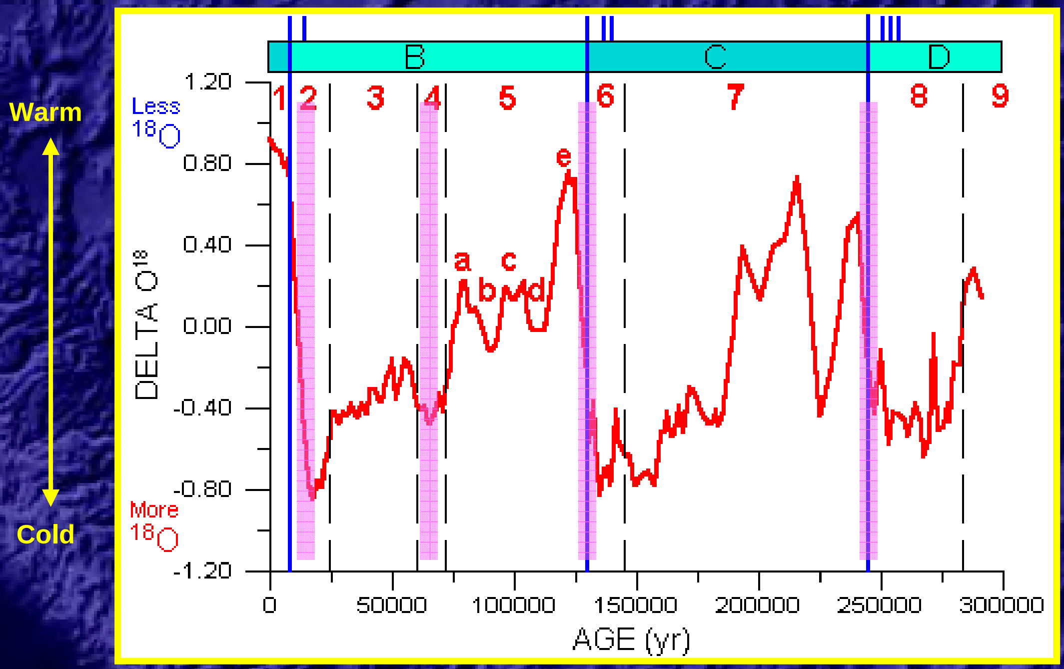
Much of this presentation is based on M. Machette's presentation at the WSSPC Basin and Range Seismic Hazards II Workshop (2004); published in Lund, W.R, 2005, Proceedings volume, Basin and Range Province Seismic-Hazards Summit II: Utah Geological Survey Miscellaneous Pub. 05-2.

USGS
science for a changing world

Constraints of Geological Data:

Determining the Age of Surface-Rupturing Events

- **Regional reconnaissance data:**
  - ✓ **Information is influenced by age of deposits that are widely preserved on the landscape**
  - ✓ **Distribution of Quaternary deposits influenced by major climatic events**



Late Quaternary Marine Oxygen-isotope stages

General ages of commonly preserved deposits in the western U.S:

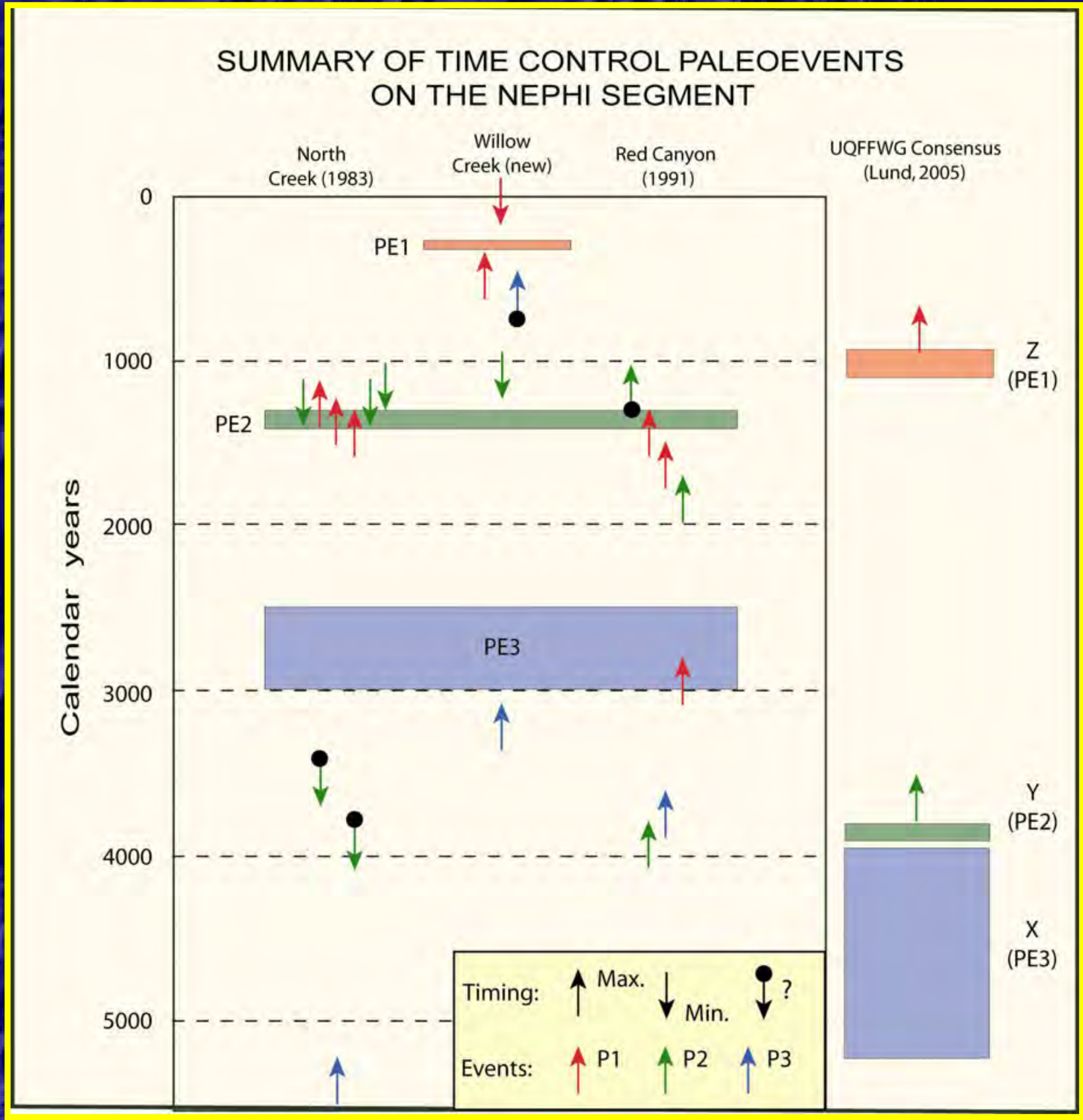
15-20 ka
60 ka
120-130 ka
240-250 ka

Pink vertical bars show the age ranges of commonly preserved deposits in western U.S.

USGS
science for a changing world

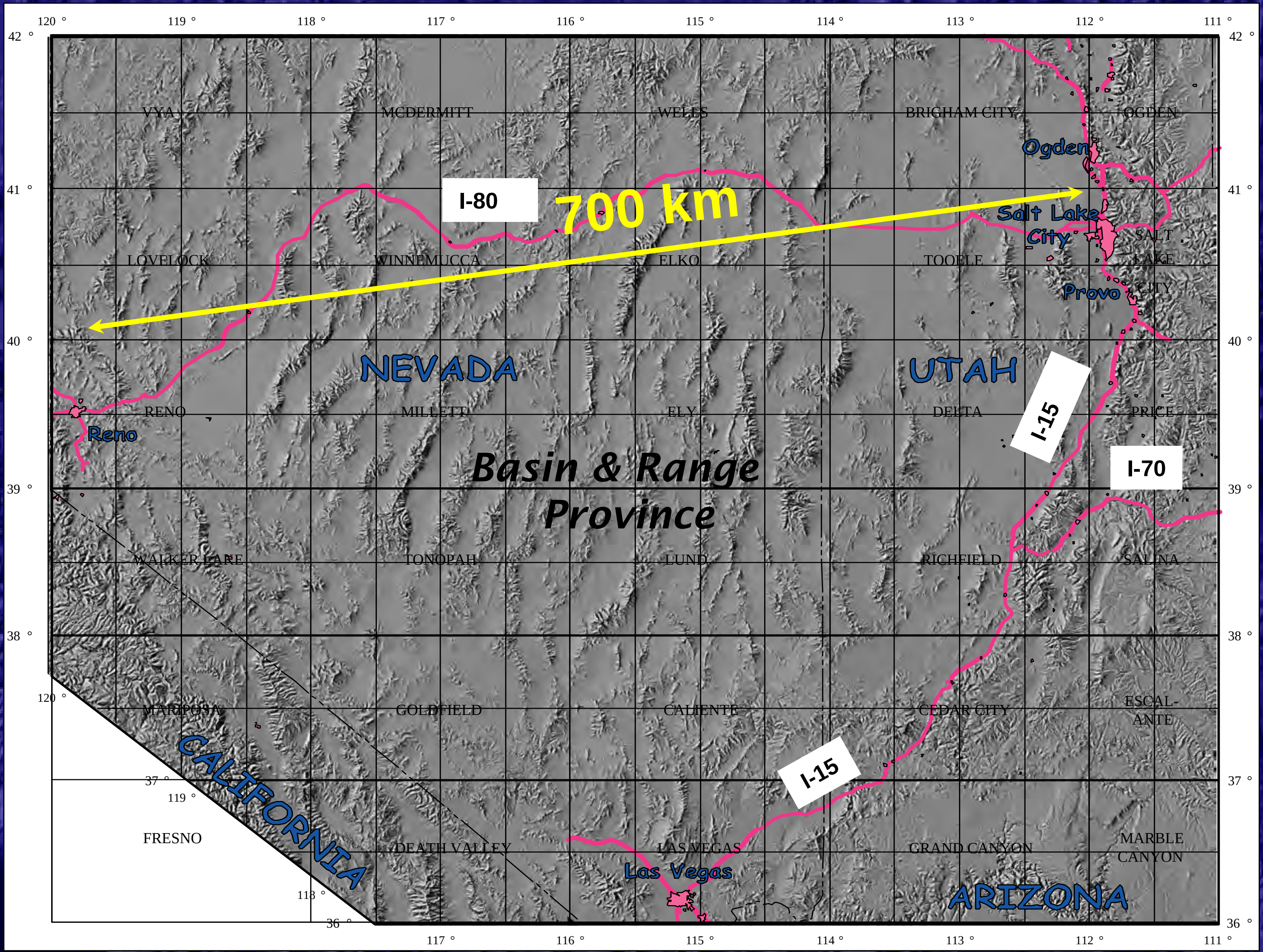
Constraints of Geological Data:
Determining the Age of Surface-Rupturing Events

- **In site-specific studies (trenches):**
  - ✓ **Information is influenced by the preservation of a stratigraphic record that can be directly related to individual faulting events**
  - ✓ **The ability to accurately date specific deposits and shrink the time windows that bound ages of paleoevents**



USGS
science for a changing world

Great Basin of Utah and Nevada



USGS
science for a changing world

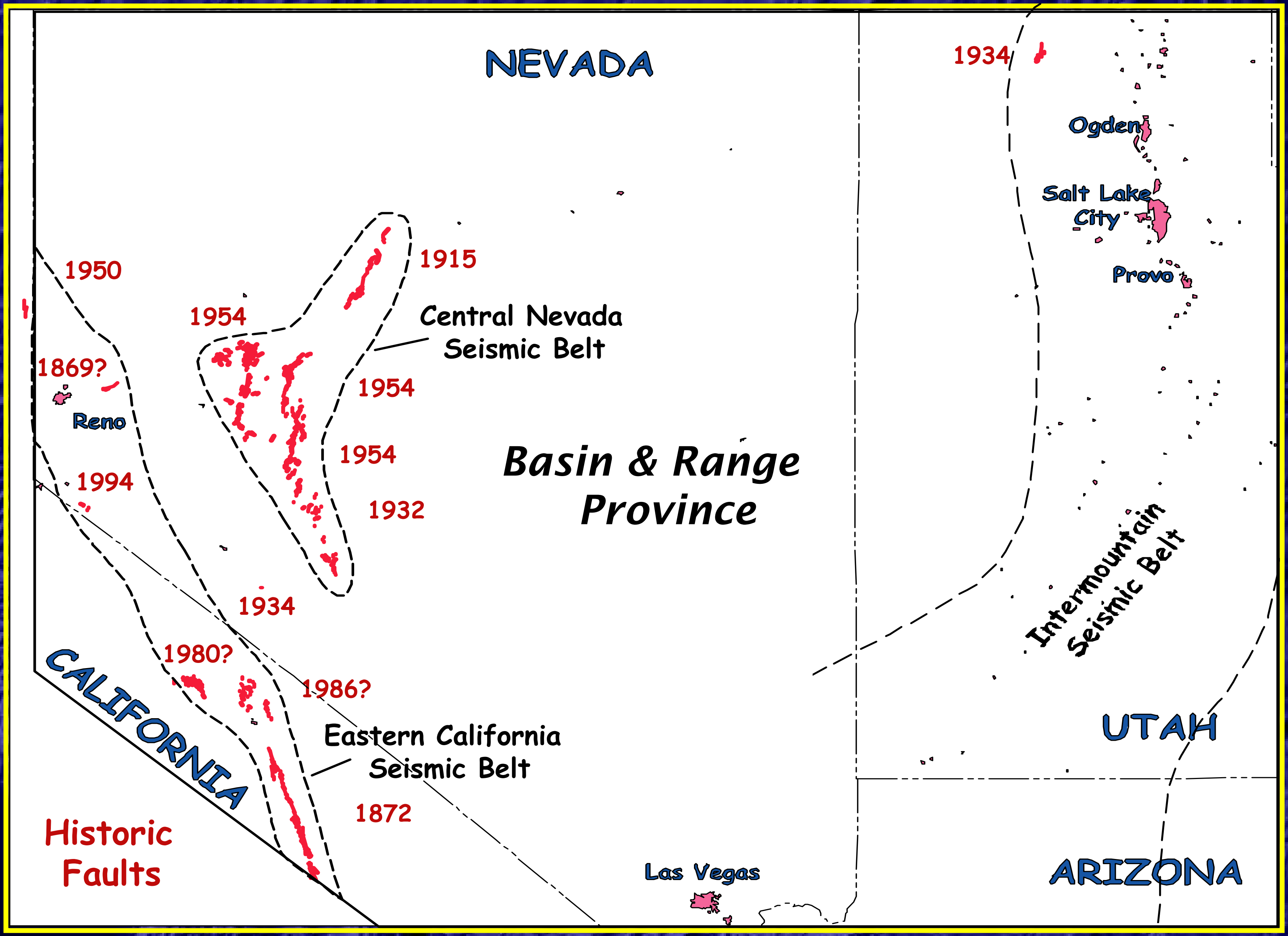
Spatial & Temporal Patterns of Faulting in the Great Basin

Time intervals used in Quaternary fault and fold database:

- Historical surface faulting (<200 yr)
- Latest Quaternary (less than 15 ka)
- Late Quaternary (less than 130 ka)
- Late and Middle Quaternary (less than 750 ka)
- Quaternary (<1.6 Ma)

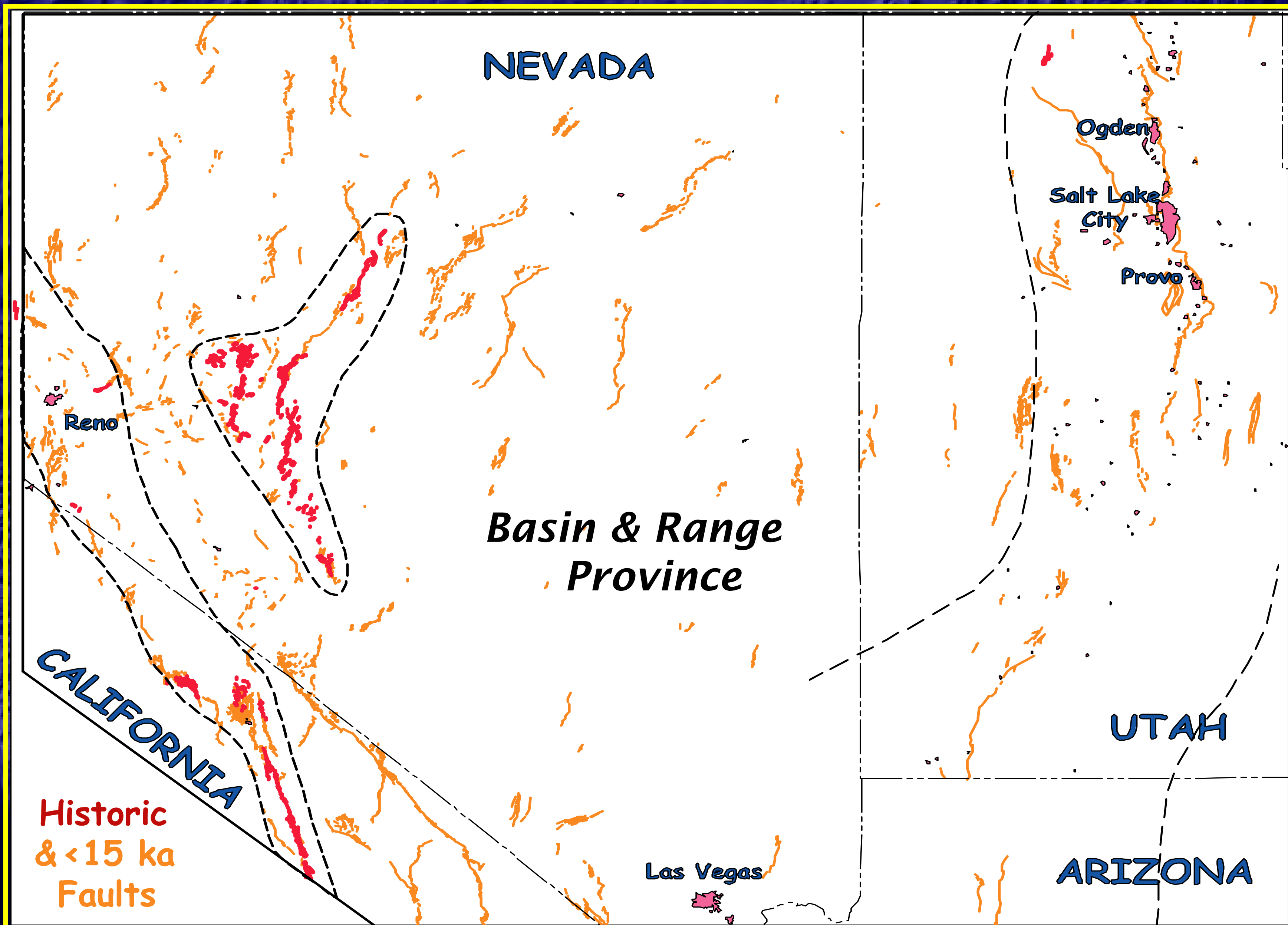
- Quaternary lakes from Reheis (USGS, 2003)

Historical Surface Faulting in Great Basin

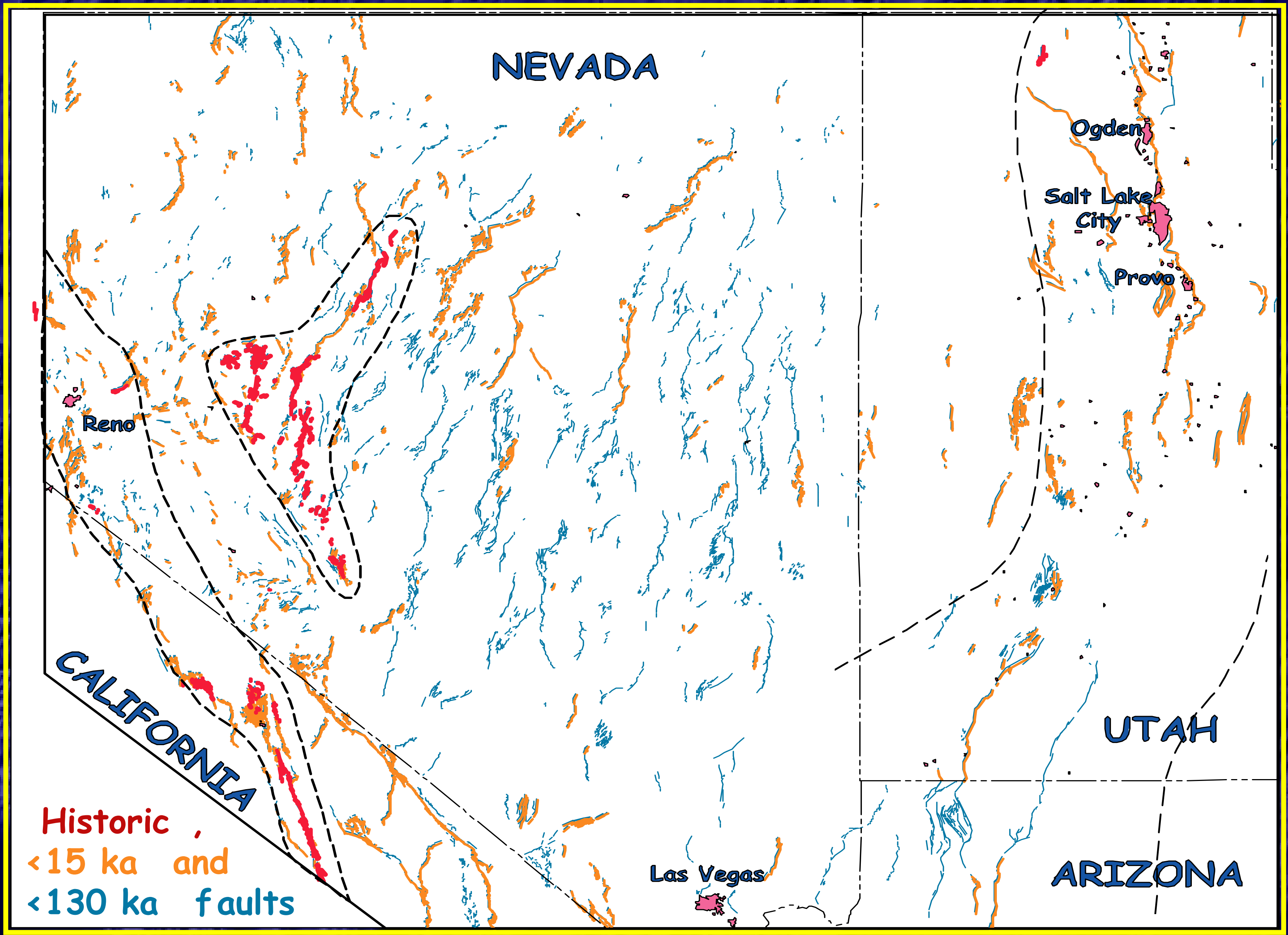


USGS
science for a changing world

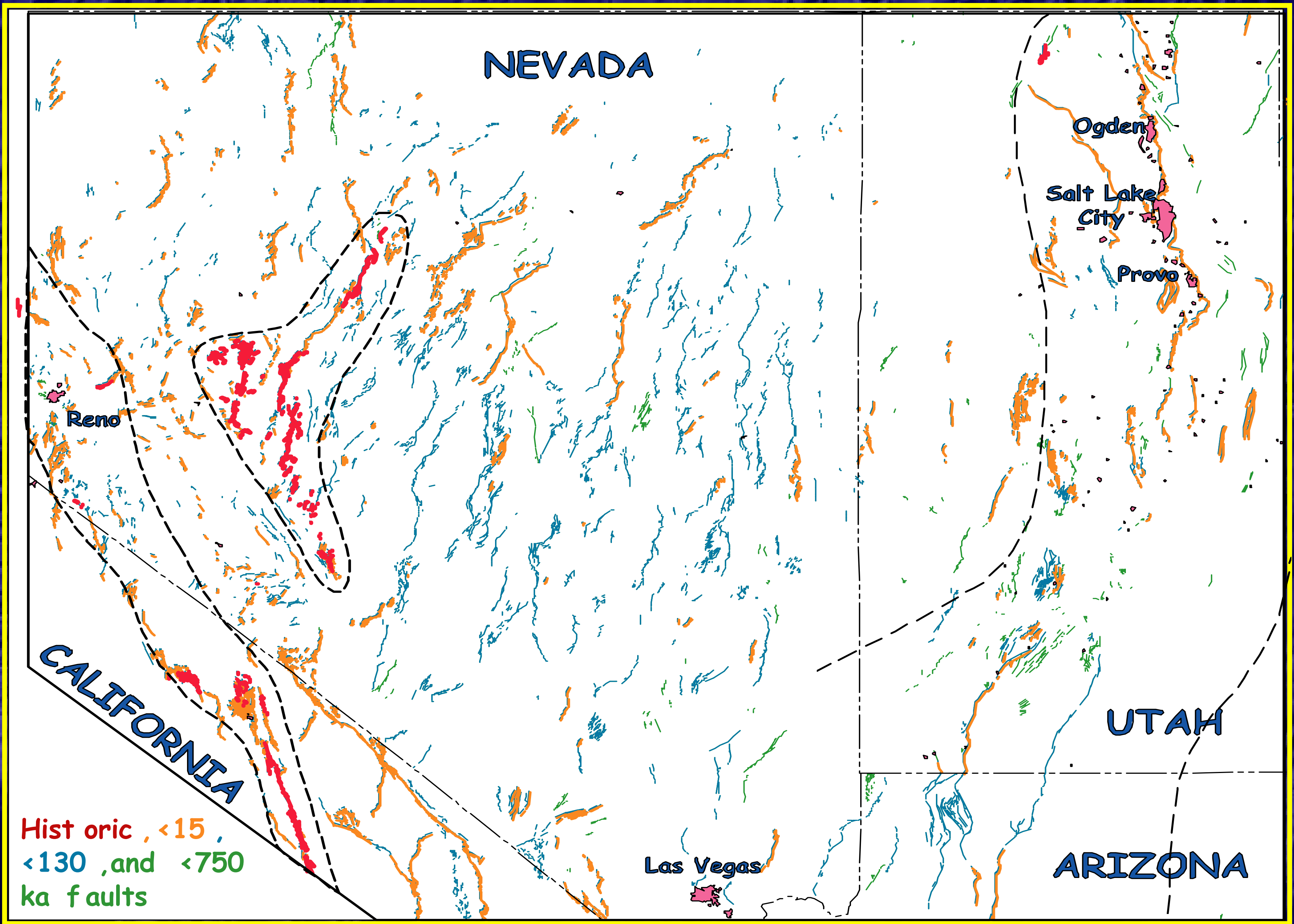
Latest Quaternary (<15 ka) Surface Faulting



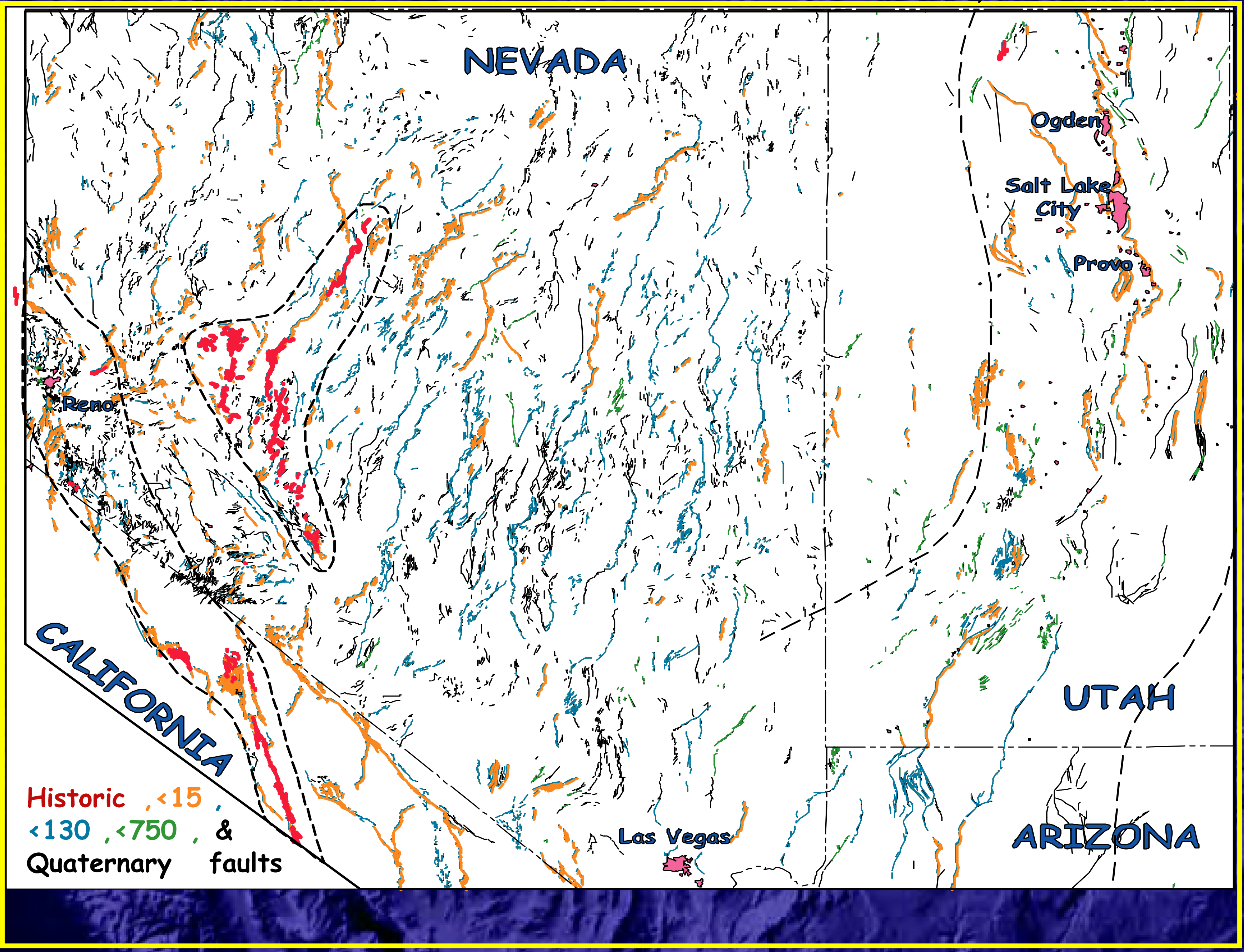
Late Quaternary (<130 ka) Surface Faulting



Late & Middle Quaternary (<750 ka) Surface Faulting

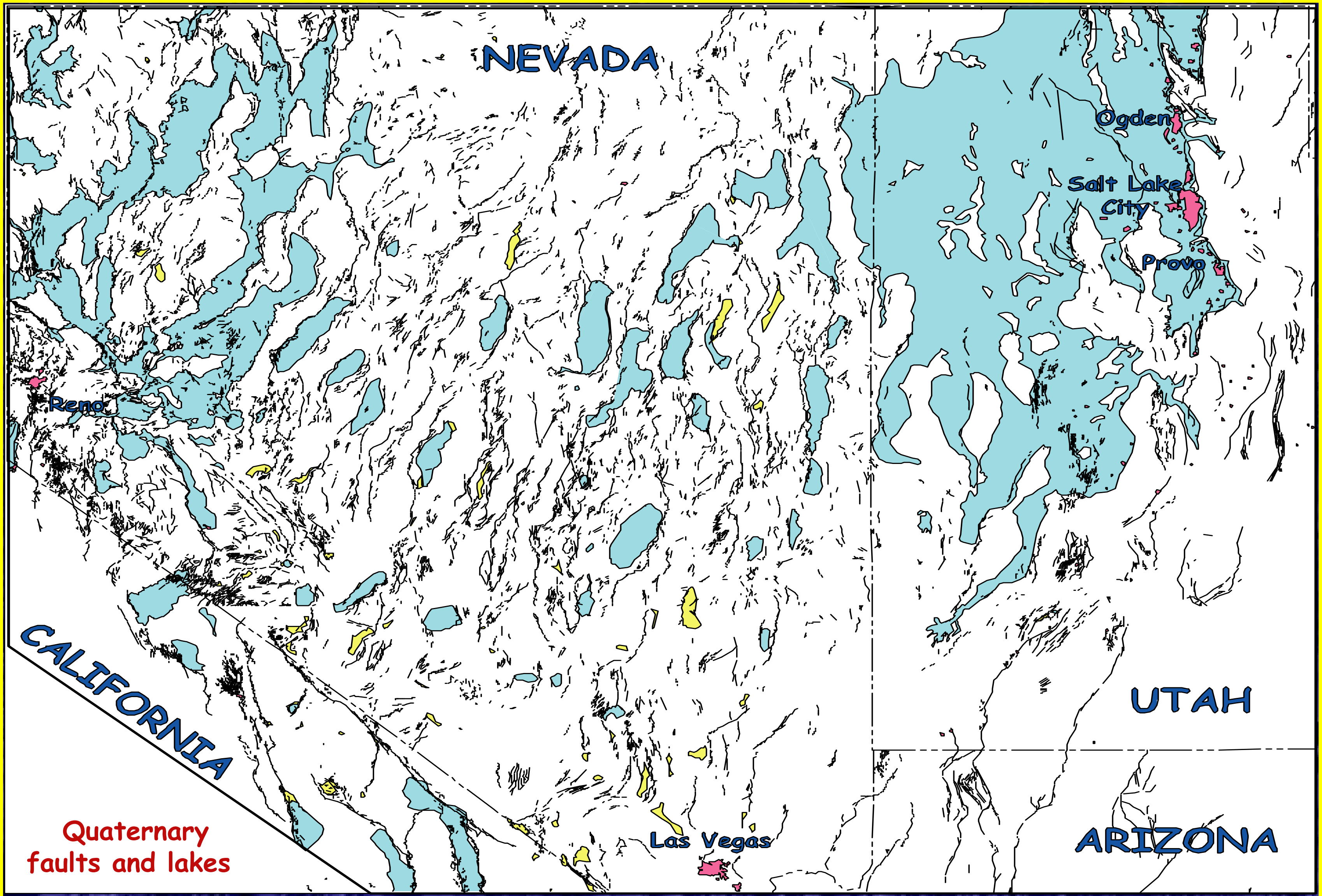


Quaternary (<1.6 Ma) Surface Faulting



USGS
science for a changing world

Quaternary Faults and Pluvial Lakes



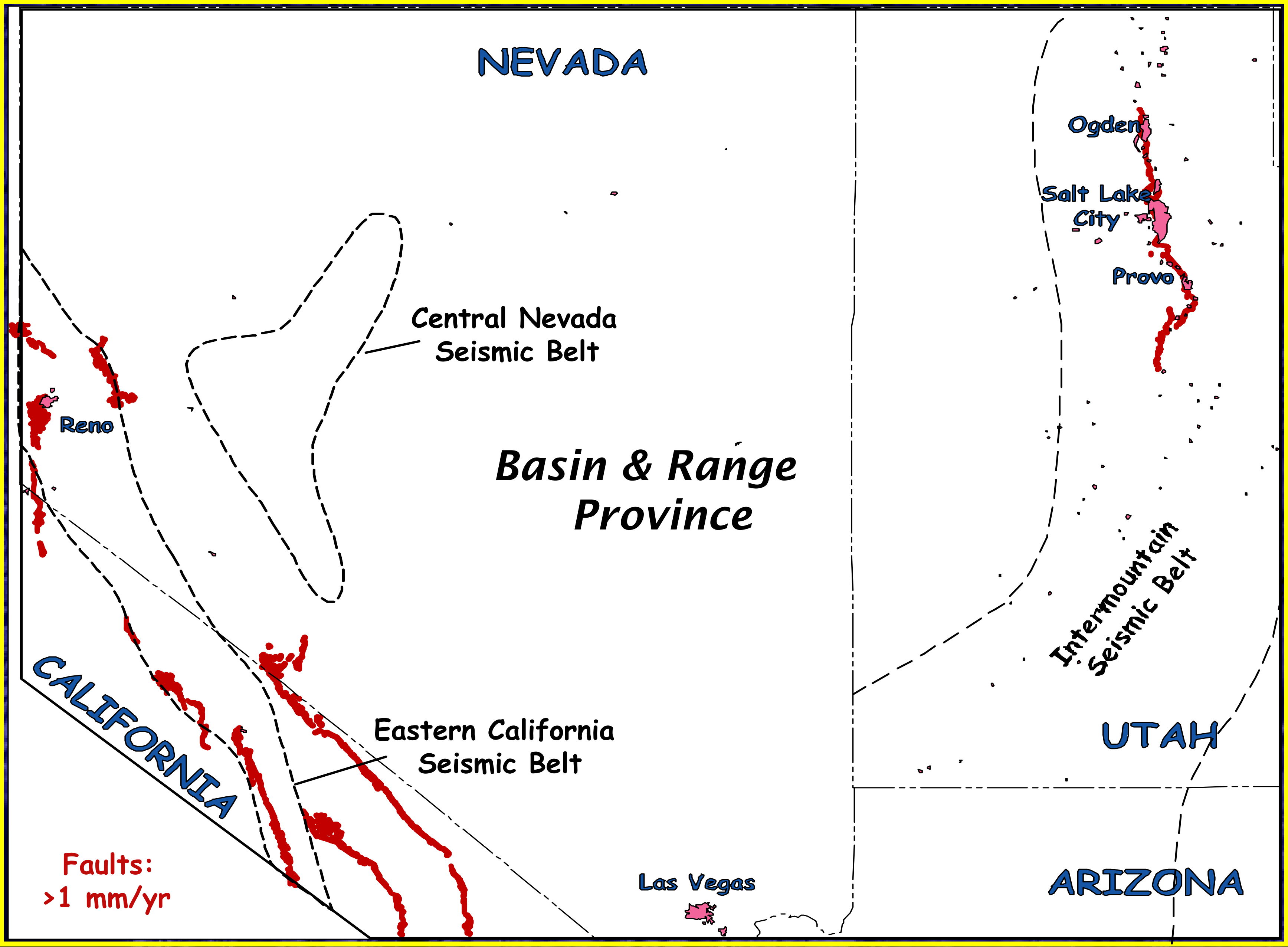
USGS
science for a changing world

Great Basin Slip-Rate Patterns

Slip rate categories used in the Quaternary fault and fold database:

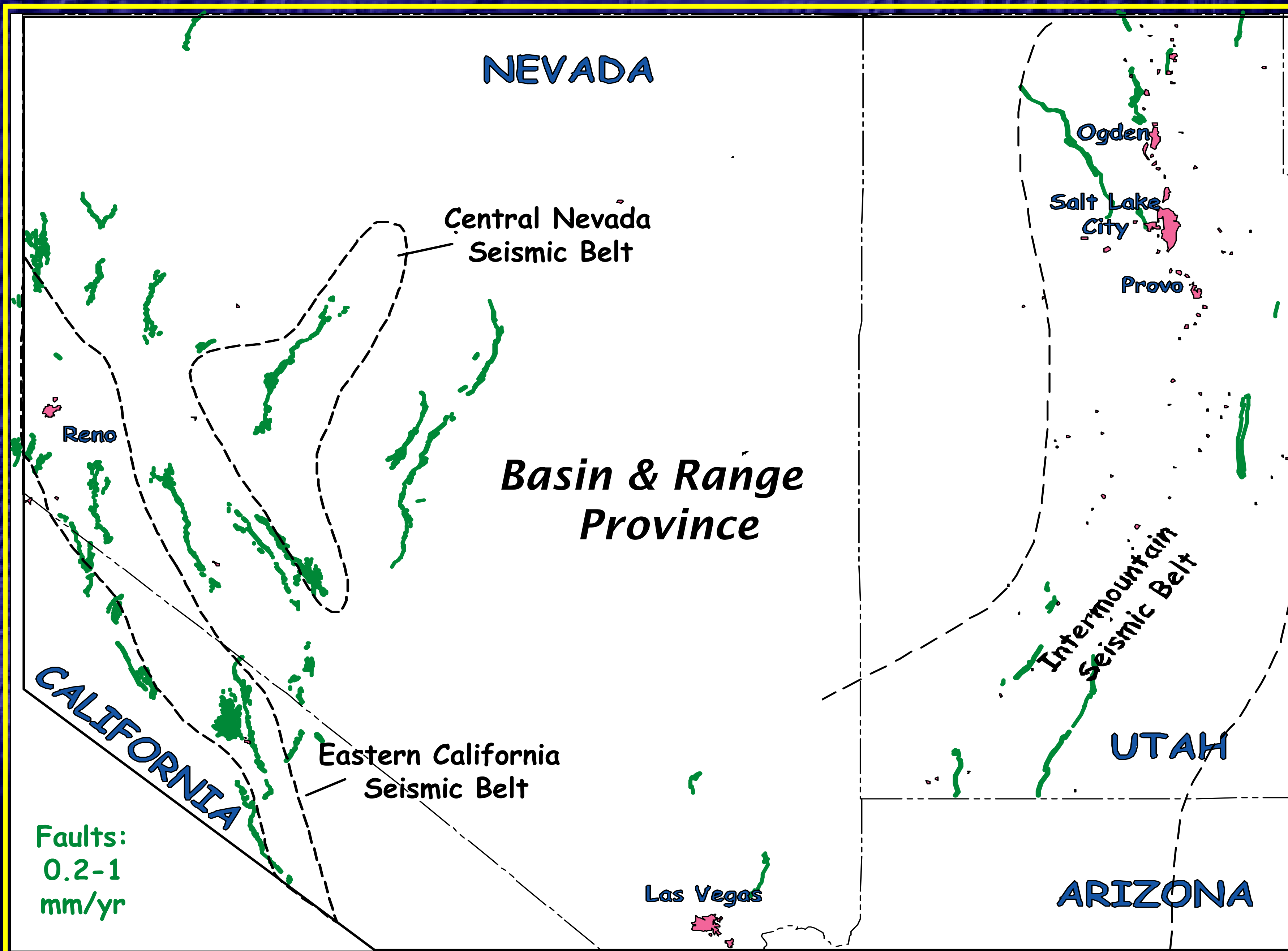
- Greater than 1 mm/yr (high slip rate; shown in red)
- 0.2-1 mm/yr (moderate slip rate; shown in green)
- Less than 0.2 mm/yr (low slip rate; shown in blue)

High Slip-Rate Faults (>1 mm/yr)



USGS
science for a changing world

Moderate Slip-Rate Faults (1-0.2 mm/yr)

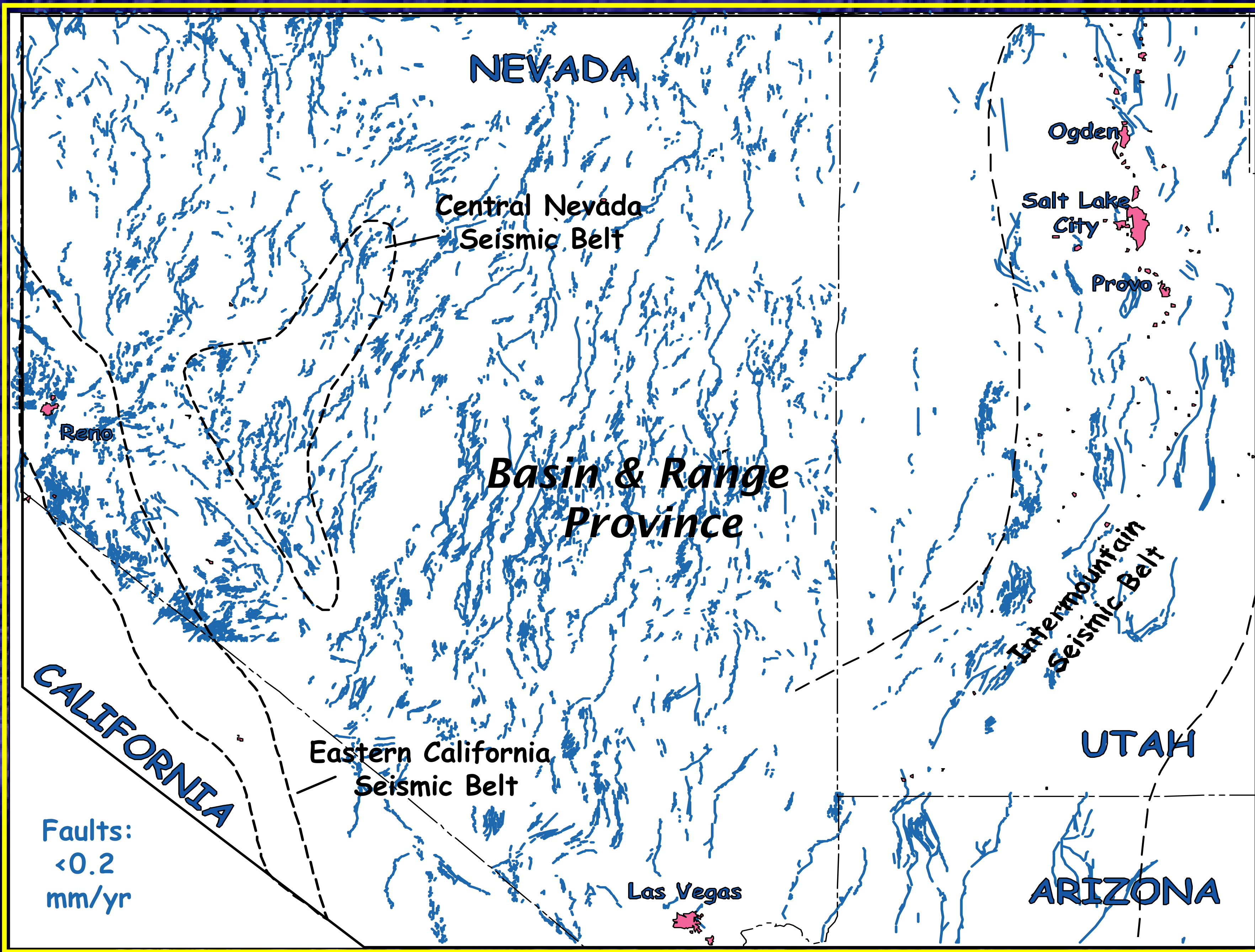


USGS
science for a changing world

Surprise Valley Fault, CA

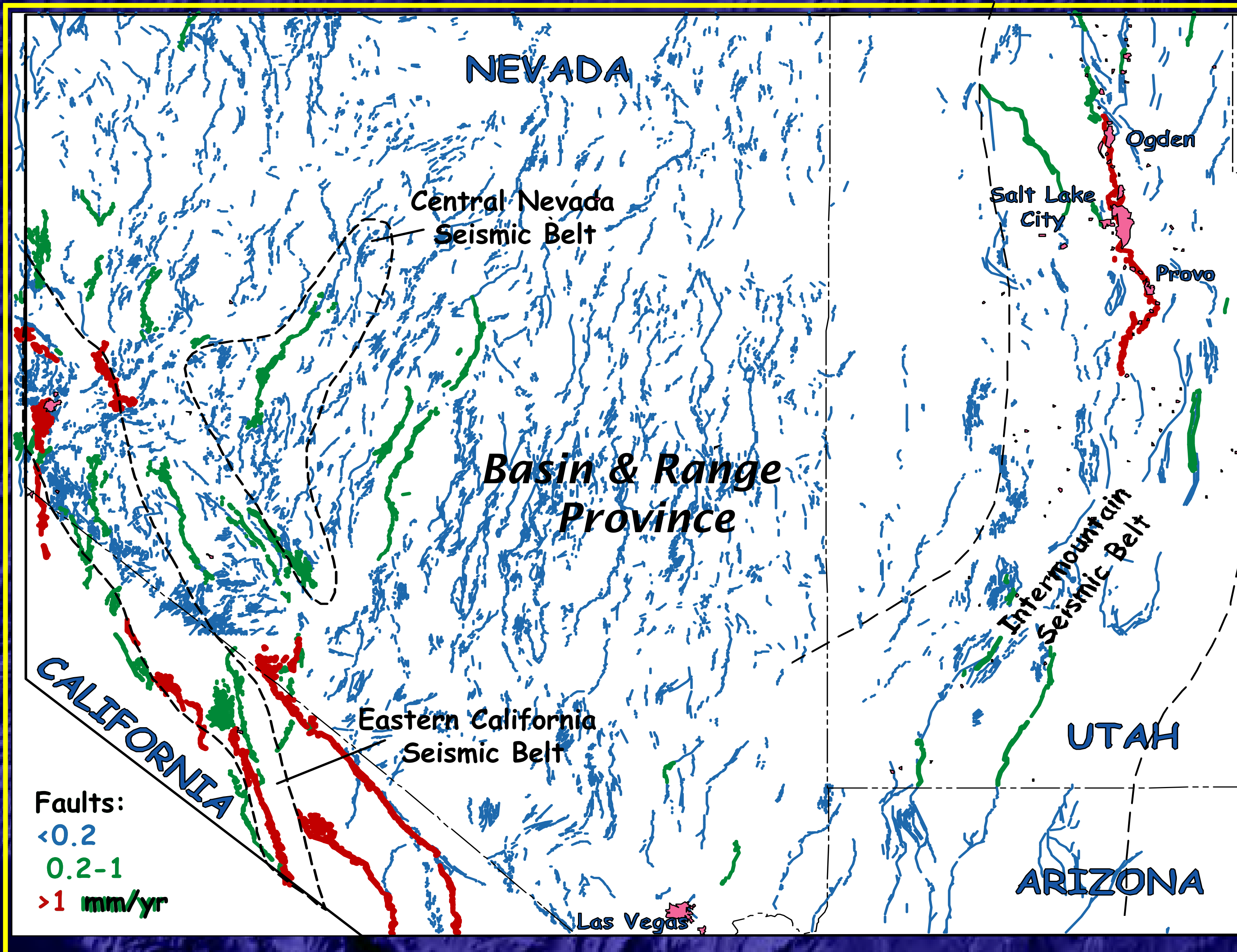
A Moderate Slip-Rate Fault (1 mm/yr)

Low Slip-Rate Faults (<0.2 mm/yr)

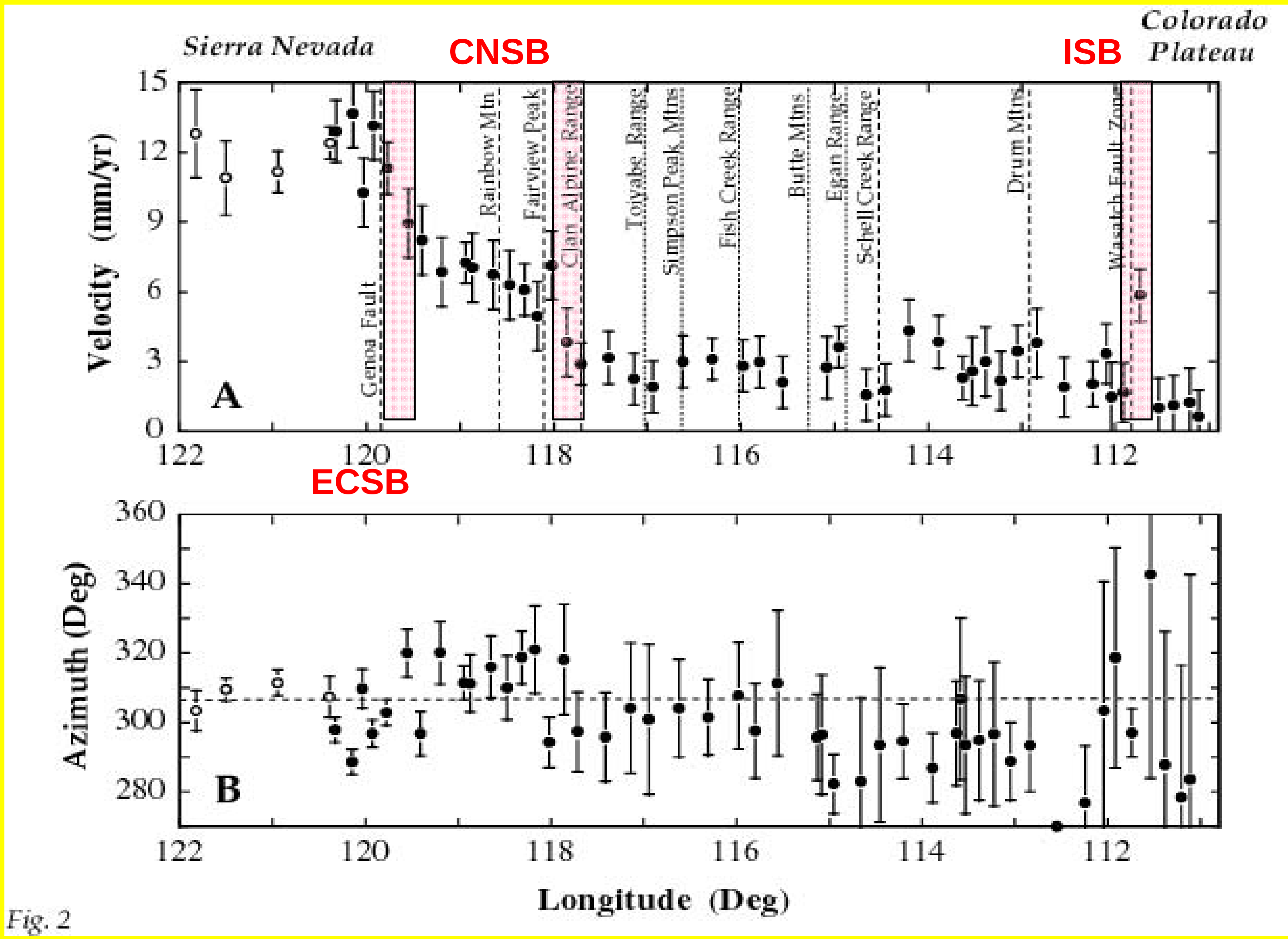


USGS
science for a changing world

Summary: Slip-Rate Patterns



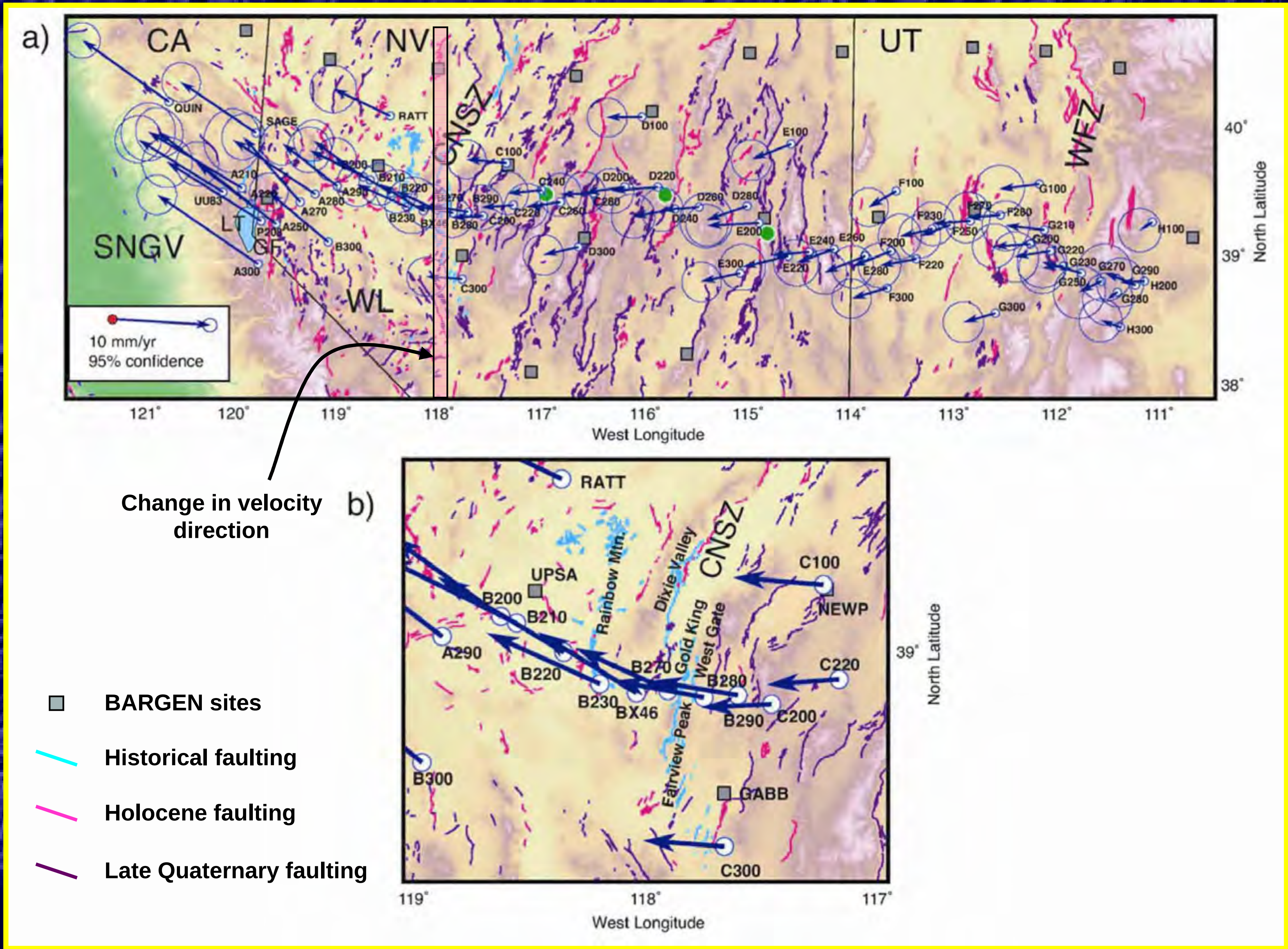
GPS Data, Northern Great Basin



- 2.8±0.5 mm/yr across Wasatch and related faults
- 3.7±0.8 mm/yr across CNSB
- 6.0±1.6 mm/yr within the ECBS/Walker Lane

from Thatcher and others, 1999

GPS Velocities Across the Basin & Range



from Hammond and Thatcher, 2004

What is a “typical” Basin and Range fault?

- Forms prominent small to large range fronts
- Many have faceted spurs, implying long movement history (Pliocene-Pleistocene?)
- Tend to be centrally located (not along margins of the province).
- Have low slip rates (0.10±0.05 mm/yr), and
- Recurrence intervals on the order of 10 k.y. or more
- Cluster of historical activity in the CNSB is an anomaly; geologic studies do not support this type of clustering in late Quaternary time in CNSB

USGS
science for a changing world

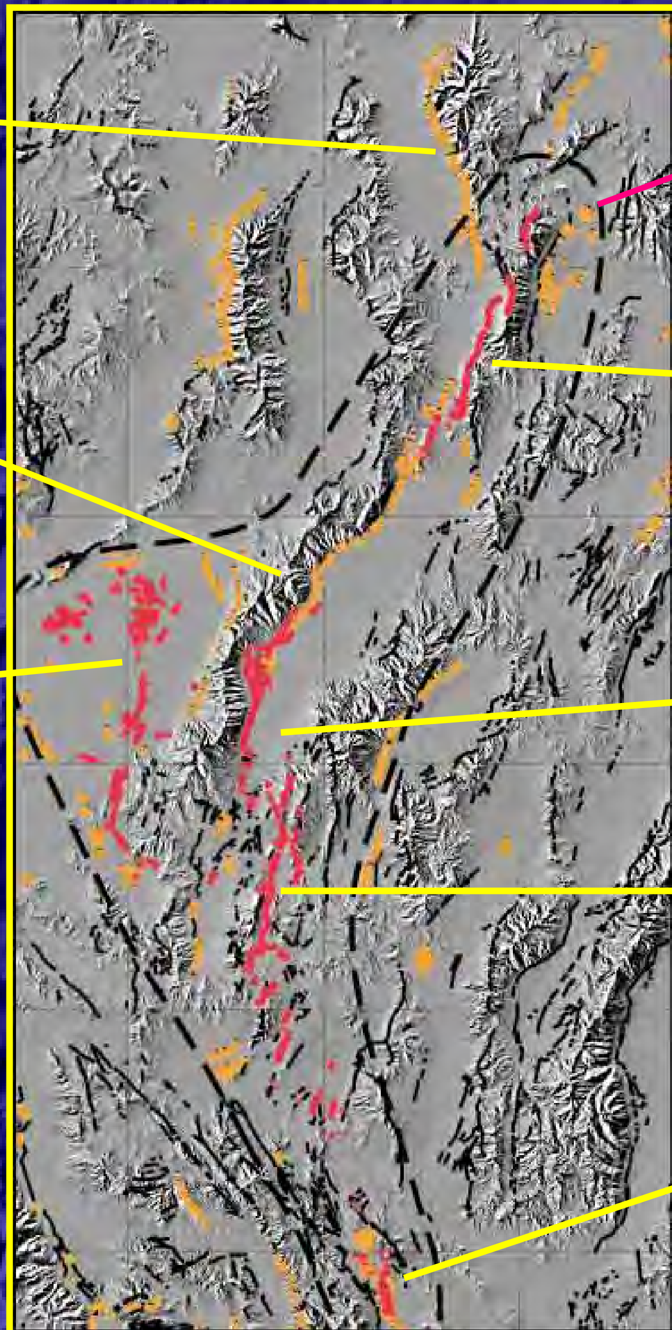
Central Nevada Seismic Belt (CSNB)

Temporal clustering with six major earthquakes:

- **1915**
- **1932**
- **1954 (4)**

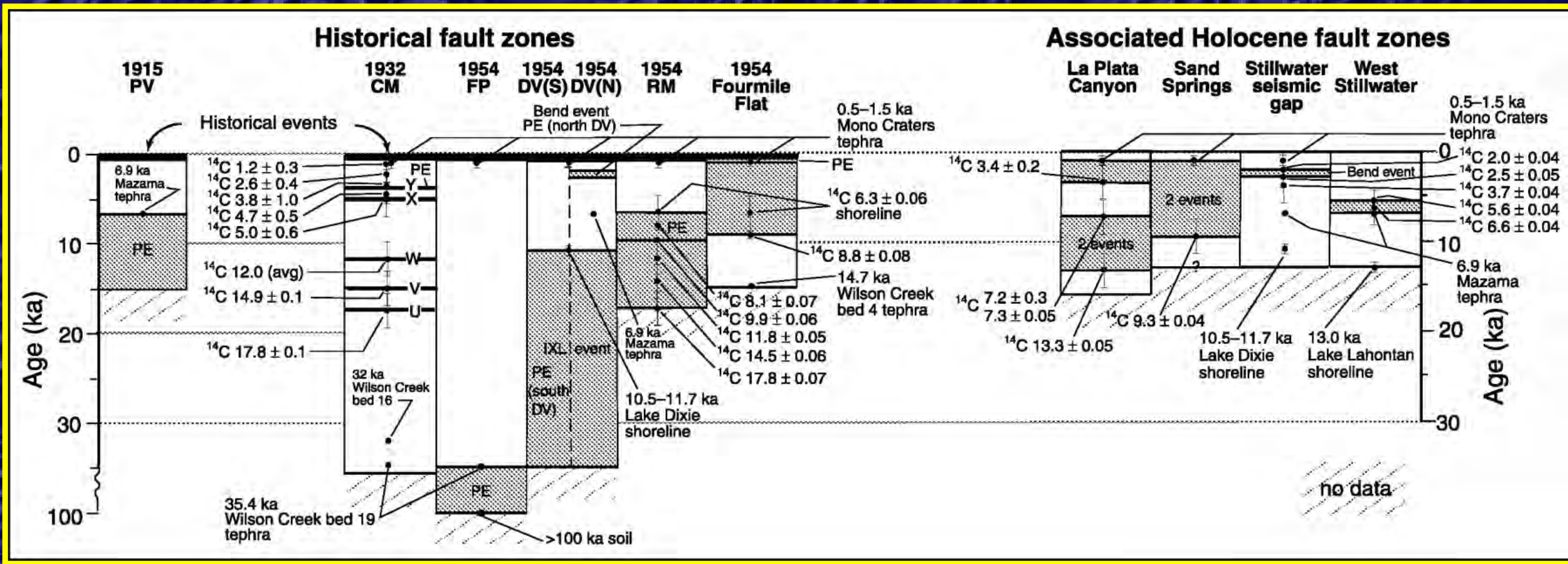
Is this a viable model for assessing the hazards of Basin and Range faults?

Historic Activity and Prehistoric Faults



Paleoseismology of the CNSB

(from Bell and others, 2004, BSSA)



- The 300-km-long rupture pattern of 1915-1954 is unique in paleoseismic record of these fault zones
- No possibility of this type of sequence occurring within the past 35 ka
- Paleoseismic data permits various scenarios of multiple fault ruptures, but none that replicate the 1915-1954 sequence

Central Nevada Seismic Belt

- Conclusions:
- The CNBS has no late Quaternary precursor
- Recurrence intervals are long (10^3 yrs or more)
- Penultimate events are not clustered
- <u>Questions (and speculative answers):</u>
- Will gaps fill in future earthquakes?
  - ✓ Probably, but time scale is unknown
- Why here? Are there unique qualities of the CNSB that make it amenable to such clustering?
  - ✓ Unknown, coincides with rotation in extension direction. Is this significant?
- Will the cycle repeat itself?
  - ✓ Geological evidence indicates that this is not likely
- Could a similar sequence occur elsewhere in B&R?
  - ✓ Maybe, but is it likely enough to consider as part of regional hazard assessments?
- Are there prehistoric analogs elsewhere in the B&R?
  - ✓ Possibly, but we do not have sufficient data to confirm this

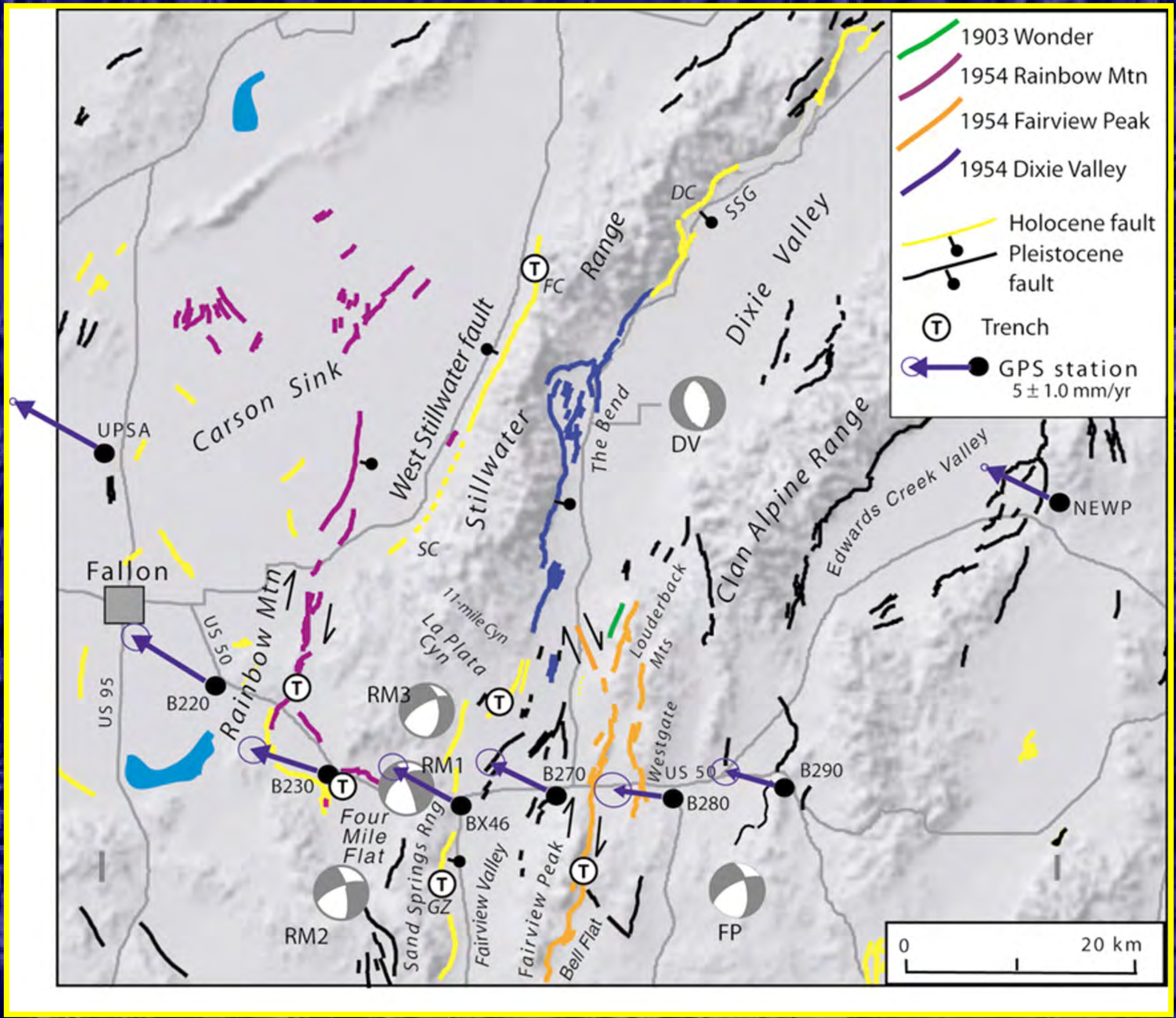
USGS
science for a changing world

Summary & Comments

- Late Quaternary faults are concentrated along margins of the Great Basin and in NW Nevada
- Utah/Nevada border region appears least active, but deposits from pluvial lakes may affect this impression. Late Quaternary lakes bury and obscure evidence of many pre-15 ka faults
- Most slip rates are slow and recurrence intervals are long, except along margins of the Great Basin
- 130 k.y. window captures most Quaternary faulting—time span is long enough to encompass multiple earthquake cycles on most faults
- Historical activity in the CNSB is a geologic anomaly
- If this burst of historical activity is anomalous, then can the locations and rates of GPS-determined deformation fluctuate greatly over time spans that are relevant to hazard assessments?

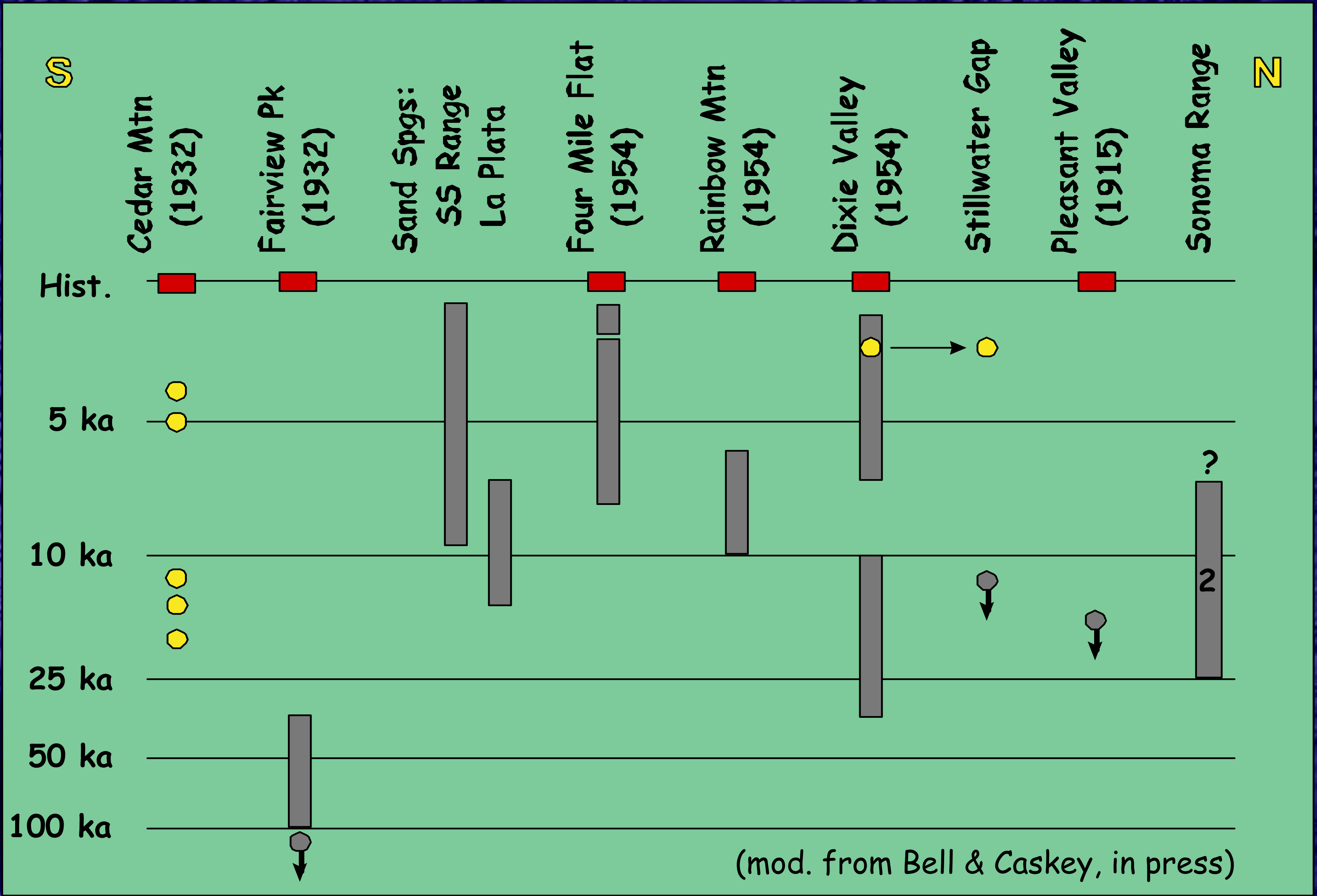
USGS
science for a changing world

Historical Surface Ruptures in the Central Nevada Seismic Belt



From Bell et al., BSSA, 2004

Late Quaternary faulting along the CNSB



USGS
science for a changing world


ENTERING THE GREAT BASIN

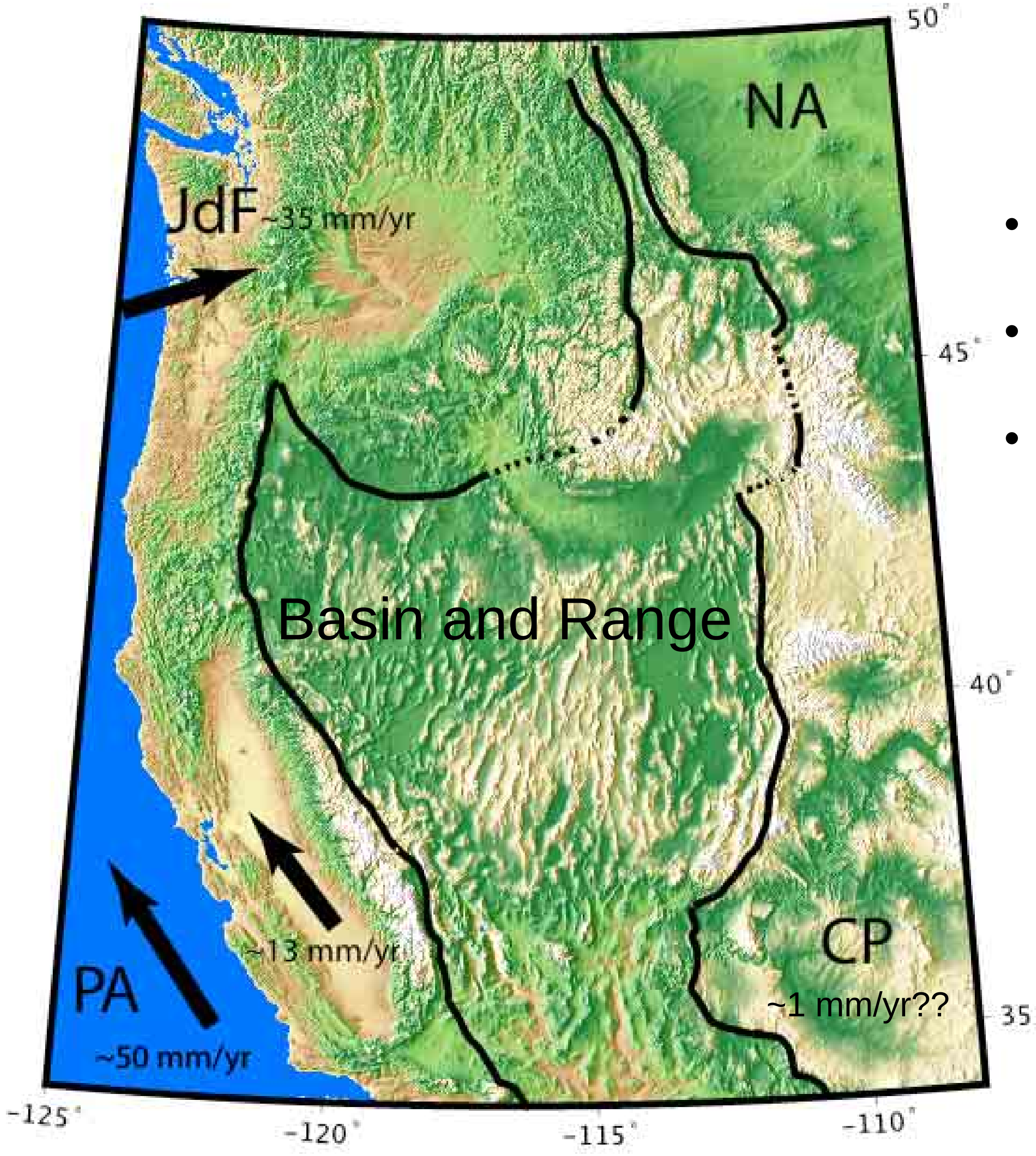
Active Basin and Range Deformation Measured with GPS: A Kinematic Overview

Bill Hammond
Nevada Geodetic Laboratory
Nevada Bureau of Mines and Geology

University of Nevada, Reno

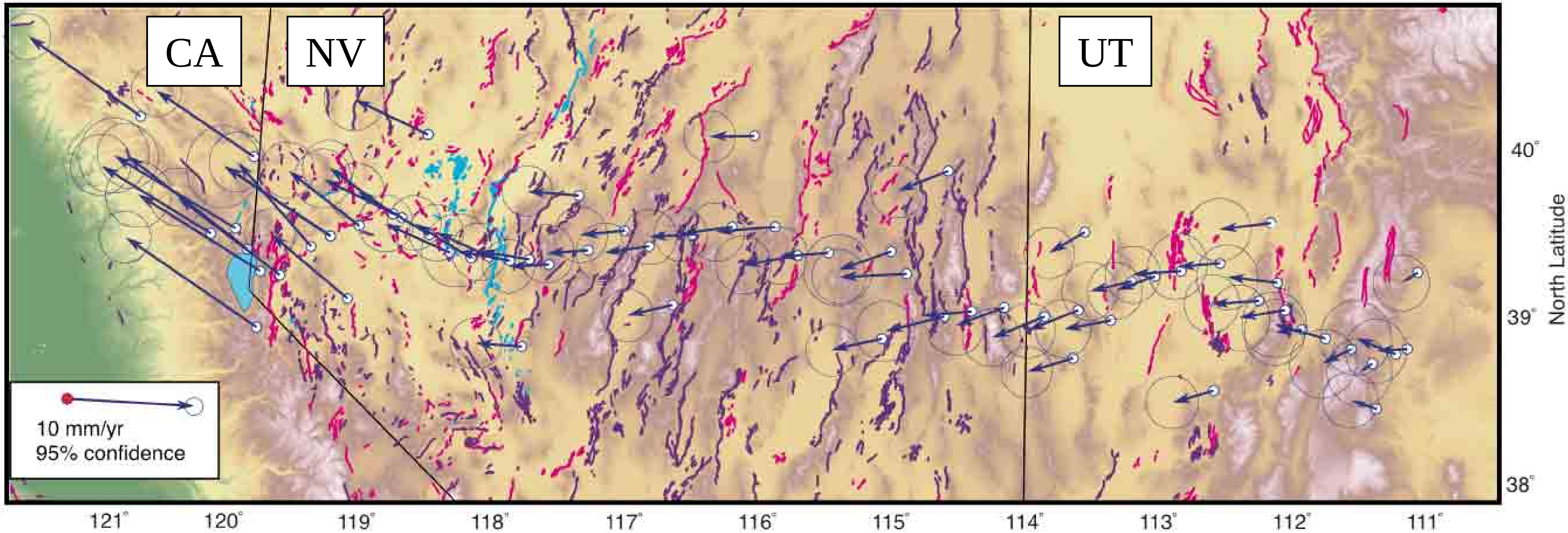
1) Review Results from Campaigns/Continuous GPS
2) Properties of the geodetic velocity field
3) Anomaly. CNSB
4) Discuss Recommendations

Kinematic Boundary Conditions



- Our Most Robust Observations
- Need To Be Obeyed
- Slip Rates are a Model of Deformation.

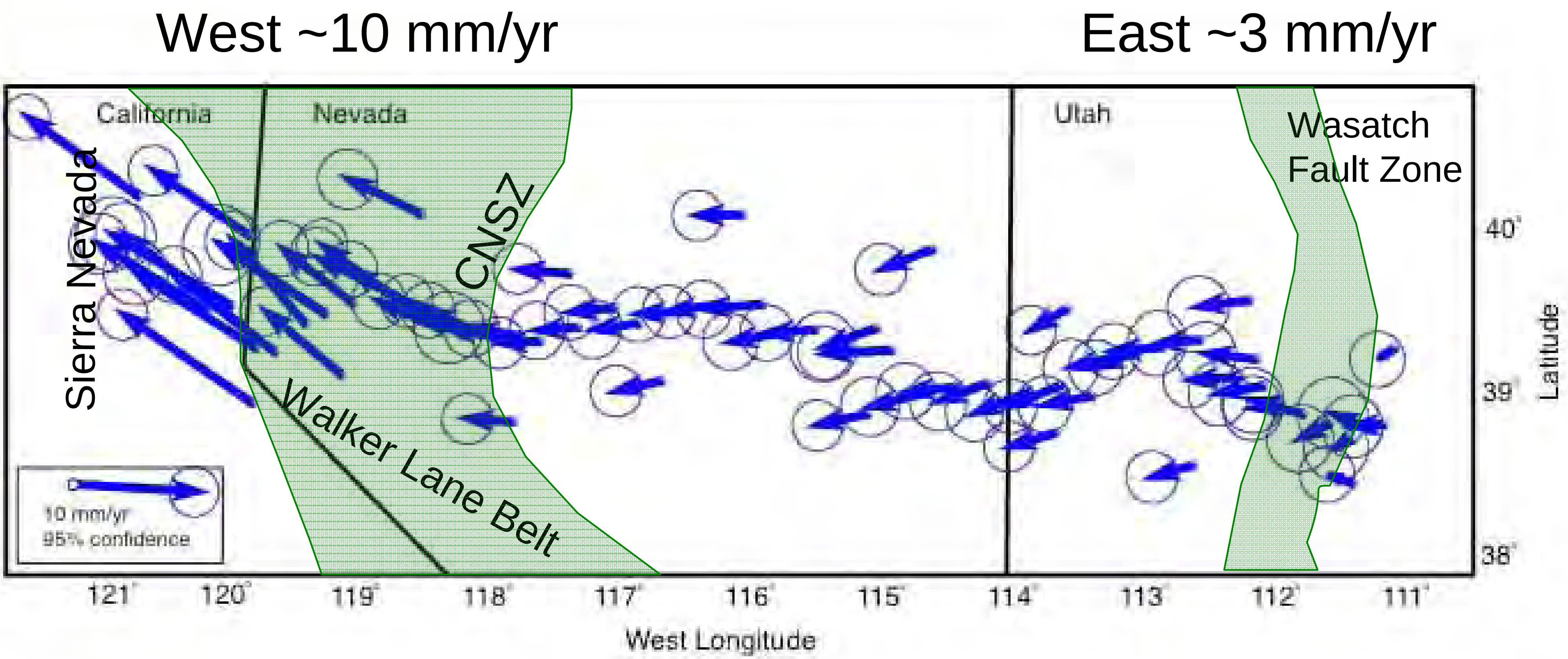
Campaign GPS Results
e.g. Highway 50



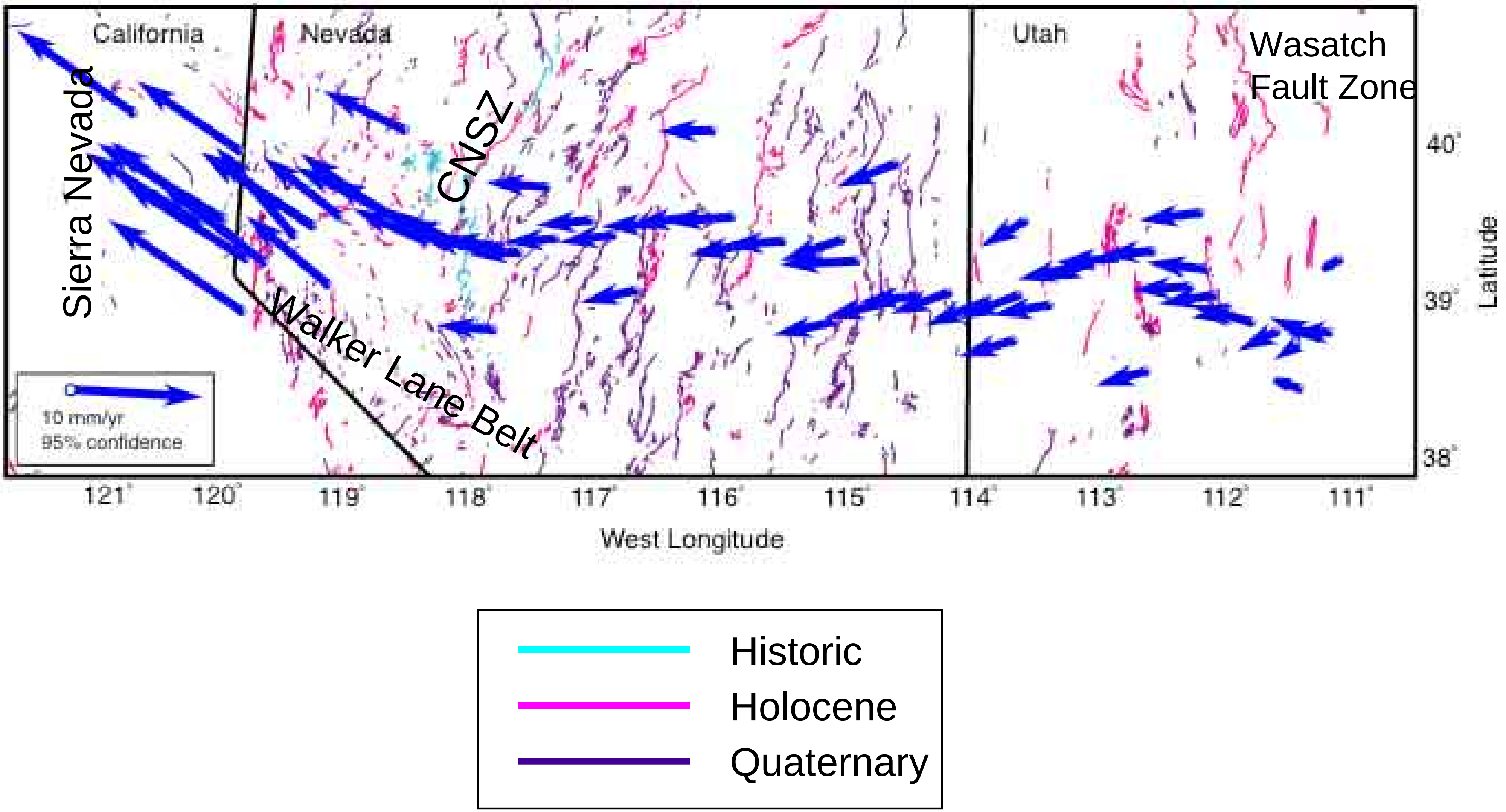
Hammond and Thatcher, 2004

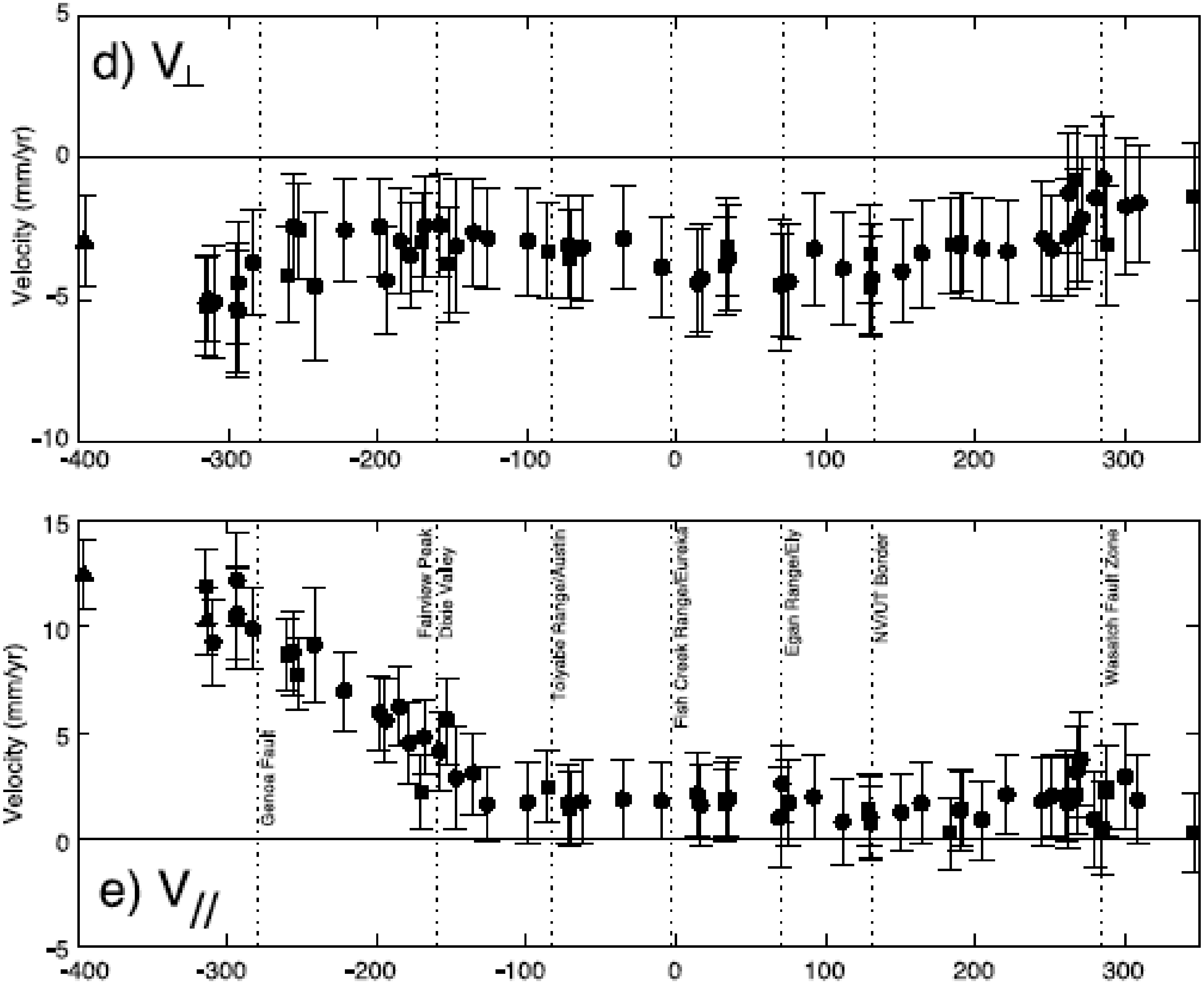
For .pdfs hit: http://geodesy.unr.edu

Most Deformation is Confined to the Province Boundaries



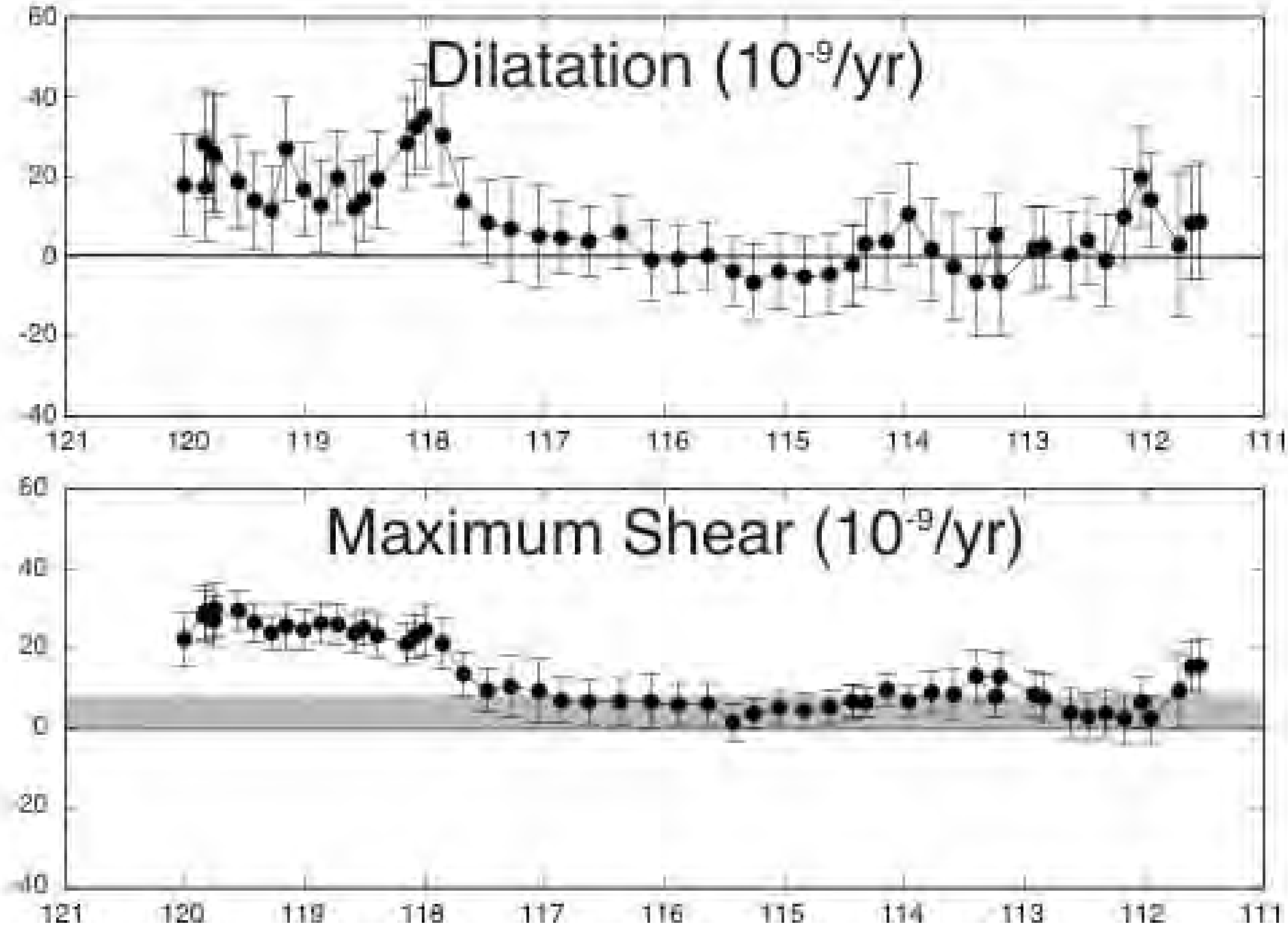
GPS Velocity Gradients and Faulting



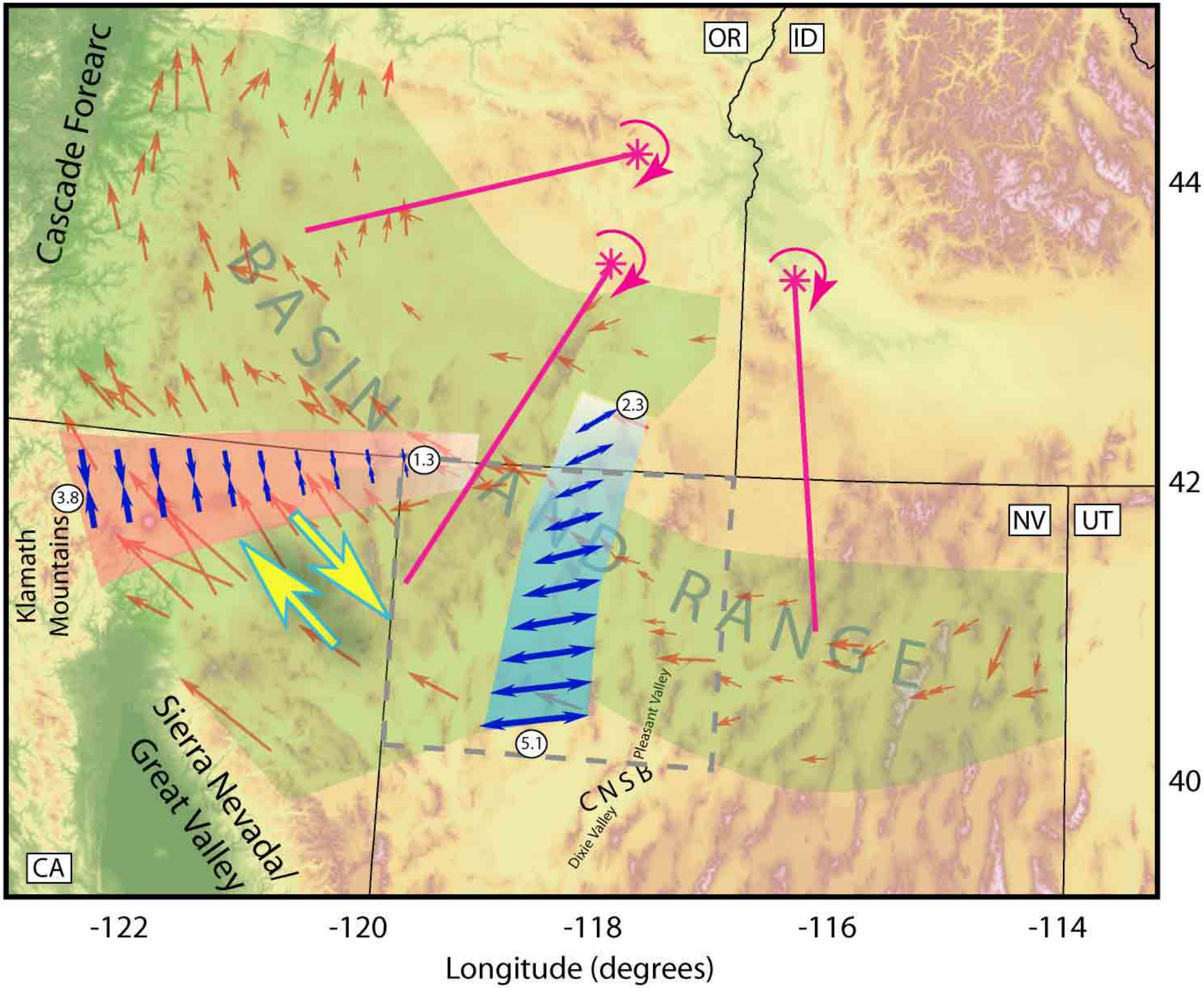


d) V⊥
Velocity (mm/yr)
5
0
-5
-10
-400
-300
-200
-100
0
100
200
300
e) V//
15
10
Genoa Fault
Fairview Peak
Dixie Valley
Toiyabe Range/Austin
Fish Creek Range/Eureka
Egan Range/Ely
NV/UT Border
Wasatch Fault Zone

Tensor Strain Rates Across the Province
Highway 50

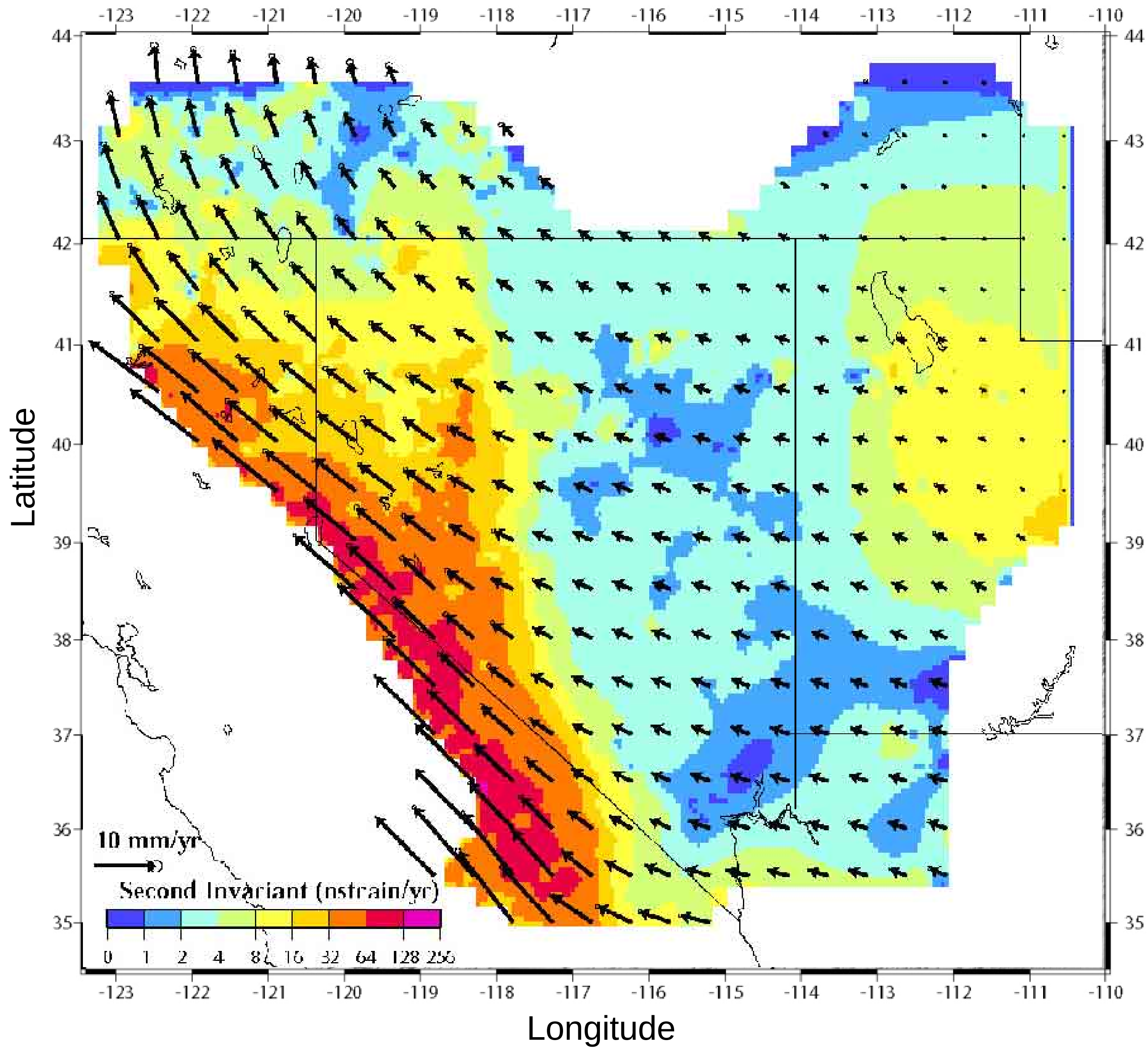


Longitude



OR
ID
NV
UT
CA
Cascade Forearc
BASIN AND RANGE
Klamath Mountains
Sierra Nevada/ Great Valley
CNSB
Pleasant Valley
Dixie Valley
2.3
1.3
3.8
5.1
44
42
40
Latitude (degrees)
-122
-120
-118
-116
-114
Longitude (degrees)

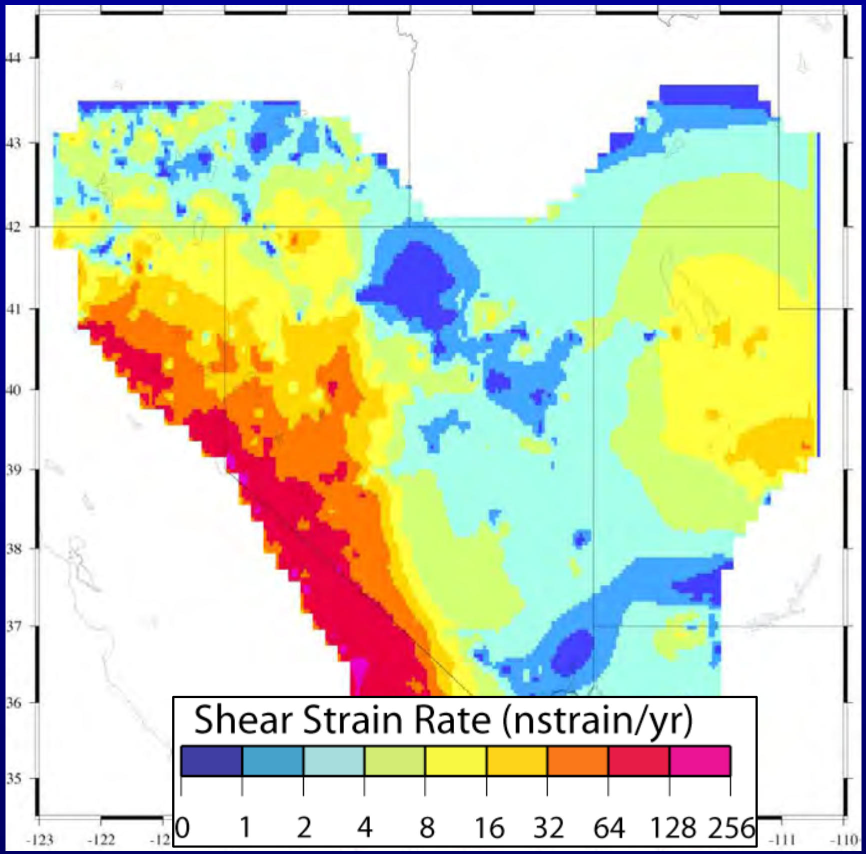
Basin and Range Tensor Strain Rate Map



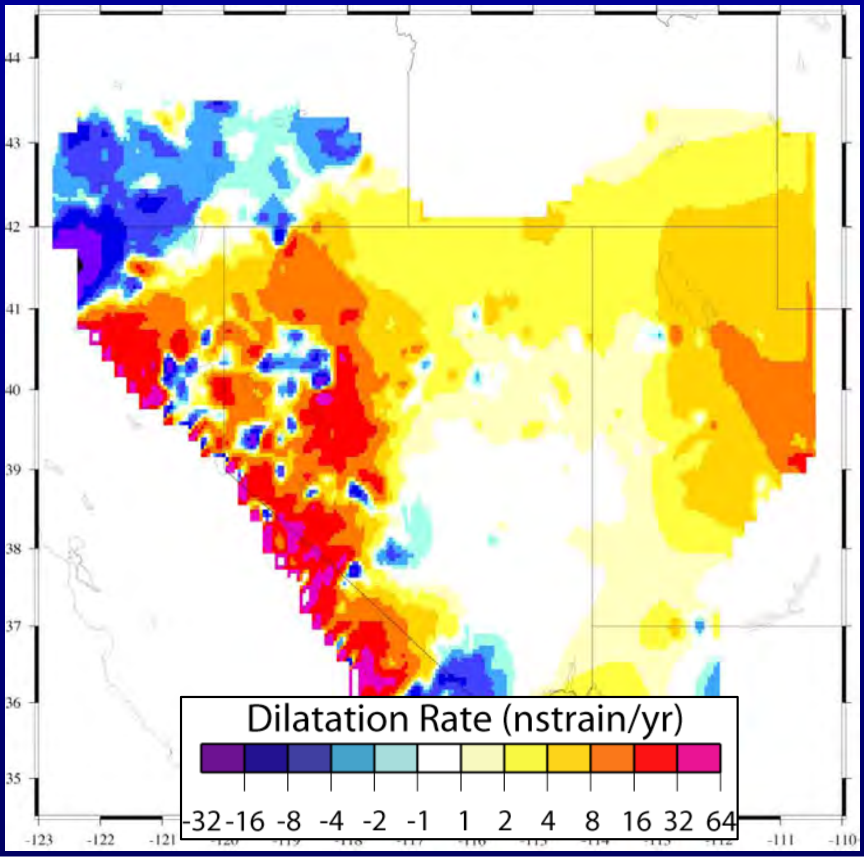
Kreemer, Blewitt, Hammond, submitted manuscript

Dilatation at the CNSB is Anomalously High

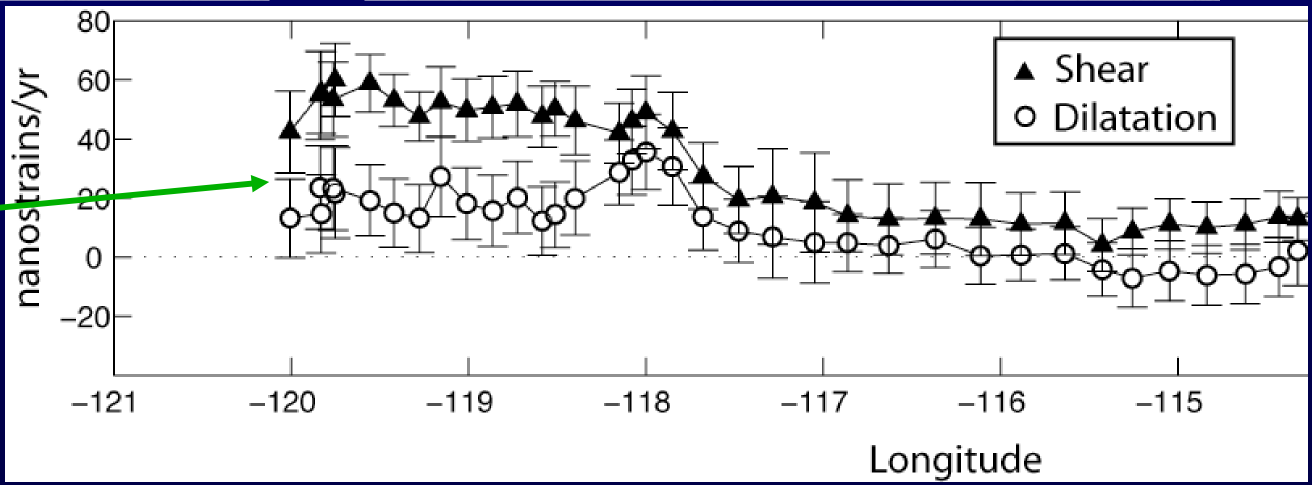
SHEAR

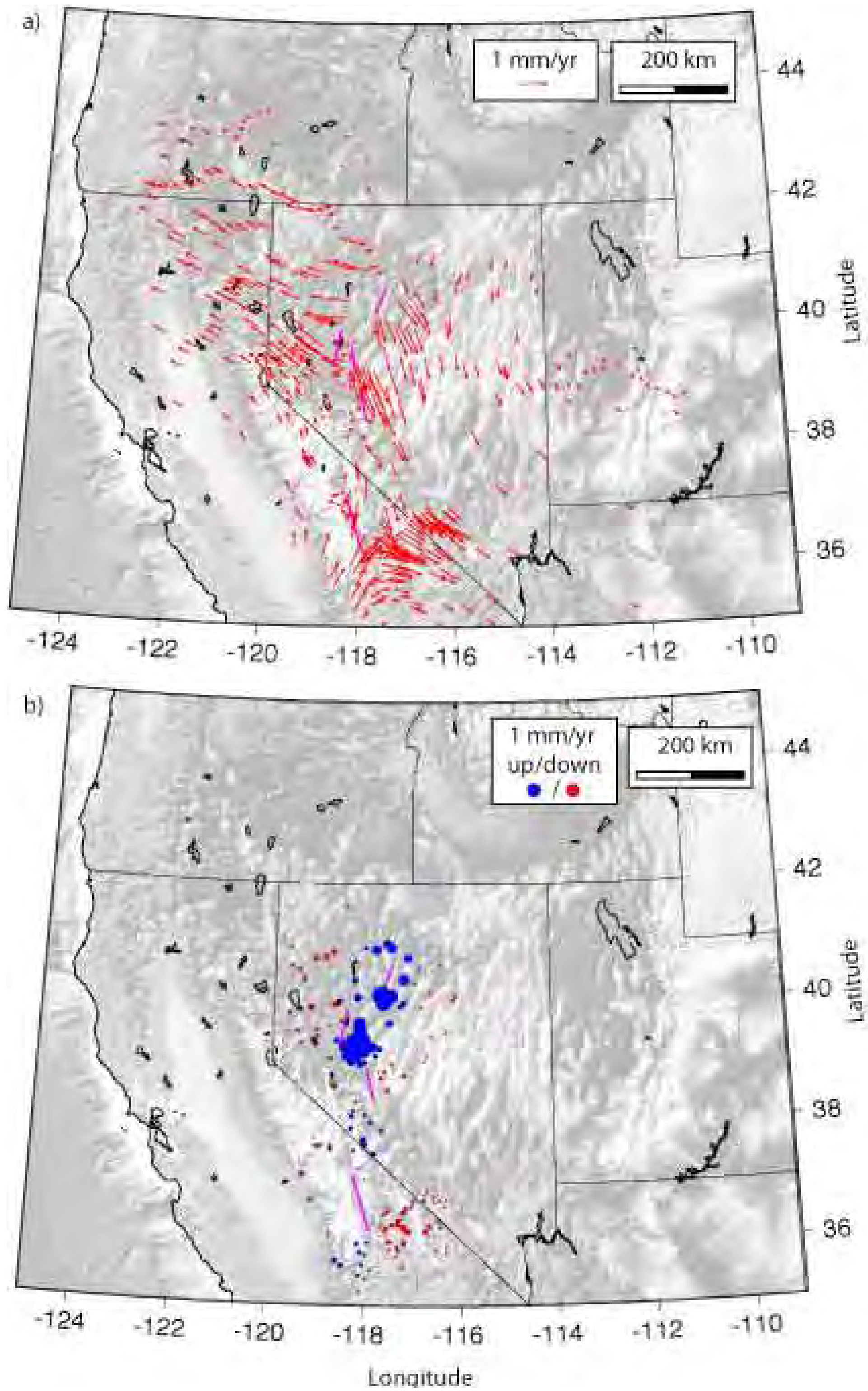


DILATATION

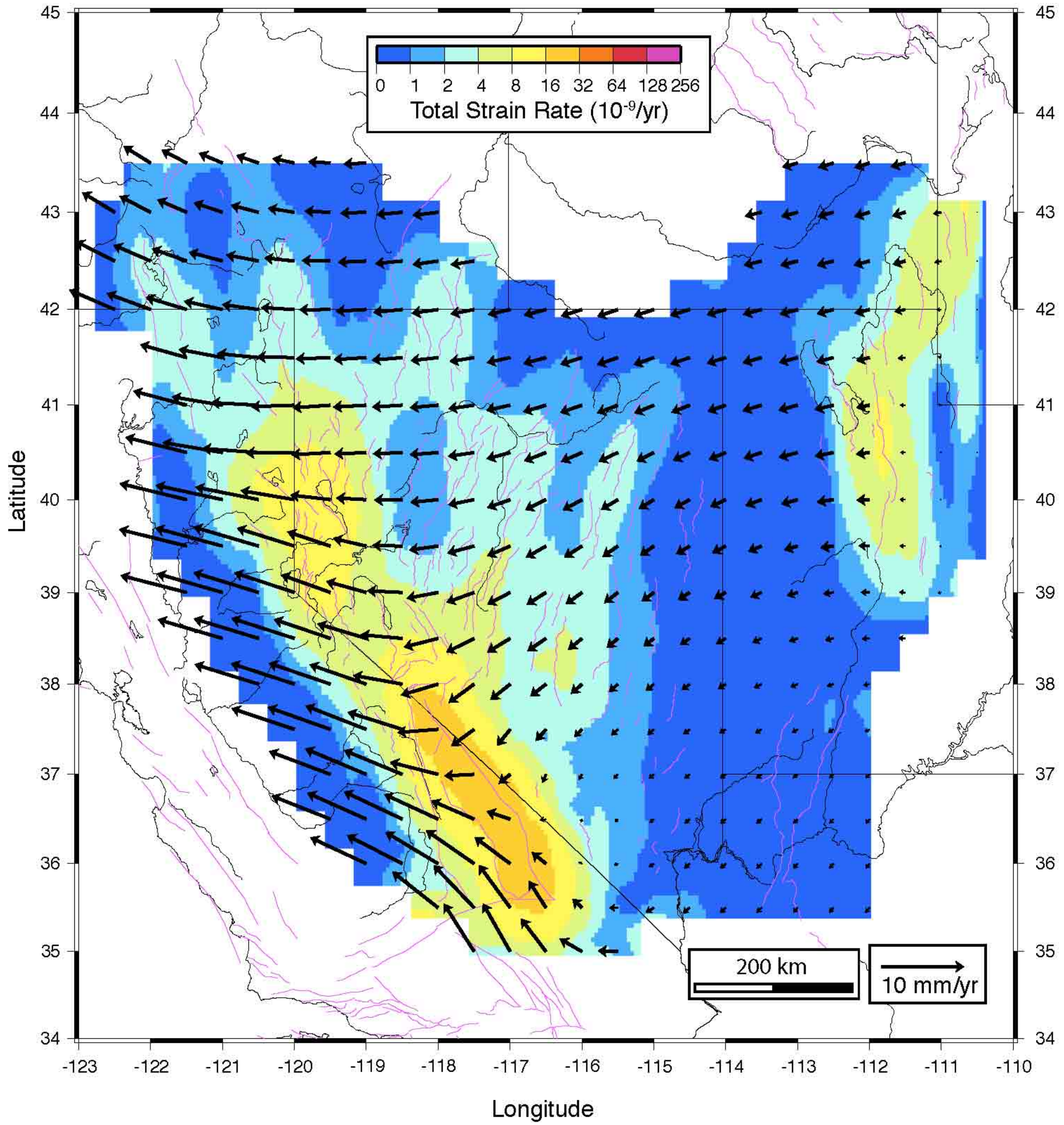


Highway 50 GPS Strain Rates



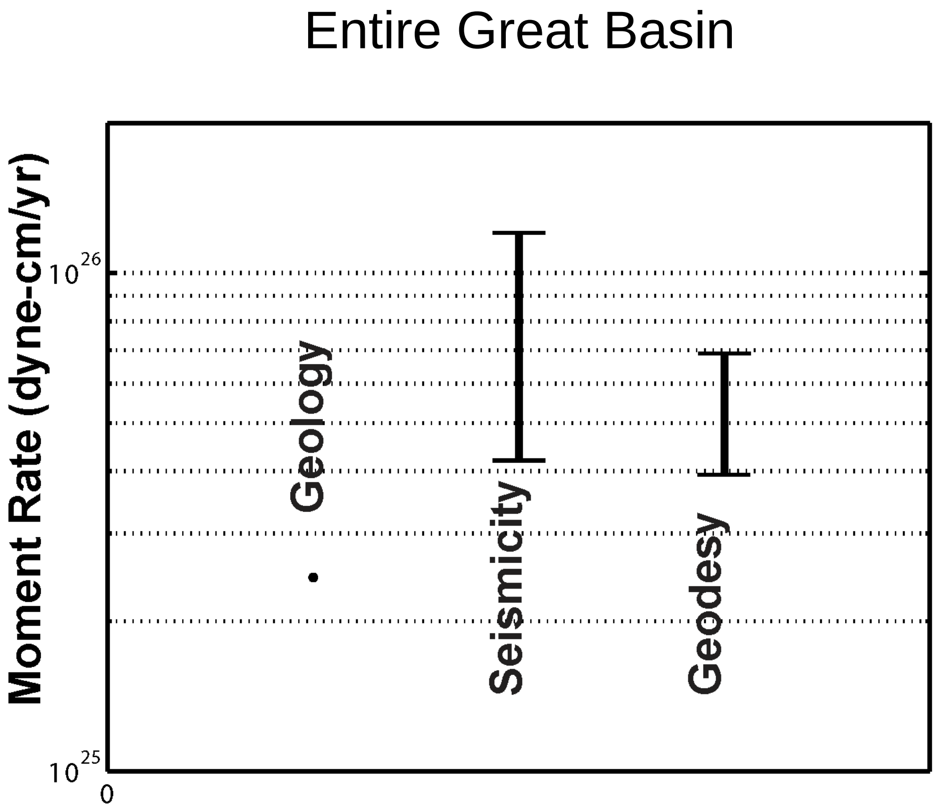


a)
1 mm/yr
200 km
44
42
40
38
36
Latitude
-124
-122
-120
-118
-116
-114
-112
-110
b)
1 mm/yr
up/down
/
200 km
44
42
40
38
36
Latitude
-124
-122
-120
-118
-116
-114
-112
-110
Longitude

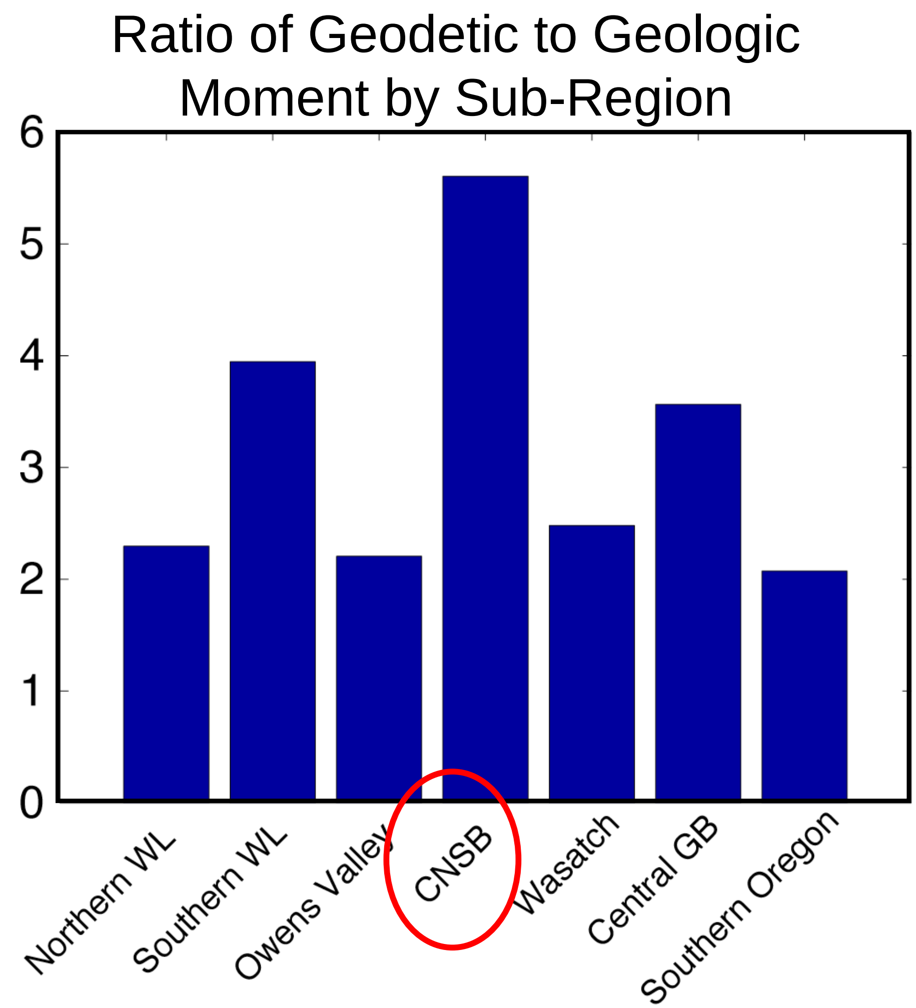


0 1 2 4 8 16 32 64 128 256
Total Strain Rate (10^{-9}/yr)
200 km
10 mm/yr
Latitude
Longitude
45 44 43 42 41 40 39 38 37 36 35 34
-123 -122 -121 -120 -119 -118 -117 -116 -115 -114 -113 -112 -111 -110

Geodesy Sees More Moment than Geology



Pancha et al., 2006



Source: Kreemer strain rate model
And USGS Quaternary fault database

Preliminary Recommendation: Use the data!

Short Term?

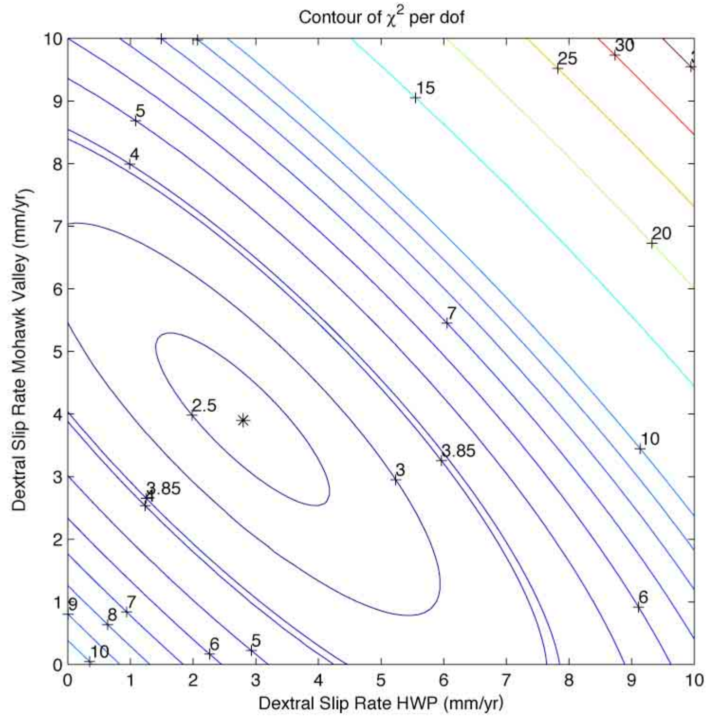
• Incorporate the Province kinematic boundary conditions as a constraint on the sum of slip rates.

Long Term Topics of Research

• A topic of research: Evaluate the added utility of using the entire geodetic dataset (strain map and/or velocity field) for use in PSHA maps.

• In specific instances (e.g. CNSB) employ physical models of lithospheric deformation to estimate time-variable seismic hazard, e.g. account for postseismic relaxation in the geodetic velocity field.


LEAVING THE GREAT BASIN



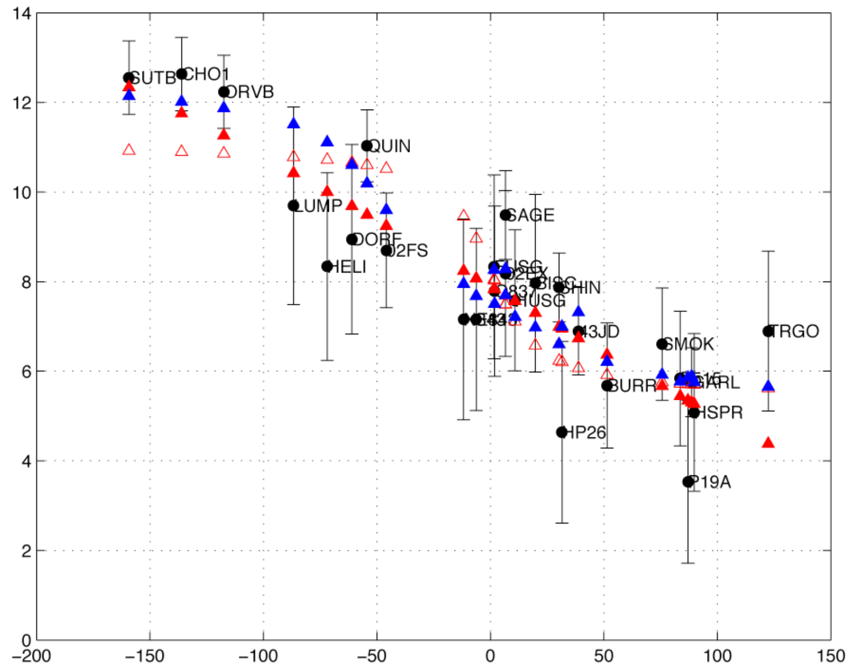
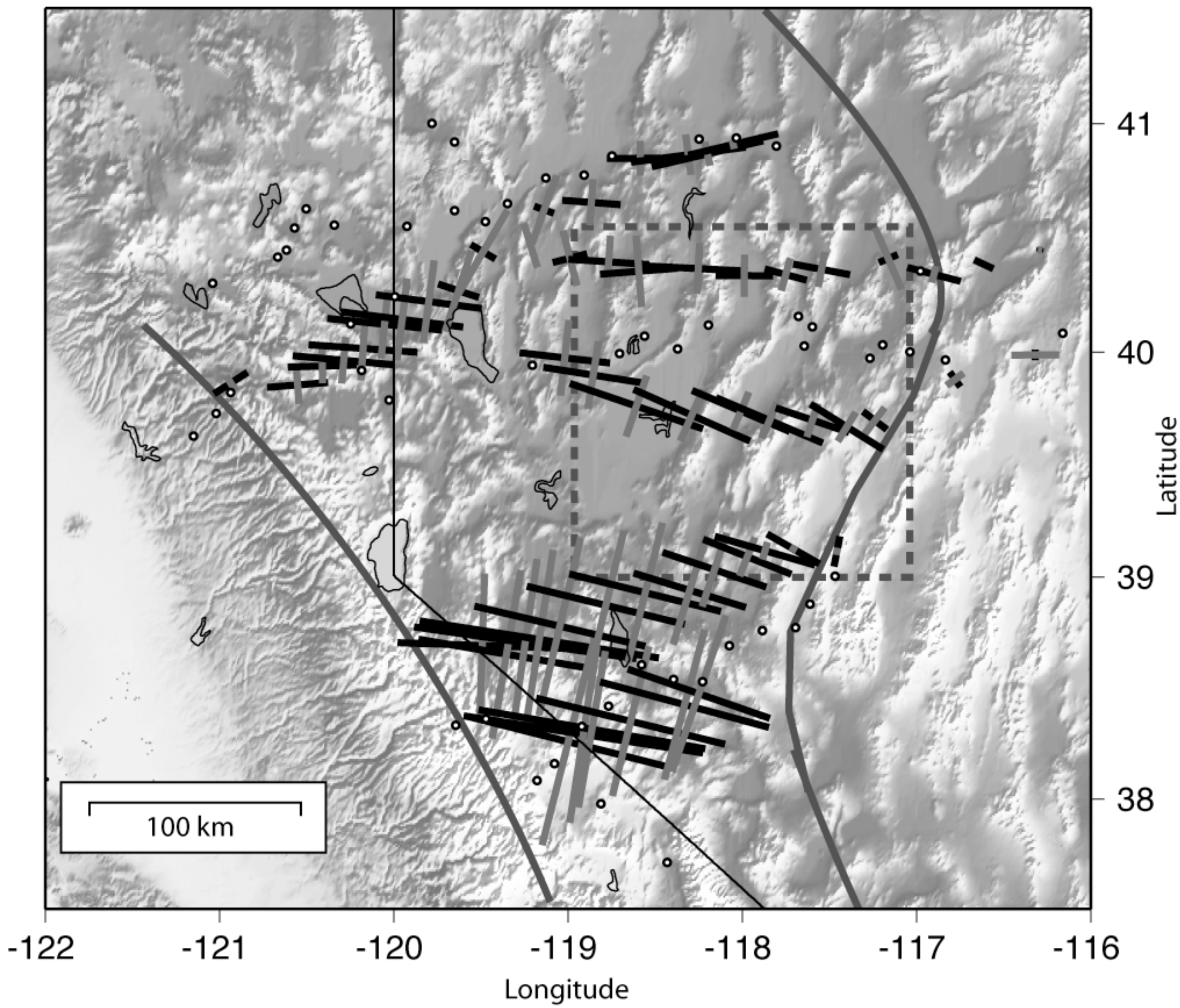
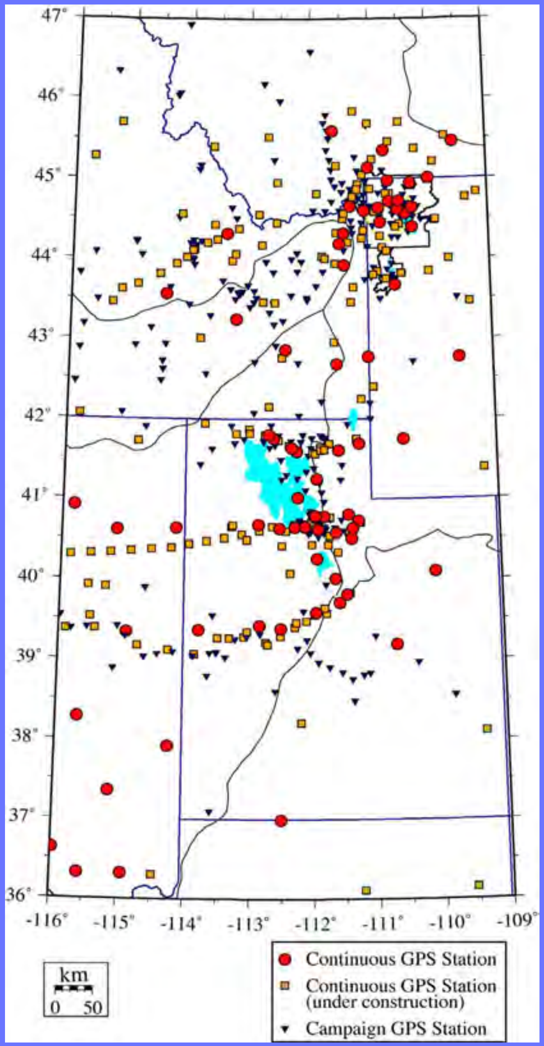


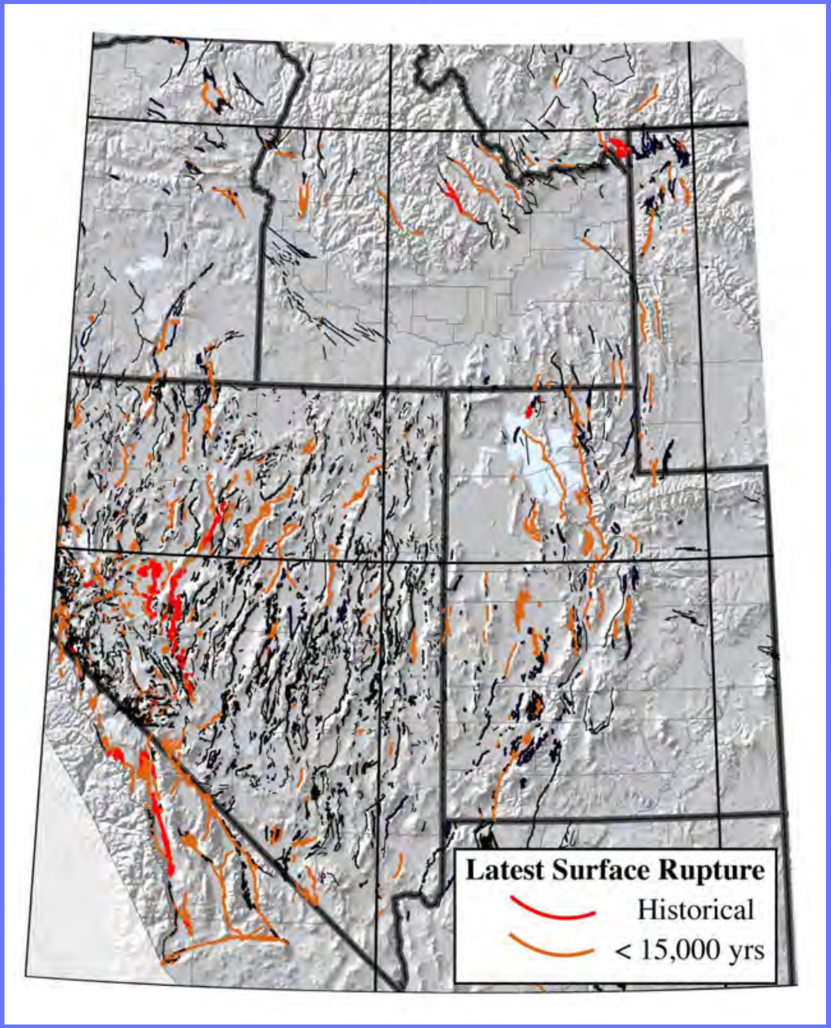
Figure 7: Hammond and Thatcher, 2006



100 km
41
40
39
38
Latitude
-122
-121
-120
-119
-118
-117
-116
Longitude

Integrated Earthquake Hazard Assessment
Eastern Basin-Range

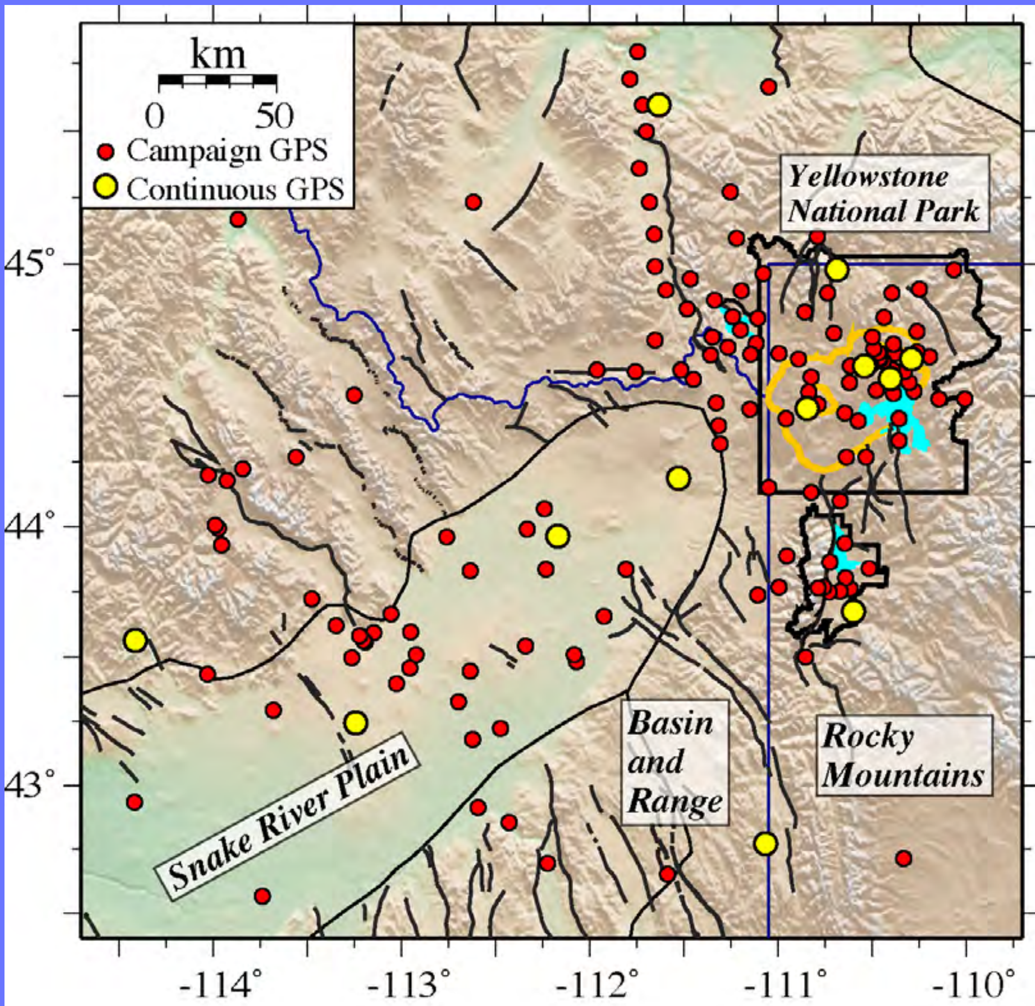




- Permanent GPS in blue and red including in-process construction PBO sites (~100) including the *Hebgen Lake, Borah Peak and Wasatch fault* arrays (UU, PBO, INEL, other agencies).
- Campaign GPS stations (UU, INEL, etc.) in green (~250)

R. B. Smith and W. Chang,
Department of Geology and Geophysics
University of Utah

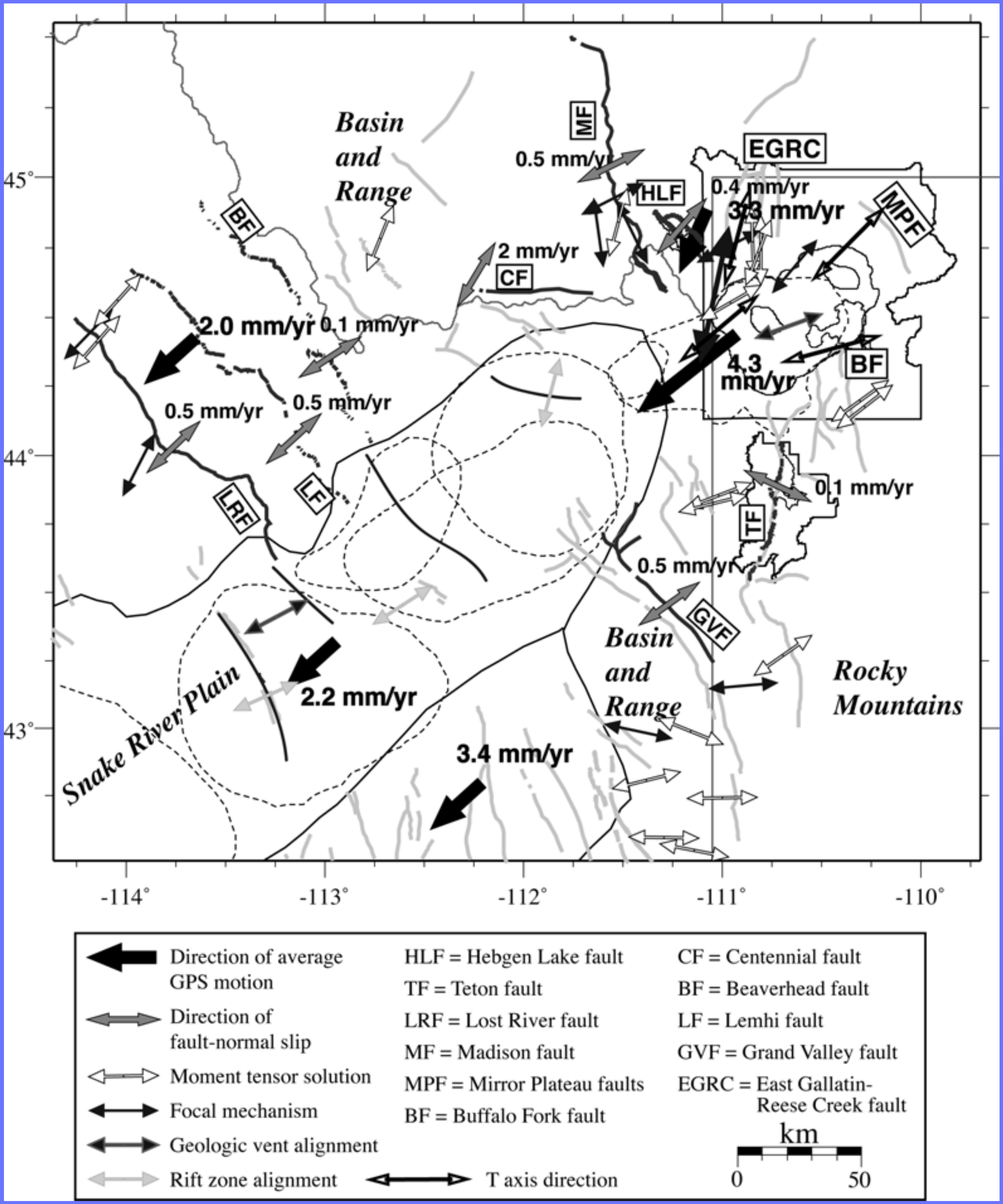
University of Utah Yellowstone-SRP-N. Basin-Range GPS Network



- GPS campaigns
  - Campaigns in 1987, 1989, 1991, 1993, 1995, 2000, 2003
  - 150 sites
- Continuous GPS (CGPS) network
  - Operation began in 1996
  - Presently has 21 stations
  - Station velocity precision < 1 mm/yr
- Campaign network covers more area, but continuous solutions are more precise

Puskas et al. 2006

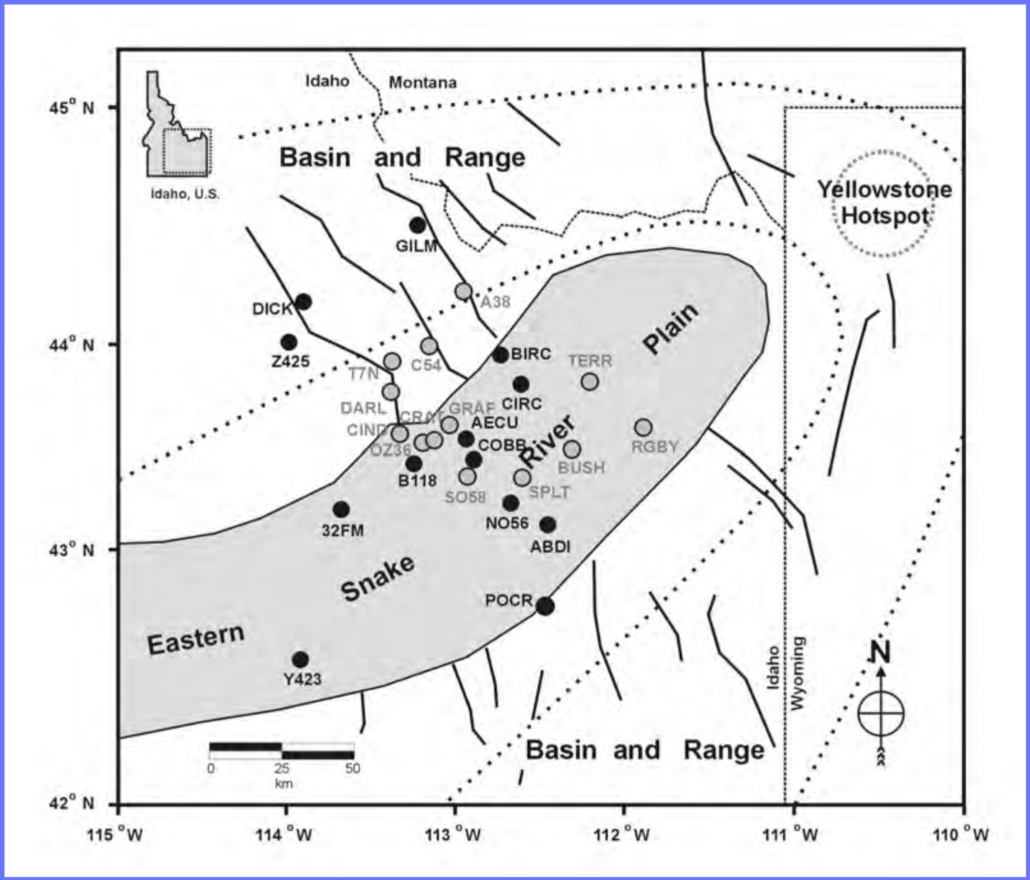
Summary map of GPS-measured deformation rates, horizontal fault slip rates, and minimum principal stress indicators.

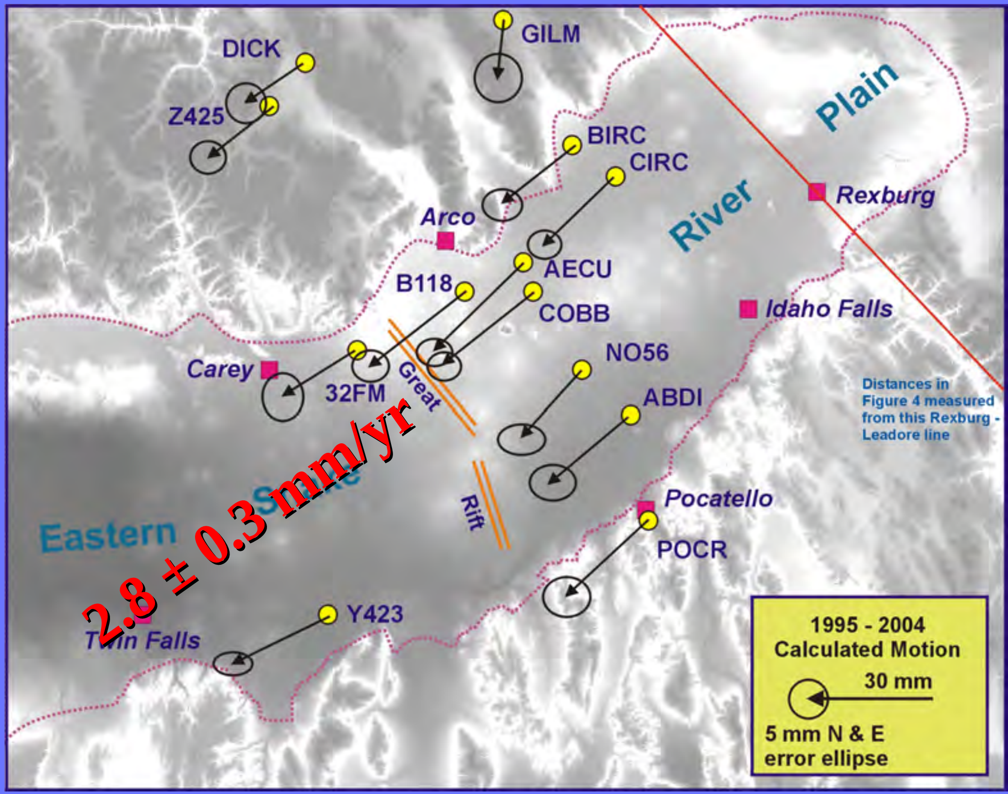


- Yellowstone caldera: avg SW extension at 4.4 ± 0.5 mm/yr from campaign GPS
- Snake River Plain: avg SW extension at 2.2 ± 0.4 mm/yr from campaign GPS and 2.1 ± 0.2 mm/yr from CGPS
- Adjacent Basin-Range faults have similar deformation rates to SRP

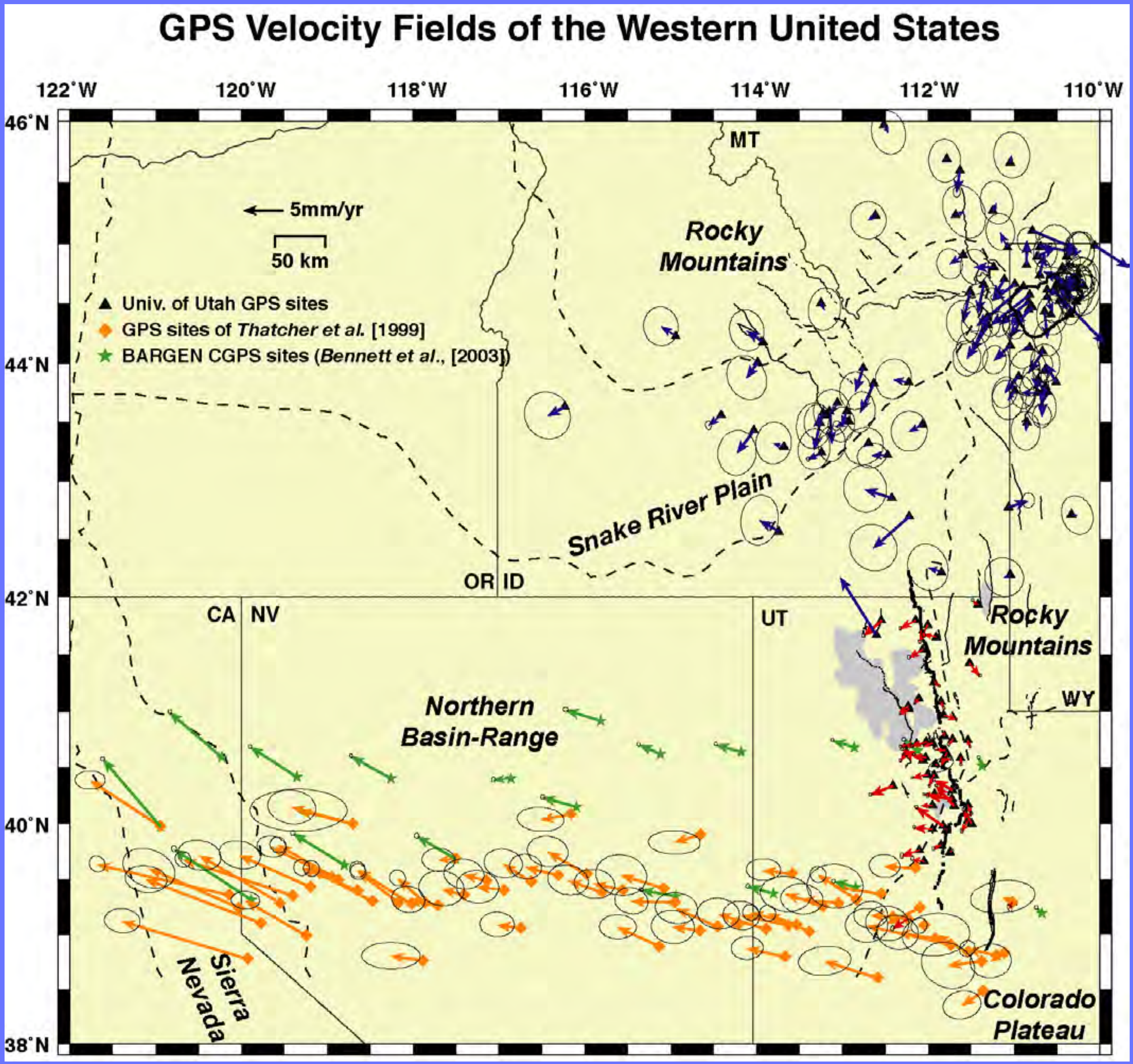
Puskas et al. 2006

1995-2004 SRP and N. BR Results
INEL sponsored (Chadwick et al., 2006)





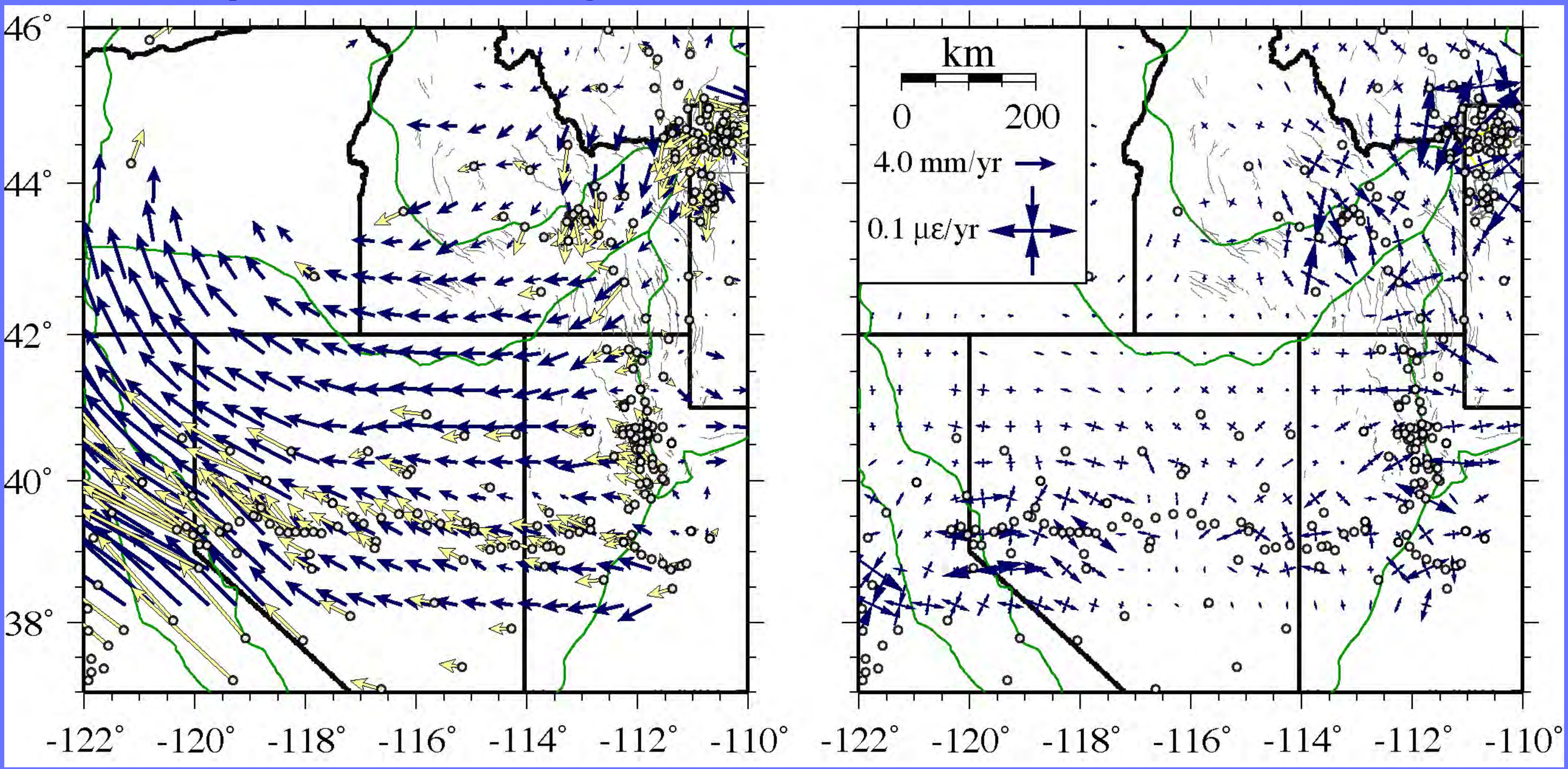
Chadwick et al. 2006



Data from Univ of Utah, BARGEN and USGS

Puskas et al. 2006

Northern Basin and Range-YSRP Deformation



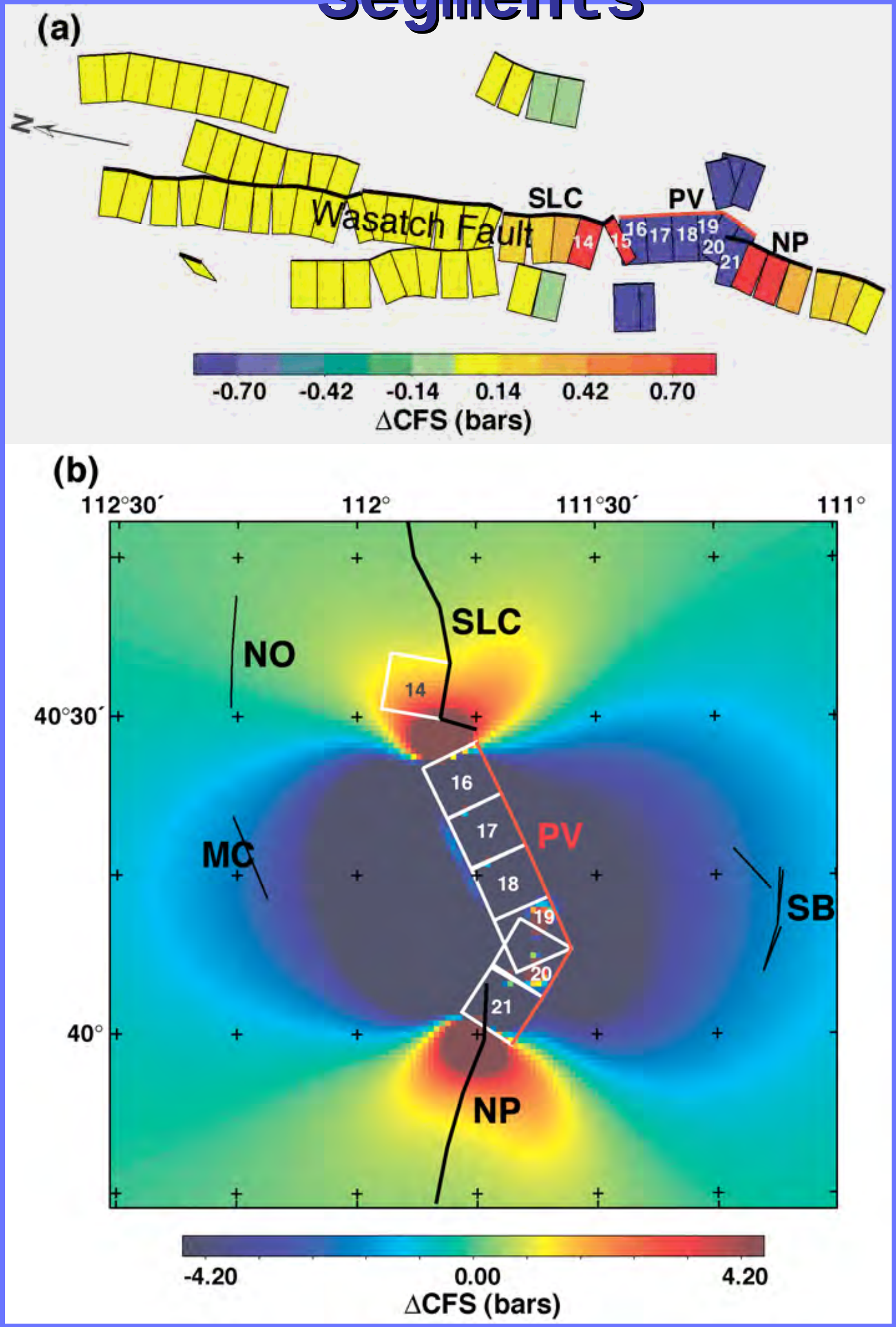
- Yellowstone Plateau: 4.4 mm/yr
- N. BR and YSRP: 2.5 mm/yr
- Wasatch Front: 2 mm/yr
- West Nevada: 13 mm/yr

- Strain is concentrated at Yellowstone, the Wasatch Front, western Nevada

- Yellowstone Plateau: 0.06 x 10^{-6} /yr
- Wasatch Front: 0.05 x 10^{-6} /yr
- West Nevada: 0.09 x 10^{-6} /yr

Puskas et al. 2006

Contagion of Wasatch Fault Segments

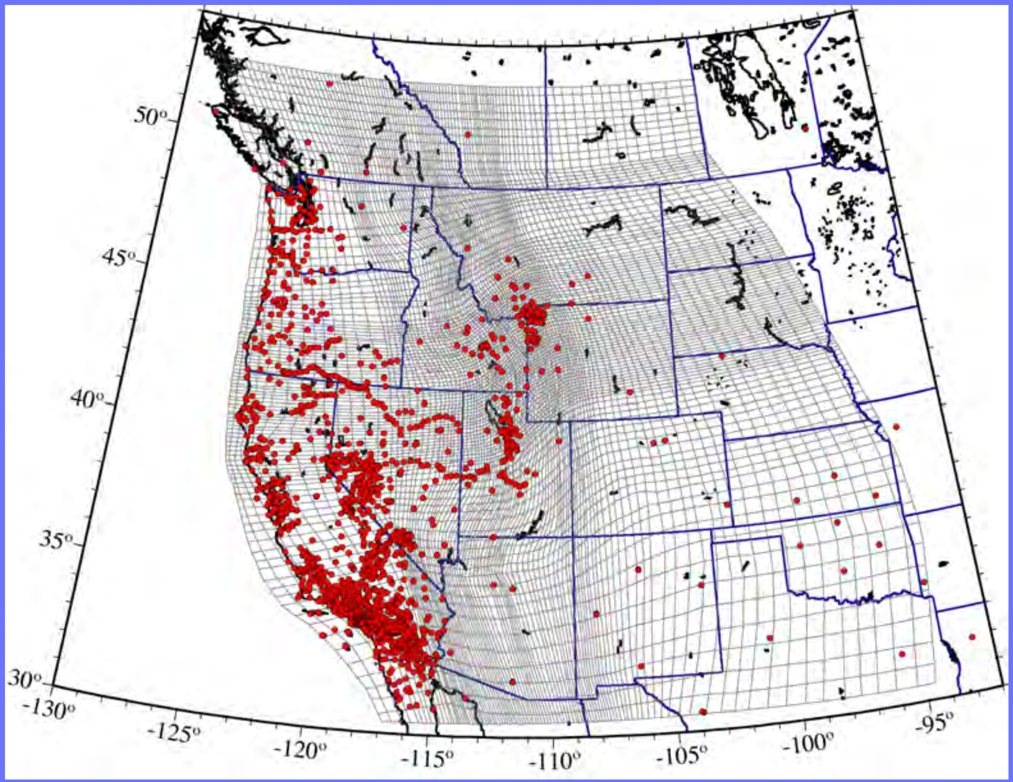


An earthquake on the Provo segment (PV and blue) increases the stress on the Salt Lake segment.

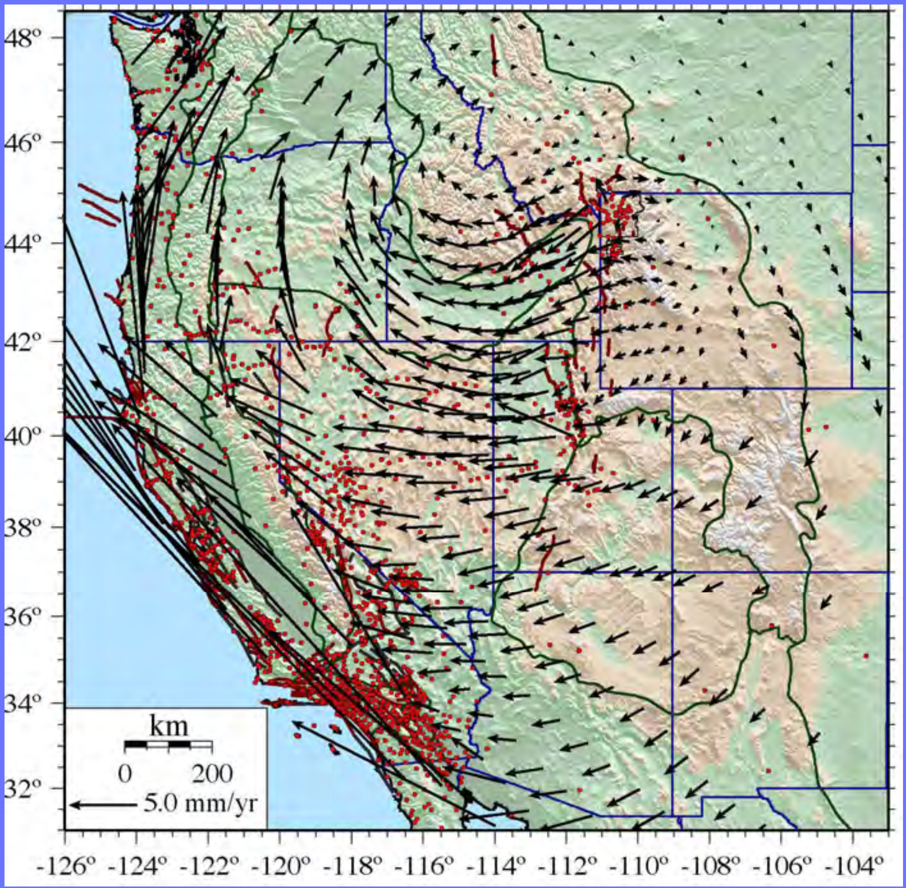
A large earthquake on the Provo segment can increase the failure stress of the Salt Lake City segment (SLC) that *in turn can advance the time of the next SLC segment rupture*

Kinematic Deformation of western US

Map of GPS Stations



Regional GPS Velocity Field

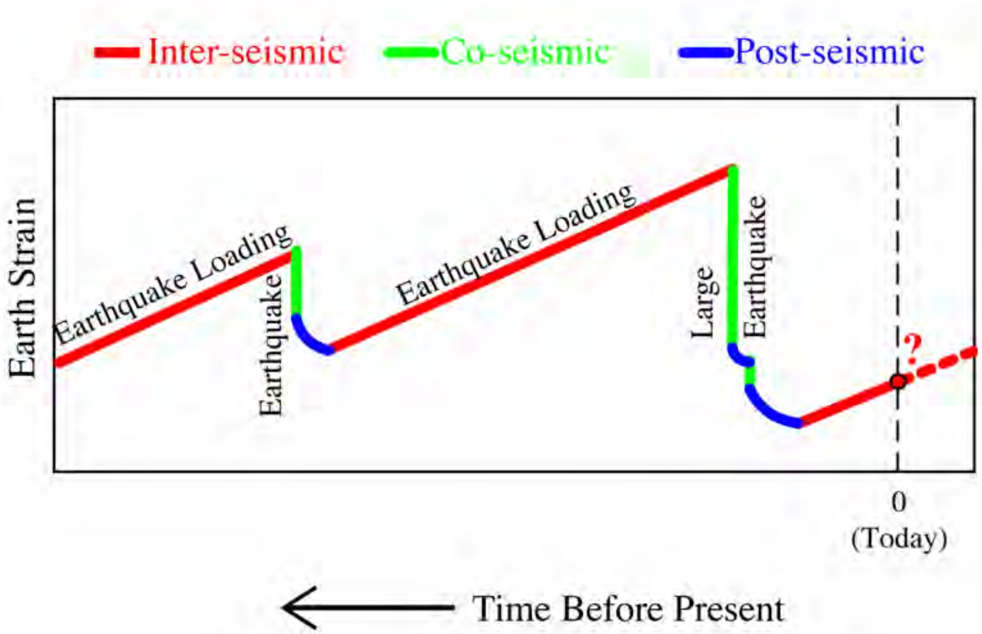


- GPS data can be used as proxy for fault slip or moment rates in areas of unknown fault rates

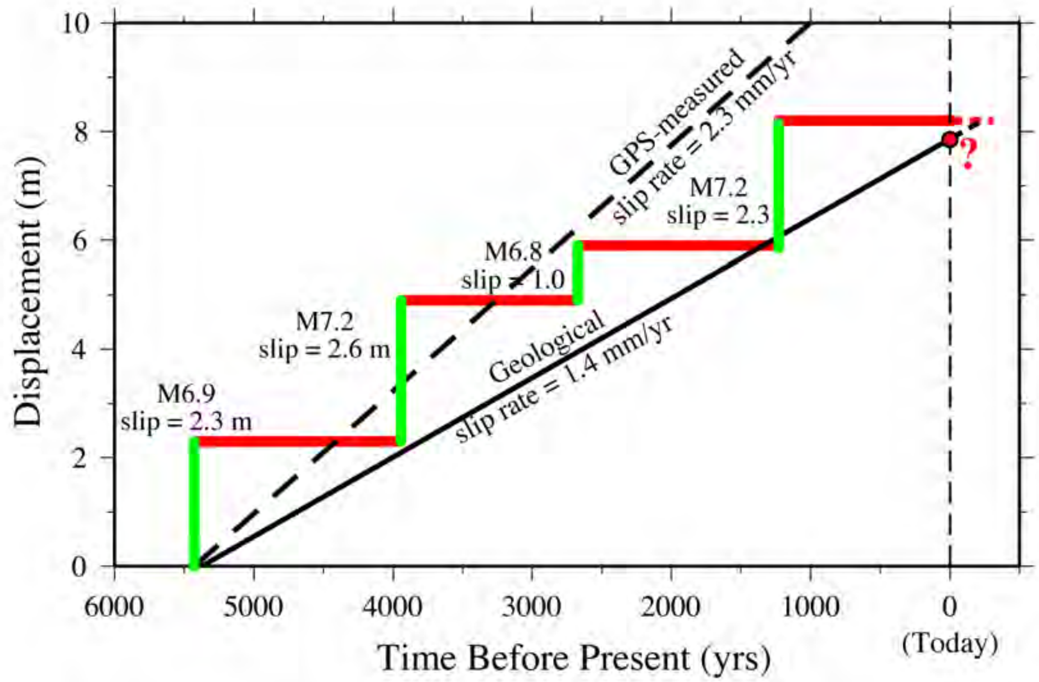
Puskas et al. 2006

Earthquake Cycle

History of earthquakes and earthquake loading



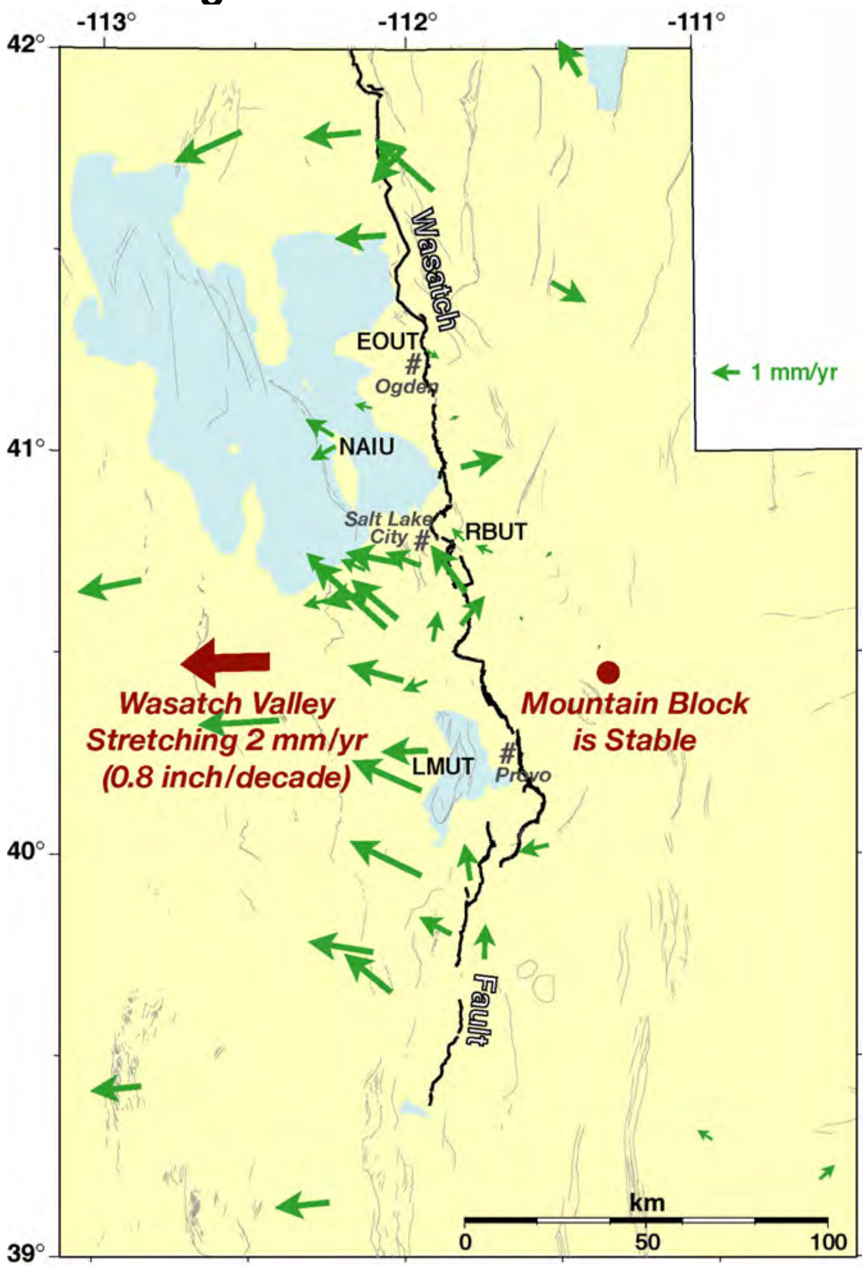
Wasatch fault earthquake history

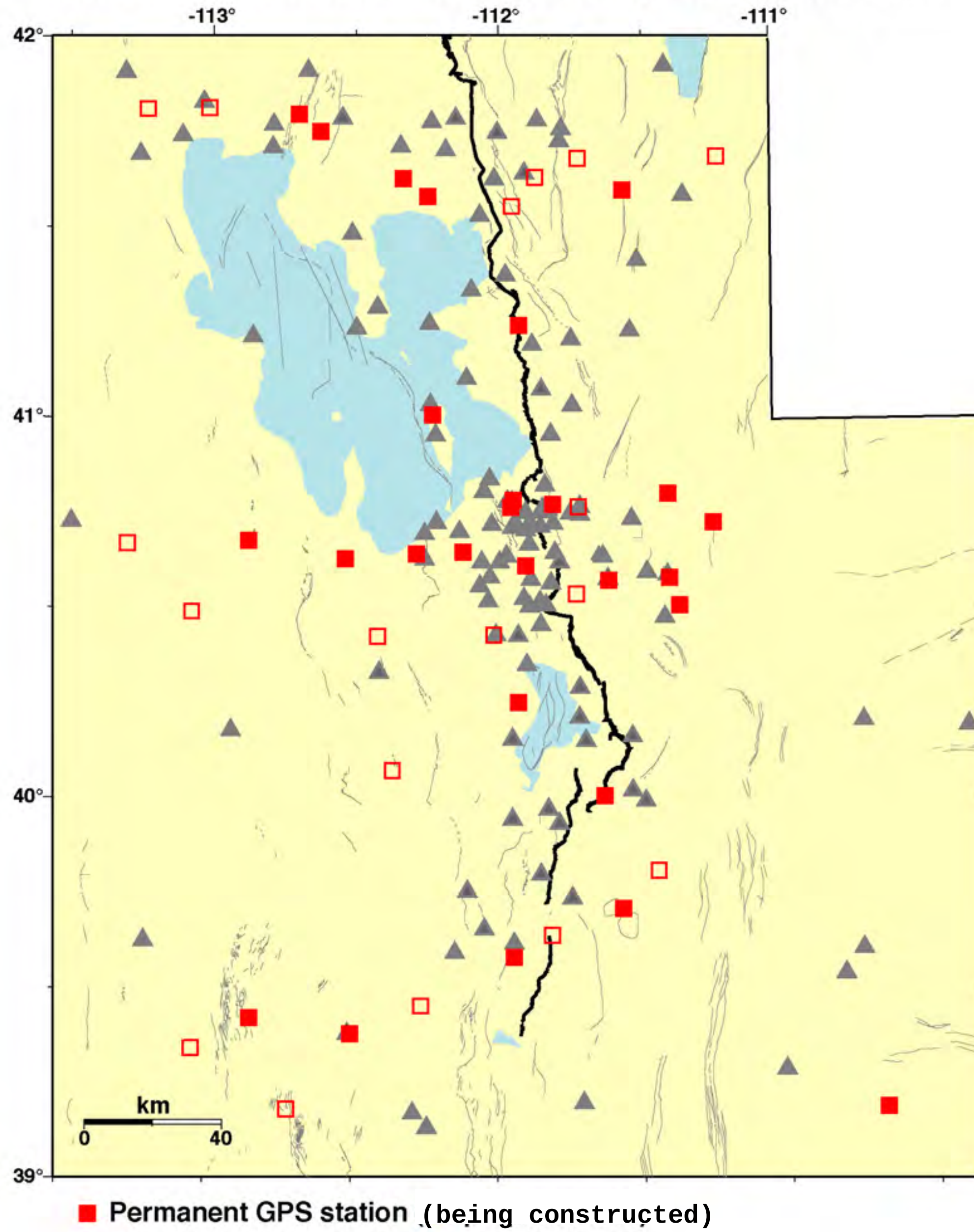


GPS measures interseismic loading rate that is taken as proxy for geologically determined fault slip rate.

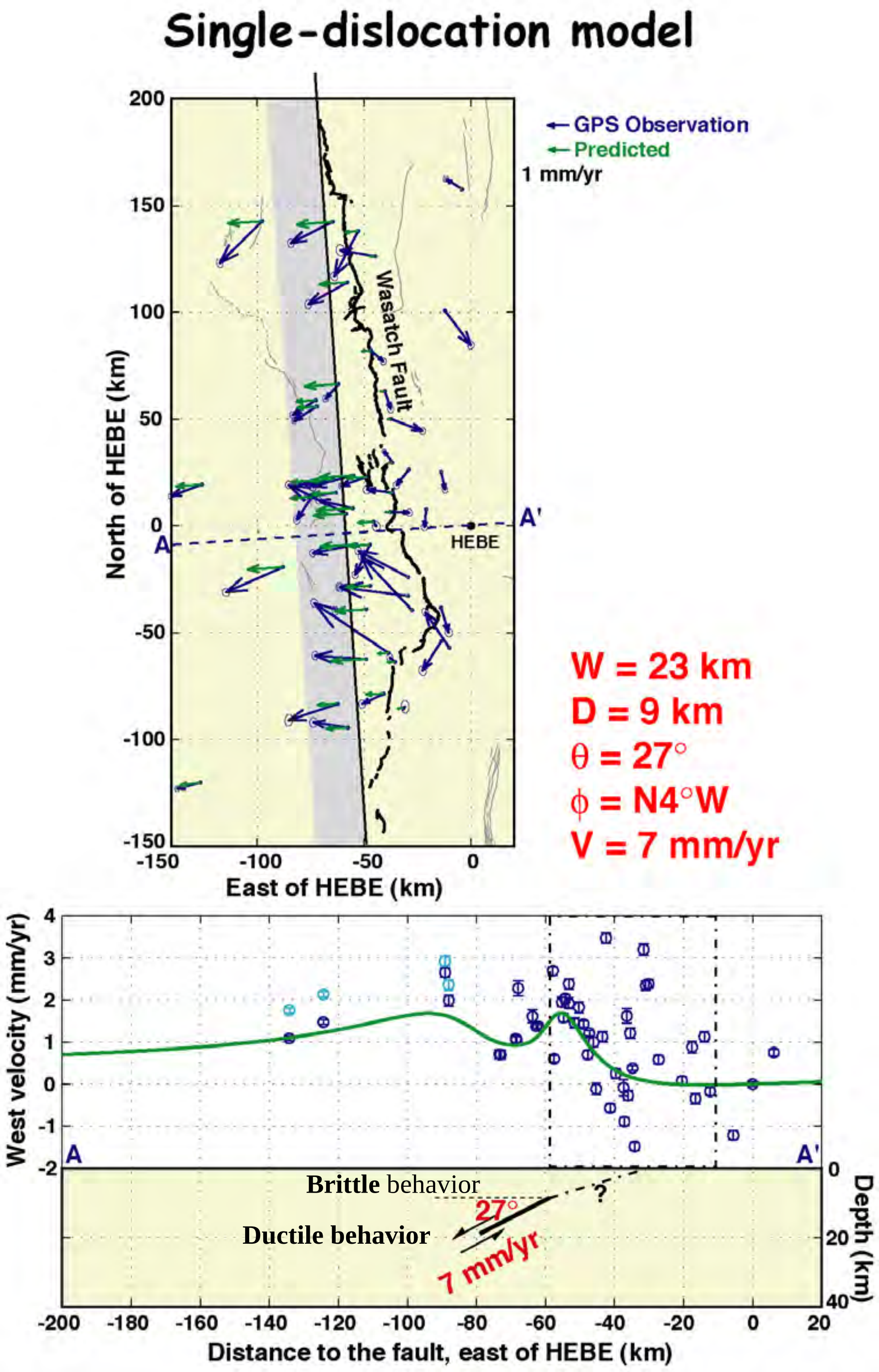
Utah GPS determined deformation, 1992-2005

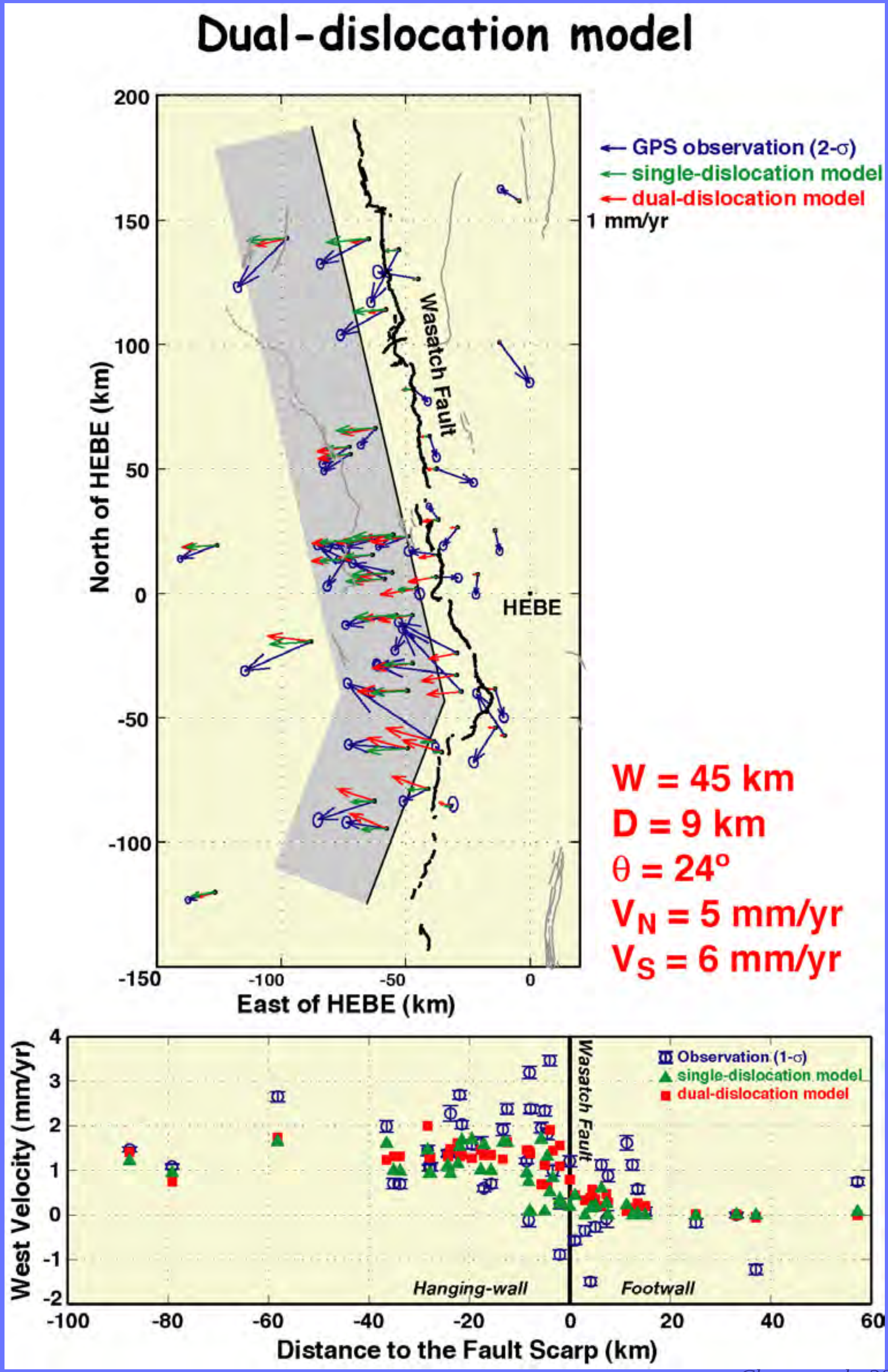
Contemporaneous Wasatch Fault Loading Rates





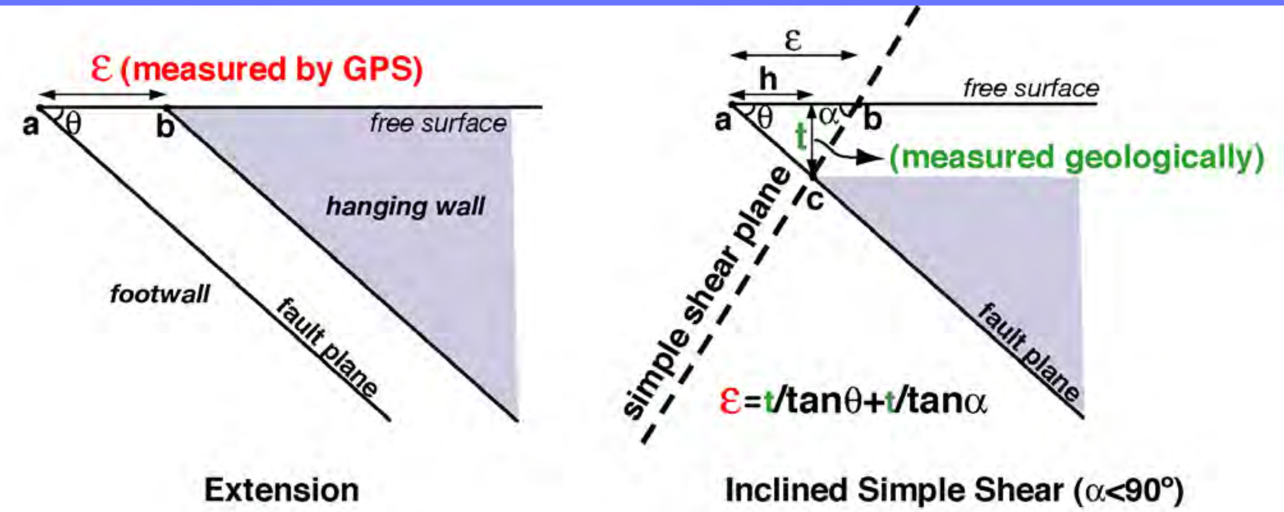
Chang et al., 2006





Chang et al., 2006

Finite strain fault model



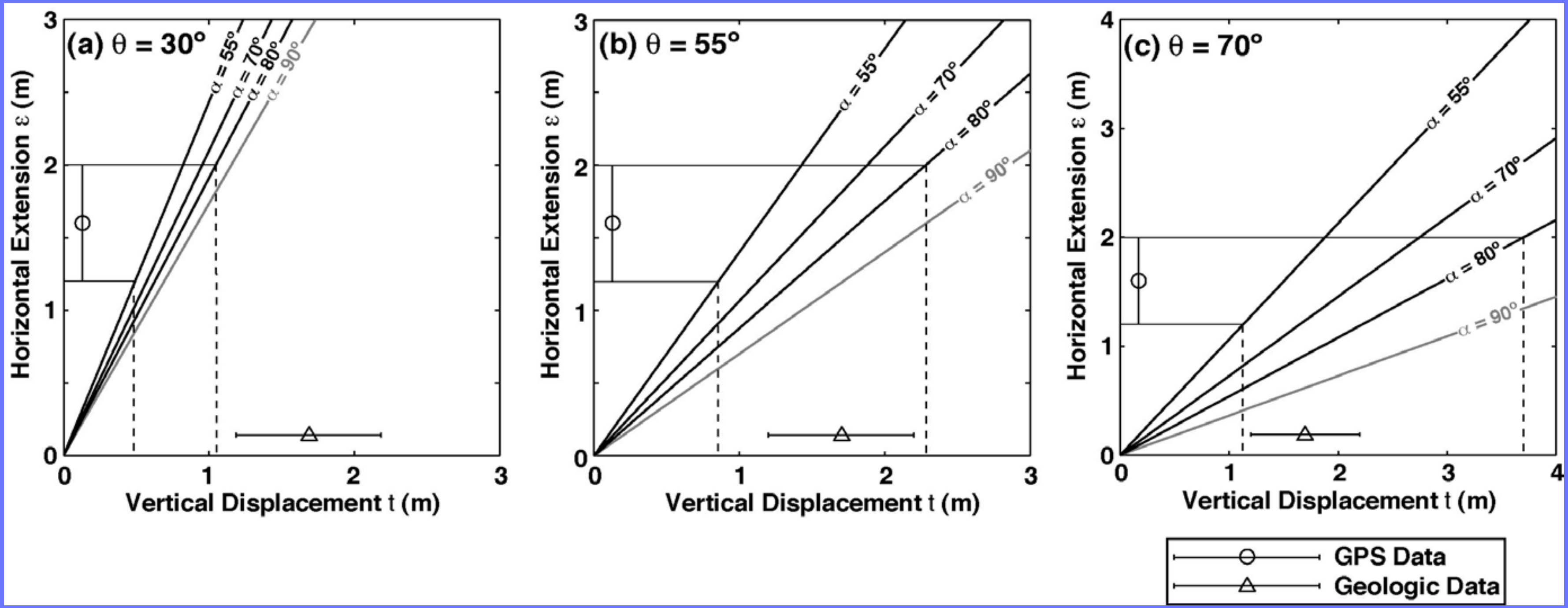
Horizontal Extension = Vertical Displacement × (1/tanθ + tanα)

Fault plane dip θ	Simple-shear plane dip α	Geologic rate (mm/yr)	Estimated horizontal extension rate (mm/yr)	Comparing to observed GPS-rate of 1.6±0.4 mm/yr
55°W	55°E ~ 80°E	1.7 ± 0.5	2.4 ~ 1.5	comparable
30°W	55°E	1.7 ± 0.5	4.4	geologic > geodetic (Holocene clustering?)
70°W	80°E	1.7 ± 0.5	0.9	geologic < geodetic (current fast loading?)

Simple-Shear Model for Converting Geologic Vertical Displacement To Geodetic Horizontal Extension for Normal Fault

Chang et al. 2006

Slip rates are model dependent



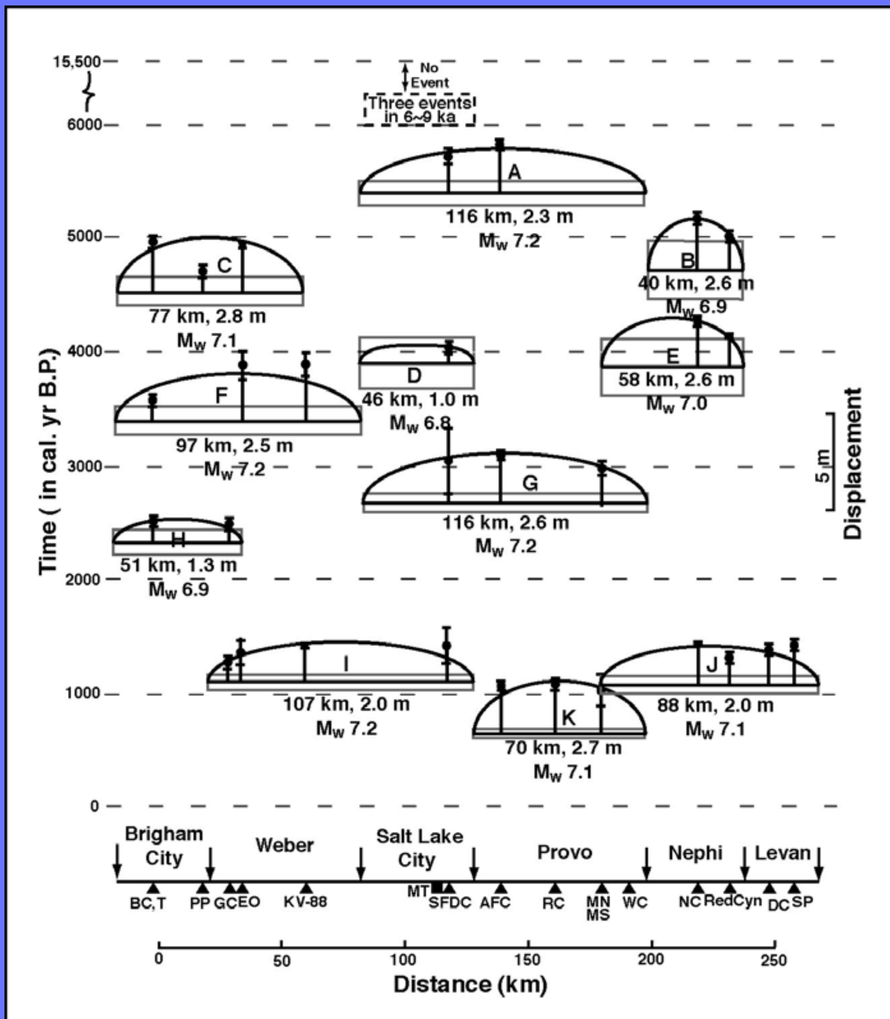
Comparison of Deformation Rates Across the Wasatch Fault From GPS and Geologic Determinations

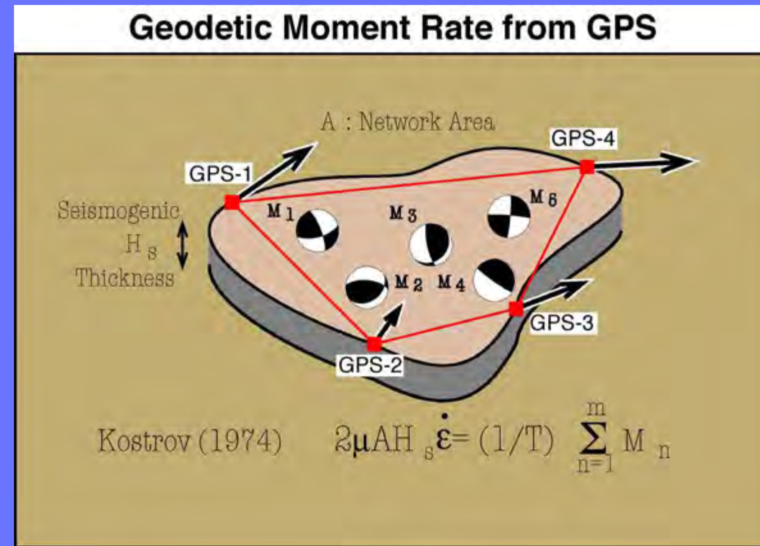
Dip of the Wasatch Fault	Dip of Simple-Shear Plane (Antithetic Fault)	Vertical Displacement Rate from GPS Data, mm/yr	Geologic Fault Slip Rate (0-10 ka), mm/yr	Comparison of GPS Rate with Geologic Rate
θ = 30°	**α = 55°E-80°E**	0.5 - 1.0	1.7 ± 0.5	**GPS < Geologic**
	α = 90°	0.7 - 1.2	1.7 ± 0.5	**GPS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

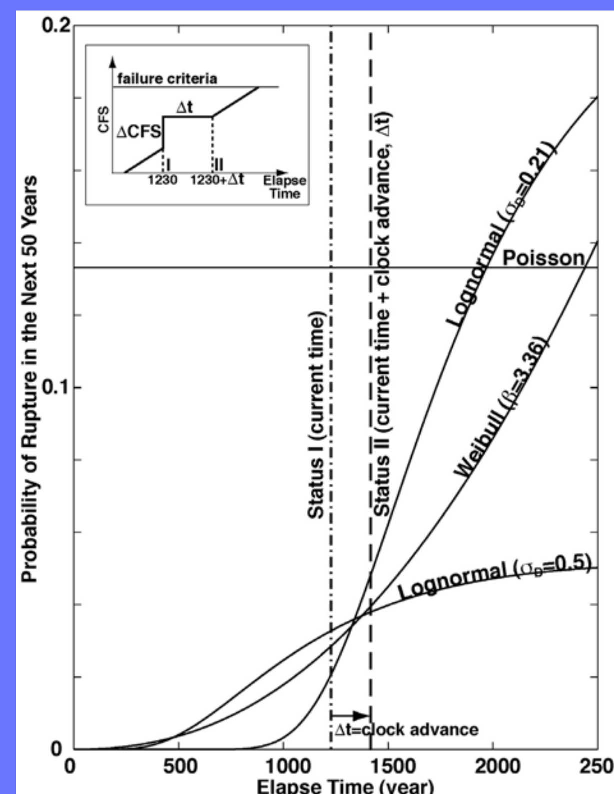
Chang et al., 2006

Components of an integrated PSHA

Multi-segment Model







Chang and Smith [2002]

Integration of Various Types of Earthquake Source Information Into A Probabilistic Seismic Hazard Assessment

Source Type	Name of Fault or Fault Segment	Recurrence Model
Type A	BC, WB, SLC, PV, NP (Wasatch Fault).	Characteristic Model (from paleoseismic data): Lognormal distribution (σ_D=0.21 or 0.5)
Type B	LV (Wasatch Fault), EC, HV, NO, SB, MC, EGSL, EBL, BR, RC.	Characteristic Model (from fault slip rate)[1]: $\dot{M}_{seismic} = \mu LWV$; $M(m_u) = 10^{1.5m_u+9}$; $N_B = \frac{\dot{M}_{seismic}}{M(m_u)}$

$$\dot{M}_{seismic} = \mu LWV$$
$$N_C(6.6) = \frac{\dot{M}_{seismic}}{C_d(6.6, m_u)},\ \mathrm{b} = 0.76$$

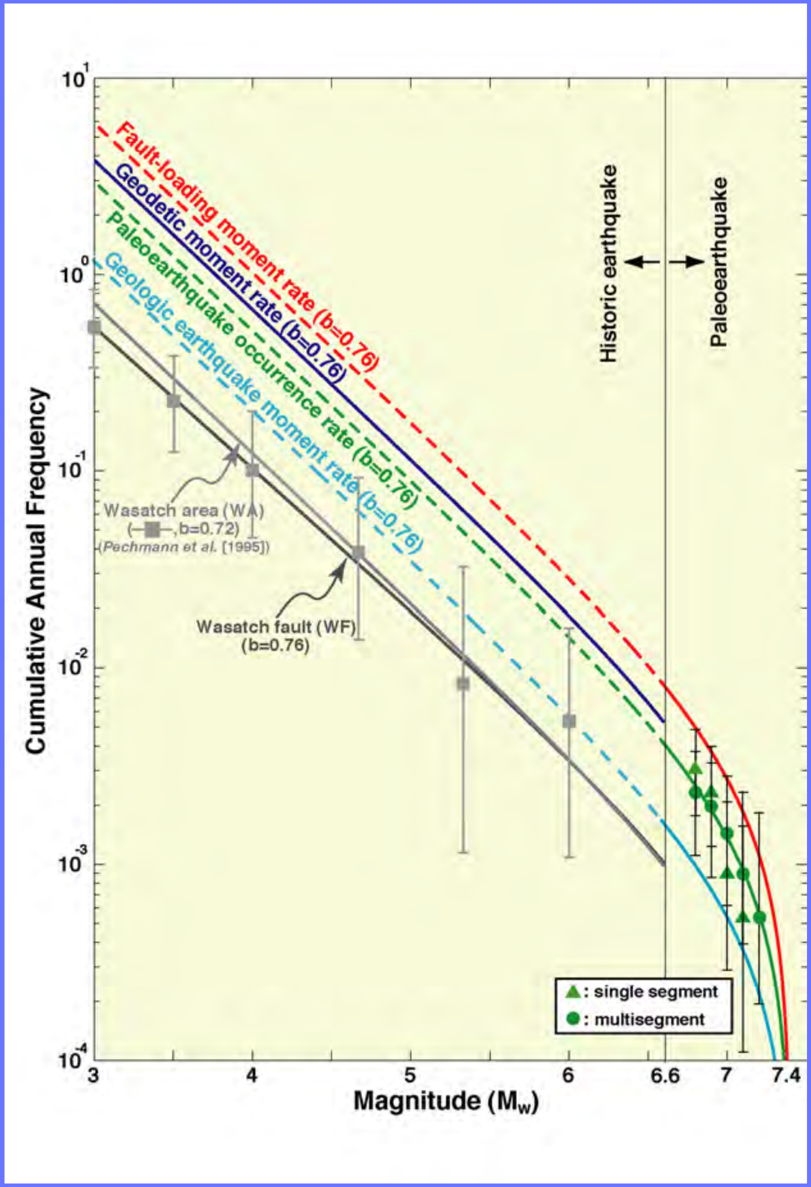
$$\dot{M}_{seismic} = 2\mu HLW\dot{\varepsilon} - \mu LWV$$
$$N_C(3.0) = \frac{\dot{M}_{seismic}}{C_d(3.0, m_u)},\ \mathrm{b} = 0.76$$

$\dot{M}_{seismic}$, seismic moment rate; $M(m)$, seismic moment of magnitude m; μ, rigidity.

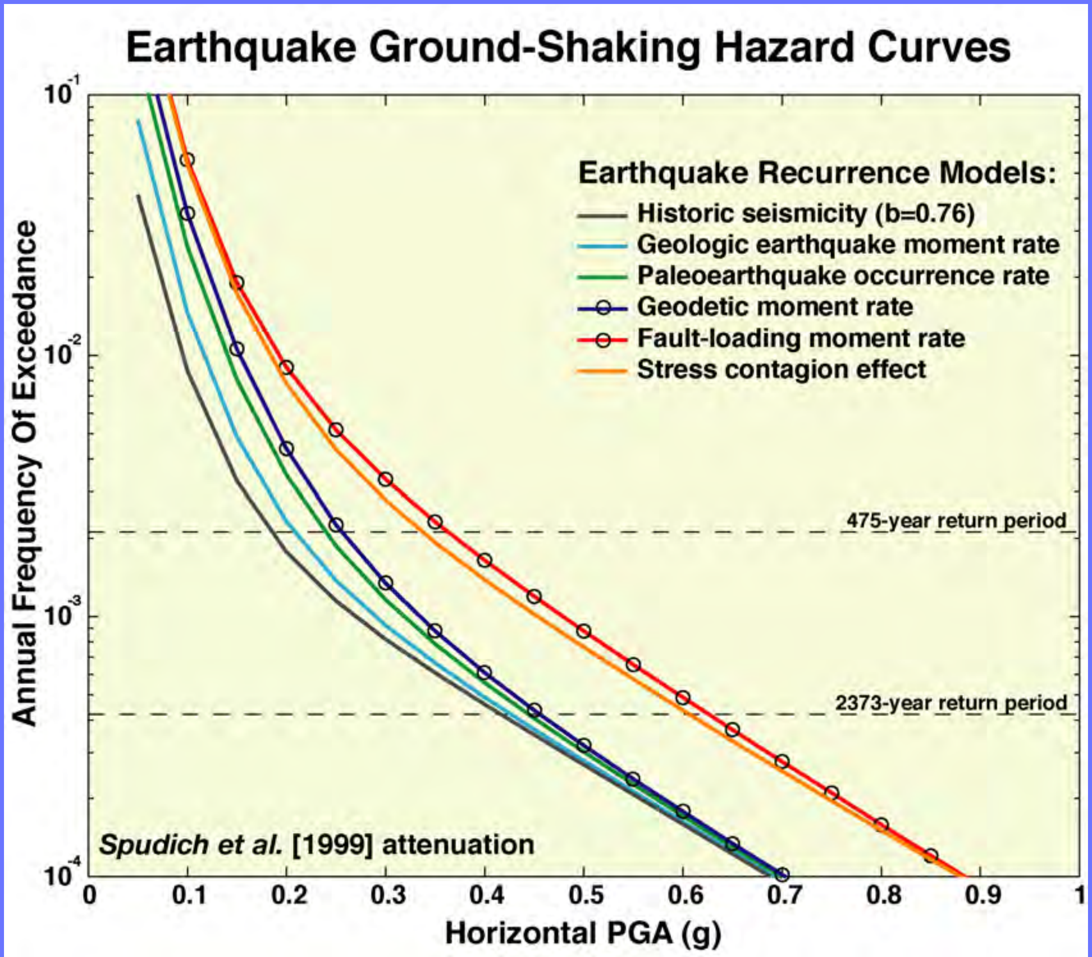
Chang and Smith [2002]

Integrated PSHA

Frequency of Occurrence



Hazard



Chang and Smith [2002]

Some BRPEWG questions for 2006 Hazard Maps

How to incorporate GPS as equivalent *moment* rate, *slip* rate, etc.?

Slip-rates are *model* dependent and that is an even broader question.

How do we implement GPS rates that differ from geologic rates?

What weight for contemporaneous geodetically determined rates, i.e. which time periods count most?

Balance of geologic with geodetic moment rates?

Use of GPS rates in areas of sparse geologic data.

How will GPS rates be explicitly used in the 2006 maps:

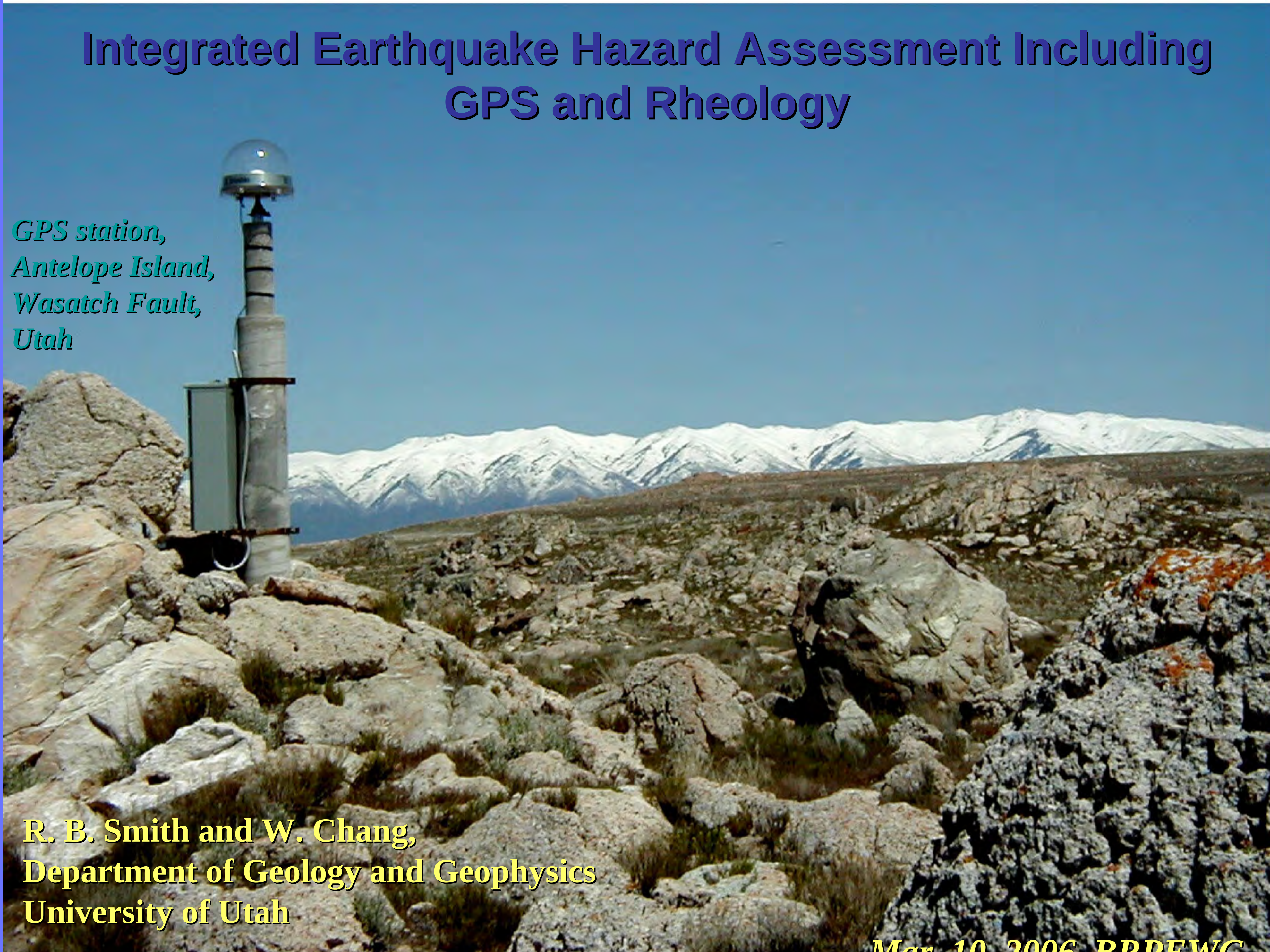
1. PSHA and PDHA
2. Time dependent models and in conditional probabilities
3. Time dependent stress-interaction models.

Implicitly, earthquake time-dependent models require viscoelastic rheology. How do we determine rheology for the Basin-Range?

Need for a community model for B-R faulting and deformation rates.

end

Integrated Earthquake Hazard Assessment Including GPS and Rheology



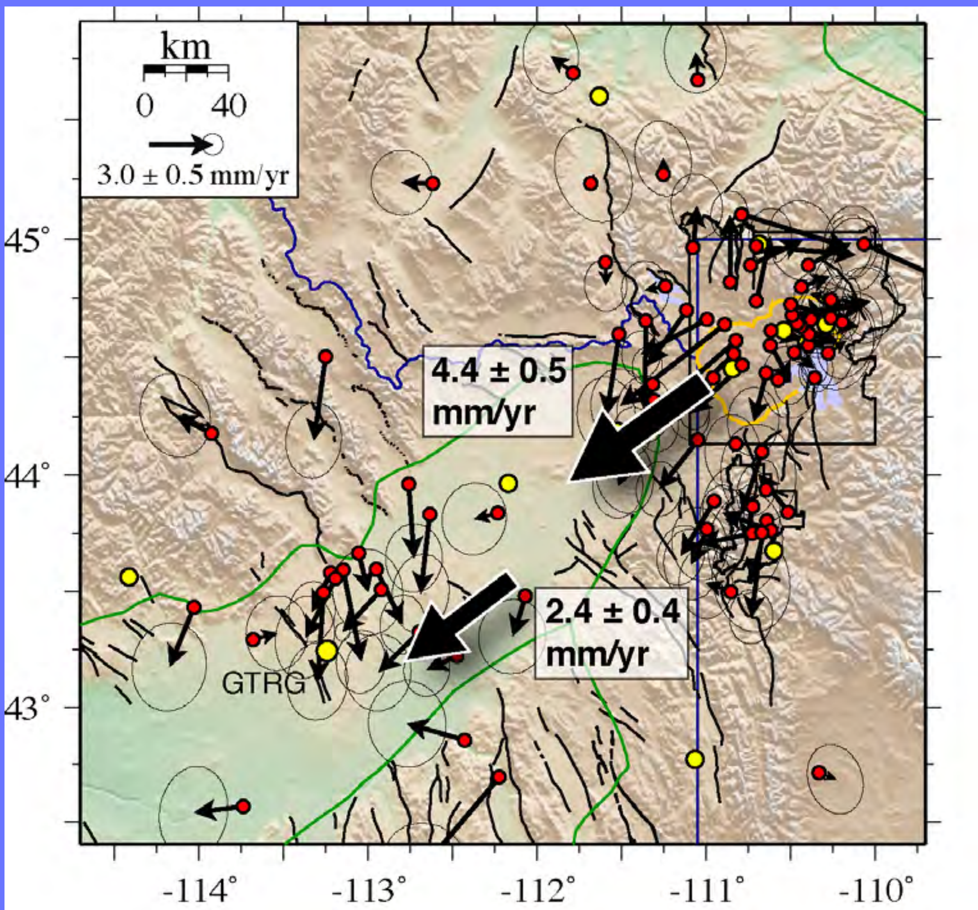
GPS station, Antelope Island, Wasatch Fault, Utah

R. B. Smith and W. Chang,
Department of Geology and Geophysics
University of Utah

Mar. 10, 2006, BRPEWG

YSRP-NBR Velocities from GPS

Campaign GPS Velocities (1995-2000)

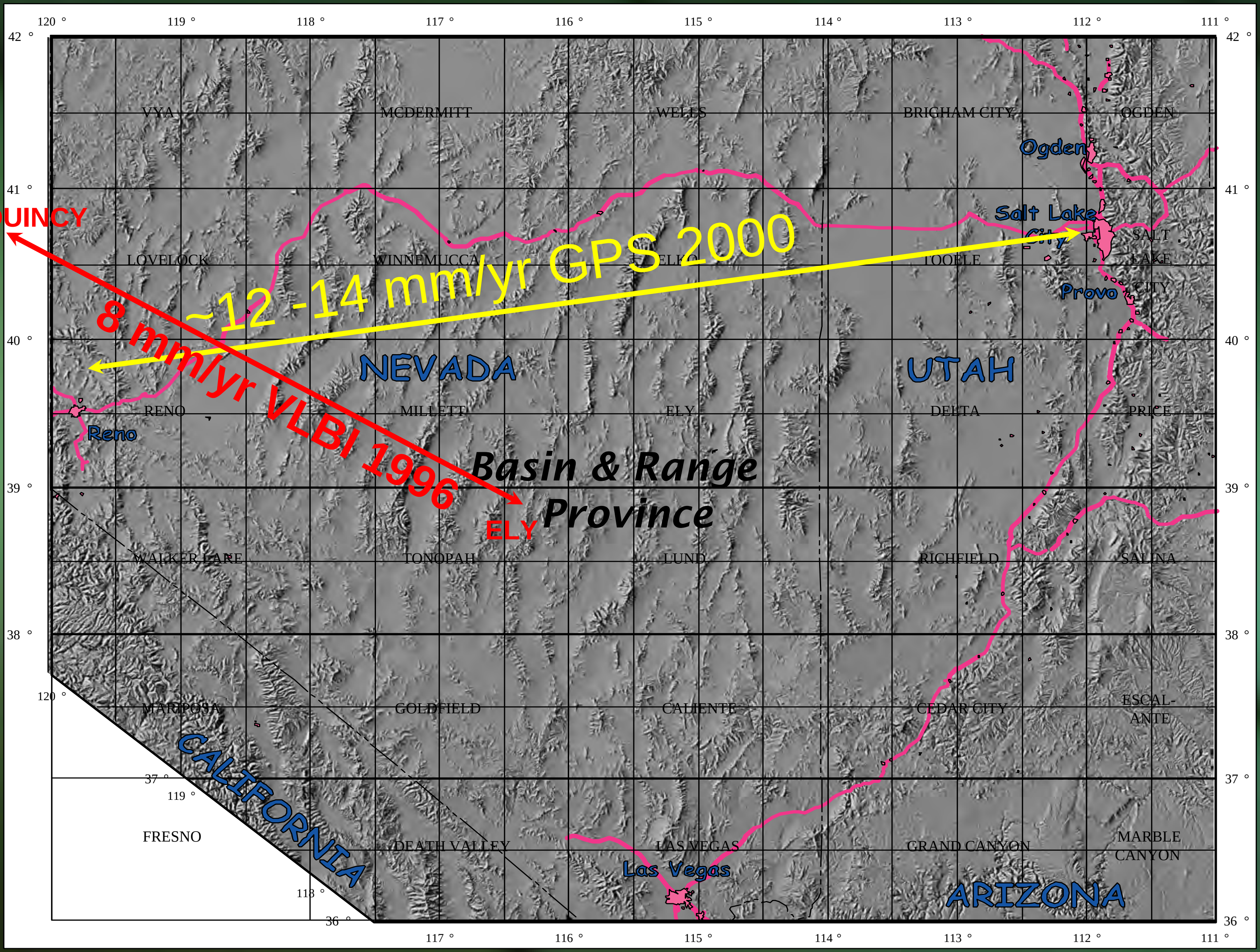


- Yellowstone caldera: avg SW extension at 4.4 ± 0.5 mm/yr from campaign GPS
- Snake River Plain: avg SW extension at 2.4 ± 0.4 mm/yr from campaign GPS and 2.1 ± 0.2 mm/yr from CGPS
- Adjacent Basin-Range faults deformation have similar deformation rates to SRP

Puskas et al. 2006

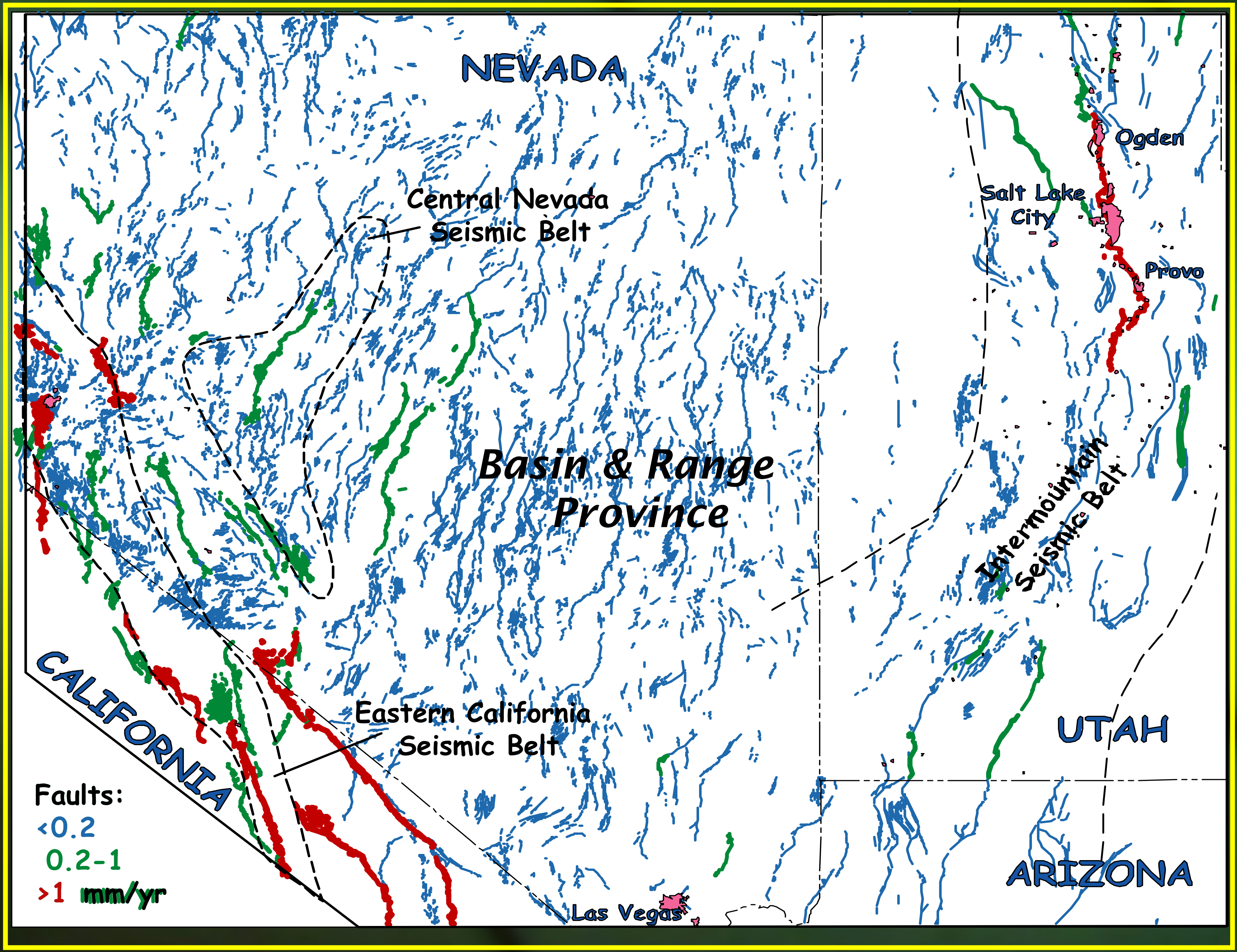
Geodetic/Geologic Slip Rates & Hazard Maps for B&R

Sierra Nevada-Colorado Plateau Relative Motion



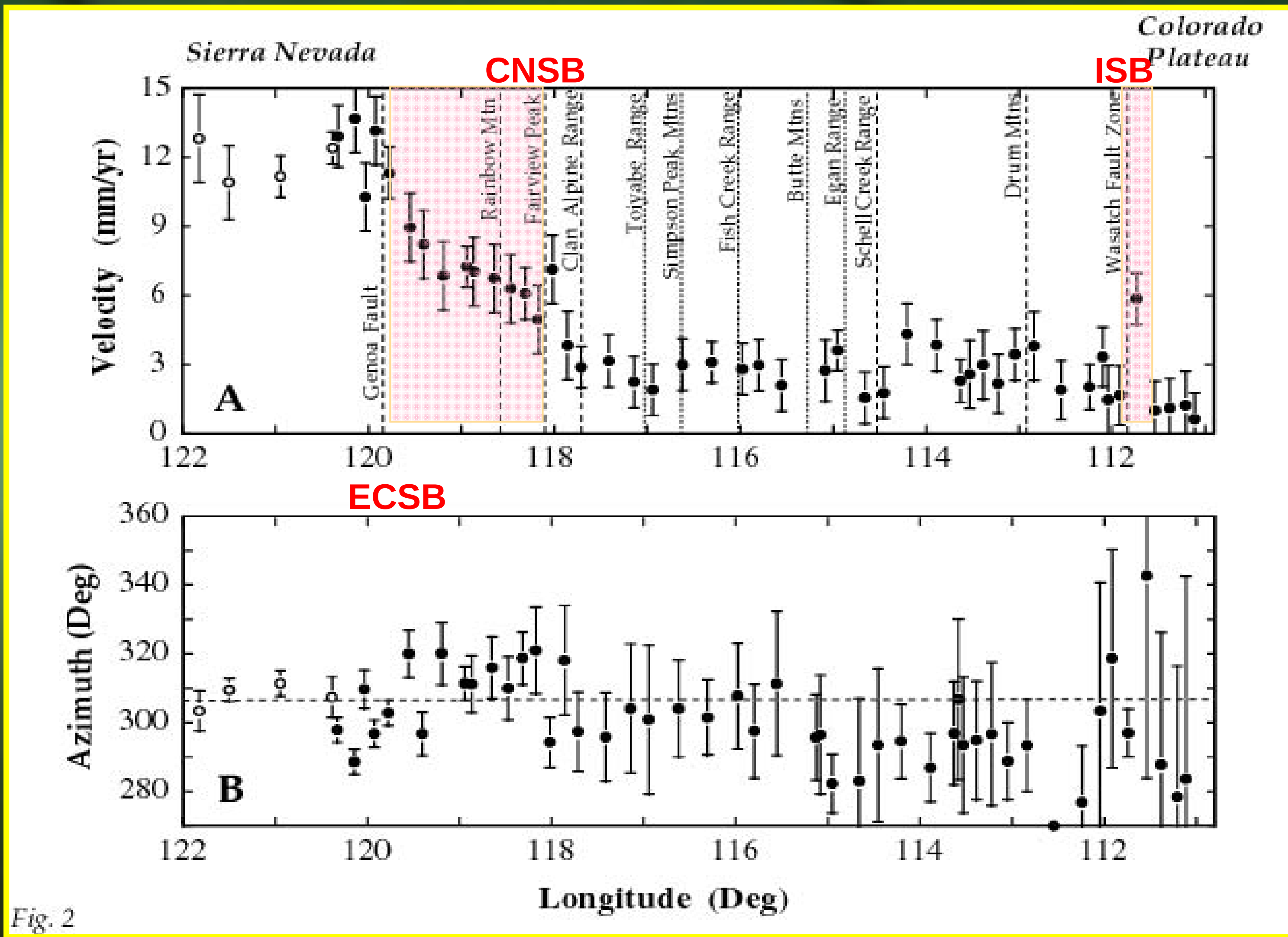
USGS
science for a changing world

Summary: Slip-Rate Patterns
Highest Rates at B&R Boundaries



USGS
science for a changing world

GPS Data Show Most Deformation at Boundaries Too



- 2.8±0.5 mm/yr across Wasatch and related faults
- 9.0±1.6 mm/yr within CNSB/ECBS/Walker Lane

Geology/GPS Slip Rate Comparisons

- Wasatch and related faults: 2.8±0.5 mm/yr GPS versus ~1.5 mm/yr Geologic
- 9.0±1.6 mm/yr within CNSB/ECBS/Walker Lane versus ~?? (but less) Geologic
- CNSB: 3.7±0.5 mm/yr GPS versus ~1.5 mm/yr Geologic
    - BUT: CNSB GPS contaminated by 1954 postseismic effects
    - Geologic Rate correct!
    - Score so far : Geologists 1 GPSers 0

USGS
science for a changing world

Potential Recommendations
Geology/GPS Slip Rate Comparisons

FOR 2007 MAPS

- **Hazard Maps should be consistent with 12-14 mm/yr relative motion**
  - **ALL SEISMIC**
- **Wasatch Fault 2.0 ± 0.5 mm/yr**
- **CNSB: 1.0 ± 0.5 mm/yr**
- **Northern Walker Lane: ~9 mm/yr**

RESEARCH

- **Target new geology & GPS on ‘important’ B&R faults**
- **Resolve Outstanding GPS/Geologic slip rate discrepancies**

  (Wasatch, Norther Walker Lane, others?)
- **Compile Coseismic surface offsets versus GPS slip estimates**

USGS
science for a changing world

GPS-Geology Short-term Recommendations

a) Convert vertical slip rates to extensional rates for consistency with GPS data
- ✓Involves resolving question of dip of normal faults
- ✓Currently use 60° dip
- ✓Modify to 50 ° ±10°

b) Use Province-wide kinematic (GPS) boundary condition as a constraint on the sum of the geologic slip rates

c) Modify the boundaries of the geodetic zones in western Great Basin used in 1996 maps to better reflect the areas of high strain depicted on the GPS-based strain-rate map

d) Use the GPS data as the total strain budget. Ideally, the cumulative moment inferred from the fault sources, the seismicity, and the GPS zones in the 1996 maps should match the GPS budget. Differences that exist between these moment differences should these be fully assimilated into the 2007 maps.

e) USGS should test models to evaluate the effect of releasing the GPS strain as 80% coseismic and 20% aseismic

f) USGS should evaluate the impact on hazard maps of partitioning the geodetic strain in a zone to individual faults (assigning default slip rates) versus distributing the geodetic strain uniformly across the zone

GPS-Geology Long-term Recommendations

a) Move toward assigning minimal slip rates to specific faults; first develop strategy of how to assign slip rates based on geodetic+geologic criteria. This could be the charge for a working group.

b) Develop consistent-resolution fault map for western margin of Great Basin as a first step toward an integrated/geodetic geologic model.

c) Develop sound geologically based (paleoseismic) slip rates in the source zones where geodesy shows significant strain accumulatio

d) Geoscience community should work toward goal of determining if geodesy can identify specific faults where strain is being localized; indicator of higher hazard.

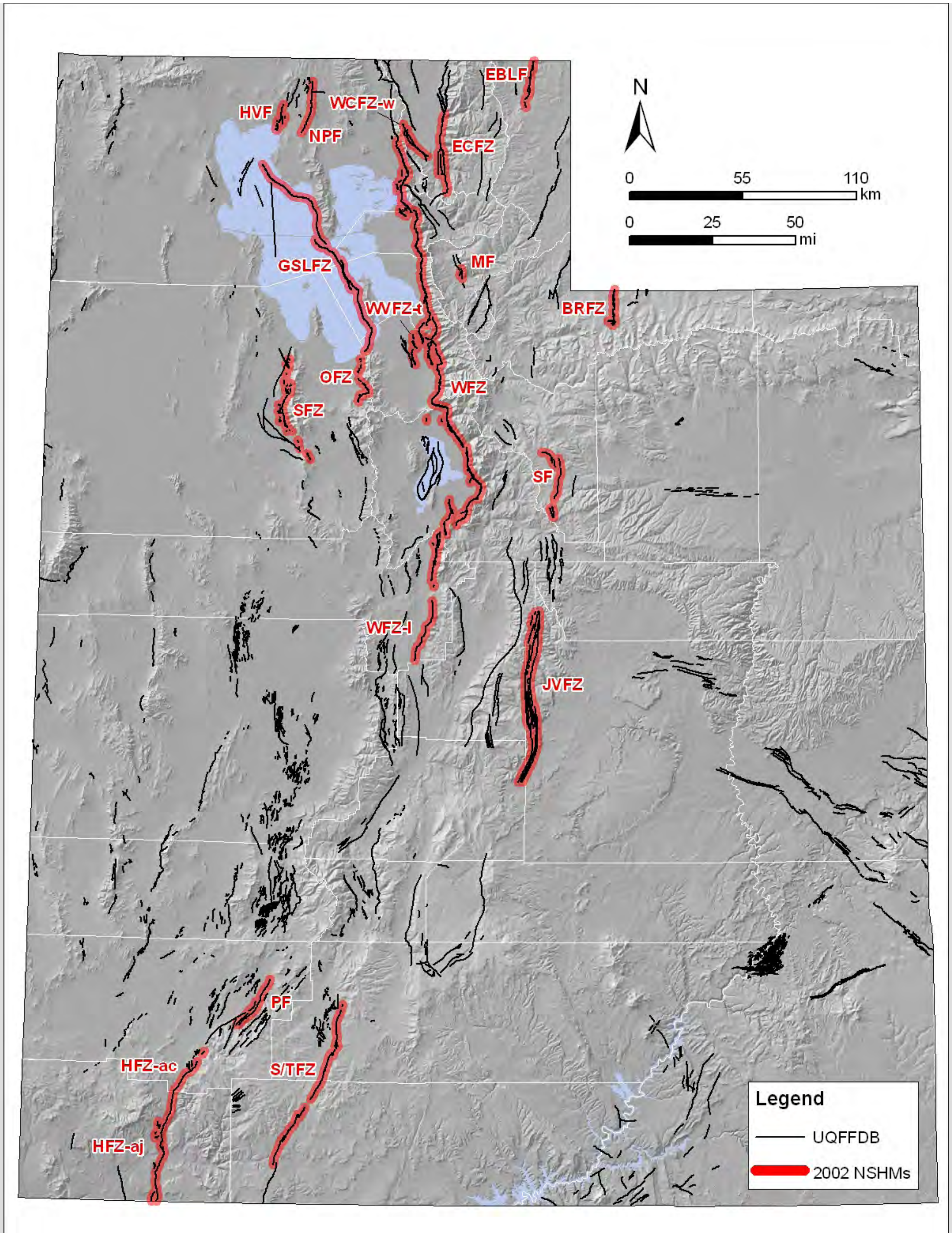
e) Where we have adequate data, develop an integrated model that incorporates GPS, seismicity and fault data.

Red:

Faults in 2002 NSHMs

Black:

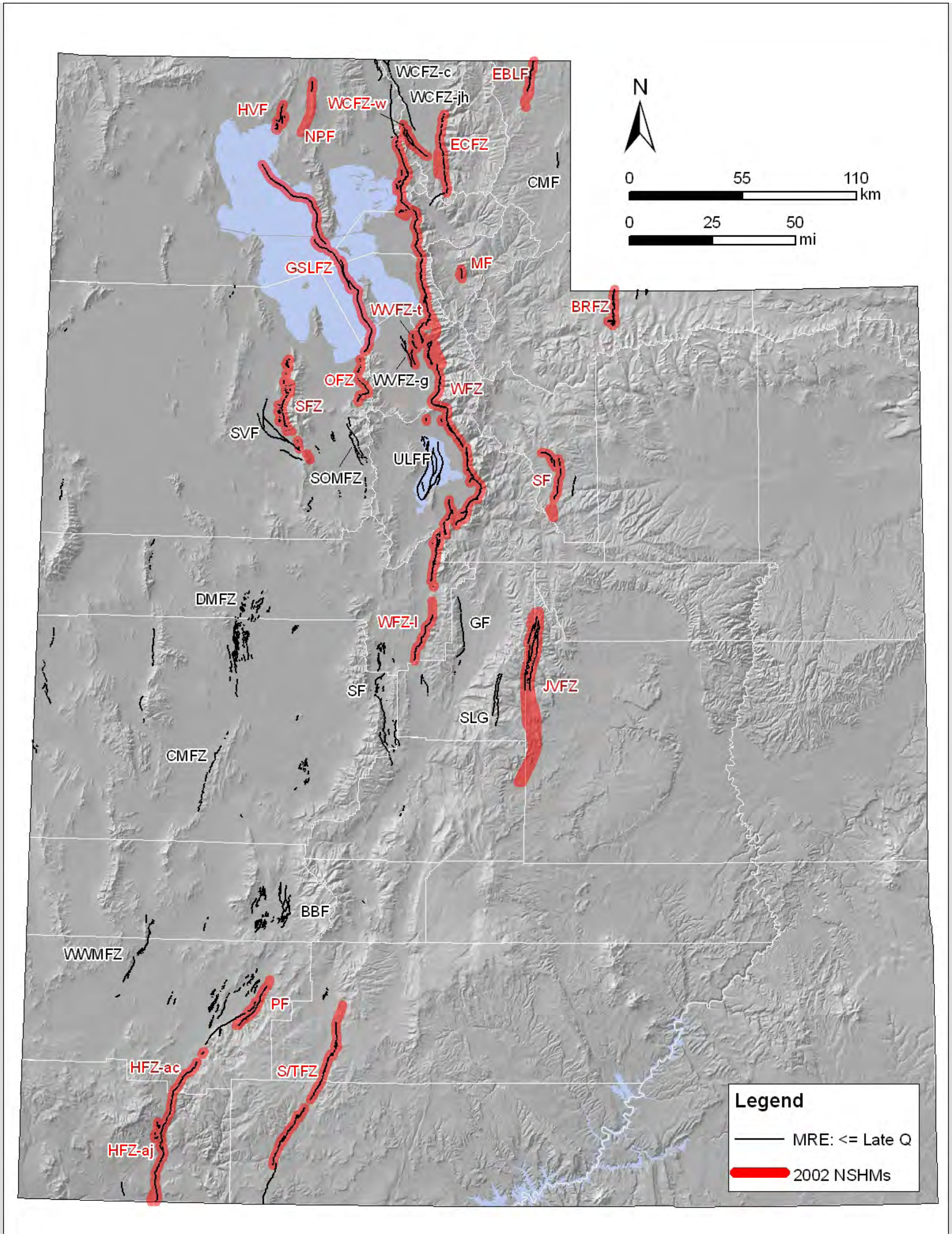
Utah Quaternary fault & fold database (UQFFDB)



Black:

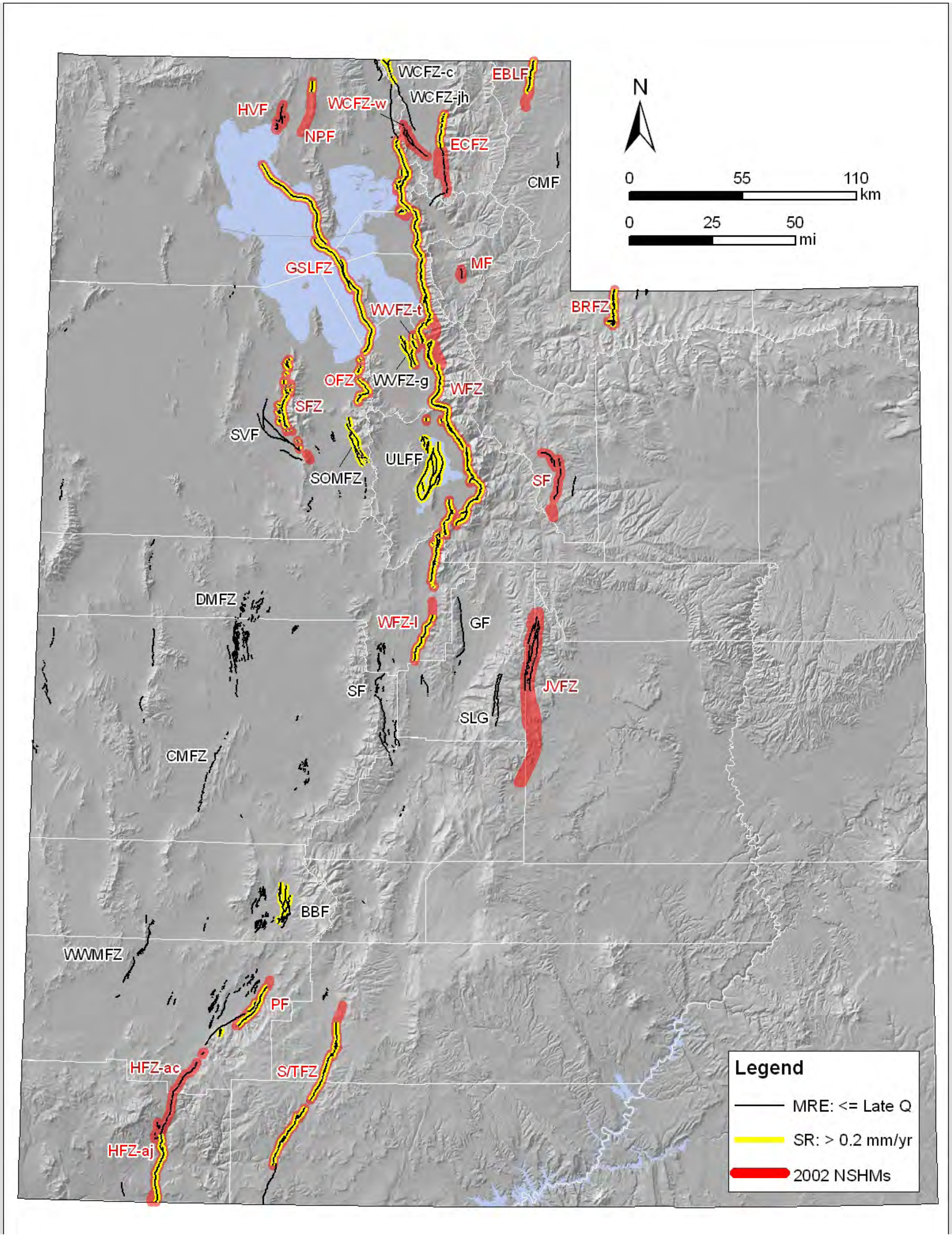
Faults with a **Late Quaternary** or younger most recent event (MRE)

(excluding all suspected faults but Joes Valley FZ)



Yellow:

Faults with a slip rate (SR) > **0.2** mm/yr



Yellow:

Faults not in 2002 NSHMs that satisfy MRE and SR tests

WCFZ-c – West Cache FZ, Clarkston fault

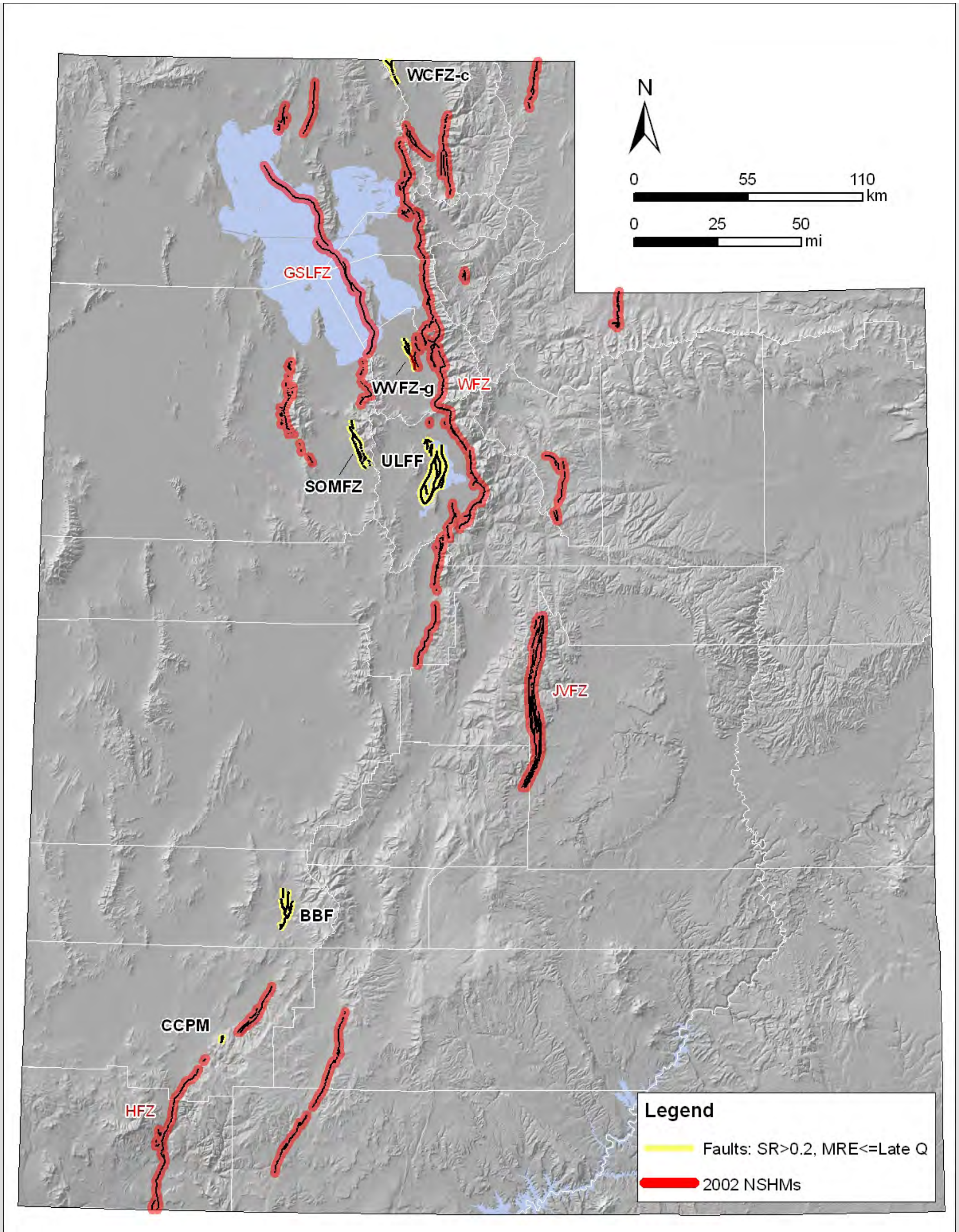
WVFZ-g – West Valley FZ, Granger F

ULFF – Utah Lake F&F

SOMFZ – Southern Oquirrh Mountains FZ

BBF – Beaver Basin F

CCPM – Cedar City-Parowan Monocline



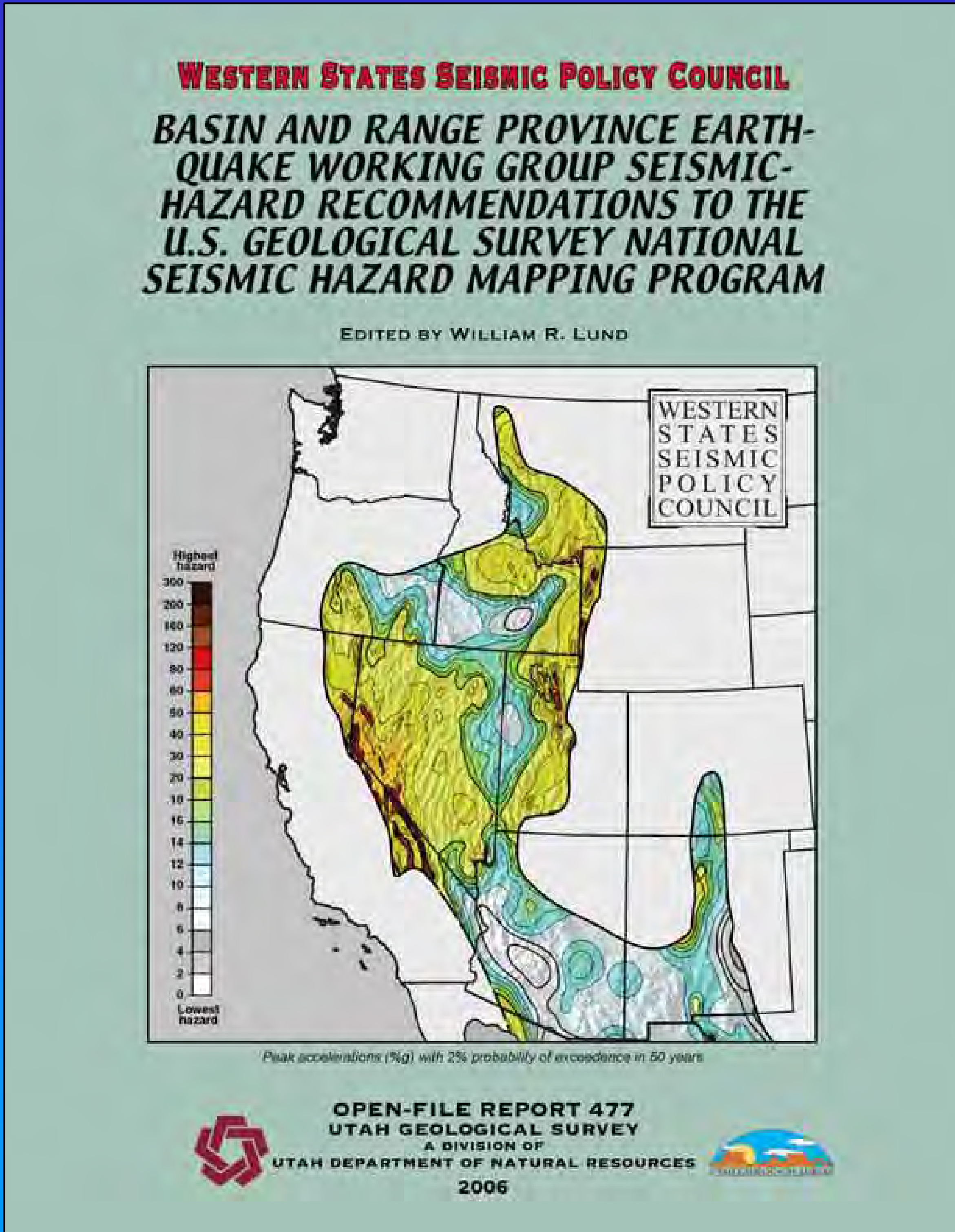
BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP

Seismic-Hazard Recommendations to the U.S. Geological Survey National Seismic Hazard Mapping Program

WESTERN STATES SEISMIC POLICY COUNCIL

Basin and Range Province Committee

WESTERN STATES SEISMIC POLICY COUNCIL


WESTERN STATES SEISMIC POLICY COUNCIL

BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP SEISMIC-HAZARD RECOMMENDATIONS TO THE U.S. GEOLOGICAL SURVEY NATIONAL SEISMIC HAZARD MAPPING PROGRAM

EDITED BY WILLIAM R. LUND

Peak accelerations (%g) with 2% probability of exceedence in 50 years

OPEN-FILE REPORT 477
UTAH GEOLOGICAL SURVEY
A DIVISION OF
UTAH DEPARTMENT OF NATURAL RESOURCES
2006

Available on the
Utah Geological Survey
Web Page at
http://geology.utah.gov

Basin and Range Province Seismic-Hazard Summits I & II

- ***In 1997 WSSPC, USGS, FEMA, and several BRP state geological surveys convened the first Basin and Range Province Seismic Hazard Summit in Reno, Nevada. The purpose was to gather technical experts, emergency planners, and policy makers to review technical issues related to seismic hazards in the BRP.***

- ***In 2004 the same organizations convened BRPSHSII in Sparks, Nevada. The goal was to review advances in BRP earthquake-hazard research since BRPSHSI, and to evaluate the research implications to hazard reduction and public policy.***

BRPSHSII Results

The scientists attending BRPSHSII identified six seismic-hazard issues in the Basin and Range Province that they considered important to the 2007 update of the National Seismic Hazard Maps.

Seismic-Hazard Issues

1. *Use and relative weighting of time-dependent, Poisson, and clustering models to characterize BRP fault behavior.*
2. *Proper magnitude-frequency distributions (Gutenberg-Richter vs. characteristic earthquake models) for BRP faults.*
3. *Use of length vs. displacement relations to estimate earthquake magnitudes.*
4. *Probabilities and magnitudes of multi-segment ruptures on BRP faults.*
5. *Resolving discrepancies between horizontal geodetic extension rates and vertical geologic slip rates.*
6. **Appropriate attenuation relations, stress drop, and kappa in modeling ground motions, including consideration of evidence from precarious rock studies.**

Western Sates Seismic Policy Council Policy Recommendation 04-5

WSSPC recommends convening a technical Basin and Range Province Earthquake Working Group (BRPEWG) to develop scientific consensus regarding fault behavior, ground-shaking and ground-failure modeling, and research priorities relevant to seismic policy and the USGS National Seismic Hazards Maps in the Basin and Range Province. <u>The BRPEWG will be convened under the auspices of the USGS NSHM Program</u>.

BRPEWG Goals

- ***Convene a panel of subject-matter experts to evaluate the five seismic-hazard-policy issues identified in WSSPC PR 04-5.***

- ***Develop consensus recommendations to the USGS regarding those issues including both short-term recommendations for the 2007 NSHMs update, and long-term recommendations for additional research to improve the NSHMs beyond 2007.***

BRPEWG Members

1. John Anderson* – University of Nevada Reno Seismological Laboratory
2. *Walter Arabasz – University of Utah Seismograph Stations*
3. Glenn Biasi* – University of Nevada Reno Seismological Laboratory
4. *Tony Crone - USGS Denver*
5. Craig dePolo* – Nevada Bureau of Mines & Geology
6. *Chris DuRoss – Utah Geological Survey*
7. *Kathy Haller – USGS Denver*
8. *Bill Hammond – Nevada Bureau of Mines & Geology*
9. *Suzanne Hecker – USGS Menlo Park*
10. Mark Hemphill-Haley* – Humboldt State University
11. *David Love – New Mexico Bureau of Geology & Mineral Resources*
12. *William Lund – Utah Geological Survey*
13. *Vince Matthews – Colorado Geological Survey*
14. *Jim McCalpin – GeoHaz, Inc.*
15. Susan Olig* – URS Corp.
16. *Dean Ostenna – USBR, Denver*
17. *Phil Pearthree – Arizona Geological Survey*
18. Jim Pechmann* – University of Utah Seismograph Stations
19. *Mark Petersen – USGS Denver*
20. *Bill Phillips – Idaho Geological Survey*
21. Dave Schwartz* – USGS Menlo Park
22. *Burt Slemmons – University of Nevada Reno, emeritus*
23. Robert Smith* – University of Utah
24. *Mike Stickney – Montana Bureau of Mines & Geology*
25. Wayne Thatcher* – USGS Menlo Park
26. *Chris Wills – California Geological Survey*
27. Ivan Wong* – URS Corp.

**Issue discussion leader*

BRPEWG Process

- *Meeting convened March 8, 9, & 10, 2006, in Salt Lake City.*
- *Six four-hour sessions, one for each seismic-hazard issue, and a final session to finalize the consensus recommendations.*
- *Session leaders and invited speakers made presentations on issue topics followed by discussion and formulation of recommendations.*
- *The UGS compiled the meeting results and summarized each session, which were then reviewed/revised by the session leaders.*
- *The UGS prepared a Recommendations Document (UGS OFR-477) for submittal to the USGS NSHMP.*

BRPEWG Results

- *Twenty short-term recommendations for the 2007 NSHM update .*

- *Eighteen long-term recommendations to guide the USGS in setting priorities for both their internal and external research programs to improve the NSHMs beyond 2007.*

#1 Use and Relative Weighting of Time-dependent, Poisson, and Clustering Models to Characterize BRP Fault Behavior

Short-Term Recommendation for the 2007 NSHMs

1. *The USGS should incorporate uncertainties in slip rates and recurrence intervals for the more significant BRP faults.*
   a. *Most studies giving slip rates and recurrence intervals identify the range of uncertainties.*
   b. *In Utah, use the slip-rate/recurrence distributions developed by the Utah Quaternary Fault Parameters Working Group.*

Long-Term Recommendations

1. *Regional working groups are needed to develop consensus slip-rate and/or recurrence-interval distributions for significant faults.*
   a. *These rate distributions should represent temporal variation of the rates, if any, and other uncertainties.*

#1 Use and Relative Weighting of Time-dependent, Poisson, and Clustering Models to Characterize BRP Fault Behavior (cont.)

- *b.* ***A high-level working group needs to recommend guidelines for establishing these distributions.***
- *c.* ***Each regional group needs a "champion" who will take "ownership" to lead the group and secure results.***
- *d.* ***Regions will not necessarily be by state. Some organizations (e.g., USGS or WSSPC) need to take responsibility to assure complete geographic coverage.***

2. ***The USGS should continue to develop time-dependent maps as a research product.***

   - *a.* ***In general, research needs to focus more on the timing of the most recent earthquake, average recurrence, and determining coefficients of variation for recurrence.***

#2 Proper Magnitude-frequency Distributions (Gutenberg-Richter vs. Characteristic Earthquake Models) for BRP Faults

Short-Term Recommendations for the 2007 NSHMs

1. *The USGS "floating exponential" (truncated Gutenberg-Richter) model should be validated to the extent possible, or at least made consistent with the paleoseismic and historical earthquake record in the BRP. The USGS model should also be compared with magnitude-frequency models used in state-of-the-practice PSHAs.*

2. *The USGS should use the same recurrence models and weights for all BRP faults unless there is a technical basis to do otherwise.*

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

#2 Proper Magnitude-frequency Distributions (Gutenberg-Richter vs. Characteristic Earthquake Models) for BRP Faults (cont.)

4. *To avoid double-counting earthquakes in the range of M 6.5 to the characteristic earthquake magnitude, zones surrounding BRP faults should be removed from the areas included in the Gaussian smoothing of background seismicity.*

5. *The methodology used for constructing the NSHMs must be fully transparent. The USGS is urged to publish, if only as a short note, how recurrence modeling is performed for the NSHMs, especially for fault-specific sources.*

#3 Use of Length vs. Displacement Relations to Estimate Earthquake Magnitudes

Short-Term Recommendations for the 2007 NSHMs

Estimating Displacement and Length

1. Include uncertainty in surface rupture length (SRL) and its consequences for magnitude.
2. Constrain the minimum magnitude assigned to surface-faulting earthquakes to M 6.5 to be consistent with the hazard set by background seismicity.
3. Use magnitude-displacement regressions to improve magnitude estimates where the magnitude from SRL appears inconsistent.
4. Have a working group look at the faults for which displacement data are available (thought to be ~20 in Nevada), and suggest a weighting between displacement and SRL estimates of magnitude to achieve a combined fault magnitude estimate.

#3 Use of Length vs. Displacement Relations to Estimate Earthquake Magnitudes (cont.)

Long-Term Recommendations

Regressions

1. ***Revisit the Wells and Coppersmith (1994) regressions to update the database and evaluate the need to censor short rupture lengths and small magnitudes.***
2. ***Develop a Mw versus SRL*displacement scaling as a tool for improving use of displacement in making magnitude estimates.***
3. ***Develop a multivariate regression for magnitude, given SRL and displacement, to improve magnitude estimates on faults for which both are available.***
4. ***Invest in determining whether regional regressions materially improve ground-motion predictions; for long strike-slip faults (western BRP) consider using the Hanks and Bakun (2002) Mw versus area regression relation.***
5. ***For short faults, consider whether Wells and Coppersmith (1994) is appropriate considering the results of Stirling and others (2002).***

#3 Use of Length vs. Displacement Relations to Estimate Earthquake Magnitudes (cont.)

Long-Term Recommendations (cont.)

Regressions

6. Evaluate whether an estimate of magnitude based on area (with an assumed width) is more appropriate than a magnitude based on SRL.

Displacement

1. There should be a concerted effort to assess:

a. the variability of displacement along rupture strike for historical surface ruptures for the entire range of magnitude (e.g., a follow-up to McCalpin and Slemmons, 1998), and

b. whether surface-faulting data for the BRP support regional (BRP-specific) regressions.

#4 Probabilities and Magnitudes of Multi-Segment Ruptures on BRP Faults

Short-Term Recommendations for the 2007 NSHMs

1. *Hazard calculations for the NSHMs should consider the possibility of multi-segment ruptures on BRP faults.*
2. *For BRP faults for which single-segment-rupture models are being used to compute the hazard, the 2007 NSHMs should also use an unsegmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The unsegmented model should be given a relatively low weight.*
3. *The two faults that ruptured together in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the 2007 NSHM hazard calculations.*

Short-Term/Long-Term Recommendation

1. *Where available, displacement data should be used to provide a consistency check for segmentation models – especially to identify segments on which ruptures longer than the mapped length could occur.*

#4 Probabilities and Magnitudes of Multi-Segment Ruptures on BRP Faults (cont.)

Long-Term Recommendations

1. Newly developed methods for probabilistically constructing rupture scenarios from paleoearthquake timing and displacements should be applied to the Wasatch fault.
2. Research needs to be conducted on the following topics to facilitate segmentation modeling in the BRP:
   a. how to recognize and characterize fault-rupture segments,
   b. the quality and quantity of paleoseismic data needed to support segmented earthquake models along BRP faults, and
   c. construction of earthquake-segmentation models for important BRP faults.

#5 Resolving Discrepancies Between Horizontal Geodetic Extension Rates and Vertical Geologic Slip Rates

Short-Term Recommendations for the 2007 NSHMs

1. Convert vertical slip rates to extensional rates for consistency with GPS data. This involves resolving the question of dip of normal faults. The NSHMs currently use a dip of 60°; the BRPEWG recommends using a dip of 50°±10°.
2. For the BRP, use the province-wide kinematic (GPS) boundary condition (12-14 mm/yr) as a constraint on the sum of geologic slip rates. Enhance the fault catalog used in the NSHMs if necessary to achieve the far-field rates.
3. Modify the boundaries of the geodetic zones in the western Great Basin used in the 1996 NSHMs to better reflect the areas of high strain depicted on the GPS-based strain-rate map.

#5 Resolving Discrepancies Between Horizontal Geodetic Extension Rates and Vertical Geologic Slip Rates (cont.)

Short-Term Recommendations for the 2007 NSHMs

4. *Use the geodetic data as the total strain budget. Ideally, the moment rates from the faults, areal source zones, and GPS zones should add up to the full geodetic budget. This total should be comparable to the seismicity, which is a separate estimate of moment rate. Differences that exist between these individual moment sources should be fully accounted for in the 2007 NSHMs.*
5. *The USGS should test models to evaluate the effect of releasing geodetic strain as 80% coseismic and 20% aseismic.*
6. *The USGS should evaluate the impact on the NSHMs of partitioning geodetic strain on individual faults within a zone (assigning default slip rates) versus distributing the geodetic strain uniformly across the zone.*

#5 Resolving Discrepancies Between Horizontal Geodetic Extension Rates and Vertical Geologic Slip Rates (cont.)

Long-Term Recommendations

1. *Move toward assigning minimum slip rates to specific faults. To this end, develop a strategy of how to assign slip rates based on combined geodetic and geologic criteria; this could be a charge for a future working group.*
2. *Develop a consistent-resolution fault map for the western margin of the Great Basin as a first step toward an integrated geodetic/geologic model.*
3. *Develop robust, geologically based (paleoseismic) slip rates in the source zones where geodesy shows significant strain accumulation, giving priority to urban and rapidly urbanizing areas.*
4. *The geoscience community should work toward the goal of determining if geodesy can identify specific faults where strain is being localized (i.e., indicator of higher hazard).*

#5 Resolving Discrepancies Between Horizontal Geodetic Extension Rates and Vertical Geologic Slip Rates (cont.)

Long-Term Recommendations (cont.)

5. ***Where adequate data exist, develop an integrated model that incorporates geodetic, seismicity, and fault data.***
6. ***The USGS should fully explain in an easily accessible publication or Web page the methodology behind the NSHMs, including the properties of each version of the maps so that changes in the maps over time can be completely understood.***

ACKNOWLEDGEMENTS

- *The 27 scientists from across the Basin and Range Province who served on BRPEWG in a volunteer capacity.*
- *The 10 scientists on BRPEWG who also served as session organizers and leaders.*
- *The USGS provided partial funding for BRPEWG through NEHRP grant 03HQAG0008; the UGS provided additional funding and logistical support.*