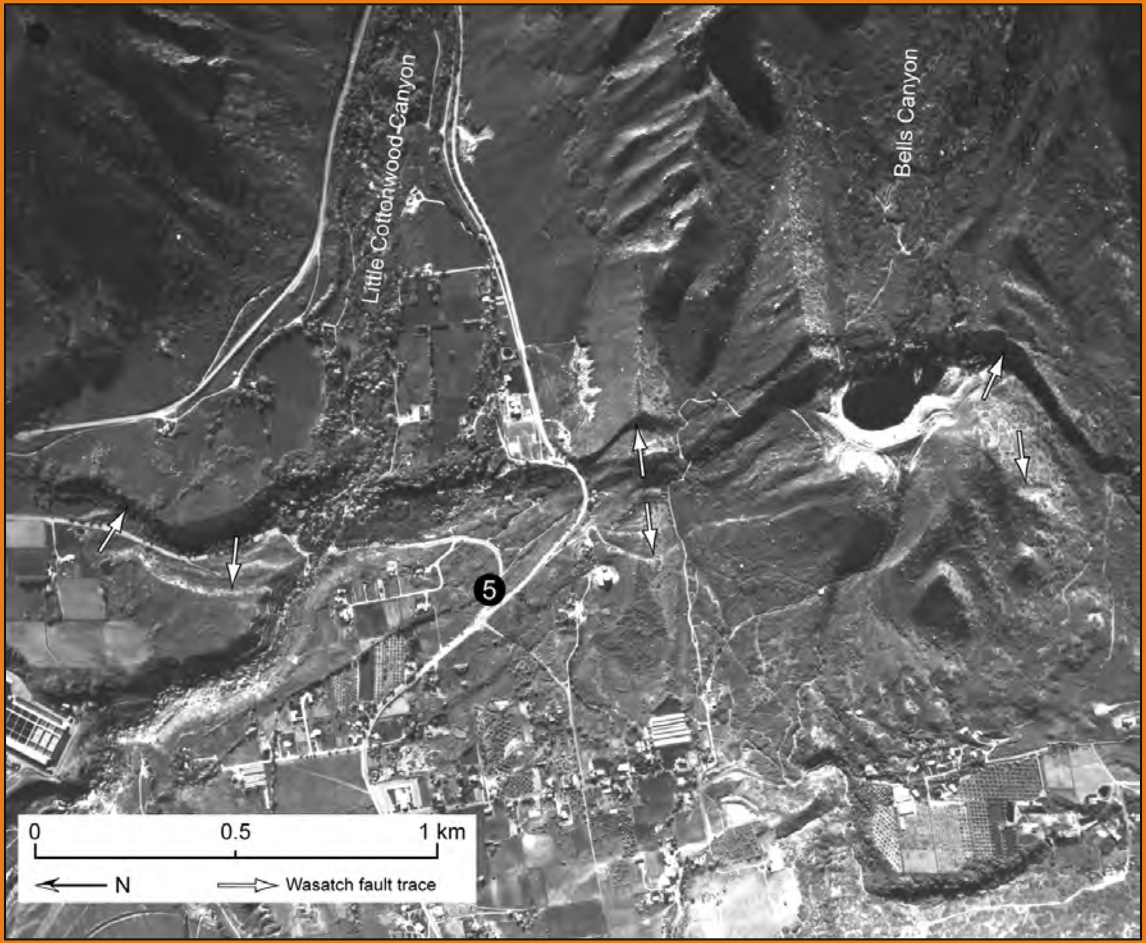
WORKING GROUP ON UTAH EARTHQUAKE PROBABILITIES
MEETING #3



December 1 & 2, 2010

WGUEP Members

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

Steve Bowman – UGS Liaison

WGUEP AGENDA
Tuesday, December 1, 2010

7:30 – 8:00	Continental Breakfast	
8:00 – 8:15	Welcome	Bill
8:15 – 8:30	Overview of Agenda	Ivan
8:30 – 9:30	Report from Paleoseismology Subgroup – Revised Earthquake Timing, Recurrence, and Strawman Rupture Scenarios for Central Wasatch Fault	Chris
10:00 – 10:15	Break	Chris
10:15 – 12:00	Discussion of Rupture Scenarios and Final Model Selection and Weighting	Chris
12:00 – 1:00	Lunch	
1:00 – 1:30	Final Slip Rates for Wasatch Fault End Segments	Mike
1:30 – 2:00	Update on Salt Lake City Fault Trenches	Chris
2:00 – 2:45	Update on West Valley Fault Zone Trenches	Mike
2:45 – 3:00	Break	
3:00 – 4:00	Earthquake Recurrence Models	Ivan/Nico
4:00 – 5:00	General Discussion	Ivan

WGUEP AGENDA
Thursday, December 2, 2010

7:30 – 8:00	Continental Breakfast	
8:00 – 9:00	Conversion of Horizontal Geodetic Extension Rates to Fault Dip-Slip Rates	Mark
9:00 – 9:30	Mmax Calculations	Susan
9:30 – 10:30	Moment Balancing	Mark
10:30 – 10:45	Break	
10:45 – 11:30	Time-Dependent Recurrence for Great Salt Lake Fault?	Jim
11:30 – 12:00	Other Faults that Should be Time-Dependent?	Bill
12:00 – 1:00	Lunch	
1:00 – 1:30	Other Faults on the Bubble	Bill
1:30 – 2:00	Update on Wasatch Front Background Earthquakes	Jim/Walter
2:00 – 3:00	Discussion and Path Forward	Ivan
3:00	Adjourn	

Revised Earthquake Timing, Recurrence, and Strawman Rupture Models for the Central Wasatch Fault

Paleoseismology Subgroup

(Chris DuRoss, Steve Personius, Tony Crone, Susan Olig, and Bill Lund)

Working Group on Utah Earthquake Probabilities, December, 2010

Paleoseismology Subgroup

Main Tasks:

- Discuss OxCal/Matlab methods and finalize earthquake timing and recurrence per segment

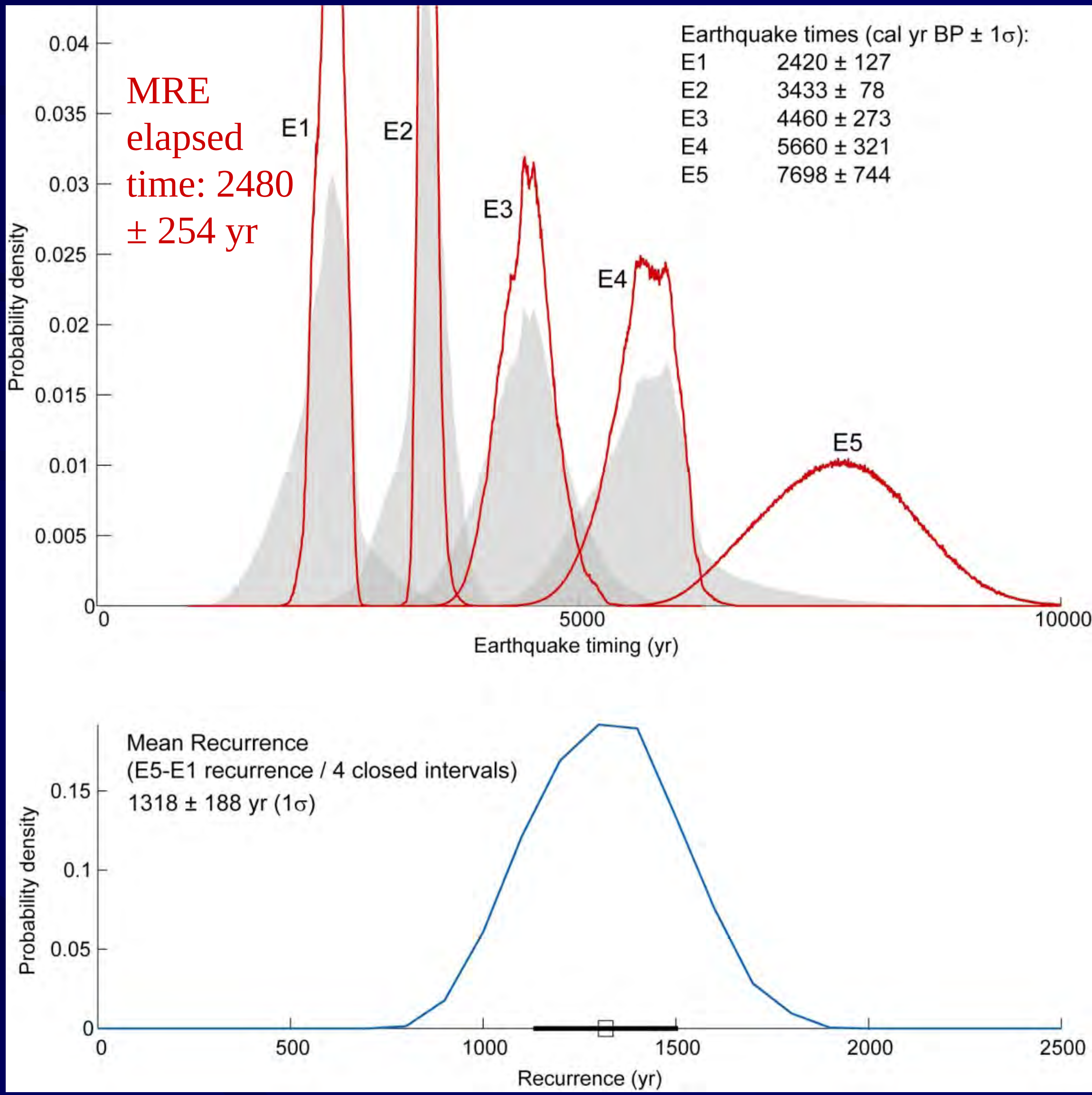
- Develop WFZ rupture models and determine rupture lengths for various rupture models

Revised Earthquake Timing and Recurrence

- Final earthquake timing (and uncertainties)
  - Final results based on product-PDF method of refining segment PDFs
  - Review of product method by Glenn Biasi
    - Reasonable approach – especially for broadly constrained PDFs
    - Supported by literature (~maximum likelihood estimation method)
    - Careful not to over constrain events
  - We reviewed all site PDFs and final segment PDFs, paying close attention to those that could be considered over constrained (and revised as necessary)
- Average recurrence
  - Using closed intervals: Elapsed time between oldest and youngest events divided by number of intervals
  - Using open interval from most recent earthquake to 2010 (but not open interval prior to oldest event)
  - Mean of individual EQ recurrence intervals (e.g., E4-E3, E3-E2, E2-E1)

Brigham City Segment Summary

- EQ Chronology (no changes)
  - E1 2.4 ± 0.3 ka (2σ)
  - E2 3.4 ± 0.2 ka
  - E3 4.5 ± 0.5 ka
  - E4 5.7 ± 0.6 ka
  - E5 7.7 ± 1.5 ka
- Recurrence
  - Average recurrence (4 closed intervals between E5 and E1): 1.3 ± 0.4 ky
  - E5–present (including MRE elapse time): 1.5 ± 0.3 ky
  - Mean of individual recurrence intervals (E5–E1): 1.3 ± 1.3 ky (2σ)
- Miscellaneous
  - PC1 occurred at ~1.2 ka as partial rupture of southern BCS in 1.1-1.3 ka Weber segment earthquake

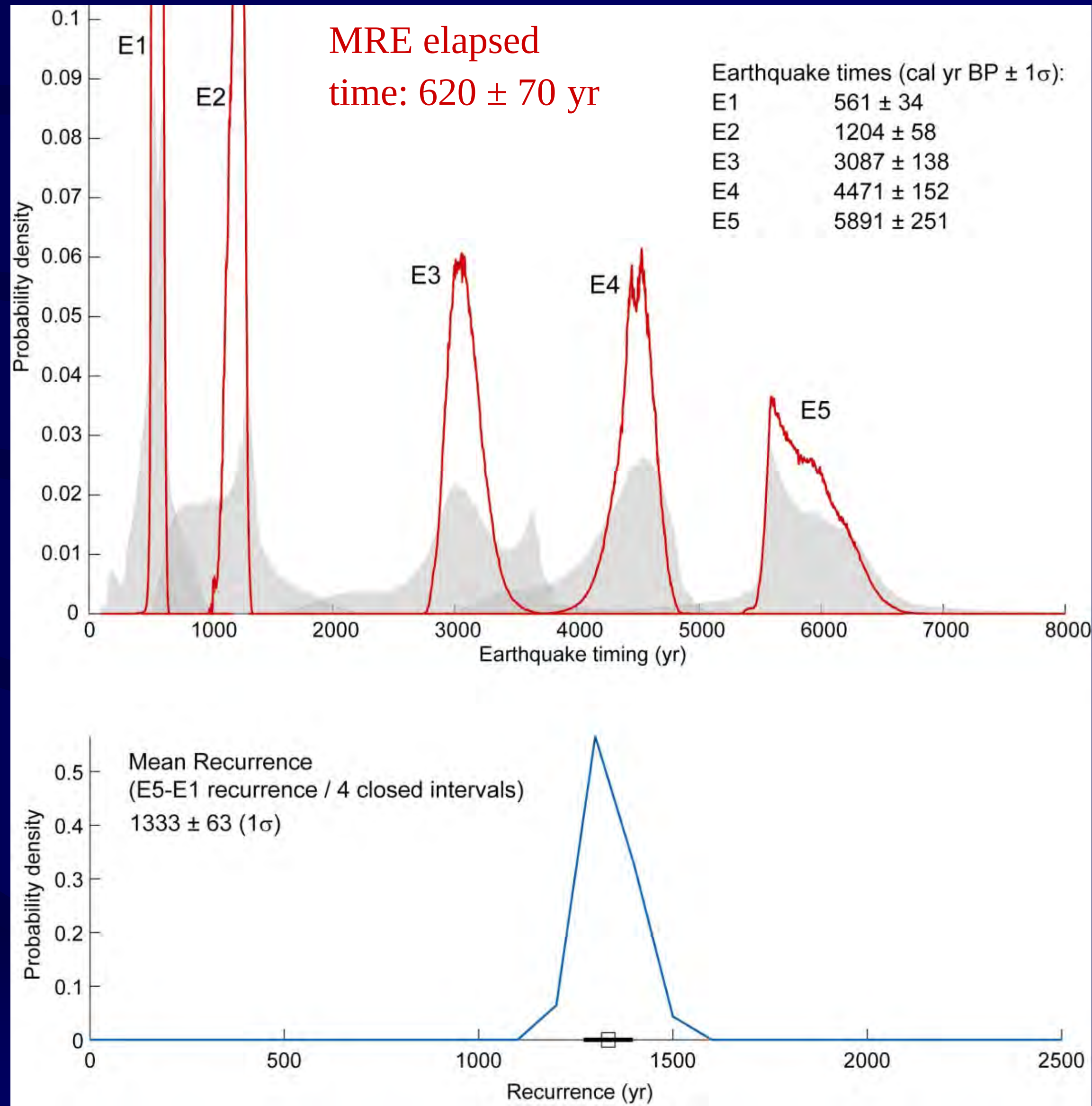


Weber Segment Summary

- EQ Chronology (no changes)
  - E1 0.6 ± 0.1 ka (2σ)
  - E2 1.2 ± 0.1 ka
  - E3 3.1 ± 0.3 ka
  - E4 4.5 ± 0.3 ka
  - E5 5.9 ± 0.5 ka

- Recurrence
  - Average recurrence (4 closed intervals between E5 and E1): 1.3 ± 0.1 ky
  - E5–present (including MRE elapse time): 1.2 ± 0.1 ky
  - Mean of individual recurrence intervals (E5–E1): 1.3 ± 1.0 ky (2σ)

- Miscellaneous
  - Southern extent of E2 rupture (at Kaysville site) uncertain (but this doesn't affect E2 mean time)

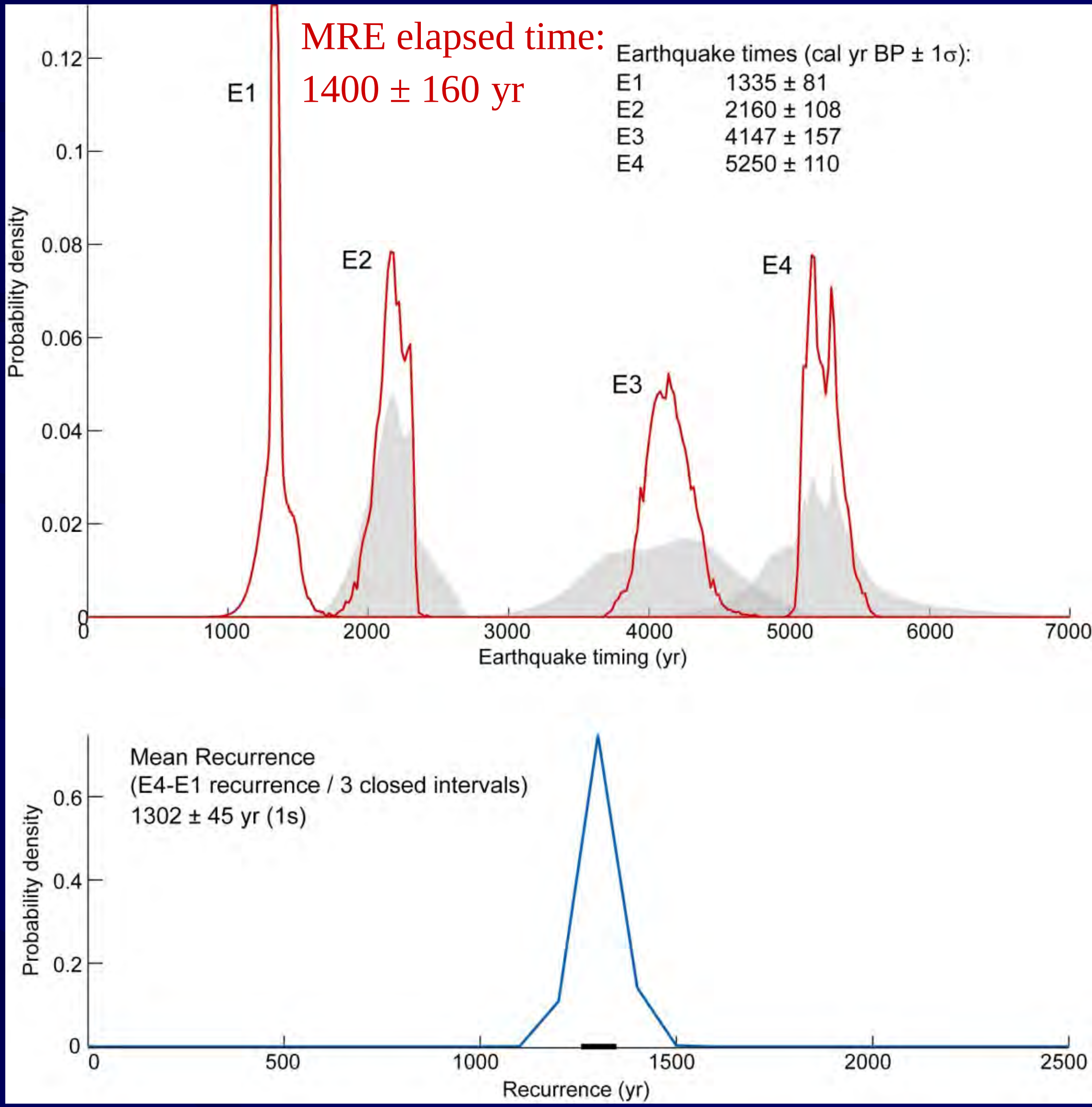


Salt Lake City Segment Summary

- EQ Chronology (change to E1)
  - E1 1.3 ± 0.2 ka (2σ)
  - E2 2.2 ± 0.2 ka
  - E3 4.1 ± 0.3 ka
  - E4 5.3 ± 0.2 ka

- Recurrence
  - Average recurrence (3 closed intervals between E4 and E1): 1.3 ± 0.1 ky
  - E4–present (including MRE elapse time): 1.3 ± 0.05 ky
  - Mean of individual recurrence intervals (E4–E1): 1.3 ± 1.1 ky (2σ)

- Miscellaneous
  - Using average, rather than product, of site PDFs for E1
  - No data (yet) for northern SLCS

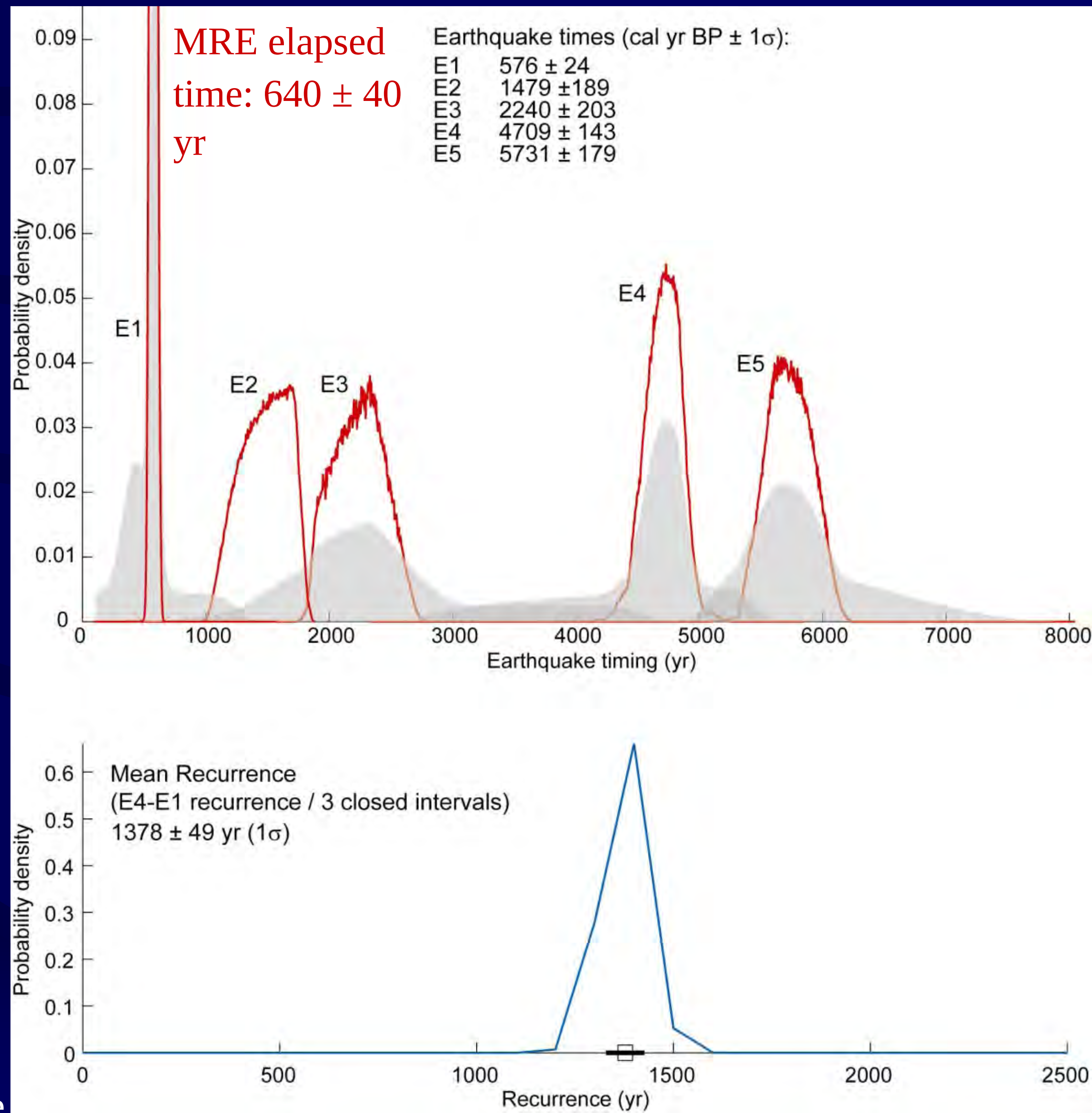


Provo Segment Summary

- EQ Chronology (using maximum record, but without E0)
  - E1 0.6 ± 0.05 ka (2σ)
  - E2 1.5 ± 0.4 ka
  - E3 2.2 ± 0.4 ka
  - E4 4.7 ± 0.3 ka
  - E5(?) 5.7 ± 0.4 ka

- Recurrence
  - Average recurrence (3 closed intervals between E4 and E1): 1.4 ± 0.1 ky
  - E4–present (including MRE elapse time): 1.2 ± 0.1 ky
  - Mean of individual recurrence intervals (E4–E1): 1.4 ± 1.6 ky (2σ)

- Miscellaneous
  - Chronology based on preferred correlation of site PDFs; other correlation schemes are possible, but these do not affect timing of E1 and E4, or the average recurrence

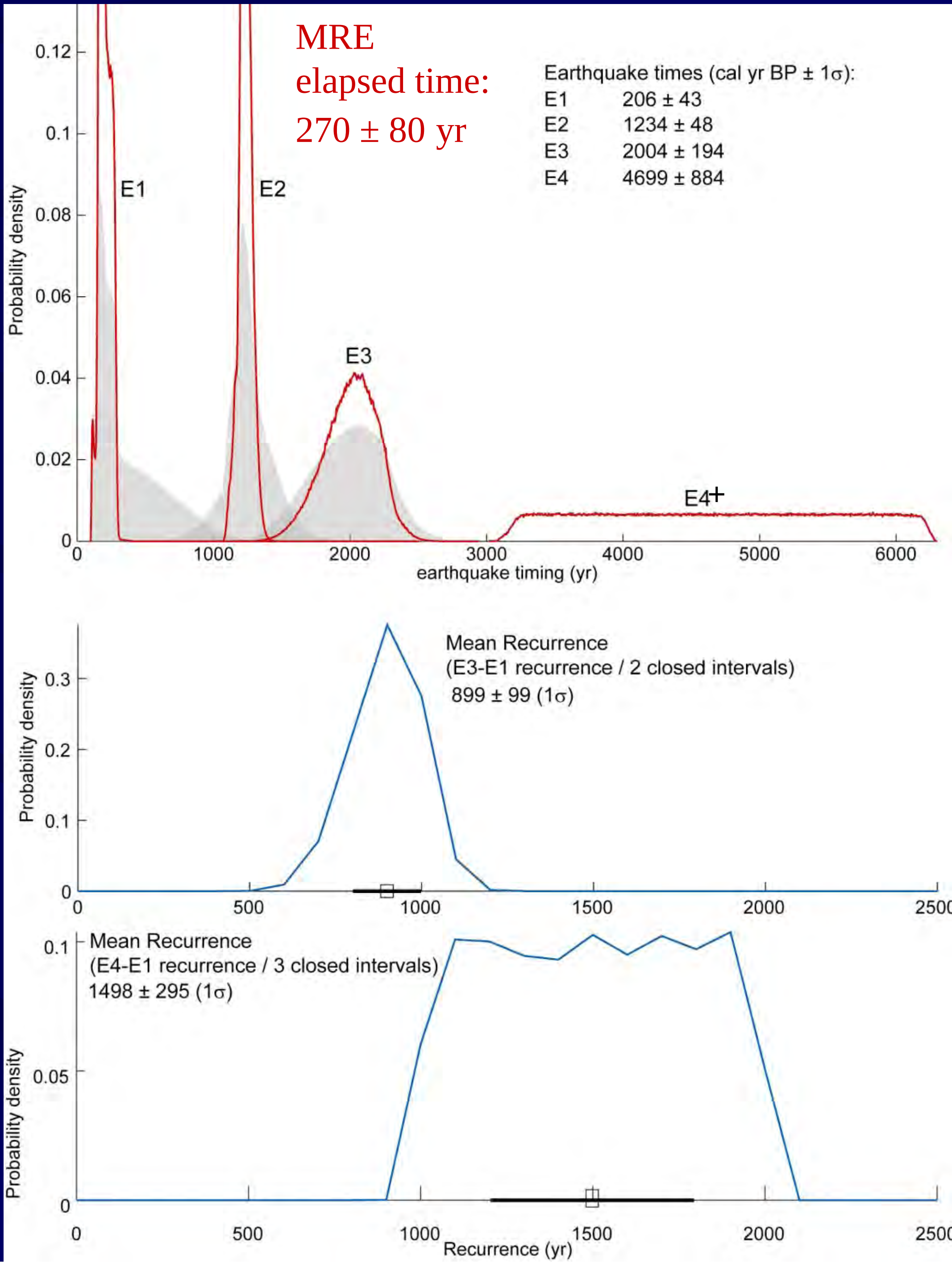


Nephi Segment Summary

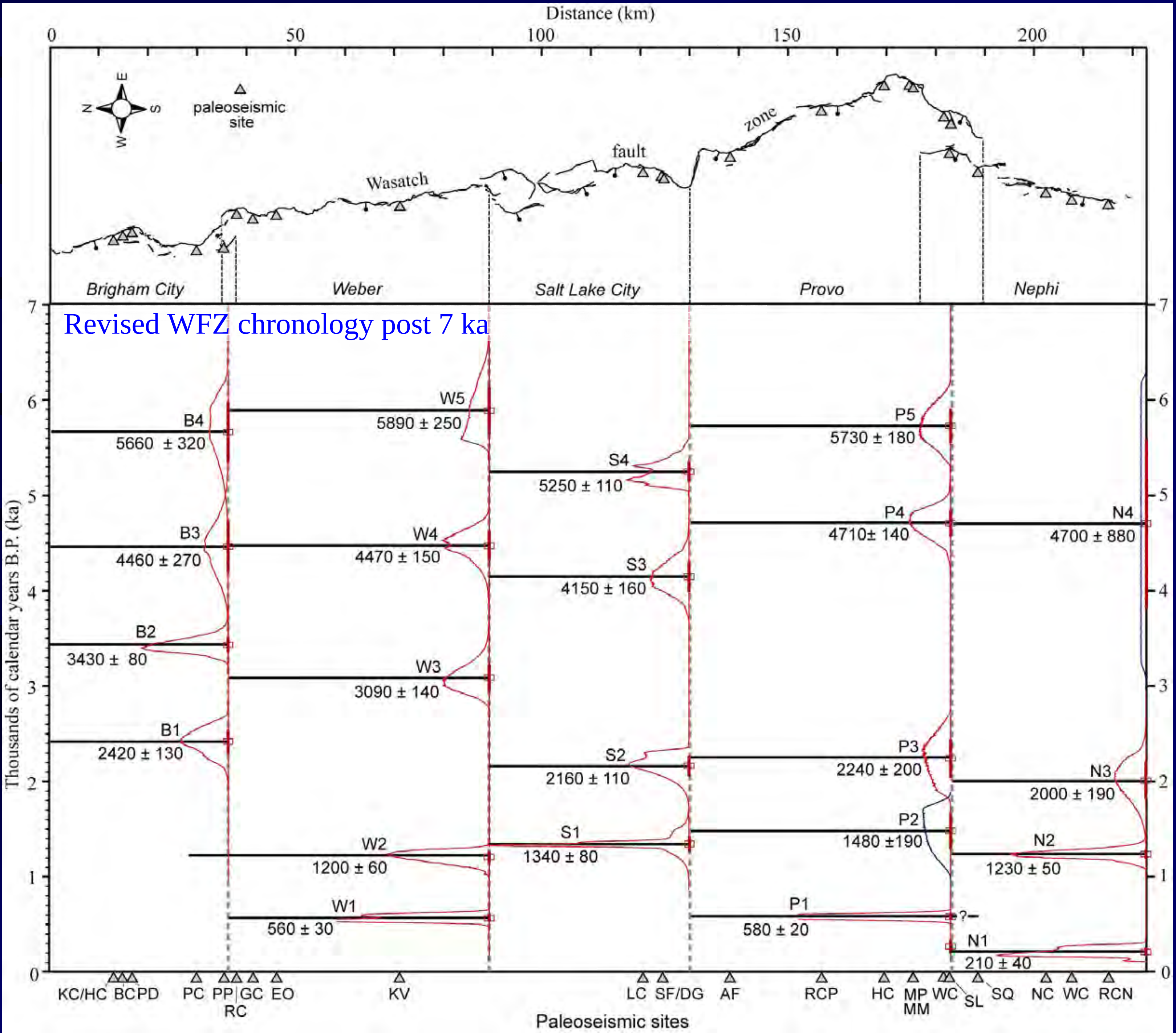
- <u>EQ Chronology</u> (no changes)
  - E1 0.2 ± 0.1 ka (2σ)
  - E2 1.2 ± 0.1 ka
  - E3 2.0 ± 0.4 ka
  - E4(?) 4.7 ± 1.8 ka

- <u>Recurrence</u>
  - Average recurrence (2σ)
    - 2 intervals (E3-E1): 0.9 ± 0.2 ky
    - ≥3 intervals (E4-E1): ≤1.5 ± 0.6 ky
  - E3–present: 0.7 ± 0.1 ky
  - E4–present: 1.2 ± 0.4 ky
  - Mean of individual recurrence intervals (E3–E1): 0.9 ± 0.4 ky

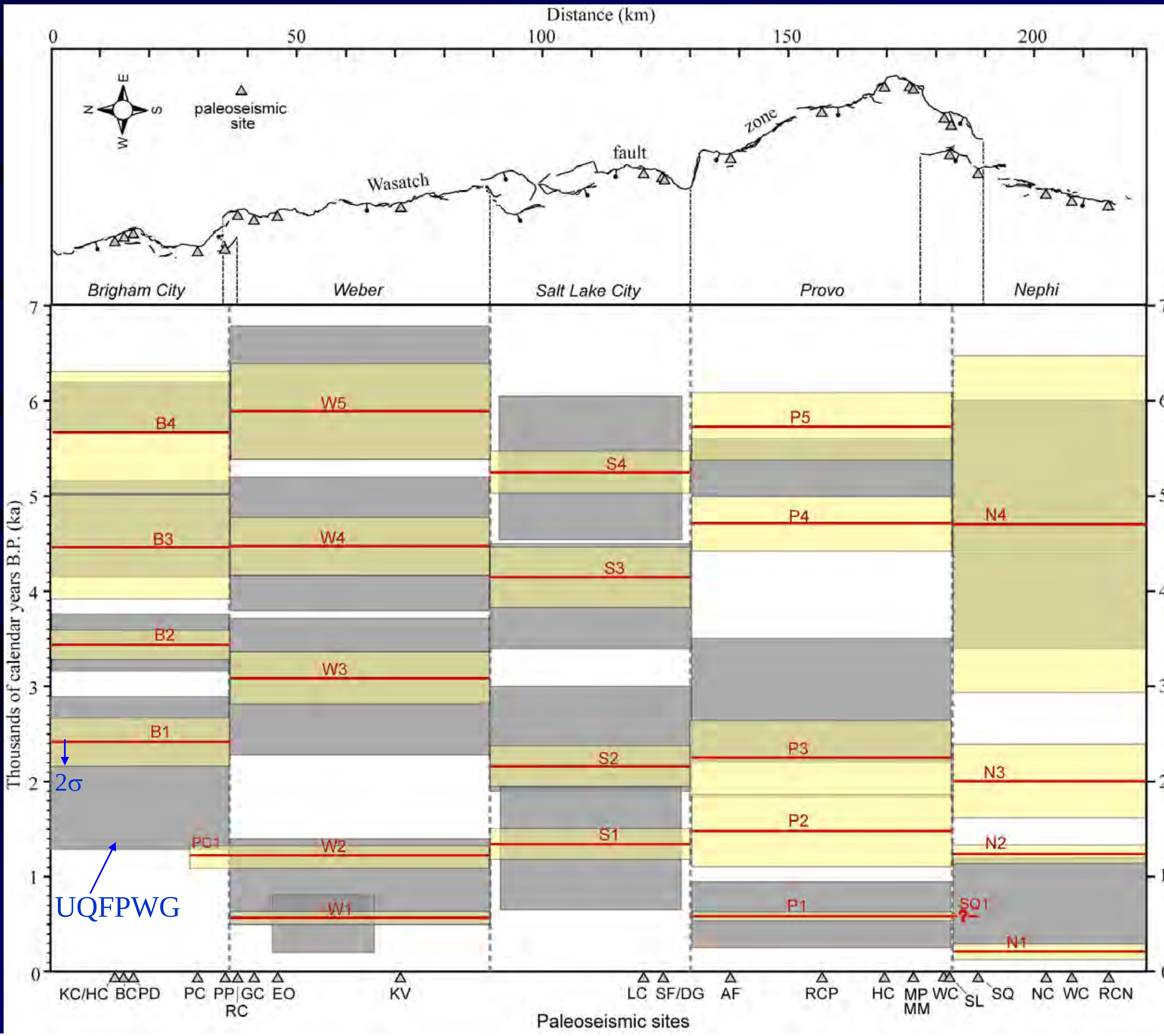
- <u>Miscellaneous</u>
  - Does Santaquin SQ1 correlate with Nephi (N1) or Provo (P1) segment?



Final WFZ Chronology



Comparison with UQFPWG



Strawman Rupture Models

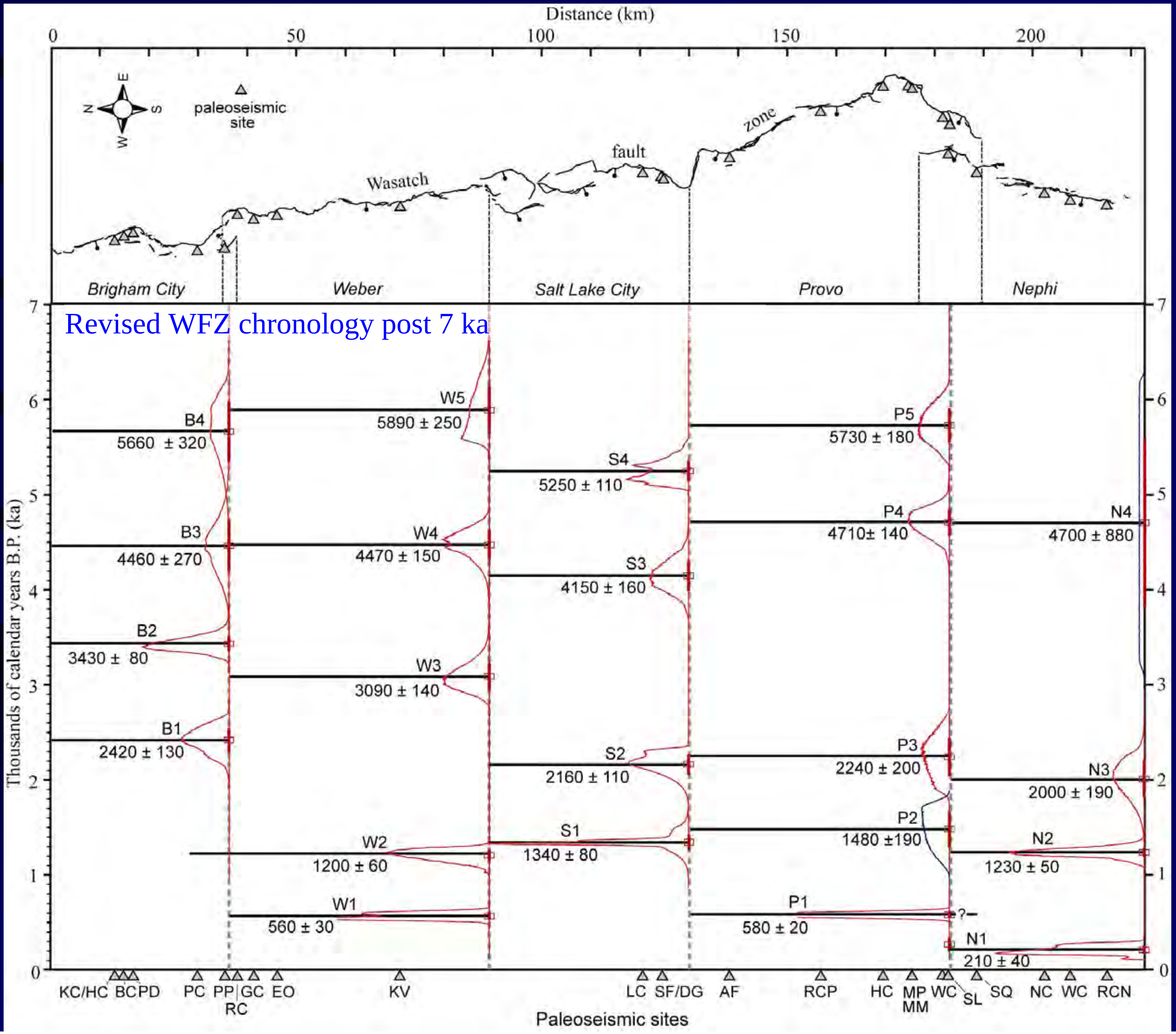
Strawman Rupture Models

- Maximum. Includes single-segment ruptures and one case of leaky-boundary rupture, but no partial segment ruptures.

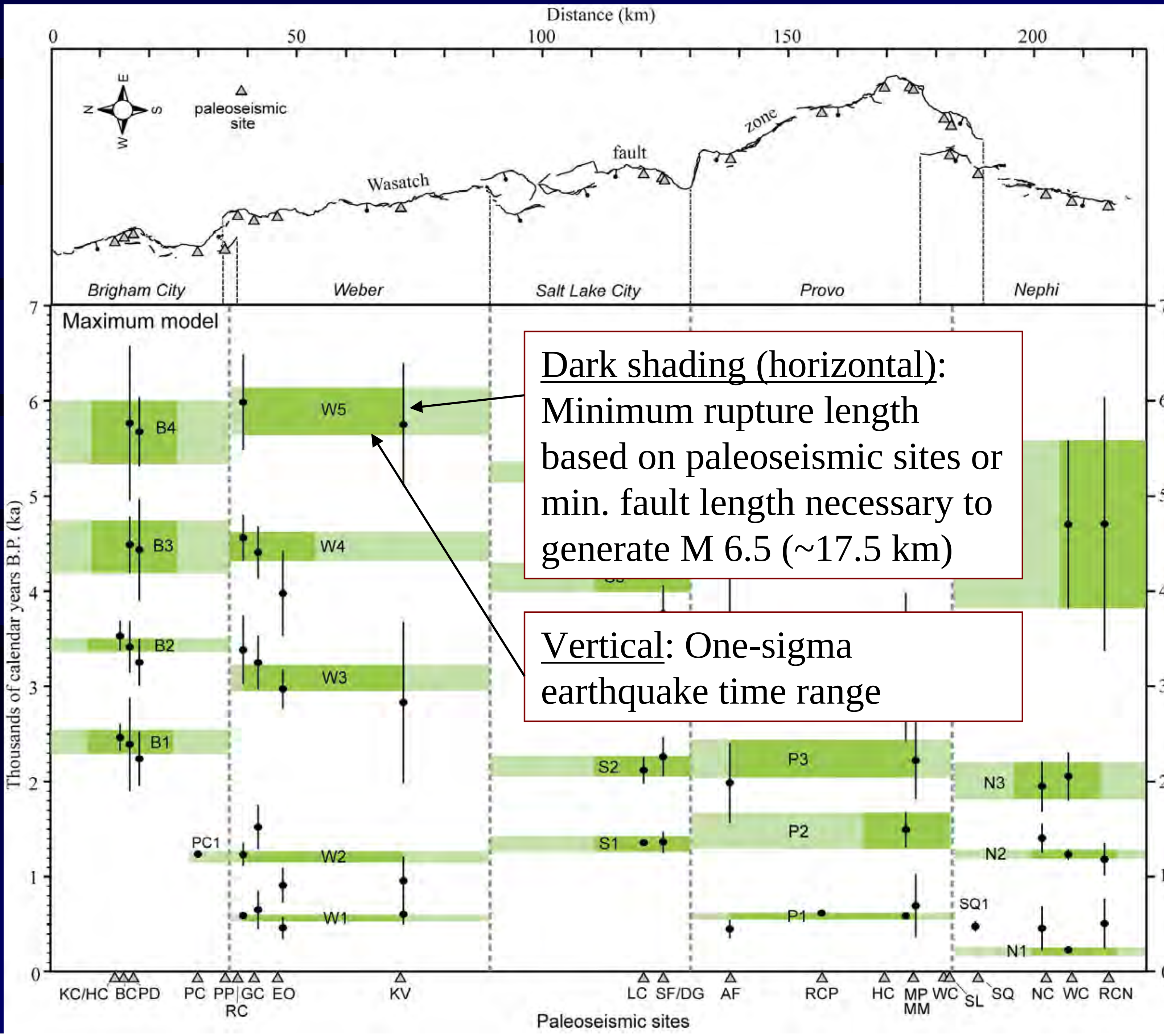
- Minimum. Fewest possible ruptures (extreme scenario). Generally considered two-segment ruptures (with exception) relying on earthquake-timing data and segment PDF overlap.

- Preferred. Mostly single-segment ruptures, keeping only "preferred" multi-segment ruptures from minimum model that have compelling evidence (timing data, displacements, rupture lengths).

Final WFZ Chronology



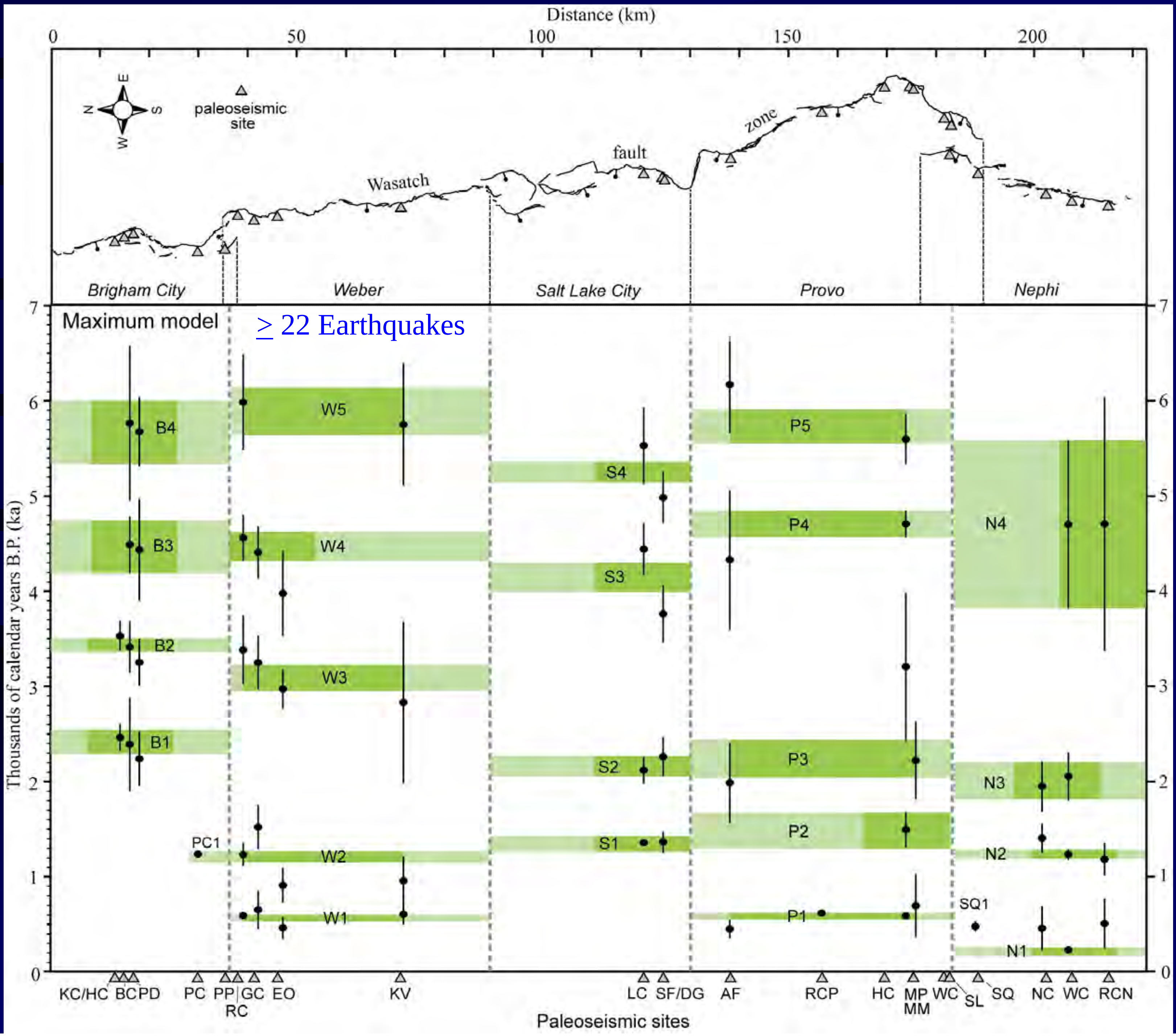
Maximum Rupture Model



Dark shading (horizontal): Minimum rupture length based on paleoseismic sites or min. fault length necessary to generate M 6.5 (~17.5 km)

Vertical: One-sigma earthquake time range

Maximum Rupture Model



Maximum Rupture Model

Rupture	Minimum Surface Rupture Length (SRL)		Maximum SRL		Average SRL
B4	17.5	Min L for M 6.5	36	BCS	27
B3	17.5	Min L for M 6.5	36	BCS	27
B2	17.5	Min L for M 6.5	36	BCS	27
B1	17.5	Min L for M 6.5	36	BCS	27
W5	33	Rice Cr to Kaysville	56	WS	45
W4	17.5	Min L for M 6.5	36	Northern end WS to Kaysville	27
W3	33	Rice Cr to Kaysville	56	WS	45
PC1-W2	41	Pearson Cyn to Kaysville	65	Willard Cyn to end of WS	53
W1	33	Rice Cr to Kaysville	56	WS	45
S4	20	Cottonwood fault length	40	SLCS	30
S3	20	Cottonwood fault length	40	SLCS	30
S2	20	Cottonwood fault length	40	SLCS	30
S1	20	Cottonwood fault length	40	SLCS	30
P5	39	American Fork to Mapleton N	59	PS	49
P4	39	American Fork to Mapleton N	59	PS	49
P3	39	American Fork to Mapleton S	59	PS	49
P2	17.5	Min L for M 6.5	59	PS	38
P1	39	American Fork to Mapleton S	59	PS	49
N4	17.5	Min L for M 6.5	43	NS (both strands)	30
N3	17.5	Min L for M 6.5	43	NS (both strands)	30
N2	17.5	Min L for M 6.5	43	NS (both strands)	30
N1	17.5	Min L for M 6.5	43	NS (both strands)	30

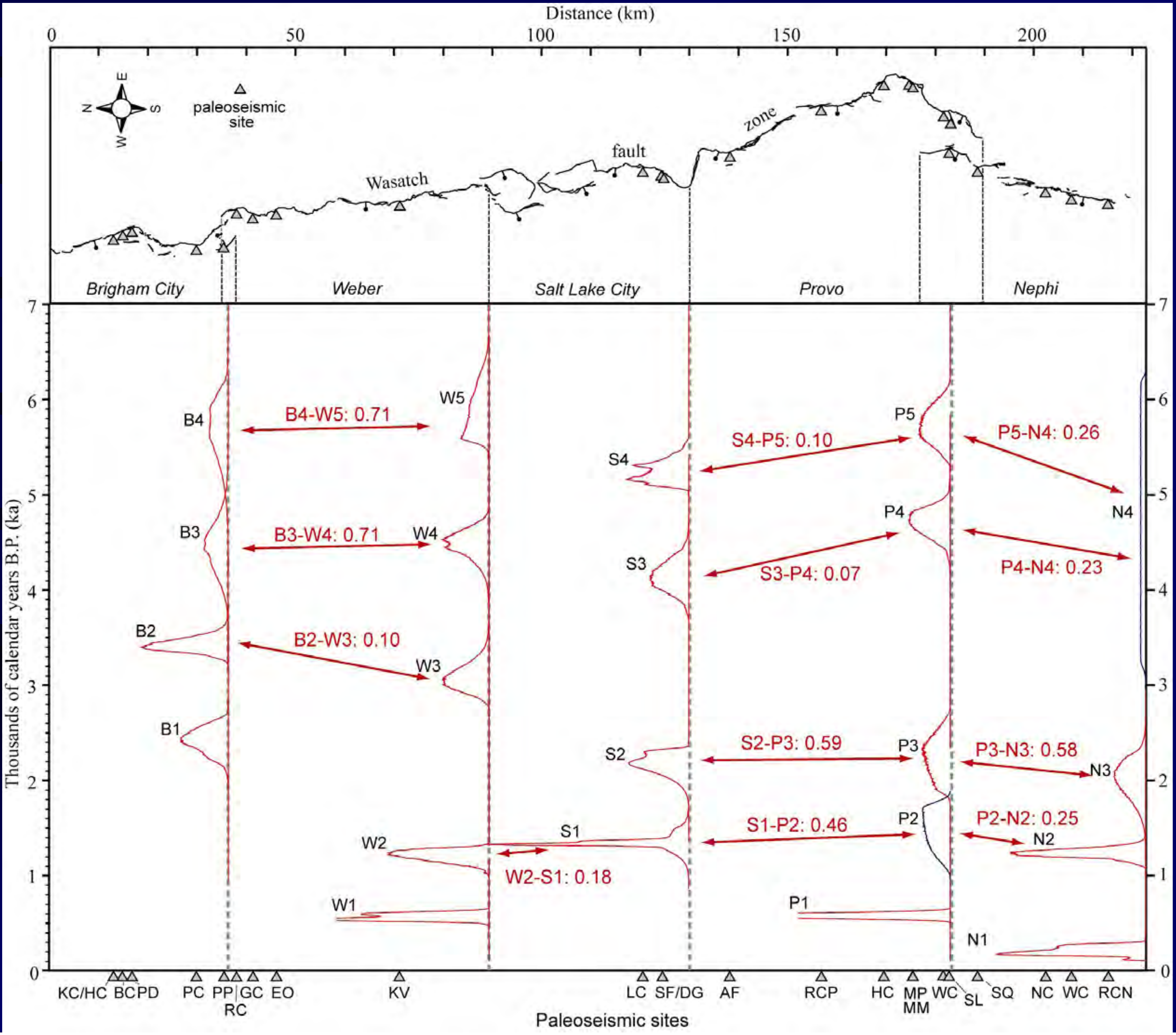
≥ 22 earthquakes younger than ~6.4 ka (W5 mean time 5.9 ka + 2s [0.5 ka])

Minimum Rupture Model

Fewest ruptures, based on:

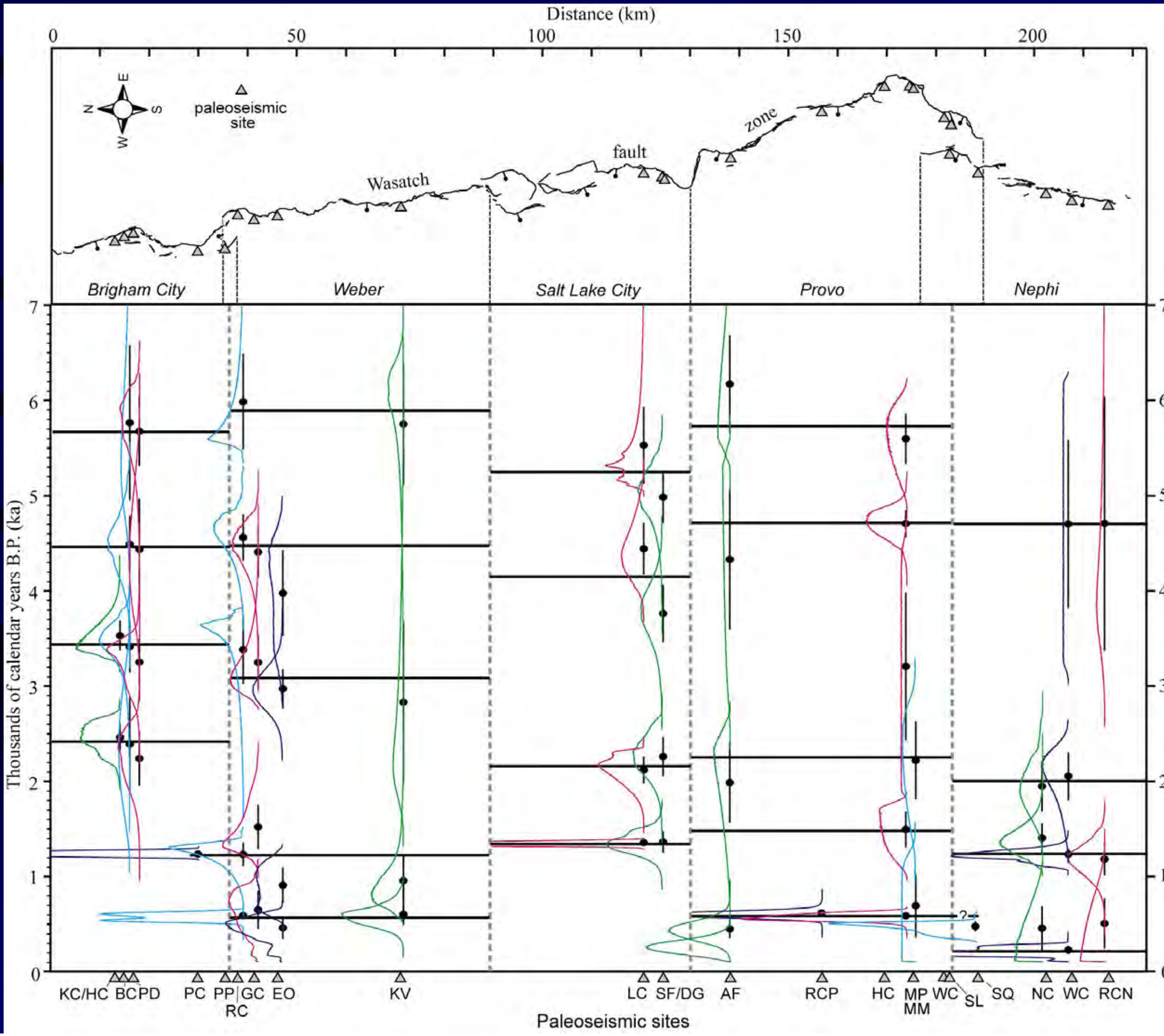
1. Final OxCal/Matlab results
2. PDF overlap (percent overlap in segment EQ time PDFs)
3. OxCal site data (site locations, mean times, uncertainties, rupture extents where known, unknowns)
4. Displacement (per event and along-strike profiles)
5. Common sense (how to treat two tightly constrained ruptures on separate segments having similar EQ times but low PDF overlap)

PDF Overlap

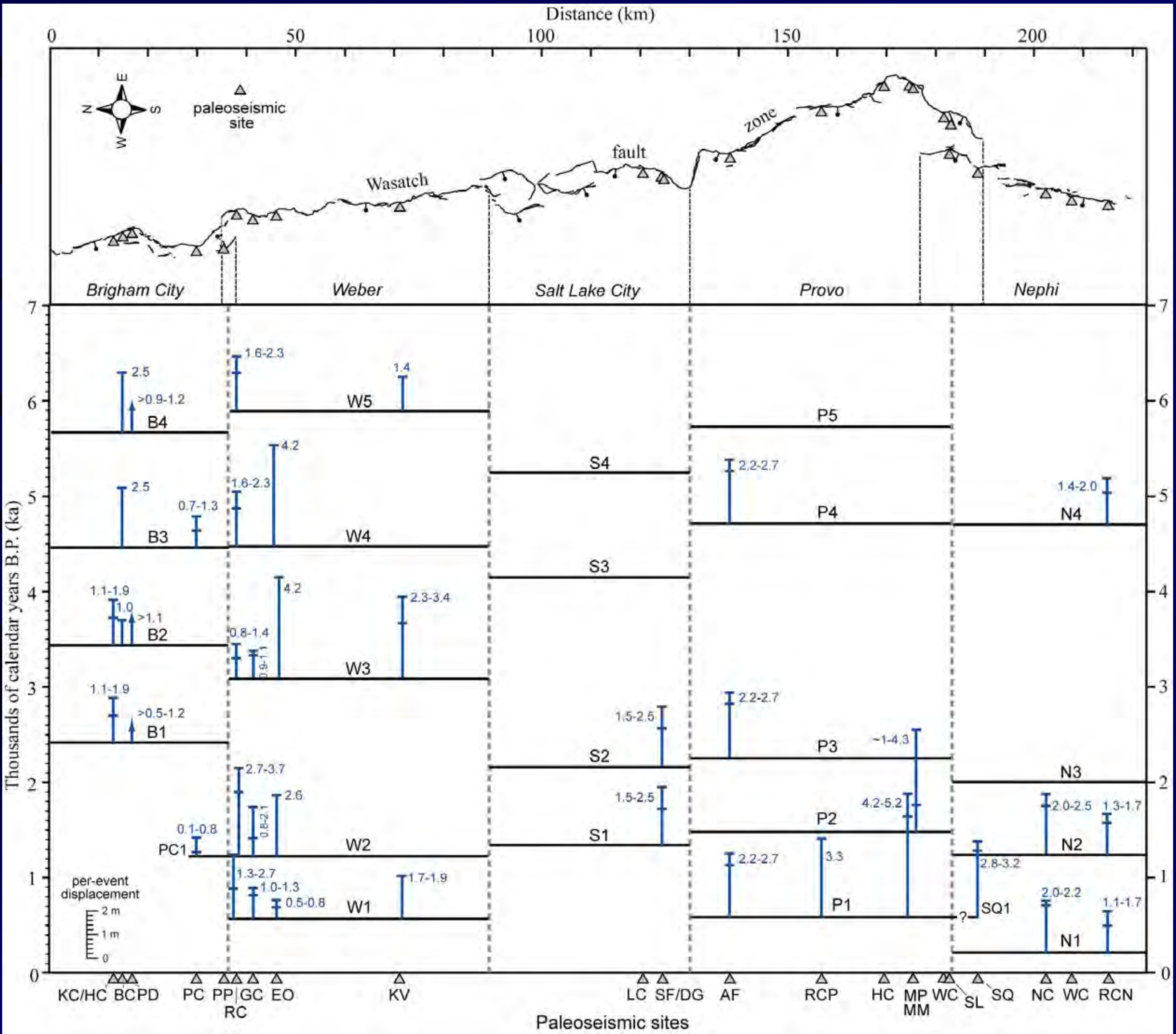


Distance (km)
0
50
100
150
200
paleoseismic site
Wasatch
fault
zone
Brigham City
Weber
Salt Lake City
Provo
Nephi
Thousands of calendar years B.P. (ka)
B4-W5: 0.71
B3-W4: 0.71
B2-W3: 0.10
W2-S1: 0.18
S4-P5: 0.10
S3-P4: 0.07
S2-P3: 0.59
S1-P2: 0.46
P5-N4: 0.26
P4-N4: 0.23
P3-N3: 0.58
P2-N2: 0.25
B1
B2
B3
B4
W1
W2
W3
W4
W5
S1
S2
S3
S4
P1
P2
P3
P4
P5
N1
N2
N3
N4
KC/HC BC PD PC PP GC EO KV LC SF/DG AF RCP HC MP WC SL SQ NC WC RCN
RC
MM
Paleoseismic sites

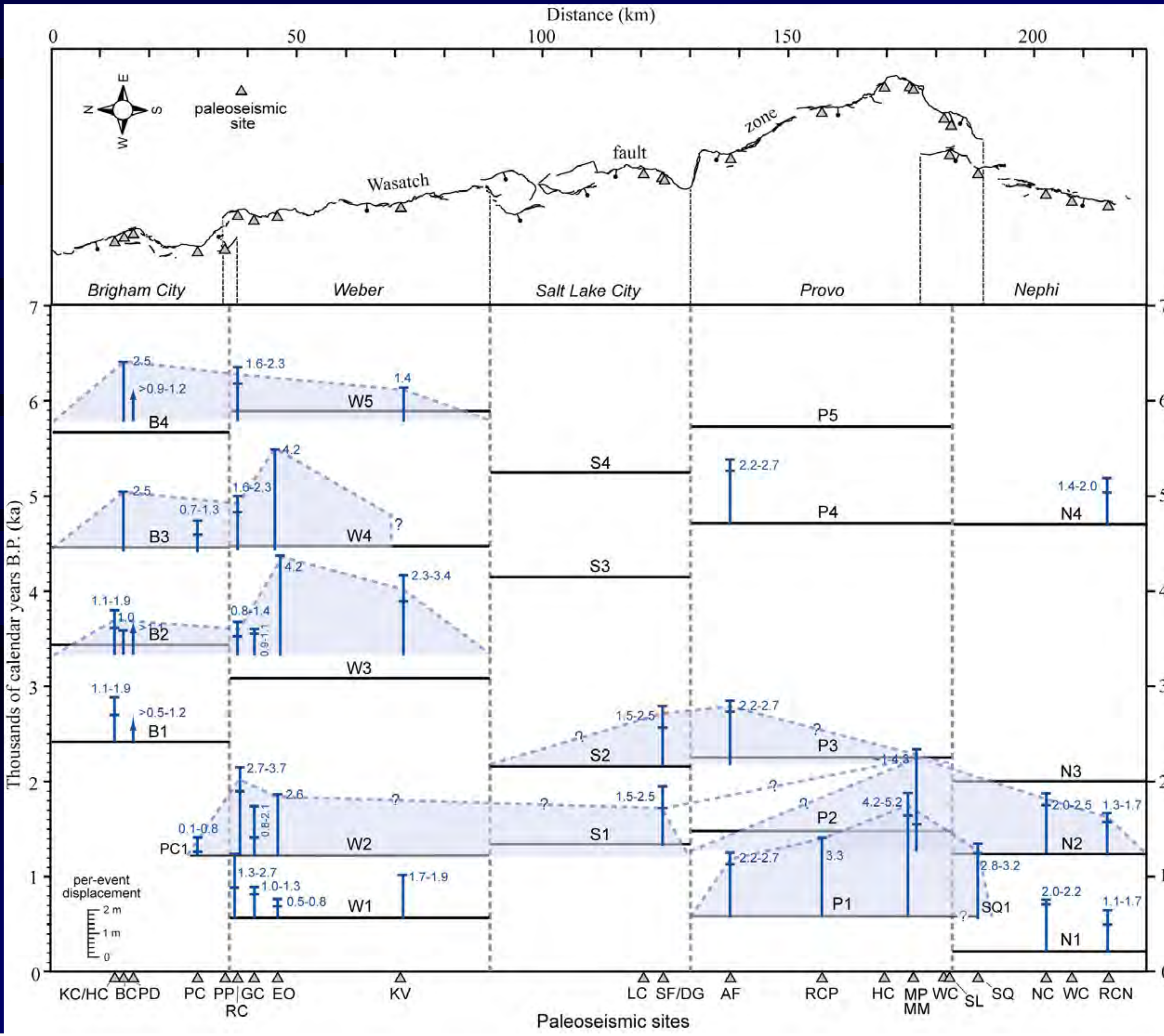
Site PDFs (OxCal)



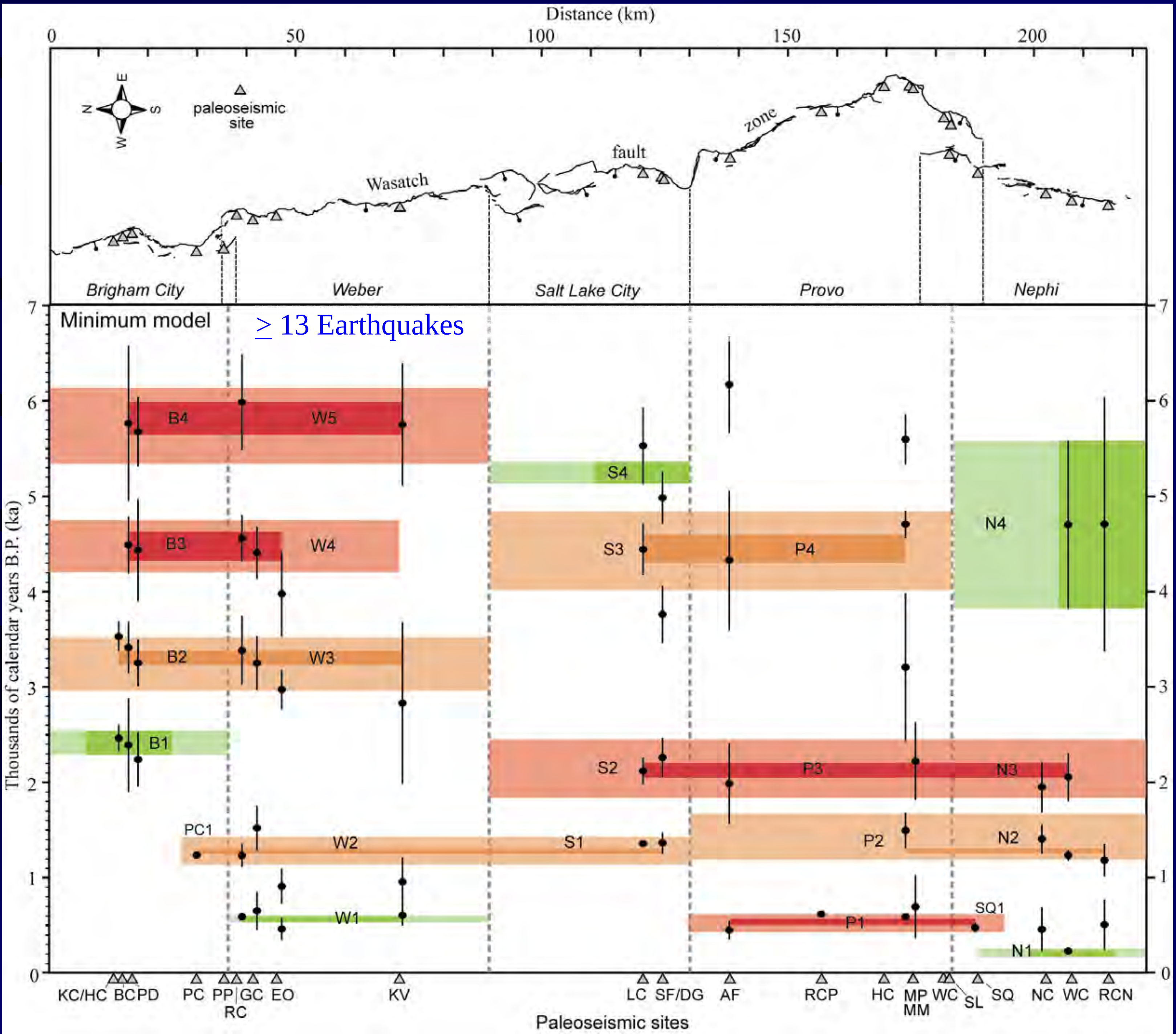
Per-event Displacements



Along-Strike Displacement



Minimum Rupture Model

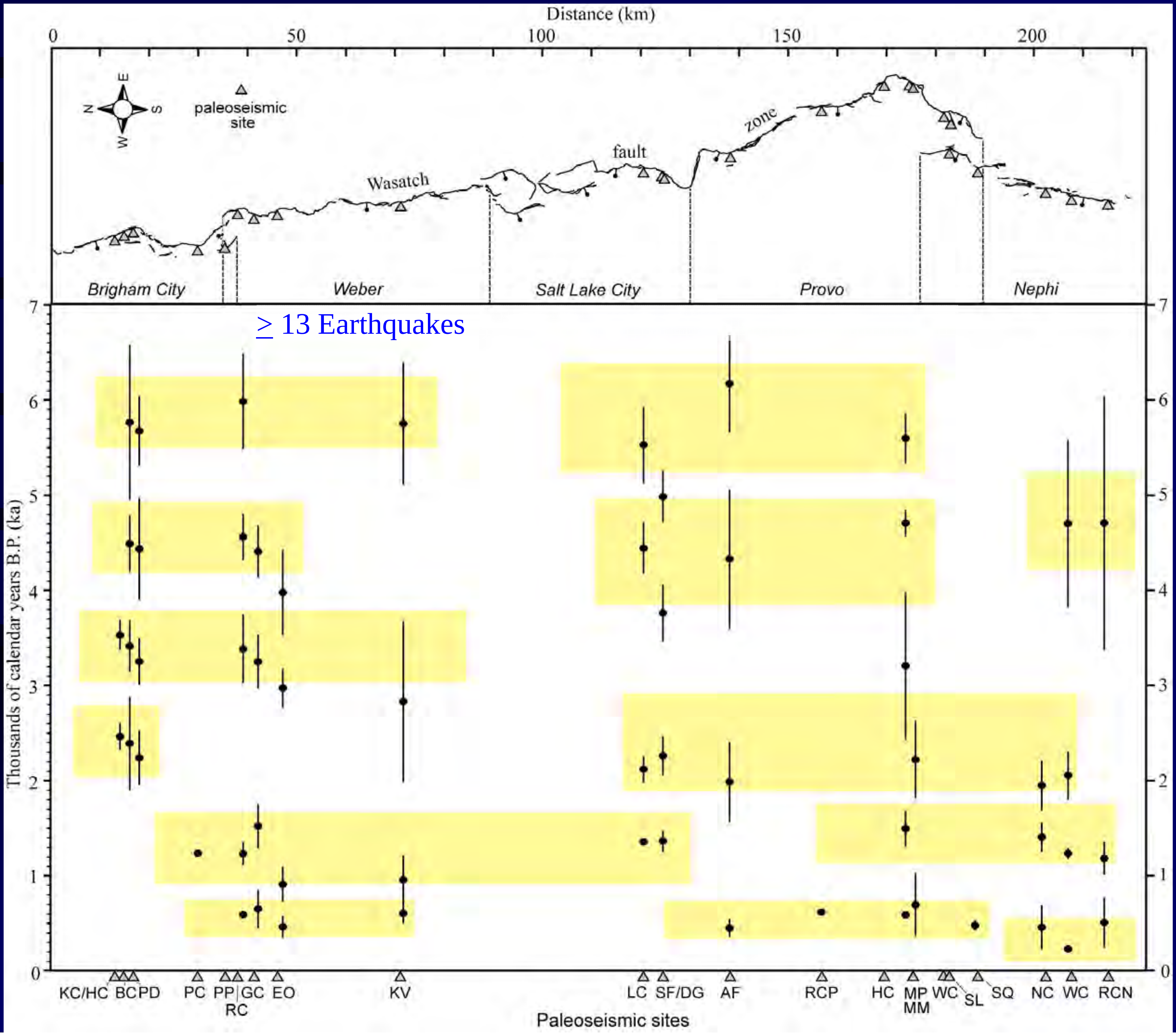


Minimum Rupture Model

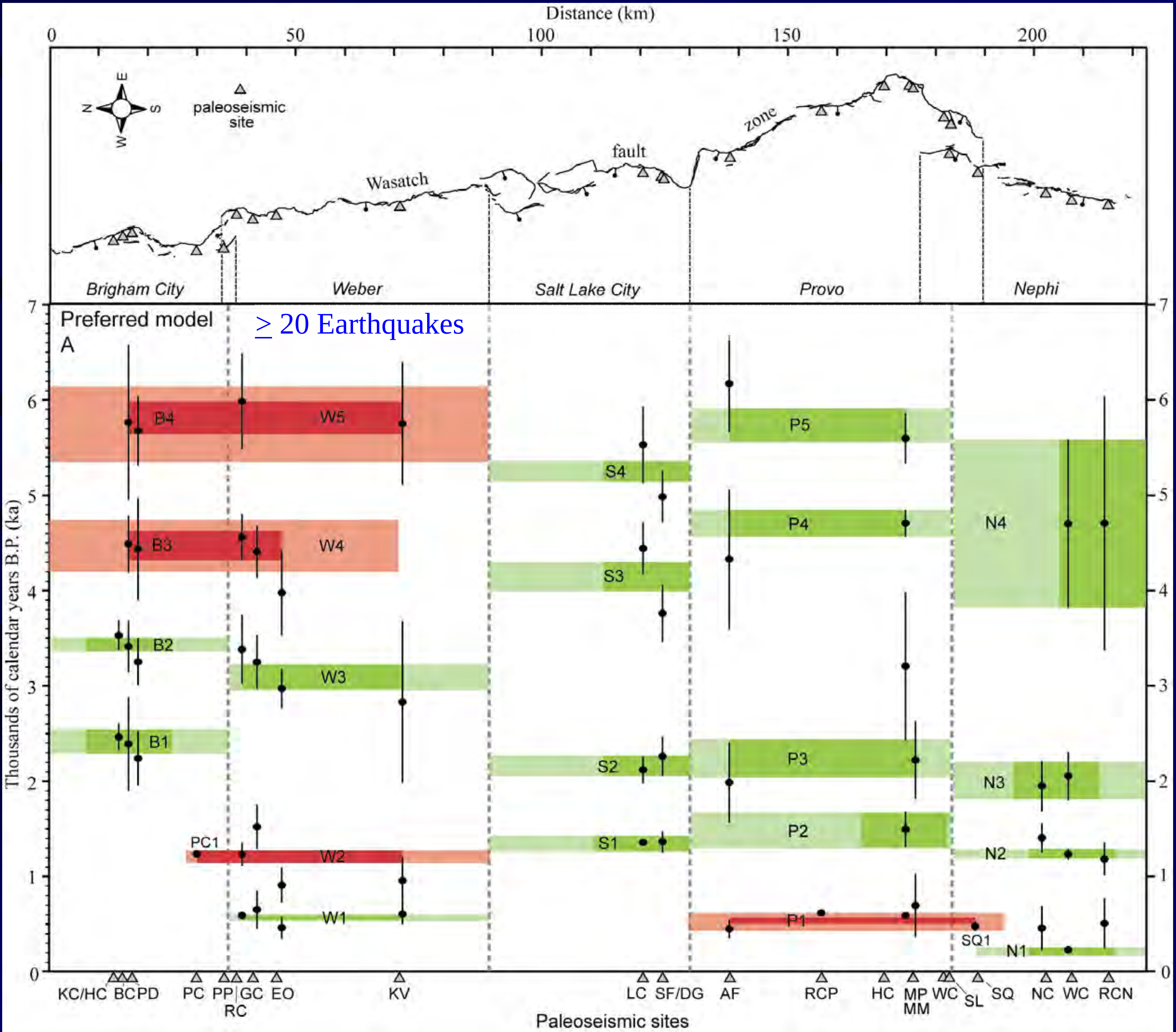
Rupture	Minimum SRL		Maximum SRL		Average SRL
B4-W5	58	Kotter to Kaysville	91	BCS + WS	75
B3-W4	33	Kotter to East Ogden	71	BCS to Kaysville	52
B2-W3	58	Kotter to Kaysville	91	BCS + WS	75
B1	17.5	Min L for M 6.5	36	BCS	27
PC1-W2-S1	95	Pearsons Cyn to South Fork Dry Cr.	104	Willard Cyn to end of SLCS	100
W1	33	Rice Creek to Kaysville	56	WS	45
S4	20	Cottonwood fault length	40	SLCS	30
S3-P4	56	Little Cottonwood to Mapleton N	99	SLCS + PS	78
S2-P3-N3	87	Little Cottonwood to Willow Cr.	127	SLCS + PS + NS (or max 110 km?)	107
P2-N2	41	Mapleton N to Red Cyn	88	PS + NS (both strands)	65
P1-SQ1	50	American Fork to Santaquin	63	PS to end of northern strand, NS	57
N4	17.5	Min L for M 6.5	43	NS (both strands)	30
N1	17.5	Min L for M 6.5	31	Southern strand, NS to Santaquin	24

≥ 13 earthquakes younger than ~6.4 ka

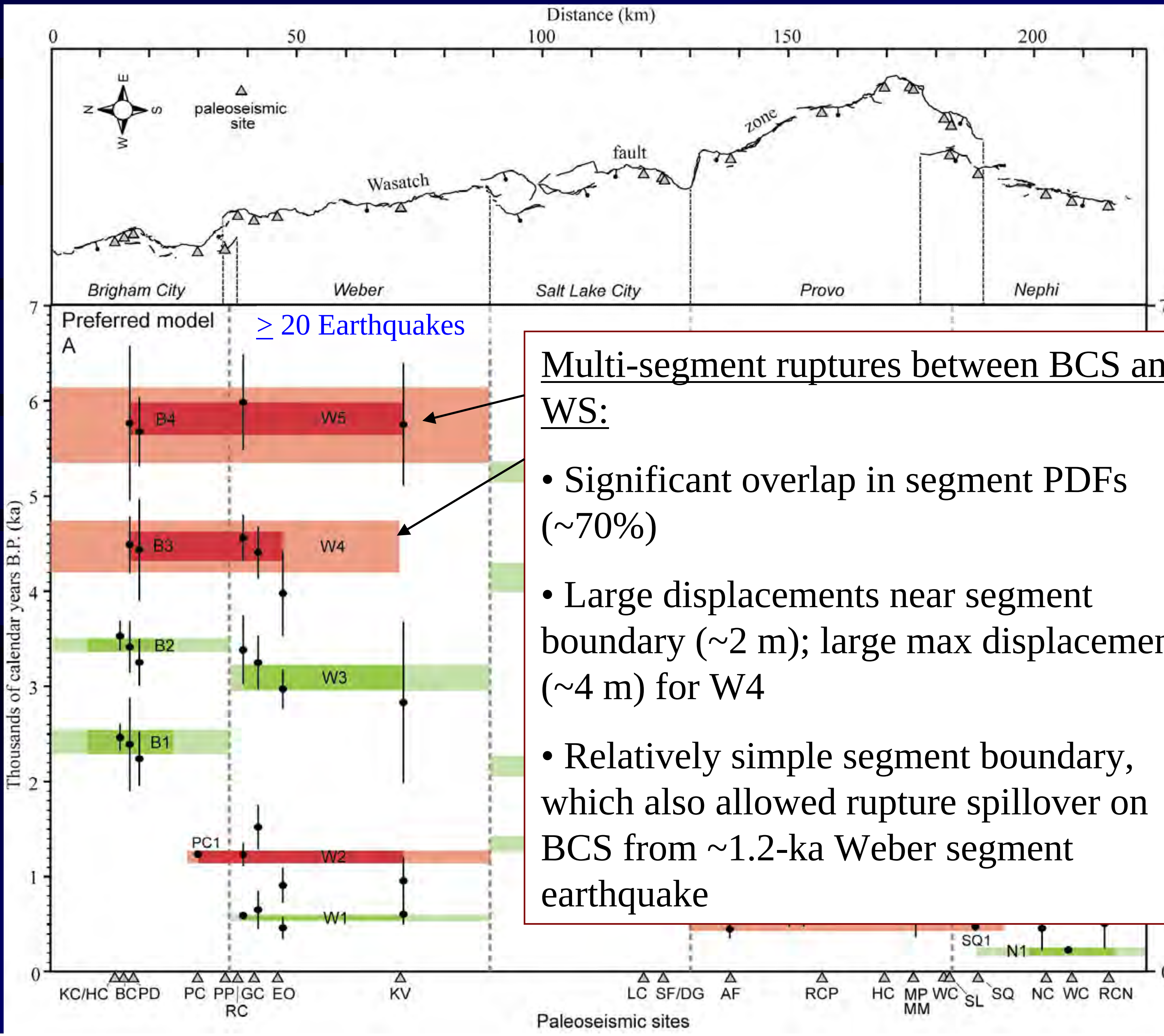
Floating Earthquake Model (test)



Preferred Rupture Model



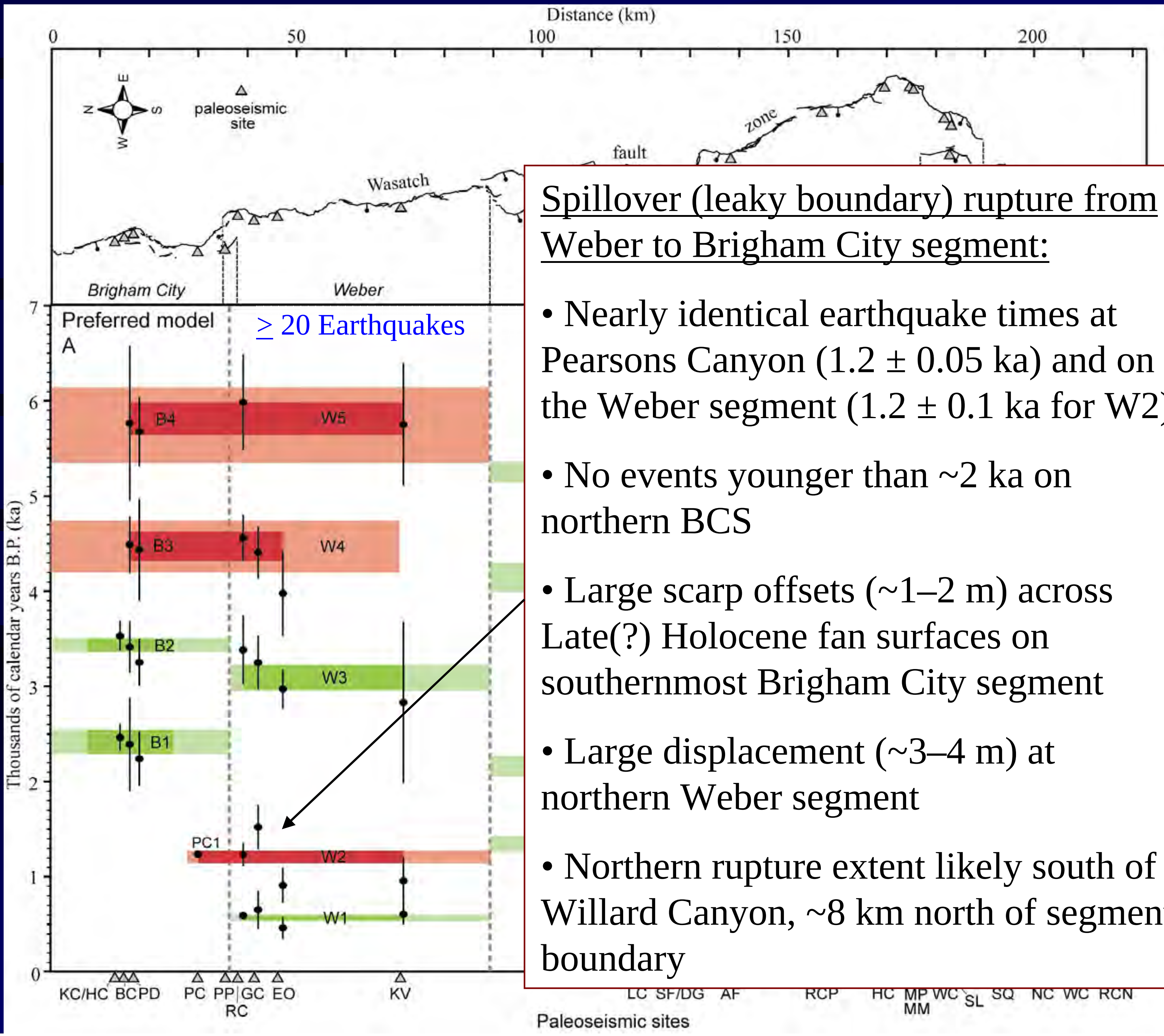
Preferred Rupture Model



<u>Multi-segment ruptures between BCS and WS:</u>

- Significant overlap in segment PDFs (~70%)
- Large displacements near segment boundary (~2 m); large max displacement (~4 m) for W4
- Relatively simple segment boundary, which also allowed rupture spillover on BCS from ~1.2-ka Weber segment earthquake

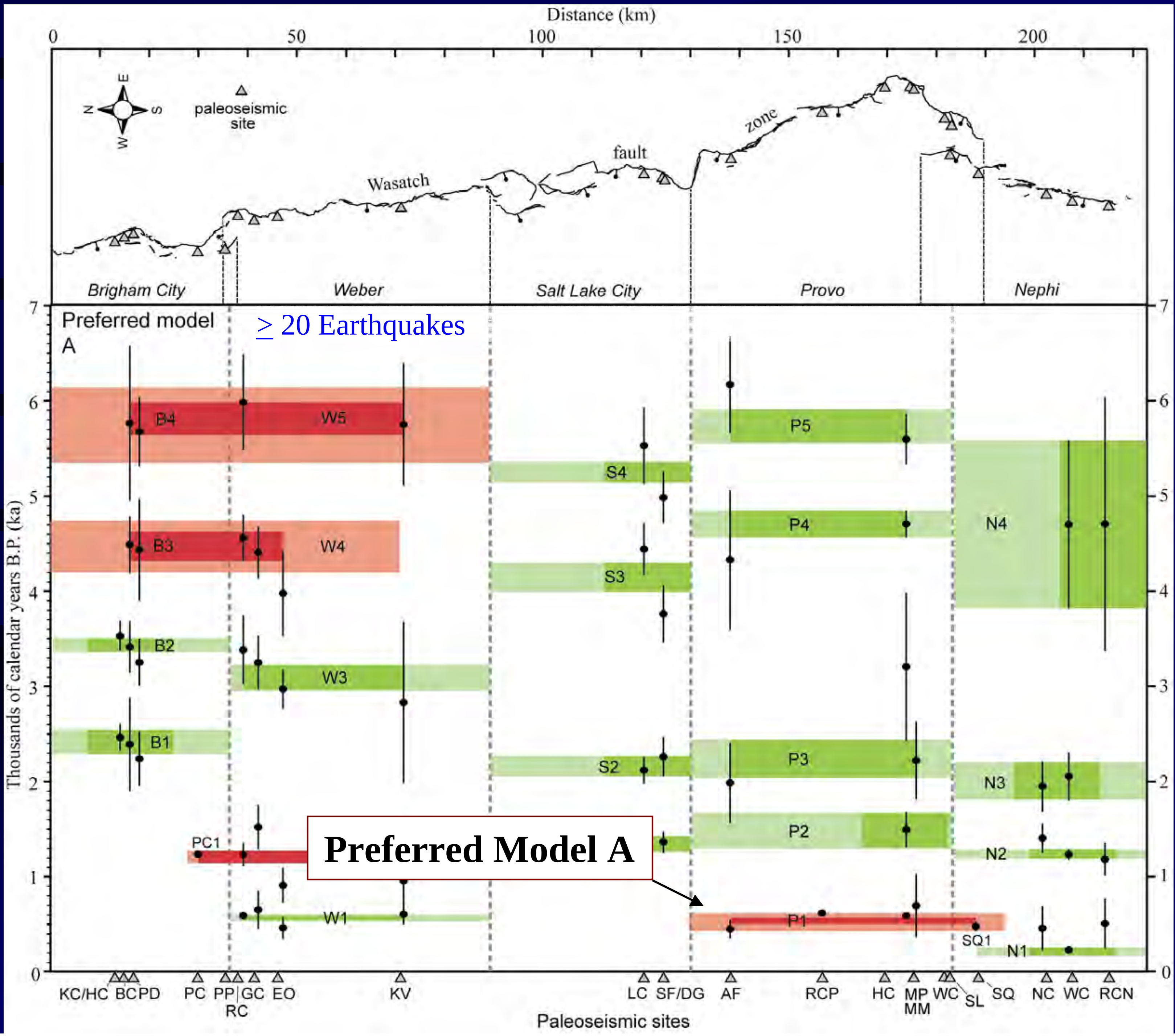
Preferred Rupture Model



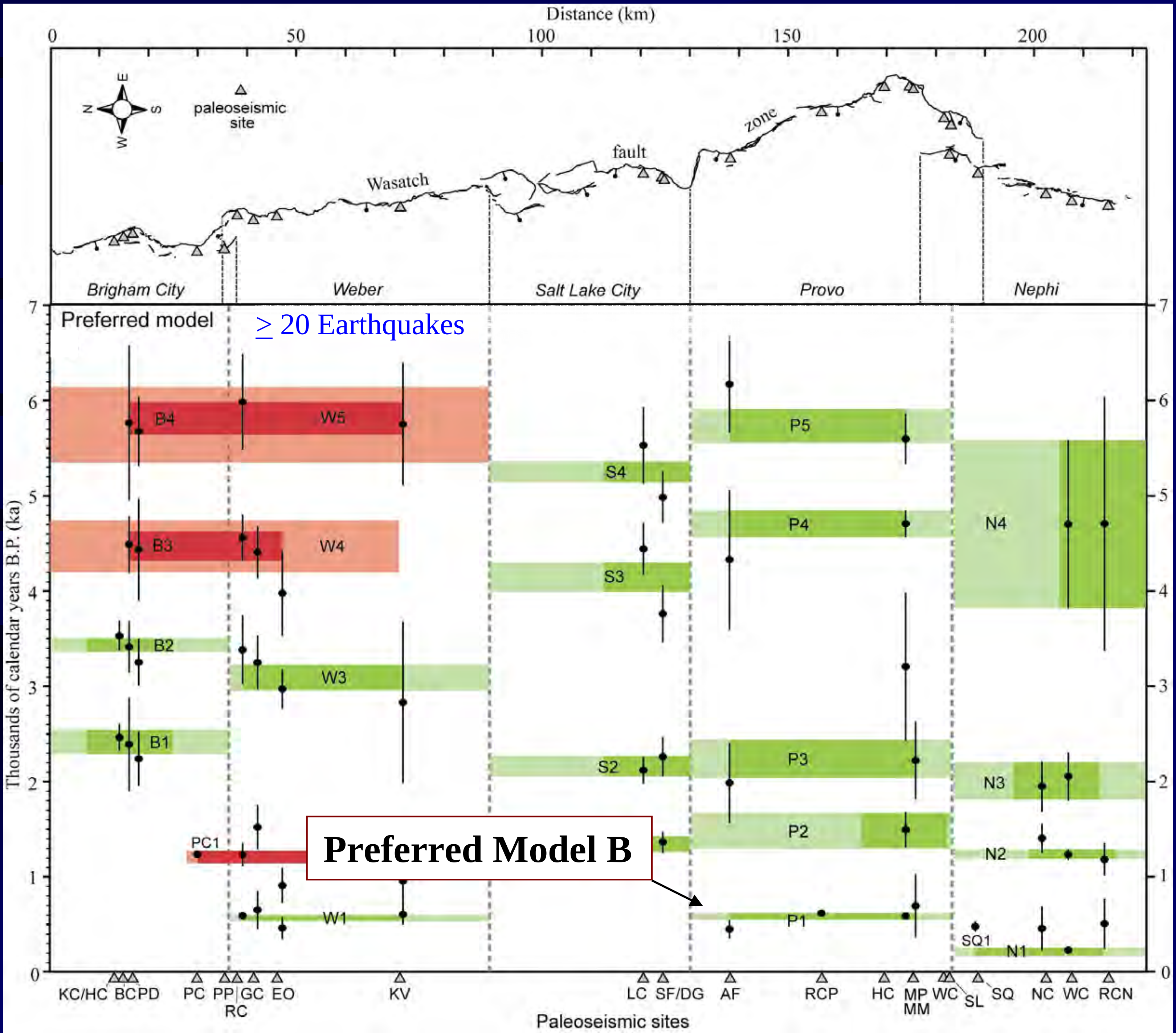
Spillover (leaky boundary) rupture from Weber to Brigham City segment:

- Nearly identical earthquake times at Pearsons Canyon (1.2 ± 0.05 ka) and on the Weber segment (1.2 ± 0.1 ka for W2)
- No events younger than ~2 ka on northern BCS
- Large scarp offsets (~1–2 m) across Late(?) Holocene fan surfaces on southernmost Brigham City segment
- Large displacement (~3–4 m) at northern Weber segment
- Northern rupture extent likely south of Willard Canyon, ~8 km north of segment boundary

Preferred Rupture Model

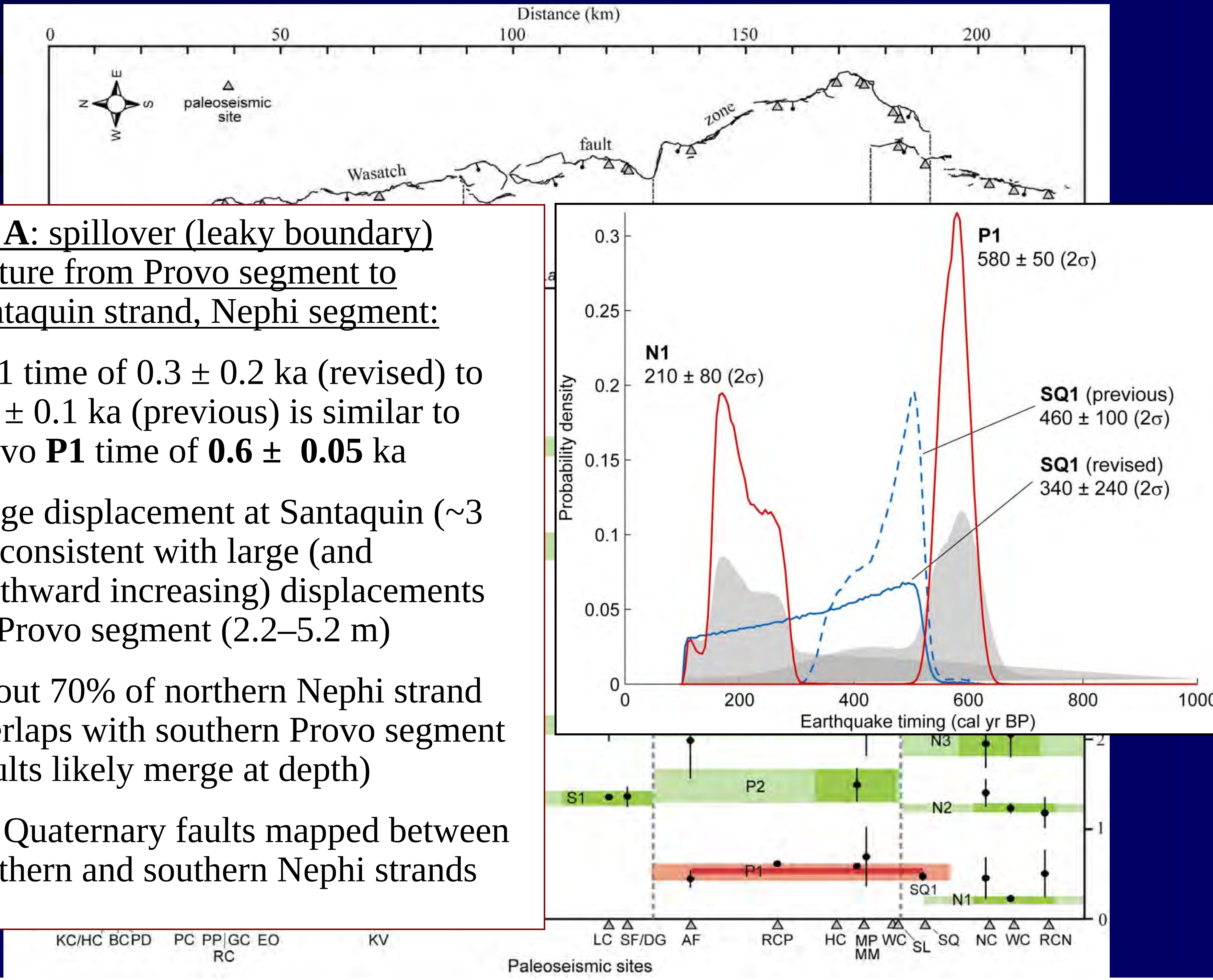


Preferred Rupture Model



Preferred Rupture Model

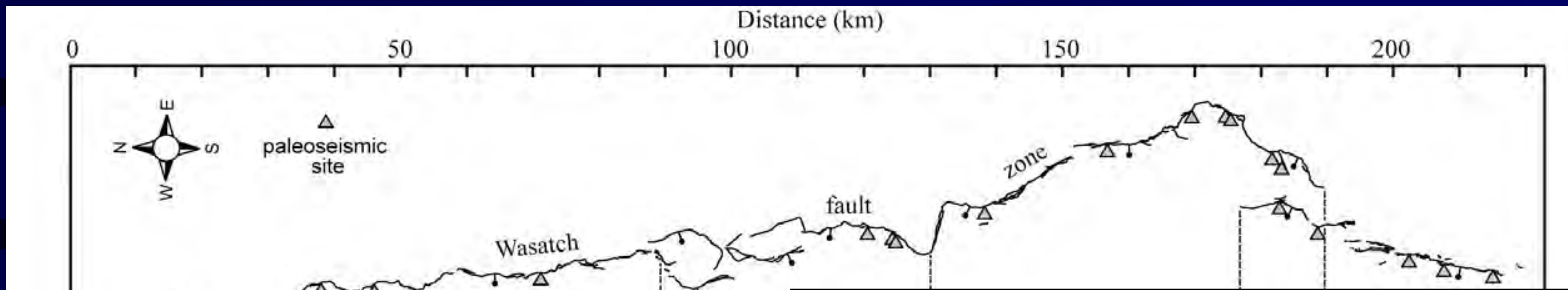
Preferred Rupture Model



Model A: <u>spillover (leaky boundary) rupture from Provo segment to Santaquin strand, Nephi segment:</u>

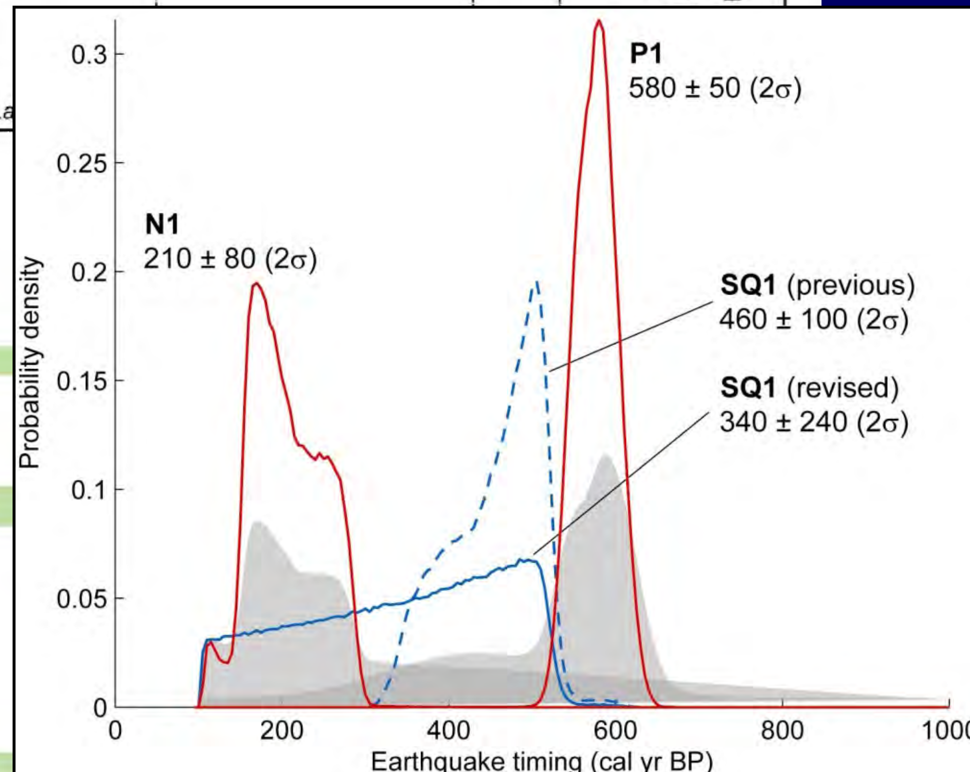
- SQ1 time of 0.3 ± 0.2 ka (revised) to 0.5 ± 0.1 ka (previous) is similar to Provo **P1** time of **0.6 ± 0.05** ka
- Large displacement at Santaquin (~3 m) consistent with large (and southward increasing) displacements on Provo segment (2.2–5.2 m)
- About 70% of northern Nephi strand overlaps with southern Provo segment (faults likely merge at depth)
- No Quaternary faults mapped between northern and southern Nephi strands

Preferred Rupture Model



Model B: Santaquin rupture is part of southern Nephi event N1 (separate P1 earthquake):

- SQ1 time of 0.3 ± 0.2 ka (revised) to 0.5 ± 0.1 ka (previous) is similar to southern Nephi **N1** time of **0.2 ± 0.1** ka
- Less structural relief at ~4-km-wide step over between the northern and southern Nephi strands. ~6-km step over to Provo segment is composed of 9000-ft Dry Mountain

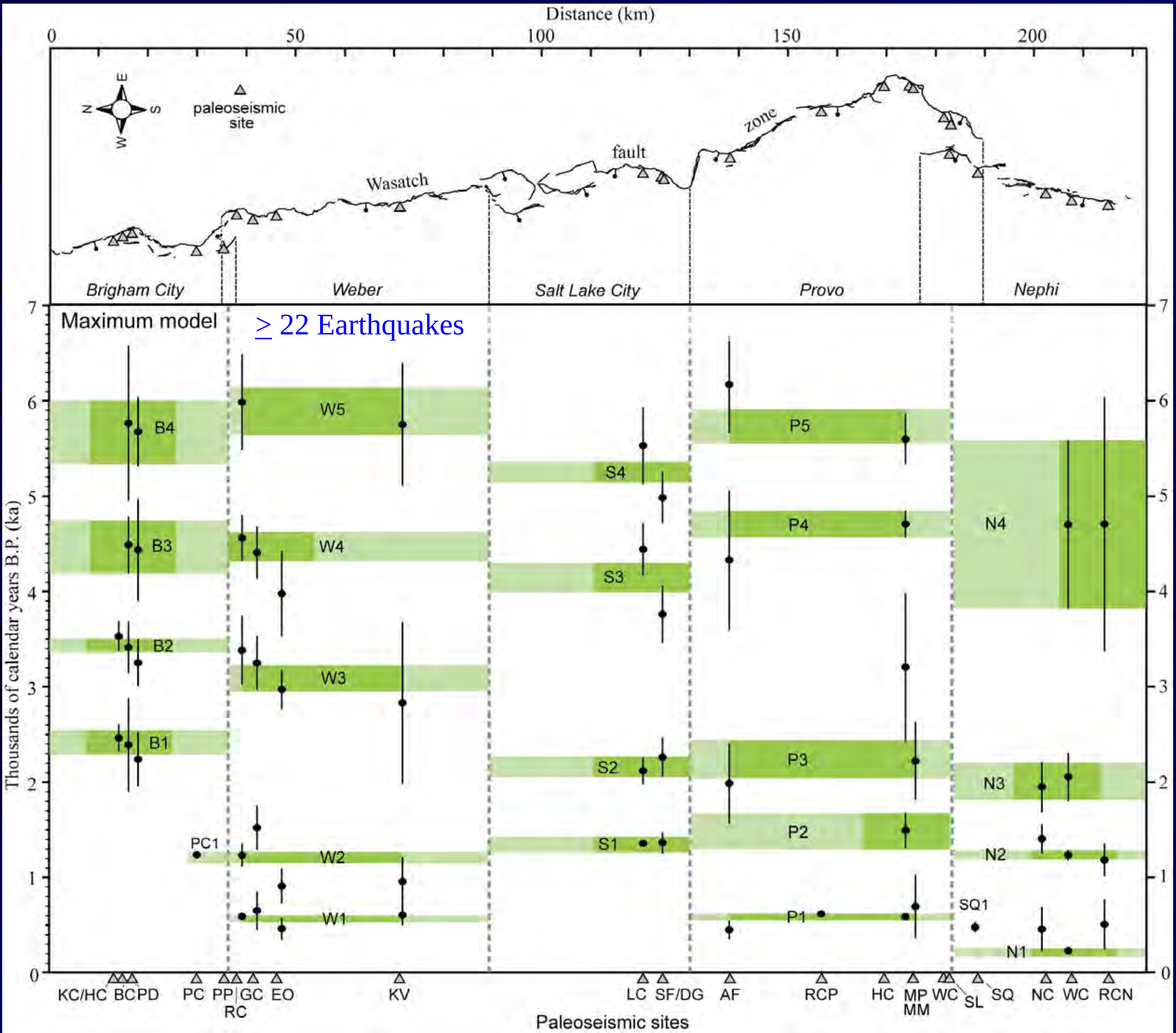


Preferred Rupture Model

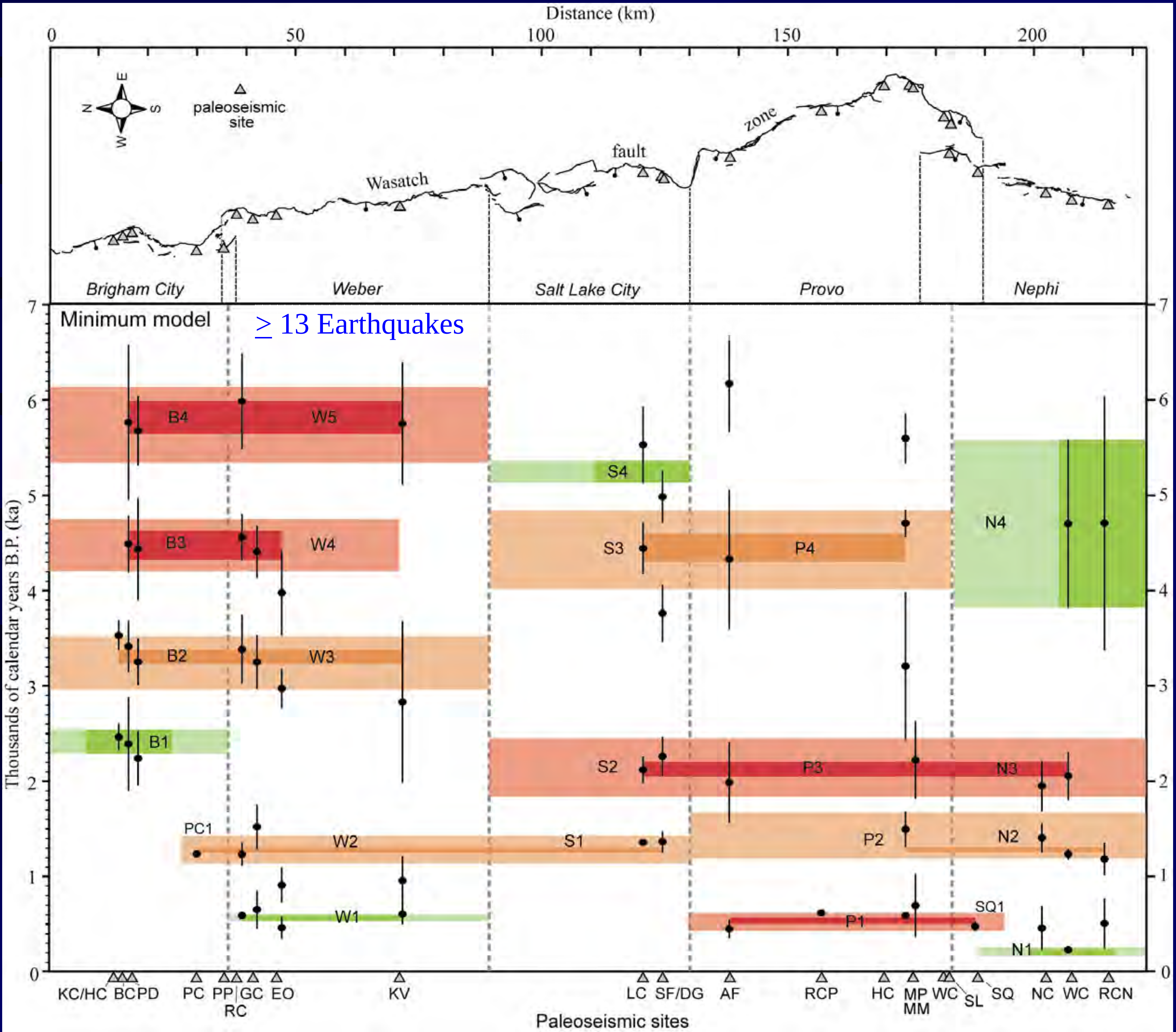
Rupture	Min SRL	Notes	Max SRL	Notes	Average SRL
B4-W5	58	Kotter to Kaysville	91	BCS + WS	75
B3-W4	33	Kotter to East Ogden	71	BCS tov Kaysville	52
B2	17.5	Min L for M 6.5	36	BCS	27
B1	17.5	Min L for M 6.5	36	BCS	27
W3	33	Rice Cr to Kaysville	56	WS	45
PC1-W2	41	Pearson Cyn to Kaysville	65	Willard Cyn to end of WS	53
W1	33	Rice Cr to Kaysville	56	WS	45
S4	20	Cottonwood fault length	40	SLCS	30
S3	20	Cottonwood fault length	40	SLCS	30
S2	20	Cottonwood fault length	40	SLCS	30
S1	20	Cottonwood fault length	40	SLCS	30
P5	39	American Fork to Mapleton N	59	PS	49
P4	39	American Fork to Mapleton N	59	PS	49
P3	39	American Fork to Mapleton S	59	PS	49
P2	17.5	Min L for M 6.5	59	PS	38
N4	17.5	Min L for M 6.5	43	NS (both strands)	30
N3	17.5	Min L for M 6.5	43	NS (both strands)	30
N2	17.5	Min L for M 6.5	43	NS (both strands)	30
Scenario A					
P1-SQ1	50	American Fork to Santaquin	63	PS to end of northern strand, NS	57
N1	17.5	Min L for M 6.5	31	Southern strand, NS to Santaquin	24
Scenario B					
P1	39	American Fork to Mapleton S	59	PS	49
N1	27	Santaquin to Red Canyon	43	NS (both strands)	35

$\geq$ 20 earthquakes younger than ~6.4 ka

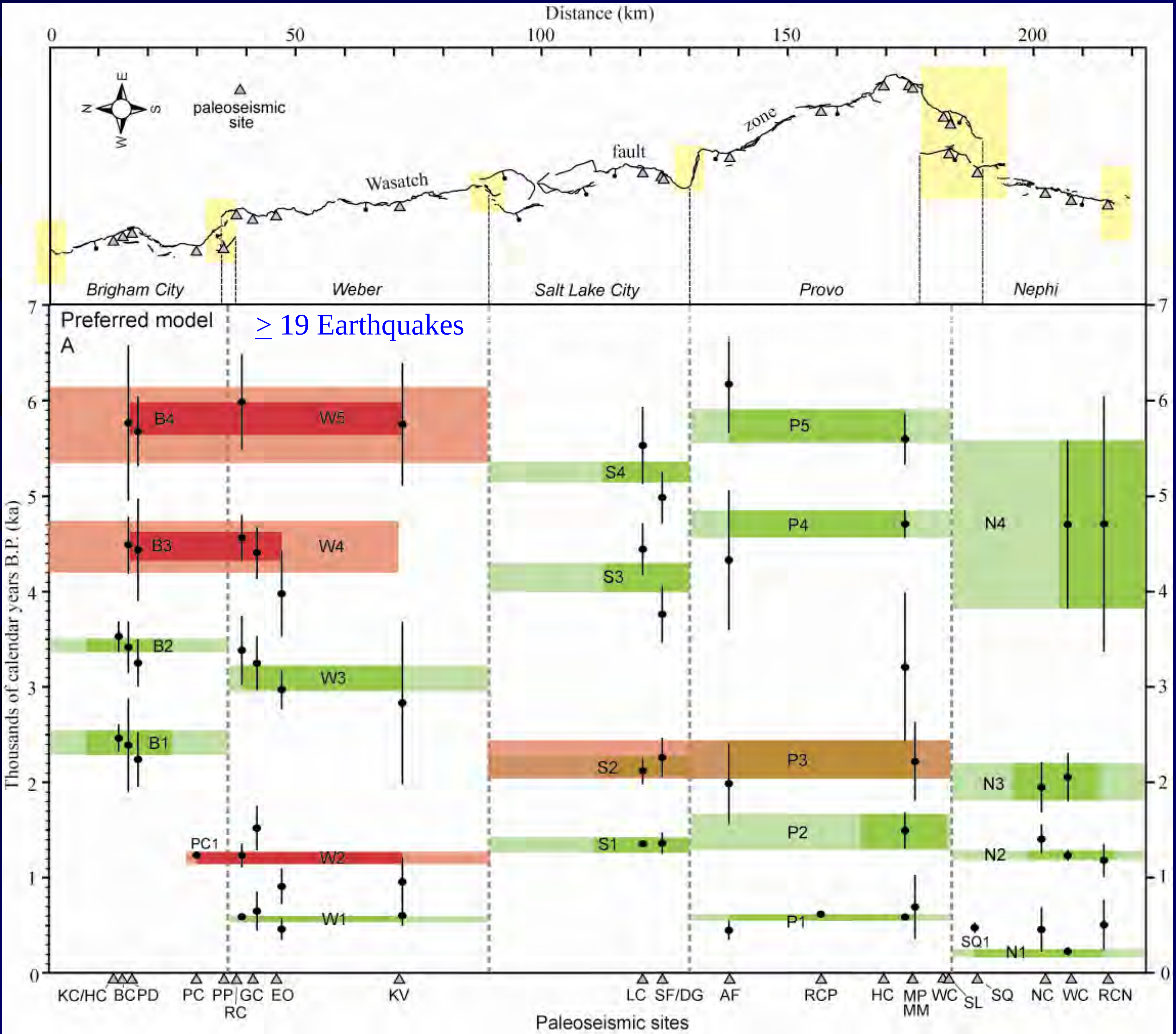
Maximum Rupture Model



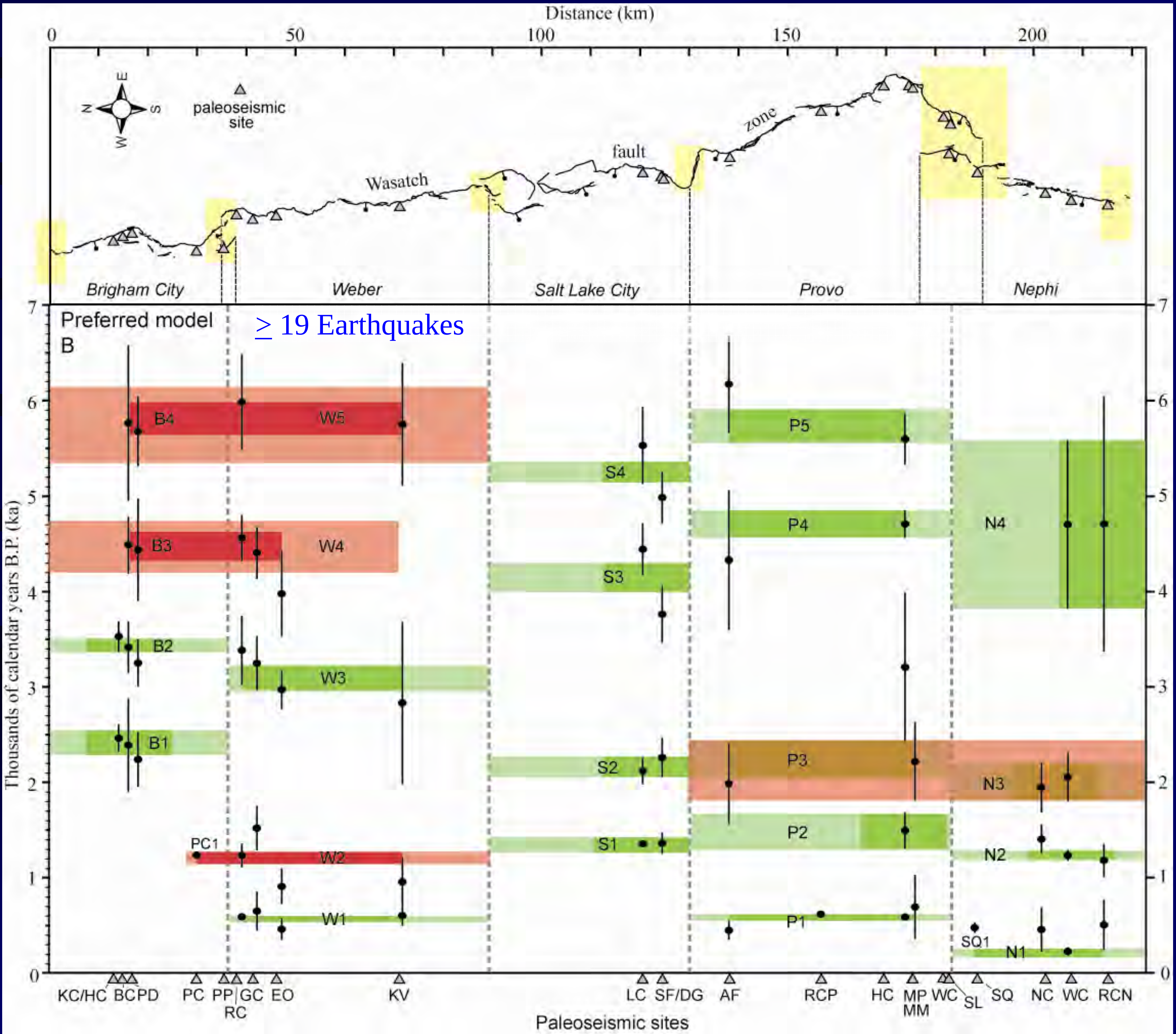
Minimum Rupture Model



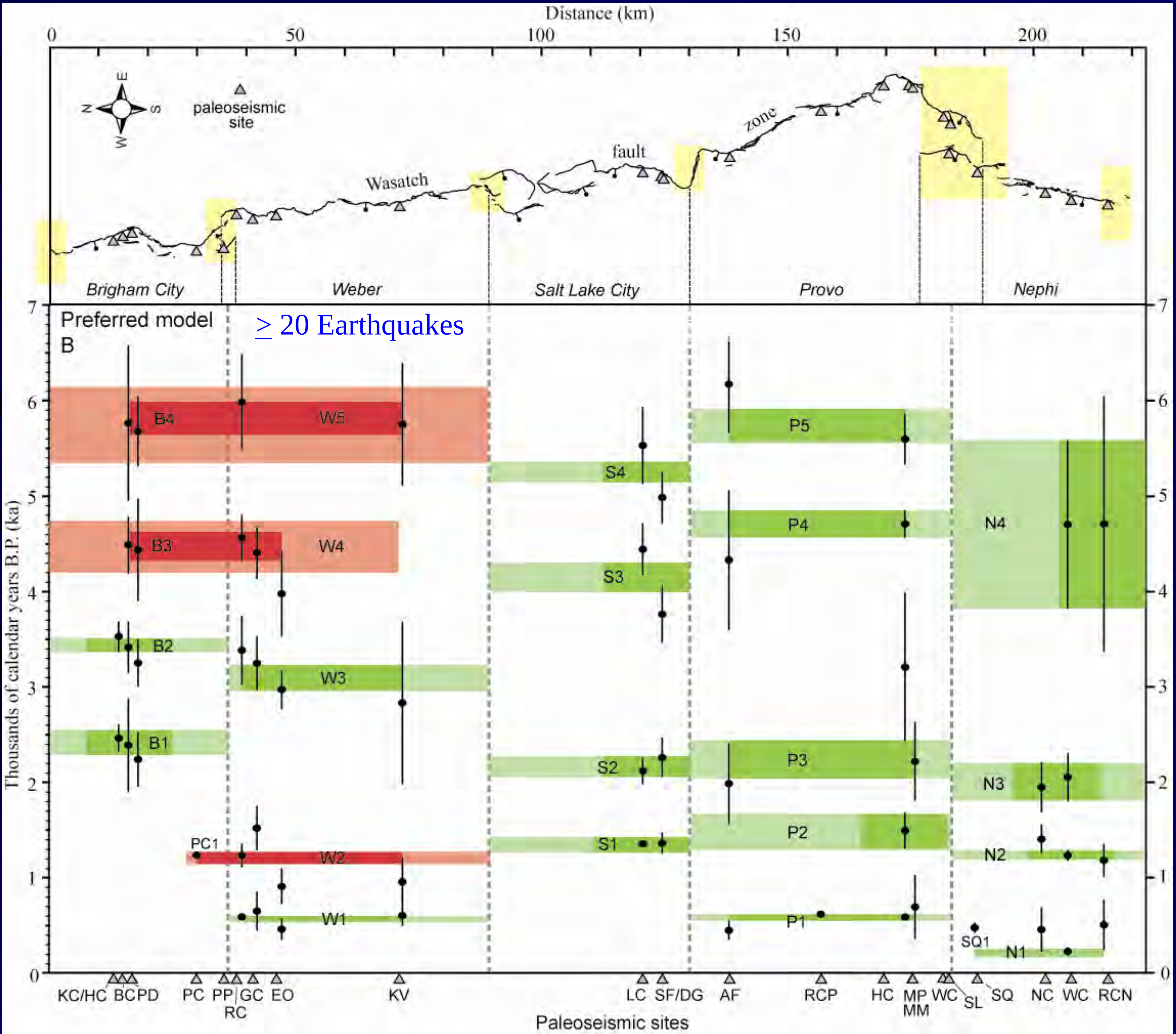
Intermediate Model A



Intermediate Model B



Intermediate Model C



Path Forward

Rupture Scenario	Weight
Maximum Rupture Model (22 EQs <6.4 ka)	___%
Minimum Rupture Model (13 EQs <6.4 ka)	___%
Intermediate Rupture Model A (S2-P3 combined (19 EQs <6.4 ka)	___%
Intermediate Rupture Model B (P3-N3 combined (19 EQs <6.4 ka)	___%
Intermediate Rupture Model C (S2/P3/N3 separate (20 EQs <6.4 ka)	___%
Unsegmented Earthquake Model	___%

Revised Earthquake Timing and Recurrence for the Central Wasatch Fault

Paleoseismology Subgroup

(Chris DuRoss, Steve Personius, Tony Crone, Susan Olig, and Bill Lund)

Working Group on Utah Earthquake Probabilities, December, 2010

Paleoseismology Subgroup

Main Tasks:

- Discuss OxCal/Matlab methods and finalize earthquake timing and recurrence per segment
- Develop WFZ rupture models and determine rupture lengths for various rupture models

Revised Earthquake Timing and Recurrence

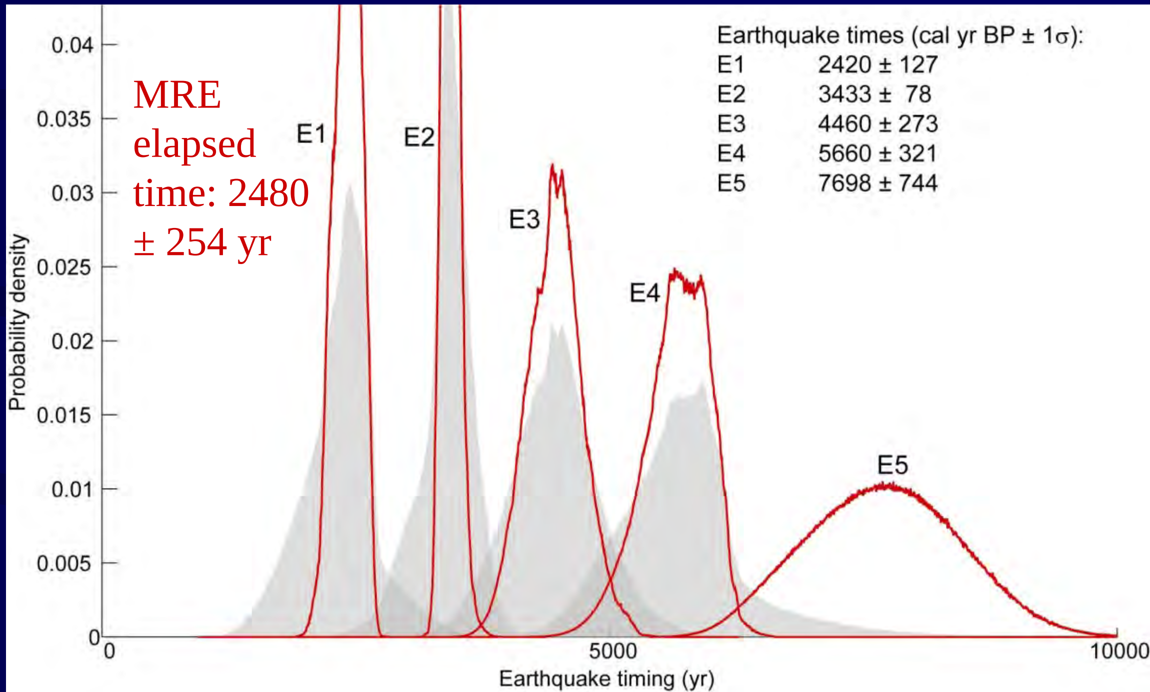
- <u>Final earthquake timing</u> (and uncertainties)
  - Final results based on <u>product-PDF method</u> of refining segment PDFs
  - Review of product method by Glenn Biasi
    - Reasonable approach – especially for broadly constrained PDFs
    - Supported by literature (~maximum likelihood estimation method)
    - Careful not to over constrain events
  - We reviewed all site PDFs and final segment PDFs, paying close attention to those that could be considered over constrained (and revised as necessary)
- <u>Average recurrence</u>
  - Using closed intervals: Elapsed time between oldest and youngest events divided by number of intervals
  - Using open interval from most recent earthquake to 2010 (but not open interval prior to oldest event)
  - Mean of individual EQ recurrence intervals (e.g., E4-E3, E3-E2, E2-E1)

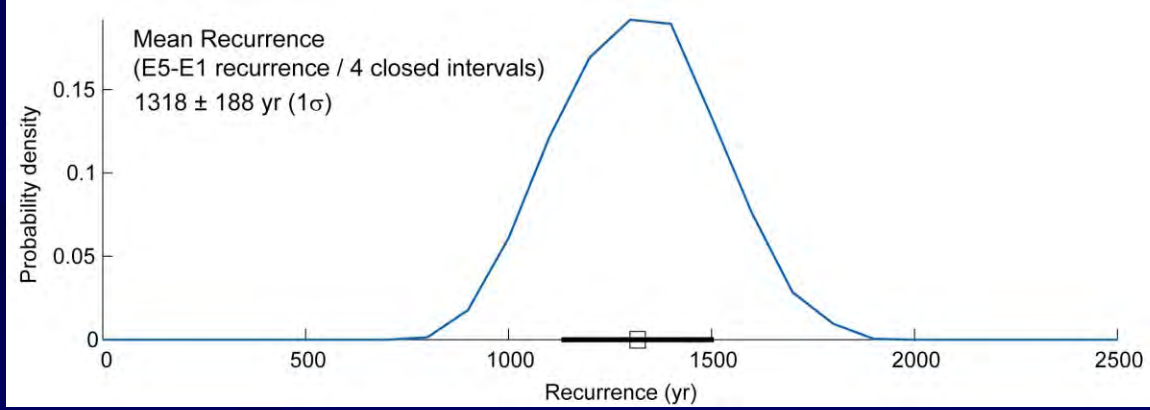
Brigham City Segment Summary

- EQ Chronology (no changes)
  - E1 2.4 ± 0.3 ka (2σ)
  - E2 3.4 ± 0.2 ka
  - E3 4.5 ± 0.5 ka
  - E4 5.7 ± 0.6 ka
  - E5 7.7 ± 1.5 ka

- Recurrence
  - Average recurrence (4 closed intervals between E5 and E1): 1.3 ± 0.4 ky
  - E5–present (including MRE elapse time): 1.5 ± 0.3 ky
  - Mean of individual recurrence intervals (E5–E1): 1.3 ± 1.3 ky (2σ)

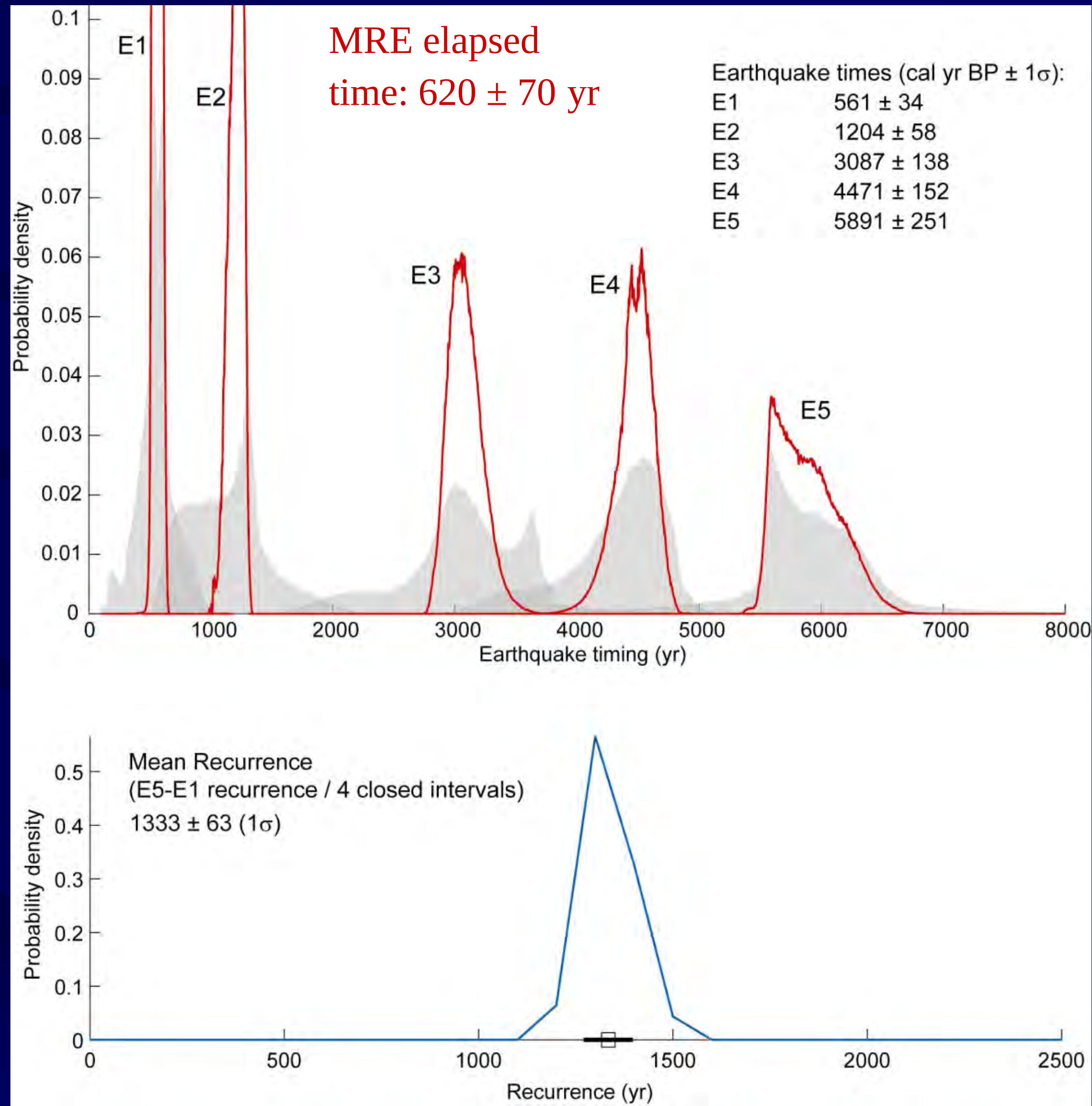
- Miscellaneous
  - PC1 occurred at ~1.2 ka as partial rupture of southern BCS in 1.1-1.3 ka Weber segment earthquake





Weber Segment Summary

- EQ Chronology (no changes)
  - E1 0.6 ± 0.1 ka (2σ)
  - E2 1.2 ± 0.1 ka
  - E3 3.1 ± 0.3 ka
  - E4 4.5 ± 0.3 ka
  - E5 5.9 ± 0.5 ka
- Recurrence
  - Average recurrence (4 closed intervals between E5 and E1): 1.3 ± 0.1 ky
  - E5–present (including MRE elapse time): 1.2 ± 0.1 ky
  - Mean of individual recurrence intervals (E5–E1): 1.3 ± 1.0 ky (2σ)
- Miscellaneous
  - Southern extent of E2 rupture (at Kaysville site) uncertain (but this doesn't affect E2 mean time)

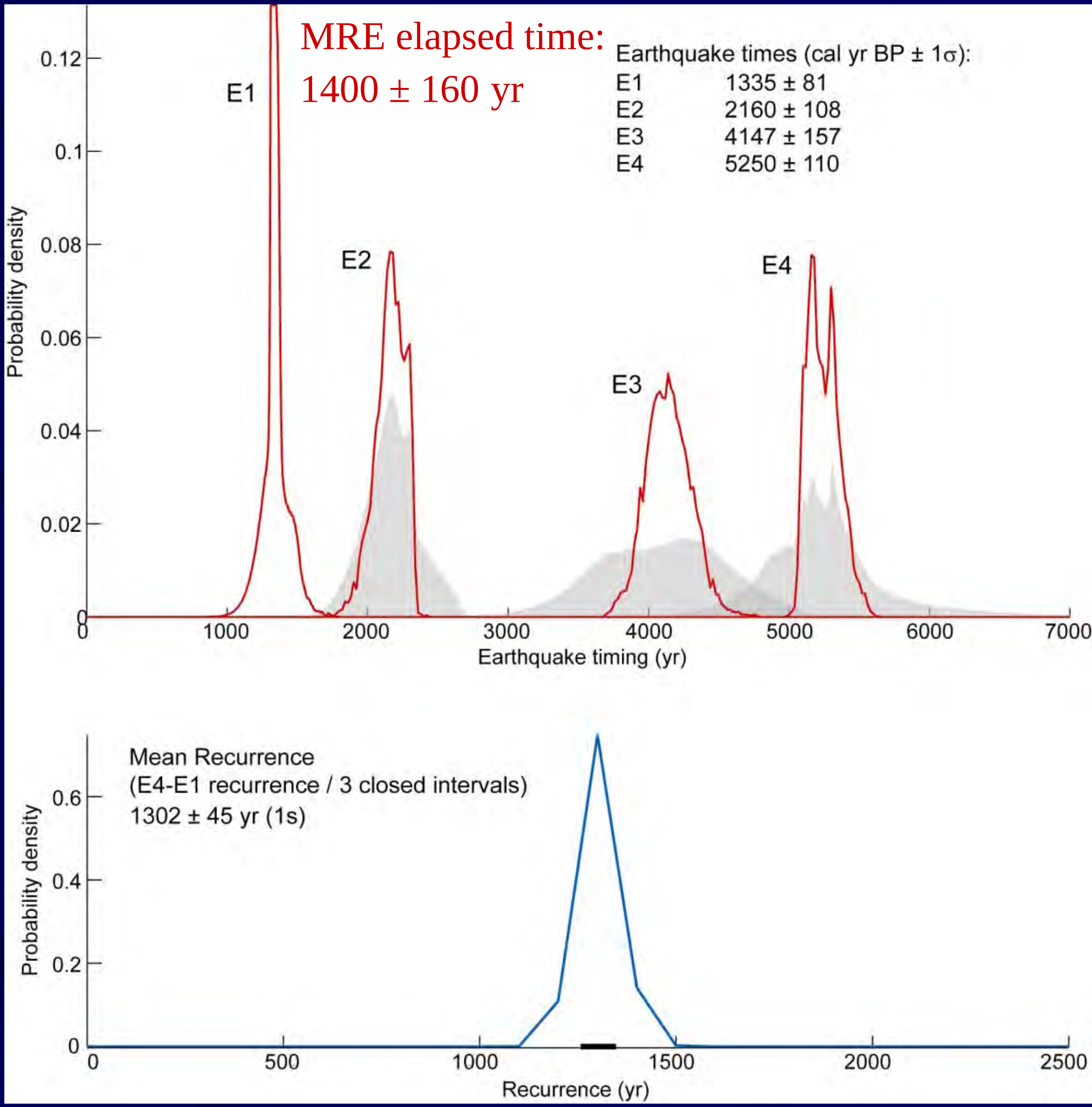


Salt Lake City Segment Summary

- EQ Chronology (change to E1)
  - E1 1.3 ± 0.2 ka (2σ)
  - E2 2.2 ± 0.2 ka
  - E3 4.1 ± 0.3 ka
  - E4 5.3 ± 0.2 ka

- Recurrence
  - Average recurrence (3 closed intervals between E4 and E1): 1.3 ± 0.1 ky
  - E4–present (including MRE elapse time): 1.3 ± 0.05 ky
  - Mean of individual recurrence intervals (E4–E1): 1.3 ± 1.1 ky (2σ)

- Miscellaneous
  - Using average, rather than product, of site PDFs for E1
  - No data (yet) for northern SLCS

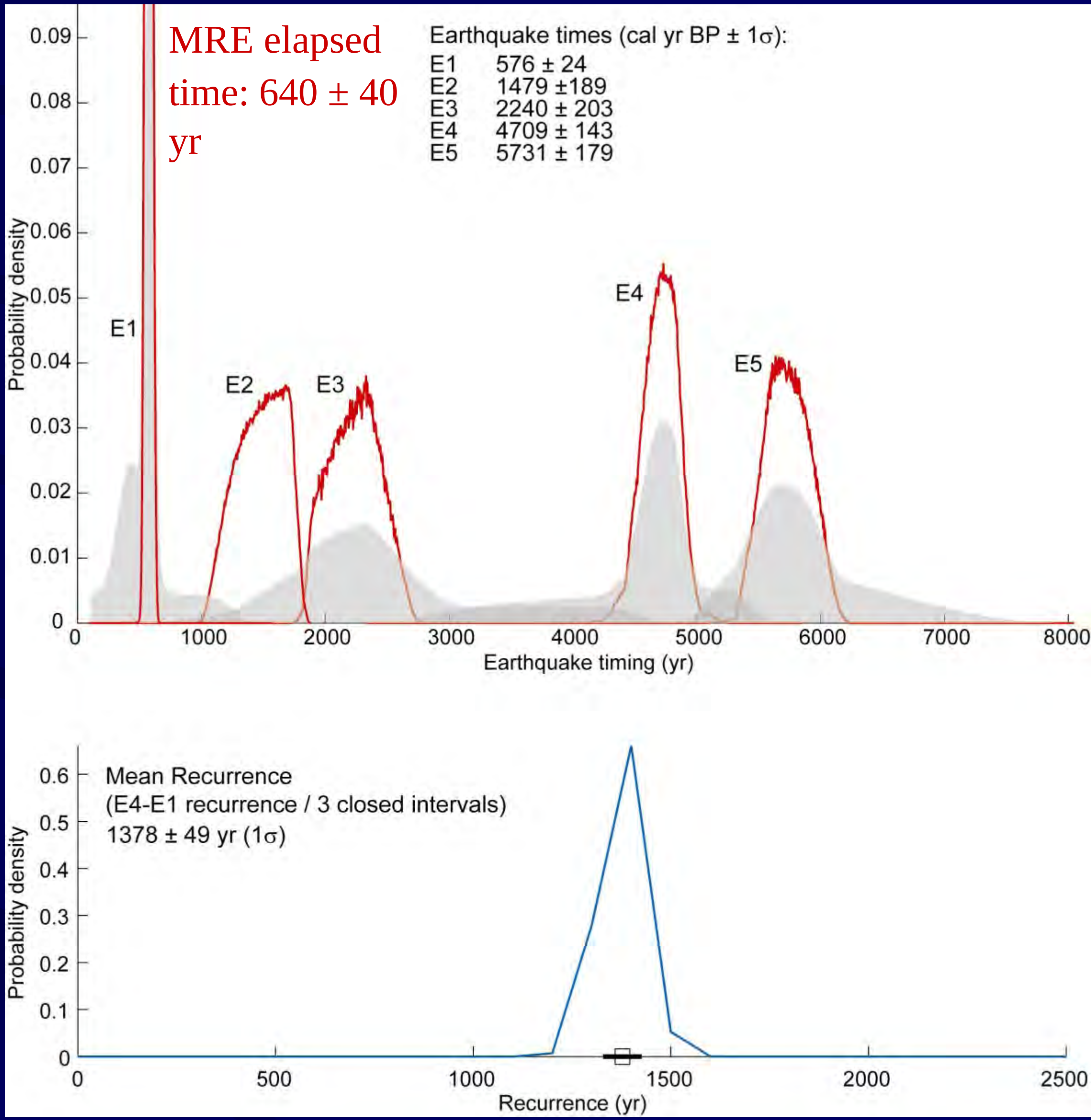


Provo Segment Summary

- EQ Chronology (using maximum record, but without E0)
  - E1 0.6 ± 0.05 ka (2σ)
  - E2 1.5 ± 0.4 ka
  - E3 2.2 ± 0.4 ka
  - E4 4.7 ± 0.3 ka
  - E5(?) 5.7 ± 0.4 ka

- Recurrence
  - Average recurrence (3 closed intervals between E4 and E1): 1.4 ± 0.1 ky
  - E4–present (including MRE elapse time): 1.2 ± 0.1 ky
  - Mean of individual recurrence intervals (E4–E1): 1.4 ± 1.6 ky (2σ)

- Miscellaneous
  - Chronology based on preferred correlation of site PDFs; other correlation schemes are possible, but these do not affect timing of E1 and E4, or the average recurrence

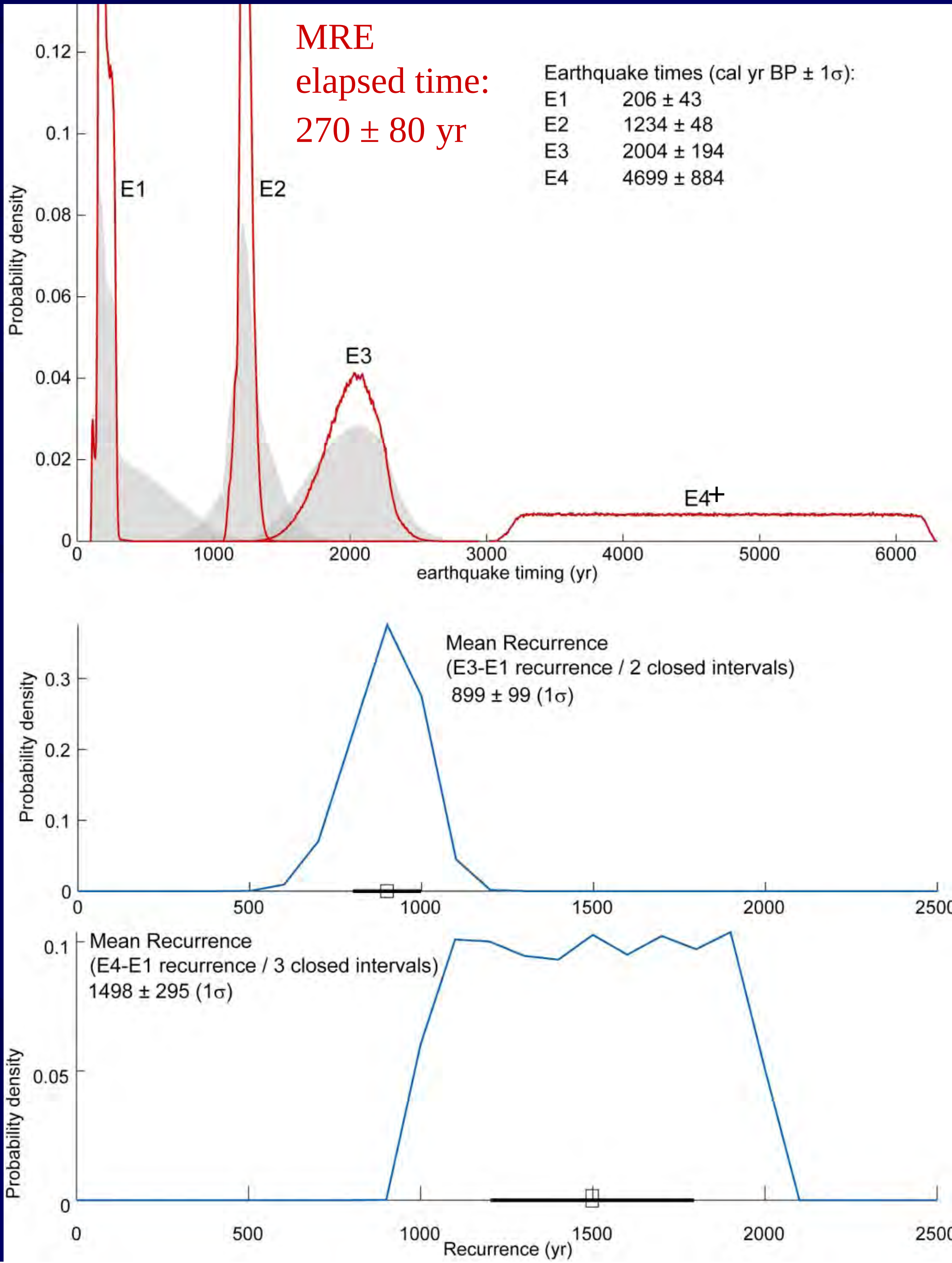


Nephi Segment Summary

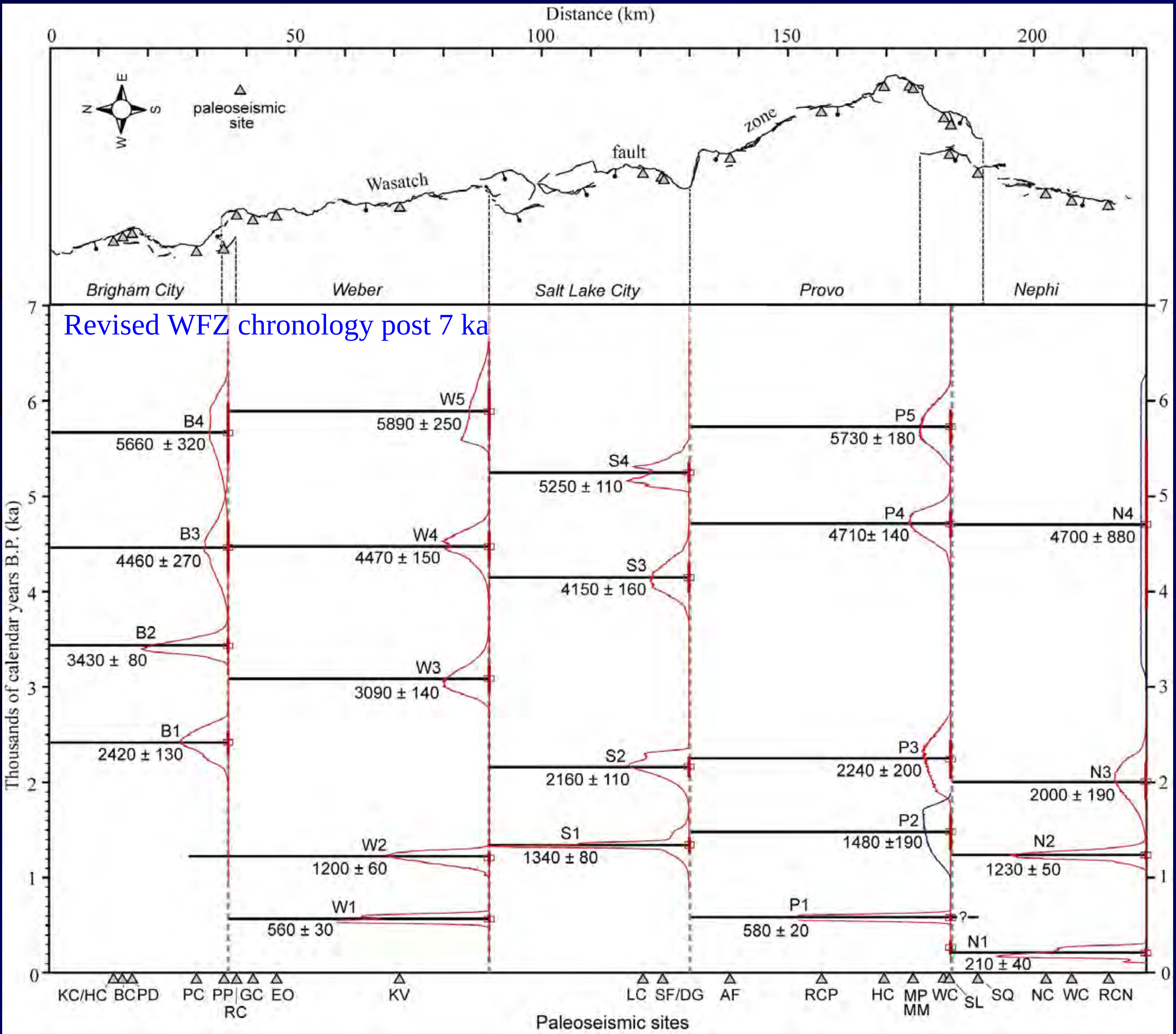
- EQ Chronology (no changes)
  - E1 0.2 ± 0.1 ka (2σ)
  - E2 1.2 ± 0.1 ka
  - E3 2.0 ± 0.4 ka
  - E4(?) 4.7 ± 1.8 ka

- Recurrence
  - Average recurrence (2σ)
    - 2 intervals (E3-E1): 0.9 ± 0.2 ky
    - ≥3 intervals (E4-E1): ≤1.5 ± 0.6 ky
  - E3–present: 0.7 ± 0.1 ky
  - E4–present: 1.2 ± 0.4 ky
  - Mean of individual recurrence intervals (E3–E1): 0.9 ± 0.4 ky

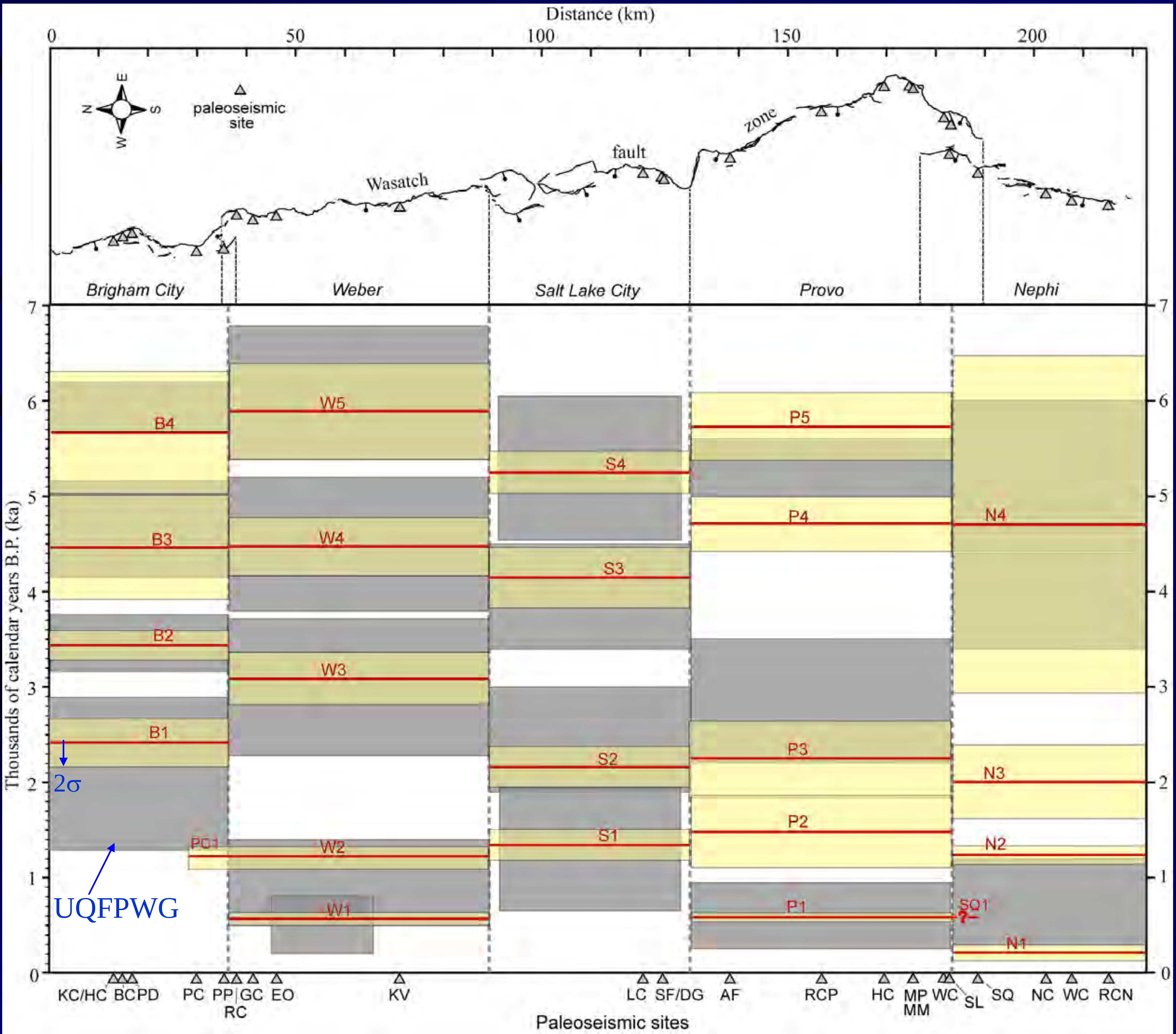
- Miscellaneous
  - Does Santaquin SQ1 correlate with Nephi (N1) or Provo (P1) segment?



Final WFZ Chronology



Comparison with UQFPWG



The Wasatch Fault Zone End Segments

(Malad City, Clarkston Mountain, Collinston, Levan, & Fayette)

Geologic and Paleoseismic Constraints on Displacement, Slip Rate, and Recurrence

Michael Hylland
Utah Geological Survey

Working Group on Utah Earthquake Probabilities – July 2010

Northern Segments

Malad City Segment

Paleoseismic data: none

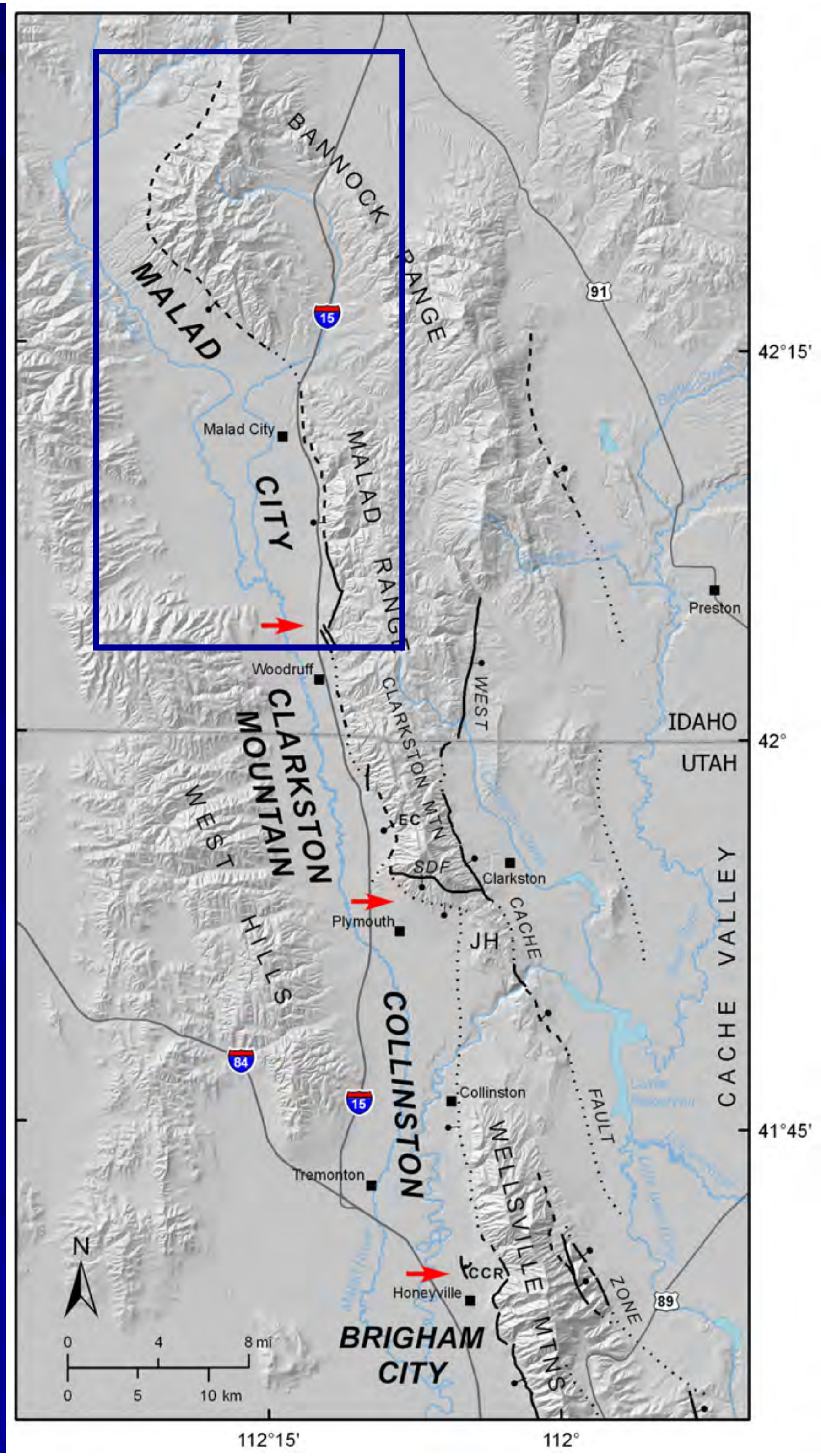
Geologic constraints:
•Bonneville lake-cycle deposits are not faulted
•Fault scarps are present on late Quaternary deposits (“older” alluvium)
•Steep range-front geomorphology
•Steep, linear gravity gradients

Earthquake timing:
Geologic data suggest active faulting during the late Pleistocene (pre-Bonneville)

Slip rate:
•Database slip rate category: <0.2 mm/yr
•Slip rate estimate:
≤1.5 m in >18,000 yr = 0.08 mm/yr (max)

Recurrence interval: NA (no individual earthquake timing data)

Sources:
Cluff et al. (1974), Machette et al. (1992), Pope et al. (2001)

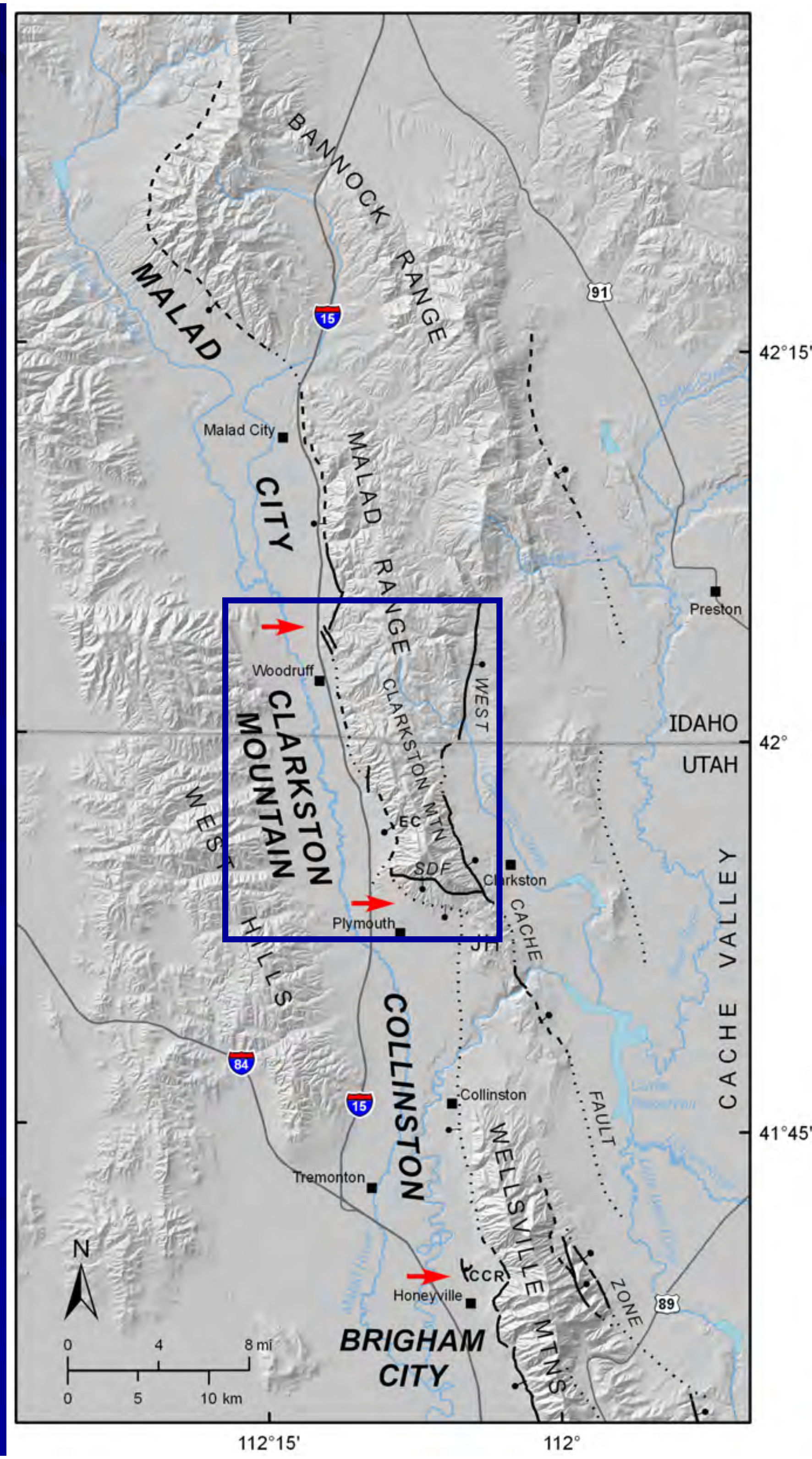


Northern Segments

Clarkston Mountain Segment

Paleoseismic data:
- •Field reconnaissance
- •Scarp profiling and empirical analysis
  - •Elgrove Canyon
  - •Composite scarp (2 or perhaps 3 events)
  - •MRE & PE surface offset ≈2 m

Geologic constraints:
- •Bonneville lake-cycle deposits are not faulted
- •Fault scarps are present on late Quaternary deposits (“Bonneville and older” alluvium)
- •Steep range-front geomorphology
- •Steep, linear gravity gradients

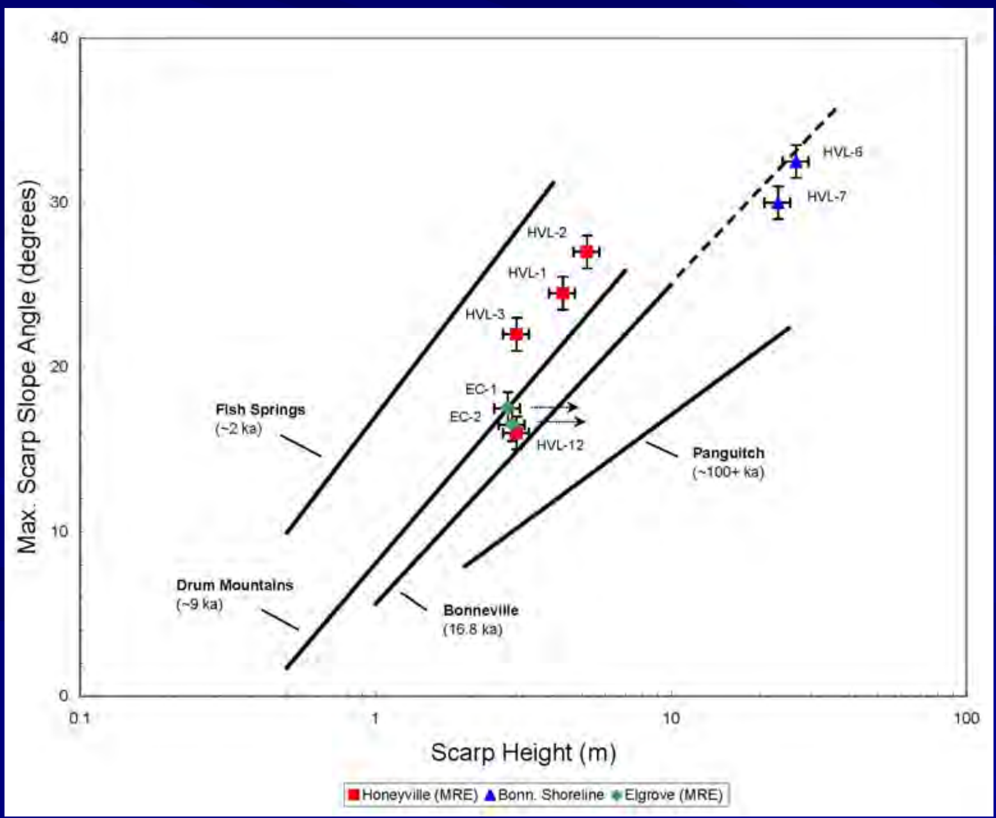


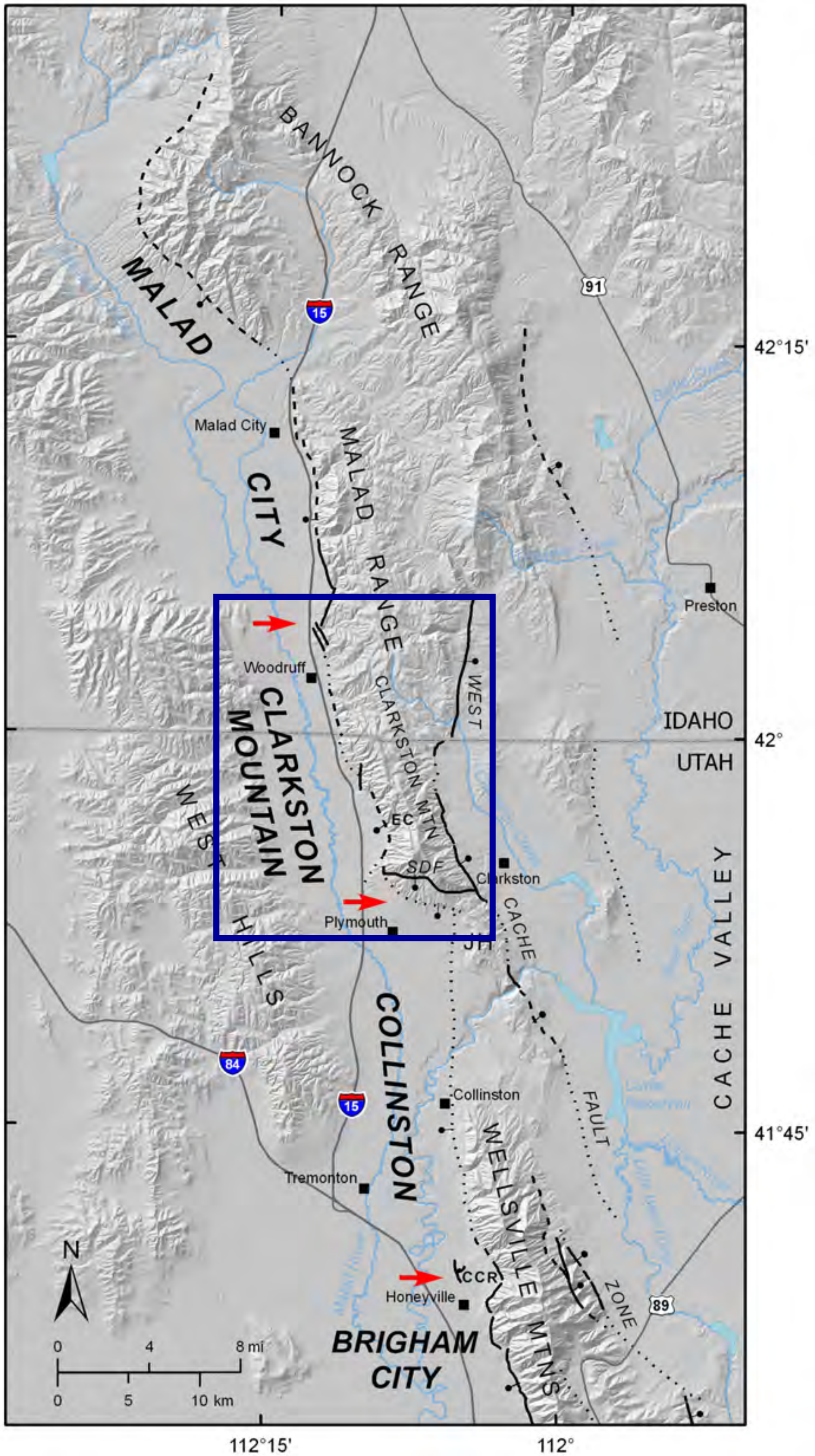
Northern Segments

Clarkston Mountain Segment

Earthquake timing:

- MRE—empirical scarp profile analysis indicates early Holocene (likely a minimum age estimate)
- PE timing unknown
- Geologic data suggest active faulting during the late Pleistocene (during or before end of Bonneville lake cycle)





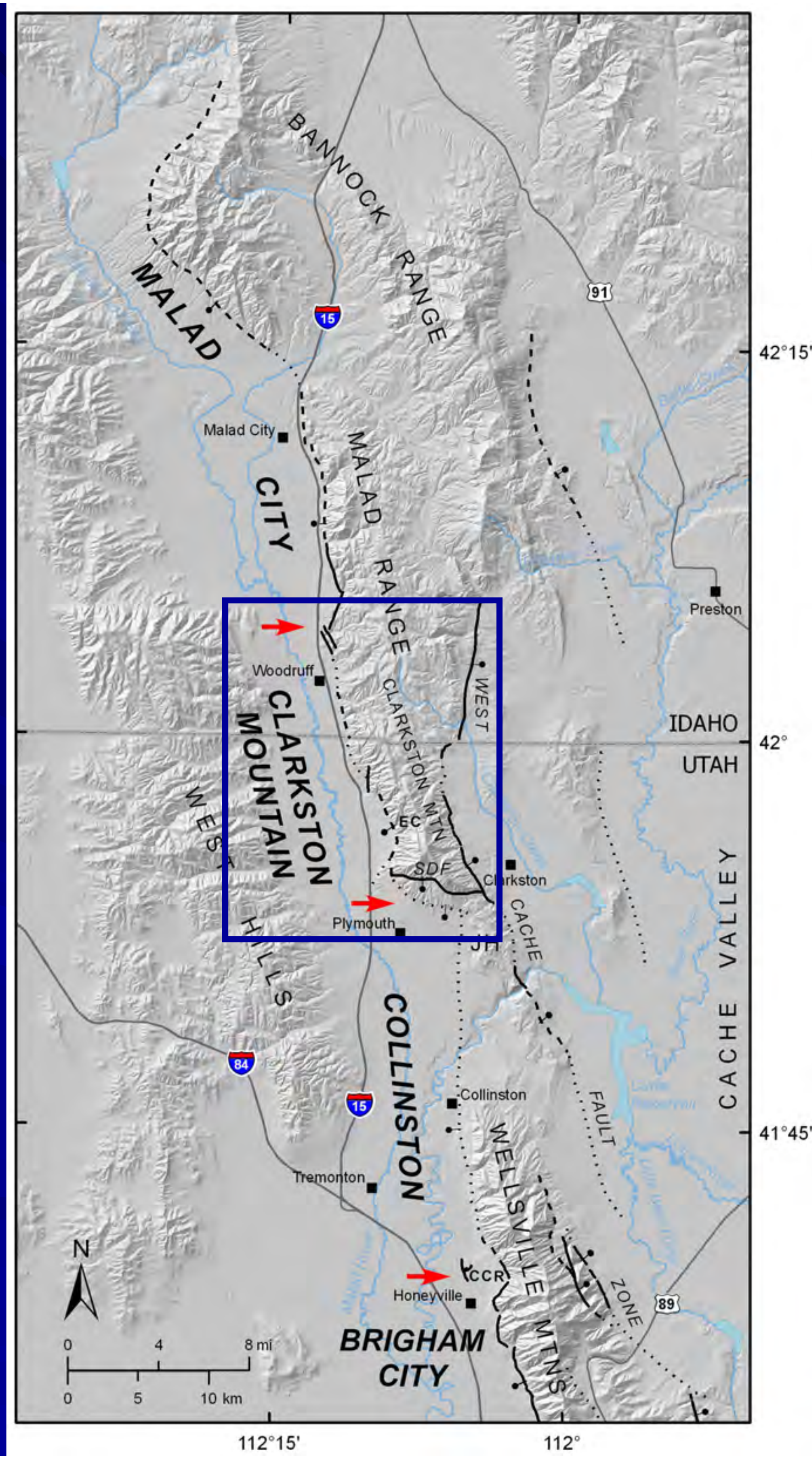
Northern Segments

Clarkston Mountain Segment

Slip rate:
•Database slip rate category: <0.2 mm/yr
•Slip rate estimate:
2 m in >18,000 yr = 0.1 mm/yr (max)

Recurrence interval: NA (MRE timing poorly constrained, no timing data for the PE)

Sources:
Machette et al. (1992), Biek et al. (2003), Hylland (2007)

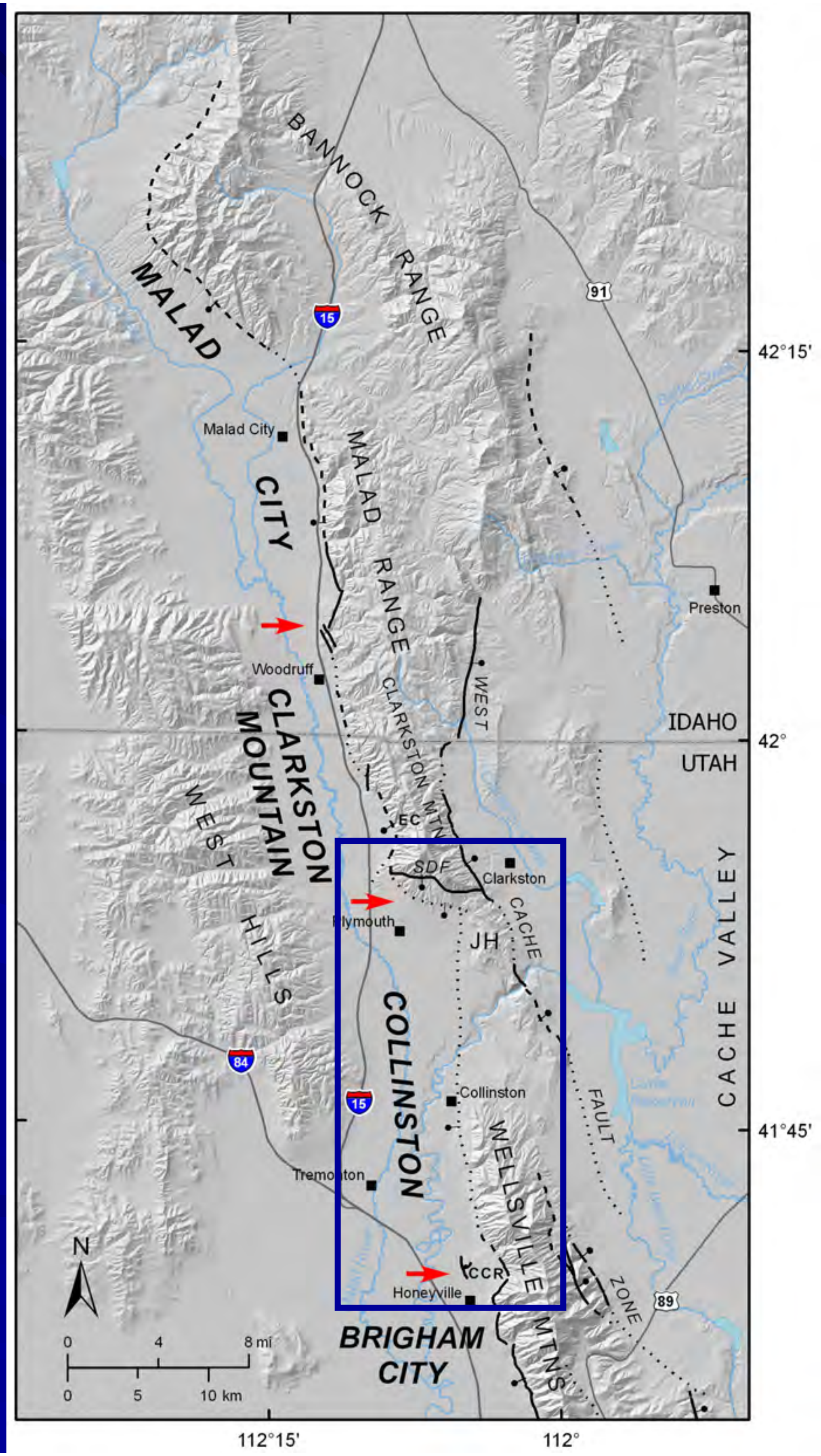


Northern Segments

Collinston Segment

Paleoseismic data:
•Field reconnaissance
•Scarp profiling and empirical analysis
  •Coldwater Canyon reentrant (S segment boundary)
  •Small single-event to large composite scarps

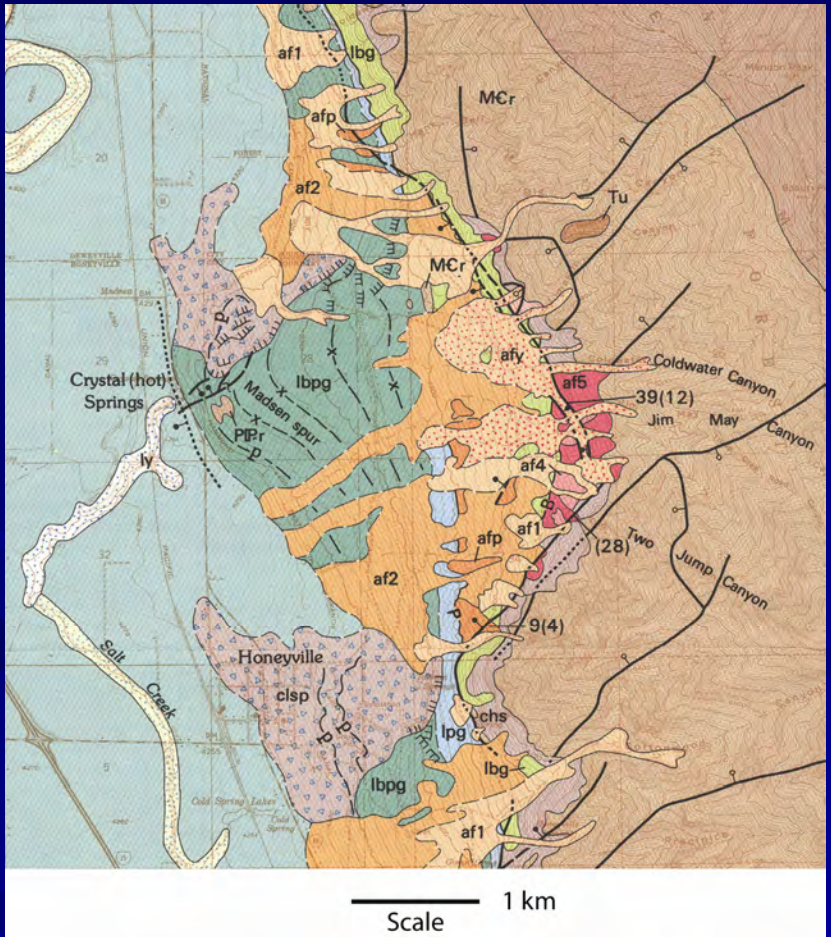
Geologic constraints:
•Bonneville lake-cycle deposits are faulted, but only in CCR (unfaulted to the N)
•Steep range-front geomorphology S, topographic saddle N (West Cache fault may be a factor; Holocene faulting)
•Steep, linear gravity gradients

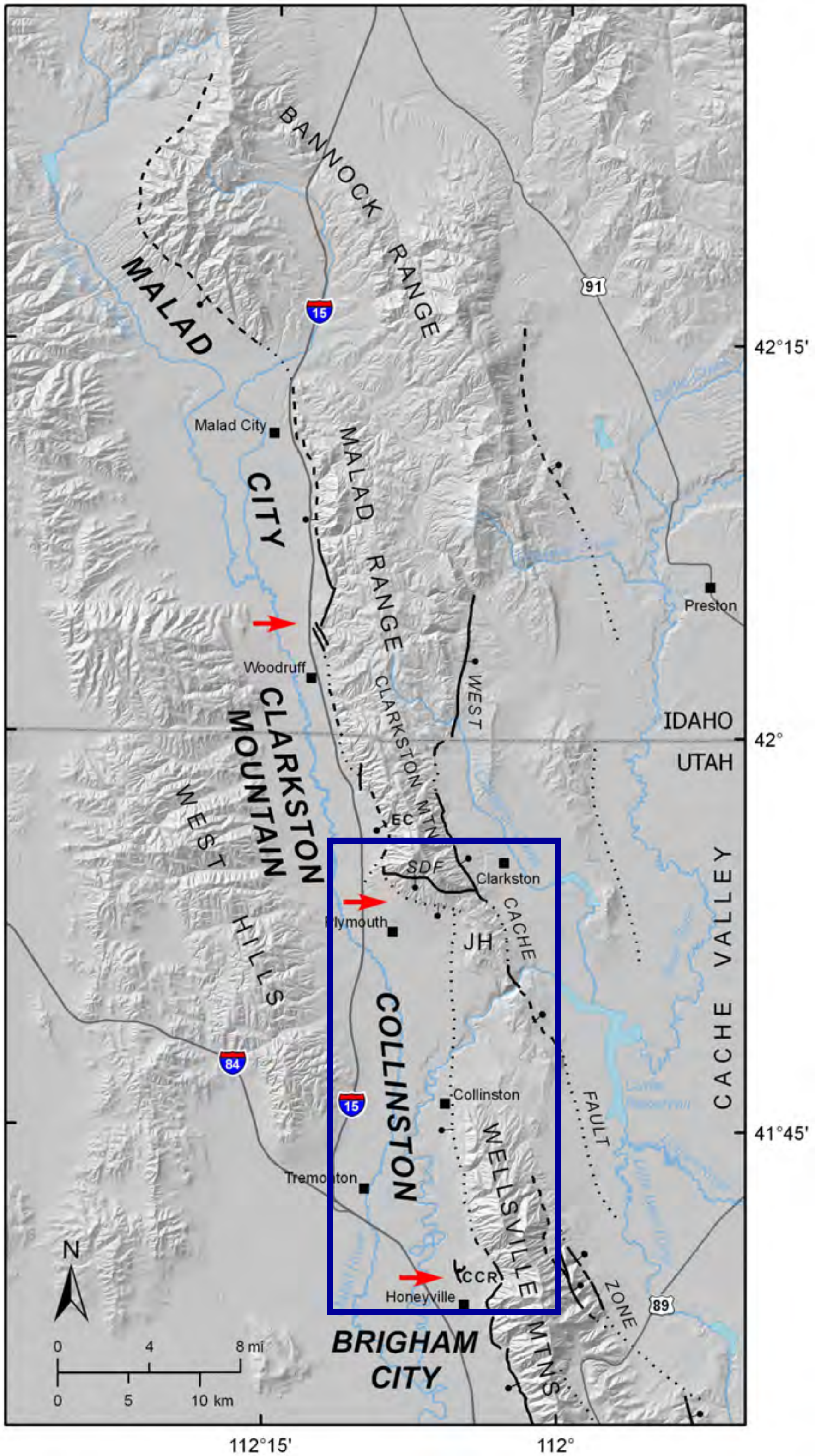


Northern Segments

Collinston Segment

Earthquake timing:
- Holocene and latest Pleistocene events, but only in CCR (likely northern end of ruptures on Brigham City segment)
- Geologic data suggest active faulting during the late Pleistocene (pre-Bonneville)





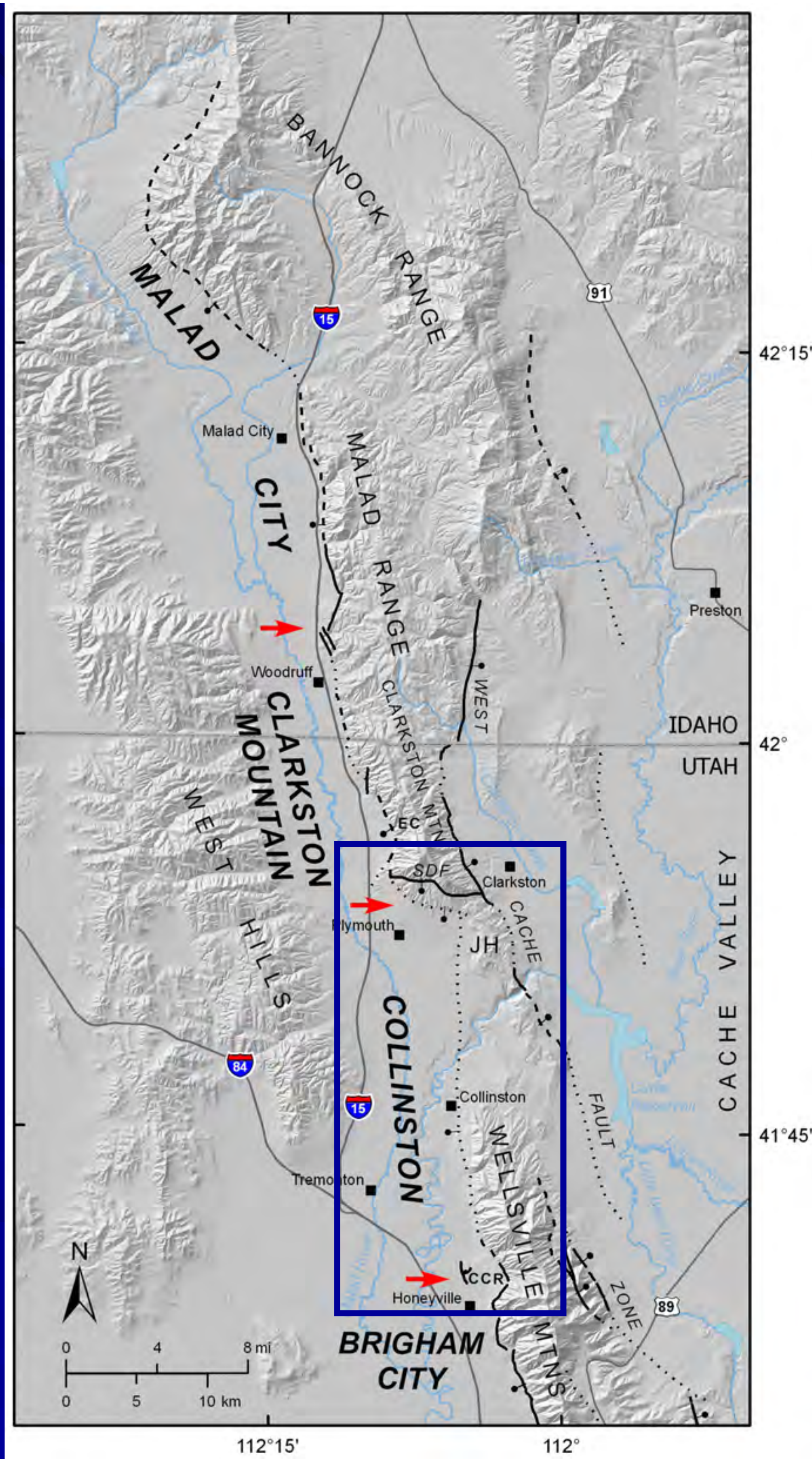
Northern Segments

Collinston Segment

Slip rate:
•Database slip rate category: <0.2 mm/yr
•Slip rate estimate:
≤2 m in >18,000 yr = 0.1 mm/yr (max)
•Long-term average slip rate:
<12 m in ~300,000 yr = 0.04 mm/yr (max)

Recurrence interval: NA (no individual earthquake timing data)

Sources:
Oviatt (1986a, b), Personius (1990), Machette et al. (1992), Hylland (2007)



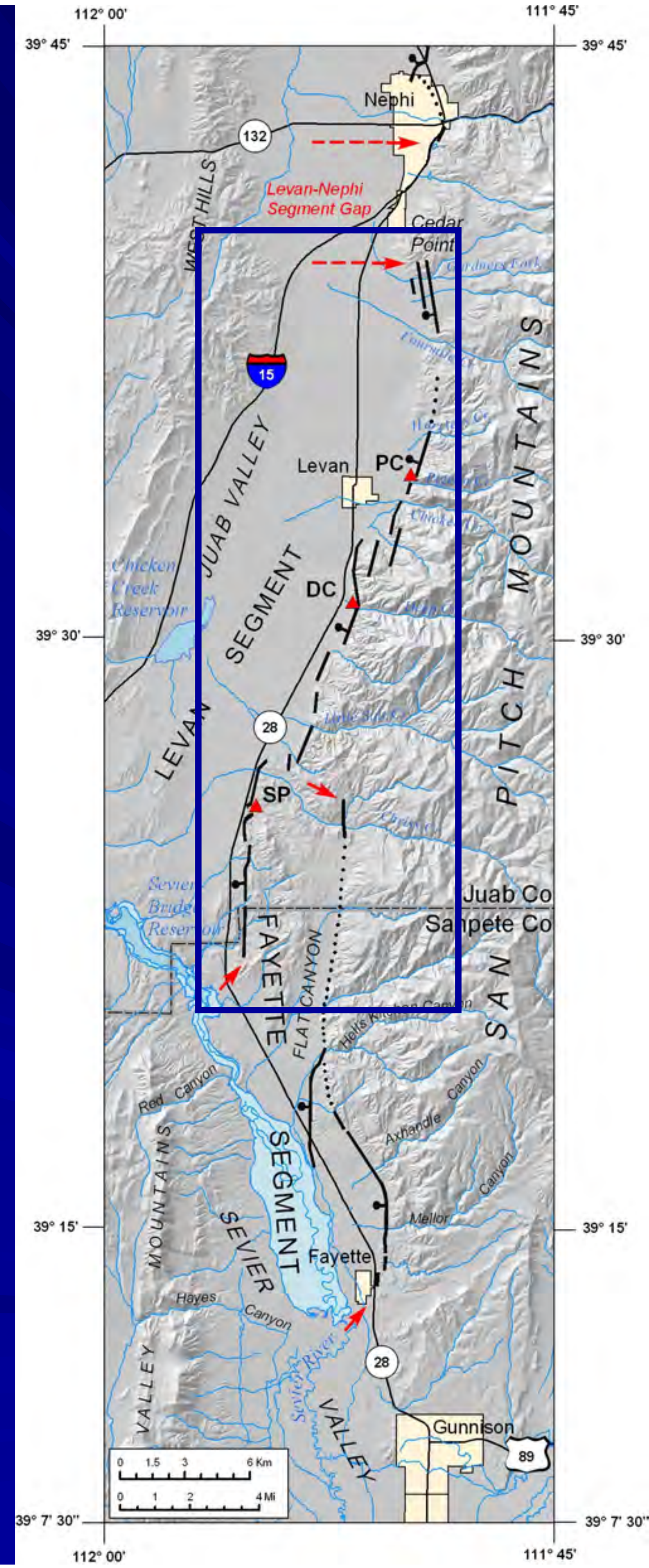
Southern Segments

Levan Segment

Paleoseismic data:
•Scarp profiling and empirical analysis
•Diffusion equation modeling
•Dated charcoal from faulted fan alluvium (Pigeon Creek)
•Natural exposure of fault—displacement and timing data (Deep Creek)
•Fault trench (Skinner Peaks)

Geologic constraints:
Fault scarps are present on late Quaternary deposits
 •Faulted late Holocene alluvium
 •Large (12 m) fault scarps on late to middle Pleistocene alluvium

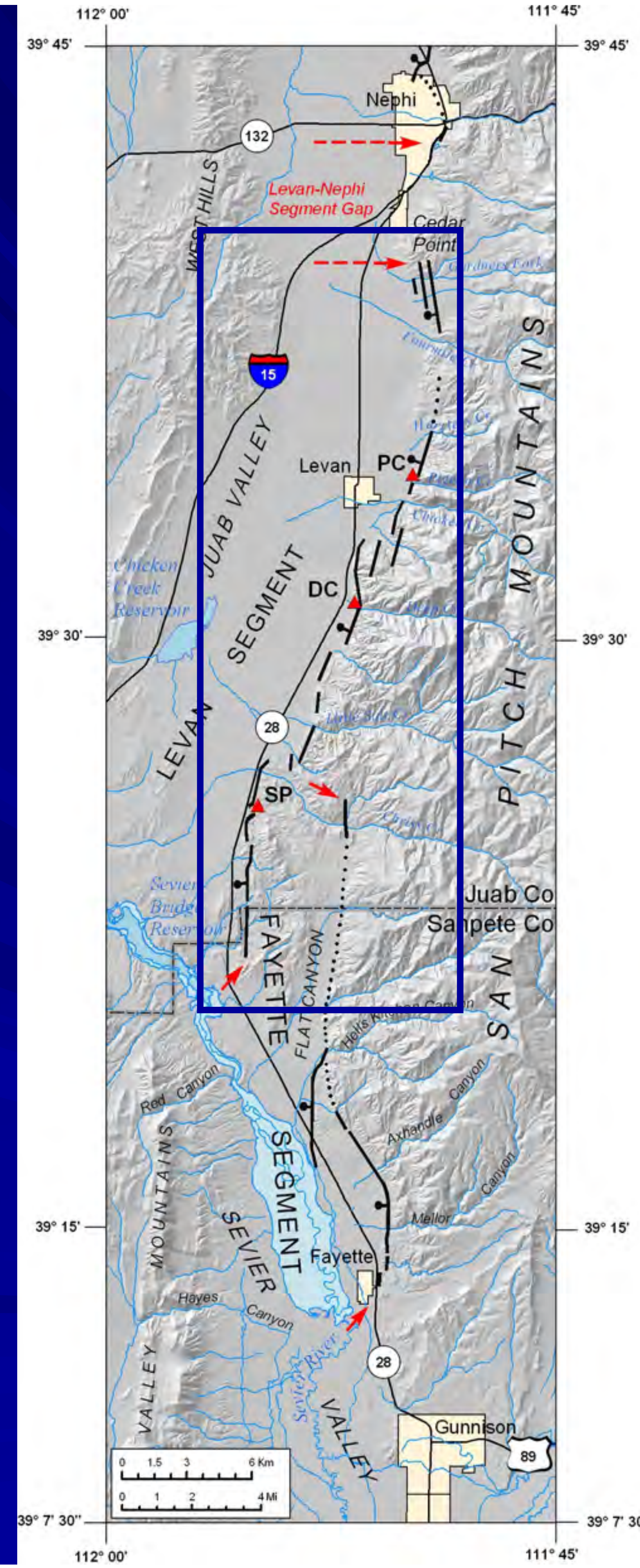
Earthquake timing:
Pigeon Creek:
 •MRE postdates fan alluvium containing charcoal dated at 2100 ± 300 yr B.P. (1410–2760 cal yr B.P.) and 1750 ± 350 yr B.P. (950–2490 cal yr B.P.)



Southern Segments

Levan Segment

Earthquake timing (cont.):
Deep Creek:
- MRE closely postdates age of buried soil, dated at:
  - 1200 ± 80 yr B.P. (870–1180 cal yr B.P.; bulk sample, 100 yr MRT correction)
  - 1000 ± 100 yr (TL)
- PE predates(?) fan alluvium containing charcoal dated at 7300 ± 1000 yr B.P. (5980–10,590 cal yr B.P.)

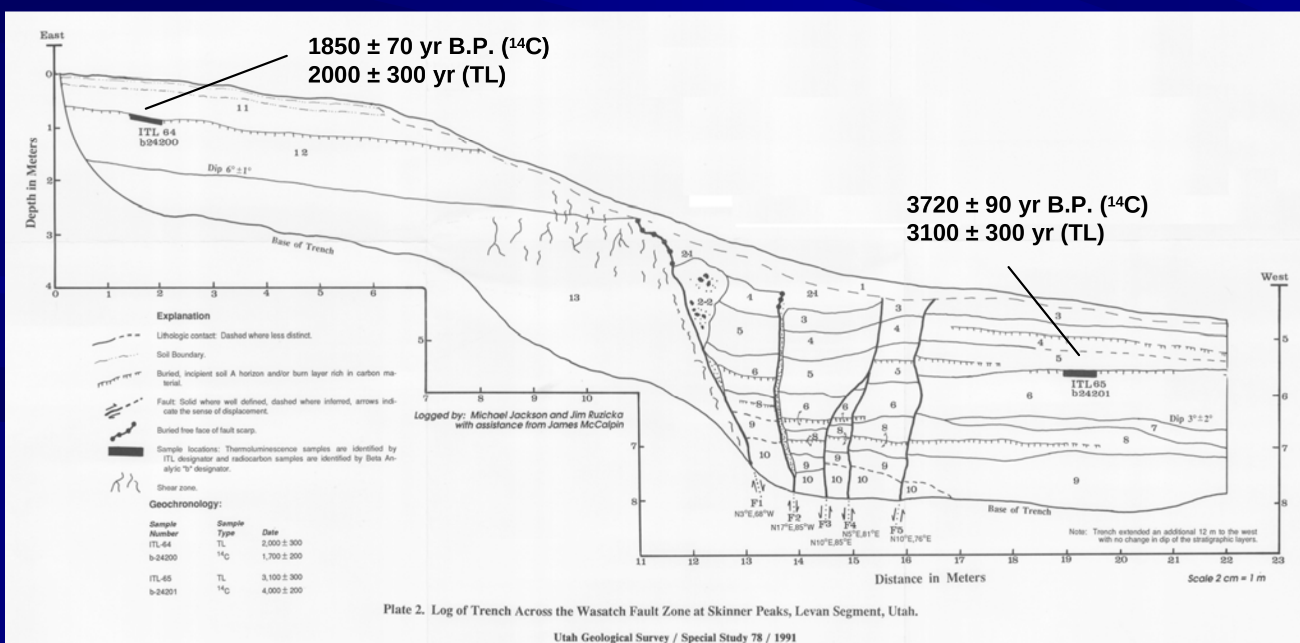


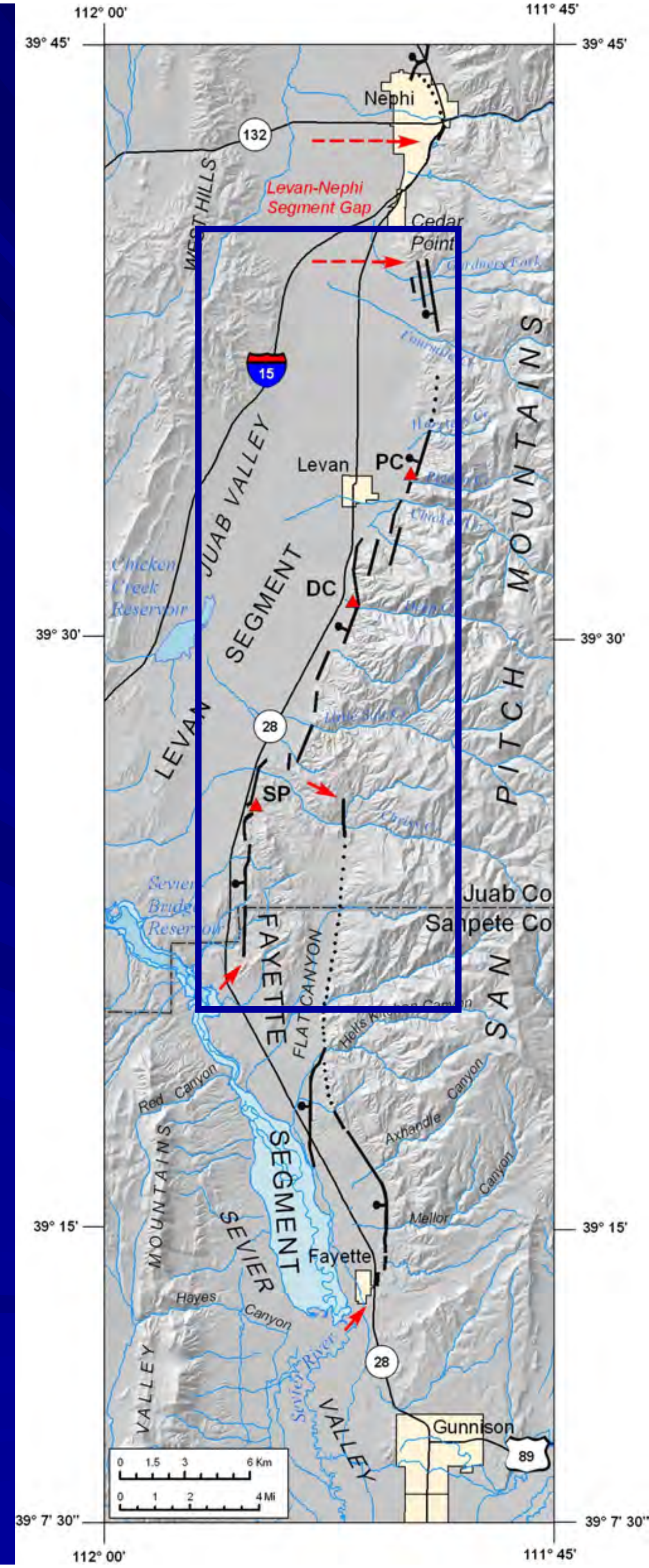
Southern Segments

Levan Segment

Earthquake timing (cont.):
Skinner Peaks:

- MRE postdates age of “burn layer” on footwall, dated at:
  - 1850 ± 70 yr B.P. (1610–1940 cal yr B.P.; charcoal)
  - 2000 ± 300 yr (TL)
  - Jackson (1991) preferred range: 1000–1500 cal yr B.P.
- PE likely predates hanging-wall alluvium containing buried “incipient A horizon” dated at:
  - 3720 ± 90 yr B.P. (3740–4200 cal yr B.P.; charcoal concentrate, 100 yr MRT correction)
  - 3100 ± 300 yr (TL)



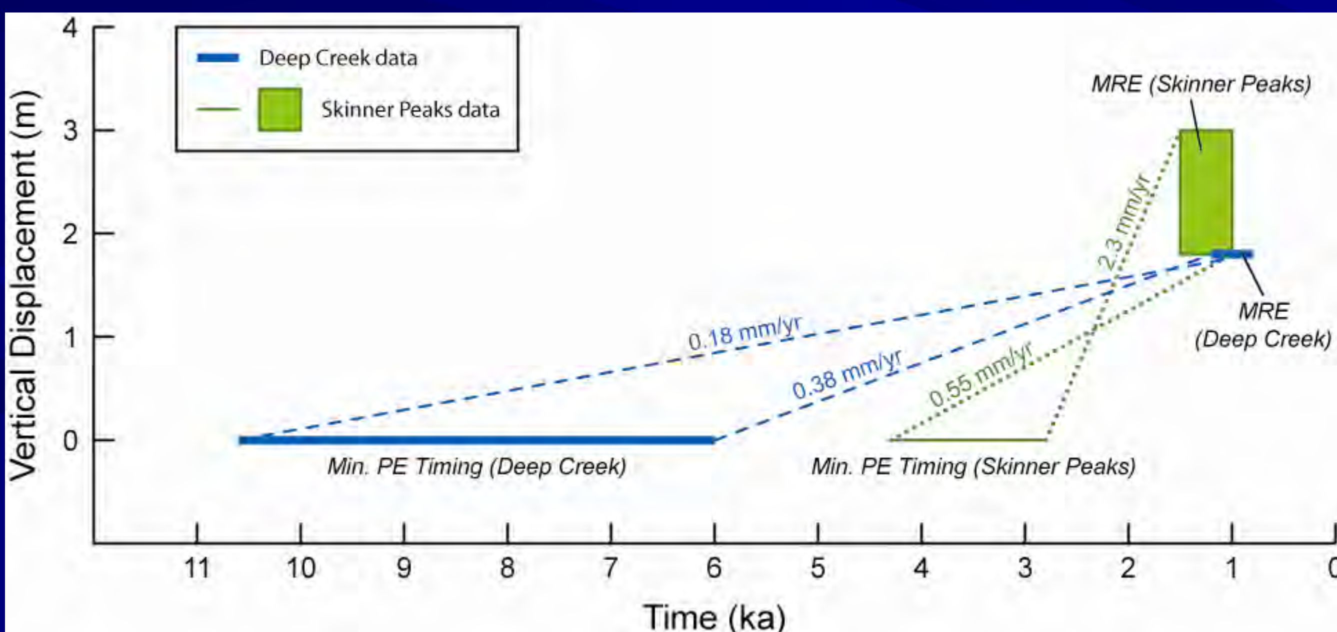


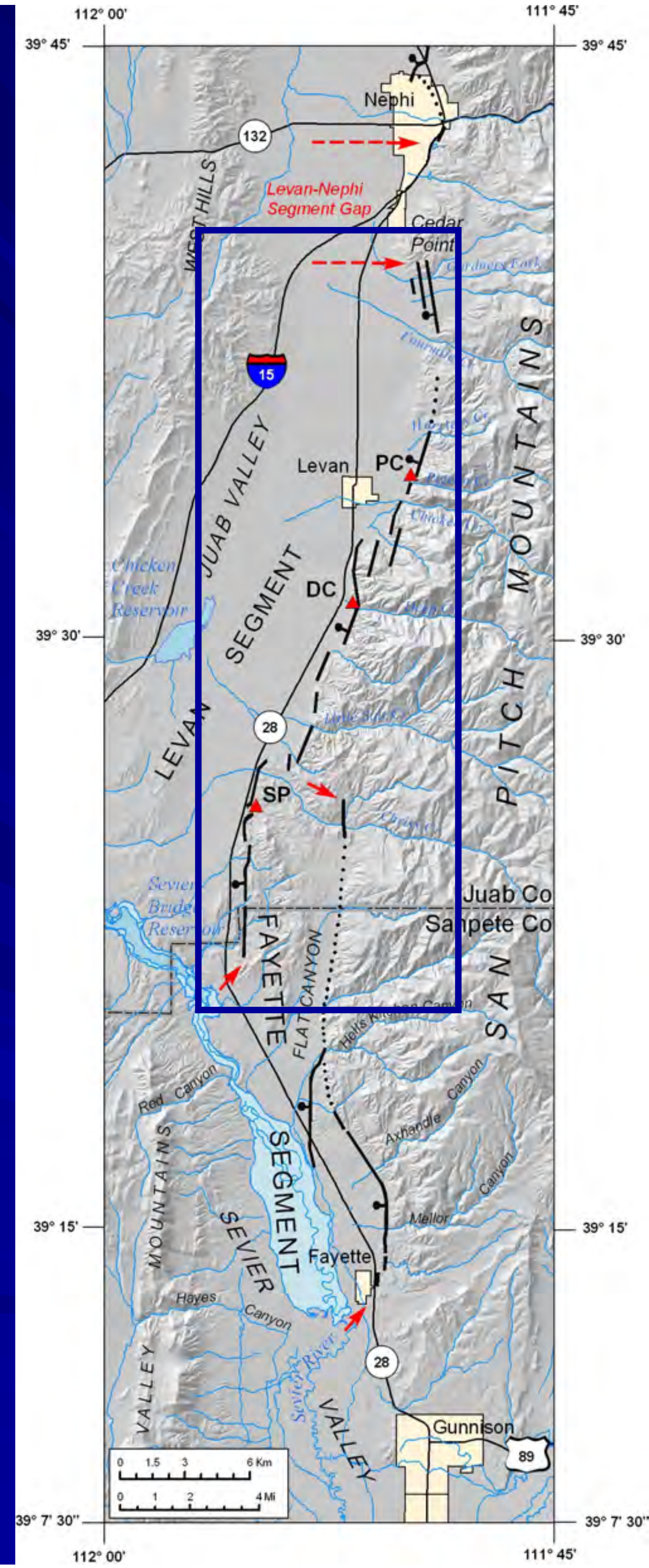
Southern Segments

Levan Segment

Slip rate:
•Database slip rate category: <0.2 mm/yr
•Slip rate estimate:

Site	***NVTD (m)***	***MRE Timing (cal yr B.P.)***	***PE Timing (cal yr B.P.)***	***Inter-event Time (yr)***	***Slip Rate (mm/yr)***
Deep Creek	1.8	<800-1200	>6000-10,600	>4800-9800	<0.18-0.38
Skinner Peaks	1.8-3.0	1000-1500	>2800-4300	>1300-3300	<0.55-2.3



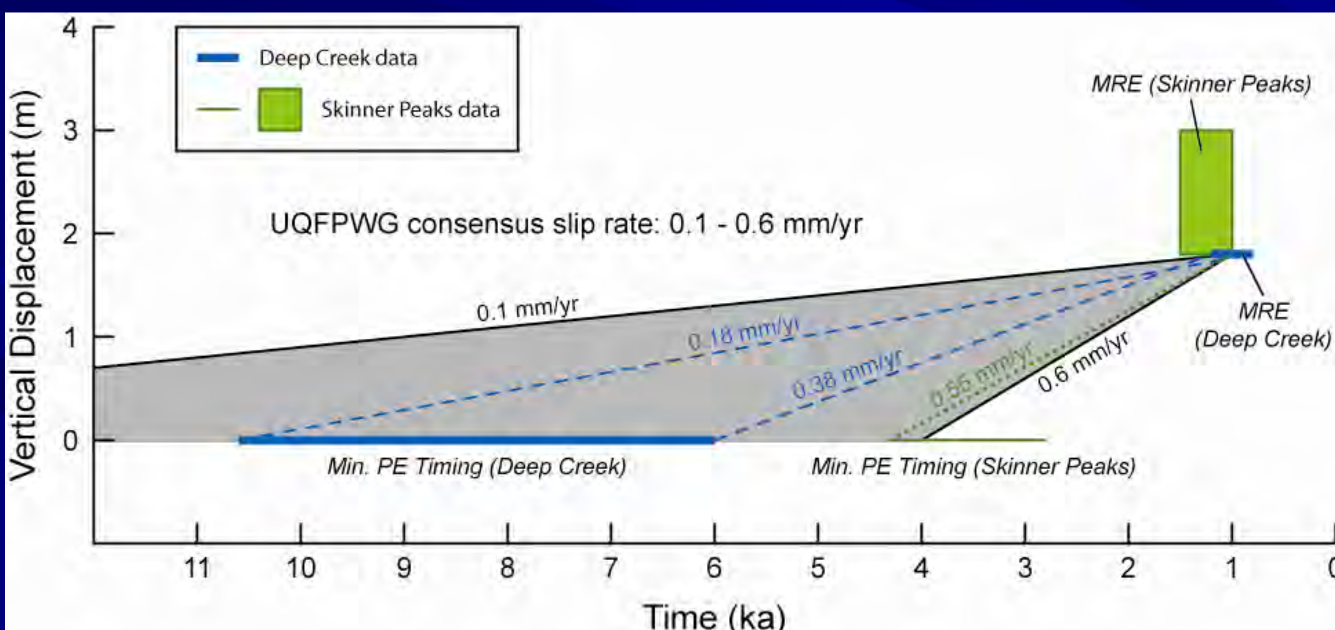


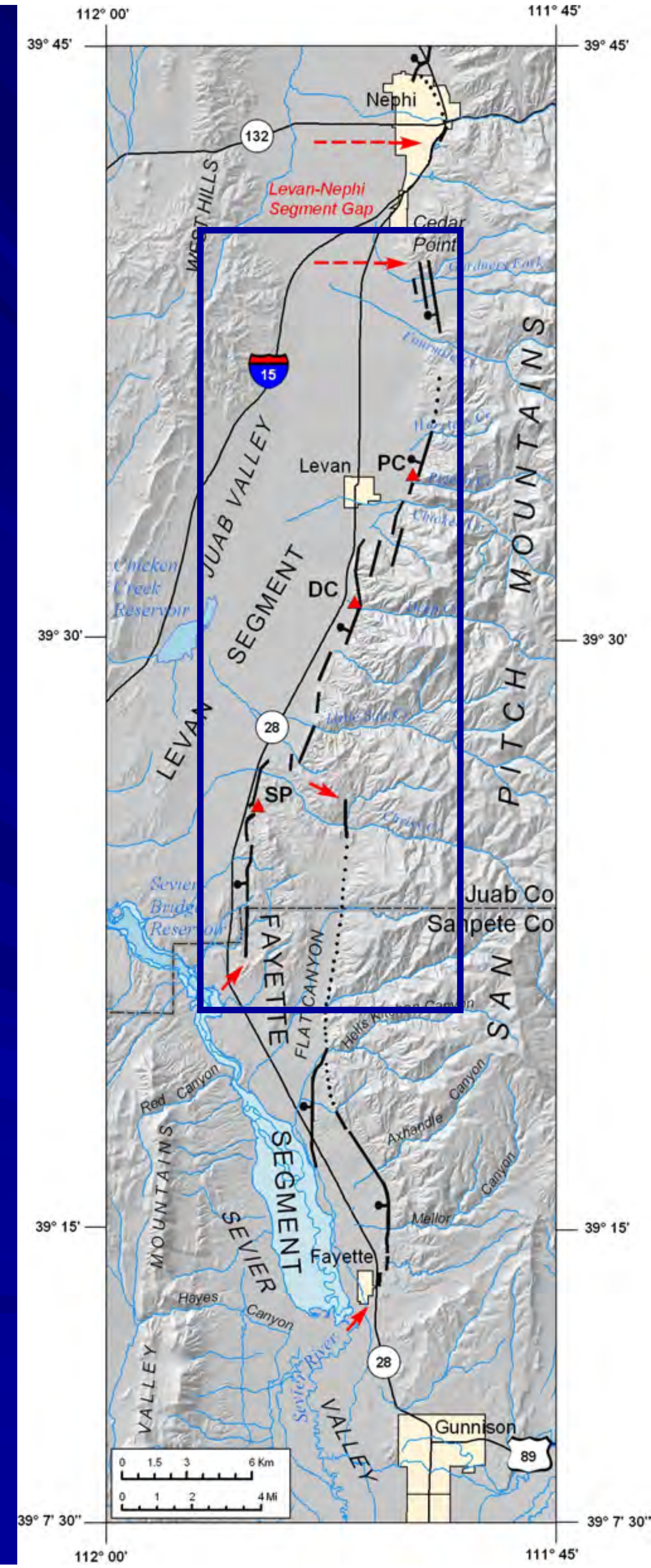
Southern Segments

Levan Segment

Slip rate:
•Database slip rate category: <0.2 mm/yr
•Slip rate estimate:

Site	*NVTD (m)*	*MRE Timing (cal yr B.P.)*	*PE Timing (cal yr B.P.)*	*Inter-event Time (yr)*	*Slip Rate (mm/yr)*
Deep Creek	1.8	<800-1200	>6000-10,600	>4800-9800	<0.18-0.38
Skinner Peaks	1.8-3.0	1000-1500	>2800-4300	>1300-3300	<0.55-2.3





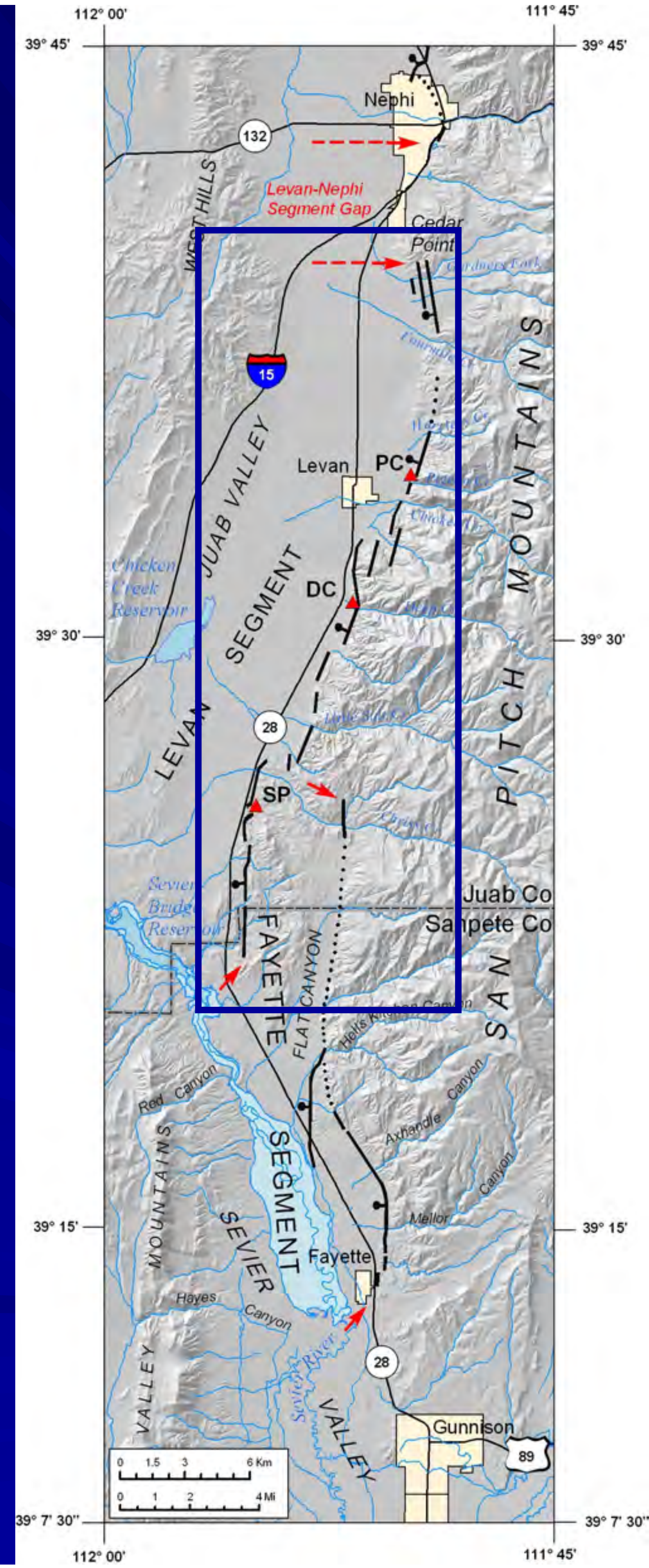
Southern Segments

Levan Segment

Slip rate (cont.):
•Database slip rate category: <0.2 mm/yr
•Hylland and Machette (2008) preferred value: 0.3 ± 1 mm/yr (max)
•UQFPWG consensus range: 0.1–0.6 mm/yr
•Long-term average slip rate:
4.8 m in 100–250 kyr = 0.02–0.05 mm/yr

Recurrence interval:
•Recurrence interval not calculated because timing of PE is poorly constrained
•UQFPWG consensus range: >3000 and <12,000 yr
(based on 2 Holocene events and approximate 2σ confidence limits)

Sources:
Crone (1983), Schwartz and Coppersmith (1984), Jackson (1991), Machette et al. (1992), Hylland (2007), Hylland and Machette (2008)

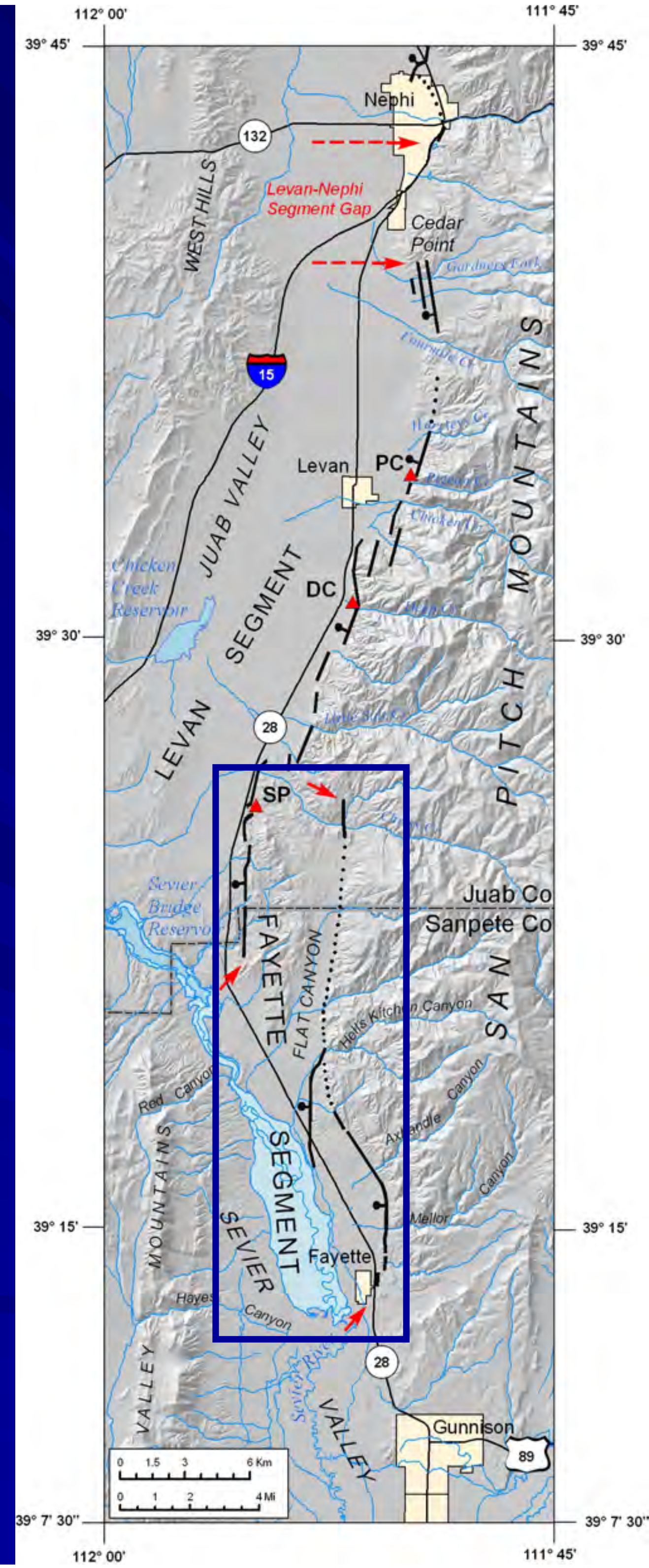


Southern Segments

Fayette Segment

Paleoseismic data:
•Scarp profiling and empirical analysis
•Diffusion equation modeling

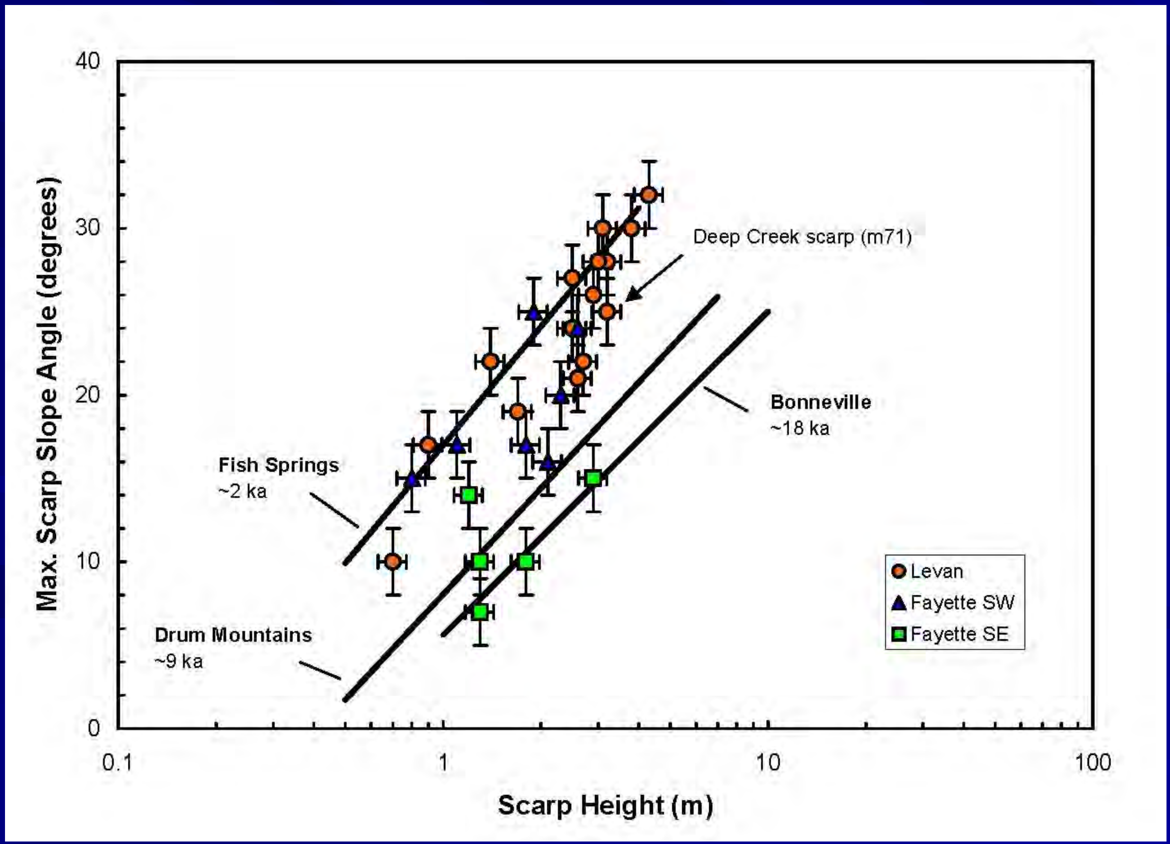
Geologic constraints:
•Fault scarps are present on late Quaternary deposits
•Holocene to late Pleistocene alluvium is faulted, but late Holocene alluvium is not
•Scarps on late to middle Pleistocene alluvium typically 4–6 m high
•Anomalously high scarps (~20 m) at north end of SW strand

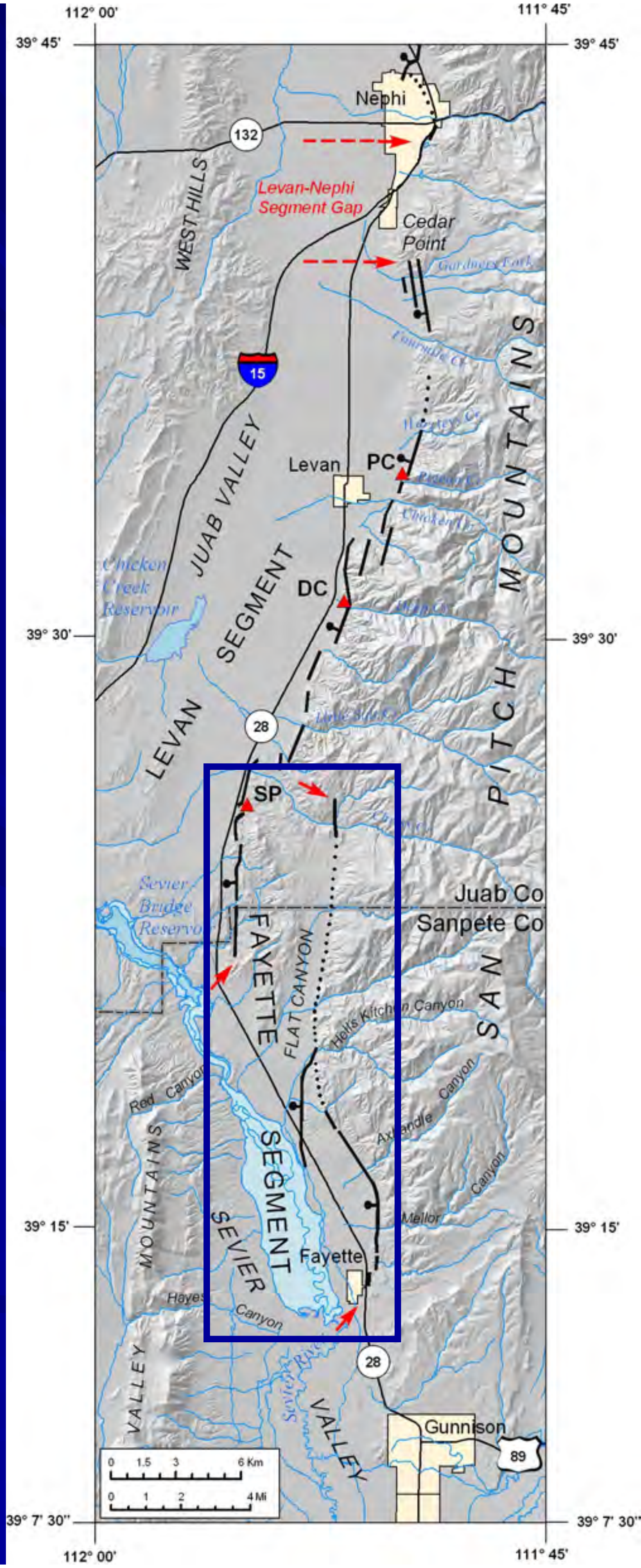


Southern Segments

Fayette Segment

Earthquake timing:
•MRE—cross-cutting relations and empirical scarp profile analysis indicates:
- •Early or middle Pleistocene(?) (N strand)
- •Latest Pleistocene (SE strand)
- •Holocene (SW strand)





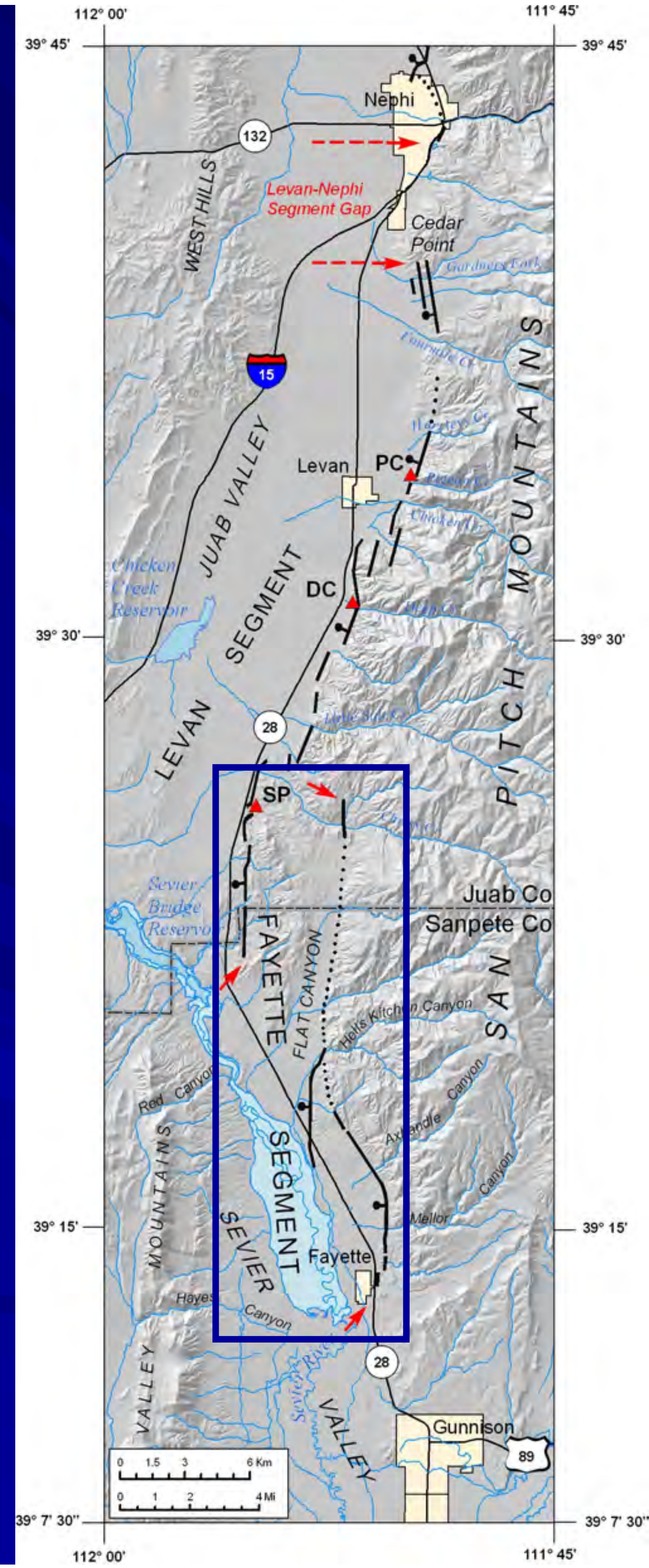
Southern Segments

Fayette Segment

Slip rate:
•Database slip rate category: <0.2 mm/yr
•Slip rate estimates:
  0.8–1.6 m in <11,500 yr = 0.07–0.1 mm/yr (min) (SW strand)
  0.5–1.3 m in <18,000 yr = 0.03–0.07 mm/yr (min) (SE strand)
  3 m in 100–250 kyr = 0.01–0.03 mm/yr

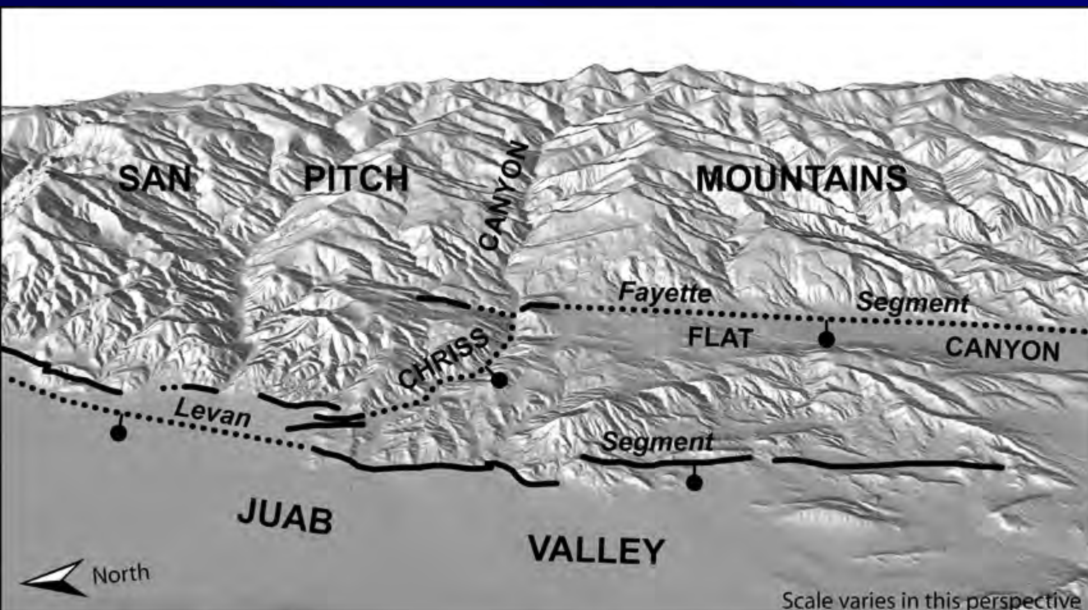
Recurrence interval: NA (MRE timing poorly constrained, no timing data for the PE)

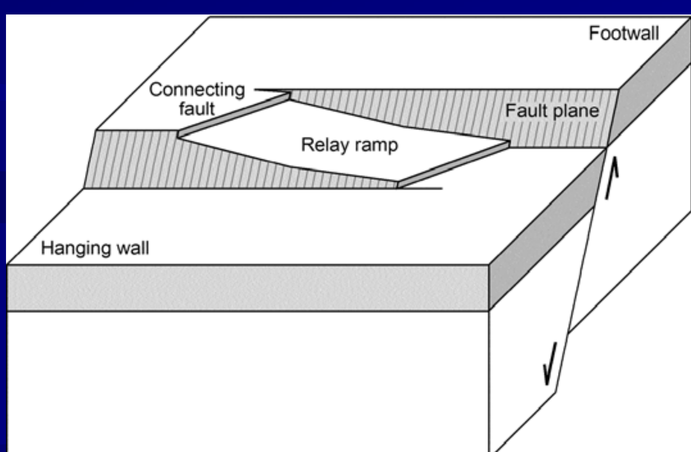
Sources:
Machette et al. (1992), Hylland (2007), Hylland and Machette (2008)

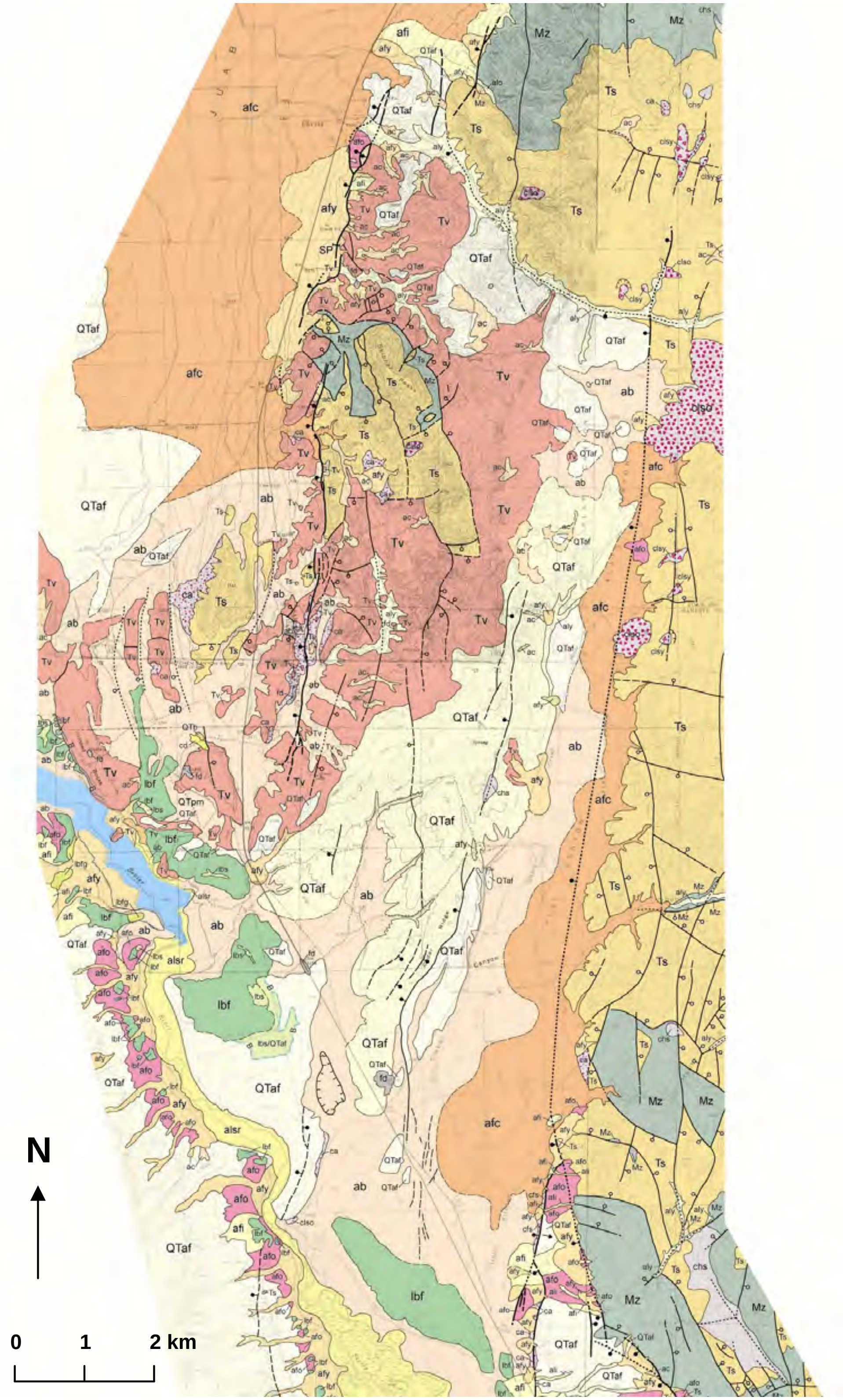


Southern Segments

Levan–Fayette Segment Boundary







The Wasatch Fault Zone End Segments

Summary of Earthquake Parameters

Segment	*MRE Timing*	*Displacement/ Surface Offset (m)*	*Time Interval (kyr)*	*Est. Slip Rate (mm/yr)*	*Recurrence Interval (kyr)*
Malad City	Late Pleistocene	≤1.5 (est.)	>18	<0.08	NA
Clarkston Mountain	Late Pleistocene	2	>18	<0.1	NA
Collinston	Late Pleistocene	≤2 (est.) <12	>18 300	<0.1 <0.04	NA
Levan	≤1000 cal yr B.P. 1000–1500 cal yr B.P.	1.8 1.8–3.0 4.8	>4.8–9.8 >1.3–3.3 100–250	<0.2–0.4 <0.5–2.3 <0.3±0.1 (H&M, 2008) 0.1–0.6 (UQFPWG) 0.02–0.05	>3 & <12 (UQFPWG)
Fayette	Early(?) Holocene (SW strand) Latest Pleistocene (SE strand)	0.8–1.6 0.5–1.3 3	<11.5 <18 100–250	>0.07–0.1 >0.03–0.07 0.01–0.03	NA

Update on Utah Geological Survey fault trenching of the Salt Lake City segment

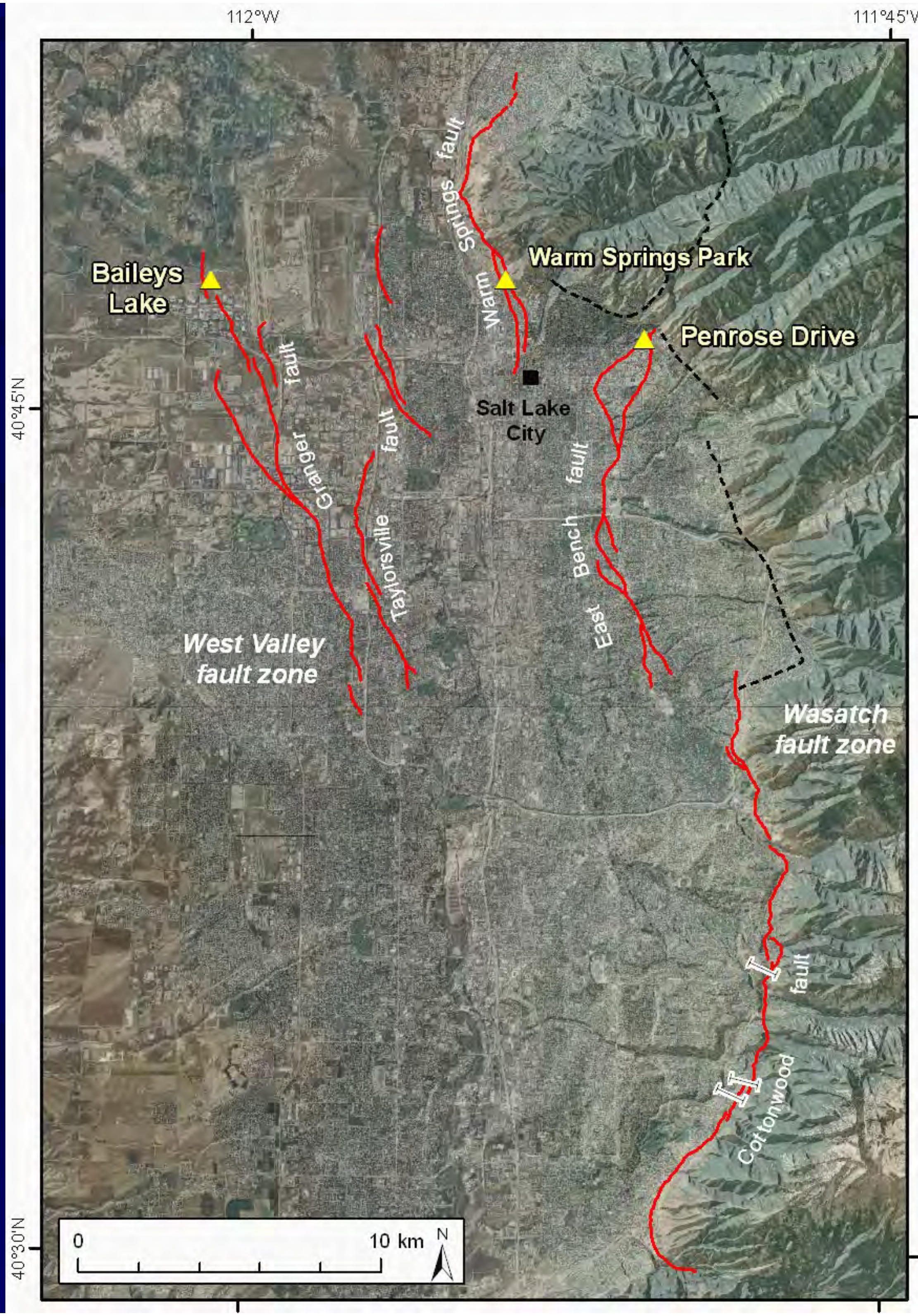
Chris DuRoss
Mike Hylland
Greg McDonald
(UGS)

Tony Crone
Steve Personius
Ryan Gold
Brad King
(USGS)

Working Group on Utah Earthquake Probabilities, December, 2010

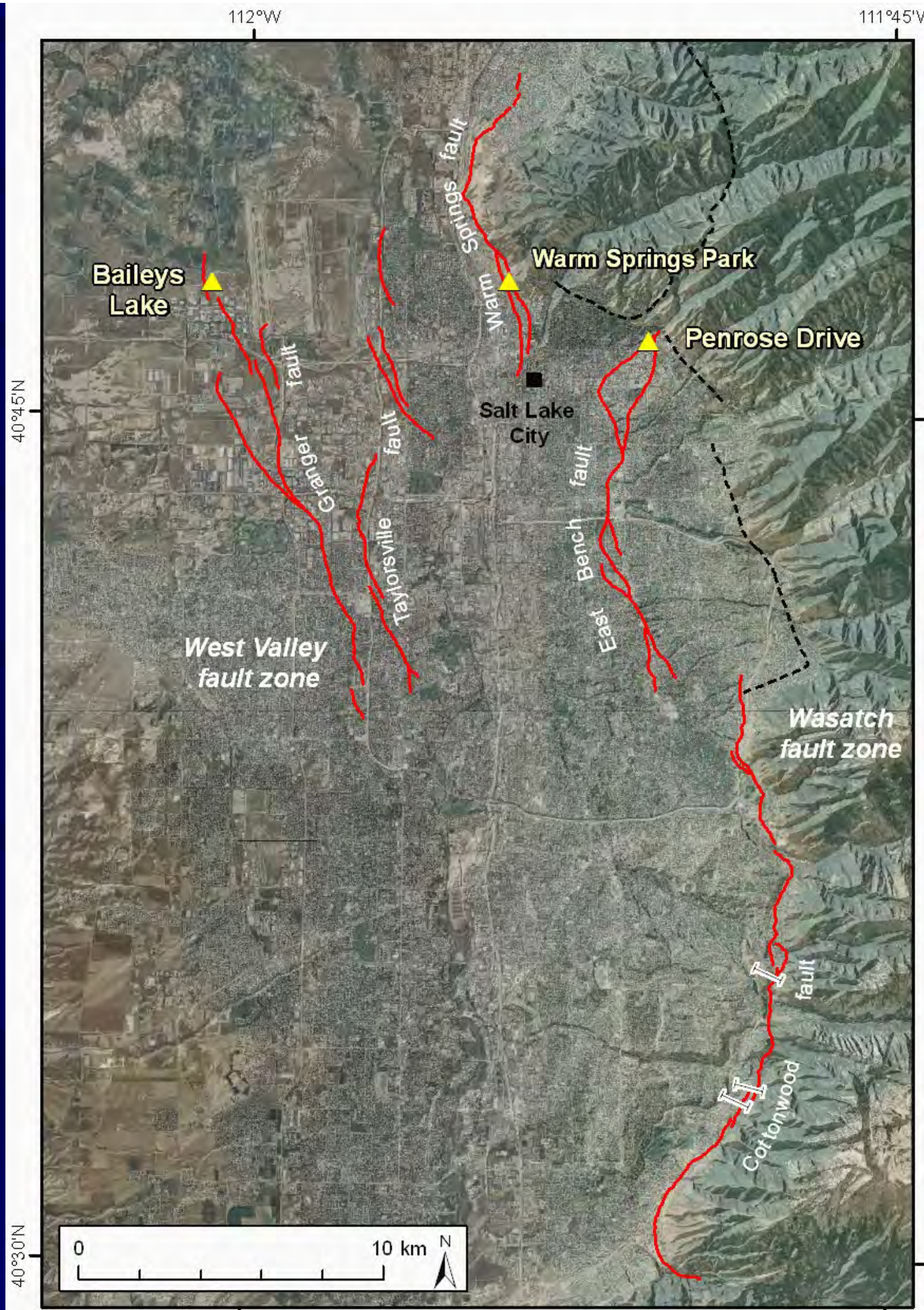
Wasatch and West Valley fault zones

- Salt Lake City segment (WFZ)
  - Warm Springs fault
  - East Bench fault
  - Cottonwood fault
- West Valley fault zone
  - Granger fault
  - Taylorsville fault



Wasatch and West Valley fault zones

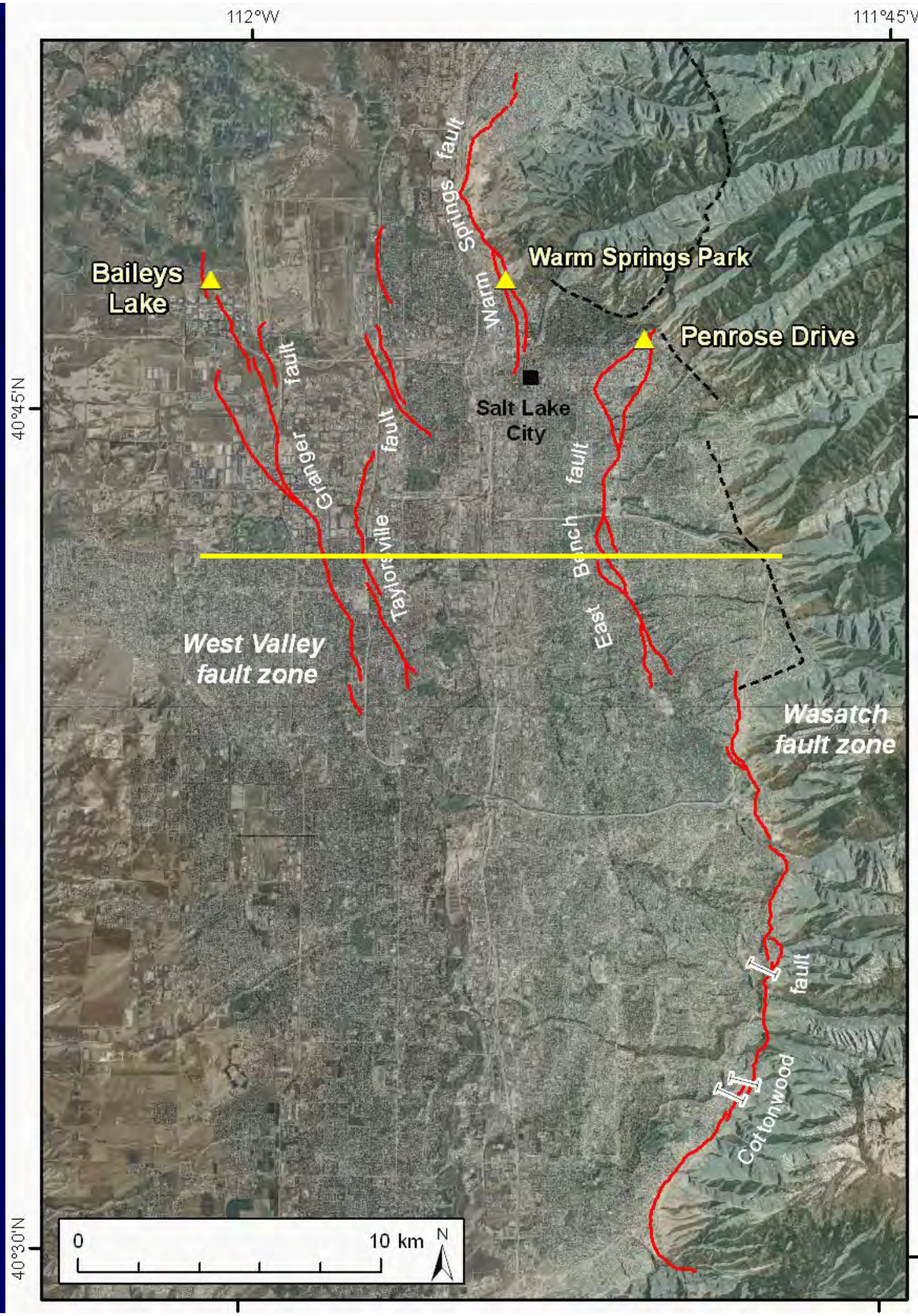
- Ongoing studies:
  - Penrose Drive (SLCS)
  - Baileys Lake (WVFZ)
- Primary goals:
  - Resolve the timing and displacement of individual surface-faulting earthquakes on the northern part of the SLCS and the WVFZ
  - Clarify the seismogenic relation (dependent or independent) between these two faults.



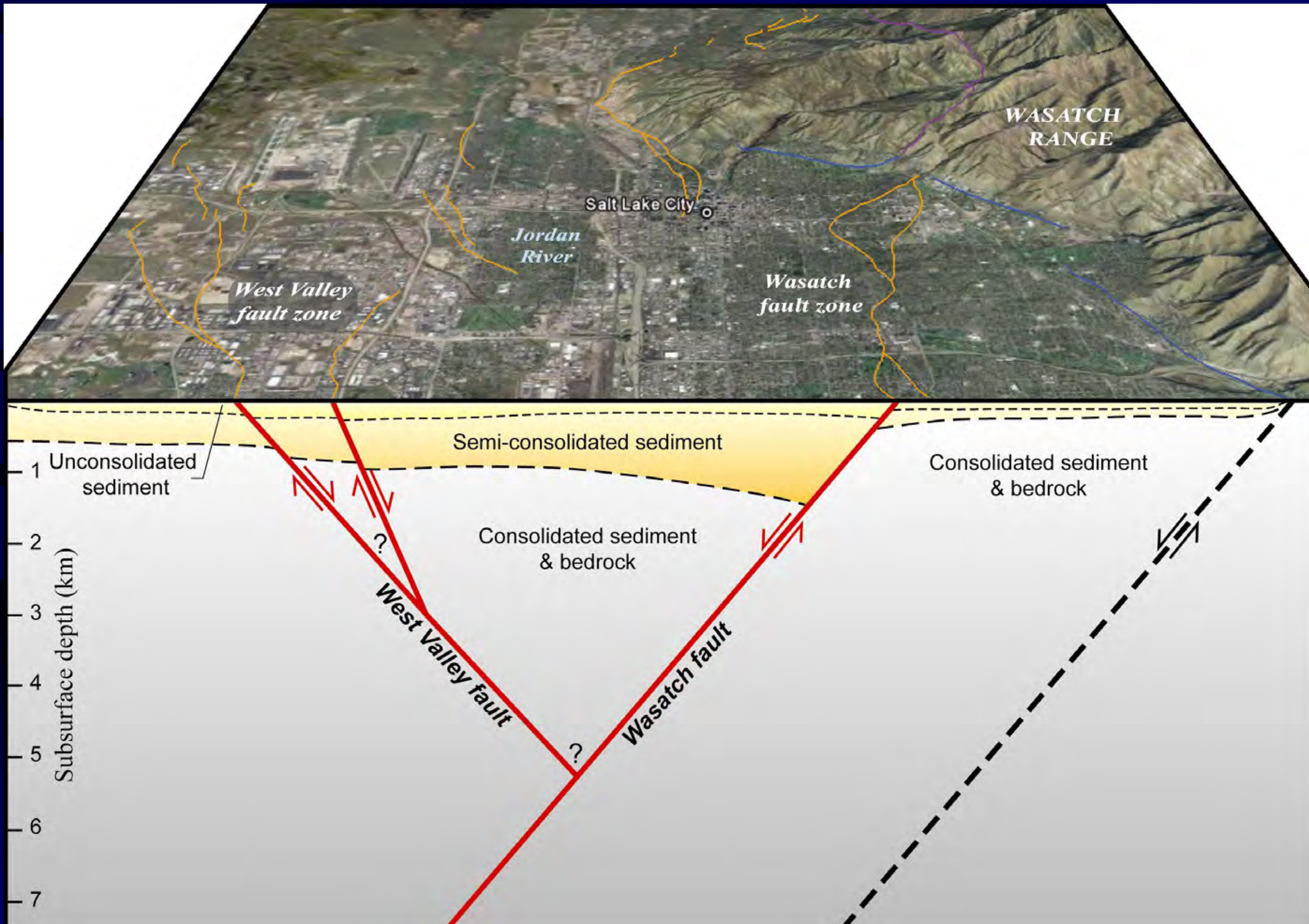
Wasatch and West Valley fault zones

- Ongoing studies:
  - Penrose Drive (SLCS)
  - Baileys Lake (WVFZ)

- Primary goals:
  - Resolve the timing and displacement of individual surface-faulting earthquakes on the northern part of the SLCS and the WVFZ
  - Clarify the seismogenic relation (dependent or independent) between these two faults.

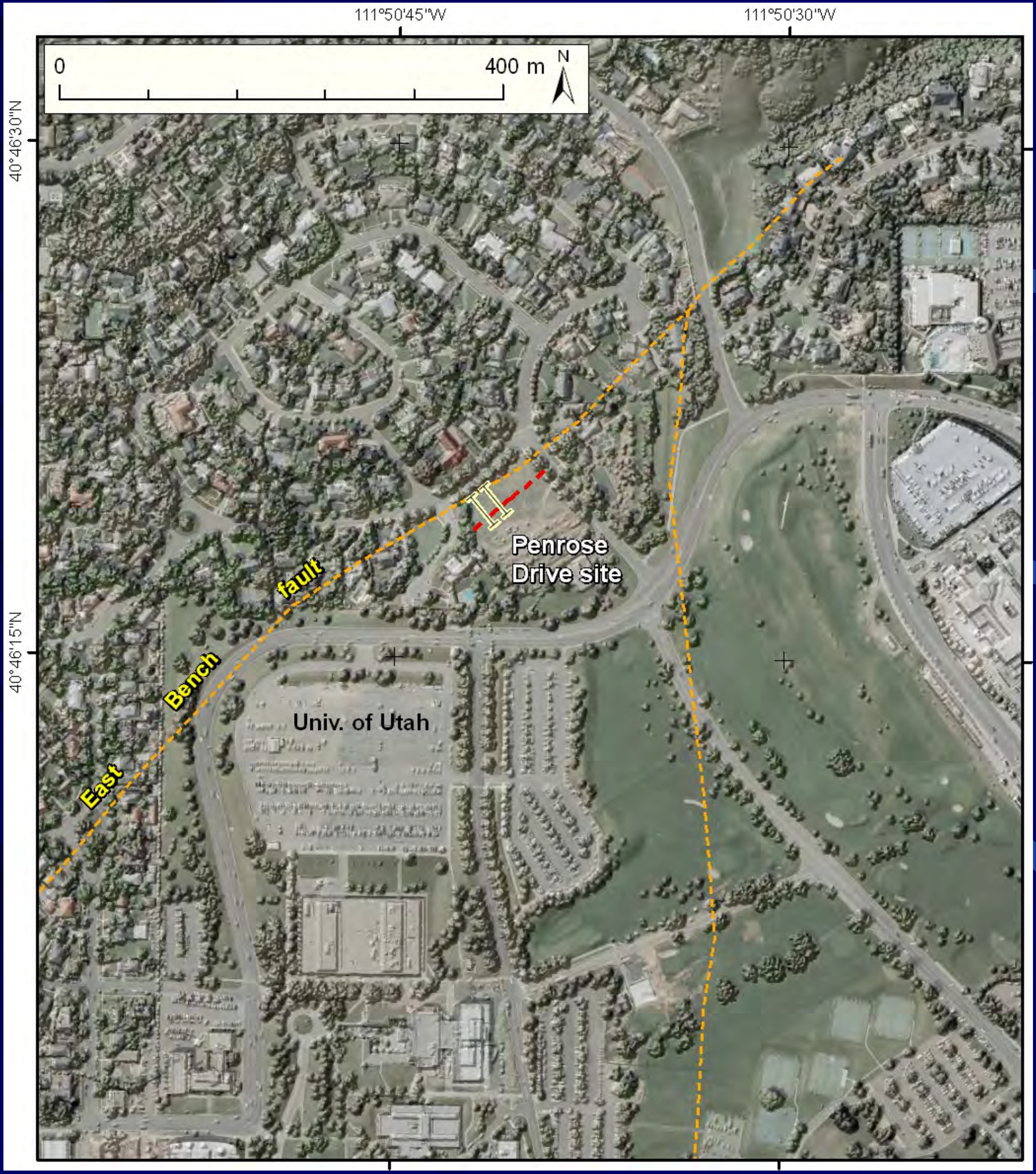


Salt Lake Valley



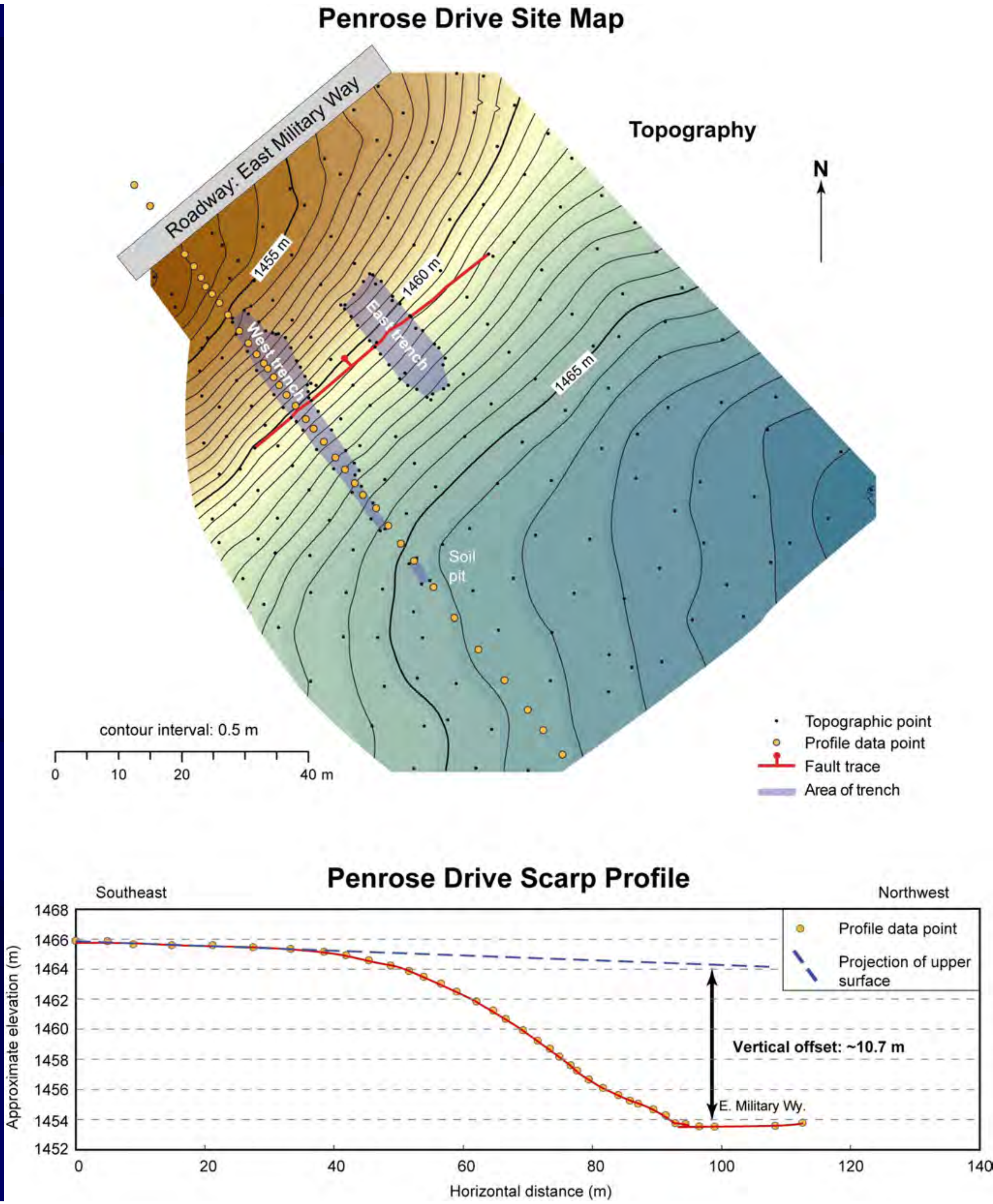
Penrose Drive site

- Fault trace and Holocene activity well known from mapping and consultant's trenches
- Timing of individual events unknown



Penrose Drive site

- Scarp vertical offset ~11 m
- Two trenches exposed:
  1. Pre Bonneville alluvial-fan deposits
  2. Lake Bonneville sediments (deep water and shoreline)
  3. Scarp-derived colluvium



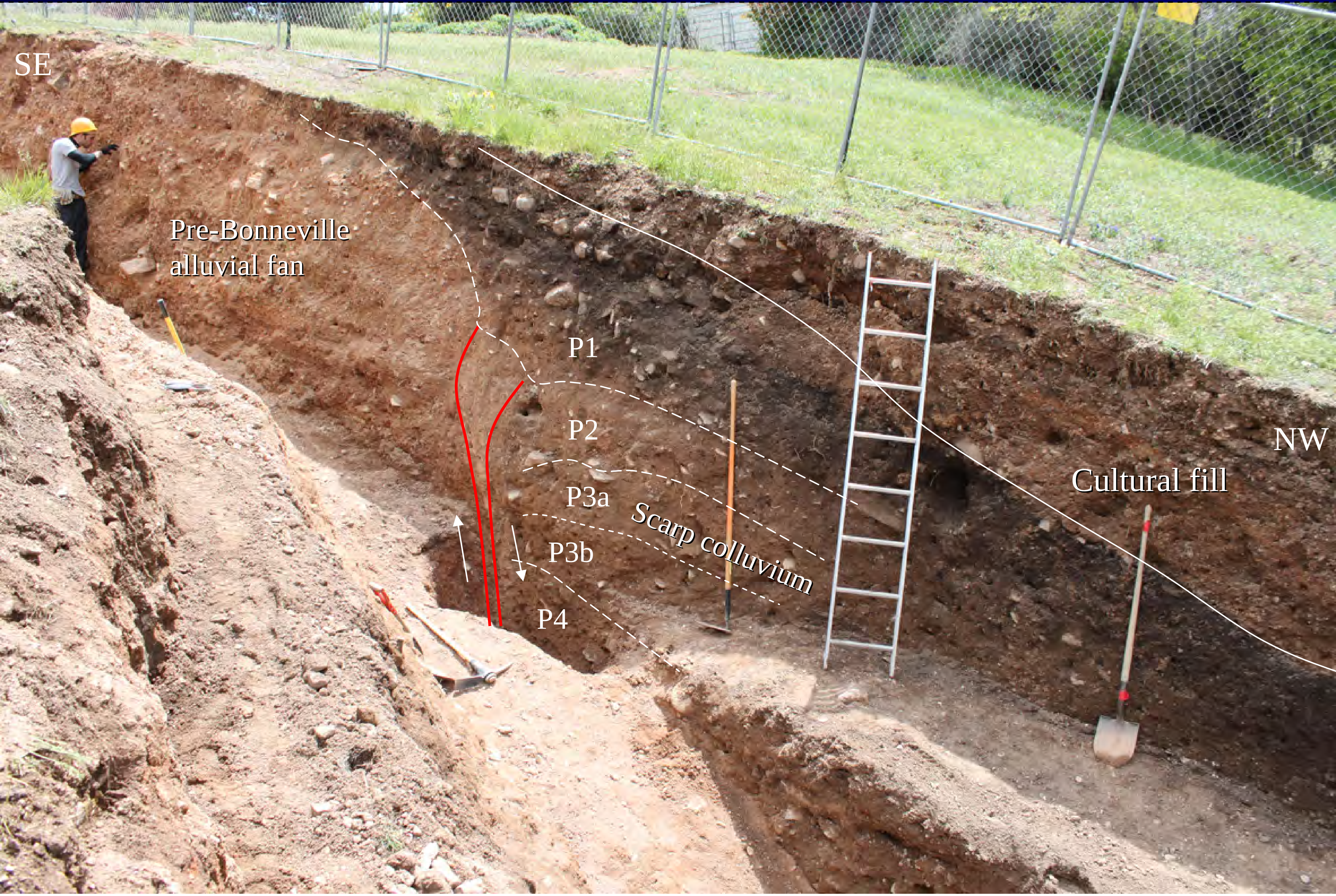
Penrose Drive site

View to the southwest

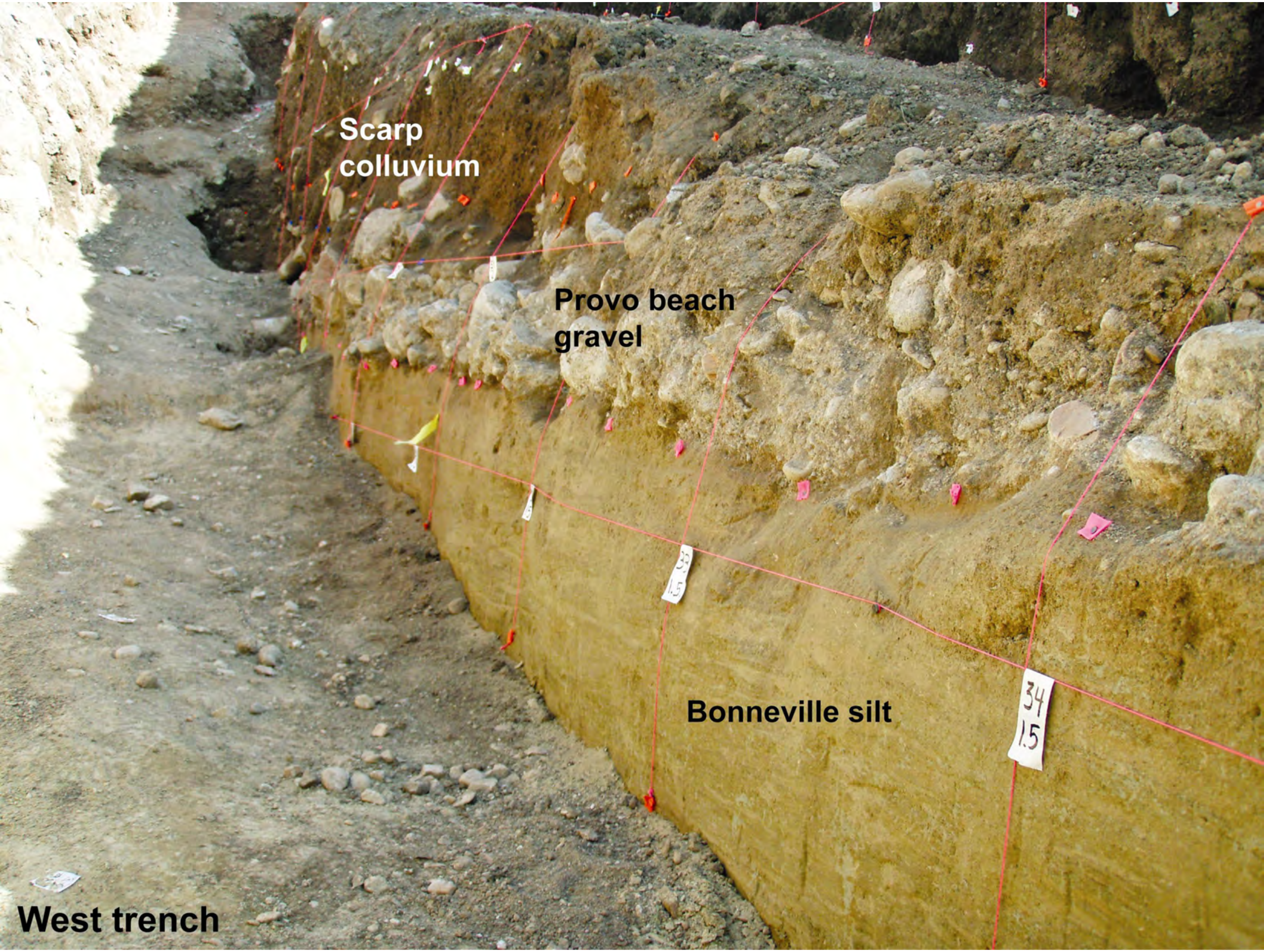
West Trench

West Trench

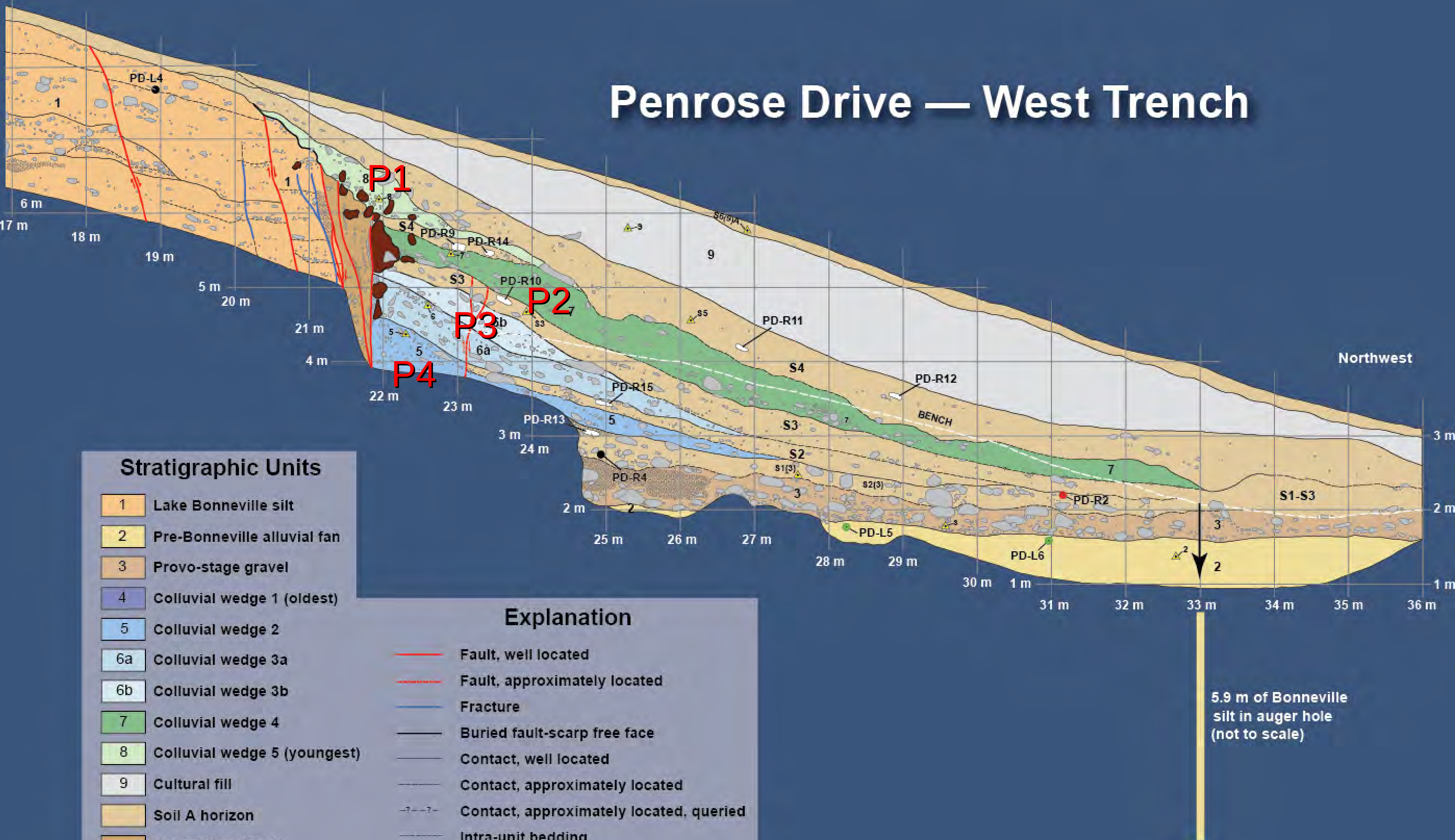
West Trench



SE
Pre-Bonneville
alluvial fan
P1
P2
P3a
P3b
P4
Scarp colluvium
NW
Cultural fill


Scarp colluvium
Provo beach gravel
Bonneville silt
West trench
33
1.5
34
1.5

Penrose Drive — West Trench



Stratigraphic Units

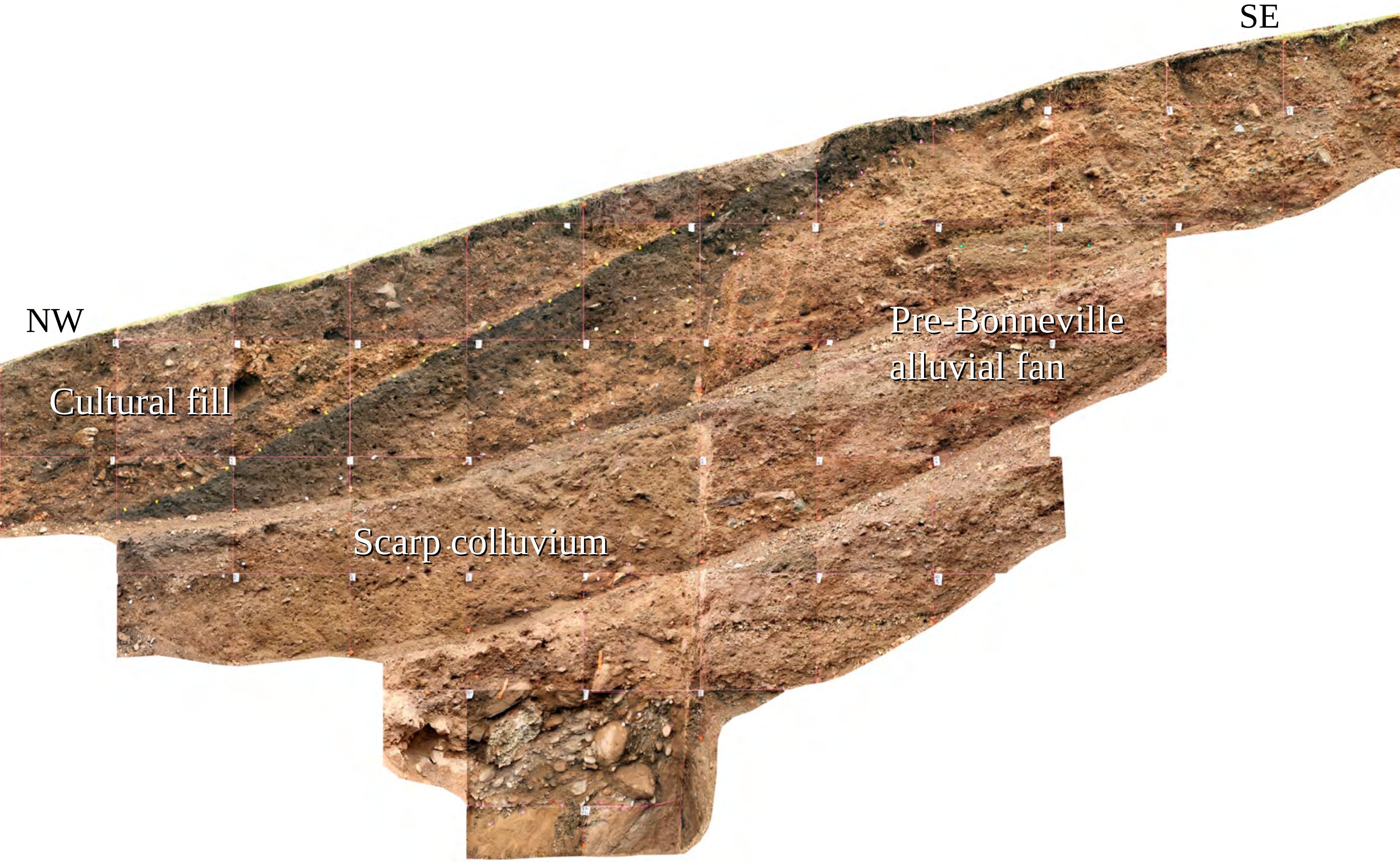
1	Lake Bonneville silt
2	Pre-Bonneville alluvial fan
3	Provo-stage gravel
4	Colluvial wedge 1 (oldest)
5	Colluvial wedge 2
6a	Colluvial wedge 3a
6b	Colluvial wedge 3b
7	Colluvial wedge 4
8	Colluvial wedge 5 (youngest)
9	Cultural fill
	Soil A horizon
	Sheared sediment
	Burrowed sediment
	Clast
	Sample site

Explanation

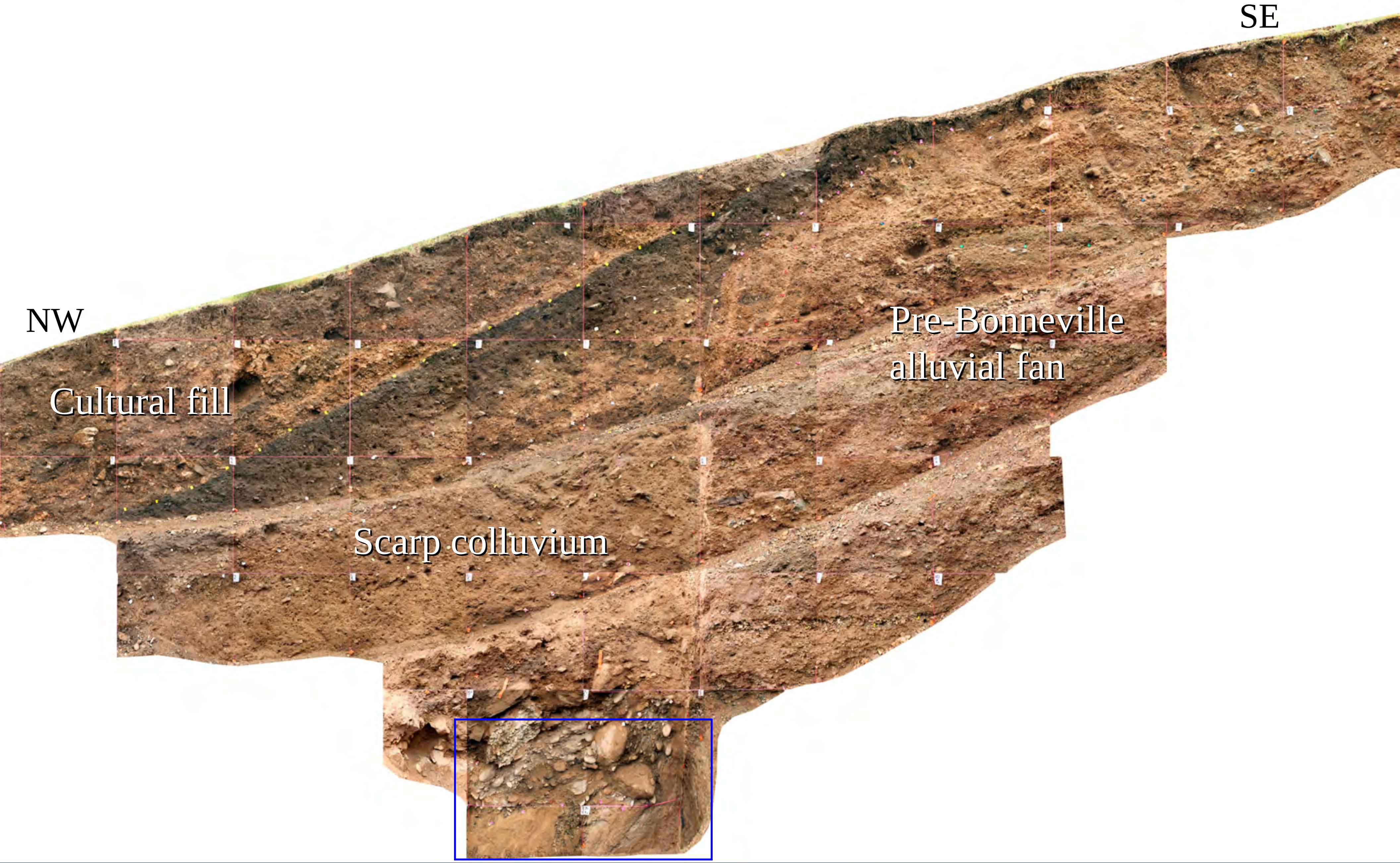
- Fault, well located
- Fault, approximately located
- Fracture
- Buried fault-scarp free face
- Contact, well located
- Contact, approximately located
- Contact, approximately located, queried
- Intra-unit bedding
- Base of soil A Horizon
- Radiocarbon sample
- Luminescence sample
- Unit description


East Trench

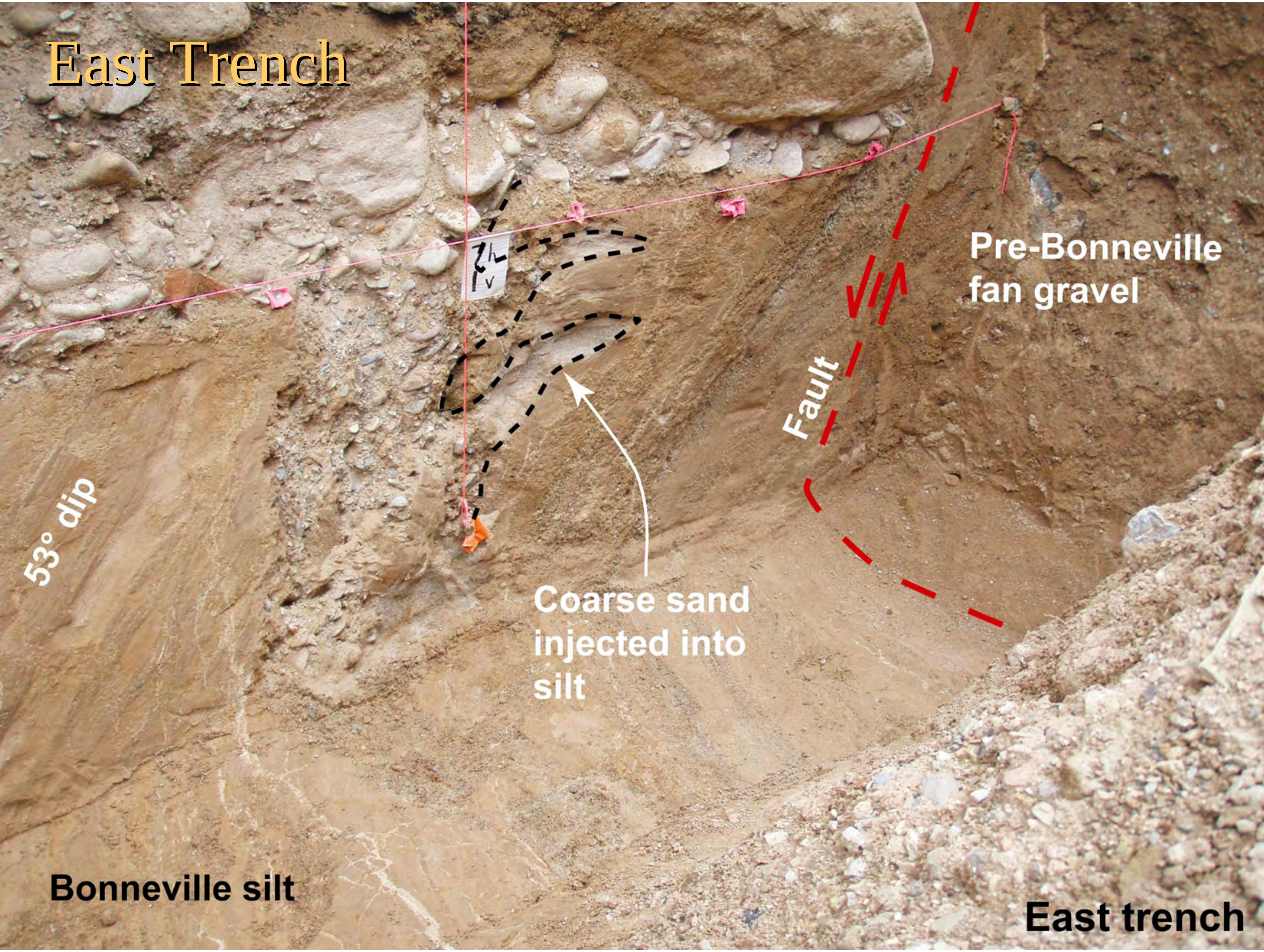
East Trench


SE
NW
Pre-Bonneville
alluvial fan
Cultural fill
Scarp colluvium

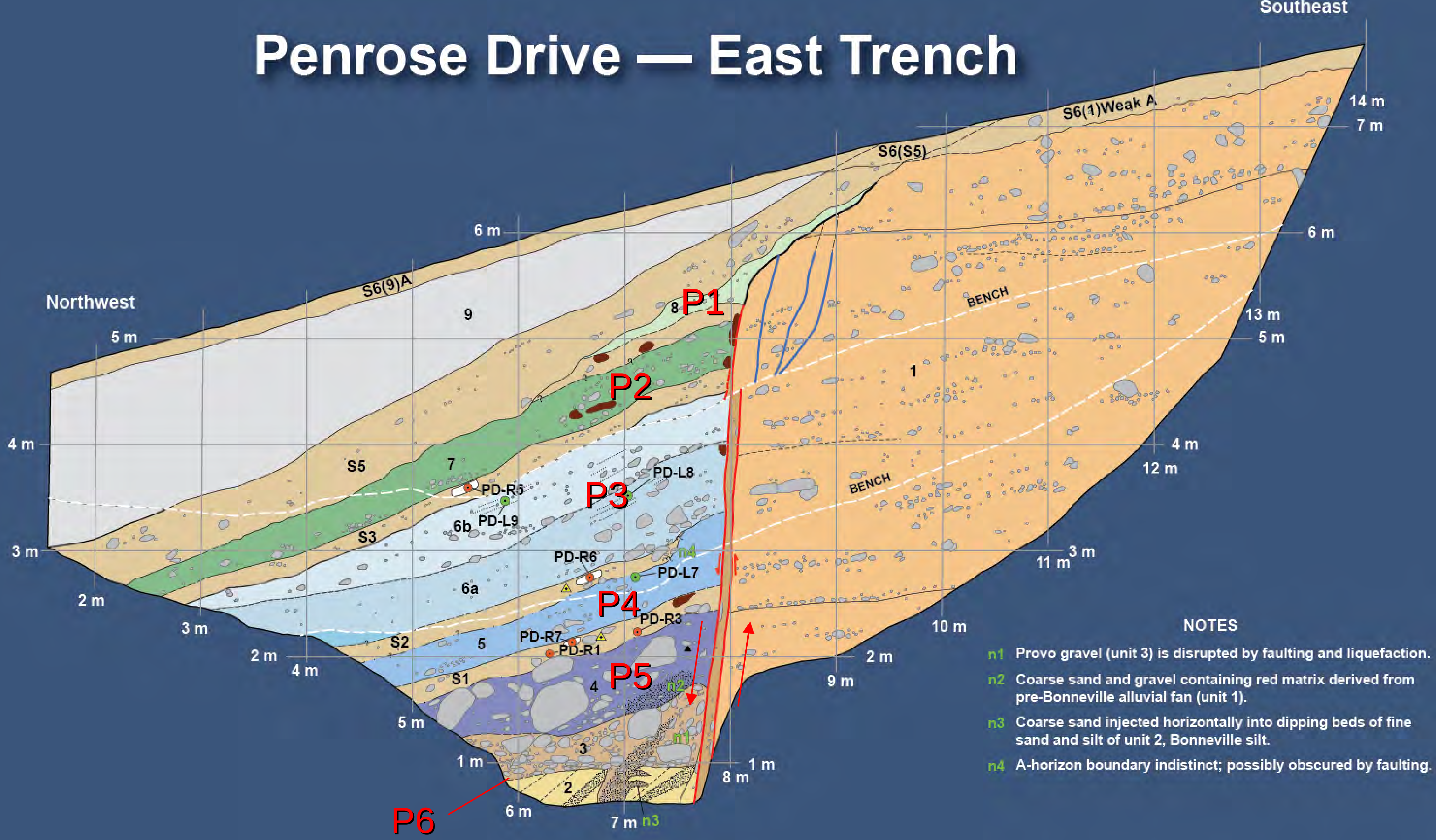
East Trench



SE
NW
Pre-Bonneville
alluvial fan
Cultural fill
Scarp colluvium


East Trench
Pre-Bonneville fan gravel
Fault
53° dip
Coarse sand injected into silt
Bonneville silt
East trench

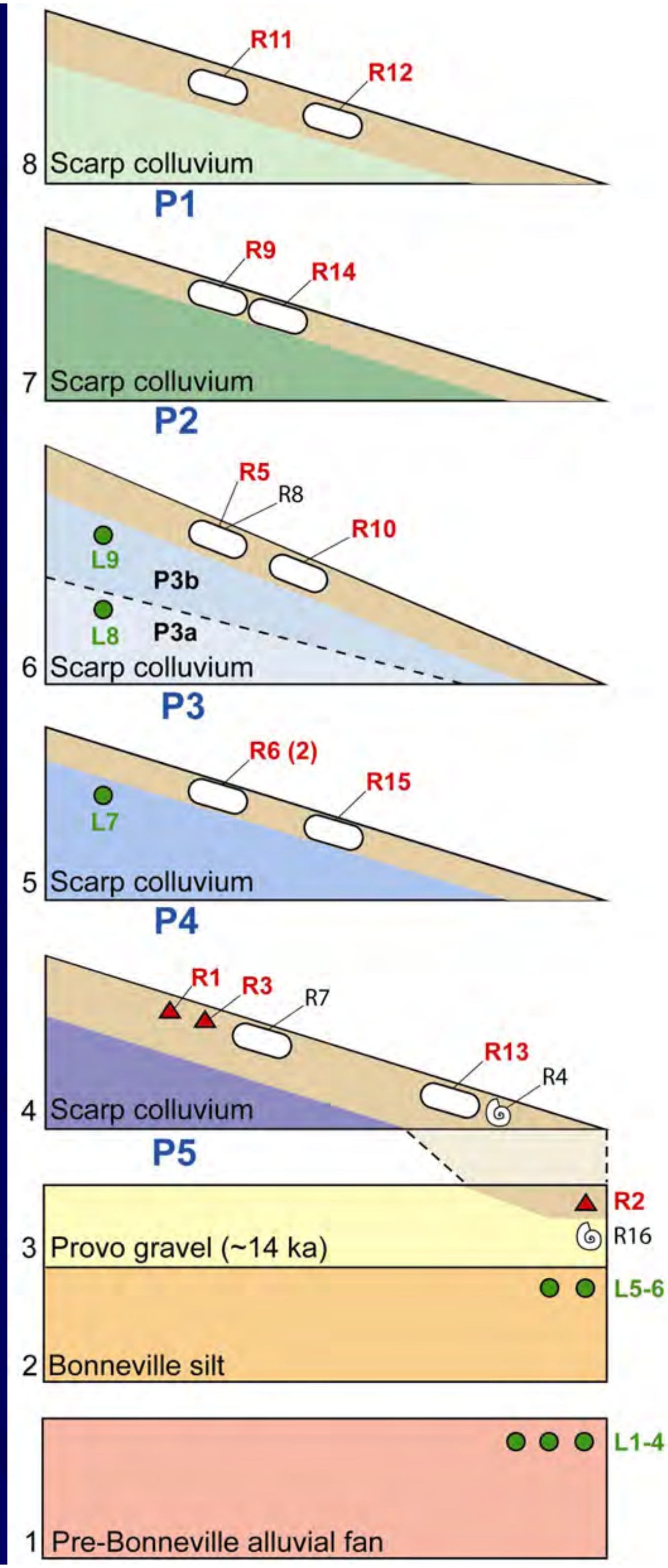
Penrose Drive — East Trench



Sampling Strategy

- 16 samples for radiocarbon dating
  - 3 macro charcoal
  - 11 bulk soil sediment, which yielded numerous charcoal fragments
  - 2 samples of gastropod shells
  - 13 charcoal fragments (red bold in figure) submitted for dating (results in early 2011)

- 6 samples for luminescence dating (OSL) (green in figure)
  - All samples submitted for dating (results in December?)



Significant Observations

1) Pre-Bonneville alluvial-fan gravels are exposed in the footwall but not the hanging wall of the fault. The oldest hanging-wall unit is Lake Bonneville silt, which is not present in the footwall block of the fault.

2) The fault zone is narrow, planar, and steeply dipping. Only minor faulting is present in the footwall.

3) In the West trench we interpreted four and possibly five colluvial wedges in the deposits adjacent to the fault.

4) In the East trench we interpreted five and possibly six colluvial wedges based on an exposure of the entire sequence of colluvial deposits to the top of the Bonneville silt.

5) Weak to very weak soils are developed on the separate colluvial wedges, with the exception of the 6a/6b boundary, which is defined by a stone line.

Significant Observations (continued)

6) Each colluvial wedge is on the order of 60-80 cm thick with the exception of unit 6, which is about 1.1 m thick near the fault.

7) In the East trench we mapped an angular unconformity between 53°-dipping Bonneville silt beds and near-horizontal Provo-stage beach gravels adjacent to the fault.

8) An auger hole in the West trench bottom penetrated 5.9 m of Bonneville silt, and at refusal, did not encounter the pre-Bonneville fan gravels.

Conclusions

1) Based on colluvial-wedge evidence, we interpret five and possibly six surface-faulting earthquakes on the SLCS (East Bench fault) that occurred after the Provo stage of Lake Bonneville (~17–14 ka)

2) Each colluvial wedge is on the order of 60-80 cm thick, suggesting that the vertical displacement per event is probably 0.6-1.6 m (0.8 m x 2).

3) An older event may have occurred between the high stand of Lake Bonneville (~20–17 ka at site) and the Provo stage (~17–14 ka) based on the angular unconformity between the tilted Bonneville silt beds and near-horizontal Provo-stage beach gravels.

Conclusions (continued)

4) This part of the SLCS may have a significant <u>component of lateral slip</u> based on the <u>narrow, planar, near-vertical character of the fault zone</u>. This is also supported by the northeasterly strike of this part of the fault compared to the generally east-west regional extension direction.

5) The <u>pre-Bonneville fan gravels are vertically offset a minimum of 16–17 m</u> based on the auger hole in the bottom of the West trench.

6) The presence of at least 6.5 m of Bonneville silt on hanging wall versus virtually no silt on the uplifted footwall suggests that a subaqueous scarp was likely present at this site. The presence of such a scarp would help explain the large difference in silt thickness on opposite sides of the fault scarp.

Update on Fault Trenching at the Baileys Lake Site, West Valley Fault Zone

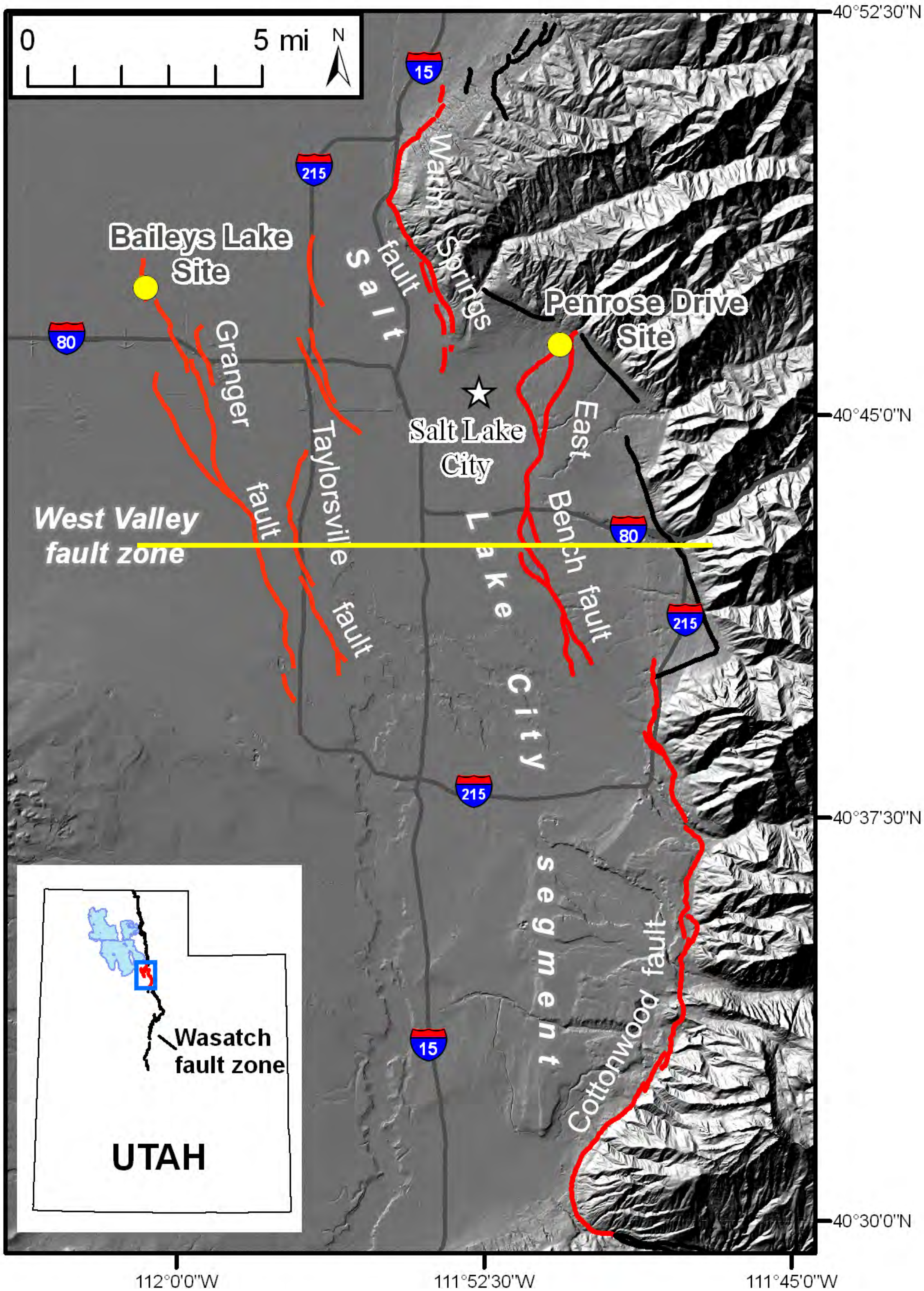
Mike Hylland and Chris DuRoss (UGS)

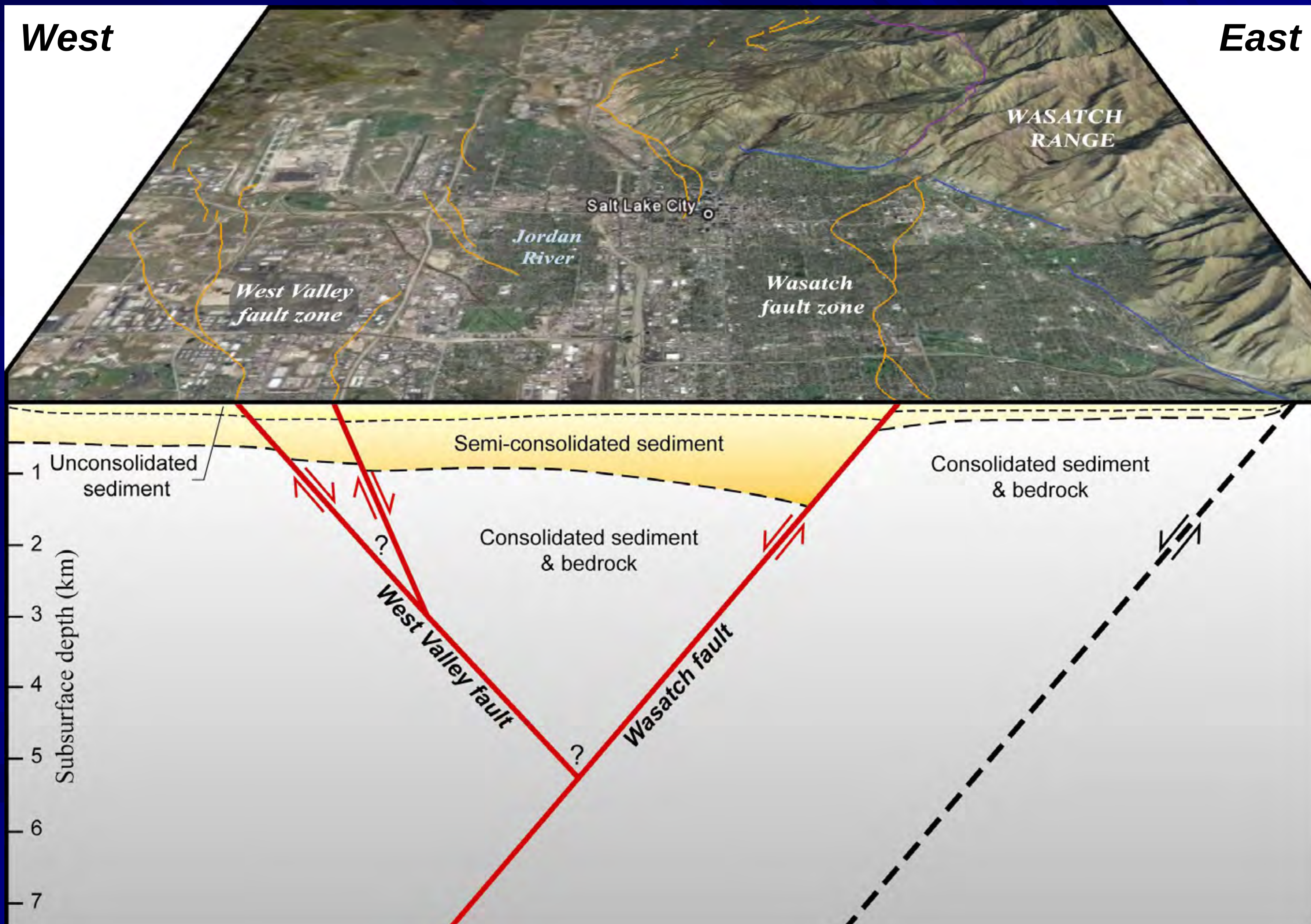
With help from Greg McDonald (UGS), Susan Olig (URS),
Tony Crone (USGS), Steve Personius (USGS), and Bill Lund (UGS)

Research funded by the Utah Geological Survey and U.S. Geological Survey, National Earthquake Hazards Reduction Program

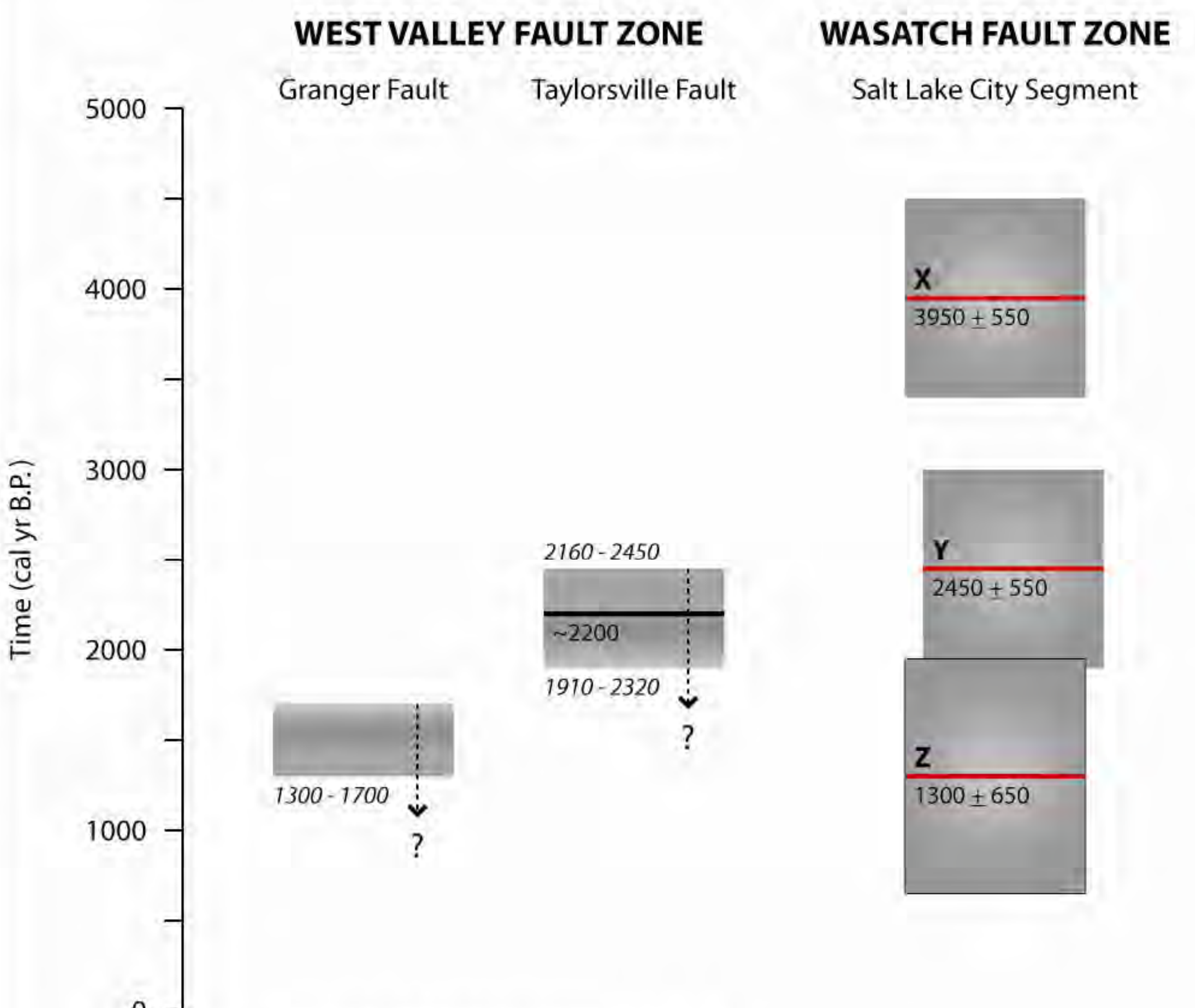
West Valley and Wasatch fault zones

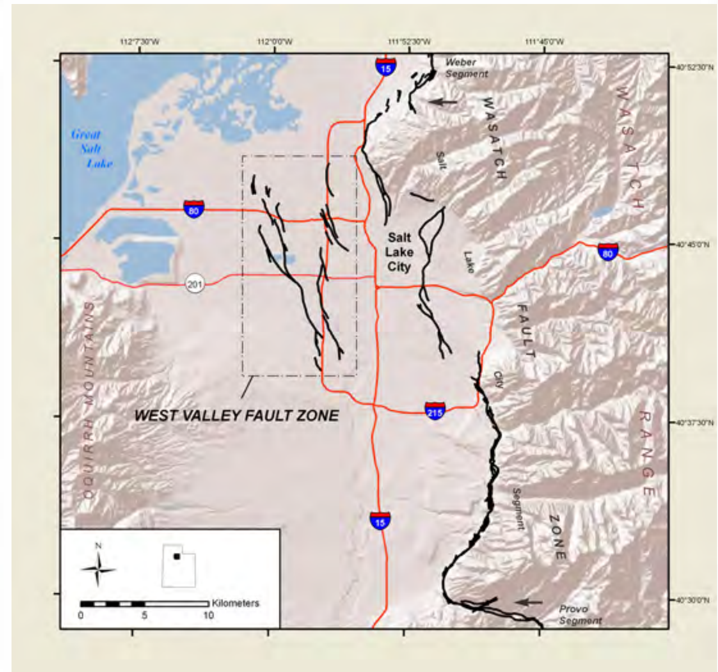
- Ongoing studies:
  - Penrose Drive (SLCS)
  - Baileys Lake (WVFZ)
- Primary goals:
  - Resolve the timing and displacement of individual surface-faulting earthquakes on the northern part of the SLCS and the WVFZ
  - Clarify the seismogenic relation (dependent or independent) between these two faults




West
East
WASATCH RANGE
Salt Lake City
Jordan River
West Valley fault zone
Wasatch fault zone
Semi-consolidated sediment
Unconsolidated sediment
Consolidated sediment & bedrock
Consolidated sediment & bedrock
West Valley fault
Wasatch fault
Subsurface depth (km)
1
2
3
4
5
6
7

Evidence for possible coseismic rupture of the West Valley fault and Salt Lake City segment





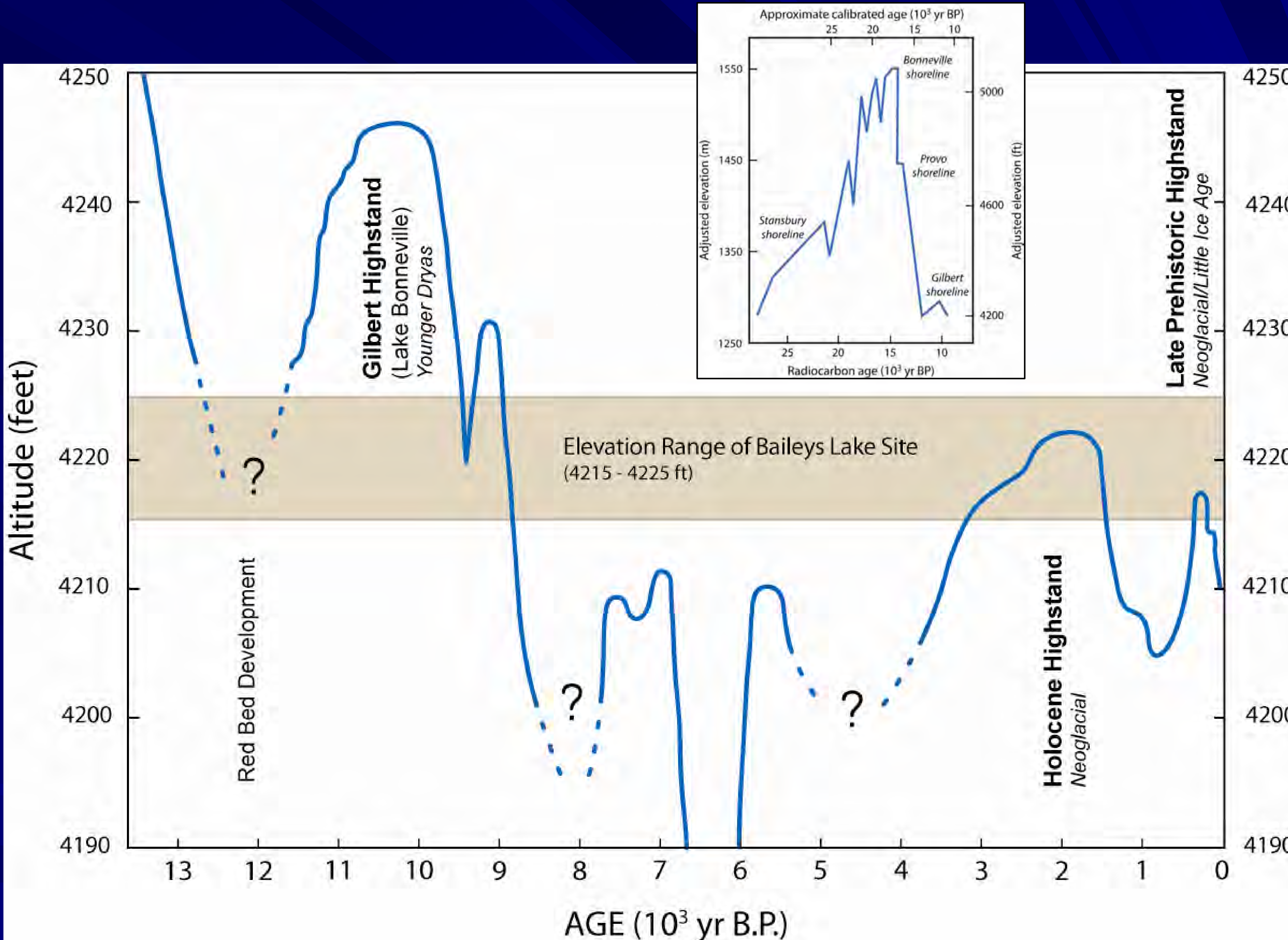
Granger fault data from *westernmost* strand.
Taylorsville fault data from *northernmost* strand.
Salt Lake City segment data from *south end* of Cottonwood sub-section.

UQFPWG consensus preferred earthquake timing and uncertainty (Lund, 2005)

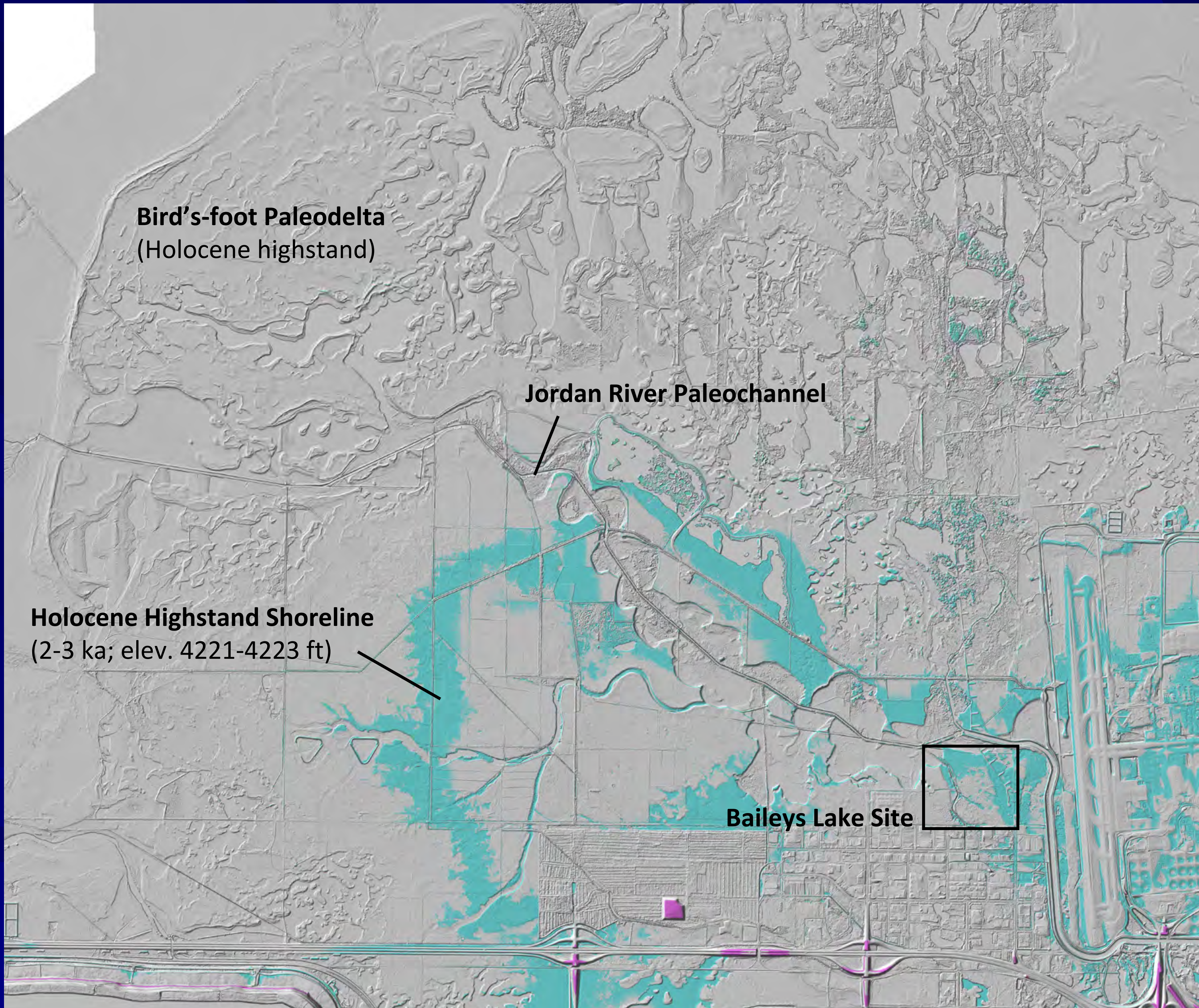
Average of maximum-limiting ages (Solomon, 1998)

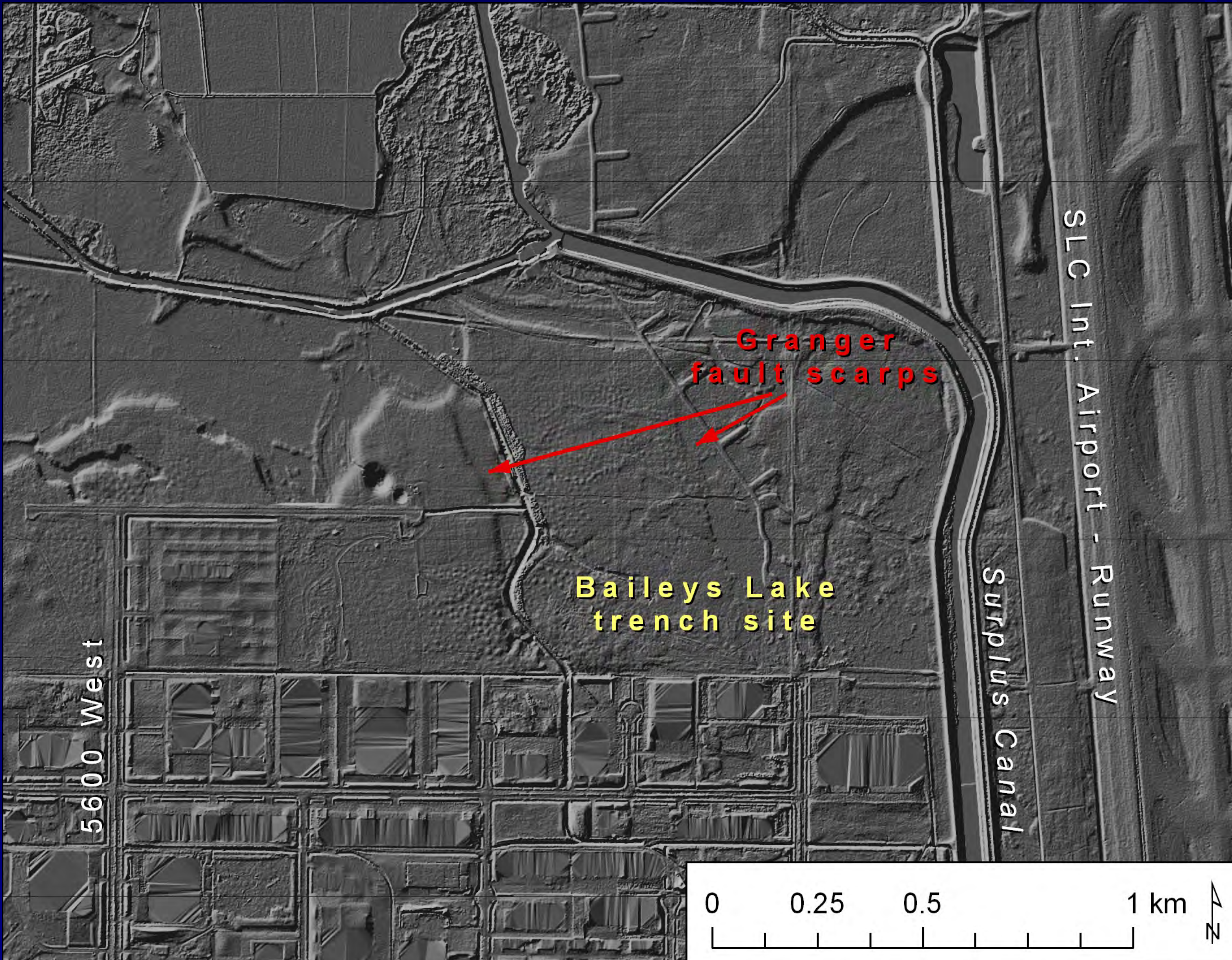
Minimum limit on timing unknown

?



Great Salt Lake hydrograph from Murchison (1989)

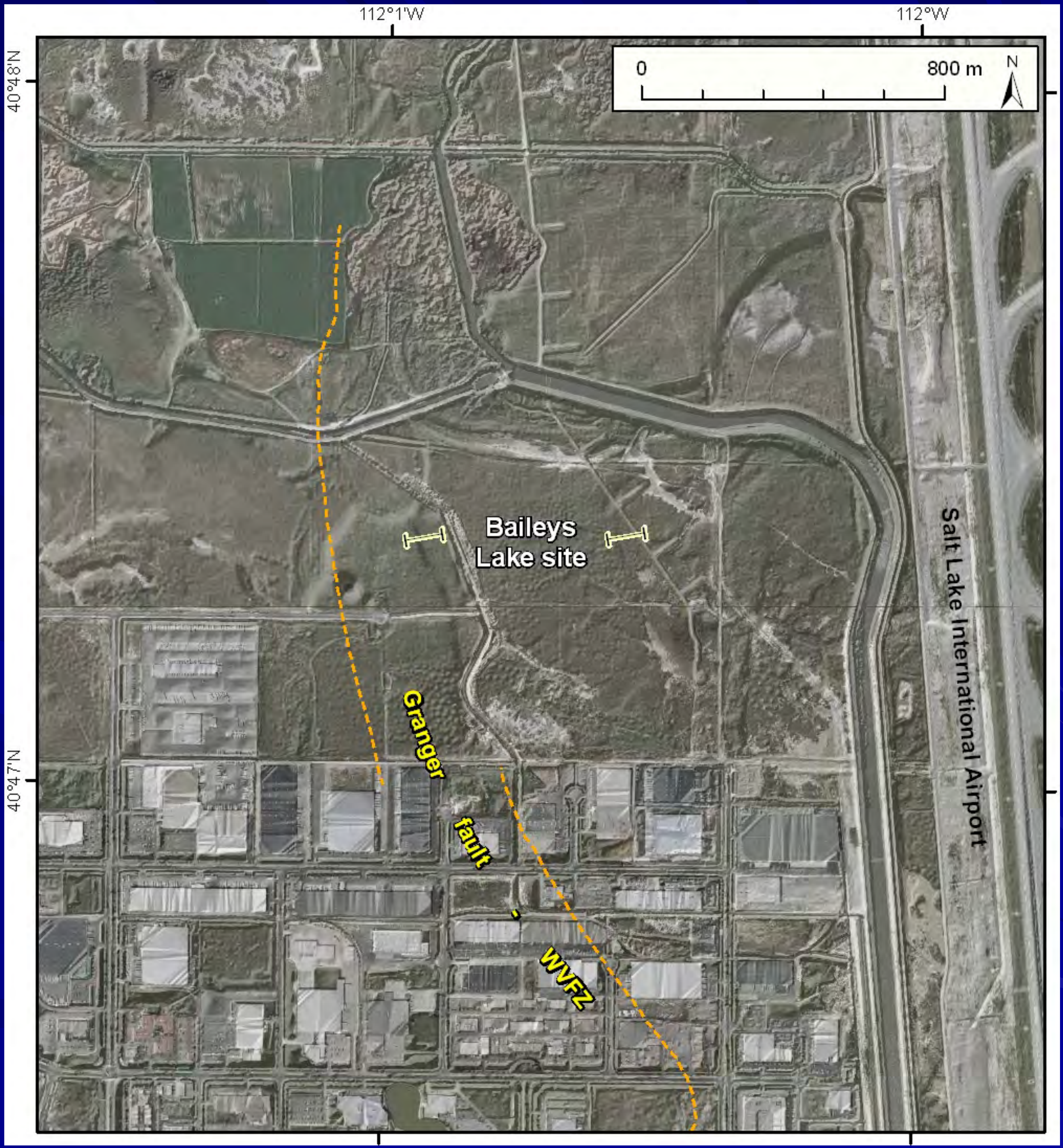

Bird's-foot Paleodelta
(Holocene highstand)
Jordan River Paleochannel
Holocene Highstand Shoreline
(2-3 ka; elev. 4221-4223 ft)
Baileys Lake Site

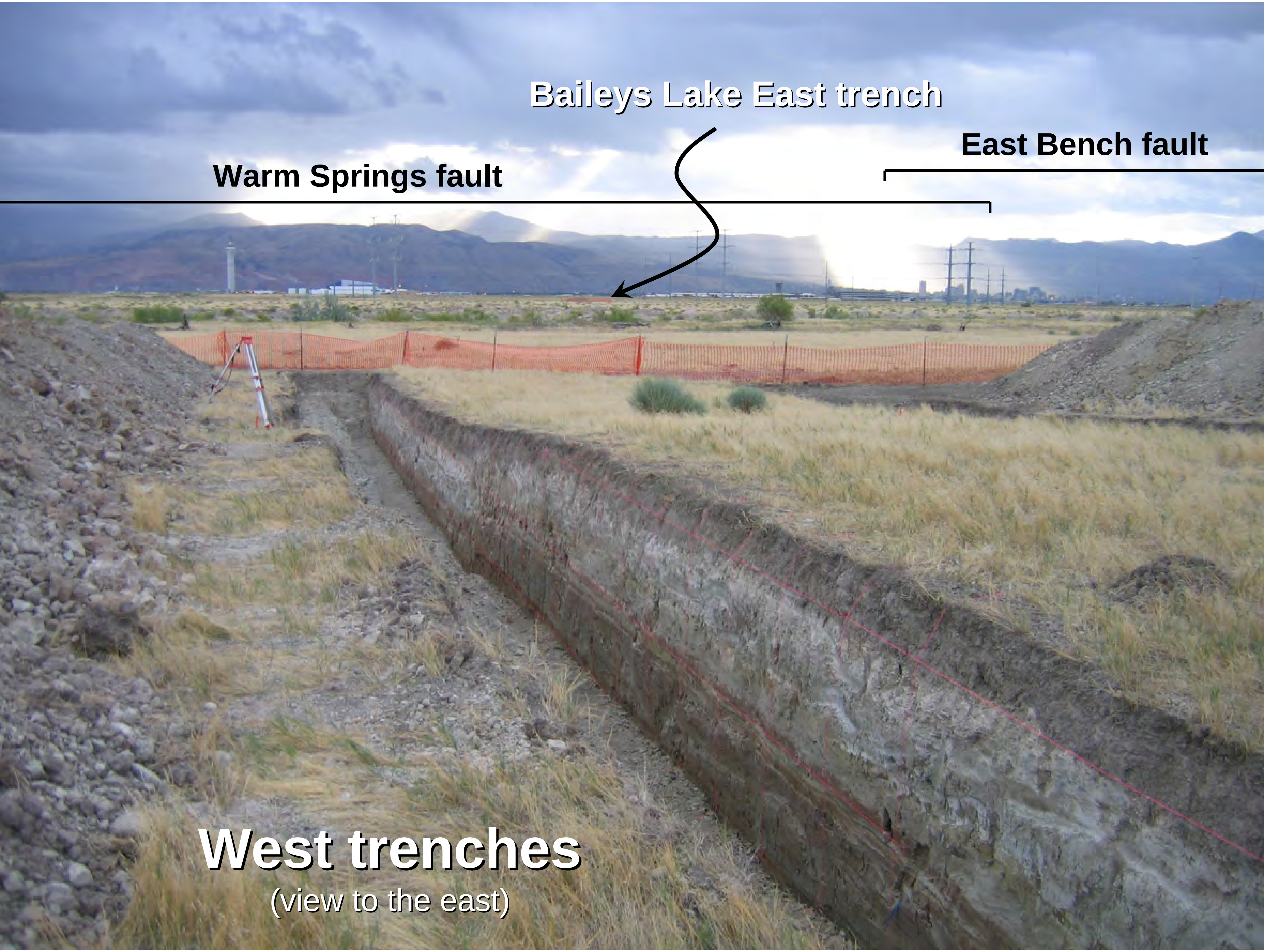

Granger fault scarps
Baileys Lake trench site
SLC Int. Airport - Runway
Surplus Canal
5600 West
0
0.25
0.5
1 km
N

Baileys Lake Trench Site

Three trenches:

- Two across western scarp
    - scarp ~1 m high
    - trenches 44 and 21 m long, max. 3 m deep
- One across eastern scarp
    - scarp ~0.25 m high
    - trench 52 m long, max. 2 m deep



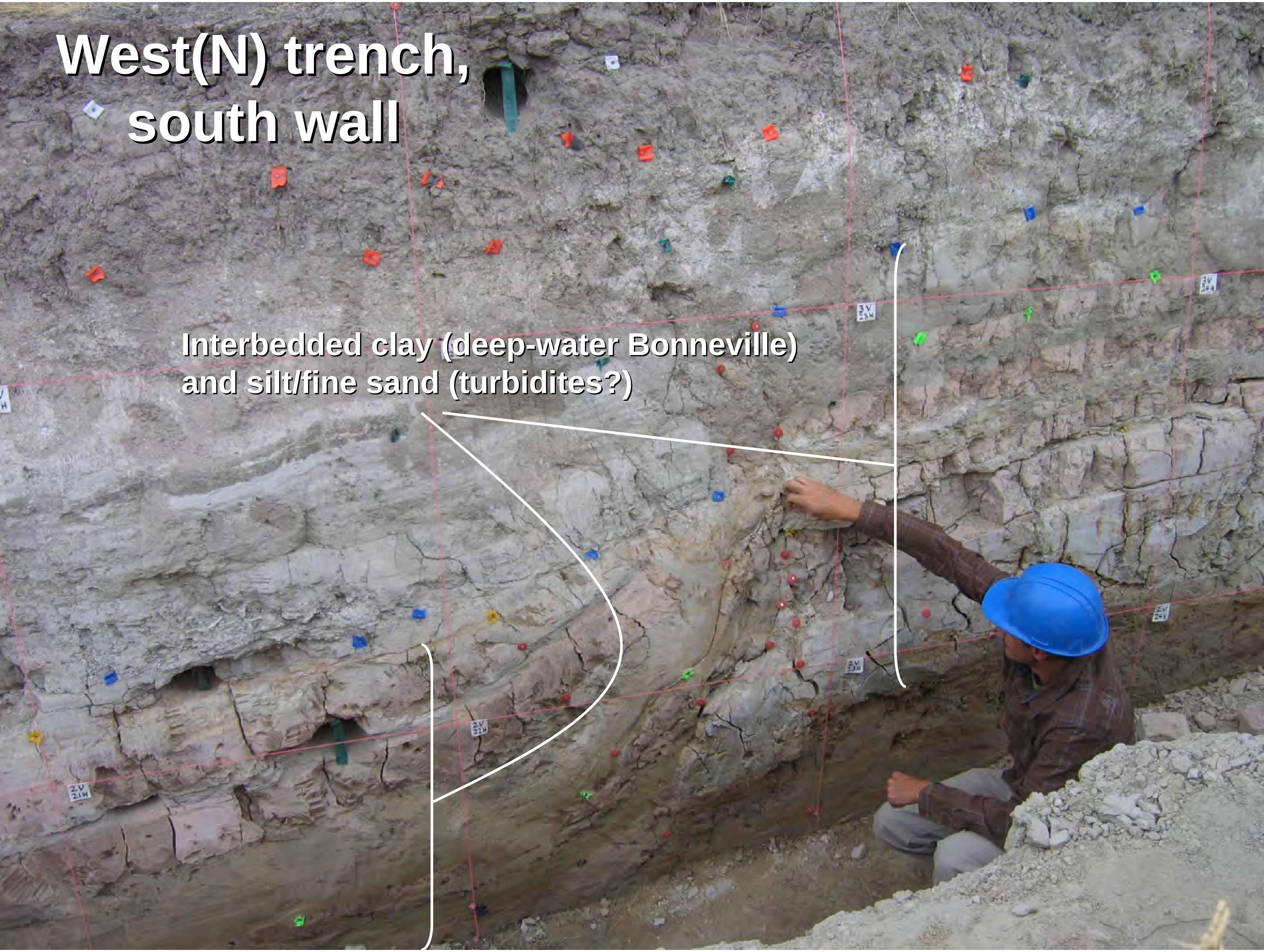

Baileys Lake East trench
East Bench fault
Warm Springs fault
West trenches
(view to the east)

West(S) trench


West(N) trench,
south wall


West(N) trench,
south wall
Ripple-laminated sand, clay
(Bonneville transgressive(?))

West(N) trench, south wall

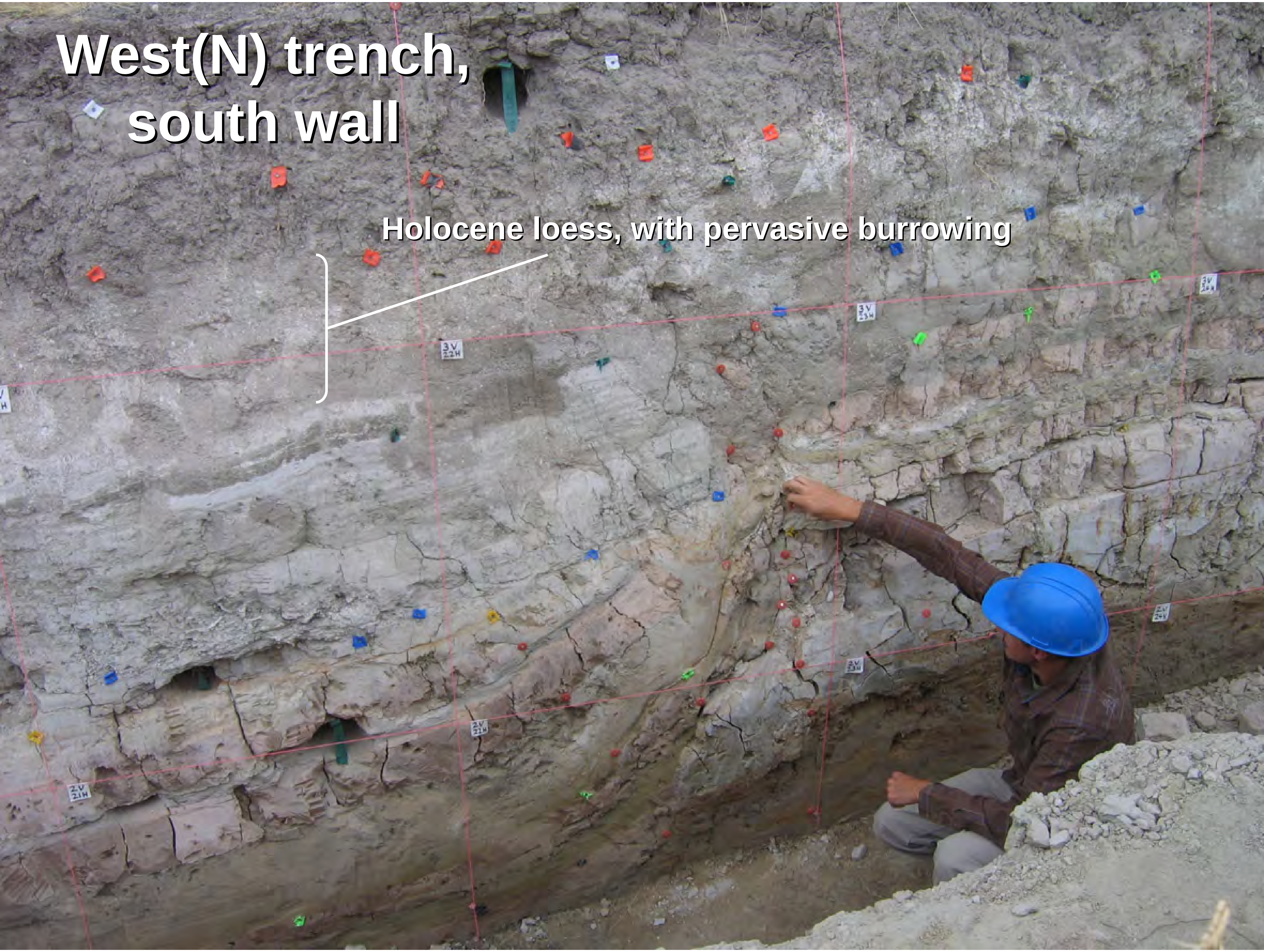


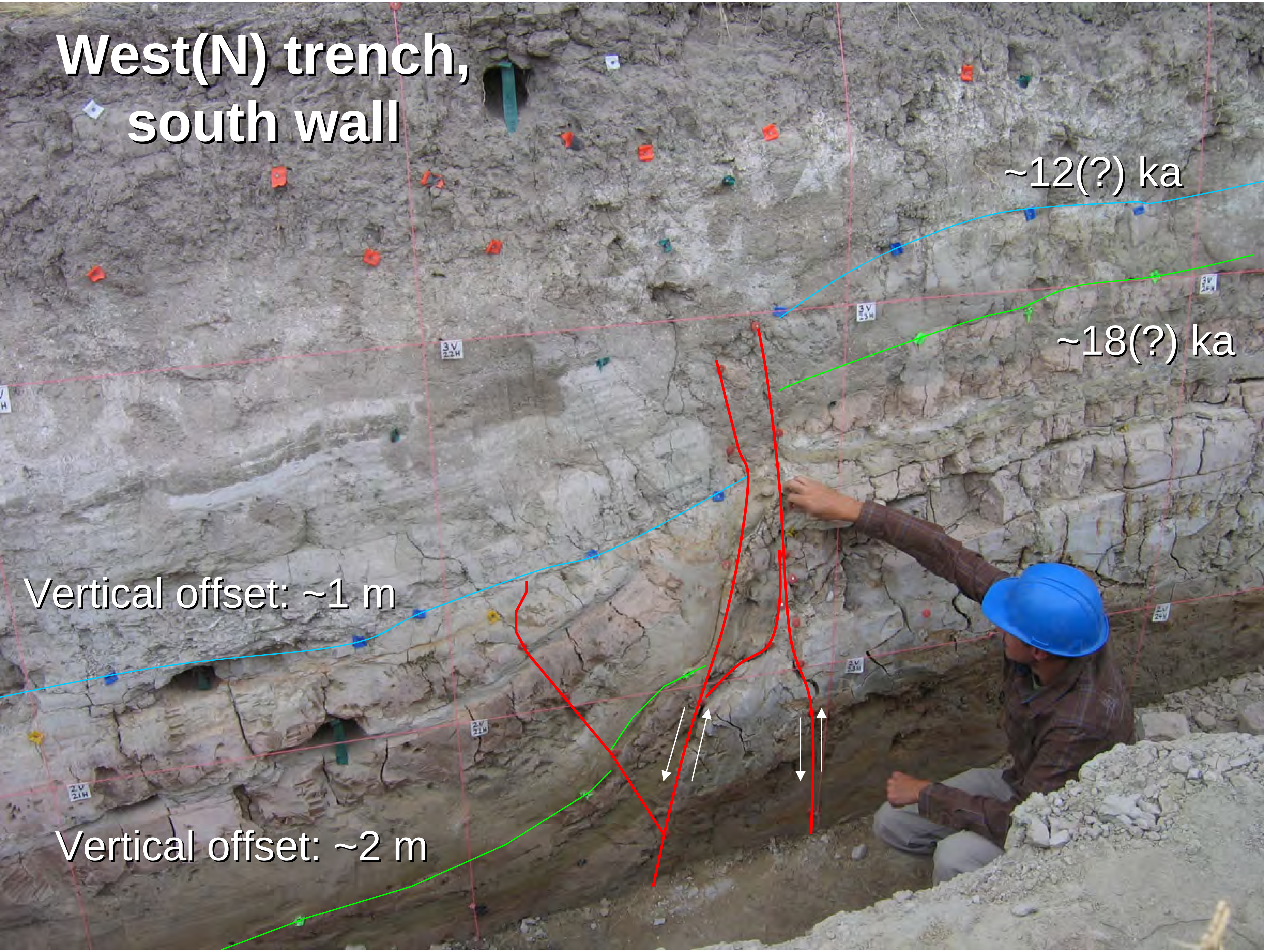

West(N) trench,
south wall
Laminated, organic-rich marl
(pre-Gilbert wetland/lacustrine?)


West(N) trench,
south wall
Shoreline tufa (hash)
(Gilbert transgression?)


West(N) trench,
south wall
Finely laminated marl,
conformable on topography
(Gilbert lake cycle?)

West(N) trench, south wall

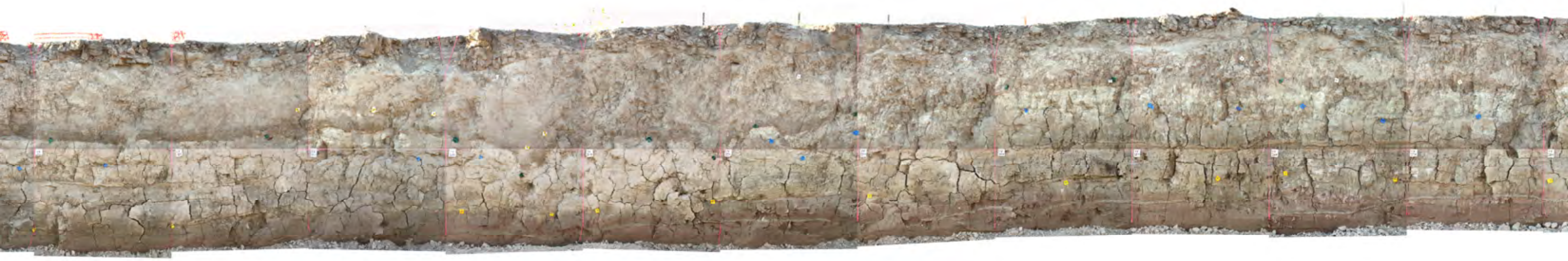

West(N) trench,
south wall
Holocene loess, with pervasive burrowing


West(N) trench,
south wall
~12(?) ka
~18(?) ka
Vertical offset: ~1 m
Vertical offset: ~2 m

~25-cm-high, east-facing scarp (zone of warping)

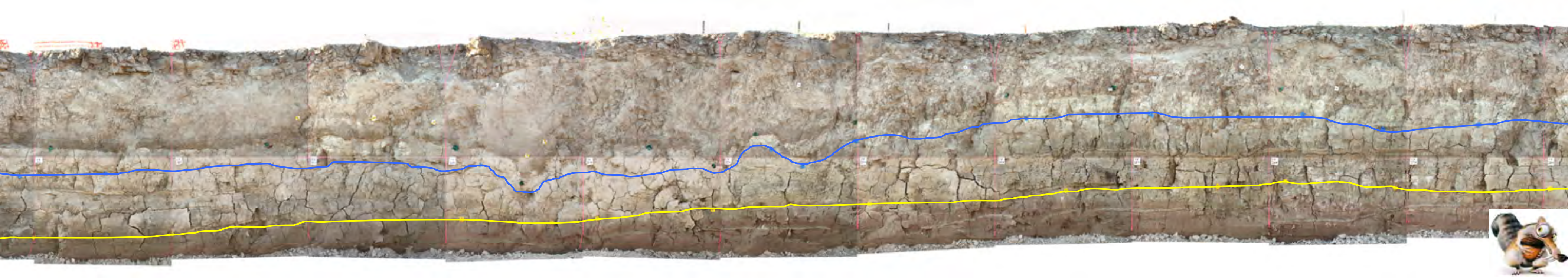
East trench

(view to the east)



East trench, south wall

Vertical offset: ~0.5 m



East trench, south wall

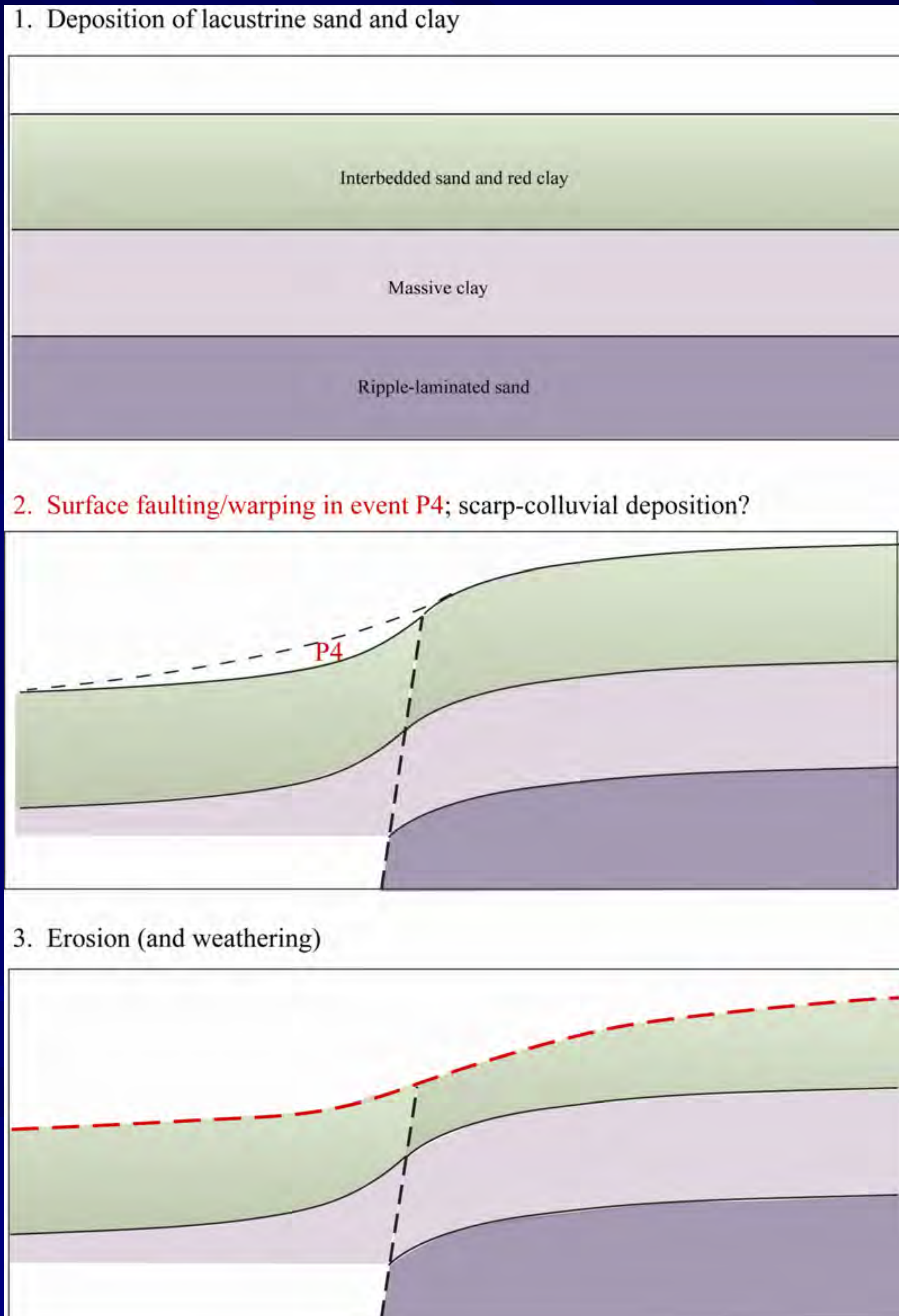
Evidence for 4 (5?) paleoearthquakes:

Post-Gilbert lake cycle { P1 (most recent paleoearthquake)
P2

Post-Bonneville highstand { P3
P4 (earliest paleoearthquake)

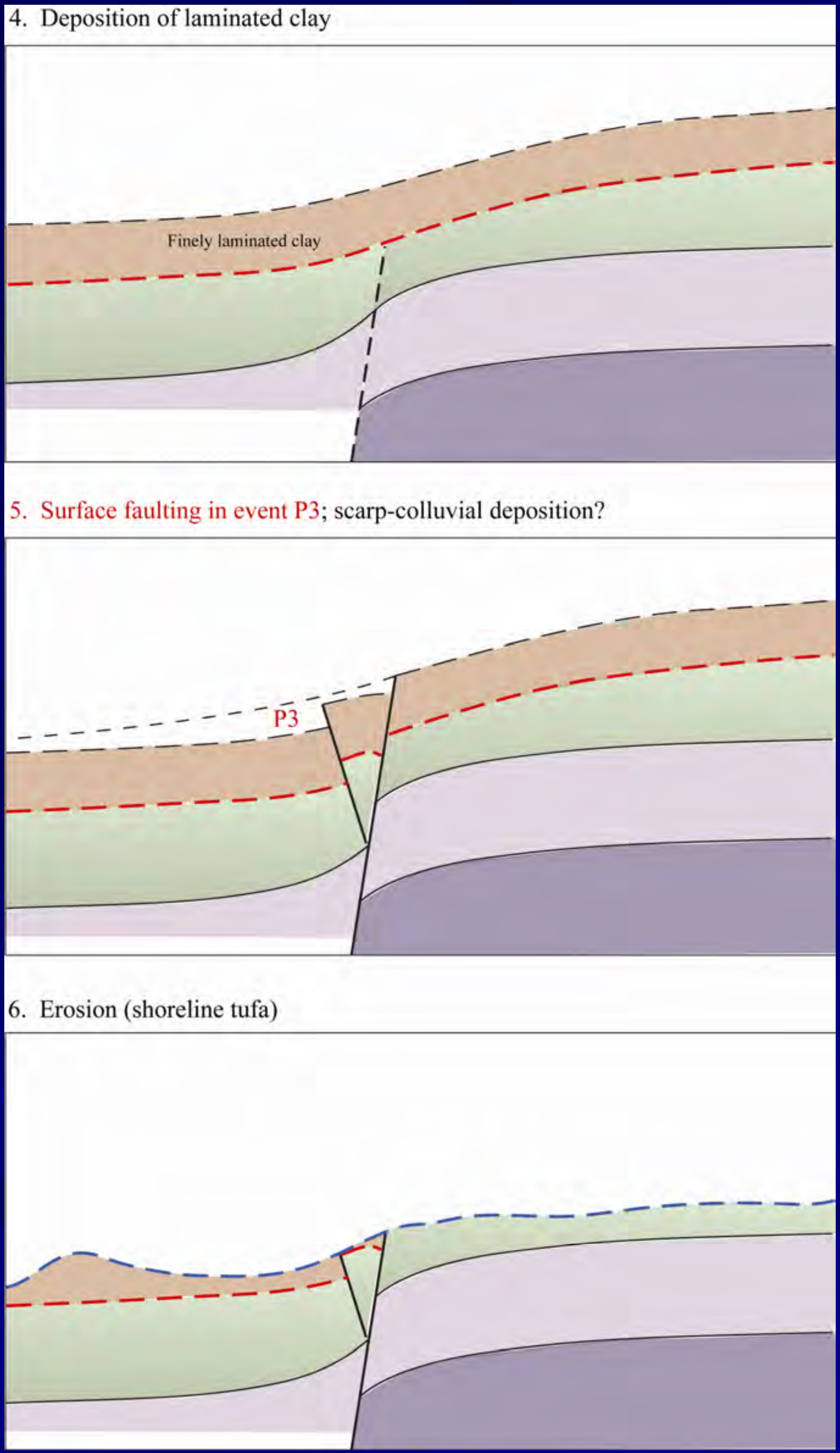
*Single warping event recorded at eastern scarp may or may not correlate with one of the four events recorded at the western scarp.

P4 – Warping of Bonneville strata (sub-lacustrine event)

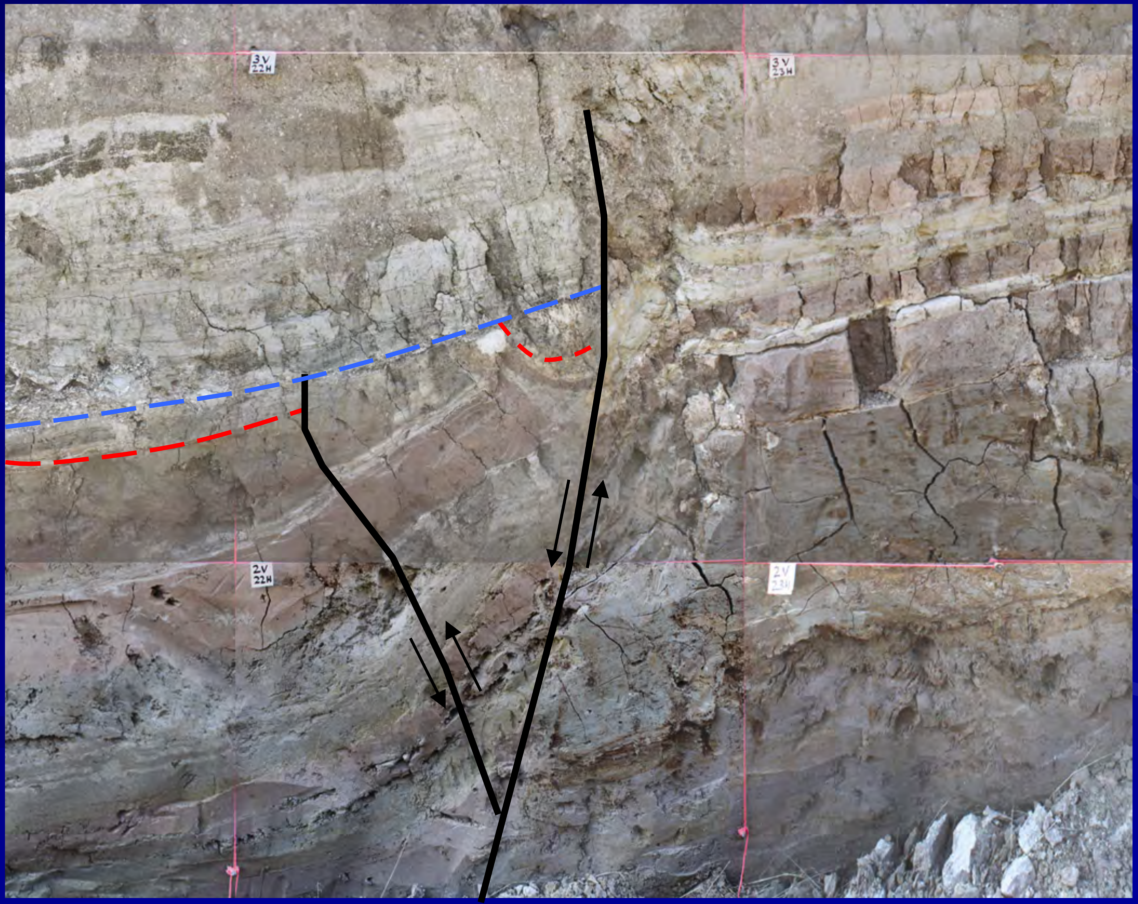


West(N) trench, south wall

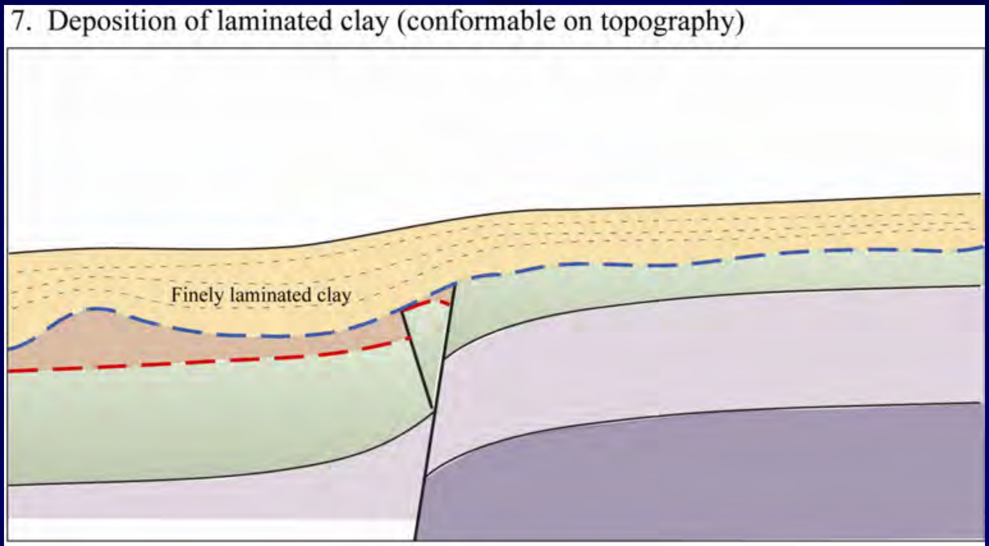

2V
17H

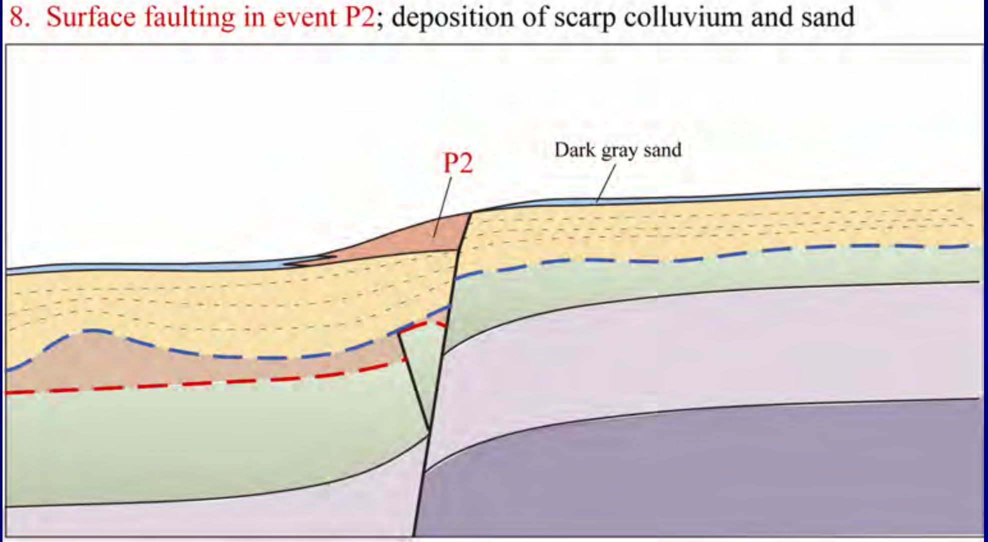


P3 – Fault-zone deformation (shear and folding) of warped beds and unconformity

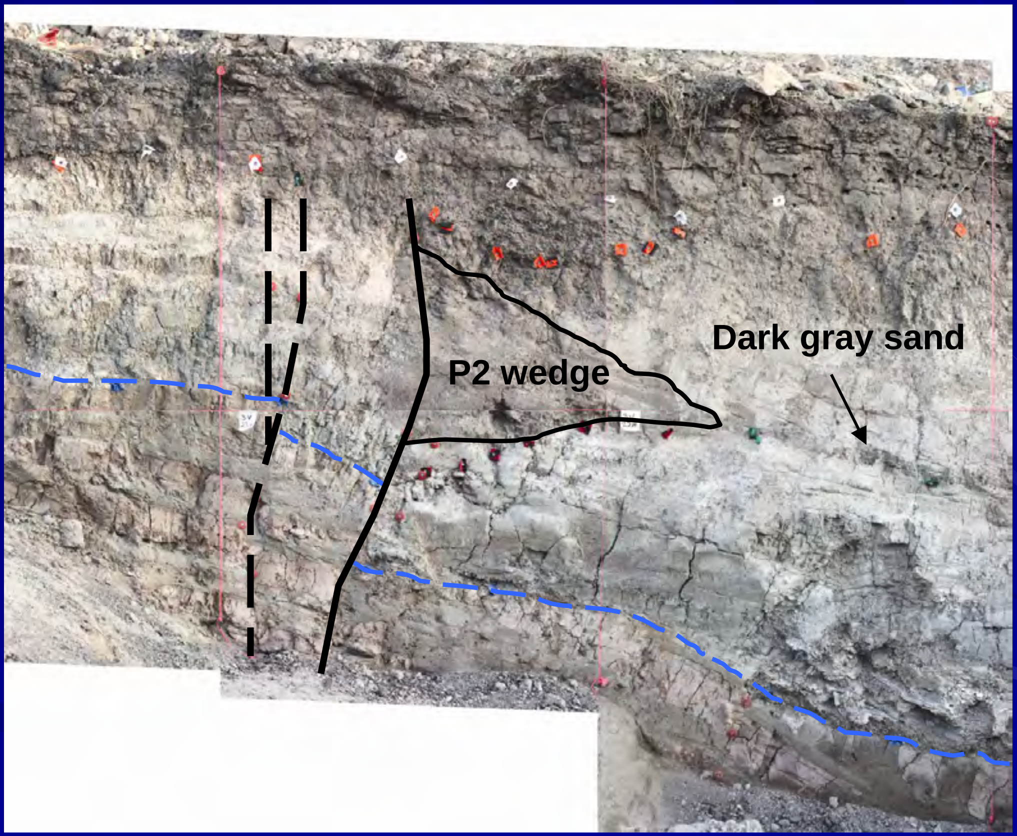


West(N) trench, south wall



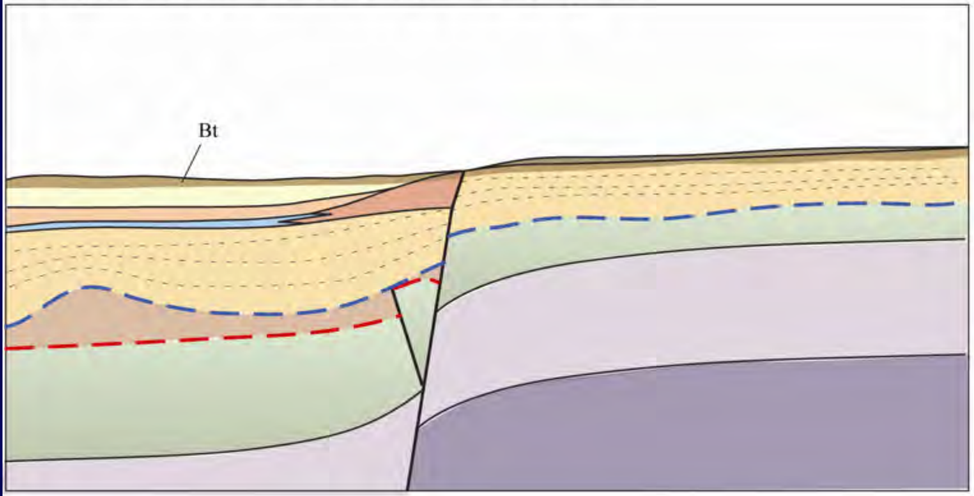


P2 – Shear of laminated clay, deposition of stratified "colluvial" wedge

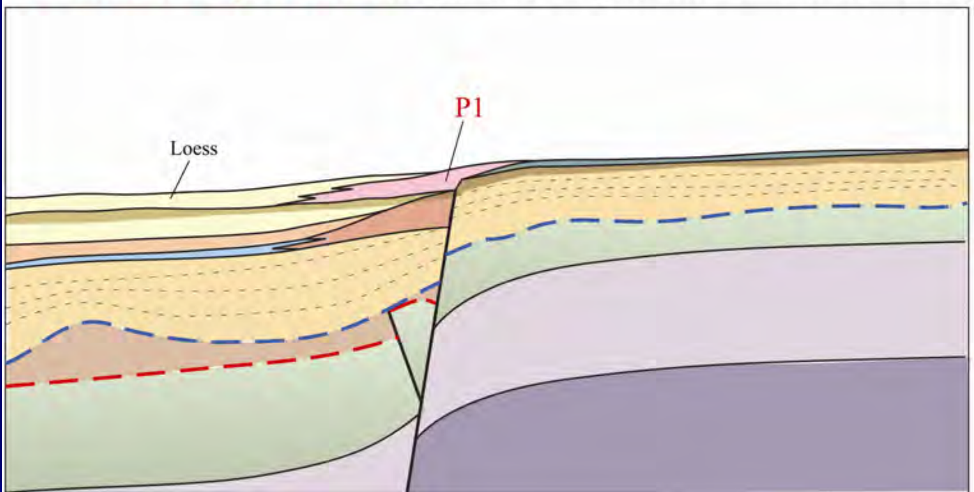


West(N) trench, north wall

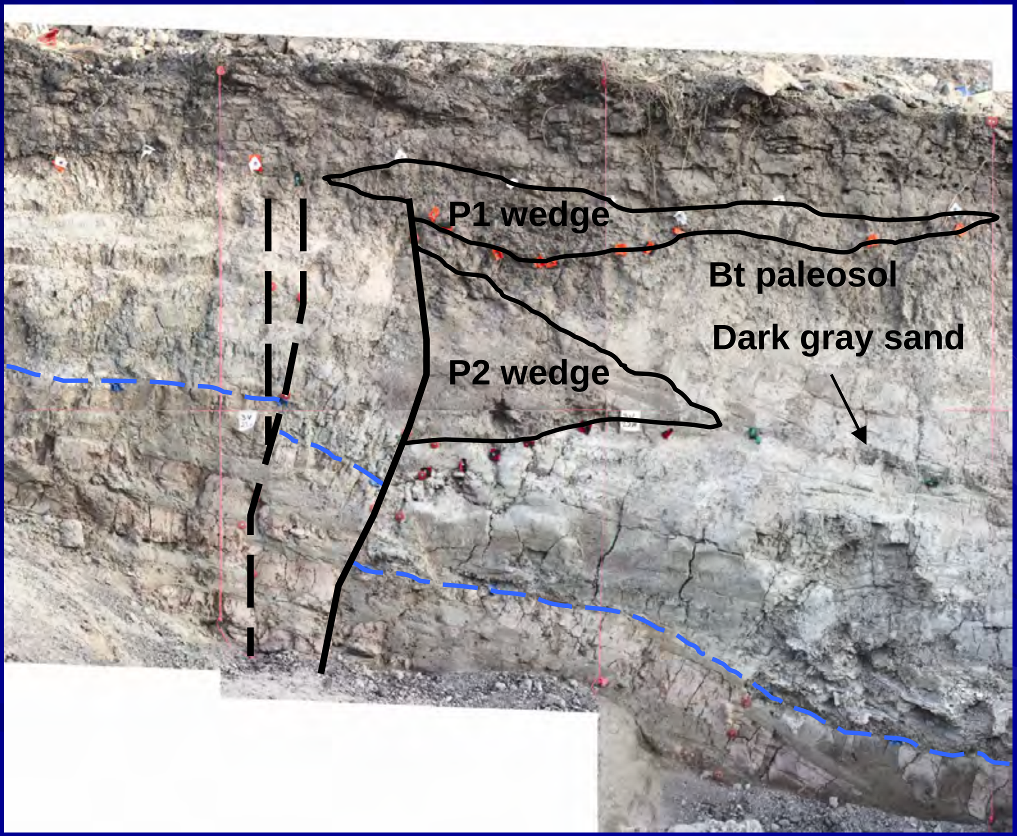
9. Deposition of wind-blown silt; Bt soil development



10. Surface faulting in event P1; depostion of scarp colluvium and wind-blown silt



P1 – Shear of P2 wedge, deposition of organic-rich scarp colluvium



West(N) trench, north wall

Numerical Constraints on Earthquake Timing

• Luminescence (16 samples)
• Radiocarbon (5 bulk samples, analyzed for charcoal)
+ Ostracode biostratigraphy (13 samples)

Preliminary Findings

Evidence for 4 (5?) large earthquakes that post-date the Bonneville highstand (~18 ka)

- P4 – sub-lacustrine, Bonneville cycle
- P3 – subaerial, between Bonneville dessication and Gilbert cycle
- P2 – post-Gilbert cycle; subaerial, but under wet climatic conditions(?)
- P1 – typical subaerial scarp-colluvial deposition

Average per-event vertical displacement ~0.5 m (western scarp)

Vertical displacement (~0.5 m) at eastern scarp produced only broad warping

UCERF Model Construction

Components of the Uniform California Earthquake Rupture Forecast

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

→

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

→

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

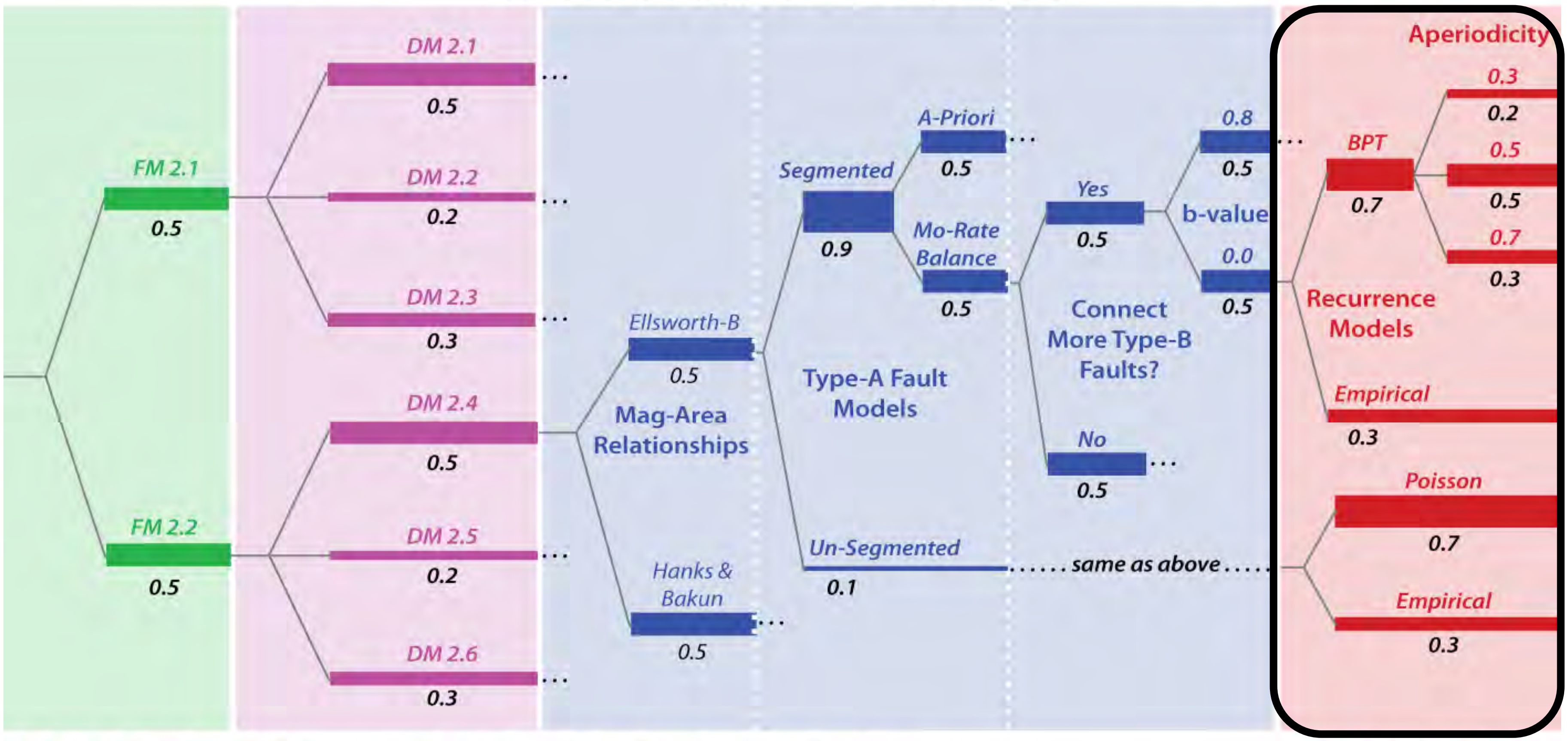
→

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

Earthquake Probability Models

Components of the Uniform California Earthquake Rupture Forecast 2

(abbreviated logic tree of 480 branches)



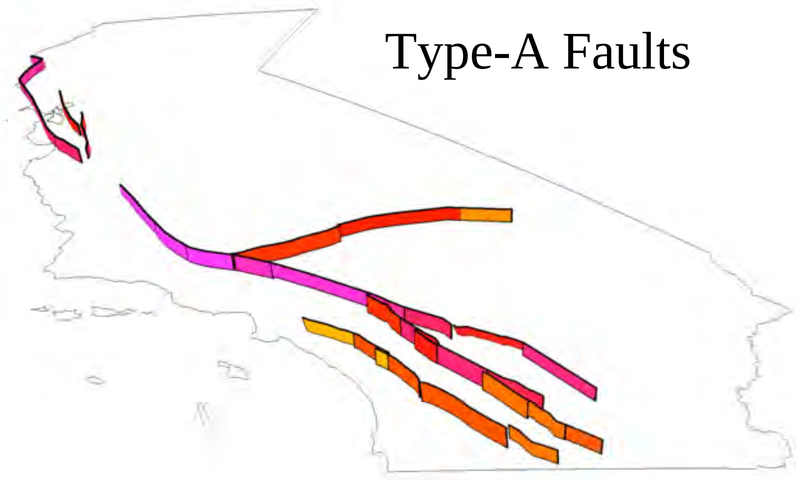
A. Fault Models
Specifies the spatial geometry of larger, more active faults.

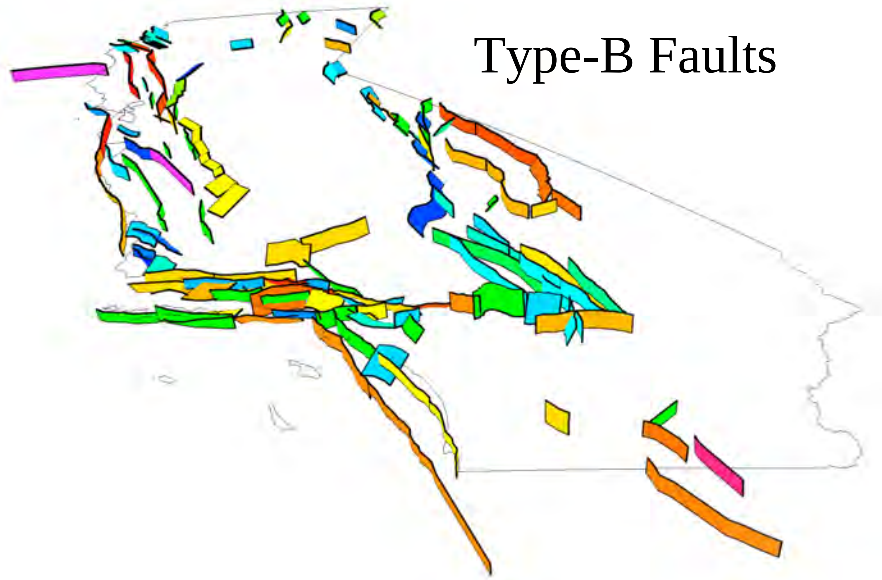
B. Deformation Models
Provides fault slip rates used to calculate seismic moment release.

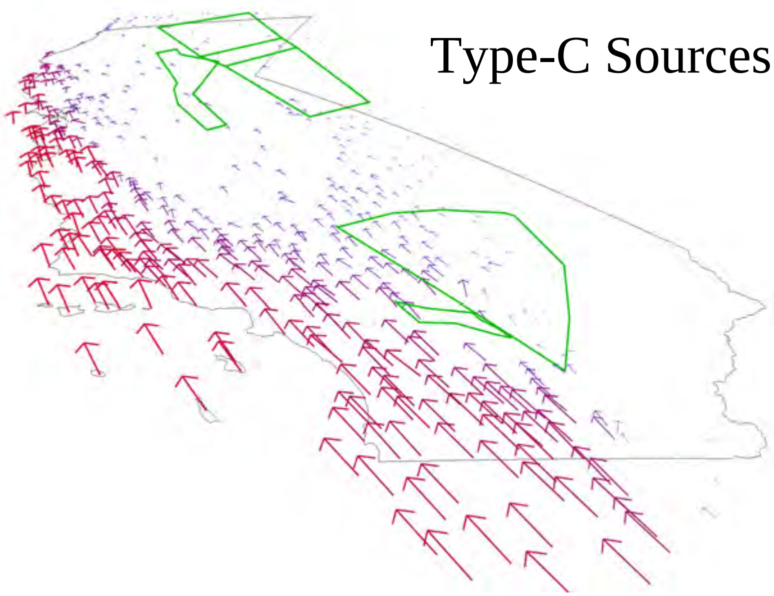
C. Earthquake-Rate Models
Gives the long-term rate of all possible damaging earthquakes throughout a region.

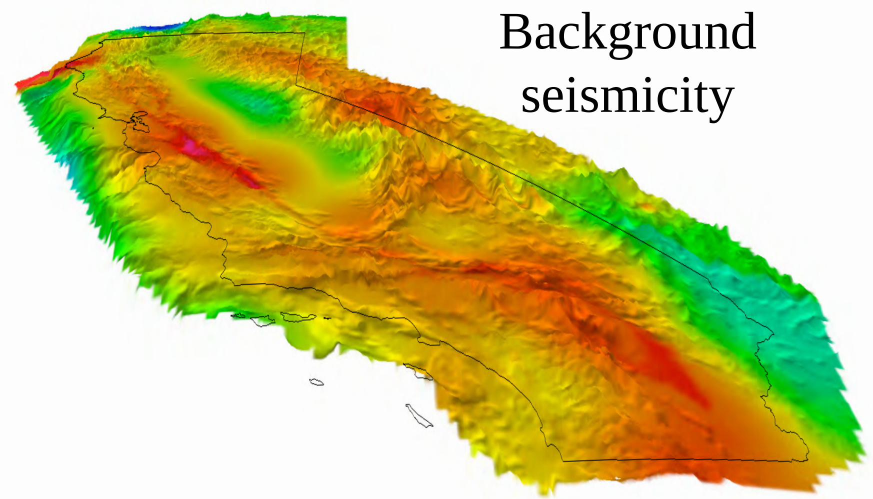
D. Probability Models
Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

Earthquake Probability Model





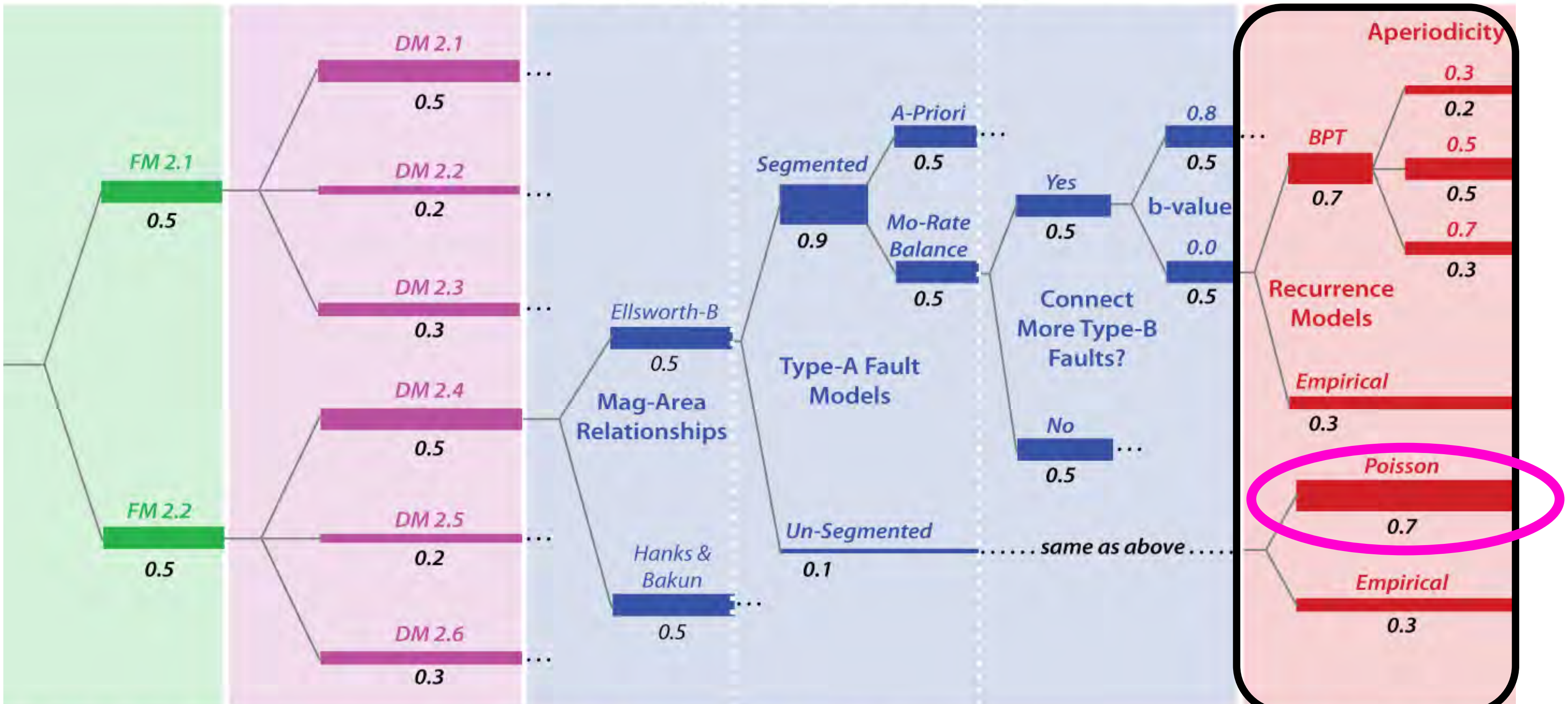




Earthquake Probability Model

Components of the Uniform California Earthquake Rupture Forecast 2

(abbreviated logic tree of 480 branches)



A. Fault Models

Specifies the spatial geometry of larger, more active faults.

B. Deformation Models

Provides fault slip rates used to calculate seismic moment release.

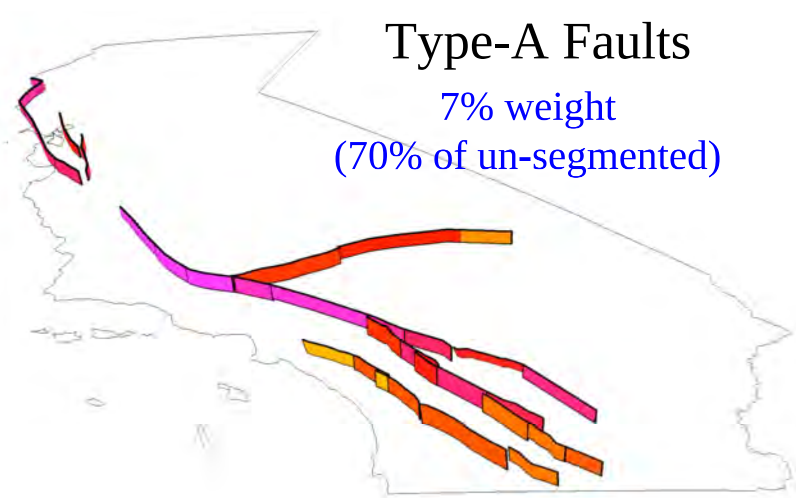
C. Earthquake-Rate Models

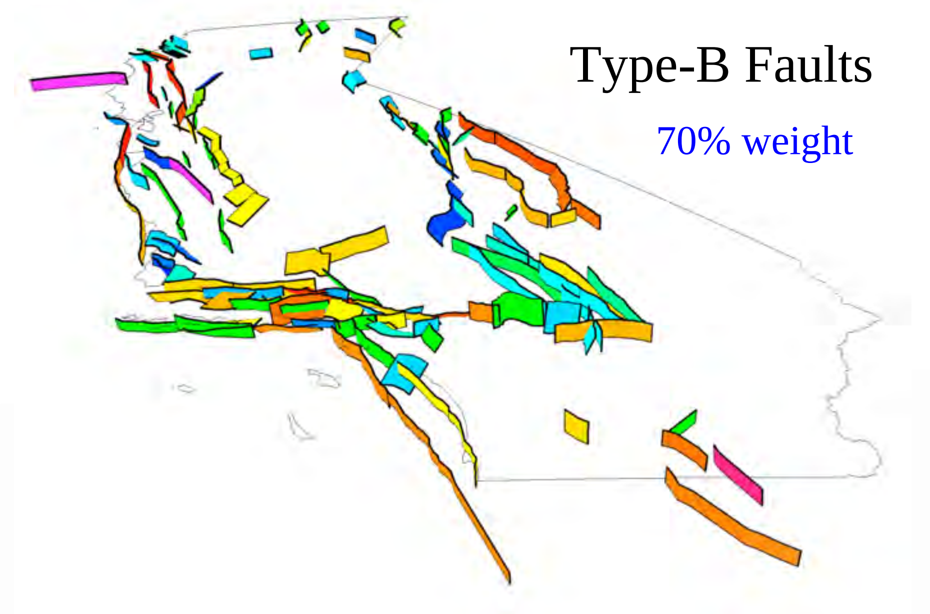
Gives the long-term rate of all possible damaging earthquakes throughout a region.

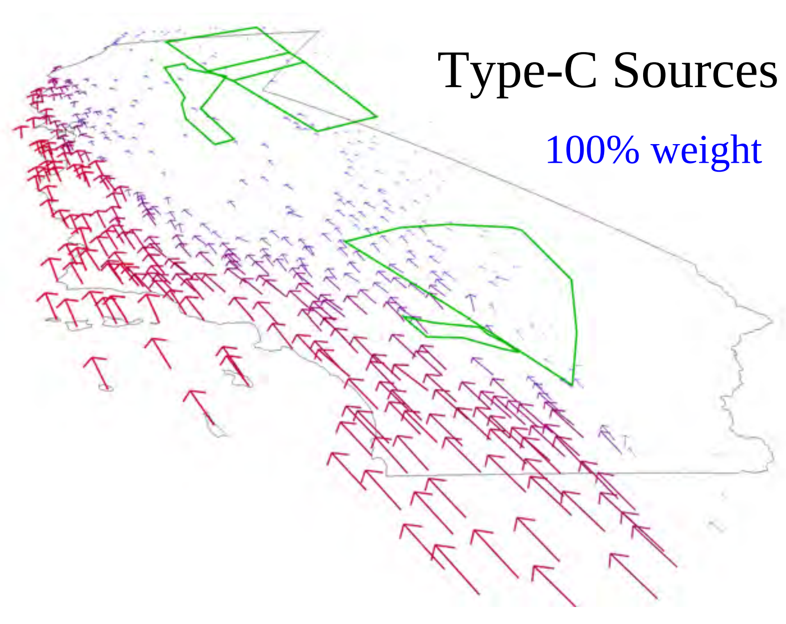
D. Probability Models

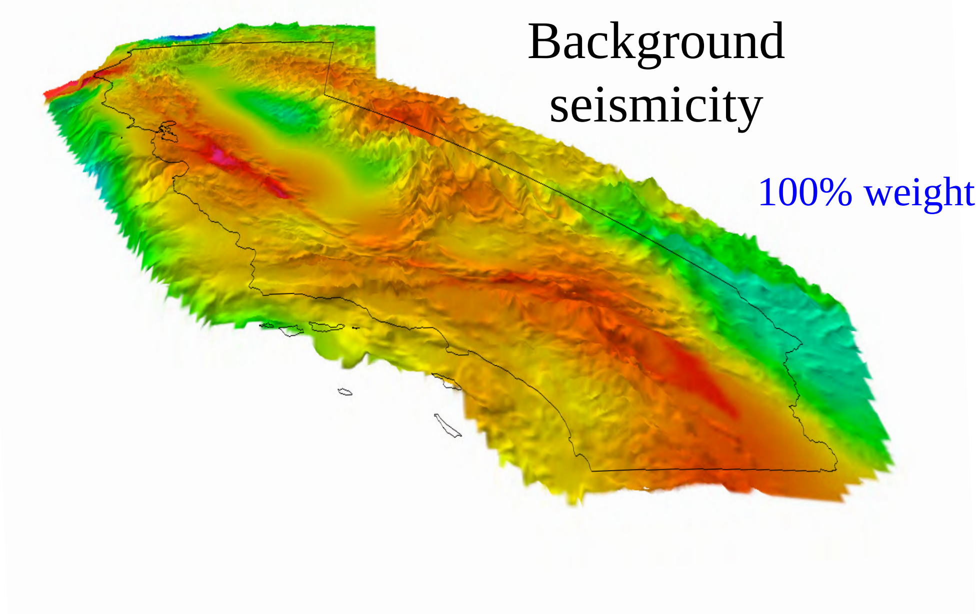
Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

Poisson Probability Model ($P = 1\text{-}exp^{-R*T}$)

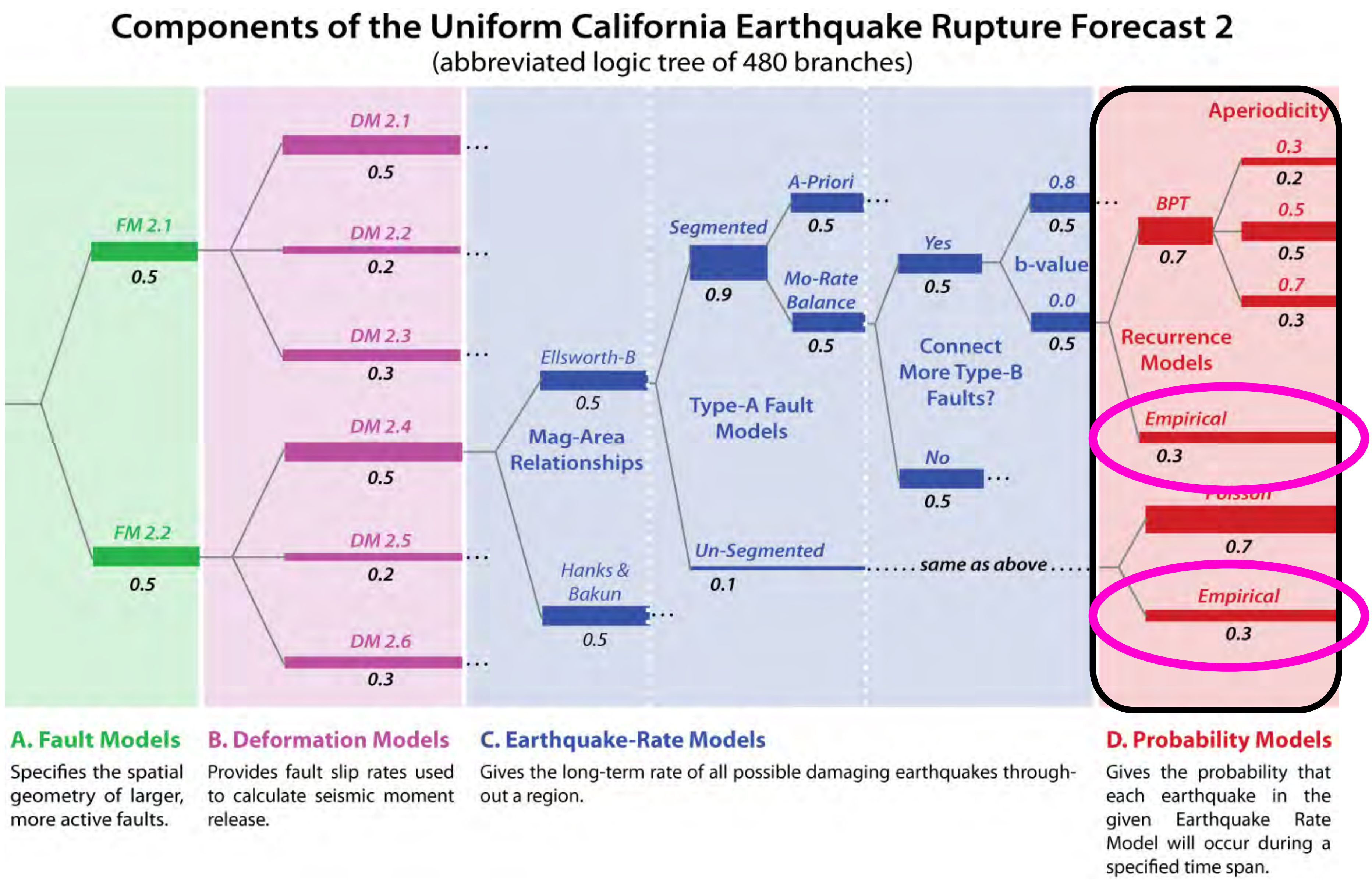




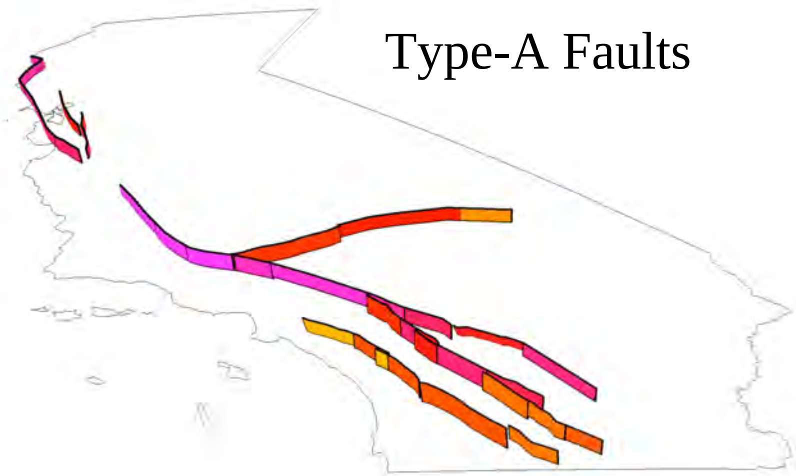


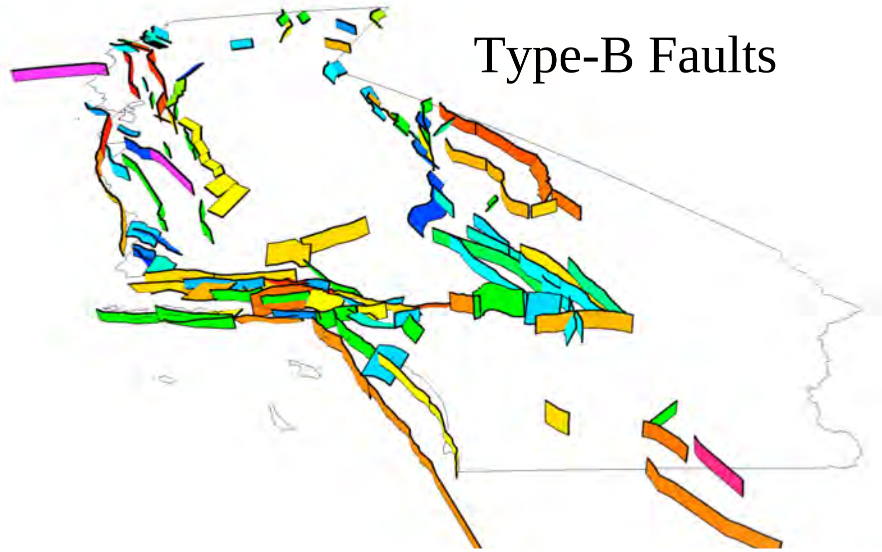


Earthquake Rate Model

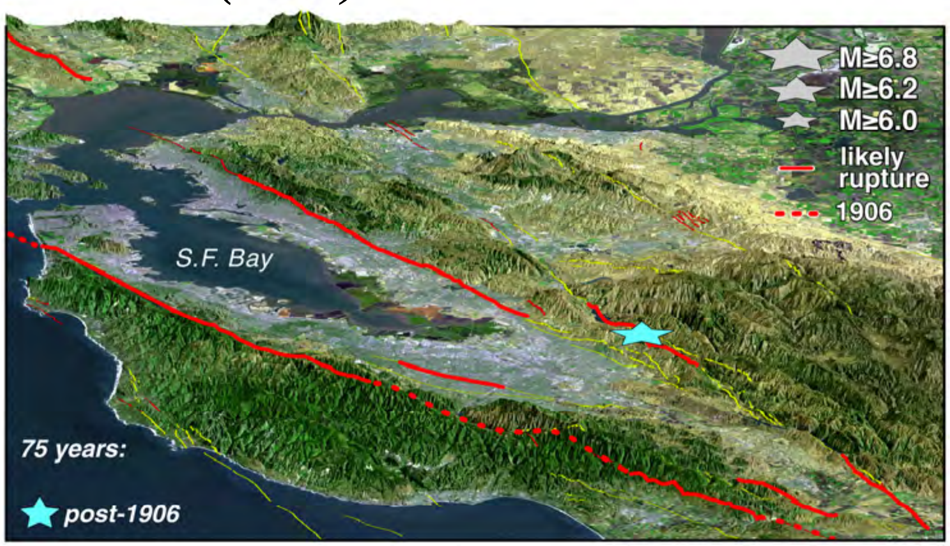


Empirical Probability Model



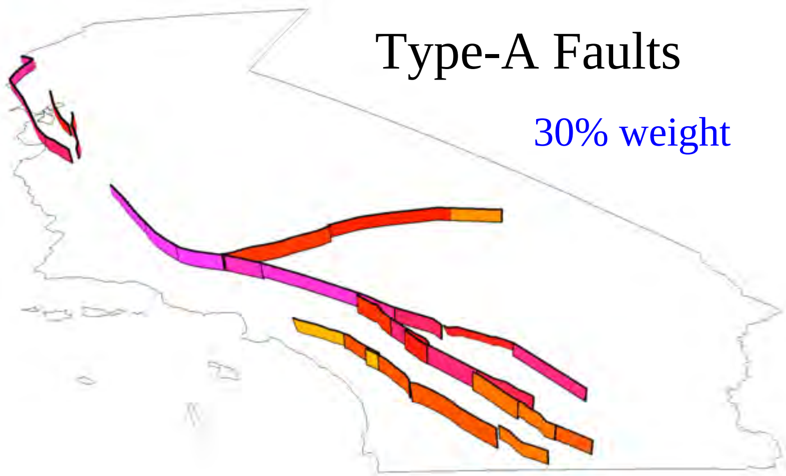


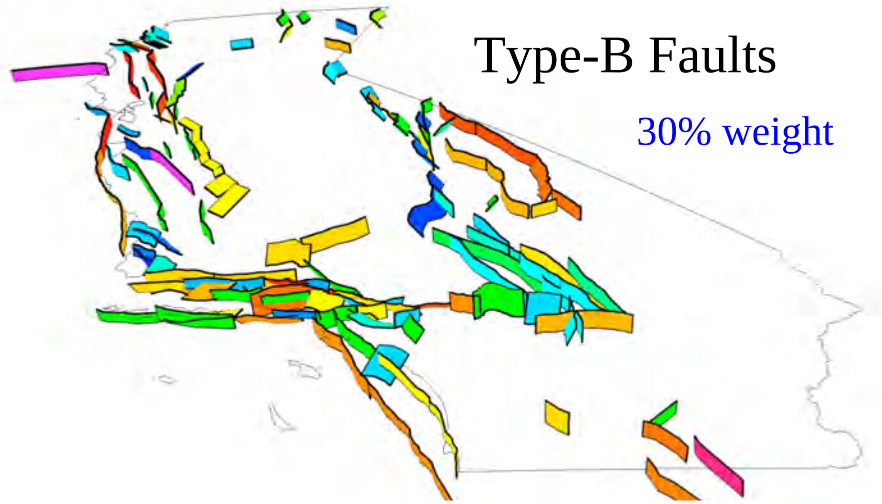
Like that applied by WGCEP (2003)

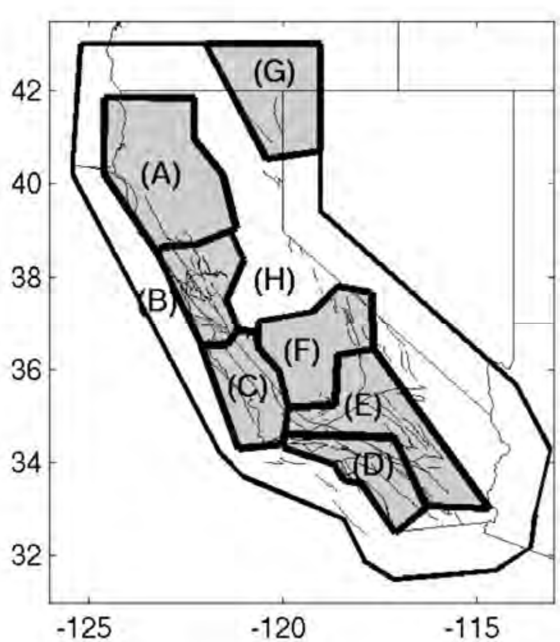


(long-term rates scaled to agree with recent seismicity lull)

Empirical Probability Model







Best estimate of the ratio between current and long term seismicity rates in the different regions.*

Region	Full catalog	Declustered catalog
A. North	0.71 ± 0.52	0.81 ± 0.63
B. San Francisco	0.42 ± 0.11	0.57 ± 0.25
C. Central Coast	0.58, -0.38, +0.62	0.69, -0.41, +0.90
D. Los Angeles	0.60 ± 0.27	0.55 ± 0.29
E. Mojave	Š	Š
F. Mid	0.58 ± 0.38	0.61 ± 0.45
G. Northeast	Š	Š
H. Rest of state	0.70, -0.36, + 0.58	0.86, -0.34, +0.61

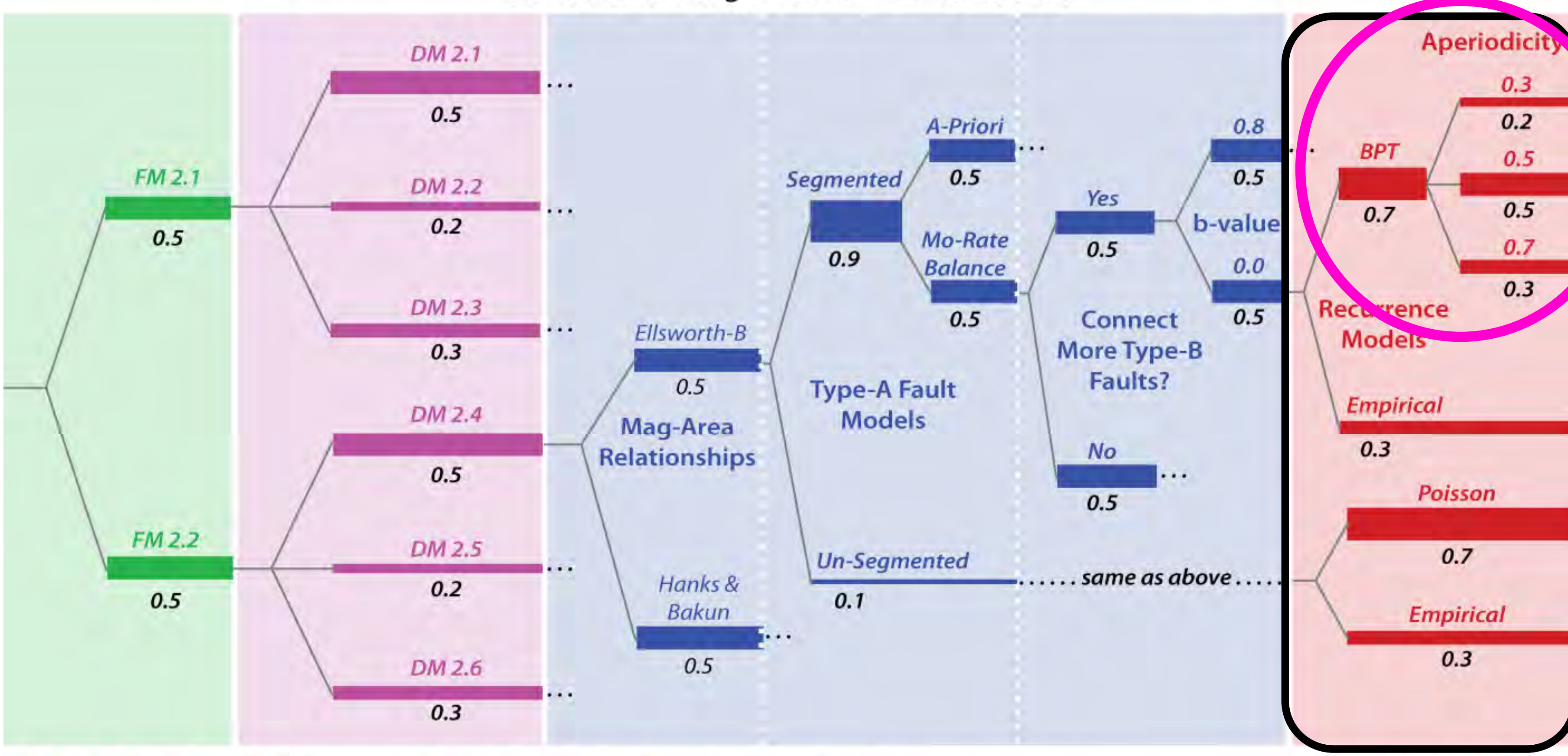
Karen Felzer
Appendix I

(long-term rates scaled to agree with recent seismicity lull)

Earthquake Rate Model

Components of the Uniform California Earthquake Rupture Forecast 2

(abbreviated logic tree of 480 branches)



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

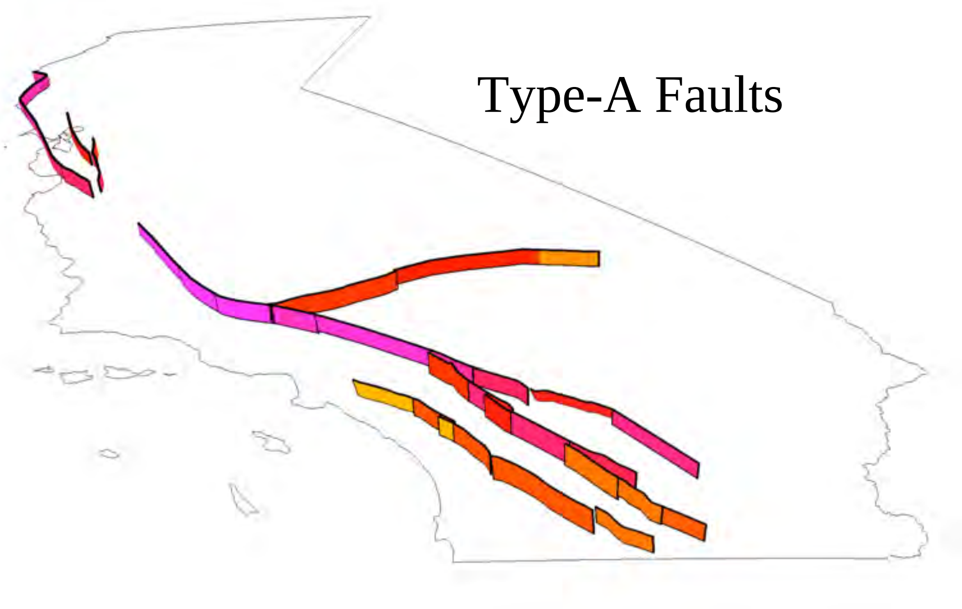
B. Deformation Models
Provides fault slip rates used to calculate seismic moment release.

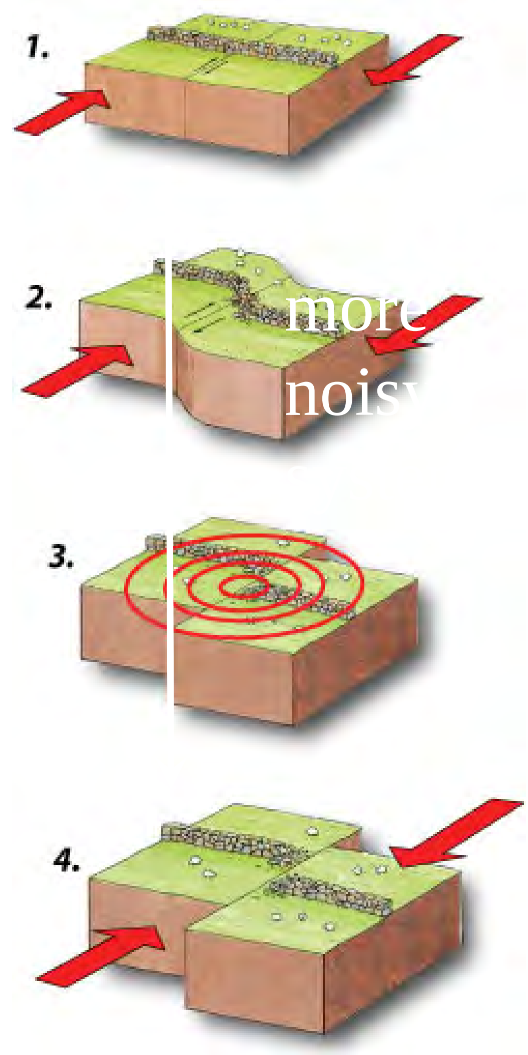
C. Earthquake-Rate Models
Gives the long-term rate of all possible damaging earthquakes throughout a region.

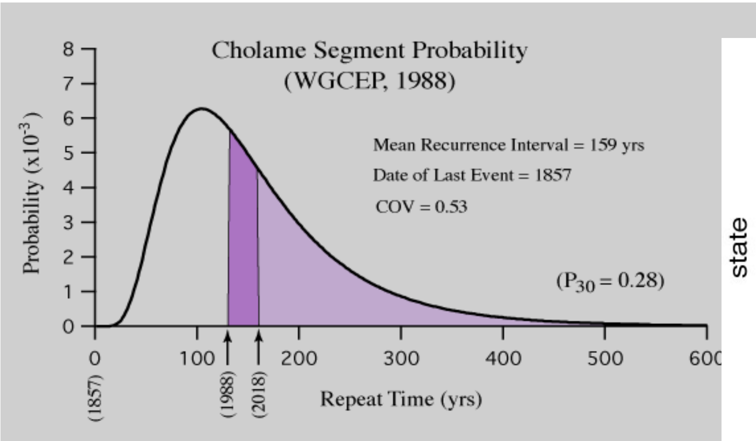
D. Probability Models
Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.

BPT Probability Model

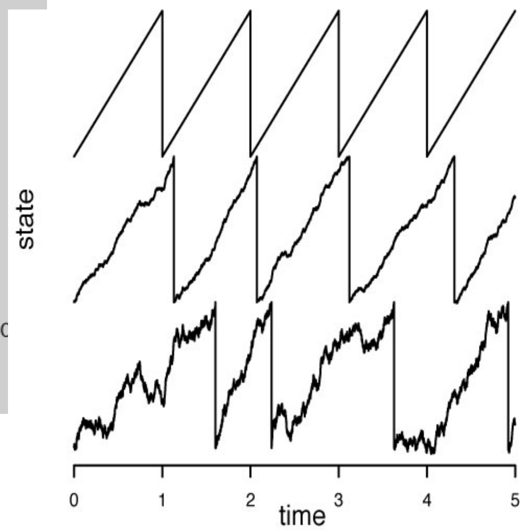
Motivated by Reid's (1910) Elastic Rebound Theory





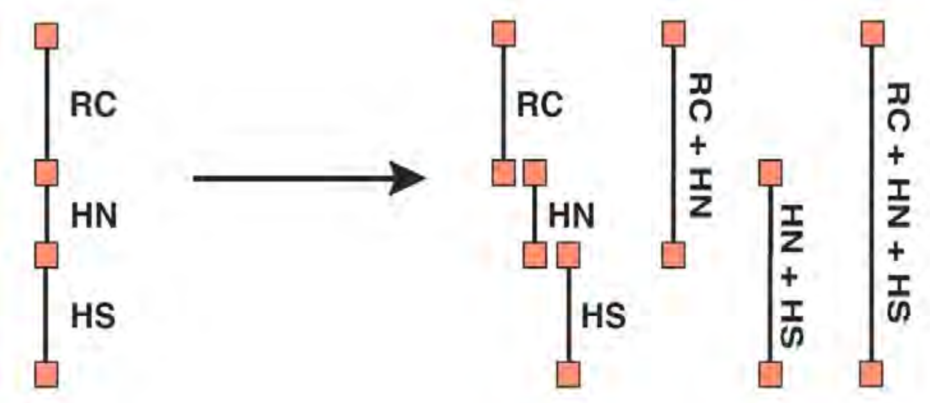


BPT distribution



UCERF2 adopted WGCEP (2003) methodology for computing rupture probabilities:

Hayward-Rodgers Creek Fault

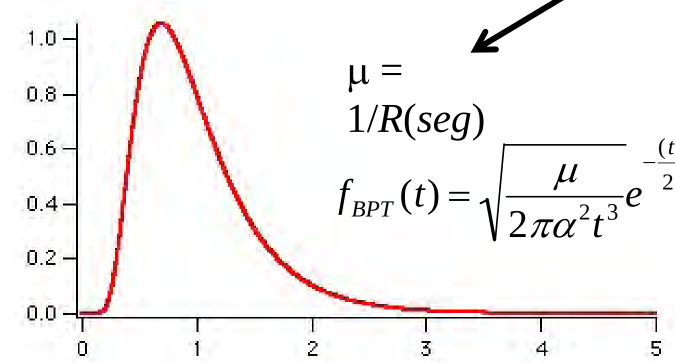


From Eqk Rate Model

Rupture	Rate (/yr)
HS	0.00128
HN	0.00102
RC	0.00332
HS+HN	0.00216
HN+RC	0.00032
HS+HN+RC	0.00044

Segment	Rate (/yr)
HS	0.00408
HN	0.00395
RC	0.00387

Segment probabilities:



μ = 1/$R(seg)$

$$f_{BPT}(t) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}}\, e^{-\frac{(t-\mu)^2}{2\mu t\alpha^2}}$$

(their exact calculation)

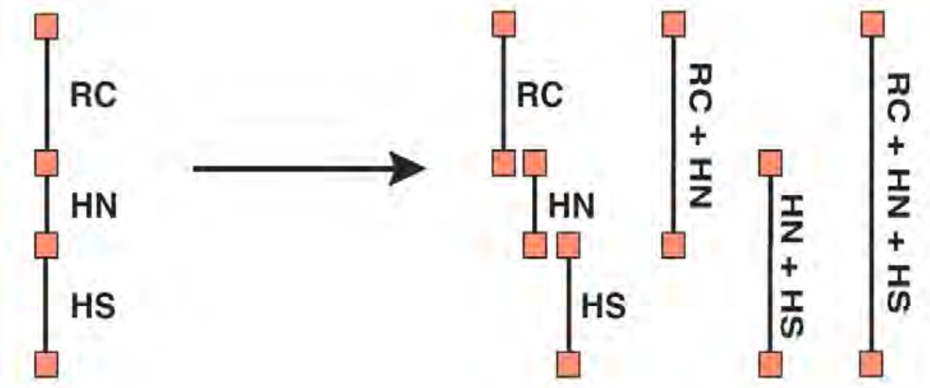
Rup Probs: $$P(rup) = \sum_{segs\_in\_qk} P(seg)\frac{R(rup)}{R(seg)}\frac{\dot{M}o(seg)}{\sum_{segs\_in\_qk}\dot{M}o(seg)}$$

$$\approx P_{pois}(rup)\frac{\sum_{segs\_in\_qk}\left(\frac{P(seg)}{P_{pois}(seg)}\right)\dot{M}o(seg)}{\sum_{segs\_in\_qk}\dot{M}o(seg)}$$

Pois prob multiplied by wt-ave prob gain of segs

UCERF2 adopted WGCEP (2003) methodology for computing rupture probabilities:

Hayward-Rodgers Creek Fault



From Eqk Rate Model

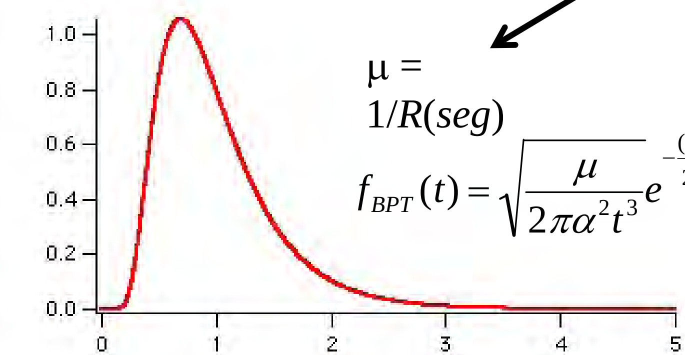
Rupture	Rate (/yr)
HS	0.00128
HN	0.00102
RC	0.00332
HS+HN	0.00216
HN+RC	0.00032
HS+HN+RC	0.00044

Segment	Rate (/yr)
HS	0.00408
HN	0.00395
RC	0.00387

(their exact calculation)

Segment probabilities:

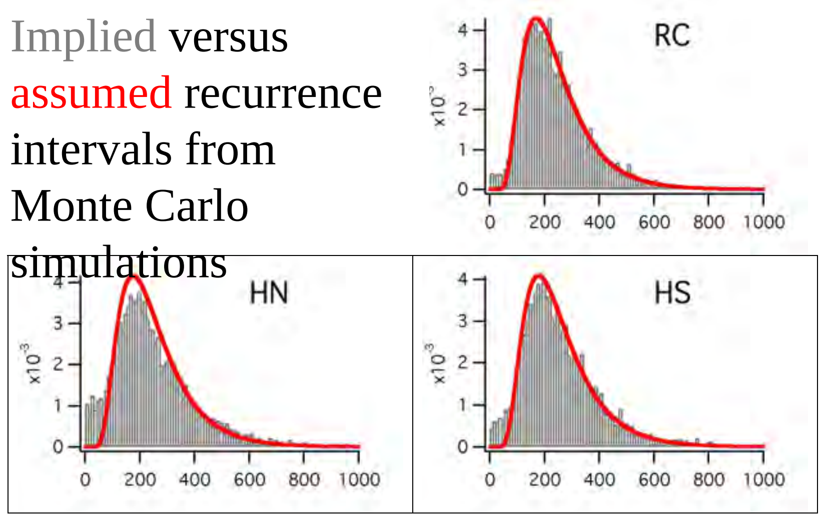
Rup Probs: $$P(rup) = \sum_{segs\_in\_qk} P(seg) \frac{R(rup)}{R(seg)} \frac{\dot{M}o(seg)}{\sum_{segs\_in\_qk} \dot{M}o(seg)}$$



μ = 1/$R(seg)$

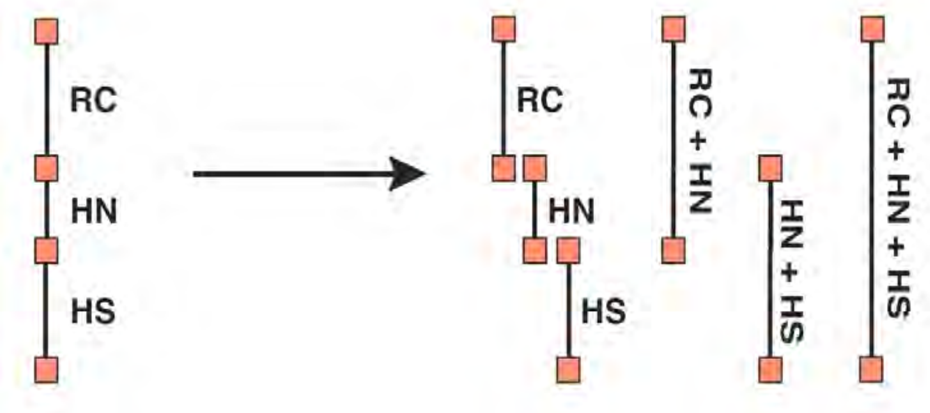
$$f_{BPT}(t) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}} e^{-\frac{(t-\mu)^2}{2\mu t \alpha^2}}$$

Implied versus assumed recurrence intervals from Monte Carlo simulations



UCERF2 adopted WGCEP (2003) methodology for computing rupture probabilities:

Hayward-Rodgers Creek Fault

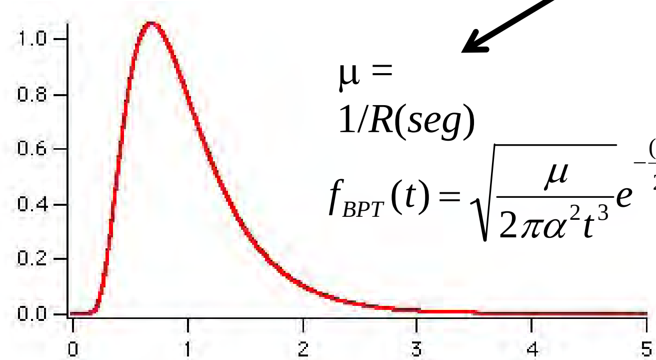


From Eqk Rate Model

Rupture	Rate (/yr)
HS	0.00128
HN	0.00102
RC	0.00332
HS+HN	0.00216
HN+RC	0.00032
HS+HN+RC	0.00044

Segment	Rate (/yr)
HS	0.00408
HN	0.00395
RC	0.00387

Segment probabilities:



$\mu =$ $1/R(seg)$

$$f_{BPT}(t) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}}\, e^{-\frac{(t-\mu)^2}{2\mu t\alpha^2}}$$

(their exact calculation)

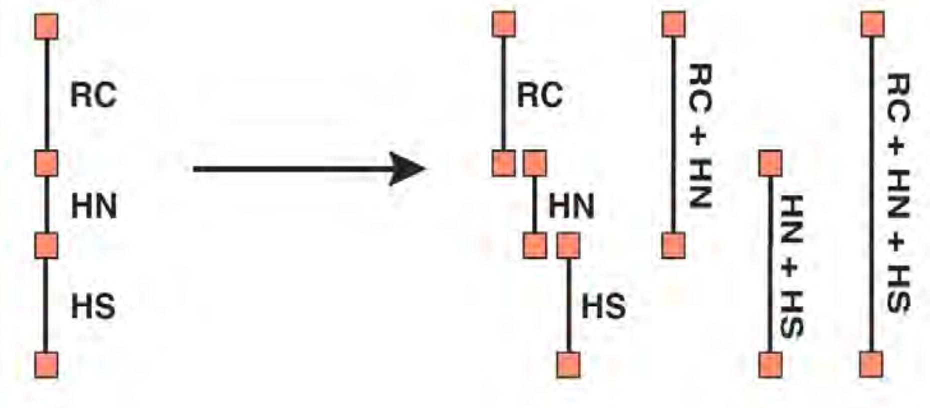
Rup Probs: $$P(rup) = \sum_{segs\_in\_qk} P(seg)\frac{R(rup)}{R(seg)}\frac{\dot{M}o(seg)}{\sum_{segs\_in\_qk}\dot{M}o(seg)}$$

Another manifestation:

Final aggregate segment probabilities are not the same as the BPT computed segment probabilities

UCERF2 adopted WGCEP (2003) methodology for computing rupture probabilities:

Hayward-Rodgers Creek Fault



From Eqk Rate Model

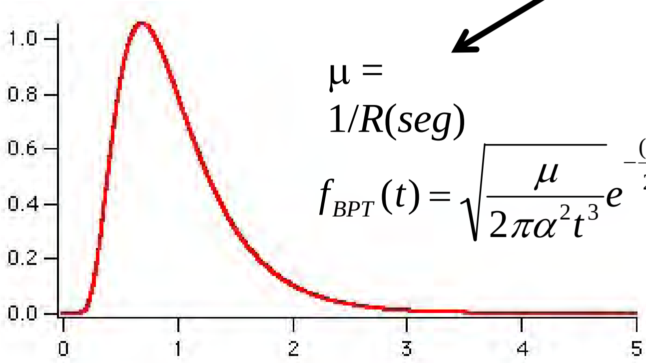
Rupture	Rate (/yr)
HS	0.00128
HN	0.00102
RC	0.00332
HS+HN	0.00216
HN+RC	0.00032
HS+HN+RC	0.00044

Segment	Rate (/yr)
HS	0.00408
HN	0.00395
RC	0.00387

(their exact calculation)

Segment probabilities:

Rup Probs: $$P(rup) = \sum_{segs\_in\_qk} P(seg) \frac{R(rup)}{R(seg)} \frac{\dot{M}o(seg)}{\sum_{segs\_in\_qk} \dot{M}o(seg)}$$

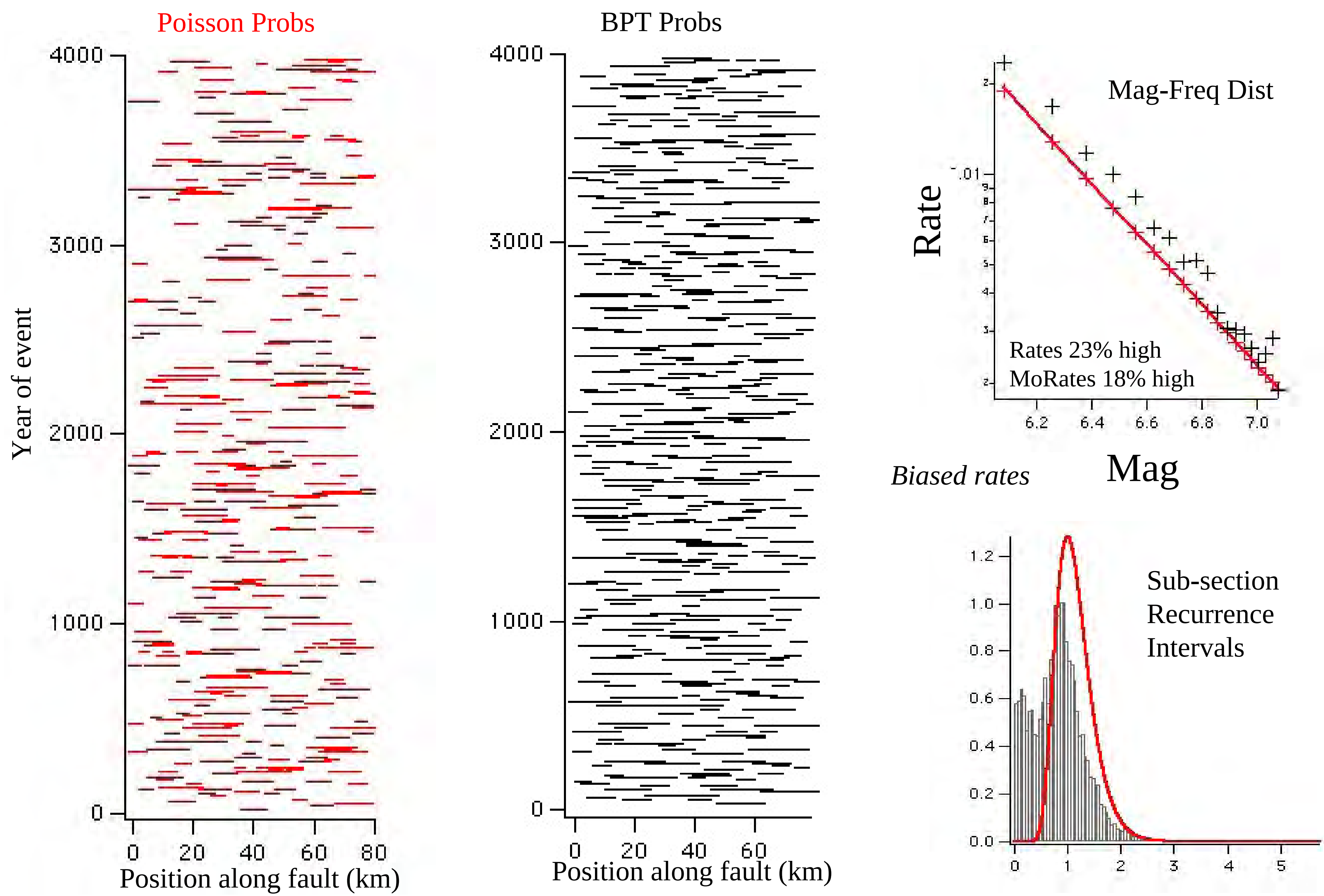


μ = 1/$R(seg)$

$$f_{BPT}(t) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}} e^{-\frac{(t-\mu)^2}{2\mu t \alpha^2}}$$

Problem gets worse as models become less segmented…

WG02 Approach for "Unsegmented" GR fault (5km subsections) :



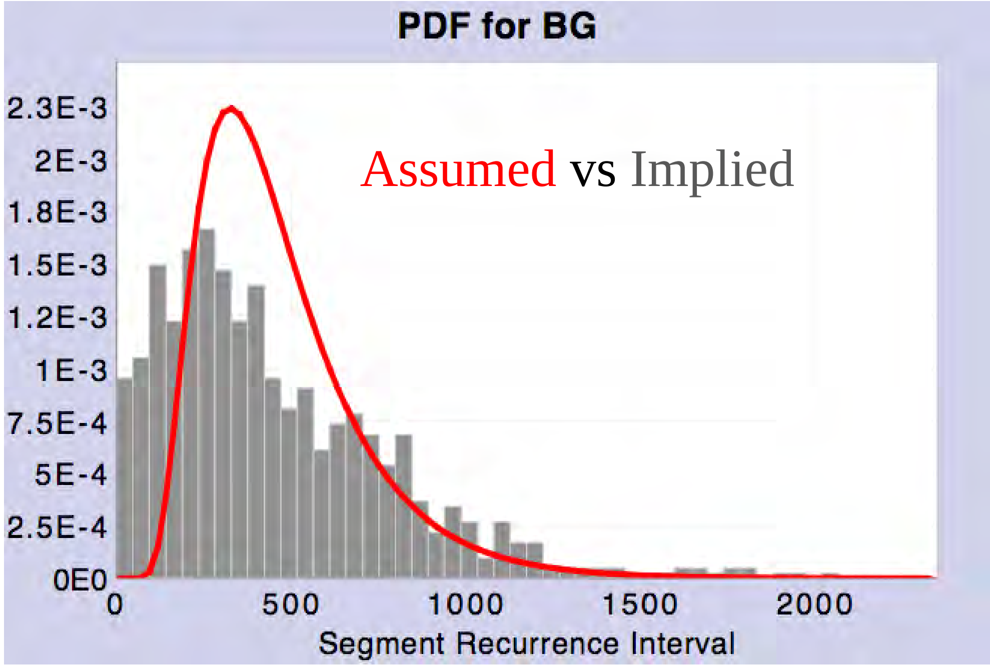
Components of the Uniform California Earthquake Rupture Forecast 3

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

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

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

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



UCERF3 Questions/Issues

1) Develop self-consistent elastic-rebound motivated renewal models

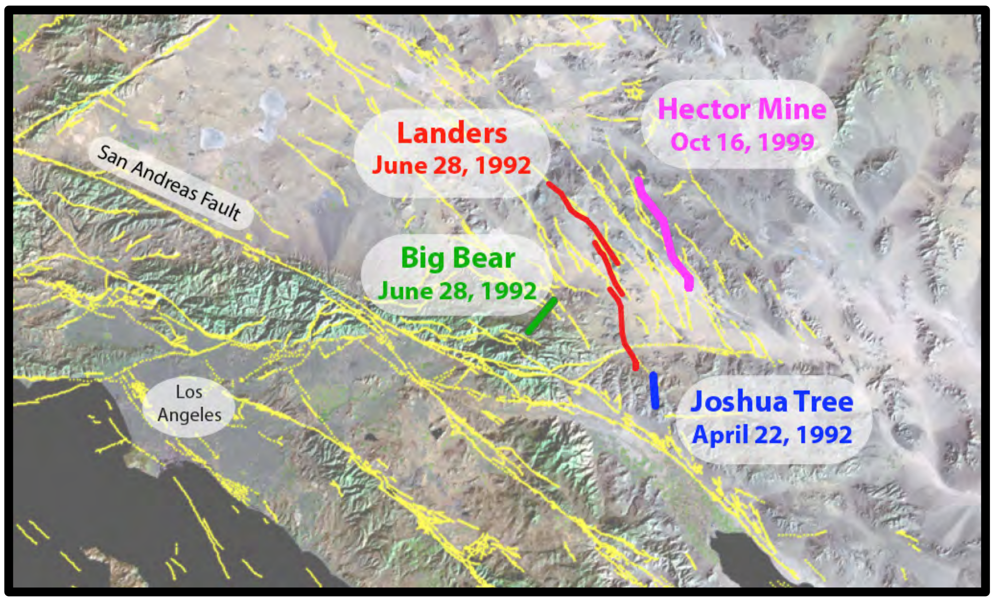
Components of the Uniform California Earthquake Rupture Forecast 3 (?)

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

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

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

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



A coincidence? Negligible?

UCERF3 Questions/Issues

1) Develop self-consistent elastic-rebound-motivated renewal models

1) Add spatial-temporal clustering

Components of the Uniform California Earthquake Rupture Forecast 3 (?)

Fault Models

Specifies the spatial geometry of larger, more active faults.

Deformation Models

Provides fault slip rates used to calculate seismic moment release.

Earthquake-Rate Models

Gives the long-term rate of all possible damaging earthquakes throughout a region.

Probability Models

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

UCERF3 Questions/Issues

1) Develop self-consistent elastic-rebound motivated renewal models

2) Add spatial-temporal clustering

3) Interpretation of the Empirical Model

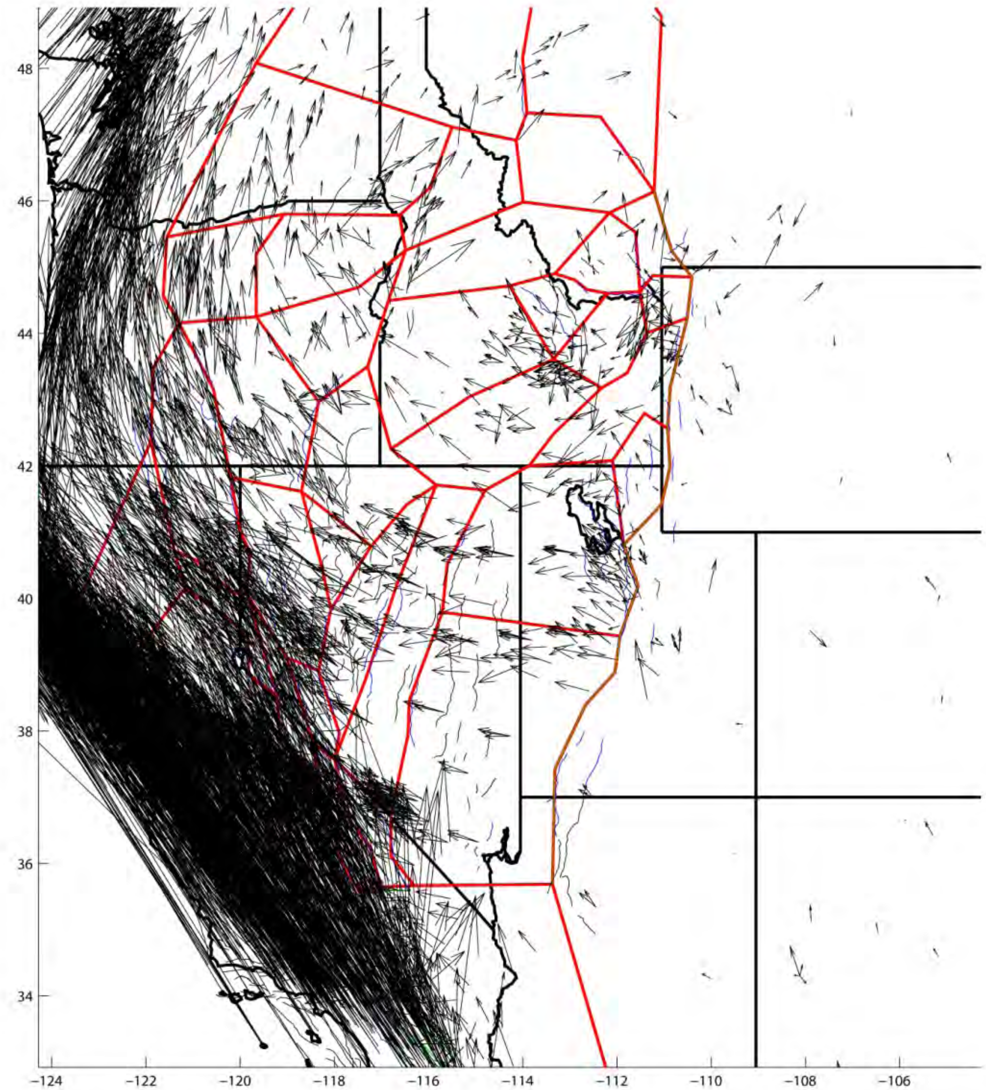
Geodetic data analysis

Mark Petersen and Yuehua Zeng
(data and zones from Puskas and Smith)

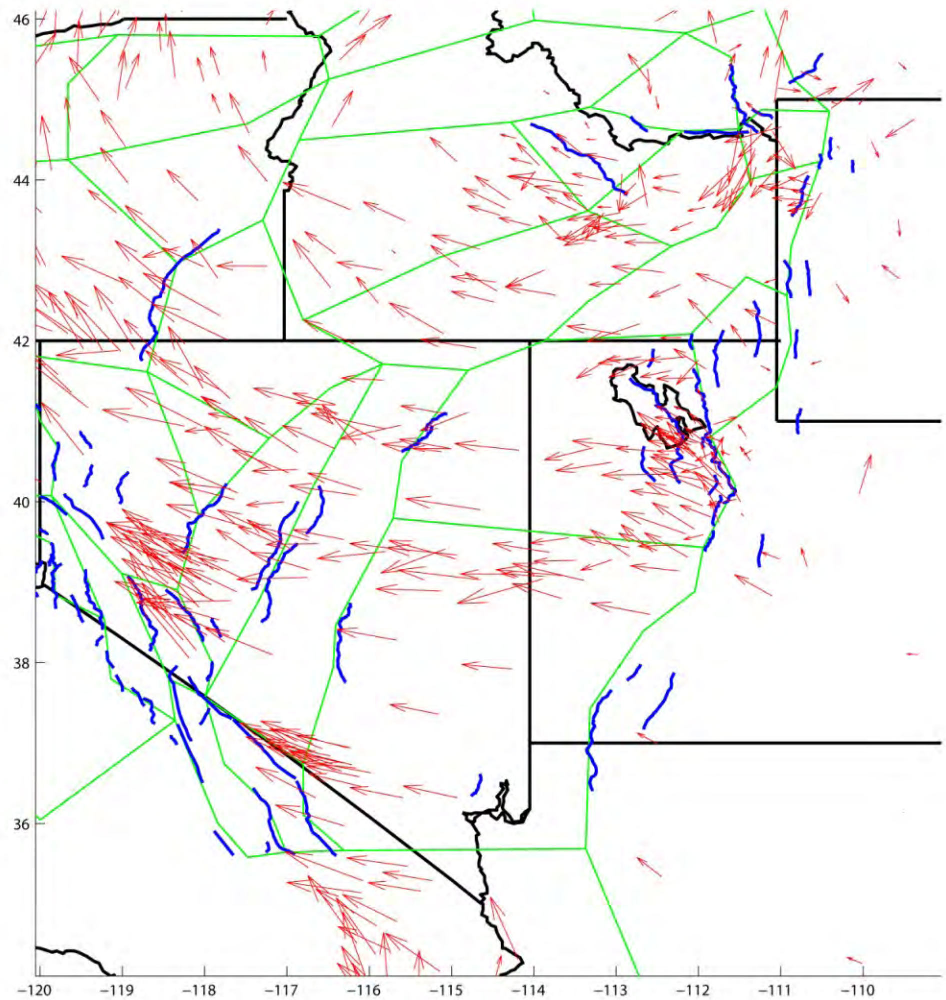
Methodology (Zeng)

- Started with GPS data from Puskas and Smith
- Cleaned out the spurious data
- Extrapolated to make strain rate maps
- Modified Puskas and Smith block model (not continuum model, use buried fault model)
- Inverted for slip rate on Wasatch Fault using block model of elastic upper layer and creeping lower layer

GPS velocity field

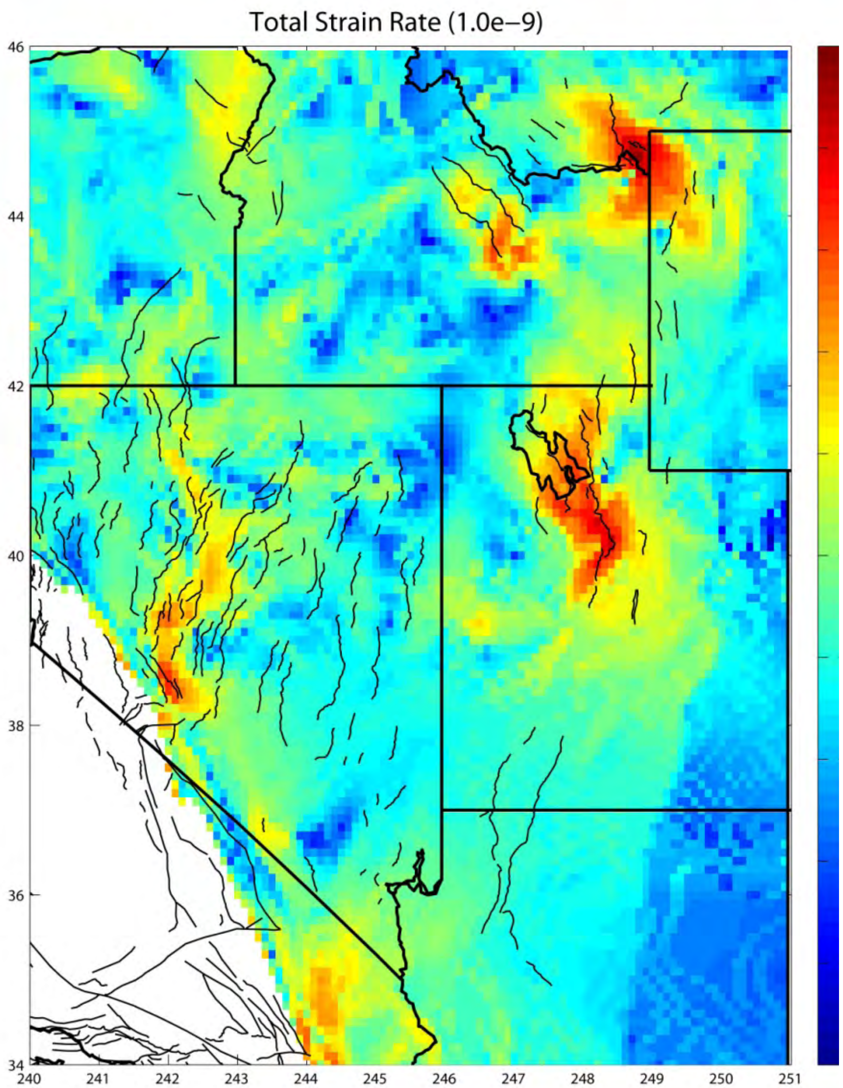


Processed GPS data

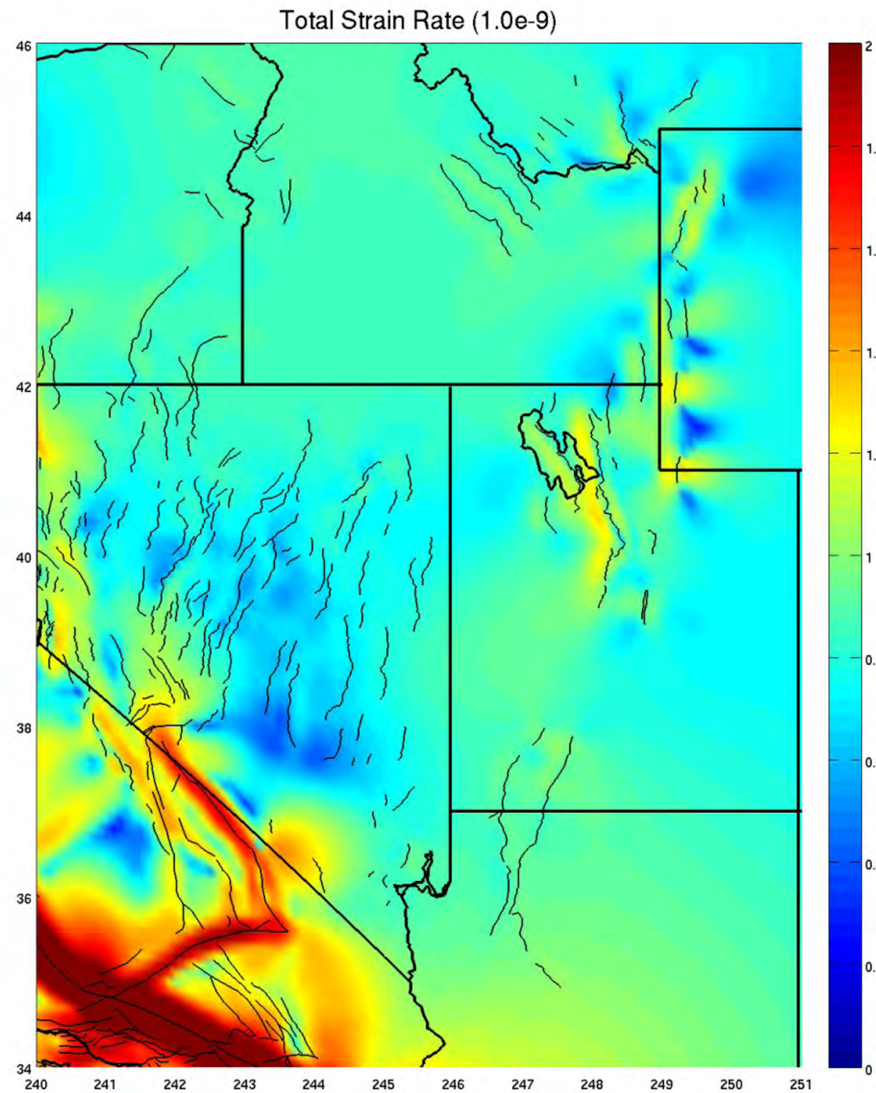


Comparison of GPS and Geology strain rates

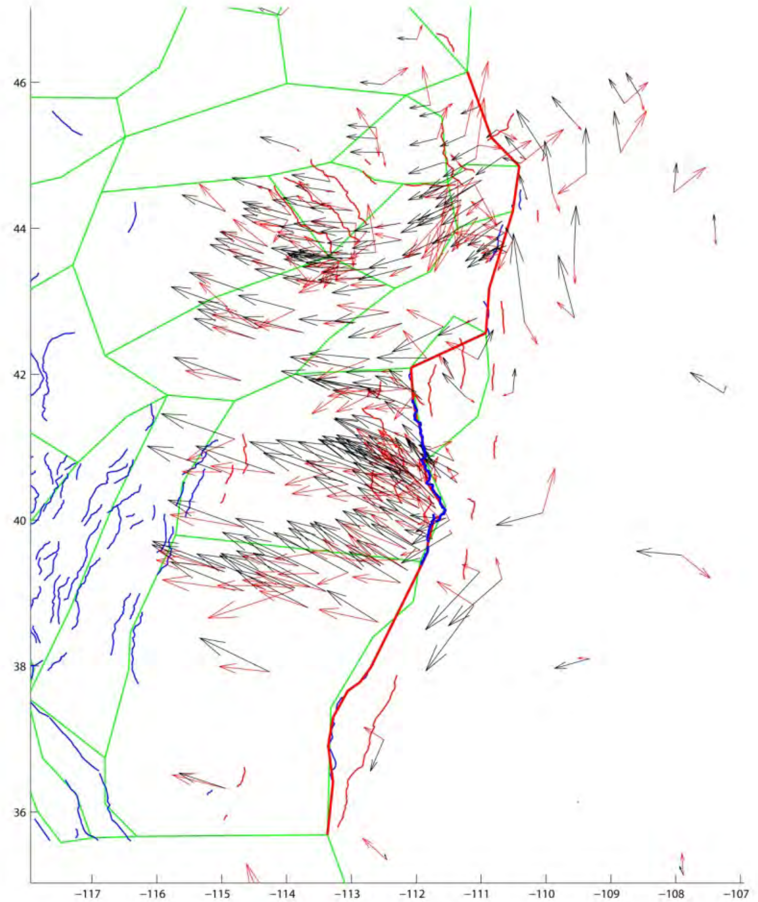
GPS strain rate

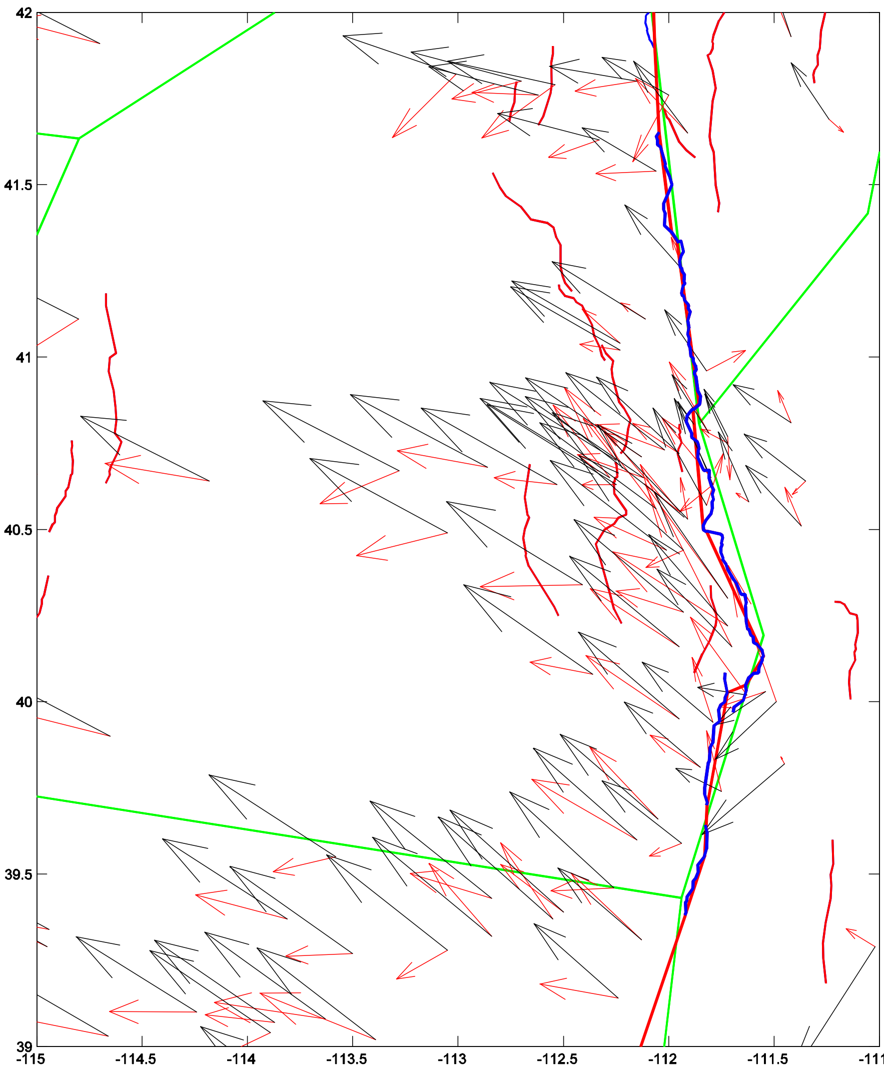


Geology strain rate



Block Model





Red: data, Black predicted

Chang Thesis

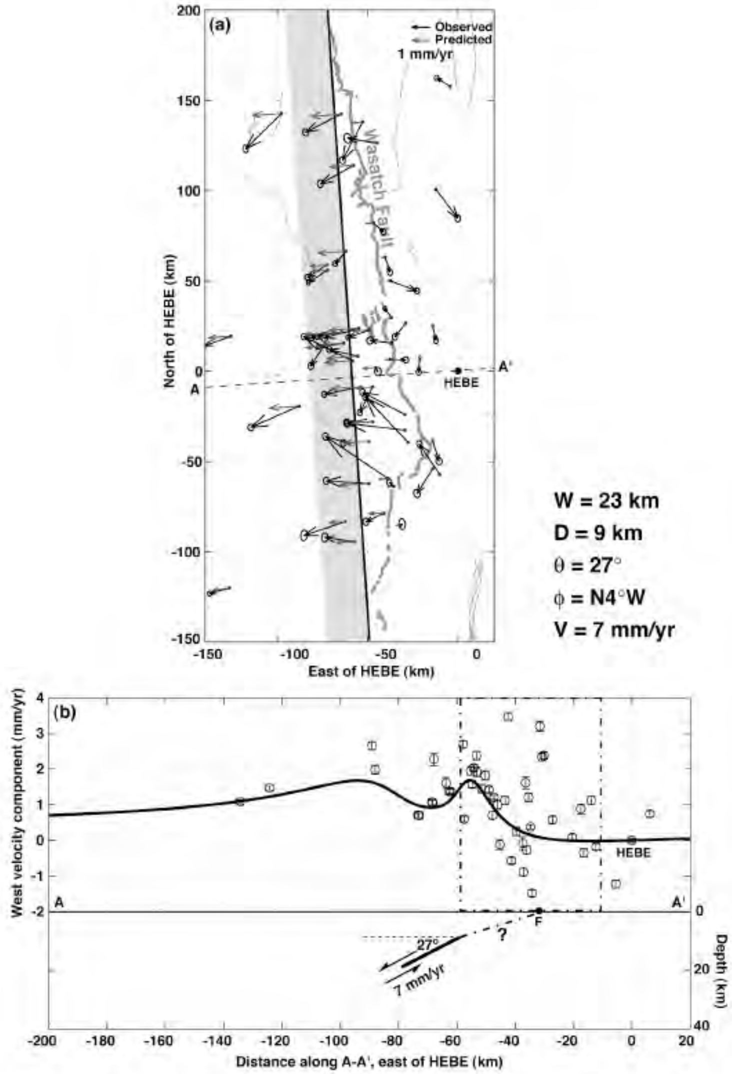


Figure 4.9. A narrow-dislocation model for the Wasatch fault, with the EBAR background extension removed. See Figure 4.6 for detailed discriptions.

Chang thesis

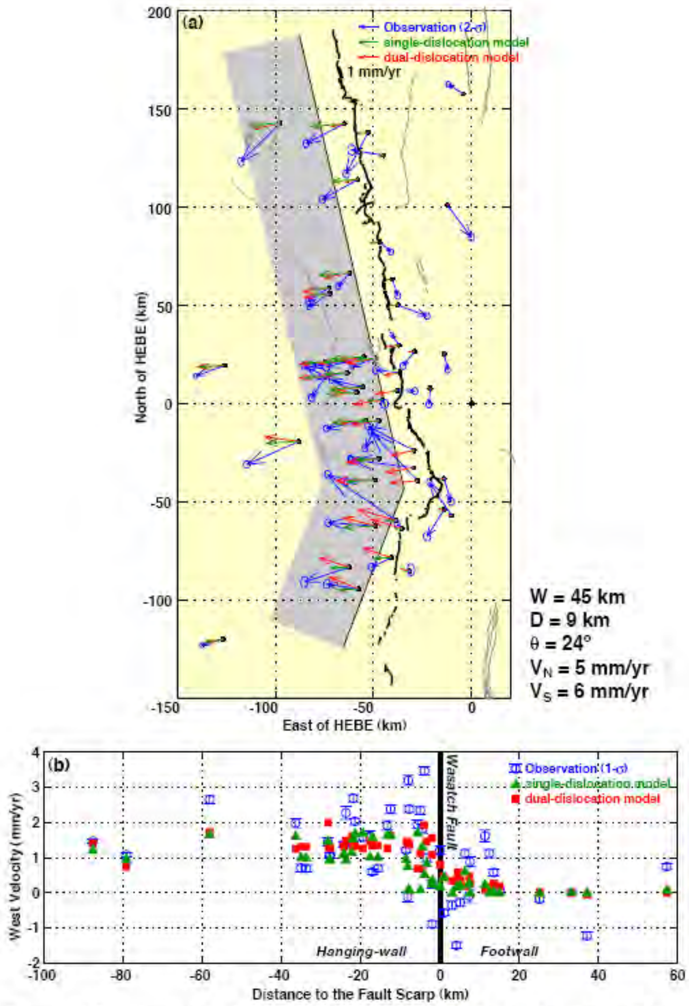


Figure 4.15. Inverted dual-dislocation model that best fits the horizontal GPS velocities. (a) The predicted (red arrows) and observed (blue arrows) velociy vectors are plotted with that derived from the single-dislocation model shown in Figure 4.9 (green arrows). V_N and V_S are the loading rates of the northern and southern fault patches, rspectively. (b) The west velocity components are plotted with respect to the distances from GPS sites to the Wasatch fault scarp (bold line).

Comparison of Slip Rates

Segment	Geologic slip rate (mm/yr +/- 15%)	RI based slip rate (mm/yr +/- 15%)	Geodetic slip rate (Zeng)	Geodetic slip rate (Chang and Smith)	Puskas and Smith
Brigham City	1.83	0.80	2.2	5-12	2-3
Weber	1.57	1.36	2.6	5-12	2-3
Salt Lake City	1.57	0.97	4.1	5-12	2-3
Provo	1.57	1.31	4.3	5-12	2-3
Nephi	1.44	0.55	4.3	5-12	2-3
Levan	0.39	0.22	3.3	5-12	2-3

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

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

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

Supported by USGS NEHRP
University of UTah,
EarthScope NSF

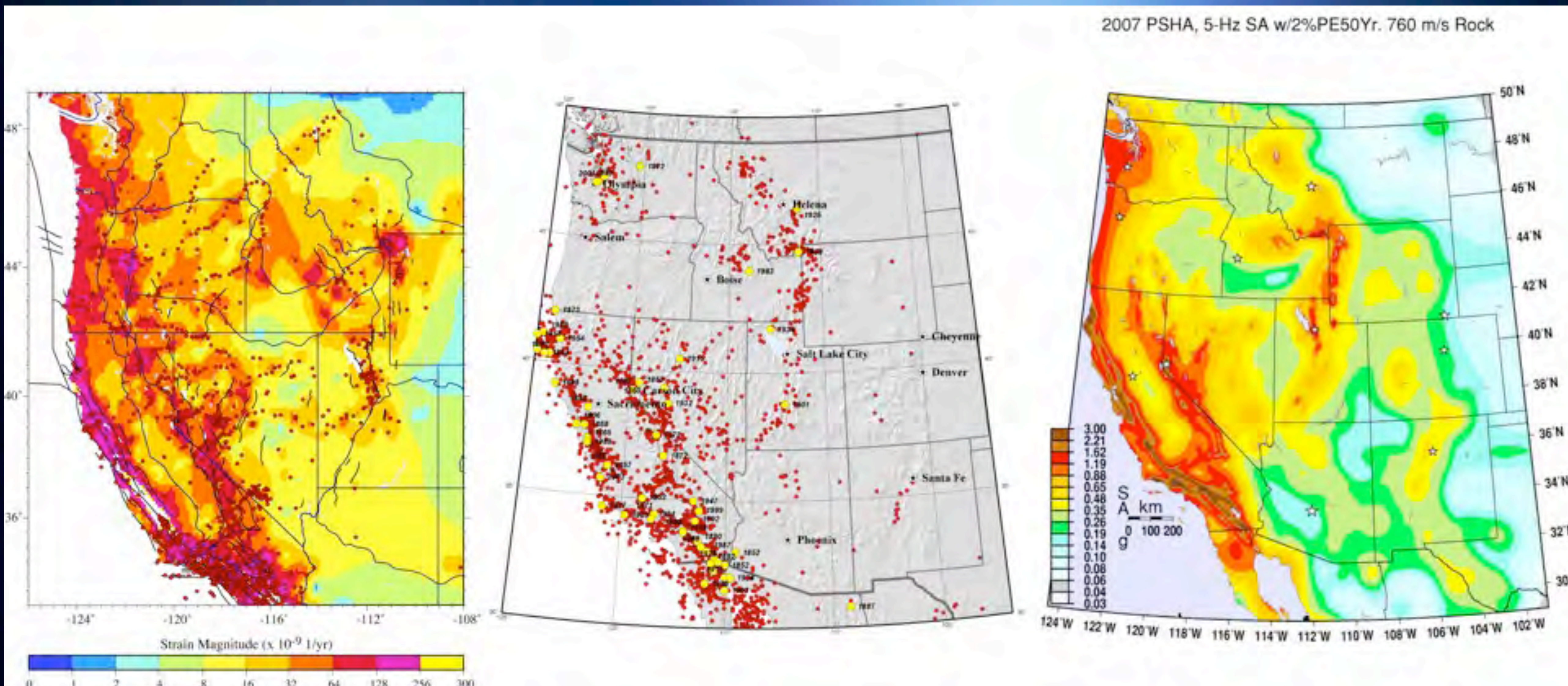
The University of Utah Seismology and Active Tectonics Research Group

GPS Deformation Closely Correlates With Earthquake Hazards

GPS derived strain rate

Earthquakes in the Western US

Spectral Acceleration 2% Probability of Exceedance in 50 Years



High deformation rates correlate with

- Seismically active areas
- Regions of increased seismic hazard

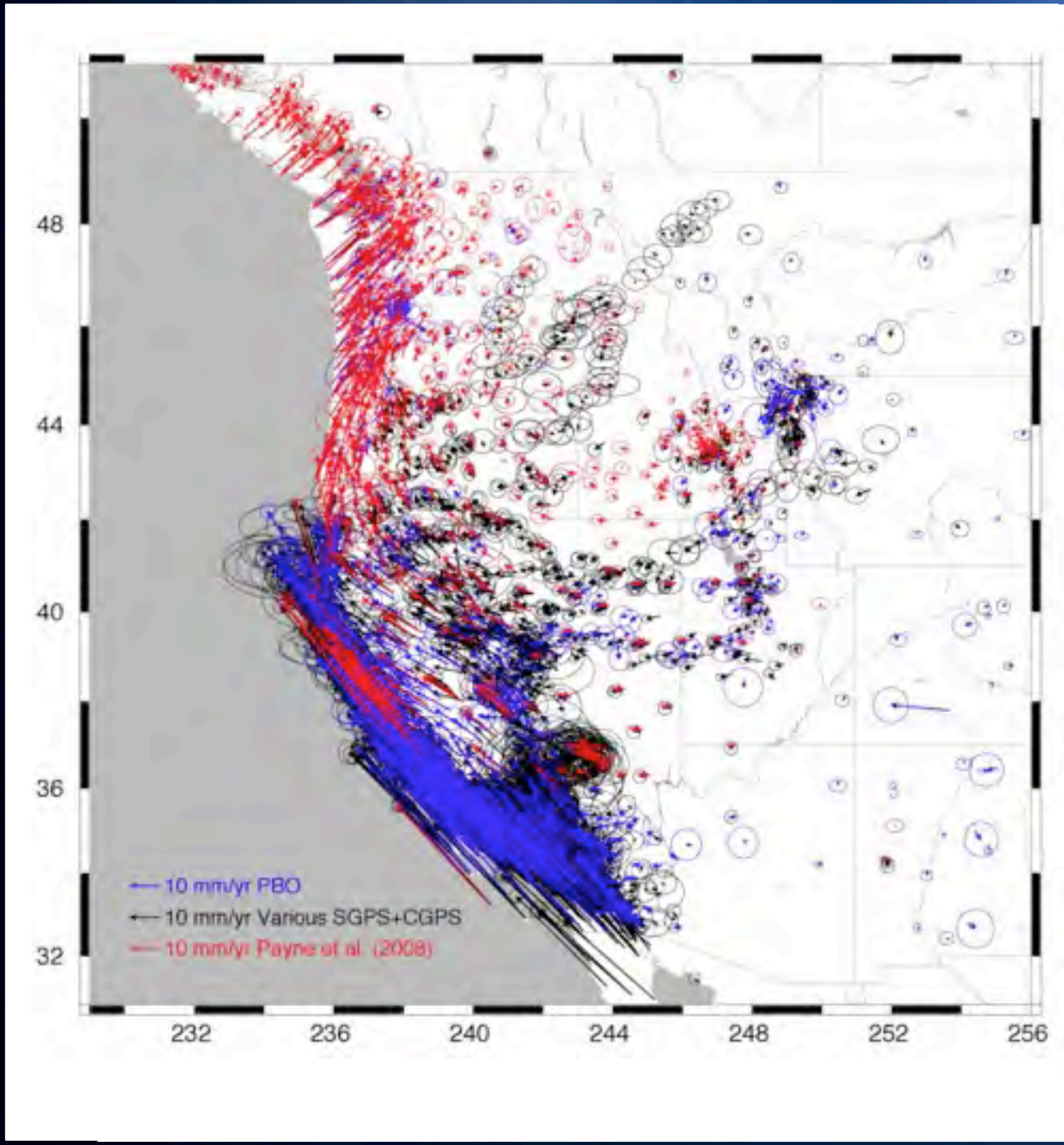
Requires integration into hazard modeling

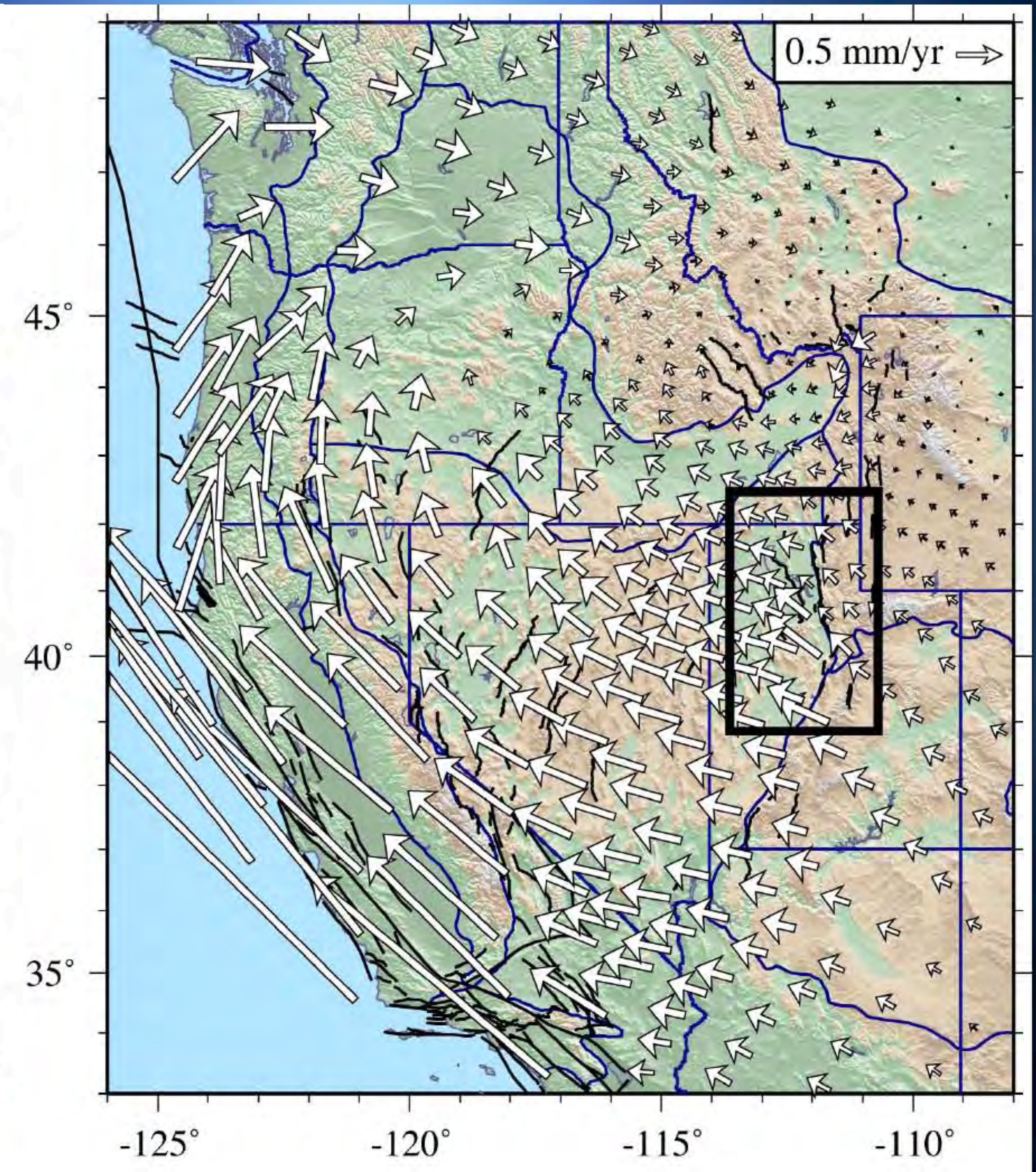
- Improving geodetic data set
- Deformation data available where paleoearthquake info. not well-known

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

GPS determined velocities, 2500 stations

Velocity vectors. The Wasatch fault focuses deformation at the intraplate boundary

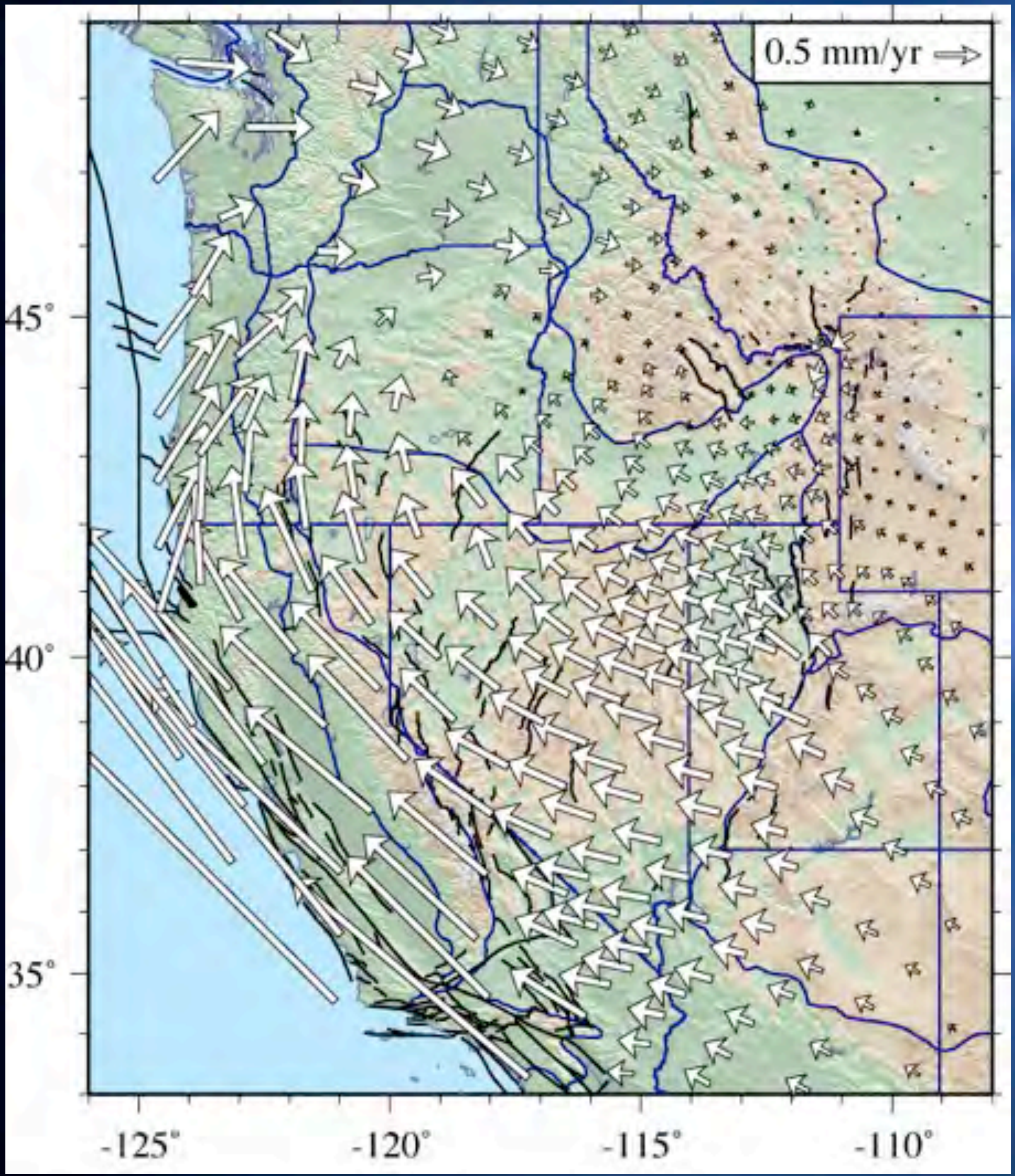




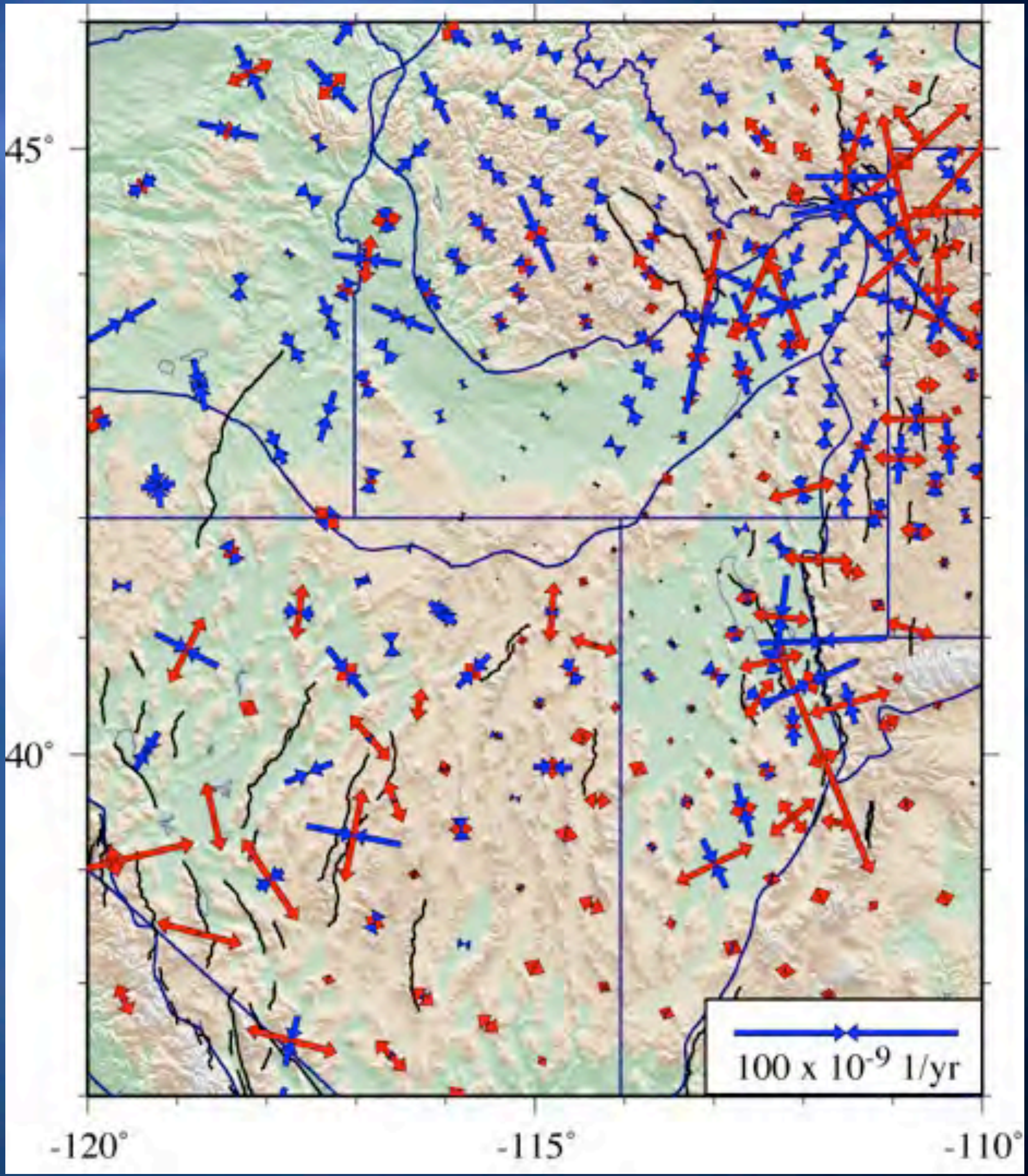
(Puskas and Smith 2007, 2008)

Kinematics

Velocity Field

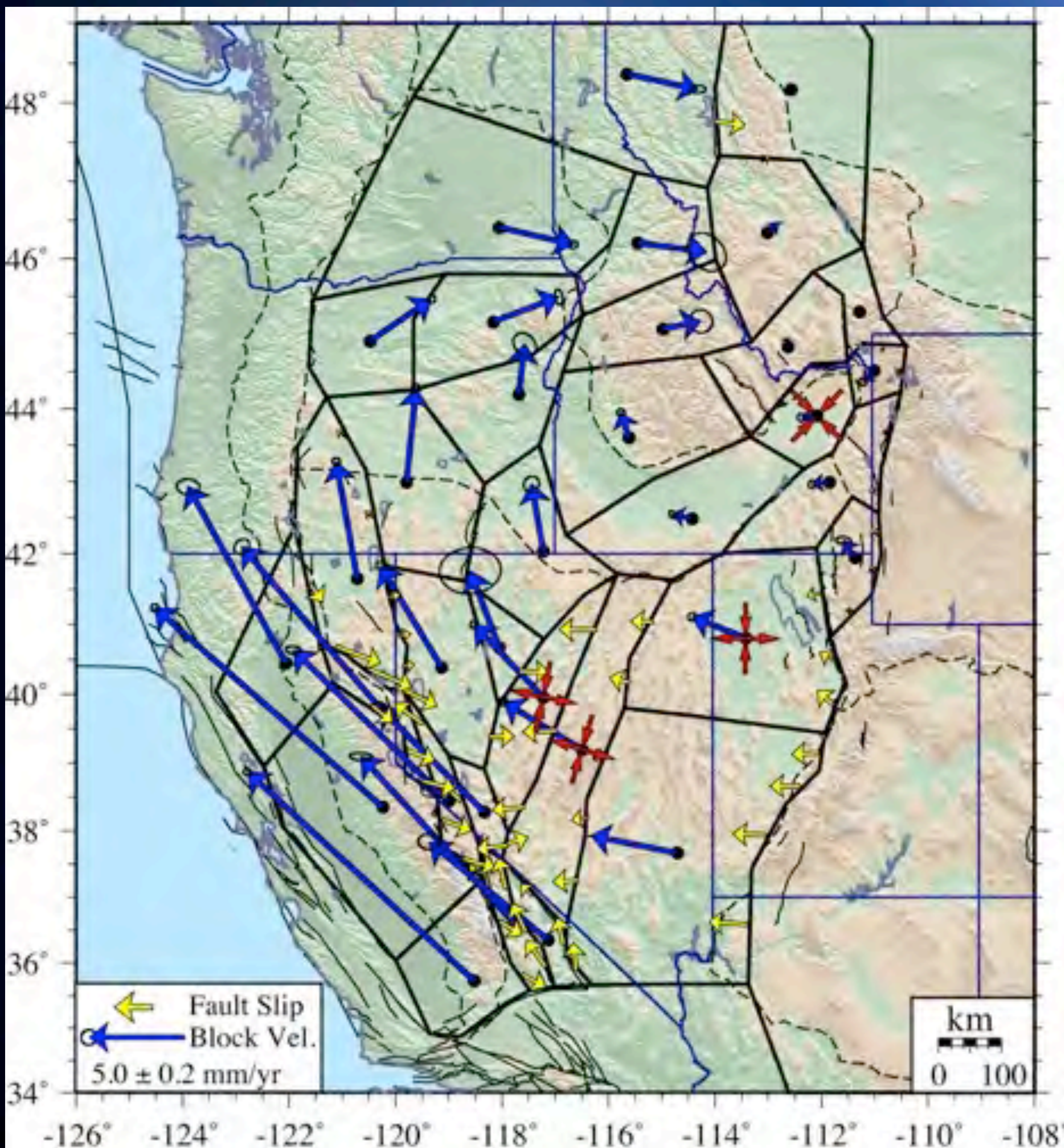


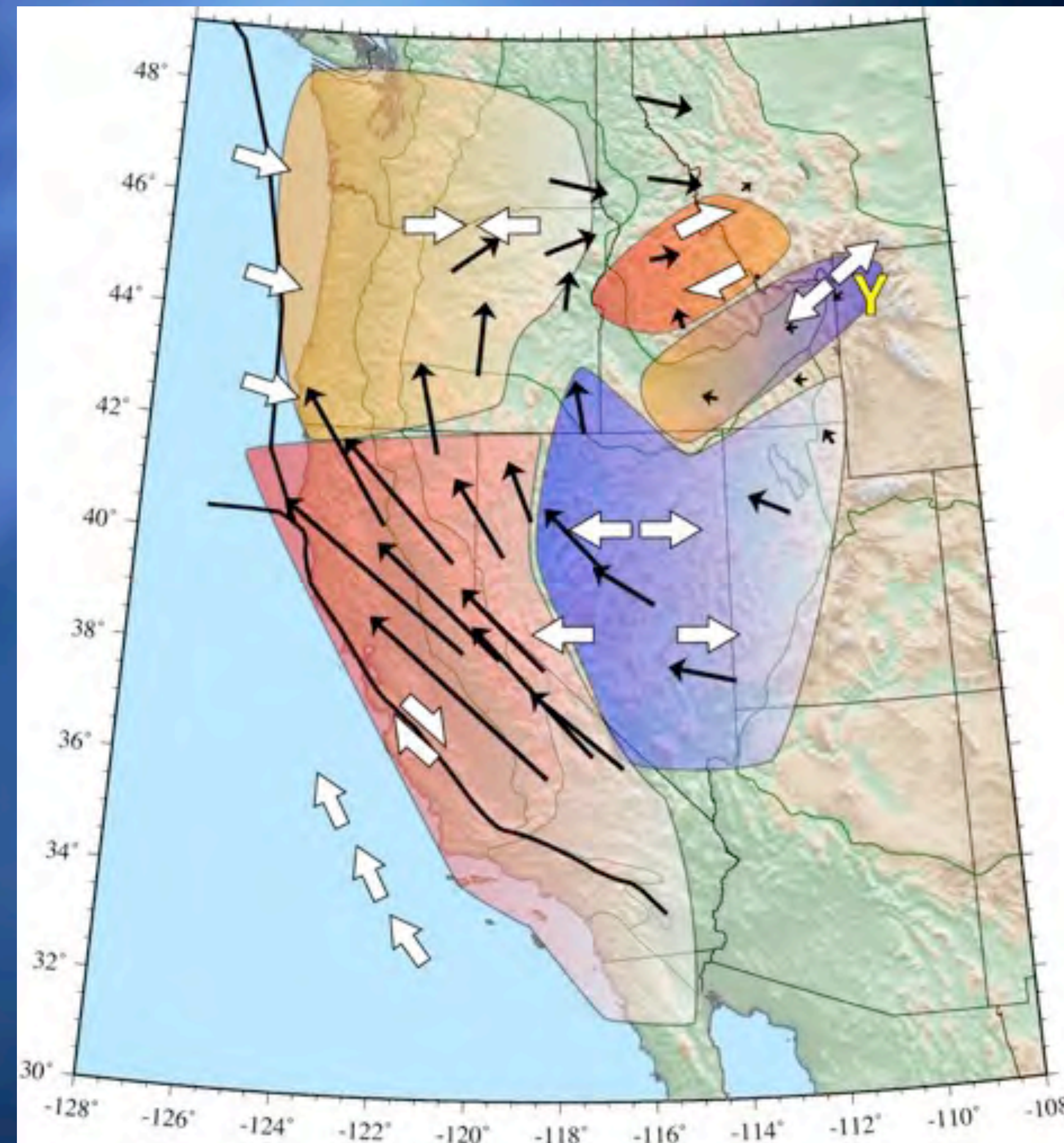
Strain Rate Field



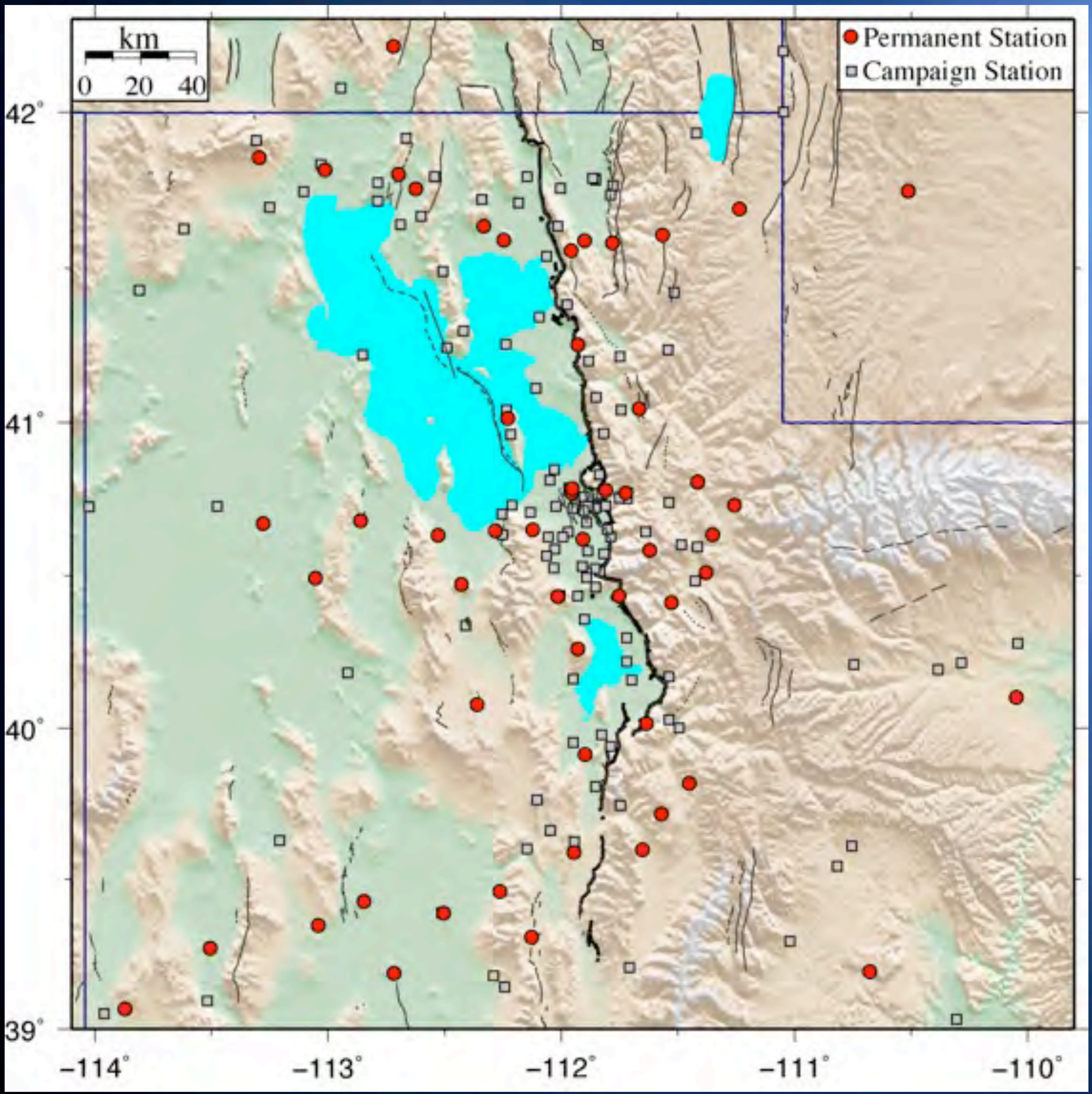
Continuum model solves for strain rates and velocities

- Obtain extension at Yellowstone Plateau and Basin-Range
- Contraction+shear in Eastern Snake River Plain
- Clockwise rotation of velocities


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


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

Wasatch fault GPS network



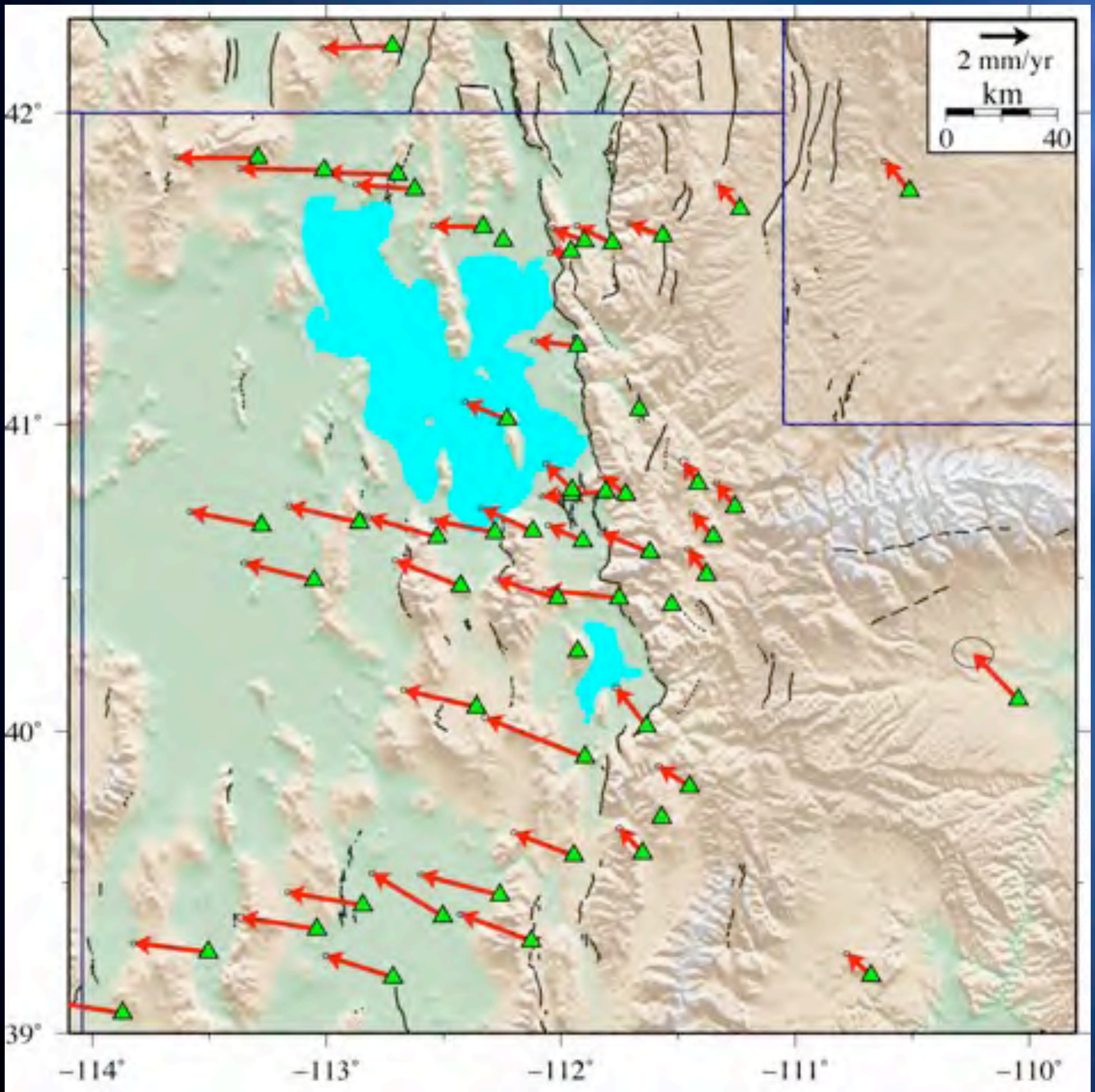
Data recorded and transmitted daily

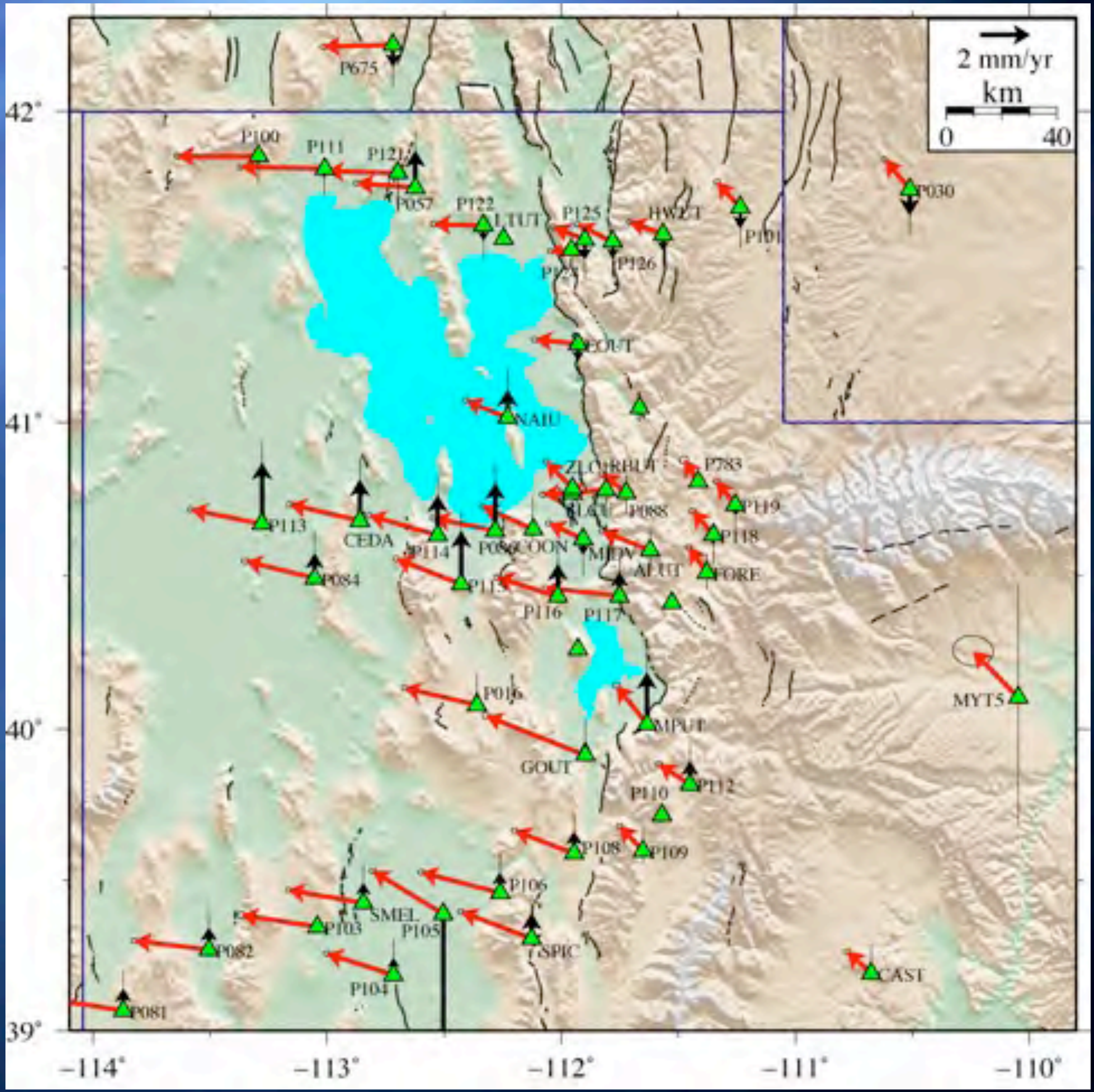
- 55 permanent stations (Univ of Utah and PBO)
- Installed as part of the “Tectonic extensional regime” EarthScope program
- Total resource ~$6M
- 90 campaign, temporary stations

Processed data real-time products

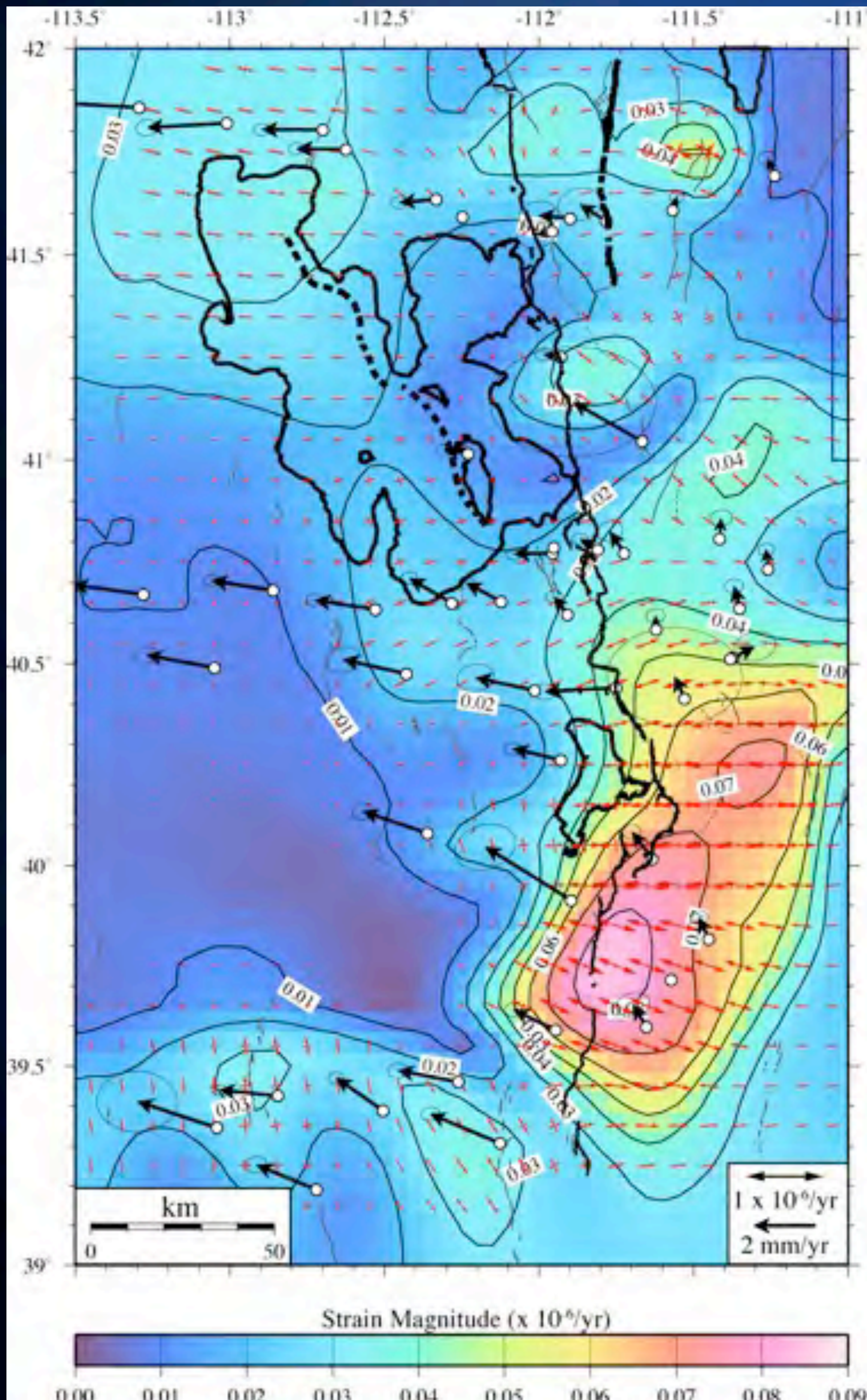
- Position solutions
- Site velocities

2007-2010 GPS horizontal and vertical velocities

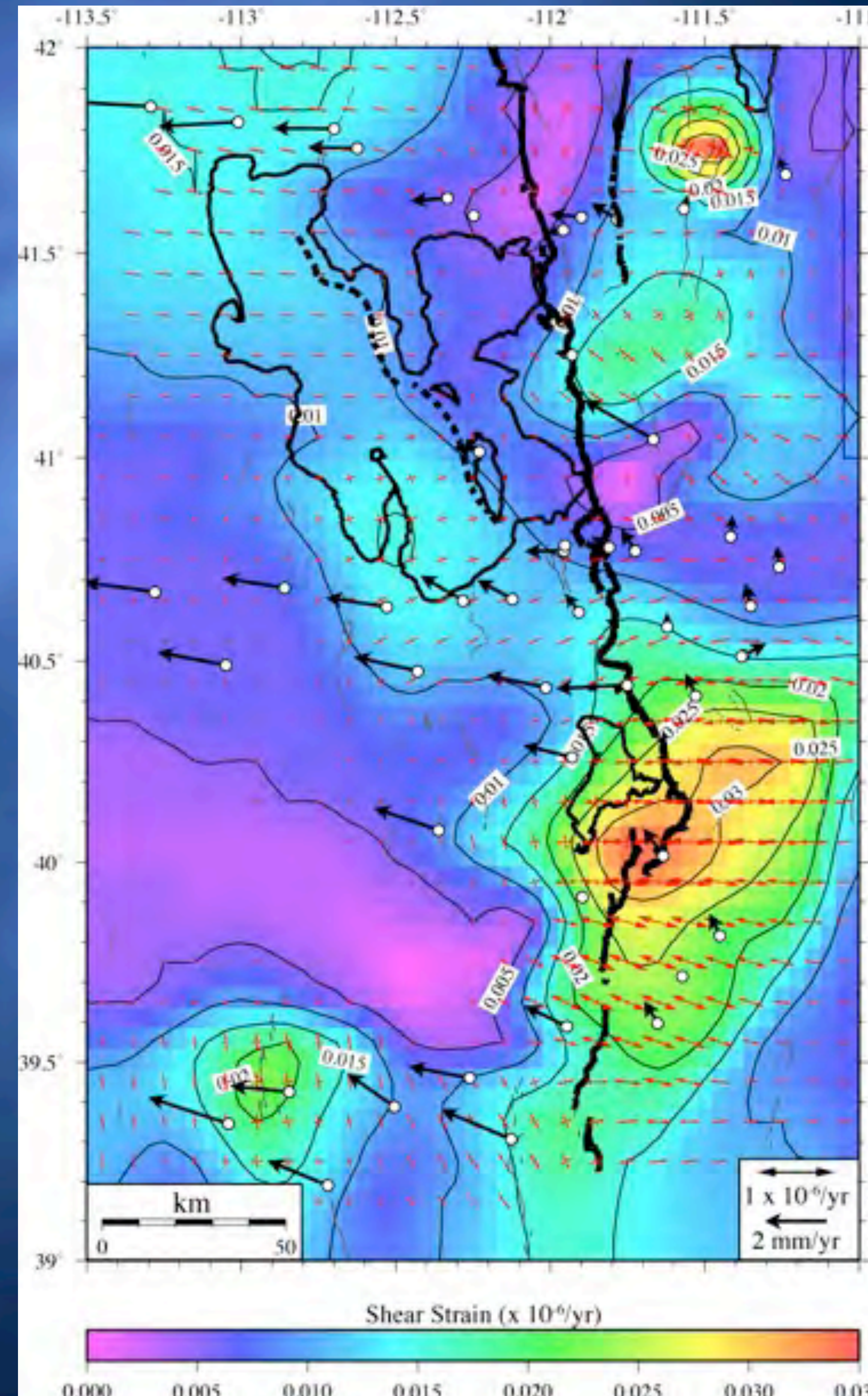




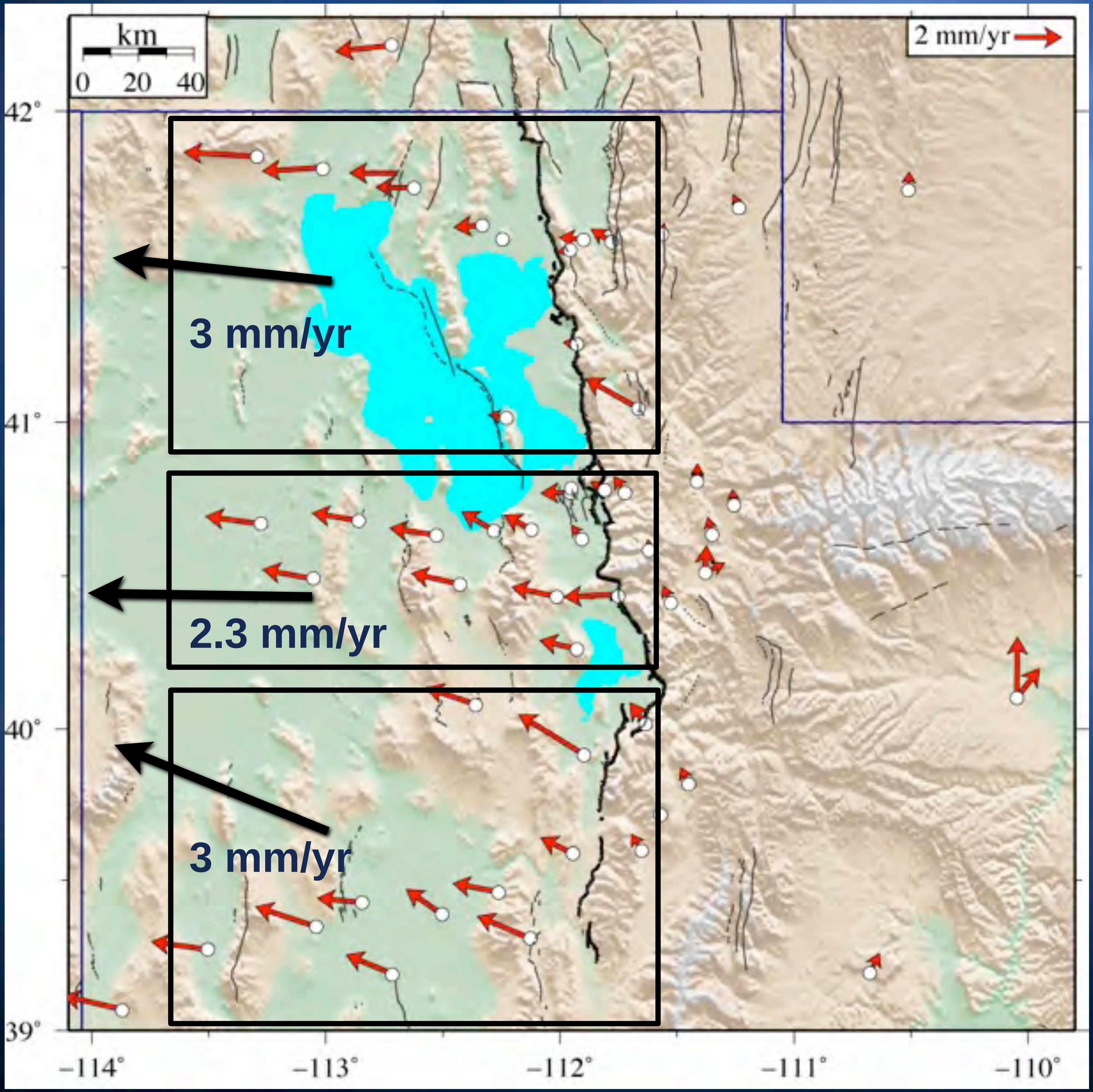
Wasatch GPS (black arrows), horizontal strain rates (red crosses), and strain magnitudes (background)



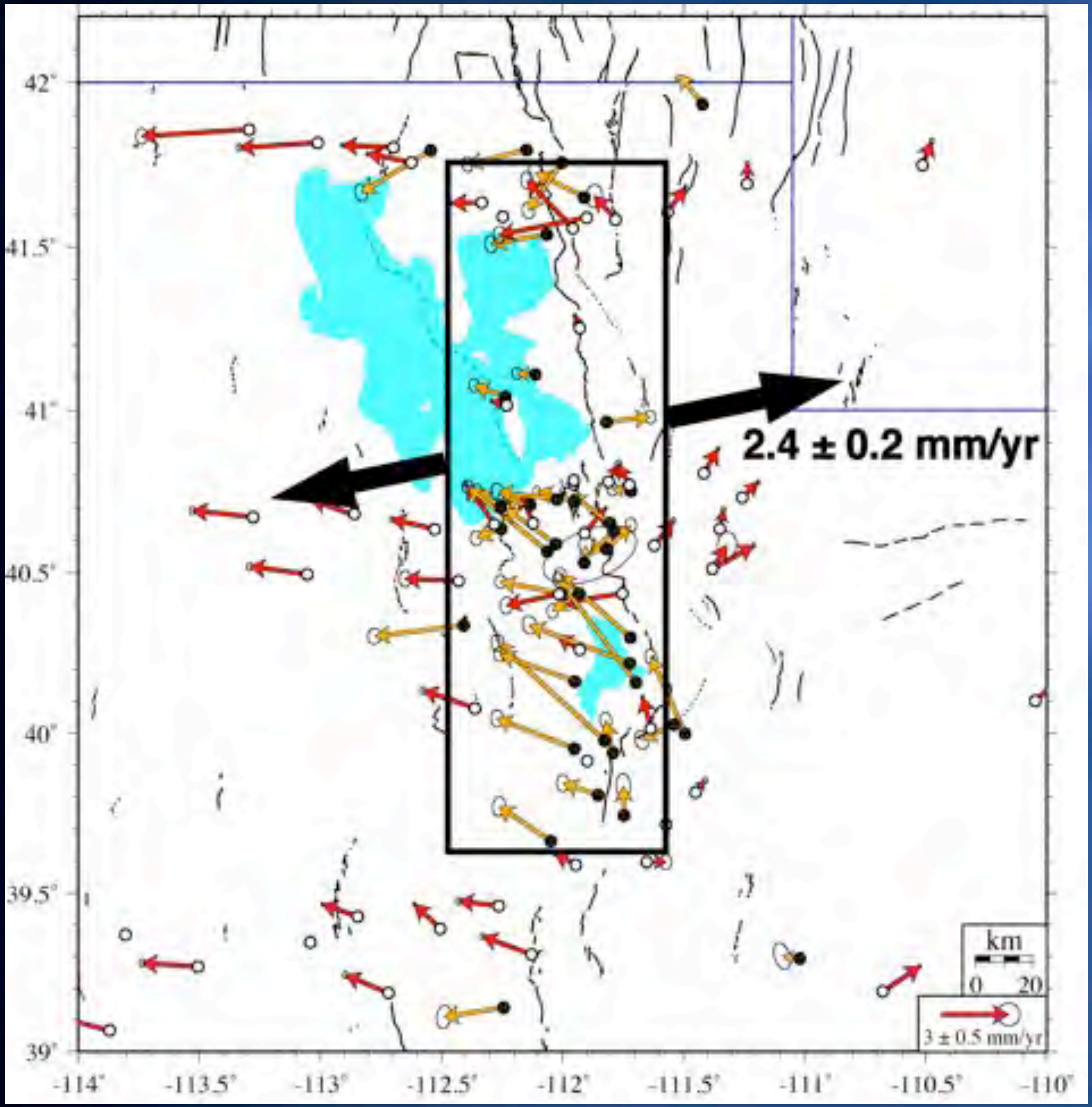
Wasatch GPS (black arrows), horizontal strain rates (red crosses), and shear strain (background)



Wasatch horizontal GPS velocities



Deformation rates across the Wasatch fault



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

Monitoring of Wasatch fault

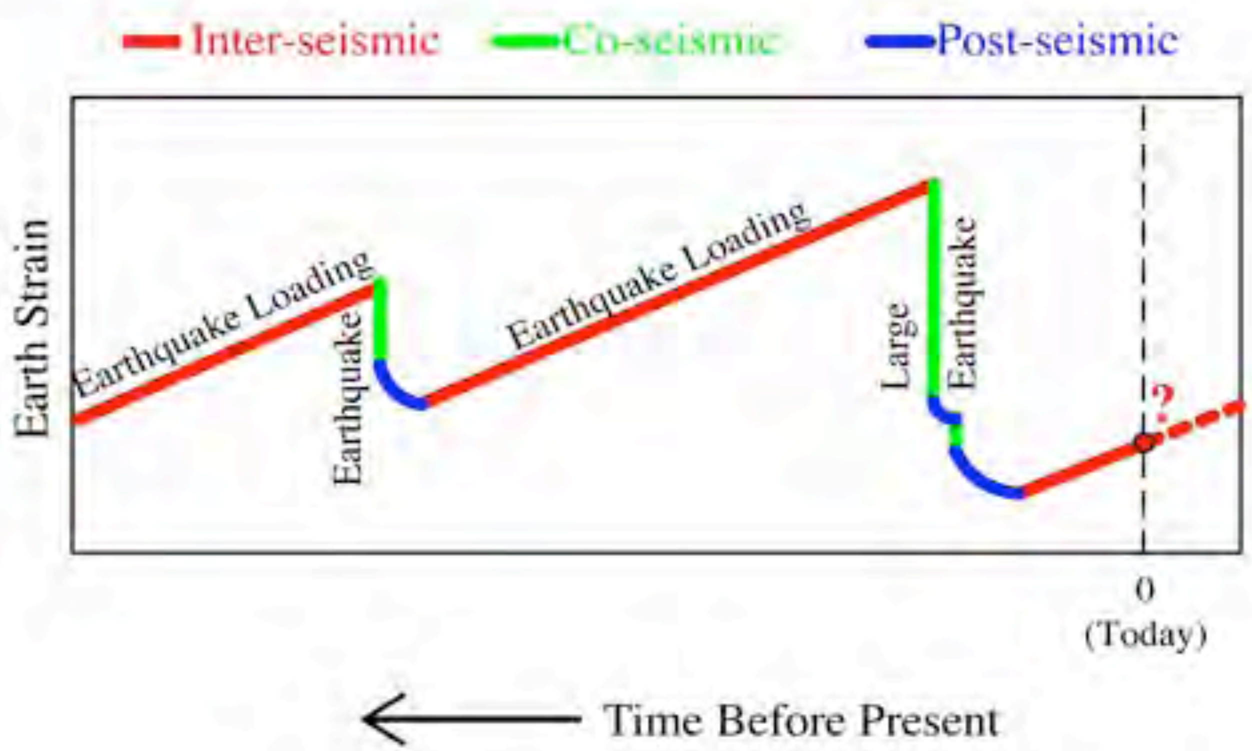
- Campaign GPS: 1992-2003
- Permanent GPS: 1996-2010

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

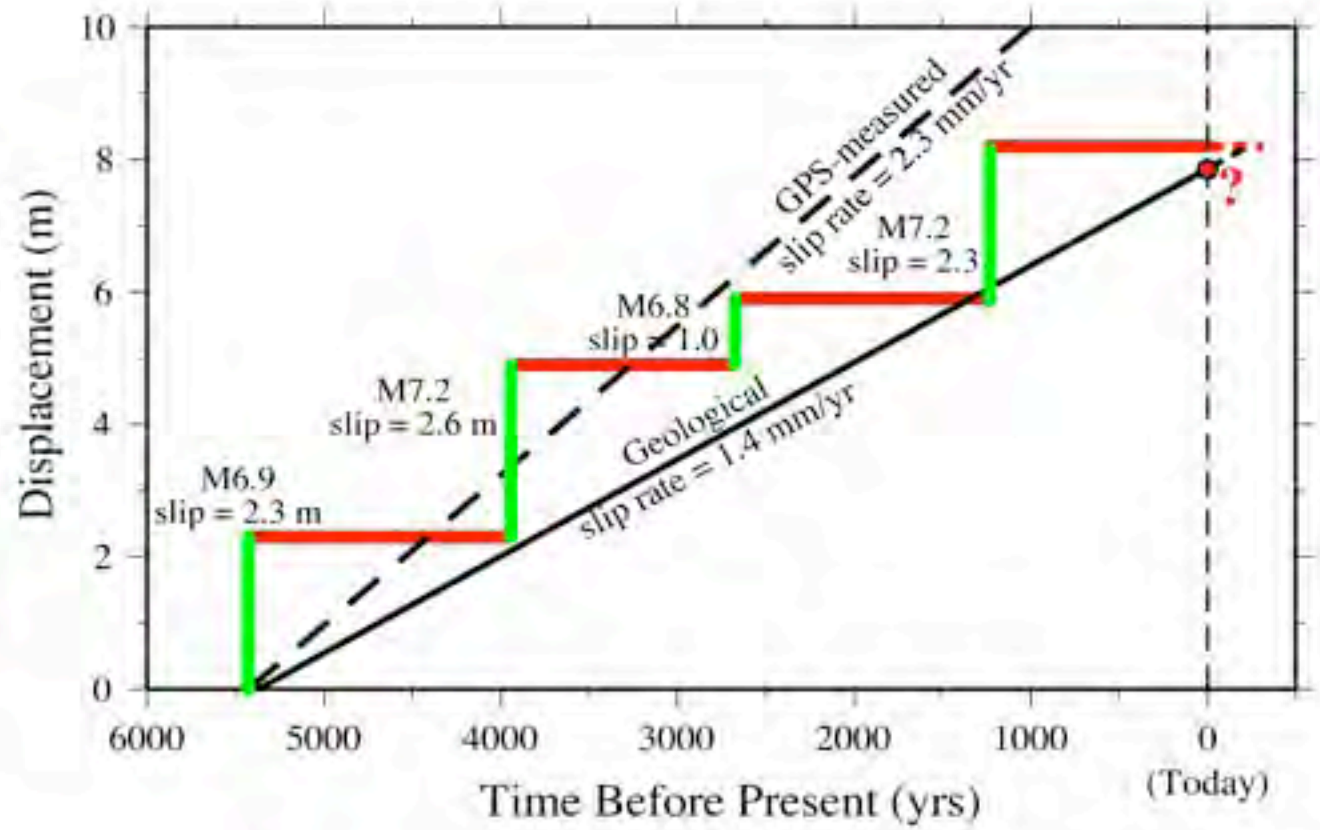
How are you going to deal with this discrpancy in a PSHA!

Earthquake cycle

History of earthquakes and earthquake loading

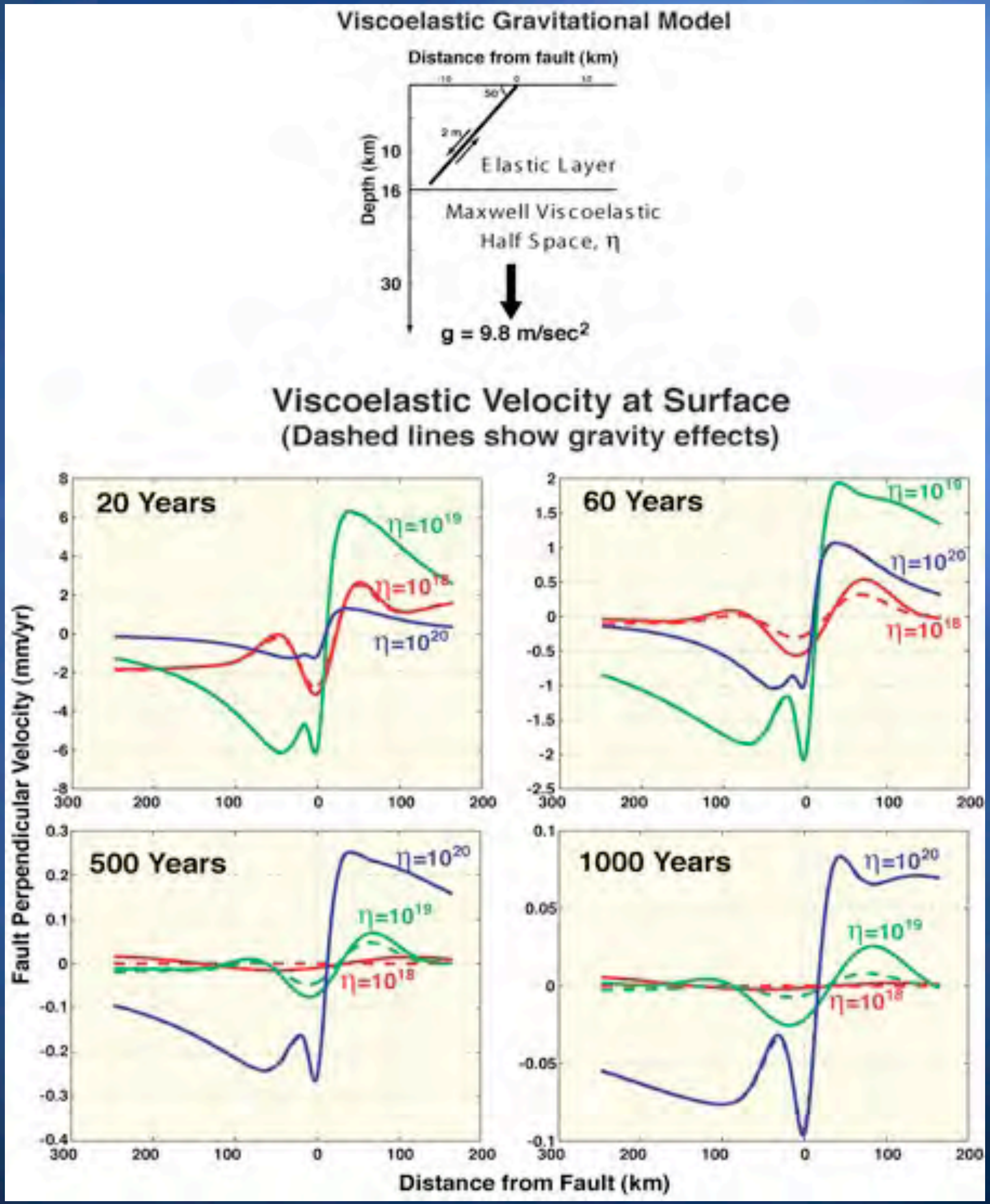


Wasatch fault earthquake history



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

Faults never stop moving?

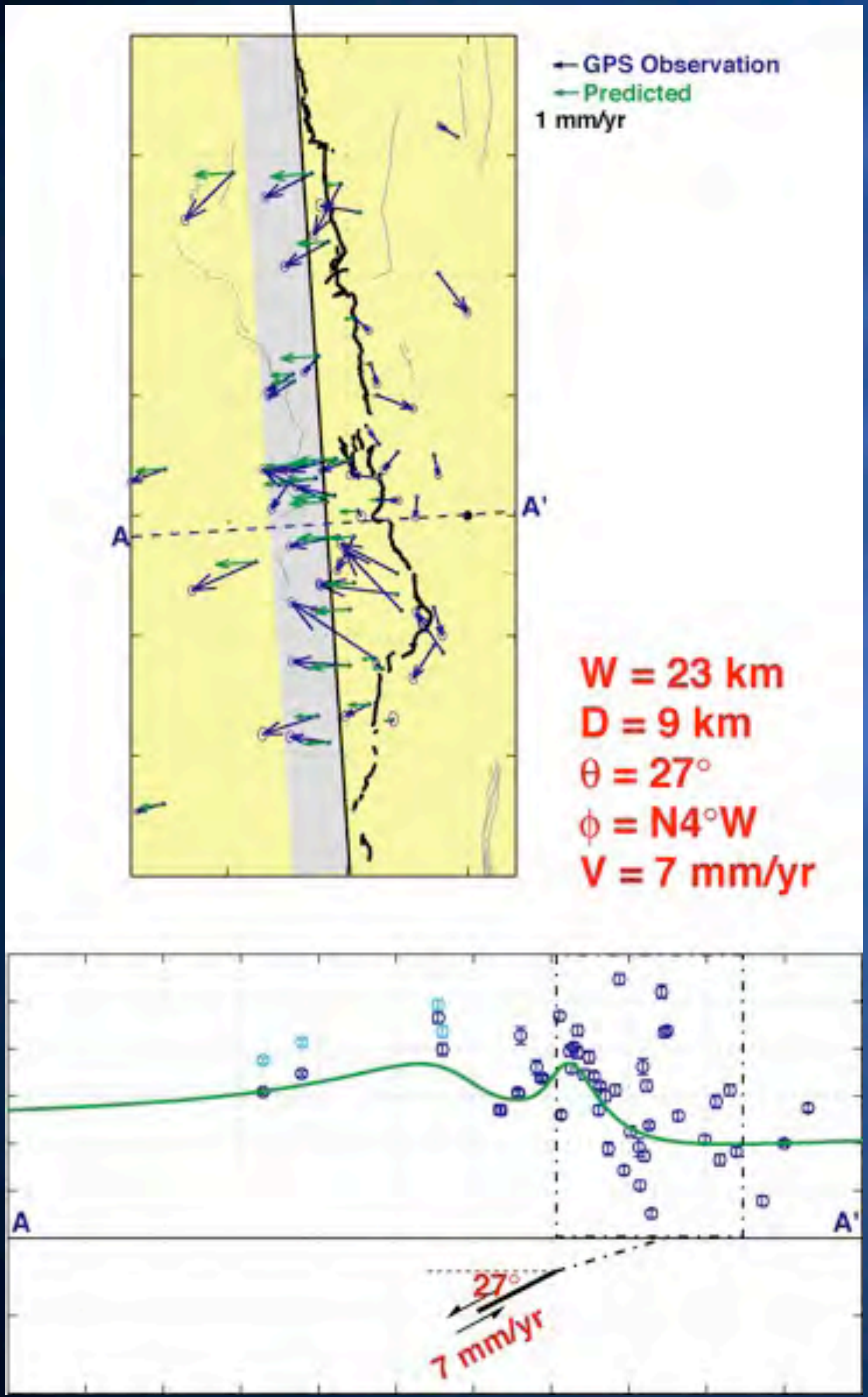


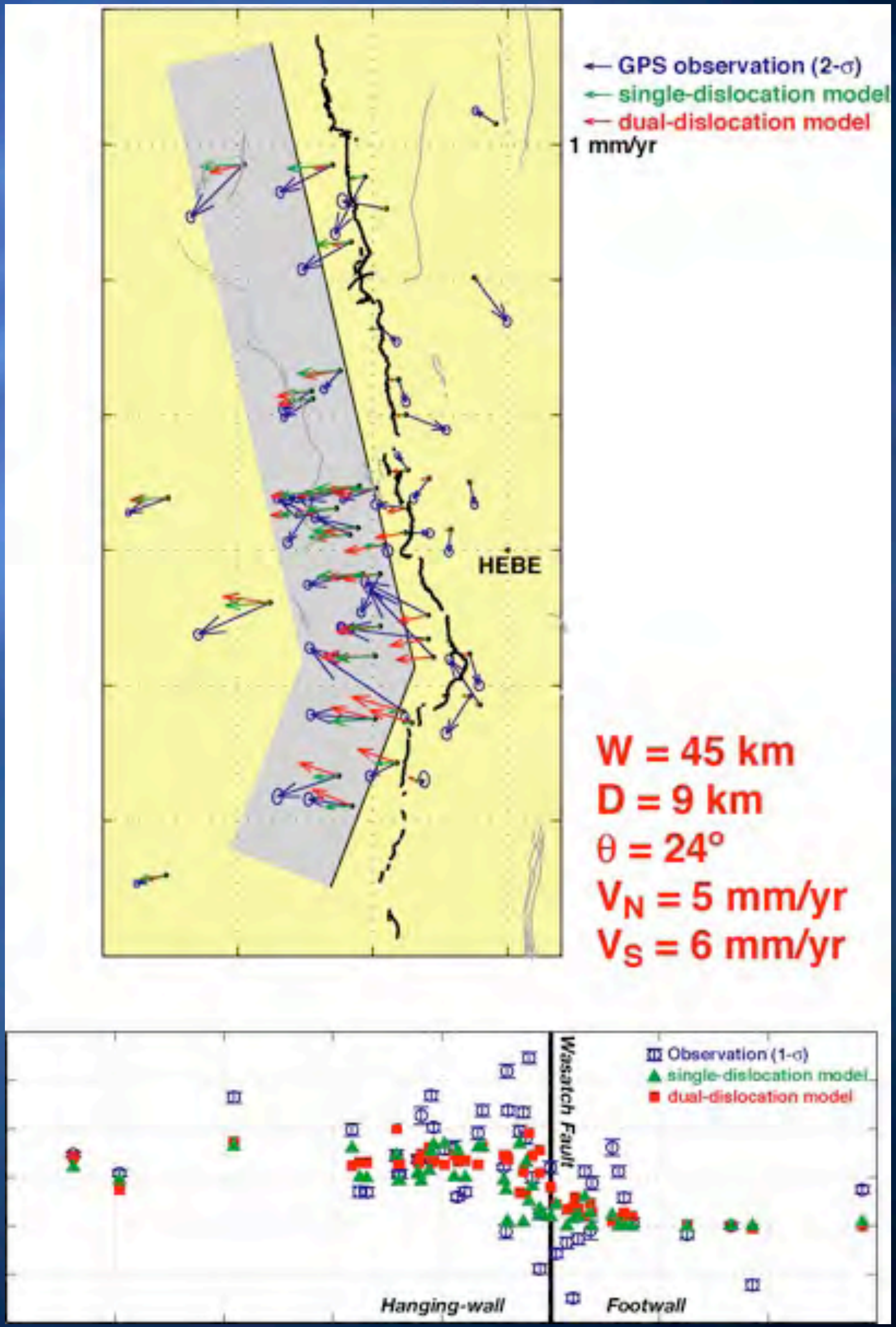
Wasatch fault measured motion

Best solution is for $\eta = 10^{19}$ Pa-sec.

Time-dependent motion:
normal-faulting earthquake and interseismic loading

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

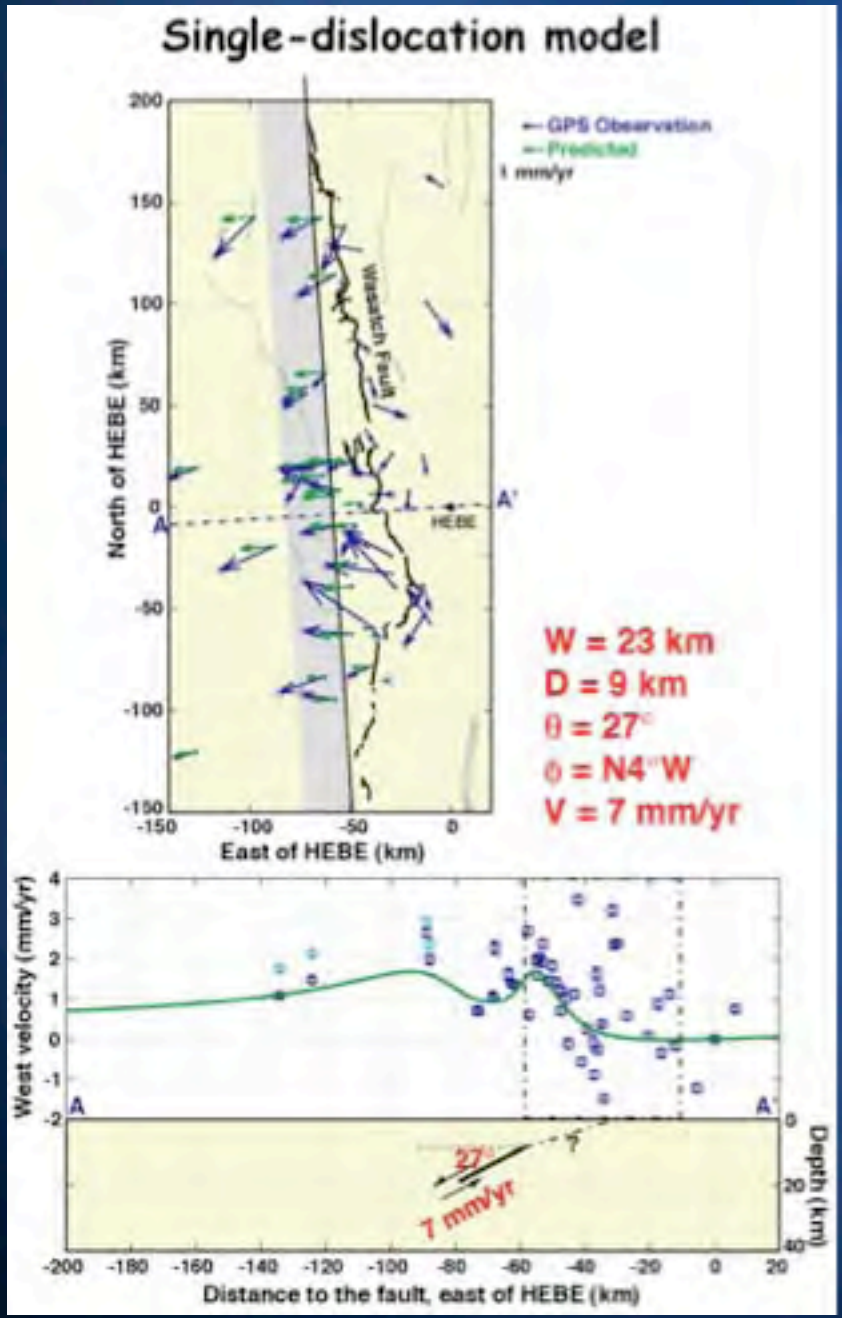


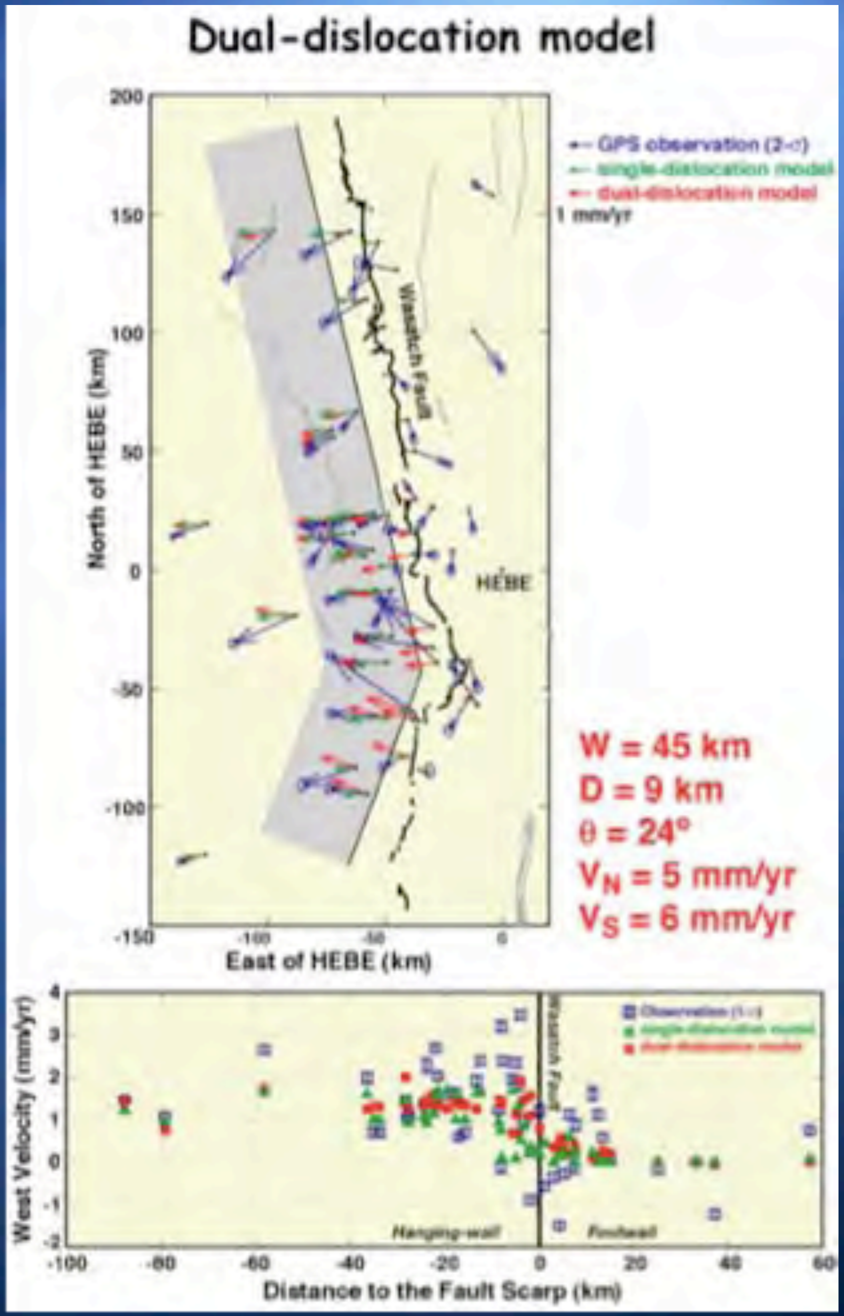


(Chang and Smith, 2002)

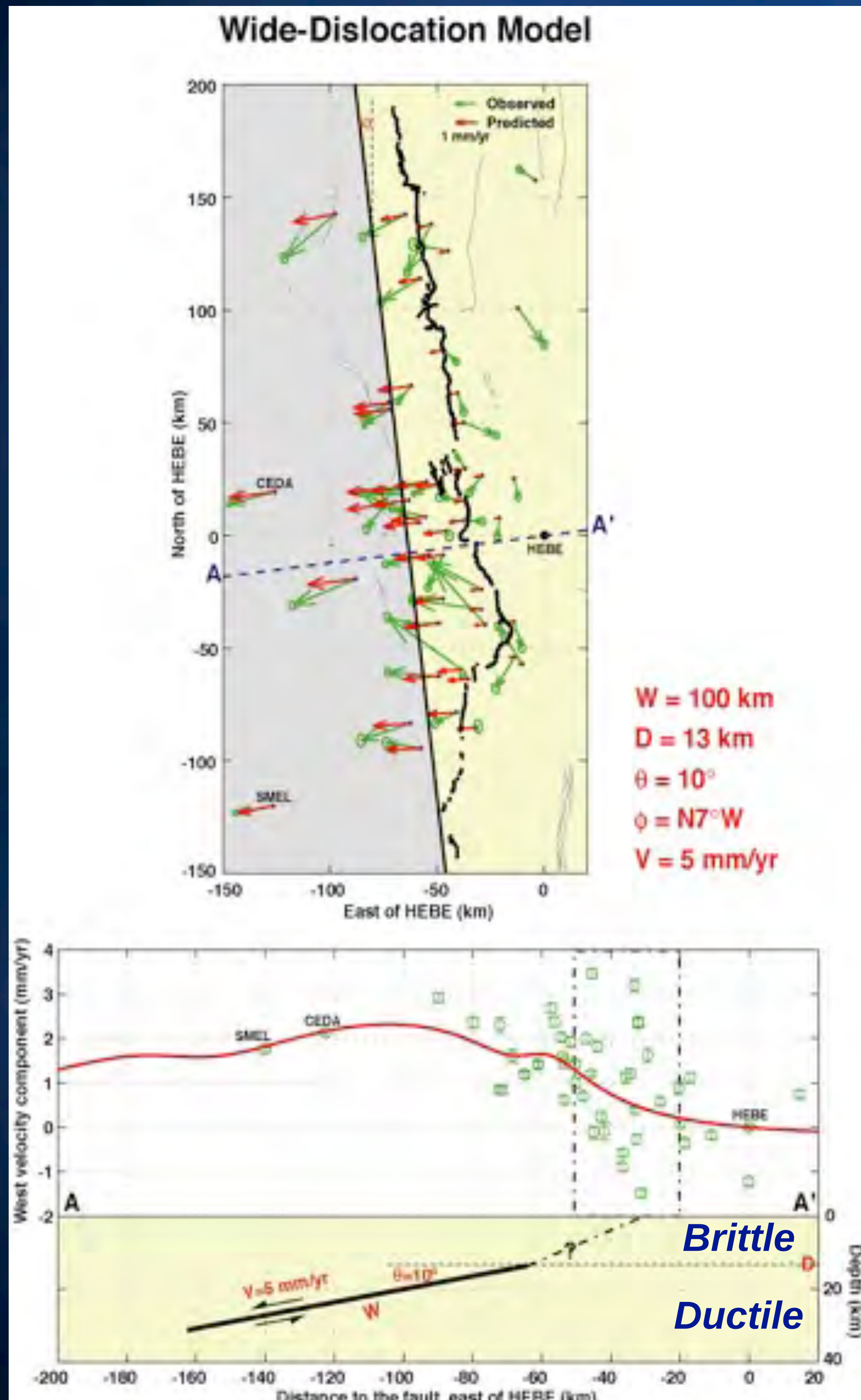
Chang et al. [2006, in preparation]

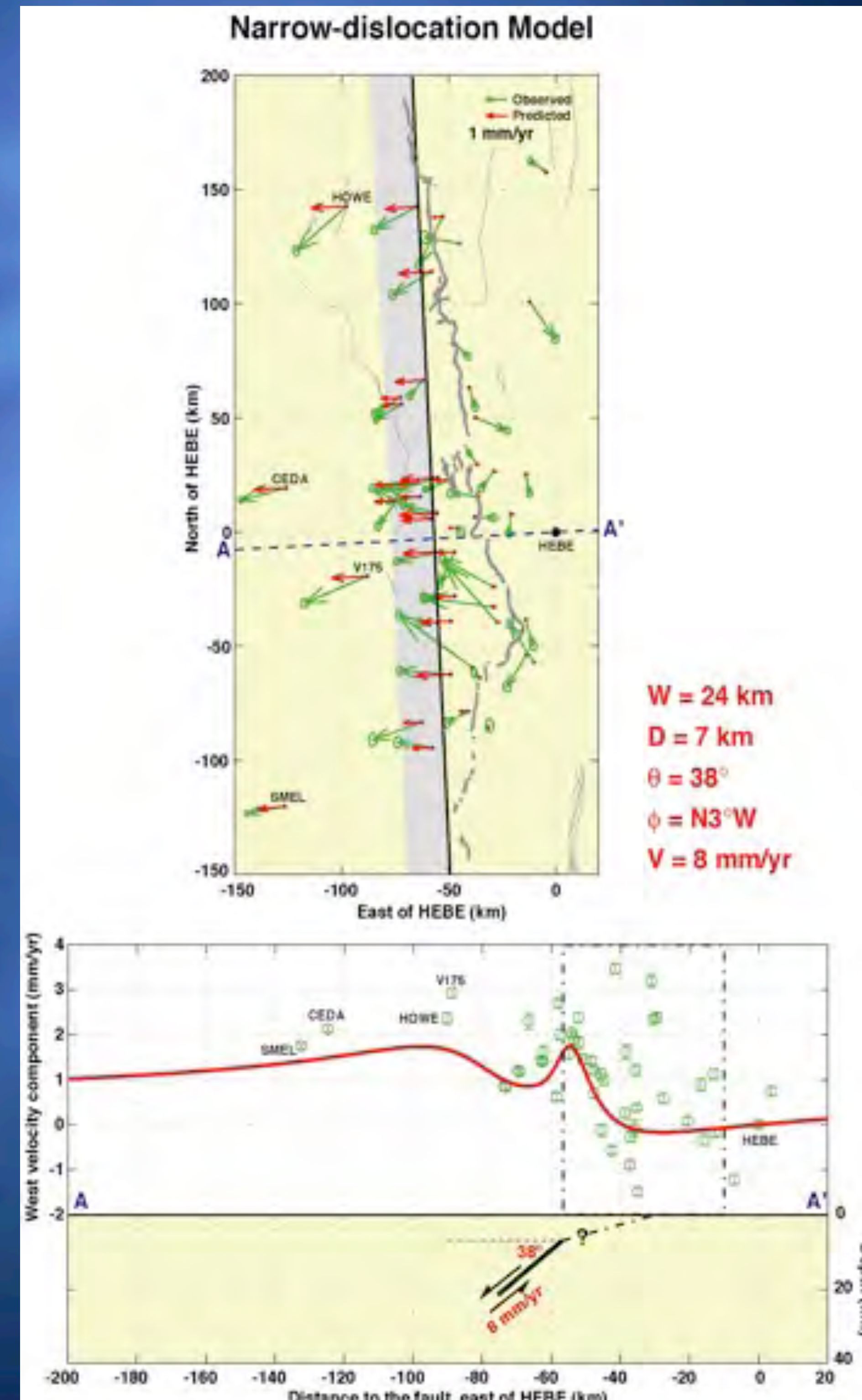
Models of contemporary Wasatch fault deformation --
loading in ductile layer in turns loads the seismogenic layer





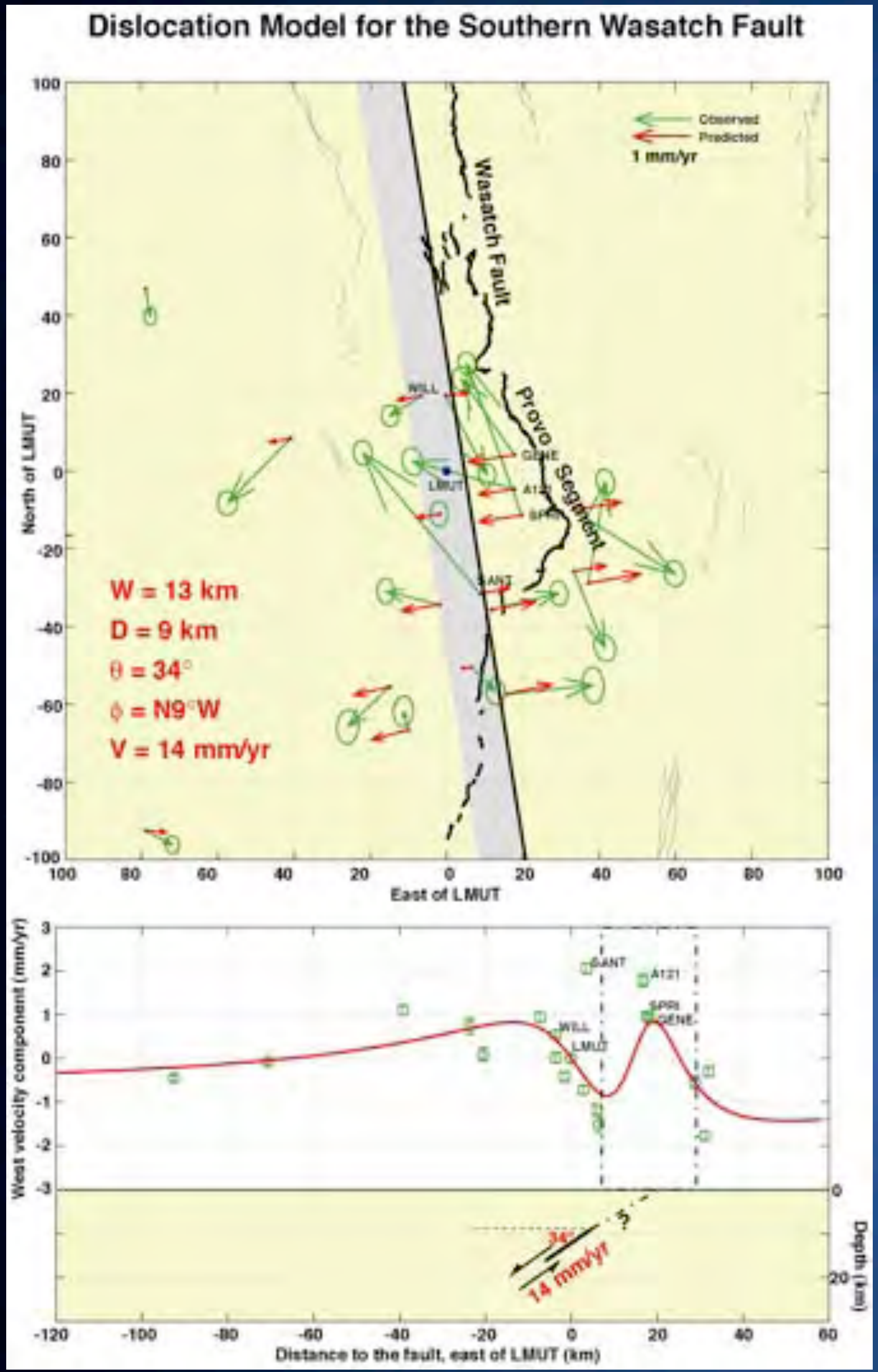
(after the methodlogy of Chang and Smith, 2002)

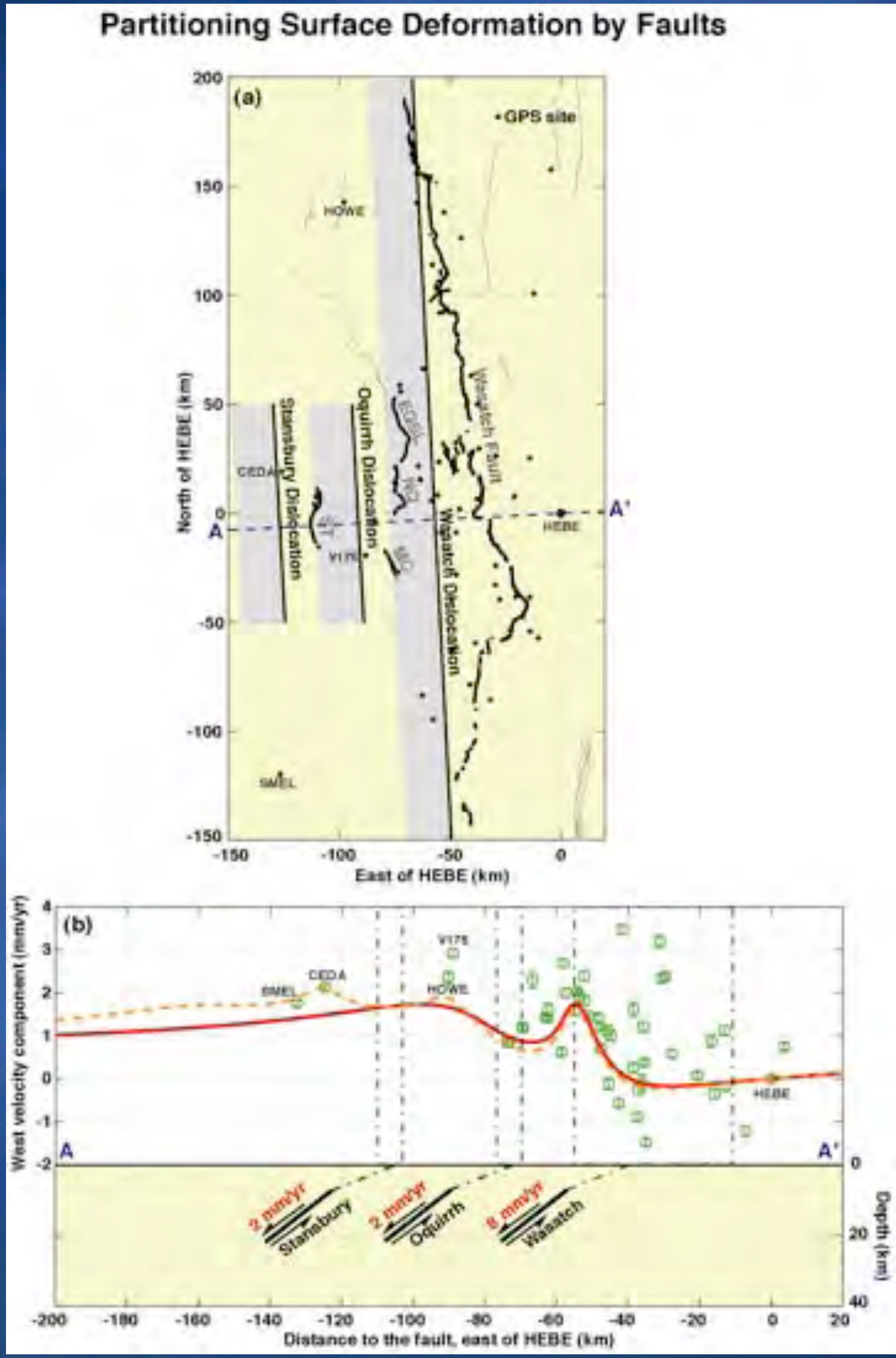


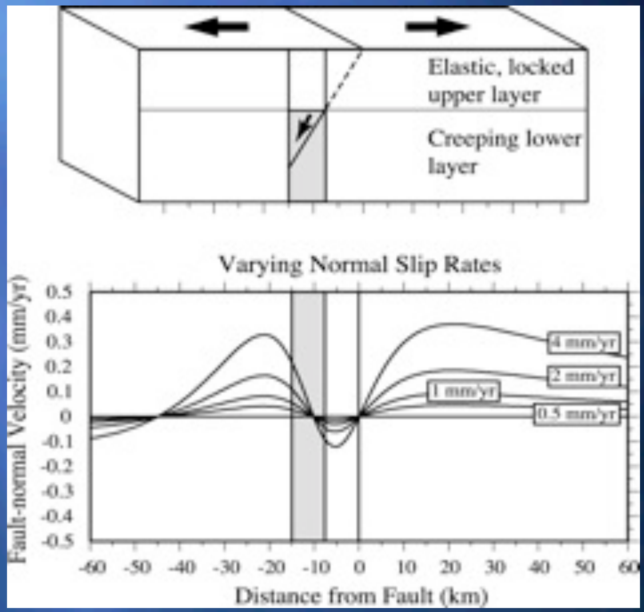


(after the methodlogy of Chang and Smith, 2002)

Fault Loading Models of Wasatch Fault GPS Motions



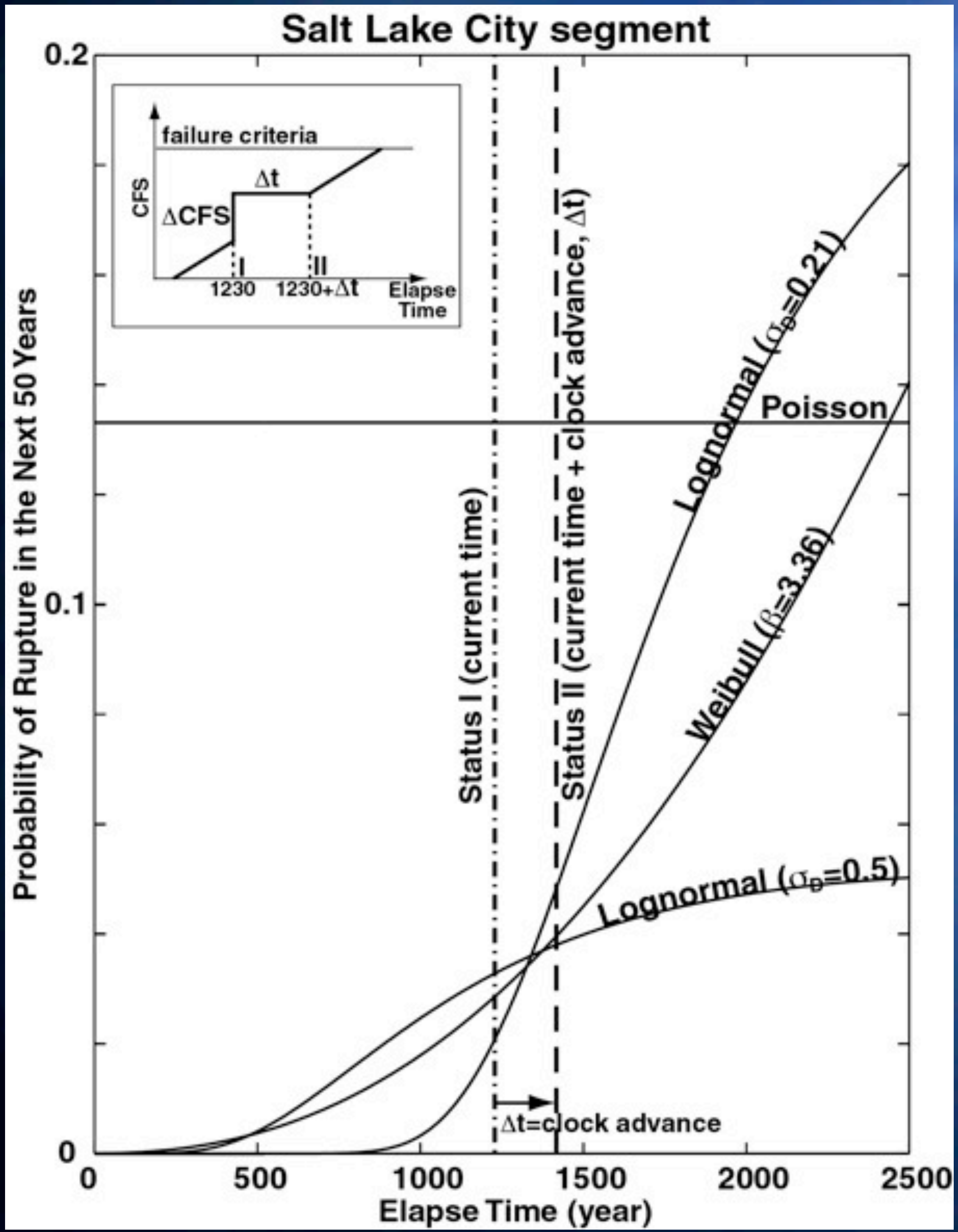




Fault loading models

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

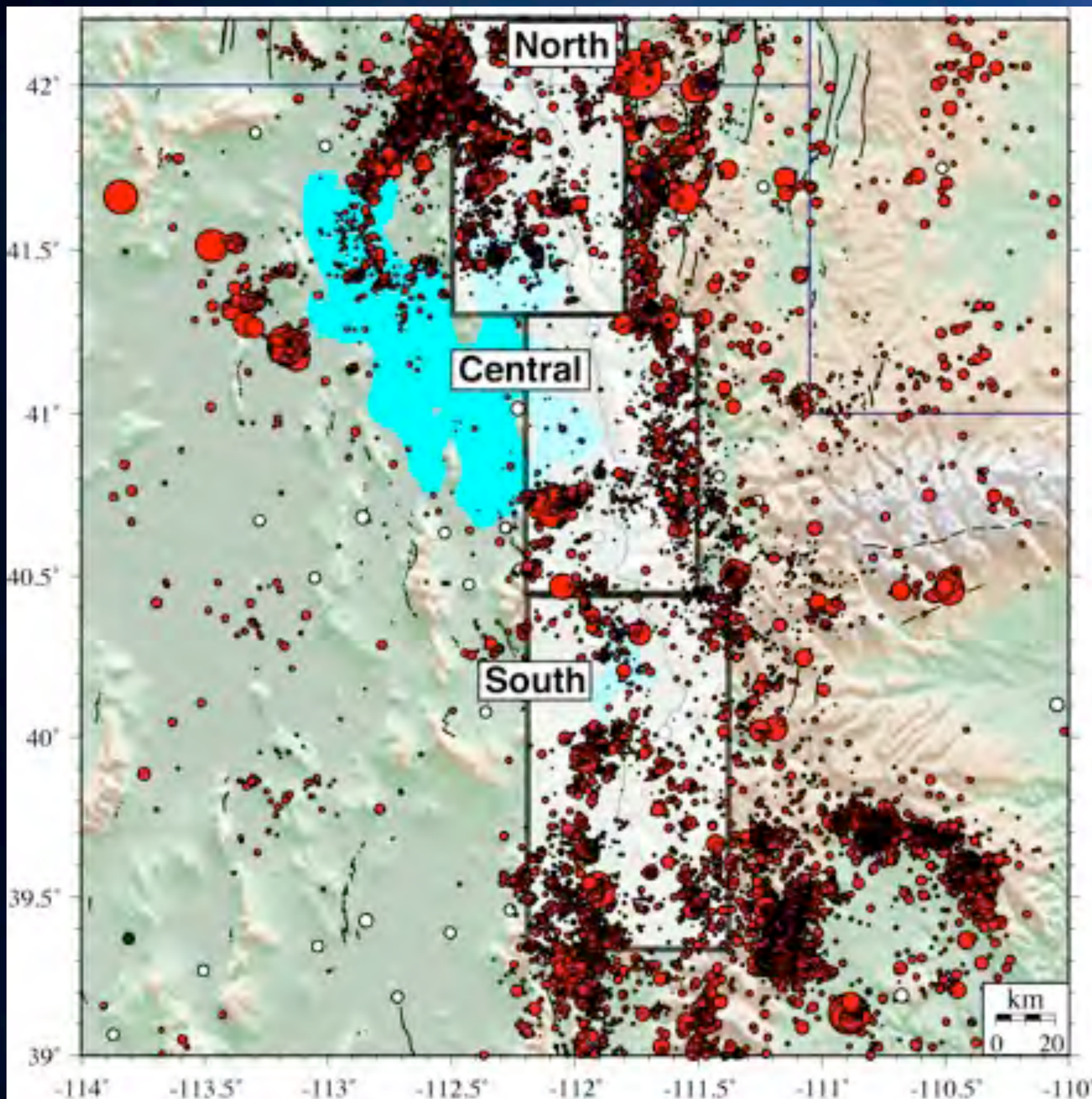
Time-dependent modeling of Wasatch fault rupture (advancement of rupture because of stress contagion)

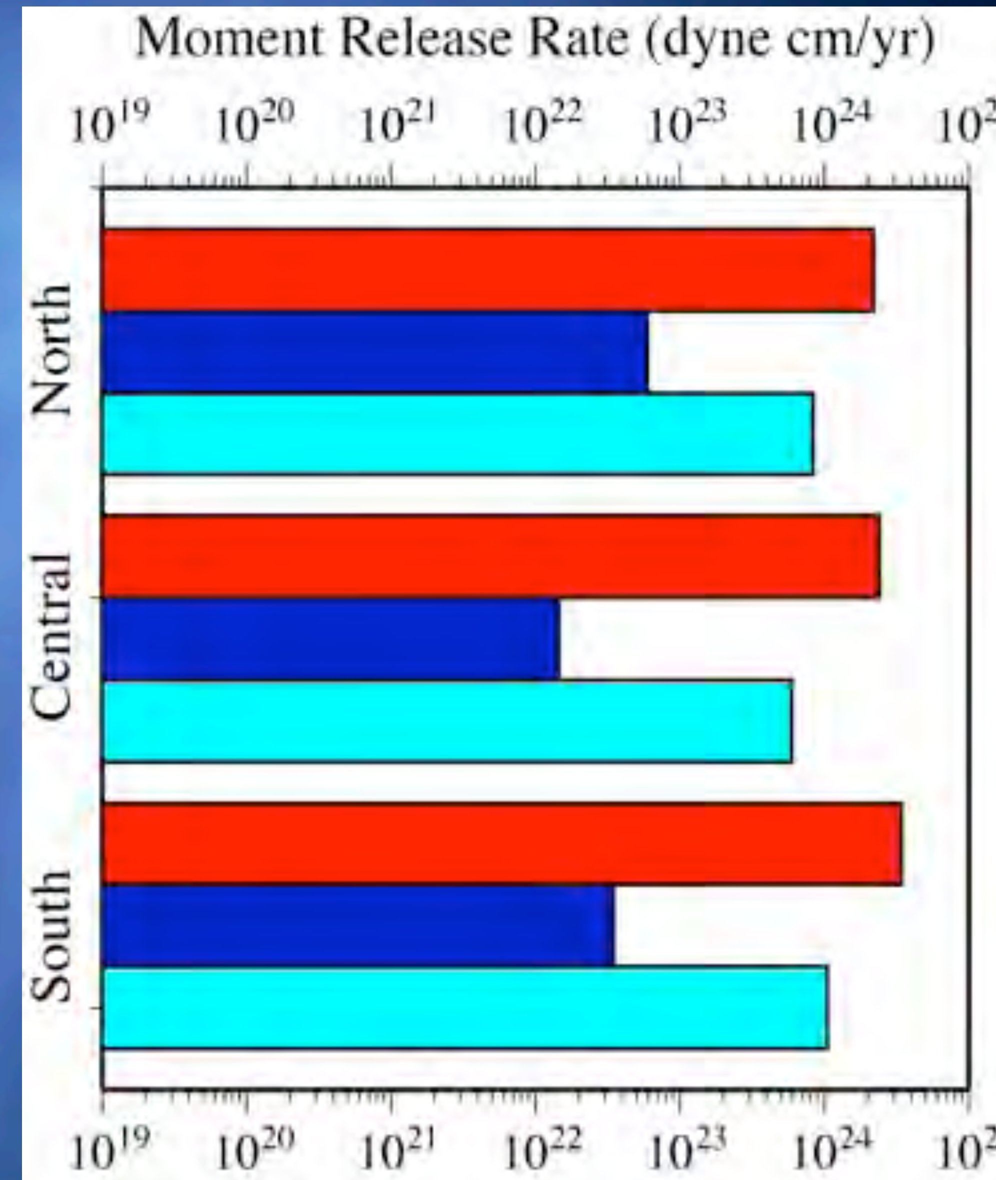


Time-dependent (elastic) probabilistic earthquake risk, conditional on the elapsed times and the number of events of relevant fault segments

(Chang and Smith, 2004)

Comparative moment release rates



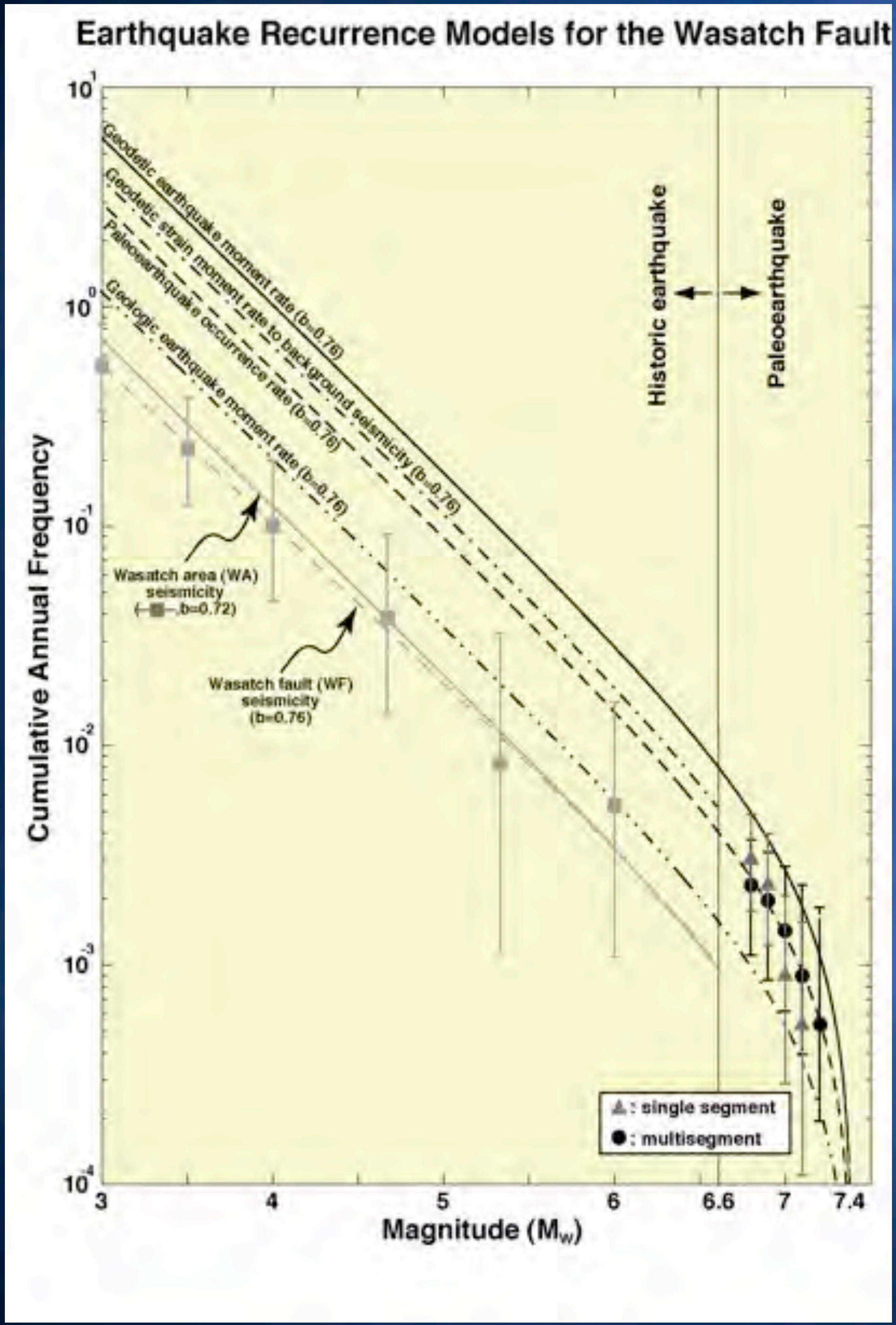


Section	Total (dyne cm/yr)	Seismic (dyne cm/yr)	Fault Slip (dyne cm/yr)
North	2.18×10^{24}	5.94×10^{22}	8.26×10^{23}
Central	2.39×10^{24}	1.44×10^{22}	5.91×10^{23}
South	3.42×10^{24}	3.45×10^{22}	1.04×10^{24}

Seismic moment budget

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

A Big Deficit!



Geologic moment rate

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

Geodetic moment rate

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

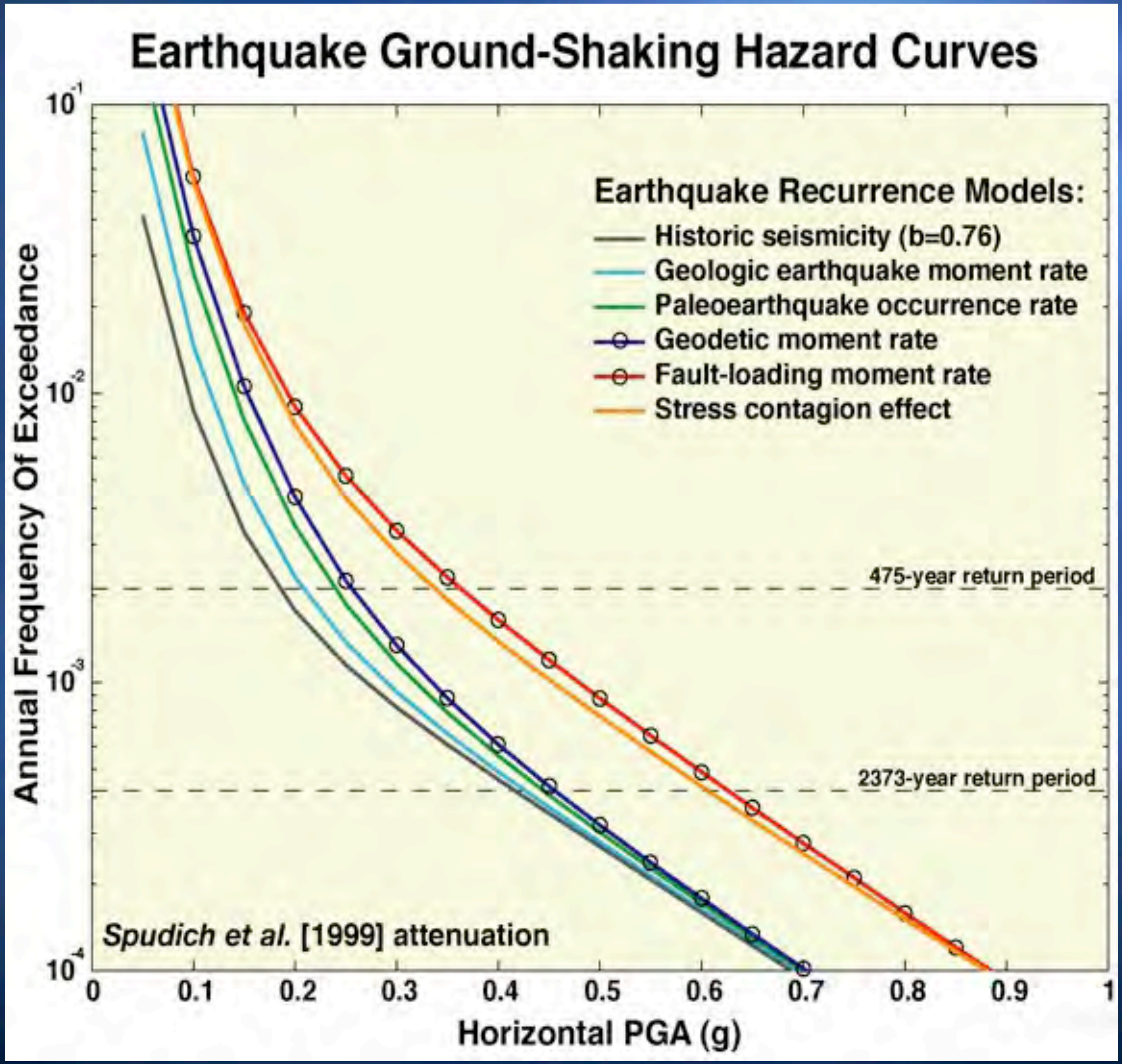
$$N(3.0,6.5) = \frac{\dot{M}_g - \sum_{\substack{\text{faults in} \\ \text{geodetic area}}} \dot{M}_f}{C_d(3.0,6.5)}$$

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

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

Wednesday, December 8, 2010

Integrated earthquake probabilistic seismic hazard assessment for the middle of Salt Lake Valley



Chang and Smith [2002]

Suggestions for Utah PSHA

- Include geodetic (GPS) data into any new PSHA.
- Time-dependent hazard (elastic) models should be included
- Fault slip and GPS rates data should be evaluated probabilistically.
- Will dynamic-stress strong ground motions models incorporated in PSHA
- Is the propsed PSHA being done as SSHAC level X product
- Time-dependent hazard (viscoelastic) models should be considered
- Extreme ground motion, ExGM, ranges and sensitivities for normal faults (ExGM) need to be incorporated in new PSHAs.

Questions

Moment Rate for Utah

Mark Petersen, Stephen Harmsen, Yuehua Zeng, Tony Crone, Kathy Haller

Parameters to calculate moment/moment rate

1. Moment = rigidity*area*displacement

2. Moment rate = rigidity*area*slip rate

3. Slip rate = Moment rate/(rigidity*area)

4. Kostrov's formula converts strain rate to Moment rate:
   Moment rate~rigidity X length X width X strain rate
   (dependent on fault geometry)

We assume a 3X 10^10 rigidity constant
M_0=10**(1.5*M+9.05)
Lengths (l) are based on segmentation model

Parameters to calculate moment/moment rate

For USGS NSHMs we assume a 15 km vertical depth and a planar fault:

1. 50 degree dip (0.6 wt) –> 19.6 km down-dip width
2. 60 degree dip (0.2 wt) –> 17.3 km down-dip width
3. 40 degree dip (0.2 wt) –> 23.3 km down-dip width

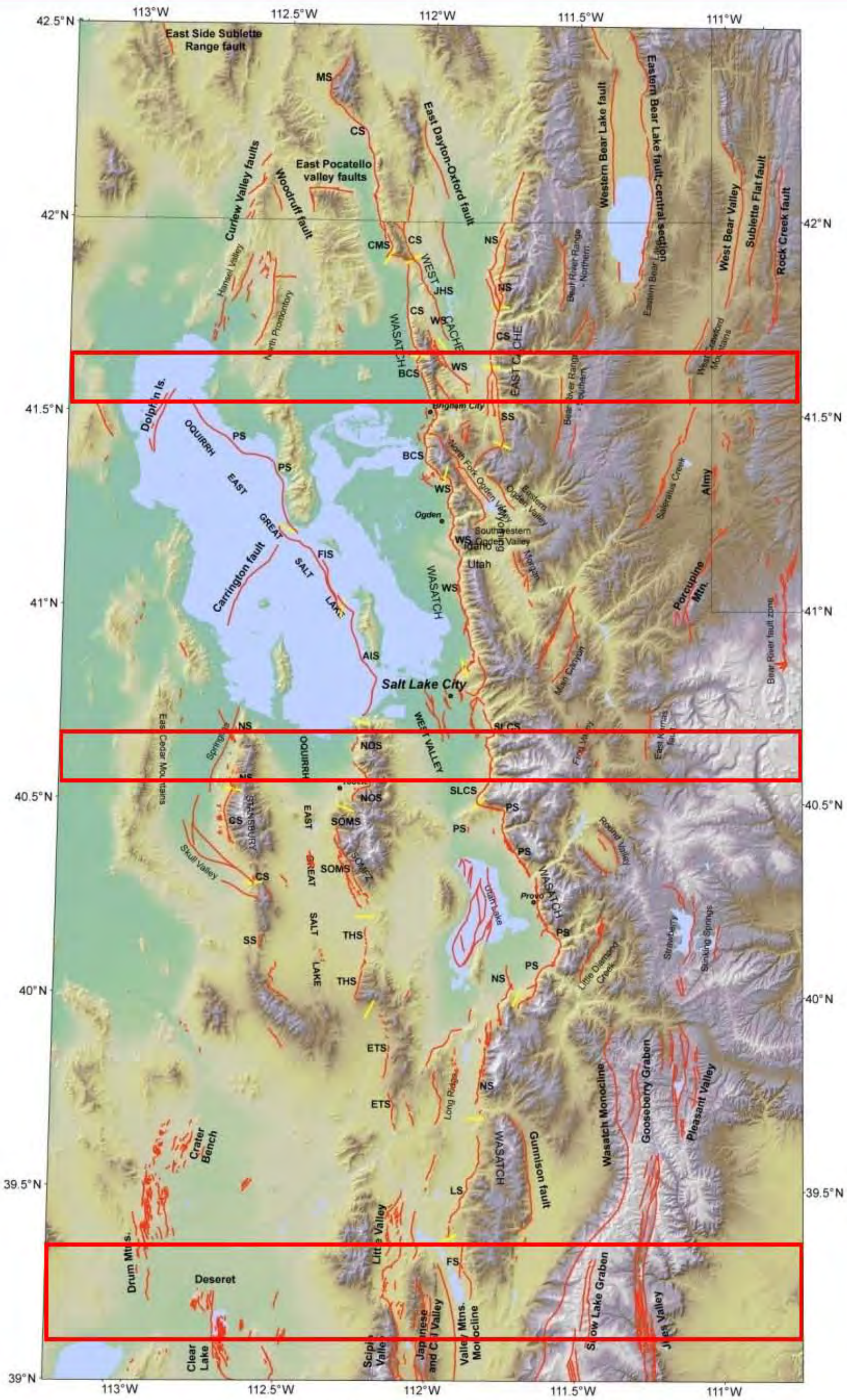
Other models - Wulung Chang and Bob Smith: (approximate numbers shown)

1. listric fault with 10 degree dip between 13-35 km (5 mm/yr)
2. listric fault with 38 degree dip between 7-24 km (8 mm/yr)
3. listric fault with ~40 degree Wasatch 8-20 km (8 mm/yr), Oquirrh 5-20 km (2 mm/yr), and Stansbury 5-20 km (2 mm/yr)
4. listric fault 27 degree dip between 9-20 km (7 mm/yr)

Wasatch Lengths and Magnitudes

Segment	Length (km)	USGS Assigned Magnitude	Calculated Magnitude
all	305	7.4	7.97
Brigham City	41	6.9	6.95
Weber	63	7.2	7.17
Salt Lake City	48	7.0	7.04
Provo	77	7.4	7.27
Nephi	44	7.0	7.02
Levan	32	6.8	6.84

Puskas and Smith suggest that Wasatch is capable of producing M 7.5 earthquakes
Based on paleoseismic studies of fault slip (McCalpin and Nishenko, 1996 and Chang and Smith, 2002)



WGUEP WASATCH FRONT REGION

(latitude 39.00° - 42.50°, longitude 110.75° - 113.25°)

PROFILE 1:

a. East Great Salt Lake Fault (dips west) 0.78 mm/yr (downdip), 0.6 mm/yr (vertical), 0.5 (horizontal)

b. Brigham City Wastatch (dips west) 1.5 mm/yr geologic, M 6.9 at 7.7X10-4/yr, this gives equivalent rate of between 1-3 mm/yr (downdip), 2 mm/yr vert→1.29 horiz

c. East Casche (dips west) 0.26 mm/yr (downdip), 0.20 mm/yr (vertical), 0.17 (horizontal)

NET SLIP TO WEST 0.5, 1.3, 0.17

PROFILE 2:

a. Stansbury (dips west) 0.52 mm/yr (downdip), 0.4 mm/yr (vertical), 0.34 (horizontal)

b. Oquirrh (dips west) 0.26 mm/yr (downdip), 0.20 mm/yr (vertical), 0.17 mm/yr (horizontal)

c. West Valley (dips east) 0.52 mm/yr (downdip), 0.4 mm/yr (vertical), 0.34 mm/yr (horizontal)

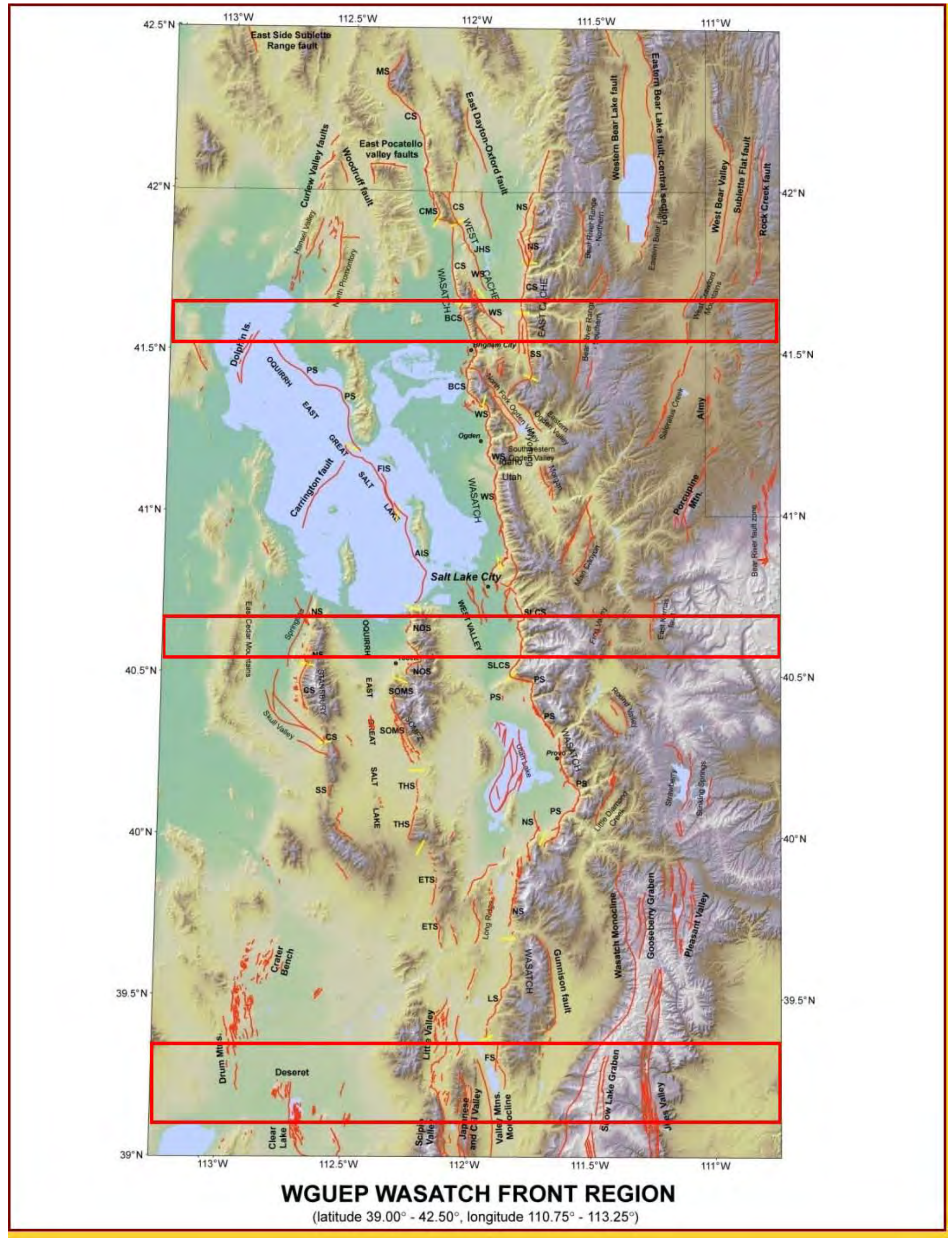
d. SLC Wasatch (dips west) 1.5 mm/yr geologic, M 7.0 at 7.7X10-4/yr, this gives equivalent rate of 1-3 mm/yr

NET SLIP TO WEST 0.34, 0.17, 0.34, 1.3

PROFILE 3:

a. Joes Valley (dips west) 0.26 mm/yr (downdip), 0.20mm/yr (vertical), 0.17 mm/yr (horizontal)

NET SLIP TO WEST 0.17 mm/yr



Characteristic earthquakes

Characteristic	M	wt(M)	MoRate	Rate*10**-4	length		moment ratet*wt	Moment (eq)	Moment rate	50deg SR	60degSR	40degSR
Provo	7.4	0.6	5.93	4.2	77		3.56E+16	1.41E+20	5.93E+16	1.31	1.48	1.10
	7.2	0.2	2.97	4.2			5.95E+15	7.08E+19	2.97E+16	0.66	0.74	0.55
	7.6	0.2	11.8	4.2			2.37E+16	2.82E+20	1.18E+17	2.61	2.96	2.20
Nephi	7	0.6	1.42	4	44		8.52E+15	3.55E+19	1.42E+16	0.55	0.62	0.46
	6.8	0.2	0.71	4			1.42E+15	1.78E+19	7.11E+15	0.27	0.31	0.23
	7.2	0.2	2.83	4			5.66E+15	7.08E+19	2.83E+16	1.09	0.71	0.92
Levan	6.8	0.6	0.42	2.37	32		2.53E+15	1.78E+19	4.21E+15	0.22	0.25	0.19
	6.6	0.2	0.21	2.37			4.22E+14	8.91E+18	2.11E+15	0.11	0.13	0.09
	7	0.2	0.84	2.37			1.68E+15	3.55E+19	8.41E+15	0.45	0.51	0.38
Brigham City	6.9	0.6	1.93	7.7	41		1.16E+16	2.51E+19	1.93E+16	0.80	0.91	0.67
	6.7	0.2	0.97	7.7			1.94E+15	1.26E+19	9.69E+15	0.40	0.46	0.34
	7.1	0.2	3.86	7.7			7.72E+15	5.01E+19	3.86E+16	1.60	1.81	1.35
Weber	7.2	0.6	5.03	7.1	63		3.02E+16	7.08E+19	5.03E+16	1.36	1.54	1.14
	7	0.2	2.52	7.1			5.04E+15	3.55E+19	2.52E+16	0.68	0.77	0.57
	7.4	0.2	10.03	7.1			2.01E+16	1.41E+20	1.00E+17	2.71	3.07	2.28
Salt Lake City	7	0.6	2.73	7.7	48		1.64E+16	3.55E+19	2.73E+16	0.97	1.10	0.81
	7.2	0.2	5.45	7.7			1.09E+16	7.08E+19	5.45E+16	1.93	2.19	1.62
	6.8	0.2	1.37	7.7			2.74E+15	1.78E+19	1.37E+16	0.49	0.55	0.41
						SUM	1.92E+17					

Floating and GR

Float 7.4 (10% weight-1.2 mm/yr slip rate)	Dip	wt(dip)	MoRate	Rate*10**-3		Wasatch floating large-eq (7.4+-) branches	Weighted Moment rate	Moment of M7.4	Moment rate	50 degree downdip slip rate	60 degree downdip slip rate	40 degree downdip slip rate
7.4	50	0.6	28.16	2	305	19.6	1.70E+17	1.41E+20	2.83E+17	1.58	1.78	1.33
	40	0.2	42.77	3.03	305	23.3	8.56E+16	1.41E+20	4.28E+17	2.39	2.70	2.01
	60	0.2	15.5	1.1	305	17.3	3.11E+16	1.41E+20	1.55E+17	0.87	0.98	0.73
						SUM	2.86E+17					
Gutenberg-Richter (18% weight, M 5-Max mag)	dip	wt(dip)	MoRate	Dwndip SR	Vert SR	Horiz SR	Weighted Moment rate	RI(yrs)				
Provo	50	0.6	7.1	1.57	1.2	1	4.26E+16					
	40	0.2	10.08	1.87	1.2	1.4	2.02E+16					
	60	0.2	5.55	1.39	1.2	7	1.11E+16					
Nephi	50	0.6	3.92	1.44	1.1	0.9	2.35E+16					
	40	0.2	5.57	1.71	1.1	1.3	1.11E+16					
	60	0.2	3.07	1.27	1.1	0.6	6.14E+15					
Levan	50	0.6	0.75	0.39	0.3	0.25	4.50E+15					
	40	0.2	1.06	0.47	0.3	0.36	2.12E+15					
	60	0.2	0.58	0.35	0.3	0.17	1.16E+15					
Brigham City	50	0.6	4.38	1.83	1.4	1.2	2.63E+16					
	40	0.2	6.22	2.18	1.4	1.7	1.24E+16					
	60	0.2	3.42	1.62	1.4	0.8	6.84E+15					
Weber	50	0.6	5.76	1.57	1.2	1	3.46E+16					
	40	0.2	8.18	1.87	1.2	1.4	1.64E+16					
	60	0.2	4.51	1.39	1.2	0.7	9.02E+15					
Salt Lake City	50	0.6	4.45	1.57	1.2	1	2.67E+16	262				
	40	0.2	6.32	1.87	1.2	1.4	1.26E+16	185				
	60	0.2	3.48	1.39	1.2	0.7	6.96E+15	337				
						WT SUM	2.74E+17					
									M7.4	M 7		
						TOTAL M	2.16E+17		653 yrs	164 yrs		

Comparison (downdip slip rates)

Segment	Geologic slip rate (mm/yr +/- 15%)	RI based slip rate (mm/yr +/- 15%)	Geodetic slip rate (Zeng)	Geodetic slip rate (Chang and Smith)	Puskas and Smith
Brigham City	1.83	0.80	2.2	5-12	2-3
Weber	1.57	1.36	2.6	5-12	2-3
Salt Lake City	1.57	0.97	4.1	5-12	2-3
Provo	1.57	1.31	4.3	5-12	2-3
Nephi	1.44	0.55	4.3	5-12	2-3
Levan	0.39	0.22	3.3	5-12	2-3

Characteristic	M	wt(M)	MoRate	Rate*10**	length		moment ratet*wt	Moment (eq)	Moment rate	50 deg SR	60 deg SR	40 deg SR	50deg SR	60degSR	40degSR
Provo	7.4	0.6	5.93	4.2	77		3.56E+16	1.41E+20	5.93E+16	0.001310332	0.001484538	0.0011023	1.31	1.48	1.10
	7.2	0.2	2.97	4.2			5.95E+15	7.08E+19	2.97E+16	0.000656722	0.000744031	0.0005524	0.66	0.74	0.55
	7.6	0.2	11.8	4.2			2.37E+16	2.82E+20	1.18E+17	0.002614455	0.002962042	0.0021993	2.61	2.96	2.20
Nephi	7	0.6	1.42	4	44		8.52E+15	3.55E+19	1.42E+16	0.000548567	0.000621498	0.0004615	0.55	0.62	0.46
	6.8	0.2	0.71	4			1.42E+15	1.78E+19	7.11E+15	0.000274935	0.000311487	0.0002313	0.27	0.31	0.23
	7.2	0.2	2.83	4			5.66E+15	7.08E+19	2.83E+16	0.001094536	0.000708601	0.0009207	1.09	0.71	0.92
Levan	6.8	0.6	0.42	2.37	32		2.53E+15	1.78E+19	4.21E+15	0.000223986	0.000253765	0.0001884	0.22	0.25	0.19
	6.6	0.2	0.21	2.37			4.22E+14	8.91E+18	2.11E+15	0.000112259	0.000127184	9.443E-05	0.11	0.13	0.09
	7	0.2	0.84	2.37			1.68E+15	3.55E+19	8.41E+15	0.000446911	0.000506327	0.0003759	0.45	0.51	0.38
Brigham City	6.9	0.6	1.93	7.7	41		1.16E+16	2.51E+19	1.93E+16	0.000802287	0.000908949	0.0006749	0.80	0.91	0.67
	6.7	0.2	0.97	7.7			1.94E+15	1.26E+19	9.69E+15	0.000402096	0.000455554	0.0003382	0.40	0.46	0.34
	7.1	0.2	3.86	7.7			7.72E+15	5.01E+19	3.86E+16	0.001600772	0.001813592	0.0013466	1.60	1.81	1.35
Weber	7.2	0.6	5.03	7.1	63		3.02E+16	7.08E+19	5.03E+16	0.001356877	0.001537271	0.0011414	1.36	1.54	1.14
	7	0.2	2.52	7.1			5.04E+15	3.55E+19	2.52E+16	0.000680049	0.000770461	0.0005721	0.68	0.77	0.57
	7.4	0.2	10.03	7.1			2.01E+16	1.41E+20	1.00E+17	0.002707325	0.003067259	0.0022774	2.71	3.07	2.28
Salt Lake City	7	0.6	2.73	7.7	48		1.64E+16	3.55E+19	2.73E+16	0.000967993	0.001096686	0.0008143	0.97	1.10	0.81
	7.2	0.2	5.45	7.7			1.09E+16	7.08E+19	5.45E+16	0.0019314	0.002188175	0.0016247	1.93	2.19	1.62
	6.8	0.2	1.37	7.7			2.74E+15	1.78E+19	1.37E+16	0.000485146	0.000549645	0.0004081	0.49	0.55	0.41
						SUM	1.92E+17								

Float 7.4	Dip	wt(dip)	MoRate	Rate*10**-3	atch floating large-eq (7.4+-) branches										
7.4	50	0.6	28.16	2	305	19.6	1.70E+17	1.41E+20	2.83E+17	0.001575262	0.00178469	0.0013251	1.58	1.78	1.33
	40	0.2	42.77	3.03	305	23.3	8.56E+16	1.41E+20	4.28E+17	0.002386522	0.002703805	0.0020075	2.39	2.70	2.01
	60	0.2	15.5	1.1	305	17.3	3.11E+16	1.41E+20	1.55E+17	0.000866394	0.00098158	0.0007288	0.87	0.98	0.73
						SUM	2.86E+17								

Gutenberg-Richter	dip	wt(dip)	MoRate	Dwndip SR	Vert SR	Horiz SR		RI (yrs)	Wasatch Segmented GR bra	nented GR bra	ented GR br	mented GR branch (wt 0.18)			
Provo	50	0.6	7.1	1.57	1.2	1	4.26E+16								
	40	0.2	10.08	1.87	1.2	1.4	2.02E+16								
	60	0.2	5.55	1.39	1.2	7	1.11E+16								
Nephi	50	0.6	3.92	1.44	1.1	0.9	2.35E+16								
	40	0.2	5.57	1.71	1.1	1.3	1.11E+16								
	60	0.2	3.07	1.27	1.1	0.6	6.14E+15								
Levan	50	0.6	0.75	0.39	0.3	0.25	4.50E+15								
	40	0.2	1.06	0.47	0.3	0.36	2.12E+15								
	60	0.2	0.58	0.35	0.3	0.17	1.16E+15								
Brigham City	50	0.6	4.38	1.83	1.4	1.2	2.63E+16								
	40	0.2	6.22	2.18	1.4	1.7	1.24E+16								
	60	0.2	3.42	1.62	1.4	0.8	6.84E+15								
Weber	50	0.6	5.76	1.57	1.2	1	3.46E+16								
	40	0.2	8.18	1.87	1.2	1.4	1.64E+16								
	60	0.2	4.51	1.39	1.2	0.7	9.02E+15								
Salt Lake City	50	0.6	4.45	1.57	1.2	1	2.67E+16	262							
	40	0.2	6.32	1.87	1.2	1.4	1.26E+16	185							
	60	0.2	3.48	1.39	1.2	0.7	6.96E+15	337							
						WT SUM	2.74E+17								
									M7.4	M7			M 7		
						TOTAL M	2.16E+17		653.2793654	164.0963574			1.64E+02		

Estimating Maximum (Characteristic) Magnitudes for Faults

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

WGUEP Meeting, Salt Lake City, UT

2 December 2010

URS

Seismic Moment – Fundamental Measure of Earthquake Size

$$M_O = A\mu\overline{D}$$ (Aki, 1966)

M_O	**Seismic moment**
A	**Area**
μ	**Shear or rigidity modulus**
$\overline{D}$	**Average slip on fault**

URS

Empirical Relations to Estimate Maximum Magnitudes (M – moment magnitude)

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

URS

Empirical Relations for WGUEP to Consider*

- **Wells and Coppersmith (1994) – all fault types**
  - **Area (A); M = 4.07 + (0.98 x log A)**
  - **Surface rupture length (L); M = 5.08 + (1.16 x log L)**
  - **Average and maximum slip (AD & MD); M = 6.93 + (0.82 log AD); M = 6.69 + (0.74 x log MD)**
- **Hemphill Haley and Weldon (1999)**
  - **AD (from trench sites) and MVCDS, which is a mode value statistic based on n and the percent of fault length that the n samples cover; M = 6.93 + 0.82 (AD x MVCDS)**

*** Relations used by UCERF2 not included here because they are explicitly for strike-slip faults.**

URS

Empirical Relations for WGUEP to Consider*
(continued)

- Hanks and Kanamori (1979)
  - Seismic moment (M_O); $M = (2/3 \times \log M_O) - 10.7$
- Anderson et al. (1996)
  - Slip rate (Ď) and L; $M = 5.12 + (1.16 \times \log L) - (0.2 \times \log Ď)$
- Mason (1996) – normal faults
  - L and maximum vertical slip (V); $M = 6.01 + 0.48 \log (V \times L)$
- Leonard (2010) – interplate dip-slip faults
  - Area (A); $M = \log A + 4.0$
  - Surface rupture length (L); $M = (1.52 \times \log L) + 4.40$

Datasets Used by Leonard (2010)

- Wells and Coppersmith (1994)
- Henry and Das (2001)
- Hanks and Bakun (2002)
- Romanowicz and Ruff (2002)
- Manighetti et al. (2007)

Leonard's Approach

1. **Divide the data into 3 subsets:**

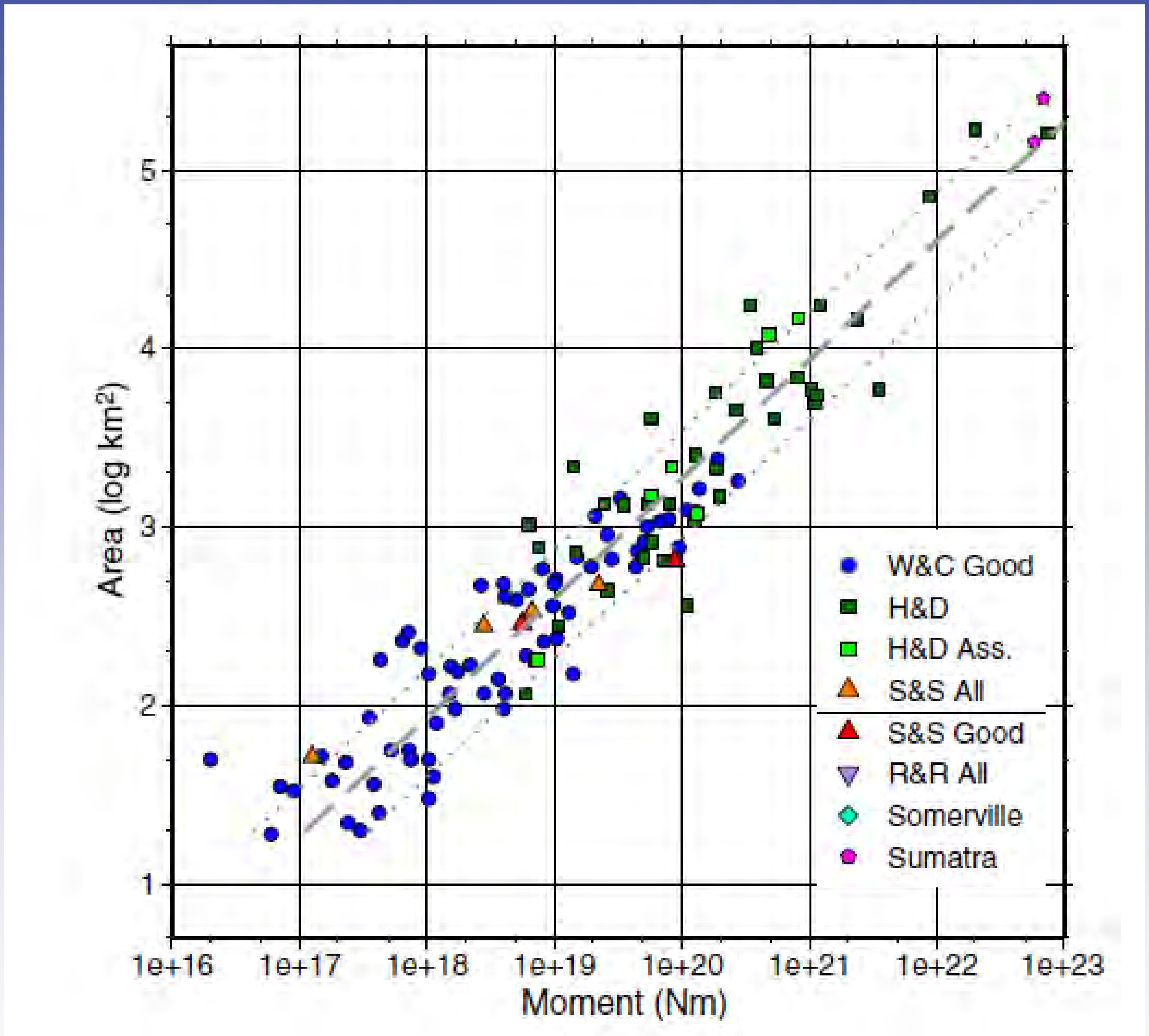
   - **Interplate and plate boundary related strike-slip earthquakes (SS)**
   - **Interplate and *plate boundary related* dip-slip earthquakes (DS)**
   - **Earthquakes in stable continental regions (SCR)**

2. **Develop self-consistent equations that describe scaling between M_O, A, L, W, and $\bar{D}$ for each data subset.**

3. **Equations have the same form (M but coefficients vary: C1- depends on size when the aspect ratio transitions from constant to power law; and,**
   C2 - depends on slip/unit area or static stress drop

URS

M_0 vs Area for Dip Slip Earthquakes



- Gray dashed line is the constrained least squares regression with a fixed slope of 2/3

- Dotted lines are $\pm 1\ \sigma$

Figure 4 from Leonard (2010)

Comparison Example for Provo Segment

- Wells and Coppersmith
  - M = 7.0 (A = 1080 km^2)
  - M = 7.1 (L = 59 km; Machette, 1992)
  - M = 7.2 (L = 63 km, with Santaquin)
  - M = 7.3 (MD = 5.73 m; Olig et al., 2010)
  - M = 7.4 (AD = 3.56; DuRoss, 2008)
- Hanks and Kanamori
  - M = 7.4 (M_O = 1.268 x 10^{27} dyne-cm)
- Anderson et al.
  - M = 7.2 (L = 59 km; Ď = 1.2 mm/yr)
- Hemphill-Haley and Weldon
  - M = 7.3 (AD = 3.56; n = 5; MVCDS = 0.78)
    (95% CL: M 7.2 – 7.6)
- Mason
  - M = 7.2 (MVD = 4.7 m; L = 59 km)
- Leonard
  - M = 7.0 (A = 1080 km^2) (vs M = 7.2 for SCR)
  - M = 7.1 (L = 59 km^2) (vs M = 7.3 for SCR)

Strawman Approach

1. Categorize faults according to available data

   A. Well-mapped with 3 or more trench sites

   B. Well-mapped with 1 or 2 trench sites (some D data)

   C. Mapped and no trench sites (no D data)

2. Use different empirical relations (and uncertainties) according to available data and segmentation model

Strawman Approach (continued)

- **For category A faults use:**
  – Wells and Coppersmith – L (all fault types)
  – Hemphill-Haley and Weldon – AD
  – Leonard – A (for interplate-related dip slip)
- **For category B faults use:**
  – Wells and Coppersmith – L (all fault types)
  – Wells and Coppersmith – AD (all fault types)
  – Wells and Coppersmith – MD (all fault types)
  – Leonard – A (for interplate-related dip slip)
- **For category C faults use:**
  – Wells and Coppersmith – L (all fault types)
  – Leonard – A (for interplate dip slip)

Example Category A Fault: Provo Segment

W & C – L	→	M 7.1 (0.3)
H-H & W – AD	→	M 7.3 (0.4)
Leonard – A	→	M 7.0 (0.3)

- **Average weighted-mean yields preferred M 7.15**
- **Use ± 0.3 for 5th and 95th (we are including various rupture scenarios, which addresses some epistemic uncertainty; this also assumes some aleatory uncertainty will be included in forecast calculations- how much?)**

URS

Example Category B Fault: Bear River Fault Zone

W & C – AD → M 7.3 (AD = 3 m; West, 1994) (0.2)

W & C – MD → M 7.0 (MD = 3 m; West, 1994) (0.2)

W & C – L → M 6.9 (L = 40 km; West, 1994) (0.3)

Leonard – A → M 6.9 (A = 732 km^2) (0.3)

- Average weighted-mean yields preferred M 7.0
- Use ± 0.3 for 5th and 9th

URS

Example Category C Fault: Carrington Fault

W & C – L → M 6.8 (L = 28 km) (0.5)

Leonard – A → M 6.7 (A = 512 km) (0.5)

- Average weighted-mean yields preferred M 6.75
- Use -0.3 for 5th and + 0.5 for 95th (extend upper bound based on analogy to adjacent Fremont Island segment, which is similar in length, and possibly rate, and has displacement/event data that yields larger expected M)

DISCUSSION

- Use other relations than proposed here?
- What weights on relations?
- Use different approach to estimate uncertainties and develop Mmax distributions?
- What to use for unsegmented rupture models for long faults (> 110 km)?

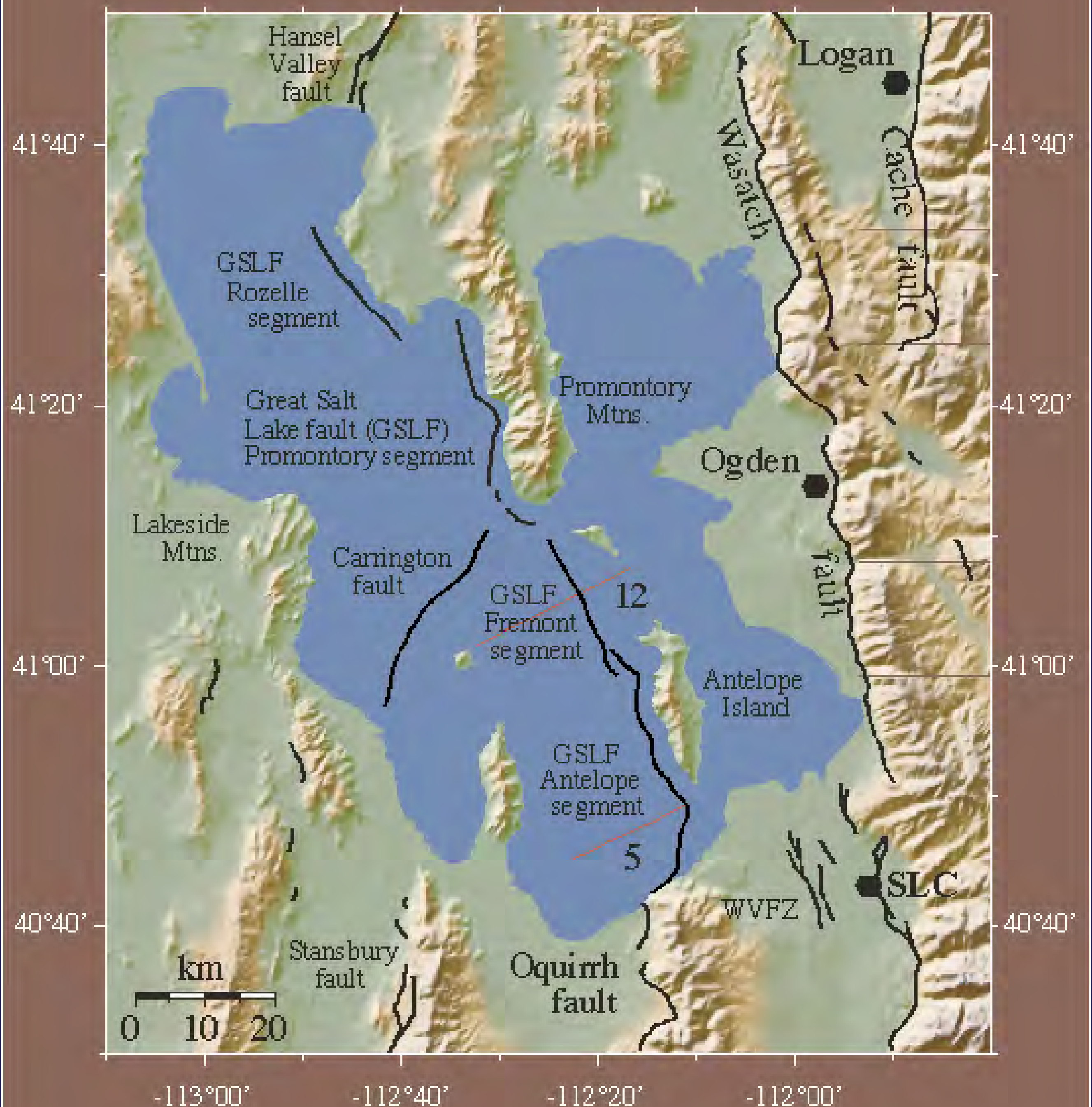
Should the WGUEP Compute Time-Dependent Probabilities for Large Earthquakes on the Great Salt Lake Fault?

David A. Dinter and James C. Pechmann

Department of Geology and Geophysics

University of Utah

Major active normal faults in the Great Salt Lake region, northern Utah



Approach – Analogous to trenching:

• Map active fault traces to determine lengths and identify segments

• Measure net vertical tectonic displacement from lake bottom topography and/or cross sections across fault

• Identify seismic event horizons

• Date event horizons to obtain earthquake


SB-216S
EZ LOADER
In our surveys, we typically use two seismic reflection syste
Simultaneously deployed from either side of a small boat.

The Geopulse "boomer" diaphragm,
mounted on a pontoon sled,
emits pulses at energies up to 280 joules with frequency content in the 700- to 1200-Hz range.

Active faults in the south arm, Great Salt Lake, Utah

• Two major segments of the GSL norma fault south of Promontory Point

• Segment boundary is a 1-2-km left ste W of White Rock Bay, N Antelope Island

• Fremont Island segment:
20 km long (revised from 30 km)
No lakebed scarp along half of it (buried)

• Antelope Island segment:
35 km long
Lakebed scarp, up to 3.6 m relief
Bends sharply SW at south end
Appears to merge with Oquirrh faul

• Numerous active intrabasin normal fault
Strikes oblique to GSLF
Lakebed scarps, up to 1.8 m relief
Probably coseismic with GSLF

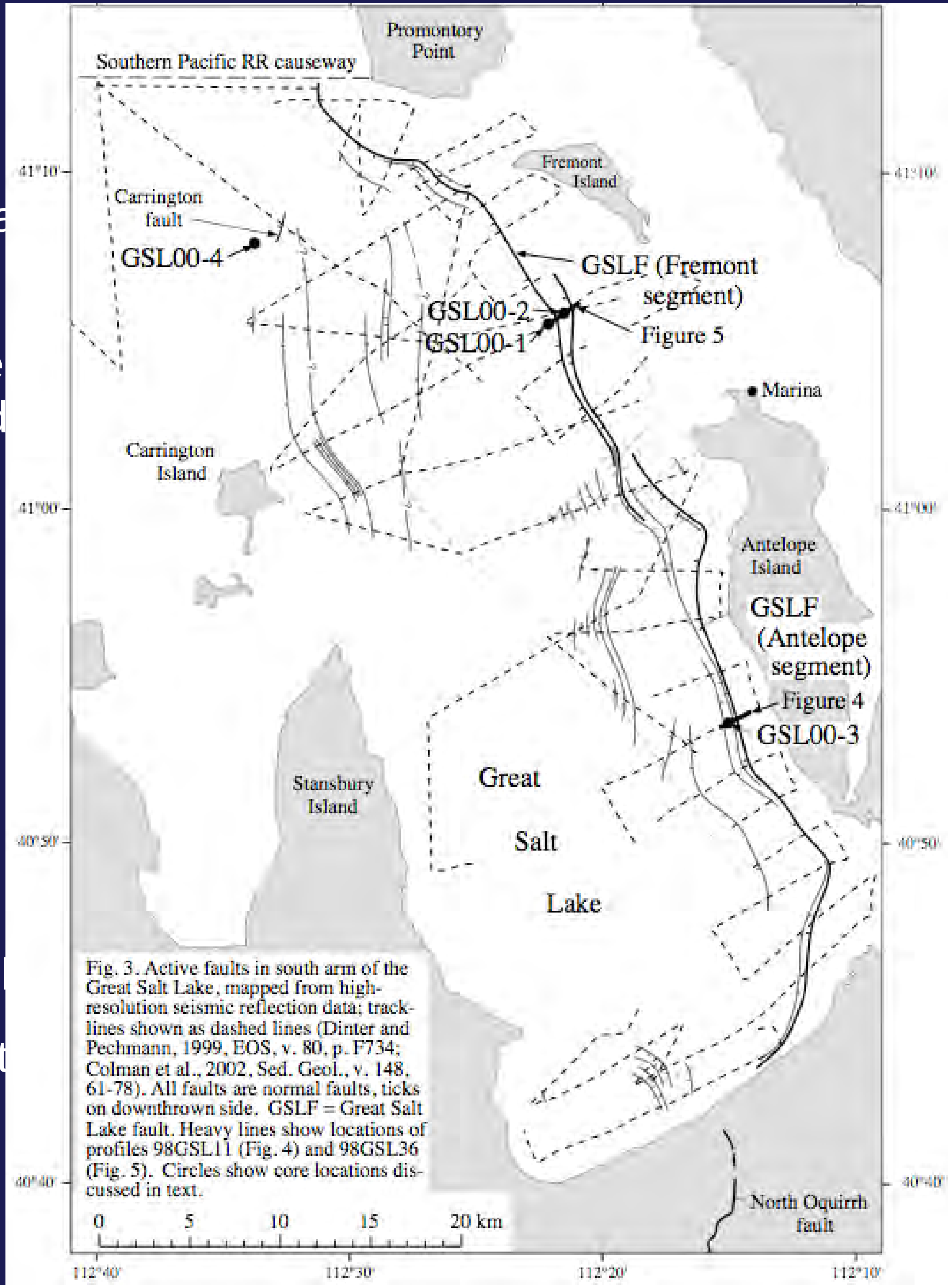


Fig. 3. Active faults in south arm of the Great Salt Lake, mapped from high-resolution seismic reflection data; track-lines shown as dashed lines (Dinter and Pechmann, 1999, EOS, v. 80, p. F734; Colman et al., 2002, Sed. Geol., v. 148, 61-78). All faults are normal faults, ticks on downthrown side. GSLF = Great Salt Lake fault. Heavy lines show locations of profiles 98GSL11 (Fig. 4) and 98GSL36 (Fig. 5). Circles show core locations discussed in text.

South arm update:

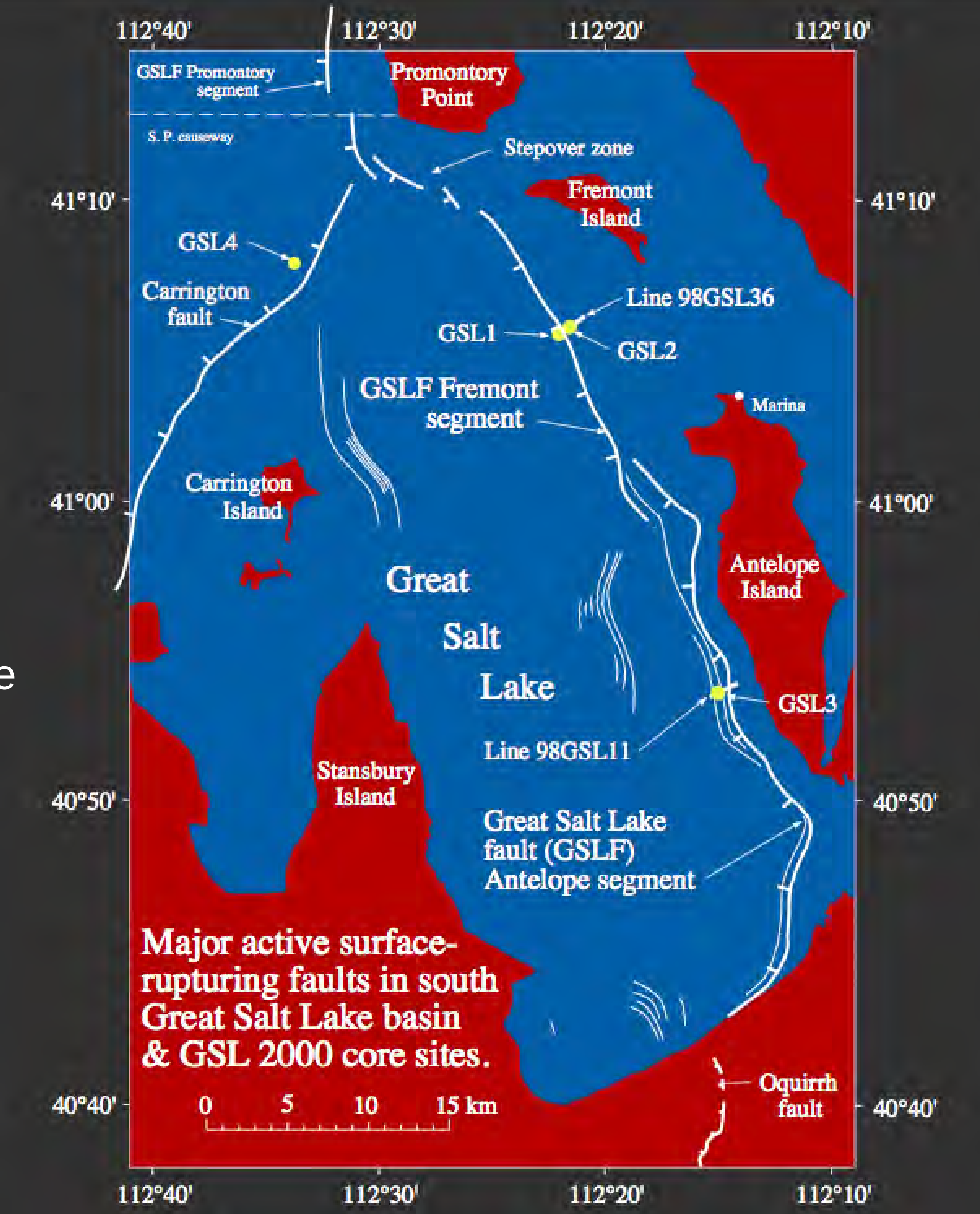
- Acquired new south arm seismic data in 2005-6, primarily north of Carrington Island to Promontory Point stepover zone.

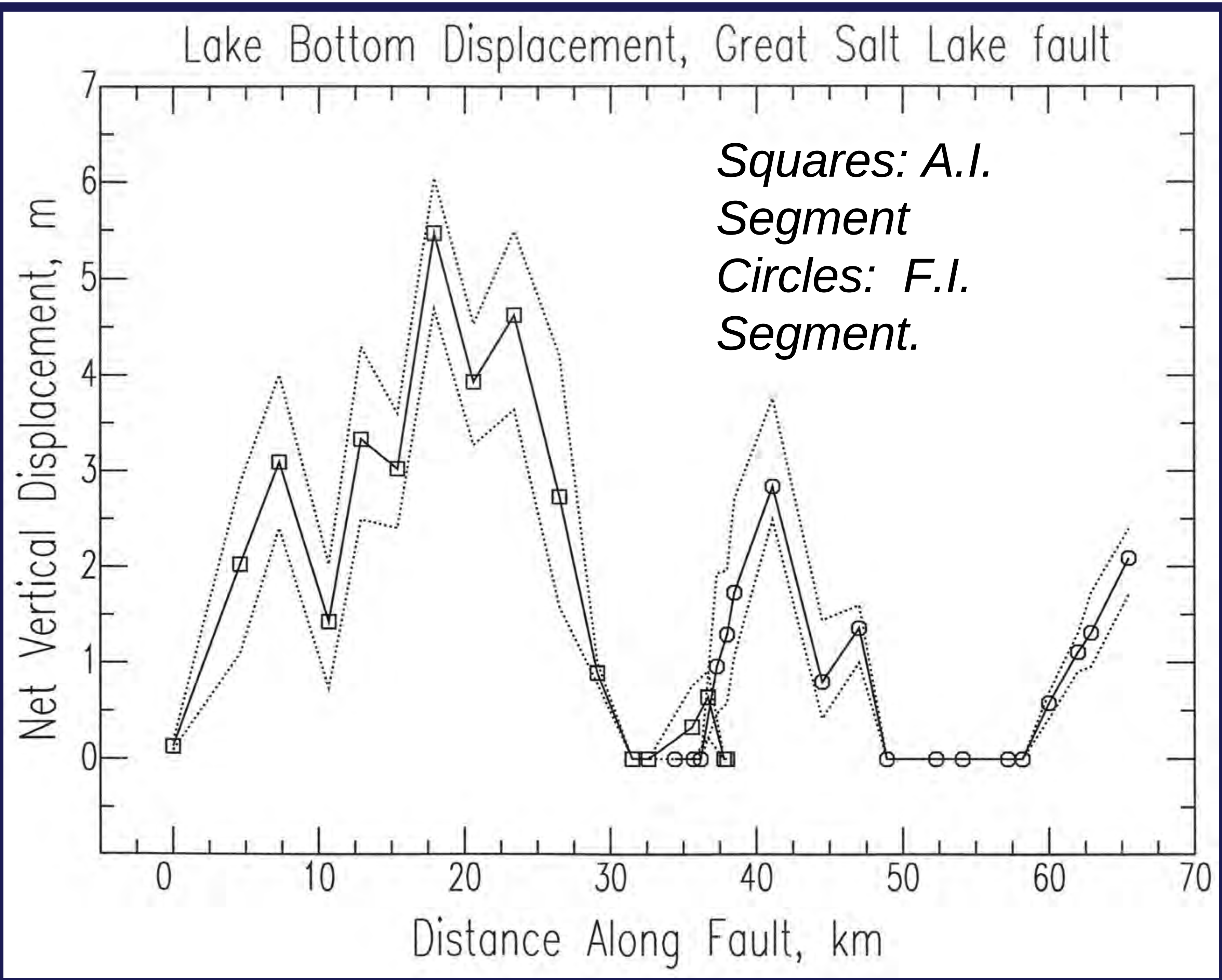
- Carrington fault is an independent seismogenic structure ~30 km long.

    Does *not* merge with GSL
    Events as large as M 6.8
    Fresh scarp -> recent earthquake

- GSLF Fremont segment is shorter than previously mapped (~20 km)

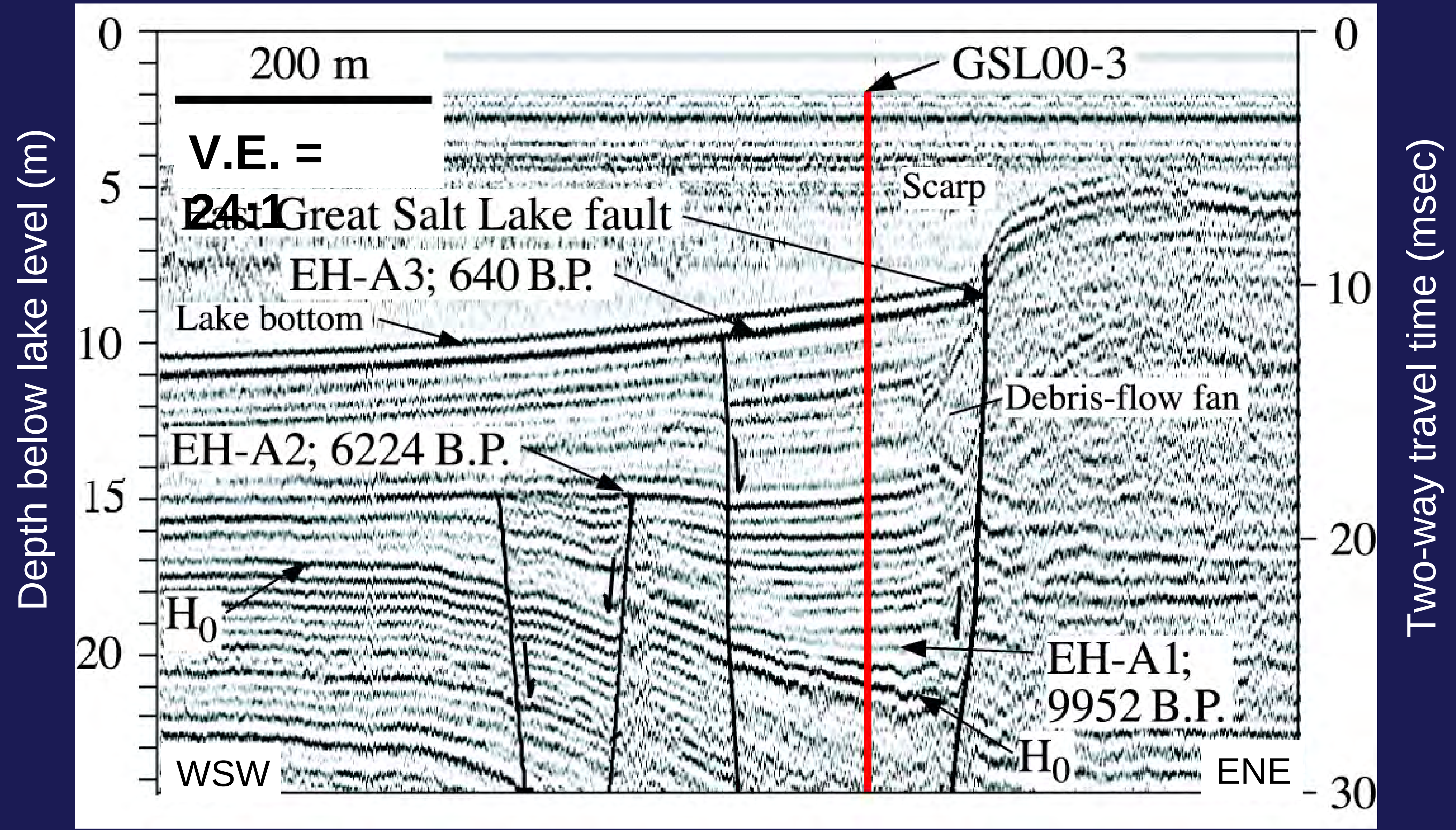
    Does not curve NW to merge with Promontory segment.
    Left stepover zone ~ 7 km wide contains short faults probably coseismic with Promontory segment.





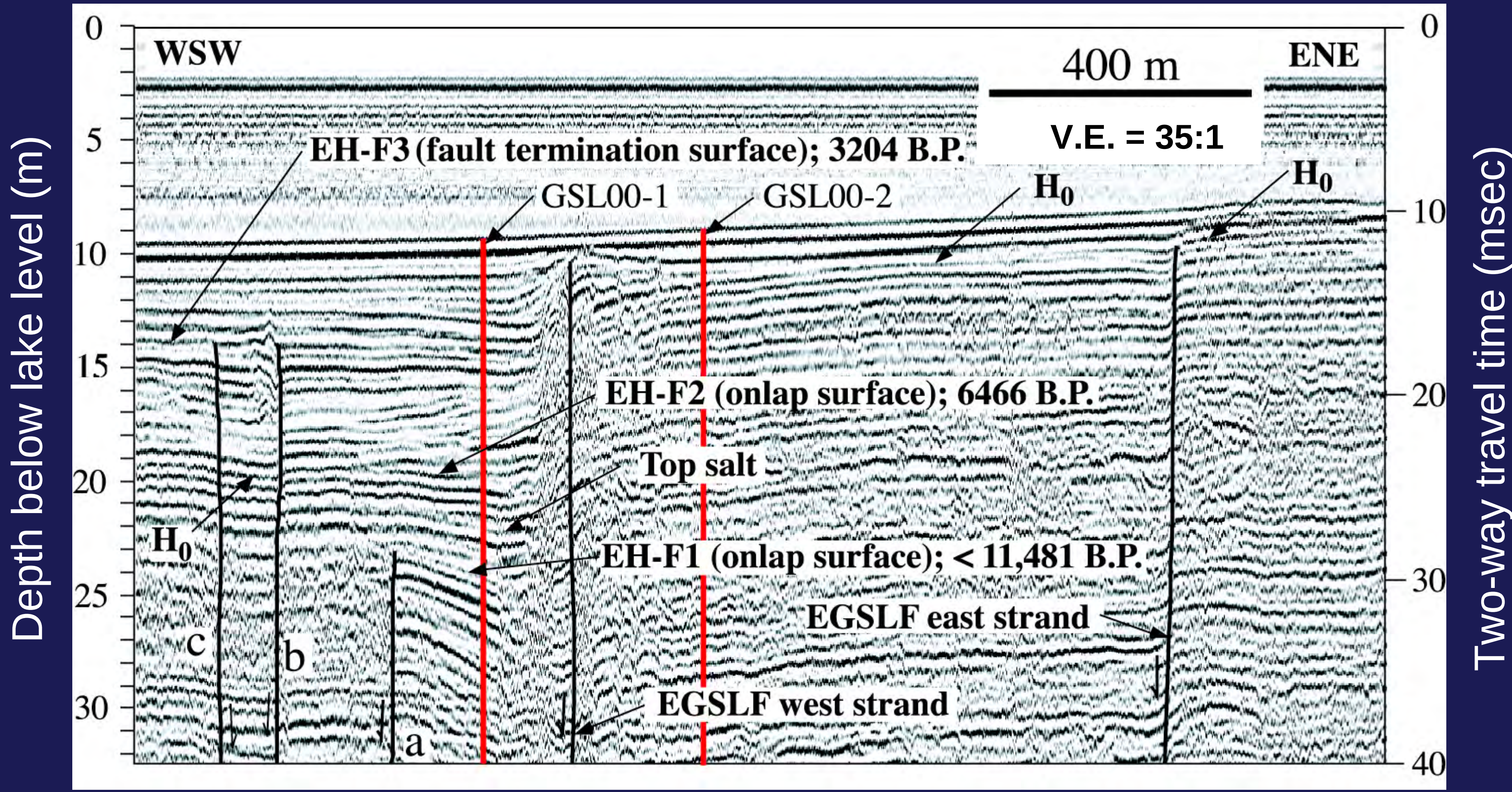
A.I. segment average vertical slip rate = 0.55 +0.5/-0.25 mm/yr (max)

Great Salt Lake fault, Antelope Island segment



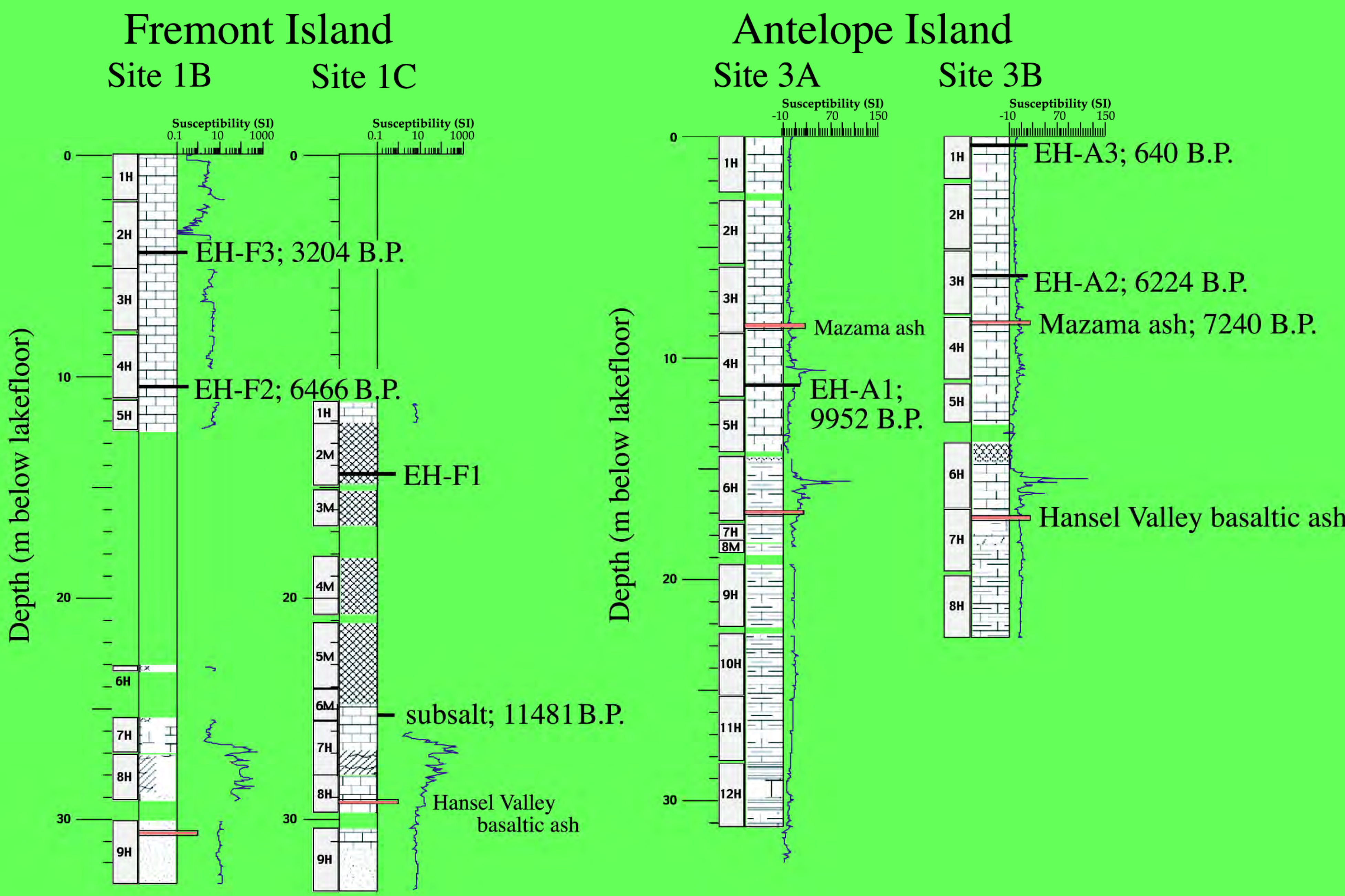
Geopulse Line 98GSL11

Great Salt Lake fault, Fremont Island segment



Geopulse Line 98GSL36

The DOSECC GLAD-1 mobile lacustrine drilling platform, 2



Fremont Island
Site 1B
Site 1C
Antelope Island
Site 3A
Site 3B
Susceptibility (SI)
0.1
10
1000
-10
70
150
Depth (m below lakefloor)
0
10
20
30
1H
2H
3H
4H
5H
6H
7H
8H
9H
2M
3M
4M
5M
6M
8M
10H
11H
12H
EH-F3; 3204 B.P.
EH-F2; 6466 B.P.
EH-F1
subsalt; 11481 B.P.
Hansel Valley basaltic ash
Mazama ash
EH-A1; 9952 B.P.
EH-A3; 640 B.P.
EH-A2; 6224 B.P.
Mazama ash; 7240 B.P.
Hansel Valley basaltic ash

Earthquake dates, Great Salt Lake fault

Earthquake	^{14}C yr BP (before 1950)[1]	Calendar yr BP (before 1950)[2]; Stuiver et al., 1998 terrestrial calibration	Residence-corrected[3] calendar years BP **(before 1950)**[2]	Residence-corrected[3] calendar years **before 2007**[2]
Antelope Island segment				
EH-A3	> 804 ± 38 < 1027 ± 44	> 706 +81/-40 < 944 +106/-147	586 +201/-241	643 +201/-241
EH-A2	5,711 ± 50	6491 +163/-135	6170 +236/-234	6227 +236/-234
EH-A1	9,068 ± 66	10,219 +178/-234	9898 +247/-302	9955 +247/-302
Fremont Island segment				
EH-F3	3,269 ± 47	3471 +161/-90	3150 +235/-211	3207 +235/-211
EH-F2	5,924 ± 44	6733 +121/-90	6412 +209/-211	6469 +209/-211
EH-F1	<10,155 ± 72	<11,748 +580/-406	<11,427 +605/-449	<11,484 +605/-449

Earthquake recurrence intervals, Great Salt Lake fault

Earthquake pairs	Dates of occurrence (residence-corrected cal yr before 1950)	Recurrence interval (yr)
Antelope Island segment (M_{max} = 6.9)		
EH-A3 **EH-A2**	596 +201/-241 6170 +236/-234	5584 +219/-172
EH-A2 **EH-A1**	6170 +236/-234 9898 +247/-302	3728 +223/-285
Fremont Island segment (M_{max} = 6.6-6.7)		
EH-F3 **EH-F2**	3150 +235/-211 6412 +209/-211	3262 +151/-184
EH-F2 **EH-F1**	6412 +209/-211 < 11,427 +605/-449	< 5015 +587/-424

Average single-segment recurrence interval = 4200 ± 1400 years

North Arm provisional results

- Obtained 40 north arm crossings of GSLF in 2009, 2010
- Detailed active fault map in preparation
- Preliminary interpretation indicates:

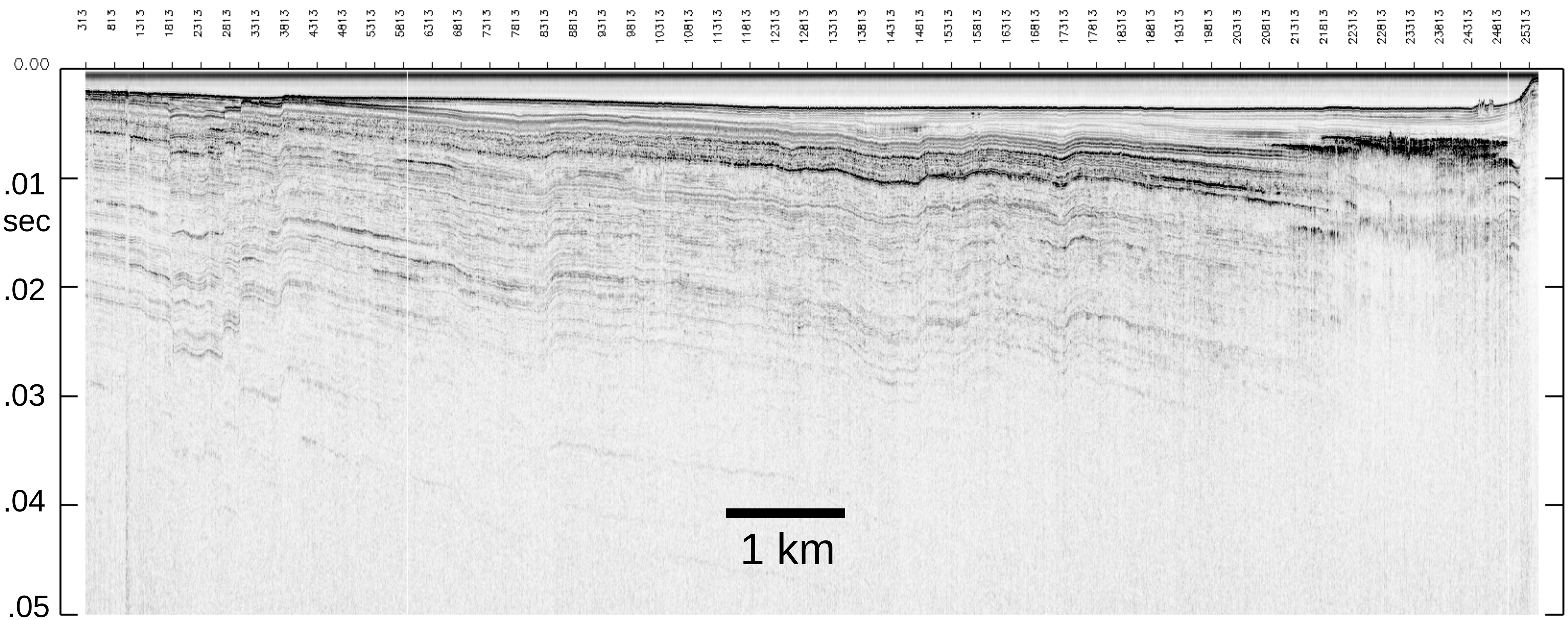
Two additional segments in the north arm:

Promontory segment has a young scarp.
Stepover faults at south end of Promontory Point also have fresh scarps; may be coseismic.
Rozelle segment is partly buried, and is the northernmost segment of GSLF system.

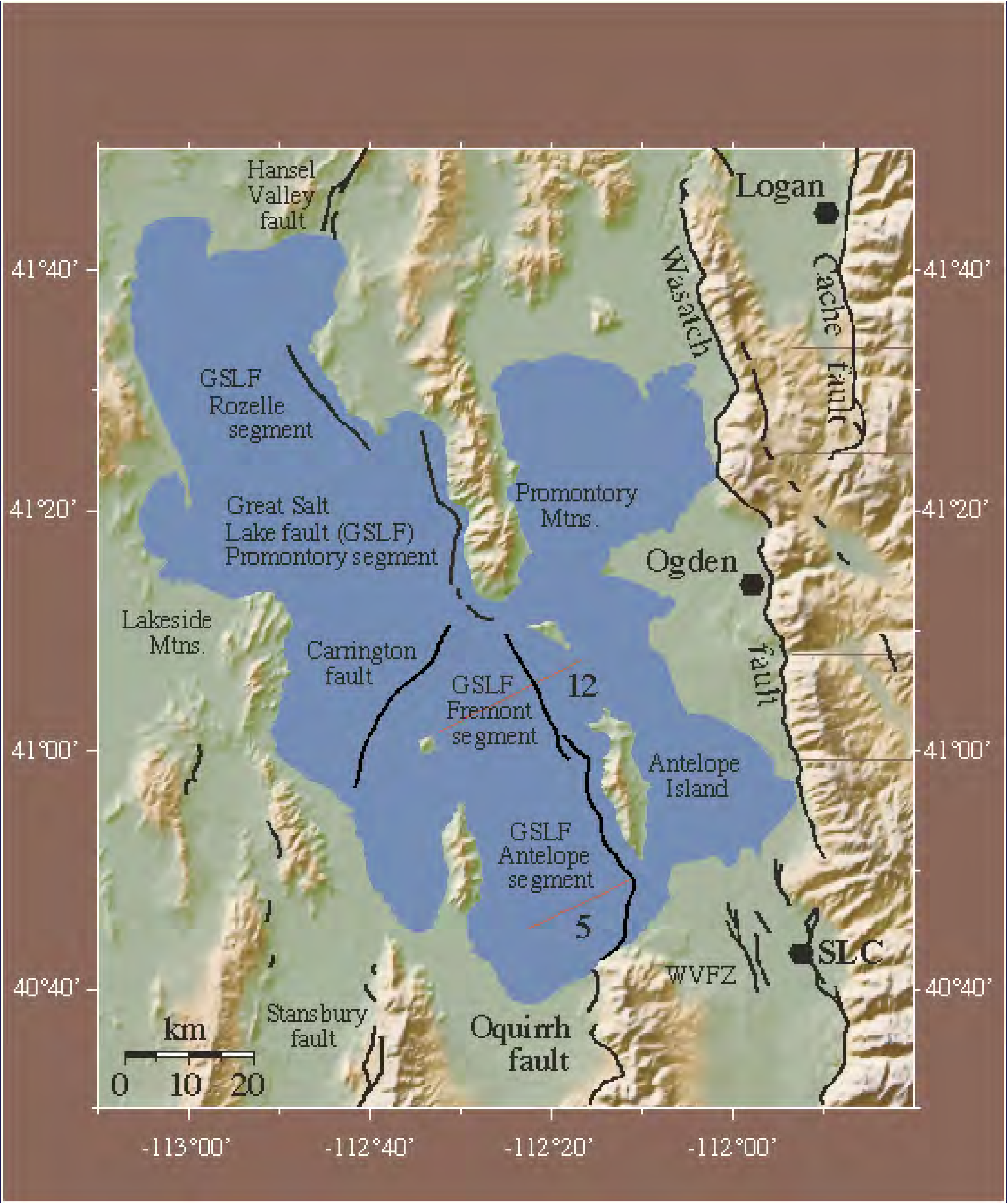
Hansel Valley fault to north has opposite dip direction.

There is likely a tear-fault system in Spring Bay.

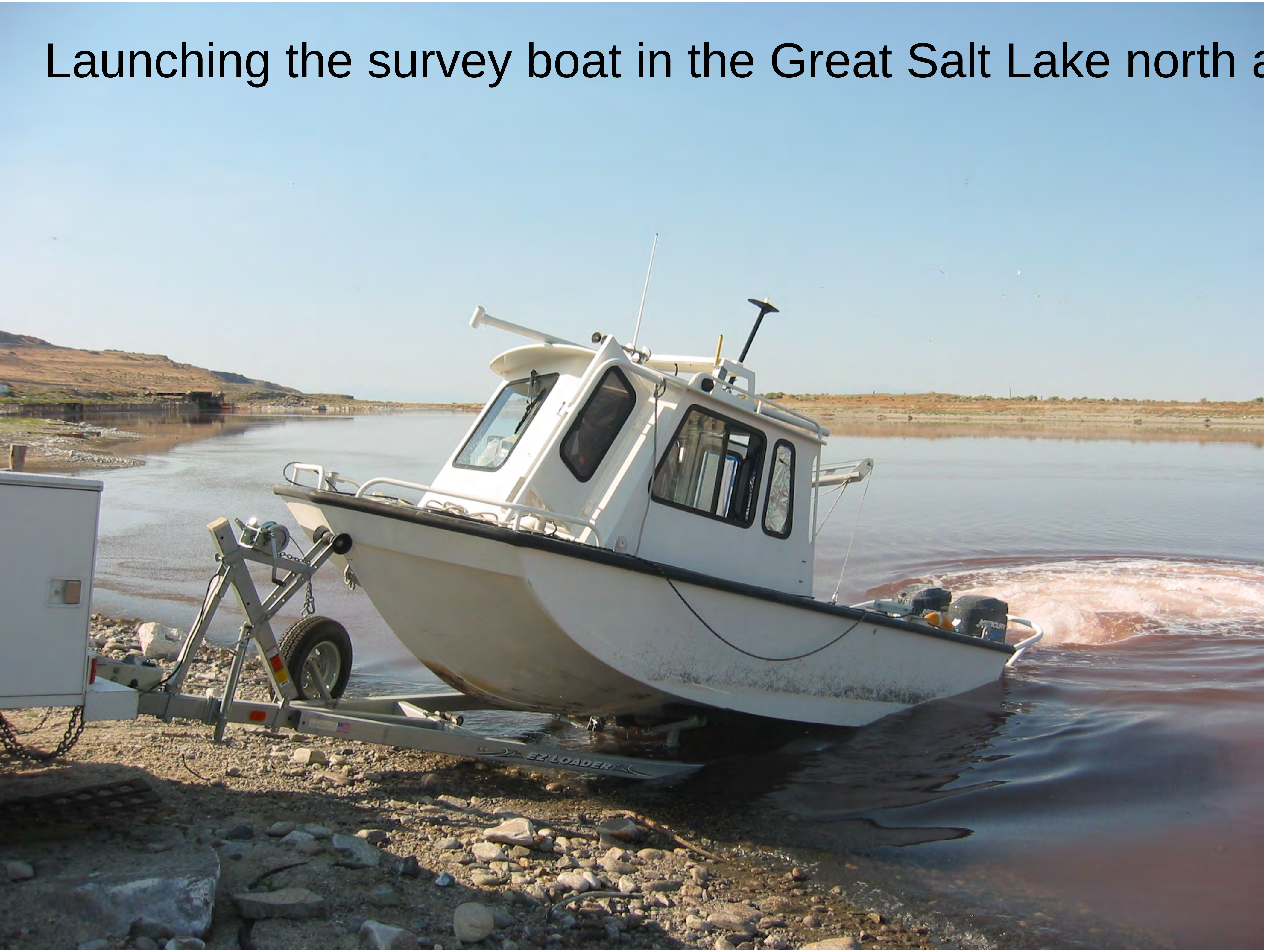
Example of North Arm Data, Great Salt Lake



Raw plot of “Ultrachirp” Line 09GSL2a, E-W crossing of GSLF Promontory segment in Great Salt Lake north arm. Note Holoc scarp at far right, auxiliary faults throughout basin.


Hansel
Valley
fault
Logan
Wasatch
Cache
fault
GSLF
Rozelle
segment
Promontory
Mtns.
Great Salt
Lake fault (GSLF)
Promontory segment
Ogden
Lakeside
Mtns.
Carrington
fault
GSLF
Fremont
segment
12
fault
Antelope
Island
GSLF
Antelope
segment
5
SLC
WVFZ
Stansbury
fault
Oquirrh
fault
km
0 10 20
41°40'
41°20'
41°00'
40°40'
-113°00'
-112°40'
-112°20'
-112°00'

Launching the survey boat in the Great Salt Lake north a



Maximum Magnitude Estimates, Great Salt Lake Fault

(from empirical relationships in Wells and Coppersmith, 1994)

Faulting Parameter	Antelope Segment	Fremont Segment
Surface Rupture Length	6.9 ± 0.3	6.6 ± 0.3
Rupture Area	6.9 ± 0.3	6.7 ± 0.3

Update and Path Forward (TBD) —Background Earthquakes in the Wasatch Front Area

Walter Arabasz

(Strawman Perspective)

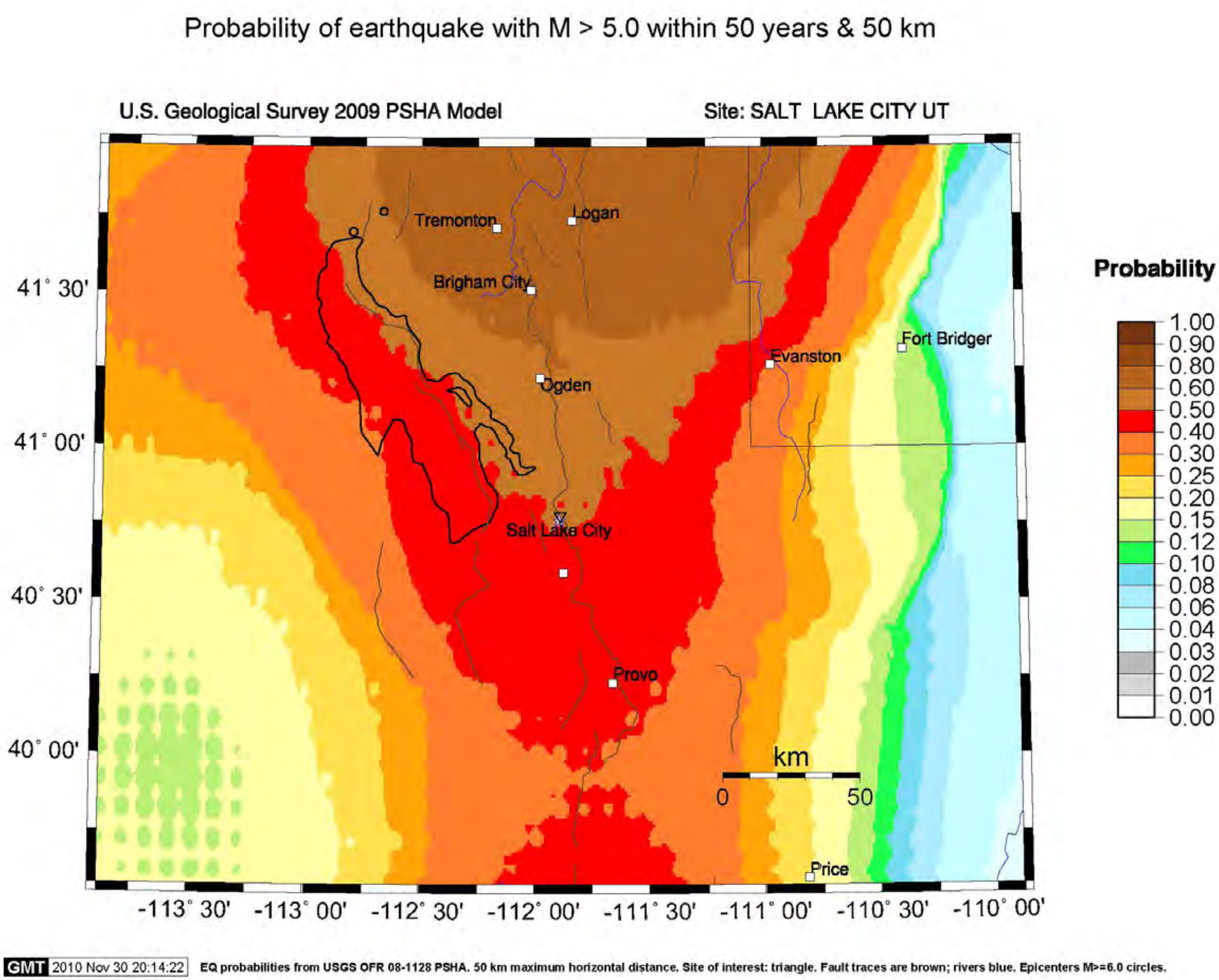
Working Group on
Utah Earthquake Probabilities
December 2, 2010

Three Starting Points

1. Decision made after the last WGUEP meeting to await the end of this year to have an earthquake catalog complete through 2010
2. The steps needed to do the analysis rigorously are apparent in state-of-practice PSHAs
3. Because this will be a USGS-endorsed product, the analysis ideally should be based on a “consensus” catalog developed collaboratively with the USGS (efforts being undertaken elsewhere to unify hazard information in the U.S.)

Example of why coordination with USGS is important

USGS: Earthquake Probability Mapping



Based on 2008 USGS National Seismic Hazard Maps

Inputs:

lat/long (or zip code)

Time Span

Minimum Magnitude

For comparison...

Average Recurrence Interval (yr) for Wasatch Front Region

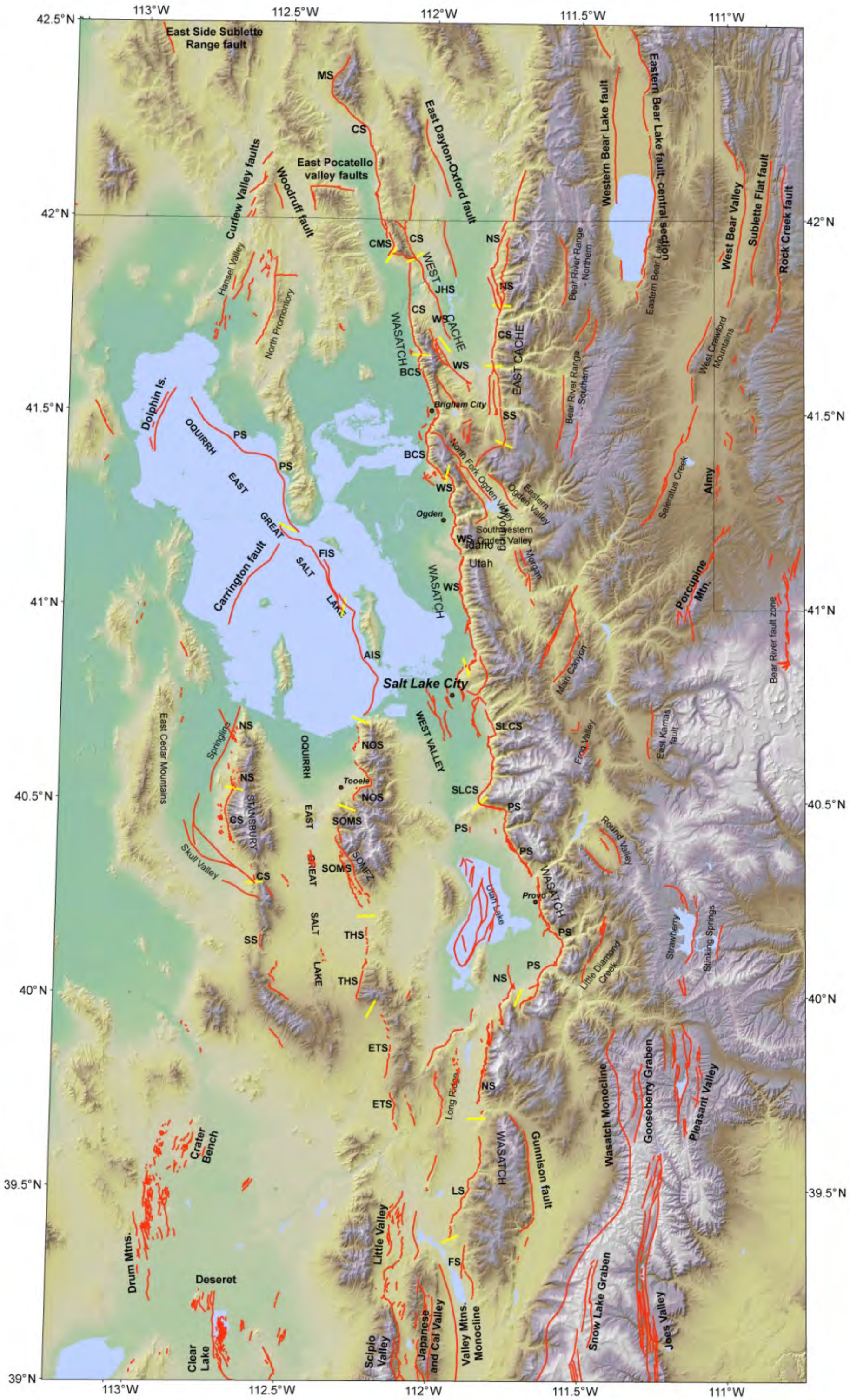
	Pechmann and Arabasz (1995)	Update for 1962.5–2006.5
$M \geq 5.0$	8.7*	12*
$M \geq 5.5$	20	30
$M \geq 6.0$	48	76
$M \geq 6.5$	120	200

*Average Probability of $M \geq 5.0$ within 50 yrs and 50 km in Wasatch Front Region = 0.31–0.41

Steps to “Do it Right”

1. Catalog compilation

- From earliest entry in 1850 through 2010
- Coordinate UUSS, USGS catalogs plus special studies of individual earthquakes

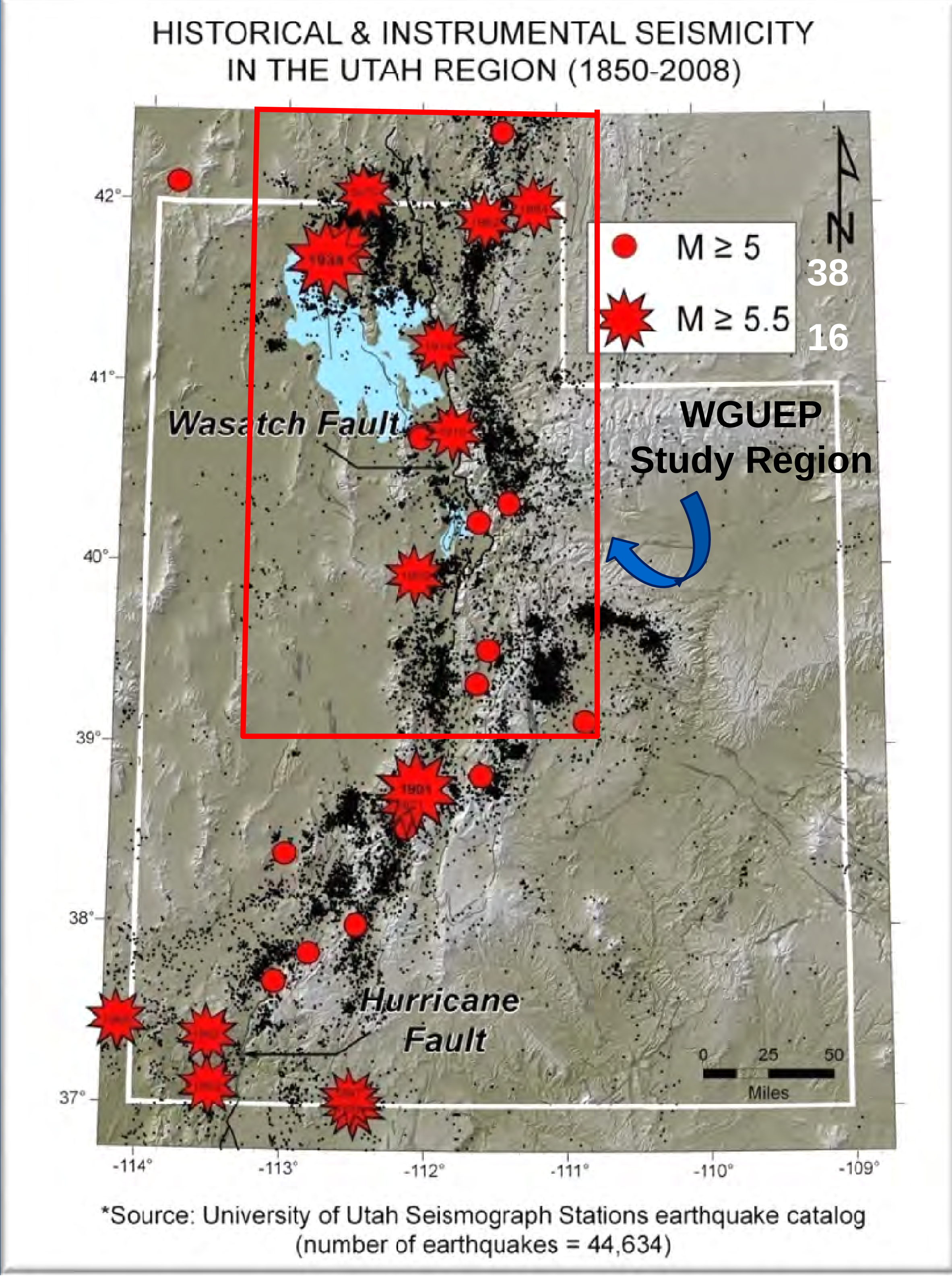


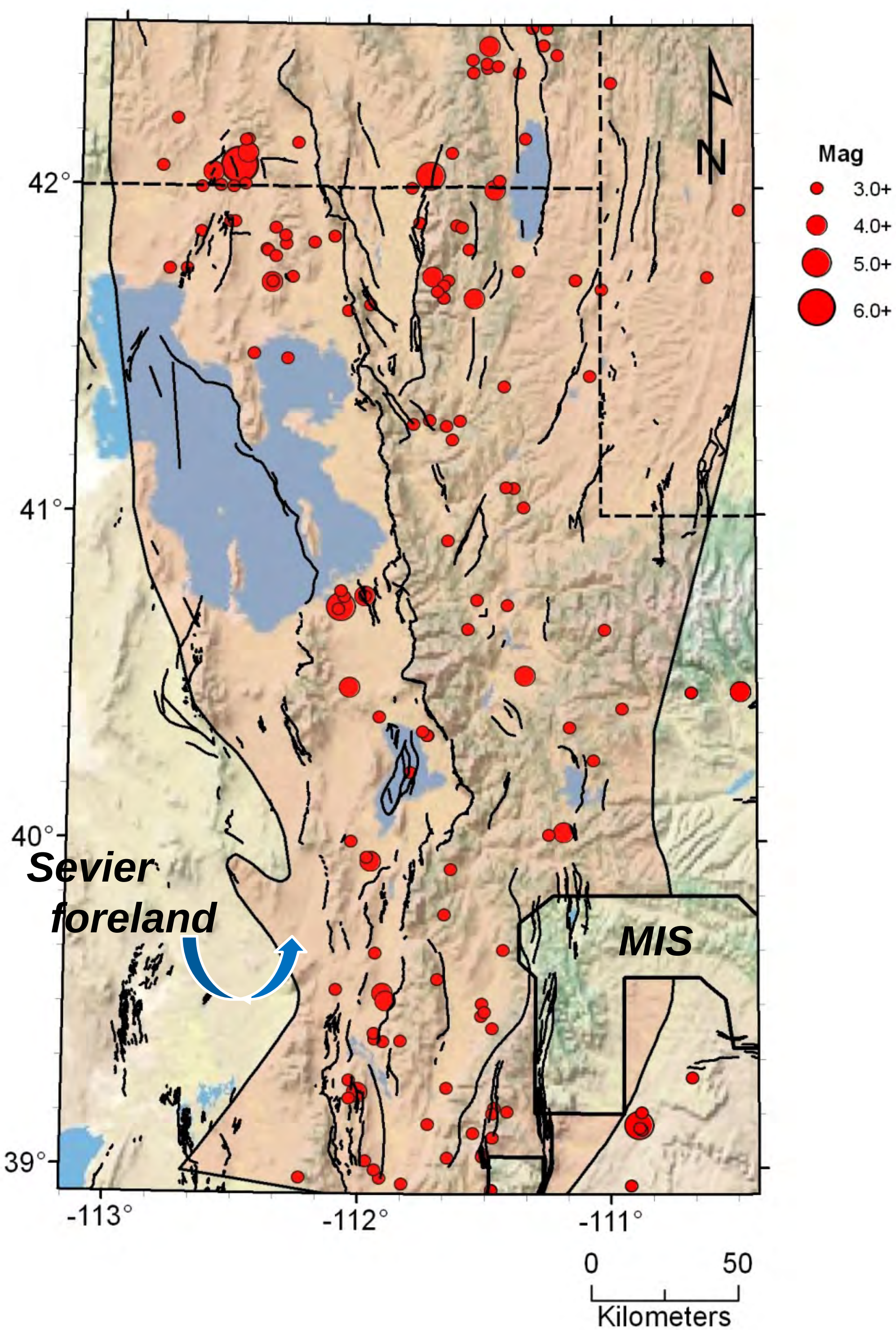
WGUEP WASATCH FRONT REGION

(latitude 39.00° - 42.50°, longitude 110.75° - 113.25°)

WGUEP Study Region

Historical Seismicity





Revisiting Pechmann and Arabasz (1995)

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

(from Feb 2010 WGUEP meeting)

Steps (cont'd)

2. Conversion to Moment magnitude, M_W

- Instrumentally-determined M_W
- Conversion from macroseismic measure (e.g., I_0)
- Conversion from other instrumental magnitudes

Steps (cont'd)

3. Uniform Magnitude Catalog

- Veneziano (EPRI, 1988) showed that earthquake recurrence rates can be biased due to uncertainties relating to the magnitude conversion process
- In a rigorous analysis, M* (an adjusted magnitude) is used to correct this bias and produce a "uniform magnitude catalog" for recurrence calculations

Steps (cont'd)

4. **Catalog Declustering***

- **Gardner & Knopoff (1974) — uses simple time and distance windows to remove foreshocks and aftershocks**
- **Reasenberg (1985) — model-based, sensitive to tuning**
- **EPRI (1986) [Veneziano & Van Dyck] — stochastic approach**

Need sample area extending beyond study region to avoid edge effects

Steps (cont'd)

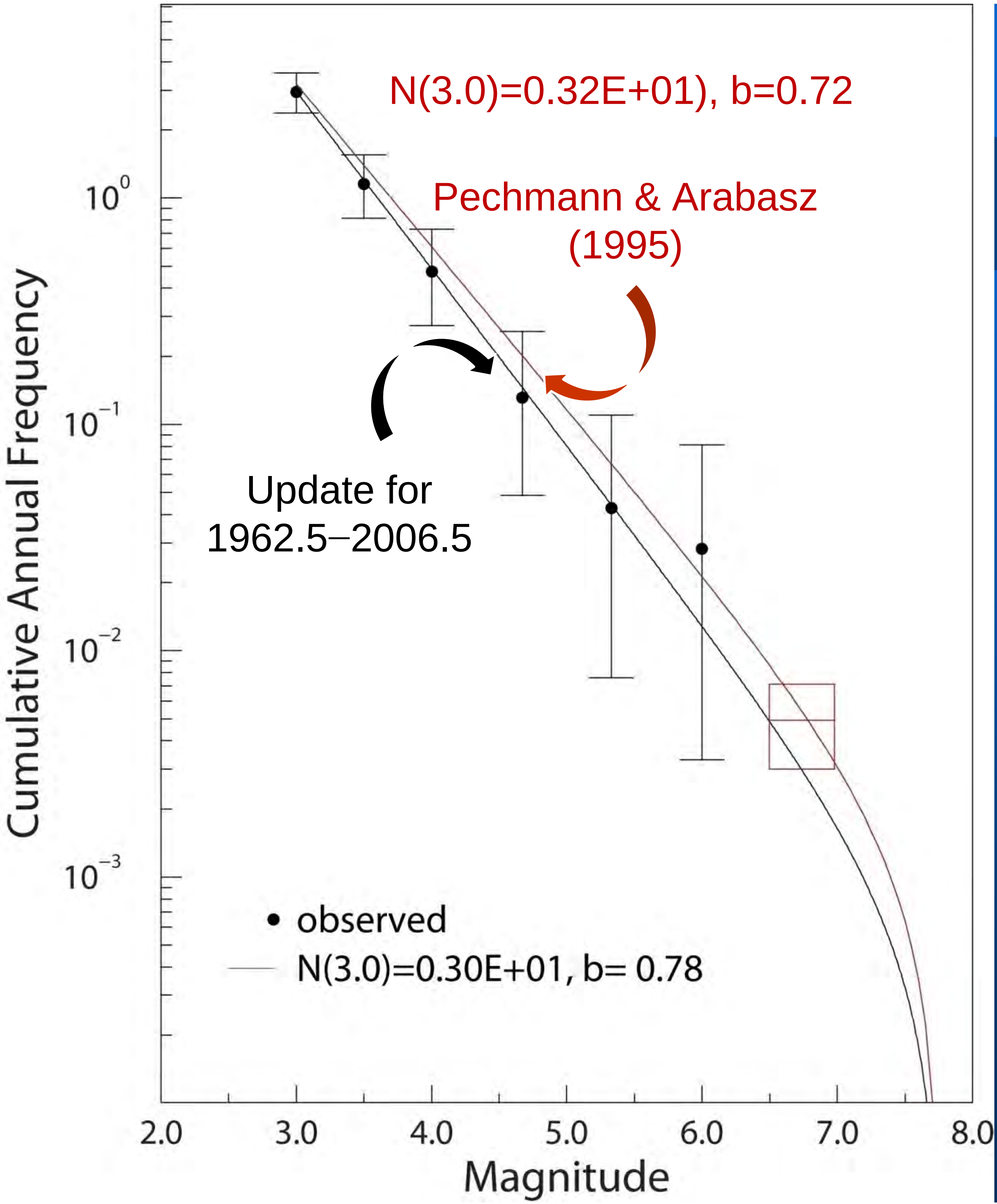
5. Catalog Completeness (in space and time)

- Can test uniformity of rate information in different magnitude bins backwards in time
- Can test linearity of Gutenberg-Richter relation as a function of time
- Can qualitatively assess likelihood of detection (by population or instrumentation
- Can rigorously assess likelihood of detection (e.g., EPRI, 1986)

Steps (cont'd)

6. Earthquake Recurrence Calculations

- State of practice is to use a maximum-likelihood approach (e.g., Weichert, 1980)
- Issue: Do mainshocks have a distribution not completely described by the Gutenberg-Richter law resulting in b-values biased on the low side? (Lombardi, 2000)



Example recurrence calculation using Weichert approach

(from Feb 2010 WGUEP meeting)

Mainshocks and the G-R Law

Lombardi (BSSA, 2003)

2084

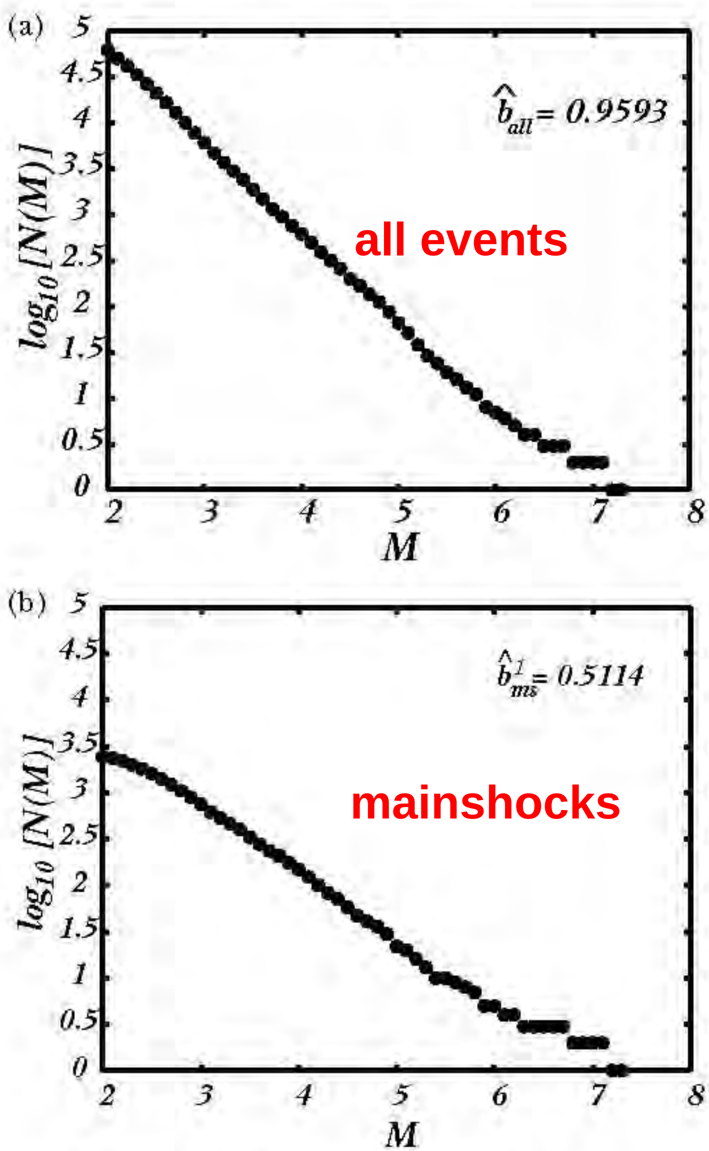


Figure 2. (a) Gutenberg–Richter law for all events (62,394) of the southern California catalog. $\hat{b}_{\mathrm{all}}$ is the maximum likelihood estimator of b (equation 3). (b) The same as (a) for southern California mainshocks; for lower values of M, data are not fitted by a line.

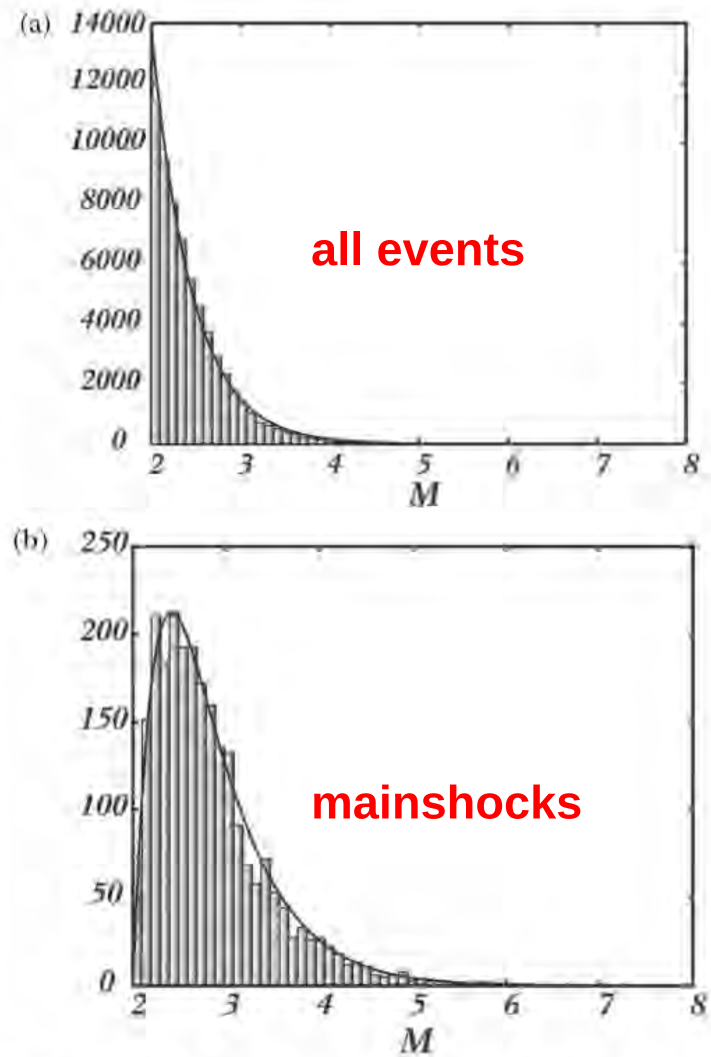


Figure 3. (a) Histogram of southern California events compared with the theoretical density function (2) (solid line), suitably normalized, so that its integral is equal to the one of the histogram. (b) The same as (a) for mainshocks; the theoretical density function is obtained by equation (5). In both cases it has been used that $b = \hat{b}_{\mathrm{all}}$. The catalog has been declustered by the Reasenberg method with the standard parameter setting.

Path Forward

1. Need to decide/agree on scope and rigor of steps for analysis
2. At least basic attempt to move in direction of a consensus catalog with USGS
3. Revisit whether probability of $M \geq 5.0$ background earthquake is to be computed for entire WGUEP study region or on some gridded basis (as being done on USGS Web site)
4. Complete steps and analysis

end