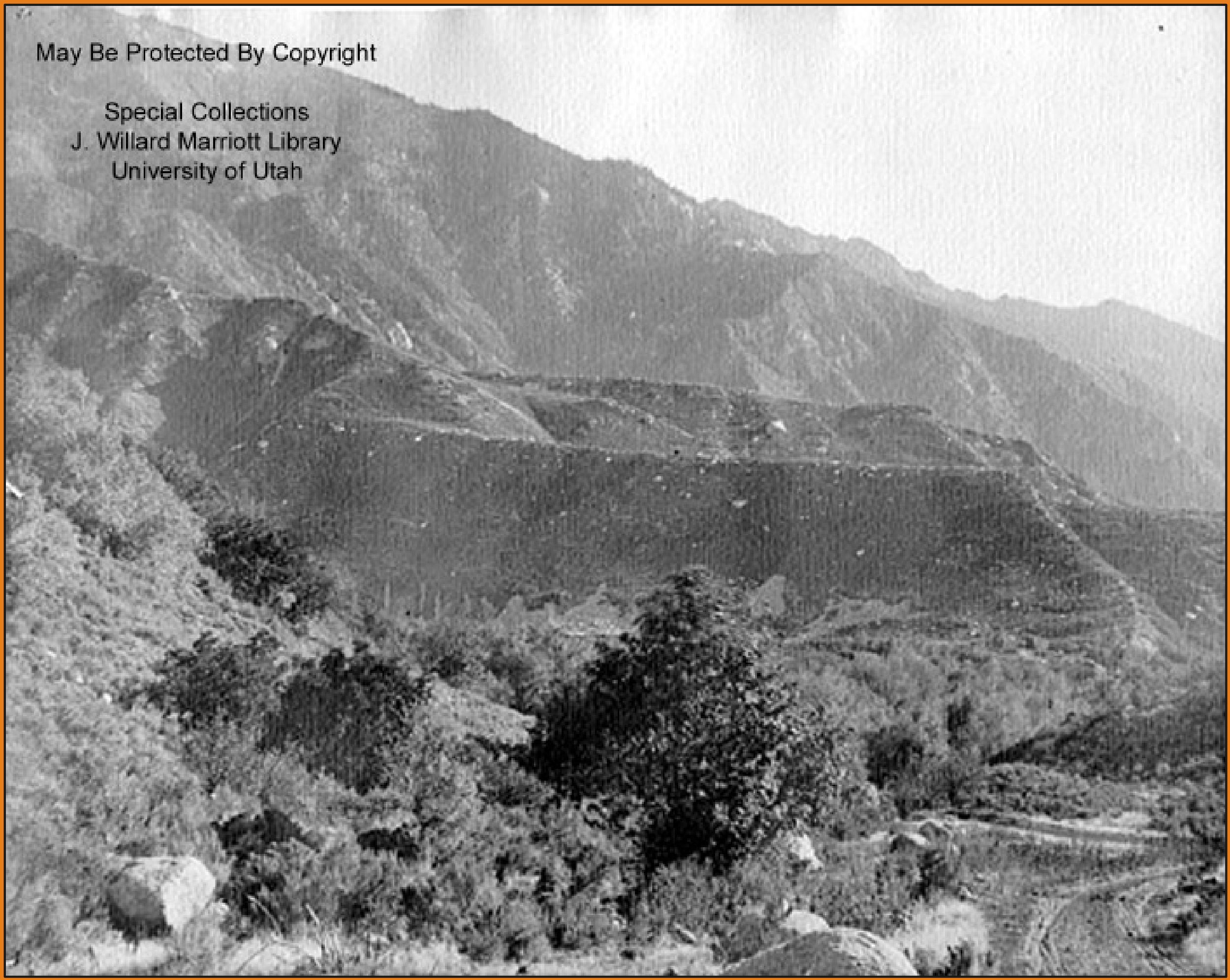
UTAH GEOLOGICAL SURVEY

WORKING GROUP ON UTAH EARTHQUAKE PROBABILITIES



Wasatch Fault at Little Cottonwood Canyon

July 21 & 22, 2010

WGUEP Members

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

WGUEP AGENDA
Wednesday, July 21, 2010

7:30 a.m.	Continental breakfast
8:00 a.m.	Methodology Summary - Use of OxCal and MATLAB to refine earthquake timing and recurrence for the five central Wasatch fault segments – Chris DuRoss
8:30 a.m.	OxCal earthquake timing and MATLAB recurrence interval models for the five central Wasatch fault segments (earthquake pdfs, individual intervals between events, average segment recurrence intervals, MRE timing) – Chris DuRoss, Steve Personius, Tony Crone, Susan Olig
10:00 a.m.	Break
10:30 a.m.	OxCal earthquake timing and MATLAB recurrence interval models for the five central Wasatch fault segments continued
12:00 p.m.	Lunch
1:00 p.m.	Summary and discussion Wasatch fault earthquake timing and recurrence intervals – Chris DuRoss
2:00 p.m.	Introduction to rupture scenario models - Bay Area faults vs. Wasatch fault - David Schwartz
2:30 p.m.	Break
3:00 p.m.	Presentation Wasatch fault strawman rupture scenario models – David Schwartz, Chris DuRoss
4:30 p.m.	Wrap up – Ivan Wong
5:00 p.m.	Adjourn

WGUEP AGENDA
Thursday, July 22, 2010

7:00 a.m.	Continental breakfast
7:30 a.m.	Final rupture scenario model selection and weighting by working group members - moderator Chris DuRoss
9:00 a.m.	Earthquake timing and slip-rate information for Wasatch fault end segments – Mike Hylland
10:30 a.m.	Break
11:00 a.m.	Summary and discussion of Wasatch fault end segment data - select end segment parameters for probability model – Mike Hylland
12:00 p.m.	Lunch
1:00 a .m.	Other faults in the Wasatch Front study region – how many, how big, how fast – Bill Lund
2:30 p.m.	The way forward – Ivan Wong
3:00 p.m.	Adjourn

Wasatch Fault Paleoseismic Chronology, Recurrence Intervals, and Rupture Scenario Models

Working Group Meeting #2

Working Group on Utah Earthquake Probabilities

Salt Lake City, UT
21-22 July 2010

URS

Agenda

<u>Wednesday July 21</u>

7:30 a.m.	Continental breakfast
8:00 a.m.	Methodology Summary - Use of OxCal and MATLAB to refine earthquake timing and recurrence for the five central Wasatch fault segments – Chris DuRoss
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4:00 p.m.	Summary and discussion of Wasatch fault end segment data - select end segment parameters for probability model – Mike Hylland
4:30 p.m.	Wrap up – Ivan Wong
5:00 p.m.	Adjourn

Agenda

Thursday July 22

7:00 a.m.	Continental breakfast
7:30 a.m.	Introduction to rupture scenario models - Bay Area faults vs Wasatch fault - David Schwartz
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1:00 p.m.	Other faults in the Wasatch Front study region – how many, how big, how fast – Bill Lund
2:30 p.m.	The way forward – Ivan Wong
3:00 p.m.	Adjourn

URS

Issues Raised Last Meeting

- Uncertainty still remains regarding segment boundaries on the Wasatch fault. Based on trench data, apparent spillover from one segment to another, e.g., 1983 Borah Peak, appears to have also occurred on the Wasatch fault.
- Do the Provo and Nephi segments, or portions of these segments, rupture coseismically?
- The Brigham City segment early Holocene earthquake record appears to be still incomplete. This incompleteness will need to be addressed in assessing recurrence along this segment.
- Questions remain regarding the timing, recurrence, and extent of mid- to late-Holocene earthquakes on the Weber segment. Discussions with the original paleoseismic investigators may help resolve these uncertainties.

URS

Issues Raised During the Meeting (cont.)

- Over what time period is the paleoseismic record complete for the Nephi segment? Are the three most recent (late Holocene) earthquakes temporally clustered?
- What is the best coefficient of variation (COV) or range of COVs to be used in the time-dependent models?
- The relation of the West Valley fault zone (WVFZ) to the Salt Lake City segment (SLCS) of the Wasatch fault zone remains uncertain. Hopefully, upcoming UGS investigations on the SLCS and WVFZ will reduce the uncertainties.
- Is the strand of the Wasatch fault located east of Salt Lake City and the East Bench fault of the SLCS at the base of the range active?

Issues Raised During the Meeting (cont.)

- What is the best way to convert horizontal geodetic extension rats to fault dip slip rates.
- The magnitudes of pre-instrumental earthquakes within the Wasatch Front, particularly those near Salt Lake City need to be revisited. Current estimates rely on the Gutenberg-Richter frequency-magnitude relation or on Modified Mercalli intensity estimates.

Tasks Identified Last Meeting

1. Re-examine background seismicity recurrence with an emphasis on pre-instrumental seismicity. Note that the region we have defined for the forecast may not exactly match the region for which the recurrence has been calculated (Walt and Jim).

2. Write up the calculation of COV for the Wasatch fault (Susan).

3. Perform OxCal analyses of remaining segments of the Wasatch fault (Chris, Susan, Tony, Steve, and Bill).

4. Compare of the extensional strain rates from the geodetic and slip rate data (Mark).

Tasks Identified Last Meeting (cont.)

5. Develop the list of faults in the forecast region (Bill).
6. Create Strawman rupture scenarios for the Wasatch fault (Chris).
7. Complete report on the megatrench and distribute to other working group members (Susan).
8. Establish a password protected website for the working group (Steve Bowman).

URS

Schedule

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

URS

Methodology Summary:

Use of OxCal and MATLAB to determine earthquake timing and recurrence for the central Wasatch fault zone

Chris DuRoss – UGS

Steve Personius – USGS

Tony Crone – USGS

Susan Olig – URS

Bill Lund – UGS

Working Group on Utah Earthquake Probabilities – July, 2010

The Problem

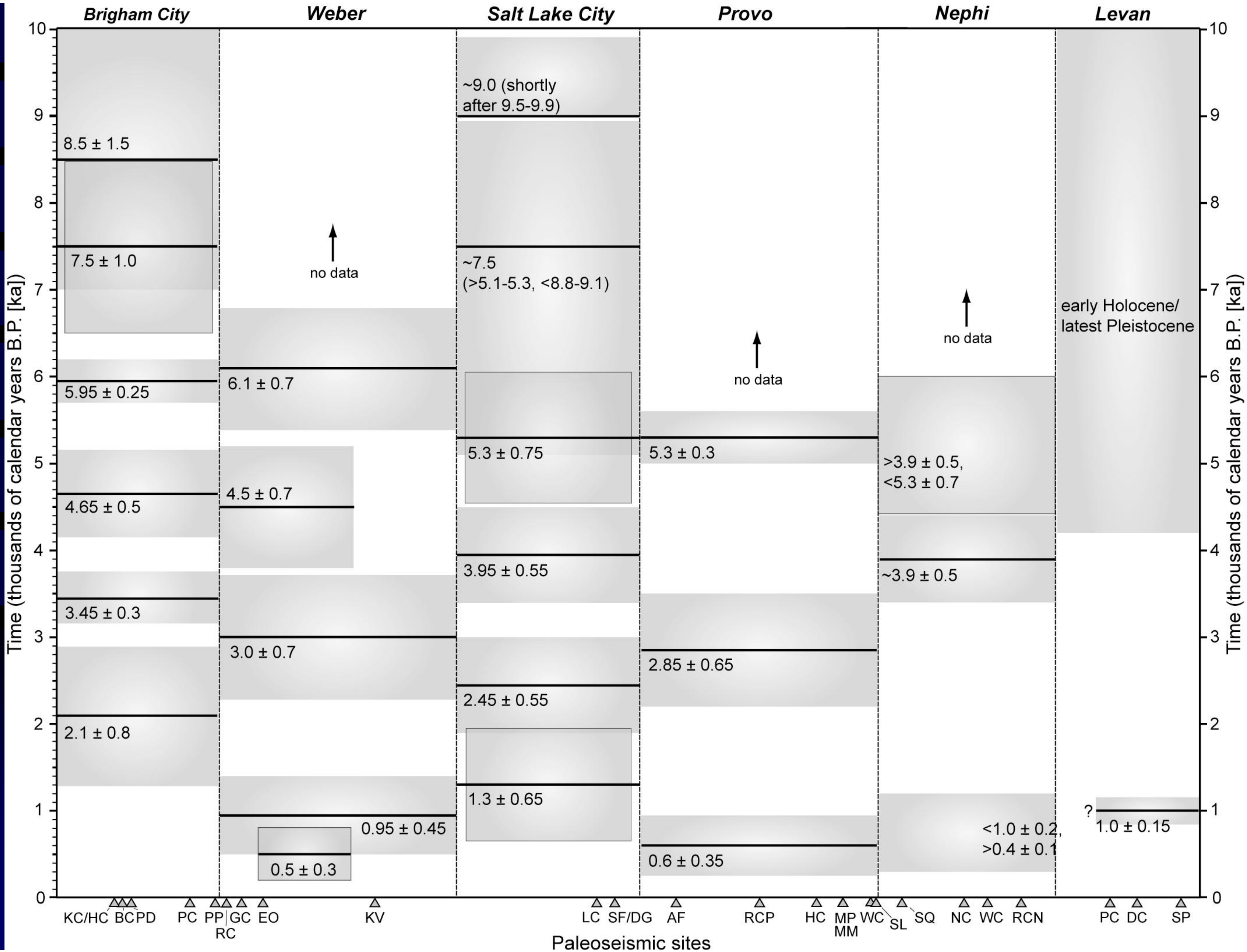
- Need up-to-date paleoseismic data for the Wasatch fault:
  - Earthquake timing information (elapsed time since MRE)
  - Recurrence intervals for segments and entire fault
  - Uncertainties in these values
  - Rupture lengths and displacements
  - Segmentation models (rupture scenarios)

The Problem

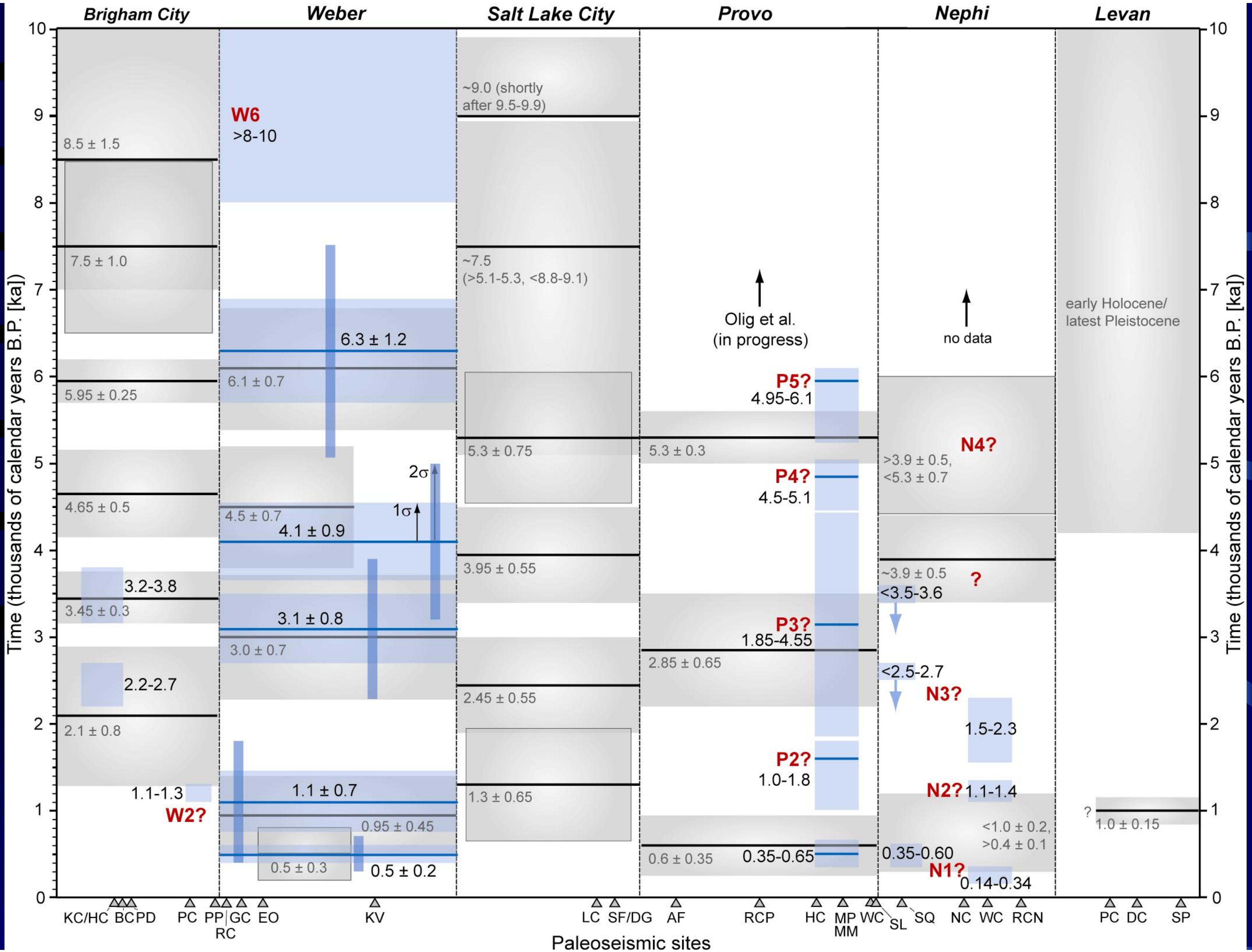
- But outstanding issues:
  - Differences in new and previous paleoseismic data
  - Charcoal versus AMRT ages (treated differently by different authors)
  - Correlation of events between trench sites
  - Recurrence estimates depend on event correlations

The Problem

- Why not just use the Utah Quaternary Fault Parameters Working Group (UQFPWG) results (Lund, 2005)?
  - UQFPWG reported mean and ~2-sigma earthquake timing and recurrence estimates, but uncertainties very large and based on qualitative analysis of data and expert opinion
  - New data post Lund (2005):
    - 3 published trench reports (Weber, Nephi)
    - 4 completed, but unpublished studies (Brigham City, Provo)
  - As a result of new data:
    - How consistently treat “legacy” ages?
    - Revise correlation of events and final EQ chronology for each segment?



Brigham City
Weber
Salt Lake City
Provo
Nephi
Levan
Time (thousands of calendar years B.P. [ka])
8.5 ± 1.5
7.5 ± 1.0
5.95 ± 0.25
4.65 ± 0.5
3.45 ± 0.3
2.1 ± 0.8
no data
6.1 ± 0.7
4.5 ± 0.7
3.0 ± 0.7
0.95 ± 0.45
0.5 ± 0.3
~9.0 (shortly after 9.5-9.9)
~7.5 (>5.1-5.3, <8.8-9.1)
5.3 ± 0.75
3.95 ± 0.55
2.45 ± 0.55
1.3 ± 0.65
no data
5.3 ± 0.3
2.85 ± 0.65
0.6 ± 0.35
no data
>3.9 ± 0.5, <5.3 ± 0.7
~3.9 ± 0.5
<1.0 ± 0.2, >0.4 ± 0.1
early Holocene/ latest Pleistocene
?
1.0 ± 0.15
KC/HC BC PD PC PP RC GC EO KV LC SF/DG AF RCP HC MP MM WC SL SQ NC WC RCN PC DC SP
Paleoseismic sites



Brigham City
Weber
Salt Lake City
Provo
Nephi
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Time (thousands of calendar years B.P. [ka])
8.5 ± 1.5
7.5 ± 1.0
5.95 ± 0.25
4.65 ± 0.5
3.2-3.8
3.45 ± 0.3
2.2-2.7
2.1 ± 0.8
1.1-1.3
W2?
W6
>8-10
6.3 ± 1.2
6.1 ± 0.7
2σ
1σ
4.5 ± 0.7
4.1 ± 0.9
3.1 ± 0.8
3.0 ± 0.7
1.1 ± 0.7
0.95 ± 0.45
0.5 ± 0.3
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~9.0 (shortly
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5.3 ± 0.75
3.95 ± 0.55
2.45 ± 0.55
1.3 ± 0.65
Olig et al.
(in progress)
P5?
4.95-6.1
5.3 ± 0.3
P4?
4.5-5.1
P3?
1.85-4.55
2.85 ± 0.65
P2?
1.0-1.8
0.6 ± 0.35
0.35-0.65
no data
N4?
>3.9 ± 0.5,
<5.3 ± 0.7
~3.9 ± 0.5
?
<3.5-3.6
<2.5-2.7
N3?
1.5-2.3
N2?
1.1-1.4
<1.0 ± 0.2,
>0.4 ± 0.1
0.35-0.60
N1?
0.14-0.34
early Holocene/
latest Pleistocene
?
1.0 ± 0.15
KC/HC
BC
PD
PC
PP
RC
GC
EO
KV
LC
SF/DG
AF
RCP
HC
MP
MM
WC
SL
SQ
NC
WC
RCN
PC
DC
SP
Paleoseismic sites

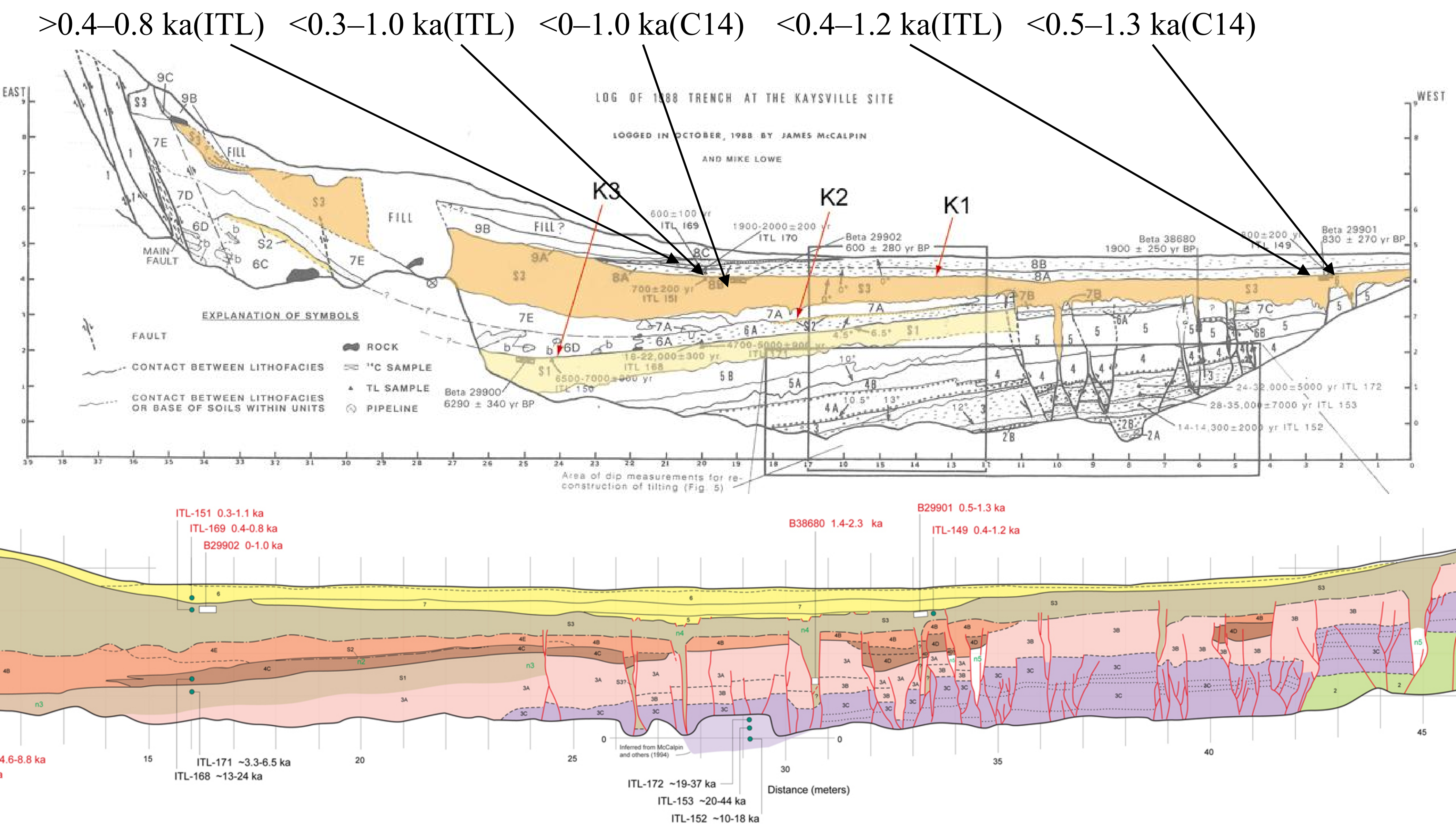
Our approach – OxCal and Matlab modeling

1. Carefully review all paleoseismic data
2. Construct OxCal models for each trench site
3. Combine OxCal models into segment chronology (Matlab)
4. Determine earthquake timing and recurrence (segment)
5. Discuss/revise results (technical subgroup meeting/email)

Approach – Step 1

1. Carefully review all paleoseismic data:
   - Evidence for earthquakes, limiting ages and uncertainties
   - Stratigraphic framework for events
   - Numerical ages
     - Sample locations and contextual uncertainties
     - Mean-residence-time (MRT) correction(s) for bulk-soil ^{14}C ages
   - Completeness of record
     - All scarps trenched?
     - Orphan (undated) colluvial wedges?
     - Events missing, but expected? (E.g., Brigham City MRE not observed at Bowden Canyon, but observed <2 km north and south)

Example – Kaysville site, Weber segment

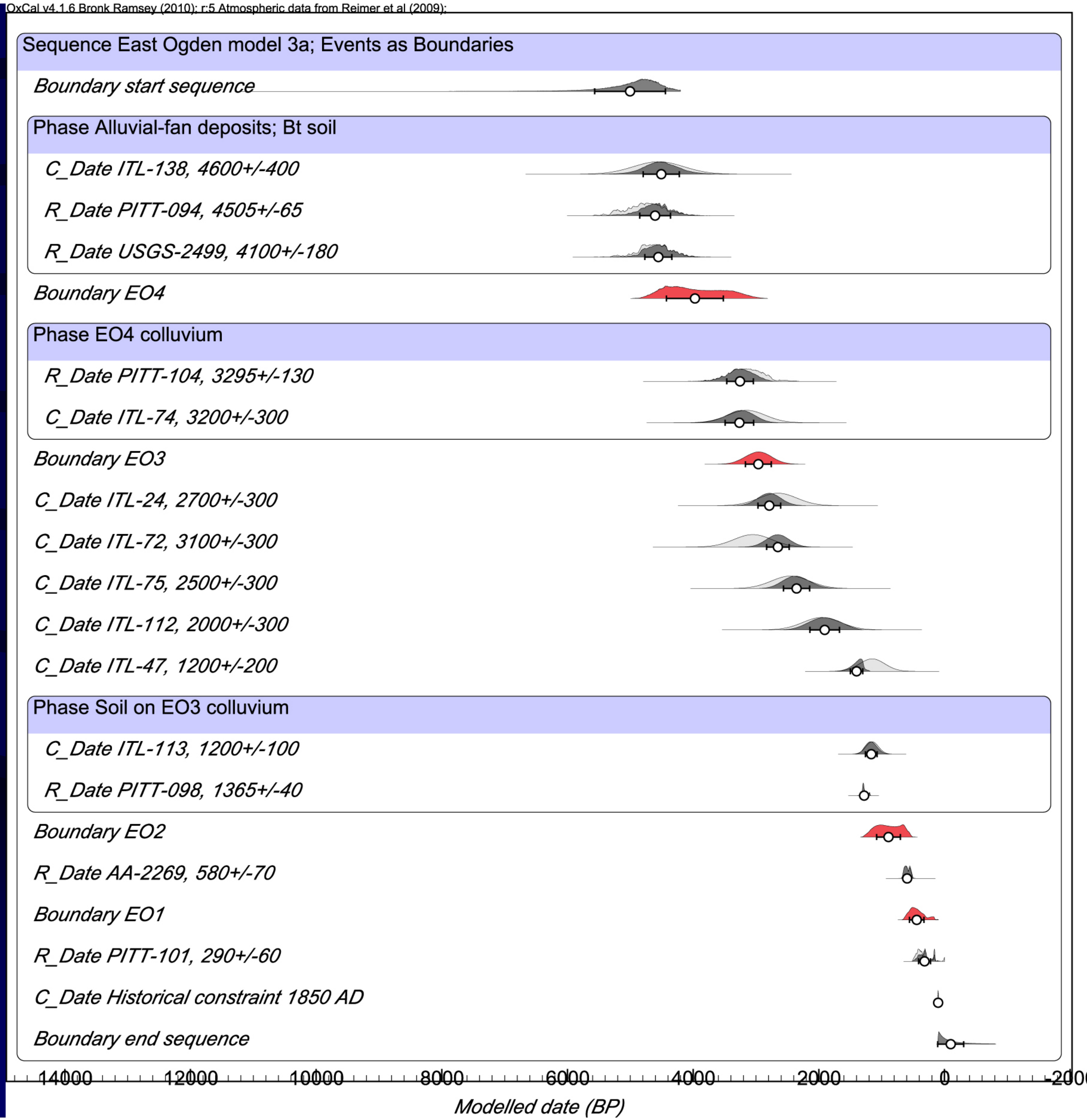


Log of Trench A; Kaysville Site
Swan, F.H., Schwartz, D.P., Hanson, K.L, Knuepfer, P.L., and Cluff, L.S.
1981

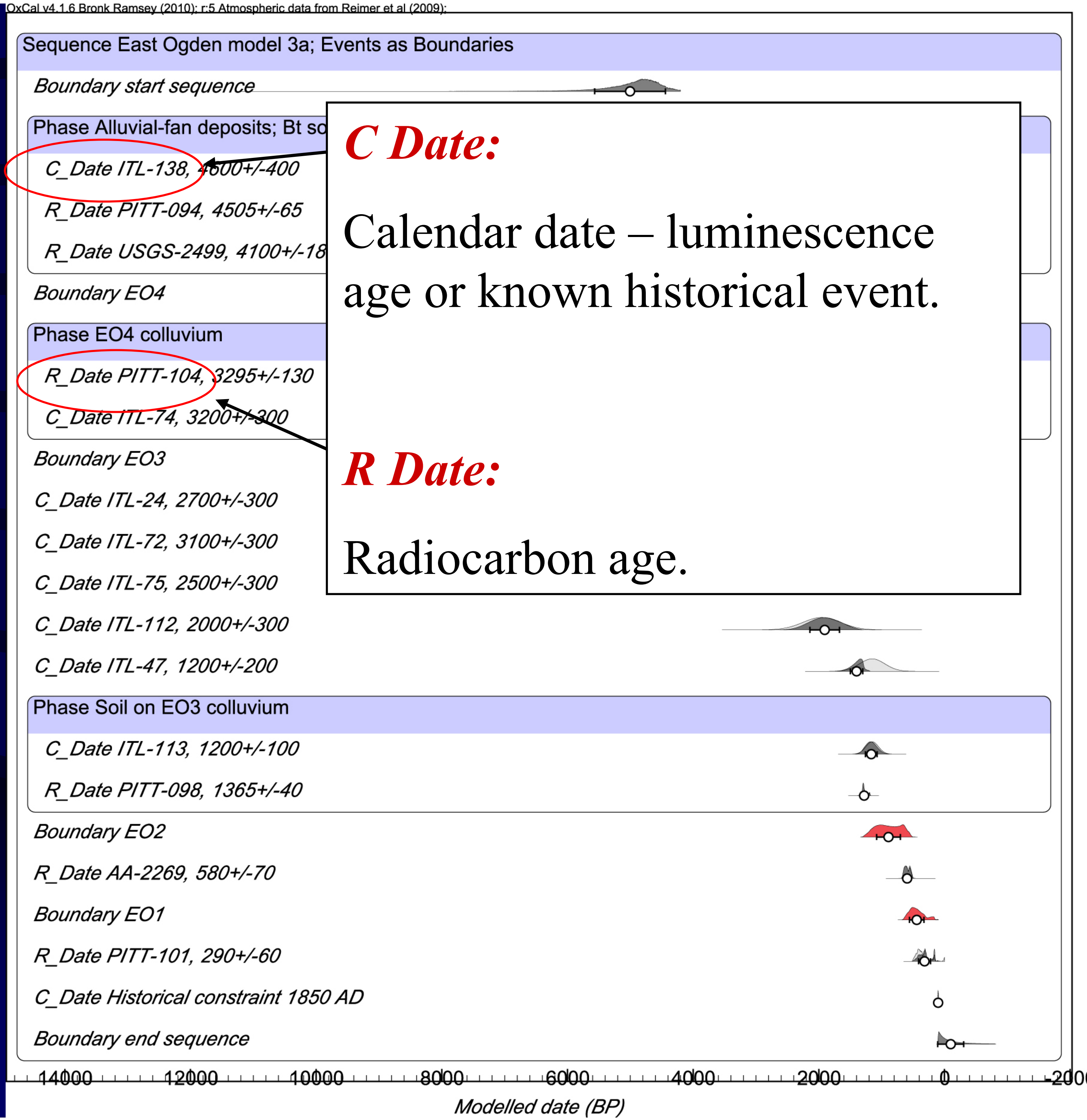
Approach – Step 2

2. Construct OxCal models for each trench site
   - Include/exclude limiting ages based on author's interpretation and discussion, trench logs
   - Apply MRT correction, with uncertainty if not specified by original authors
   - Combine multiple trenches into single model
   - Revise/improve models as necessary
   - Export PDFs for each site earthquake (***site PDFs***)

Example – East Ogden



Example – East Ogden



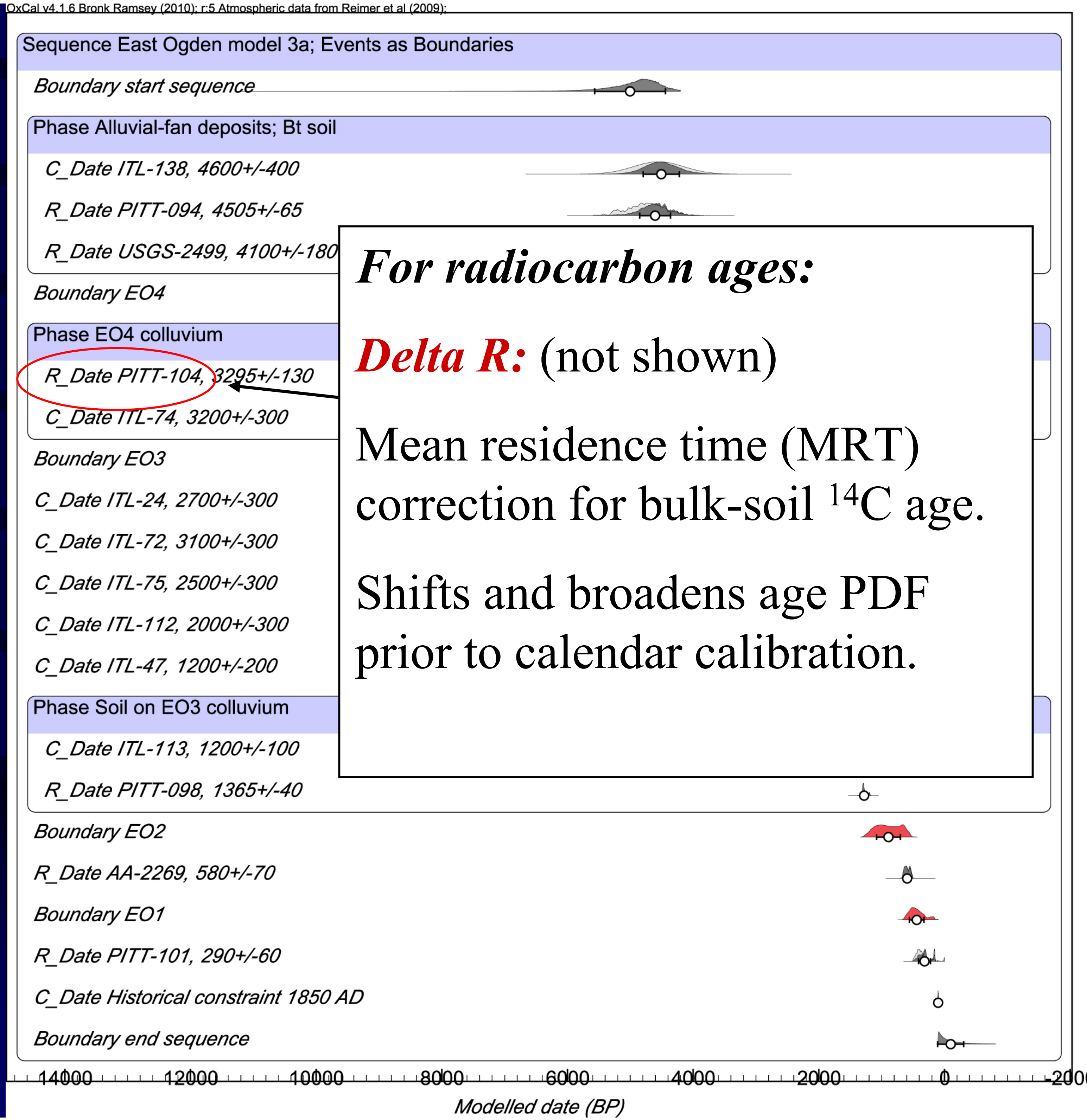
C Date:

Calendar date – luminescence age or known historical event.

R Date:

Radiocarbon age.

Example – East Ogden



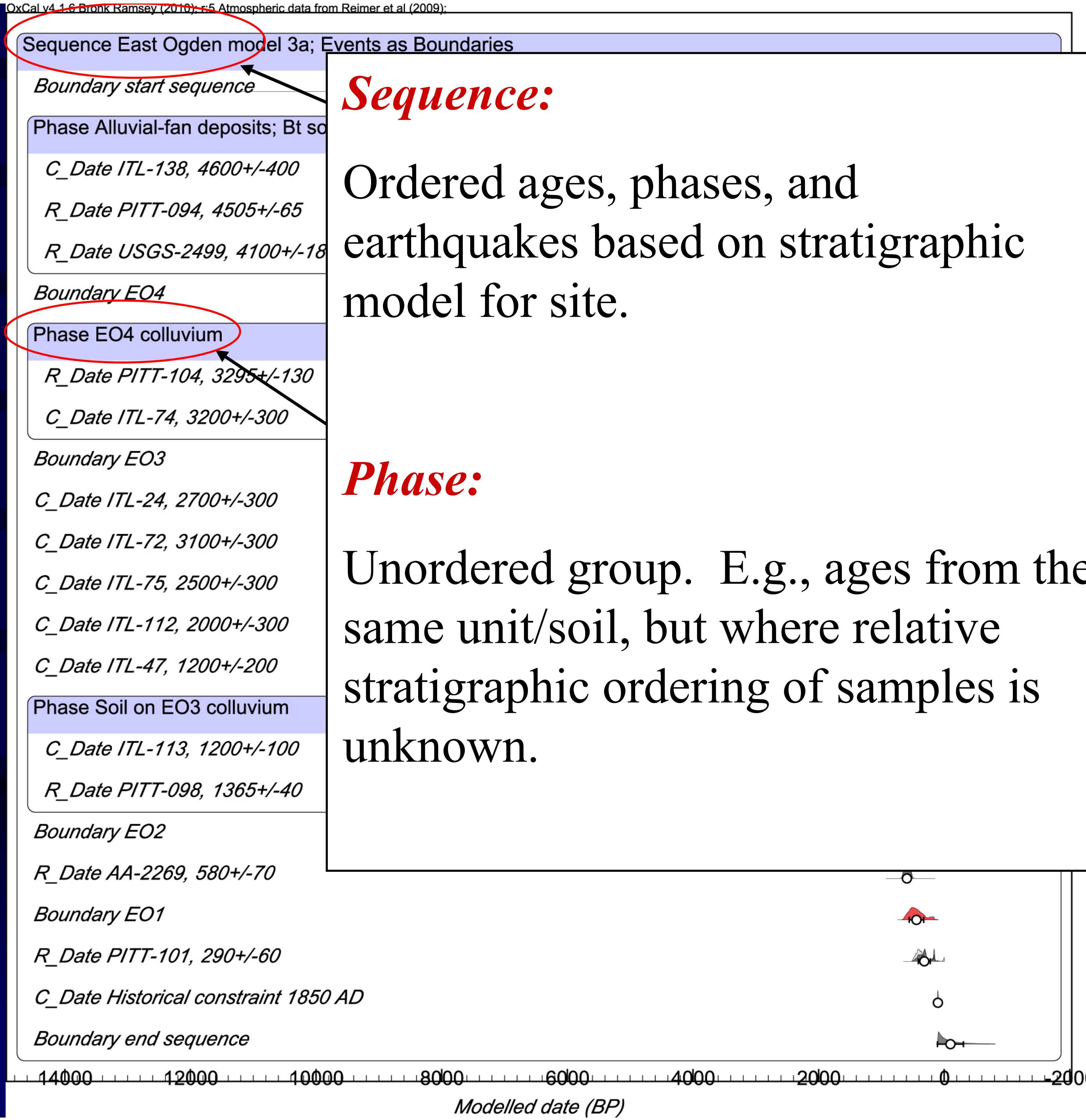
For radiocarbon ages:

Delta R: (not shown)

Mean residence time (MRT) correction for bulk-soil ^{14}C age.

Shifts and broadens age PDF prior to calendar calibration.

Example – East Ogden



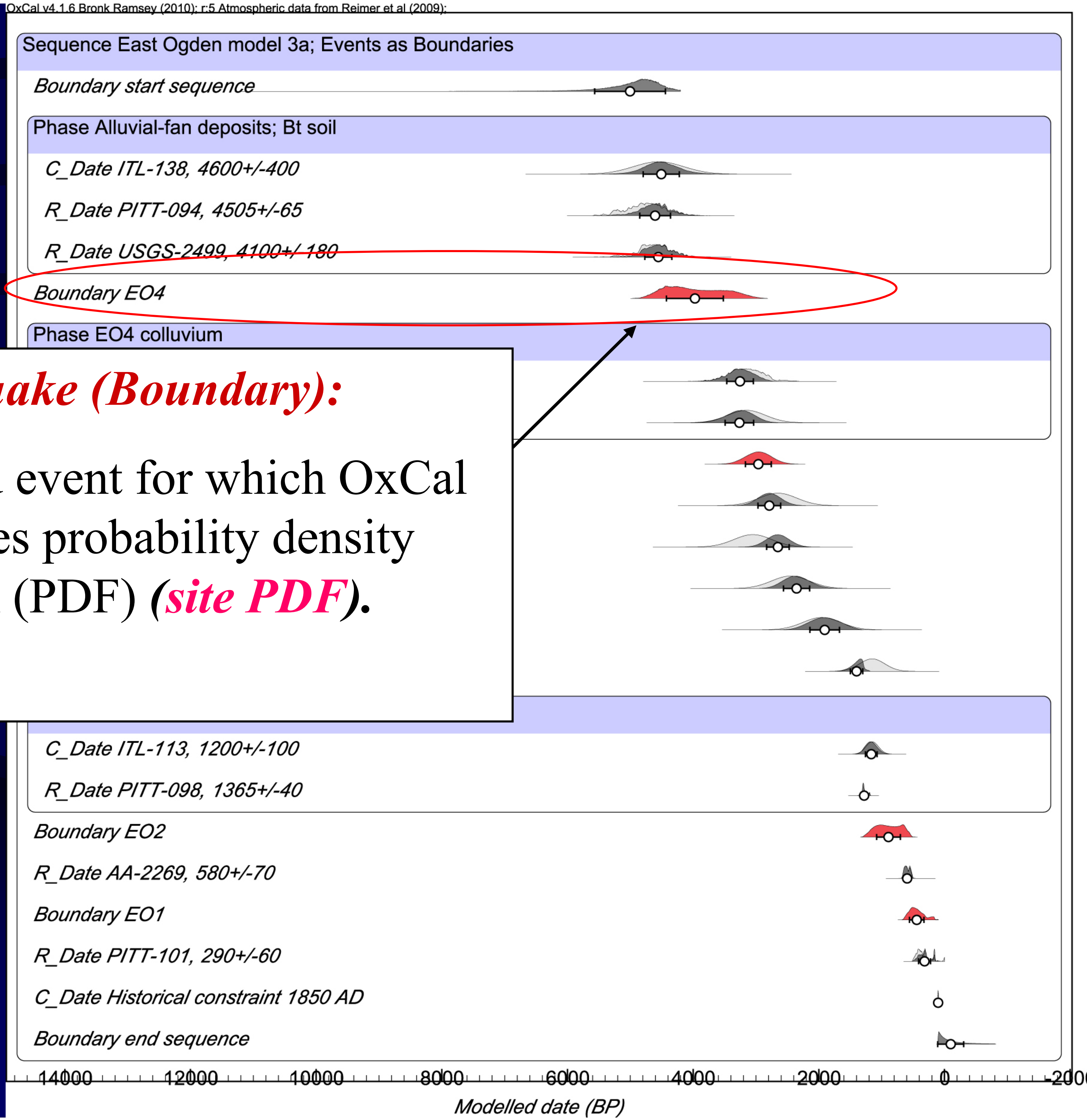
Sequence:

Ordered ages, phases, and earthquakes based on stratigraphic model for site.

Phase:

Unordered group. E.g., ages from the same unit/soil, but where relative stratigraphic ordering of samples is unknown.

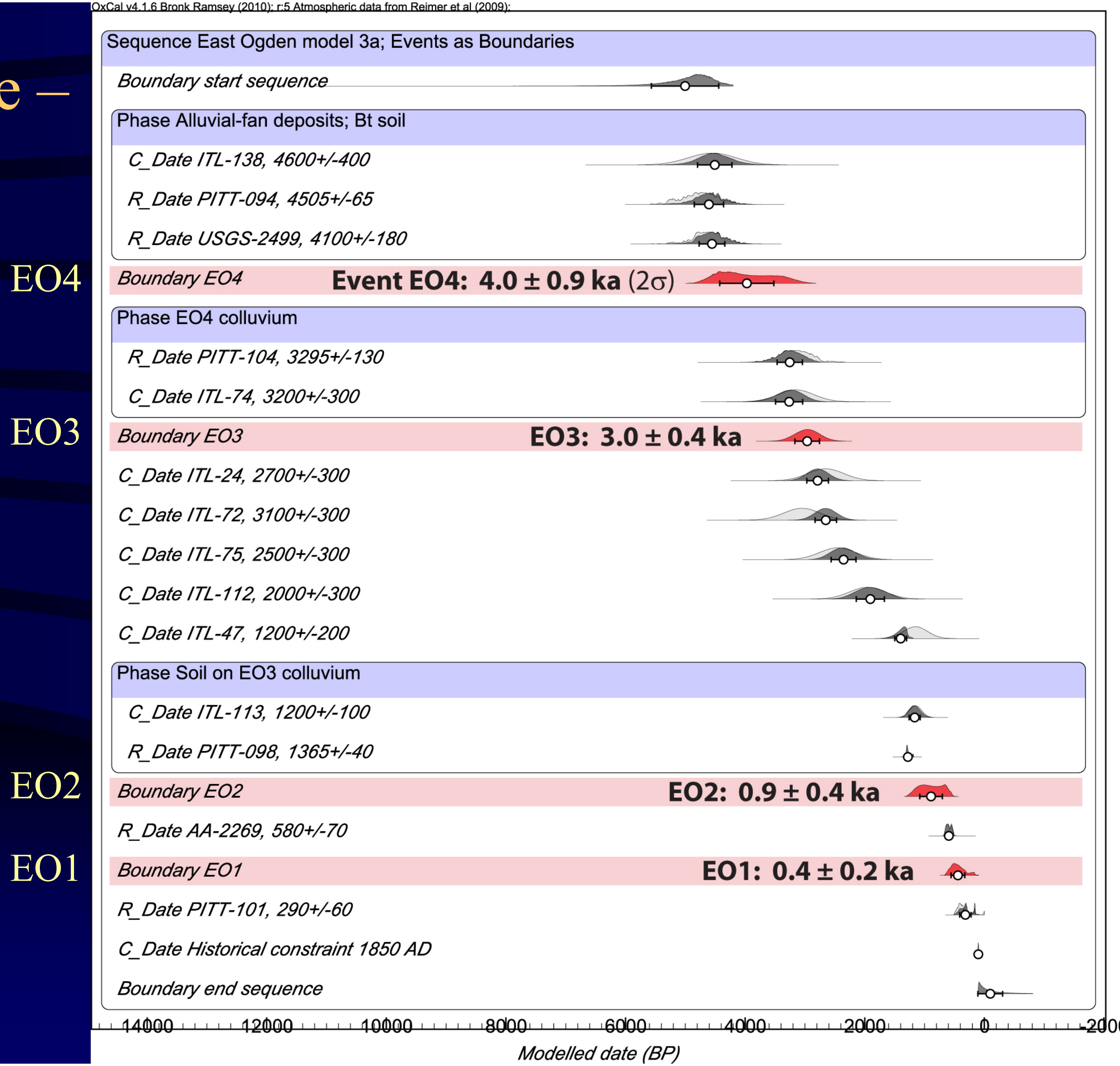
Example – East Ogden



Earthquake (Boundary):

Undated event for which OxCal calculates probability density function (PDF) ***(site PDF)***.

Example – East Ogden



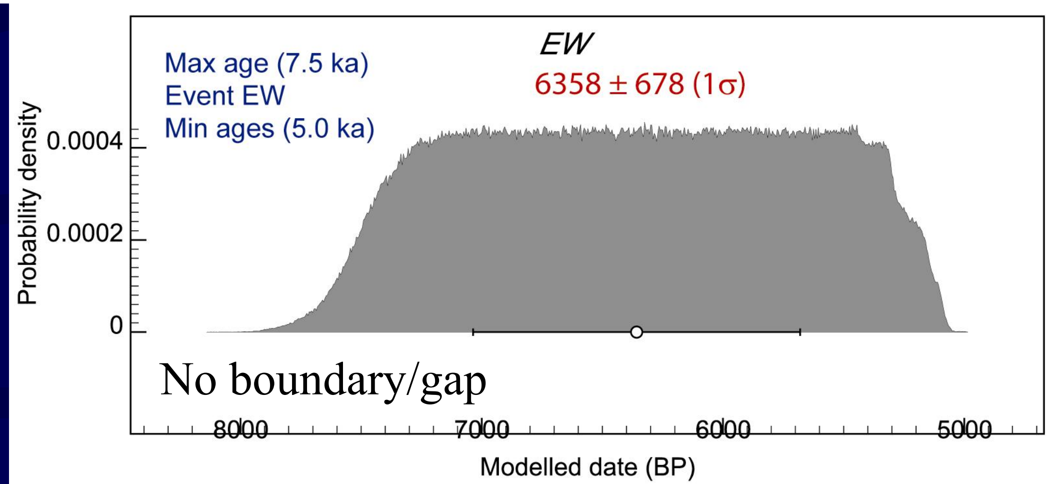
OxCal models

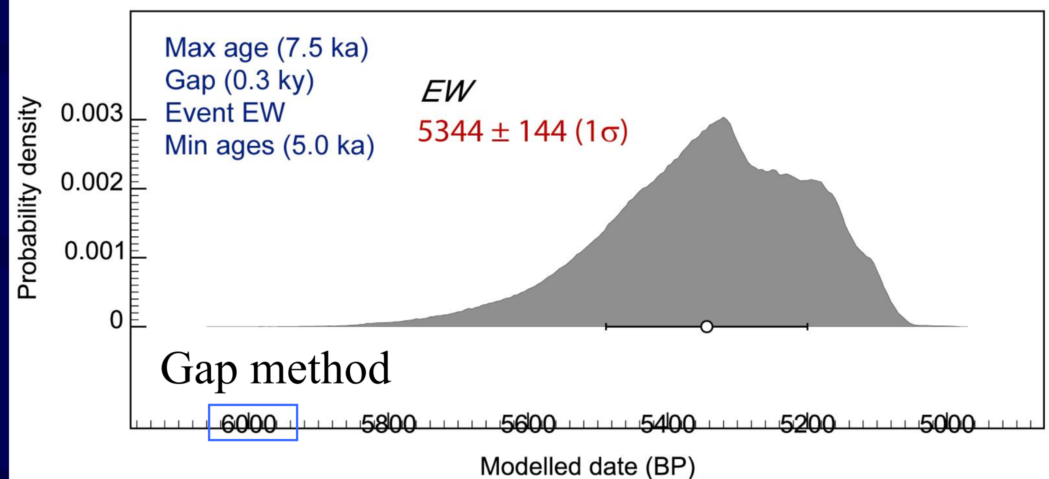
- Issue:
  - Geologic evidence indicates event occurred closer to maximum (or min) ages.

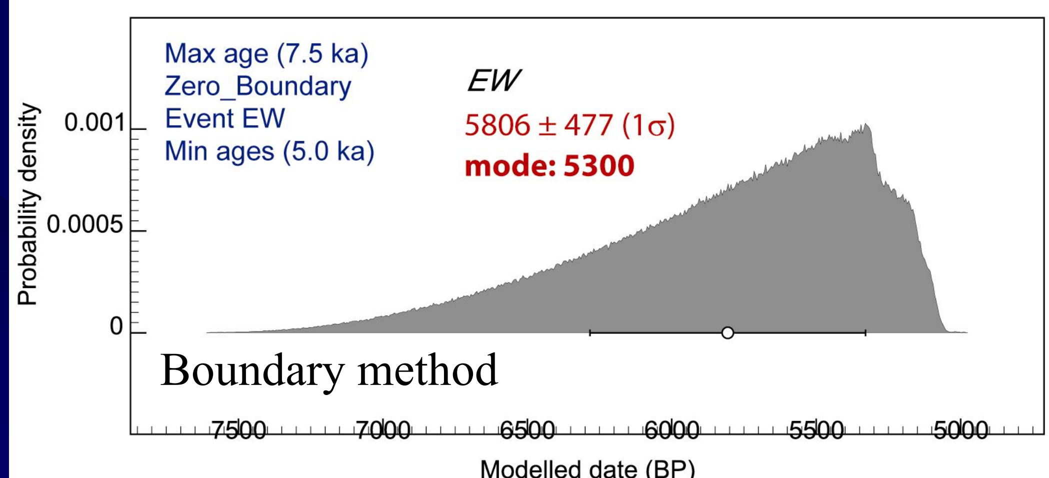
Example from SLCS:

1. Charcoal from fan (7.5 ka)
2. Fan deposition (undated)
3. Event EW
4. Soil organics from fissure fill (5.0 ka)

McCalpin: EW occurred ~5.3 ka



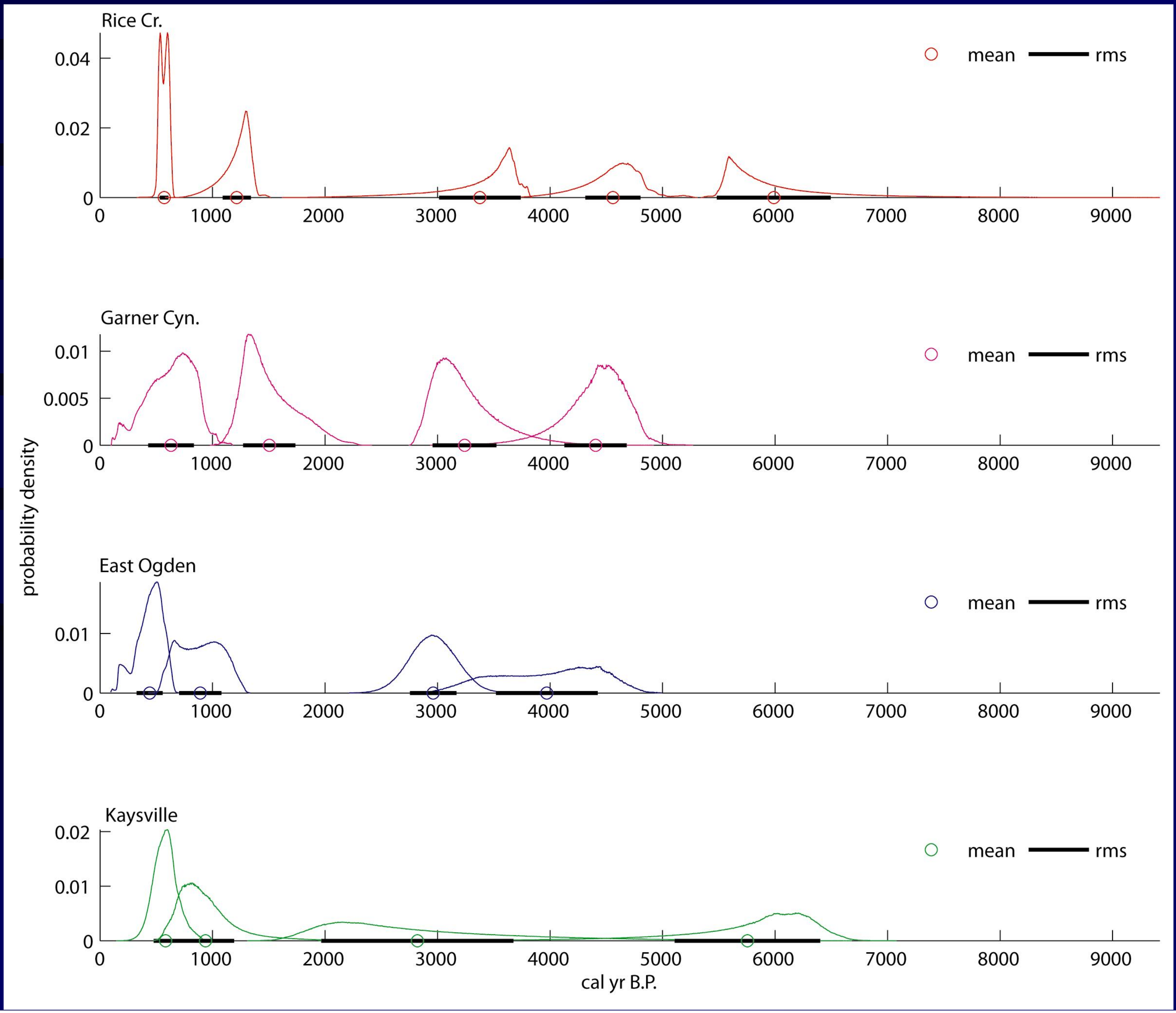




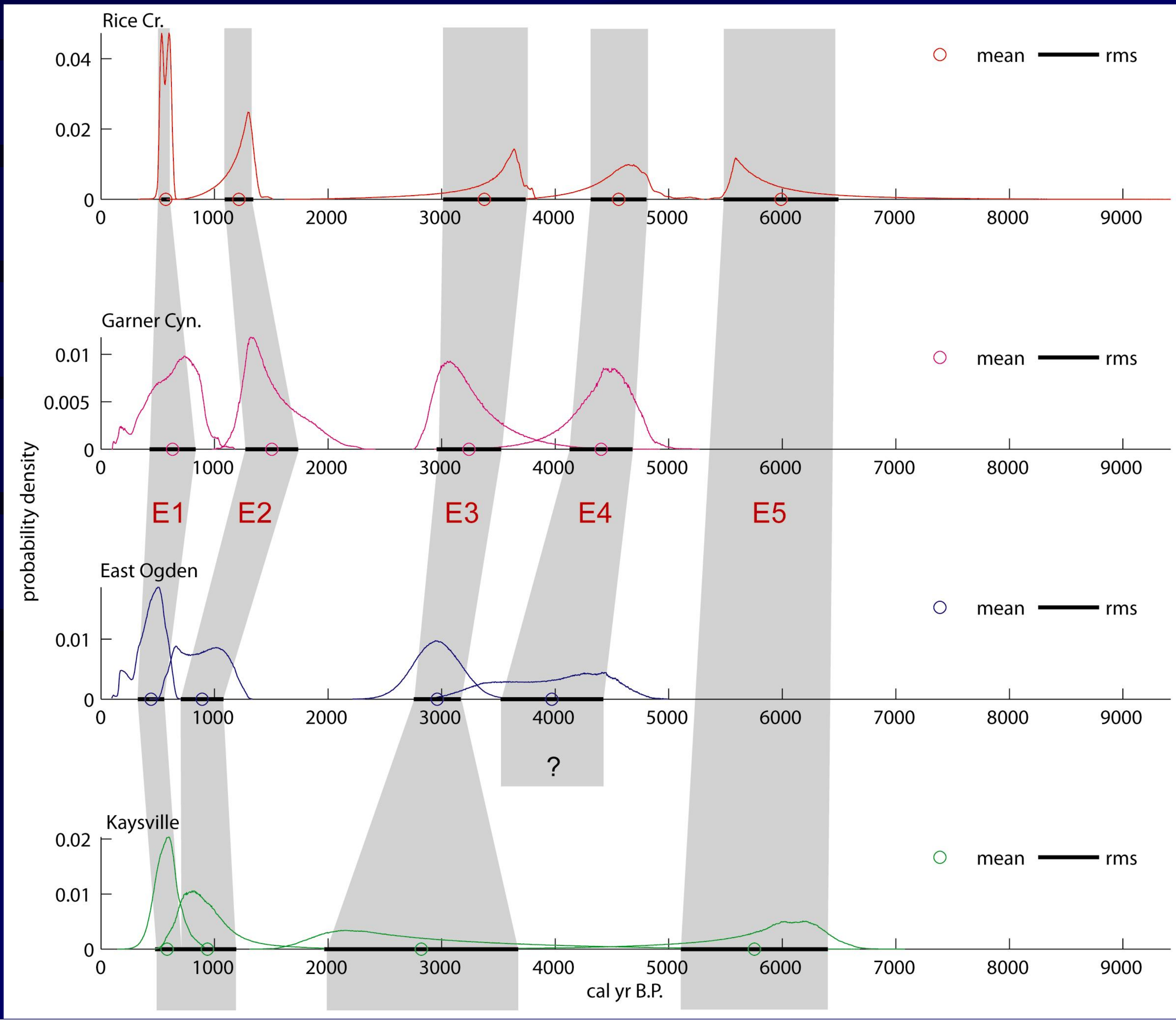
Approach – Step 3

3. Combine OxCal models into segment chronology (Matlab)
   - Overlay and compare (quantitatively) site PDFs
   - Correlate site PDFs along segment
   - Combine correlative site PDFs to form single "**segment PDF**"
     - Mean of site PDFs
     - Product of site PDFs, which focuses on overlap in PDFs

Weber segment – Matlab plot of site PDFs



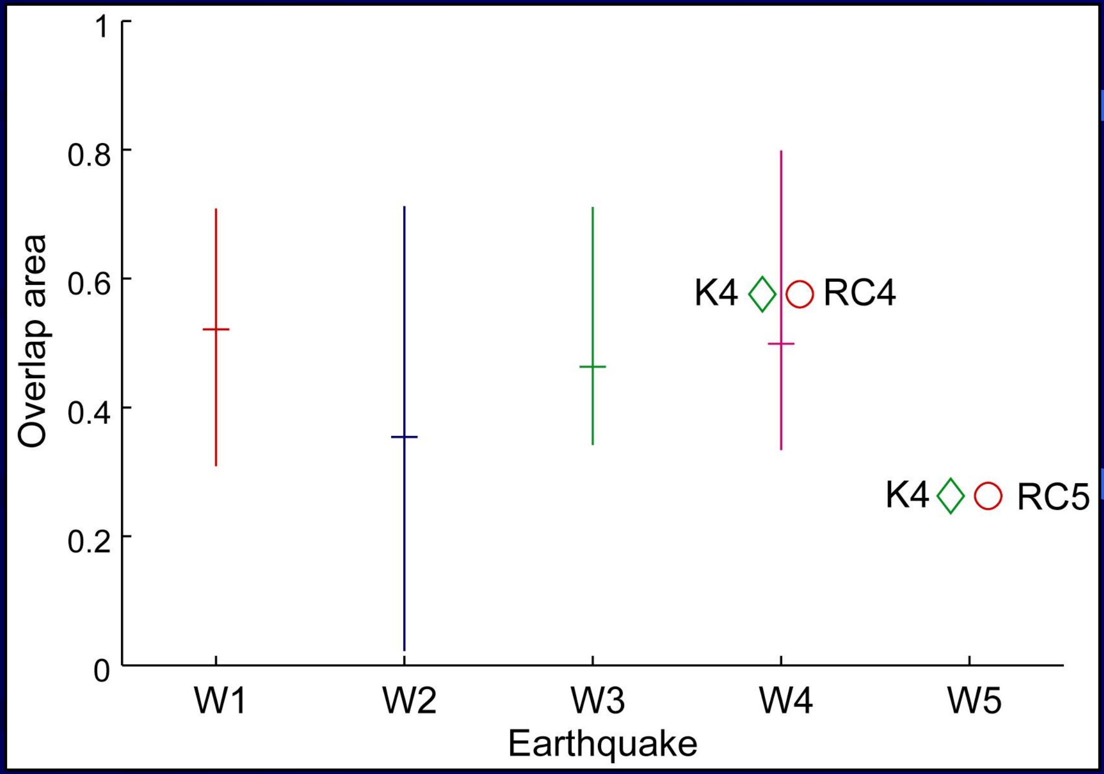
Weber segment – correlation of site PDFs



Resolving correlation issues

- Does K4 correlate with RC4 or RC5?
  (from old Weber seg. model)

- PDF overlap*
  - sum of minimum prob. of two pdfs for each time bin
  - 0–1: zero to full overlap



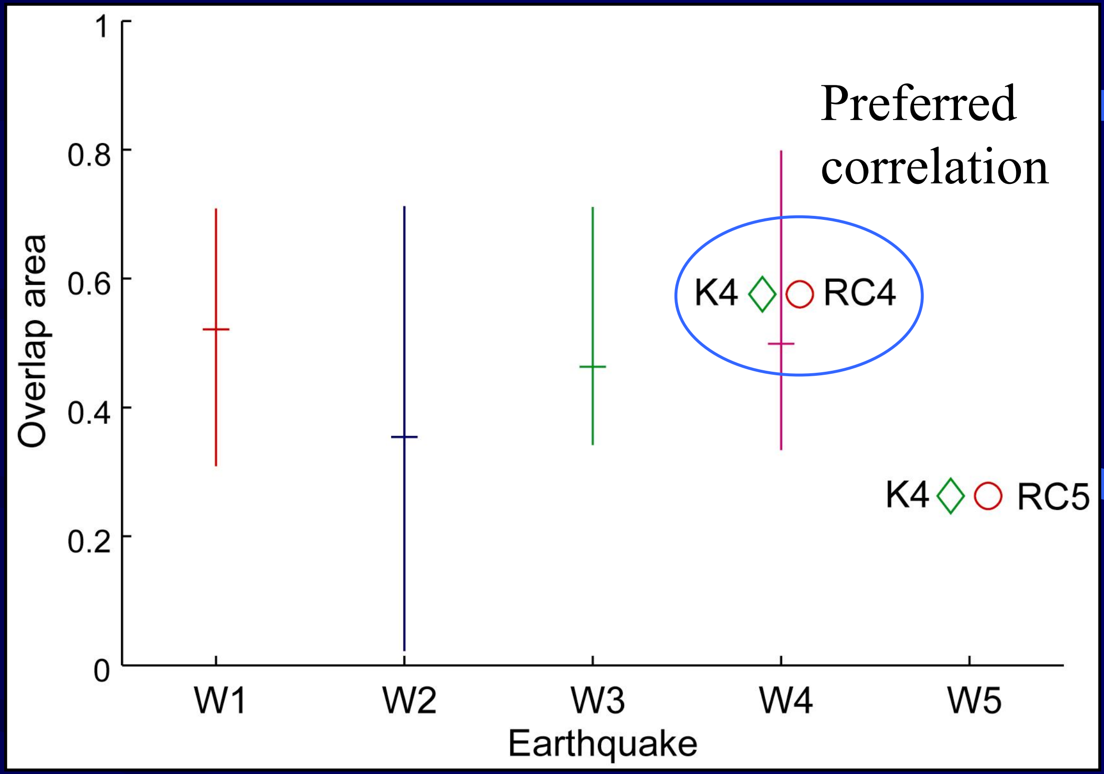
* from Biasi and Weldon (2009); BSSA v. 99, no. 2A, p. 471–498

Resolving correlation issues

- Does K4 correlate with RC4 or RC5?
  (from old Weber seg. model)

- PDF overlap*
  - sum of minimum prob. of two pdfs for each time bin
  - 0–1: zero to full overlap

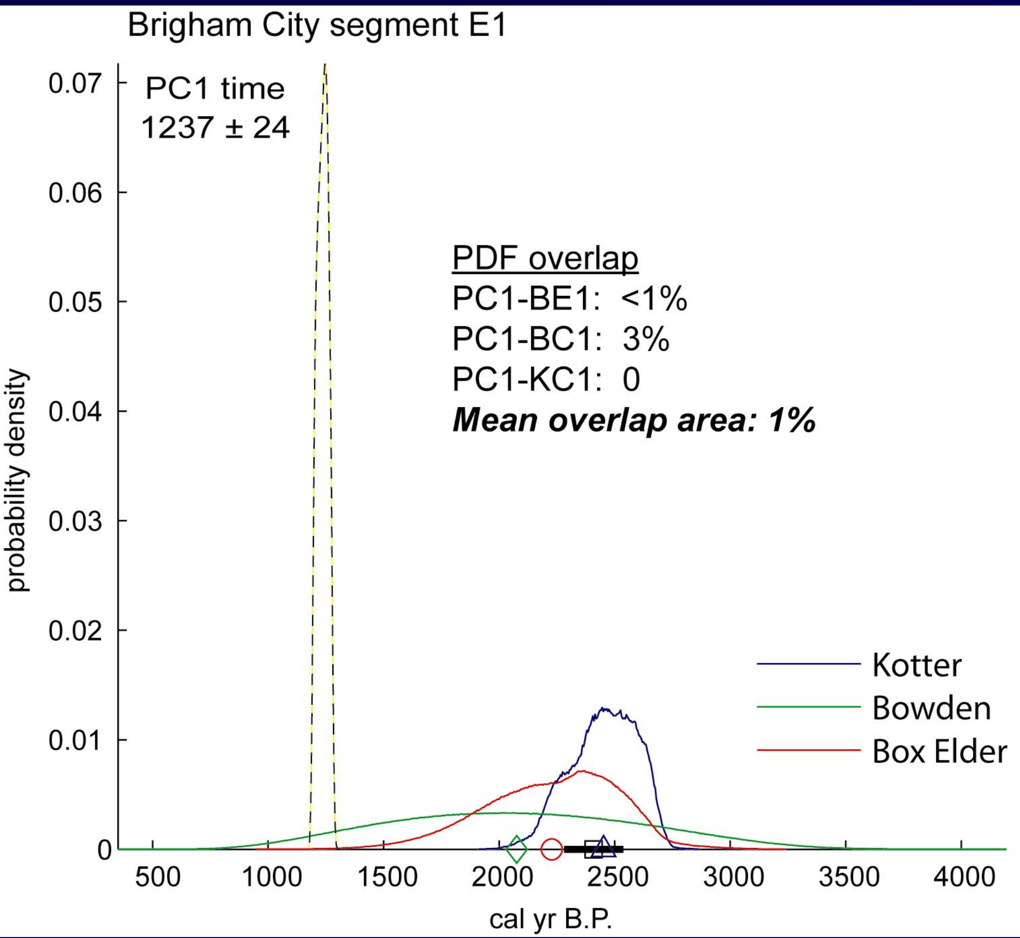
- K4–RC4 overlap about twice K4–RC5 overlap

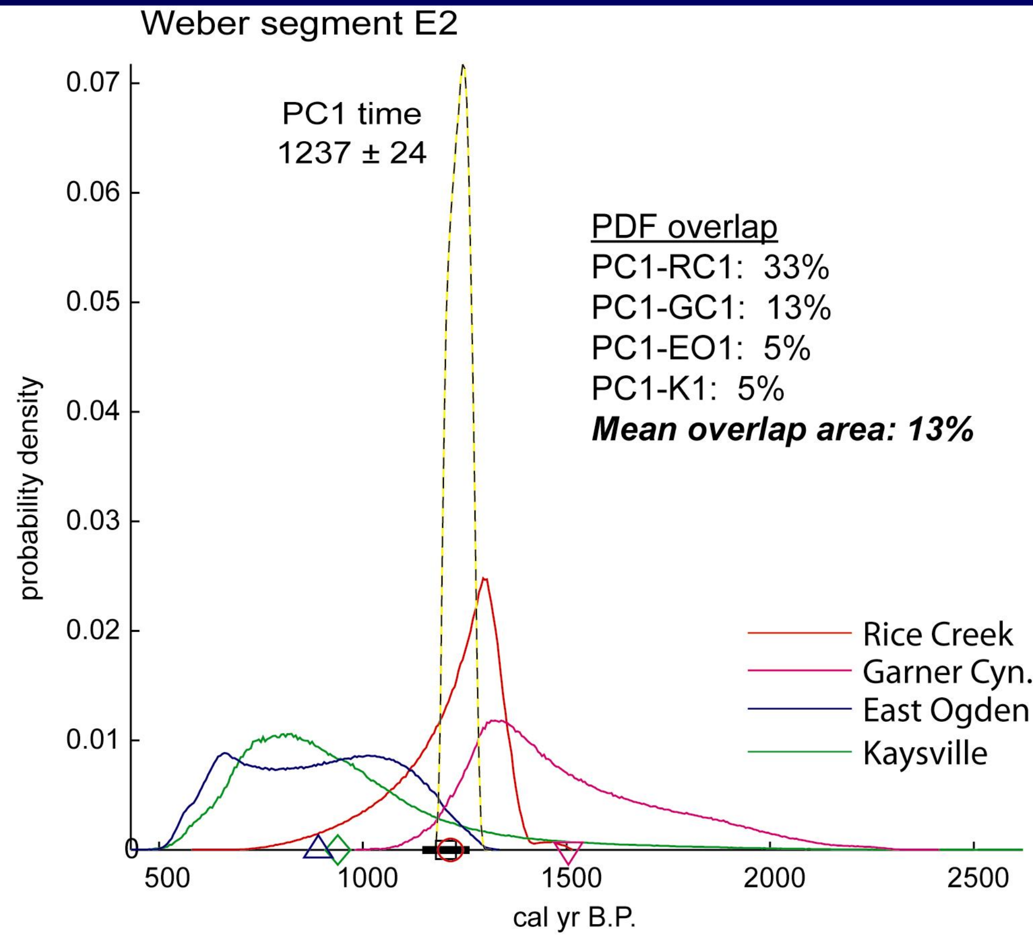


* from Biasi and Weldon (2009); BSSA v. 99, no. 2A, p. 471–498

Resolving correlation issues

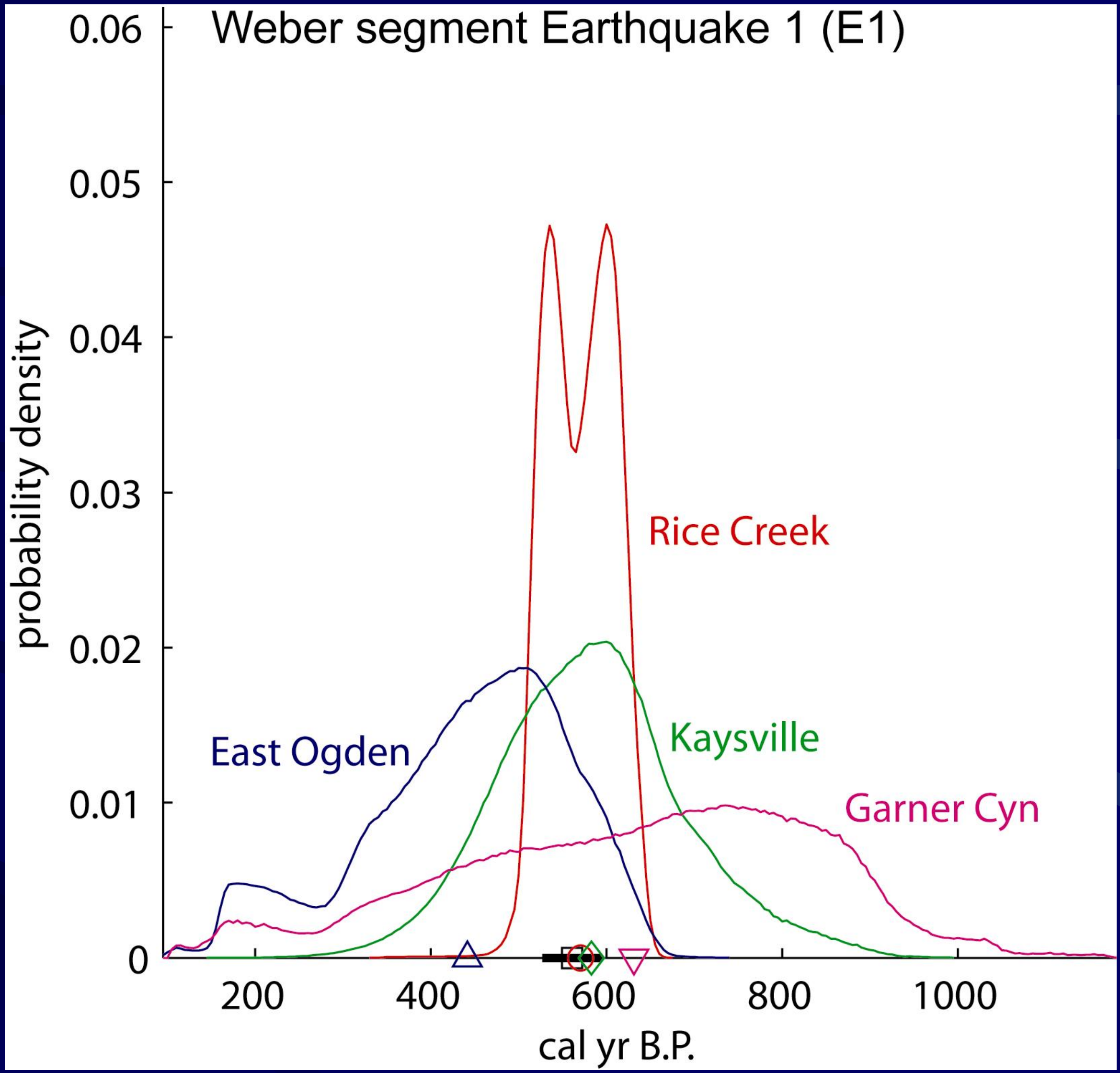
- PDF overlap useful for comparing data from adjacent segments
  - E.g., Pearsons Canyon MRE (PC1) rupture in Weber segment earthquake?





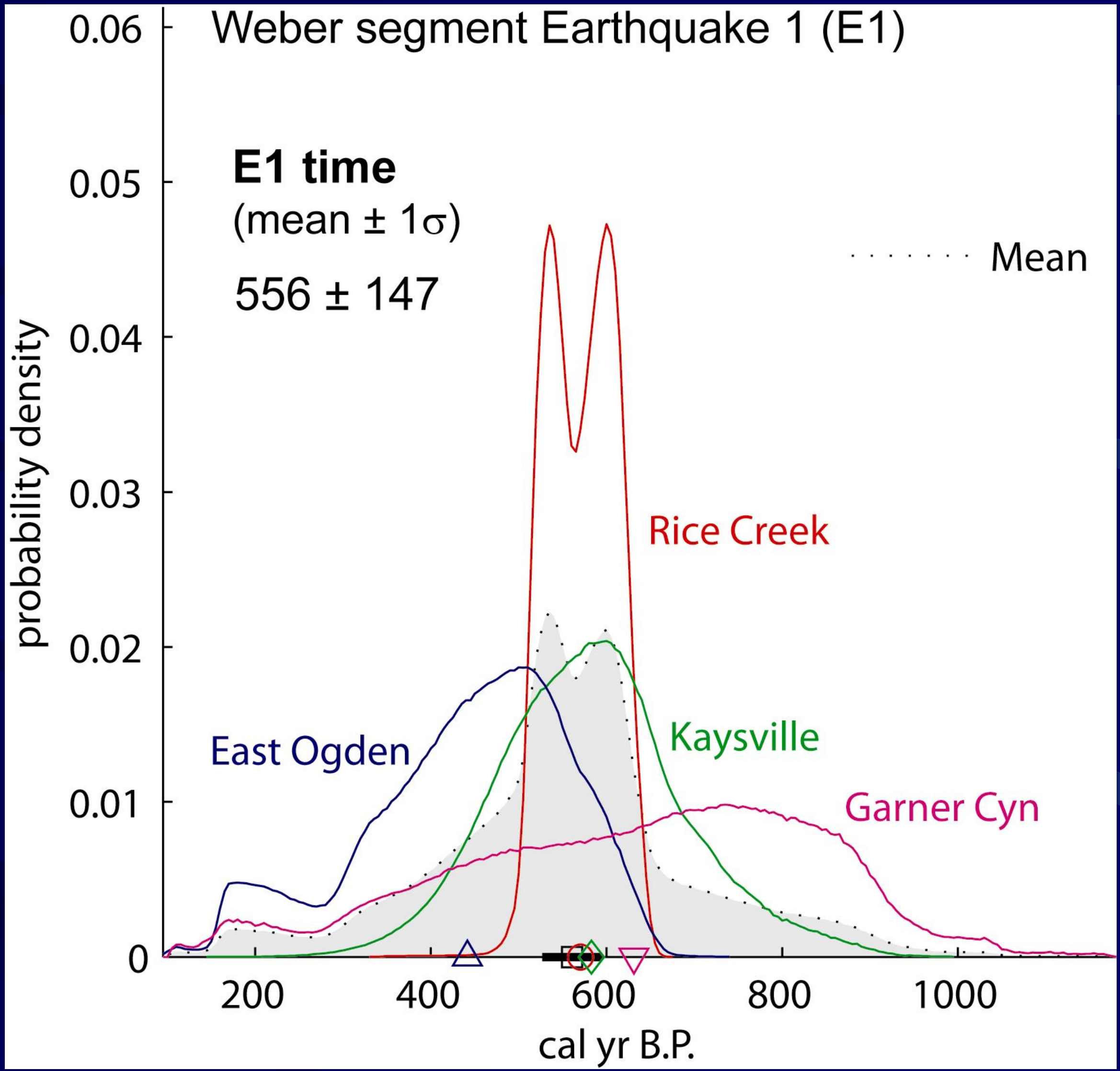
Example – Weber segment (E1)

- Comparison of site PDFs



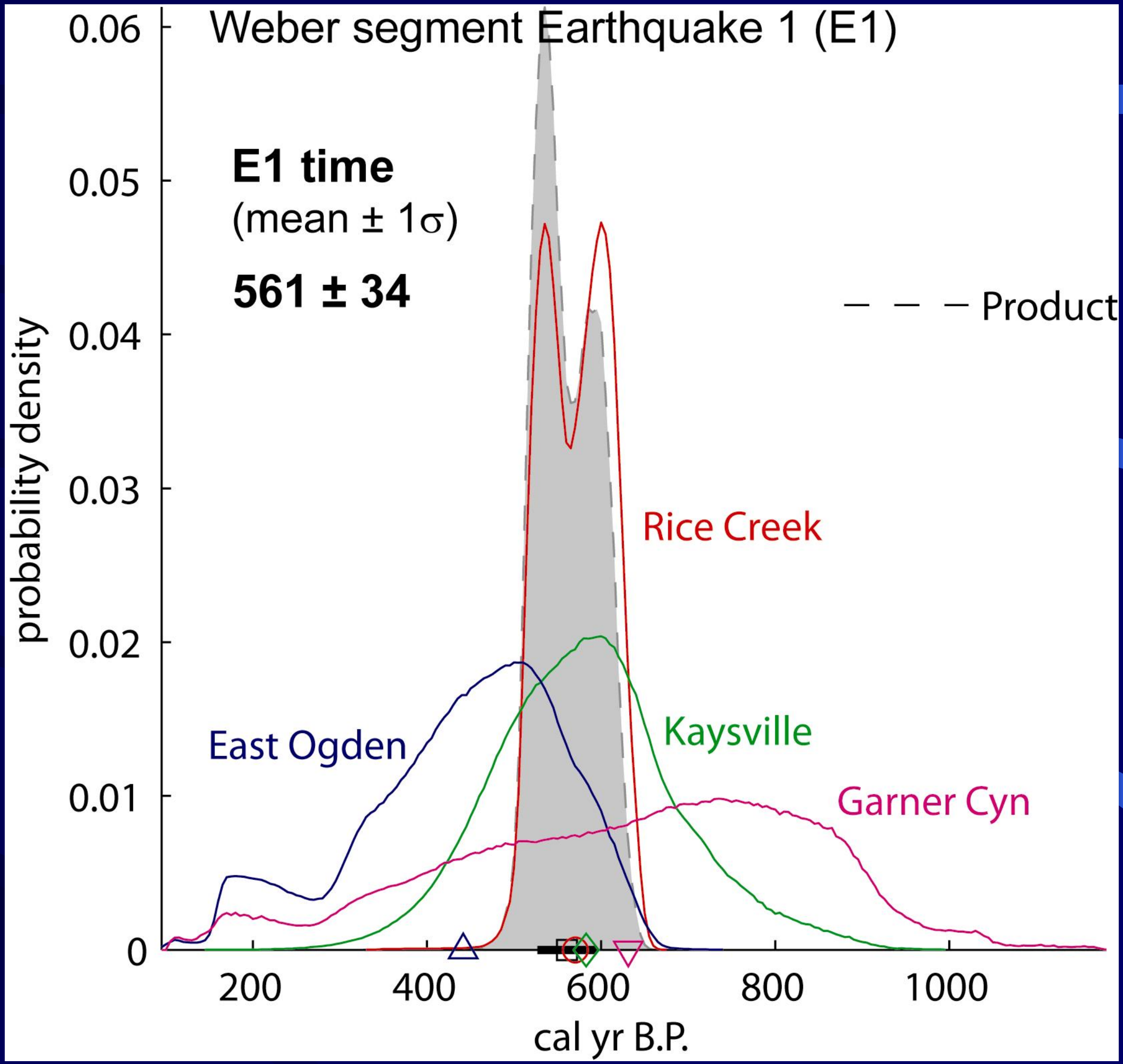
Example – Weber segment (E1)

- Mean of site PDFs (light gray)
  - All site PDFs given equal weight
  - More data = more uncertainty



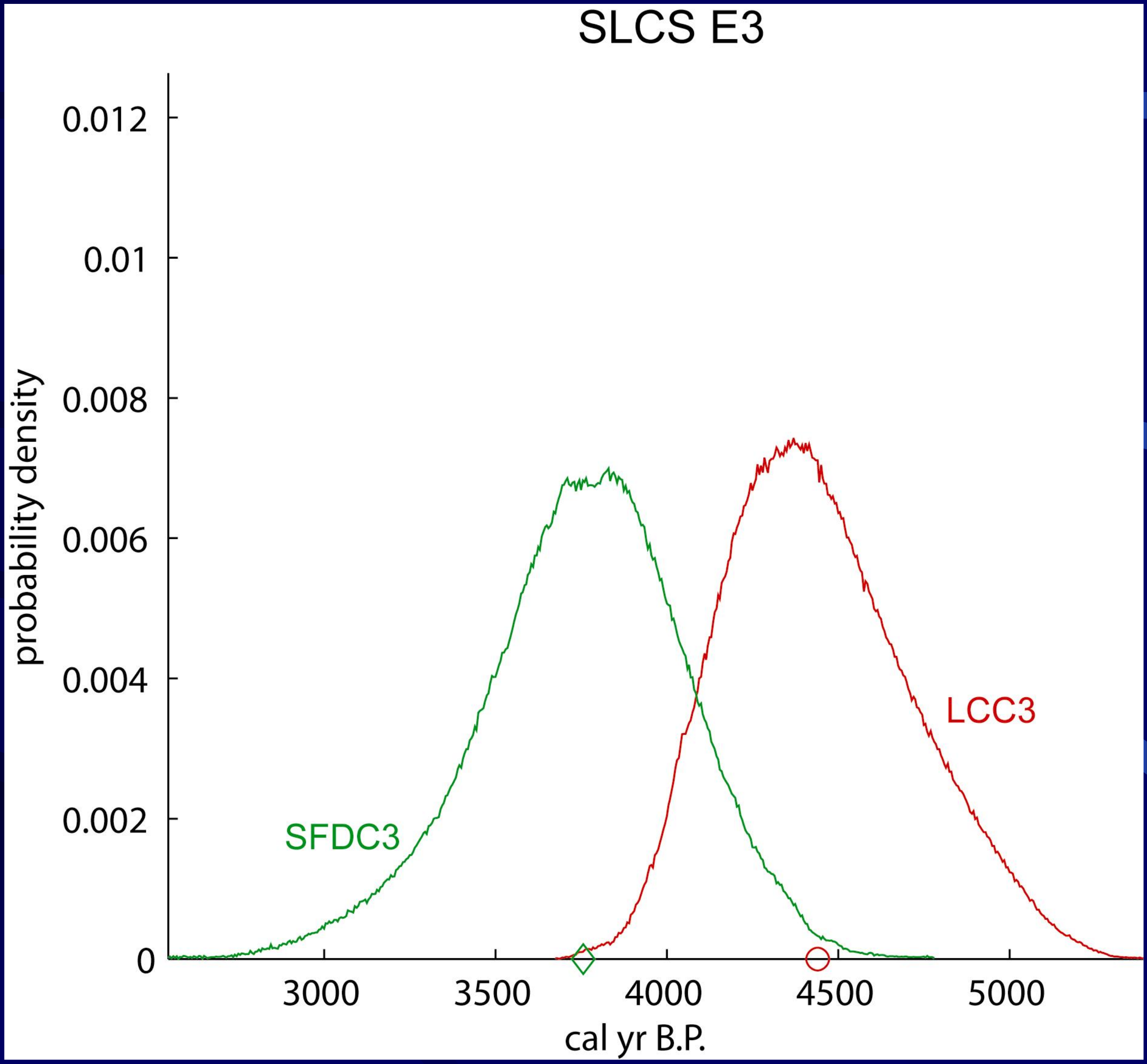
Example – Weber segment (E1) - refined

- Product of site PDFs (dark gray)
  - For independent events A & B, probability of both events occurring at time t: $P(A \text{ and } B)_t = P(A)_t * P(B)_t$
  - Only overlap in site PDFs used (honors zero probability)
  - More data = less uncertainty



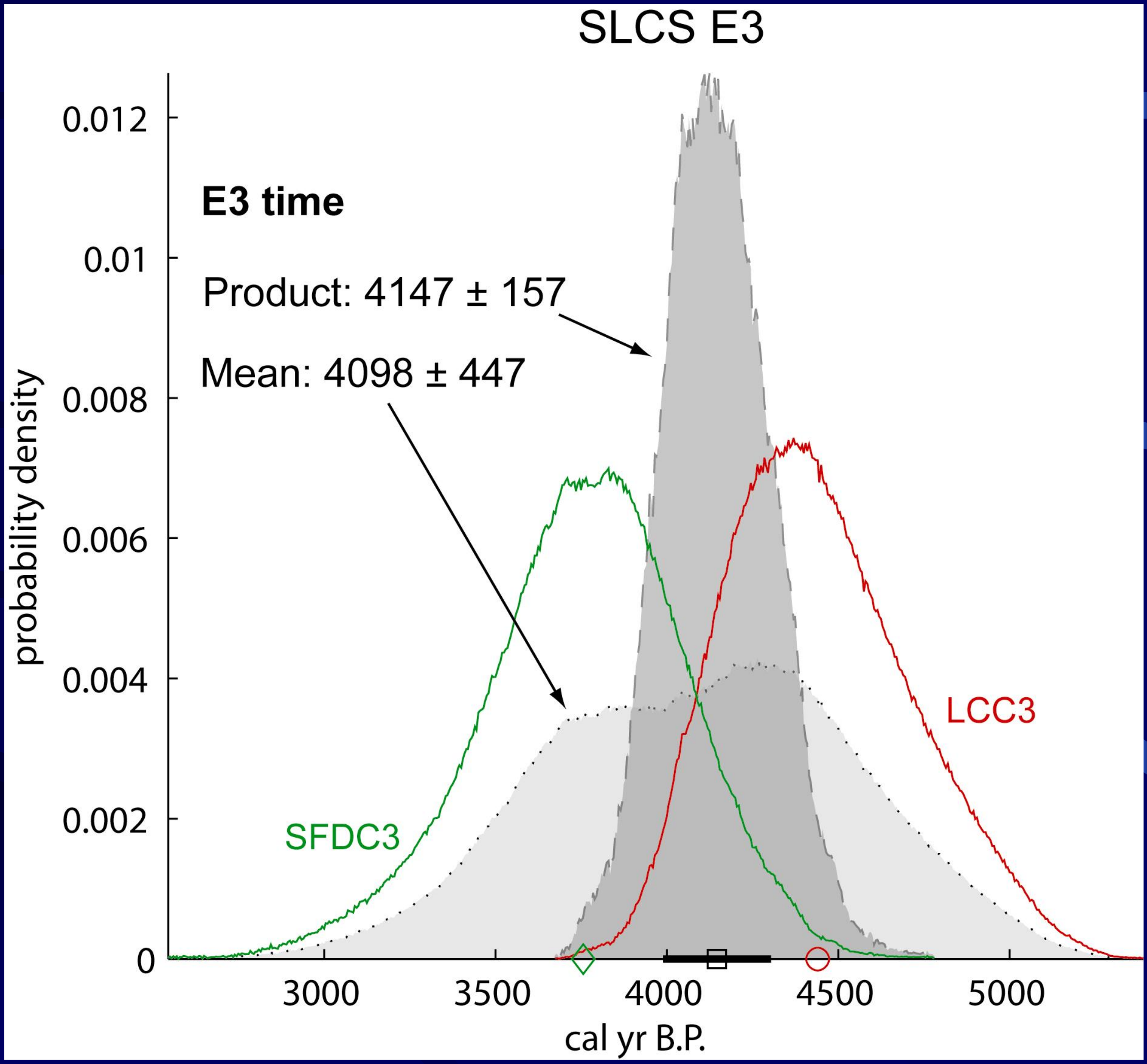
Example – Salt Lake City segment (E3)

- SLCS E3
  - SFDC: 3.8 ± 0.6 ka (2σ)
  - LCC: 4.4 ± 0.5 ka (2σ)



Example – Salt Lake City segment (E3)

- SLCS E3
  - Mean: 4.1 ± 0.9 ka (2σ)
  - Product: 4.1 ± 0.3 ka (2σ)



Example – Brigham City segment

- Matlab product method similar to combining all separate OxCal models into a single model

Brigham City segment

Event	**Matlab (ka) (1σ)**	**Combined OxCal (ka) (1σ)**
BC1	2.3 ± 0.1	2.1 ± 0.2
BC2	3.4 ± 0.1	3.4 ± 0.1
BC3	3.9 ± 0.3	4.3 ± 0.3
BC4	5.3 ± 0.4	5.6 ± 0.4
BC5	6.8 ± 0.6	6.9 ± 0.6
Recurrence		
BC5 – BC1	1.2 ± 0.5	1.2 ± 0.5

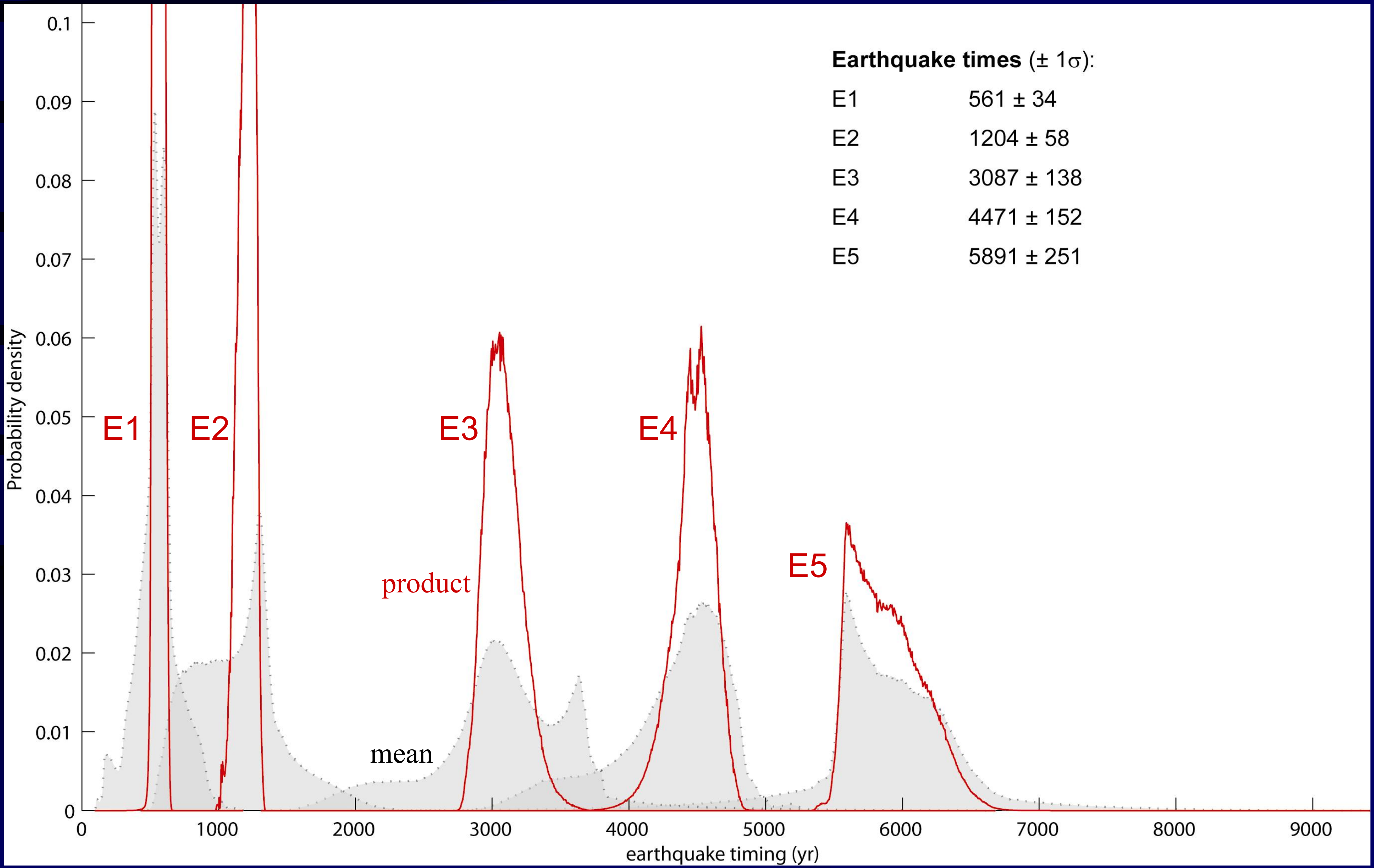
Example – Brigham City segment

- Matlab product method similar to combining all separate OxCal models into a single model
  - Honors limiting ages from each site (overlap in EQ time ranges)
  - Not "black box" calculation – know how site PDFs combined and segment PDFs calculated
  - Use segment PDFs to calculate recurrence

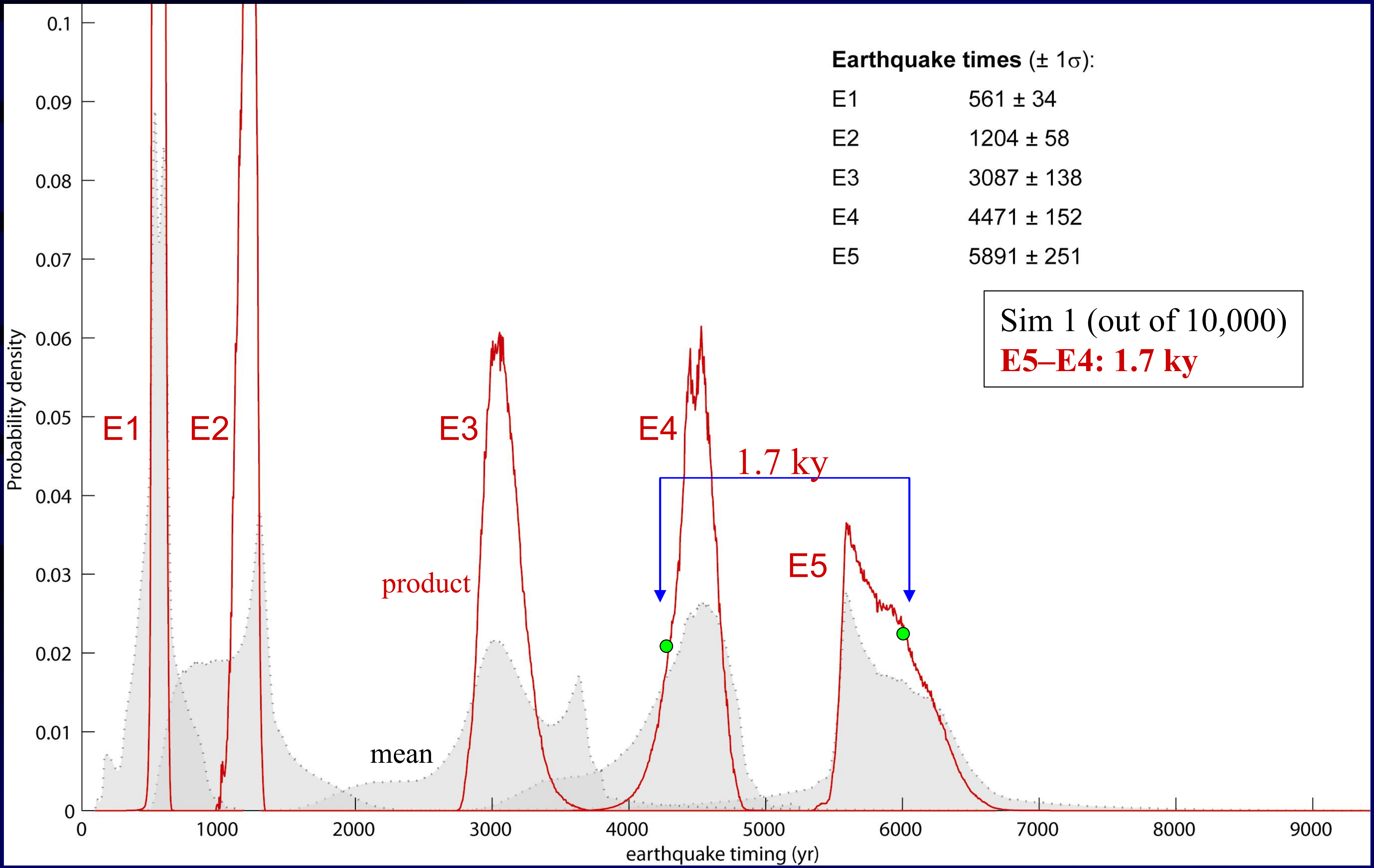
Approach – Step 4

4. Determine earthquake timing and recurrence
   - Determine mean and 2-sigma earthquake times
   - Calculate recurrence
     - Using full segment PDFs (not just mean times)
     - Inter-event and average recurrence
     - Zero recurrence not allowed (min recurrence: 300 ± 200 yrs)
   - Results
     - Inter-event and average recurrence PDFs (shape is important)
     - Mean with uncertainty based on original OxCal data

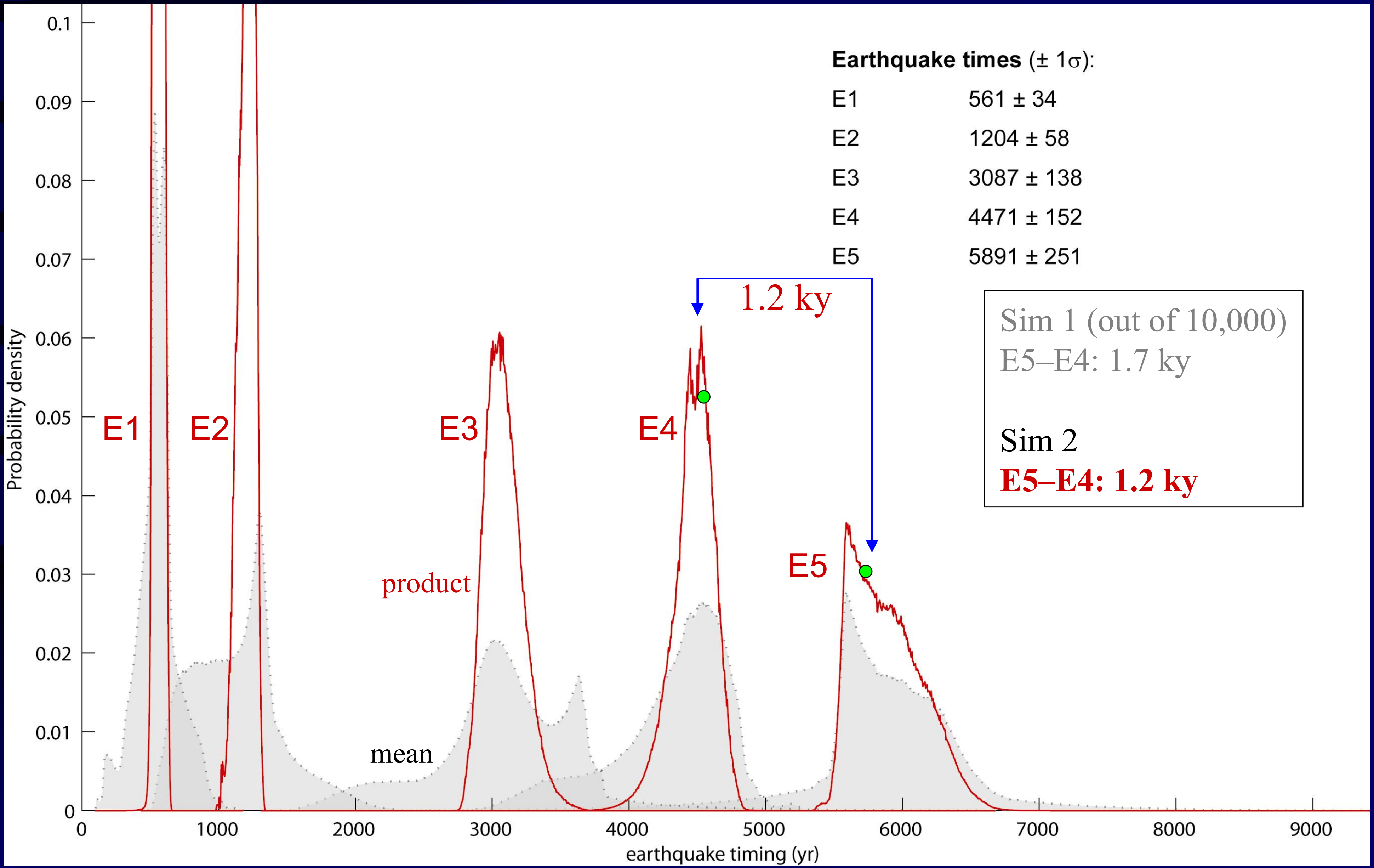
Example calculation – Weber segment



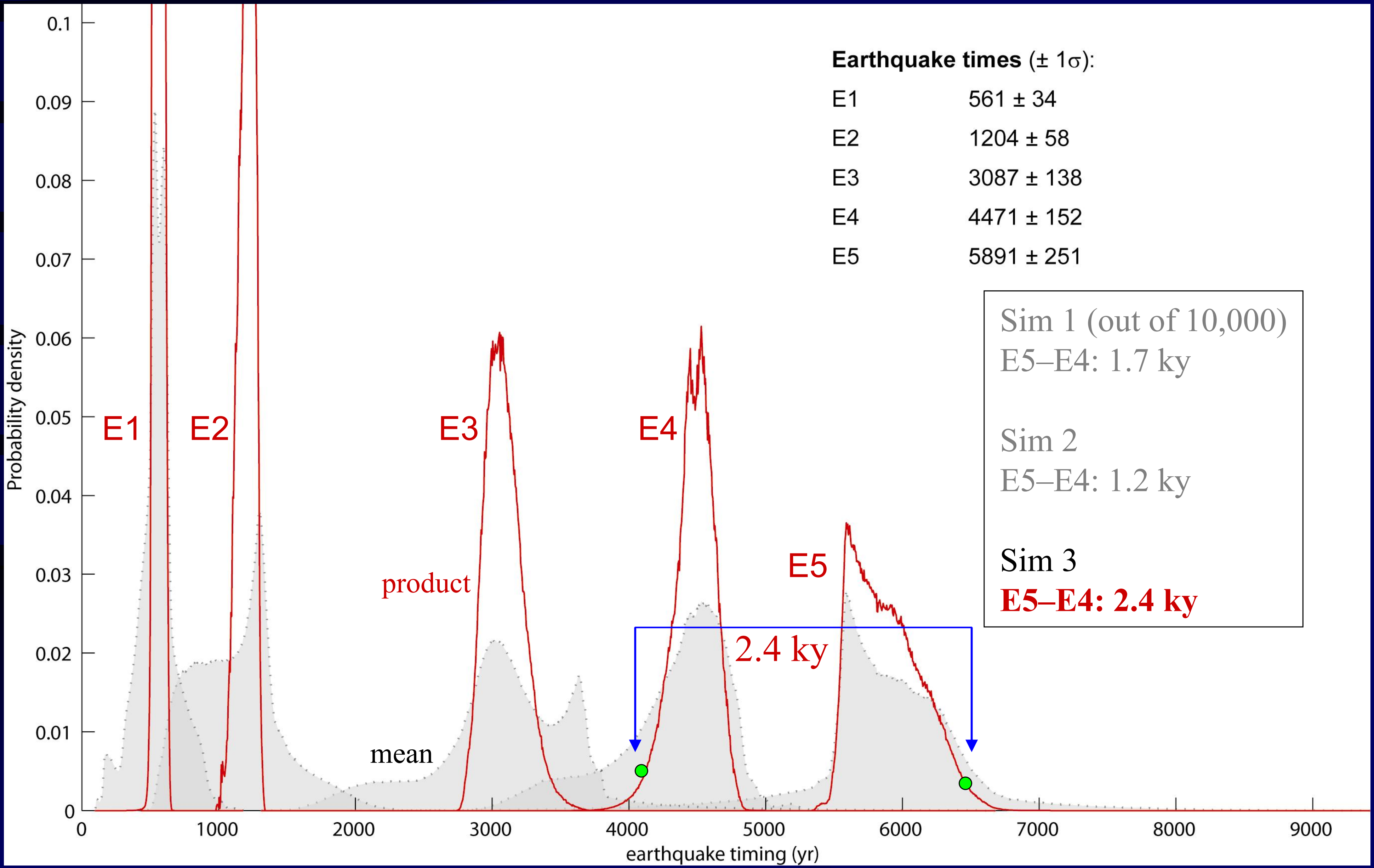
Example calculation – Weber segment



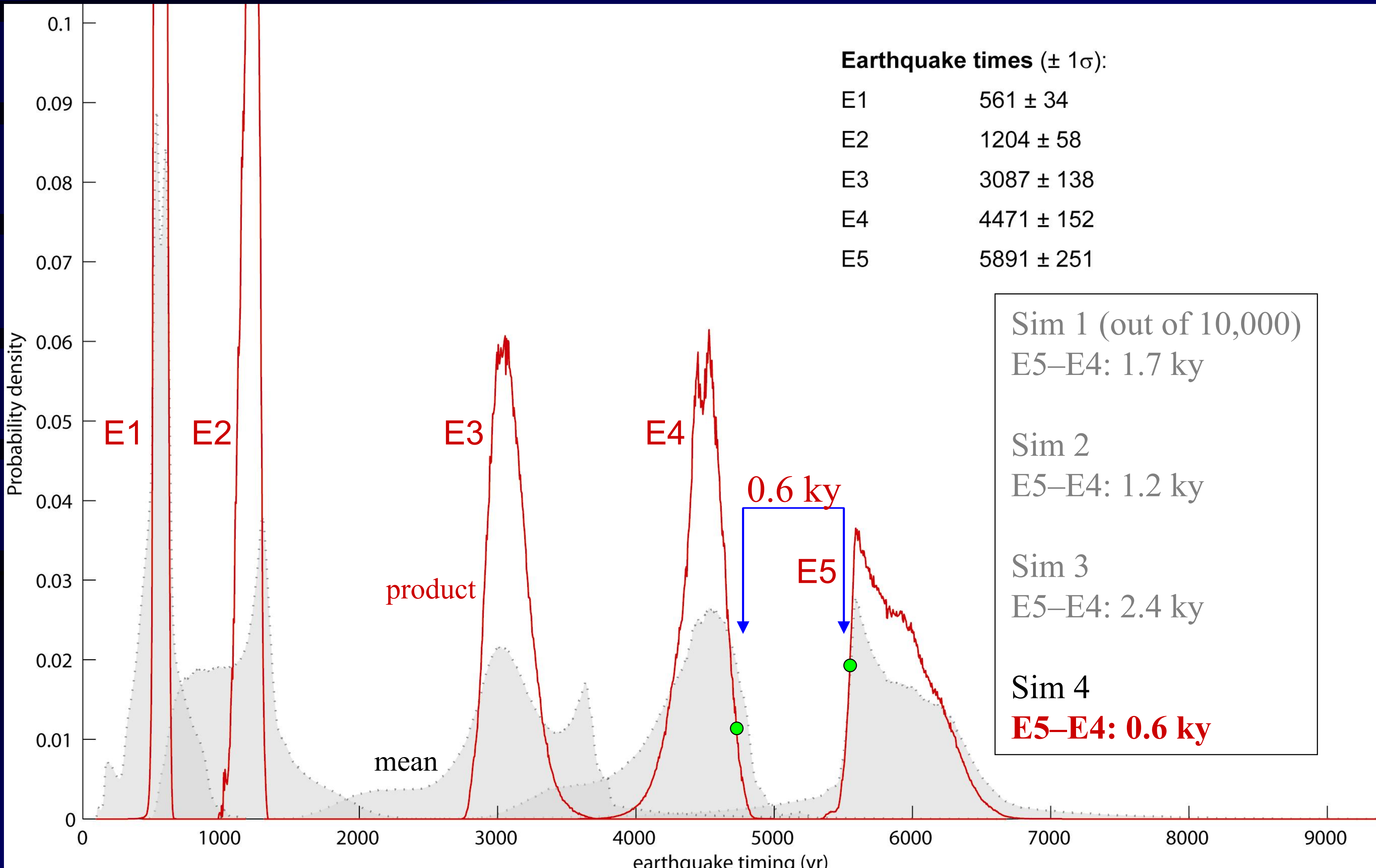
Example calculation – Weber segment



Example calculation – Weber segment

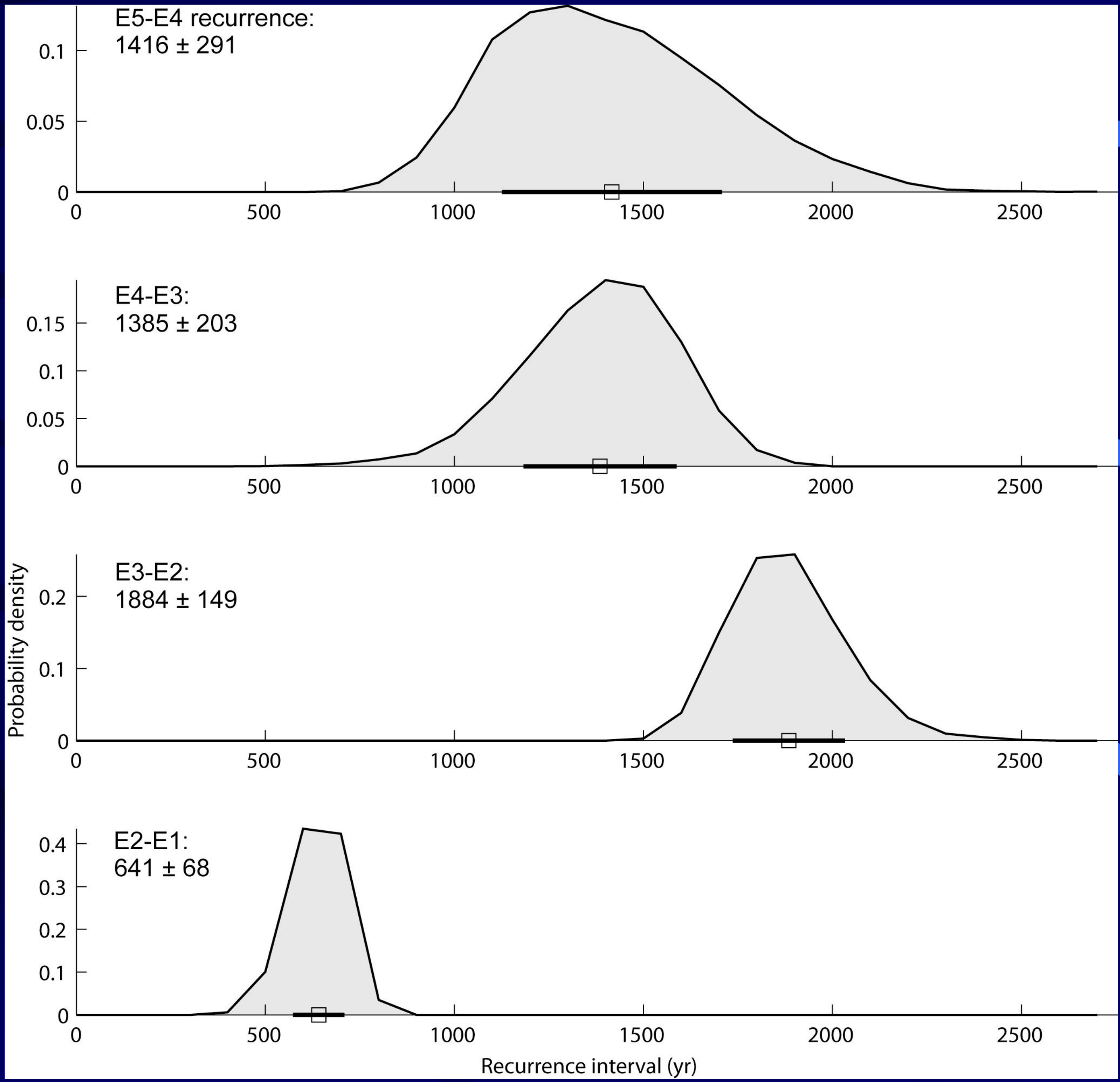


Example calculation – Weber segment



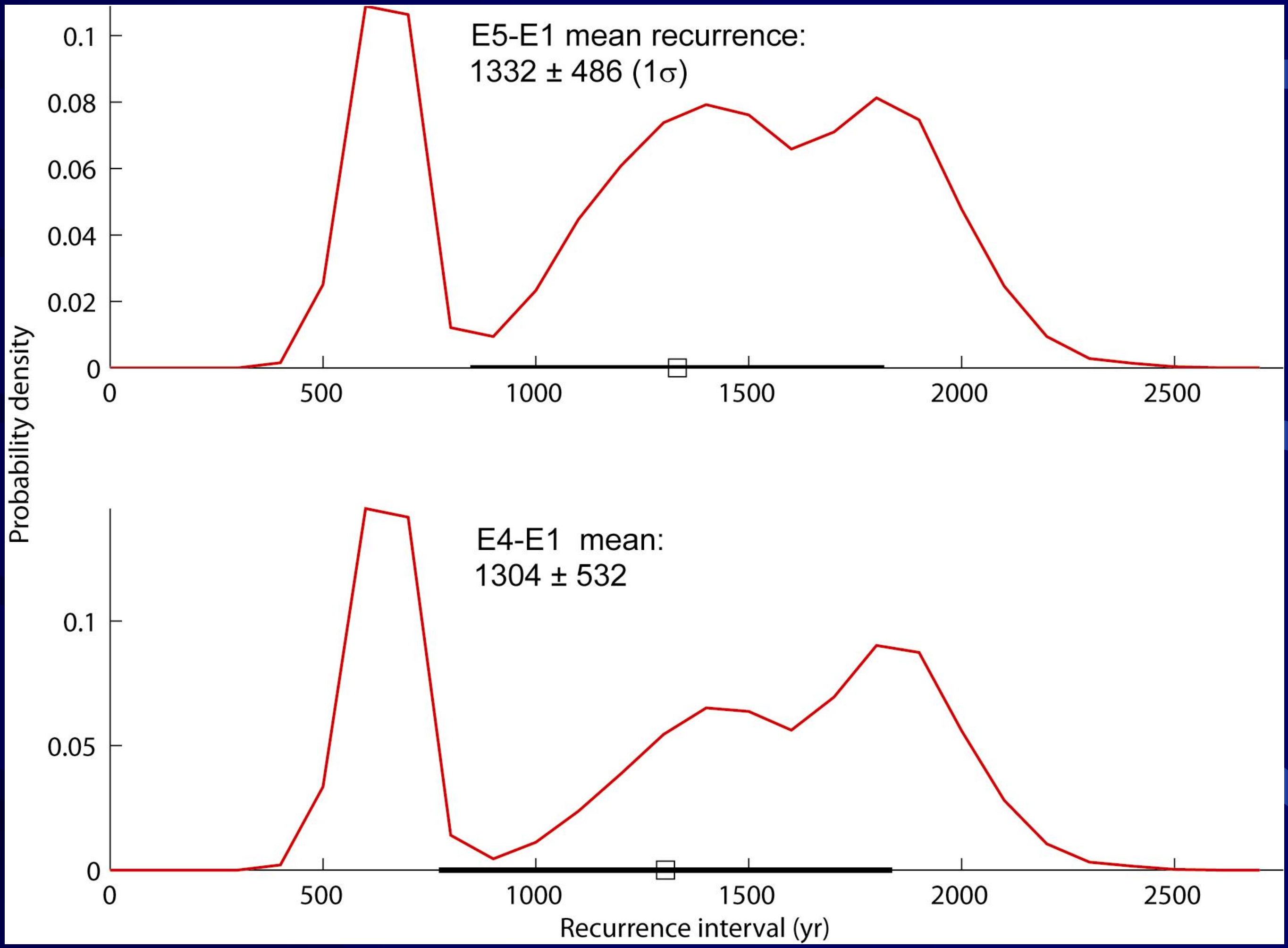
Example calculation – Weber segment

- Inter-event recurrence
  - Recurrence PDFs compiled from 10,000 simulations
  - Minimum recurrence: 300 ± 200 yr



Example calculation – Weber segment

- Average recurrence
  - Mean of inter-event recurrence PDFs (e.g., mean of E5-E4, E4-E3 … PDFs)
  - PDF shape – use mean or mode?



Approach – Step 5

5. Technical subgroup meeting (April, 2010)
   - Discuss details of paleoseismic data and OxCal models
   - Discuss correlation of events between sites
   - Consider completeness of paleoseismic record
   - Determine preferred earthquake timing and recurrence

Conclusions

- Need to include new data post UQFPWG (Lund, 2005)
  - Review of previous data necessary
  - Consistent treatment of legacy ages and modeling of site earthquake times (OxCal)
  - Unbiased determination of segment earthquake times (Matlab)
    - Product of site PDFs – objectively weight best-shaped pdfs
    - Error (in site pdfs) propagated through model (important for recurrence)
  - Result: refined earthquake times, recurrence intervals, and uncertainties

Conclusions

- <u>Not without challenges</u>
  - OxCal models are critically important
    - Stratigraphic model, ages, events, MRT correction not always straight forward (e.g., issue of skewing age toward max/min limiting ages)
    - Some sites are better suited to limiting earthquake times
  - Charcoal ages have their own issues (detrital, burrowed ages)
  - Conflicting data
    - Correlation of site PDFs between trenches
    - Multiple earthquake-correlation scenarios affect earthquake timing and recurrence estimates (and uncertainties)
    - Some average recurrence PDFs – bimodally distributed

Presentations of OxCal/Matlab Results

- <u>Presentations</u>
  1. Brigham City segment (DuRoss/Personius/Crone)
  2. Weber segment (DuRoss)

  (break)

  3. Salt Lake City segment (DuRoss)
  4. Provo segment (Olig)
  5. Nephi segment (Crone/Personius)

- Summary of previous data, remaining questions, OxCal models, correlation of events

- Revised earthquake timing and recurrence estimates

Summary of OxCal/Matlab results for the Brigham City segment

Chris DuRoss (UGS)

Steve Personius (USGS)

Tony Crone (USGS)

Susan Olig (URS)

Bill Lund (UGS)

Working Group on Utah Earthquake Probabilities, July, 2010

Brigham City segment (BCS)

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

Bowden Canyon

- Personius (1991)
  - One trench across single 8-m-high fault scarp
  - Older(?) fault splay 150 m to east not trenched (incomplete record?)
  - 3 events younger than 5-7 ka
  - Events broadly dated with 5 ^{14}C (bulk-soil) ages

Event	Personius (1991)	This study
BC1	-Not observed*	2.4 ± 1.0 ka (2σ)*
BC2	3.6 ± 0.5 ka	3.4 ± 0.5 ka
BC3	4.7 ± 0.5 ka	4.5 ± 0.6 ka
BC4	5–7 ka? (>4.7 ± 0.5)	5.8 ± 1.6 ka**

**BC1 (event Z of McCalpin and Forman (2002) not identified in the trench, but event age estimated in OxCal because event must have ruptured site (identified <2 km to the north and south at Kotter Canyon and Box Elder Delta trench sites)*

***using fan age estimate of 6.5 ± 1.5 ka as maximum*

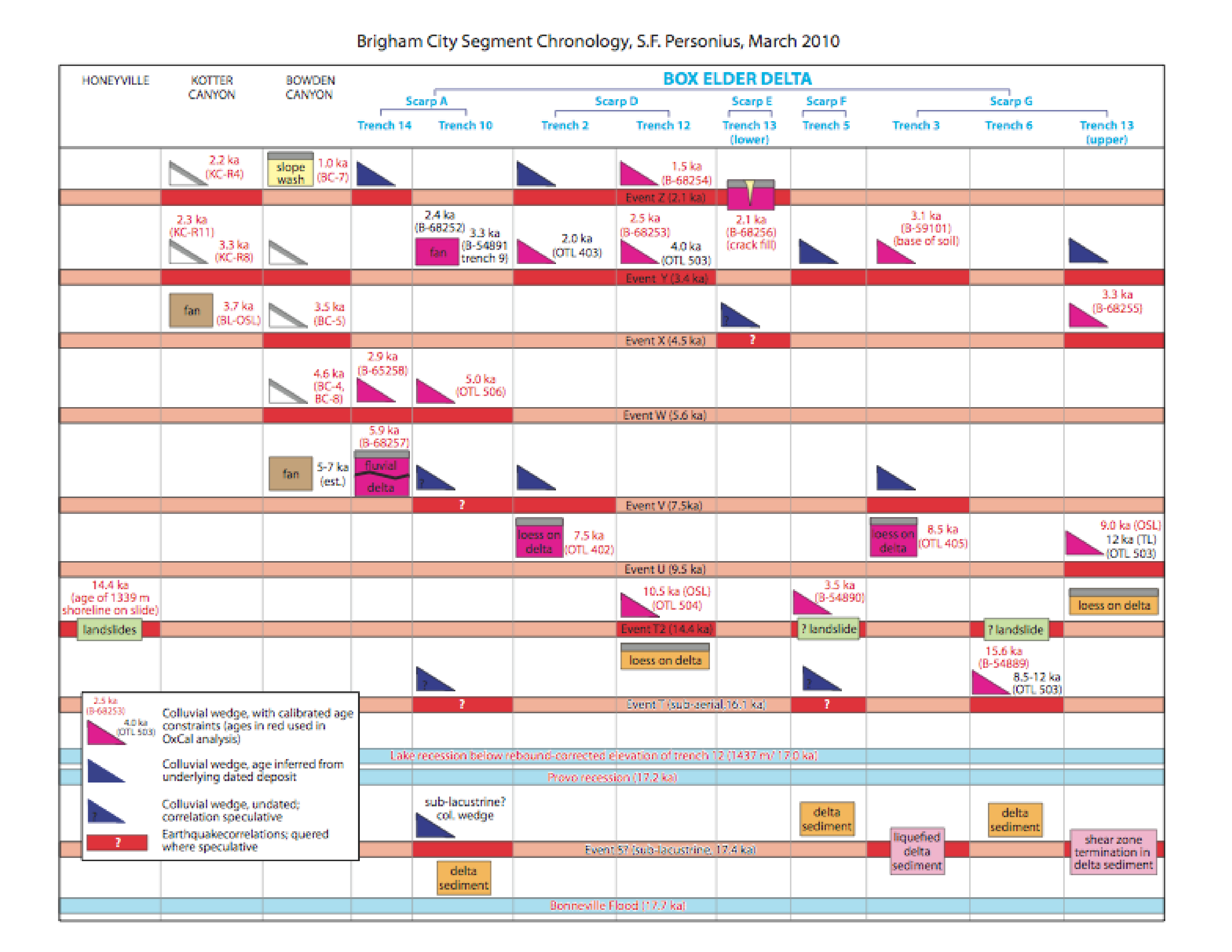
Pole Patch

- Personius (1991)
  - Three events
  - Only single radiocarbon age of ~4.6 ka constraining youngest event
  - Insufficient data to build OxCal model

Box Elder Delta

- McCalpin and Forman (2002)
  - 14 trenches across 8 scarps in complex zone on Provo delta surface
  - Not all scarps trenched
  - 7 or 8 documented post-Provo paleoearthquakes
  - Last 6 events better dated
  - Earthquake timing based on luminescence and ^{14}C bulk soil ages
  - MRE ~2 ka at Delta not observed at Bowden Canyon
  - Event BC3 (event X) not observed in Delta trenches
  - Numerous "orphan" (undated) colluvial wedges
  - Luminescence ages have large (0.5-1.5 ky) uncertainties

Box Elder Delta chronology



Box Elder Delta

Event	McCalpin & Forman	This study
BE1 (Z)	2.1 ± 0.1 (2σ?)	2.2 ± 0.6 (2σ)
BE2 (Y)	3.4 ± 0.1	3.2 ± 0.5
BE3 (X)	4.7 ± 0.1*	4.4 ± 1.1
BE4 (W)	6.0 ± 0.2	5.7 ± 0.7
BE5 (V)	7.5 ± 1.0	7.7 ± 1.5
BE6 (U)	8.5 ± 0.8	9.5 ± 2.2
BE7 (T)	15.4 ± 1.7	not used in analysis**

- OxCal model
  - Similar age estimates but OxCal results have larger (more realistic?) uncertainties
  - *Event X not observed at site, but included in chronology by McCalpin and Forman (2002)
  - **Event T not included in OxCal analysis because of poor age constraints and doubts about completeness of paleoseismic record

Hansen Canyon

- UGS/USGS (2008)
  - Two trenches across single 4-m-high scarp
  - One event between about 2 and 6 ka
  - Broad age range from lack of minimum age constraints and recycled detrital charcoal in soil
  - Event could correlate with several Box Elder Canyon events

Kotter Canyon

- UGS/USGS (2008)
  - One trench across single 8-m-high scarp
  - 2 events post-date ~3.7 ka, OSL-dated fan deposits
  - 5 AMS 14C ages on charcoal concentrated from bulk soil samples used in OxCal analysis

Event	This study
KC1	2.5 ± 0.3 ka (2σ)
KC2	3.5 ± 0.3 ka

- OxCal model
  - Similar age estimates to Bowden Canyon and Box Elder Delta but smaller uncertainties

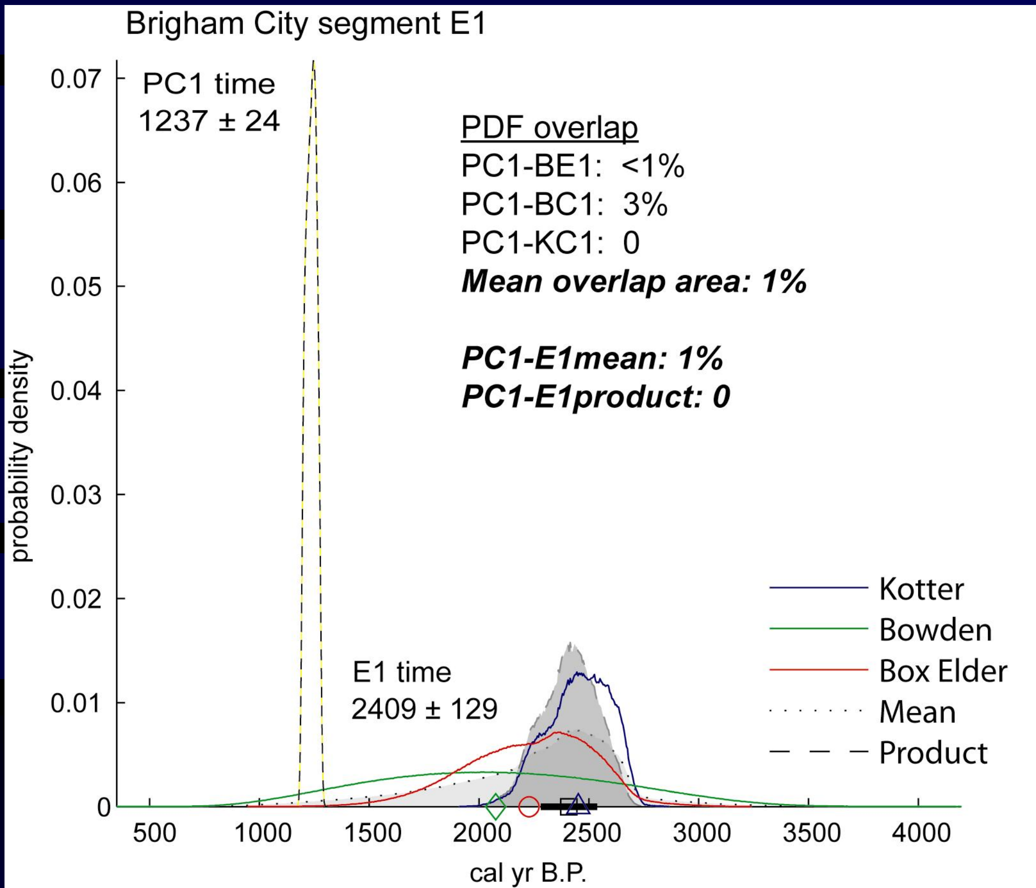
Pearsons Canyon

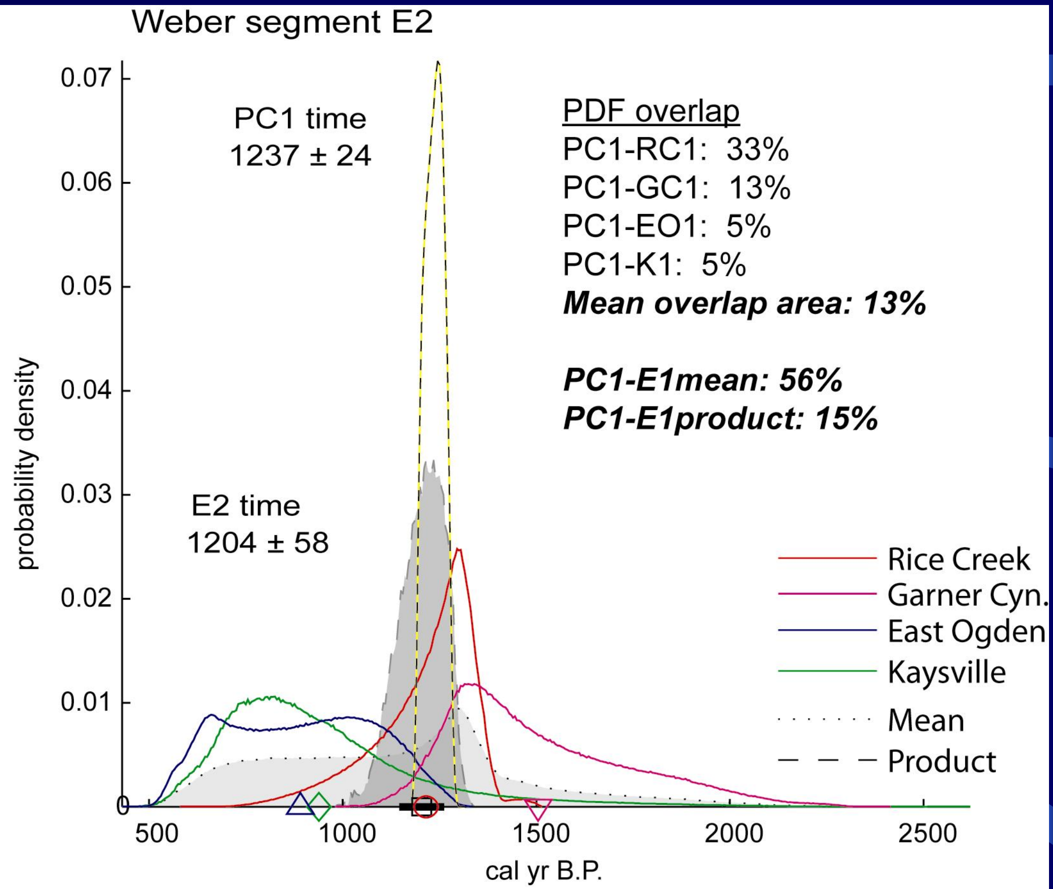
- UGS/USGS (2008)
  - Site located 6 km north of Brigham City/Weber segment boundary
  - Two trenches across 1- to 3-m high scarp on mid- to late-Holocene fan deposits
  - MRE tightly constrained with 6 AMS 14C ages on charcoal concentrated from bulk soil samples

Event	This study
PC1	1.2 ± 0.05 ka (2σ)

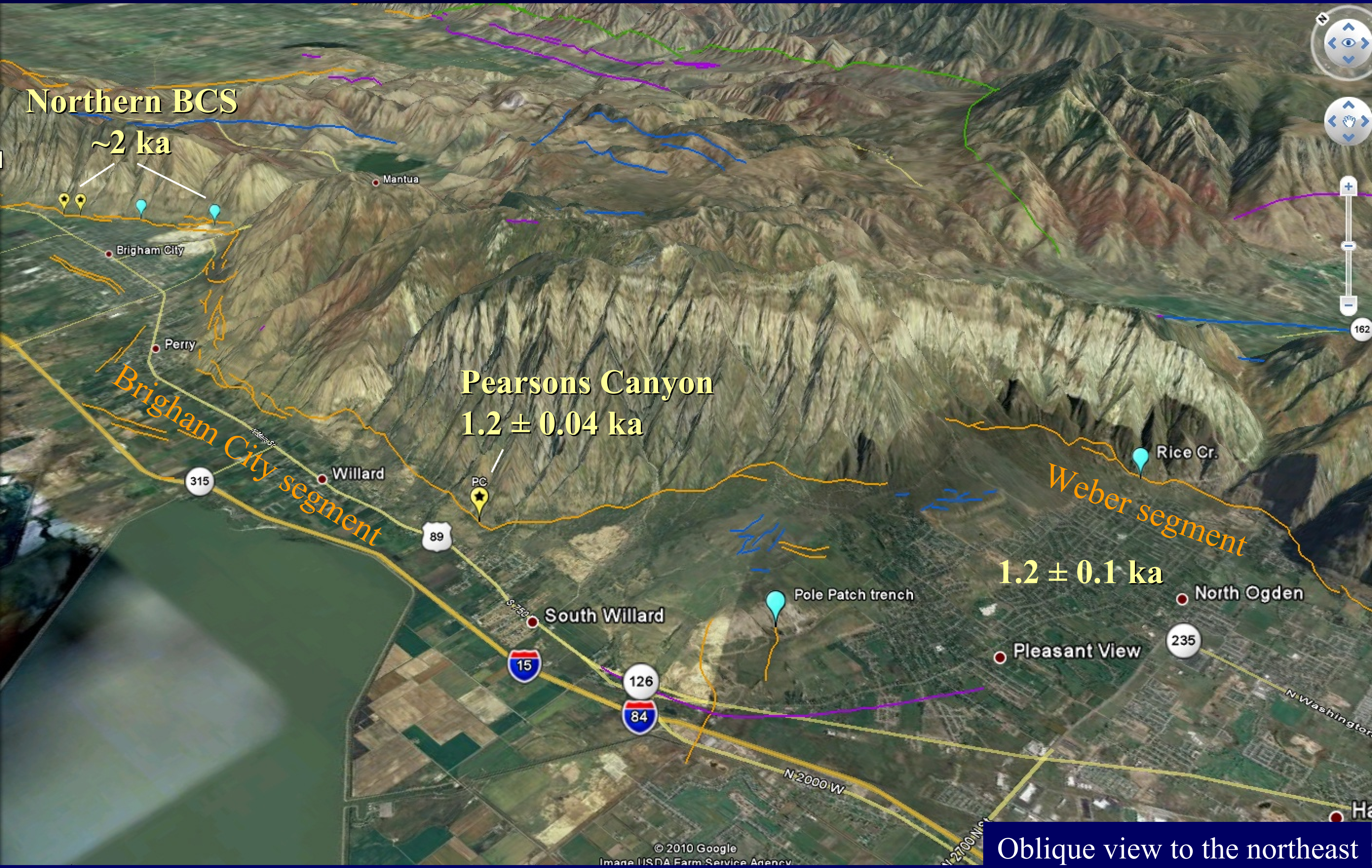
- OxCal model
  - MRE age much younger than in Brigham City area but consistent with age of penultimate event (W2) on adjacent Weber segment
  - Preliminary mapping suggests multi-segment rupture during PC1 may have extended north to the vicinity of Willard Canyon
  - Pearson Canyon MRE not included in BCS recurrence calculations

Pearsons Canyon correlation



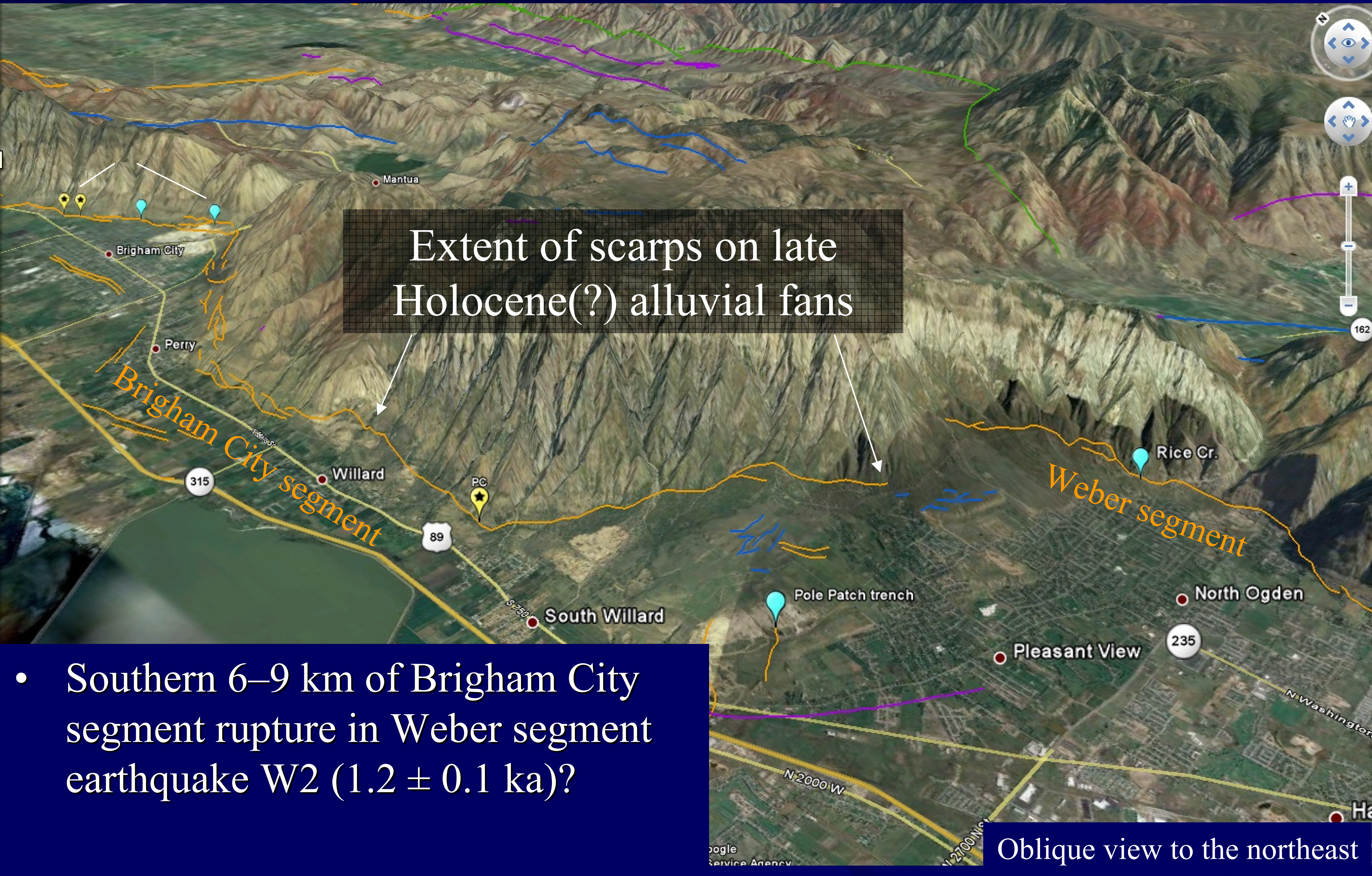


Pearsons Canyon



Oblique view to the northeast

Pearsons Canyon

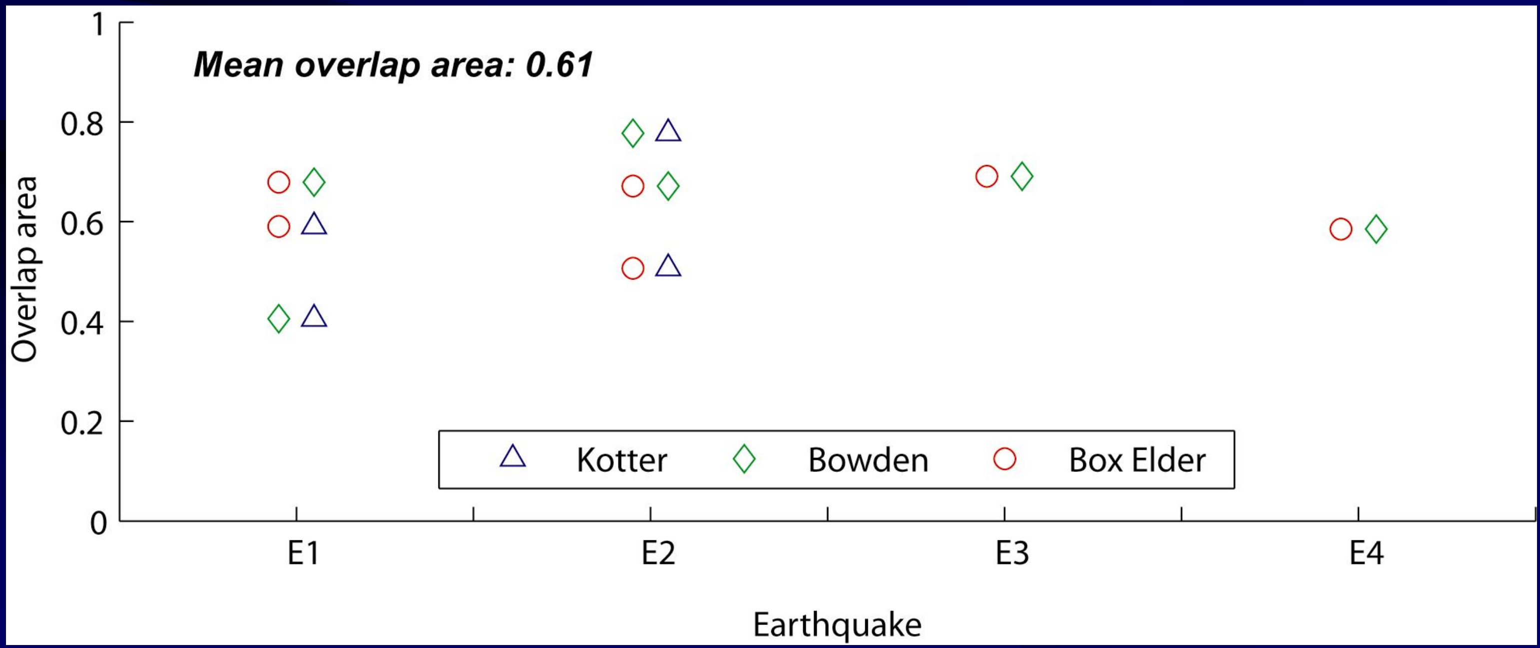


- Southern 6–9 km of Brigham City segment rupture in Weber segment earthquake W2 (1.2 ± 0.1 ka)?

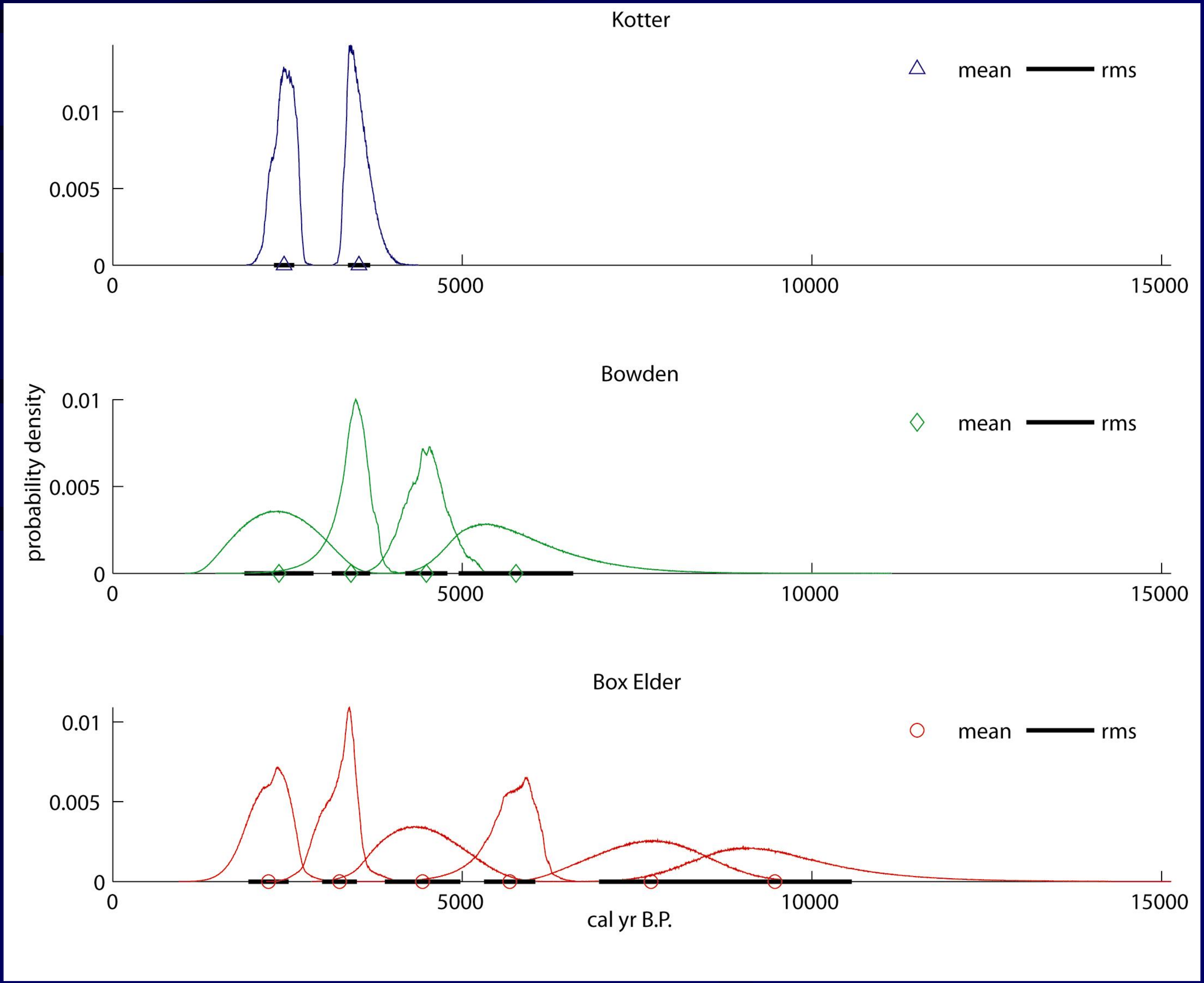
Oblique view to the northeast

BCS Correlation of events

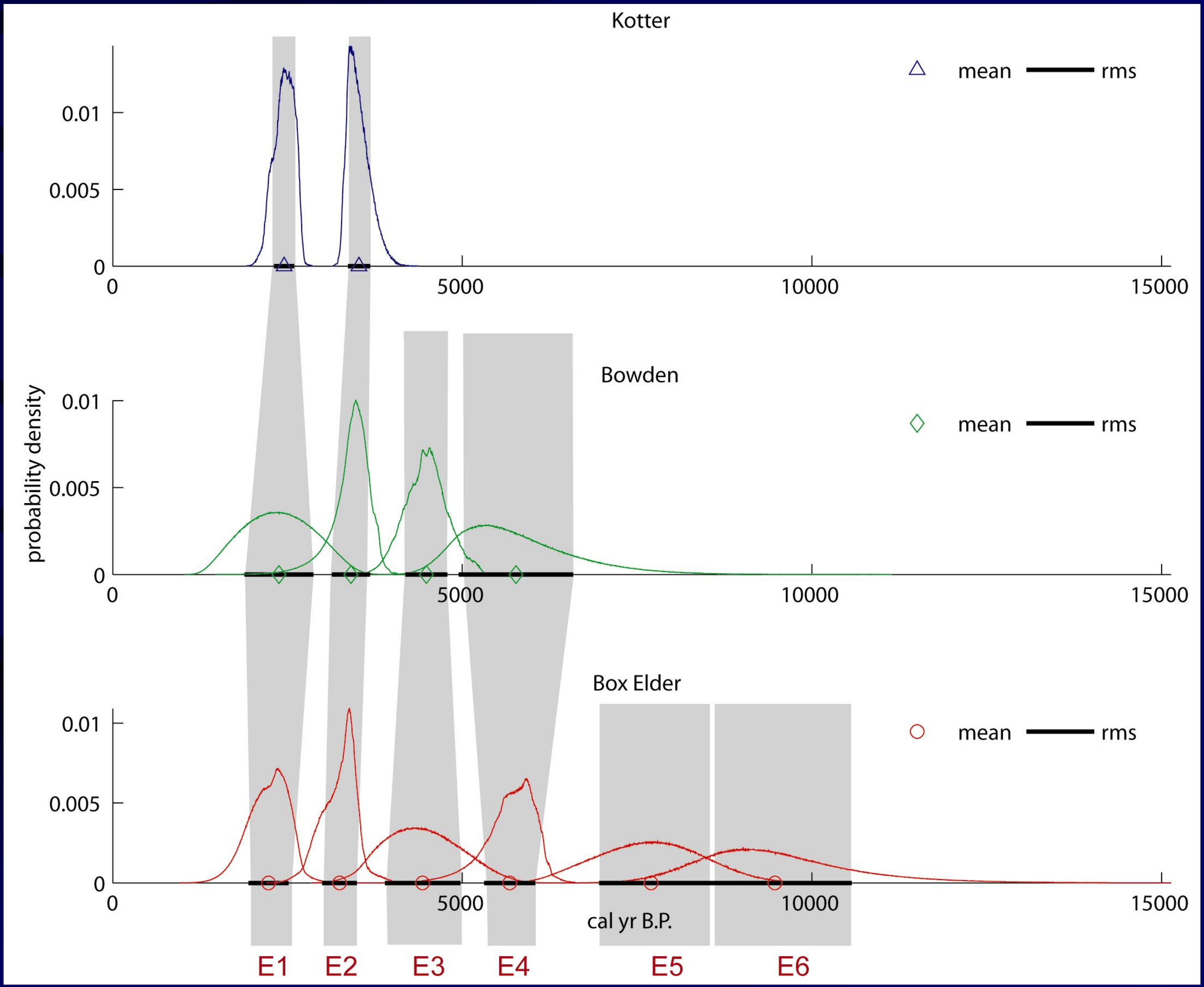
Event	Kotter	Bowden	Box Elder
E1	2.5 ± 0.3 ⟷	2.4 ± 1.0 ⟷	2.2 ± 0.6 (2σ)
E2	3.5 ± 0.3	3.4 ± 0.5	3.2 ± 0.5
E3	-	4.5 ± 0.6	4.4 ± 1.0
E4	-	5.8 ± 1.6	5.7 ± 0.7
E5	-	-	7.7 ± 1.5
E6	-	-	9.5 ± 2.2



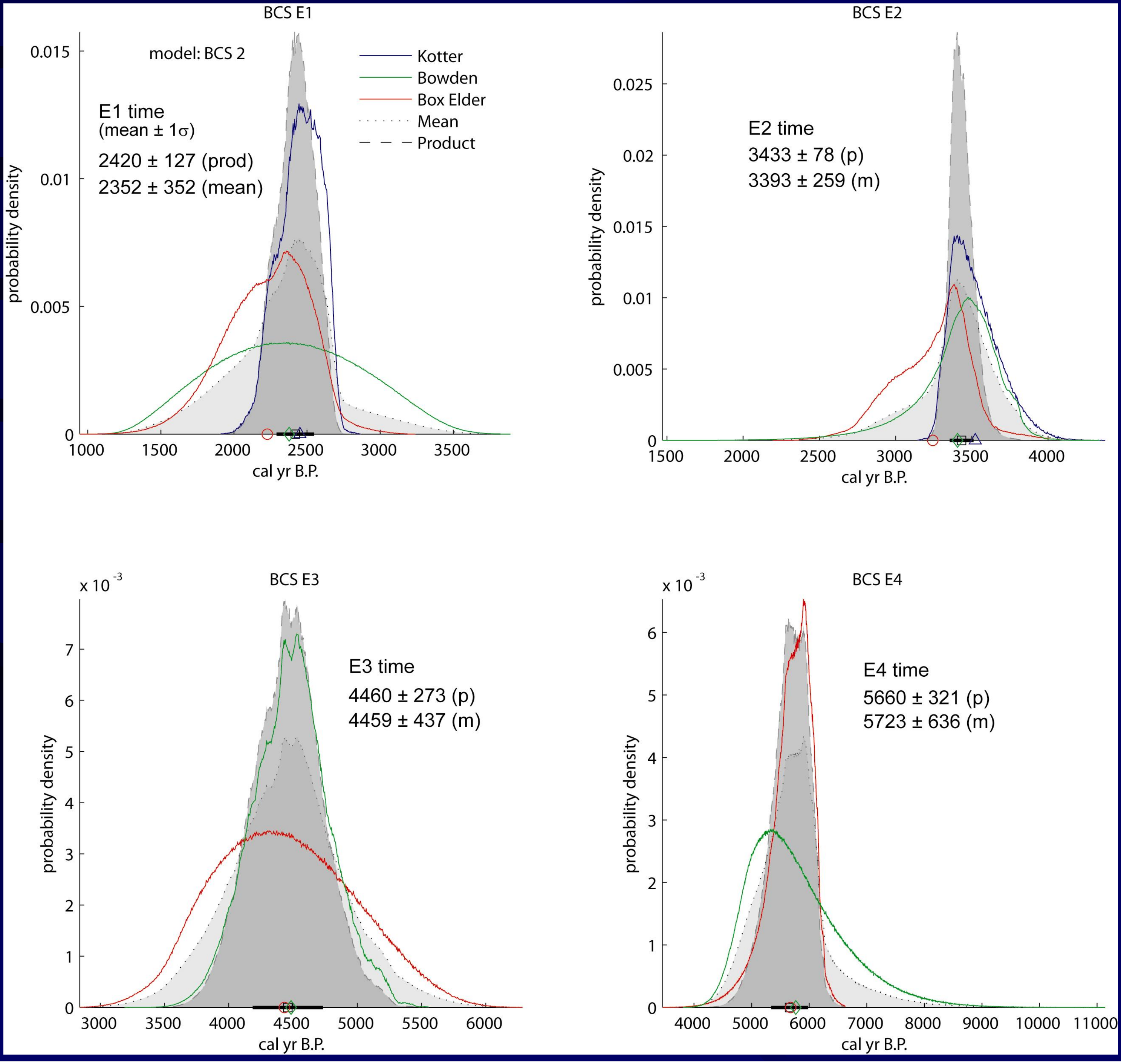
Matlab plot of BCS site PDFs



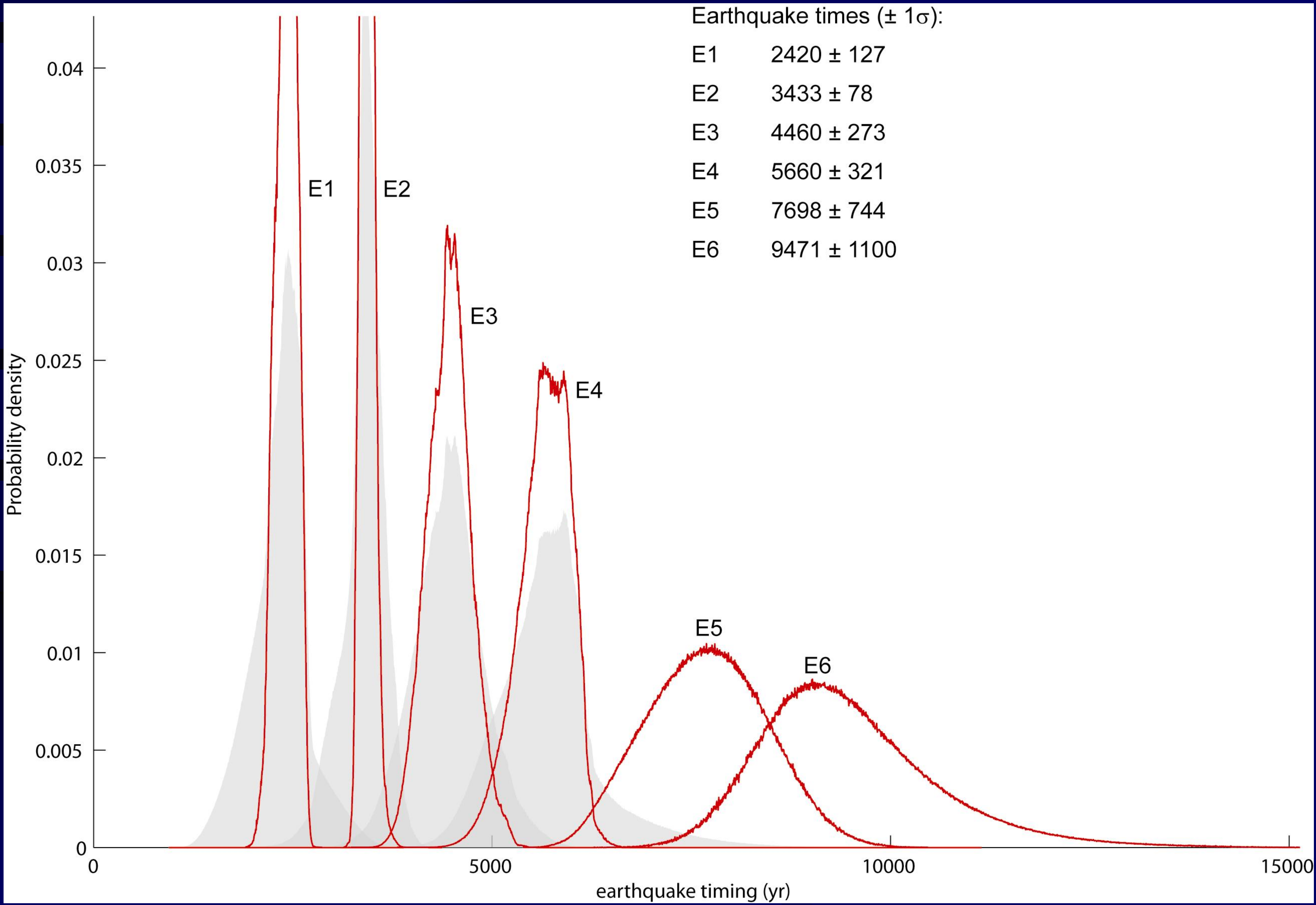
Correlation of BCS site PDFs



Matlab timing refinement-segment PDFs

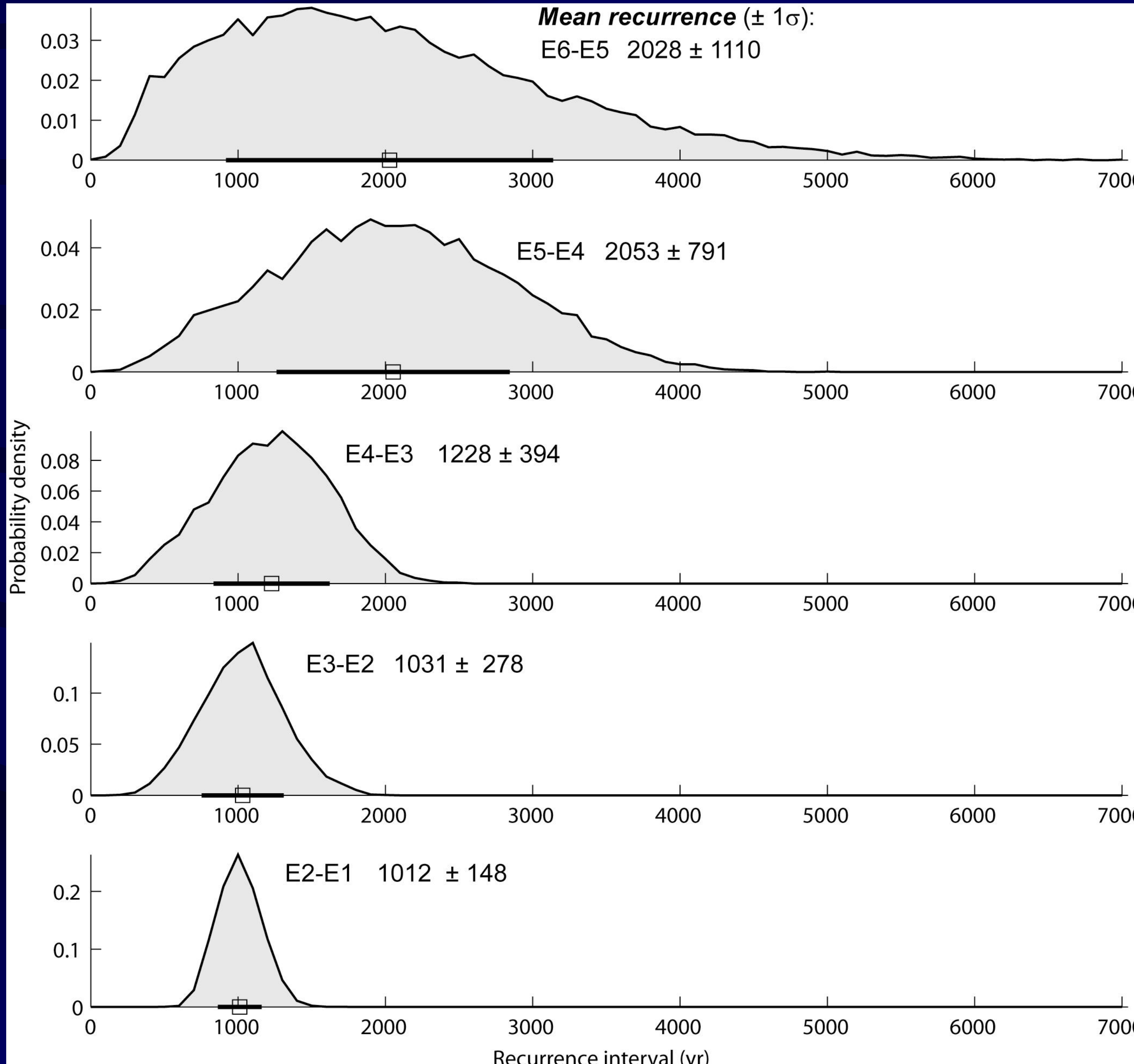


BCS earthquake history



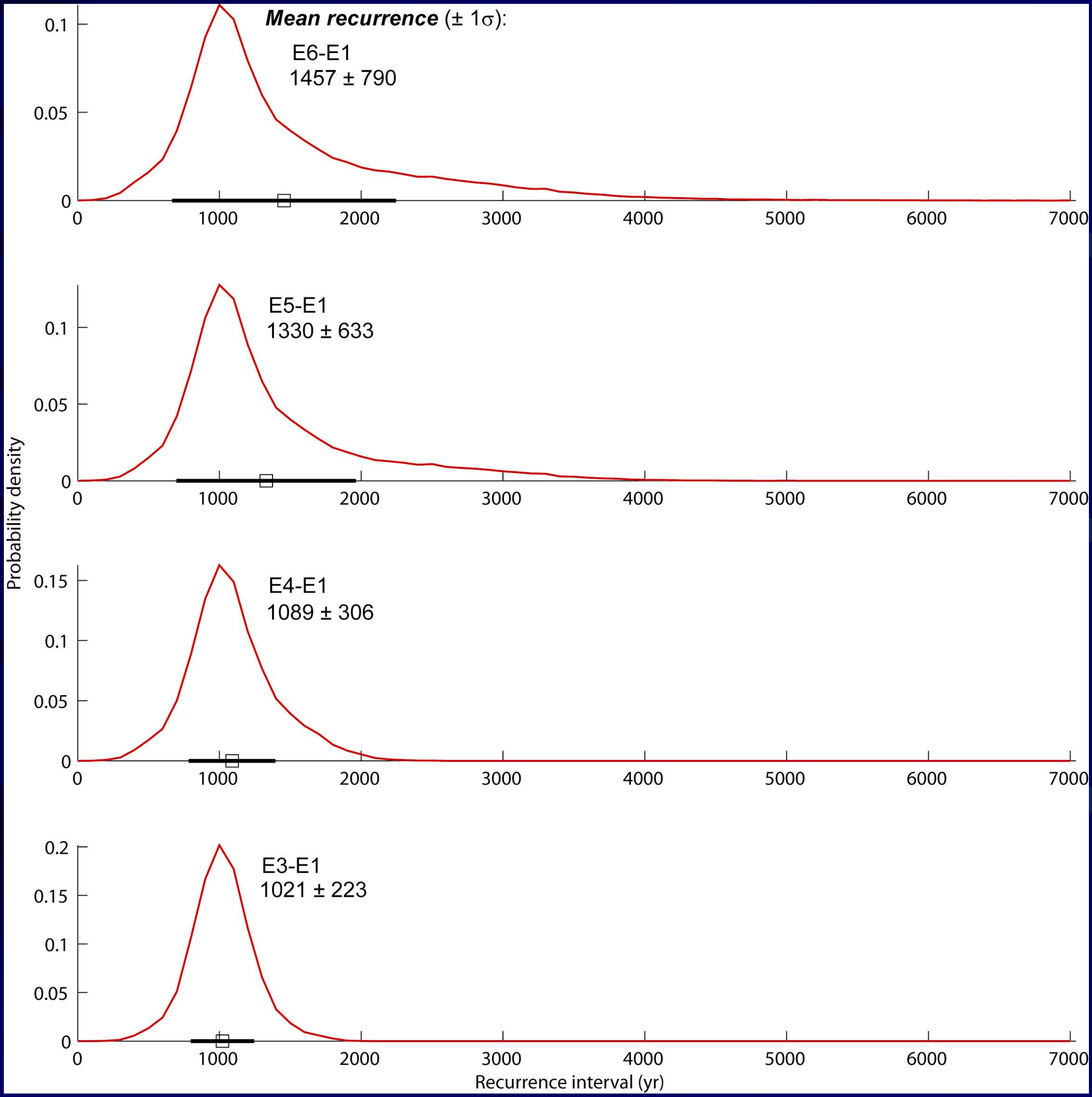
Recurrence

- Inter-event recurrence
  - E4-E1: near-uniform (1.0-1.2 ky) recurrence with smaller (~0.15-0.4 ky) uncertainties
  - E6-E4: Longer (~2 ky) recurrence with larger uncertainties (0.8-1.1 ky)



Recurrence

- Average recurrence
  - E6-E1: 1.5 ± 0.8 (1σ)
  - E5-E1: 1.3 ± 0.6 (1σ)



Summary of results

	Kotter	Bowden	Box Elder		Pearsons
E1	2.5 ± 0.3	2.4 ± 1.0	2.2 ± 0.6	— X —	1.2 ± 0.05
E2	3.5 ± 0.3	3.4 ± 0.5	3.2 ± 0.5		
E3		4.5 ± 0.6	4.4 ± 1.0		
E4		5.8 ± 1.6	5.7 ± 0.7		
E5			7.7 ± 1.5		
E6			9.5 ± 2.2		

All time ranges: ka ± 2 sigma

Summary of results

	Kotter	Bowden	Box Elder	Matlab model (ka)
E1	2.5 ± 0.3	2.4 ± 1.0	2.2 ± 0.6	2.4 ± 0.3
E2	3.5 ± 0.3	3.4 ± 0.5	3.2 ± 0.5	3.4 ± 0.2
E3		4.5 ± 0.6	4.4 ± 1.0	4.5 ± 0.6
E4		5.8 ± 1.6	5.7 ± 0.7	5.7 ± 0.6
E5			7.7 ± 1.5	7.7 ± 1.5
E6			9.5 ± 2.2	9.5 ± 2.2

All time ranges: ka ± 2 sigma

Summary of results

	Matlab (ka)	**OxCal** (combined)	**UQFPWG**
E1	2.4 ± 0.3	2.1 ± 0.3	2.1 ± 0.8 ka
E2	3.4 ± 0.2	3.4 ± 0.2	3.45 ± 0.3
E3	4.5 ± 0.6	4.5 ± 0.6	4.65 ± 0.5
E4	5.7 ± 0.6	5.6 ± 0.7	5.95 ± 0.25
E5	7.7 ± 1.5	7.5 ± 1.6	7.5 ± 1.0
E6	9.5 ± 2.2	9.5 ± 3.0	8.5 ± 1.5

(All time ranges: ka ± 2 sigma)

Comparison with previous studies

- Recurrence estimates:
  - This study: 1.3 ± 0.6 ky (1σ)

  - Previously reported recurrence estimates:
    - Bowden Canyon: 1.1 ± 1.0 ky (BC2[E3] – BC1[E1])
    - Box Elder Canyon: 1.3 ky (1.0–1.5 ky range) (BE6 – BE1)

    - McCalpin & Nishenko: 1.3 ± 0.1 ky (E5 – E1)
    - UQFPWG: 1.3 ky (0.5–2.8 ky estimated 2-sigma range)

Conclusions

- <u>OxCal</u>
  - Differences in event times related to using minimum and maximum limiting ages in OxCal versus only min or max ages in previous studies.
    - Bowden Canyon: ~200 yr difference
    - Box Elder: most ~100-300 yr difference (E6[U] ~1000 yr difference)

- <u>Correlation of events</u>
  - Correlations in at least two trenches of four youngest events near Brigham City
  - Most-recent event at Pearsons (~1.2 ka) separate, younger event than ~2-ka MRE near Brigham City
  - Partial rupture of southern Brigham City segment in a Weber segment earthquake W2 at 1.1–1.3 ka

Conclusions

- Earthquake timing (segment PDFs)
  - E1 fairly well constrained: ± 0.3 ka (2σ) vs. ± 0.8 ka of UQFPWG
    - E1 elapse time: 2480 ± 260 yr (2σ)
  - E4 to E2 moderately well constrained, good agreement between models (but broad site PDFs)
  - E6 and E5 poorly constrained – only identified at single site

- Average recurrence
  - Moderately well constrained to 1.3 ± 0.6 ky (1σ) (E5–E1)
  - Not bimodally distributed!
  - Final estimate similar to all previously reported values

Summary of OxCal/Matlab results for the Weber segment

Chris DuRoss (UGS)

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Tony Crone (USGS)

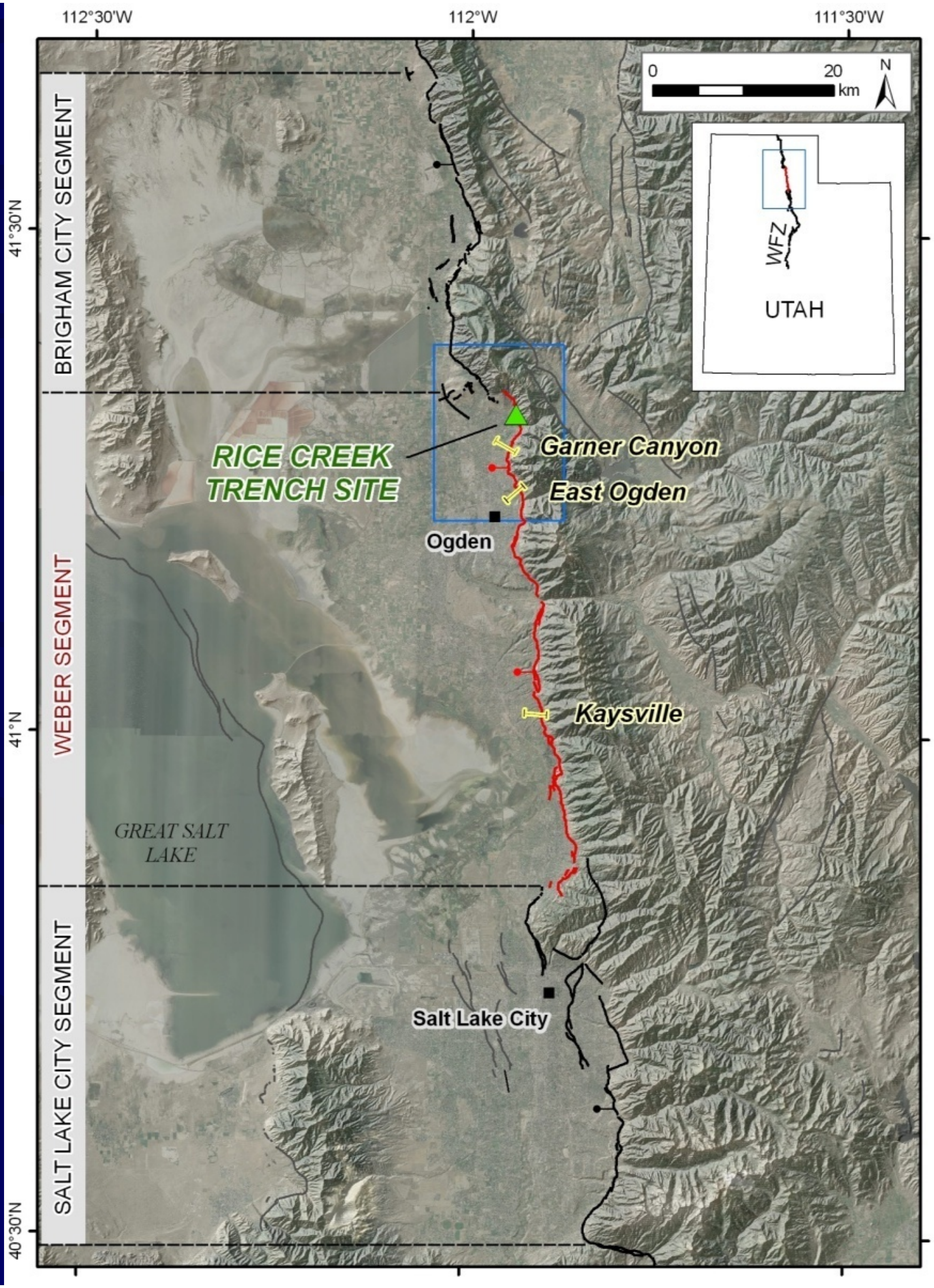
Susan Olig (URS)

Bill Lund (UGS)

Working Group on Utah Earthquake Probabilities, July, 2010

Weber segment

- Paleoseismic studies:
  - Rice Creek (RC) (DuRoss et al., 2009)
  - Garner Canyon (GC) (Nelson et al., 2006)
  - East Ogden (EO) (Nelson et al., 2006)
  - Kaysville (K) (Swan et al., 1981; McCalpin et al., 1994)



Kaysville

<u>Kaysville trench investigations:</u>

- Swan et al. (1981)
  - 3 or more events at site
  - Only single radiocarbon age of ~1.5 ka constraining 2+ events

- McCalpin et al. (1994)
  - Reoccupied Swan site
  - 5-6 events post Provo shoreline; youngest 3 occurred after ~5–7 ka
  - Good timing control for youngest event
  - Only maximum ages for 2^{nd} and 3^{rd} events

Kaysville

Paleoseismic data (pre 2007):

Garner Cyn (GC)	***East Ogden (EO)***	***Kaysville (K)***
GC1: ~0.4–1.4 ka	EO1: 0.2–0.6 ka	K1: before 0.6–0.8 ka
GC2: 1.2–2.8 ka	EO2: 0.5–1.7 ka	K2: 2.8 ± 0.7 ka
GC3: 2.3–4.0 ka	EO3: 2.4–3.9 ka	K3: ~3.8–7.9 ka
GC4: unknown	EO4: 2.8–4.8 ka	

Kaysville

Previous interpretation:

Garner Cyn (GC)	*East Ogden (EO)*	*Kaysville (K)*
GC1: ~0.4–1.4 ka	EO1: 0.2–0.6 ka	K1: before 0.6–0.8 ka
GC2: 1.2–2.8 ka	EO2: 0.5–1.7 ka	K2: 2.8 ± 0.7 ka
GC3: 2.3–4.0 ka	EO3: 2.4–3.9 ka	K3: ~3.8–7.9 ka
GC4: unknown	EO4: 2.8–4.8 ka	

- McCalpin et al./Nelson et al.:
  - – 500-yr most recent event (MRE) at East Ogden (EO1) did not rupture Kaysville MRE (K1 at > ~600-800 yr)
  - – EO2–EO4 correlate with GC1–GC3 and K1–K2

Kaysville

Previous interpretation:

Garner Cyn (GC)	*East Ogden (EO)*	*Kaysville (K)*
GC1: ~0.4–1.4 ka	EO1: 0.2–0.6 ka	K1: before 0.6–0.8 ka
GC2: 1.2–2.8 ka	EO2: 0.5–1.7 ka	K2: 2.8 ± 0.7 ka
GC3: 2.3–4.0 ka	EO3: 2.4–3.9 ka	K3: ~5–7 (3.8–7.9?) ka
GC4: unknown	EO4: 2.8–4.8 ka	

- McCalpin et al./Nelson et al.:
  - – EO4 at ~3–5 ka did not rupture Kaysville site
  - – K3 at ~5–7 ka predates EO4

Kaysville

Our interpretation: (based on OxCal results)

	Rice Creek (RC)		GC		EO		K
E1:	0.6 ± 0.1 (2σ)	⟷	0.6 ± 0.4	⟷	0.4 ± 0.2	⟷	0.6 ± 0.2
E2:	1.2 ± 0.2	⟷	1.5 ± 0.5	⟷	0.9 ± 0.4	⟷ ?	0.9 ± 0.5
E3:	3.4 ± 0.7	⟷	3.2 ± 0.6	⟷	3.0 ± 0.4	⟷	2.8 ± 1.7
E4:	4.6 ± 0.5	⟷	4.4 ± 0.6	⟷	4.0 ± 0.9	?	-
E5:	6.0 ± 1.0	⟷					5.8 ± 1.3

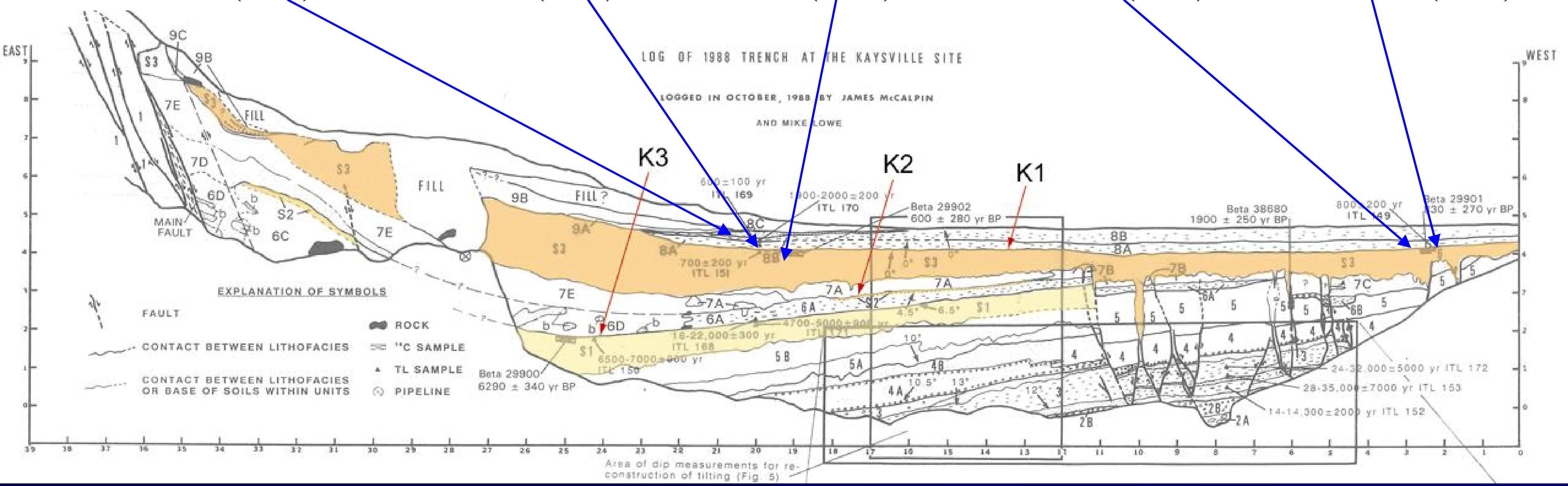
(All time ranges to 2 sigma)

- 5 events correlate across segment
  - MRE (E1) at 500–600 yr
  - Evidence for rupture of E2 at Kaysville
  - Oldest Kaysville event (5.8 ka) likely corresponds with oldest Rice Creek event (~6 ka)

Kaysville – McCalpin (1994)

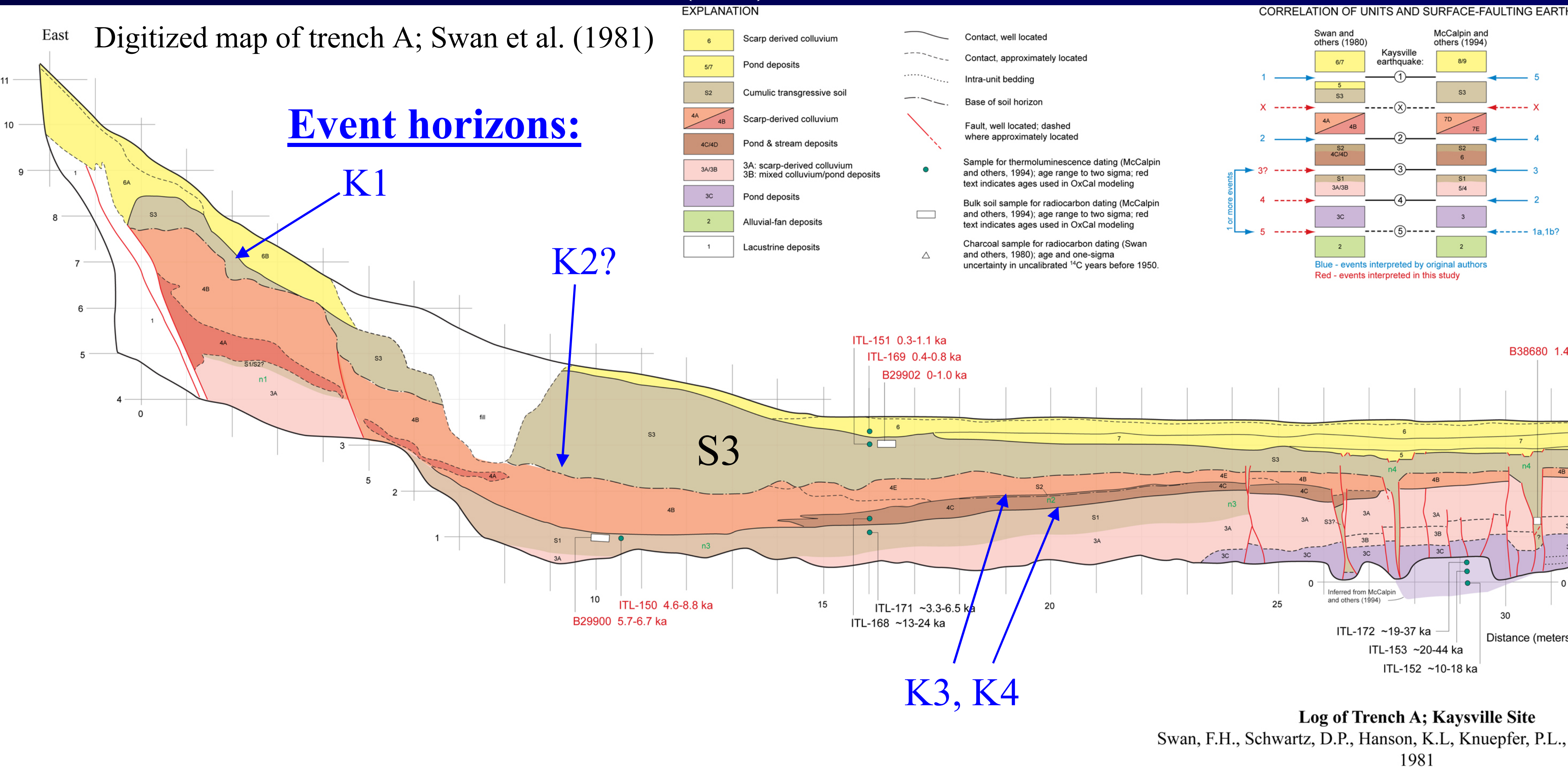
- <u>Basis for younger MRE (K1) at ~600 years:</u>
  - K1: older than 0.4–0.6 ka, younger than ~0.3–1.3 ka (2σ)
  - OxCal age is nearly identical if graben ages are excluded

>0.4–0.8 ka(ITL) <0.3–1.0 ka(ITL) <0–1.0 ka(C14) <0.4–1.2 ka(ITL) <0.5–1.3 ka(C14)



Kaysville – Swan (1981)

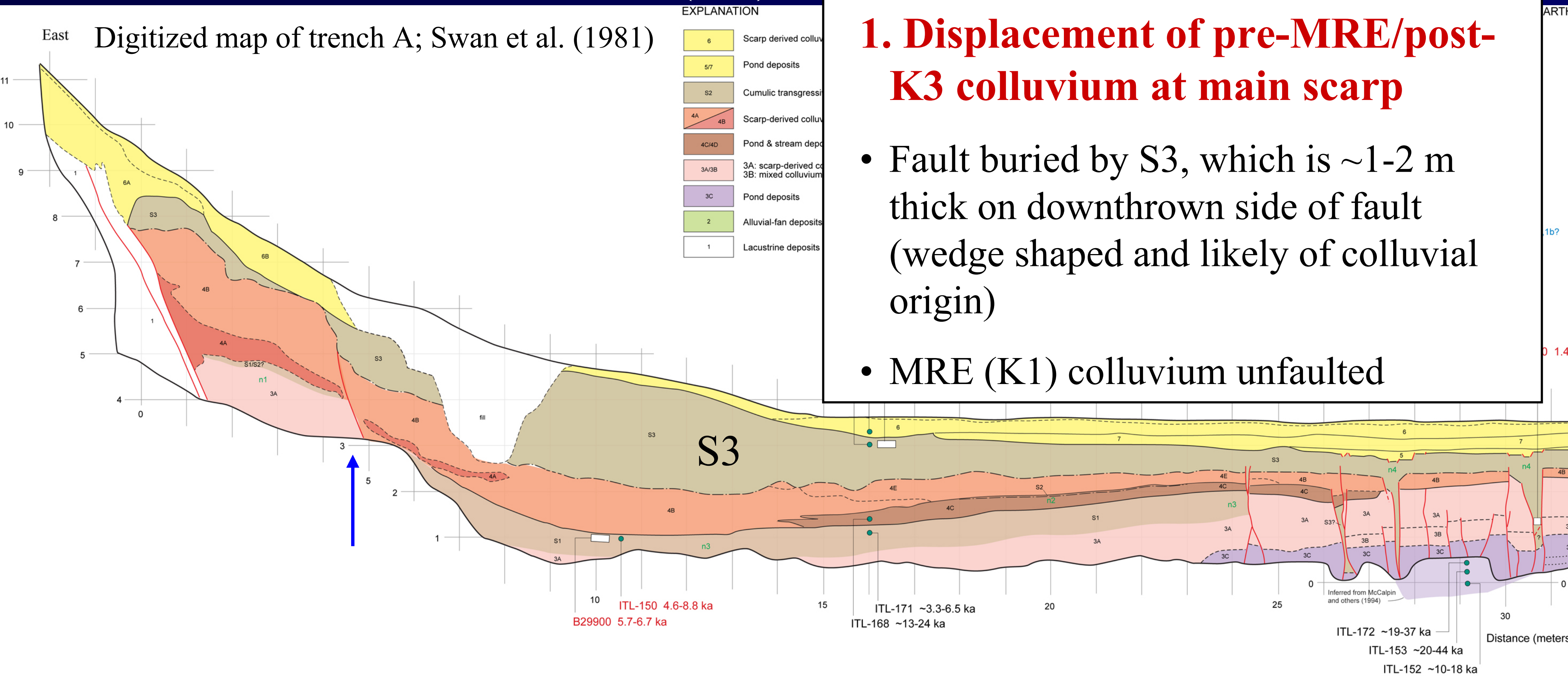
- Basis for additional event (K2)



Kaysville – Swan (1981)

- Basis for additional event (K2)

Digitized map of trench A; Swan et al. (1981)



1. Displacement of pre-MRE/post-K3 colluvium at main scarp

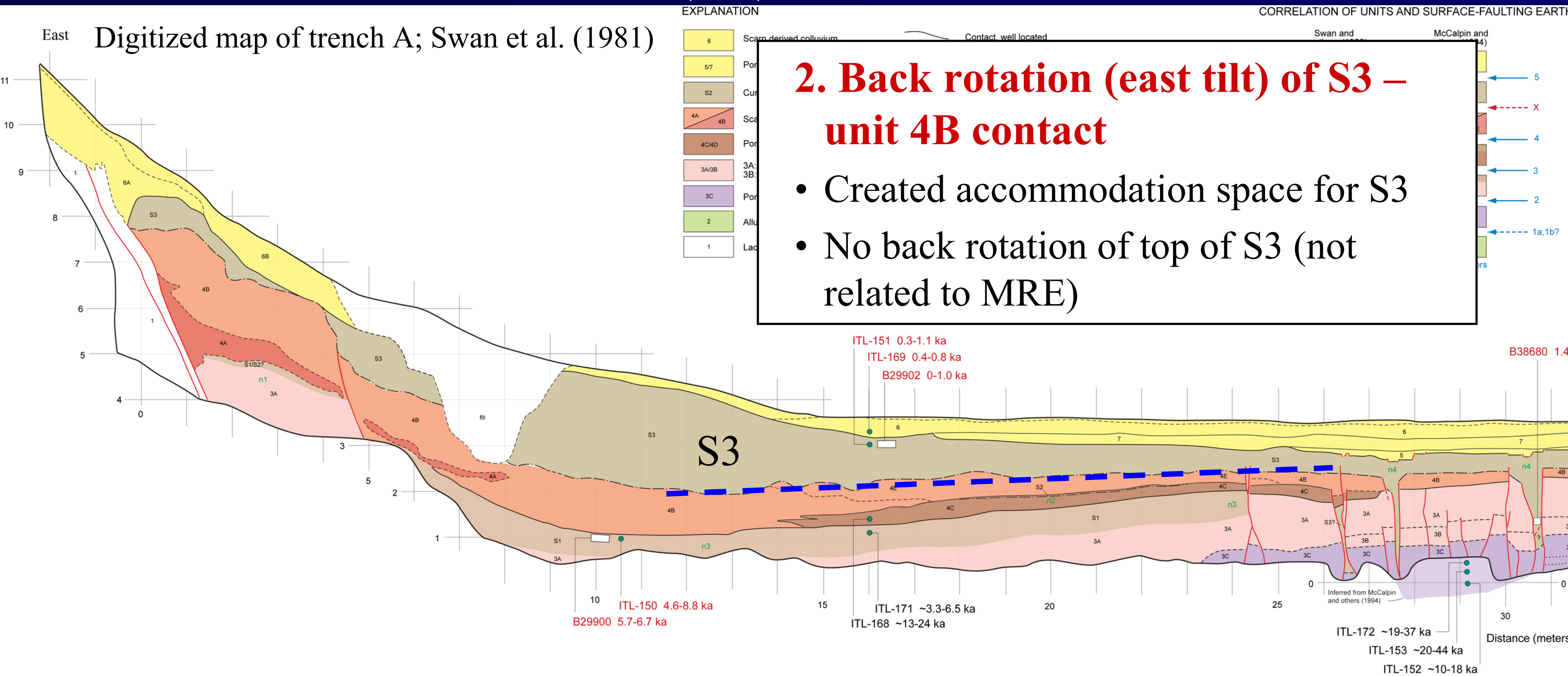
- Fault buried by S3, which is ~1-2 m thick on downthrown side of fault (wedge shaped and likely of colluvial origin)
- MRE (K1) colluvium unfaulted

Log of Trench A; Kaysville Site
Swan, F.H., Schwartz, D.P., Hanson, K.L, Knuepfer, P.L., 1981

Kaysville – Swan (1981)

- Basis for additional event (K2)

Digitized map of trench A; Swan et al. (1981)



2. Back rotation (east tilt) of S3 – unit 4B contact

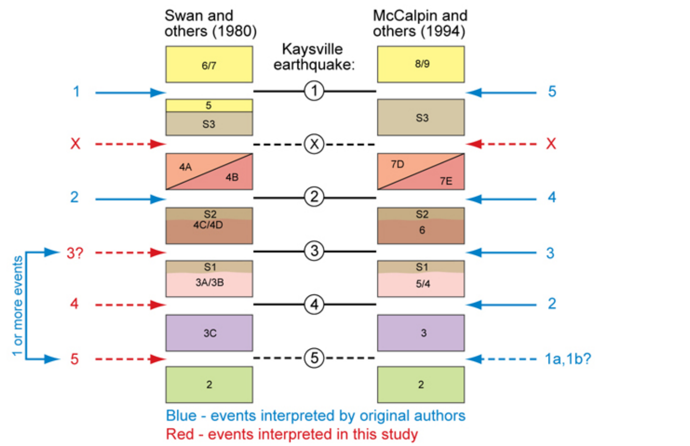
- Created accommodation space for S3
- No back rotation of top of S3 (not related to MRE)

Log of Trench A; Kaysville Site

Swan, F.H., Schwartz, D.P., Hanson, K.L, Knuepfer, P.L., 1981

Kaysville – Swan (1981)

CORRELATION OF UNITS AND SURFACE-FAULTING EARTHQUAKES

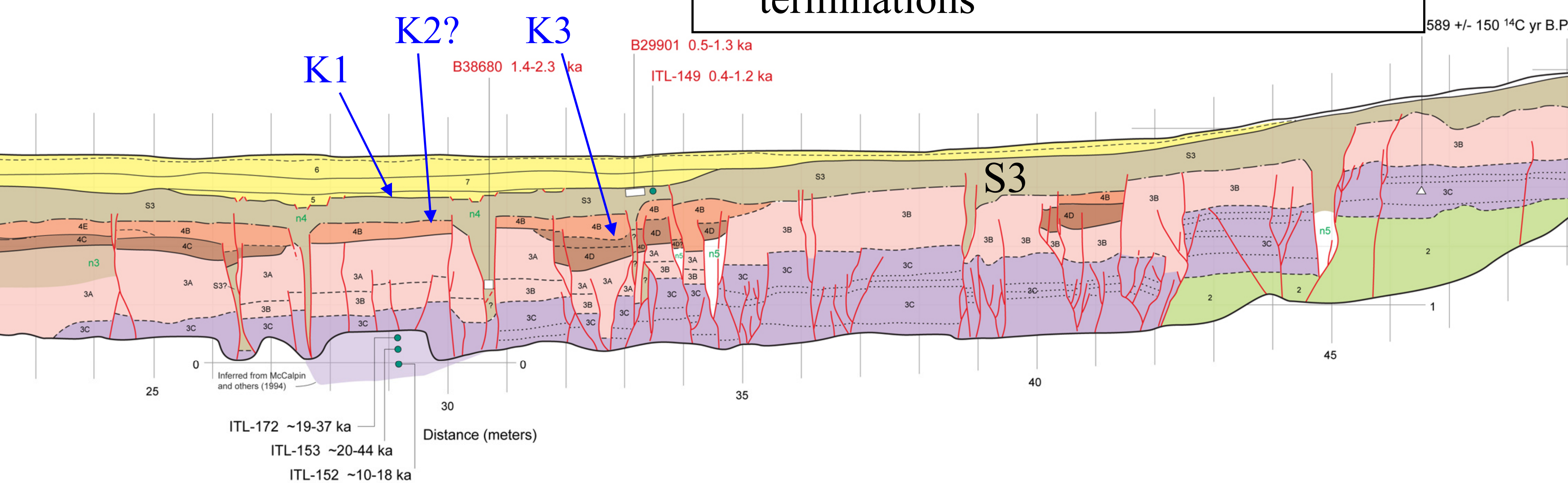


NOTES

n1 Soil S1/S2? at horizontal meter marks 1.5-5.0 m is based on mapping by McCalpin and others (1994), who mapped a "thin cumulic" soil developed on their scarp-colluvial unit 6 (Swan and others [1980] unit 4C/D) deposited in response to their third earthquake (see Correlation of Units and Surface-Faulting Earthquakes). Swan and others (1980) interpreted the sediment as colluvium from an older earthquake (unit 3A), but did not map a soil on this unit.

3. Additional evidence for K2 at S3 – unit 4B boundary:

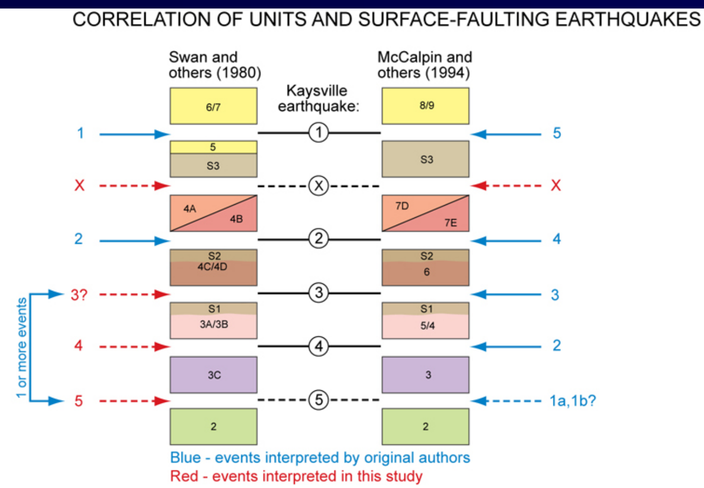
- Possible eroded scarp free faces
- Differential offsets and fault terminations



Log of Trench A; Kaysville Site

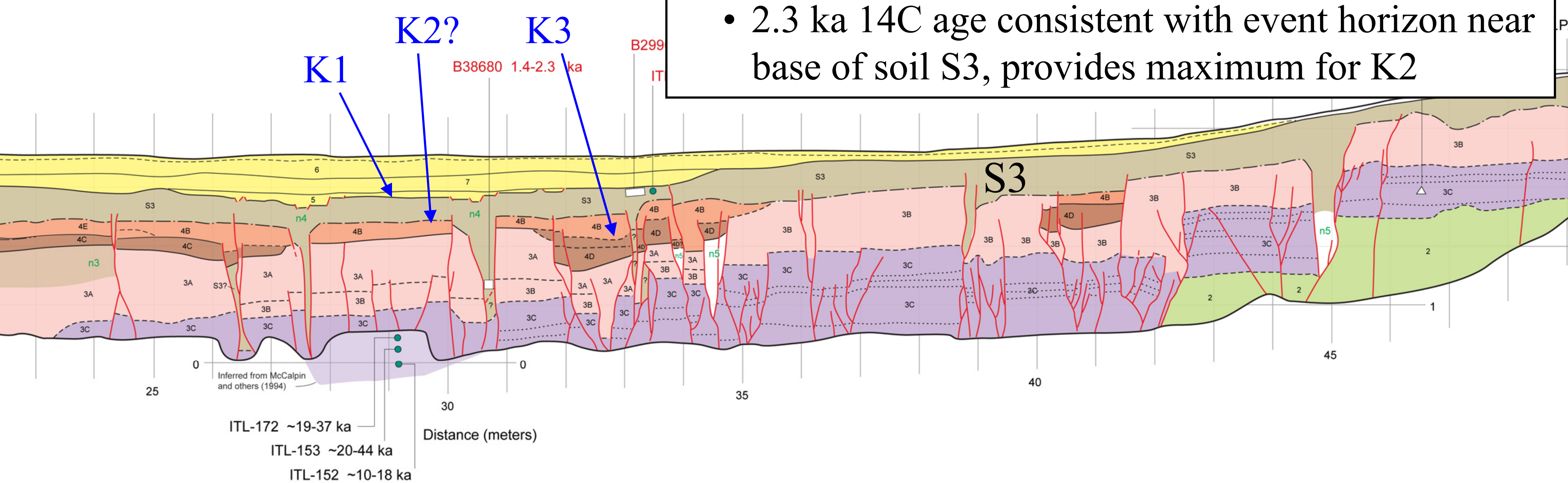
Swan, F.H., Schwartz, D.P., Hanson, K.L, Knuepfer, P.L., and Cluff, L.S. 1981

Kaysville – Swan (1981)



4. Origin of crack fill?

- Fissures likely formed by faulting/rotation/ tension in 4B during K2 (prior to S3) rather than by shearing in K1 (post S3)
- Fissures later faulted by MRE (K1)
  - Faulted fissure boundaries and fill; minor displacement faults extend into pond deposits
- 2.3 ka 14C age consistent with event horizon near base of soil S3, provides maximum for K2



Log of Trench A; Kaysville Site

Swan, F.H., Schwartz, D.P., Hanson, K.L, Knuepfer, P.L., and Cluff, L.S. 1981

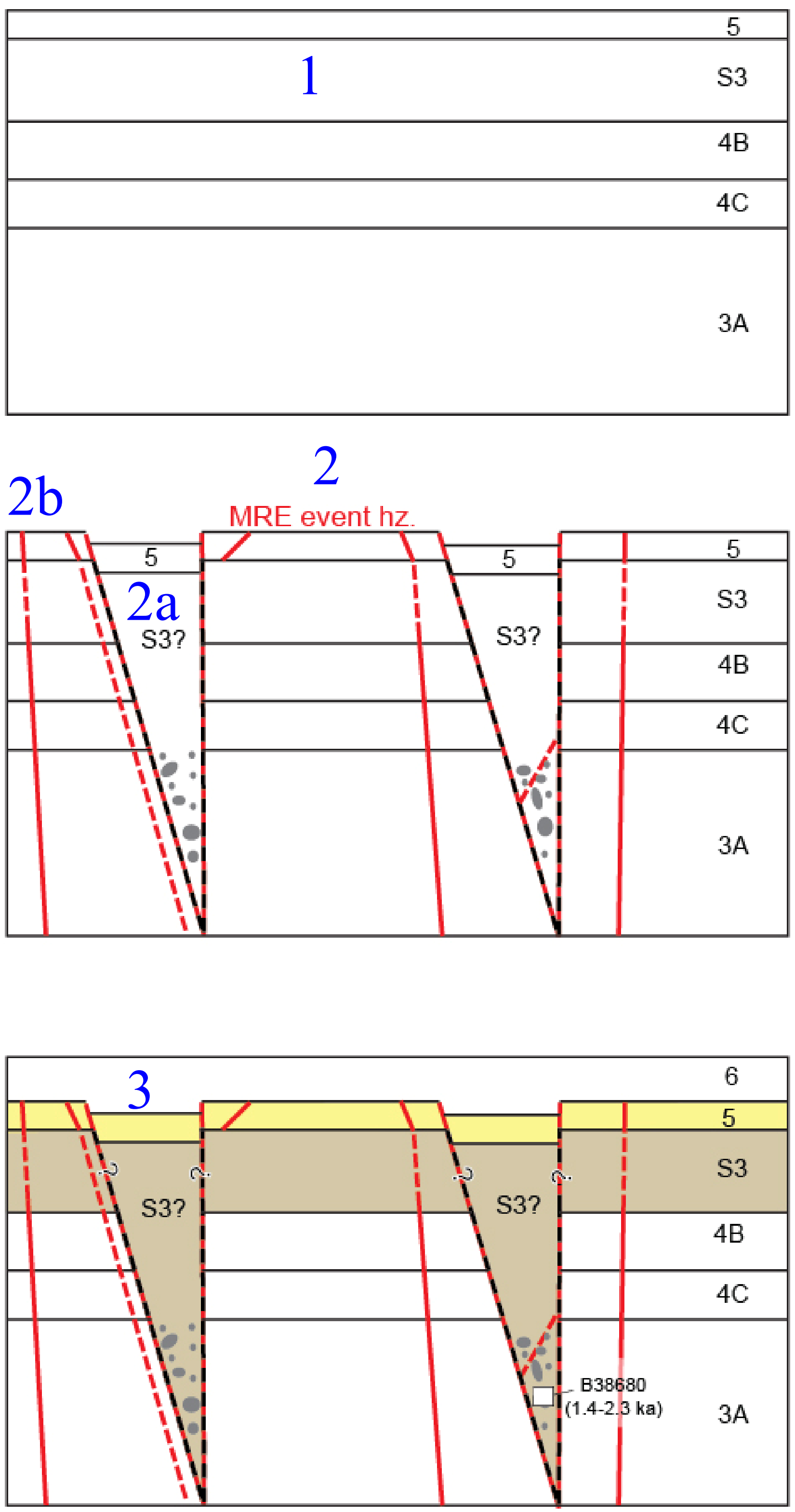
Kaysville

<u>A – Fissures formed by shearing in K1:</u>

1. Formation of soil S3 on unit 4B and deposition of unit 5

2. Most recent earthquake (MRE) (K1)
   - 2a. Fissures formed in S3 and unit 5 by shearing
   - 2b. Small-displacement faults form in unit 5

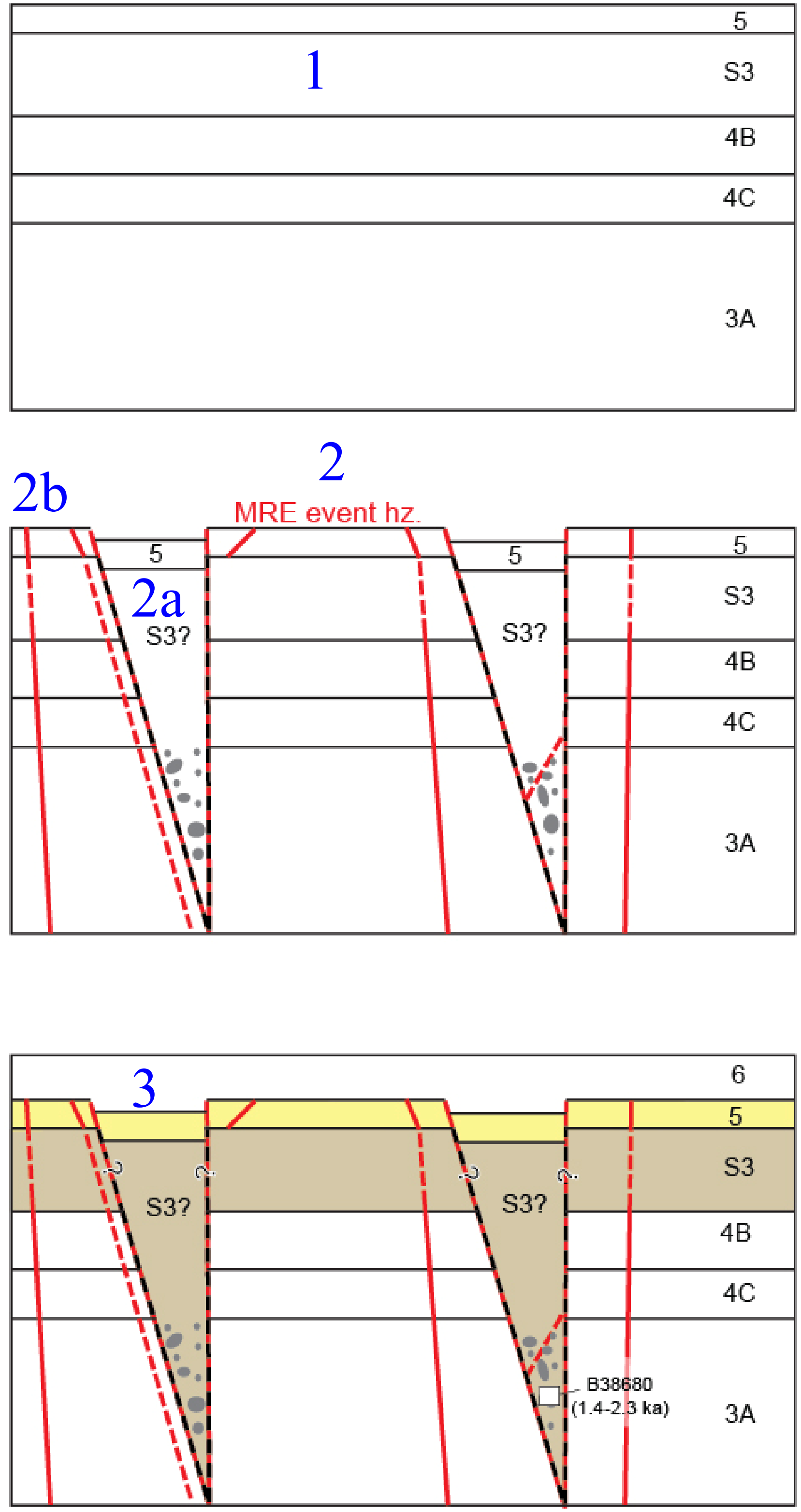
3. Fissures/shears buried by unit 6 (pond deposits)



Kaysville

A – Fissures formed by shearing in K1:

- Issues:
  - Origin of organic sediment (S3) in fissure?
    - "*Thick vertical slice of S3 fell…into fissure*" not possible
    - Unit 5 (yellow) continuous across fissure (no extensive open cracking at surface)
    - S3 not exposed by MRE
    - No net offset across fissures (shearing origin unlikely)
  - Fault terminations/differential offset at 4B/S3 contact?
  - Back rotation of base of S3?
  - 1-2-m thickness of S3 near main fault?



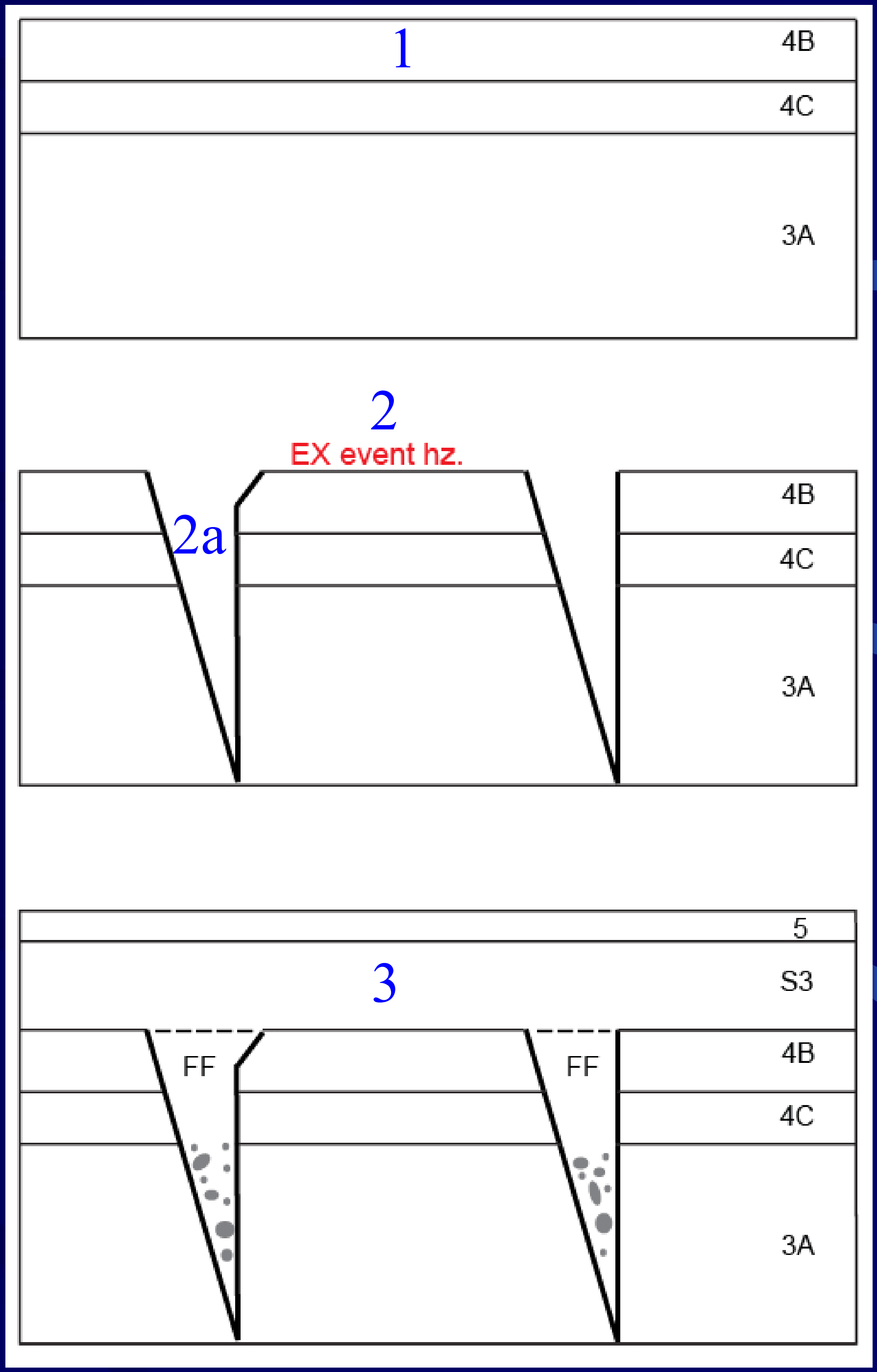
Kaysville

B – Fissures formed by tension in K2

1. Formation of unit 4b

2. Earthquake EX (K2)
   - 2a. Fissures form in 4B as a result of tilting/tension in event EX (K2)

3. Deposition/formation of colluvium/soil unit S3.

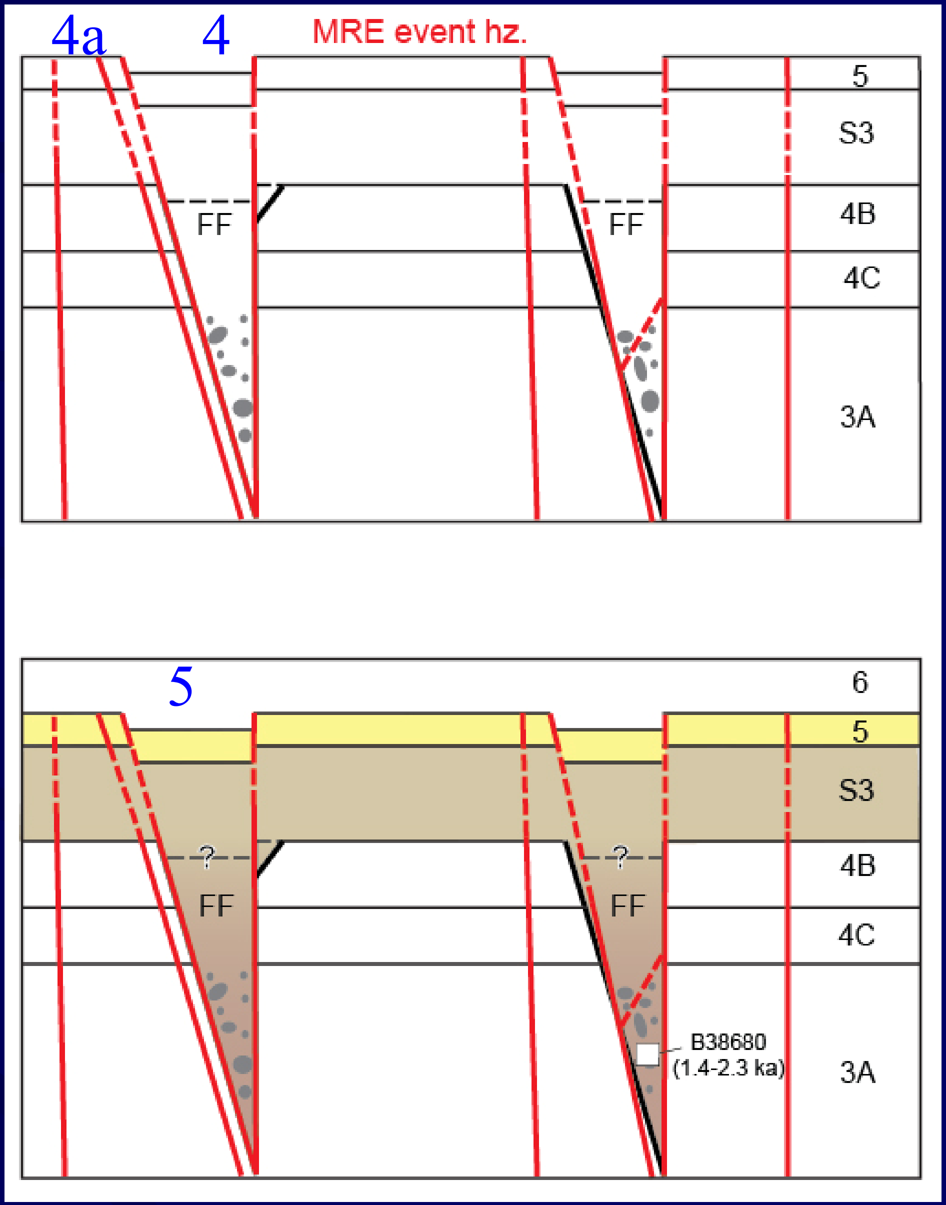


Kaysville

B – Fissures formed by tension in K2

4. Faulting in MRE (K1)
   - 4a. Minor displacement of unit 5 and fissure boundaries

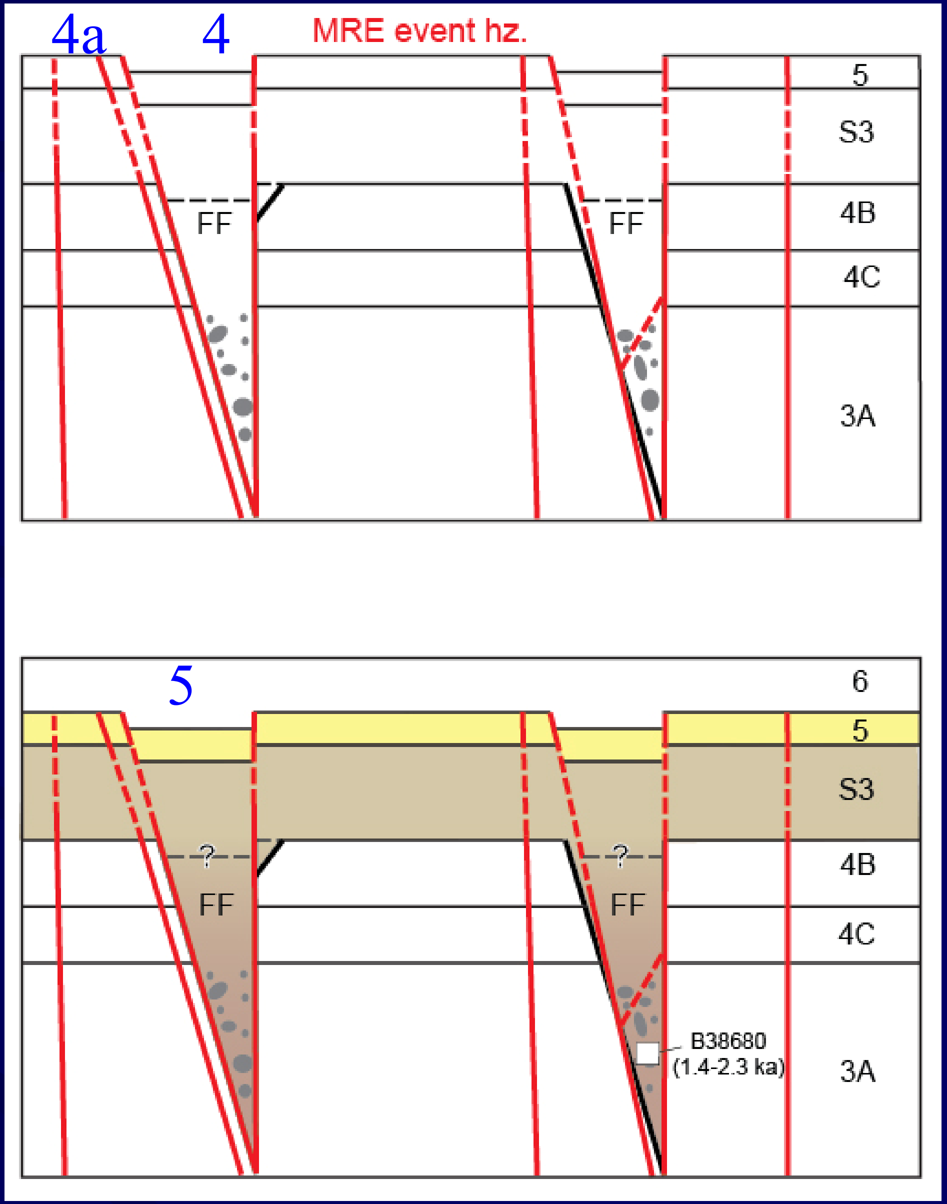
5. Deposition of unit 6 (colluvium/pond deposit)



Kaysville

B – Fissures formed by tension in K2

- Issues resolved:
  - Fissures formed by tension, rather than shearing
  - Organic sediment in fissures related to erosion of fissure walls, slope wash, and soil development
  - Thickness of S3 and apparent back rotation of S3/4B contact explained by faulting/back rotation of unit 4B and colluvial origin of S3



Kaysville

Event	McCalpin et al (1994)	This study (OxCal)
K1 (Z)	shortly before 0.6–0.8	0.6 ± 0.2 (2σ)
K2 (Y)	-	0.9 ± 0.5
K3 (X)	2.8 ± 0.7	2.8 ± 1.7
K4 (W)	5.7–6.1 (3.8-7.9 possible)	5.8 ± 1.3

(All time ranges to 2 sigma)

- OxCal model
  - Similar earthquake timing results, but with addition of K2
  - OxCal: generally larger (more realistic) uncertainties for K3 and K4, which don't have limiting ages between them

East Ogden

- Nelson et al. (2006)
  - 4 events in ~5 ky
  - Numerous limiting ages for EO2, EO3, EO4
  - EO1 at ~500 yr – partial rupture of northern Weber segment?

  - Did not trench all scarps (complete record?)

East Ogden

Event	Nelson et al. (2006)	This study
EO1	0.2–0.6 ka	0.4 ± 0.2 (2σ)
EO2	0.5–1.7 ka	0.9 ± 0.4 ka
EO3	2.4–3.9 ka	3.0 ± 0.4 ka
EO4	2.8–4.8 ka	4.0 ± 0.9 ka

(All time ranges to 2 sigma)

- OxCal model
  - Similar EQ times and slightly smaller uncertainties (result of OxCal trimming)
  - MRT correction 300 ± 200 yr, except for youngest C14 age

Garner Canyon

- Nelson et al. (2006)
  - 4 post-mid Holocene(?) events
  - Good limiting ages for GC1 and GC2
  - Only minimum age for GC3 (no maximum), but event likely correlates with 3rd event at East Ogden

  - Limited exposure (foundation excavation)

Garner Canyon

Event	Nelson et al. (2006)	This study
GC1:	>0–0.4; <1.0–1.4 ka	0.6 ± 0.4 ka (2σ)
GC2:	1.2–2.8 ka	1.5 ± 0.5 ka
GC3:	2.3–4.0 ka	3.2 ± 0.6 ka*
GC4:	unknown, but ~4-5 ka?	4.4 ± 0.6 ka*

(All time ranges to 2 sigma)

- OxCal model
  - Very similar EQ times and uncertainties
  - MRT correction: 300 ± 200 yr (after Nelson et al., 2006)
  - Maximum limiting ages for GC3 and GC4 are alluvial-fan ages from East Ogden (Based on correlation of events discussed in Nelson et al. (2006) and mapping by Nelson and Personius (1993)

Rice Creek

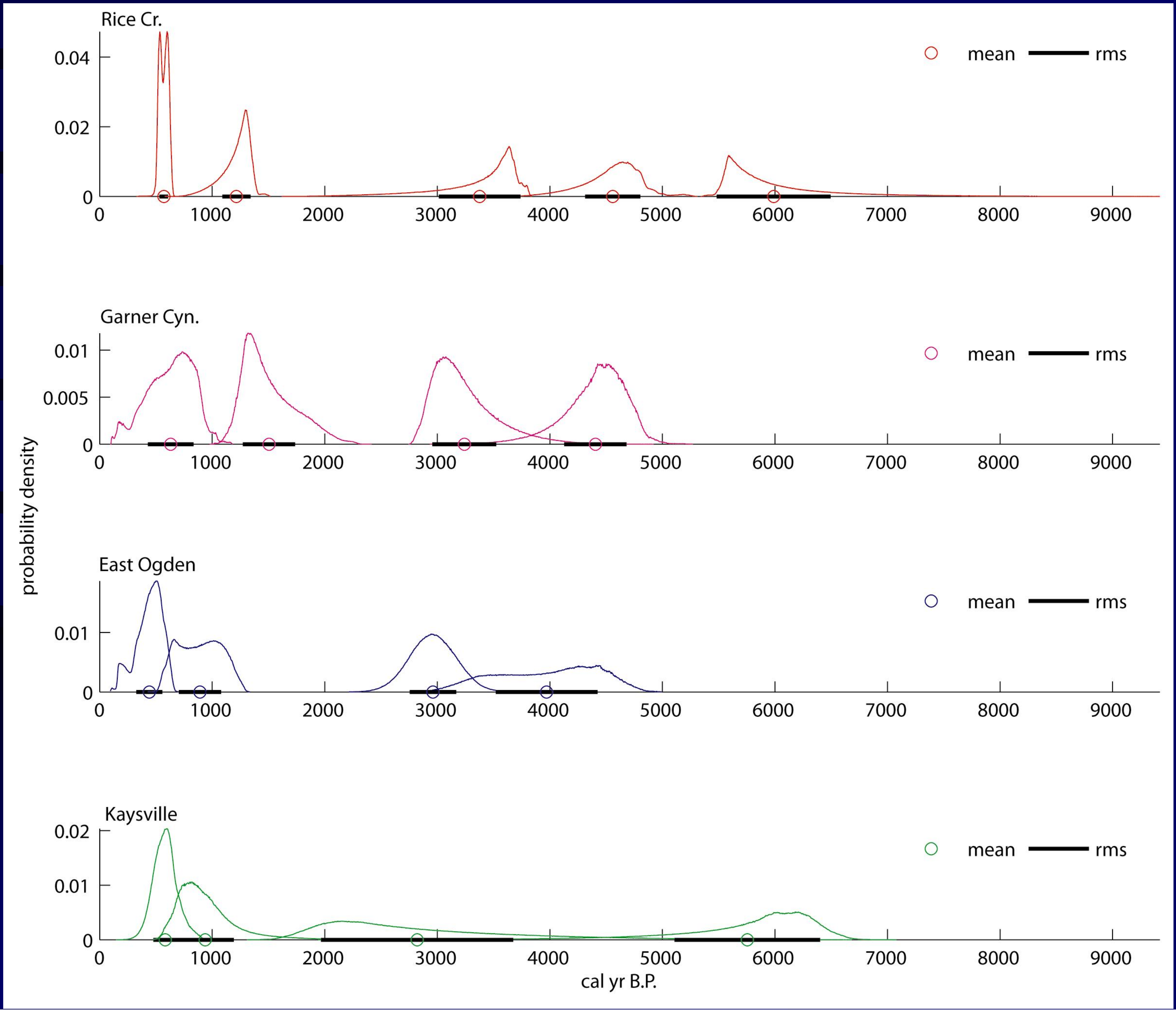
- UGS/USGS (2007) (DuRoss et al., 2009)
  - 6 Holocene events, 5 younger than ~7.5 ka
  - RC1: additional evidence for Weber event at ~500 years

Event	DuRoss et al. (2009)	This Study
RC1	0.5–0.6 ka (2σ)	0.6 ± 0.1
RC2	0.8–1.4 ka	1.2 ± 0.2
RC3	1.8–3.7 ka	3.4 ± 0.7
RC4	3.7–5.4 ka	4.6 ± 0.5
RC5	5.5–7.5 ka	6.0 ± 1.0

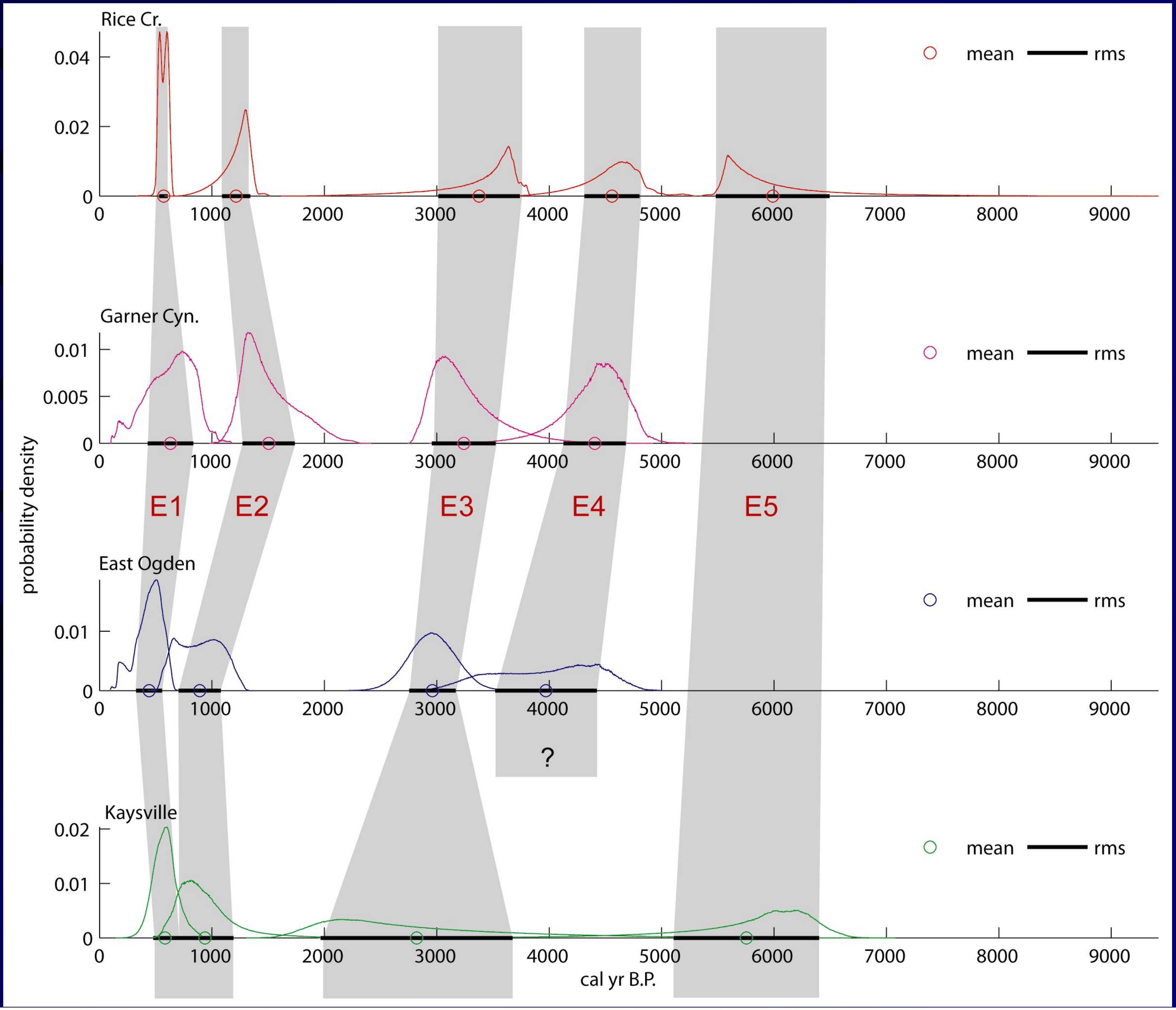
(All time ranges to 2 sigma)

- OxCal model
  - Differences related to different modeling methods (Boundary command)
  - No MRT correction (charcoal samples)

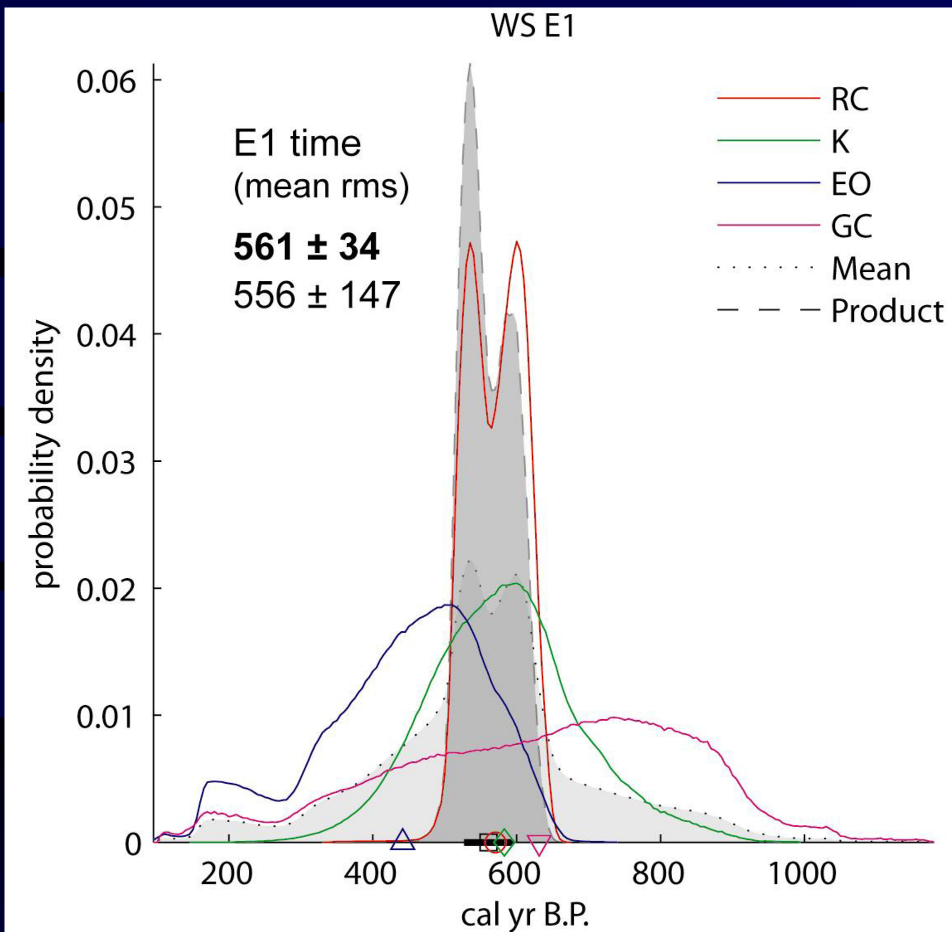
Matlab plot of Weber segment site PDFs



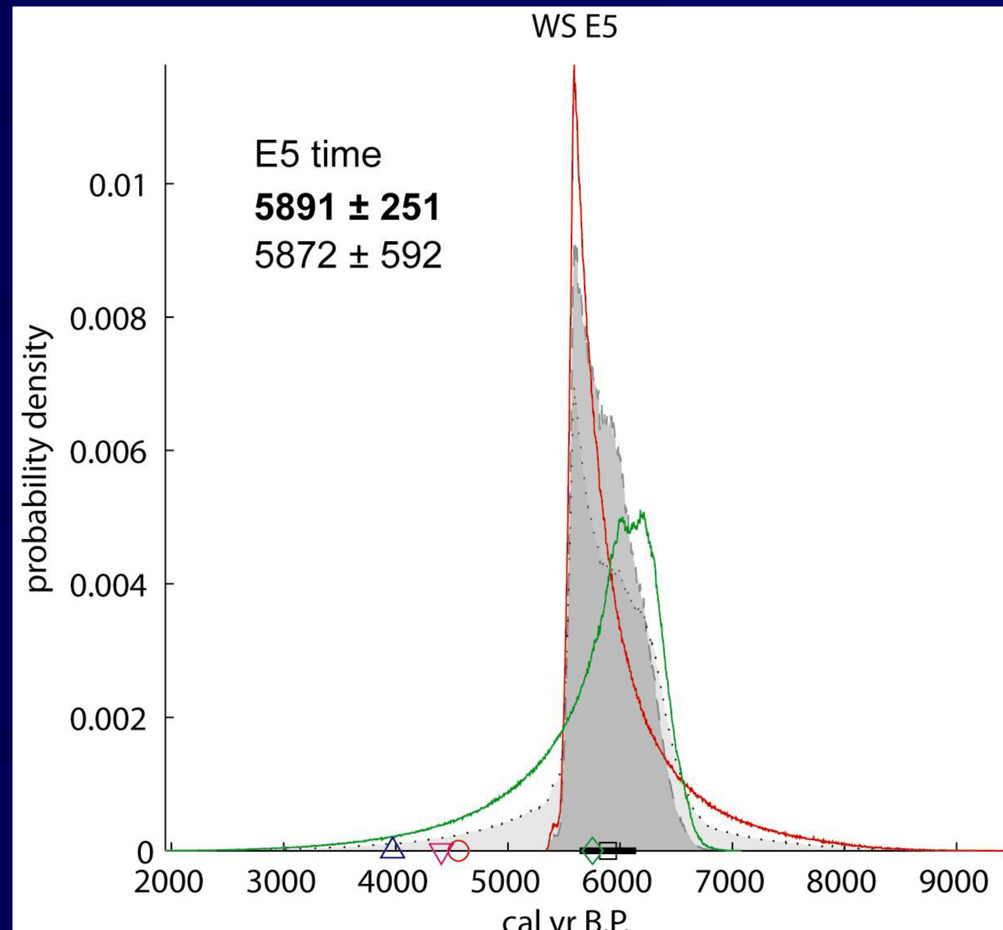
Correlation of Weber segment site PDFs



Matlab timing refinement – segment PDFs

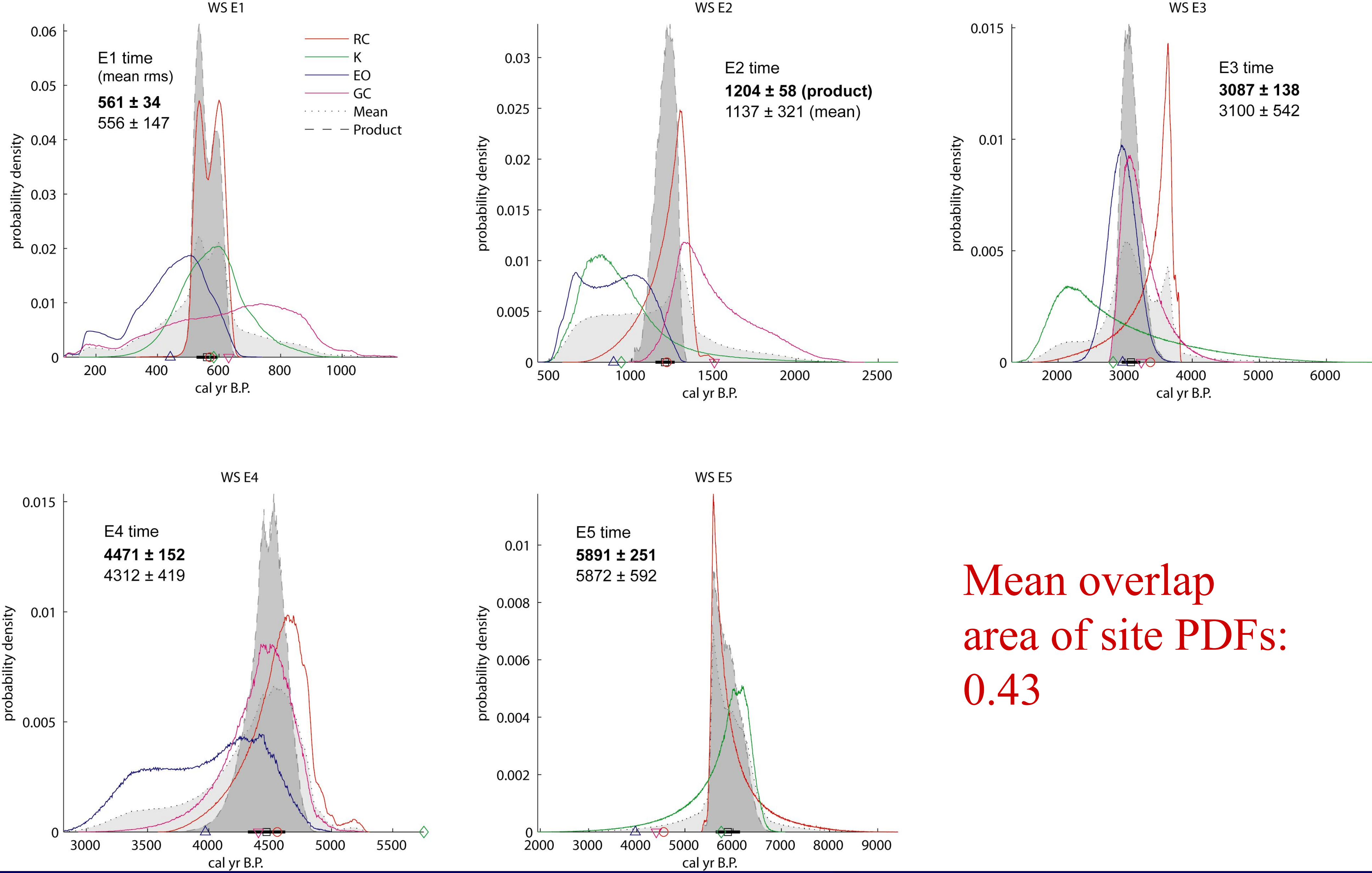


E1: 560 ± 70 yr (2σ)



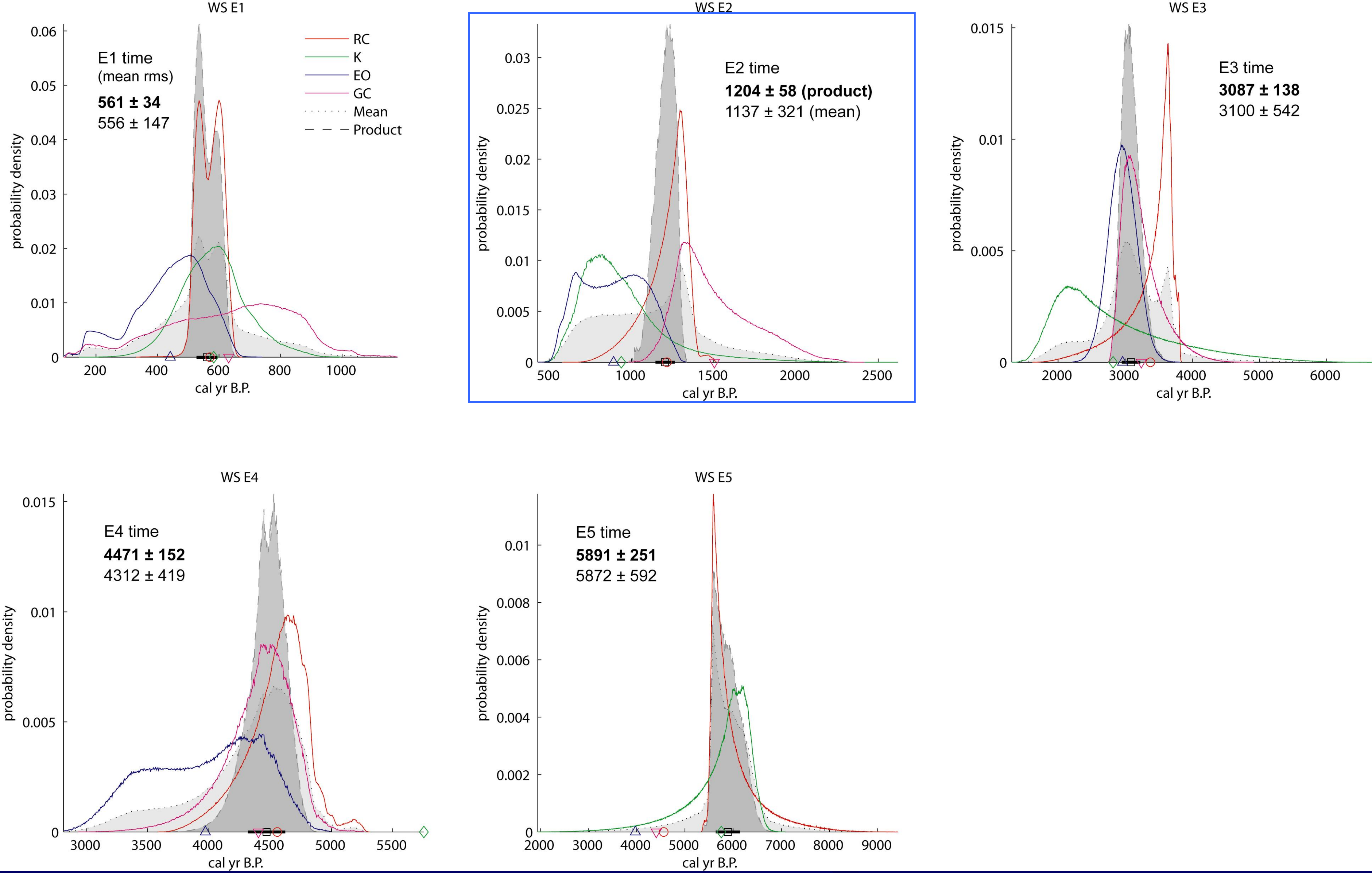
E5: 5890 ± 500 yr (2σ)

Matlab timing refinement – segment PDFs



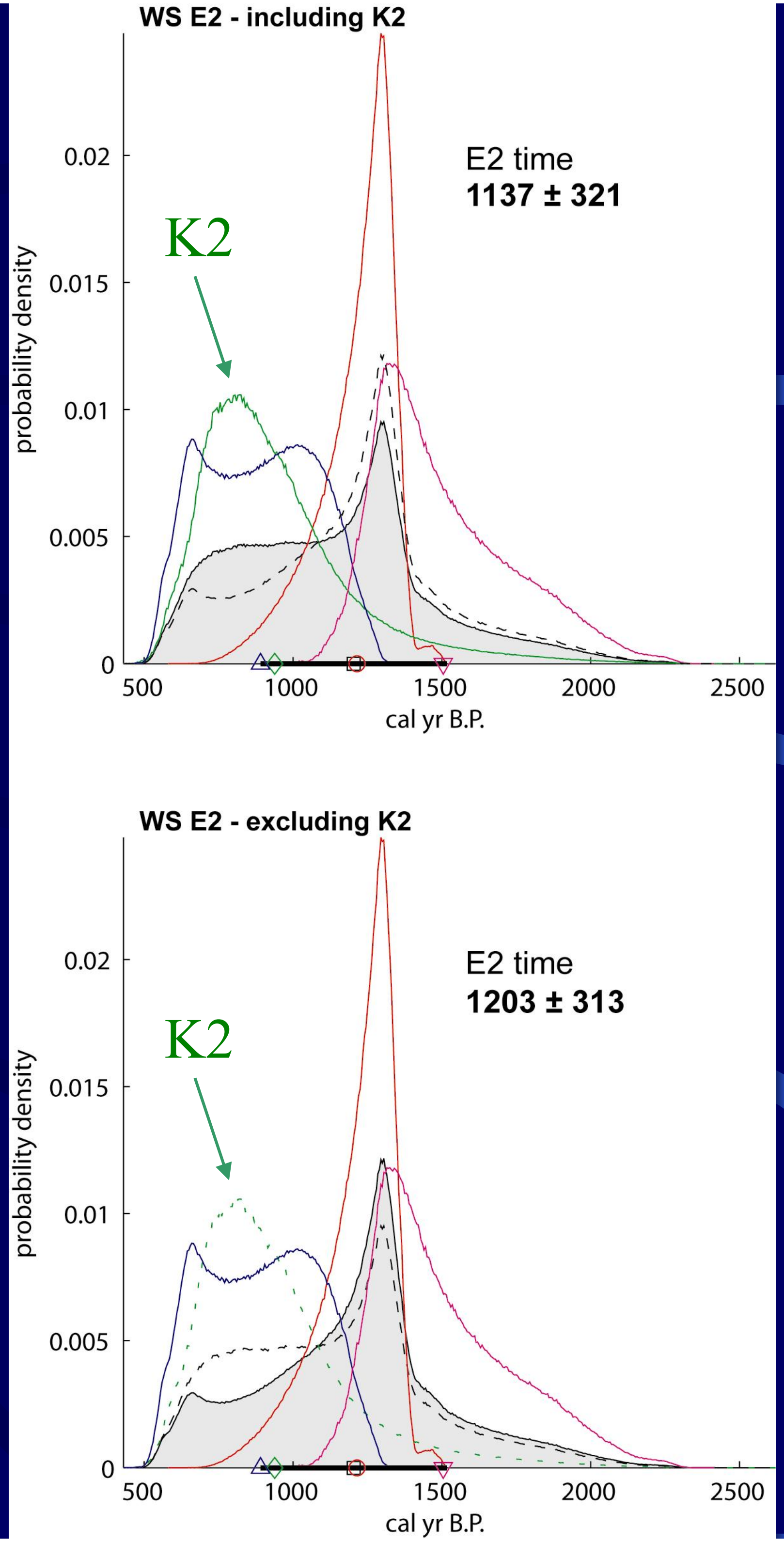
Mean overlap area of site PDFs: 0.43

Matlab timing refinement – segment PDFs



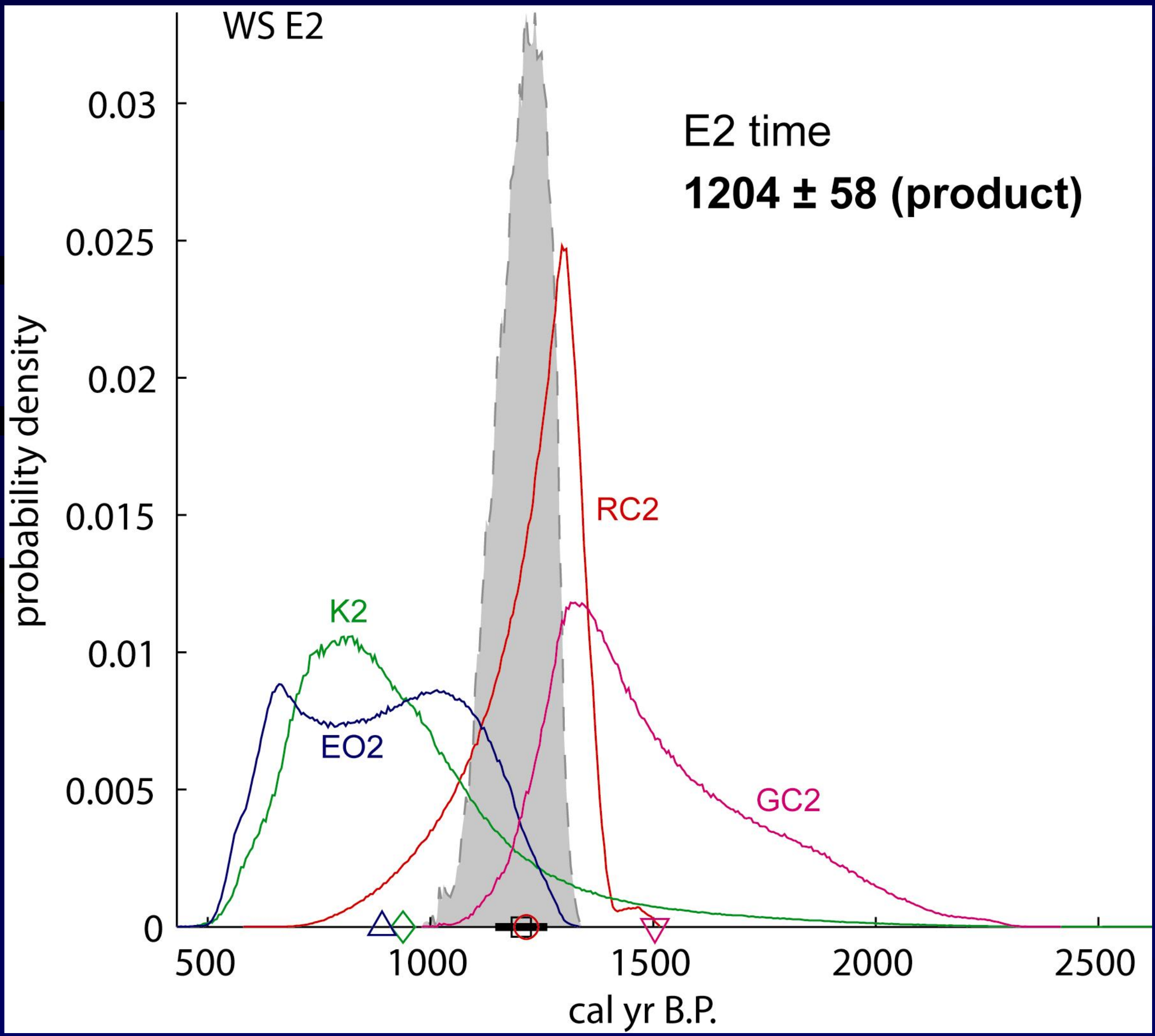
Weber segment event E2

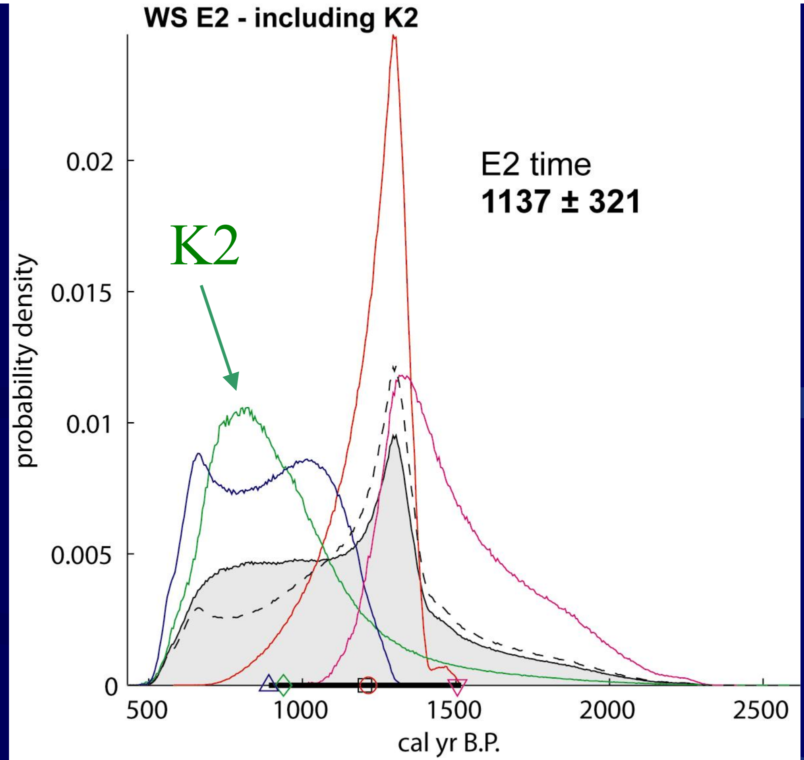
- Model <u>including</u> K2
  - E2: 1140 ± 640 ka (2σ)
- Model <u>excluding</u> K2
  - E2: 1200 ± 630 ka (2σ)

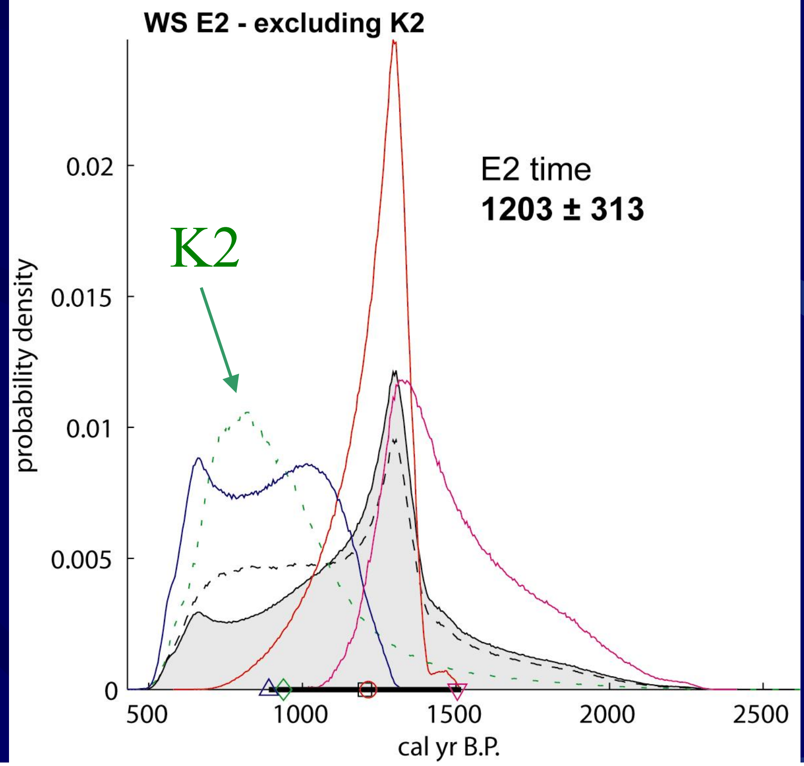


Weber segment event E2

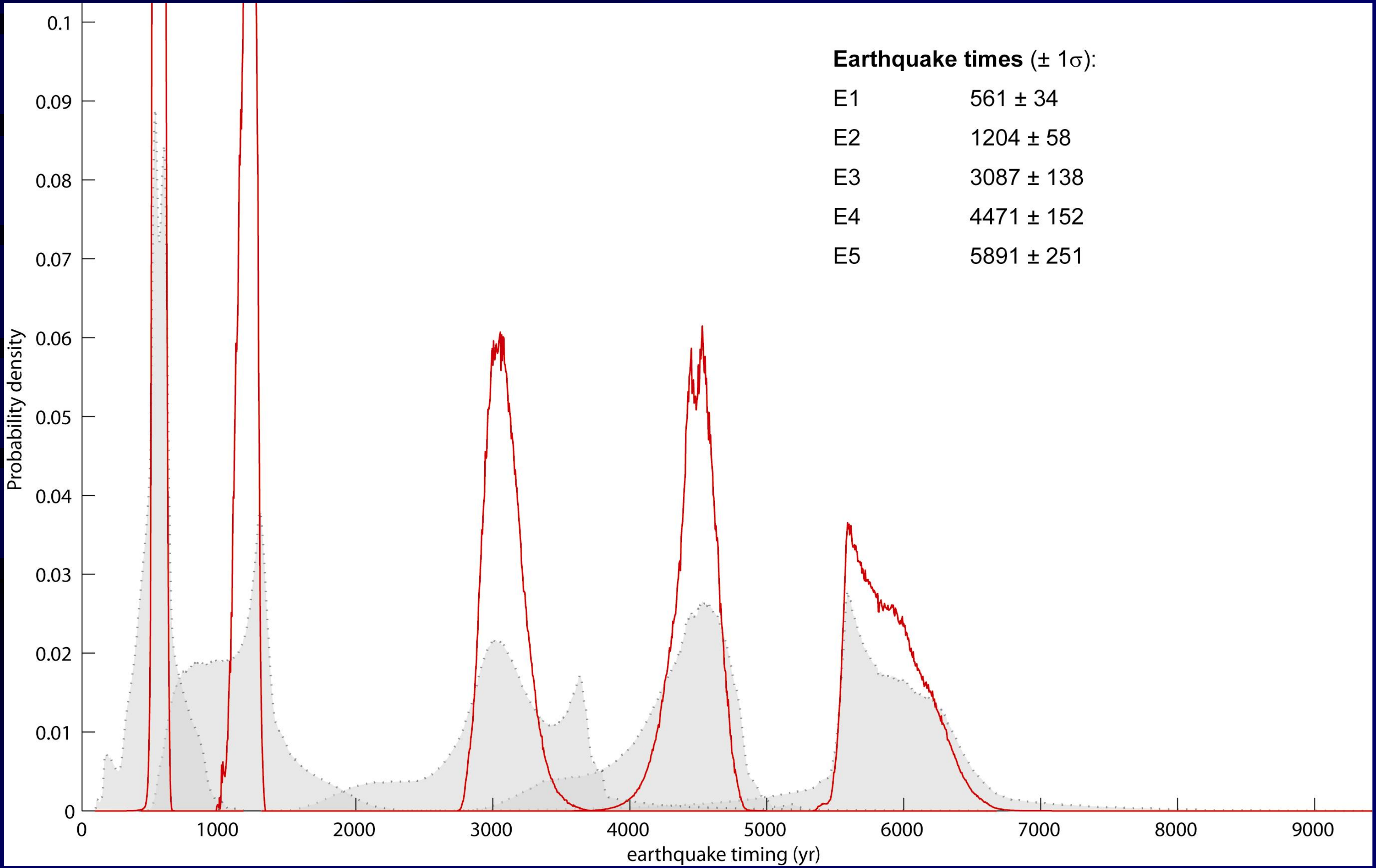
- Model 7 (product of site PDFs)
  - K2 doesn't affect model





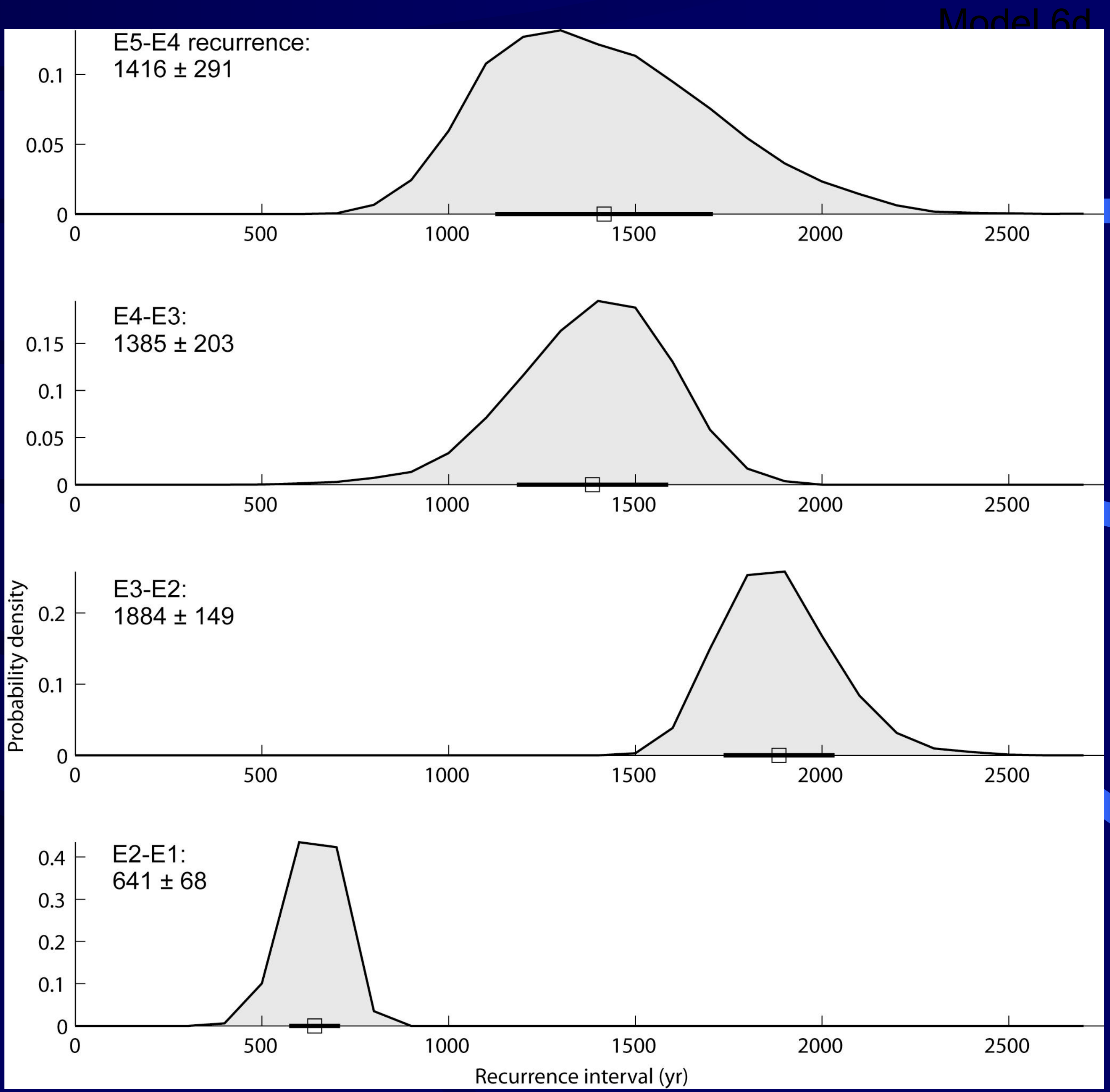


Weber segment earthquake history



Recurrence

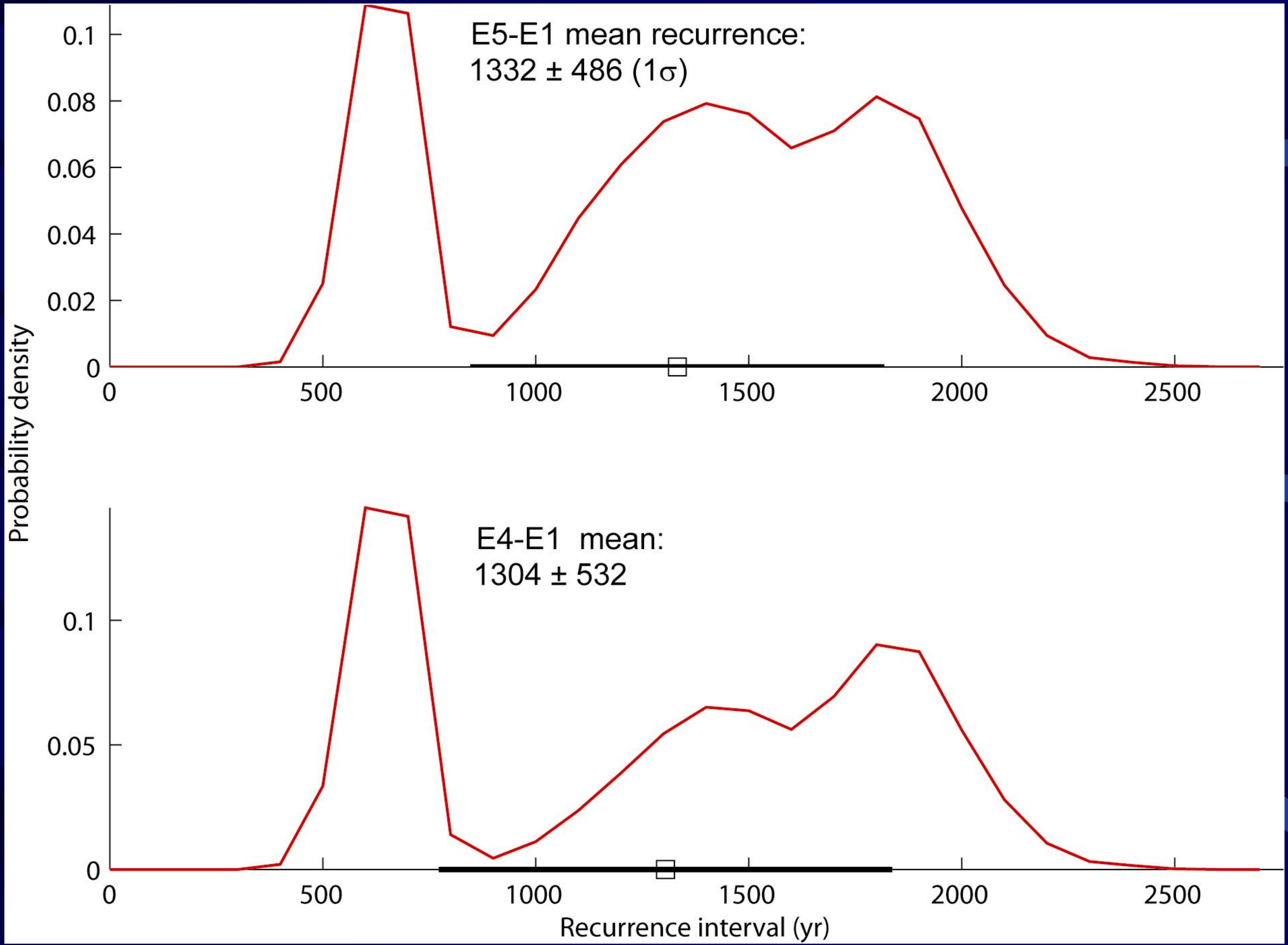
- Inter-event recurrence
  - Small (~0.1-ky) to moderate (0.2–0.3-ky) uncertainties
  - Short (<1 ky) to long (~2 ky) recurrence



Recurrence

Model 6d

- Average recurrence
  - E5–E1: 1.3 ± 0.5 (1σ)
  - <u>Bimodal distribution:</u>
    - ~0.6 ky
    - ~1.6 ky



Summary of Results

	RC	GC	EO	K
E1:	0.6 ± 0.1	0.6 ± 0.4	0.4 ± 0.2	0.6 ± 0.2
E2:	1.2 ± 0.2	1.5 ± 0.5	0.9 ± 0.4	0.9 ± 0.5
E3:	3.4 ± 0.7	3.2 ± 0.6	3.0 ± 0.4	2.8 ± 1.7
E4:	4.6 ± 0.5	4.4 ± 0.6	4.0 ± 0.9	-
E5:	6.0 ± 1.0	-	-	5.8 ± 1.3

(All time ranges to 2 sigma)

Summary of Results

	Matlab (mean site PDFs) w K2	w/o K2	**Matlab** (product)	**UQFPWG**
E1:	0.6 ± 0.3		0.6 ± 0.1	0.5 ± 0.3
E2:	1.1 ± 0.6	1.2 ± 0.6	1.2 ± 0.1	0.95 ± 0.45
E3:	3.1 ± 1.1		3.1 ± 0.3	3.0 ± 0.7
E4:	4.3 ± 0.8		4.5 ± 0.3	4.5 ± 0.7
E5:	5.9 ± 1.2		5.9 ± 0.5	6.1 ± 0.7
E5–E1:	1.5 ± 0.7 ky		1.3 ± 0.5 ky	1.4 ± ~1 ky

(All time ranges to 2 sigma)

Comparison with previous studies

- Recurrence estimates:
  - This study: 1.3 ± 0.5 ky (1σ)

  - Previously reported recurrence estimates:
    - Kaysville: 2.7 ky (K3–K1, excluding additional event)
    - East Ogden: 1.5–1.6 ky (0–~3 ky possible range) (EO4–EO2)
    - Garner Canyon: <2.2 ky (GC2–GC1)
    - Rice Creek: 1.5 ky (0.5–3.1 ky at 2σ) (RC6–RC1)

    - McCalpin & Nishenko: 1.8 ± 0.1 ky (E4 – E1)
    - UQFPWG: 1.4 ky (0.5–2.4 ky estimated 2-sigma range; E5–E1)

Conclusions

- <u>OxCal</u>
  - East Ogden and Garner Canyon earthquake time ranges similar to published results
  - Kaysville additional event
    - Doesn't significantly affect earthquake timing/recurrence
    - Does affect rupture length (but lack of evidence for event at one site is not convincing argument for partial rupture)

- <u>Correlation of events</u>
  - 5 events correlate between four paleoseismic sites
  - 4th event didn't rupture Kaysville (?)

Conclusions

- Earthquake timing (segment PDFs)
  - Mean times very similar to UQFPWG, but with smaller uncertainties
  - E1 well constrained: 560 ± 70 yr (2σ) vs. ± 300 yr of UQFPWG
    - E1 elapse time: 620 ± 70 yr (2σ)
    - Rupture of entire segment
  - E2: narrow earthquake time, but uncertainty in rupture length
  - E3–E5: Moderate uncertainties in segment PDFs (moderate overlap, straight forward correlation of site PDFs)

- Average recurrence
  - Poorly constrained to 1.3 ± 0.5 ky (1σ) (E5–E1)
  - Bimodal recurrence PDF from short (<1 ky) and long (~2 ky) intervals
  - Mean estimate similar to Nelson et al. (2006), DuRoss et al., (2009), and UQFPWG (Lund, 2005)

Summary of OxCal/Matlab results for the Salt Lake City segment

Chris DuRoss (UGS)

Steve Personius (USGS)

Tony Crone (USGS)

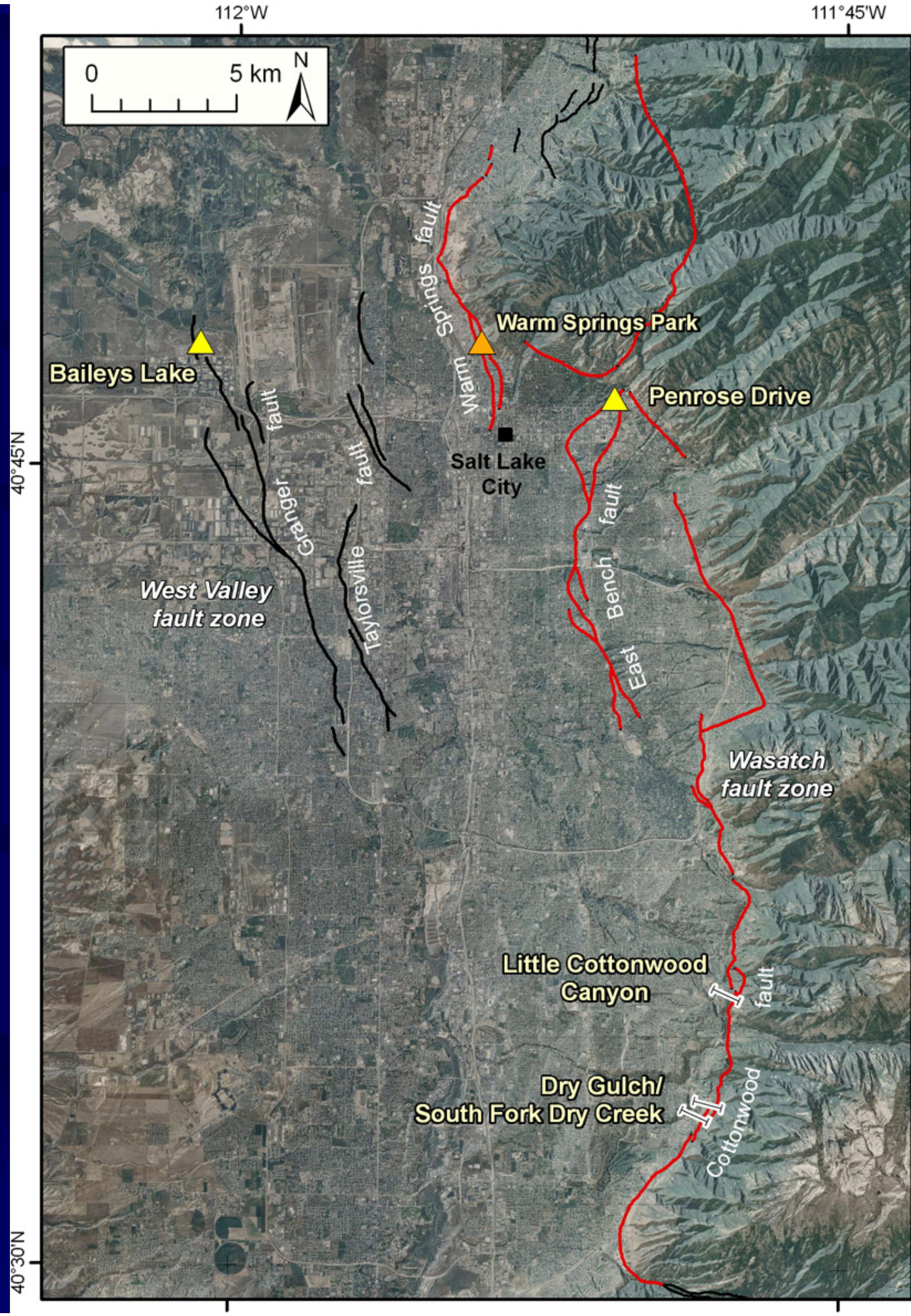
Susan Olig (URS)

Bill Lund (UGS)

Working Group on Utah Earthquake Probabilities, July, 2010

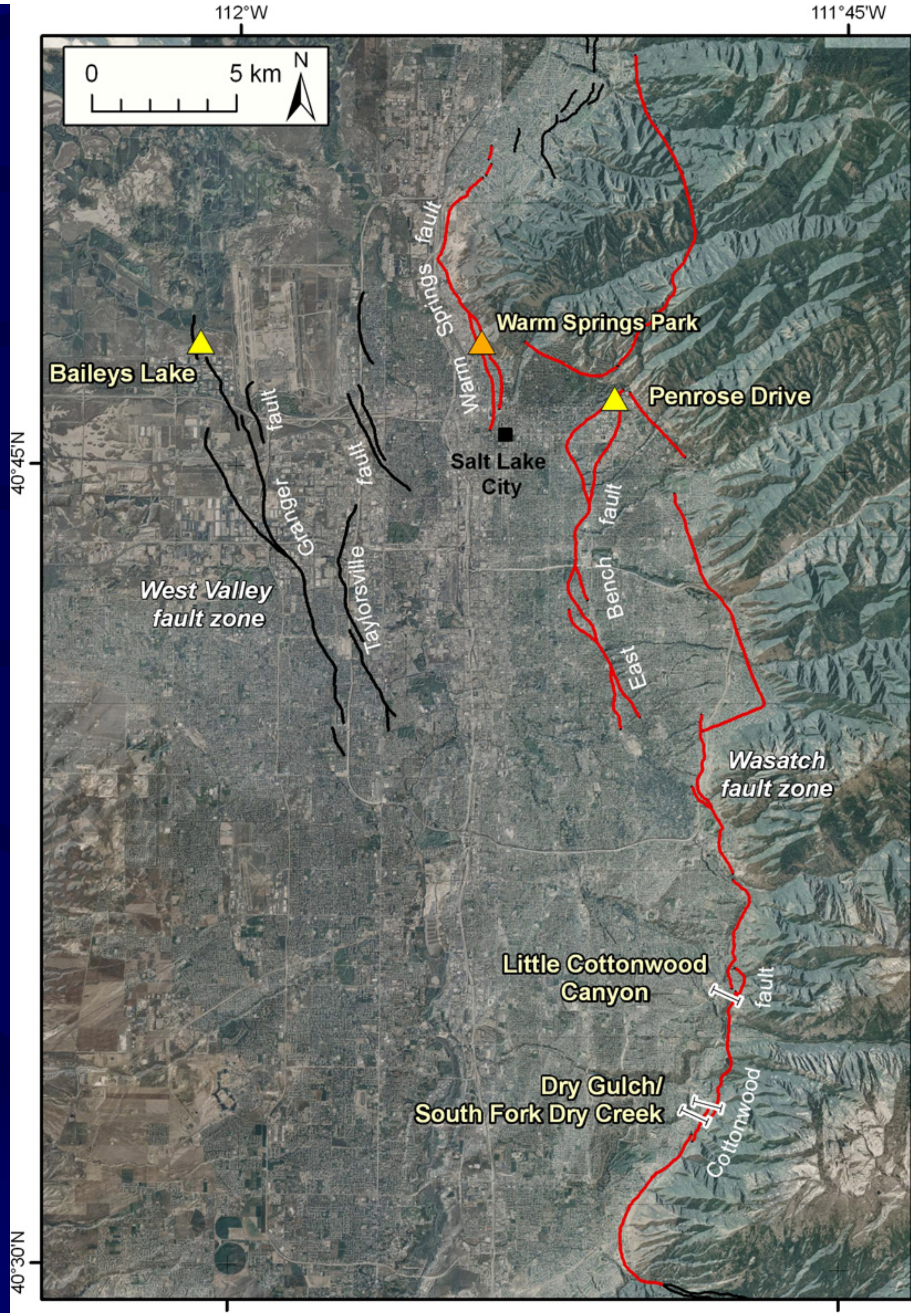
Salt Lake City segment (SLCS)

- SLCS fault strands
  - Warm Springs fault
  - East Bench fault
  - Cottonwood fault
- West Valley fault zone
  - Granger fault
  - Taylorsville fault



SLCS

- Paleoseismic studies:
  - South Fork Dry Cr/Dry Gulch (Black et al., 1996)
  - Little Cottonwood Canyon megatrench (McCalpin, 2002)
  - Warm Springs Park (UGS/USGS – no fault)
  - Penrose Drive (UGS/USGS – ongoing)



South Fork Dry Creek/Dry Gulch (SFDC)

- Black et al. (1996):
  - 8 trenches across 6 down-to-the-west fault scarps
  - Four events in ~5 ky
  - Events well dated – 20 ^{14}C ages (bulk soil)
  - All scarps trenched, but orphan wedges

SFDC

Event	Black et al. (1996) (ka)	This study (OxCal model 6f)
SFDC1 (Z)	~1.3 +0.25/-0.2	1.3 ± 0.2 (2σ)
SFDC2 (Y)	~2.45 ± 0.35	2.2 ± 0.4
SFDC3 (X)	~3.95 +0.55/-0.45	3.8 ± 0.6
SFDC4 (W)	~5.3 +0.45/-0.35	5.0 ± 0.5
	~ implies *shortly after*	

- OxCal model
  - Very similar results and uncertainties
  - MRT: Black et al.'s value ± 50 – 100% (depending soil sampling methods)
  - Differences in timing of events 3, 4, & 5 related to using both the minimum and maximum ages in OxCal versus only maximum ages (Black et al.)

Little Cottonwood Canyon (LCC)

- McCalpin (2002)
  - Megatrench across 2 large, down-to-the-west scarps
  - 2 events near time of Bonneville transgression/highstand
  - 6 events <10 ka (younger than Provo regression)
  - 3 events in same time period as 4 youngest SFDC events?
  - Most events well dated (20 ^{14}C bulk soil ages); few have only single min/max limiting age

LCC

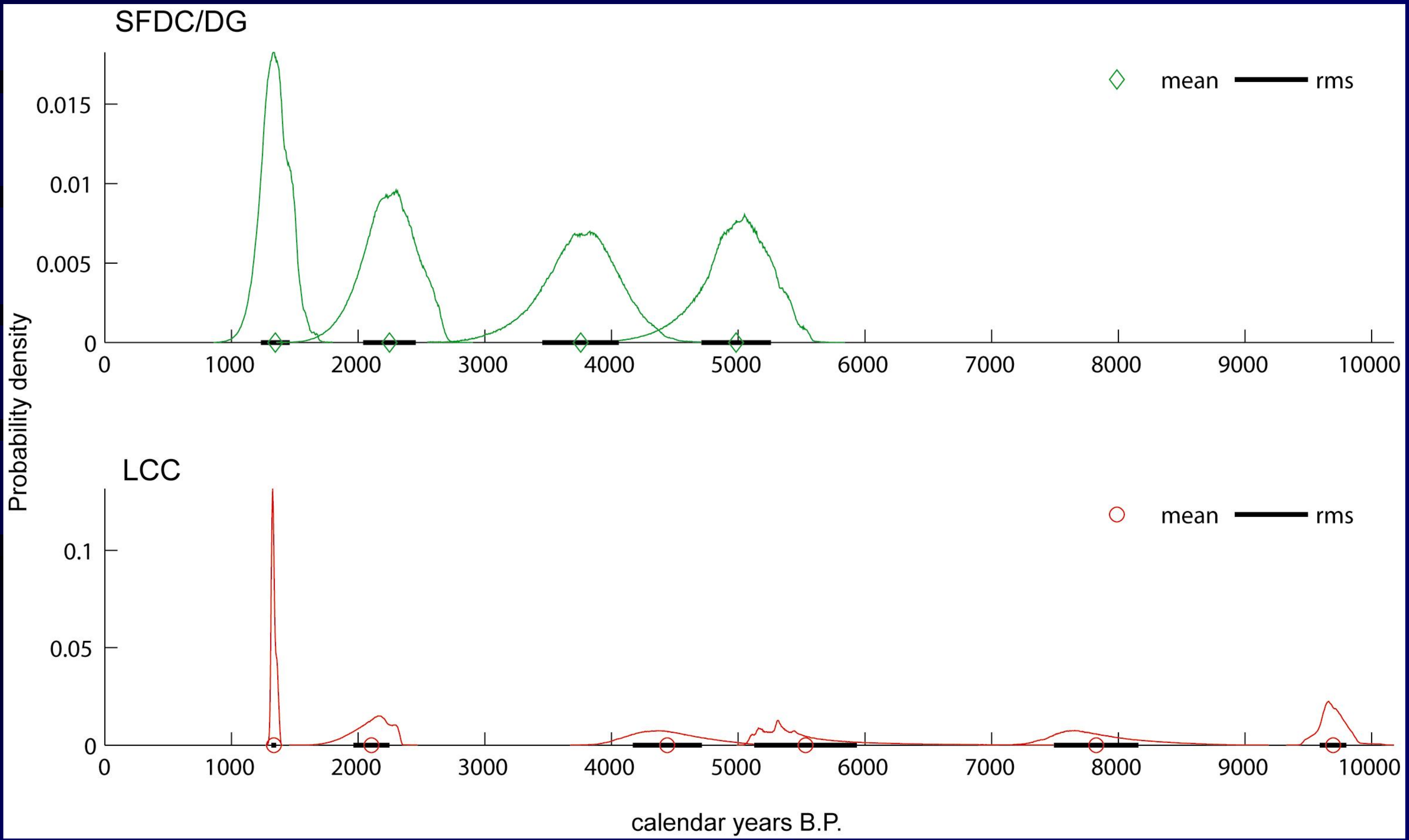
Event	McCalpin (2002) (ka)	This study (OxCal model 3d)
LCC1 (Z)	1.3	1.3 ± 0.04 (2σ)
LCC2 (Y)	2.3	2.1 ± 0.3
LCC3 (X)	3.5	4.4 ± 0.5
LCC4 (W)	5.3	5.5 ± 0.8 (mode: 5.3 ka)
LCC5 (V)	7.5	7.8 ± 0.7
LCC6 (U)	9	9.5 ± 0.2
LCC7 (T)	17	18.1 ± 0.8
LCC8 (S)	17-20	19.1 ± 1.2

- OxCal model
  - Similar results and uncertainties
  - Differences in timing of events 3 & 4 related to using both the minimum and maximum ages in OxCal versus only minimum ages (McCalpin)

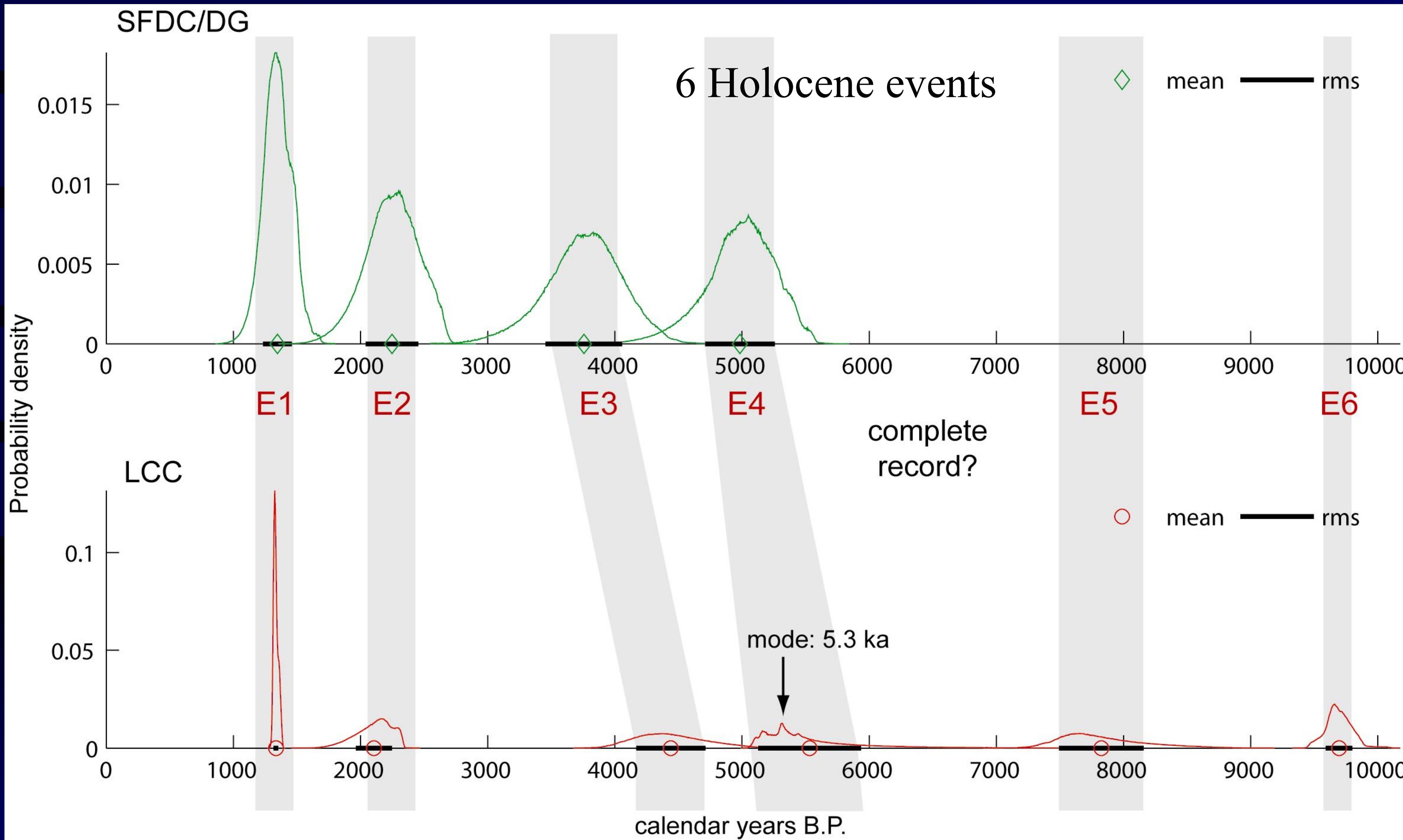
Penrose Drive

- UGS/USGS (2010 – ongoing)
  - Two trenches across large, down-to-the-west scarp on northern East Bench fault (north of U of U)
  - 1 event between Bonneville transgression (~22 ka at site) and Provo regression (17 ka)
  - 5 to 6 events post Provo shoreline (~14 ka)
  - 14 soil samples for 14C dating
    - 11 bulk soil (to be analyzed for charcoal)
    - 3 charcoal fragments
    - Dating results – possibly by November

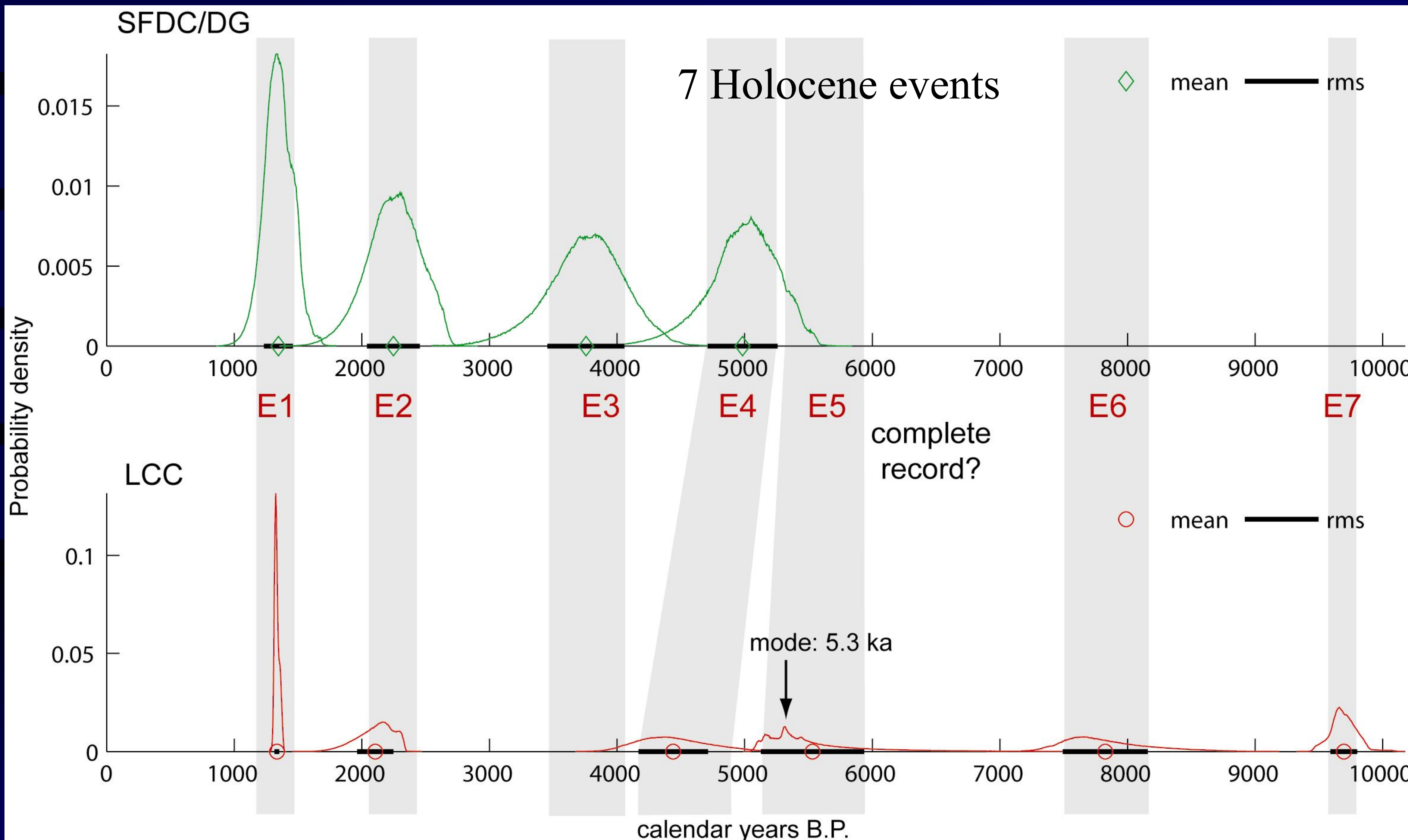
Matlab plot of SLCS site PDFs



Correlation of SLCS site PDFs – 6 events



Correlation of SLCS site PDFs – 7 events



Correlation of events – 6-event model

6-events (Holocene)

Event	SFDC (ka)	LCC (ka)
E1	1.3 ± 0.2	1.3 ± 0.04
E2	2.2 ± 0.4	2.1 ± 0.3
E3	3.8 ± 0.6	4.4 ± 0.5
E4	5.0 ± 0.5	5.5 ± 0.8
E5	-	7.8 ± 0.7
E6	-	9.5 ± 0.2

(All time ranges to 2 sigma)

Correlation of events – 6-event model

6-events (Holocene)

Event	**SFDC (ka)**		**LCC (ka)**	
E1	1.3 ± 0.2		1.3 ± 0.04	PDF overlap 30%
E2	2.2 ± 0.4		2.1 ± 0.3	PDF overlap 64%
E3	3.8 ± 0.6		4.4 ± 0.5	PDF overlap 22%
E4	5.0 ± 0.5	⟷	5.5 ± 0.8	PDF overlap 36%
E5	-		7.8 ± 0.7	
E6	-		9.5 ± 0.2	

(All time ranges to 2 sigma)

- 6-event model - Preferred
  - Event times very similar between sites
  - Correlation of McCalpin (2002) and UQFPWG (Lund, 2005)

Correlation of events – 6-event model

6-events (Holocene)

Event	SFDC (ka)	LCC (ka)
E1	1.3 ± 0.2	1.3 ± 0.04
E2	2.2 ± 0.4	2.1 ± 0.3
E3	3.8 ± 0.6	4.4 ± 0.5
E4	5.0 ± 0.5	5.5 ± 0.8
E5	-	7.8 ± 0.7
E6	-	9.5 ± 0.2

?

(All time ranges to 2 sigma)

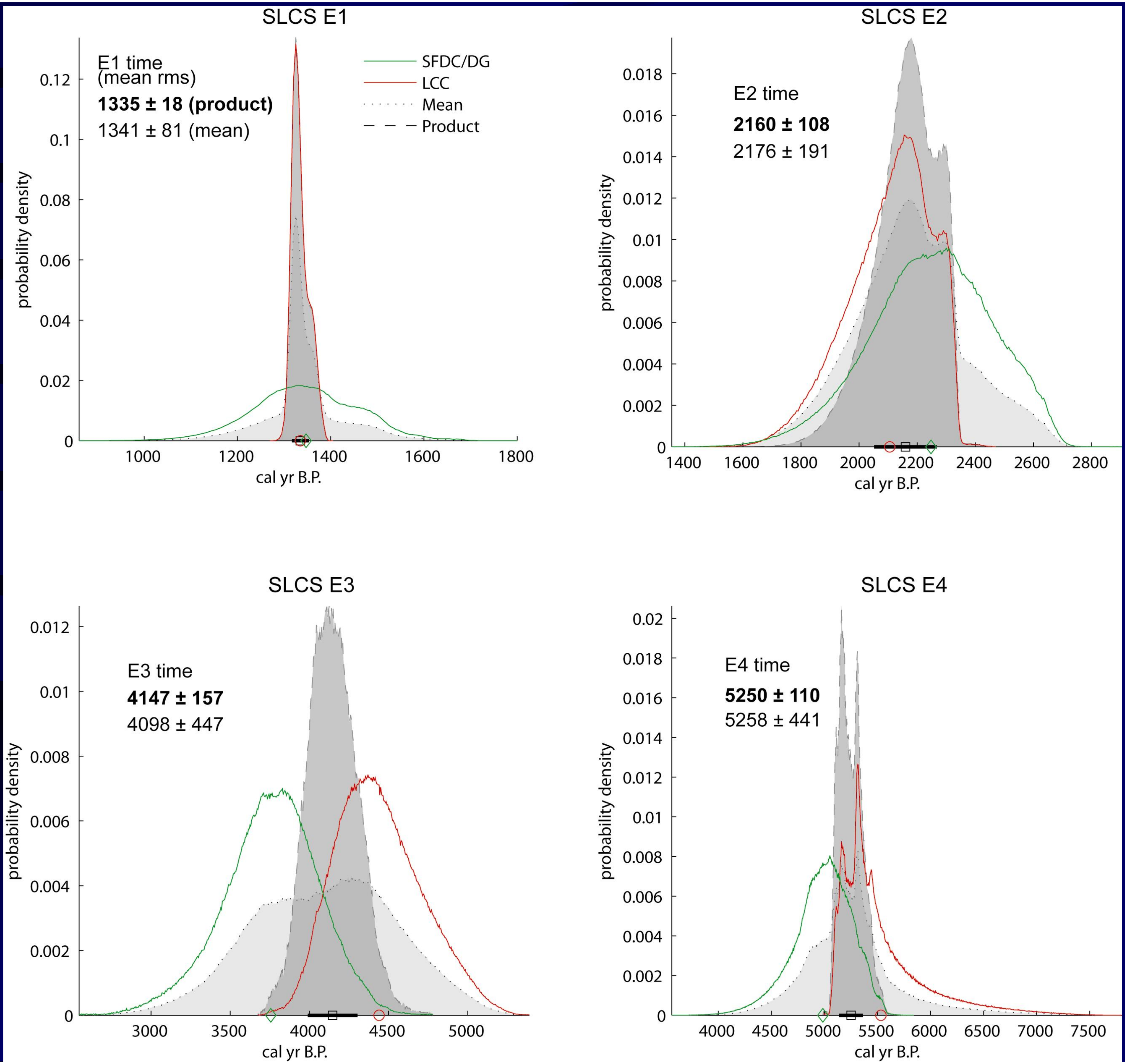
Correlation of events – 7-event model

7-events (Holocene)

Event	SFDC (ka)		LCC (ka)	
E1	1.3 ± 0.2		1.3 ± 0.04	
E2	2.2 ± 0.4		2.1 ± 0.3	
E3	3.8 ± 0.6		-	
E4	5.0 ± 0.5	⟷	4.4 ± 0.5	PDF overlap 32%
E5	-		5.5 ± 0.8	
E5	-		7.8 ± 0.7	
E6	-		9.5 ± 0.2	

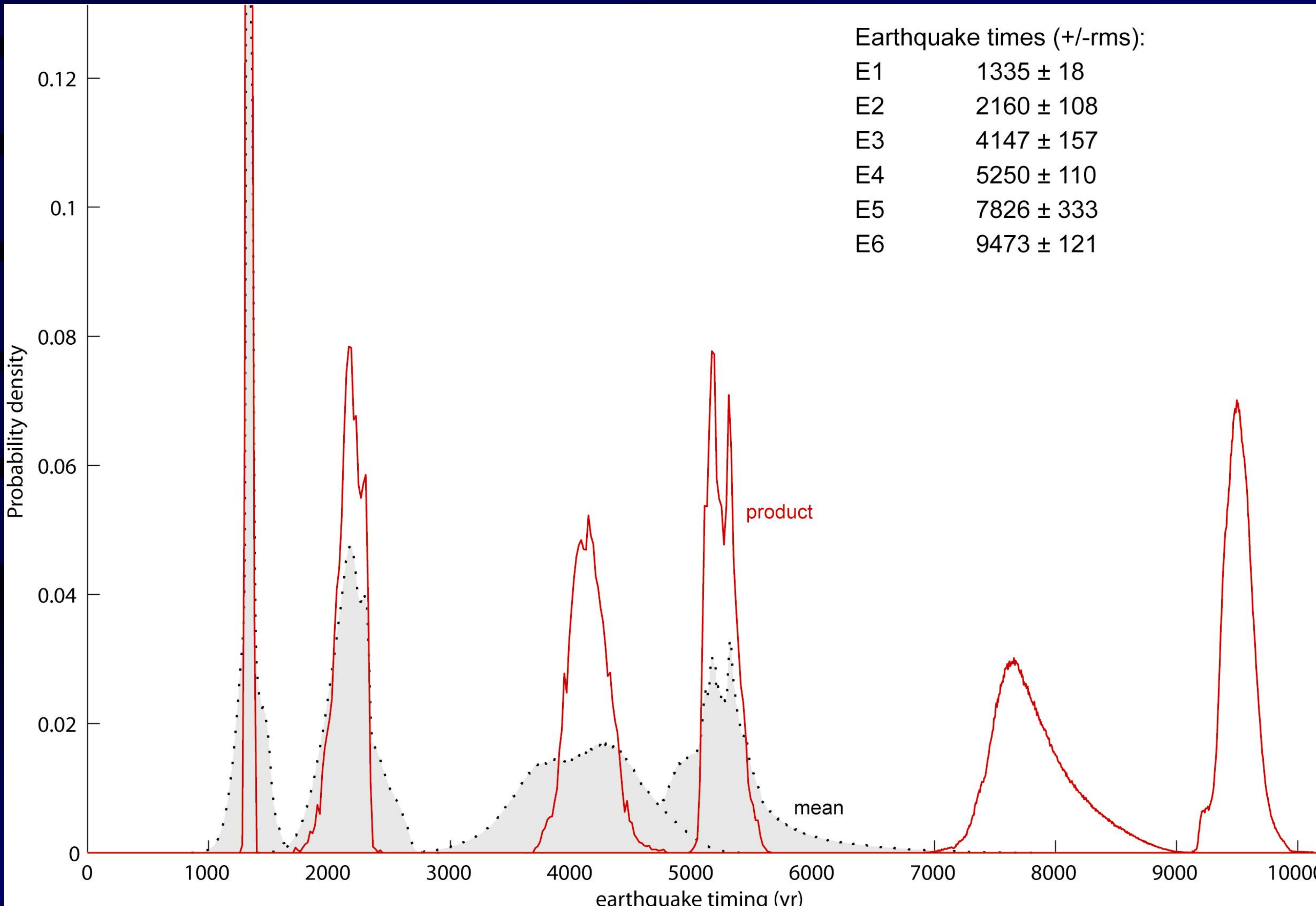
(All time ranges to 2 sigma)

- 7-event model
  - Results in 3 events between 3.8 and 5.5 ka
  - Slightly reduced overlap in PDFs for E4
  - Doesn't significantly change earthquake history (4 events in ~5 ka)



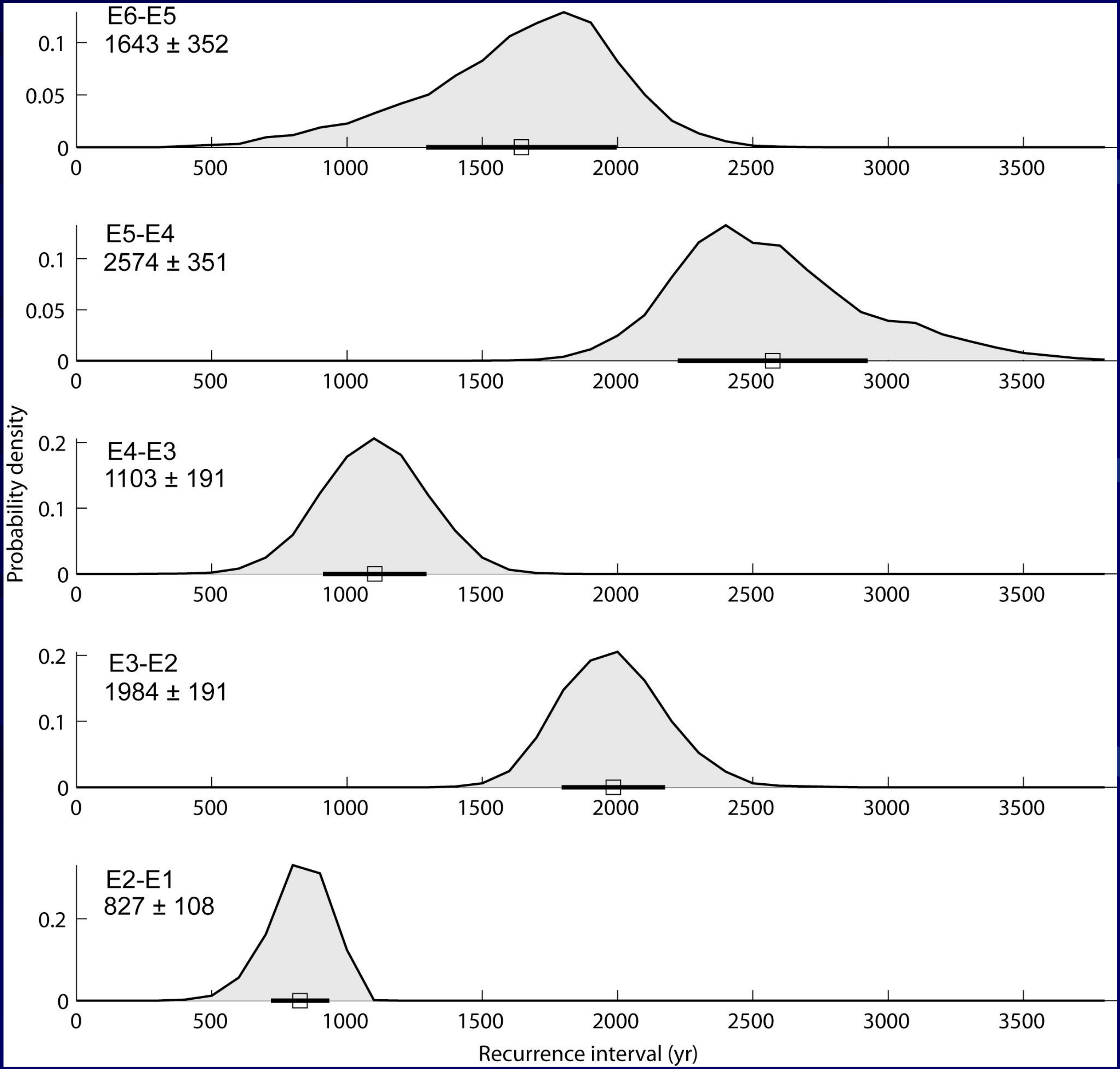
SLCS E1
E1 time
(mean rms)
1335 ± 18 (product)
1341 ± 81 (mean)
SFDC/DG
LCC
Mean
Product
probability density
cal yr B.P.
SLCS E2
E2 time
2160 ± 108
2176 ± 191
probability density
cal yr B.P.
SLCS E3
E3 time
4147 ± 157
4098 ± 447
probability density
cal yr B.P.
SLCS E4
E4 time
5250 ± 110
5258 ± 441
probability density
cal yr B.P.

SLCS earthquake history (6-event model)



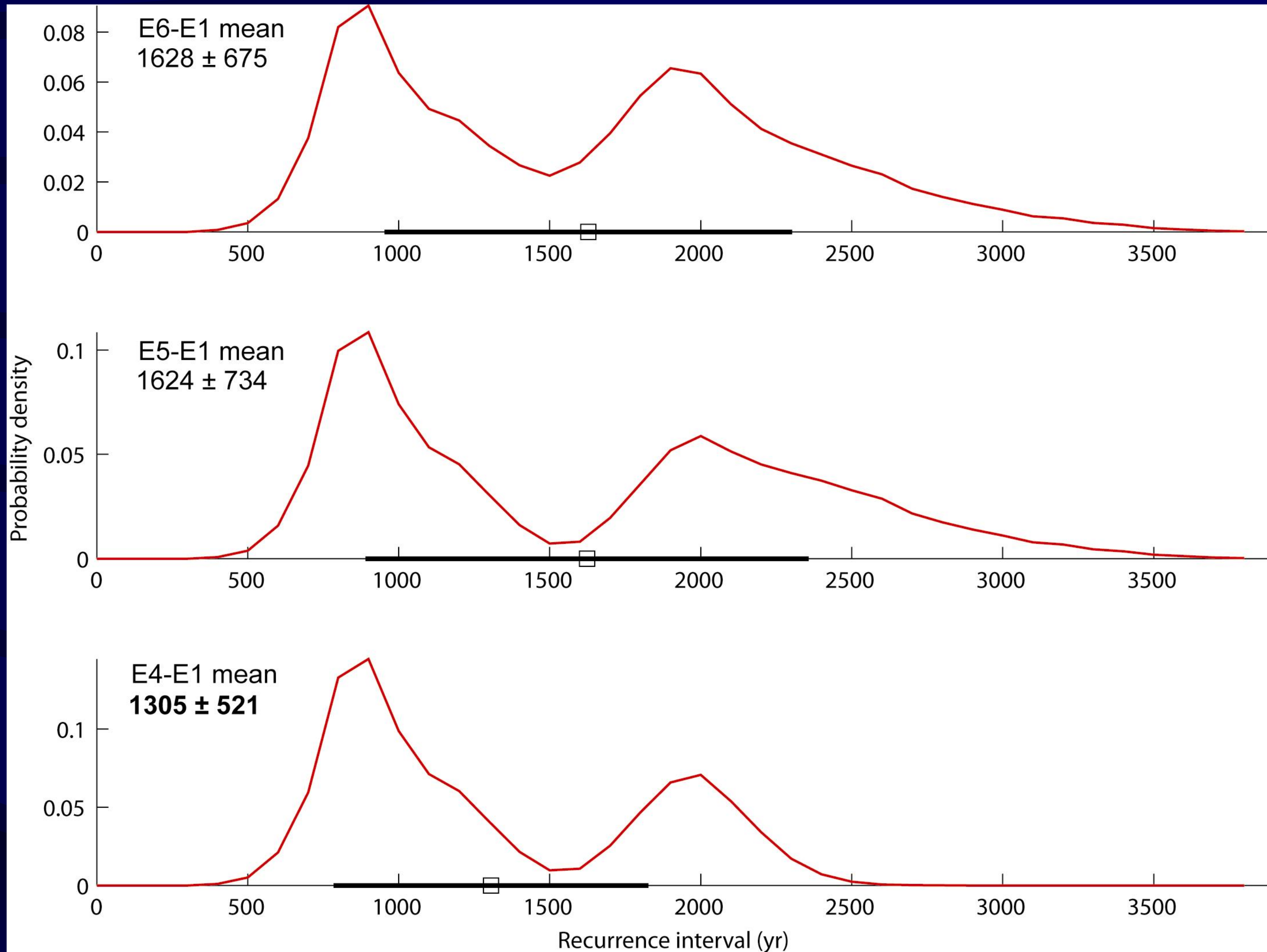
Recurrence (6-event model)

- Inter-event recurrence
  - Small (~0.1-0.2-ky) to moderate (~0.4-ky) uncertainties
  - Short (~1 ky) to long (~2 ky) recurrence



Recurrence (6-event model)

- Average recurrence
  - E4–E1: 1.3 ± 0.5 (1σ)
  - Bimodal distribution: ~1 ky and ~2 ky modes



Summary of results

	SFDC	LCC	Matlab (6 events)	UQFPWG
E1	1.3 ± 0.2	1.3 ± 0.04	1.3 ± 0.04	1.3 ± 0.65
E2	2.2 ± 0.4	2.1 ± 0.3	2.2 ± 0.2	2.45 ± 0.55
E3	3.8 ± 0.6	4.4 ± 0.5	4.1 ± 0.3	3.95 ± 0.55
E4	5.0 ± 0.5	5.5 ± 0.8 (5.3)	5.3 ± 0.2	5.3 ± 0.75
E5	-	7.8 ± 0.7	7.8 ± 0.5	~7.5 (5–9)
E6	-	9.5 ± 0.2	9.5 ± 0.2	~9 (<9.5–9.9)

(All time ranges: ka ± 2 sigma)

Summary of results

	SFDC	LCC	Matlab (6 events)	UQFPWG
E1	1.3 ± 0.2	1.3 ± 0.04	1.3 ± 0.04	1.3 ± 0.65
E2	2.2 ± 0.4	2.1 ± 0.3	2.2 ± 0.2	2.45 ± 0.55
E3	3.8 ± 0.6	4.4 ± 0.5	4.1 ± 0.3	3.95 ± 0.55
E4	5.0 ± 0.5	5.5 ± 0.8 (5.3)	5.3 ± 0.2	5.3 ± 0.75

E4 – E1 recurrence 1.3 ± 0.5 (1σ)

(All time ranges: ka ± 2 sigma)

- E4 – E1: complete record

Comparison with previous studies

- Recurrence estimates:
  - This study: 1.3 ± 0.5 ky (1σ) (E4-E1, 6-event model)

  - Previously reported recurrence estimates:
    - South Fork Dry Cr: 1.35 ± 0.2 ky (SFDC4–SFDC1)
    - Little Cottonwood Canyon: 1.3 – 1.4 ky (using SFDC data)

    - McCalpin & Nishenko: 1.4 ± 0.2 ky (SFDC4–SFDC1)
    - UQFPWG: 1.3 ky (0.5–2.4 ky estimated 2-sigma range)

Conclusions

- OxCal
  - Differences in event times related to using minimum and maximum limiting ages in OxCal versus only min or max ages in previous studies.
    - SFDC: 0 – 300 yr difference (E4 – E1)
    - LCC: 0 – ~1000 yr difference (E6 – E1)

- Correlation of events
  - 4 events correlate between sites – 6 event model preferred – good overlap in E3 and E4 site PDFs
  - 7-event model results in similar overlap in E4 site PDFs, but does not change E4 – E1 record

Conclusions

- Earthquake timing (segment PDFs)
  - E1 very well constrained: 1335 ± 40 yr (2σ) vs. ± 650 yr of UQFPWG
    - E1 elapse time: 1395 ± 40 yr (2σ)
  - E2 to E3 well constrained, good agreement between all models
  - E4 less well constrained, timing depends on correlation
  - Event times very similar to previously published values (± ~200 yr)

- Average recurrence
  - 6-event model: 1.3 ± 0.5 (1σ) for E4 to E1
  - Bimodal recurrence PDF from short (~1 ky) and long (~2 ky) intervals
  - Mean estimates similar to previous reports

Summary of OxCal/Matlab Results for the Nephi Segment

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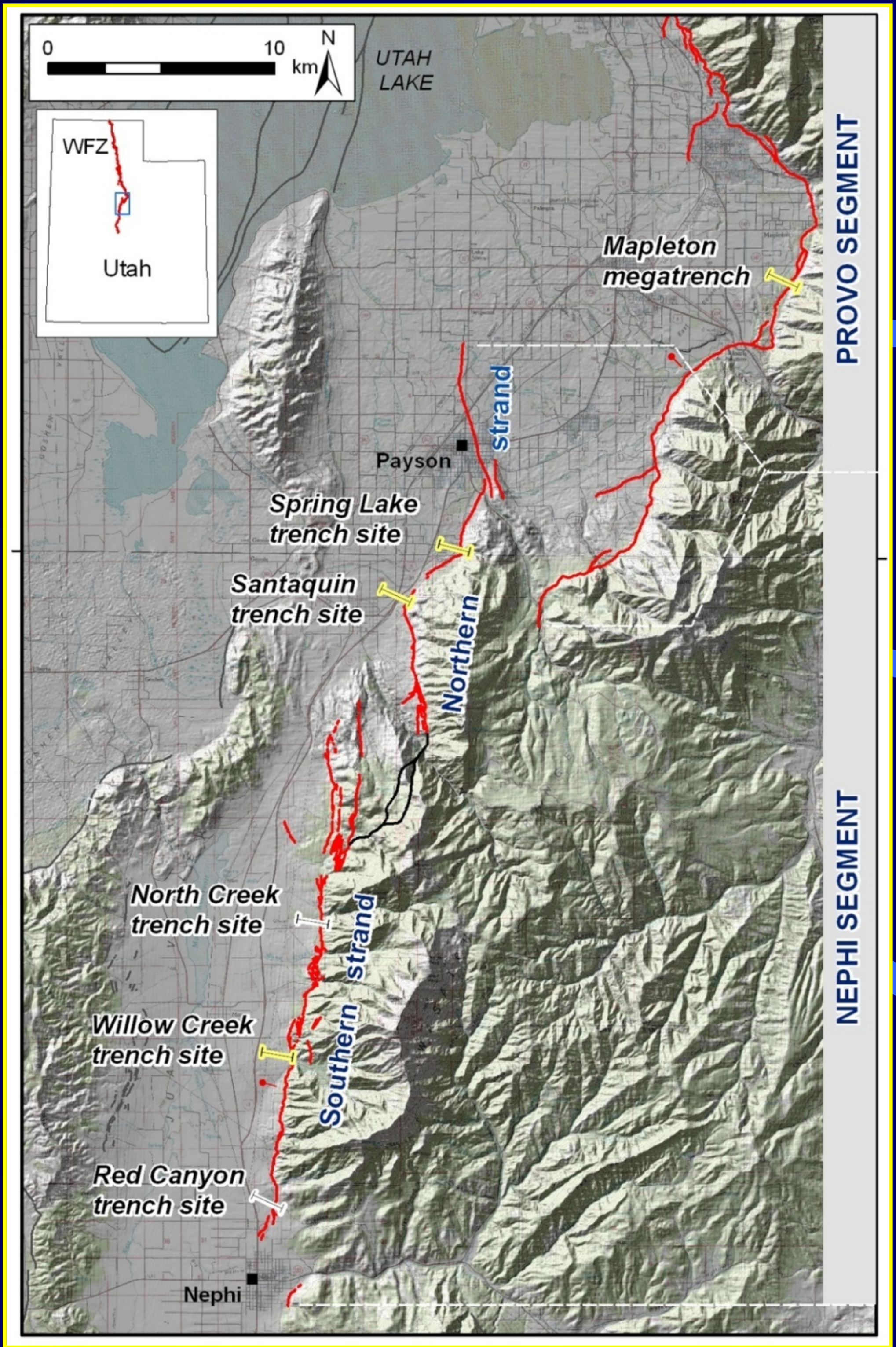
Working Group on Utah Earthquake Probabilities, July, 2010

Nephi segment (NS)

- Segment: 42 km long
- Northern Strand
  - 17 km long
  - Includes Benjamin fault
  - Trenches: Santaquin (2008)
  - Spring Lake (2007 & in progress)
- Southern Strand
  - 25 km long
  - North Creek (1981)
  - Willow Creek (2007)
  - Red Canyon (1991)



Spring Lake

- Horns and others, 2009, GSA Abstract:
  - Trench across separate strand of NS near boundary with Provo segment.
  - Reported two surface-faulting events that produced 3 m of vertical displacement.
  - Interpreted events to have occurred about 2.5 ka and 3.5 ka.
  - Noted absence of evidence for 500-yr-old event at site and conclude that the MRE at Santaquin site did not rupture the Spring Lake strand.
  - Plans to excavate another trench on nearby scarp in summer 2010.
  - Not included in OxCal models.

Santaquin (SQ)

- DuRoss and others, 2008, UGS Special Study 124:
  - Two trenches across 3- to 4-m-high scarps.
  - One surface-faulting event that displaces early to mid-Holocene alluvial fan.
  - Maximum age of MRE: 500-550 cal. yr B.P. (charcoal from faulted soil).
  - Minimum age for MRE: 425 cal. yr B.P. (charcoal from organic horizon in unfaulted colluvium).
  - Preferred age of MRE: 500+100/-150 yr.
  - Evidence for older events not exposed in trenches.
  - Age of older event(s): at least >1.5 ka and likely >6.1-7.0 ka.

Santaquin Summary (SQ)

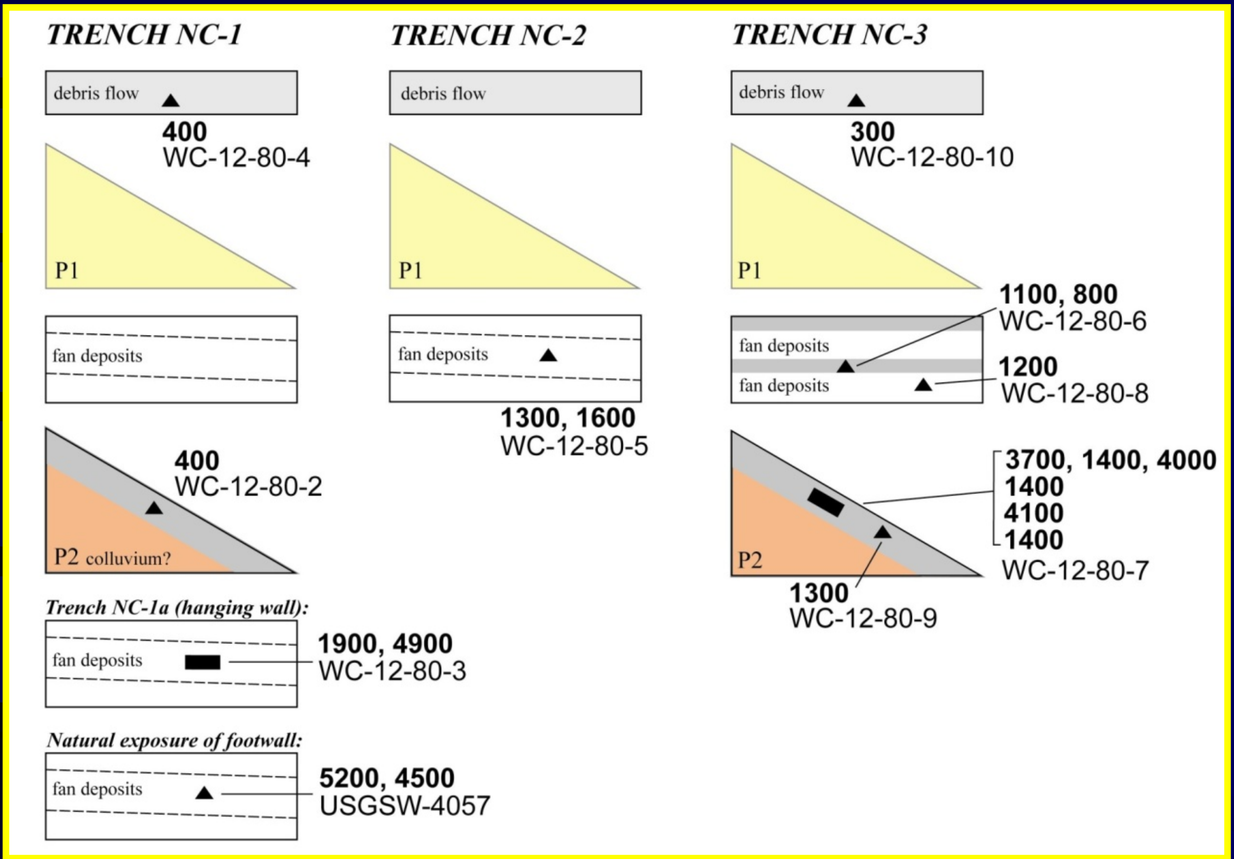
Event	DuRoss et al. (2008)	This study (OxCal model)
SQ1 (Z)	~0.5 +0.1/-0.15	0.46 ± 0.1 (2σ)
SQ2 (Y)	>1.5 (min); likely >6.1-7.0 ka	------

- **Remaining Issues:**
  - Correlation of event SQ1 with MREs on Nephi or on Provo segment?
  - Lack of older events that correspond to events on southern strand of Nephi segment or on Provo segment.

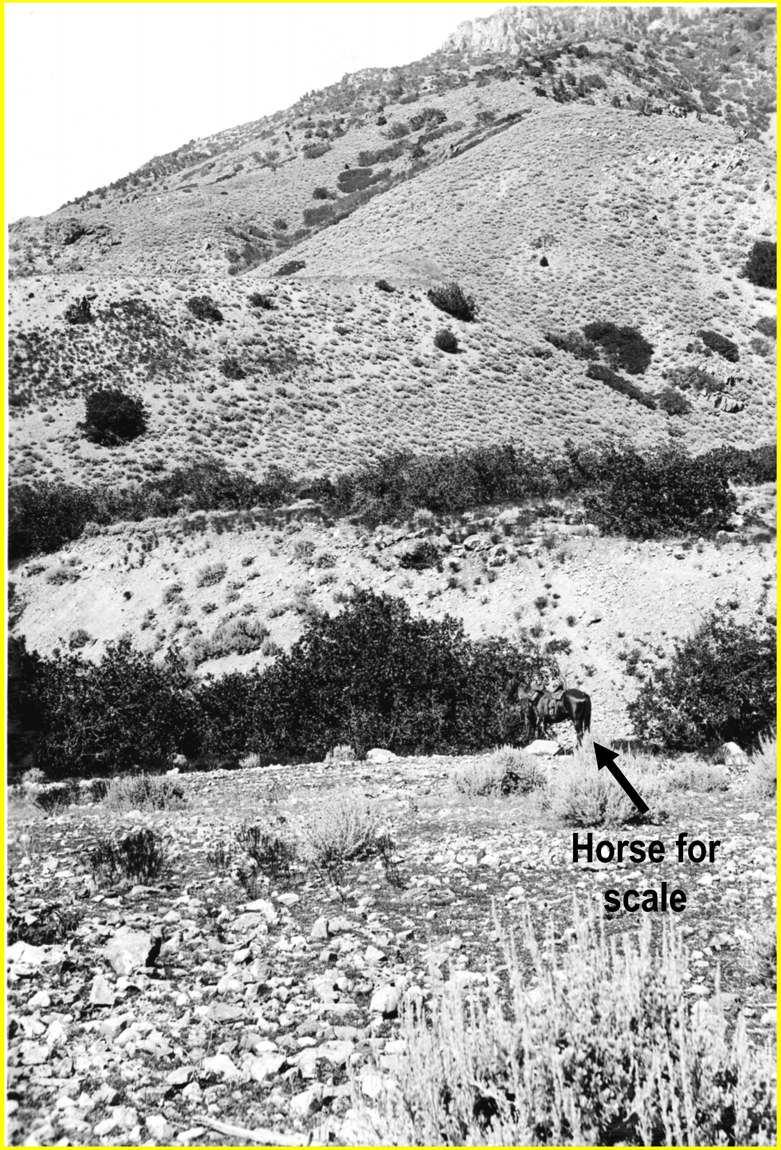
North Creek (NC)

- Hanson and others (1981, 1982); Schwartz and Coppersmith (1984)
  - Three trenches across scarps at main canyon and at "South" Creek.
  - Colluvial wedges document two surface-faulting events and third event inferred from inset, 2.6-m-high strath terrace.
  - Maximum age of faulted alluvial-fan deposits: 4.5-5.2 ka based on three radiocarbon ages.
  - Most radiocarbon dates provide minimum age for penultimate event (N2) and maximum age for MRE (N1). No radiometric ages to define time between N2 and inferred older event N3.
  - Uncalibrated radiocarbon ages between events N1 and N2 cluster in two sets: 3,700-4,100 ^{14}C yr and 1,100-1,600 ^{14}C yr.
  - Previous studies favor older suite of ages and attribute younger ages to contamination by young carbon.

North Creek (NC)



Schematic diagram of stratigraphic relations at North Creek



Fault scarp at North Creek
F.B. Weeks photo
August 1903

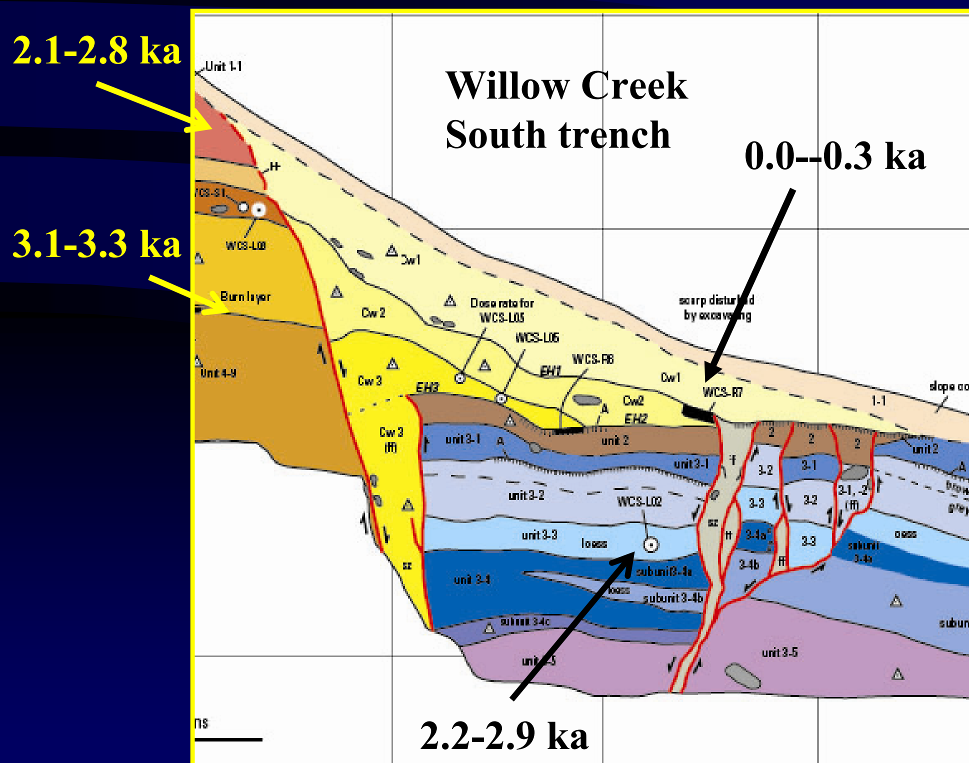
North Creek Summary (NC)

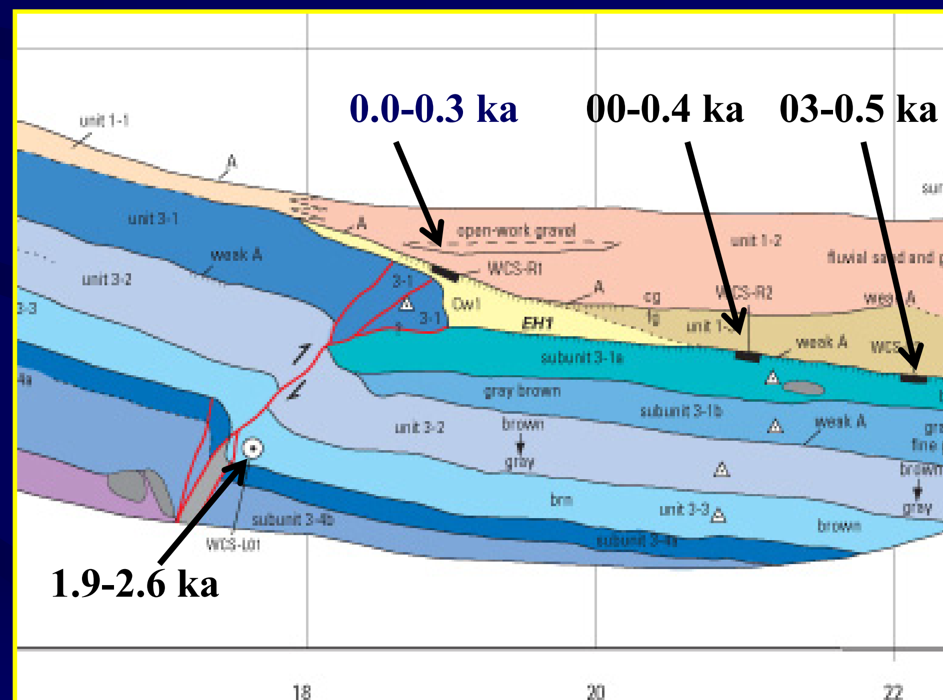
Event	Hanson and others (1981, 1982)	This study (OxCal ; North Ck 2)
N1 (Z)	<1.1-1.3 ka prefer 0.3-0.5 ka	0.4 ± 0.5 (2σ)
N2 (Y)	>3.6 ka	1.4 ± 0.3
N3 (X)	<4.6 ka	1.9 ± 0.5

- **OxCal modeling**
  - Results from Willow Creek strongly suggest that younger suite of dates are viable minimum constraint on event N2. Older suite of ages: detrital charcoal.
  - Use of younger suite of ages in model yields results for age of event N2 that are consistent with two other sites on the “Southern” strand of the Nephi segment.
  - Hanson and others preferred age of 0.3-0.5 ka for event N1 is consistent with results from other “Southern” strand sites.

Willow Creek (WC)

- Machette and others, USGS Sci. Invest. Map 2966 (2007)
  - Two trenches across 6- to 8-m-high scarps on Holocene alluvial fans.
  - Exposed evidence of three events in both trenches.
  - Luminescence and radiocarbon dates show that faulted fan at Willow Creek South site has an age of about 2.5 ka. All three events are <2.5 ka.





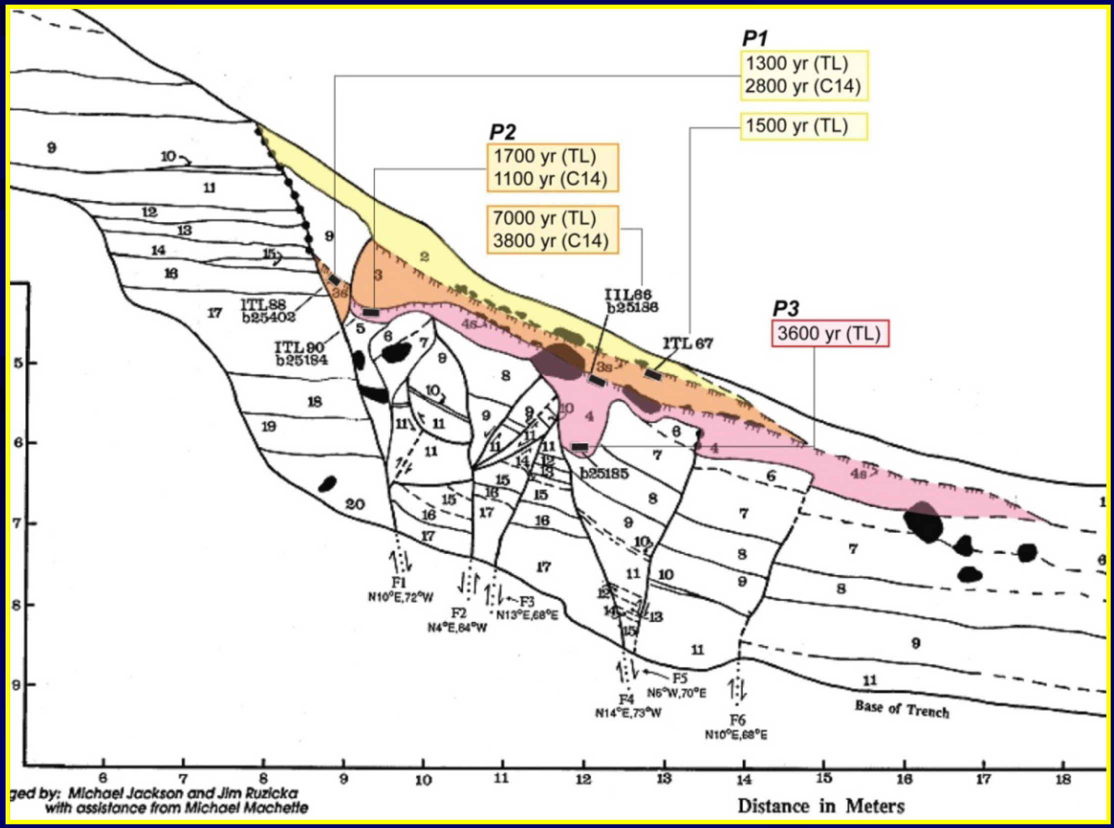
Willow Creek Summary (WC)

Event	Machette and others (2007)	This study (OxCal ; WC 10)
WC1 (Z)	0.3 ka	0.2 ± 0.1 (2σ)
WC2 (Y)	1.2 ka	1.2 ± 0.1
WC3 (X)	<2.3 ka	2.0 ± 0.5

- **OxCal modeling**
  - Age of WC1 well constrained by several, consistent radiocarbon dates.
  - Age of WC2 well constrained; bounds on WC3 less rigorous.
  - Maximum age for all three events well defined by series of luminescence and radiocarbon ages.
  - Stratigraphic relations indicate presence of older events at Willow Creek North site but no chronologic control on those events.

Red Canyon (RC)

- Jackson, UGS Special Study 78 (1991)
  - Trench across 5.5-m-high scarp on probable latest Pleistocene alluvial fan northeast of town of Nephi. Close to southern end of "Southern" strand.
  - Evidence of three discrete colluvial wedges. No age control on fan deposits.
  - Several stratigraphically inconsistent and conflicting ages in both radiocarbon and TL ages.



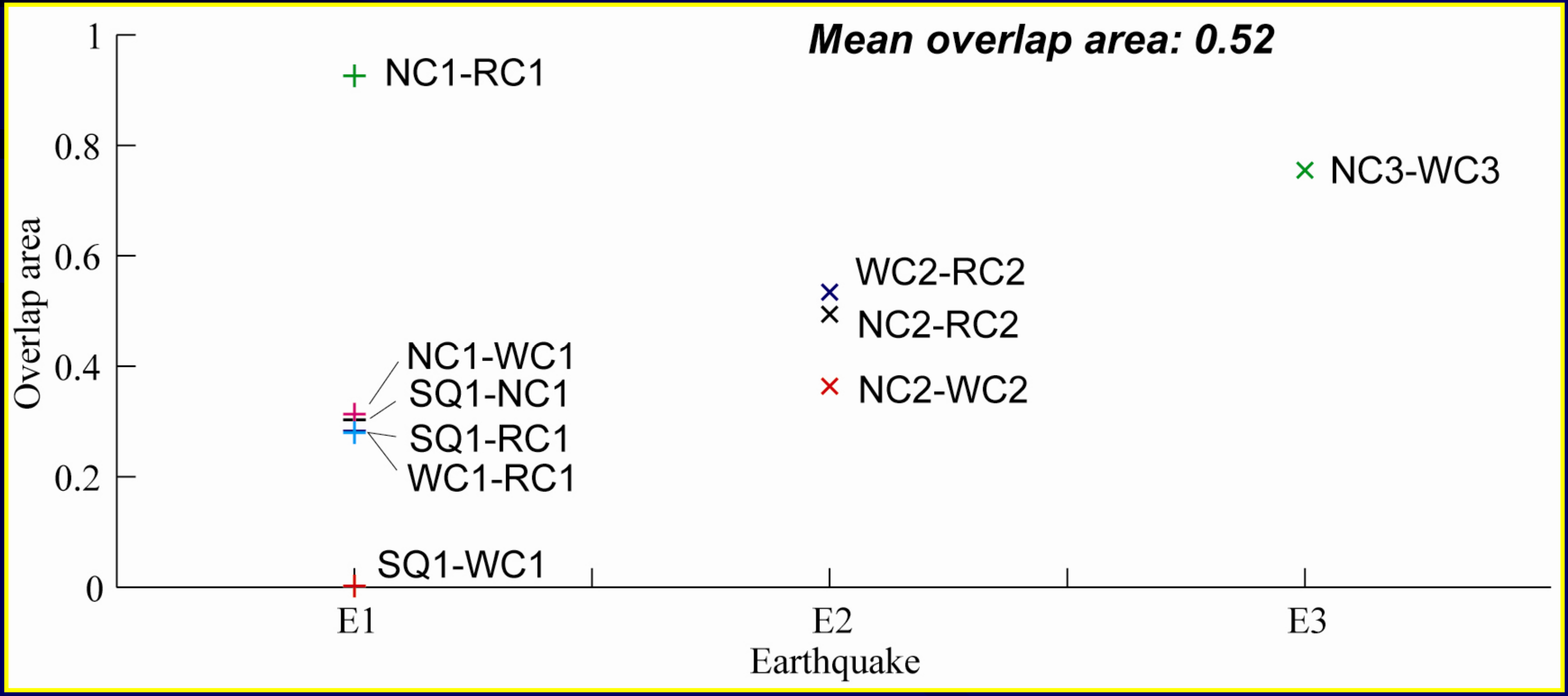
Red Canyon Summary (RC)

Event	Jackson (1991)	This study (OxCal ; RC 9)
RC1 (Z)	1.2 ka	0.5 ± 0.5 (2σ)
RC2 (Y)	3.0-3.5 ka	1.2 ± 0.3
RC3 (X)	prefers 4.0-4.5 ka	4.7 ± 2.7

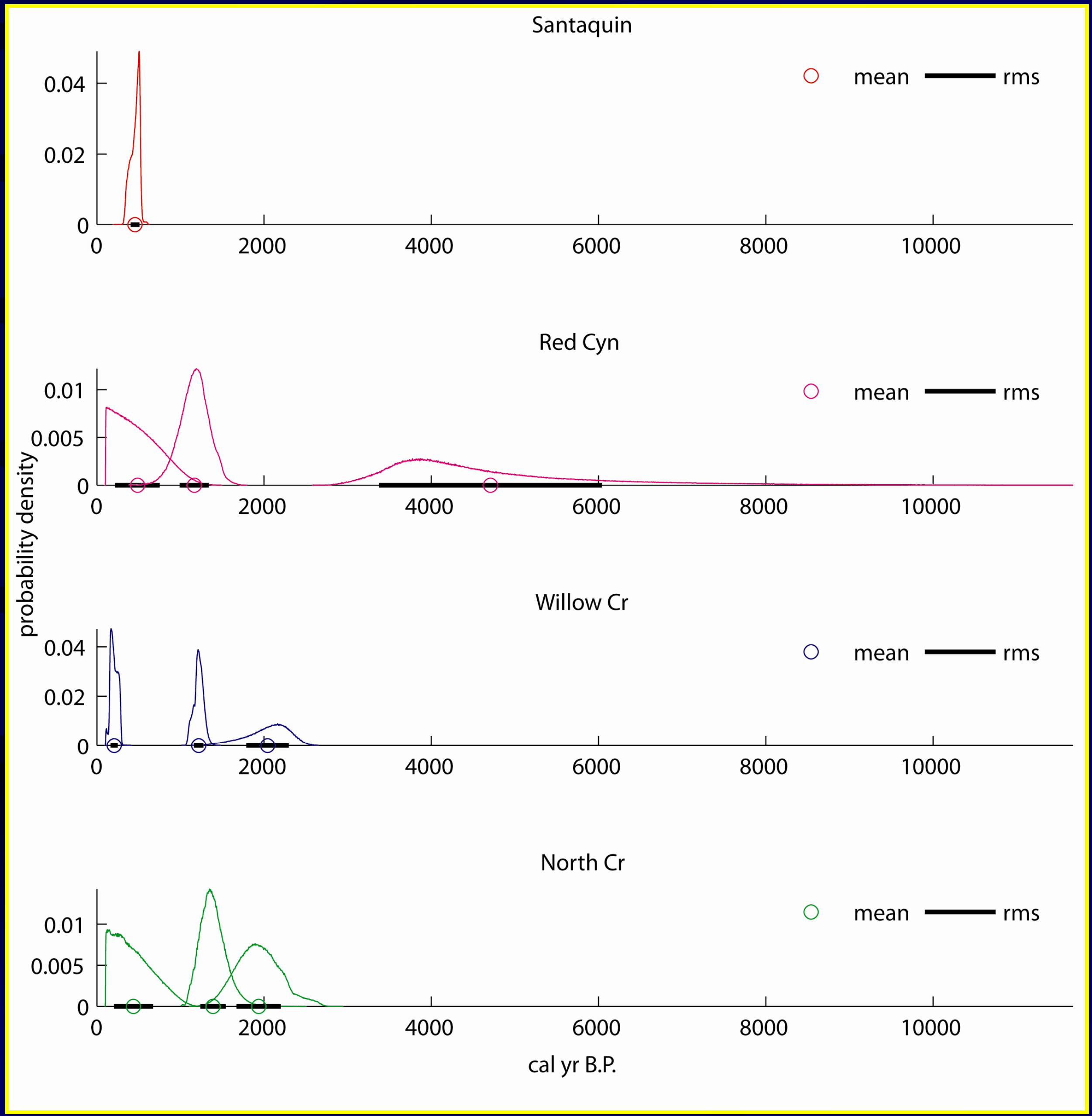
- **OxCal modeling**
  - Dismissed ages that were clearly inconsistent based on stratigraphic position or other well-dated samples.
  - No chronologic constraint on minimum age of MRE (RC1); only bounded by historical constraint.
  - No chronologic constraint on age of faulted alluvial fan; inferred to be latest Pleistocene in age.
  - One TL and two radiocarbon ages constrain time between RC2 and RC3.
  - OxCal model suggests that RC3 is older than all of the events modeled at Willow Creek and North Creek.

Correlation of Nephi Segment Events

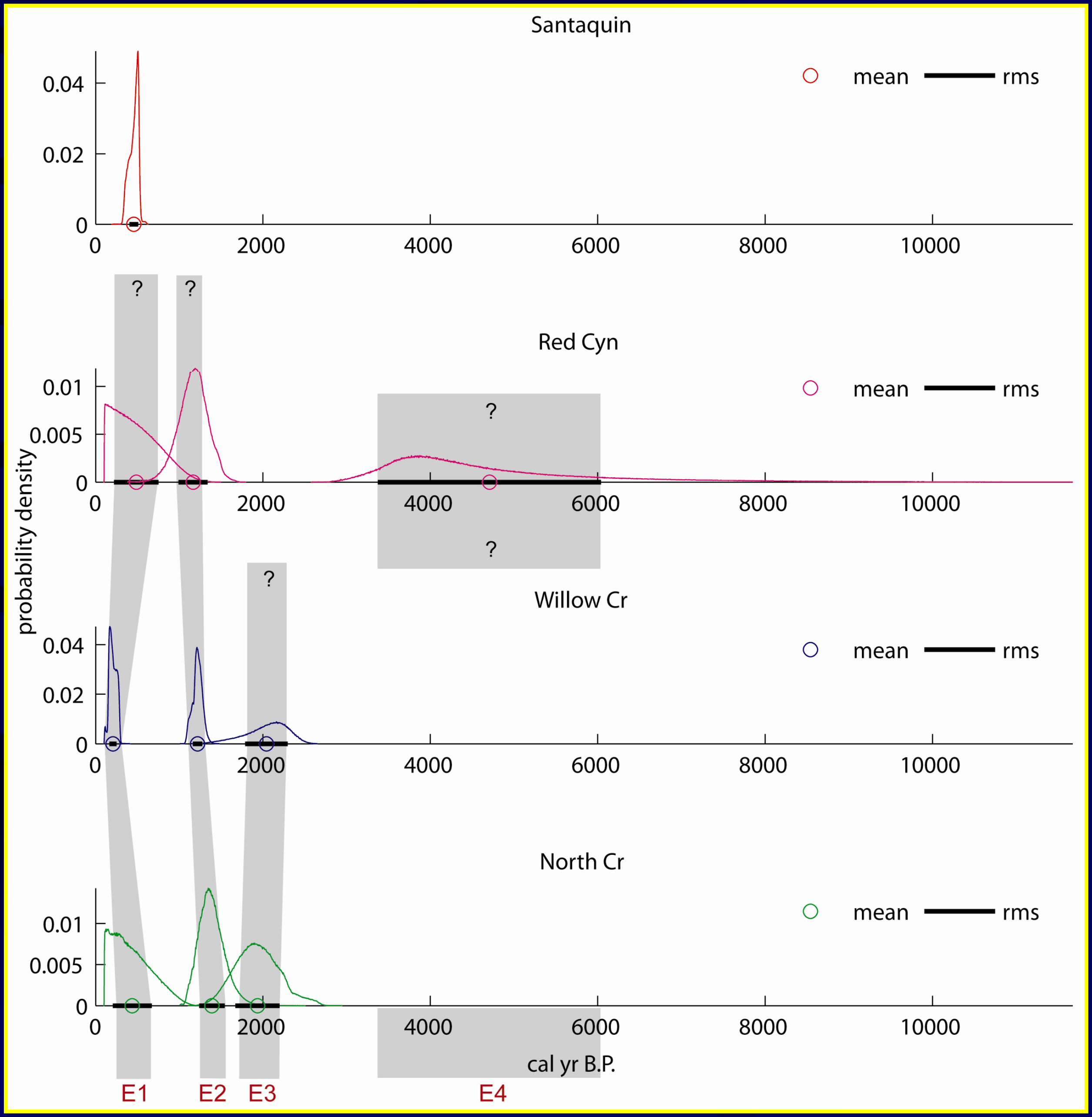
Event	North Ck.	Willow Ck.	Red Canyon
E1	0.4 ± 0.4	0.2 ± 0.1	0.5 ± 0.3 (2σ)
E2	1.4 ± 0.3	1.2 ± 0.1	1.2 ± 0.2
E3	1.9 ± 0.3	2.0 ± 0.5	----------
E4	----------	----------	4.7 ± 2.7



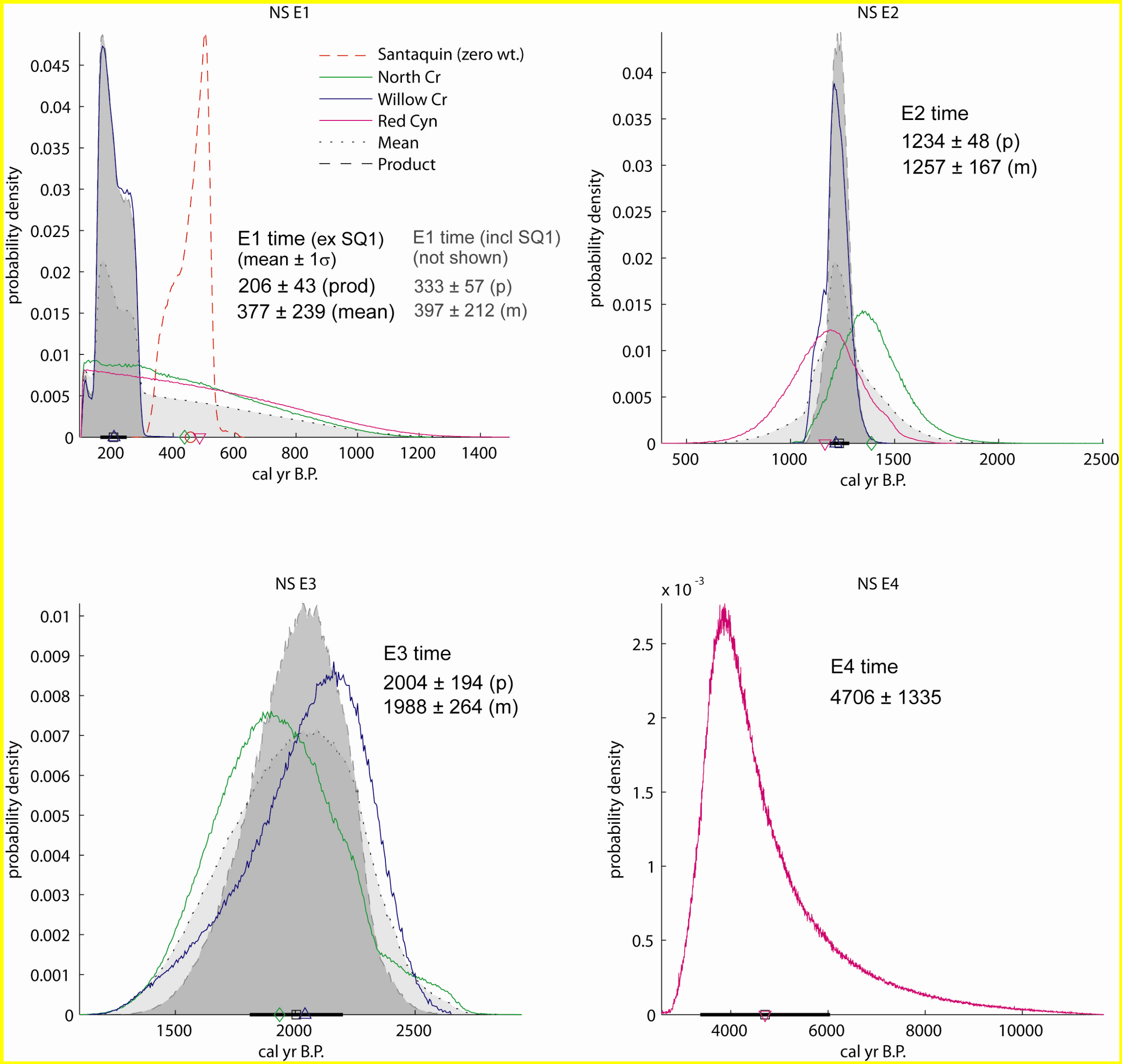
Matlab plot of NS site PDFs



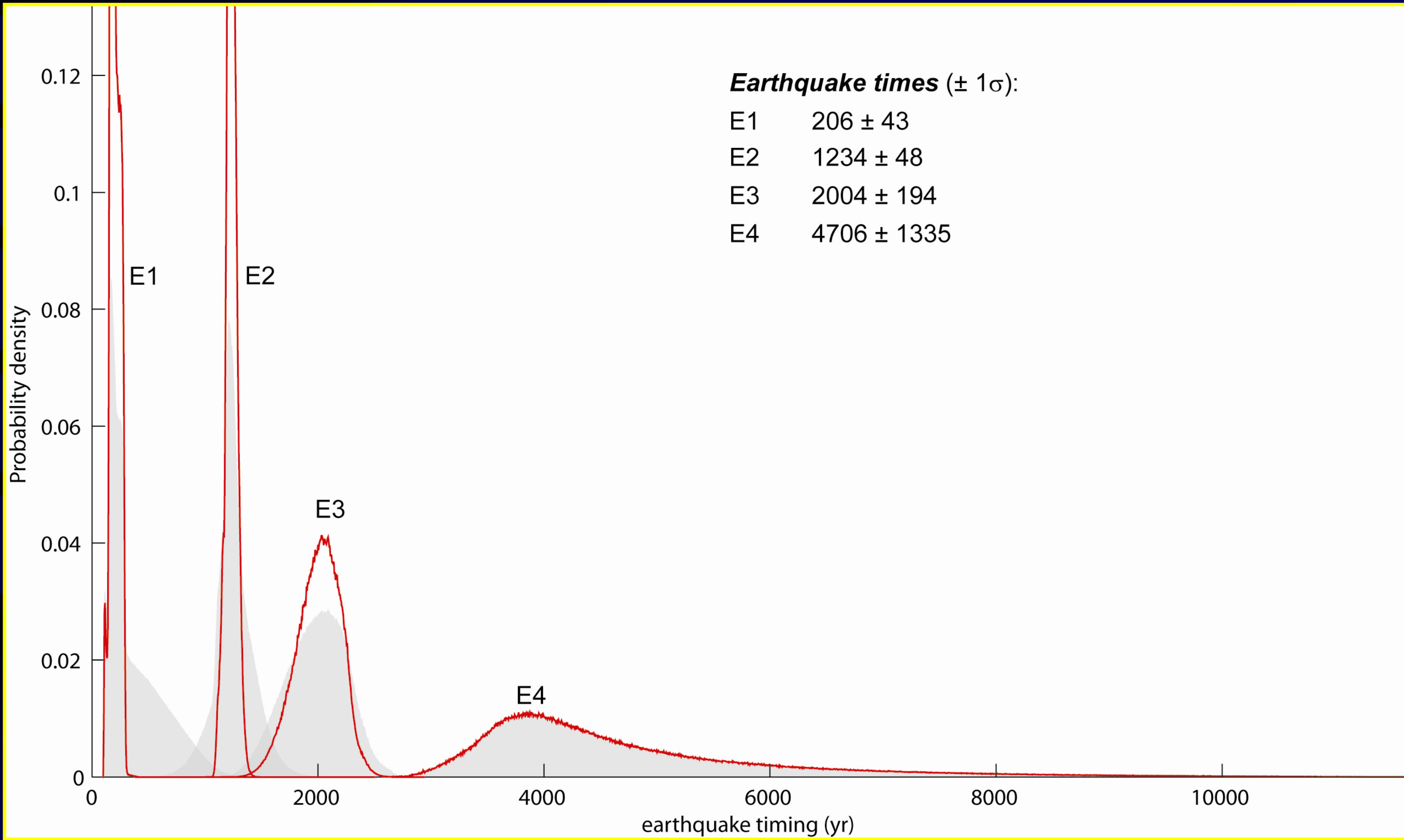
Correlation of NS site PDFs



Refined Times of NS events site PDFs



NS Earthquake History

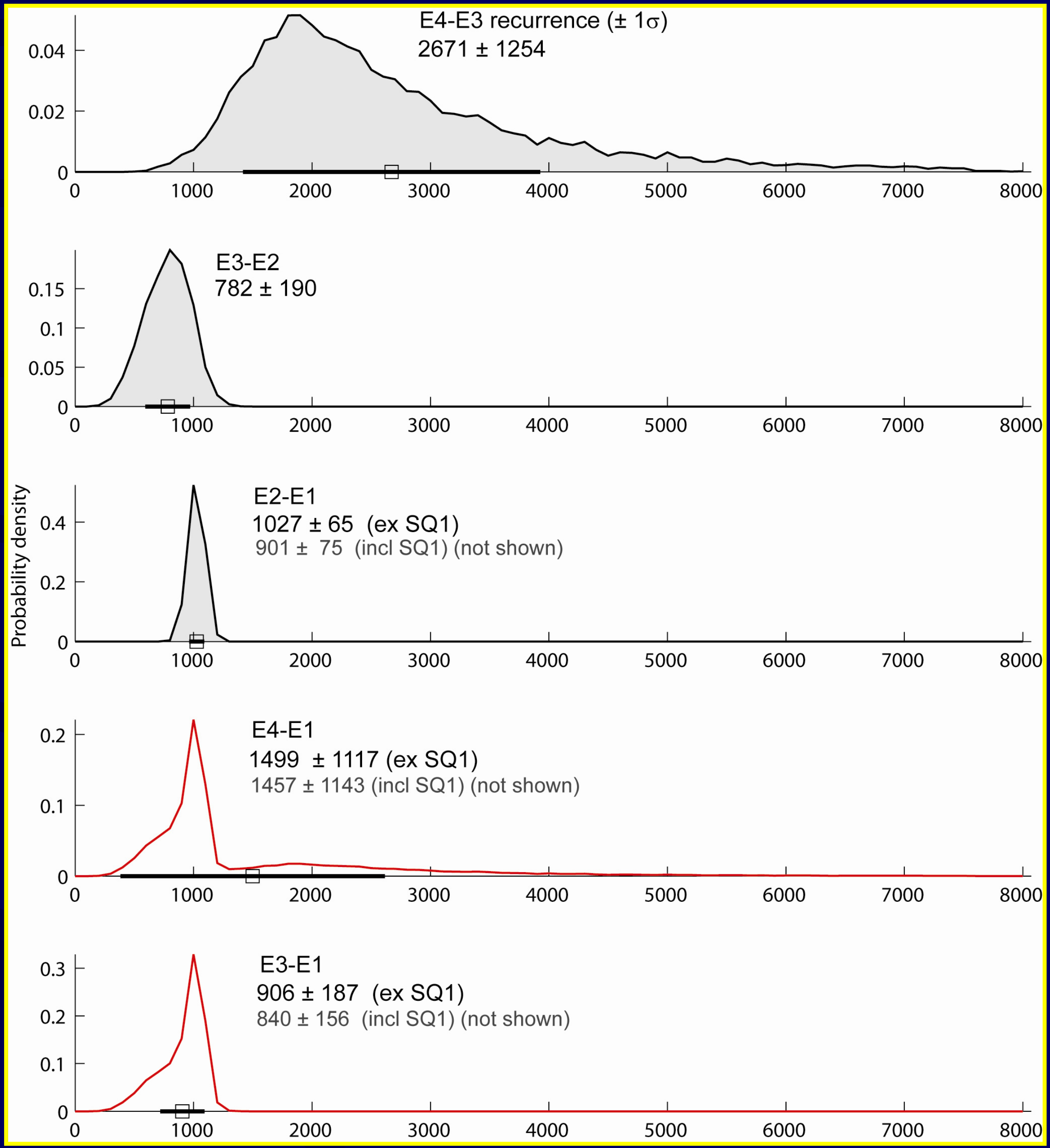


NS Recurrence

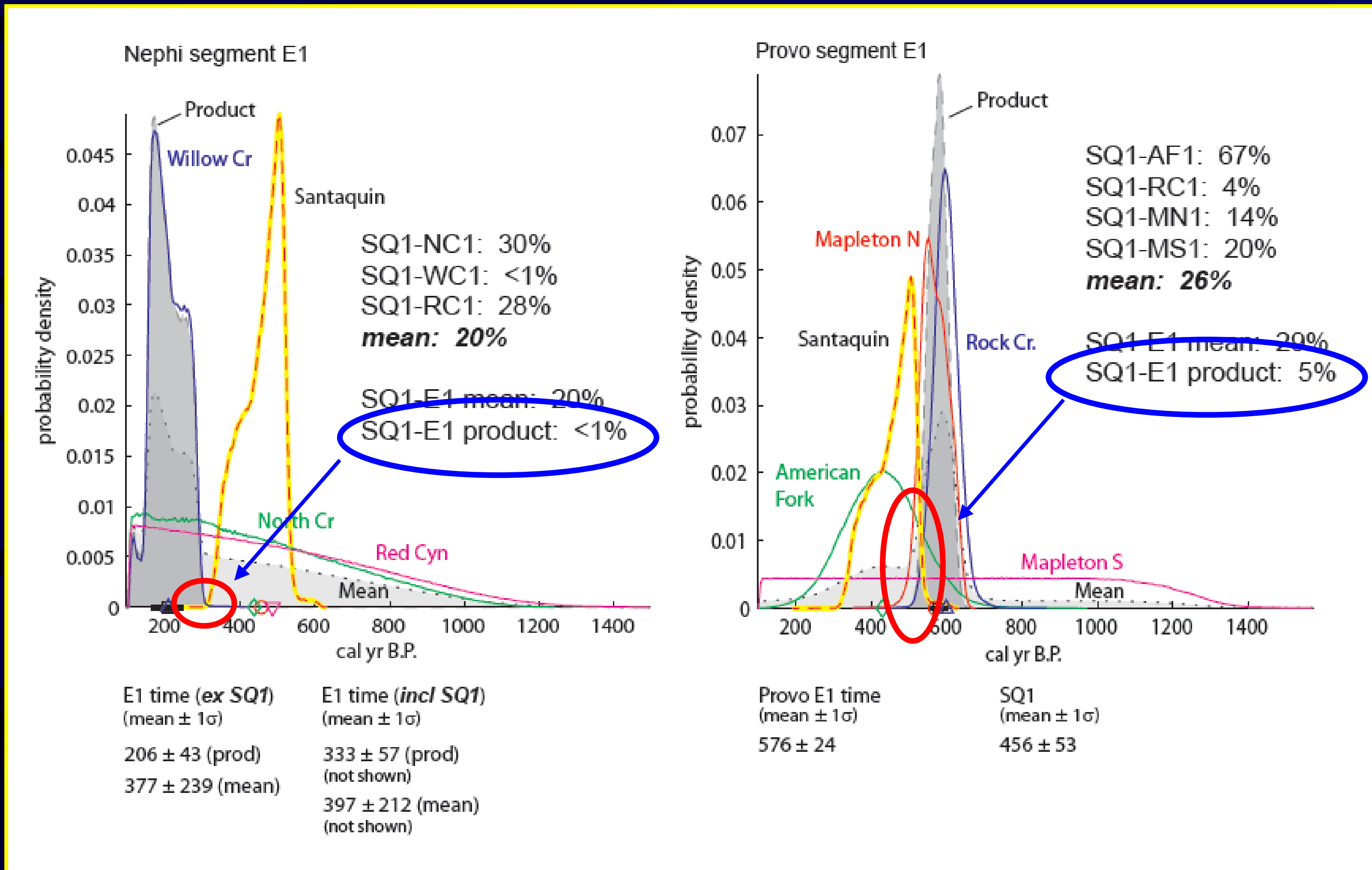
- Inter-event recurrence
  - Good constraints on events N1 and N2 yield tight bounds on recurrence of ~1 ky.
  - Weaker constraints on event E3 yields broader PDF of E3-E2.
  - Age of E4 from RC: at end of segment, has long recurrence & large uncertainty: 2.6 ±1.3 ky. Possibilities:

    1) missing events

    2) not all events rupture to end of segment.



Santaquin (SQ1): Nephi vs. Provo segment



Overlap of SQ1-Nephi E1 PDFs <1% versus SQ1-Provo E1 about 5%

Summary of results

	Matlab (4 events)	UQFPWG
E1	0.21 ± 0.09	≤1.0 ± 0.4 (Z)
E2	1.2 ± 0.1	~3.9 ± 0.5 (Y)
E3	2.0 ± 0.4	>3.9 ± 0.5; <5.3 ± 0.7 (X)
E4	4.7 ± 2.7	------------

(All time ranges: ka ± 2 sigma)

Comparison with previous studies

- Recurrence estimates:
  - This study: 0.9 ± 0.2 ky (1σ) (E3-E1, excluding SQ1)
    1.5 ± 1.1 ky (1σ) (E4-E1, excluding SQ1)
  - Previously reported recurrence estimates:
    - North Creek: 1.7-2.6 ky (median range, Hanson and others, 1981)
    - Willow Creek: not reported (Machette and others, 2007)
    - Red Canyon: not reported (Jackson, 1991)
    - Nephi segment: 2.7 ± 0.25 ky (McCalpin and Nishenko, 1996)
    - UQFPWG: ~2.5 ± 2.1 ky

Conclusions

- OxCal
  - OxCal models developed through a systematic reevaluation of ages and stratigraphic relations for previously published studies.
  - Results suggest substantial revisions in event chronology and recurrence for Nephi segment.
- Correlation of events
  - Reevaluation of data from North Creek, Willow Creek, and Red Canyon yield very consistent ages for E1 and E2.
  - Age of E3 based on data from North Creek and Willow Creek; ages are similar but have greater uncertainty than E1 and E2.
  - Interpret fourth event on segment that is only documented at Red Canyon at end of segment. Record at North Creek and Willow Creek may not extend back as far in time to capture this event. Time constraints on E4 very broad.
  - Youngest event at Santaquin on Northern Strand probably does not correlate with events on Southern Strand.

Conclusions

- Earthquake timing (modeled from site PDFs)
  - E1 very well constrained: 206 ± 86 yr (2σ) vs. <1.0 ± 0.4 ka of UQFPWG.
    - E1 elapse time: barely prehistoric.
    - Consistent with geomorphology.
  - E2 to E3 well constrained based on reinterpretation of North Creek and Red Canyon data; reinterpretation yields good agreement between all three sites.
    - E2 considerably younger than previously thought: 1.2 ka vs. ~3.9 ka.
  - E1, E2, and E3 must by younger than ~2.5 ka.
  - E4 age poorly constrained; broad PDF with large uncertainty.

- Average recurrence
  - Two-event model: 0.9 ± 0.2 (1σ) for E3 to E1.
  - Three-event model: 1.5 ± 1.1 ka for E4 to E1. Strong peak at 1 ka but broad tail because of poor constraints on time of E4.
  - Updated recurrence considerably narrower than previous UQFPWG estimate.

Provo Segment – Summary of OxCal Analyses

WGUEP OxCal Committee

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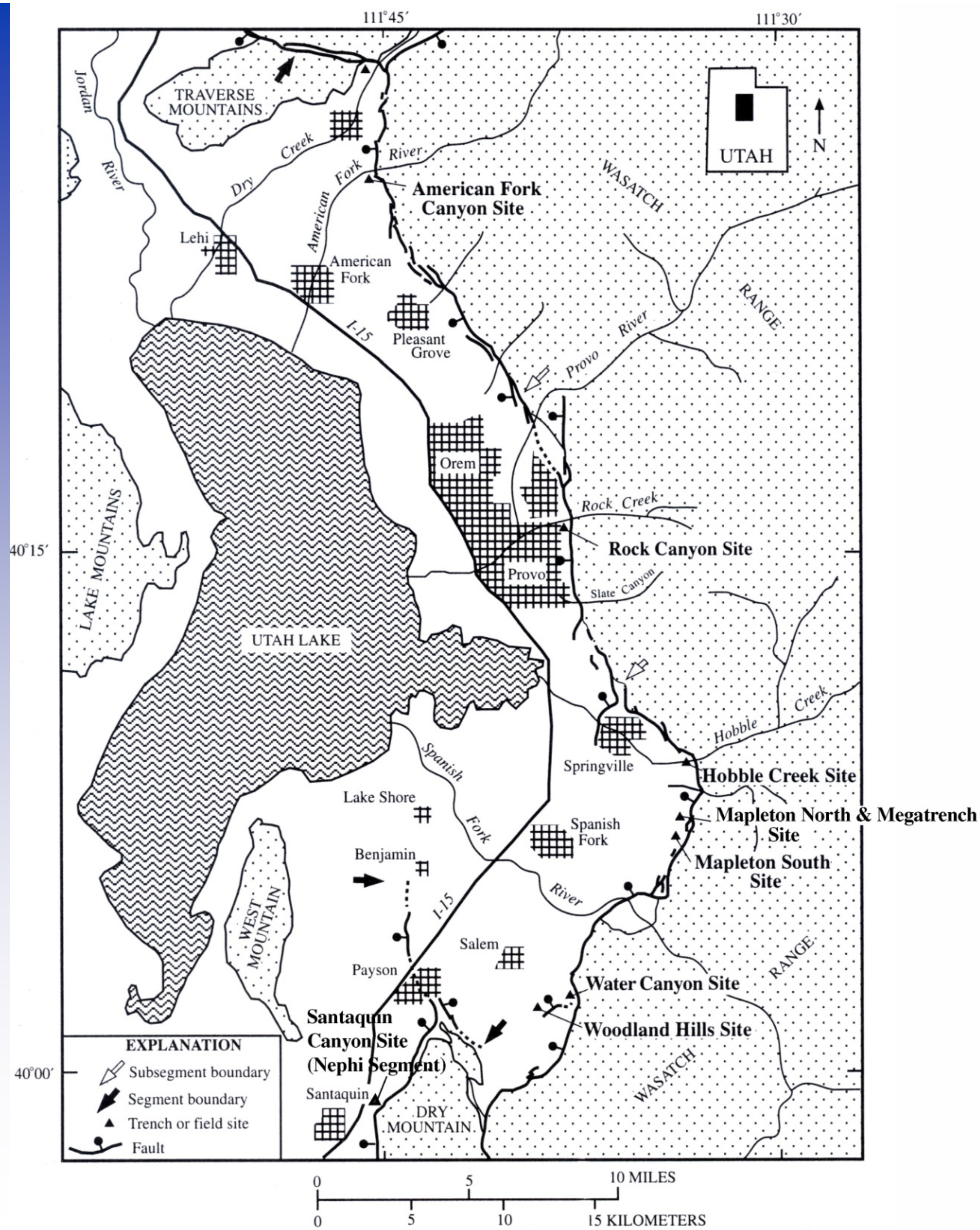
URS Corporation
1333 Broadway, Suite 800
Oakland, CA 94612

Working Group on Utah Earthquake Probabilities

July 21-22, 2010

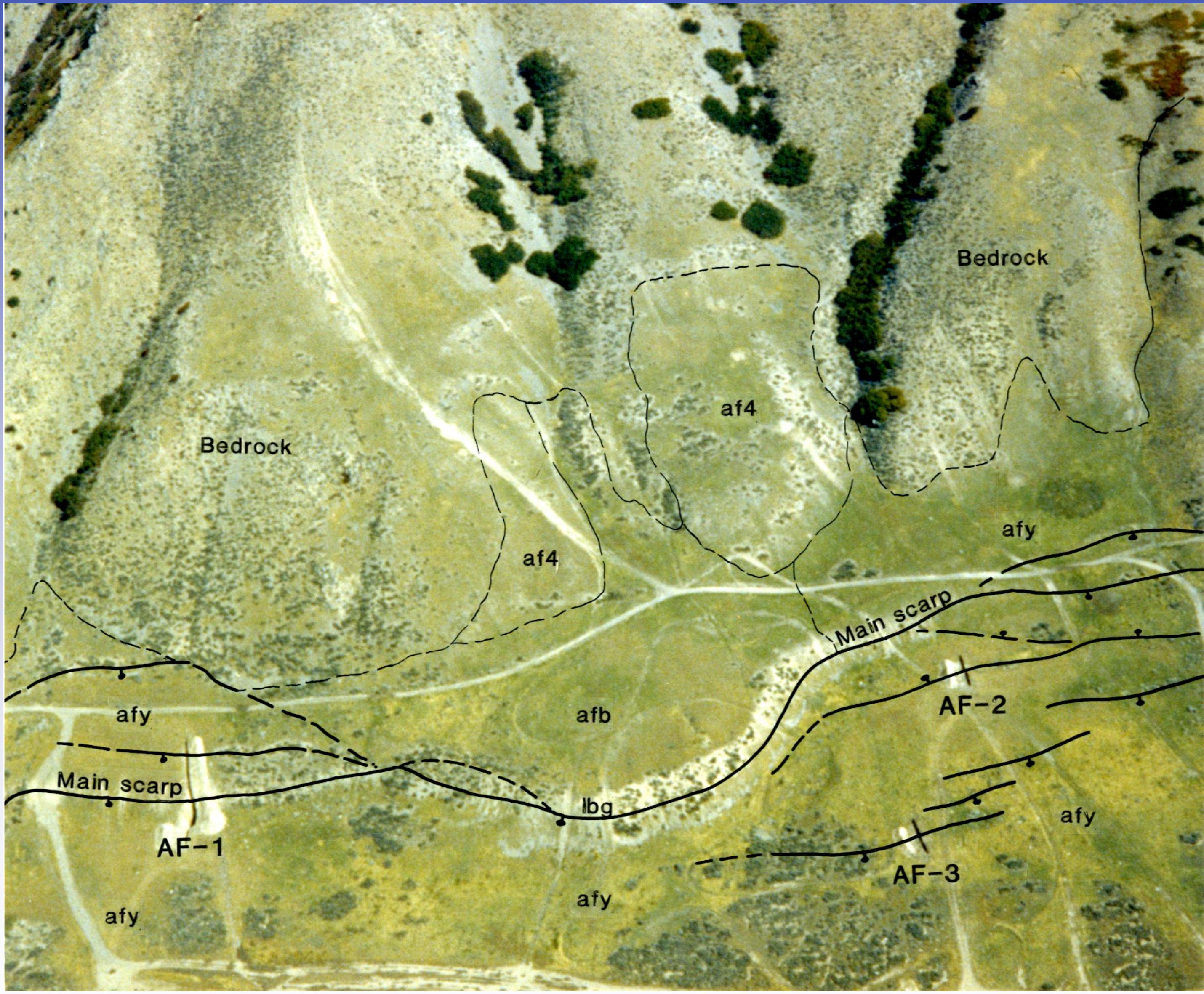
Provo Segment Trench Sites

- **American Fork Canyon (Machette et al., 1992)**
- **Rock Canyon (Lund and Black, 1998)**
- **Mapleton North (Lund et al., 1991; Olig et al., 2010)**
- **Mapleton South (Lund et al., 1991)**

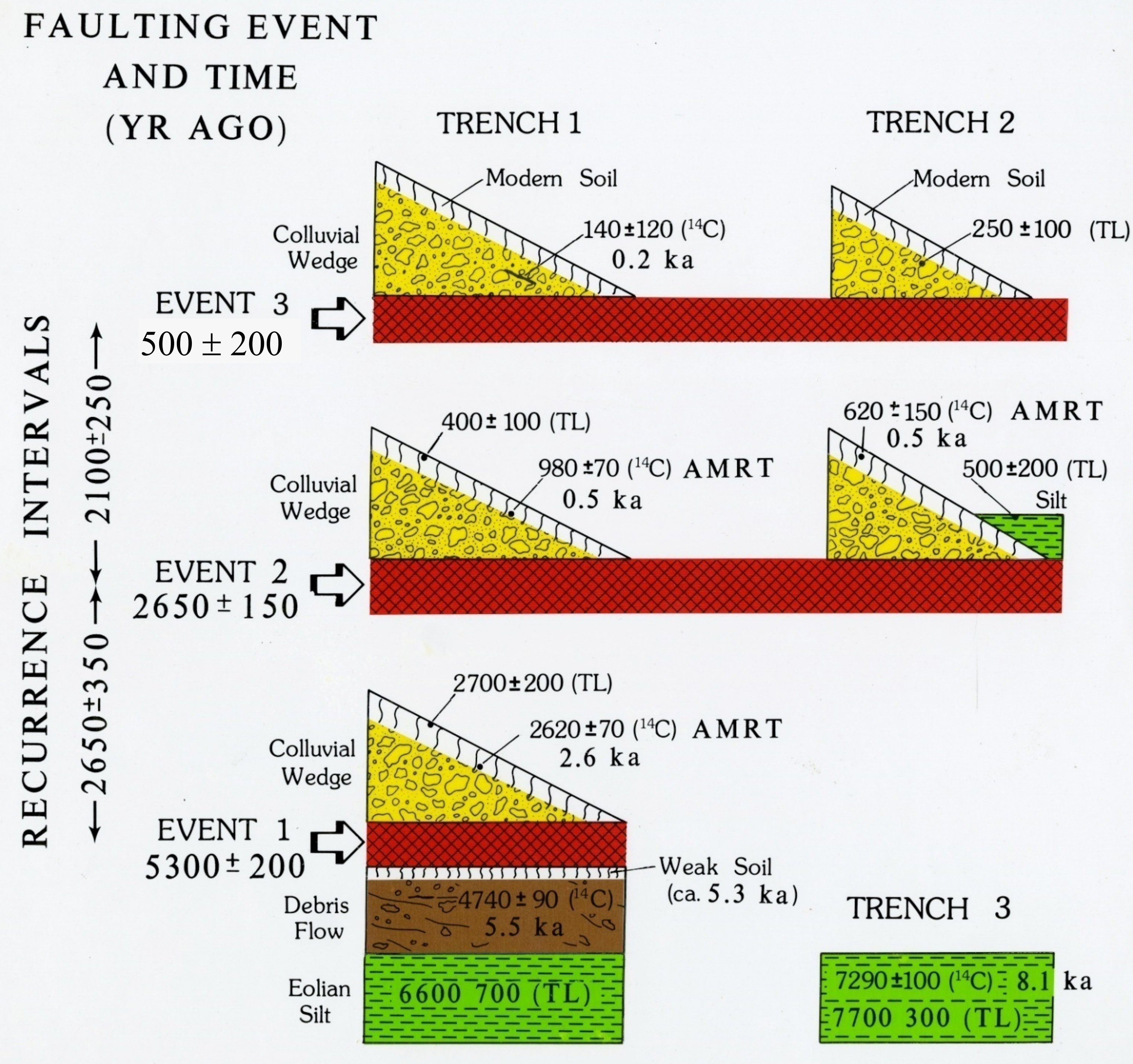


American Fork Canyon Site (A)

- **Multiple fault splays**
- **3 trenches**
- **Machette and Lund (1987)**
- **Machette (1988)**
- **Forman et al. (1989)**
- **Machette (1992)**
- **Machette et al. (1992)**



DATING OF FAULTING EVENTS AT THE AMERICAN FORK SITE, PROVO SEGMENT OF THE WASATCH FAULT ZONE, UTAH



- **3 events since mid-Holocene**
- **1 older event (5.3 – 8.1 ka)**

After Machette et al. (1992)

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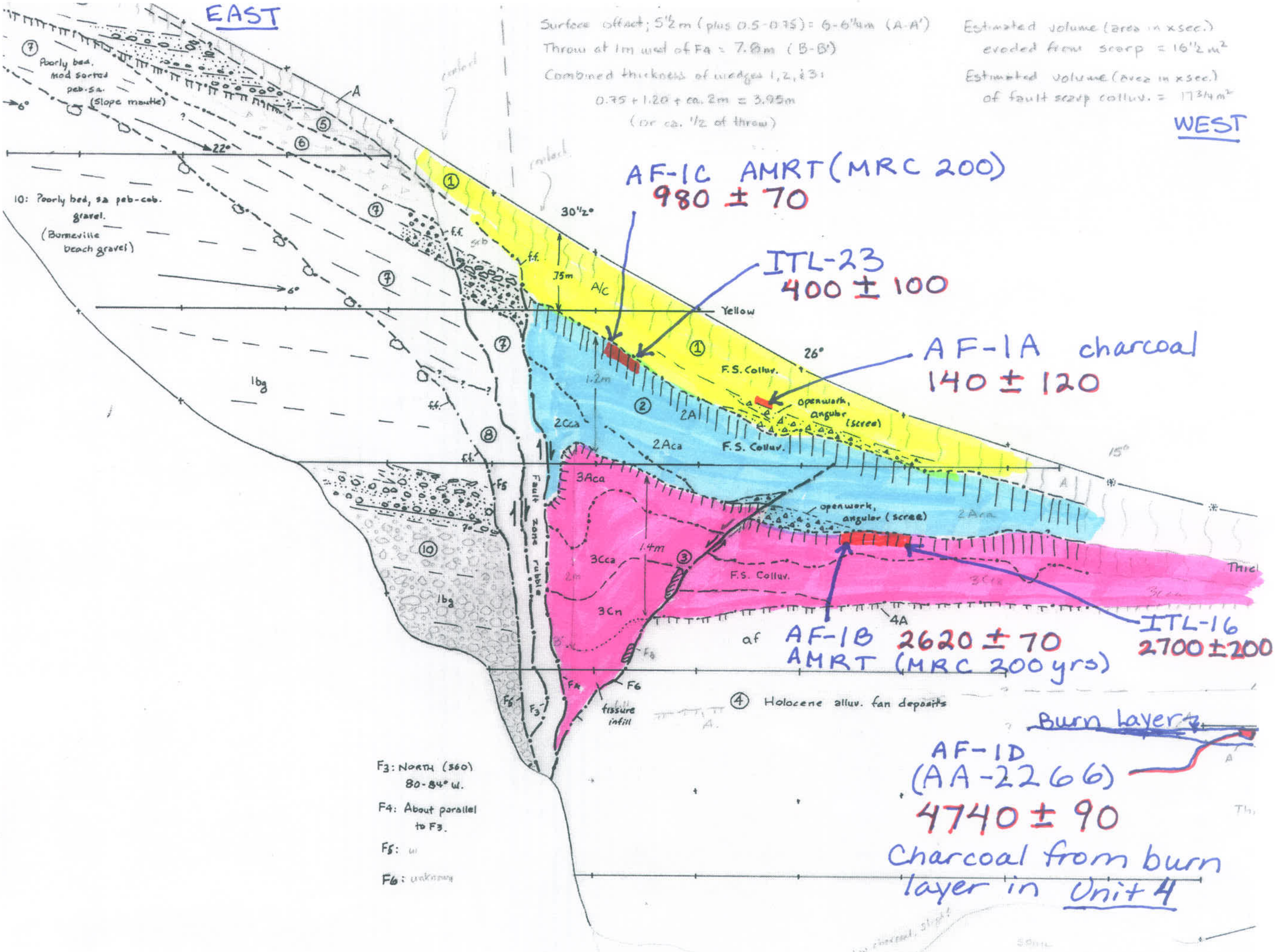
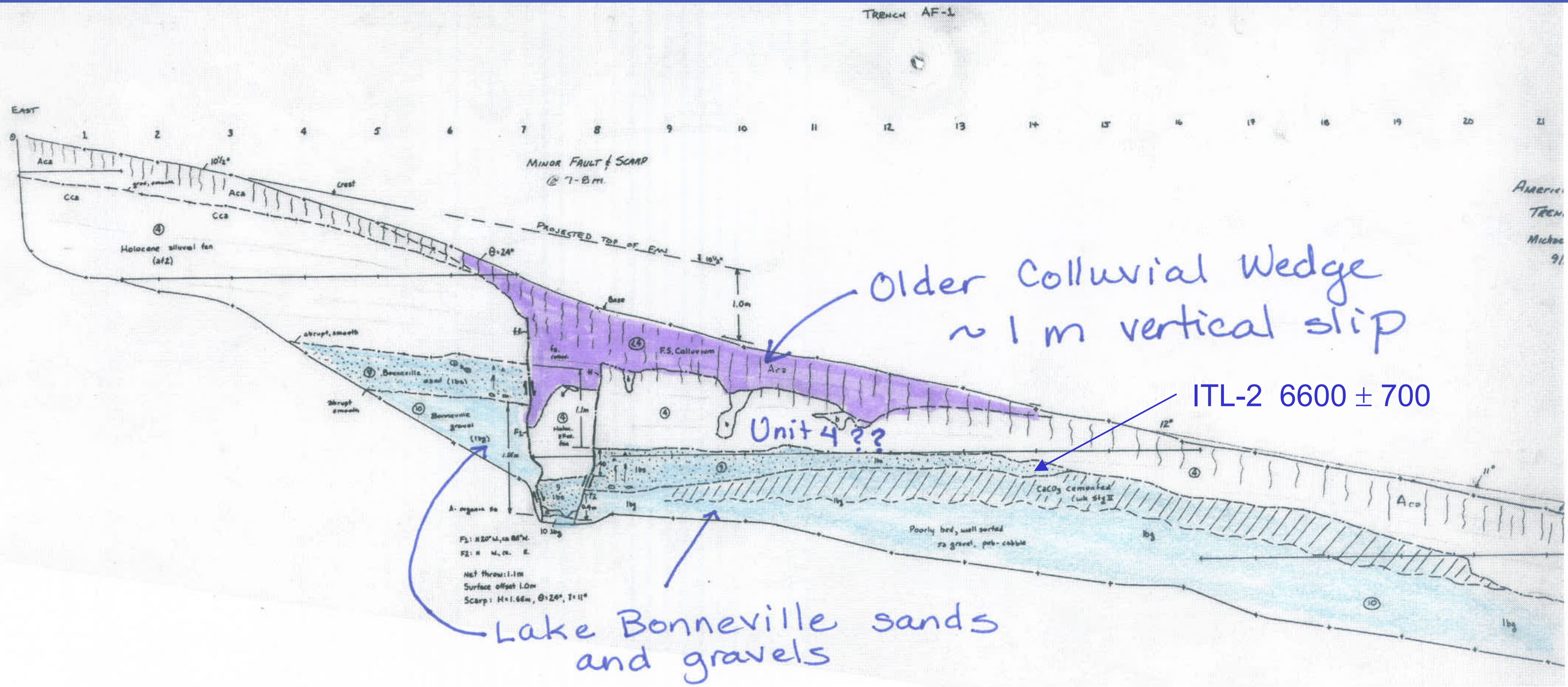
Trench AF-1: Main Scarp



Trench AF-1: Eastern Scarp



Undated colluvial wedge ≈ oldest wedge on main scarp or older?

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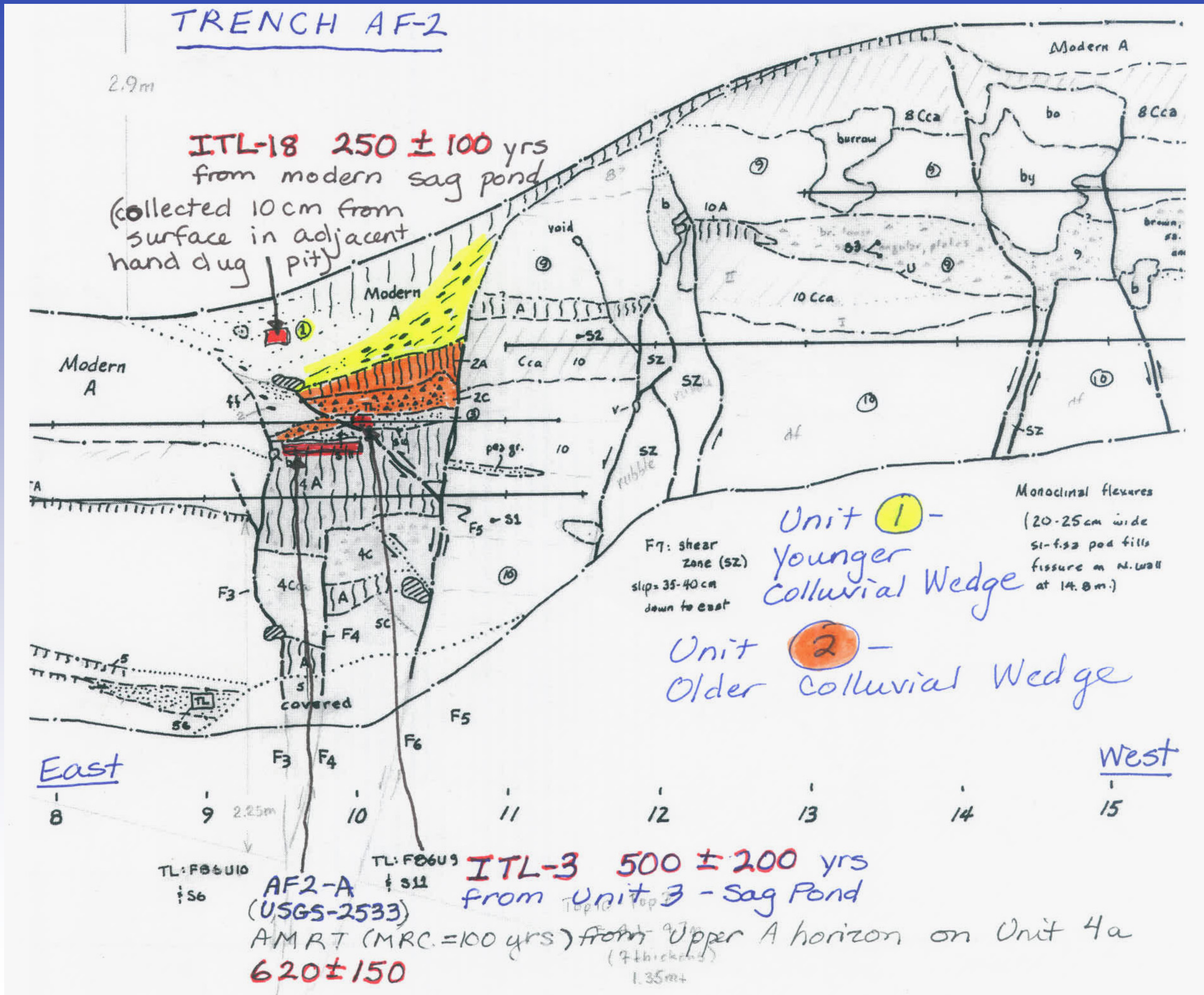
Trench AF-2



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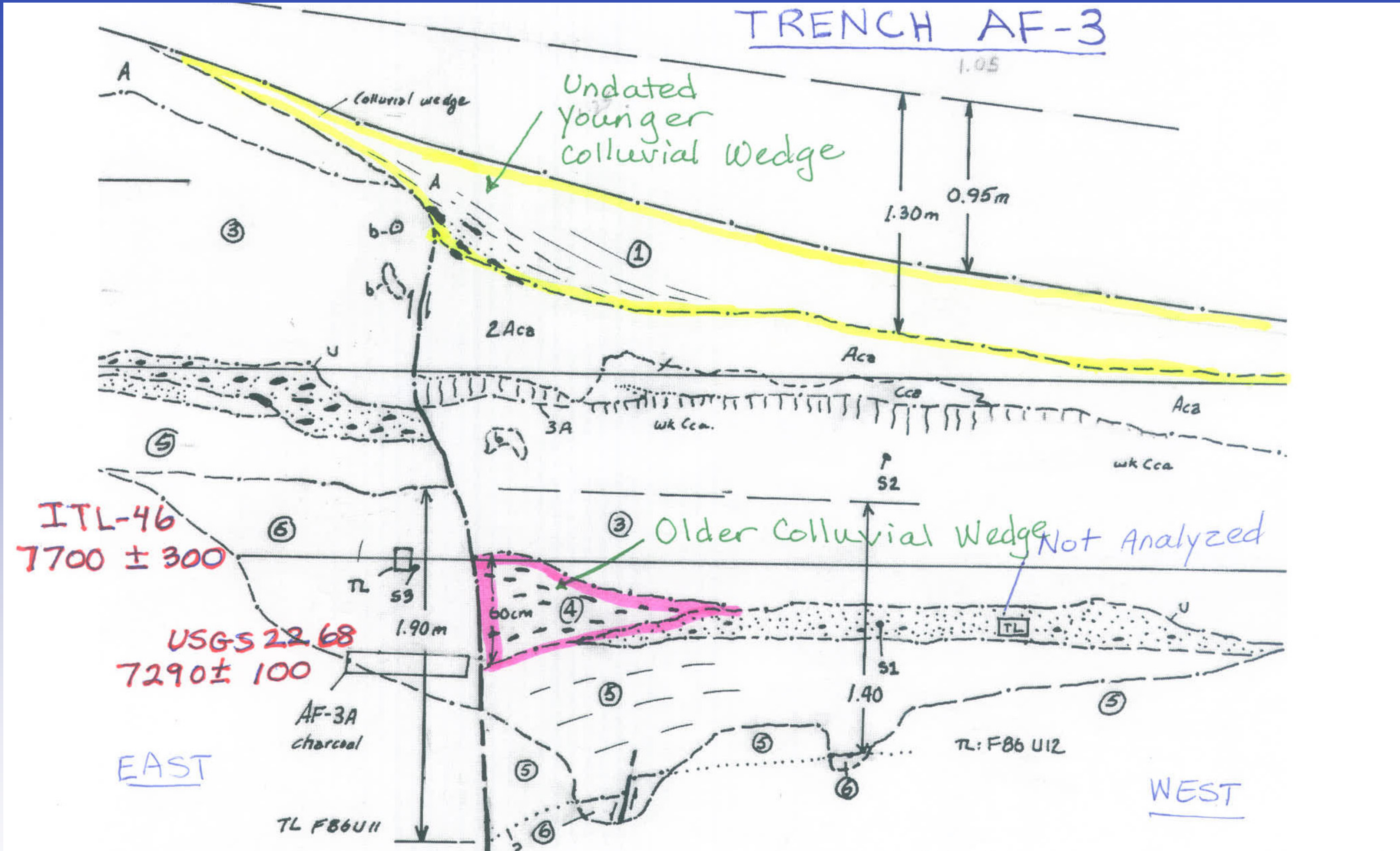
Trench AF-3



If Unit 5 in AF-3 ⇒ Unit 4 in AF-1
then older wedge ⇒ Unit 3 in AF-1 = Event A3
(Oldest event)

If Unit 3 in AF-3 ⇒ Unit 4 in AF-1
then older wedge is between 5.3-8.1 ka = Event A4
(as per Machette et al. 1992)

Summary of Issues at American Fork Canyon Site

- **One fault splay not trenched (easternmost scarp on af2 deposits).**

- **Two colluvial wedges undated (post-af2 events with ≥ 1 m offset in Trenches AF-1 and AF-3).**

- **Uncertain if oldest event in Trench AF-3 correlates to the oldest event on main scarp in Trench AF-1 or is older.**

- **Uncertain if indeed two surface-faulting events occurred since ~0.5 ka as indicated on the antithetic fault in Trench AF-2.**

→ **Use 2 models:**

Min – 3 events (A1 through A3)

Max – 5 events (A0 through A4)

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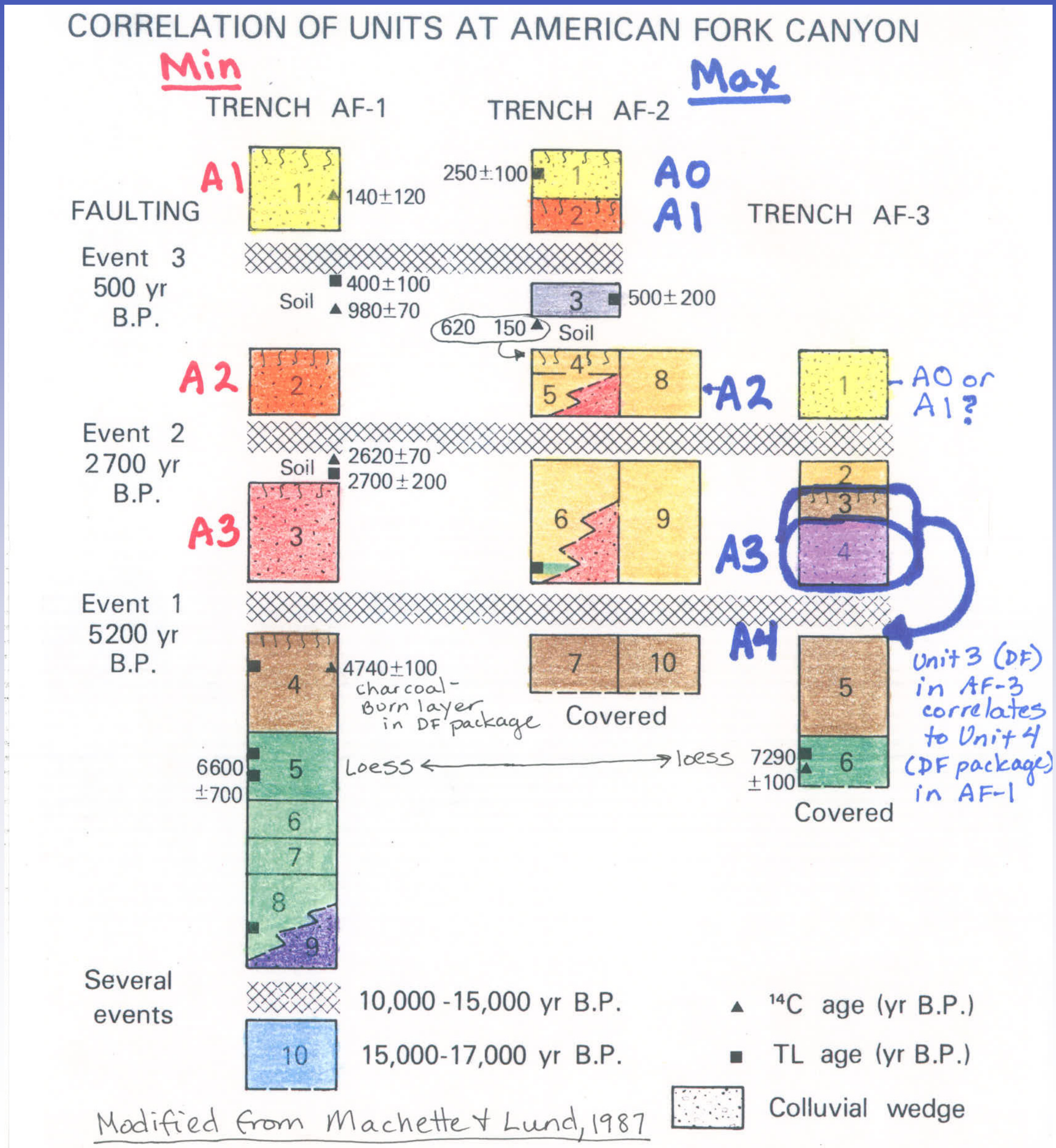
Schematic Stratigraphic Comparison of Minimum and Maximum Models



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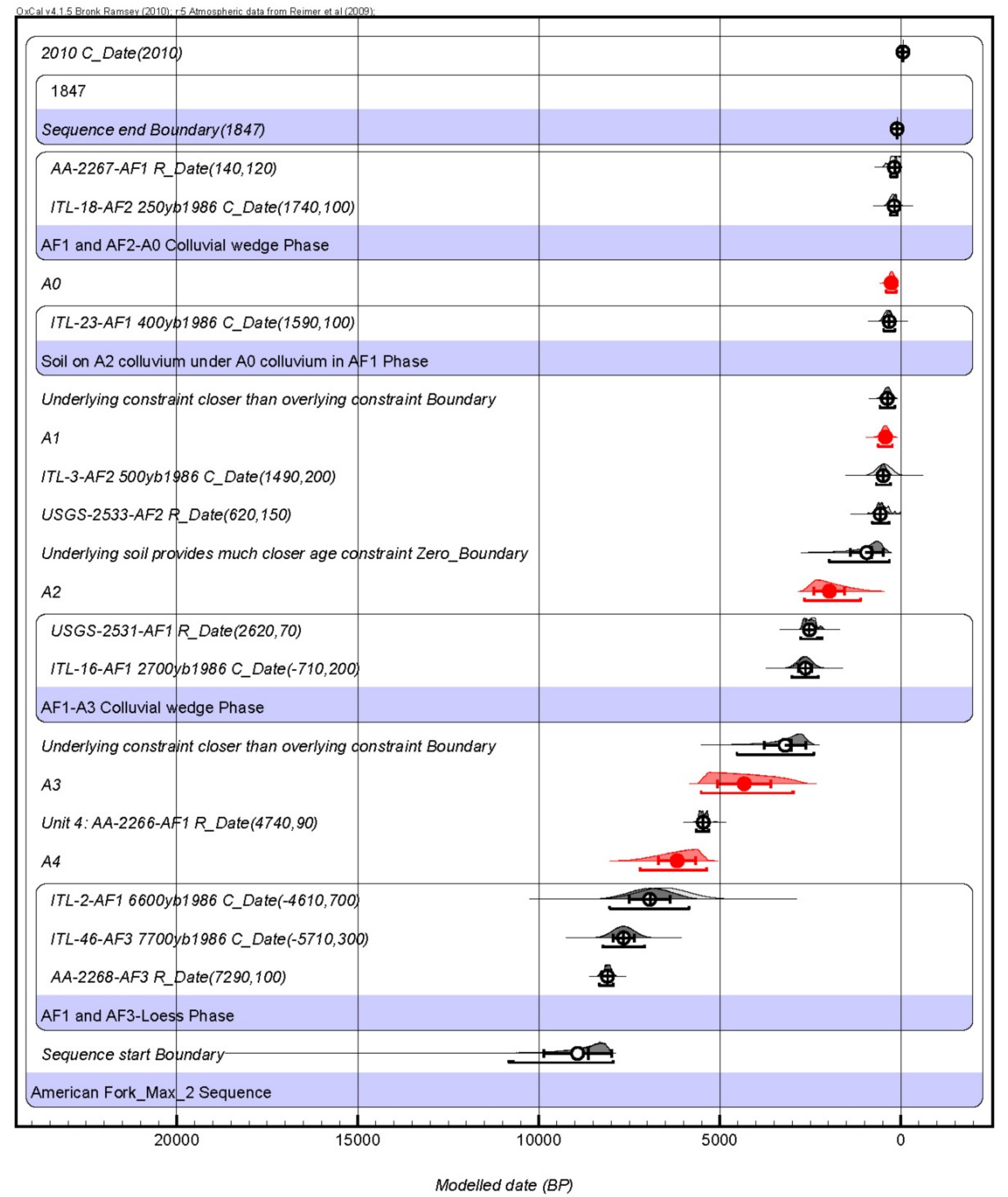
American Fork OxCal Analysis – Max Model



- **Assumes 2 events occurred post-0.5 ka and youngest in AF1 correlates to youngest in AF2**
- **Assumes oldest event in AF3 does not correlate to oldest event in AF1 but is older**
- **One outlier AMRT age excluded for this analysis (980±70; A= 29%)**

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American Fork Canyon OxCal Results and Comparison to Previous Studies

Event	Machette et al. (1992)	This Study	
		Minimum Model (OxCal Model #6)	"Maximum" Model (OxCal Model #2)
A0	Not observed	Not included	0.26 ± 0.1
A1	0.50 ± 0.2	0.39 ± 0.2	0.43 ± 0.2
A2	2.65 ± 0.15	2.1 ± 0.6 (peak @ 2.4)	2.0 ± 0.8 (peak @ 2.4)
A3	5.3 ± 0.2	4.2 ± 1.5 (peak @ 5-5.3)	4.3 ± 1.4 (peak @ 5-5.3)
A4	5.3 – 8.1	Not included	6.2 ± 1.0 (peak @ 5.8)

- **OxCal Models** *(All times of events in ky before 1950 with 2 σ)*
  - **Mean event ages generally younger than previous studies**
  - **For A2 and A3, uncertainties are larger (poor minimum constraints)**
  - **More uncertainty in number of events (A0 and A4)**
  - **Paleoseismic record is a minimum**
  - **Timing of events A1, A2, and A3 is similar for both Min and Max models**

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Rock Canyon (R)

- Lund and Black (1998)
  - One trench and a streamcut
  - One very well-constrained event (R1) since ~2 ka, with many maximum and minimum limiting ages, including additional radiocarbon ages from Machette et al. (1992)

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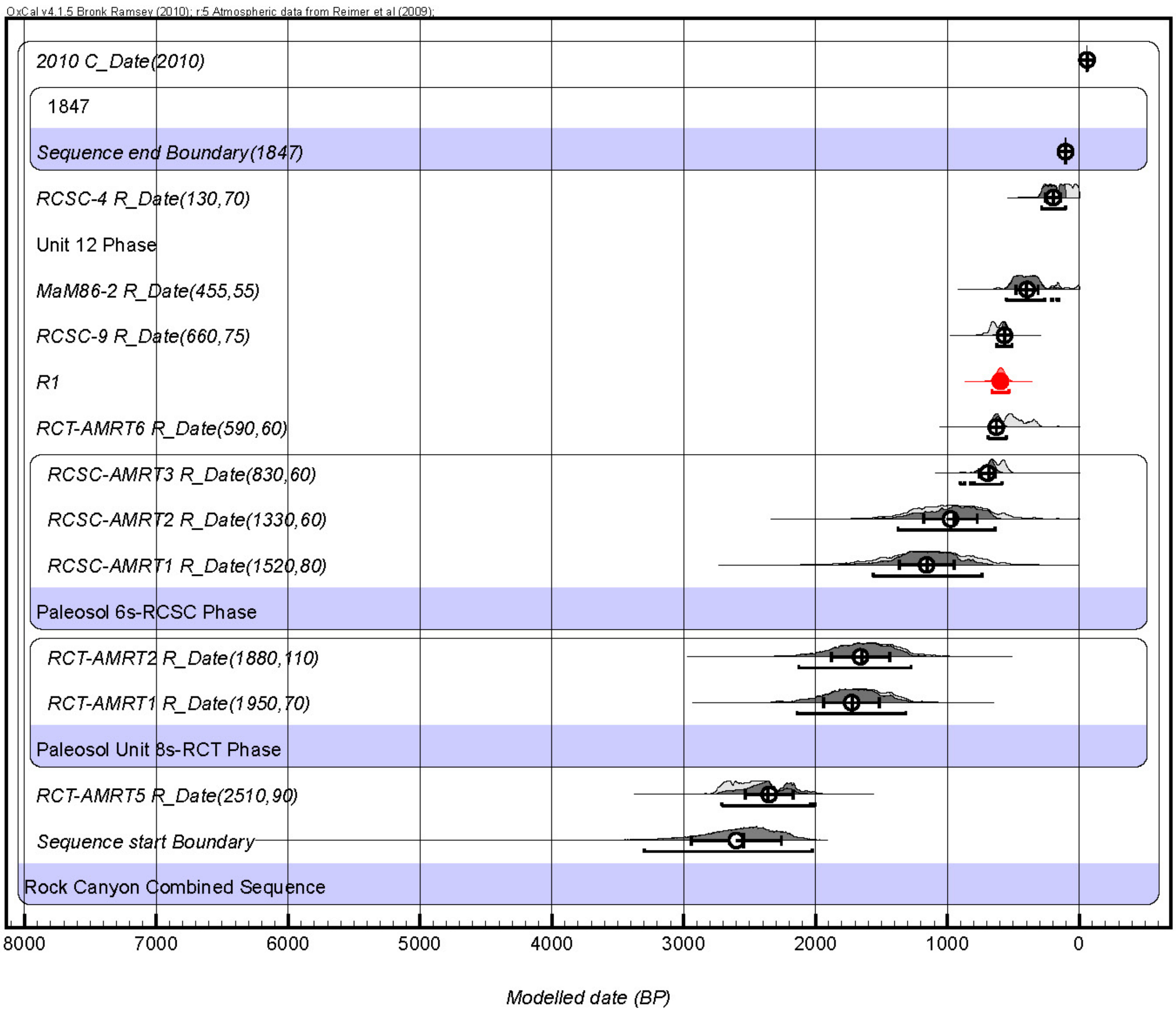
Rock Canyon OxCal Analysis



- **One event, R1, since ~2.4 ka**
- **No events post-R1, and none between 1 and 2 ka**
- **2 outlier radiocarbon ages excluded: one from wedge (Machette et al., 1992) and one from alluvium overlying wedge (unit 12 of Lund and Black, 1998)**

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Rock Canyon OxCal Results and Comparison to Previous Studies

Event	Lund and Black (1992)	This Study
R1	0.65 ± 0.1	0.6 ± 0.06

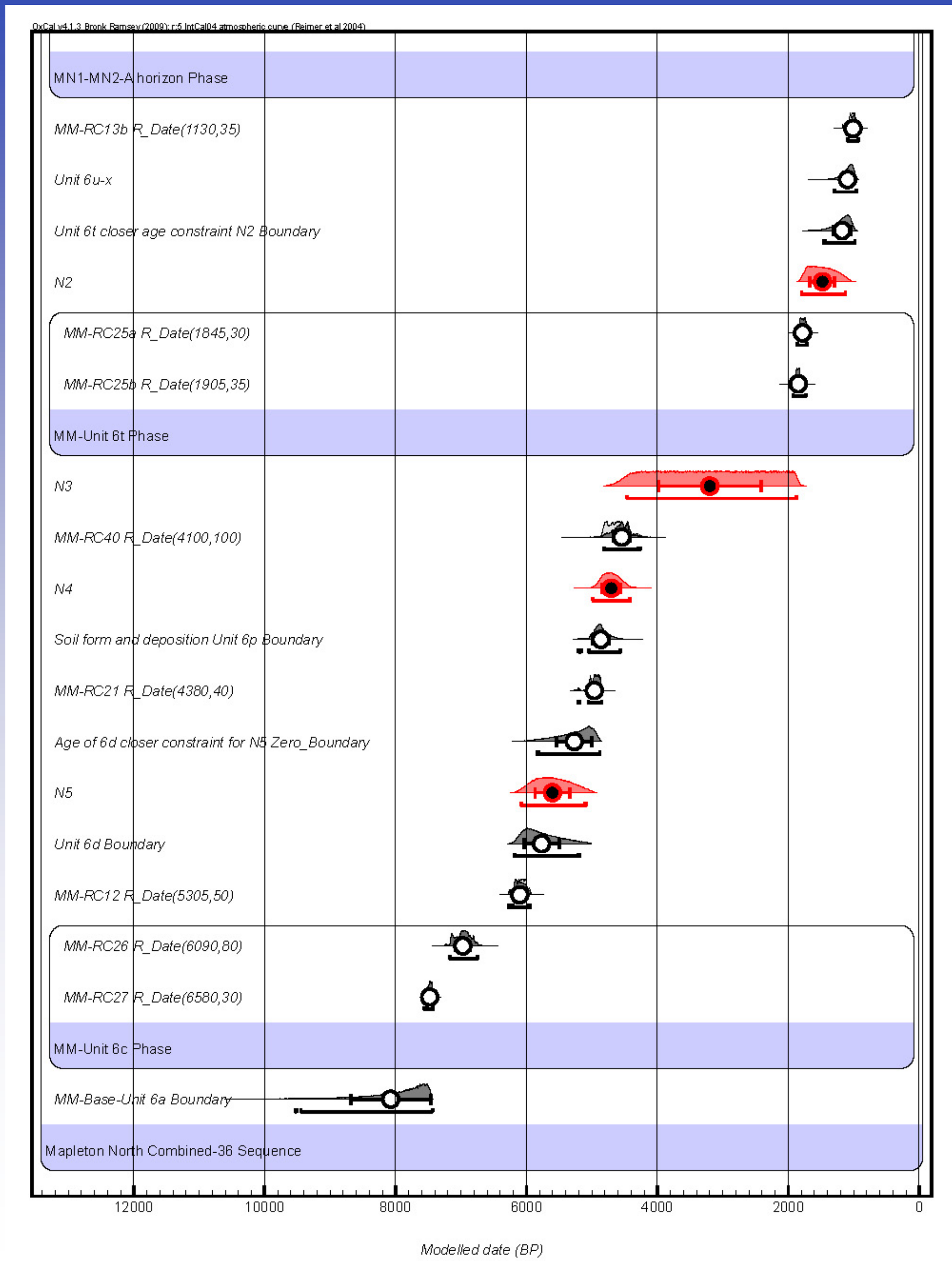
(All times of events in ky before 1950 with 2 σ)

- **OxCal Models**
  - **Similar results and uncertainties reduced**

Mapleton North (N)

- **Lund et al. (1991)**
  - Two trenches
  - Two late Holocene events
  - Very good maximum and minimum limiting ages for N1
  - N2 not dated
- **Olig et al. (2010)**
  - Megatrench with 3 semi-blind footwall faults exposed
  - At least 4, possibly 5 events occurred since ~6 ka
  - N3 age poorly constrained, other events fairly well-constrained, including possible event, N5 (?)

Mapleton North OxCal Analysis – Part 1



- One radiocarbon outlier age excluded from unit 6p below N4 (Olig et al., 2010)
- PDFs for events N2, N4 and N5(?) are all asymetric toward maximum
- N3 age is poorly constrained (max. limiting age anomalously old?)

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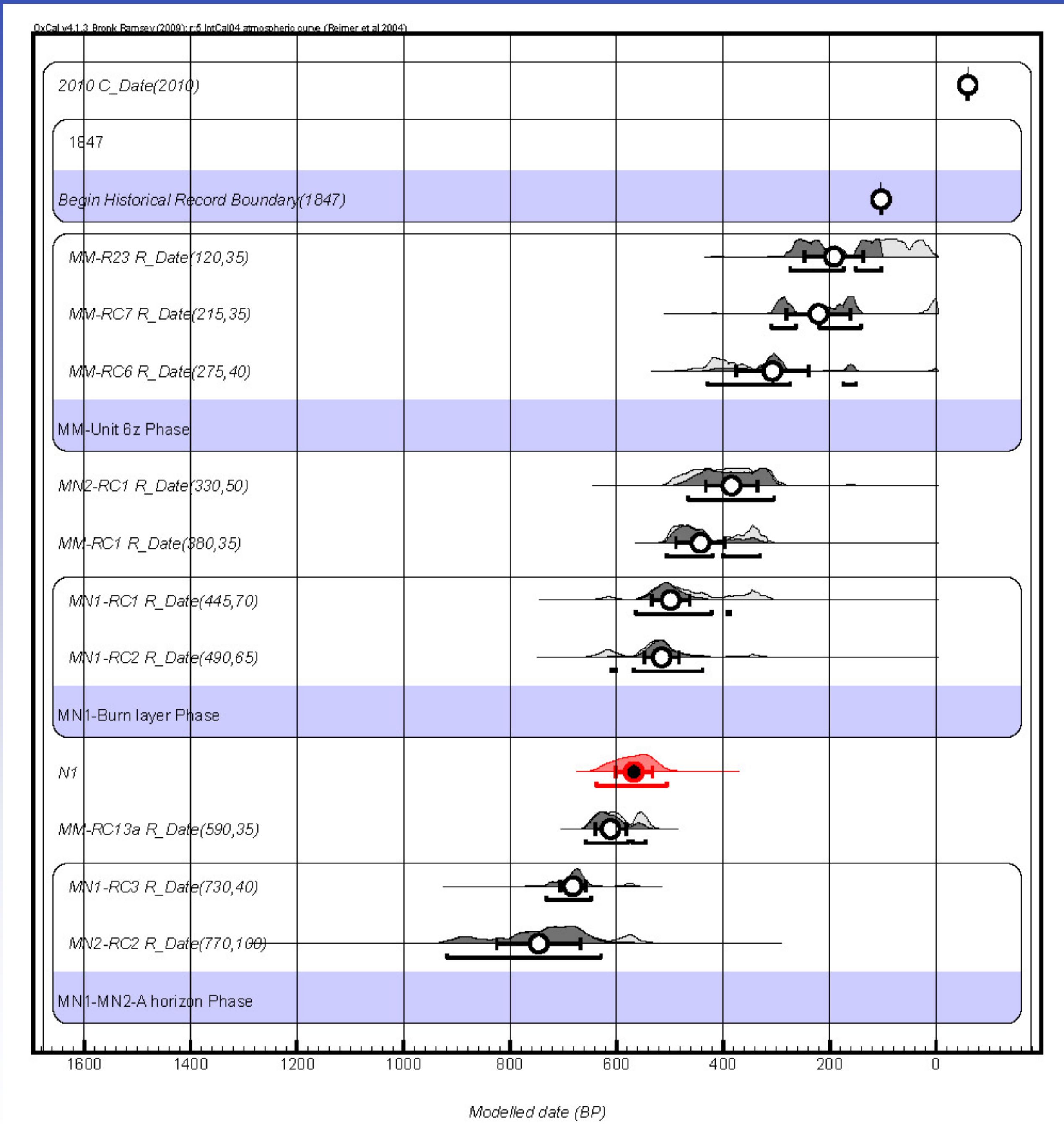
Mapleton North OxCal Analysis – Part 2



- **One radiocarbon outlier age excluded from pond deposit overlying wedge (Lund et al., 1991)**
- **Combining trench data (MN1, MN2 and MM) is fairly straightfoward and improves constraints on N1**

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Mapleton North OxCal Results and Comparison to Previous Studies

Event	Lund et al. (1992)	Olig et al. (2010)	This Study (OxCal #36)
N1	0.6 (±0.16)	0.52 ± 0.15	0.57 (± 0.08)
N2	Not dated	1.6 (-0.6, +0.2)	1.5 (±0.4) (peak @1.6)
N3	Not exposed	3.2 (± 1.3)	3.2 (± 1.6)
N4	Not exposed	4.9 (± 0.4)	4.7 ± 0.3
N5(?)	Not exposed	5.9 (-1.0, +0.2)	5.6 ± 0.5 (peak @ 5.8)

(All times of events in ky before 1950 with 2 σ)

- OxCal Models
  - Similar results to previous studies (differences mainly due to using Boundary command; reduced uncertainties for some events)
  - N5 included for comparison with A4 in American Fork Max model

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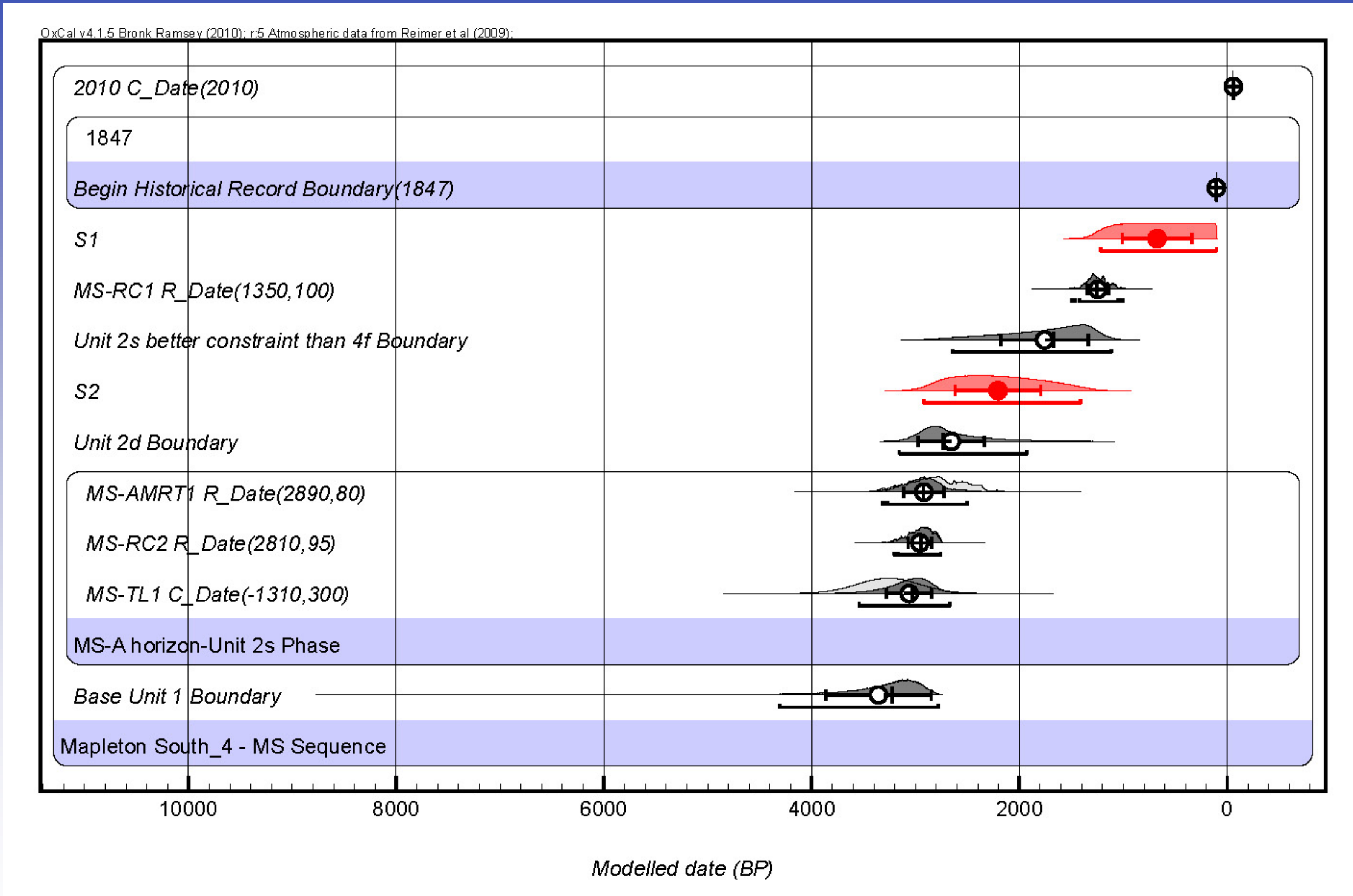
Mapleton South (S)

- Lund et al. (1991)
  - One trench (incomplete exposure of footwall?)
  - Two late Holocene events
  - N1 had no minimum age constraint and poor maximum
  - N2 fairly well-constrained maximum and minimum ages

Mapleton South OxCal Analysis



Mapleton South OxCal Results and Comparison to Previous Studies

Event	Lund et al. (1991)	This Study
S1	<<1.3	0.67 ± 0.7
S2	Shortly before 2.8 ± 0.3	2.2 ± 0.8

- **OxCal Models**
  - S1: Generally similar results, but time better constrained
  - S2: Younger age and larger uncertainties

** All times of events in ky before 1950 with 2 σ*

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Summary of OxCal Results – Provo Segment

Event	AF Min / Max	RC	MN	MS
E0	— / 0.26 ± 0.14	NO	NO	NOPI
E1	0.39 ± 0.2 / 0.43 ± 0.2	0.6 ± 0.06	0.57 ± 0.08	0.67 ± 0.7
E2	NOPI	NO	1.5 ± 0.4	NOPI
E3	2.1 ± 0.6 / 2.0 ± 0.8 (peak @ 2.4)	NE	3.2 ± 1.3	2.2 ± 0.8
E4	4.2 ± 1.5 / 4.3 ± 1.4 (peak @ 5.0-5.3)	NE	4.7 ± 0.3	NE
E5	— / 6.2 ± 1.0 (peak @ 5.8)	NE	5.6 ± 0.5 (peak @ 5.8)	NE

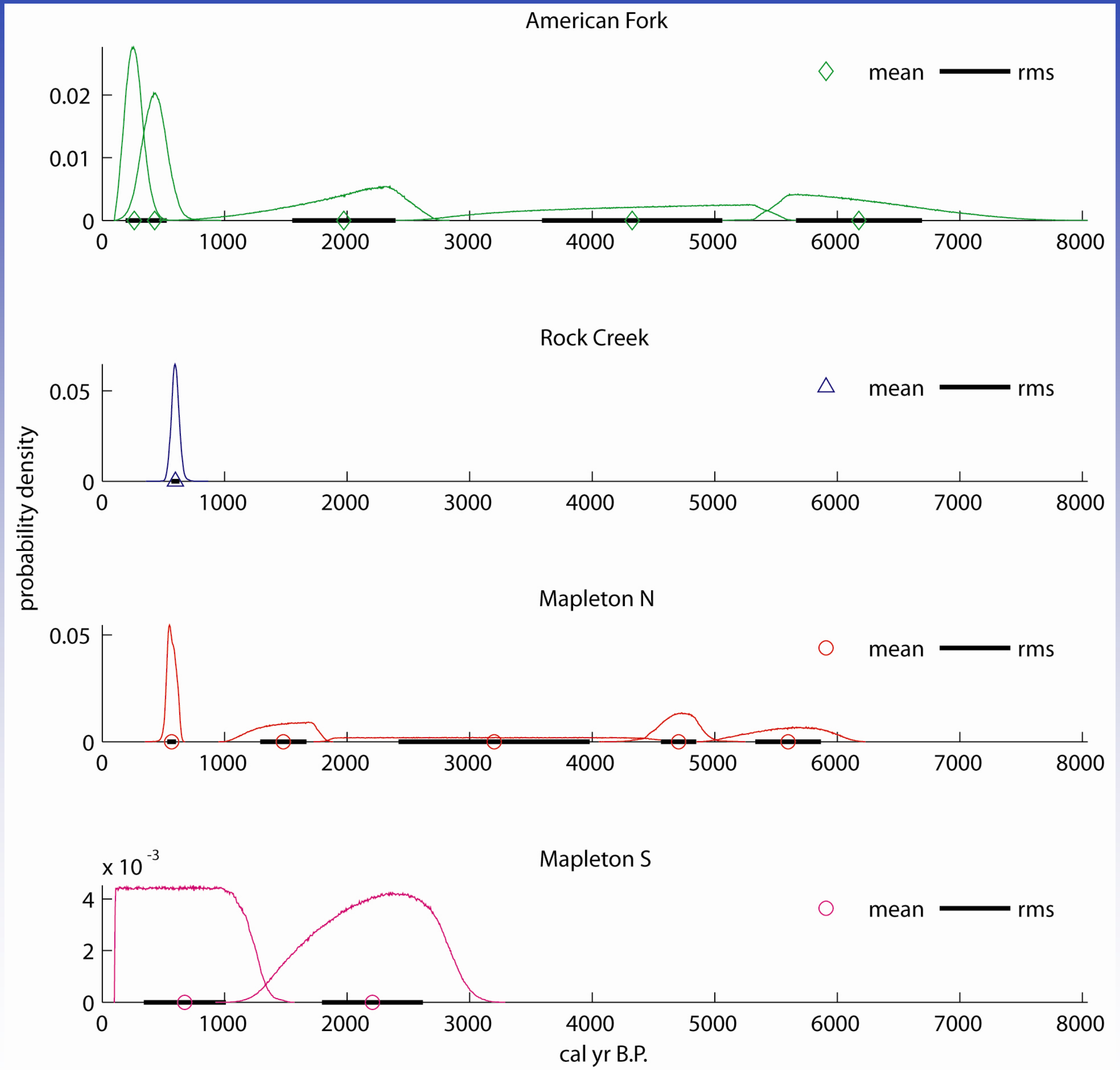
NE – not exposed; NO – not observed; NOPI – not observed, but record potentially incomplete

(all time ranges to 2 σ)

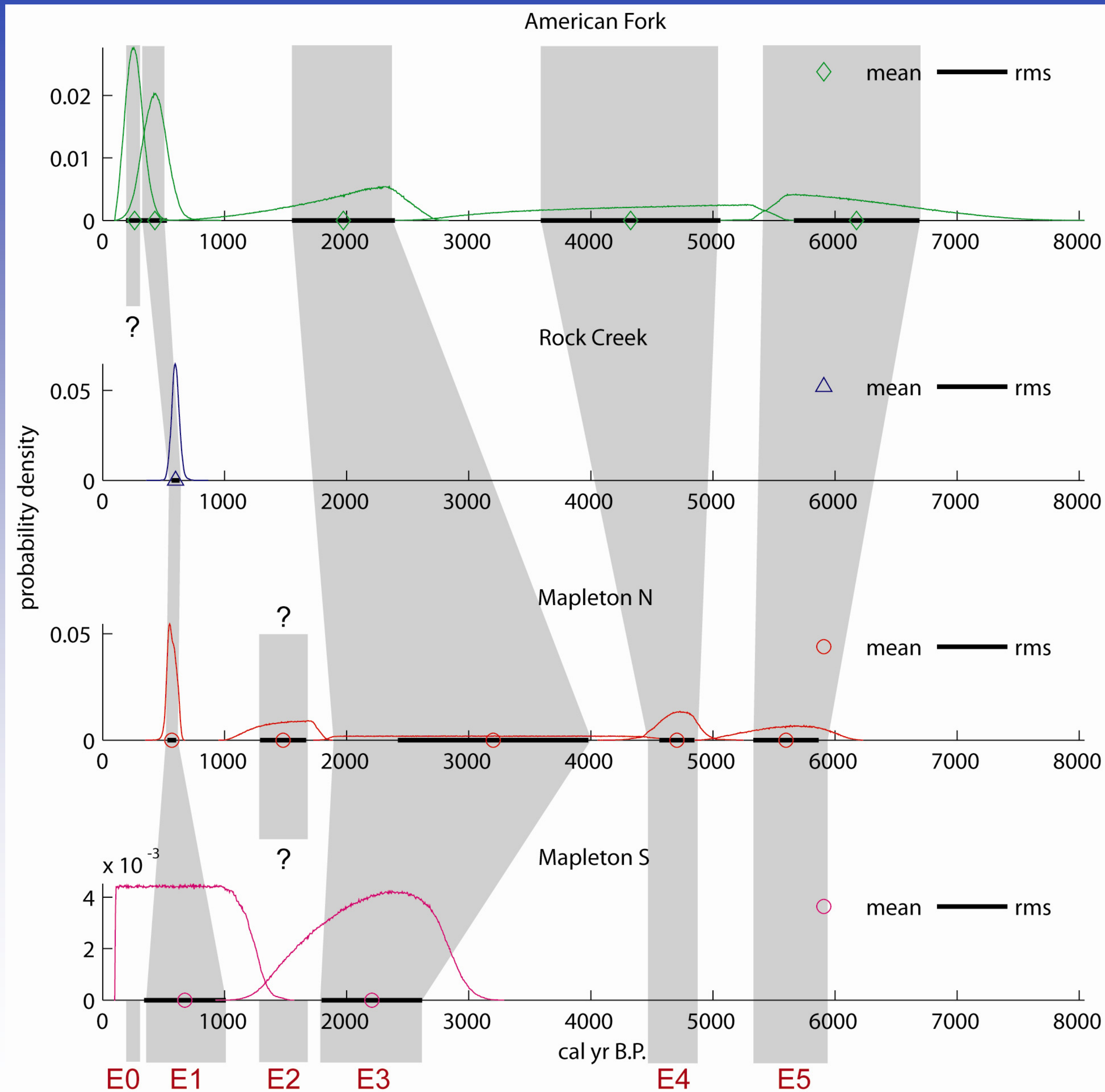
(All times of events in ky before 1950 with 2 σ)

URS

Provo Segment – Summary of Site PDFs (Max)



Provo Segment – Correlation of Site PDFs (Max)



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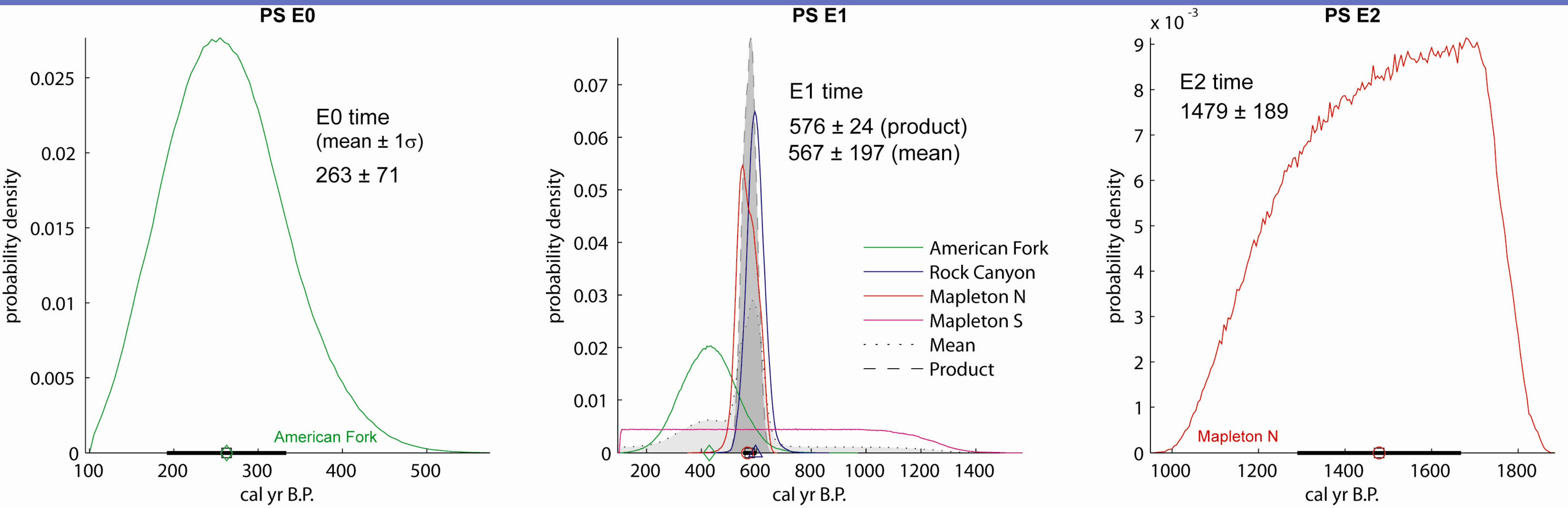
Rock Canyon Site Map

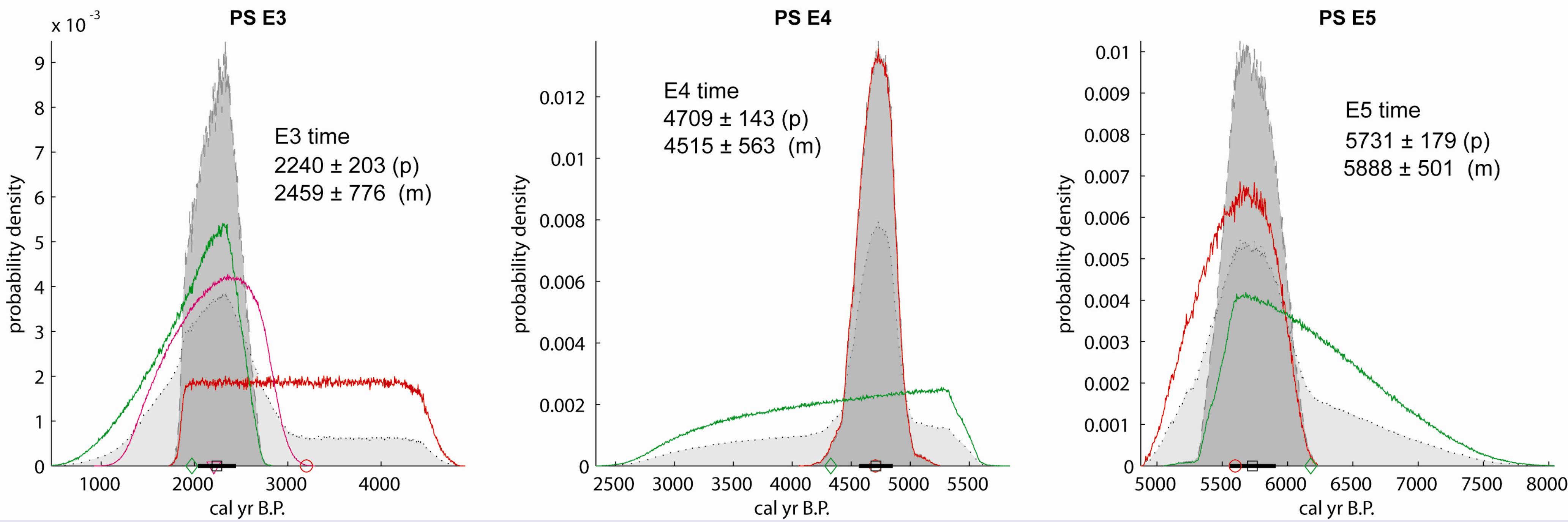
Some untrenched splays, but they are in older deposits

Correlation of Provo Segment of Site PDFs Maximum Model



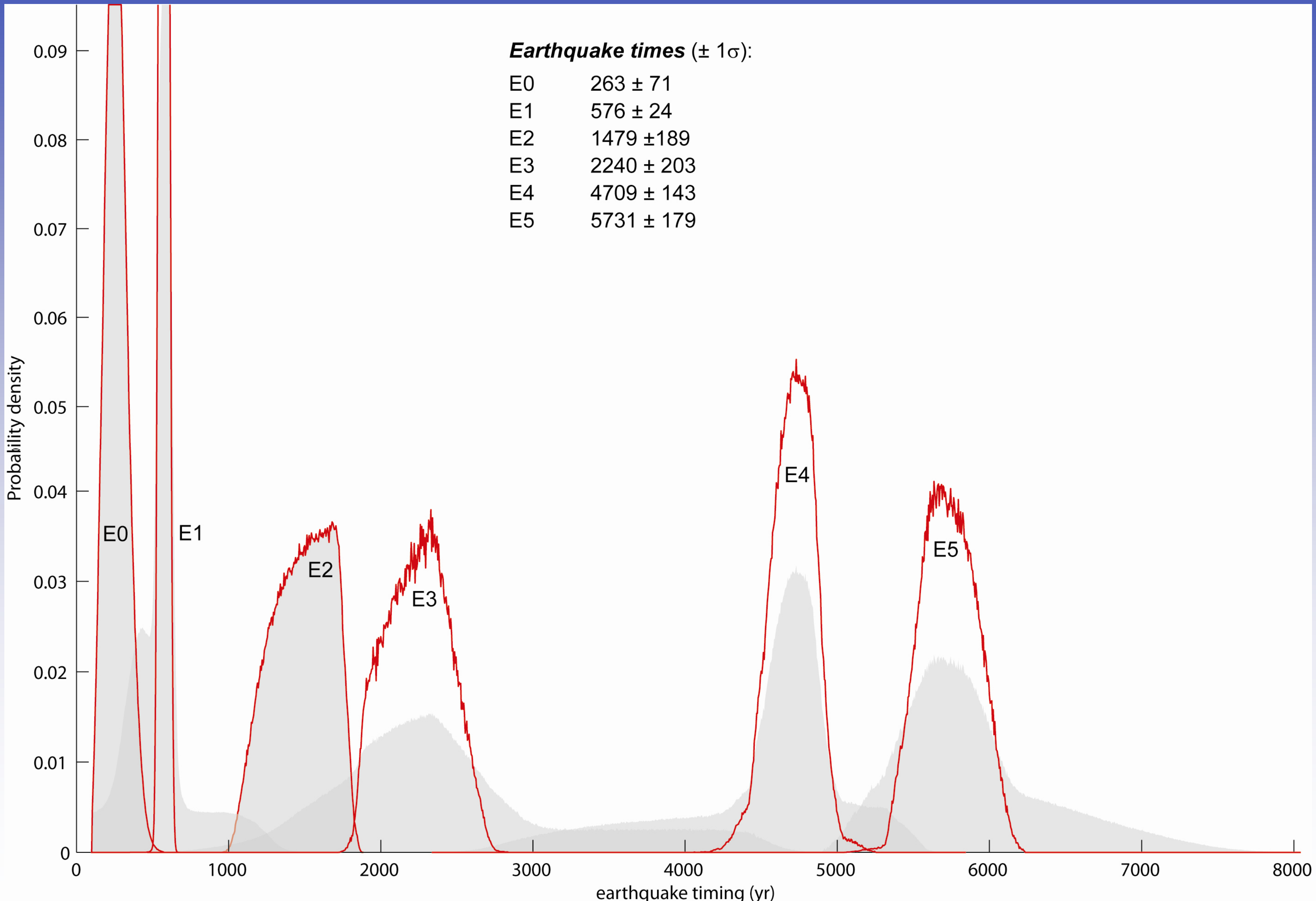
URS

Correlation of Provo Segment of Site PDFs
Max Model



URS

Provo Segment Earthquake History – Maximum Model



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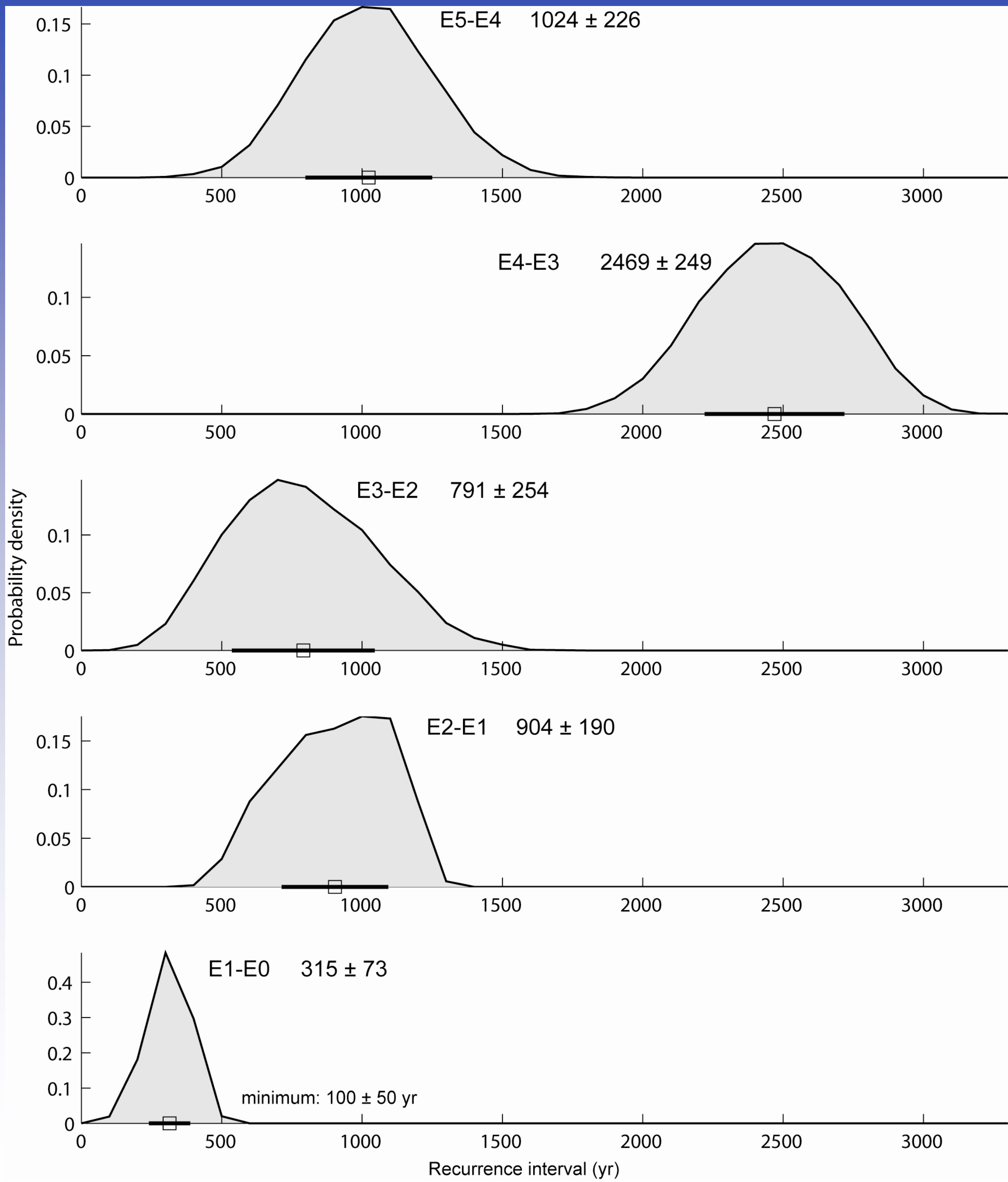
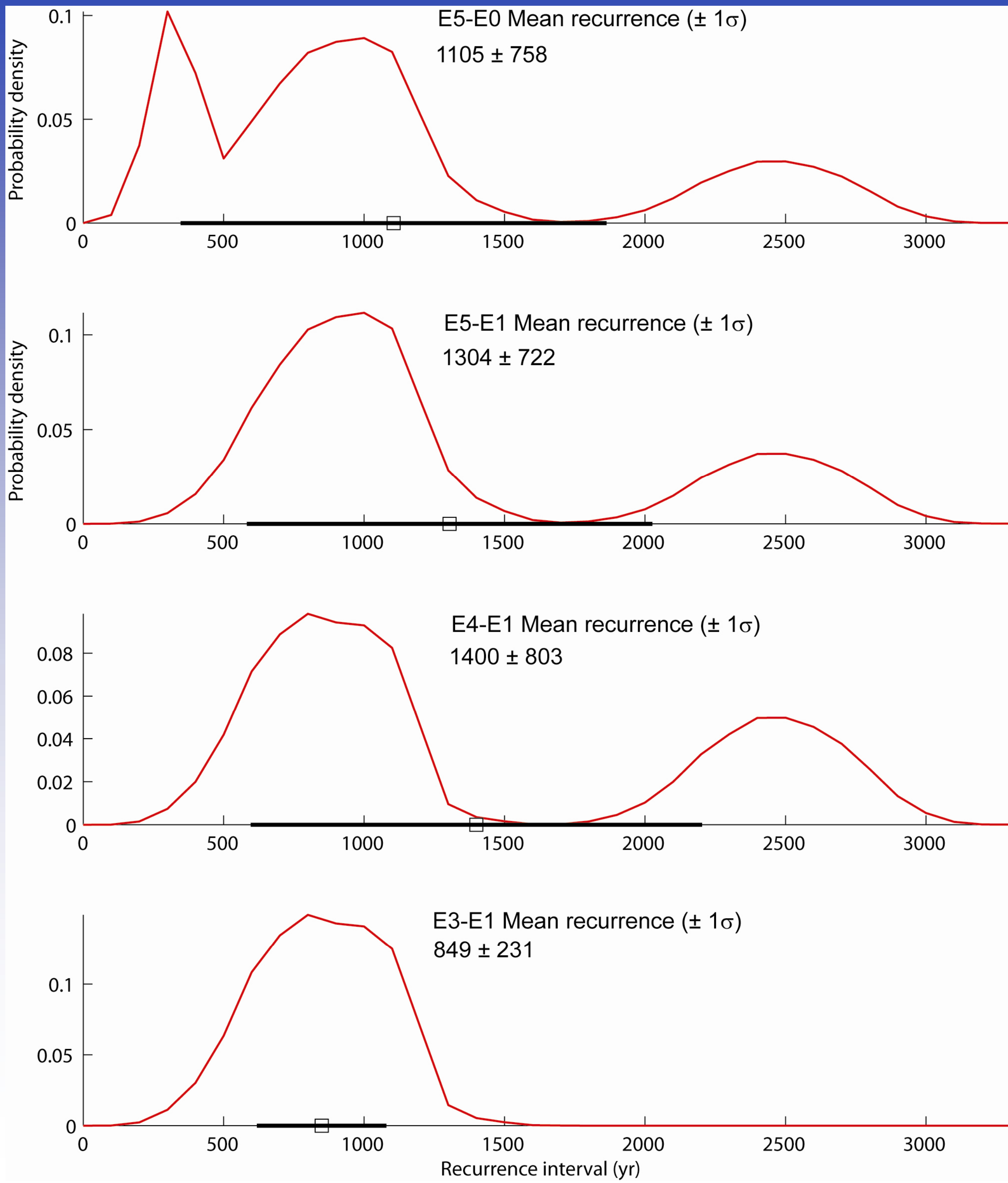
Provo Segment Recurrence Intervals (Max Model)



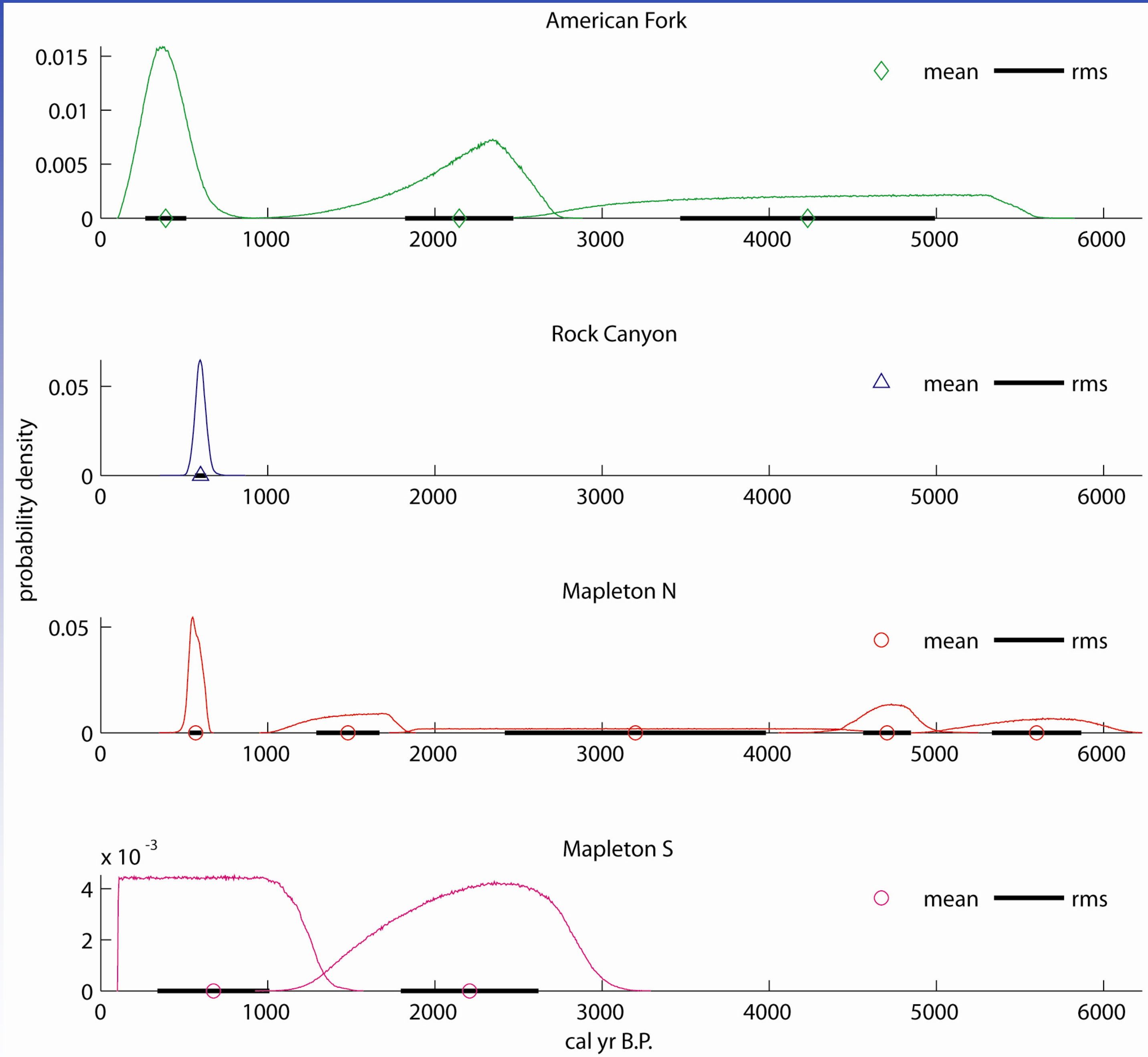
- Recurrence intervals vary from 0.3 ± 0.07 ky to 2.5 ± 0.2 ky

Provo Segment Recurrence (Max Model)

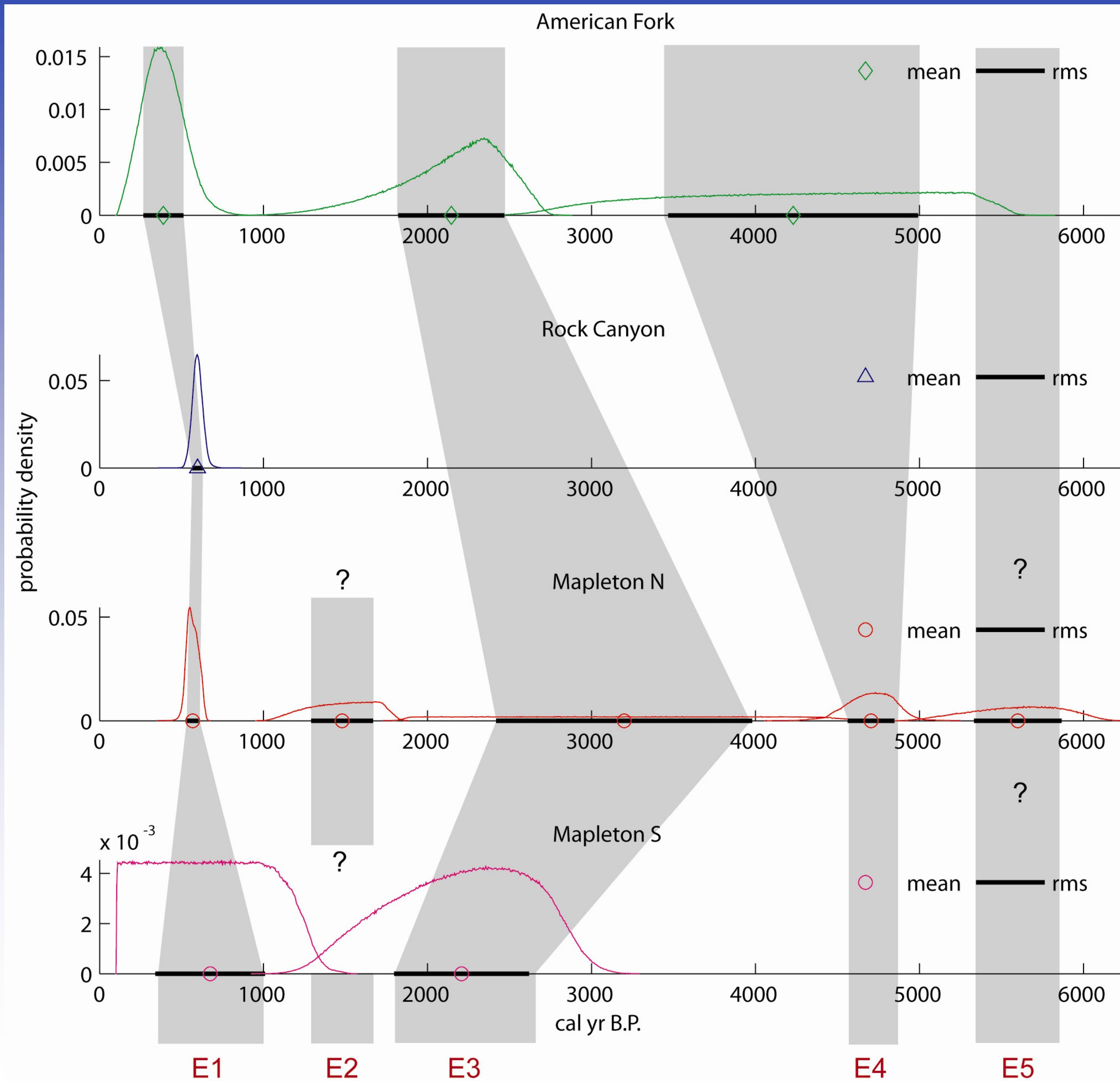


- All: 1.1 ± 0.8 ky (n = 5)
- No A0 (partial segment): 1.3 ± 0.7 ky (n = 4)
- No A0 and no A4 or N5 (similar to Min): 1.4 ± 0.8 ky (n = 3)

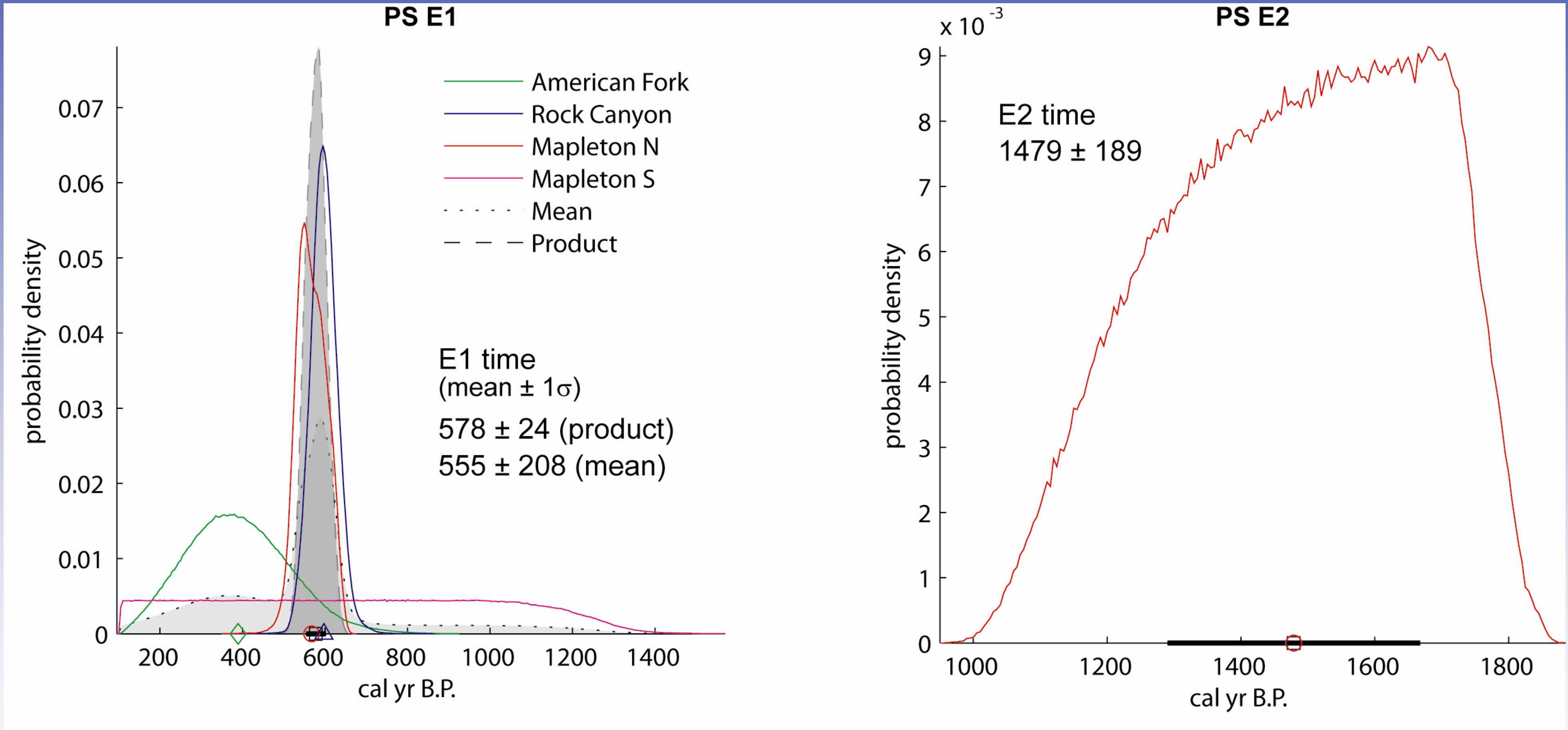
Provo Segment – Summary of Site PDFs (Min)



Provo Segment – Correlation of Site PDFs (Min)

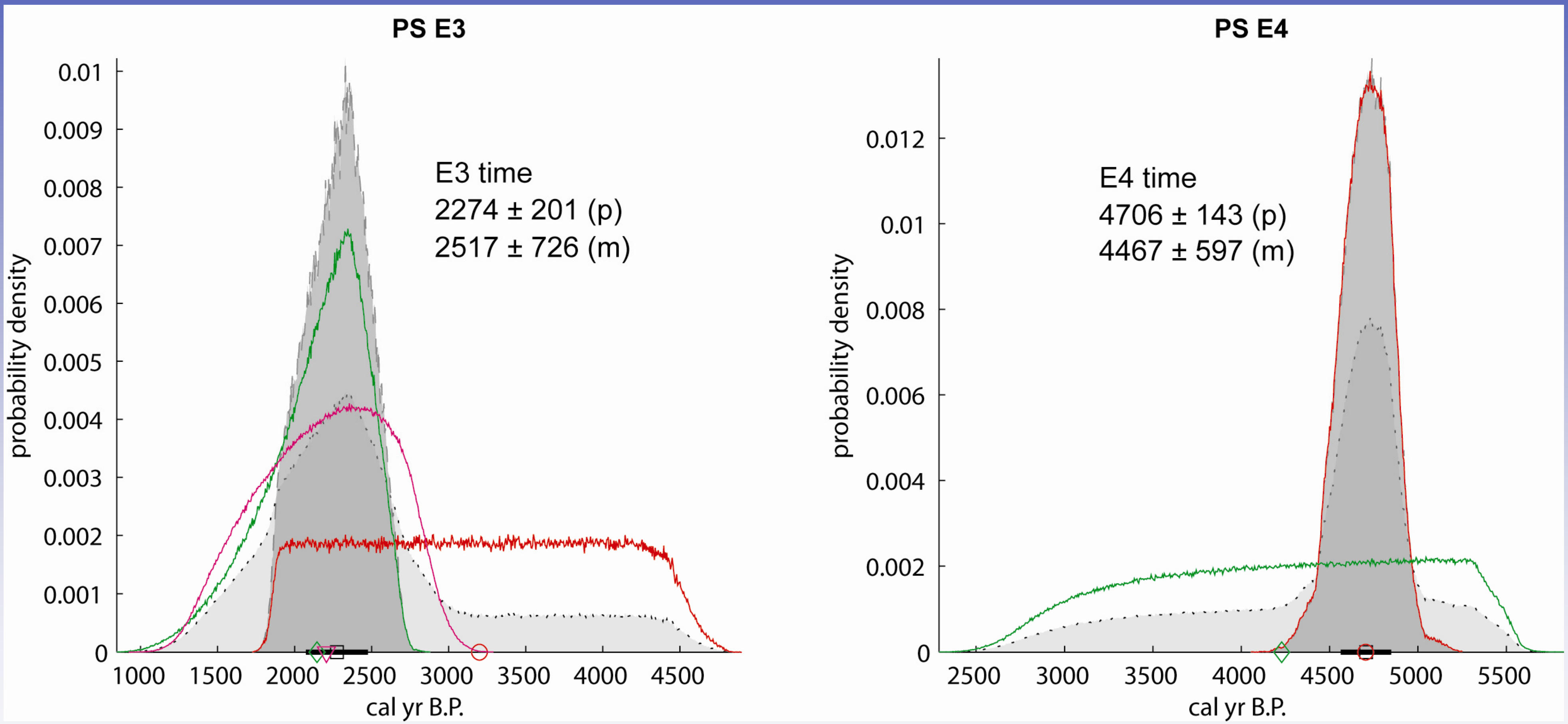


Correlation of Provo Segment of Site PDFs PS E1 and PS E2

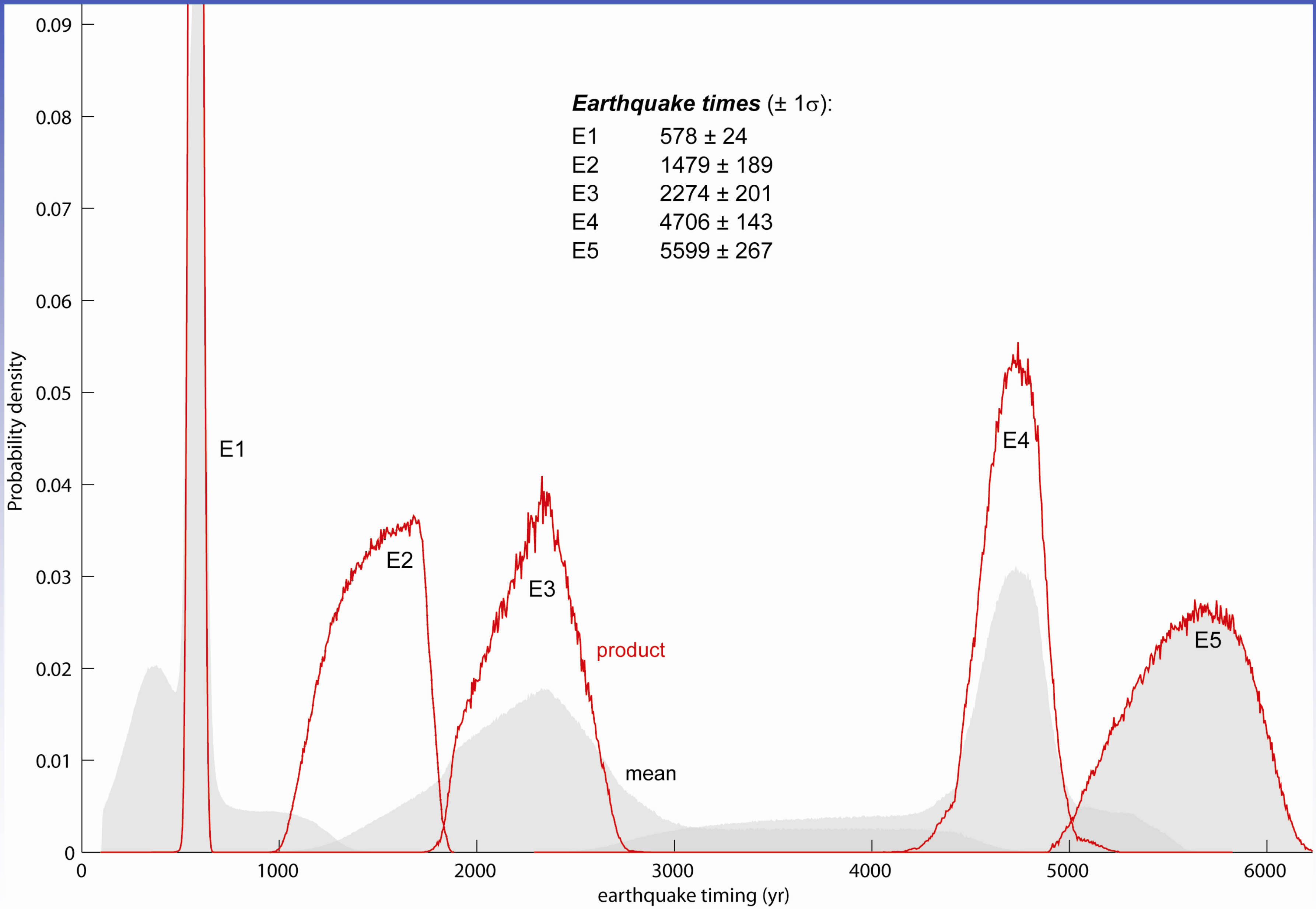


URS

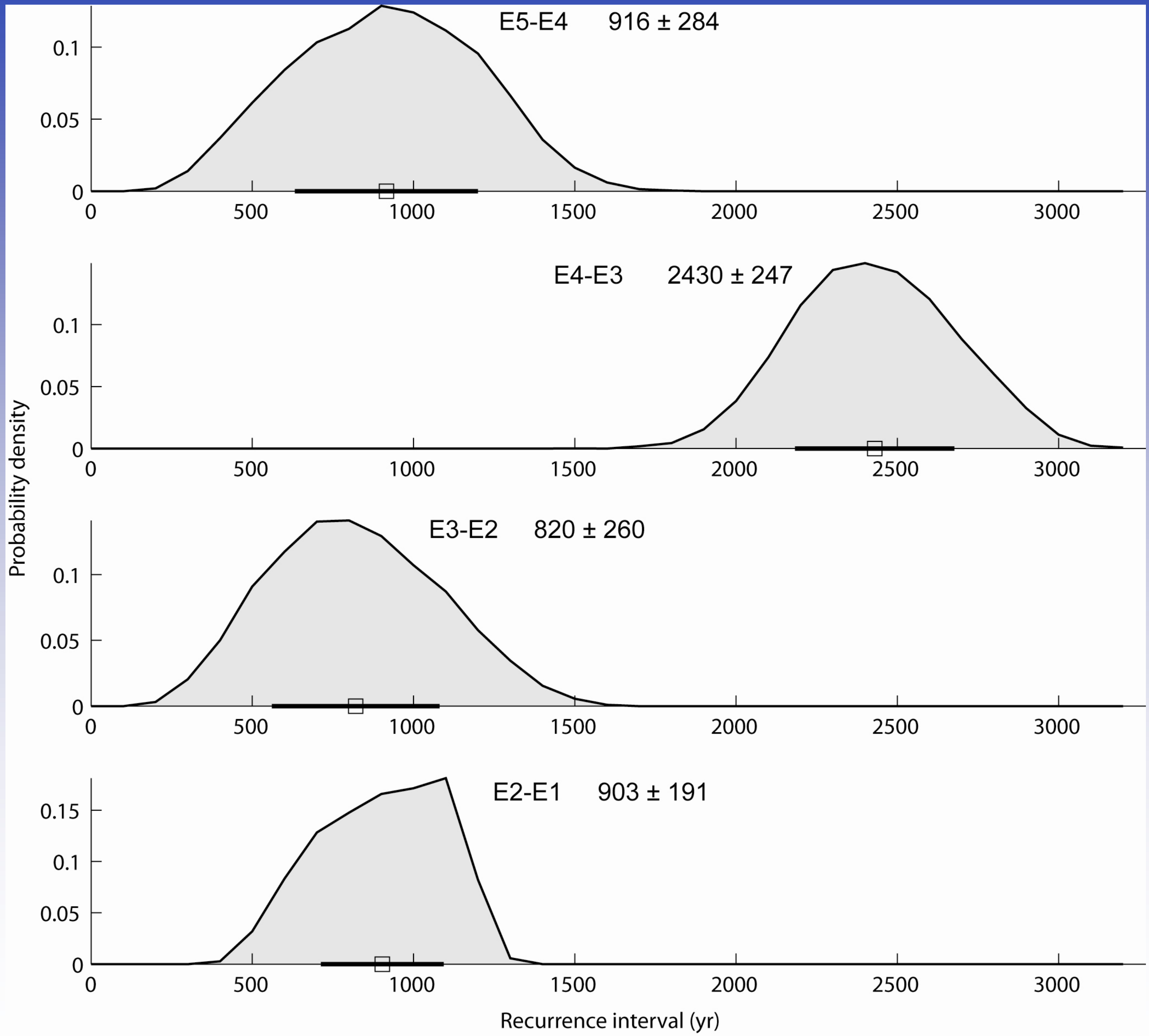
Correlation of Provo Segment of Site PDFs (Min) PS E3 and PS E4



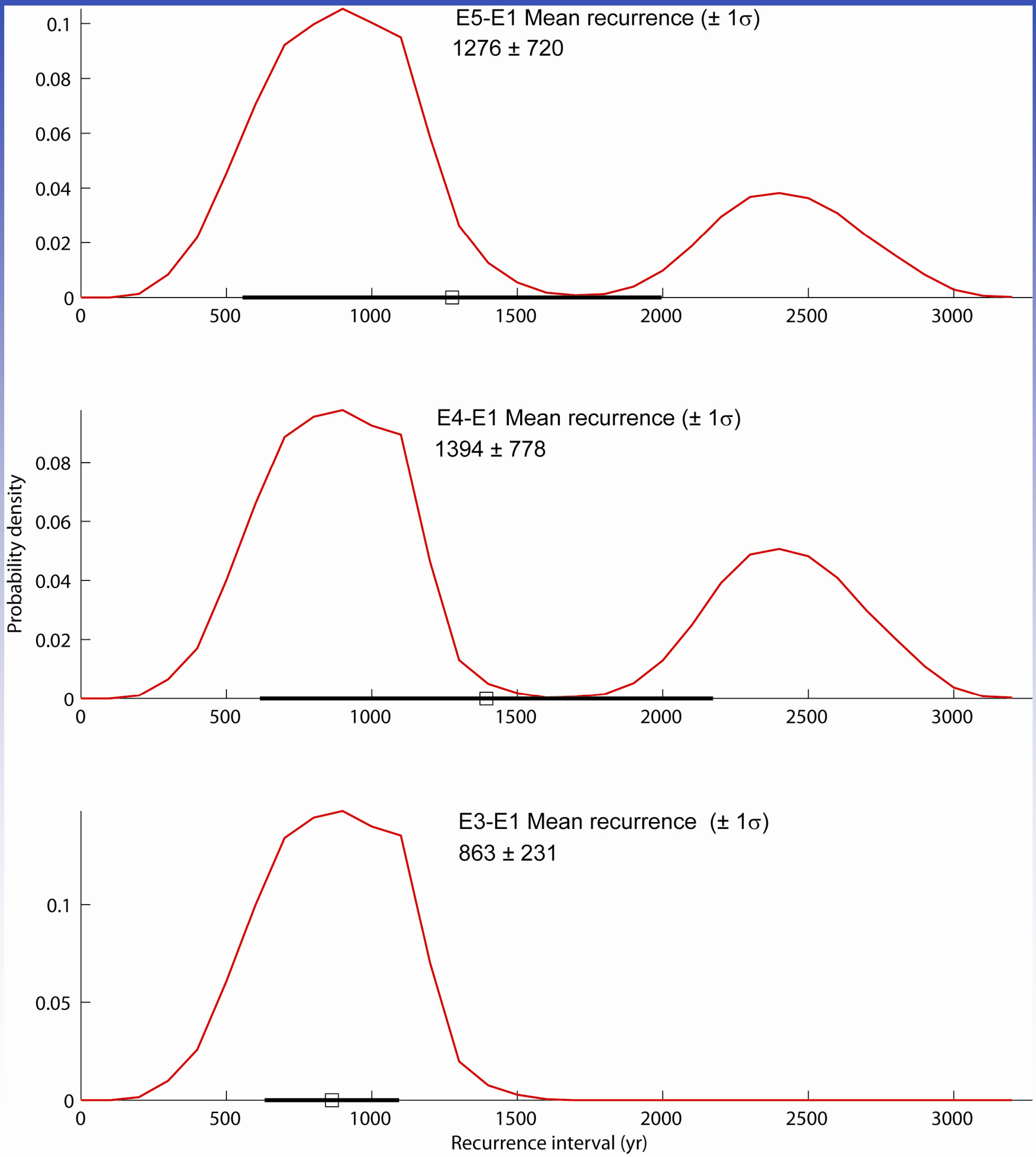
Provo Segment Earthquake History – Minimum Model



Provo Segment Recurrence Intervals (Min Model)



Provo Segment Recurrence (Min Model)



- **Average E4 – E1: 1.4 ± 0.8**
- **Bimodal? (~1 and ~ 2.5 ky)**

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Summary of Matlab Results - Provo

Event	Mean Site PDFs		Product	UQFPWG
	Min	Max		
E0	—	0.26 ± 0.1	0.26 ± 0.14	Not recognized
E1	0.56 ± 0.4	0.57 ± 0.4	0.58 ± 0.05	0.6 ± 0.35
E2	1.5 ± 0.4	1.5 ± 0.4	1.5 ± 0.4	Not recognized
E3	2.5 ± 1.5	2.5 ± 1.5	2.2 ± 0.4	2.85 ± 0.65
E4	4.5 ± 1.2	4.5 ± 1.1	4.7 ± 0.3	5.3 ± 0.3
E5	—	5.9 ± 1.0	5.7 ± 0.4	Not included

E4 – E1: 1.4 ± 1.6 ky (min and max)

E5 – E0: 1.1 ± 1.5 ky (max only)

All time ranges in thousands of yrs before 1950 with 2 σ

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Provo Segment Recurrence Comparison With Previous Studies

- **Average recurrence interval this study: 1.4 ± 1.6 ky (2σ); P4-P1**

- **Previously reported recurrence estimates:**
  - **Hobble Creek: 1.5 to 2.6 ky**
    Avg. for 6 or 7 events since 14 ka (Swan et al., 1980)
  - **Mapleton North and South: 2.2 to 2.7 ky**
    S2-N1 (Lund et al. 1991)
  - **American Fork: 2.15 ± 0.35 / 2.65 ± 0.35**
    A2-A1 / A3-A2 (Machette et al., 1992)
  - **Provo Segment: 2.3 ± 0.07**
    P3-P1 (McCalpin and Nishenko, 1996)
  - **Provo Segment: 2.4 (1.2 to 3.2) ky**
    P3-P1 UQFPWG (Lund 2005)
  - **Mapleton North (Megatrench): 1.45 (varies from 1.1 to 1.7);** N4-N1 (Olig et al., 2006; 2010)

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Conclusions

- OxCal
  - Rock Canyon and Mapleton North earthquake times similar to previous results; American Fork and Mapleton South times are younger
  - American Fork has additional uncertainty in correlations and number of events (possible new A0 and A4 separate older event from A3)
    - Developed maximum (5-event) and minimum (3-event) models
    - Does not significantly affect timing of events A1 through A3
    - Does not significantly affect average recurrence
- Correlation of events
  - P0 only observed at AF (partial segment rupture? Something else?)
  - P1 observed at all four sites
  - P2 only observed at MN (partial segment rupture vs. incomplete record?)
  - P3 at three sites (AF, MN and MS)
  - P4 observed at two sites (AF and MN)
  - P5 possibly observed at two sites (AF and MN)

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Conclusions (cont.)

- Earthquake timing
  - Mean times generally similar to UQFPWG, except for asymetric PDFs (usually with poor minimum age constraints); also uncertainties generally smaller
  - E0 moderately constrained at 260 ± 50 cal BP (2σ) but not previously recognized and uncertain as to nature or rupture extent
  - E1 well-constrained: 580 ± 50 cal BP (2σ) vs ± 350 yrs of UQFPWG
    - Elapsed time: 640 ± 50 years (2σ)
    - Rupture of entire segment
  - E2 to E4: moderate uncertainties in segment PDFs and E2 uncertain as to rupture extent

- Average recurrence
  - Poorly constrained from 1.1 ± 0.8 ky to 1.4 ± 0.8 ky (1σ)
  - Bimodal??
  - Mean estimate similar to Olig et al. (2006; 2010) but much shorter than UQFPWG preferred estimate of 2.4 ky (Lund, 2005) and other previous studies

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Summary and discussion of OxCal/Matlab results for the Wasatch fault zone

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Susan Olig (URS)

Bill Lund (UGS)

Working Group on Utah Earthquake Probabilities, July, 2010

Brigham City summary

- 5 events younger than ~7.7 ka
  - E5 – identified at 1 site, E4/E3 – 2 sites, E2/E1 – 3 sites
  - Average overlap in site PDFs: 0.61
- MRE (E1)
  - 2.4 ± 0.3 ka (2σ) (elapsed time: 2480 ± 254 yr)
  - Older than previous estimates ~2.1 ka
  - PC1 at 1.2 ka: separate, younger earthquake than 2.4 ka MRE (partial rupture of southern segment in 1.1-1.3 ka Weber segment event)
- Mean inter-event recurrence
  - E5–E1 mean : 1.3 ± 0.6 (1σ)
  - Mode: ~1 ky (mean PDF skewed by broadly constrained E5–E3 intervals)
  - Previously reported: 1.1 (Bowden) – 1.3 ky (Box Elder, M&N96, UQFPWG)

Weber segment summary

- 5 events younger than ~5.9 ka
  - E5 – identified at 2 sites, E4 – 3 sites, E3–E1 – 4 sites
  - Possibility of Kaysville event 2 doesn't significantly affect E2 time
  - Average overlap in site PDFs: 0.43

- MRE (E1)
  - 0.6 ± 0.1 ka (2σ) (elapsed time: 620 ± 70 yr)
  - Similar to previous estimates (~0.4 – 0.6 ka Nelson el al. 2006), but full segment rupture (identified at four sites)

- Mean inter-event recurrence
  - E5–E1 mean: 1.3 ± 0.5 (1σ) (peaks ~1 and ~2 ky modes
  - Previously reported: 1.4–1.5 ky (UQFPWG, East Ogden, Rice Cr.) to 1.8–2.7 ky (M&N96, Garner Cyn., Kaysville)

Salt Lake City segment summary

- 4 events younger than ~5.3 ka
  - E4 – E1 identified at both LCC and SFDC (6-event correlation)
  - OxCal/Matlab event timing very similar to published estimates
  - Average overlap in site PDFs: 0.38

- MRE (E1)
  - 1.3 ± 0.04 ka (2σ) (elapsed time: 1395 ± 40 yr)
  - Very well constrained (at LCC)

- Mean inter-event recurrence
  - E4–E1 mean: 1.3 ± 0.5 (1σ) (peaks ~1 and ~2 ky modes
  - Previously reported: 1.3–1.4 ky (SFDC, M&N96, UQFPWG)

Provo segment summary

- 4 events younger than ~4.7 ka (3 AF events) [Minimum record]
    - AF0/E0 and MN5 excluded
    - E4 identified at 2 sites, E3 – 3 sites, E1 – 4 sites
- 6 events younger than ~5.7 ka (5 AF events) [Maximum record]
    - E5–E4 identified at 2 sites, E3 – 3 sites, E1 – 4 sites,
    - E2 and E0 only identified at 1 site (MN and AF, respectively)
  - Average overlap in site PDFs: 0.35-0.36

- MRE (E1)
  - 0.6 ± 0.04 ka (2σ) (elapsed time: 640 ± 40 yr)
  - Very well constrained (at Mapleton N and Rock Canyon)
  - E0 – partial rupture of northern Provo segment at ~300 yr?

- Mean inter-event recurrence (max model)
  - E5–E1 mean: 1.3 ± 0.7 (1σ); E4–E1: 1.4 ± 0.8 (1σ); Peaks ~0.9 and ~2.5 ky modes
  - Shorter than previously reported (2.4 ky of UQFPWG)

Nephi segment summary

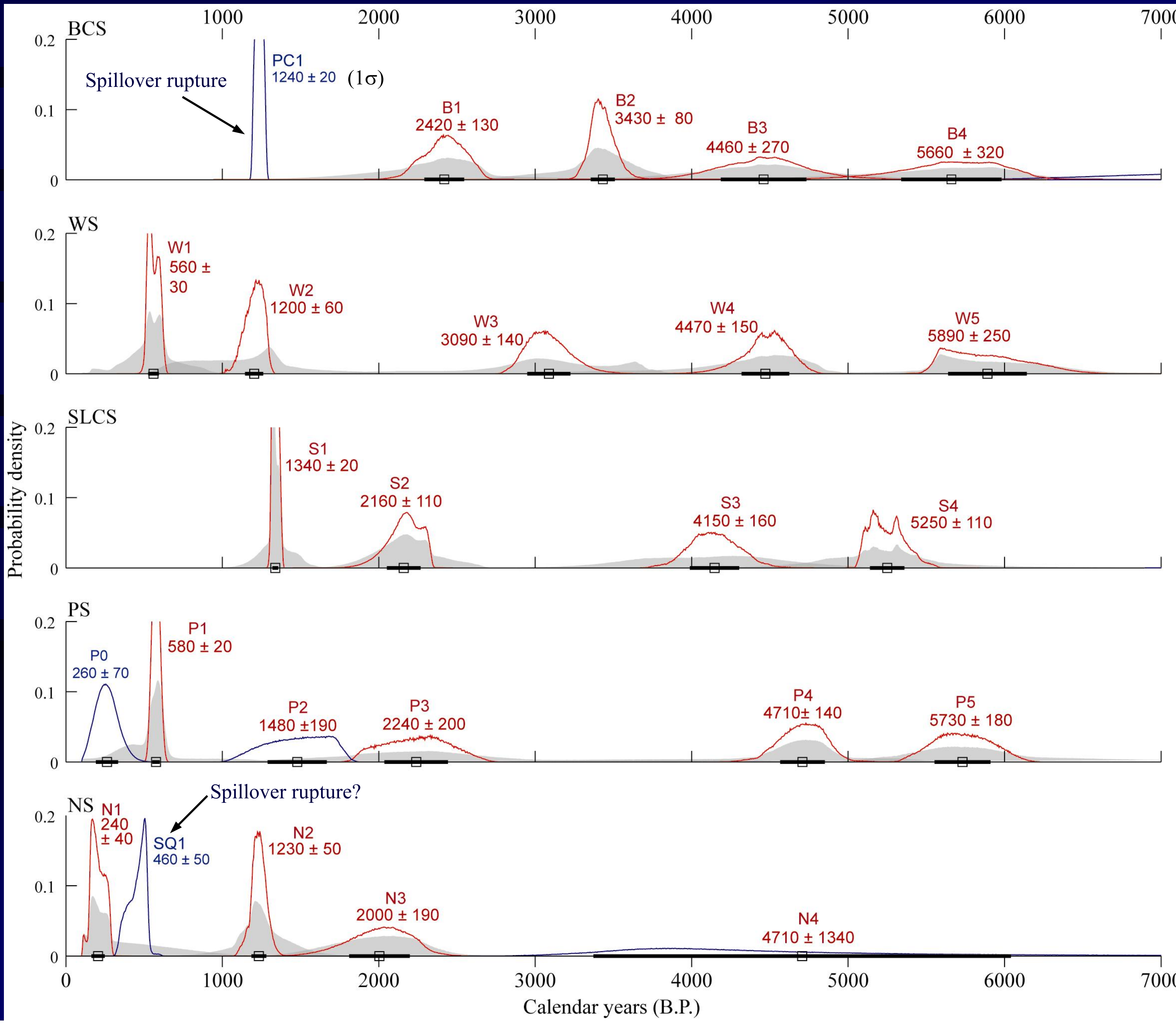
- 3 events younger than ~2.0 ka
  - E3 – identified at 2 sites, E2 and E1 – 3 sites
  - E4 – only identified at Red Cyn.; very poorly constrained
  - Average overlap in site PDFs: 0.52
- MRE (E1)
  - 0.2 ± 0.1 ka (2σ) (elapsed time: 270 ± 80 yr)
  - Well constrained at Willow Cr.; poorly constrained at Red Cyn. & North Cr.
  - Does Santaquin MRE (~0.5 ka) correspond with southern Nephi MRE? Correlating these events increases Nephi MRE to 0.3 ± 0.1 ka
- Mean inter-event recurrence
  - Mean: E4–E1: 1.5 ± 1.1 (1σ); E3–E1: 0.9 ± 0.2 (1σ)
  - Shorter recurrence than previously reported estimates (2.5 ky - UQFPWG), but also much shorter elapsed time since MRE

Summary of results – central WFZ

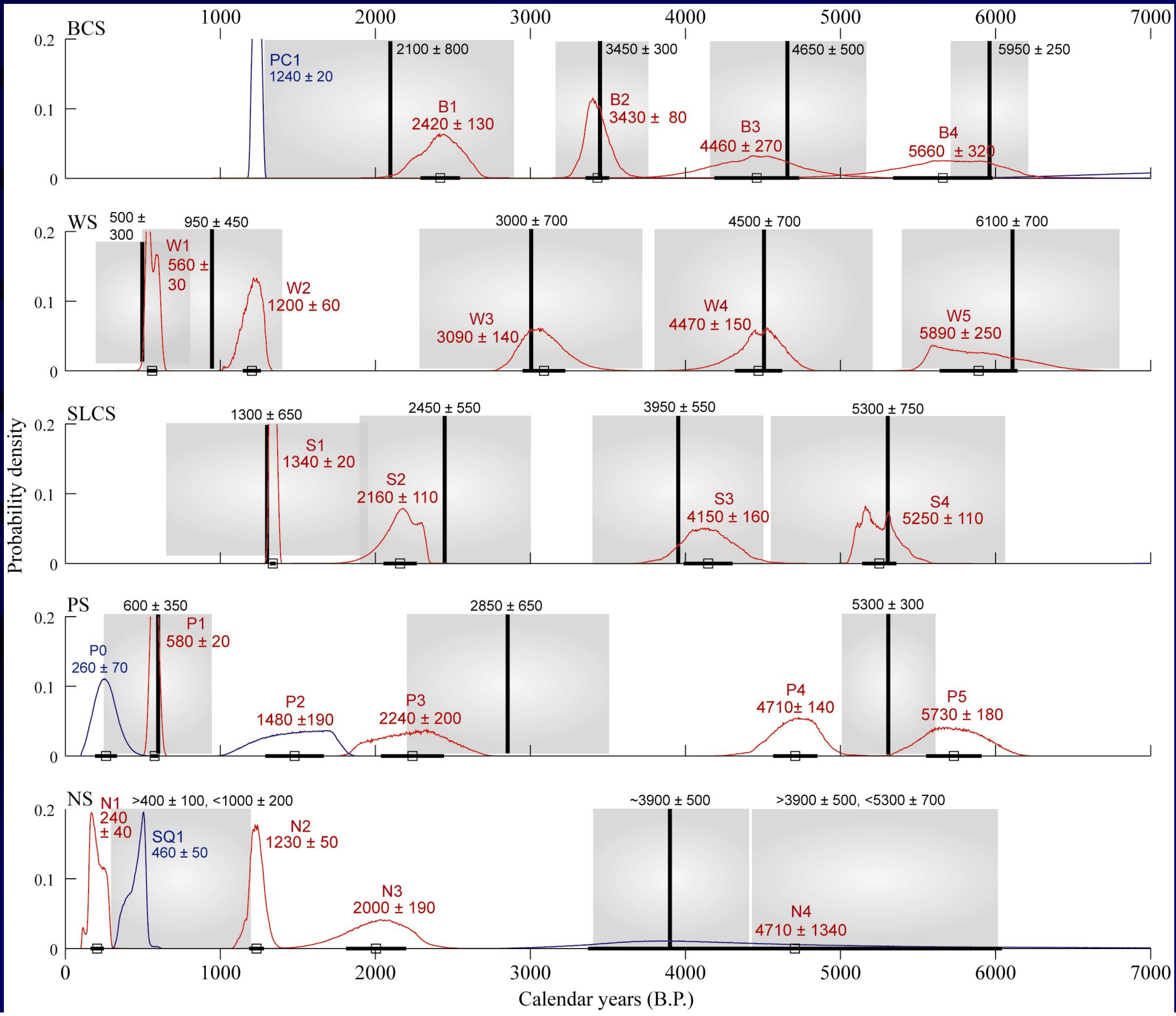
	Brigham	Weber	Salt Lake	Provo MAX	Nephi
E0 (2σ)	-	-	-	0.3 ± 0.1	-
E1	2.4 ± 0.3	0.6 ± 0.1	1.3 ± 0.04	0.6 ± 0.05	0.2 ± 0.1
E2	3.4 ± 0.2	1.2 ± 0.1	2.2 ± 0.2	1.5 ± 0.4	1.2 ± 0.1
E3	4.5 ± 0.5	3.1 ± 0.3	4.1 ± 0.3	2.2 ± 0.4	2.0 ± 0.4
E4	5.7 ± 0.6	4.5 ± 0.3	5.3 ± 0.2	4.7 ± 0.3	4.7 ± 2.7
E5	7.7 ± 1.5	5.9 ± 0.5	7.8 ± 0.5	5.7 ± 0.4	-
E5-E1 (1σ)	1.3 ± 0.6	1.3 ± 0.5	1.6 ± 0.7	1.3 ± 0.7	-
E4-E1	1.1 ± 0.3	1.3 ± 0.5	1.3 ± 0.5	1.4 ± 0.8*	1.5 ± 1.1
E3-E1	1.0 ± 0.2	-	-	-	0.9 ± 0.2

**Same as Minimum model*

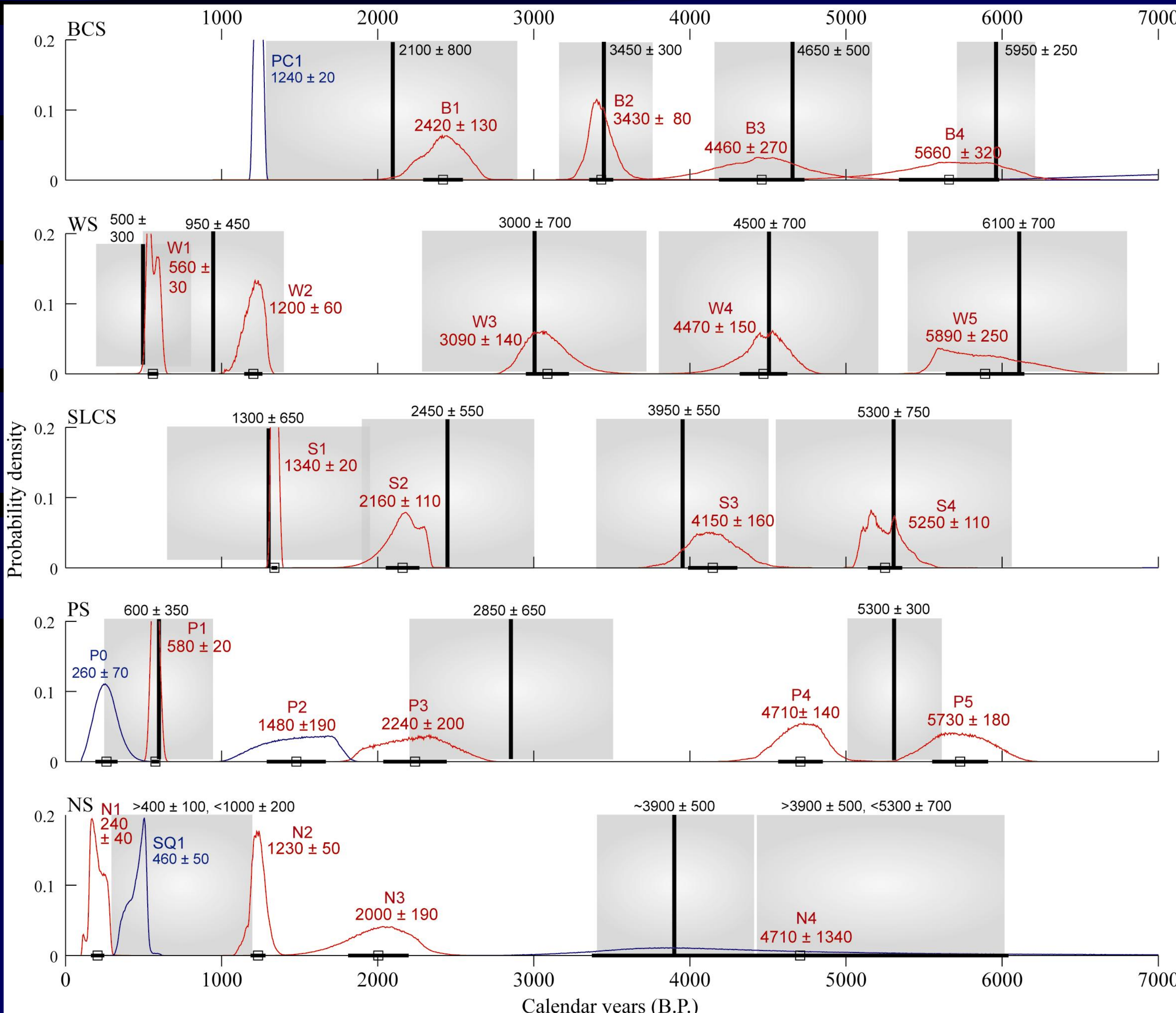
Revised WFZ chronology (OxCal/Matlab)



Comparison with UQFPWG consensus



Comparison with UQFPWG consensus



Average recurrence:	This study	UQFPWG
	1.3 ky	1.3 ky
	0.7–1.9 (1σ)	-
	0.1–2.5 (2σ)	0.5–2.8 (~2σ)
	1.3 ky	1.4 ky
	0.8–1.8 (1σ)	-
	0.2–2.3 (2σ)	0.5–2.4 (~2σ)
	1.3 ky	1.3 ky
	0.8–1.8 (1σ)	-
	0.2–2.3 (2σ)	0.5–2.4 (~2σ)
	1.4 ky	2.4 ky
	0.6–2.2 (1σ)	-
	≤3 (2σ)	1.2–3.2 (~2σ)
	0.9 ky	2.5 ky
	0.7–1.1 (1σ)	-
	0.5–1.3 (2σ)	1.2–4.8 (~2σ)

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

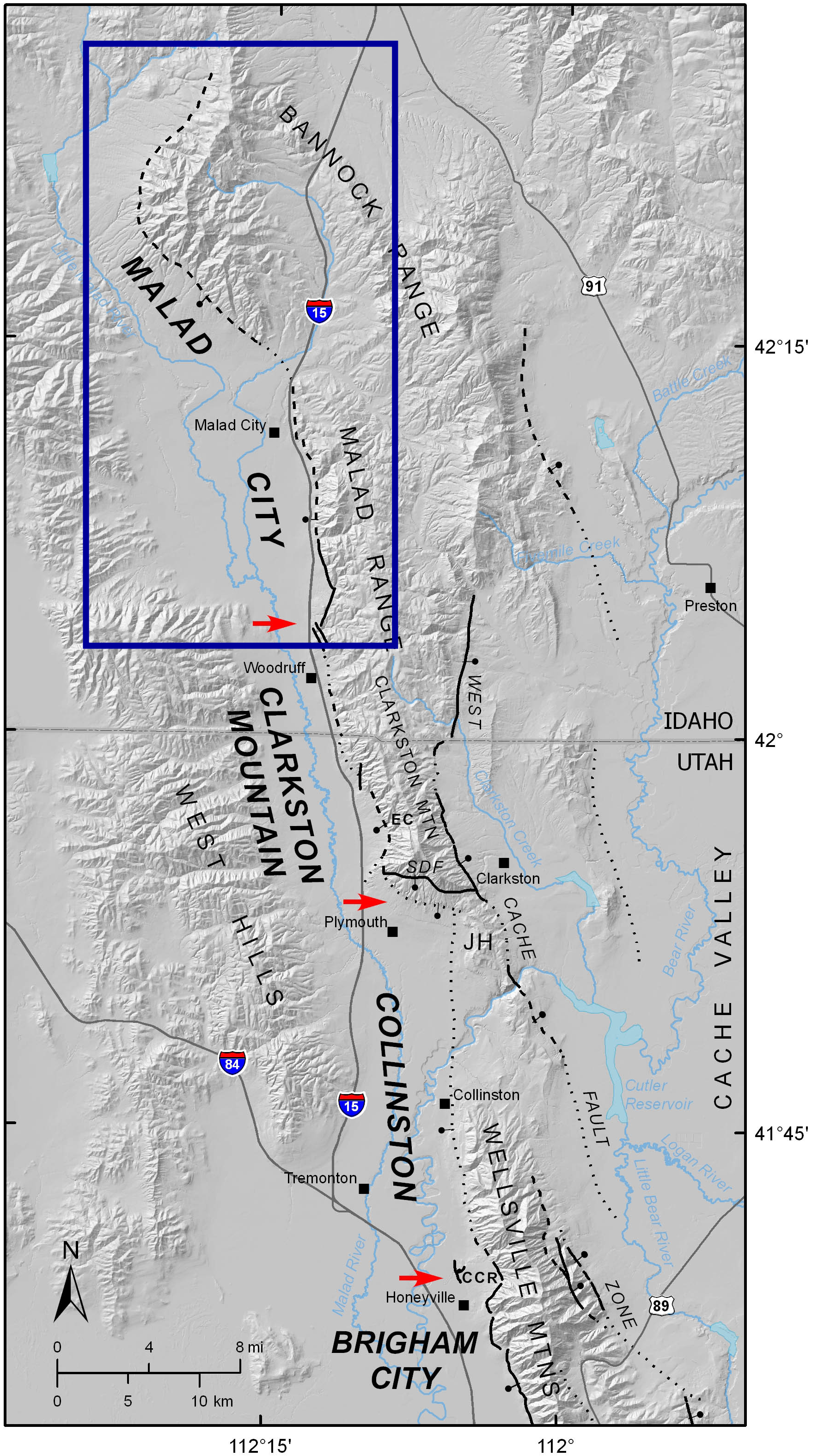
Geologic constraints:
•Bonneville lake-cycle deposits are not faulted
•Fault scarps are present on late Quaternary deposits ("older" alluvium)
•Steep range-front geomorphology
•Steep, linear gravity gradients

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)

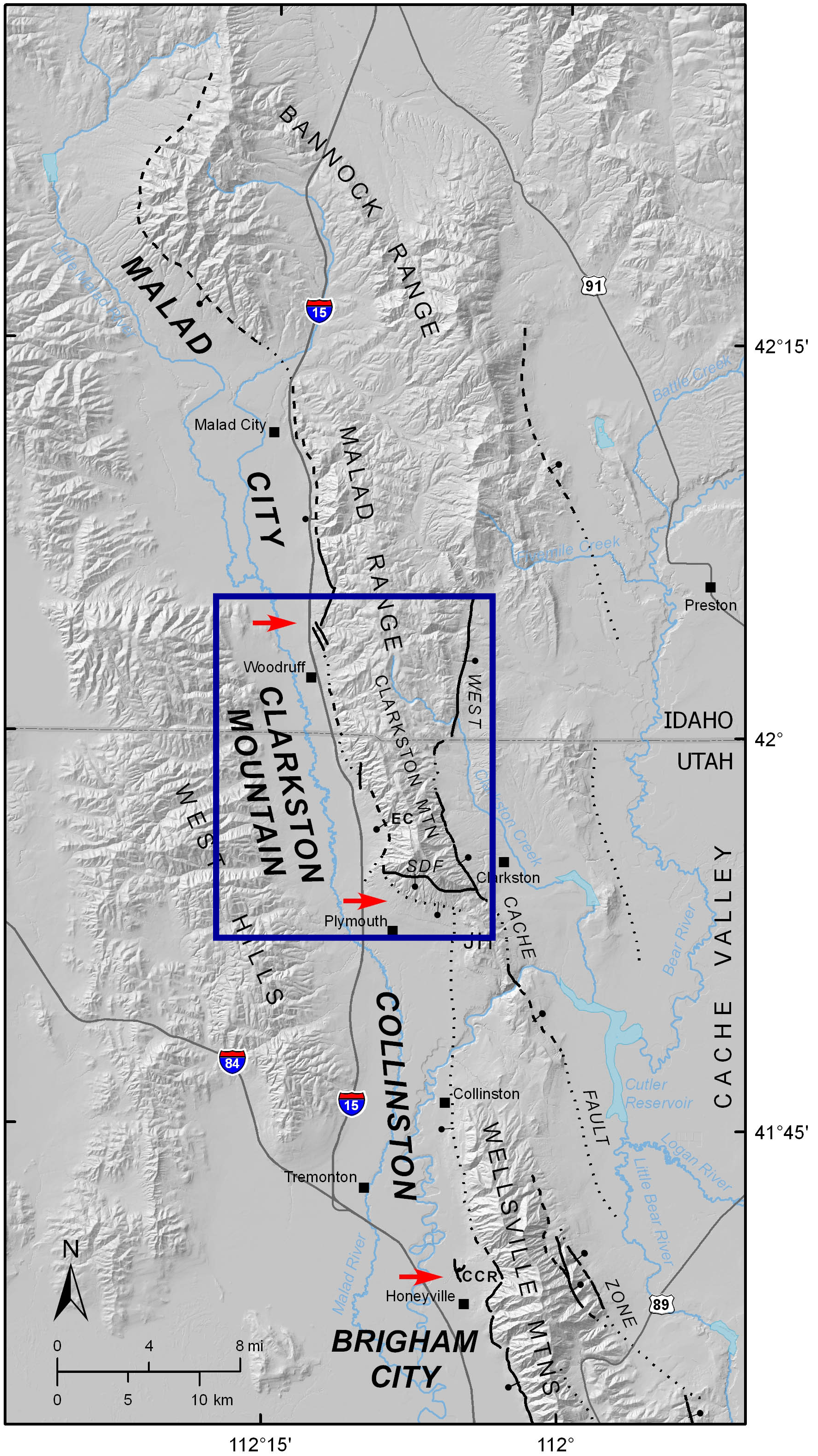


Northern Segments

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

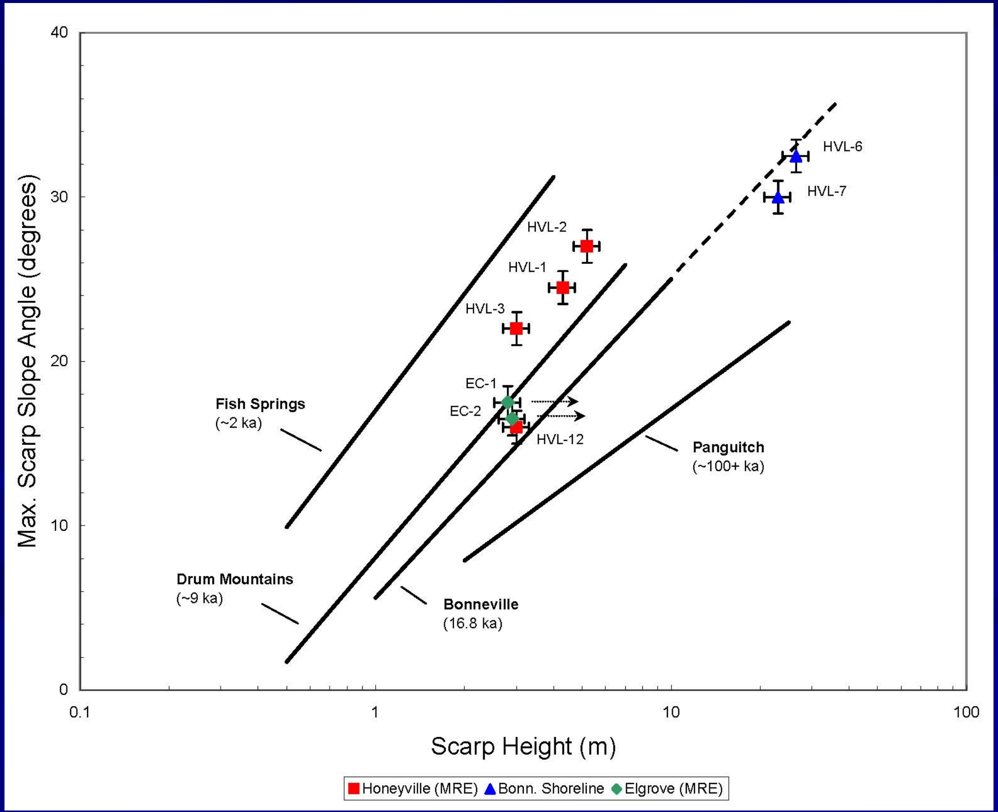


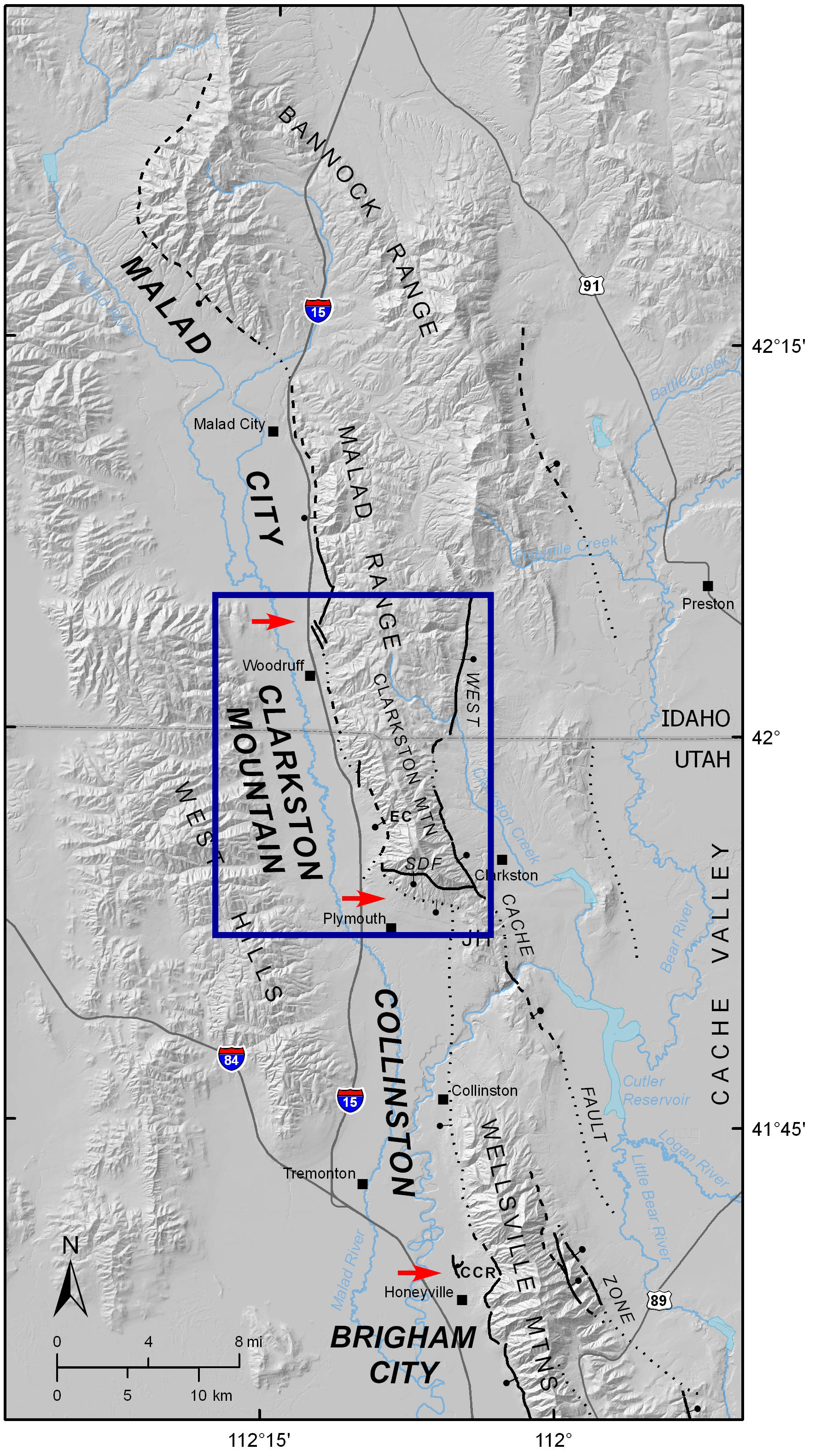
Northern Segments

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)





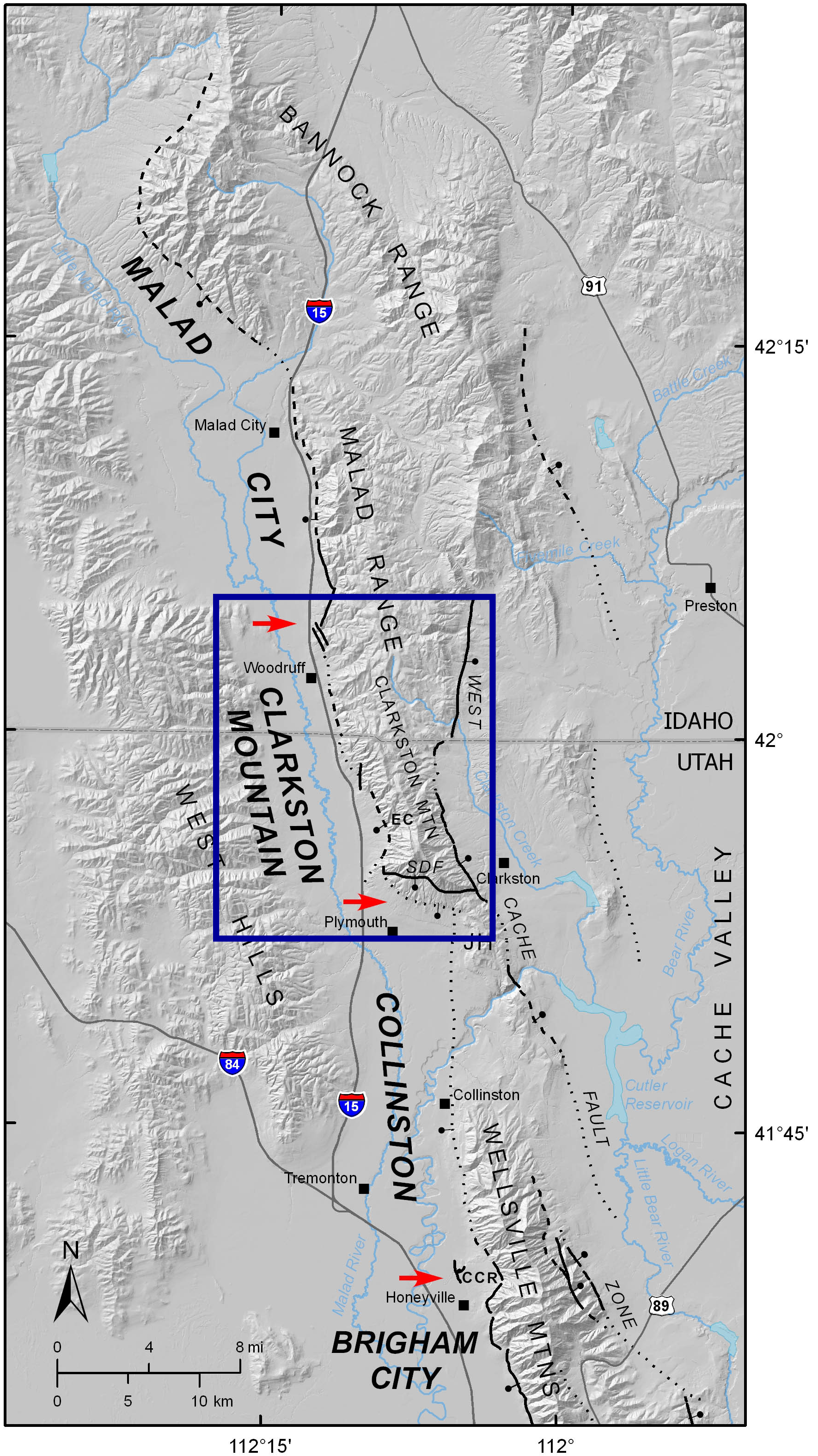
Northern Segments

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)

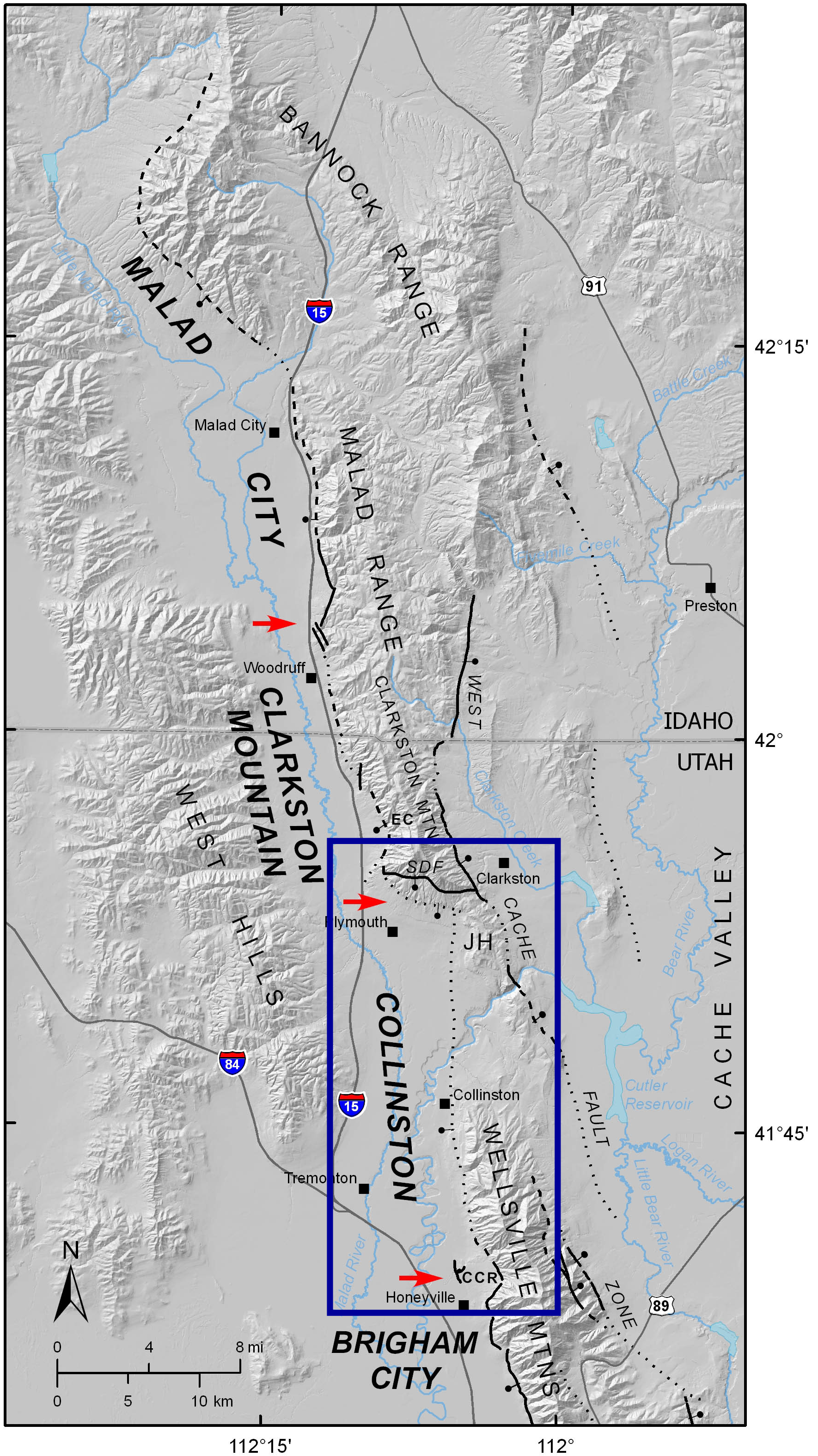


Northern Segments

Collinston Segment

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

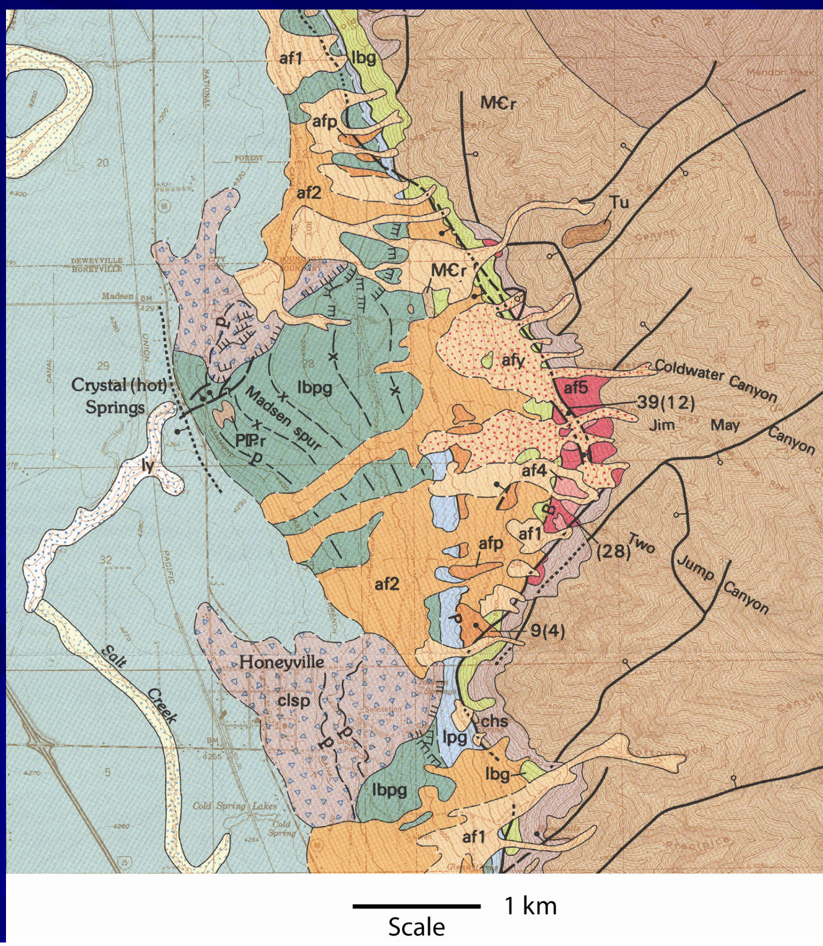
Geologic constraints:
•Bonneville lake-cycle deposits are faulted, but only in CCR (unfaulted to the N)
•Steep range-front geomorphology S, topographic saddle N (West Cache fault may be a factor; Holocene faulting)
•Steep, linear gravity gradients

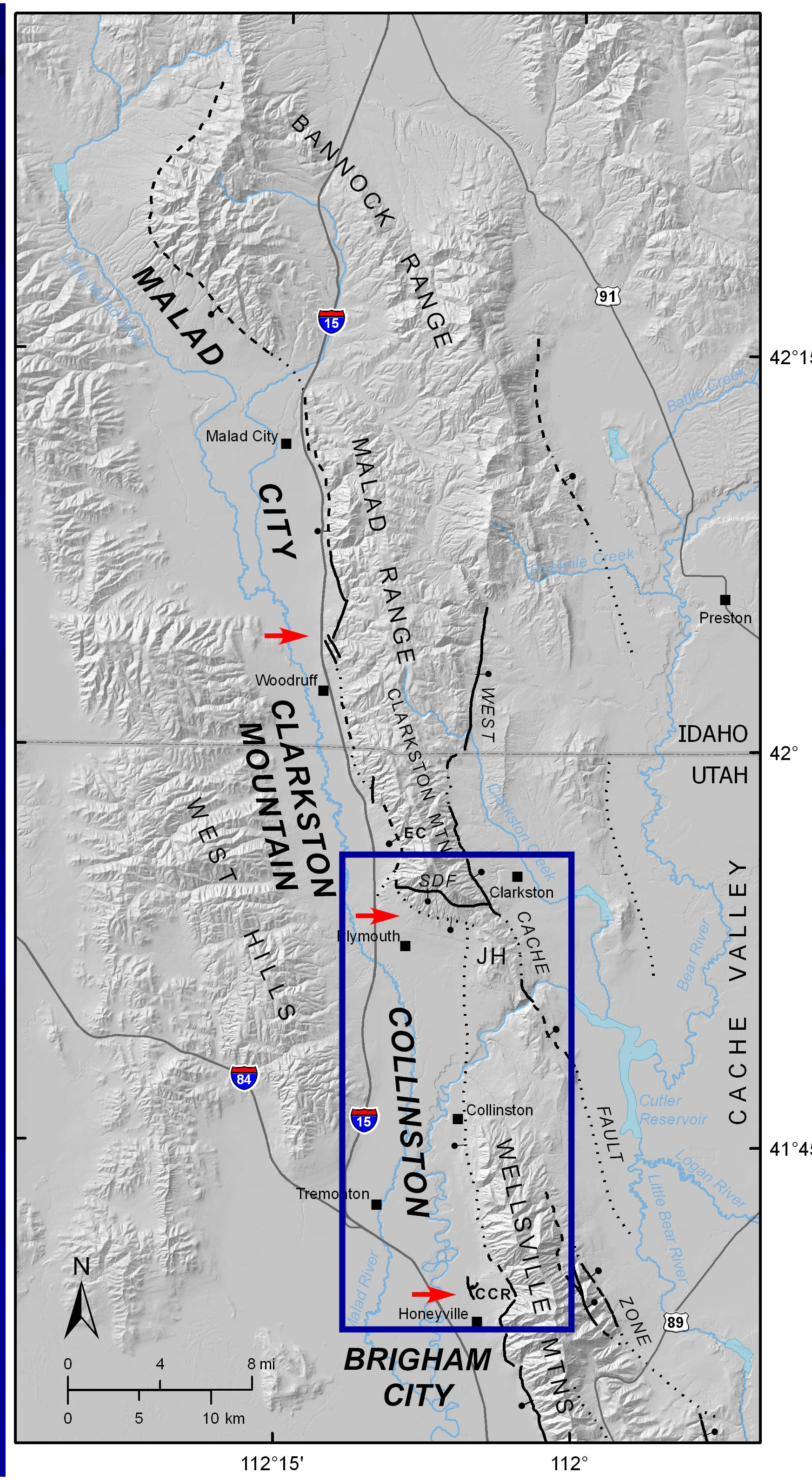


Northern Segments

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)





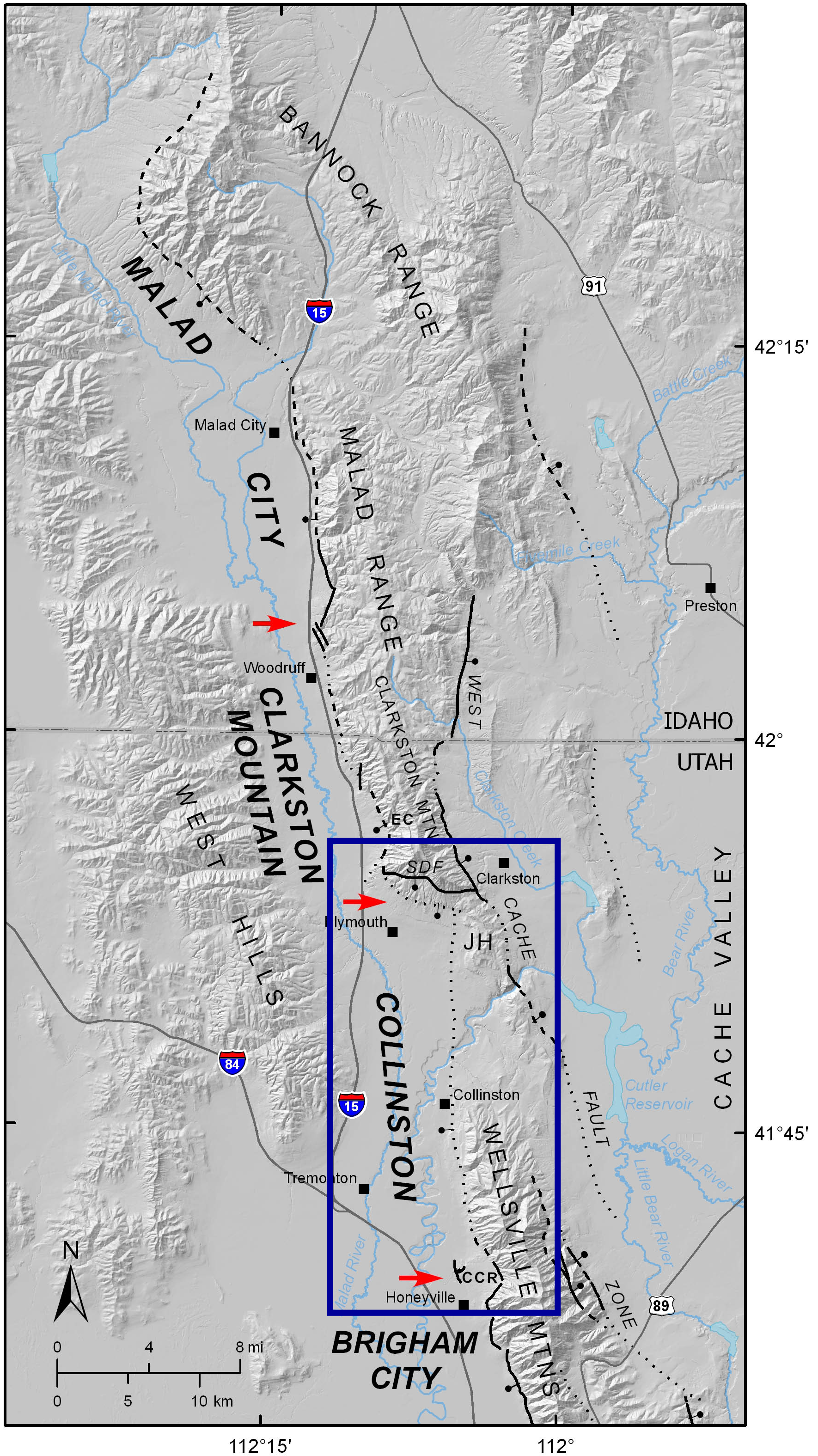
Northern Segments

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)



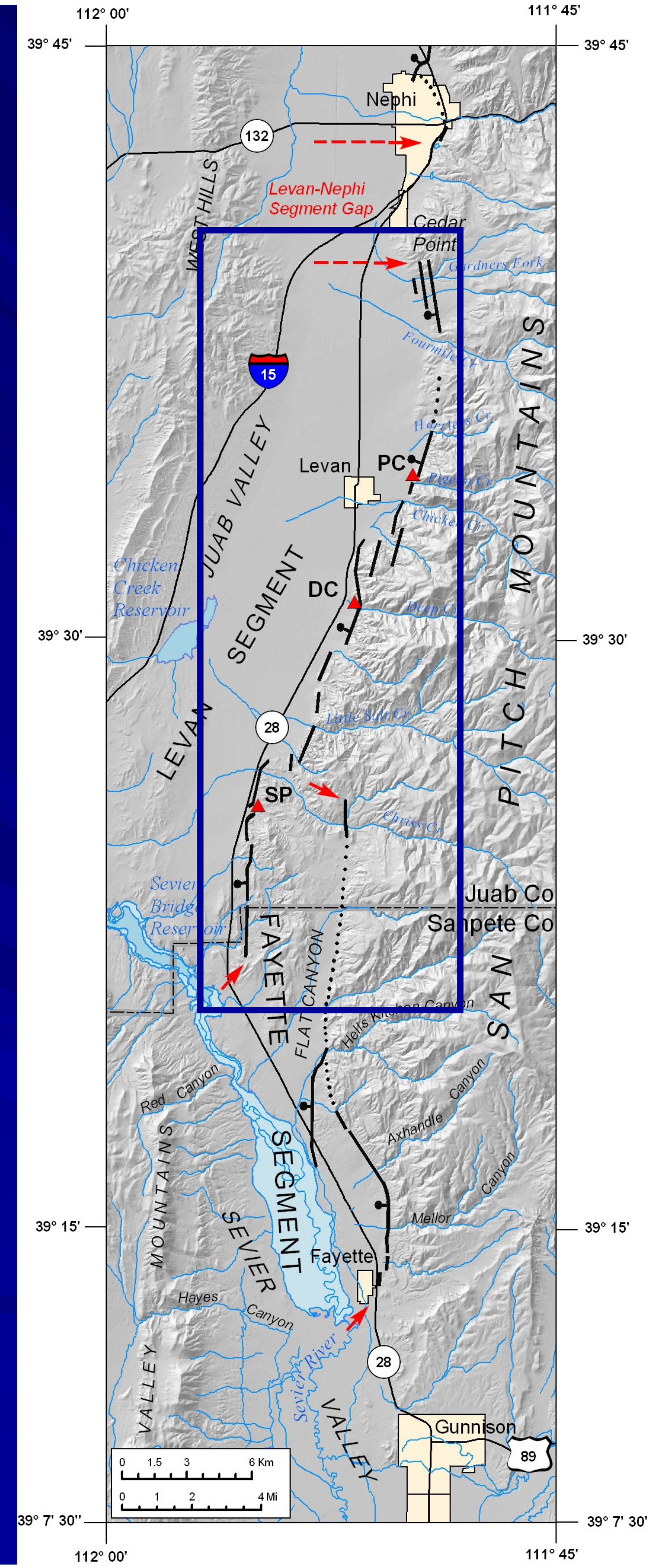
Southern Segments

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

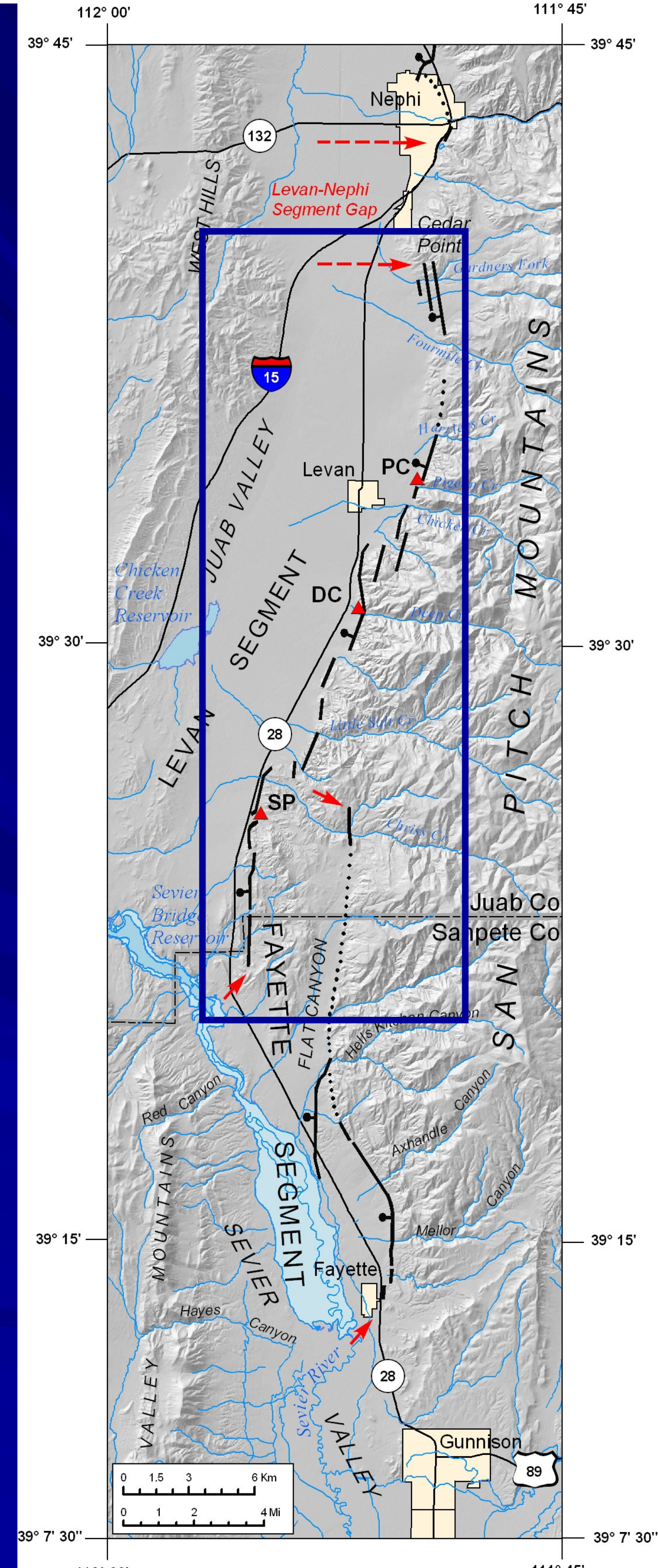
Earthquake timing:
Pigeon Creek:
•MRE postdates fan alluvium containing charcoal dated at 2100 ± 300 yr B.P. (1410–2760 cal yr B.P.) and 1750 ± 350 yr B.P. (950–2490 cal yr B.P.)



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)

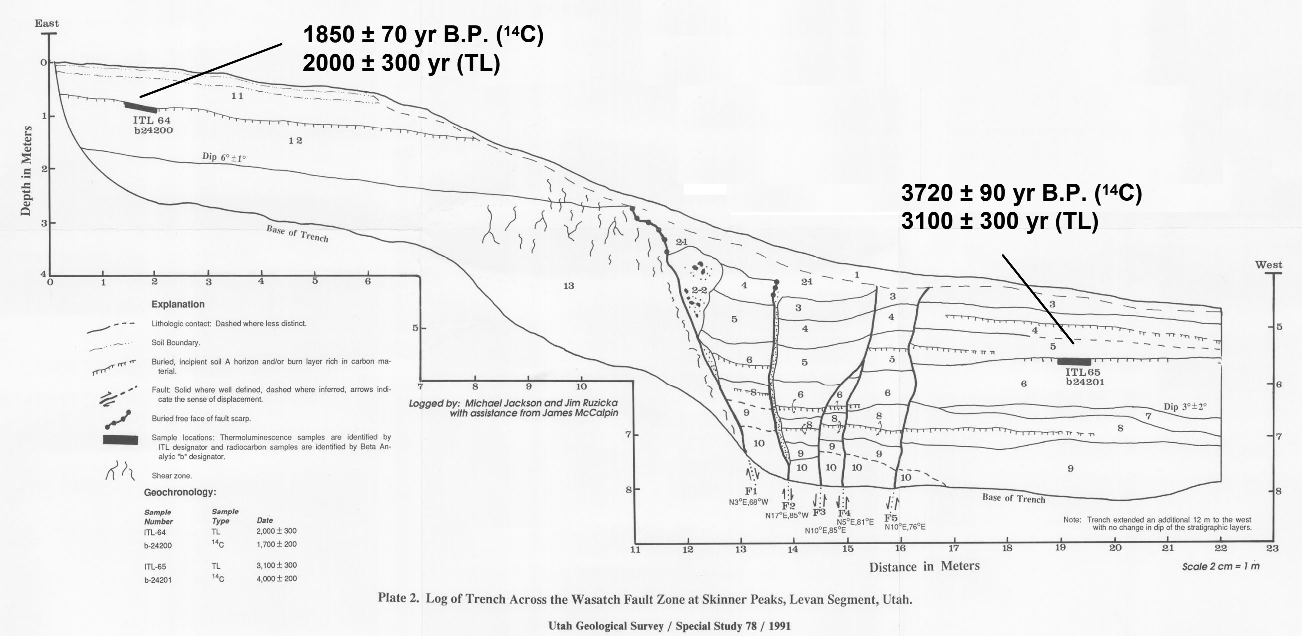
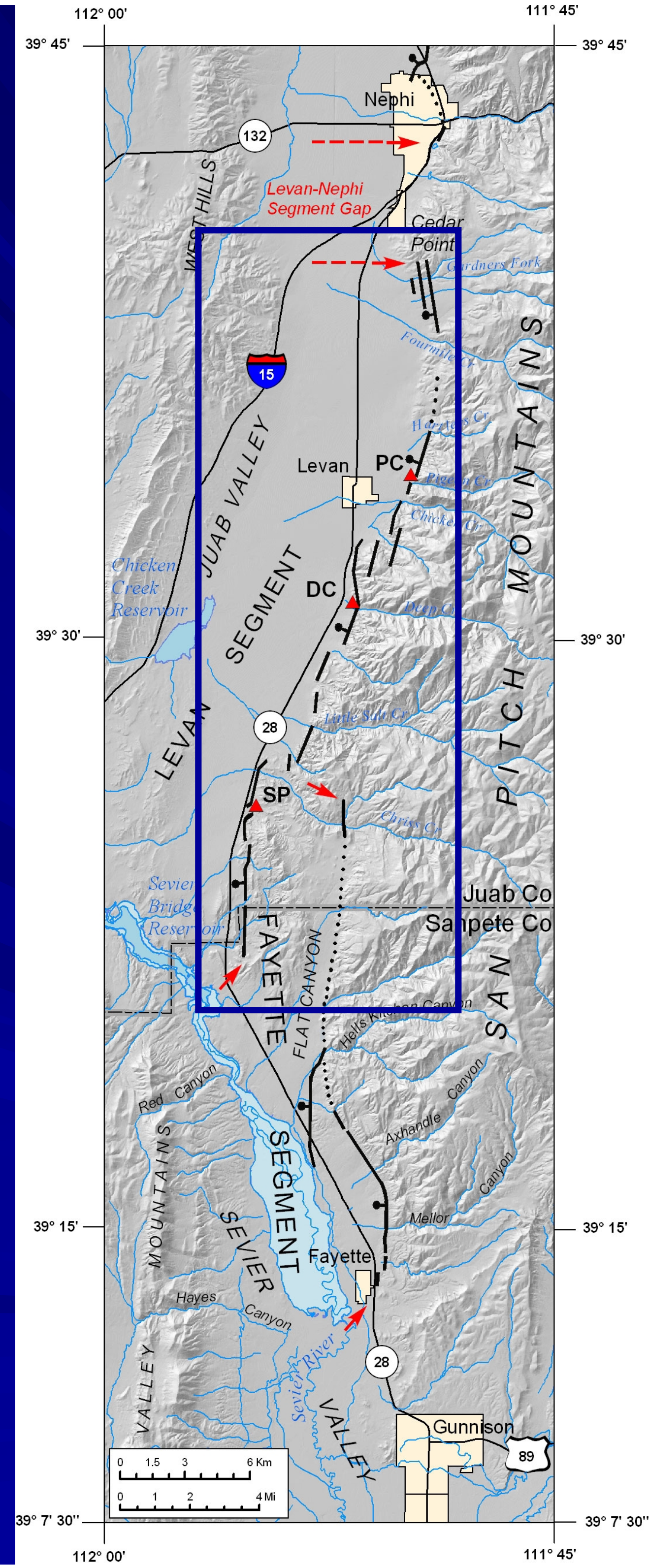


Plate 2. Log of Trench Across the Wasatch Fault Zone at Skinner Peaks, Levan Segment, Utah.

Utah Geological Survey / Special Study 78 / 1991

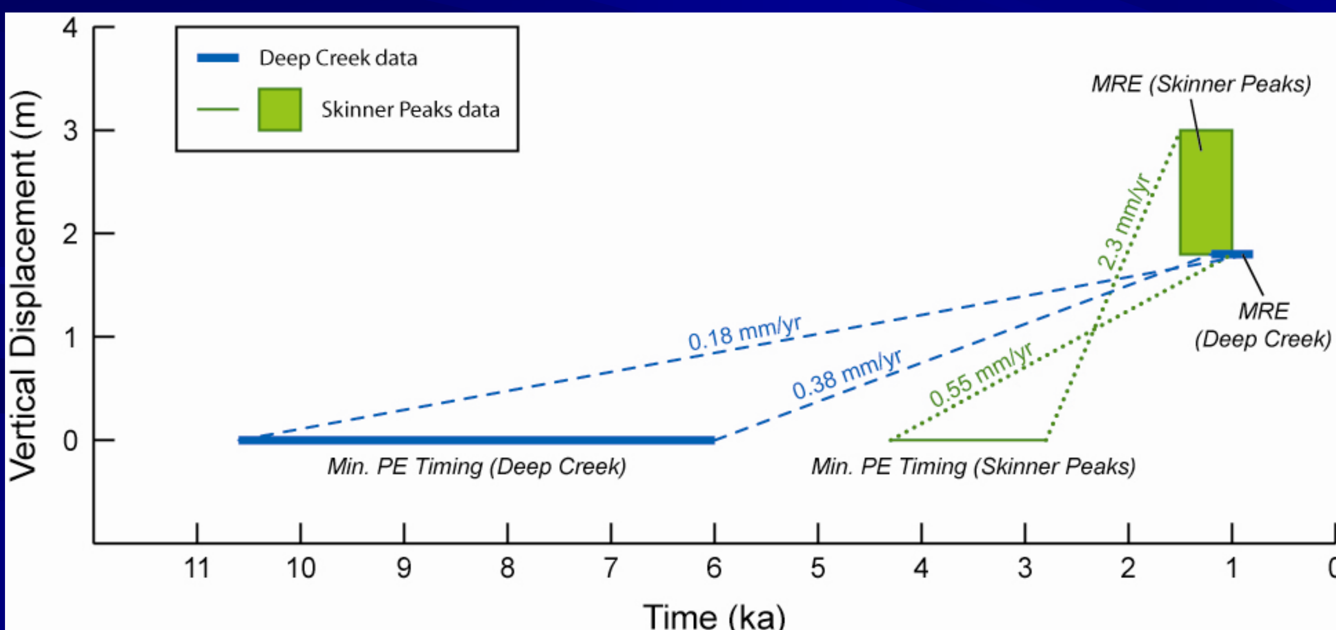


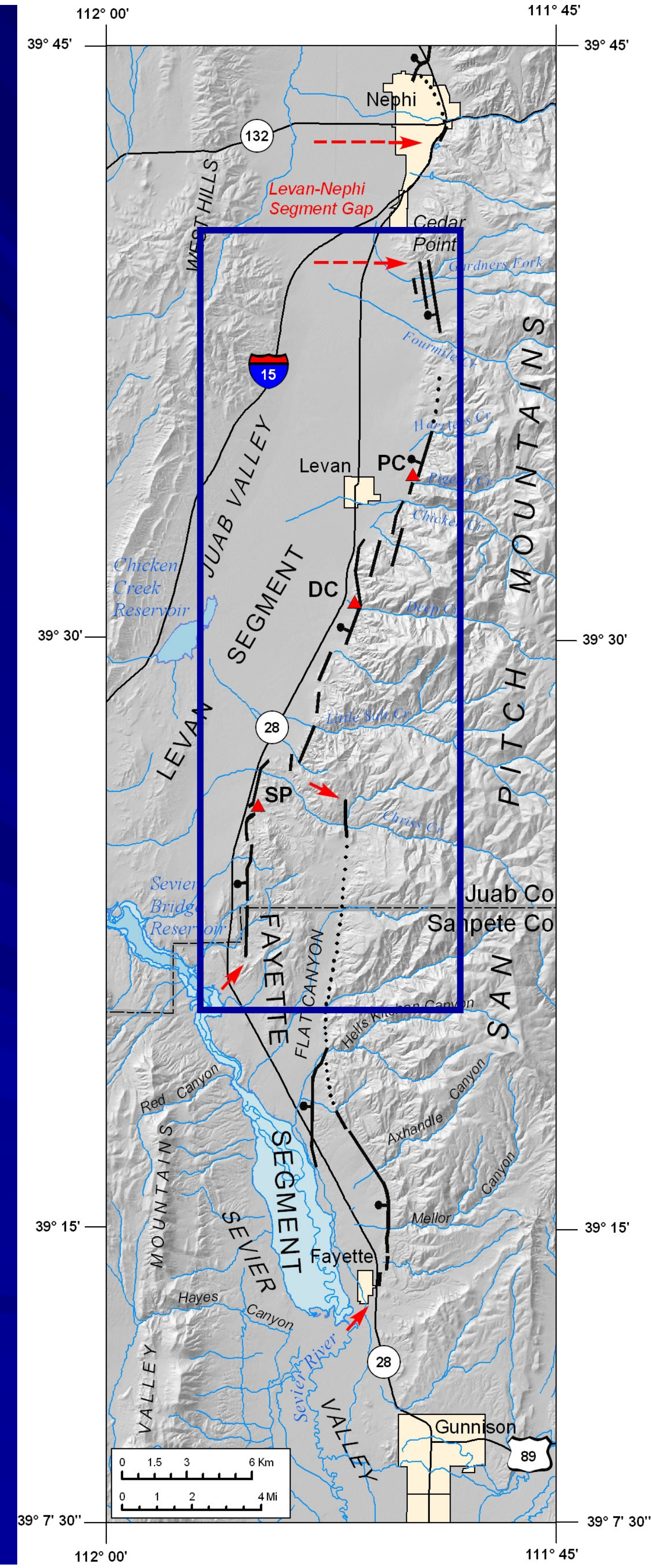
Southern Segments

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



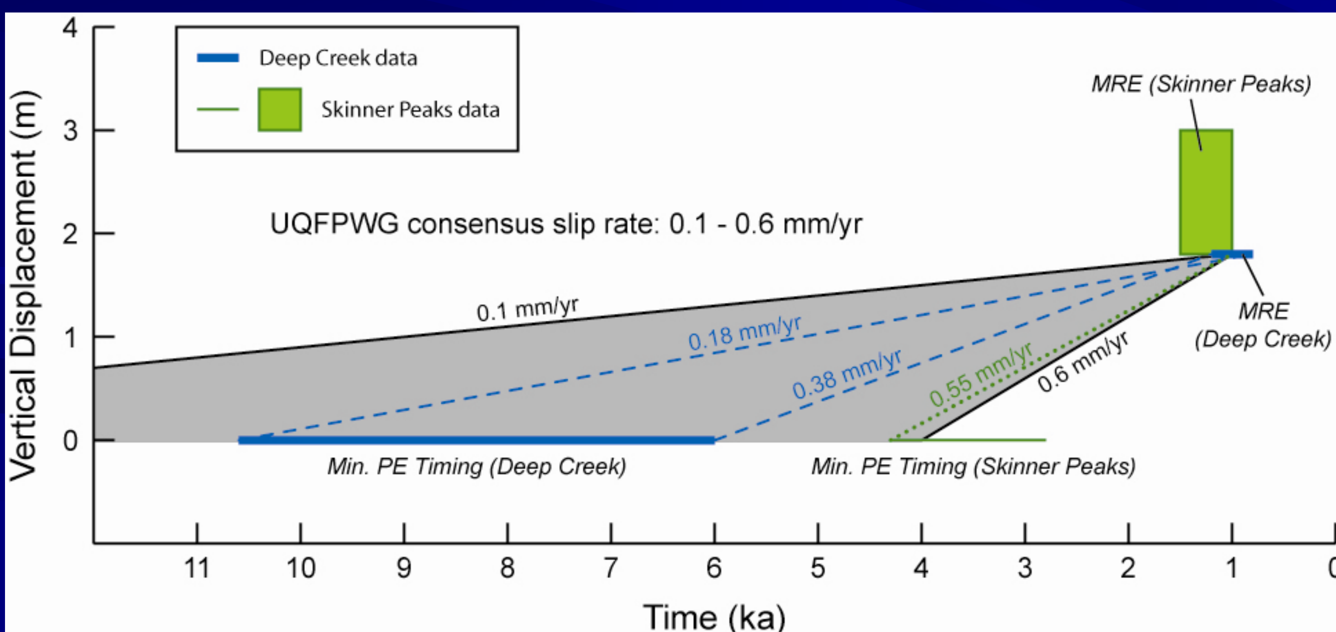


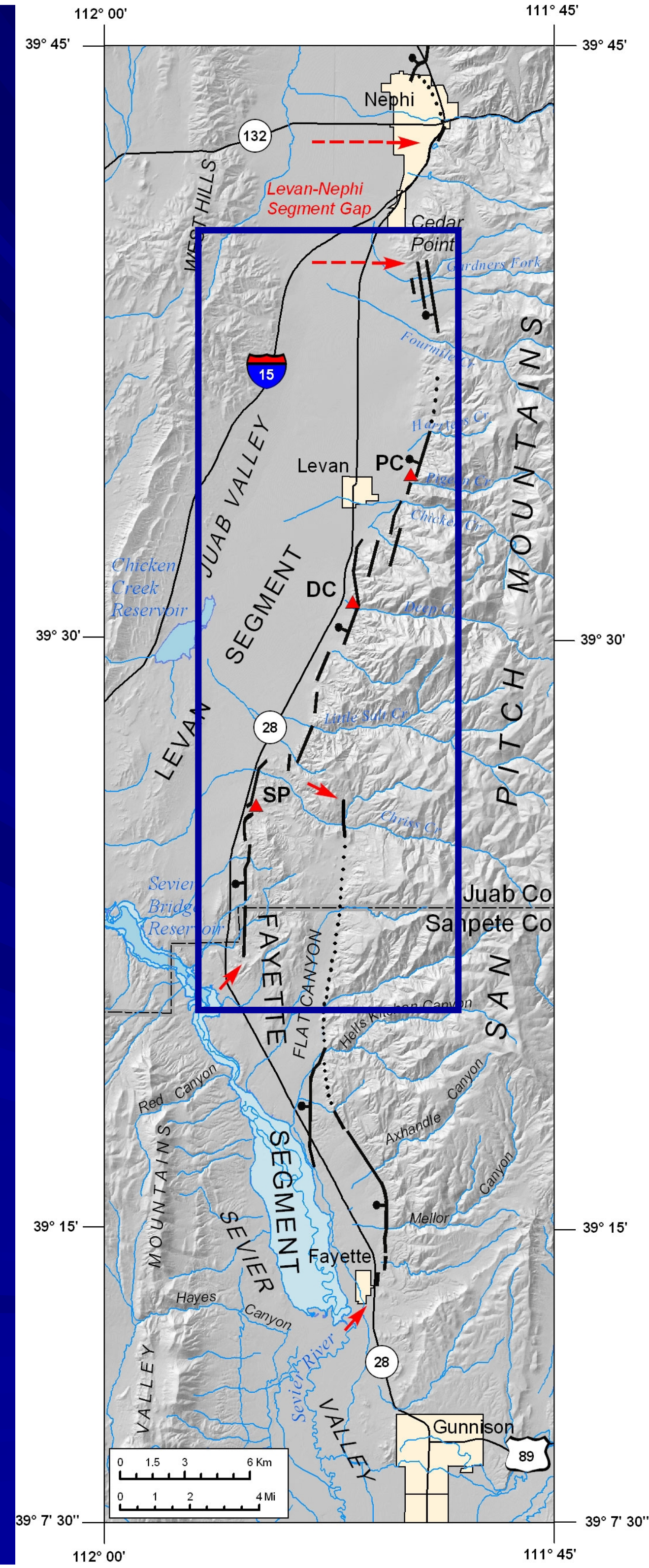
Southern Segments

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.):

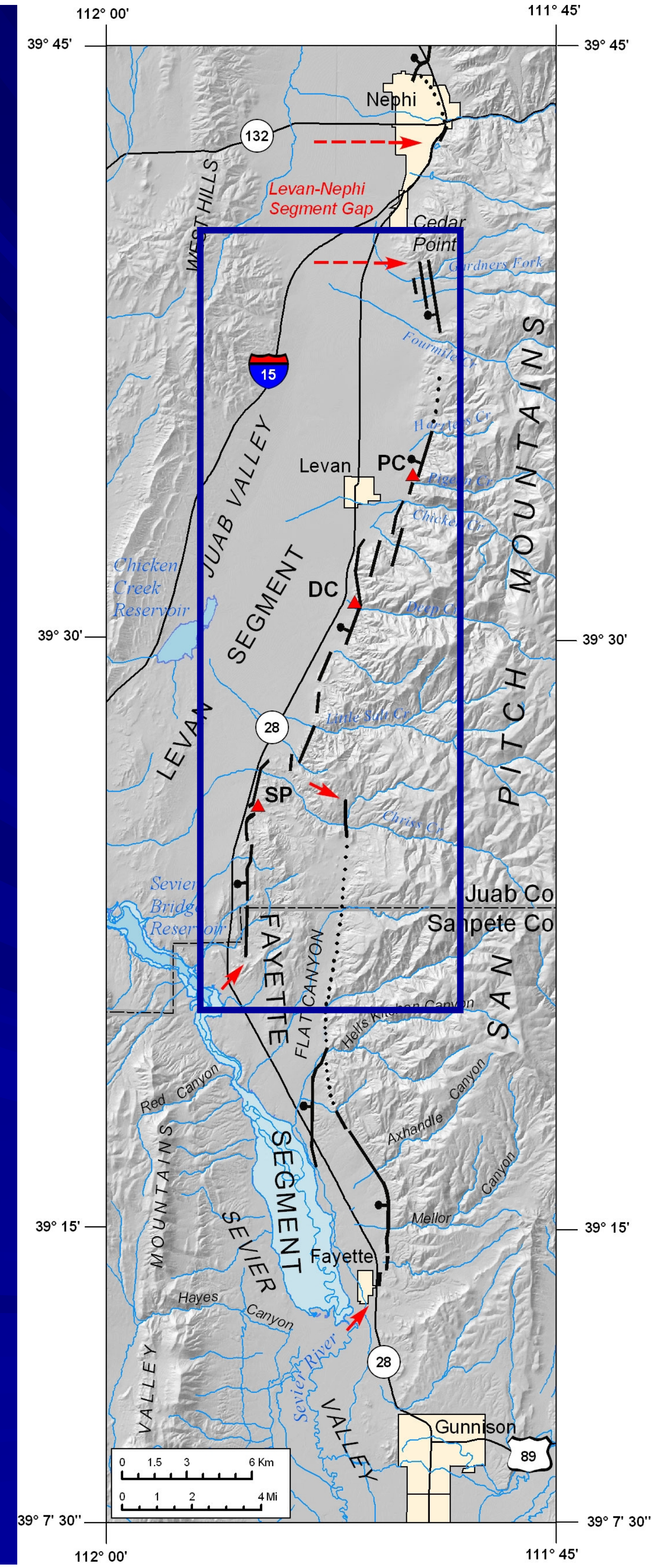
•Database slip rate category: <0.2 mm/yr
•Hylland and Machette (2008) preferred value: 0.3 ± 1 mm/yr (max)
•UQFPWG consensus range: 0.1–0.6 mm/yr
•Long-term average slip rate:
4.8 m in 100–250 kyr = 0.02–0.05 mm/yr

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)

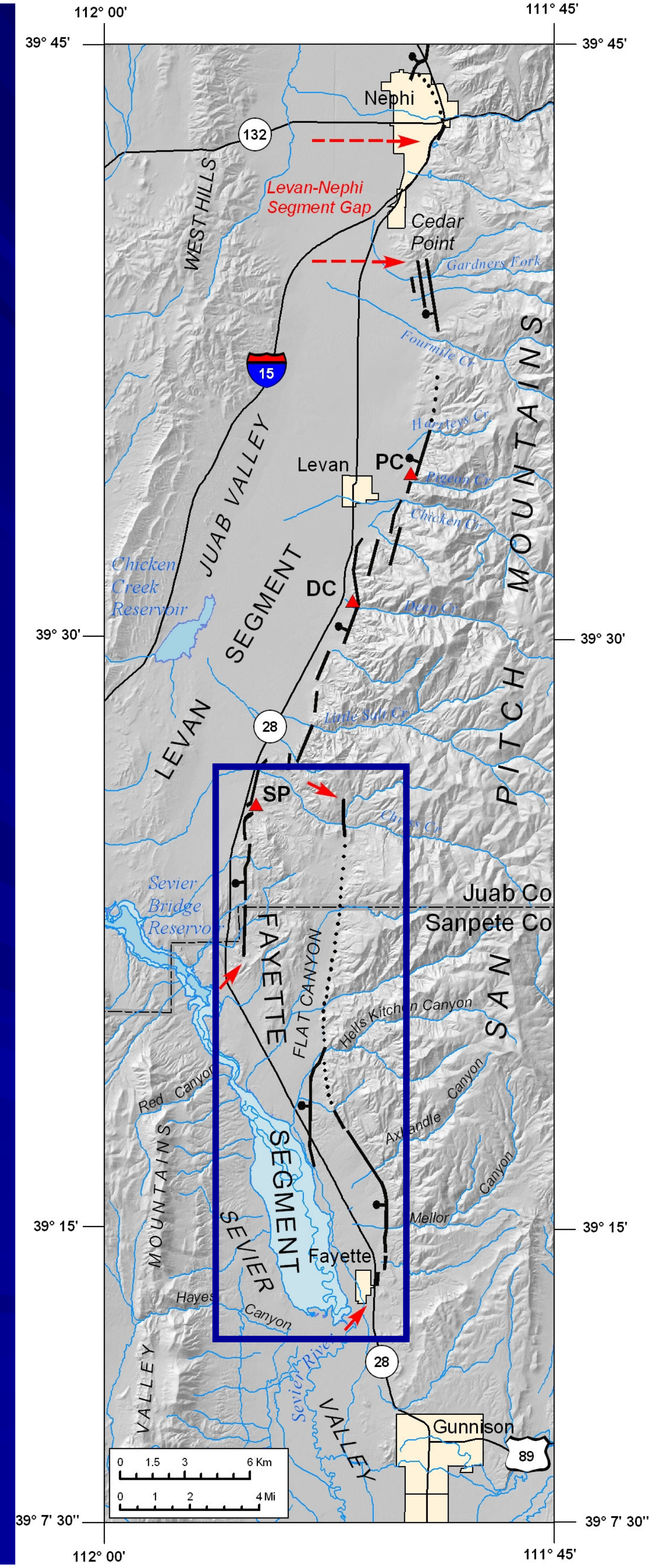


Southern Segments

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



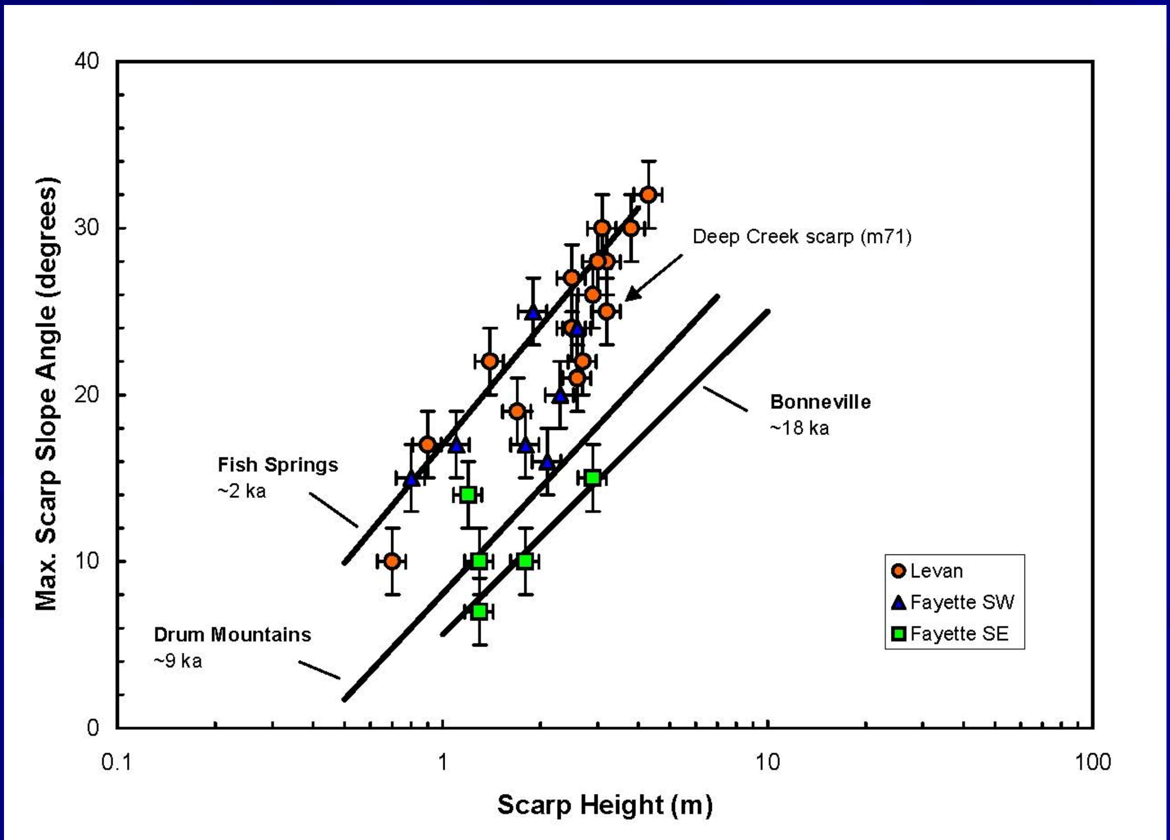
Southern Segments

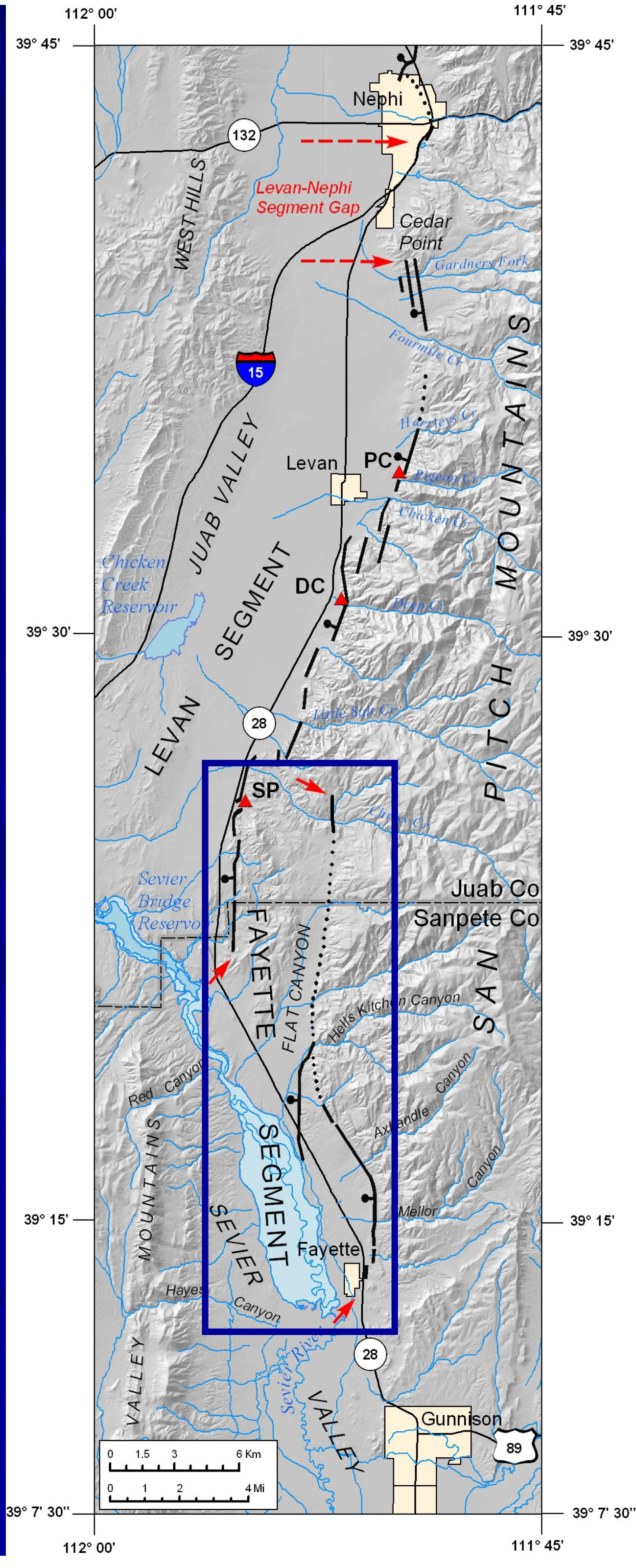
Fayette Segment

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)





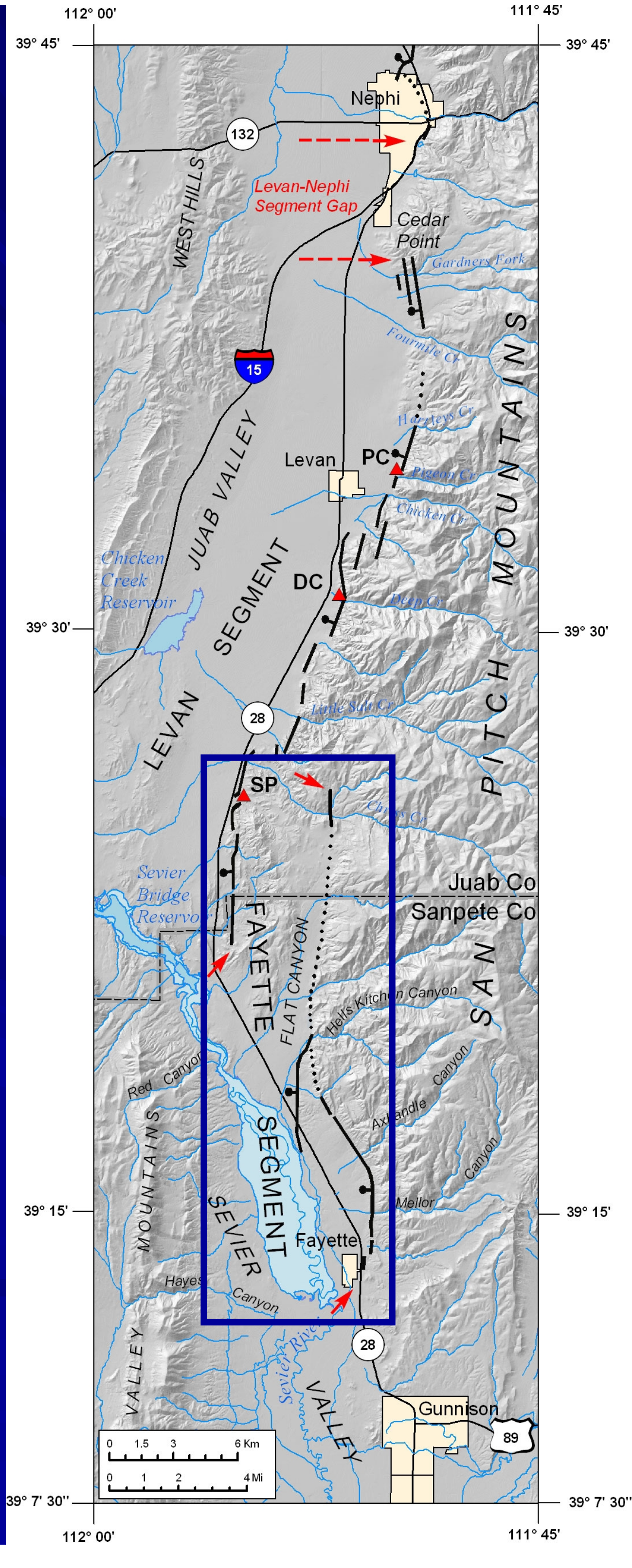
Southern Segments

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

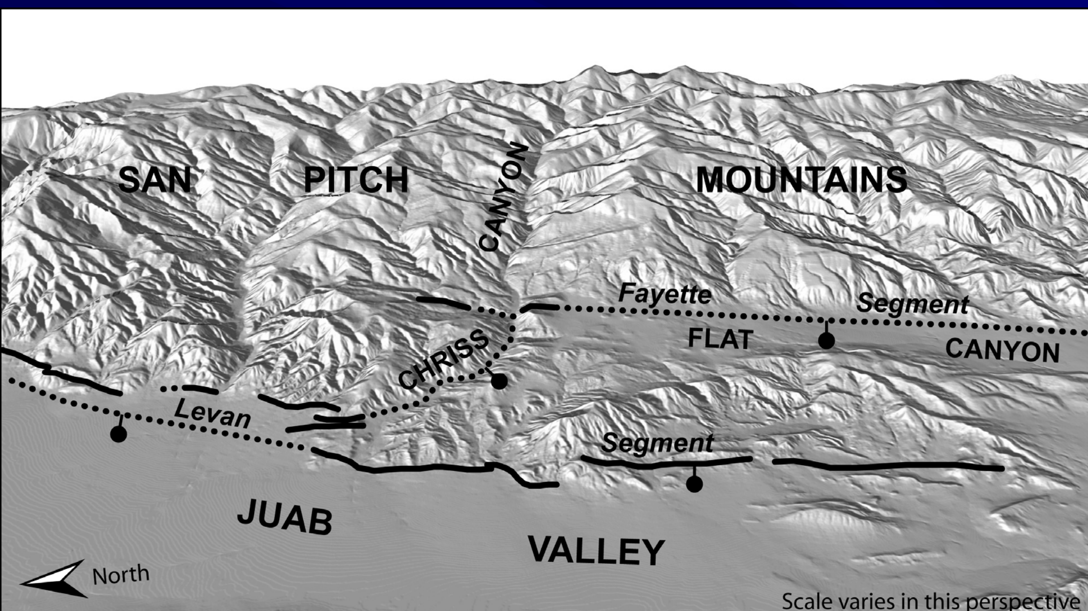
Recurrence interval: NA (MRE timing poorly constrained, no timing data for the PE)

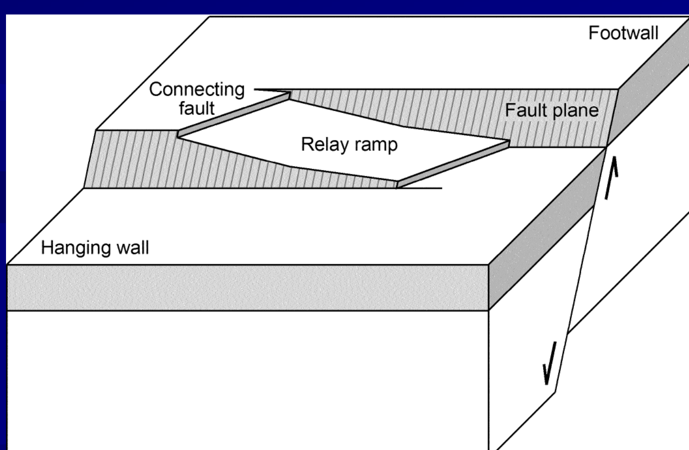
Sources:
Machette et al. (1992), Hylland (2007), Hylland and Machette (2008)

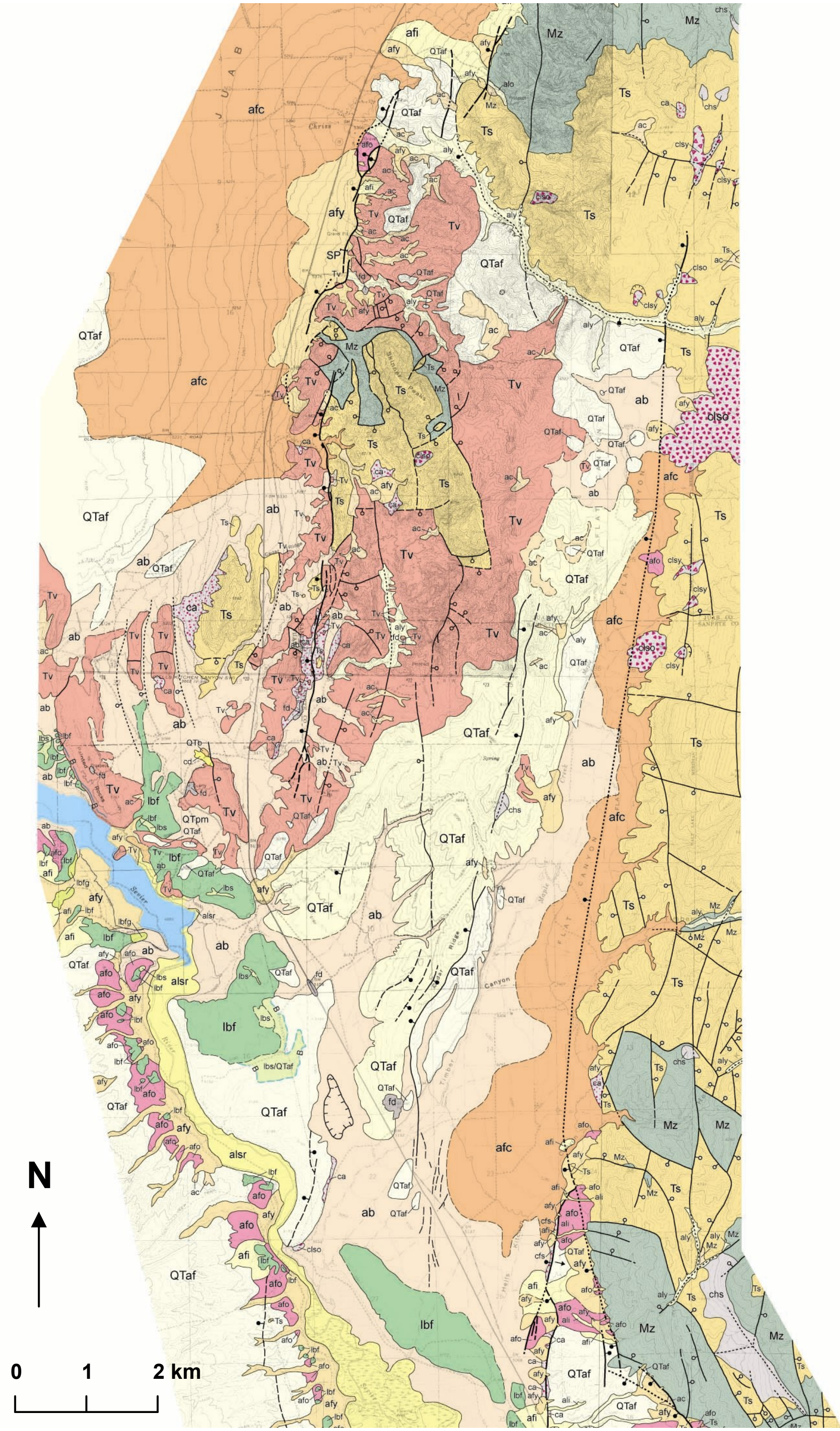


Southern Segments

Levan–Fayette Segment Boundary







The Wasatch Fault Zone End Segments

Summary of Earthquake Parameters

Segment	*MRE Timing*	*Displacement/ Surface Offset (m)*	*Time Interval (yr x 1000)*	*Est. Slip Rate (mm/yr)*	*Recurrence Interval (yr)*
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.)	>18	<0.1	NA
		<12	300	<0.04	
Levan	≤1000 cal yr B.P.	1.8	>4.8–9.8	<0.2–0.4	>3000 & <12,000 (UQFPWG)
	1000–1500 cal yr B.P.	1.8–3.0	>1.3–3.3	<0.5–2.3	
				<0.3±0.1 (H&M, 2008)	
				0.1–0.6 (UQFPWG)	
		4.8	100–250	0.02–0.05	
Fayette	Early(?) Holocene (SW strand)	0.8–1.6	<11.5	>0.07–0.1	NA
	Latest Pleistocene (SE strand)	0.5–1.3	<18	>0.03–0.07	
		3	100–250	0.01–0.03	

BASIS FOR SEGMENTATION

Historical ruptures

Event ages along strike

Slip rate variations along strike

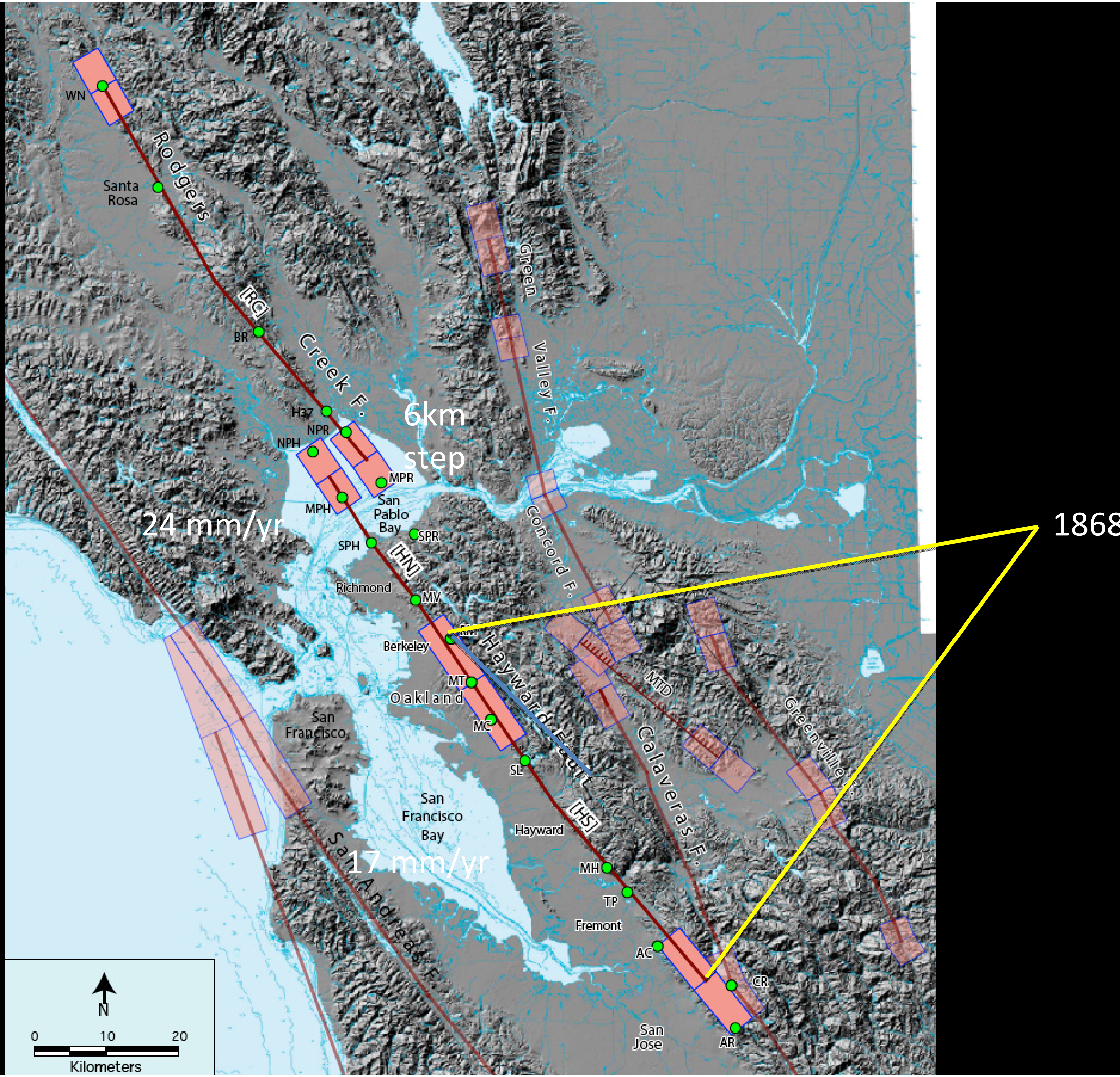
Slip in historical ruptures and paleo events

Geometric changes-steps, bends, intersections, trace complexity

Distribution and nature of microearthquake activity

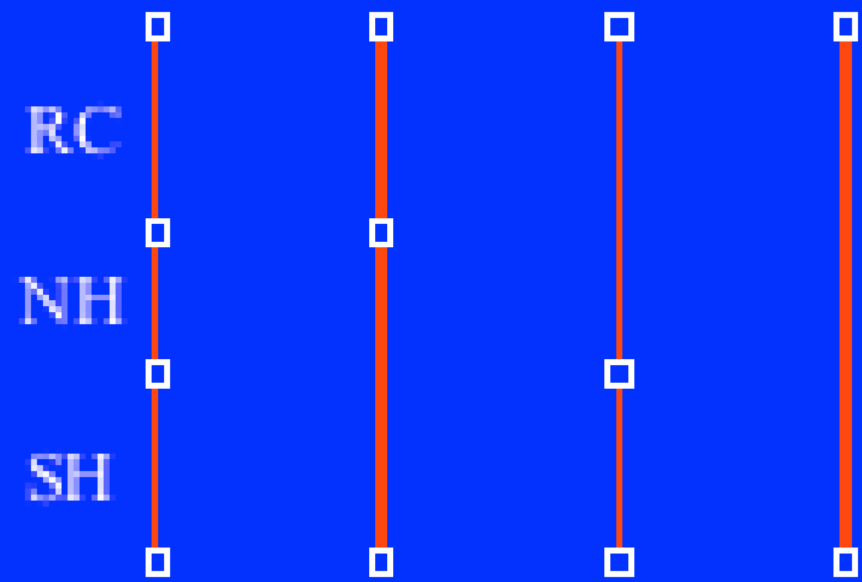
Changes in creep rate

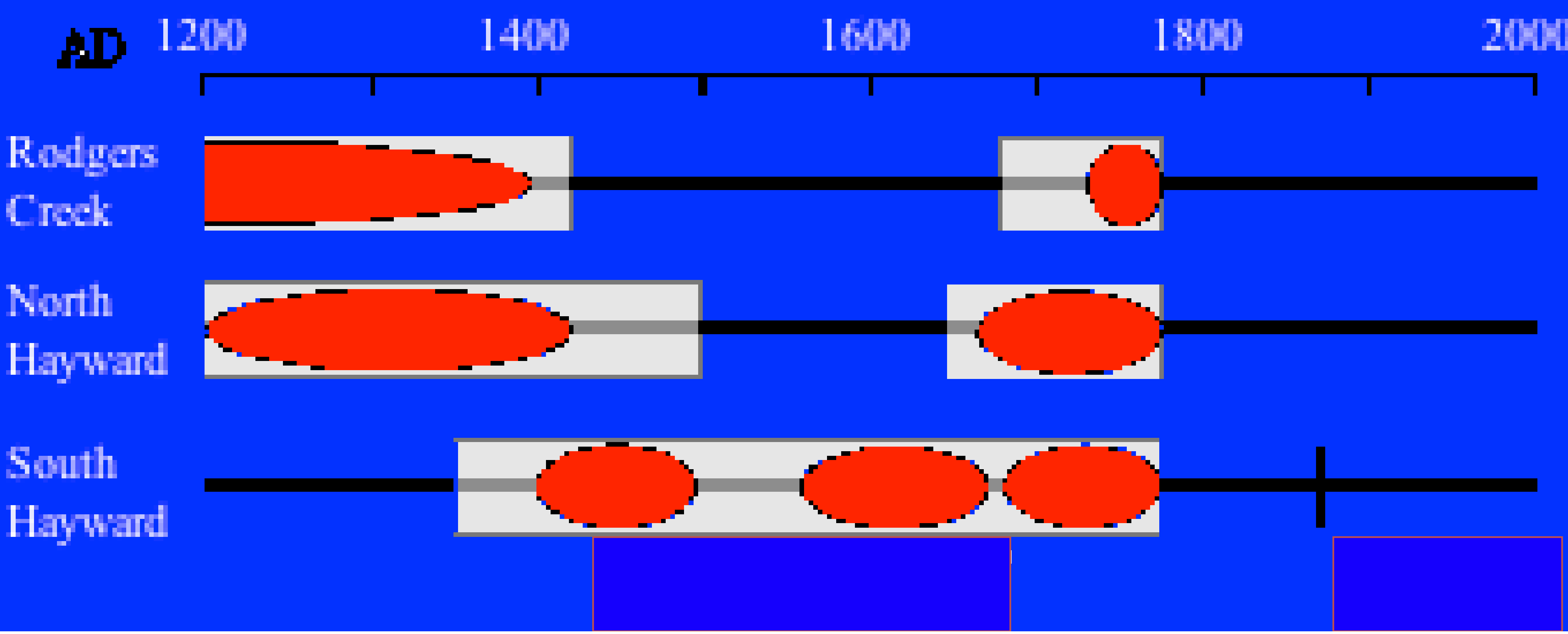
Major lithologic changes

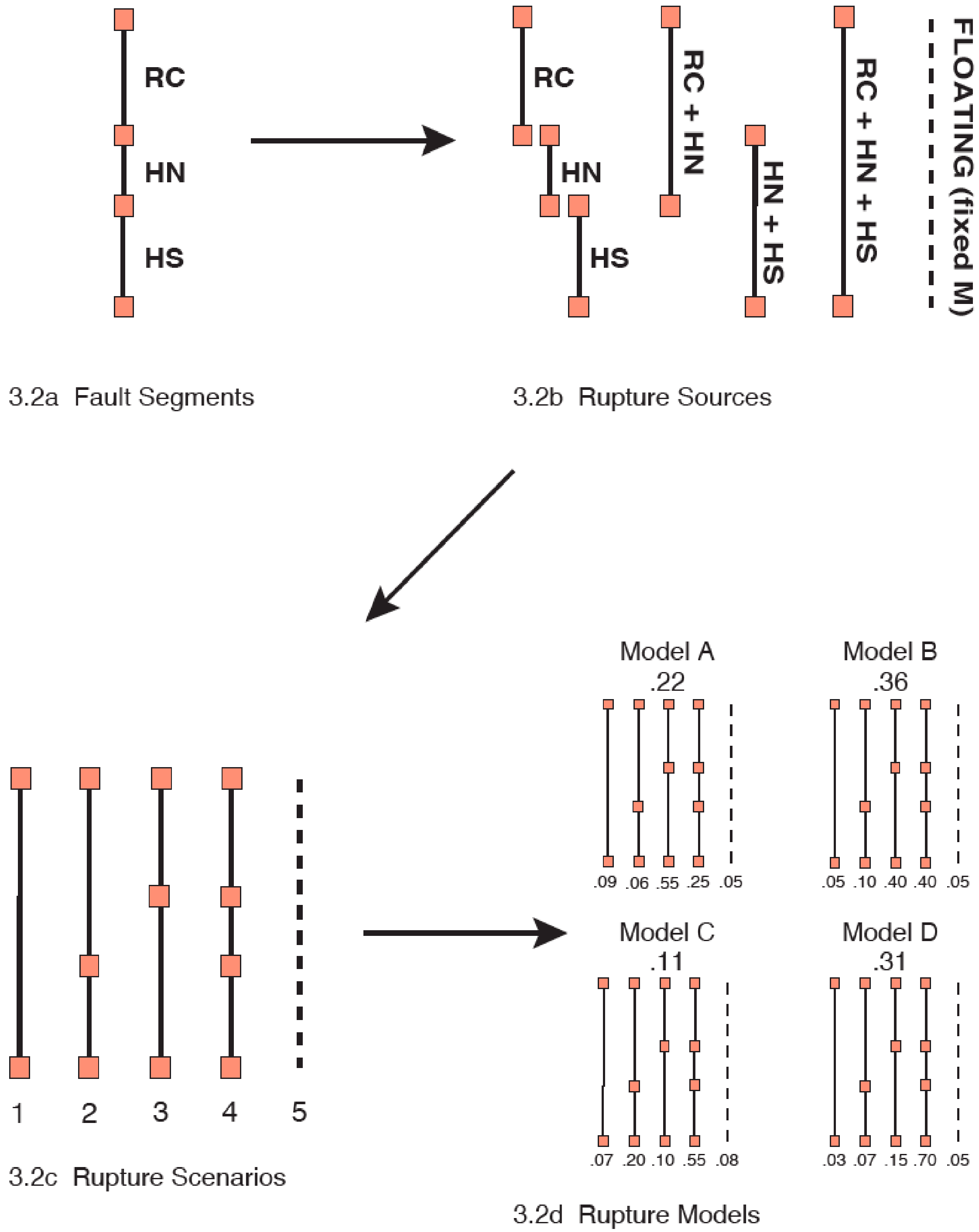


1868
6km step
24 mm/yr
17 mm/yr
WN
Santa Rosa
Rodgers
[RC]
BR
Creek F.
H37
NPR
NPH
MPR
MPH
San Pablo Bay
SPR
SPH
[HN]
Richmond
MV
Berkeley
Hayward Fault
MT
Oakland
MC
SL
[HS]
San Francisco
San Francisco Bay
Hayward
MH
TP
Fremont
AC
CR
AR
San Jose
Green Valley F.
Concord F.
MTD
Calaveras F.
Greenville F.
San Andreas F.
N
0
10
20
Kilometers

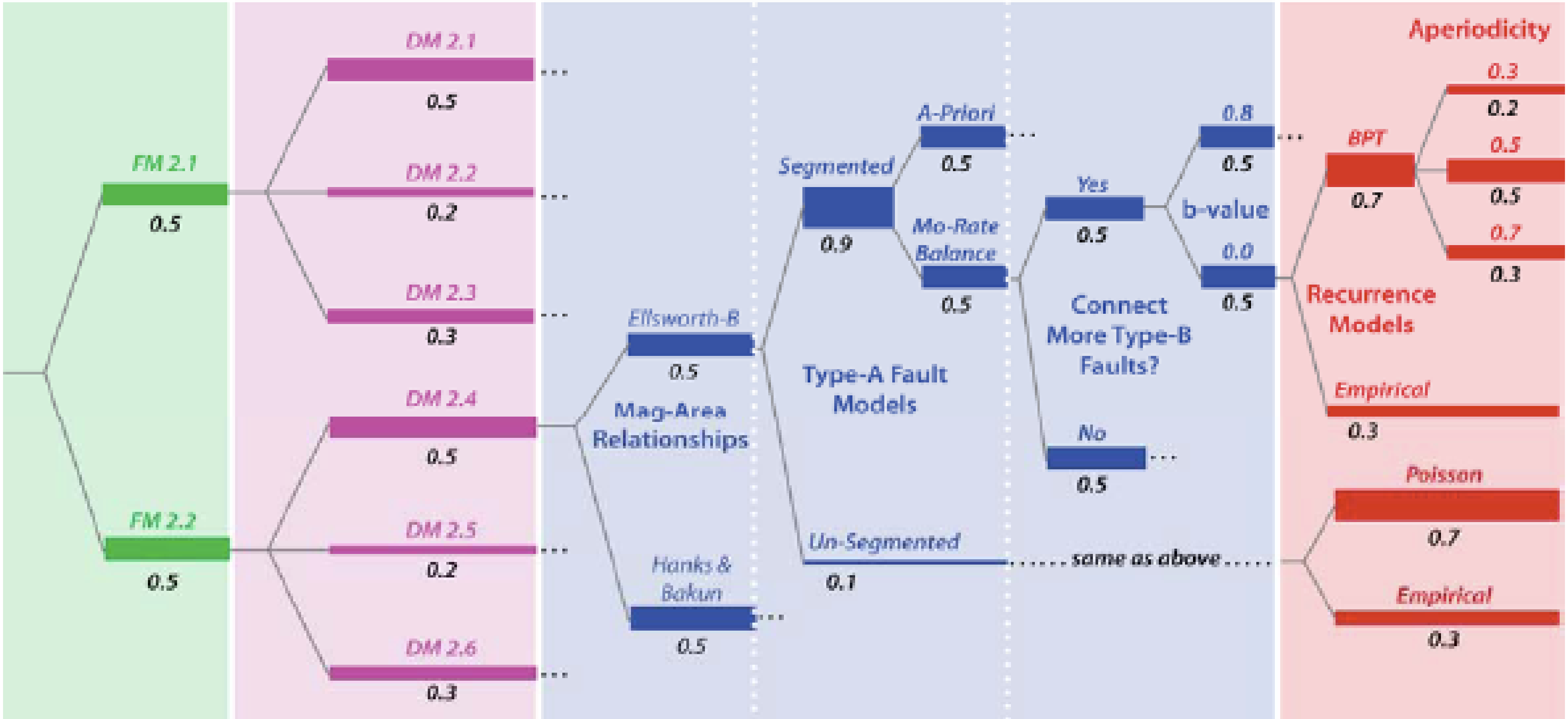
Paleoearthquake chronologies to evaluate possible rupture scenarios: Hayward-Rodgers Creek Fault Zone






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

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.

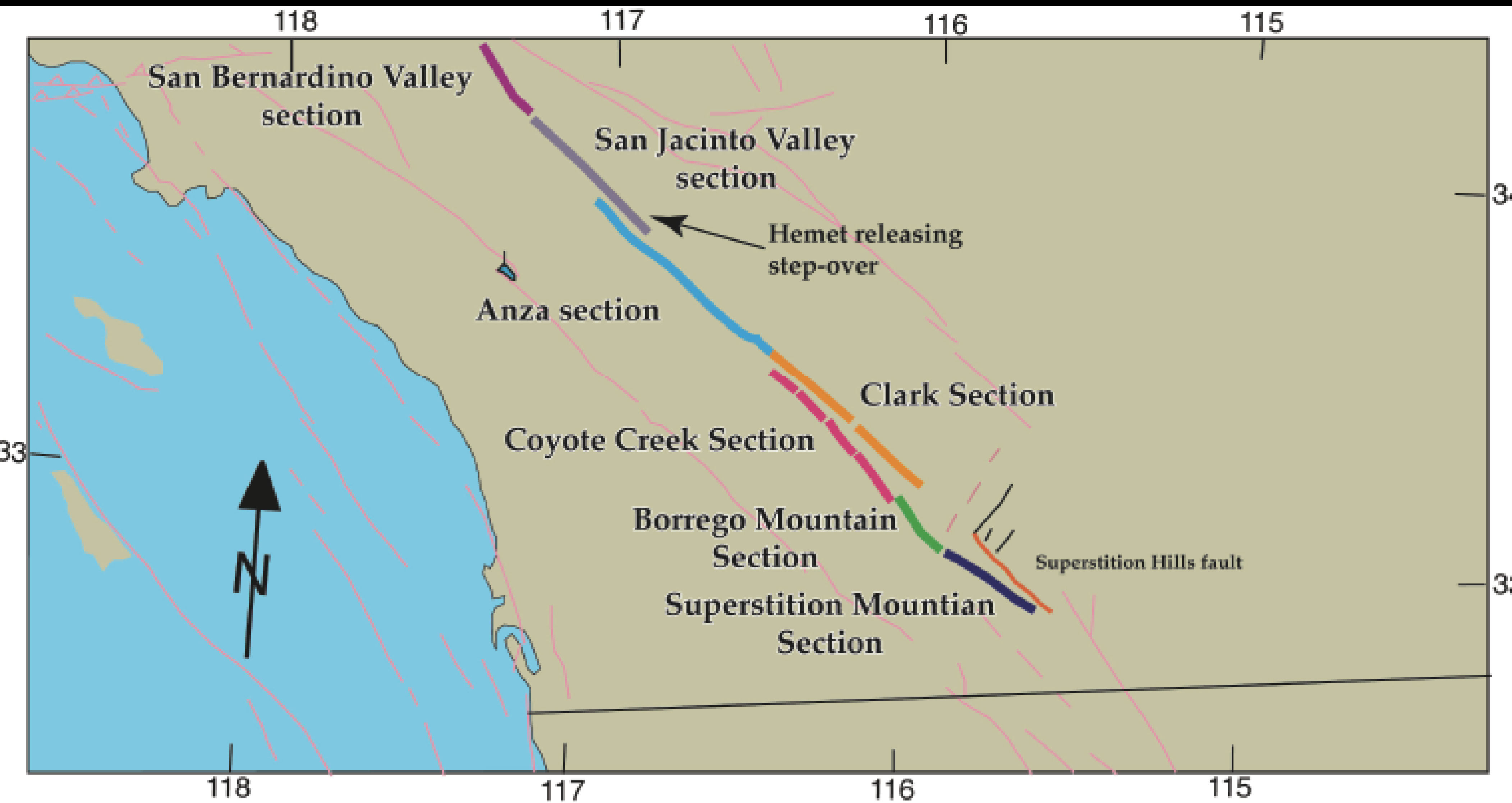


Figure 3. Location map for the San Jacinto fault showing fault sections and geometric discontinuities.

A-PRIORI MODELS: Consensus models developed by experts.

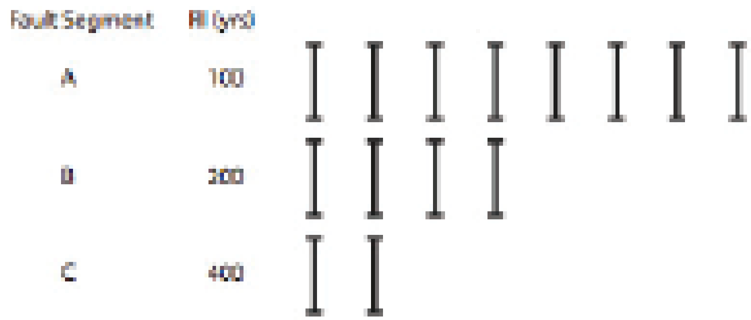
Geologic Insight Model: best estimate using all available data. Recurrence based on paleoseismic dates

Minimum Rate Model: Minimizes total rate of ruptures, longest rupture, increases M

Maximum Rate Model: Maximizes total rate of ruptures, all independent, decreases M

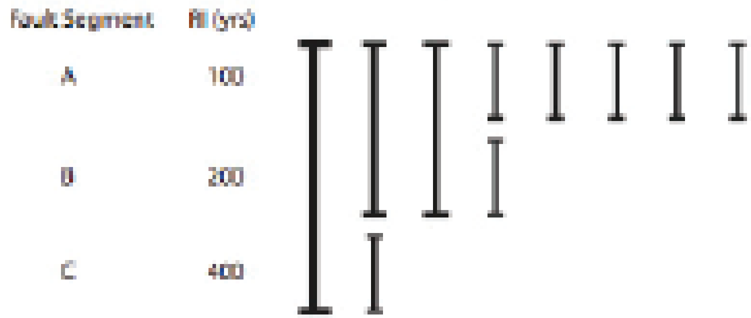
MOMENT BALANCED MODELS

Maximum earthquakes model: 14 events in 800 years



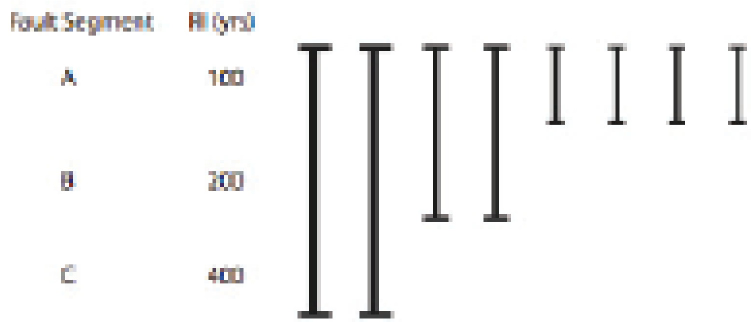
•The maximum earthquakes model is constructed by allowing all segments to slip independently.

Geologic insight model: 10 events in 800 years



• Segment B has large slip-per-event for the most recent event, so it is inferred that the rupture crossed over into adjacent segments A and C.
• Timing of events is indistinguishable for two events between segments A and B. Additionally, B has failed once during a period when A and C had no events. Based on event timing, segment C has also failed alone for one event.
• Segments A and B share a similar slip rate; however, small displacements per event of segment A suggest that it fails more frequently (five more earthquakes) than the adjacent segment B.

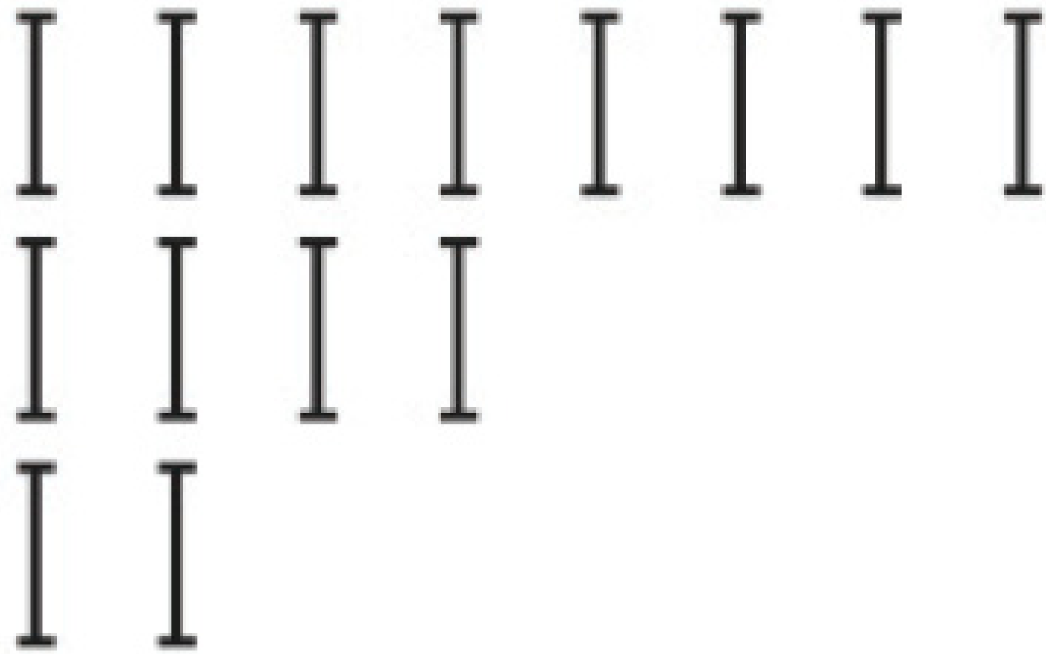
Minimum earthquakes model: 8 events in 800 years



•Minimum earthquakes model assigns as many paleo-earthquakes as possible to the longest possible rupture; in this case A+B+C; this covers all paleo-earthquakes on segment C. Next, as many paleo-earthquakes as possible are assign to the next largest rupture, A+B; this covers all paleo-earthquakes on segment B. Finally, the remainder must be only A.

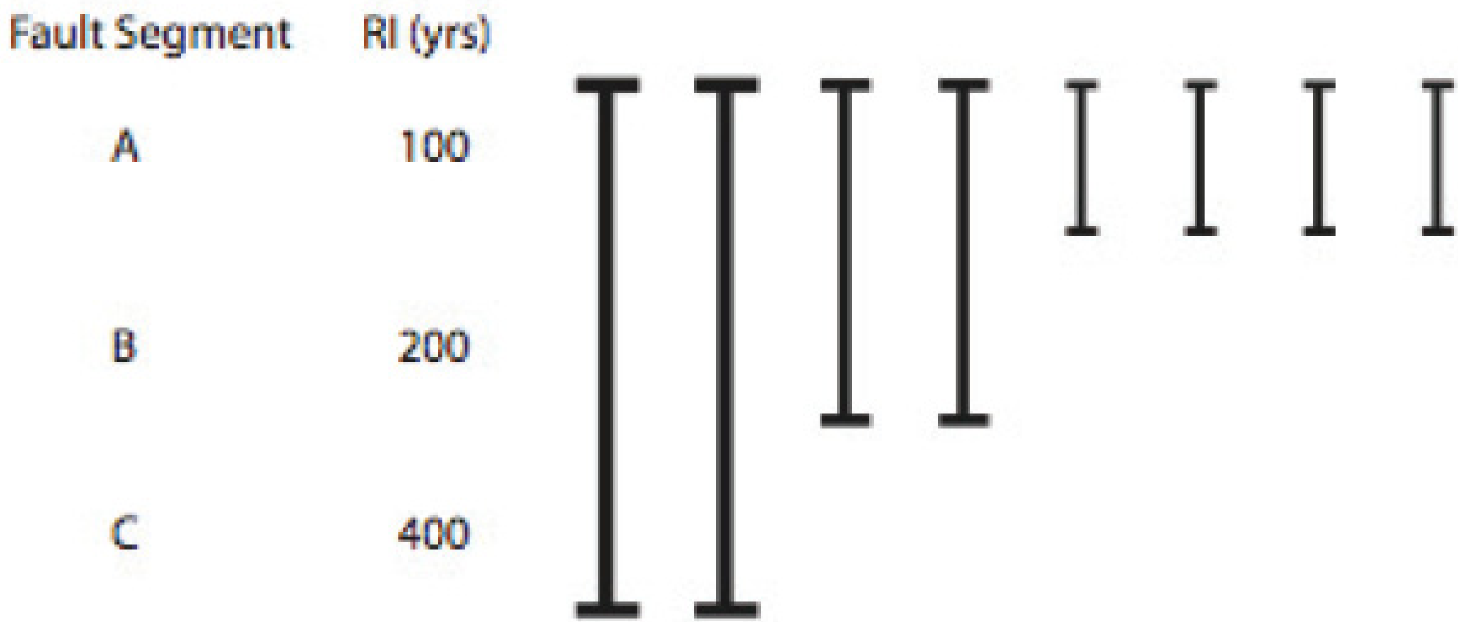
Maximum earthquakes model: 14 events in 800 years

Fault Segment	RI (yrs)
A	100
B	200
C	400



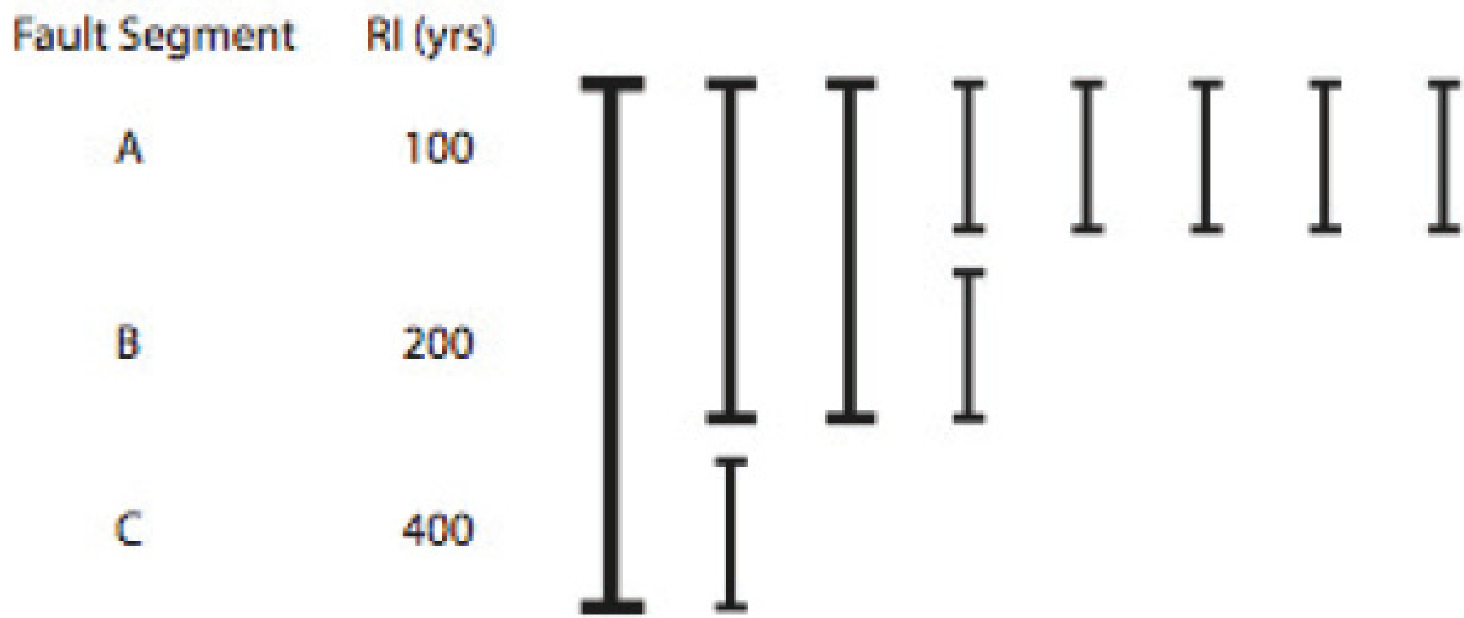
•The maximum earthquakes model is constructed by allowing all segments to slip independently.

Minimum earthquakes model: 8 events in 800 years

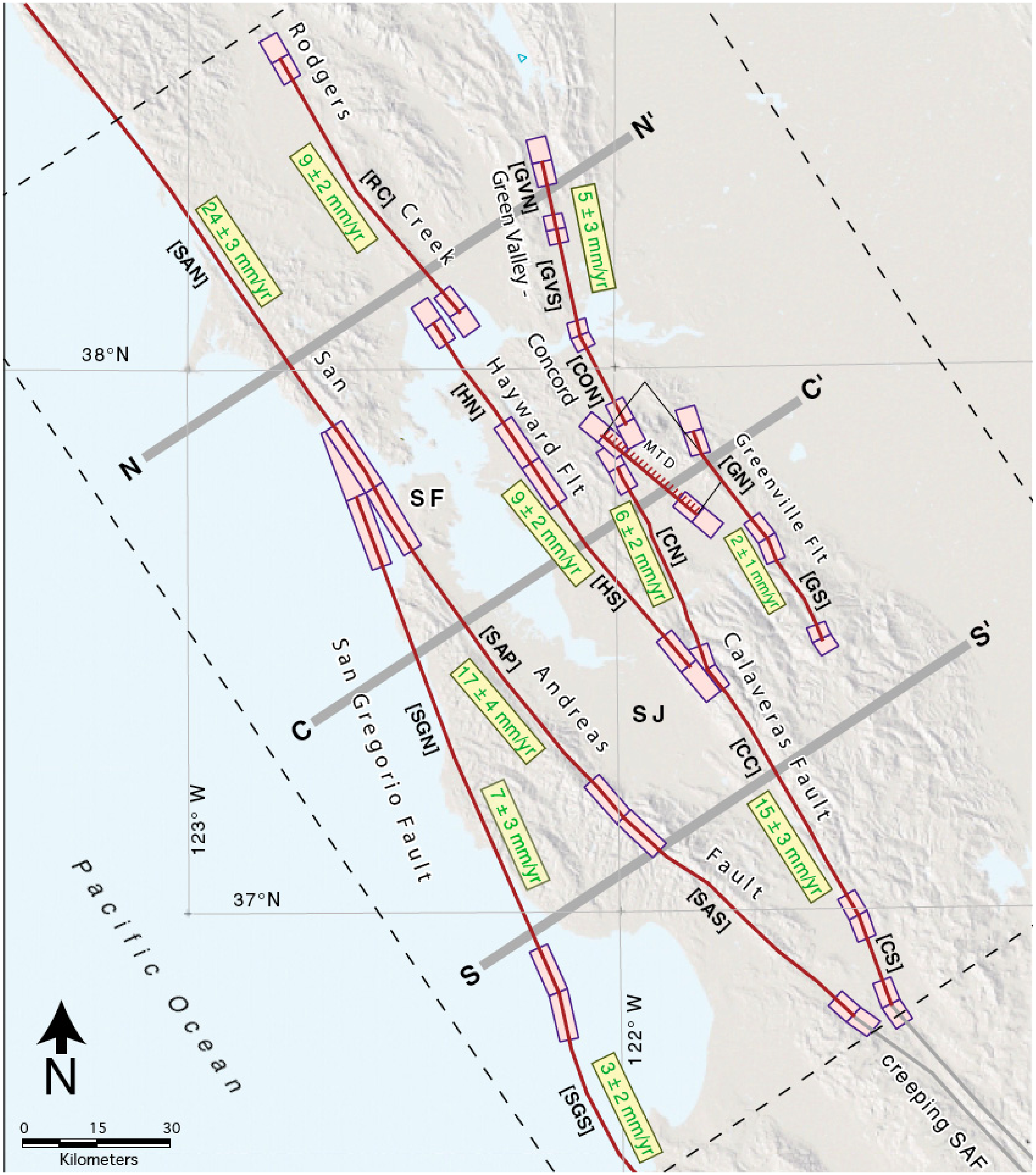


•Minimum earthquakes model assigns as many paleo-earthquakes as possible to the longest possible rupture; in this case A+B+C; this covers all paleo-earthquakes on segment C. Next, as many paleo-earthquakes as possible are assign to the next largest rupture, A+B; this covers all paleo-earthquakes on segment B. Finally, the remainder must be only A.

Geologic insight model: 10 events in 800 years

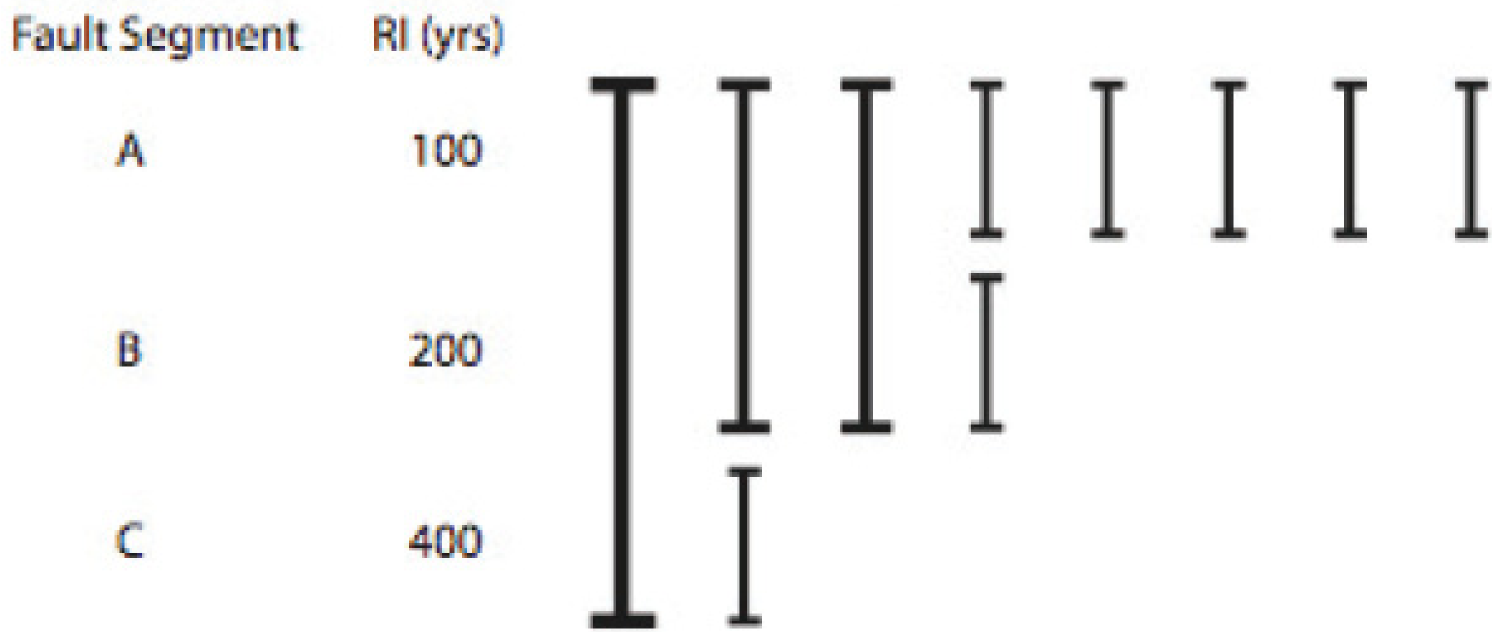


- Segment B has large slip-per-event for the most recent event, so it is inferred that the rupture crossed over into adjacent segments A and C.
- Timing of events is indistinguishable for two events between segments A and B. Additionally, B has failed once during a period when A and C had no events. Based on event timing, segment C has also failed alone for one event.
- Segments A and B share a similar slip rate; however, small displacements per event of segment A suggest that it fails more frequently (five more earthquakes) than the adjacent segment B.

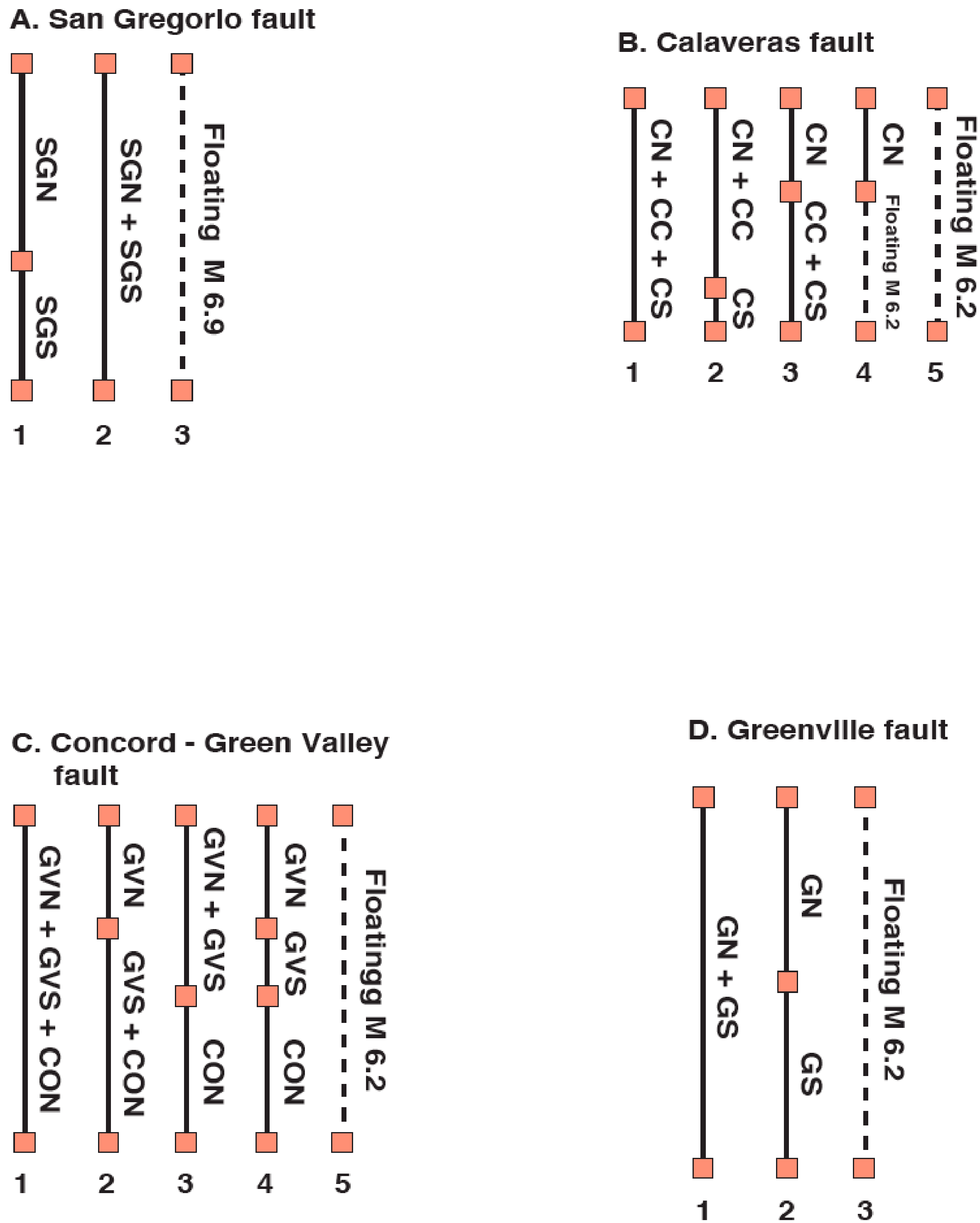


Rodgers
[RC] Creek
9 ± 2 mm/yr
[GVN]
Green Valley -
[GVS]
5 ± 3 mm/yr
N'
N
[SAN]
24 ± 3 mm/yr
38°N
San
Concord
[CON]
[HN]
Hayward Flt
MTD
Greenville Flt
[GN]
C'
SF
9 ± 2 mm/yr
6 ± 2 mm/yr
[CN]
2 ± 1 mm/yr
[GS]
[HS]
S'
San Gregorio Fault
[SAP]
Andreas
17 ± 4 mm/yr
SJ
Calaveras Fault
C
[SGN]
[CC]
123° W
7 ± 3 mm/yr
15 ± 3 mm/yr
Fault
37°N
[SAS]
[CS]
S
Pacific Ocean
122° W
N
3 ± 2 mm/yr
[SGS]
creeping SAF
0 15 30
Kilometers

Geologic insight model: 10 events in 800 years



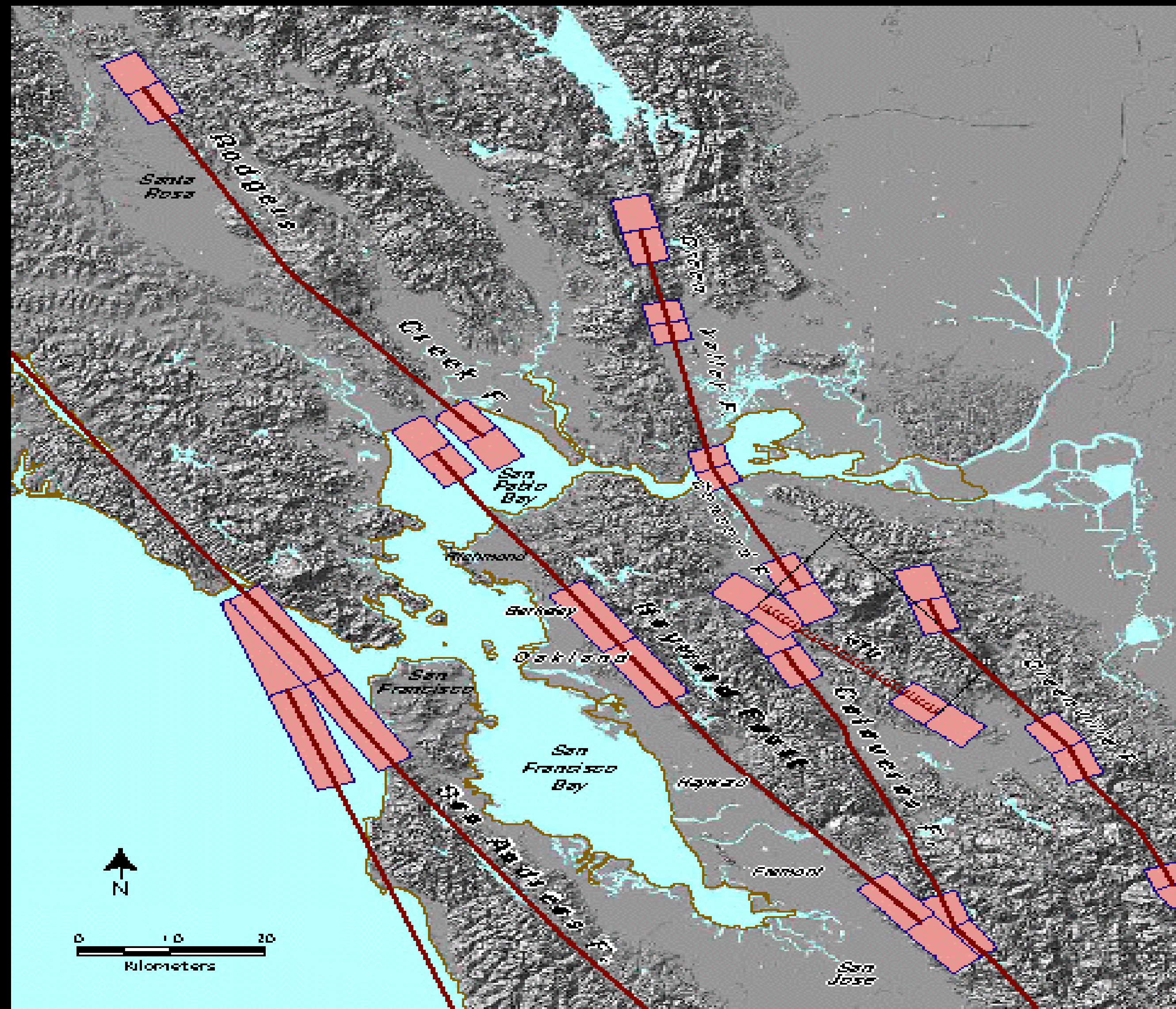
• Segment B has large slip-per-event for the most recent event, so it is inferred that the rupture crossed over into adjacent segments A and C.
• Timing of events is indistinguishable for two events between segments A and B. Additionally, B has failed once during a period when A and C had no events. Based on event timing, segment C has also failed alone for one event.
• Segments A and B share a similar slip rate; however, small displacements per event of segment A suggest that it fails more frequently (five more earthquakes) than the adjacent segment B.


A. San Gregorio fault
SGN
SGS
SGN + SGS
Floating M 6.9
1
2
3
B. Calaveras fault
CN + CC + CS
CN + CC
CS
CN
CC + CS
CN
Floating M 6.2
Floating M 6.2
1
2
3
4
5
C. Concord - Green Valley fault
GVN + GVS + CON
GVN
GVS + CON
GVN + GVS
CON
GVN
GVS
CON
Floatingg M 6.2
1
2
3
4
5
D. Greenville fault
GN + GS
GN
GS
Floating M 6.2
1
2
3

Magnitude of Paleoearthquakes

Paleo-offset

Fault segment area



WG 02 characterization

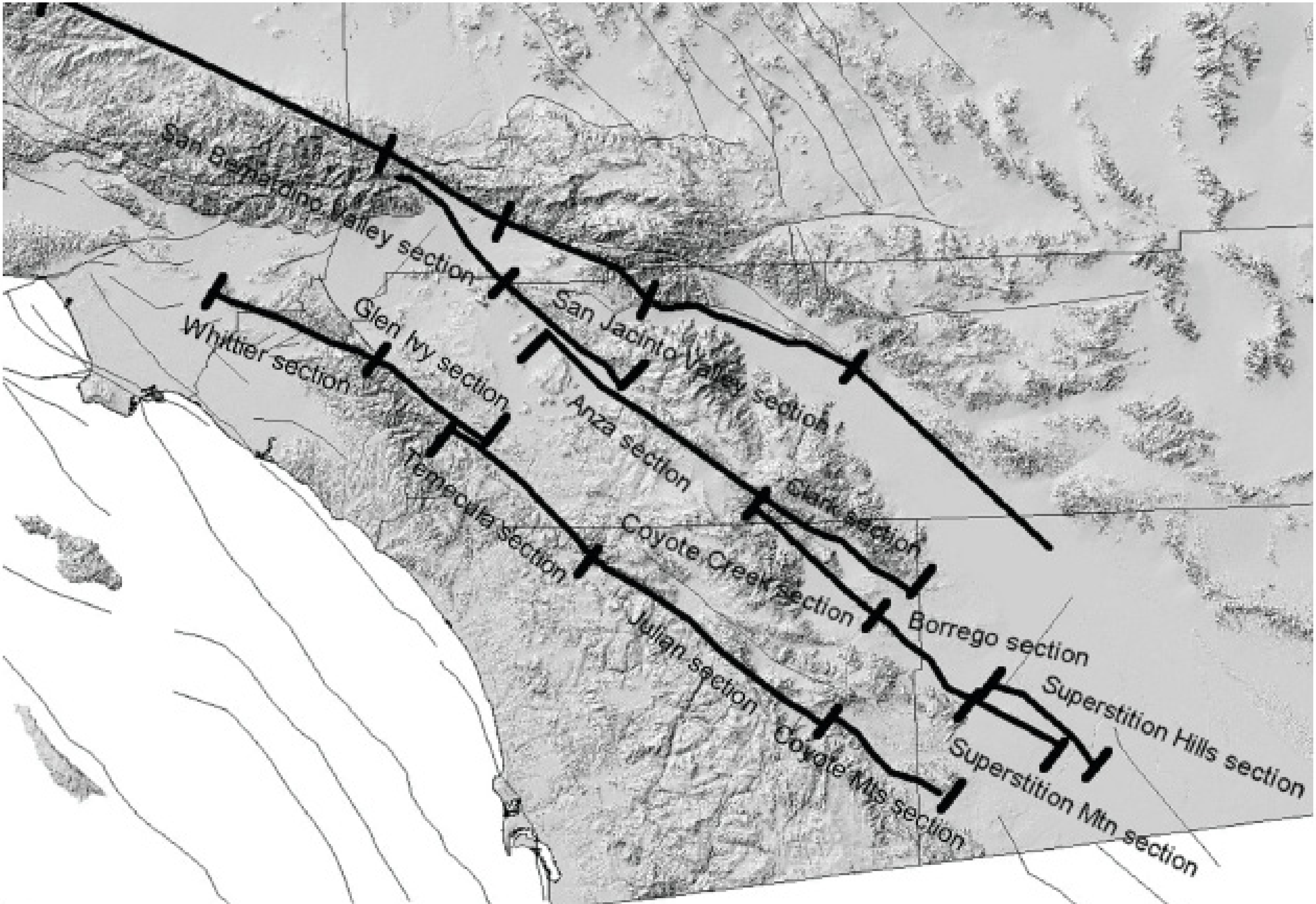


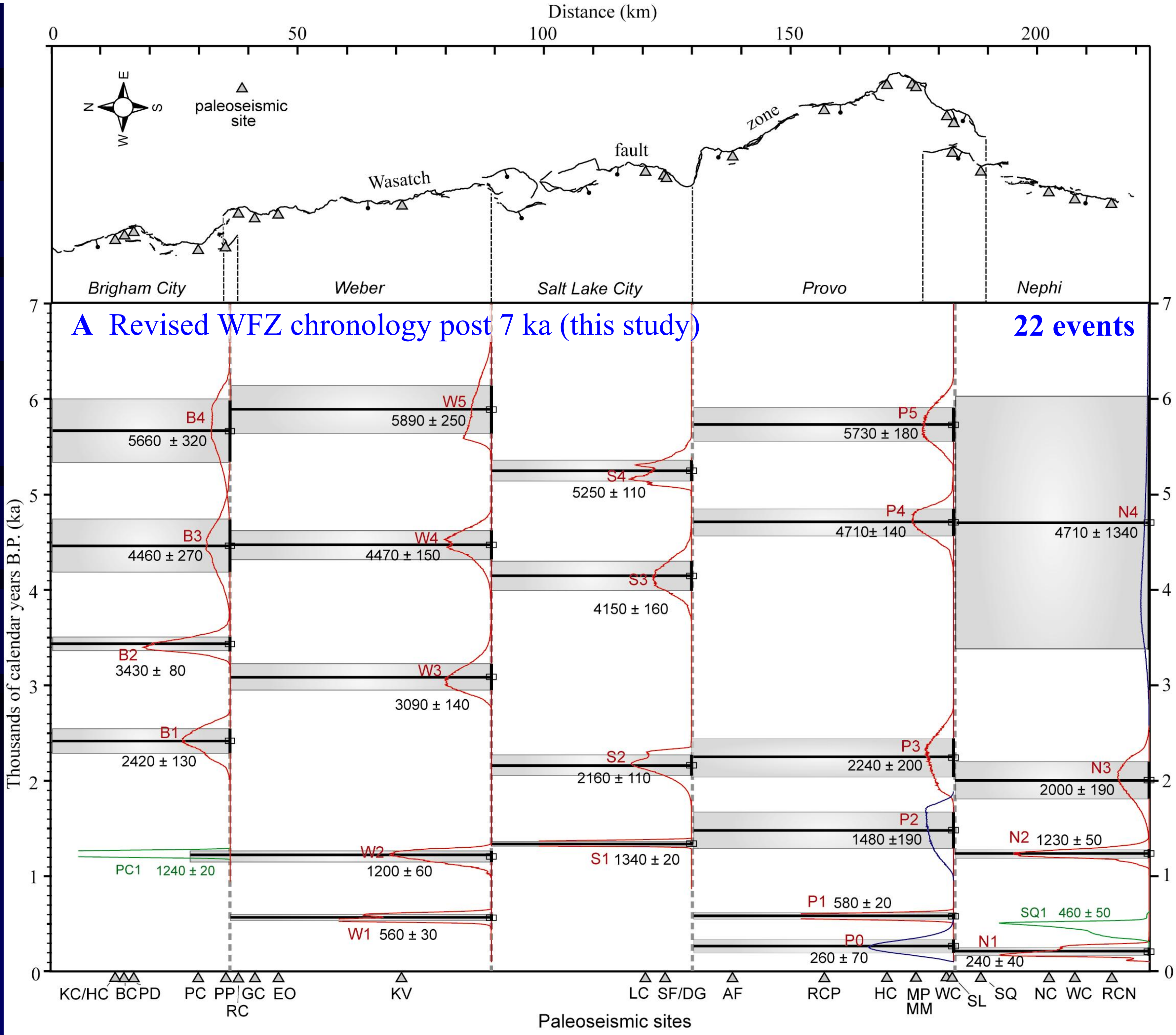
Figure 2, The Elsinore and San Jacinto faults, note the overlap between the Glen Ivy and Temecula sections of the Elsinore fault and the San Jacinto Valley and Anza sections of the San Jacinto fault. In these areas, separate sections are defined with one-half the slip rate of the adjoining sections.

Straw man rupture scenarios for the WFZ

Chris DuRoss (UGS)

David Schwartz (USGS)

Working Group on Utah Earthquake Probabilities, July, 2010



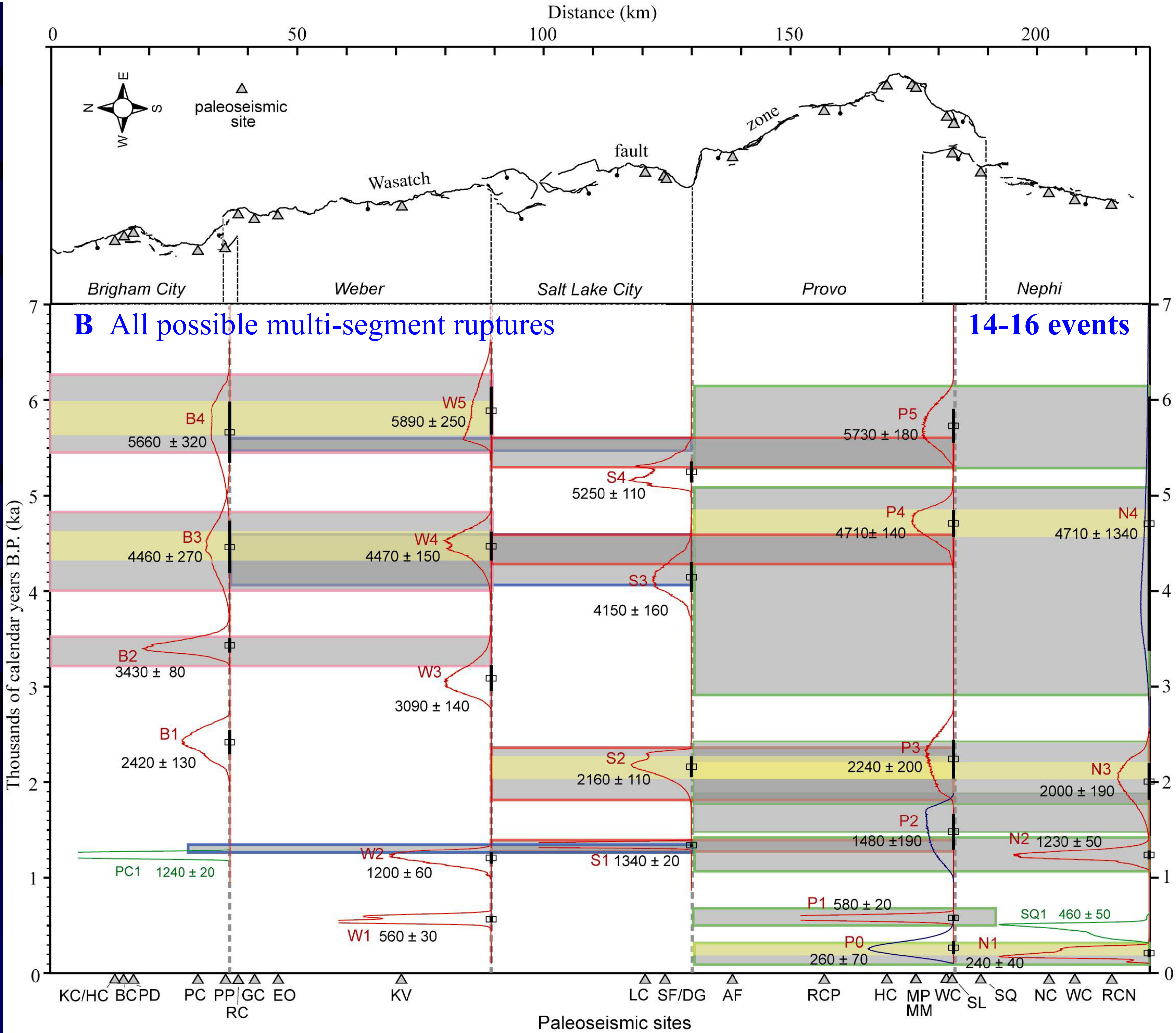
Distance (km)
0
50
100
150
200
paleoseismic site
Wasatch
fault
zone
Brigham City
Weber
Salt Lake City
Provo
Nephi
A Revised WFZ chronology post 7 ka (this study)
22 events
Thousands of calendar years B.P. (ka)
B4
5660 ± 320
B3
4460 ± 270
B2
3430 ± 80
B1
2420 ± 130
PC1 1240 ± 20
W5
5890 ± 250
W4
4470 ± 150
W3
3090 ± 140
W2
1200 ± 60
W1 560 ± 30
S4
5250 ± 110
S3
4150 ± 160
S2
2160 ± 110
S1 1340 ± 20
P5
5730 ± 180
P4
4710± 140
P3
2240 ± 200
P2
1480 ±190
P1 580 ± 20
P0
260 ± 70
N4
4710 ± 1340
N3
2000 ± 190
N2 1230 ± 50
SQ1 460 ± 50
N1
240 ± 40
KC/HC BC PD PC PP GC EO RC KV LC SF/DG AF RCP HC MP MM WC SL SQ NC WC RCN
Paleoseismic sites

Straw man rupture scenarios

Rupture	A (single)
BCS	4
WS	5
SLCS	4
PS	5**
NS	4
BCS+WS	0
WS+SLCS	0
SLCS+PS	0
PS+NS	0
Recurrence rate	22/6.3 ky*
Mean recurrence	300 yr

A: single segment

* 6.3 ky = WS5+2σ (6.4 ka) minus NS1–2σ (0.1 ka) ** Excluding P0

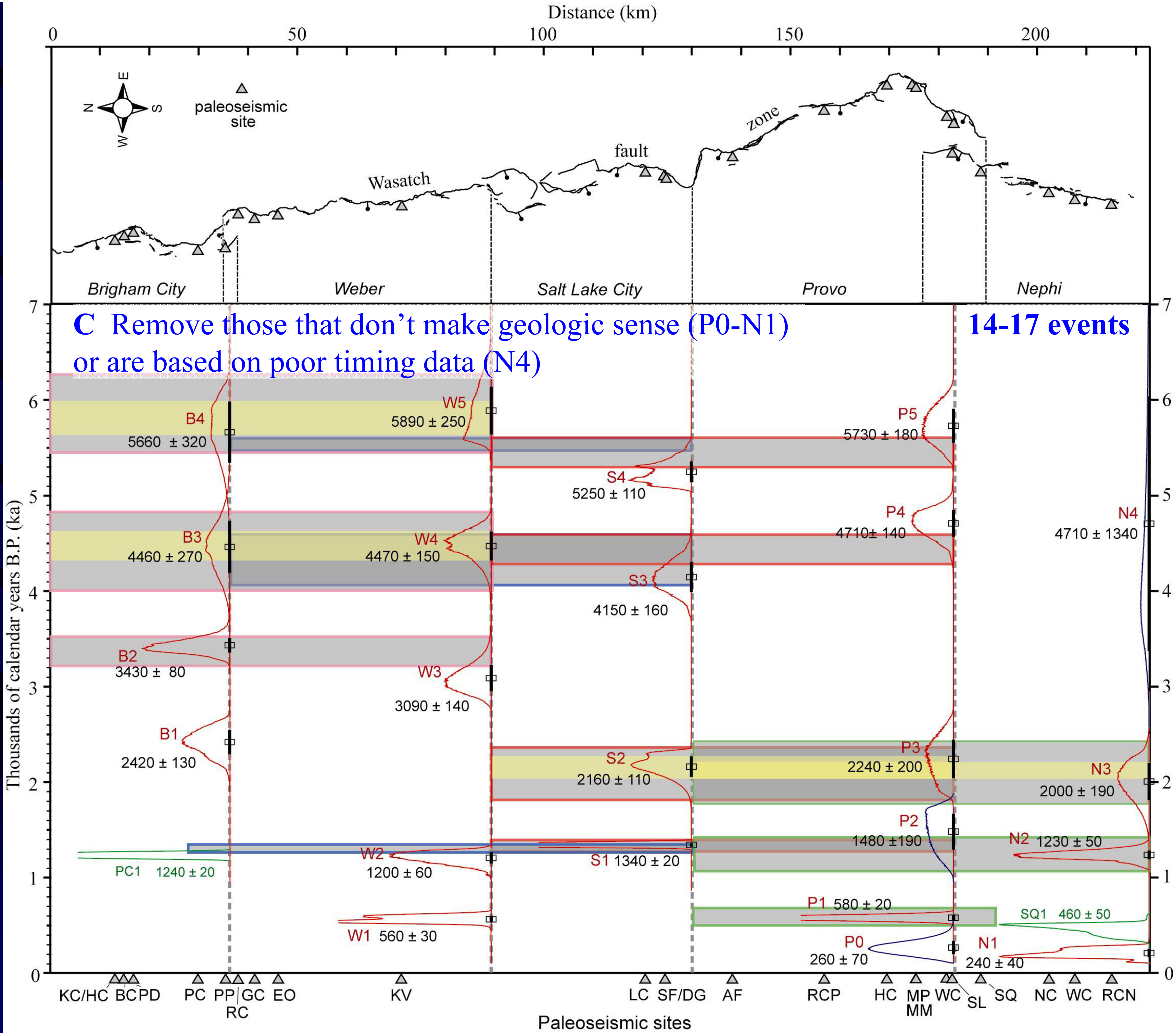

Distance (km)
0
50
100
150
200
paleoseismic site
Wasatch
fault
zone
Brigham City
Weber
Salt Lake City
Provo
Nephi
B All possible multi-segment ruptures
14-16 events
Thousands of calendar years B.P. (ka)
B4
5660 ± 320
W5
5890 ± 250
P5
5730 ± 180
S4
5250 ± 110
B3
4460 ± 270
W4
4470 ± 150
P4
4710± 140
N4
4710 ± 1340
S3
4150 ± 160
B2
3430 ± 80
W3
3090 ± 140
B1
2420 ± 130
S2
2160 ± 110
P3
2240 ± 200
N3
2000 ± 190
P2
1480 ±190
N2 1230 ± 50
PC1 1240 ± 20
W2
1200 ± 60
S1 1340 ± 20
P1 580 ± 20
SQ1 460 ± 50
W1 560 ± 30
P0
260 ± 70
N1
240 ± 40
KC/HC BC PD
PC
PP RC
GC
EO
KV
LC
SF/DG
AF
RCP
HC
MP MM
WC
SL
SQ
NC
WC
RCN
Paleoseismic sites

Straw man rupture scenarios

Rupture	A (single)	B (max)
BCS	4	1-3
WS	5	1-2
SLCS	4	0-3
PS	5**	1
NS	4	0
BCS+WS	0	1-3
WS+SLCS	0	1-3
SLCS+PS	0	0-4
PS+NS	0	1-4
Recurrence rate	22/6.3 ky*	14-16/6.3 ky
Mean recurrence	300 yr	420-480 yr

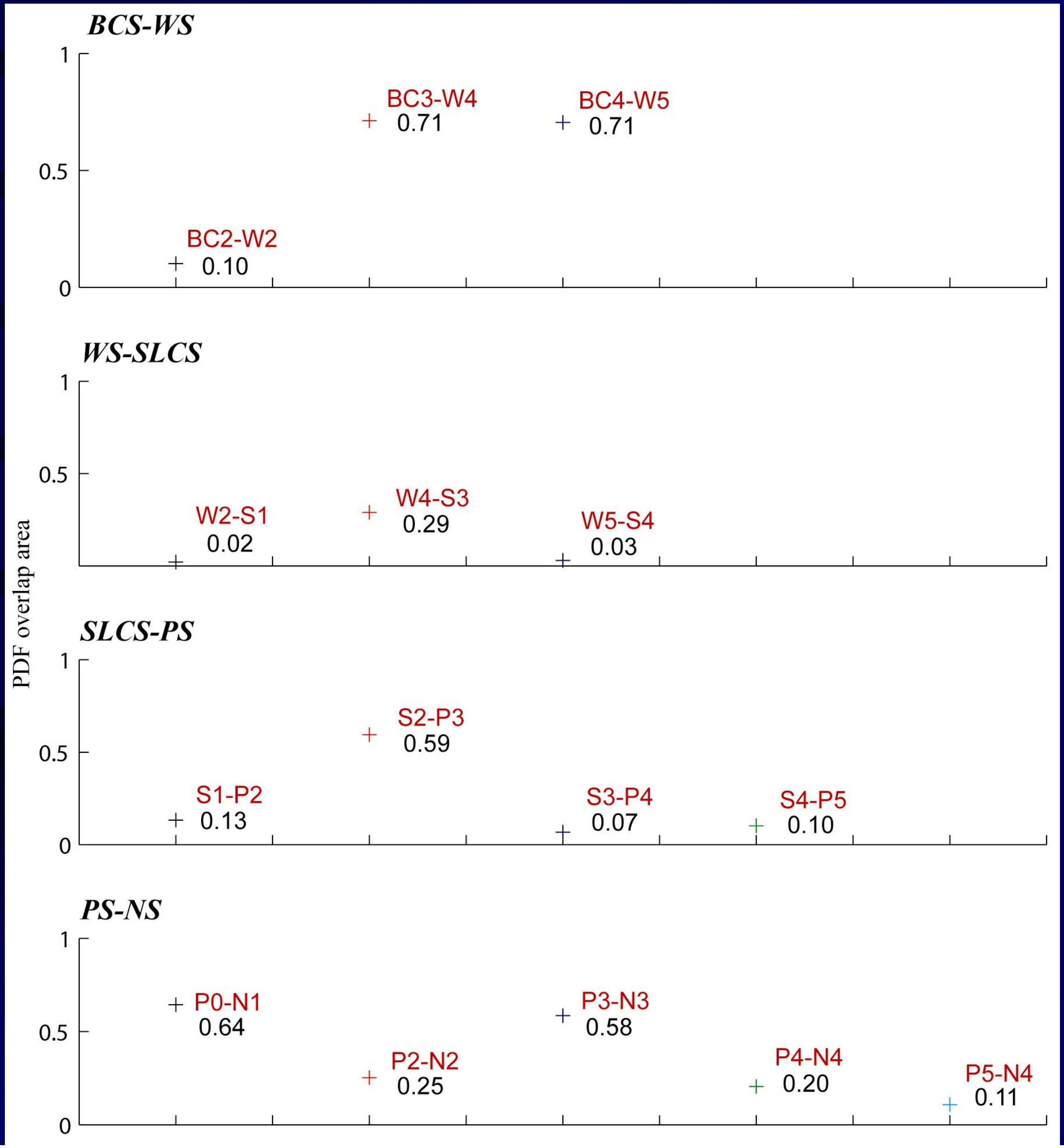
A: single segment, B: maximum MSRs

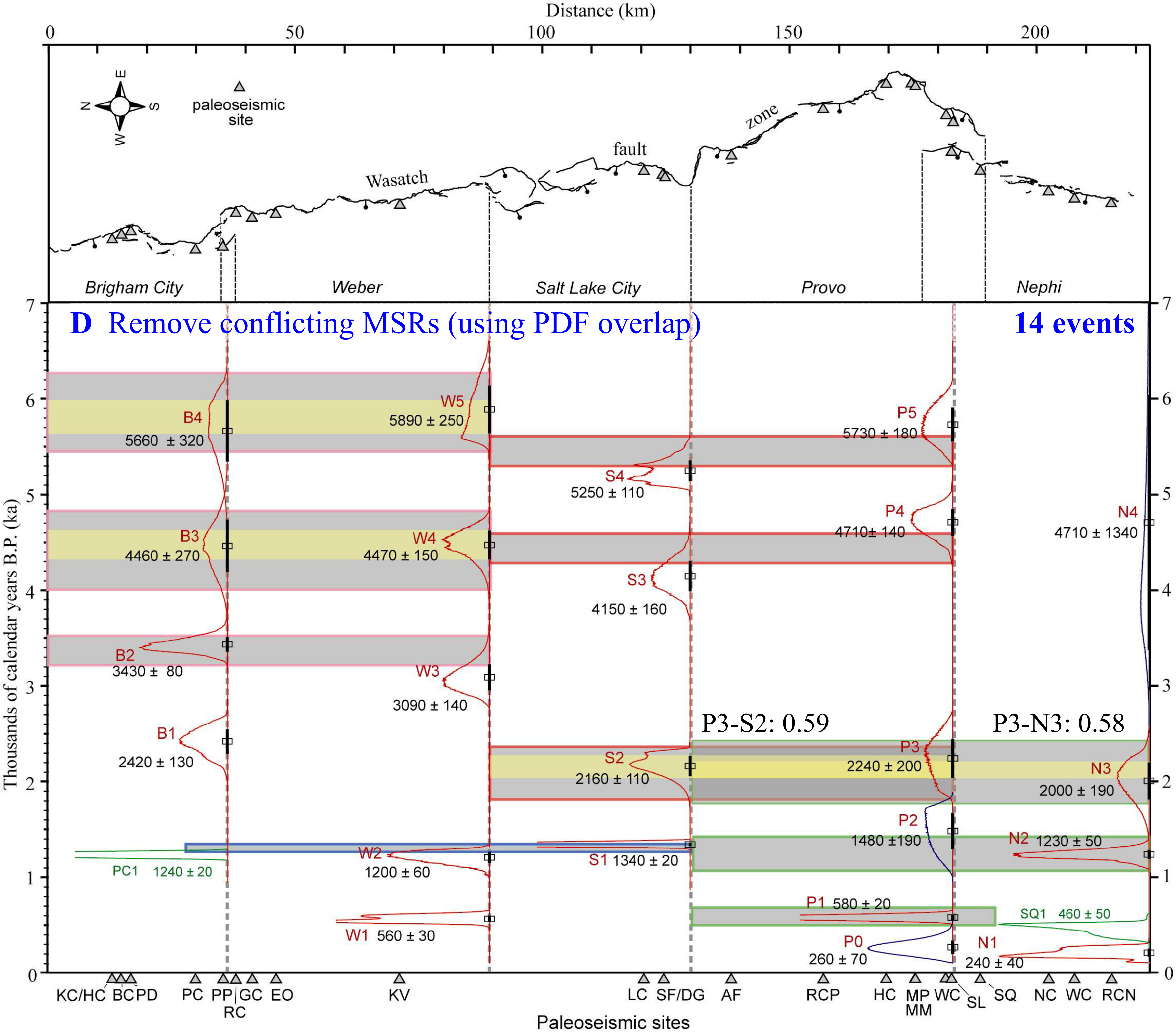
* 6.3 ky = WS5+2σ (6.4 ka) minus NS1–2σ (0.1 ka)   ** Excluding P0



C Remove those that don't make geologic sense (P0-N1) or are based on poor timing data (N4)
14-17 events
Distance (km)
paleoseismic site
Wasatch fault zone
Brigham City
Weber
Salt Lake City
Provo
Nephi
Thousands of calendar years B.P. (ka)
B4 5660 ± 320
B3 4460 ± 270
B2 3430 ± 80
B1 2420 ± 130
PC1 1240 ± 20
W5 5890 ± 250
W4 4470 ± 150
W3 3090 ± 140
W2 1200 ± 60
W1 560 ± 30
S4 5250 ± 110
S3 4150 ± 160
S2 2160 ± 110
S1 1340 ± 20
P5 5730 ± 180
P4 4710± 140
P3 2240 ± 200
P2 1480 ±190
P1 580 ± 20
P0 260 ± 70
N4 4710 ± 1340
N3 2000 ± 190
N2 1230 ± 50
N1 240 ± 40
SQ1 460 ± 50
KC/HC BC PD PC PP RC GC EO KV LC SF/DG AF RCP HC MP MM WC SL SQ NC WC RCN
Paleoseismic sites

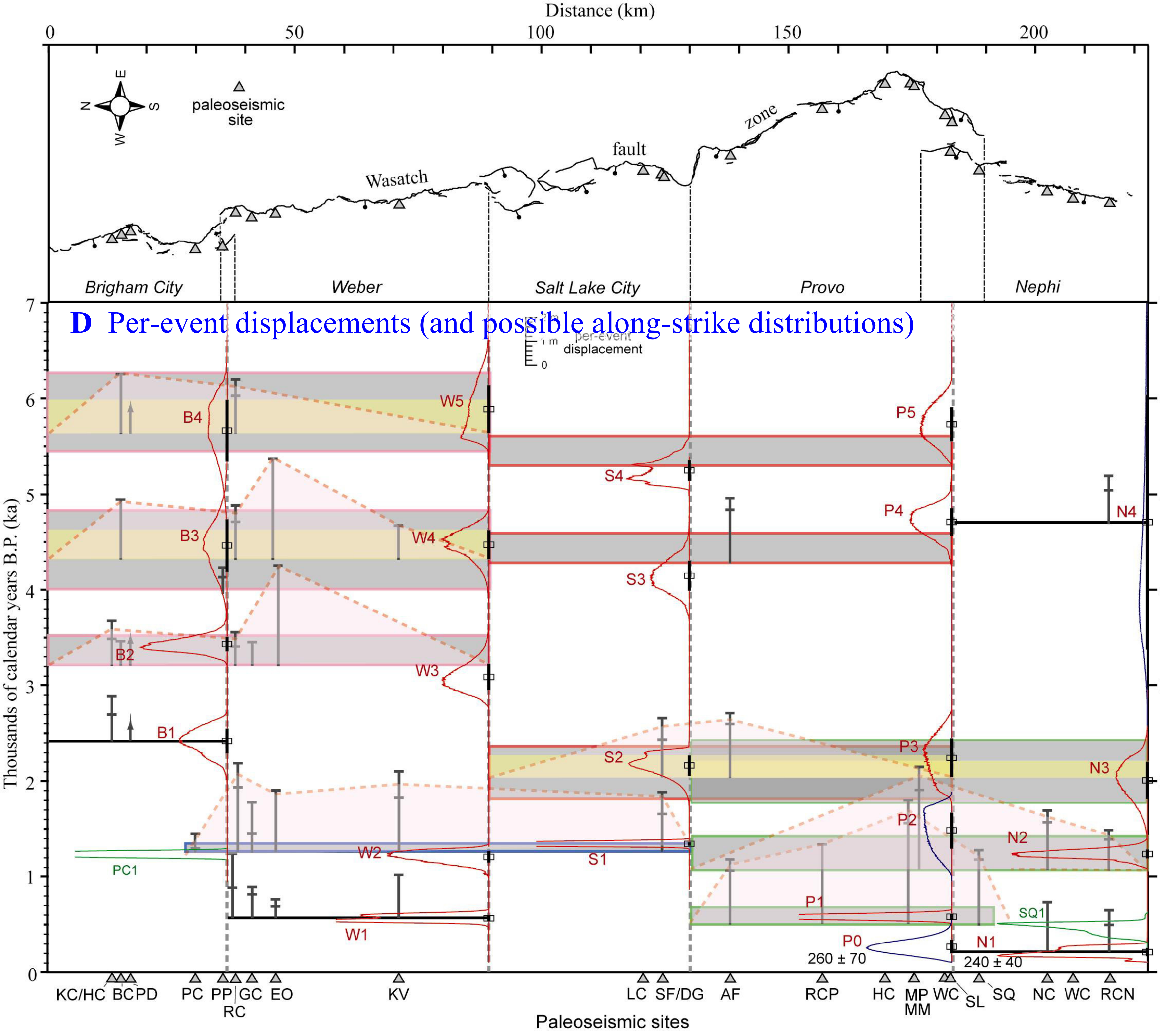
Overlap in MSR PDF pairs

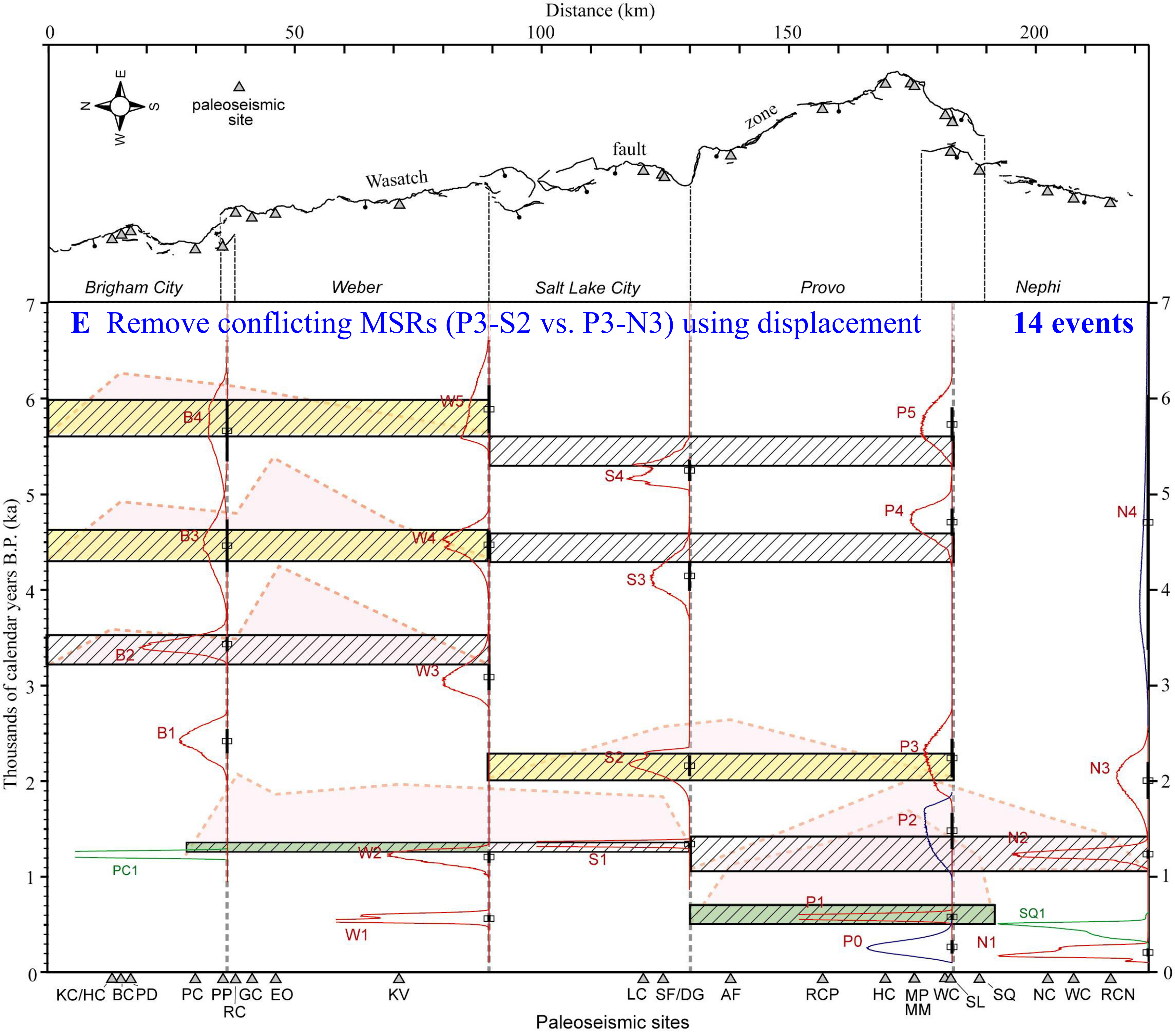




Distance (km)
D Remove conflicting MSRs (using PDF overlap)
14 events
paleoseismic site
Wasatch fault zone
Brigham City
Weber
Salt Lake City
Provo
Nephi
Thousands of calendar years B.P. (ka)
B4 5660 ± 320
W5 5890 ± 250
P5 5730 ± 180
S4 5250 ± 110
B3 4460 ± 270
W4 4470 ± 150
P4 4710± 140
N4 4710 ± 1340
S3 4150 ± 160
B2 3430 ± 80
W3 3090 ± 140
B1 2420 ± 130
P3-S2: 0.59
P3-N3: 0.58
S2 2160 ± 110
P3 2240 ± 200
N3 2000 ± 190
P2 1480 ±190
N2 1230 ± 50
PC1 1240 ± 20
W2 1200 ± 60
S1 1340 ± 20
P1 580 ± 20
SQ1 460 ± 50
W1 560 ± 30
P0 260 ± 70
N1 240 ± 40
KC/HC BC PD PC PP RC GC EO KV LC SF/DG AF RCP HC MP MM WC SL SQ NC WC RCN
Paleoseismic sites

D Per-event displacements (and possible along-strike distributions)





Distance (km)
0
50
100
150
200
paleoseismic site
Wasatch
fault
zone
Brigham City
Weber
Salt Lake City
Provo
Nephi
E Remove conflicting MSRs (P3-S2 vs. P3-N3) using displacement
14 events
Thousands of calendar years B.P. (ka)
B4
B3
B2
B1
PC1
W5
W4
W3
W2
W1
S4
S3
S2
S1
P5
P4
P3
P2
P1
P0
N4
N3
N2
N1
SQ1
KC/HC
BC
PD
PC
PP
RC
GC
EO
KV
LC
SF/DG
AF
RCP
HC
MP
MM
WC
SL
SQ
NC
WC
RCN
Paleoseismic sites

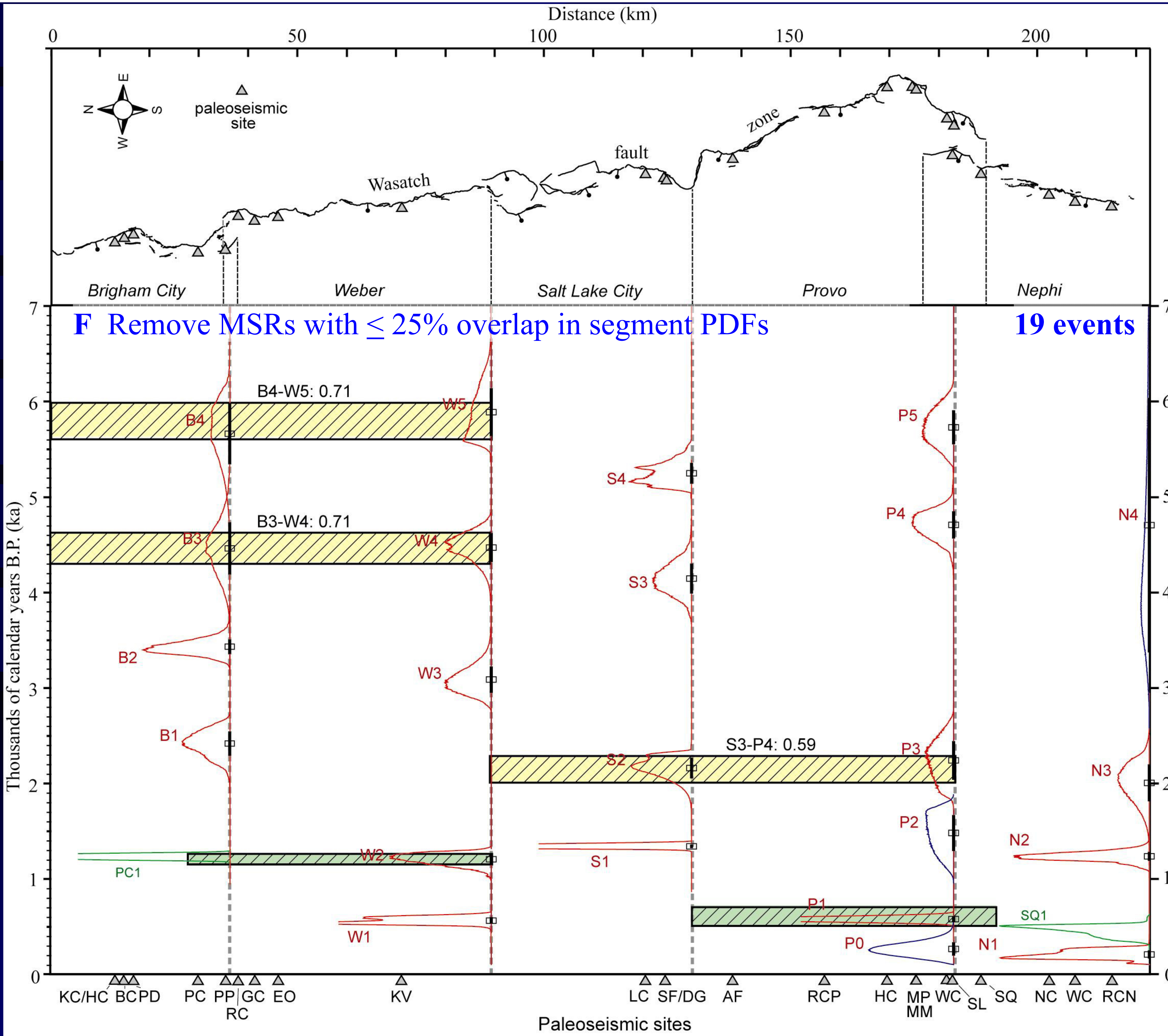
Straw man rupture scenarios

Rupture	A (single)	B (max)	C–E (steps)
BCS	4	1-3	1-3
WS	5	1-2	1-2
SLCS	4	0-3	0-1
PS	5**	1	1-3
NS	4	0	1-4
BCS+WS	0	1-3	1-3
WS+SLCS	0	1-3	1-3
SLCS+PS	0	0-4	0-4
PS+NS	0	1-4	0-2
Recurrence rate	22/6.3 ky*	14-16/6.3 ky	14-17/6.3 ky
Mean recurrence	300 yr	420-480 yr	390-480 yr

A: single segment, B: maximum MSRs

C–E: geologic sense/conflict resolution (PDF/displacement)

* 6.3 ky = WS5+2σ (6.4 ka) minus NS1–2σ (0.1 ka)   ** Excluding P0



Distance (km)
0
50
100
150
200
paleoseismic site
Wasatch
fault
zone
Brigham City
Weber
Salt Lake City
Provo
Nephi
F Remove MSRs with ≤ 25% overlap in segment PDFs
19 events
B4-W5: 0.71
B3-W4: 0.71
S3-P4: 0.59
B4
W5
B3
W4
B2
W3
B1
S4
S3
S2
S1
P5
P4
P3
P2
P1
P0
N4
N3
N2
N1
SQ1
PC1
W2
W1
Thousands of calendar years B.P. (ka)
KC/HC
BC
PD
PC
PP
GC
RC
EO
KV
LC
SF/DG
AF
RCP
HC
MP
MM
WC
SL
SQ
NC
WC
RCN
Paleoseismic sites

Straw man rupture scenarios

Rupture	A (single)	B (max)	C–E (steps)	F (>25% overlap)
BCS	4	1-3	1-3	2
WS	5	1-2	1-2	2
SLCS	4	0-3	0-1	3
PS	5**	1	1-3	3
NS	4	0	1-4	4
BCS+WS	0	1-3	1-3	2
WS+SLCS	0	1-3	1-3	0
SLCS+PS	0	0-4	0-4	1
PS+NS	0	1-4	0-2	0
Recurrence rate	22/6.3 ky*	14-16/6.3 ky	14-17/6.3 ky	19/6.3 ky
Mean recurrence	300 yr	420-480 yr	390-480 yr	350 yr

A: single segment, B: maximum MSRs

C–E: geologic sense/conflict resolution (PDF/displacement)

F: greater than 25% overlap in segment PDFs

* 6.3 ky = WS5+2σ (6.4 ka) minus NS1–2σ (0.1 ka) ** Excluding P0

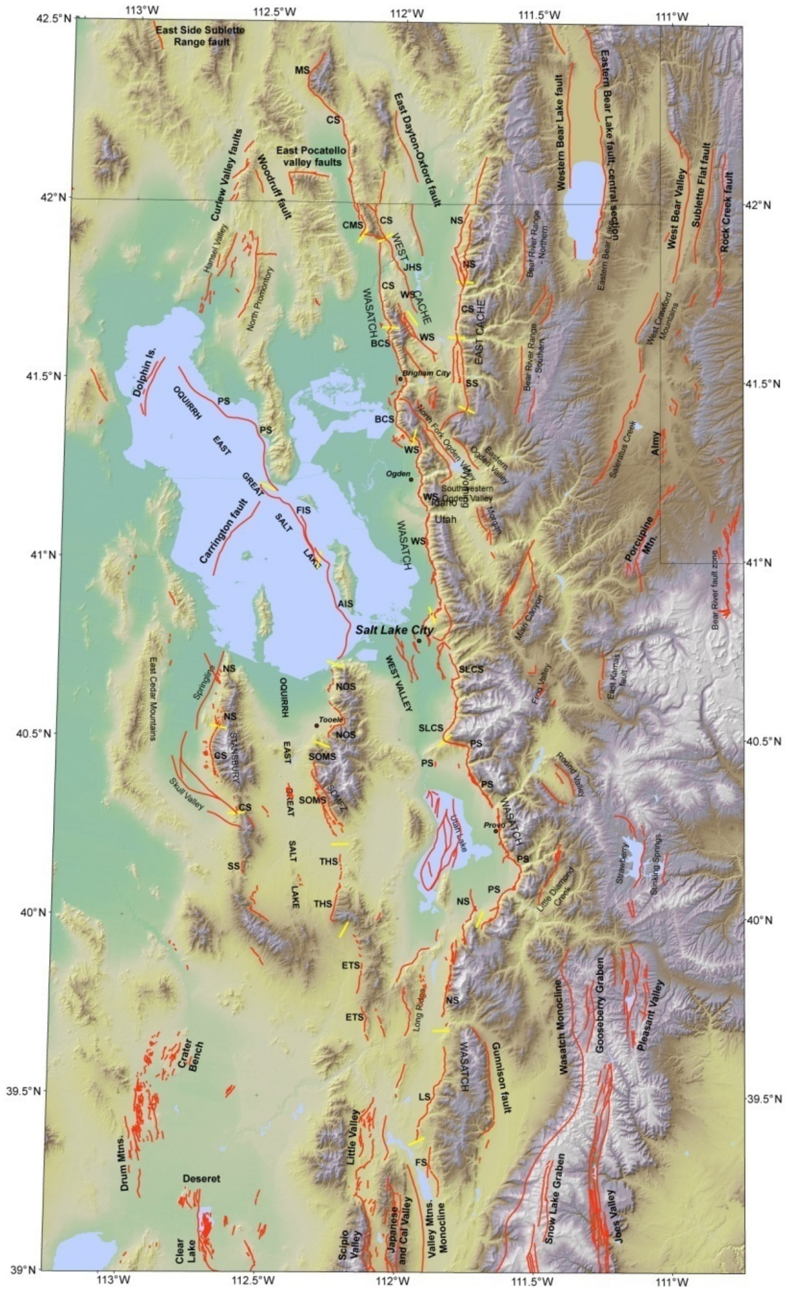
Discussion

- How many models to include?
  - Existing models, new models?
  - Minimum, maximum, geologic insight models?
  - Floating earthquake?
- Other fault data
  - Fault geometry
  - Segment boundaries (uncertainty in location)
  - Slip rates
- Weighting of various models?
- Moment balancing…

Other Faults in the Wasatch Front Study Region

Bill Lund
Utah Geological Survey

Working Group on Utah Earthquake Probabilities
July 22, 2010
Salt Lake City, Utah



WGUEP WASATCH FRONT REGION
(latitude 39.00° - 42.50°, longitude 110.75° - 113.25°)

WGUEP

Wasatch Front Study Region

Latitude 39.00° – 42.50°

Longitude 110.75° – 113.25°

Include Parts of

Three Physiographic Provinces

- Middle Rocky Mountains
- Colorado Plateau
- Basin and Range

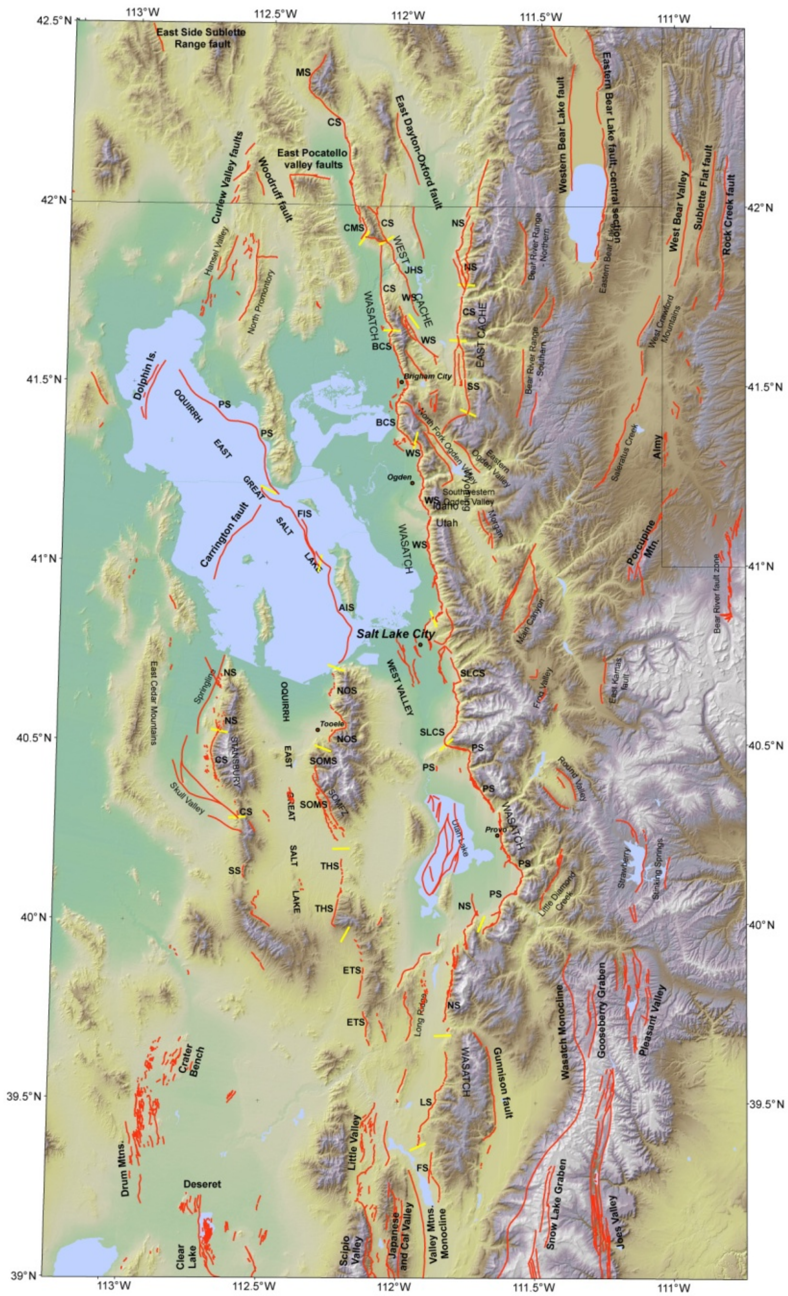
Three States

- Utah
- Idaho
- Wyoming

Total Area ~31,330 sq. miles

What Is An "Other" WGUEP Fault?

All Class A Quaternary Faults Within the WGUEP Study Area
Minus
the Five Central Segments of the Wasatch Fault Zone
Plus
the Carrington and Main Canyon Faults?



WGUEP WASATCH FRONT REGION

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

WGUEP
Wasatch Front Region Faults

117 Other Faults/Fault Segments

*Sources

USGS Quaternary Fault and Fold Database of the United States

U.S. Bureau of Reclamation

URS Corp./David Dinter, UU

Number of faults in:

• Utah	91
• Idaho	8
• Wyoming	12
• Ut/Wyo	2
• Ut/Id	4

Faulty Statistics

FAULT LENGTH				
Length	Number	Cumulative Number	Percent	Cumulative Percent
< 5 km	17	17	14.5	14.5
≥5 km <10 km	17	34	14.5	29.0
≥10 km <15 km	14	48	12.0	41.0
≥15 km <20 km	15	63	12.8	53.8
≥20 km <25 km	16	79	13.7	67.5
≥25 km <30 km	6	85	5.1	72.6
≥30 km <35 km	9	94	7.7	80.3
≥35 km <40 km	8	102	6.8	87.1
≥40 km <45 km	5	107	4.3	91.4
≥45 km <50 km	2	109	1.7	93.1
≥50 km <55 km	2	111	1.7	94.8
≥55 km <60 km	3	114	2.6	97.4
≥60 km <65 km	1	115	0.9	98.4
≥80 km <85 km	1	116	0.9	99.1
>100 km ≤105 km	1	117	0.9	100

Faulty Statistics
(cont.)

FAULT SLIP-RATE CATEGORY				
Slip Rate	Number	Cumulative Number	Percent	Cumulative Percent
<0.2 mm/yr[1]	101	101	86.3	86.3
Between 0.2 and 1.0 mm/yr	14	115	11.9	98.3
Between 1.0 and 5.0 mm/yr	1[2]	116	0.9	99.1
No Information	1[3]	117	0.9	100

[1]Susan recommends only including fault with slip rates >0.1 mm/yr
[2]Bear River fault, Utah/Wyoming
[3]Main Canyon fault (a.k.a. East of East Canyon fault)

More Faulty Statistics

TIME OF MOST RECENT DEFORMATION				
MRE Timing	Number	Cumulative Number	Percent	Cumulative Percent
Historical	1	1	0.9	0.9
Latest Quaternary (<15 ka)	43	44	36.8	37.6
Late Quaternary (<130 ka)	16	60	13.7	51.3
Middle and Late Quaternary (<750 ka)	27	87	23.1	74.4
Quaternary (<1.6 Ma)	30	117	25.6	100

Really Faulty Statistics

MRE Timing	Total Faults	Length ≥5 km	Slip Rate ≥0.2 mm/yr
Historical	1	1	0
Latest Quaternary (<15 ka)	43	42	14
Late Quaternary (<130 ka)	16	12	0
Middle and Late Quaternary (<750 ka)	27	22	0
Quaternary (<1.6 Ma)	30	23	0

Issues/Questions

1. Carrington fault – on our map but not in the USGS QF&F database – use Dinter, verbal communication (same as GSLFZ Antelope Island section)?

2. James Peak fault – reported as an independent fault in the USGS QF&F database, UQFPWG considers it the southernmost section of the ECFZ.

3. East Canyon fault southern section – class A fault? New USBR data available that says no.

4. Main Canyon fault (East of East Canyon fault) – upgrade to Class A fault? New USBR data available that says yes.

5. Martin Ranch fault (latest Q (<15 ka), 4 km long, slip rate between 0.2 and 1.0 mm/yr) – anybody buying it?

6. What, if anything, to do about faults in the study area that are too old, too short, or too slow?