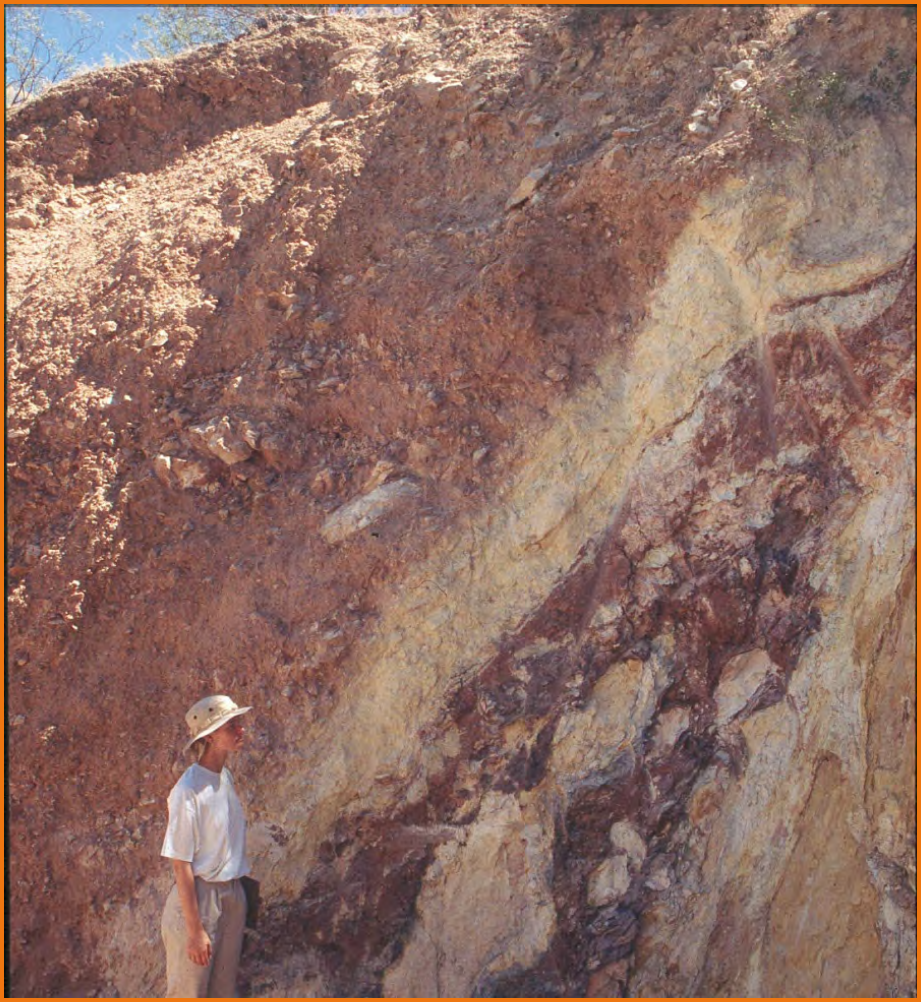
UTAH GEOLOGICAL SURVEY

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP



Hurricane Fault Near La Verkin, Utah

Wednesday, February 15, 2012

www.geology.utah.gov

UQFPWG

- **One of three standing committees created to help set and coordinate Utah's earthquake-hazard research agenda.**
- **Reviews ongoing paleoseismic research in Utah, and updates the Utah consensus slip-rate and recurrence-interval database as necessary.**
- **Provides advice/insight regarding technical issues related to fault behavior in Utah & the Basin and Range Province.**
- **Identifies and prioritizes Utah Quaternary faults for future study.**

2011 MEETING REVIEW

Presentations on Paleoseismic Work Completed or in Progress

- Salt Lake City segment trenching update; USGS
- West Valley City fault zone trenching update; UGS
- Nephi segment trenching update; UVU
- Joes Valley fault zone update; USBR
- East Canyon and Main Canyon fault updates; USBR
- Interactive Utah Quaternary fault map; UGS
- East Cache fault zone trenching update; USU [no report]
- Utah Lake faults study update; UU
- Working Group on Utah Earthquake Probabilities progress report

- **Revised Wasatch fault zone earthquake timing and recurrence; UGS**
- **Implementation: The third dimension of seismic hazard mitigation; BYU**

<u>Technical Discussion Item</u>

Recommendations (?) to the USGS for the National Quaternary Fault and Fold Map regarding the Joes Valley fault zone and the East Canyon & East of East Canyon (Main Canyon) faults – discussion

<u>UQFPWG 2012 Fault Study Priorities</u>

2012 FAULT PRIORITY LIST

2011 Highest Priority Faults/Fault Sections For Study			
Fault/Fault Section	**Priority**	**Investigation Status**	**Investigating Institution[1]**
Warm Springs fault/East Bench fault subsurface geometry and connection	1	No activity	
Penultimate event Provo segment WFZ	2	Trench site reconnaissance	UGS
Long-term earthquake record Nephi segment WFZ	3	No activity	
Washington fault	4	Two trenching investigations	UGS/Simon-Bimaster
Mid- to late-Holocene earthquake chronology southern part Weber segment WFZ	5	No activity	
Other Priority Faults/Fault Sections Requiring Further Study			
Fault/Fault Section	**Original UQFPWG Priority**	**Investigation Status**	**Investigating Institution[1]**
Cedar City-Parowan monocline/Paragonah fault[2]	10	No activity	
Enoch graben	11	No activity	
Clarkston fault[2]	13	No activity	
Gunnison fault	17	No activity	
Scipio Valley faults	18	No activity	
Faults beneath Bear Lake	19	No activity	
Eastern Bear Lake fault	20	No activity	
Carrington fault (Great Salt Lake)	2007	No activity	
Rozelle section, Great Salt Lake fault	2007	No activity	
Faults/Fault Sections Studies Complete or Ongoing			
Fault/Fault Section	**Original UQFPWG Priority**	**Investigation Status**	**Investigating Institution[1]**
Nephi segment WFZ	1	UGS Special Study 124 USGS Map 2966 UVU study ongoing	UGS/USGS/UVU
West Valley fault zone	2	Study funded for 2010	UGS/USGS
Weber segment WFZ – most recent event	3	UGS Special Study 130	UGS/USGS
Weber segment WFZ – multiple events	4	UGS Special Study 130	UGS/USGS
Utah Lake faults and folds	5	Study funded 2009	UUGG
Great Salt Lake fault zone	6	Ongoing	UUGG
Collinston & Clarkston Mountain segments WFZ	7	UGS Special Study 121	UGS
Sevier/Toroweap fault	8	UGS Special Study 122	UGS
East Cache fault zone	12	Ongoing	USU
Wasatch Range back-valley faults	14	Ongoing	USBR
Hurricane fault	15	UGS Special Study 119	UGS
Levan segment WFZ	16	UGS Map 229	UGS
Brigham City segment WFZ – most recent event	2007	Ongoing	UGS/USGS
Bear River fault zone	2007	Ongoing	USGS
Salt Lake City segment WFZ – north end	2009	Study funded for 2010	UGS/USGS

AGENDA
QUATERNARY FAULT PARAMETERS WORKING GROUP
Wednesday, February 15, 2012
Utah Department of Natural Resources Building, Rooms 1040–1050 (1st Floor)
1594 West North Temple, Salt Lake City

8:00 Continental breakfast

8:30 Introduction, overview of meeting, review of last year's activities

8:40 Technical presentations of work completed or in progress
- 8:40 – Penrose Drive site trenching update; Chris DuRoss, UGS
- 9:00 – West Valley fault zone trenching update; Mike Hylland, UGS
- 9:20 – Utah Lake study update; Ron Harris; BYU
- 9:40 – Lake Powell Pipeline Hurricane fault crossing investigation; Dean Ostenna, Fugro, Inc.

10:00 Break

10:20 Technical presentations of work completed or in progress
- 10:20 – Blue Castle nuclear power plant seismic-hazard investigation; Dean Ostenna, Fugro, Inc.
- 10:40 – Paunsaugunt fault investigation; Bob Kirkham [written summary provided]
- 11:00 – New UGS Nephi segment trenching project; Chris DuRoss, UGS
- 11:20 – Update on new Wasatch fault earthquake-timing and recurrence-interval data; Chris DuRoss, UGS
- 11:40 – Updated GPS analysis for the Wasatch Front; Christine Puskas, Univ. of Colorado

12:00 Lunch

AGENDA
(Continued)

1:00 **Technical presentations of work completed or in progress**
- **1:00 – Working Group on Utah Earthquake Probabilities update; Ivan Wong, URS/Bill Lund, UGS**
- **1:20 – Report on Basin and Range Province Earthquake Working Group II; Bill Lund, UGS**

1:40 **Technical discussion item**
- **1:40 – East Cache fault zone; Bill Lund, UGS**

2:00 **UQFPWG 2013 fault study priorities**

3:00 **Break**

3:20 **UQFPWG 2013 fault study priorities continued/meeting wrap up.**

3:45 **Adjourn**

Paleoseismicity of the Salt Lake City Segment: Results from the Penrose Drive Trench Investigation

Chris DuRoss
Mike Hylland
Greg McDonald
(UGS)

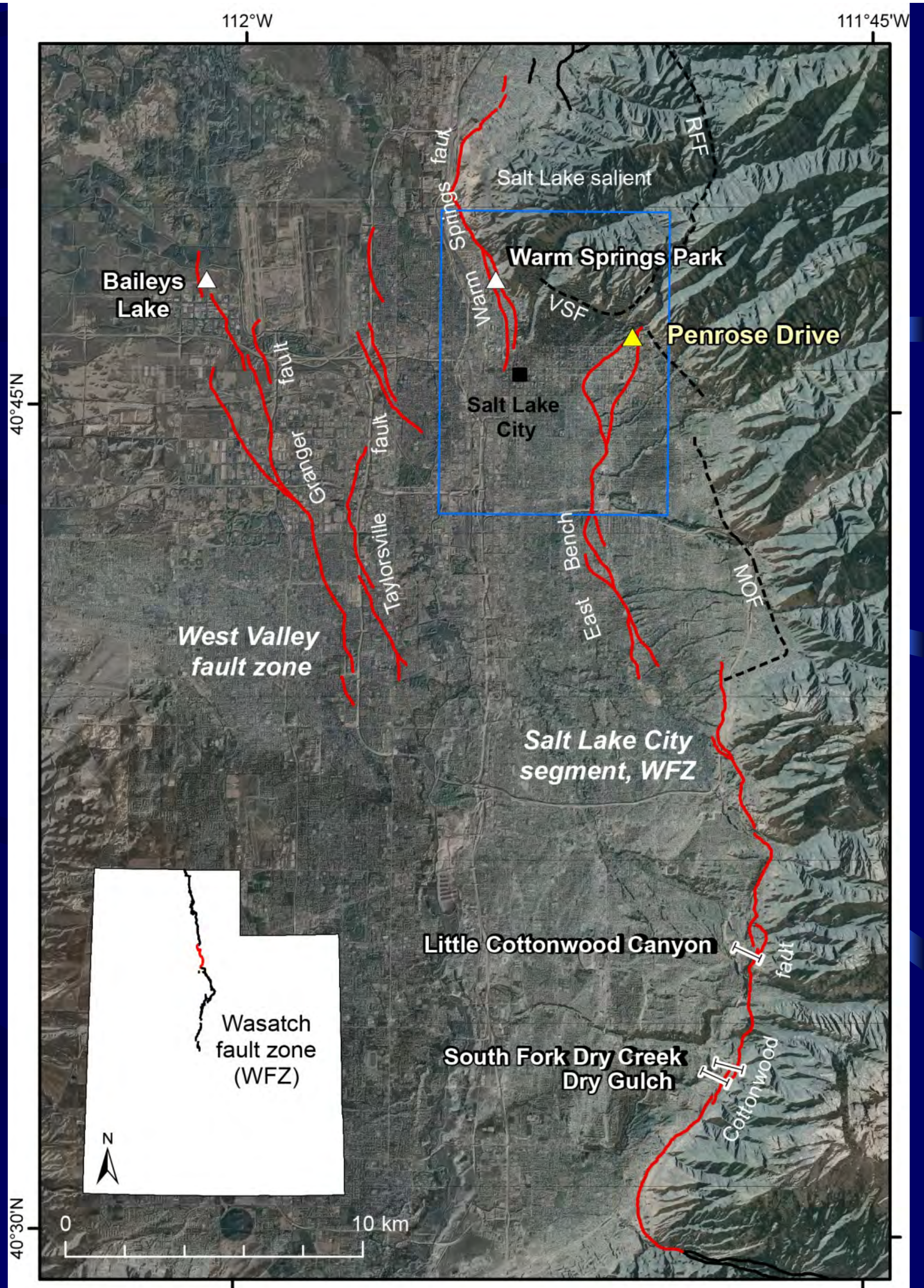
Tony Crone
Steve Personius
(USGS)

With help from:
Shannon Mahan (USGS), Brad King (USGS), Ryan Gold (USGS), Rich Giraud (UGS) and other UGS staff

Salt Lake City segment

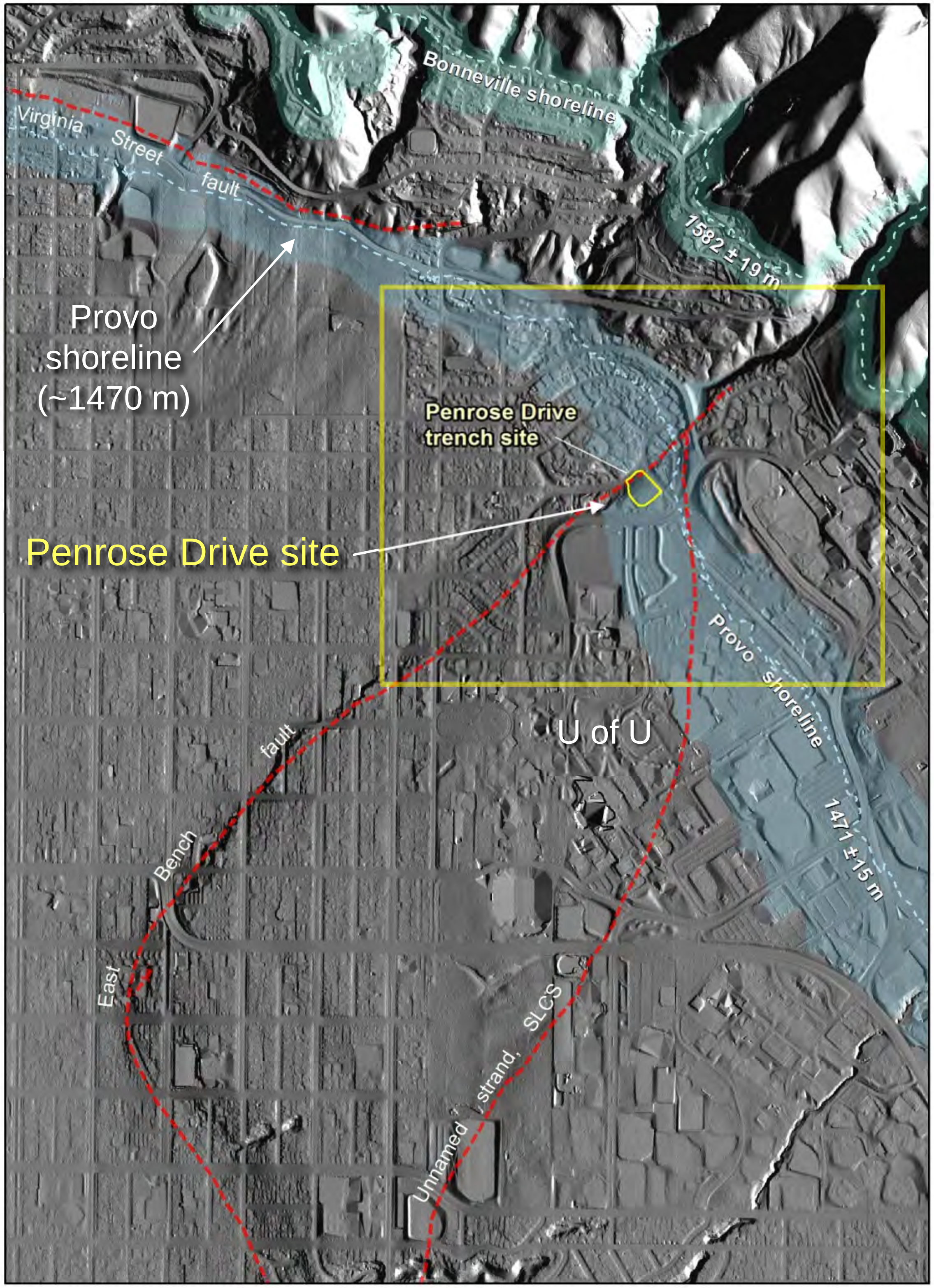
- Why trench the SLCS?
  1. What is the timing of earthquakes on the northern SLCS?
  2. Do we have a complete Holocene (and lt. Pleistocene) earthquake record for the SLCS?
  3. Does the West Valley fault zone rupture coseismically with the SLCS?

- 2010 Paleoseismic study:
  - Penrose Drive (SLCS)
  - Baileys Lake (WVFZ)



N. East Bench Fault

- East Bench fault (EBF)
  - Timing of individual events unknown
- Penrose Drive site
  - Last remaining (mostly) unmodified scarp on the EBF!



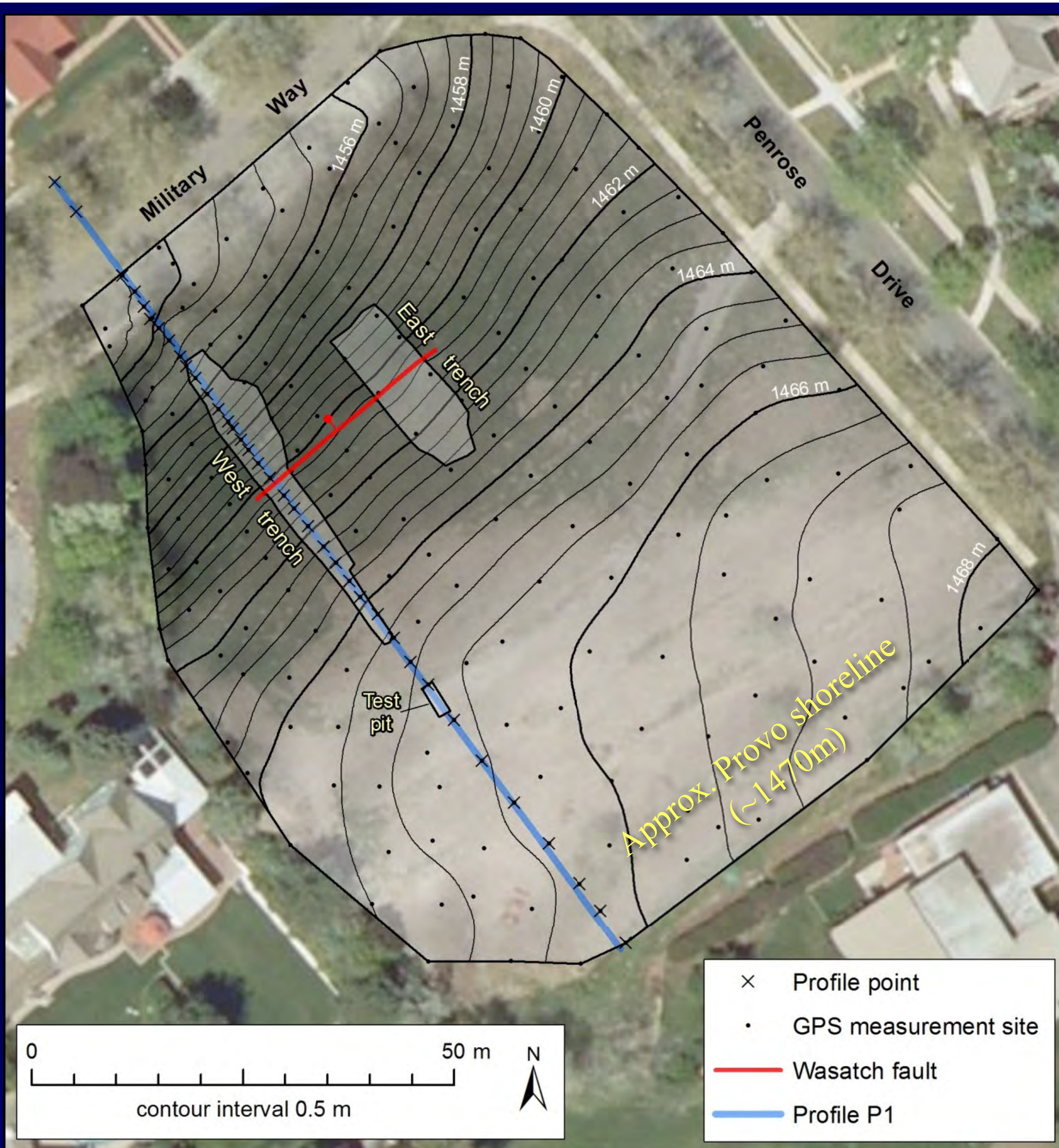
1-m LiDAR hillshade, illuminated from East

N. East Bench Fault

1937 aerial photo

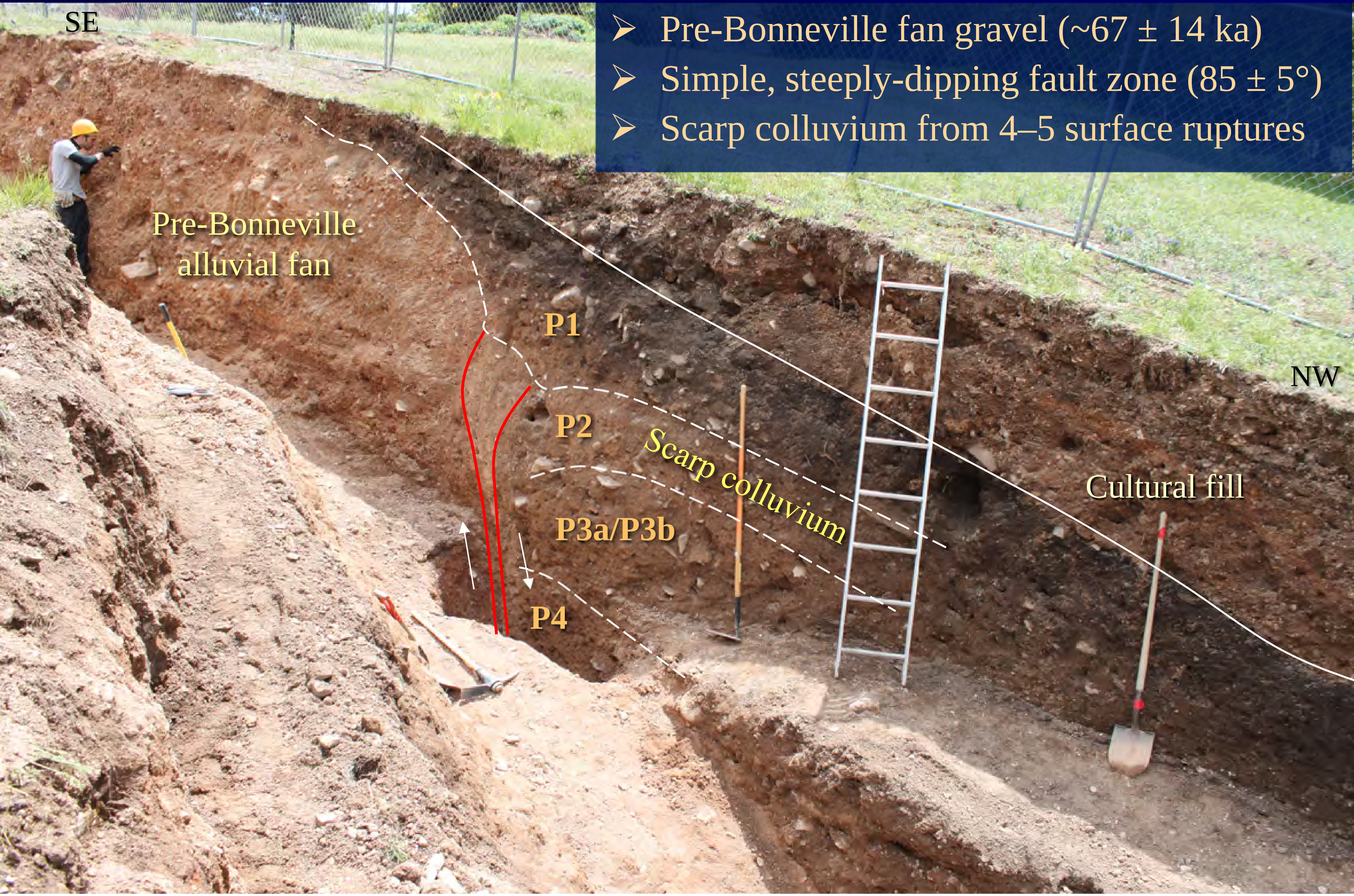
Penrose Drive Site

- NW facing scarp ~11 m high
- Two trenches
  - West trench (36 m)
  - East trench (11 m)



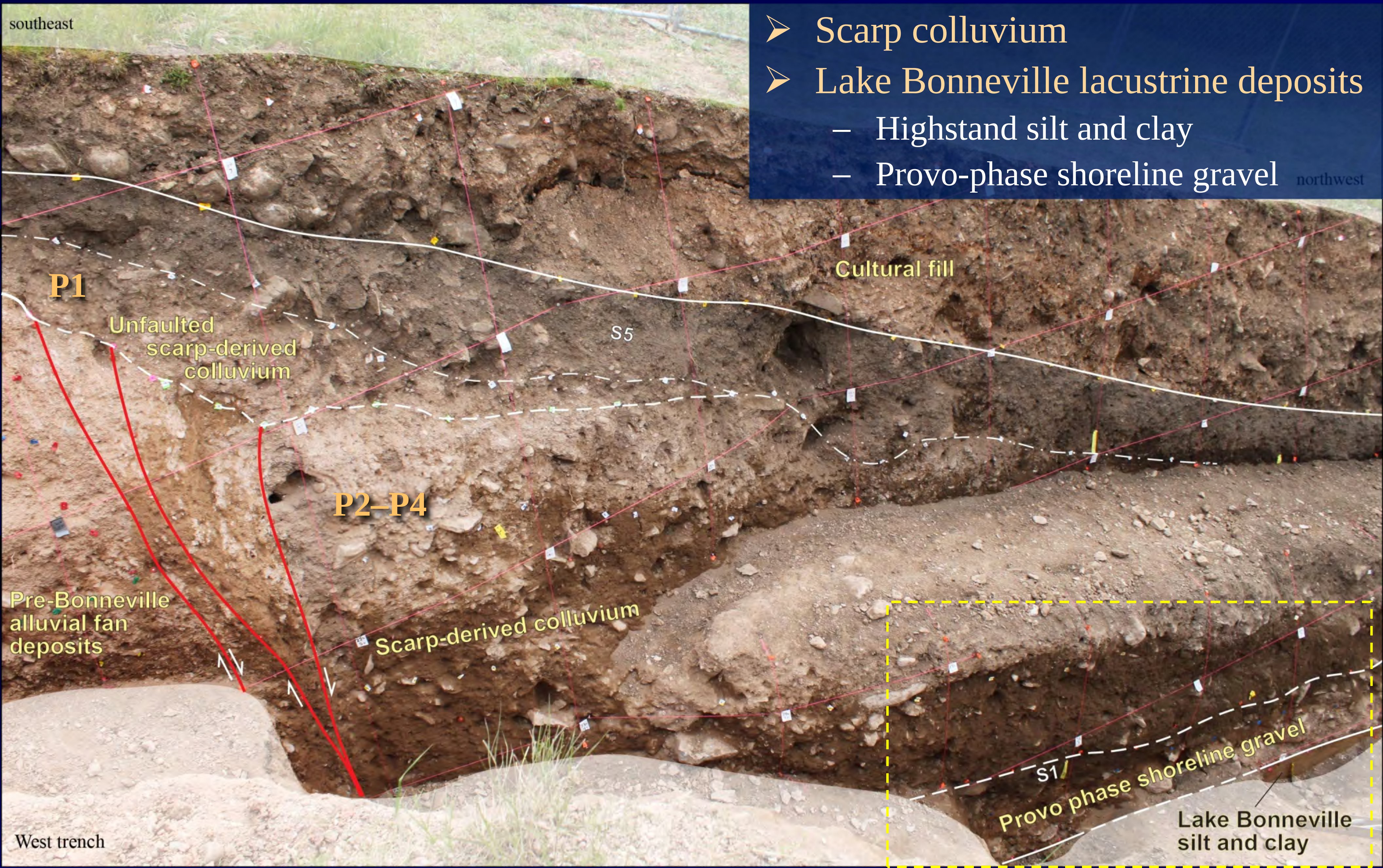
West Trench – fault zone

- Pre-Bonneville fan gravel (~67 ± 14 ka)
- Simple, steeply-dipping fault zone (85 ± 5°)
- Scarp colluvium from 4–5 surface ruptures



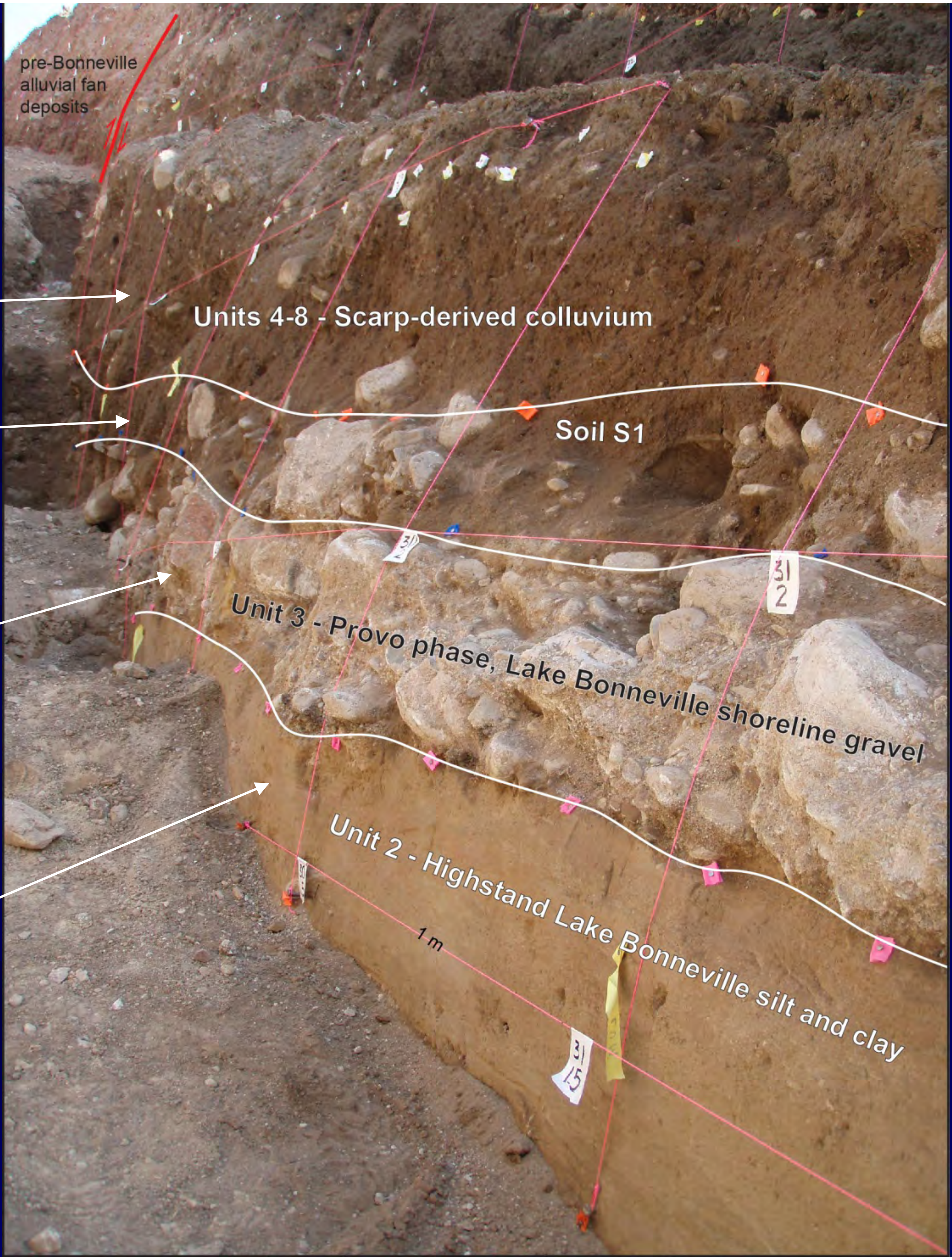
West Trench – hanging wall

- Scarp colluvium
- Lake Bonneville lacustrine deposits
  - Highstand silt and clay
  - Provo-phase shoreline gravel



West Trench – hanging wall

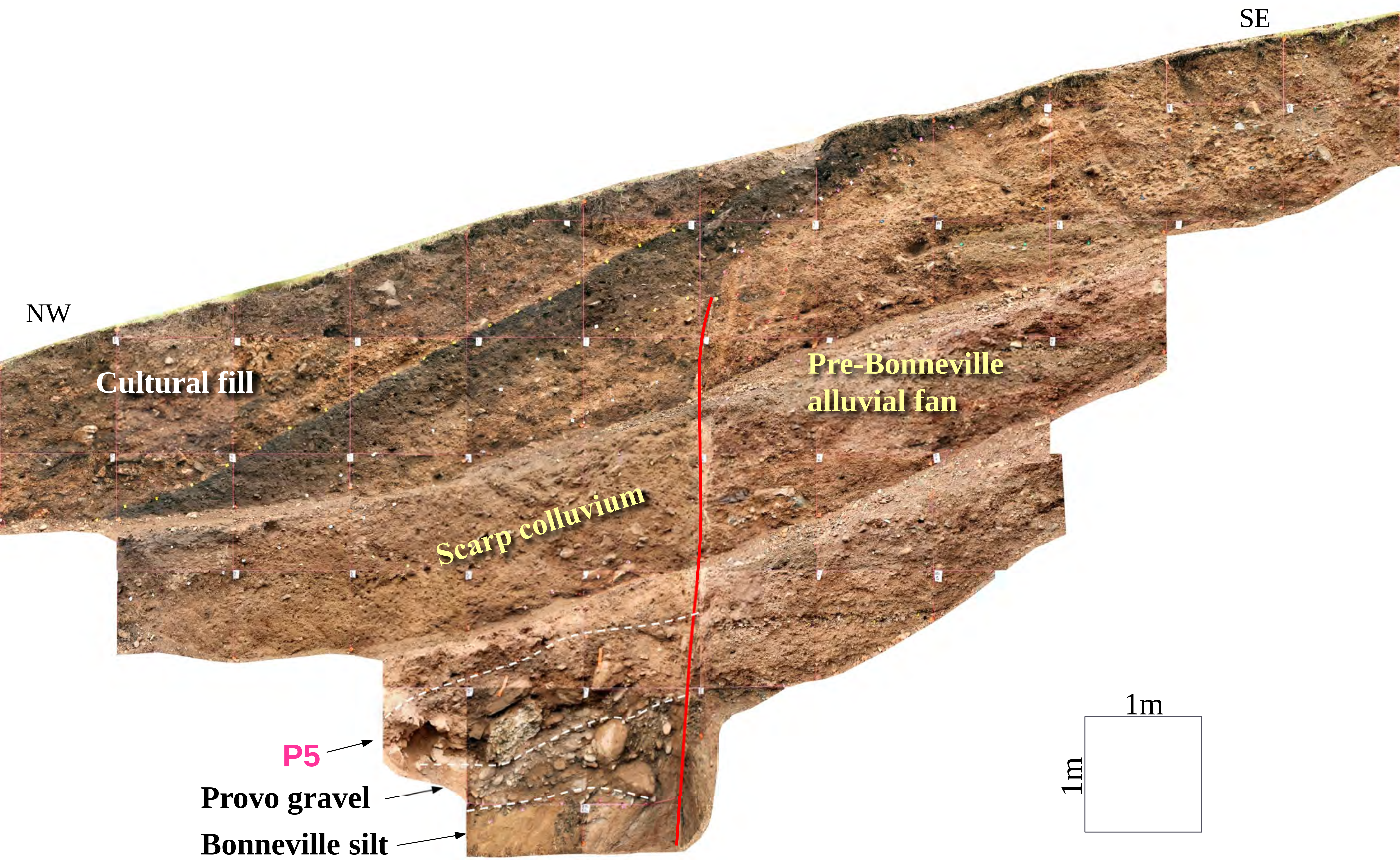
- Scarp colluvium
- Soil A horizon (S1)
  - 10.6–11.5 ka from 4 charcoal samples
- Provo-phase shoreline boulder gravel
  - ~14.0–17.6 ka (Godsey et al., 2006)
- Highstand silt and clay
  - 17.0–17.8 ka from 2 OSL samples



West Trench

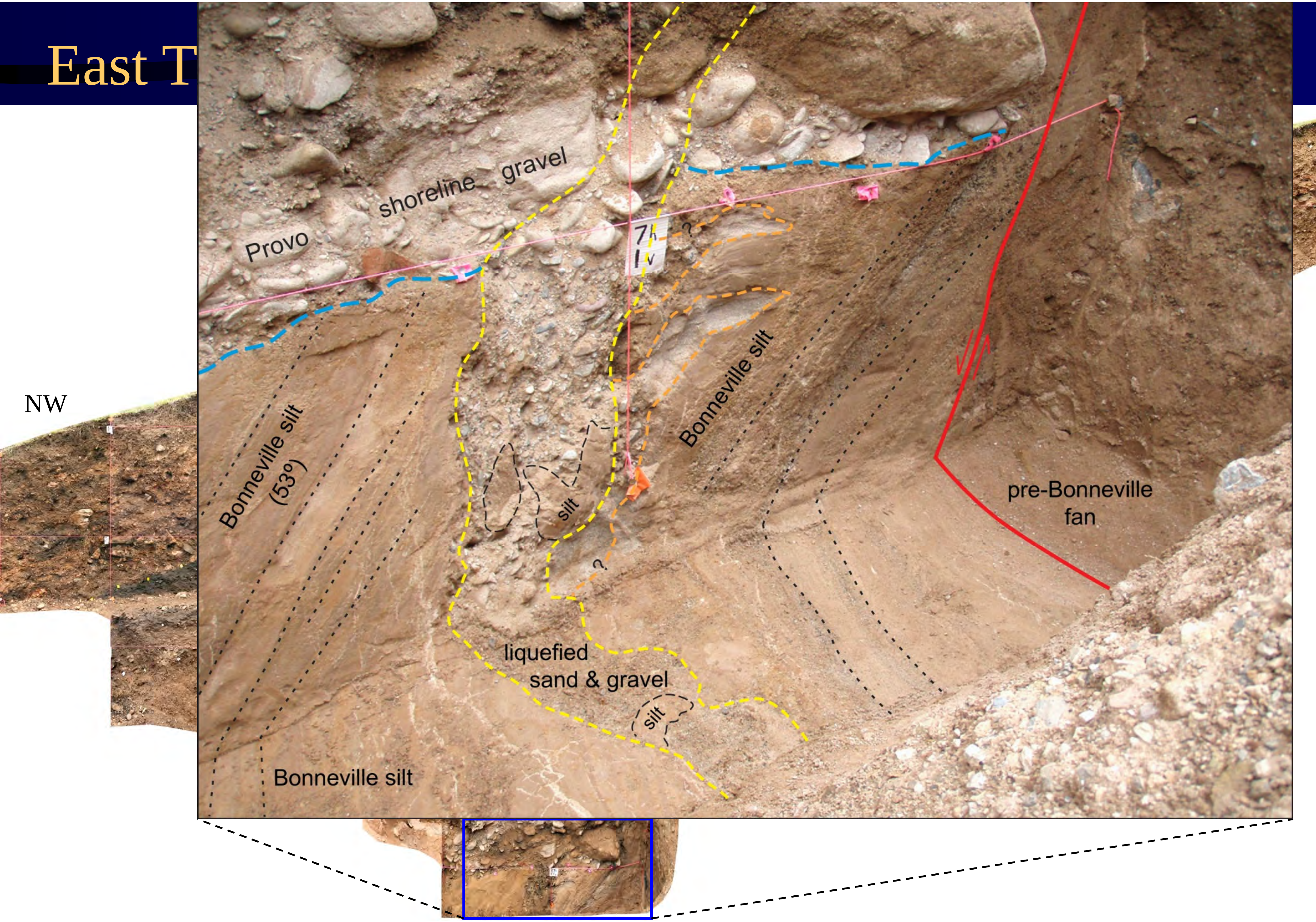
- Where are the pre-Bonneville fan gravels in the fault hanging wall?
- Auger hole in floor of W trench:
  - Refusal at 5.9 m
  - No fan gravels; only Bonneville silt/sand

East Trench

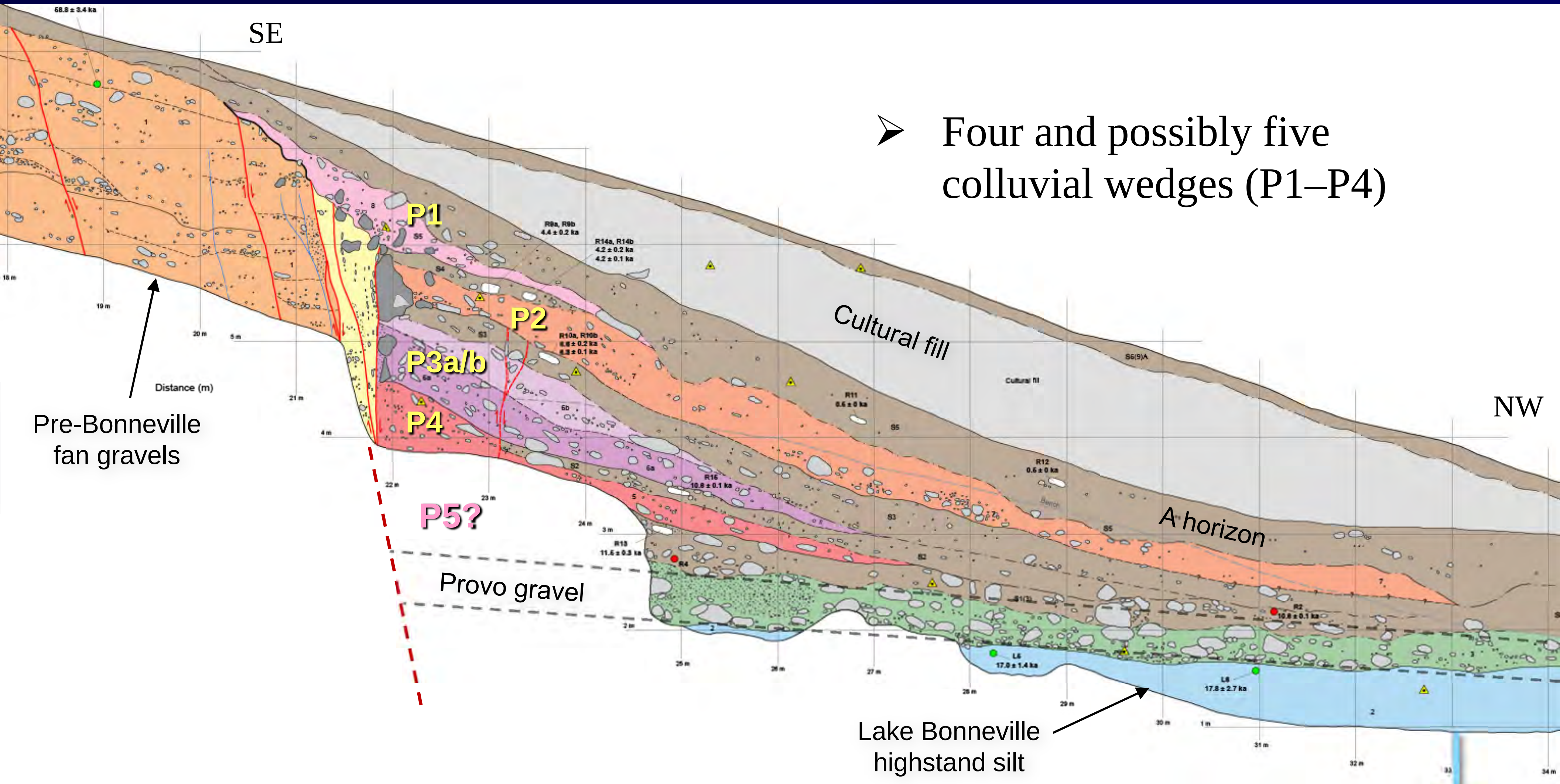


SE
NW
Cultural fill
Pre-Bonneville
alluvial fan
Scarp colluvium
P5
Provo gravel
Bonneville silt
1m
1m

East T


NW
Provo shoreline gravel
7h
1v
Bonneville silt (53°)
Bonneville silt
silt
liquefied sand & gravel
silt
Bonneville silt
pre-Bonneville fan

West Trench

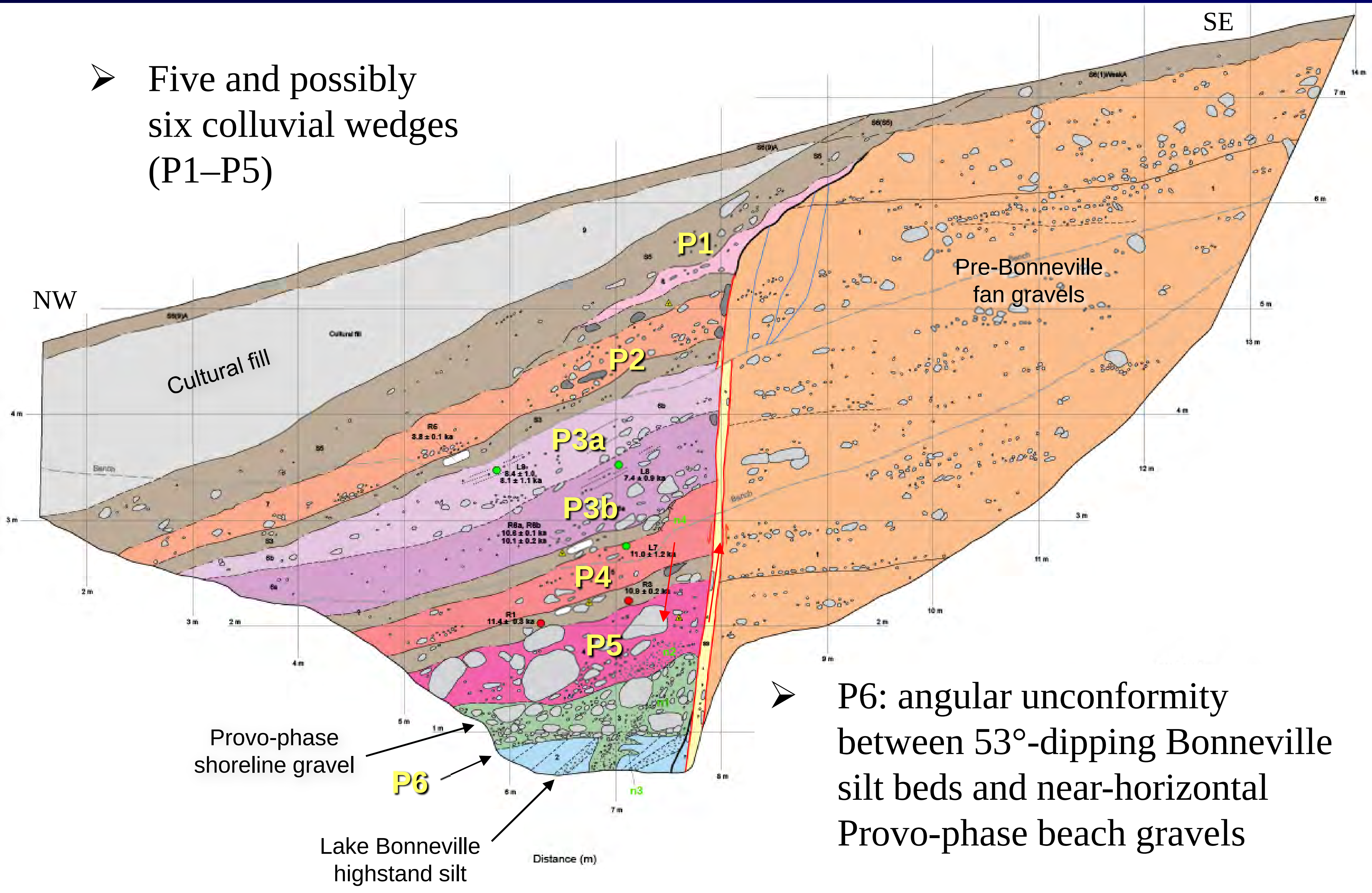


- Four and possibly five colluvial wedges (P1–P4)

- Minimum offset of pre-Bonneville alluvial fan: 16 m

East Trench

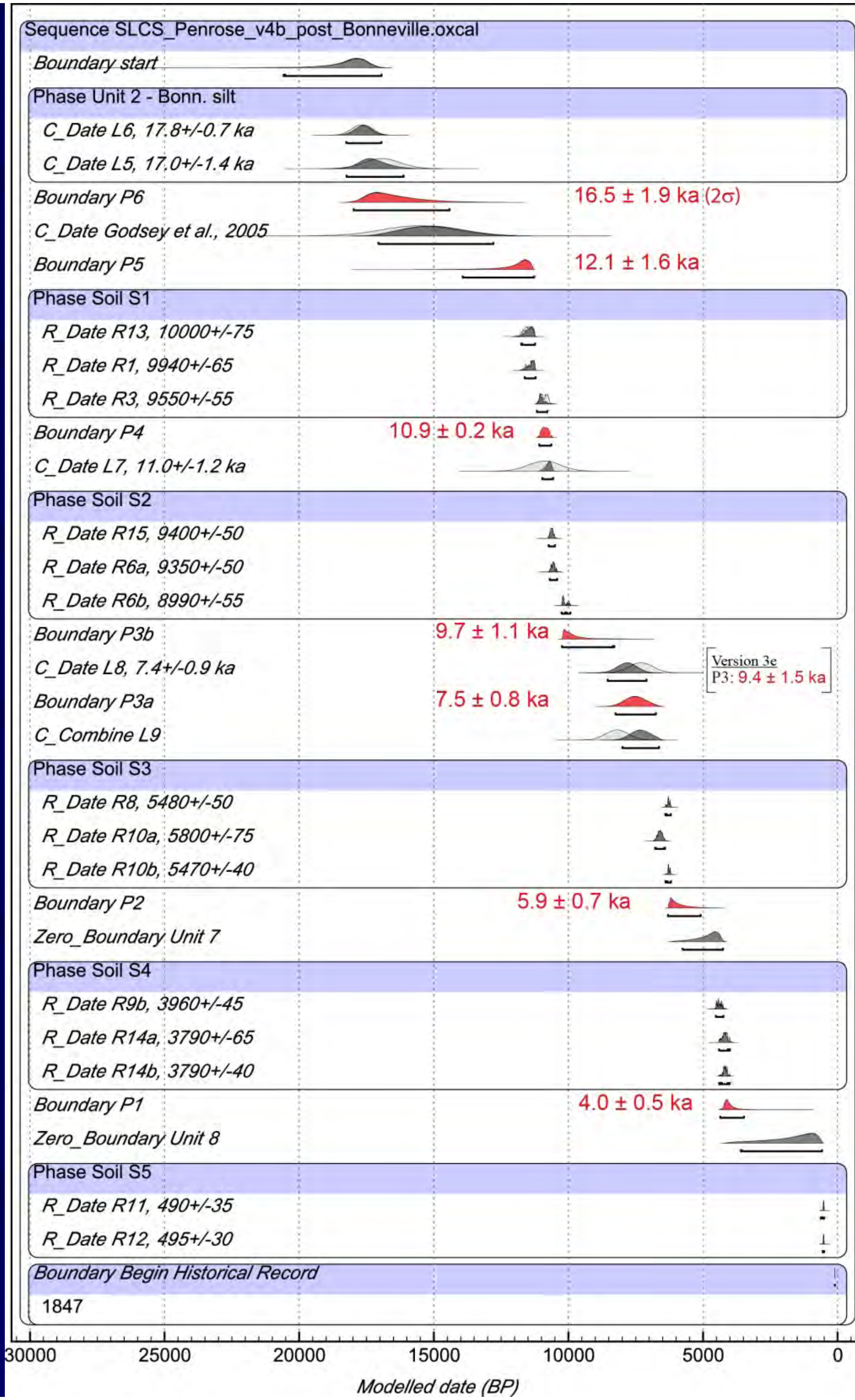
- Five and possibly six colluvial wedges (P1–P5)



- P6: angular unconformity between 53°-dipping Bonneville silt beds and near-horizontal Provo-phase beach gravels

^{14}C/OSL Ages and OxCal modeling

- 16 radiocarbon ages
  - Macro charcoal (3)
  - Bulk soil sediment (charcoal fragments) (13)
  - Gastropod shells (not dated)
- 9 OSL ages
  - Pre-Bonneville fan (4)
  - 2 top of Bonneville silt (2)
  - P3–P4 colluvium (3)



Preliminary data subject to revision

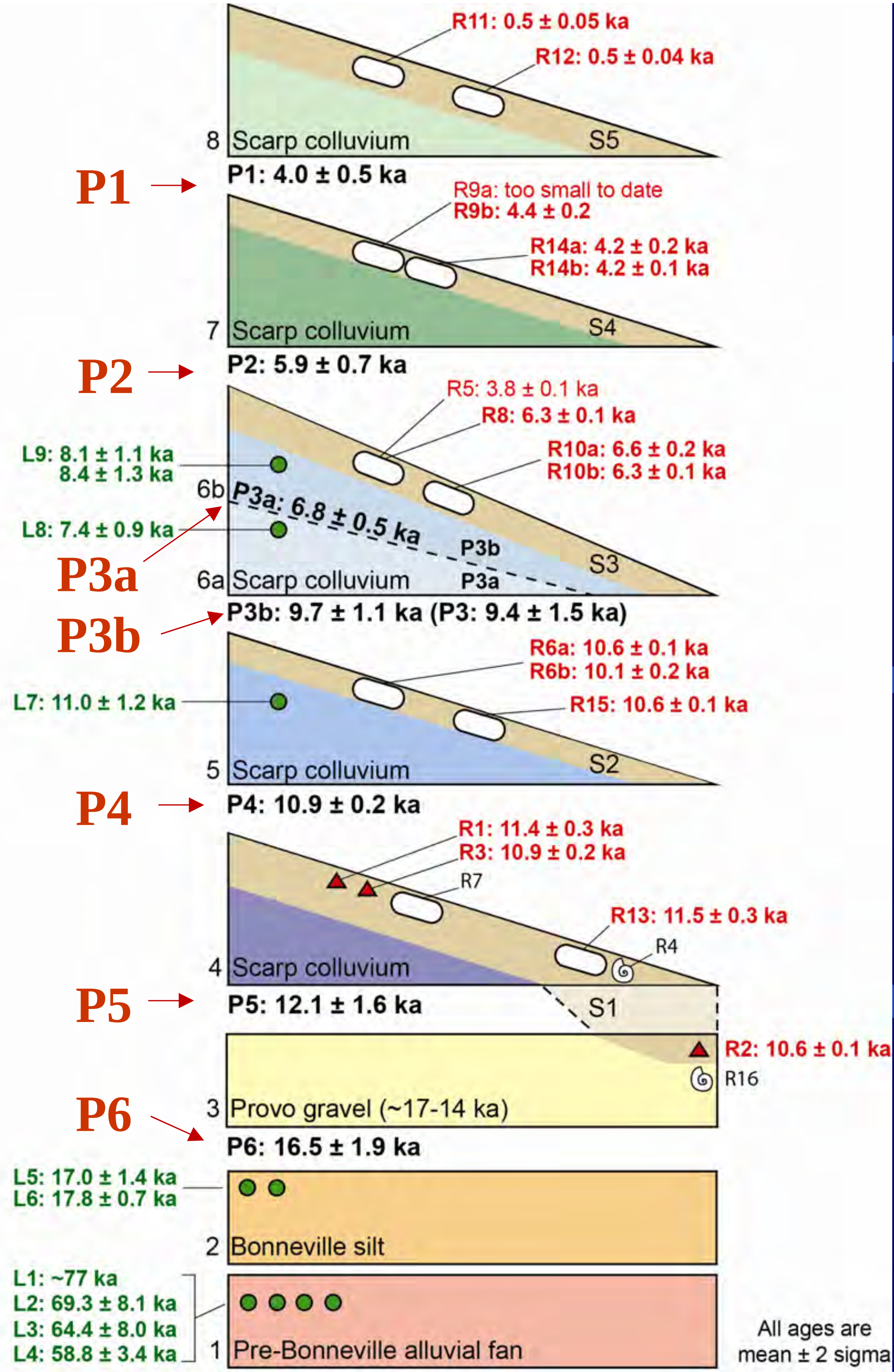
Penrose Drive EQ Times

- OxCal models

	Model 4		Model 3e
P1	4.0 ± 0.5 ka (2σ)	P1	“
P2	5.9 ± 0.7 ka	P2	“
P3a	7.5 ± 0.8 ka	–	
P3b	9.7 ± 1.1 ka	P3	9.4 ± 1.5 ka
P4	10.9 ± 0.2 ka	P4	“
P5	12.1 ± 1.6 ka	P5	“
P6	16.5 ± 1.9 ka	P6	“

- 6 and possibly 7 surface-faulting earthquakes (P1–P6) occurred on the northern EBF after the highstand of Lake Bonneville (~17 ka)

Preliminary data subject to revision



SLCS Earthquake Chronology

Correlation of SLCS earthquakes

EQ	Penrose Dr. (ka)	Little Cottonwood Cyn. (ka)	S. Fork/ Dry Cr. (ka)
S1	-	1.3 ± 0.04 (Z-1.3)	1.3 ± 0.2 (D)
S2	-	2.1 ± 0.3 (Y-2.3)	2.2 ± 0.4 (C)
S3	4.0 ± 0.5 (PD1)	4.4 ± 0.5 (X-3.5)	3.8 ± 0.6 (B)
S4	5.9 ± 0.7 (PD2)	5.5 ± 0.8 (W-5.3)	5.0 ± 0.5 (A)
S5	7.5 ± 0.8 (PD3a)	7.8 ± 0.7 (V-7.5)	-
S6	9.7 ± 1.1 (PD3b)	9.5 ± 0.2 (U-9)	-
S7	10.9 ± 0.2 (PD4)	-	-
S8	12.1 ± 1.6 (PD5)	-	-
S9	16.5 ± 1.9 (PD6)	16.5 ± 2.7 (T-17)	-

- Earthquake correlation
  - Youngest 4 Penrose events (PD3b-PD1) likely correlate with previous events
  - Oldest Penrose earthquake possibly correlates with LCC event T (both ~ time of Bonneville highstand)

Preliminary data subject to revision

SLCS Earthquake Chronology

Correlation of SLCS earthquakes

EQ	Penrose Dr. (ka)	Little Cottonwood Cyn. (ka)	S. Fork/ Dry Cr. (ka)	Prelim. SLCS chronology (ka)	Inter-event RI (kyr)
S1	-	1.3 ± 0.04 (Z-1.3)	1.3 ± 0.2 (D)	**1.3** (1.1–1.5)	-
S2	-	2.1 ± 0.3 (Y-2.3)	2.2 ± 0.4 (C)	**2.2** (1.8–2.6)	0.9 (S2-S1)
S3	4.0 ± 0.5 (PD1)	4.4 ± 0.5 (X-3.5)	3.8 ± 0.6 (B)	**4.1** (3.2–4.9)	1.9 (S3-S2)
S4	5.9 ± 0.7 (PD2)	5.5 ± 0.8 (W-5.3)	5.0 ± 0.5 (A)	**5.5** (4.5–6.6)	1.4 (S4-S3)
S5	7.5 ± 0.8 (PD3a)	7.8 ± 0.7 (V-7.5)	-	**7.7** (6.7–8.5)	2.2 (S5-S4)
S6	9.7 ± 1.1 (PD3b)	9.5 ± 0.2 (U-9)	-	**9.6** (8.6–10.8)	1.9 (S5-S5)
S7	10.9 ± 0.2 (PD4)	-	-	**10.9** (10.7–11.1)	1.3 (S7-S6)
S8	12.1 ± 1.6 (PD5)	-	-	**12.1** (10.5–13.7)	1.2 (S8-S7)
S9	16.5 ± 1.9 (PD6)	16.5 ± 2.7 (T-17)	-	**16.5** (13.8–19.2)	4.4 (S9-S8)

- Preliminary earthquake history of SLCS
  - 7 Holocene events (S7-S1) *(previously 6)*
  - 9 earthquakes postdating Lake Bonneville highstand *(previously 7)*
  - Latest Pleistocene record still poorly constrained (e.g., between S9 and S8)

Preliminary data subject to revision

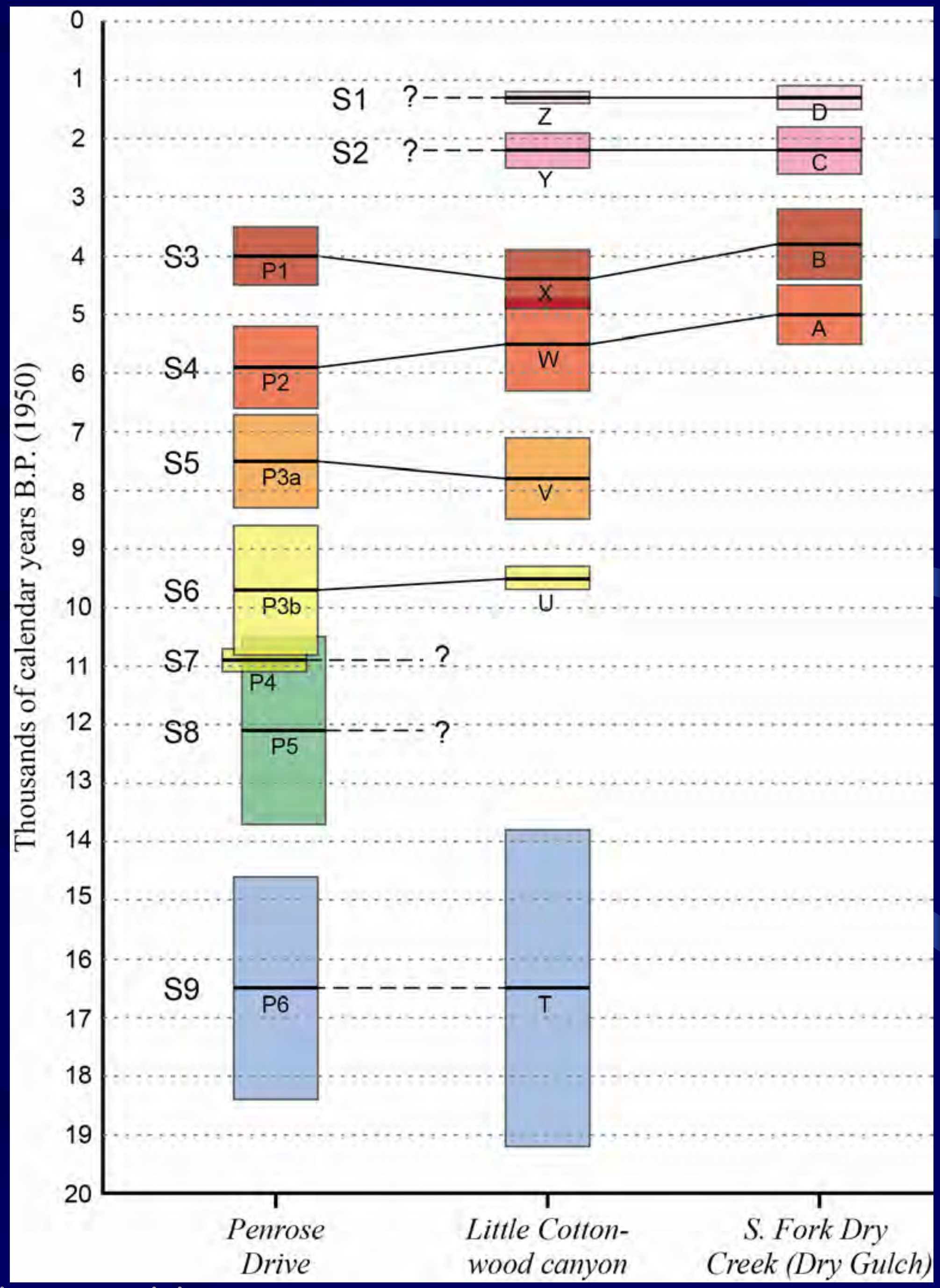
SLCS Earthquake Recurrence

Earthquake Recurrence on the SLCS

Elapsed time (kyr)		**n**	**Mean recurrence interval (kyr)**	
S9–S1	**15.2**	8	**1.9**	Bonneville HS (<18 ka)
S8–S1	**10.8**	7	**1.5**	Provo shore. (<14 ka)
S6–S1	**8.3**	5	**1.7**	Holocene (<11 ka)
S4–S1	**4.2**	3	**1.4**	mid Holocene (6 ka)

n = number of seismic intervals

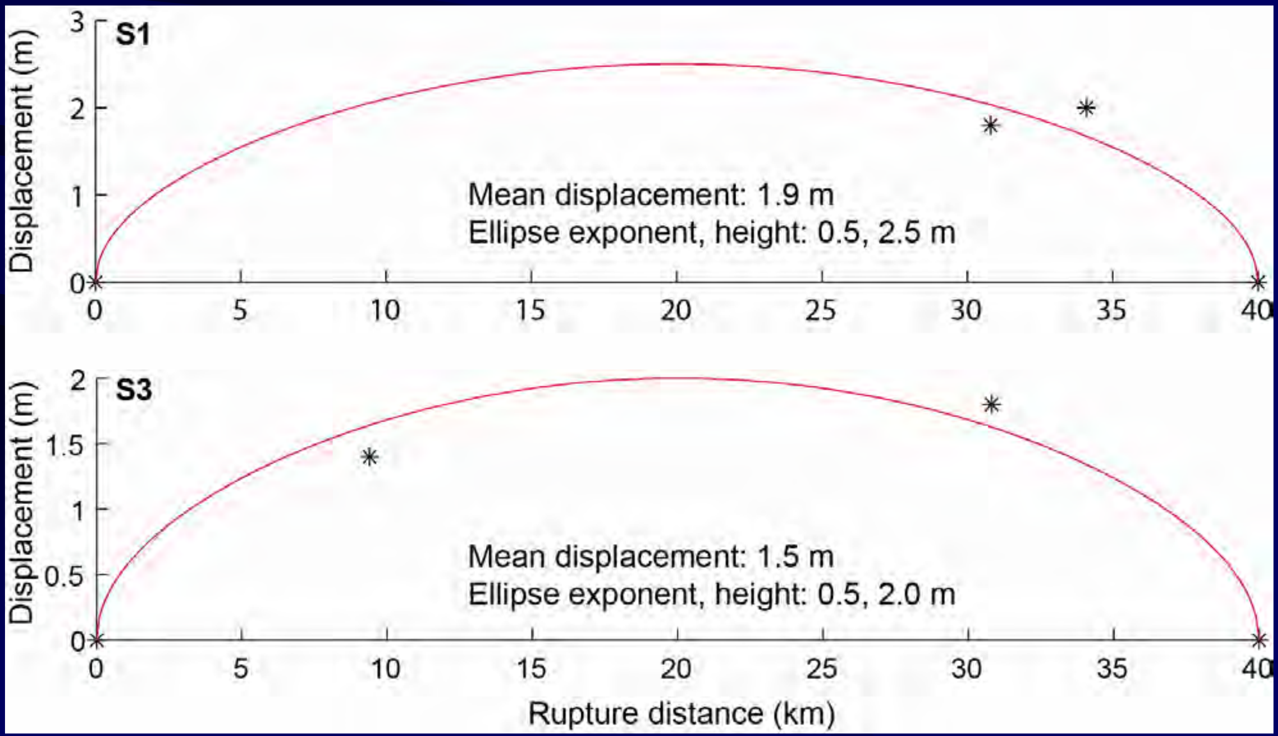
- Post mid-Holocene mean recurrence (~1.4 kyr) nearly identical to post-Provo shoreline recurrence (1.5 kyr)
- UQFPWG: 1.3 (0.5–2.4) kyr (5th–95th)



Preliminary data subject to revision

SLCS Displacement & Slip Rate

- Per-event displacements
  - Penrose Drive: ~1.2 m per event using colluvial wedge thickness (min) and total offset of Provo shorelines (9.4 m; max)
  - Little Cottonwood canyon: total displacement for 4 youngest events (1.8 m each)
  - South Fork Dry Creek: offset debris-flow levee (2.0 ± 0.5 m)



Preliminary data subject to revision

SLCS Displacement & Slip Rate

Total displacement and vertical slip rate for the SLCS

Events	**Displacement** (m) (mean, min, max)			**Time interval**	**Time** (kyr) (mean, min, max)			**Slip rate** (mm/yr) (mean, min, max)		
S8-S1	**11.5**	9.3	13.9	S9-S1 (post Bonn. HS)	**15.2**	12.3	18.1	**0.8**	0.5	1.1
S7-S1	**10.1**	8.3	12.1	S8-S1 (post Provo)	**10.8**	9.0	12.6	**0.9**	0.7	1.3
S5-S1	**7.8**	6.7	9.1	S6-S1 (Holocene <10 ka)	**8.3**	7.1	9.7	**0.9**	0.7	1.3
S4-S1	**6.6**	5.9	7.6	S5-S1 (Holocene <8 ka)	**6.4**	5.2	7.4	**1.0**	0.8	1.5
S3-S1	**5.3**	4.7	6.1	S4-S1 (mid Holocene)	**4.2**	3.0	5.5	**1.3**	0.9	2.0

- SLCS vertical slip rate
  - Holocene ~0.9–1.3 mm/yr (possible range 0.7–2.0 mm/yr)
  - Early Holocene and lt. Pleistocene rates less well constrained (displacements from single site)
- UQFPWG: 1.2 (0.6–4.0) mm/yr (Bells Canyon: 0.9 +0.8/–0.2 mm/yr)

Preliminary data subject to revision

Conclusions

- 6–7 earthquakes at Penrose Dr. after Lake Bonneville highstand (~17–18 ka)
  - Youngest events correspond well with previous data from LCC and SFDC
  - 2 events at 11–14 ka fill an 8-kyr period of seismic quiescence observed at LCC
  - Earthquake record over 14.0–17.6 ka (Provo shoreline) is possibly incomplete
- Using the preliminary SLCS chronology…
  - At least 9 earthquakes (S1–S9) after Bonneville highstand; Holocene (S1–S7) and post-Provo (S1–S8) earthquake records best constrained
  - Mean recurrence is 1.4 kyr, using well constrained events S1–S4
  - Longer-term recurrence ranges from 1.5 kyr (Provo) to 1.9 kyr (Bonneville)
  - Holocene slip rates are ~0.9–1.3 mm/yr (0.7–2.0 mm/yr range)
  - These estimates correspond well with the UQFPWG consensus values
- Remaining questions and future work
  - Extent of ruptures? Why didn't S1 and S2 rupture Penrose site?
  - Refine earthquake timing and recurrence using methods of DuRoss et al. (2011)

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

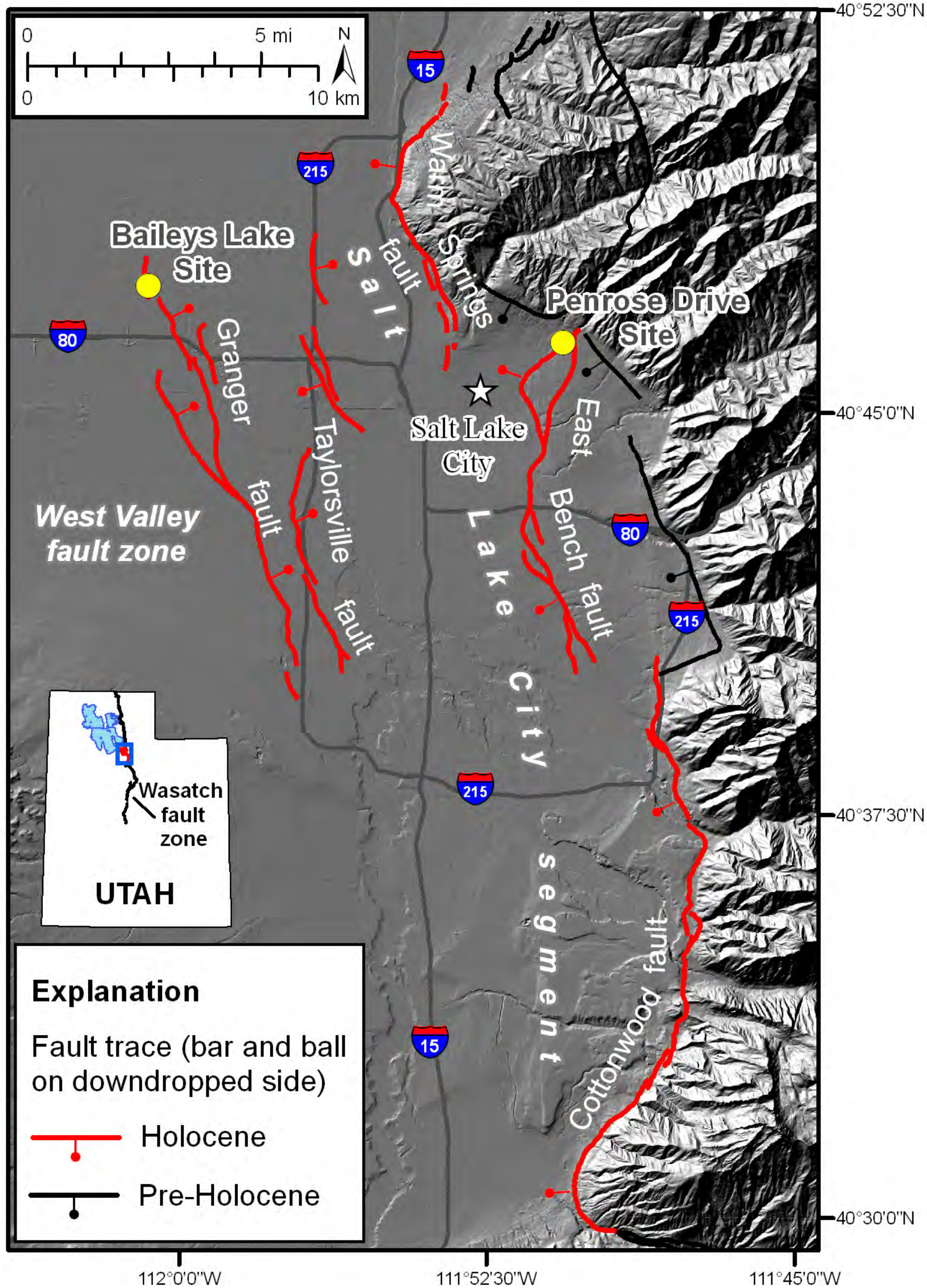
Mike Hylland, Chris DuRoss, Greg McDonald (UGS)
Susan Olig (URS)
Tony Crone, Steve Personius, Shannon Mahan (USGS)
Jack Oviatt (Kansas State University)

Utah Quaternary Fault Parameters Working Group
February 15, 2012

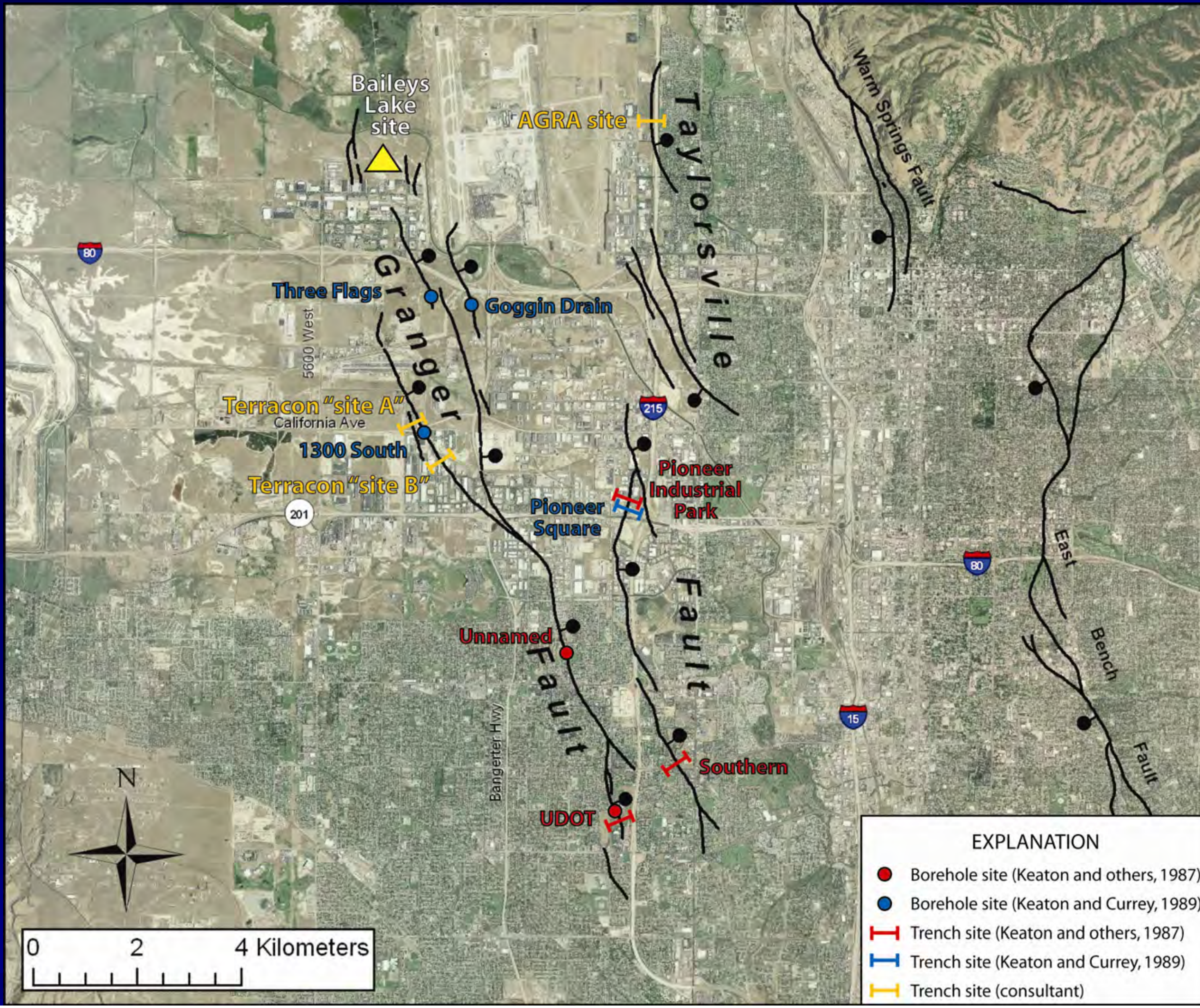
Research funded by the Utah Geological Survey and U.S. Geological Survey, National Earthquake Hazards Reduction Program

Primary goals:

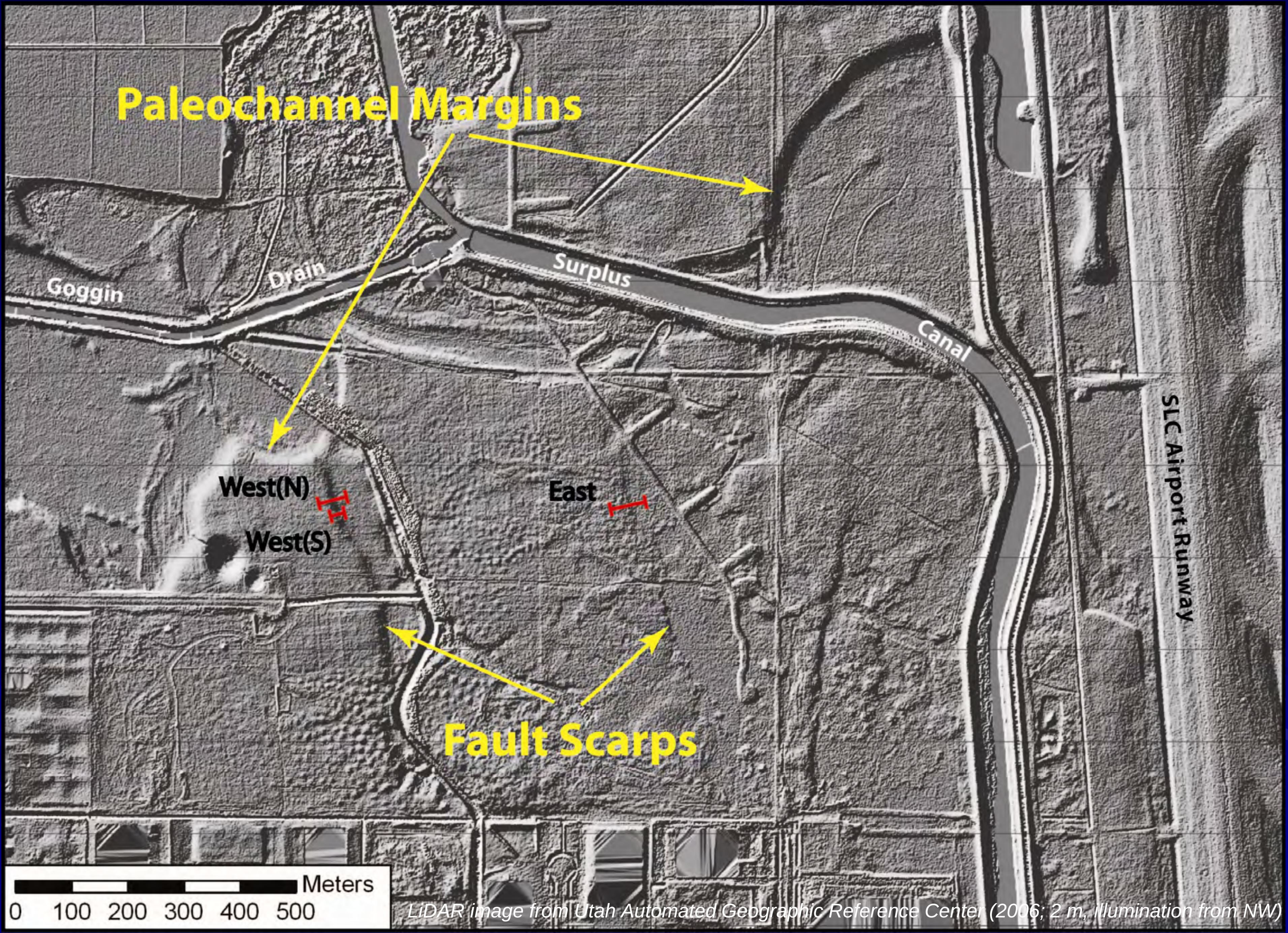
- Resolve the timing and displacement of individual surface-faulting earthquakes on the northern part of the SLCS and the WVFZ
- Clarify the seismogenic relation (dependent or independent) between these two faults



Paleoseismic Study Sites on the West Valley Fault Zone



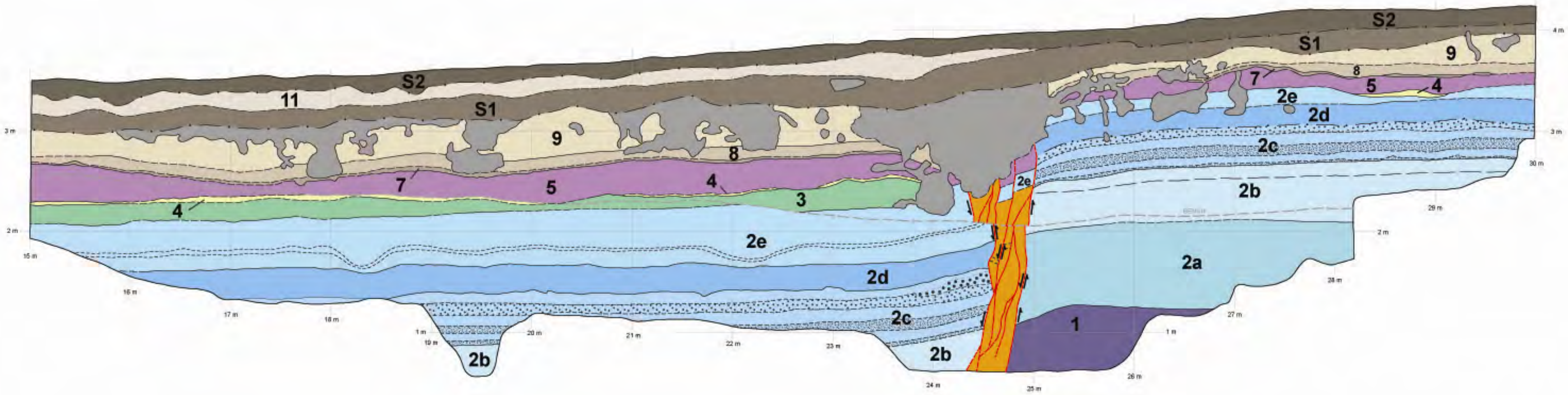
Baileys Lake Trench Site



LiDAR image from Utah Automated Geographic Reference Center (2006; 2 m, illumination from NW)

Baileys Lake West(S) Trench

South Wall

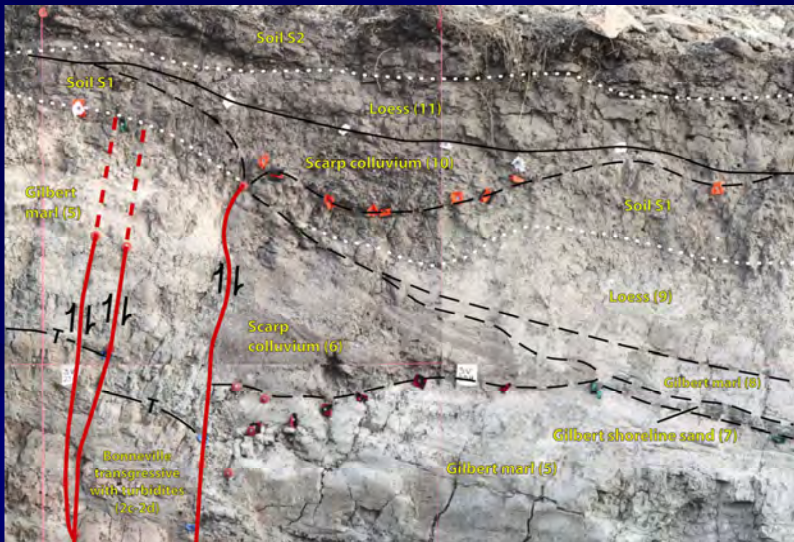


S2	Modern soil (A horizon)
S1	Buried soil (Bt horizon)
11	Loess (younger)
9	Loess (older)
8	Laminated marl (Gilbert phase)
7	Shoreline sand (Gilbert phase)
5	Laminated marl (Gilbert phase)
4	Shoreline tufa (Gilbert phase)
3	Bonneville laminated clay and silt (regressive)
2e	Bonneville clay (mid- to late transgressive)
2d	Turbidite marker bed
2c	Bonneville clay with turbidites (transgressive)
2b	Bonneville clay (transgressive)
2a	Bonneville sand, silt, clay (early transgressive)
1	Wetland/alluvial marsh (pre-Bonneville)
	Sheared sediment
	Burrowed sediment

Note: Units 6 and 10 are scarp-derived colluvial wedges associated with the two most recent surface-faulting earthquakes; not mapped on this log.

Geologic Evidence for 4* Paleoearthquakes

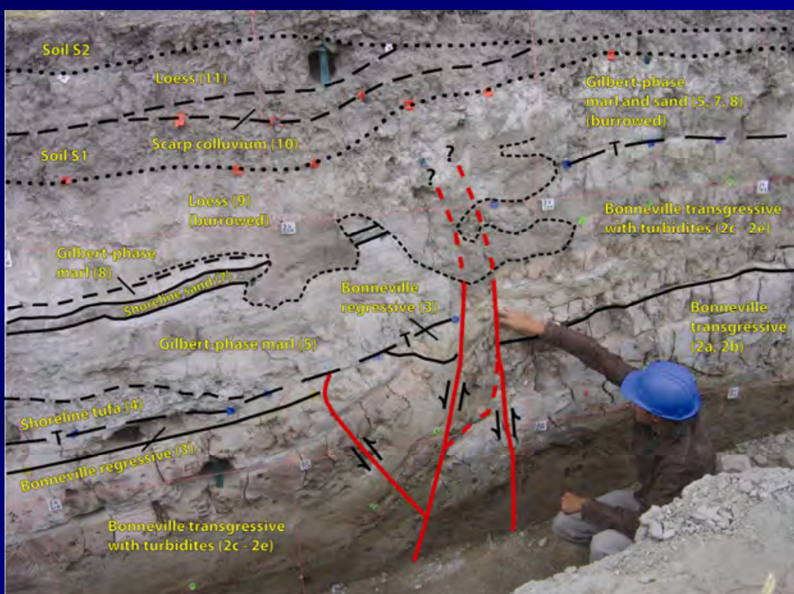
West(N) trench, north wall



	Evidence	Vertical Displacement (m)
BL1	Colluvial wedge, shear offset of unit 9 and older stratigraphy, warping	0.17 (max. wedge thickness) + 0.3 (warping) 0.47
BL2	Colluvial wedge, shear offset of unit 5 and older stratigraphy	0.5 (max. wedge thickness)

0.9 ± 0.2 m (post-13 ka)

West(N) trench, south wall



BL3	Fault-zone deformation, shear offset of unit 3 and older stratigraphy	~0.5 (av. per-event offset)
BL4	Warping of pre-unit 3 stratigraphy	~0.5 (av. per-event offset)

1.9 ± 0.2 m (post-18 ka)

* Broad warping (0.5 ± 0.1 m vertical offset) in East trench indicates 1(?) undated (but post-Bonneville) earthquake.

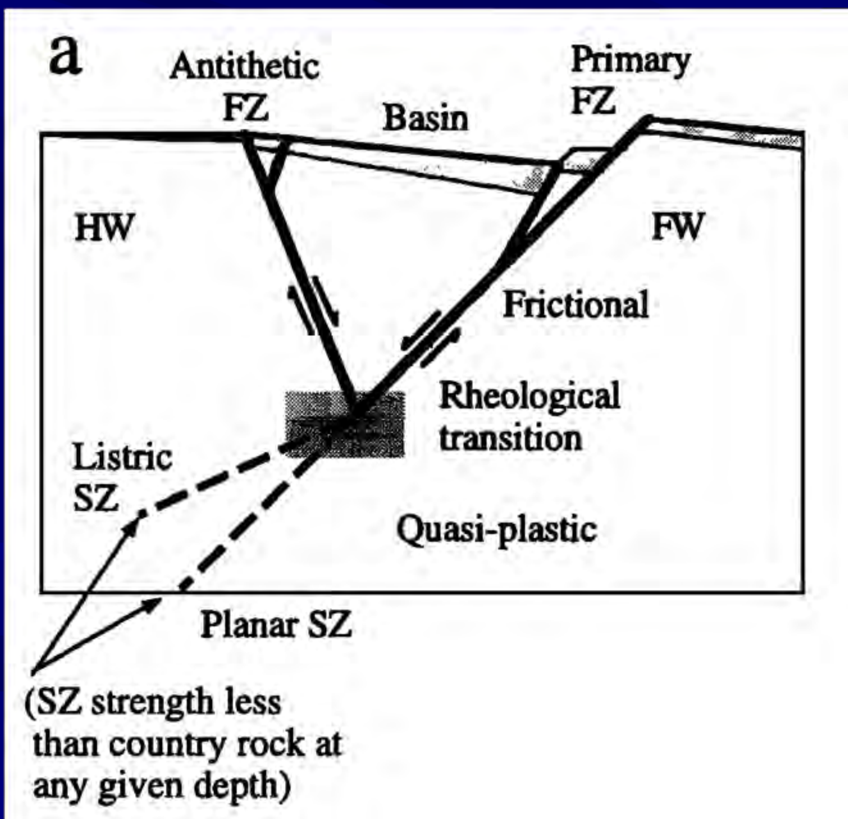
Comparison of WVFZ and SLCS Per-event Vertical Displacements

<u>West Valley Fault Zone</u>

0.5 0.1	Baileys Lake site
0.5 – 0.7	AGRA site (Solomon, 1998, UGS unpub. data)
1.2 – 1.5	(geomorphic evidence; Keaton and others, 1987)

<u>Salt Lake City Segment</u>

1.0   0.5 (S6; LCC, PD) to 2.0   1.2 (S1; LCC, SFDC)

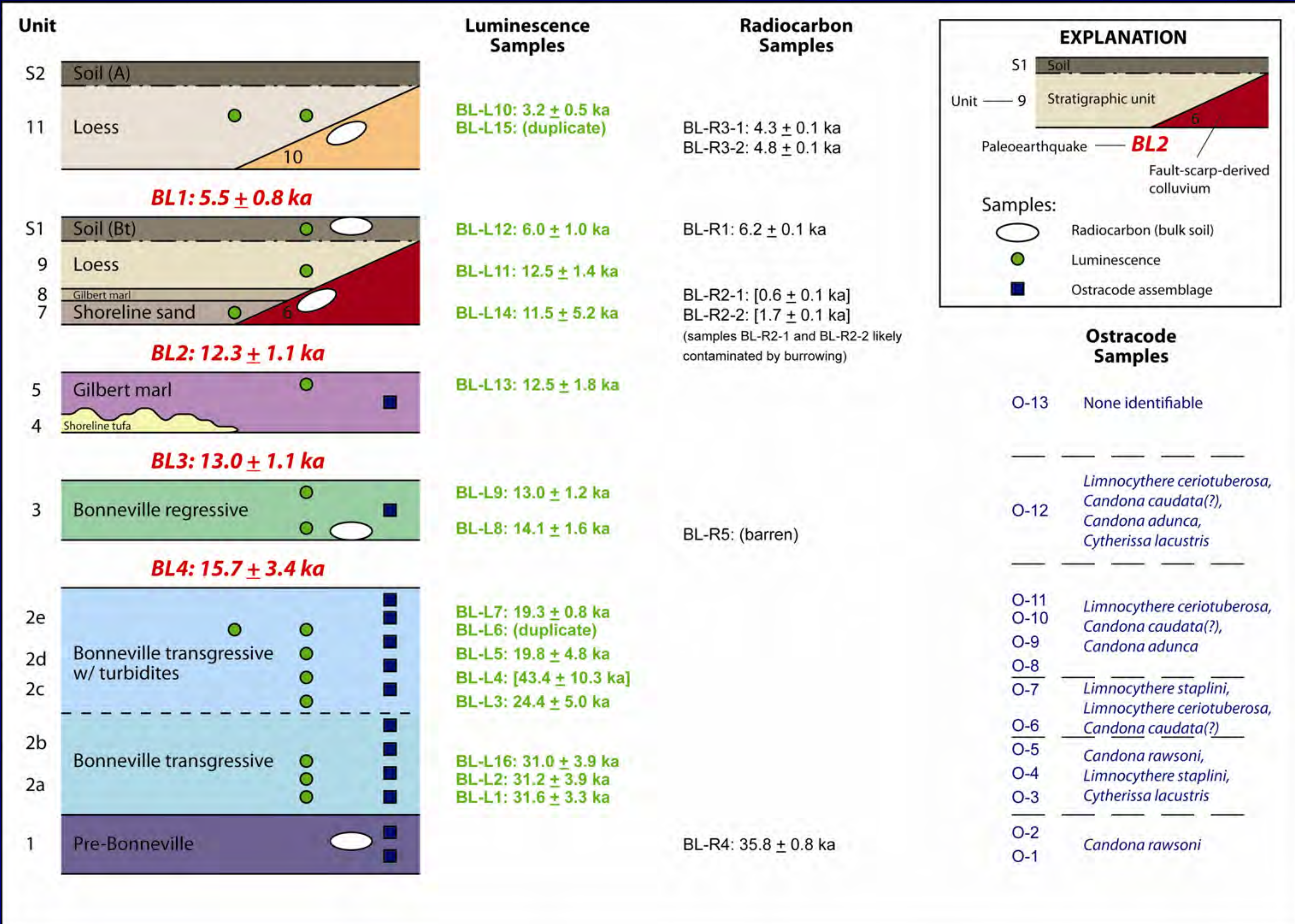


From Bruhn and Schultz (1996)

Two-dimensional boundary element modeling by Bruhn and Schultz (1996) showed that, on average, net slip and surface offset on antithetic faults was about 20–30% of the net slip on an underlying listric master fault.

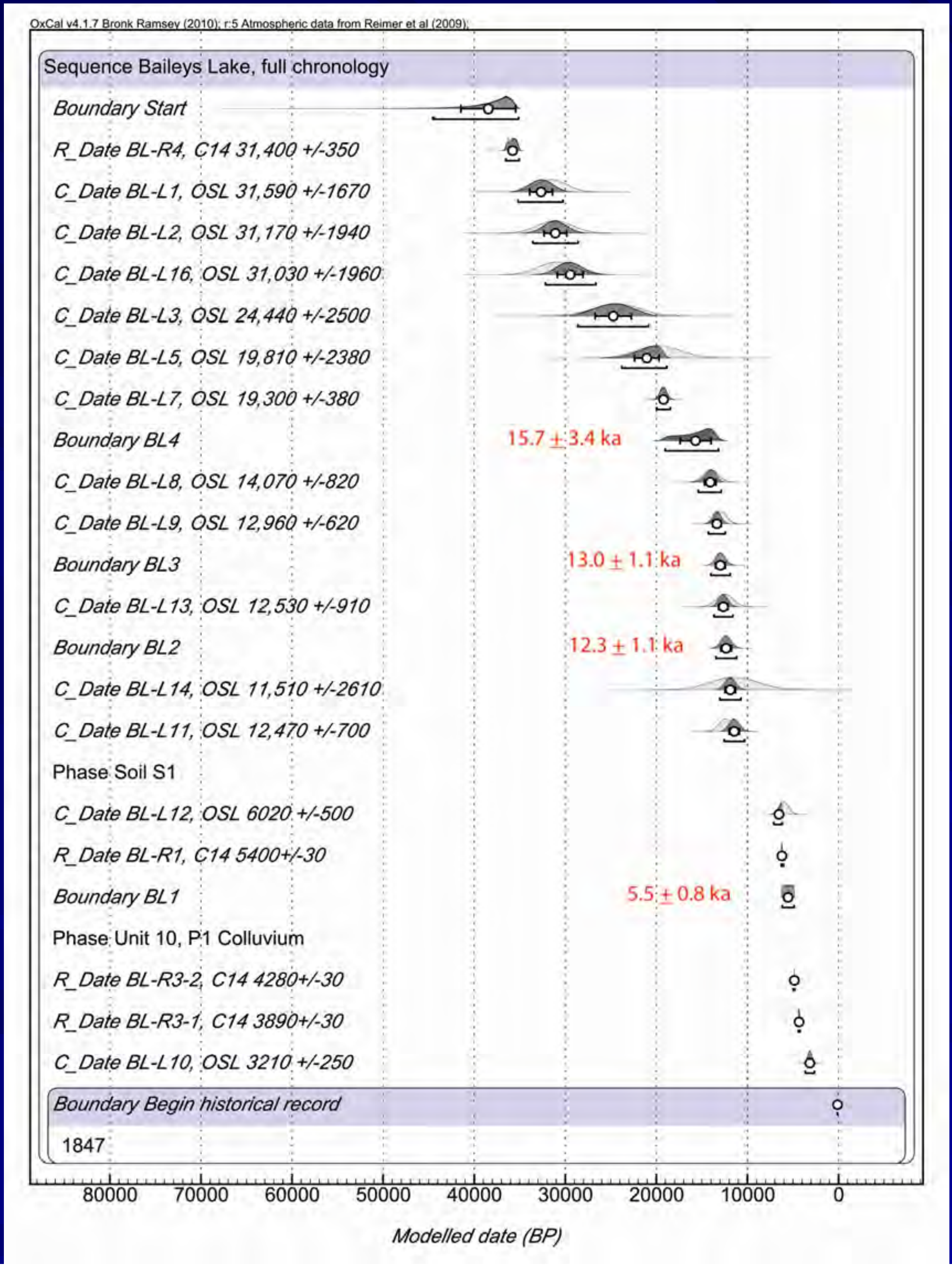
(1–2 m) x (0.20–0.30) = 0.2–0.6 m

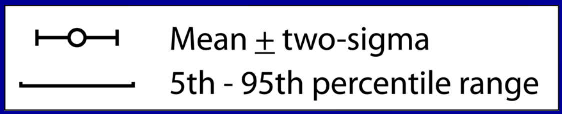
Baileys Lake Site – Chronostratigraphic Summary



Modeled earthquake times (red) and all numerical ages are reported with two-sigma uncertainty.

Baileys Lake Site – OxCal Model Results





Preliminary WVFZ Paleoearthquake Chronology and Recurrence

Preliminary chronology of surface-faulting earthquakes on the West Valley fault zone.

WVFZ Earthquake	Granger Fault (ka)	Taylorsville Fault (ka)	Preliminary Chronology (ka)	Inter-event RI (kyr)
W1	1.5 ± 0.2 (Terracon)		**1.5** (1.3–1.7)[1]	–
W2	–	1.9–2.4 (AGRA)[2]	**2.2** (1.9–2.4)	0.7 (W2-W1)
W3	5.5 ± 0.8 (BL1)	–	**5.5** (4.7–6.3)	3.3 (W3-W2)
W4	12.3 ± 1.1 (BL2)	–	**12.3** (11.2–13.4)	6.8 (W4-W3)
W5	13.0 ± 1.1 (BL3)	–	**13.0** (11.9–14.1)	0.7 (W5-W4)
W6	15.7 ± 3.4 (BL4)	–	**15.7** (12.3–19.1)	2.7 (W6-W5)
Interval	**Elapsed Time (kyr)**	**No. Intervals**	**Mean RI (kyr)**	**Notes**
W3-W1	4.0	2	2.0	mid-Holocene (<6 ka)
W4-W1	10.8	3	3.6	latest Pleistocene–Holocene (<13 ka)
W5-W1	11.5	4	2.9	post-Provo shoreline (<14 ka)
W6-W1	14.2	5	2.8	post-Bonneville highstand (<18 ka)

[1] Mean and two-sigma uncertainty of minimum limit on earthquake time.
[2] Data from Solomon (1998) and unpublished Utah Geological Survey files.
RI = recurrence interval.

Latest Pleistocene–Holocene (post-13 ka) RI estimates of Keaton and others (1987):

- 2.6–6.5 kyr (Granger fault; 1 to 5 events)
- 1.8–2.2 (WVFZ as a whole; 6 to 7 events)

Comparison of WVFZ and SLCS Paleoearthquake Chronologies

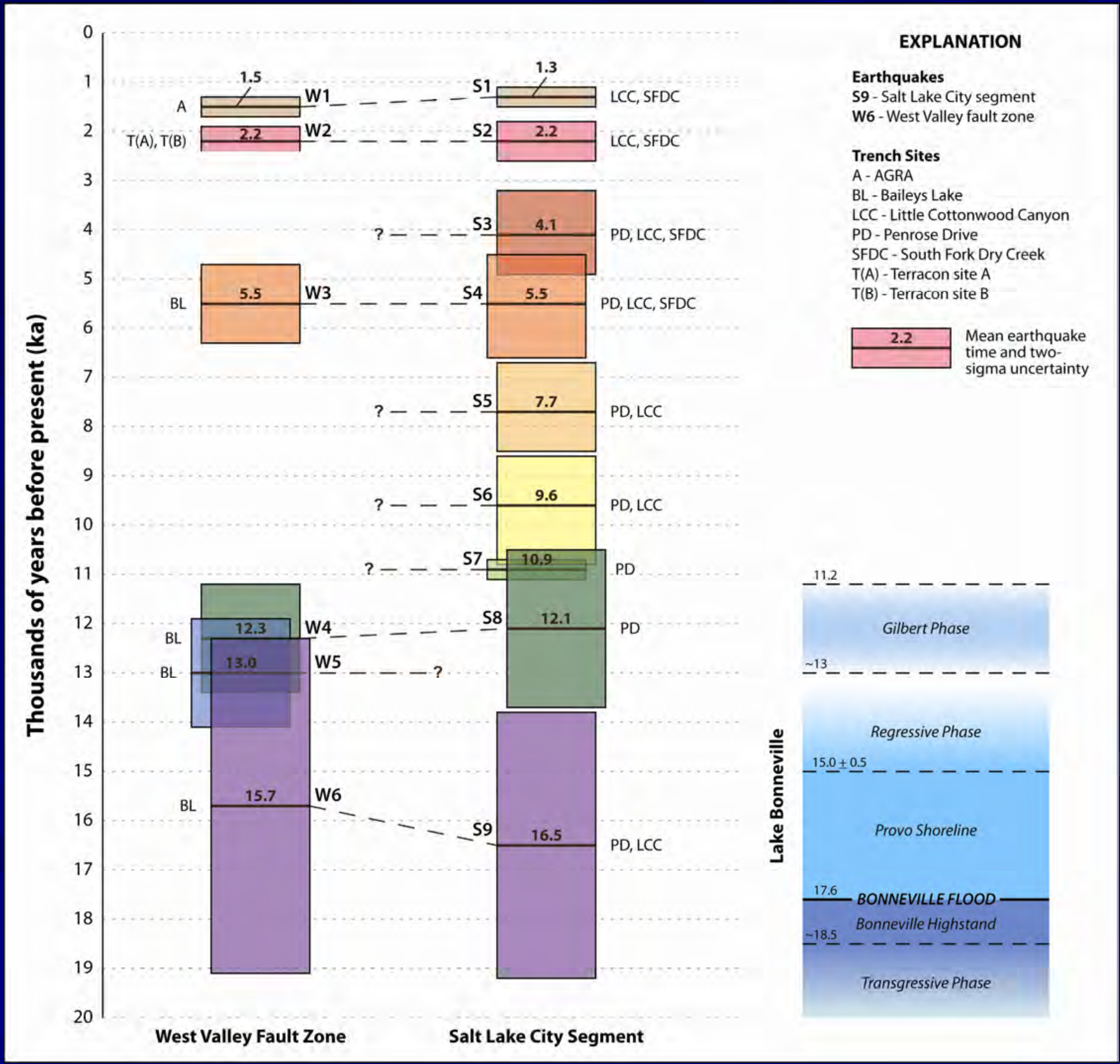
Comparison of Salt Lake City segment and West Valley fault zone earthquakes.

Preliminary SLCS chronology (ka)				**Preliminary WVFZ chronology (ka)**				**Difference in means[1] (kyr)**	**Overlap at 2σ[2] (%)**
Event	Mean	Min	Max	Event	Mean	Min	Max		
S1	**1.3**	1.1	1.5	**W1**	**1.5**	1.3	1.7	0.2	33%
S2	**2.2**	1.8	2.6	**W2**	**2.2**	1.9	2.4	0	63%
S3	**4.1**	3.2	4.9	-	-	-	-	-	-
S4	**5.5**	4.5	6.6	**W3**	**5.5**	4.7	6.3	0	76%
S5	**7.7**	6.7	8.5	-	-	-	-	-	-
S6	**9.6**	8.6	10.8	-	-	-	-	-	-
S7	**10.9**	10.7	11.1	-	-	-	-	-	-
S8	**12.1**	10.5	13.7	**W4**	**12.3**	11.2	13.4	0.2	69%
-	-	-	-	**W5**	**13.0**	11.9	14.1	-	-
S9	**16.5**	13.8	19.2	**W6**	**15.7**	12.3	19.1	0.8	98%

[1] Difference in mean earthquake times.

[2] Percent overlap in 2σ earthquake time ranges. For example, 33% overlap in the timing of S1 and W1 is based on the 0.2-kyr overlap in the time ranges (1.3–1.5 kyr) divided by the 0.6 kyr min-max elapsed time for both events (1.1–1.7 kyr).

Comparison of WVFZ and SLCS Paleoearthquake Chronologies



Baileys Lake Site – Paleoseismic Summary

Baileys Lake site shows evidence of at least 4 large earthquakes

Earthquake timing:

- BL4 – Warping event during Provo phase of Bonneville lake cycle (15.7 ± 3.4 ka)
- BL3 – Surface faulting during Bonneville lowstand just prior to the Gilbert transgression (13.0 ± 1.1 ka)
- BL2 – Surface faulting during latter part of Gilbert lake cycle (12.3 ± 1.1 ka)
- BL1 – Surface faulting during the mid-Holocene (5.5 ± 0.8 ka)
- Broad warping in East trench indicates 1(?) undated (but post-Bonneville) earthquake; may or may not correlate with BL1

Earthquake recurrence:

- 0.7–6.8 kyr (inter-event)
- 3.4 kyr (BL4–BL1 mean)

Vertical displacement:

- 0.9 ± 0.2 m (post-13 ka)
- 1.9 ± 0.2 m (post-18 ka)
- Average per-event vertical displacement 0.5 ± 0.1 m

Slip rate:

- 0.06–0.09 mm/yr (post-13 ka)
- 0.09–0.12 mm/yr (post-18 ka)

Baileys Lake Site – Paleoseismic Summary

Distributed nature of faulting (i.e., multiple strands) complicates slip rate and recurrence estimates, and comparisons with the SLCS

Modeled timing of four latest Pleistocene–Holocene earthquakes on the WVFZ (W1–W4) agree very well with timing of SLCS events, and timing of a fifth latest Pleistocene earthquake (W6) is similar to a SLCS event

- Large WVFZ earthquakes are likely dependent on SLCS fault movement (coseismic or triggered)

Searching for Evidence of Seismic Events in Lacustrine Sediments of Utah Lake

Quincy Nickens, Ron Harris, Mitchell Power, Anthony Macharia, Steve Nelson, Terik Daly, Yujiro Ogawa

Advantages

- Advantages of using lacustrine sediments over sediments in trenches across active faults
  - Constant sedimentation record
  - Higher age resolution
  - Lacustrine sediments are more deformable
  - Lacustrine sediments have the potential to record seismic events that do not rupture the surface
  - Lake sediments extend the seismic record more than three times

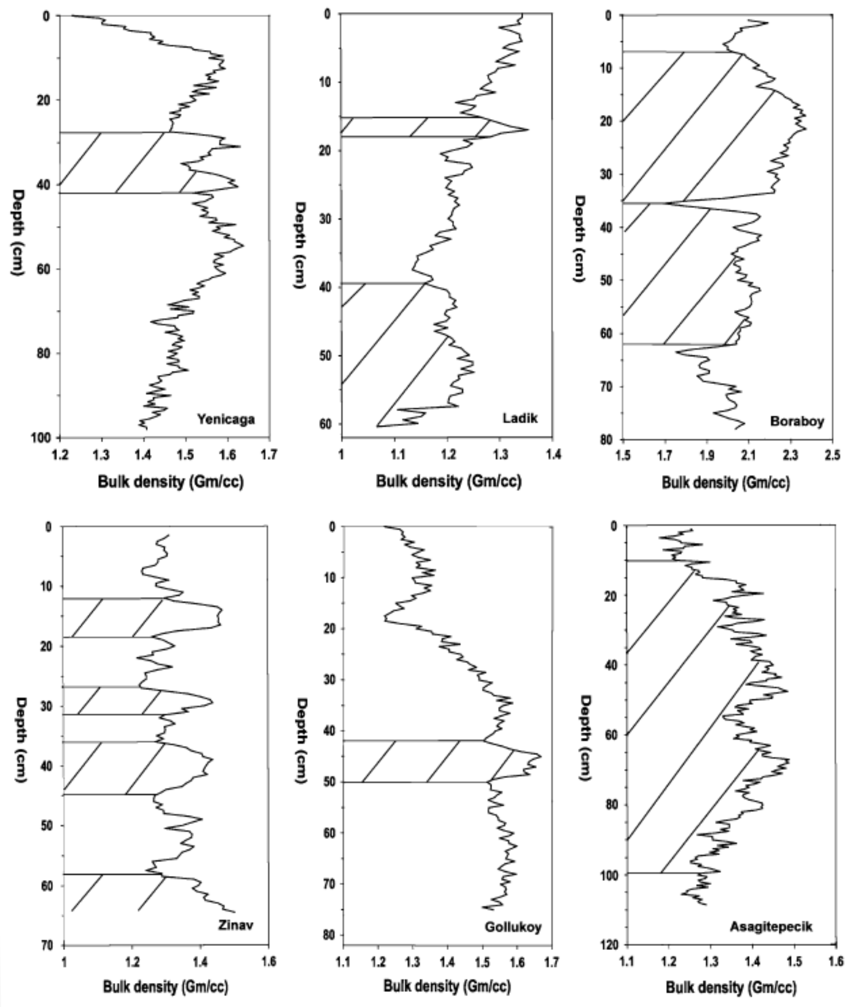
Methods

- Establish a Chronology for lake sediments
  - Tephrachronology/magnetic susceptibility
  - Radiometric (14C) and Isotopic Ages (Pb210)
- Sedimentation Rates (corrected for compaction)
- Density Variations
  - North Anatolian Fault , Turkey (Boës et al., 2010)
  - Lake Suigetsu, central Japan (Kawakami et al., 1996)
  - Lake Lucerne, central Switzerland (Schnellmann et al., 2002)
- Soft sediment deformation
  - Seismites
  - Liquefaction
  - Ball and pillow structures
  - etc

North Anatolian Fault, Turkey

(Boës et al., 2010)

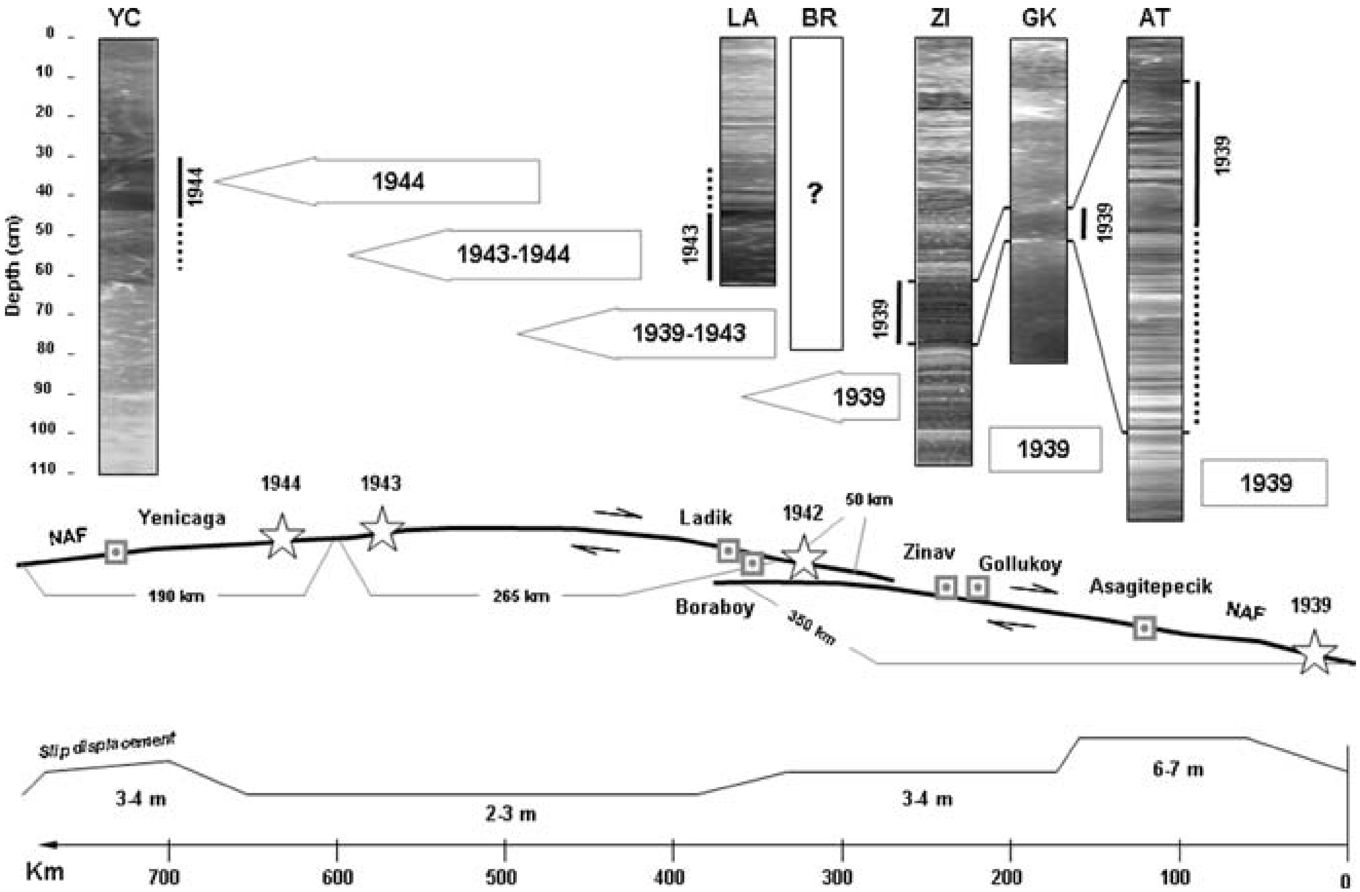
North Anatolian Fault, Turkey



- Historical Sources
- Distance from epicenter
  - 17 – 340 km
- Lacustrine Sediment Cores
  - Magnetic Susceptibility
  - X-ray
  - XRF
  - Bulk (gamma-ray) Density
- Radionuclide Analysis
  - ^{210}Pb
  - ^{226}Ra
  - ^{137}Cs

(Boës et al., 2010)

North Anatolian Fault, Turkey

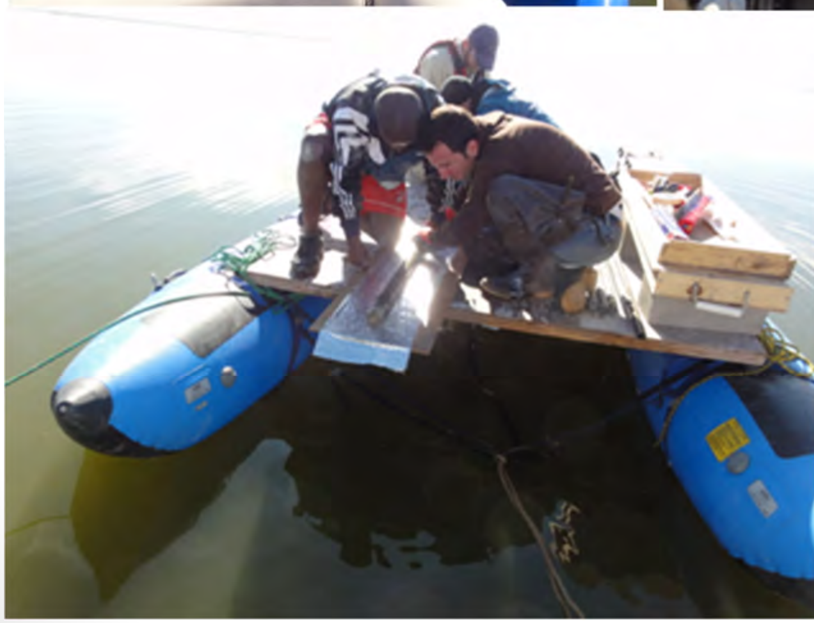
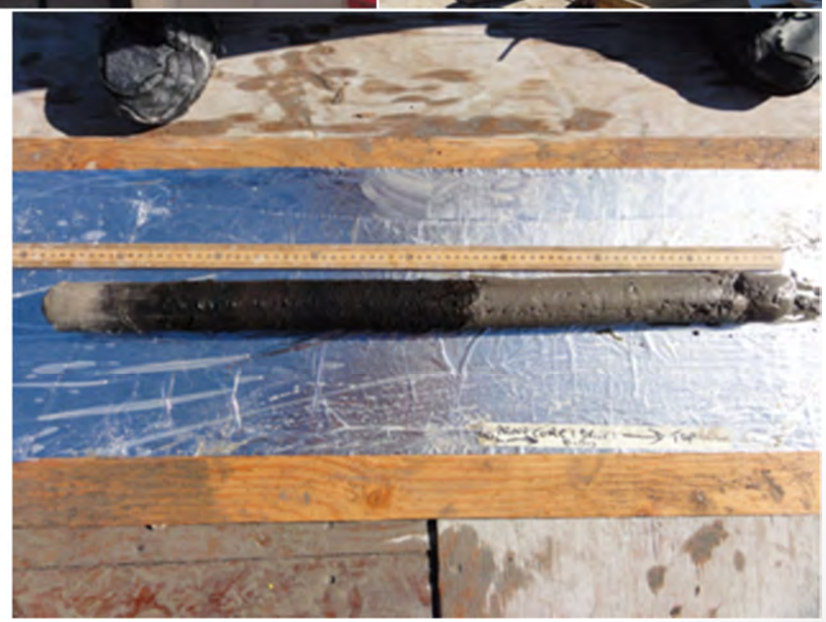


(Boës et al., 2010)

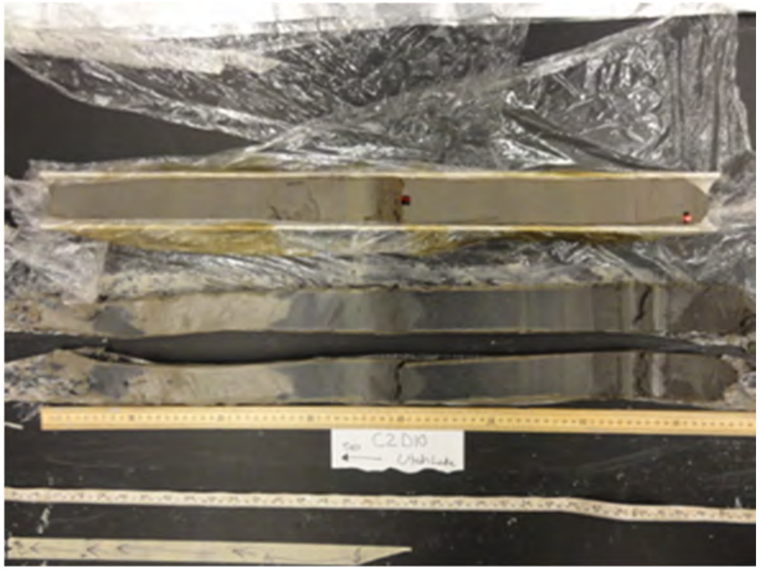
Sample Collection

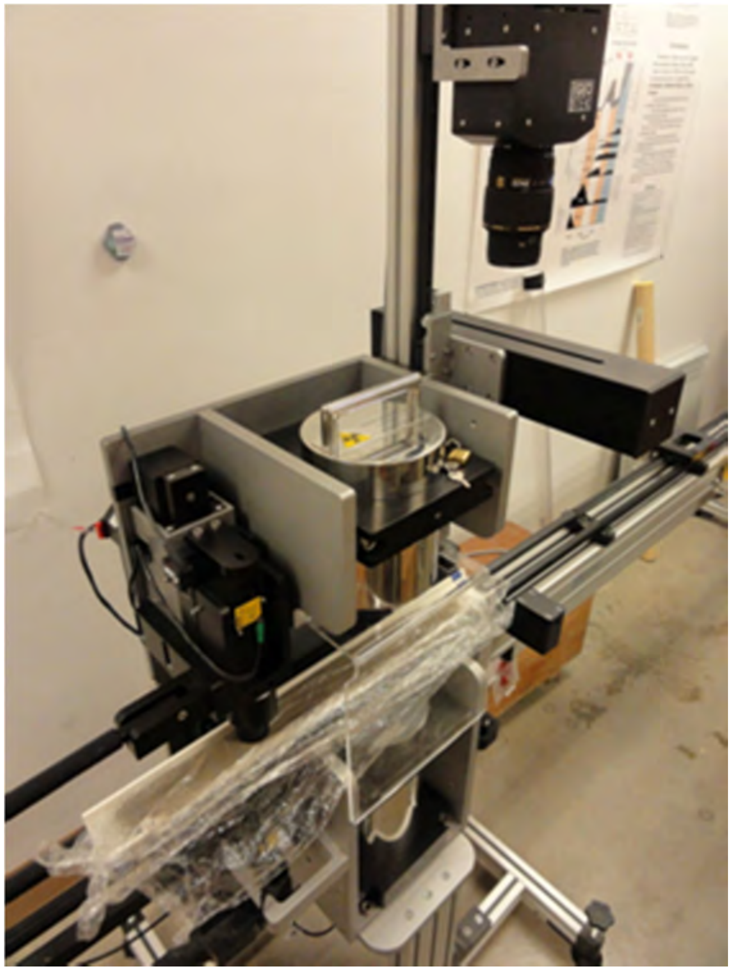
Coring Methods



Logging cores





Labs Involved

- Core Analysis
  - Utah Museum of Natural History, University of Utah
    - Mitchell Power, Anthony Macharia
  - The Shuman Laboratory, University of Wyoming
    - Bryan Shuman
- Radiometric Ages
  - Isotope Laboratory, BYU
    - Pb210/14C – Steve Nelson, Terik Daly
  - University of Georgia
    - C14, AMS

Mid-lake Core

150 yrs (Pb210) .3 m

3959 ± 26 yrs (14C) 1.5 m

7545 ± 75 yrs 3.0 m*
Mazama

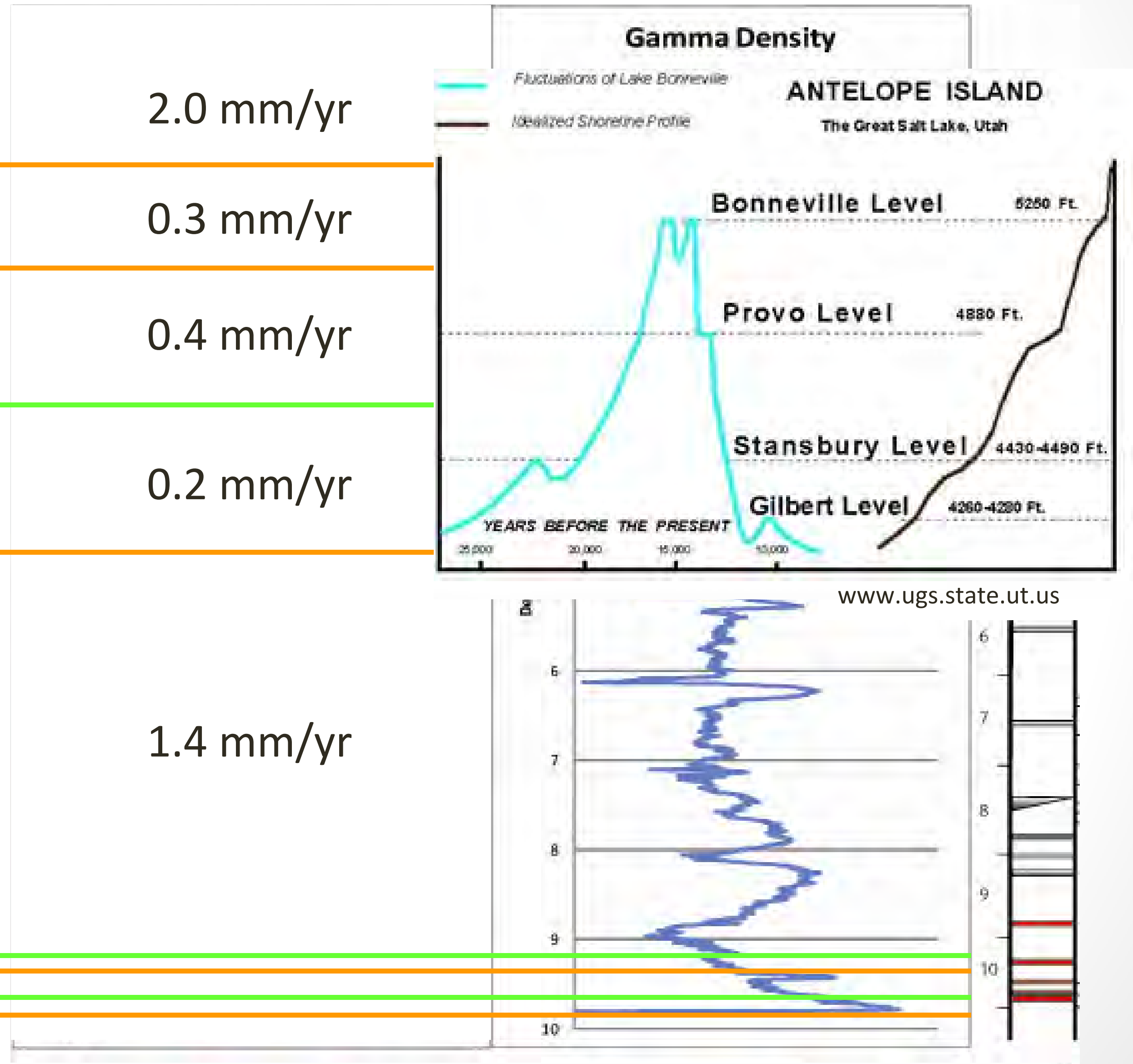
14933 ± 39 yrs (14C) 4.7 m

18200 yrs 9.4 m*
Bed A Summer Lake

18434 ± 47 yrs (14C) 9.5 m

22900 yrs 9.7 m*
Mount St. Helens

25443 ± 101 yrs (14C) 9.8 m



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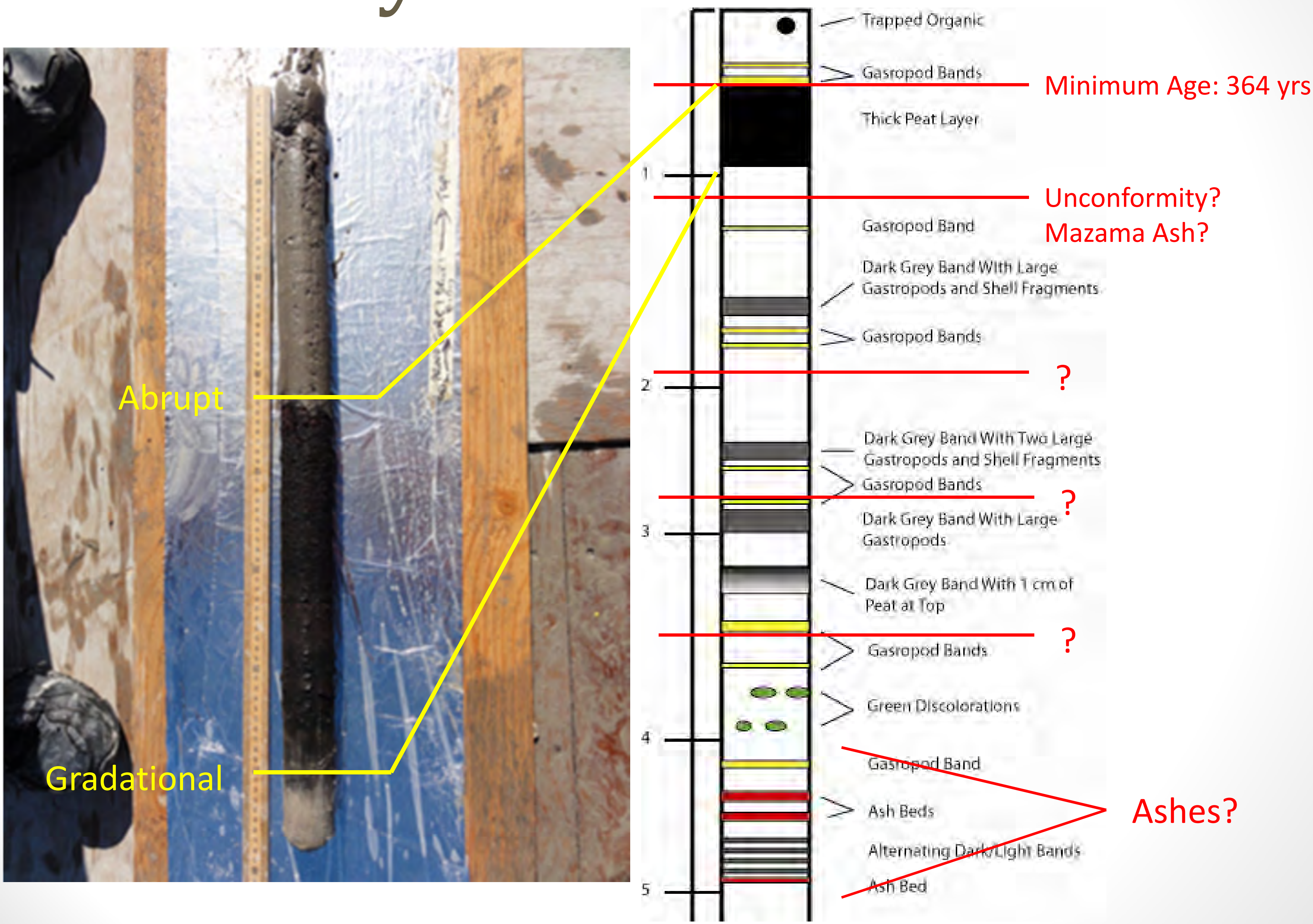
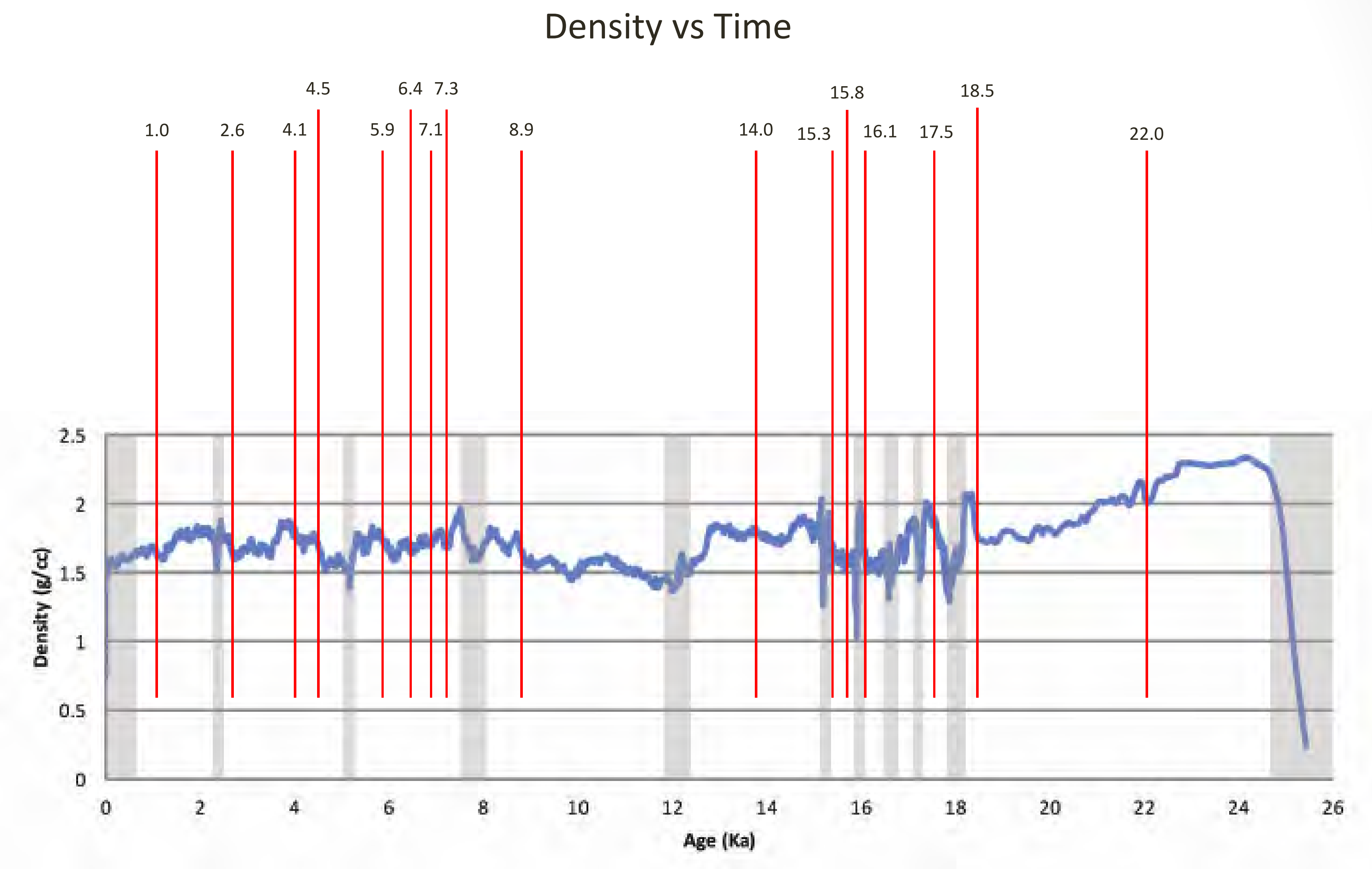
* Ash Ages from Kuehn and Begrini 2010

Provo Bay Core

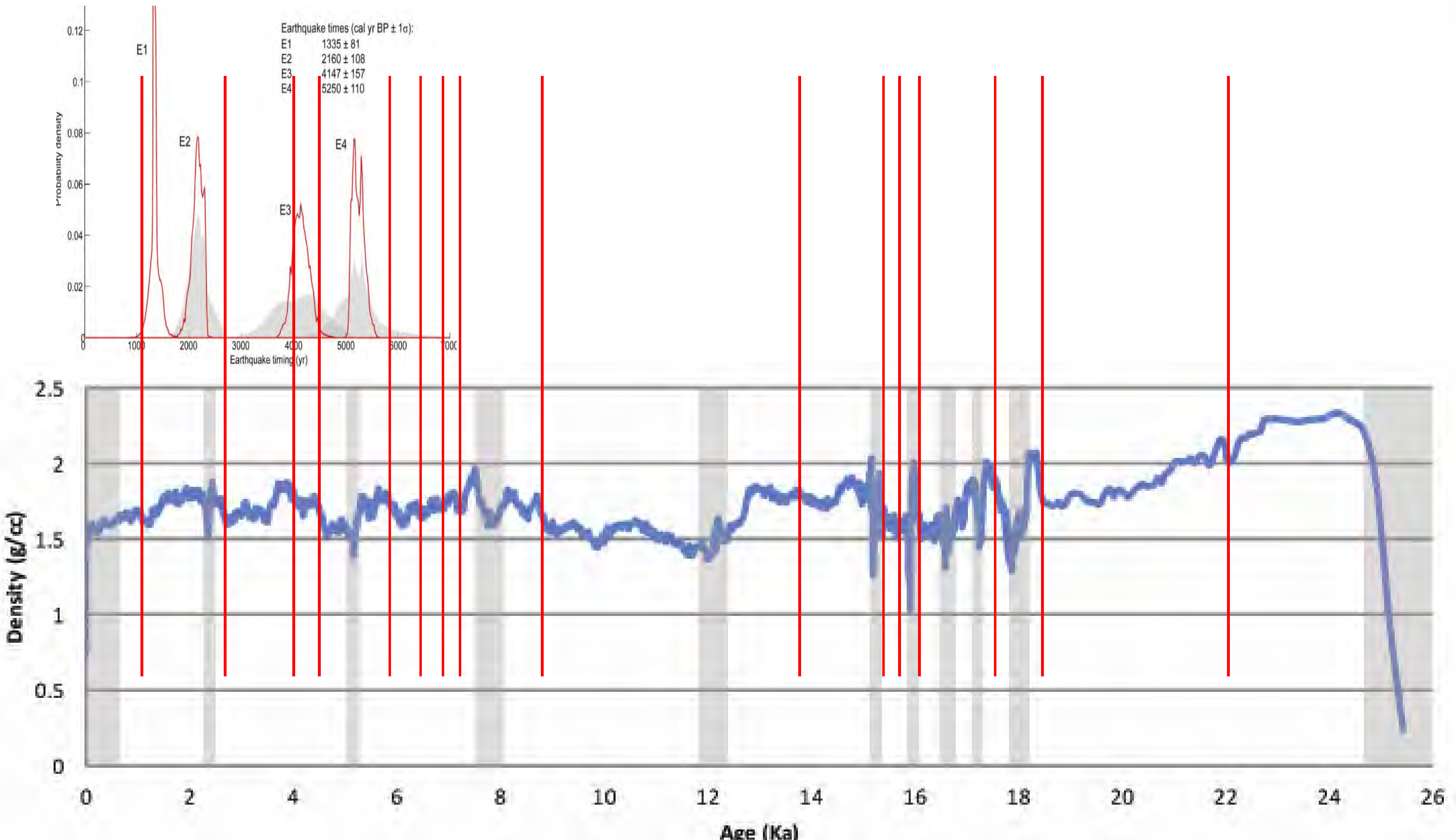


Density Anomalies



Density Anomalies

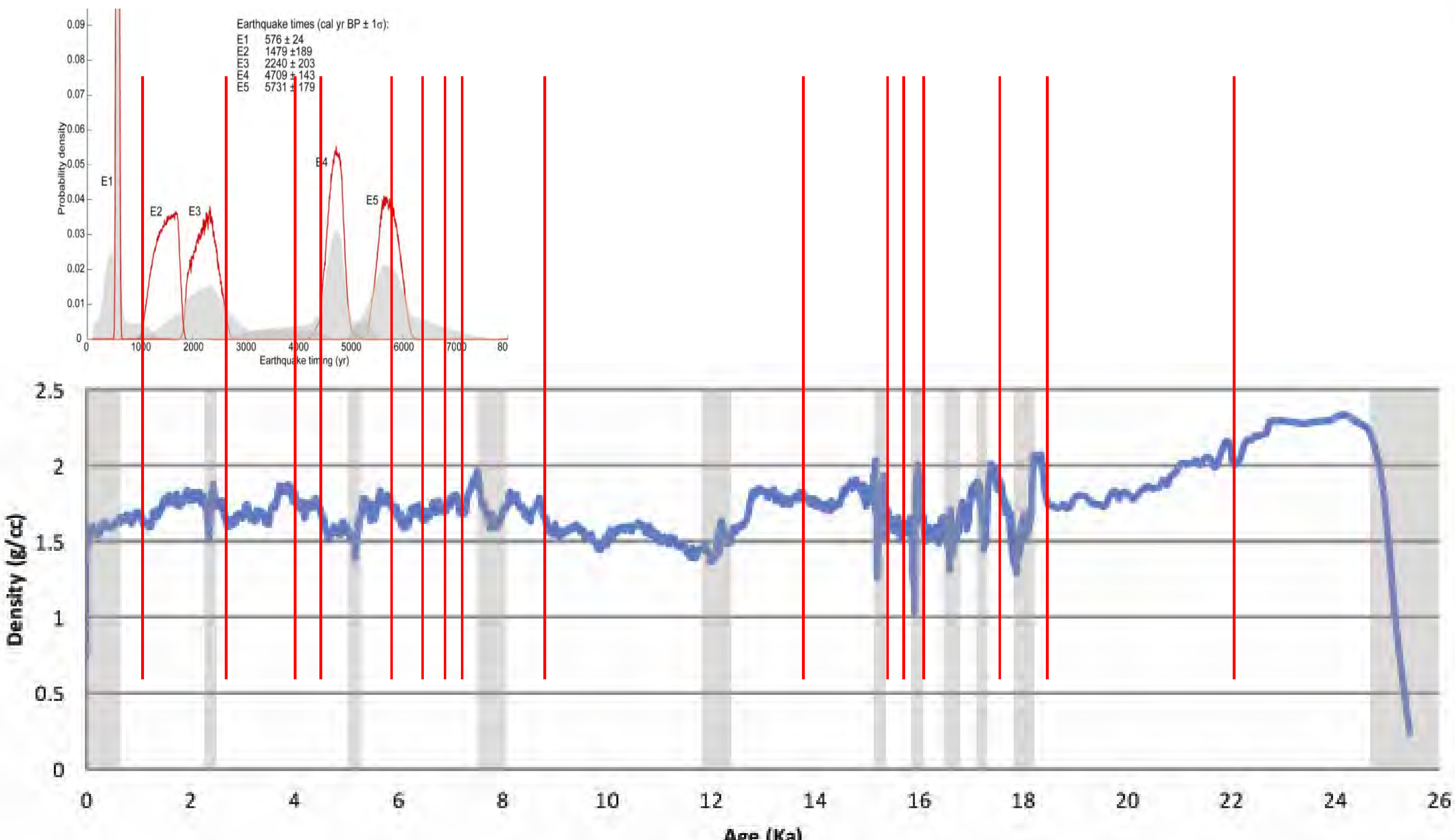
Salt Lake Segment



* Trench Data after Chris Duross

Density Anomalies

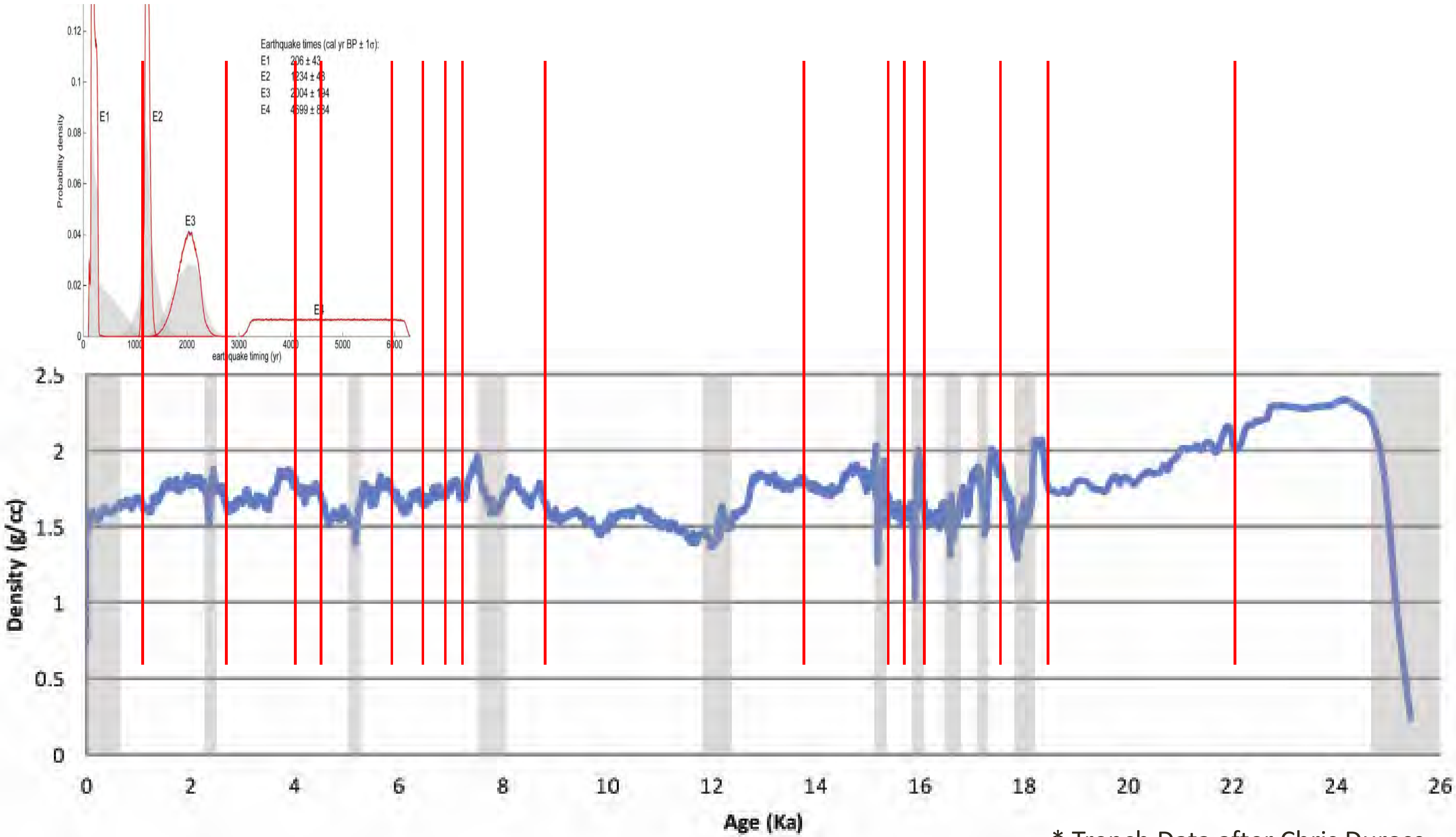
Provo Segment



* Trench Data after Chris Duross

Density Anomalies

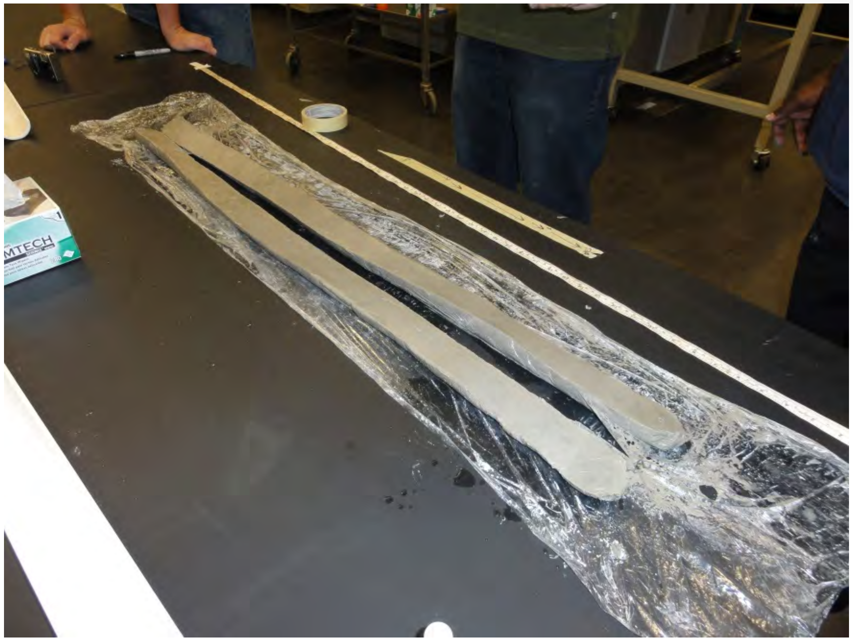
Nephi Segment

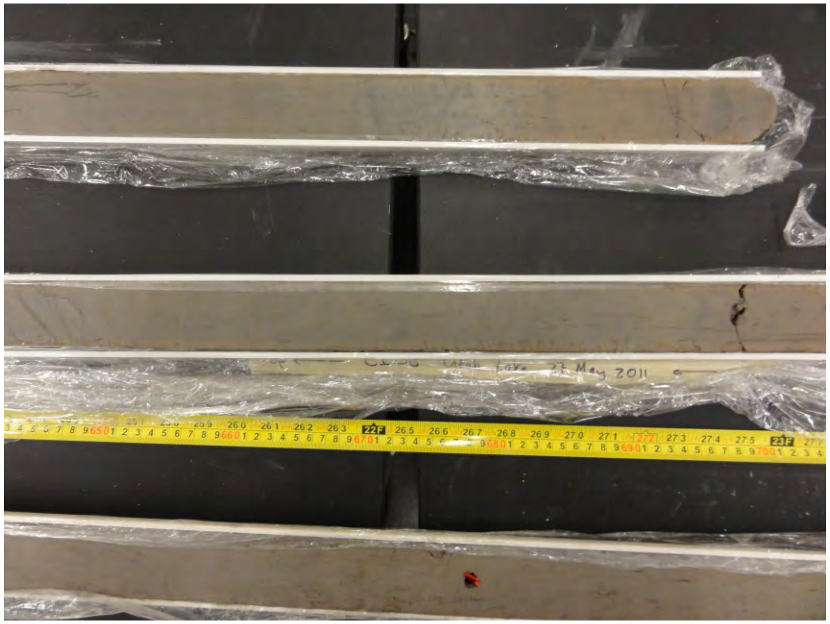


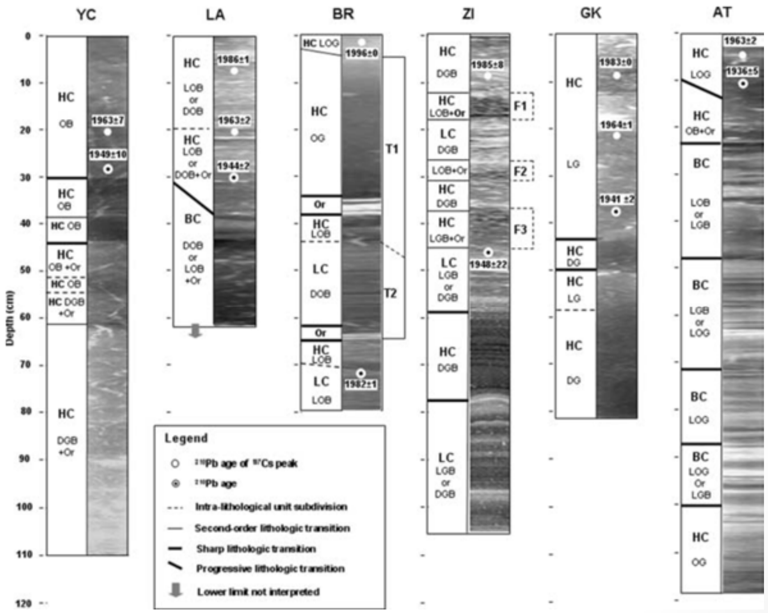
* Trench Data after Chris Duross

Future Work

- X-Ray
- Log Provo Bay Core
- GPR
- Cores and Logs







(Boës et al., 2010)

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Hurricane Cliffs Hydropower and Lake Powell Pipeline Preliminary Quaternary Fault Investigations

Dean Ostenaa, Sean Sundermann,
Dan O'Connell, Jamey Turner, Seth Dee,
and Jason Altekruse

UQFPWG
February 15, 2012

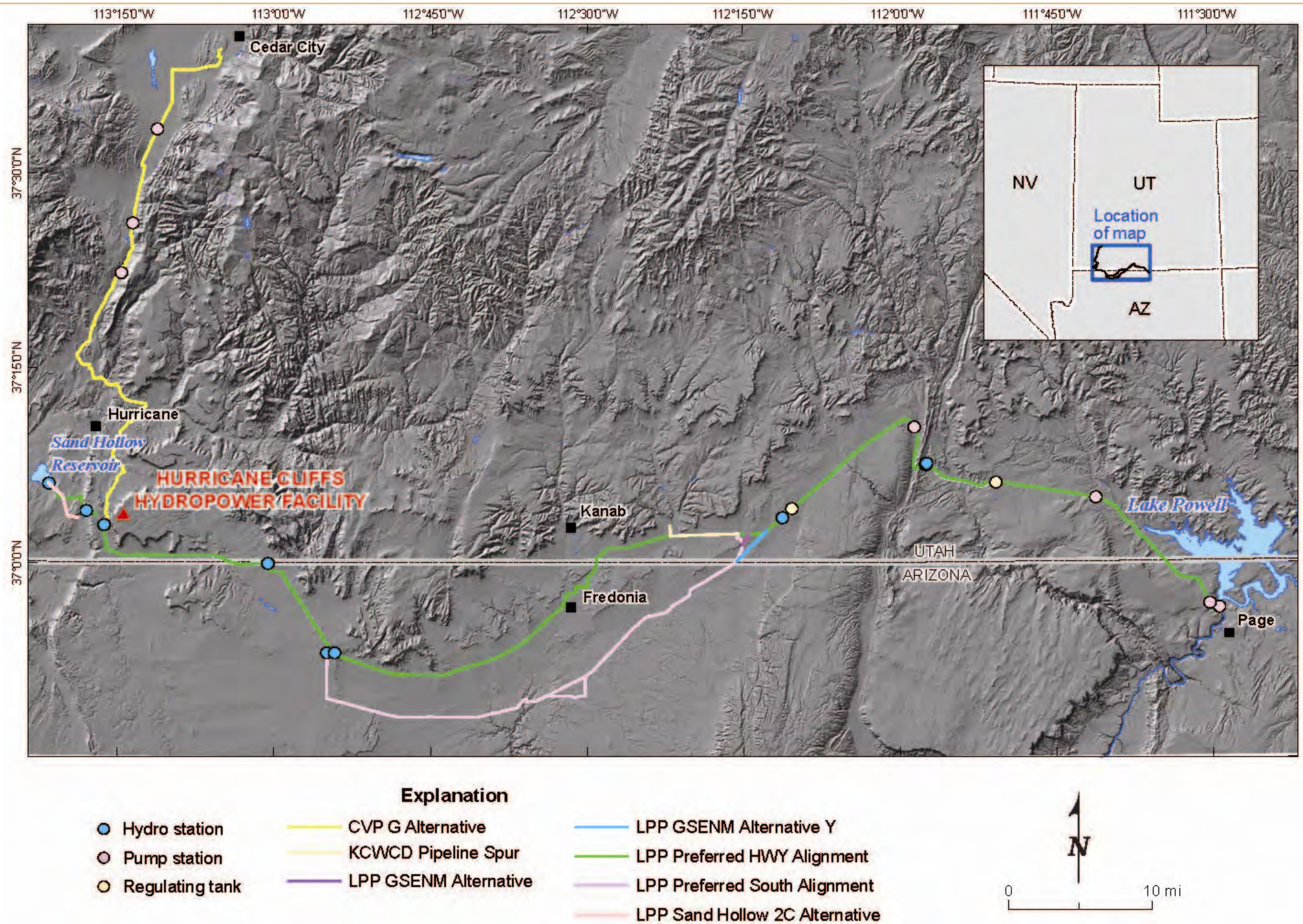
Overview of Study Purpose

- Conducted for MWH Americas – prime contractor to Utah Department of Water Resources
  - Acknowledgments to Todd Loar and Pat Naylor (MWH Americas); and Brad Price and Micheal Hansen (RB&G Engineering)
  - Conducted from Nov 2008 to Dec 2009
- Lake Powell Pipeline is a proposed water conveyance system from Glen Canyon Reservoir to St. George, UT (Sand Hollow Reservoir)
  - Approximately 130 miles long
  - Feasibility studies include several alternative alignments
    - Spur pipeline along Hurricane fault to Cedar City
  - Includes 300 Mw pumped storage facility on Hurricane Cliff
- Initial studies conducted to support engineering analyses for FERC pre-license application
  - Identify and characterize geologic hazards; specifically fault crossing displacement hazards
  - Assist in Hurricane Cliffs Hydropower site investigations with geologic mapping and geophysical investigations

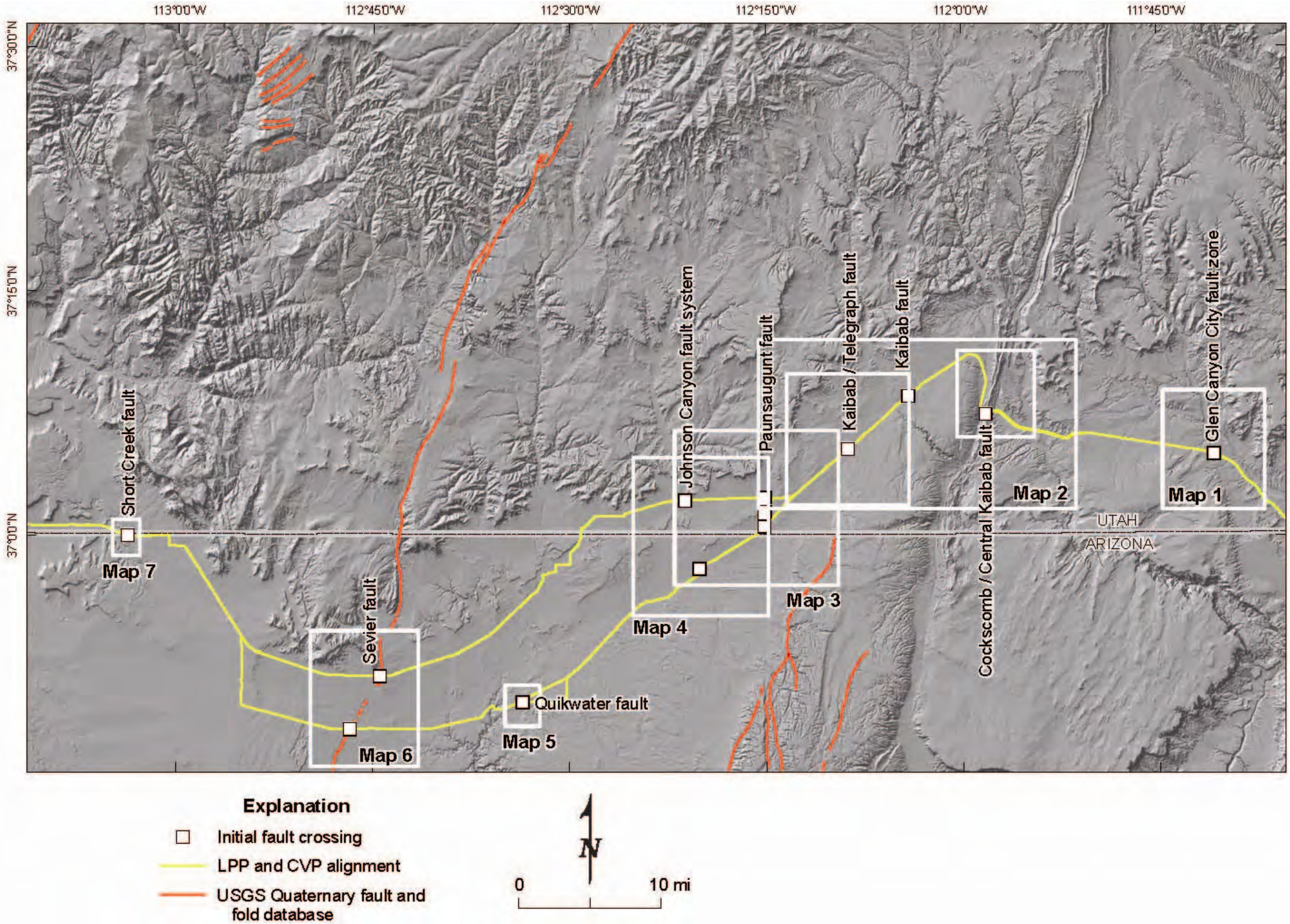
Lake Powell Pipeline Scope

- Lake Powell Pipeline
  - Primarily desktop study with limited imagery review and field reconnaissance
  - Initial review identified 48 potential fault crossings among alternative alignments
  - Preliminary characterizations considered
    - Crossing location confidence (low to high)
    - Rupture assessment (low to high significance)
    - Basis for consideration of mitigation measures if needed
  - Provided preliminary seismic source characterizations for initial seismic design assessments of project facilities

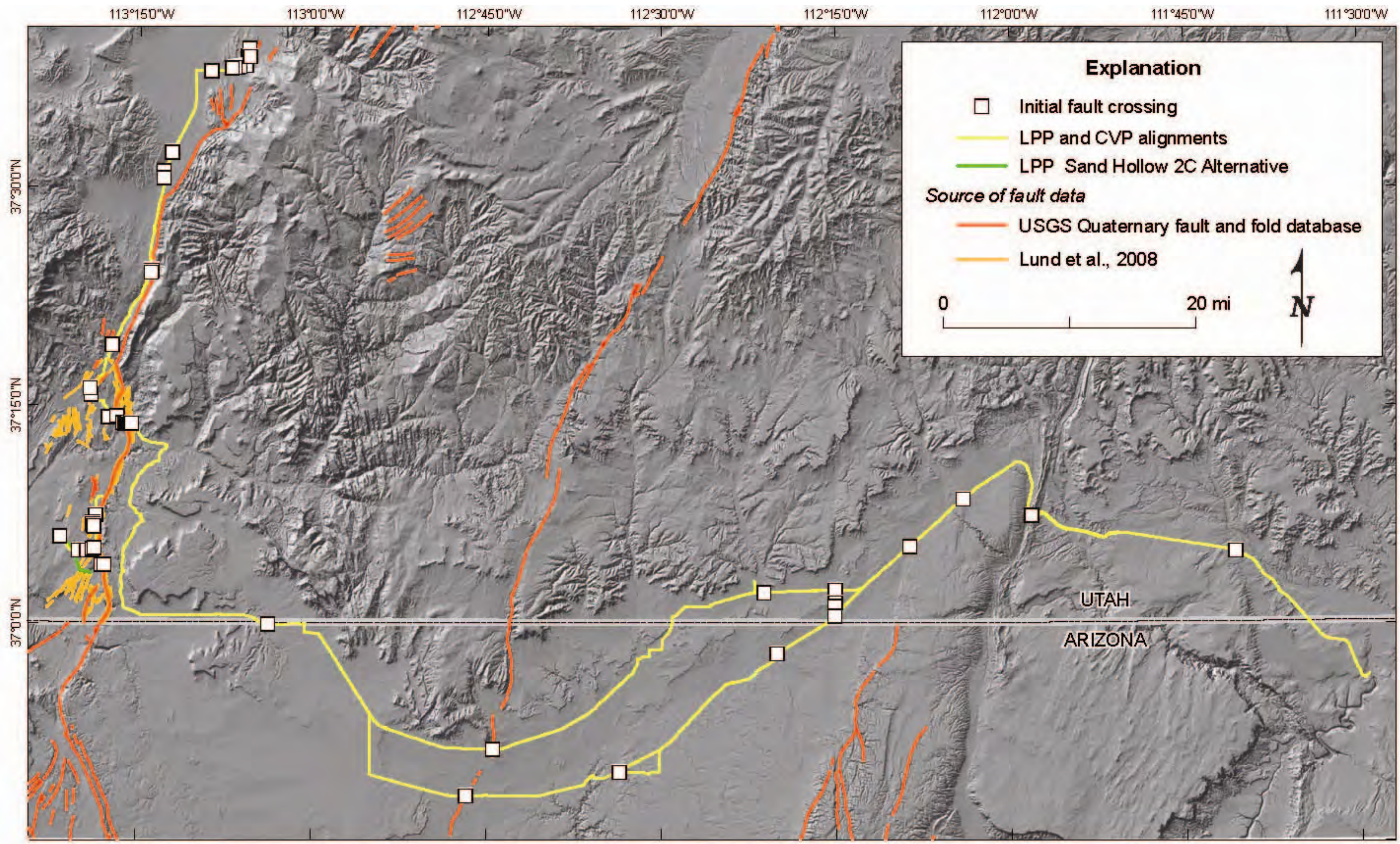
Location and Major Components



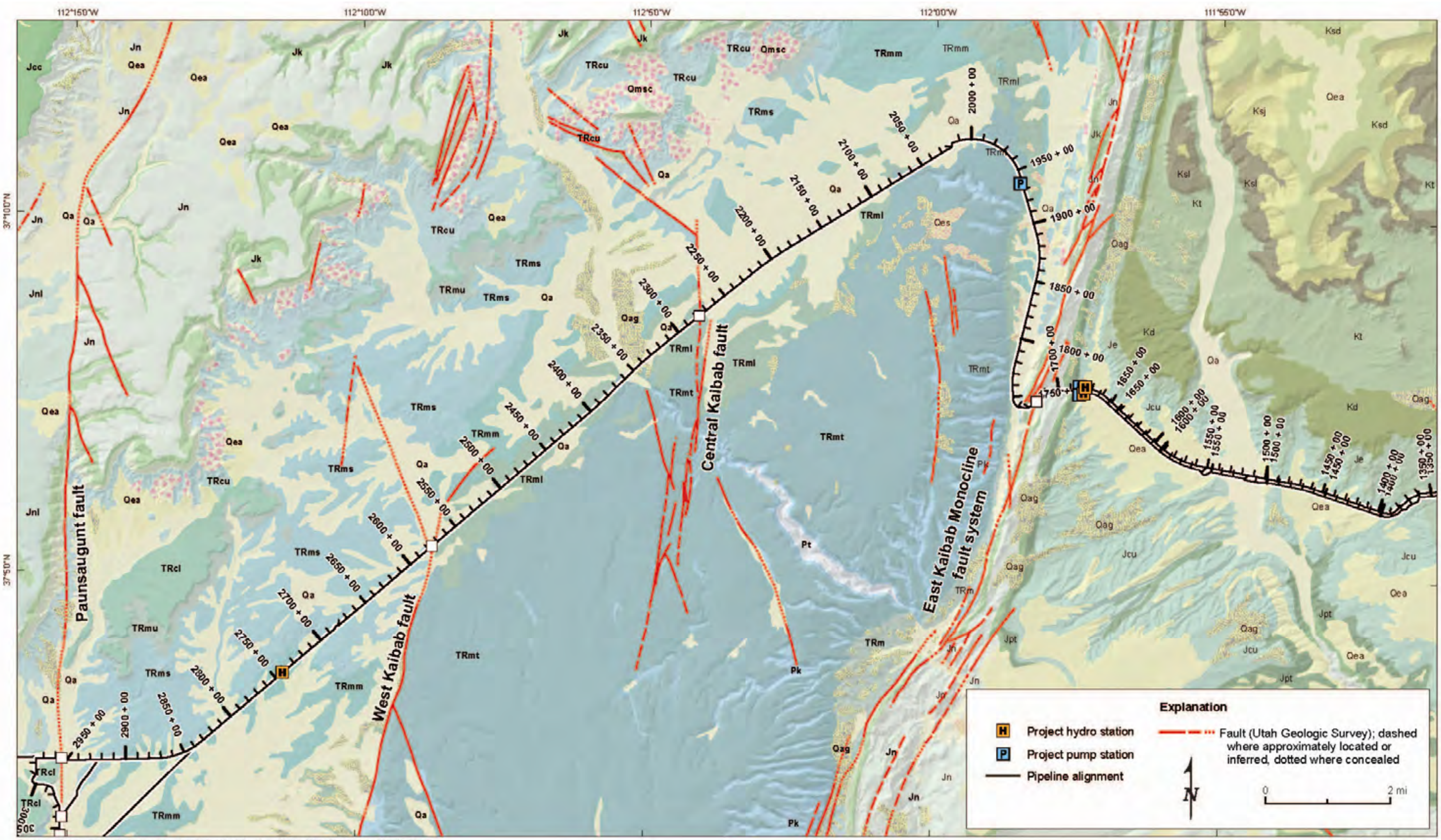
USGS Quaternary faults and LPP Crossing Locations



LPP and CVP Alternatives fault crossings

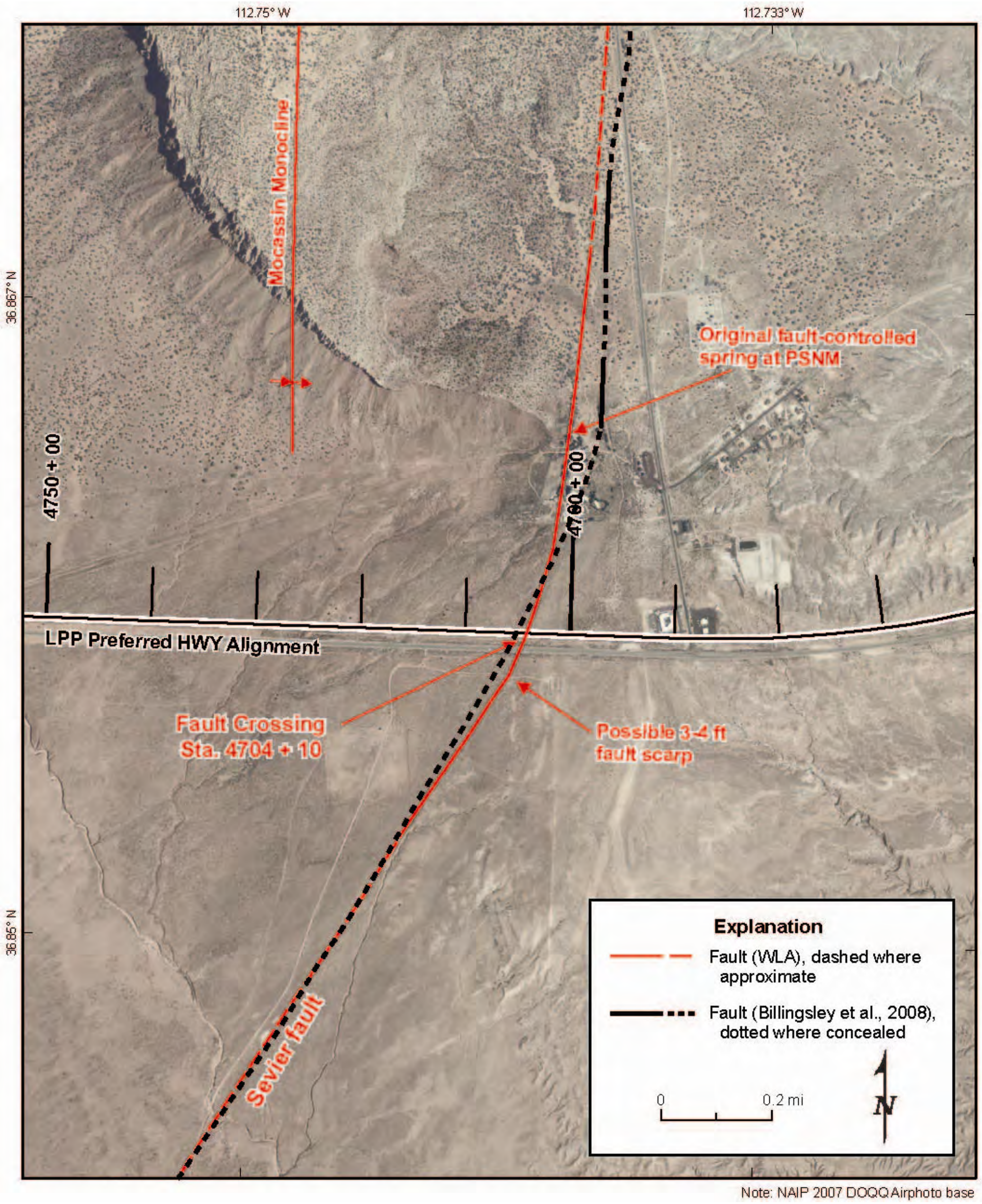


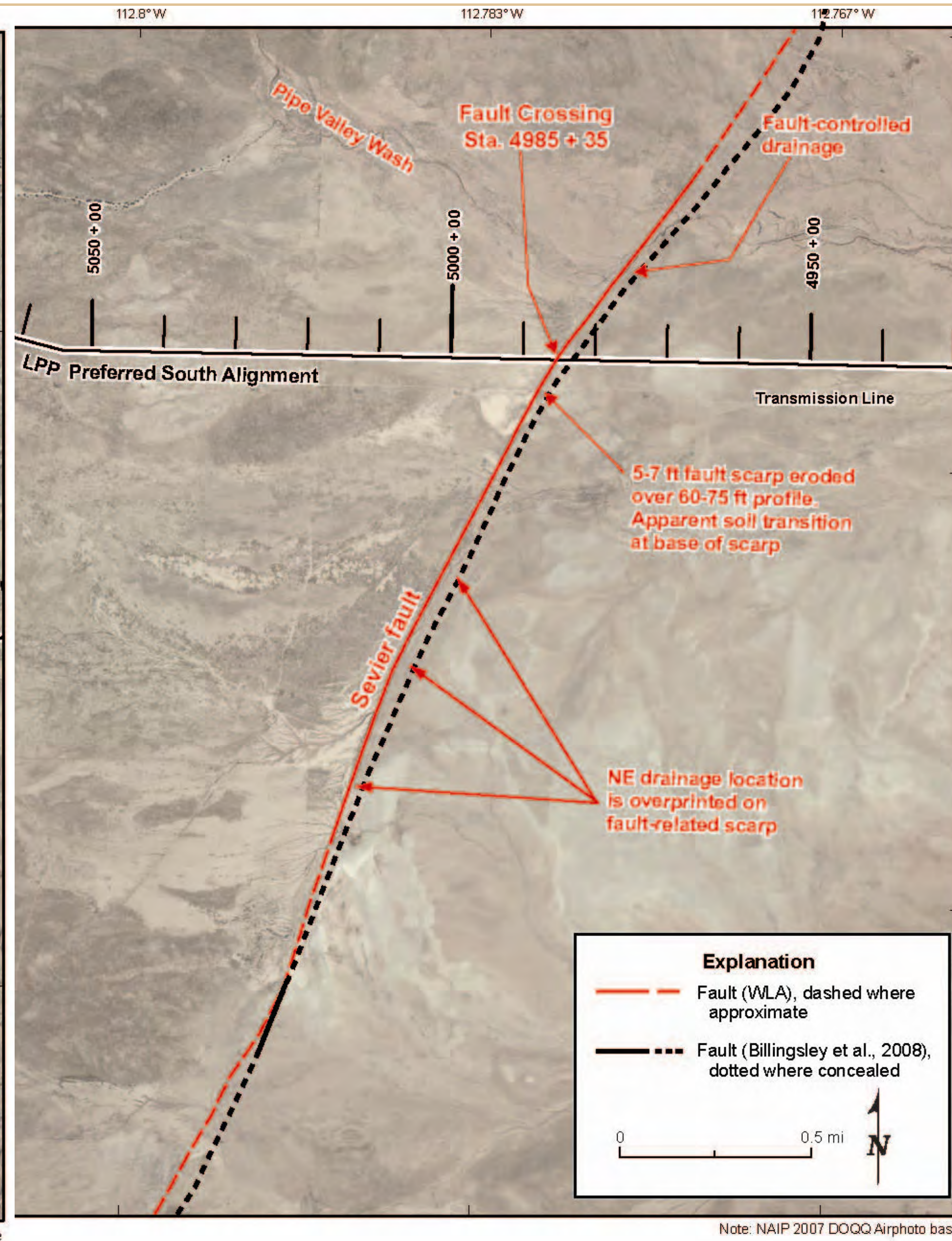
Northern Kaibab Uplift Crossings



Geology: Kanab, 2008; 100k; Doelling, 2008 / Smoky Mountain, 2006; 100k; Doelling and Willis, 2006

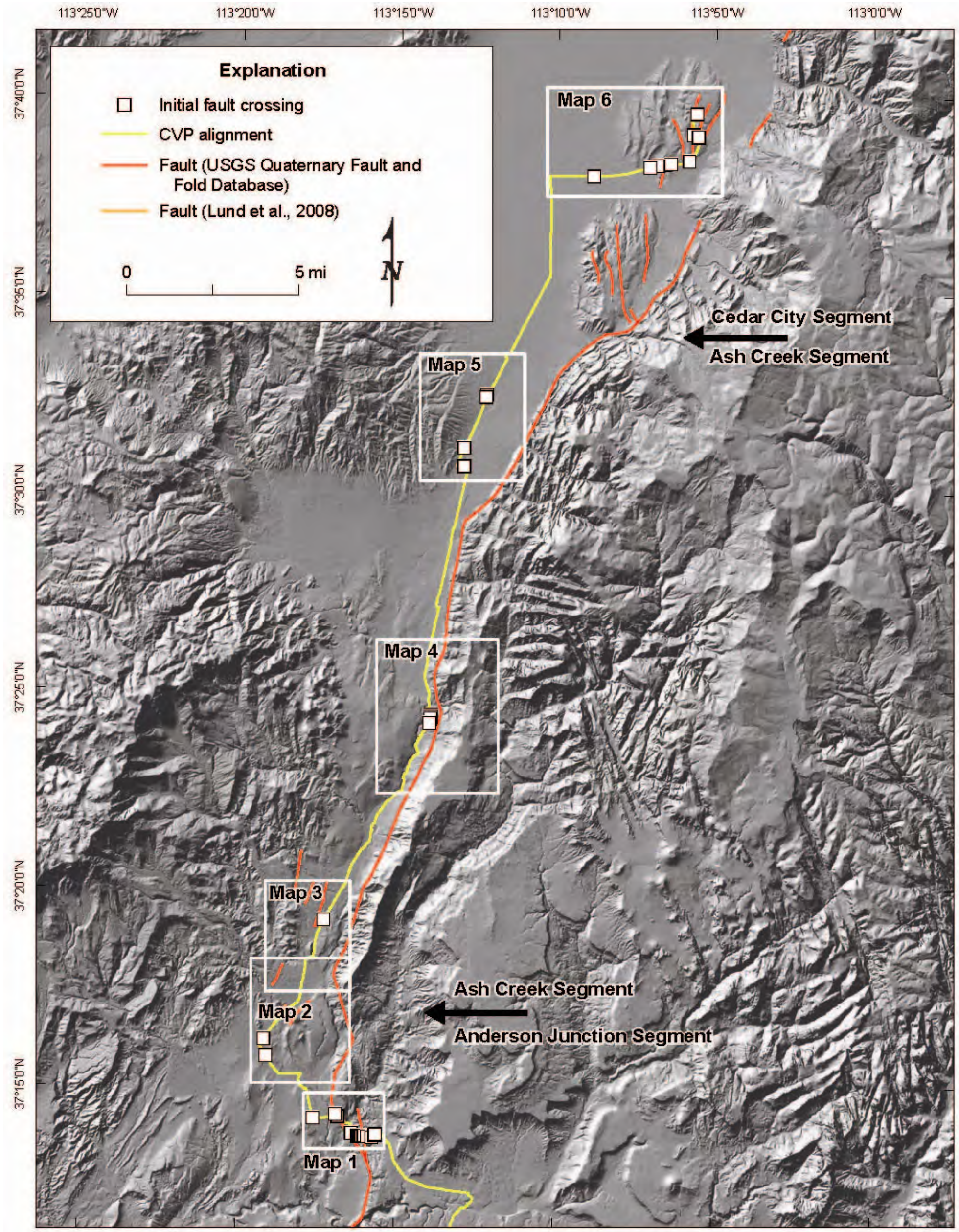
Sevier fault in Northern Arizona



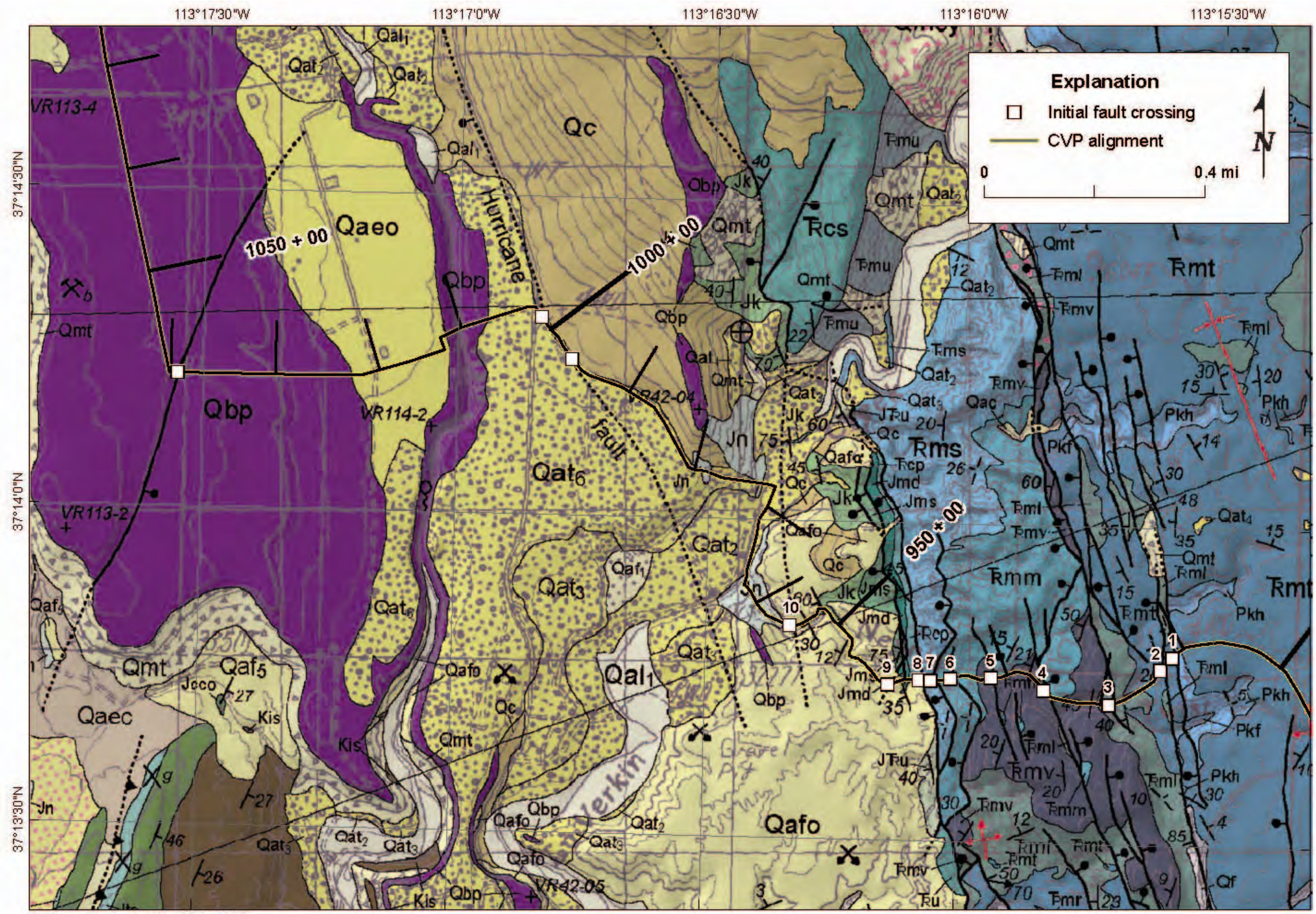


Cedar Valley Pipeline Alternative

- Crosses Hurricane fault in complex zone near northern end of Anderson Junction segment
- Crosses many un-named secondary faults on the hangingwall of the Hurricane fault



Complex Crossing of Hurricane fault



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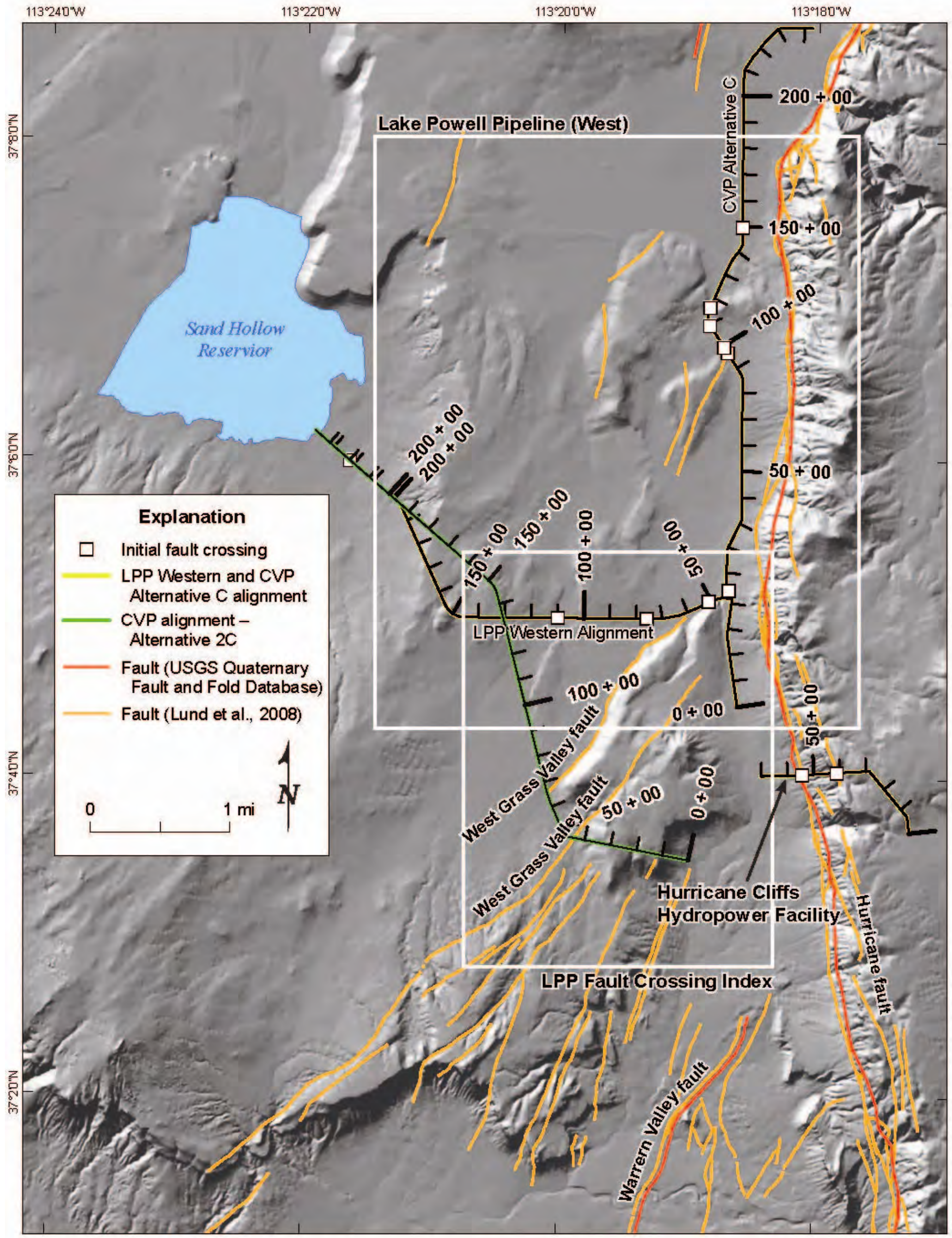
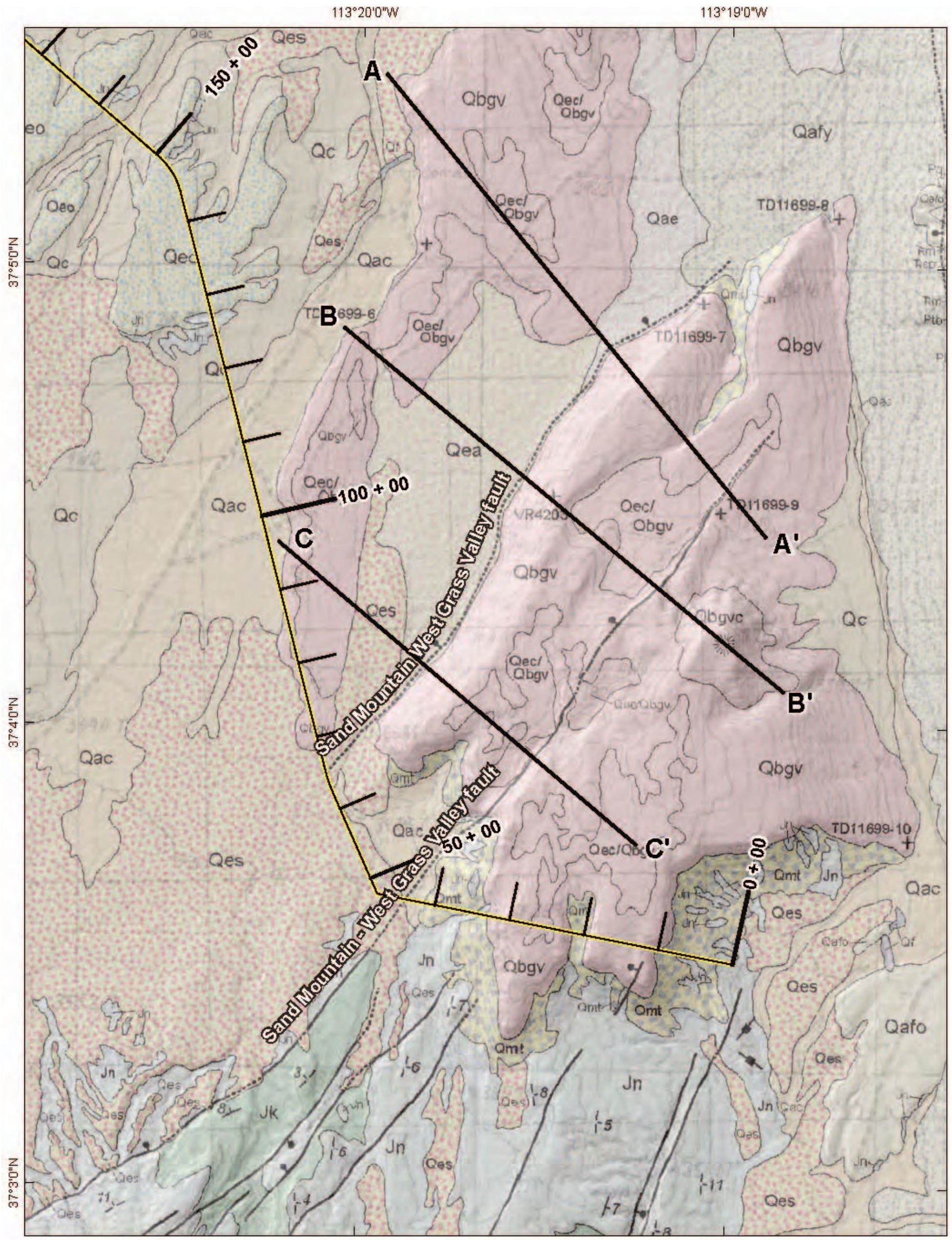
Lake Powell and southern Cedar Valley fault Crossings

- Alternative alignments between Hurricane Cliffs and Sand Hollow Reservoir may cross complex zone of transverse faulting between Hurricane and Washington faults
- Includes Warner Valley and Sand Mountain – West Grass Valley fault strands

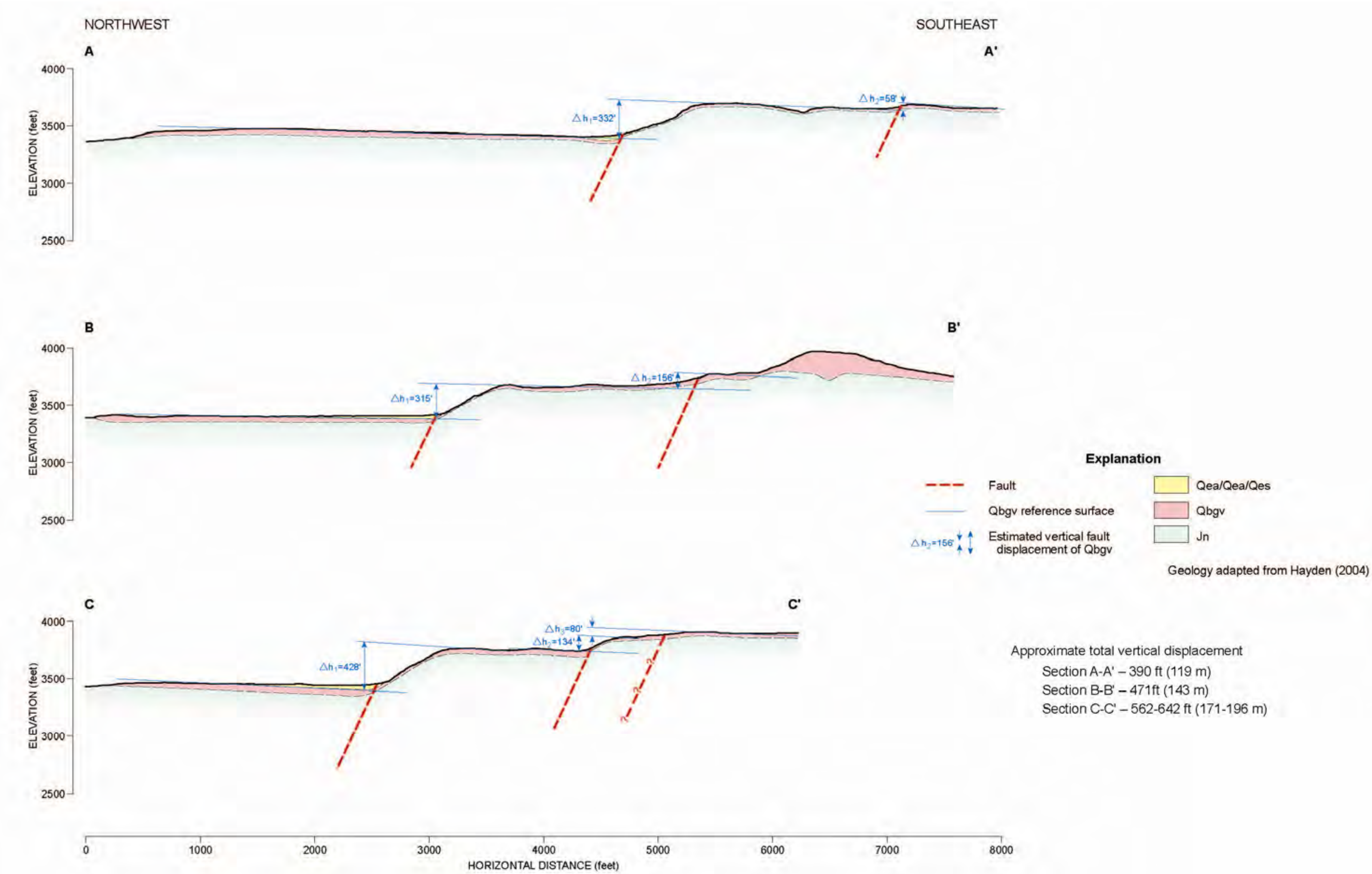


Sand Mountain – West Grass Valley faults

- Multiple traces displace and tilt ~1 Ma basalts to the east
- Slip rates likely 0.1 – 0.2 mm/yr



Sand Mountain - West Grass Valley faults

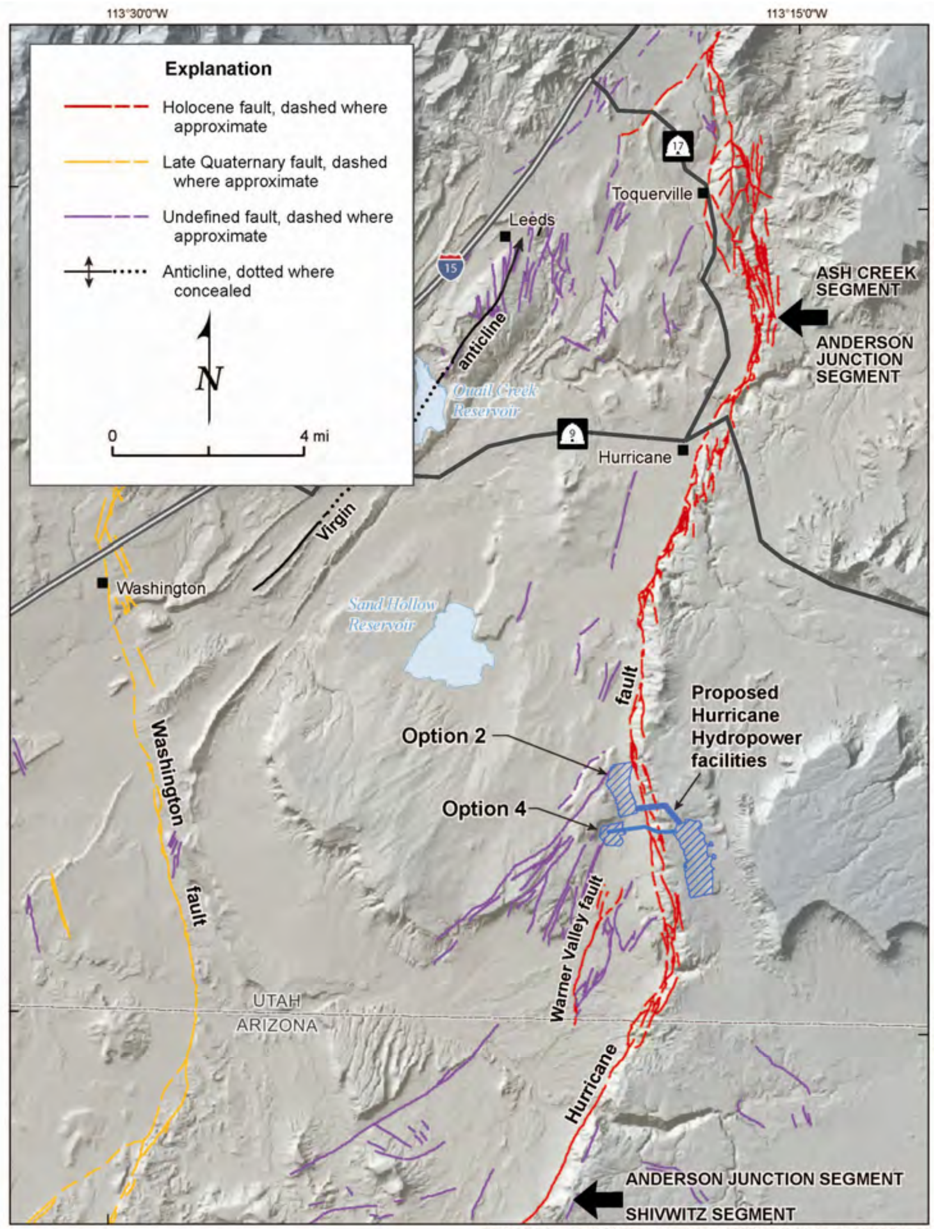


Hurricane Cliffs Hydropower Site Investigations

- Hurricane Cliffs Siting Investigations
  - Considered several alternative reservoir locations, configurations, and locations for forebay and afterbay reservoirs
    - Siting issues for embankments included seepage, collapsible soils, and fault rupture
    - Changes in reservoir locations required evaluating alternative powerhouse locations and pipeline alignments
  - Scope included desktop and field geologic mapping
    - Ground magnetic surveys
    - REMI and IMASW seismic profiles
    - Test pit logging
    - Geologic site integration and cross section development for alternative embankment locations and pipeline alignments
  - Provided preliminary seismic source characterizations for initial seismic design assessments of project facilities

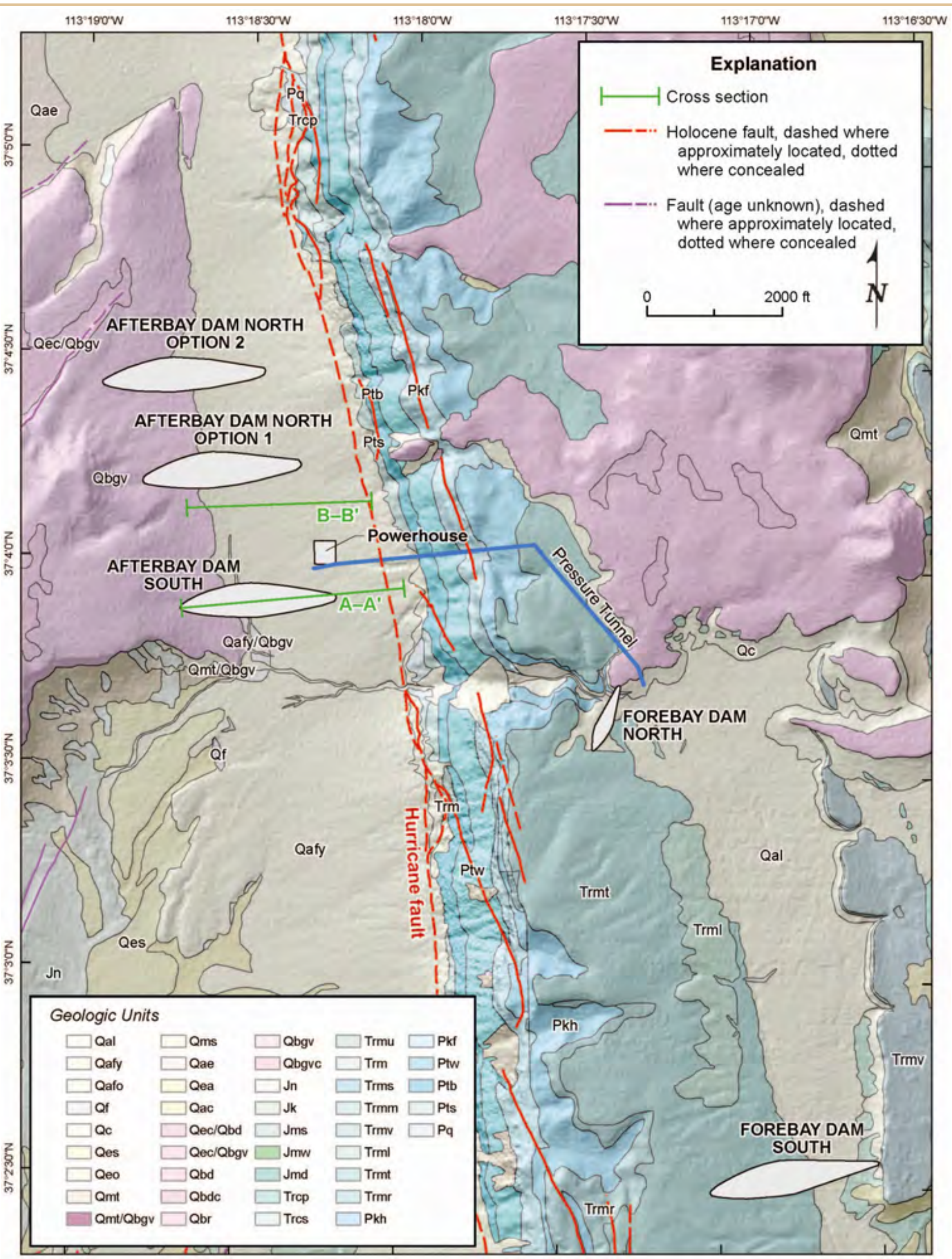
Hurricane Fault and Hurricane Hydropower Siting Options

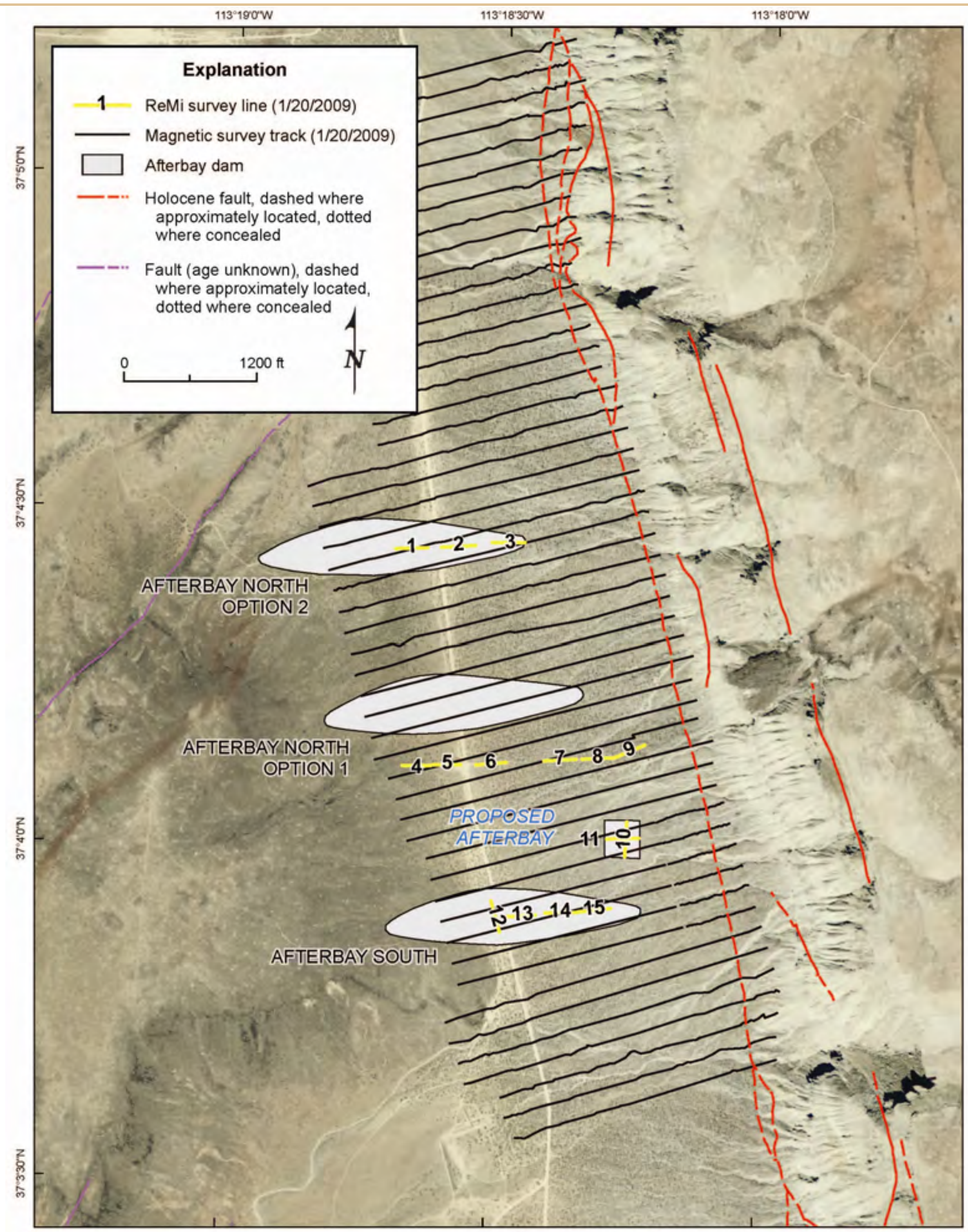
- Primary location about 10 km south of Hurricane, UT
- Near center of Anderson Junction segment
- Forebay alternatives atop Hurricane Cliffs east of fault
- Afterbay options west of Hurricane fault and near projected northern extension of Warner Valley fault



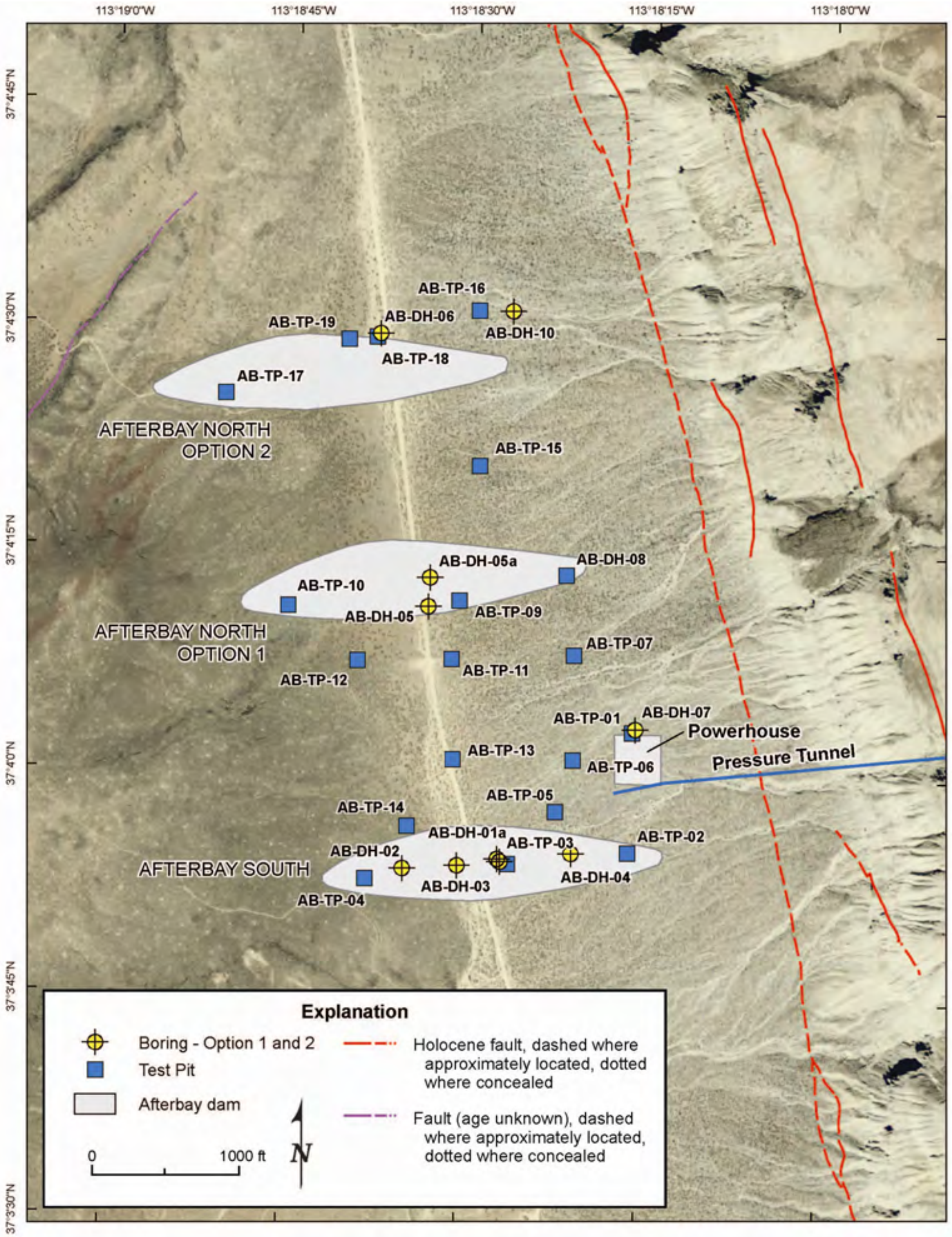
Note: Quaternary faults from Lund et al., 2008, Utah Geological SS 127 and Billingsley and Workman, 2000, U.S.G.S. Geologic Investigations Series I-2628

Hurricane Cliffs Initial Investigations – Afterbay Options 1 & 2

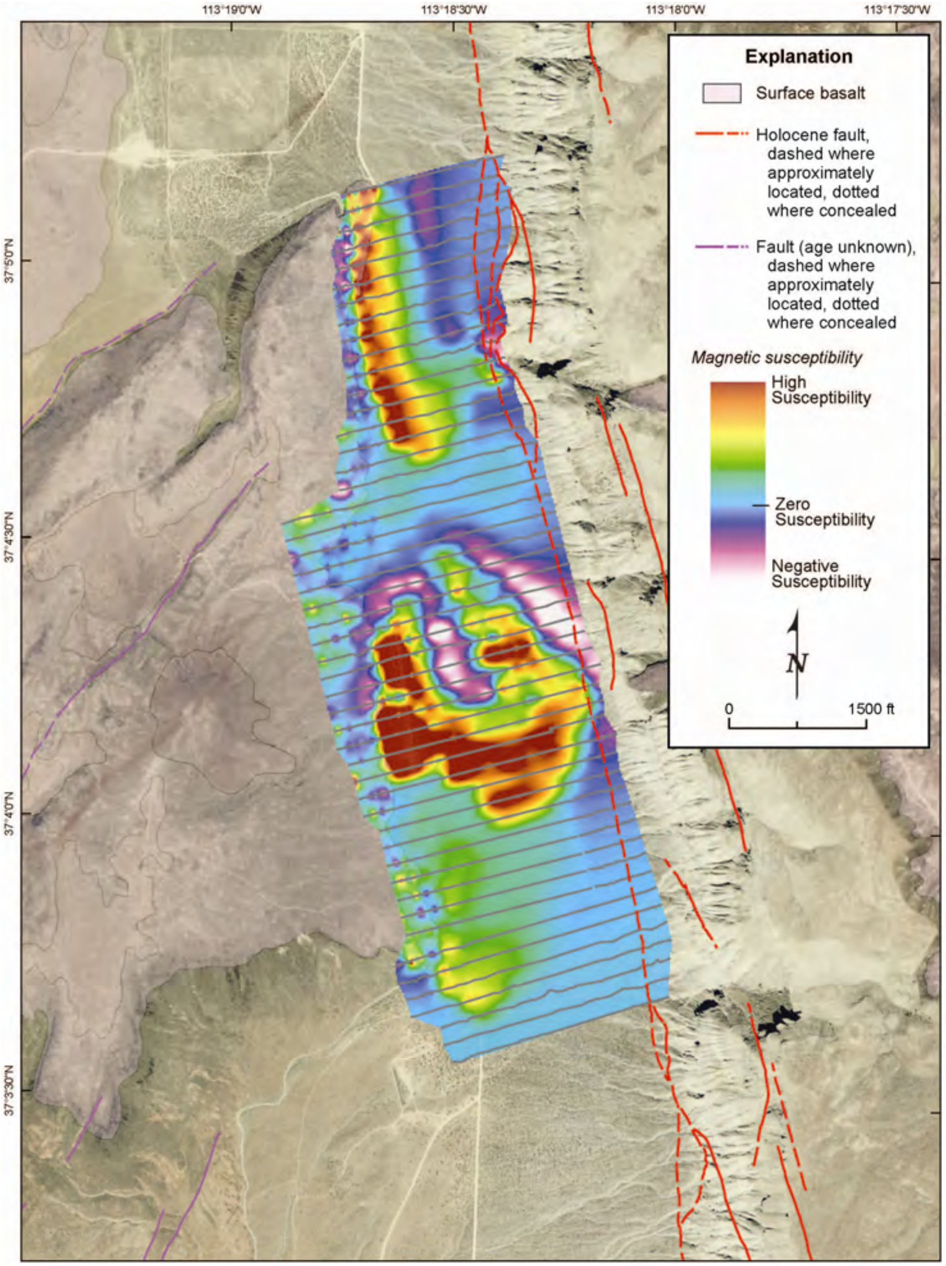


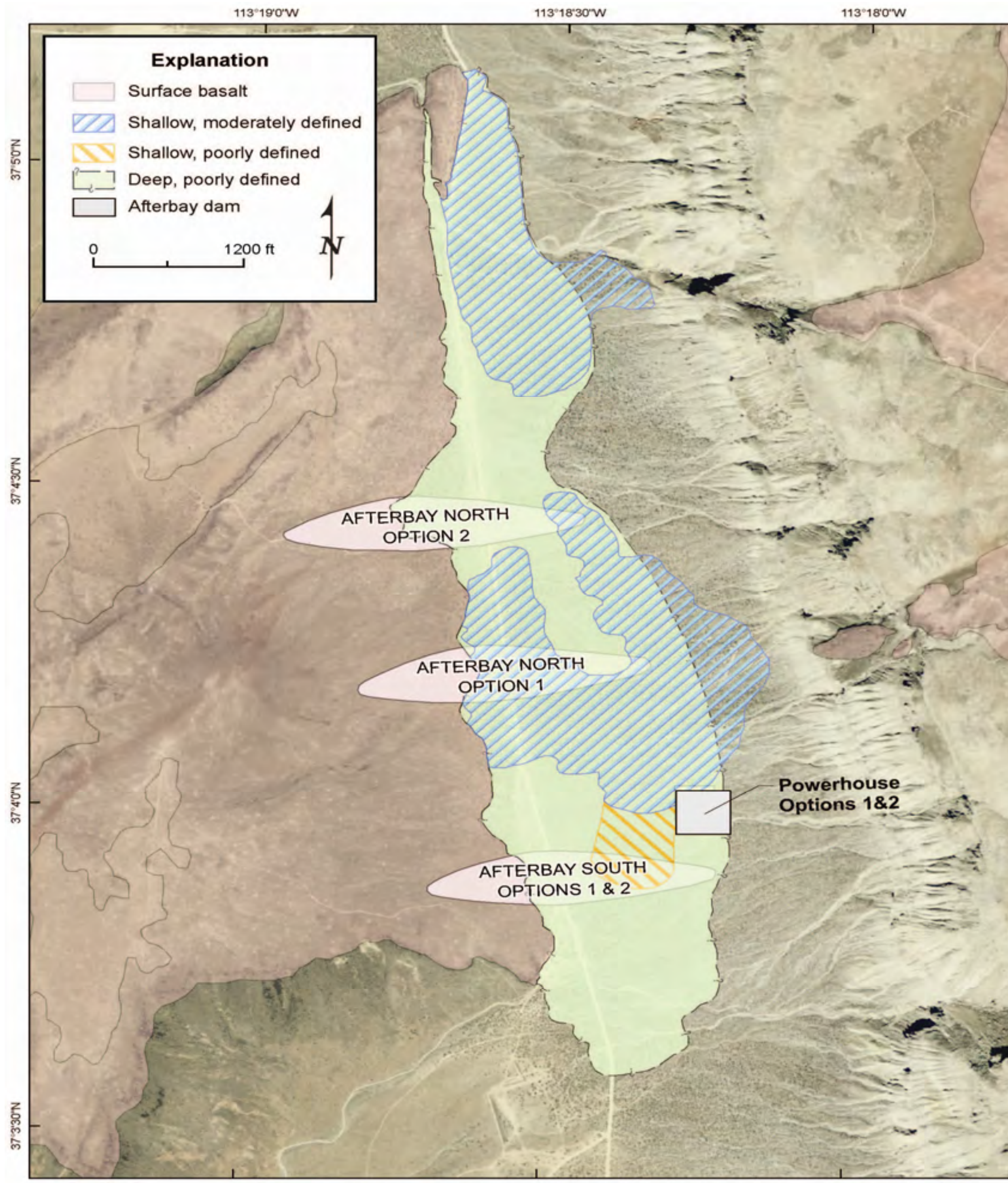


Afterbay Option 1 and 2 Test Pits and Borings

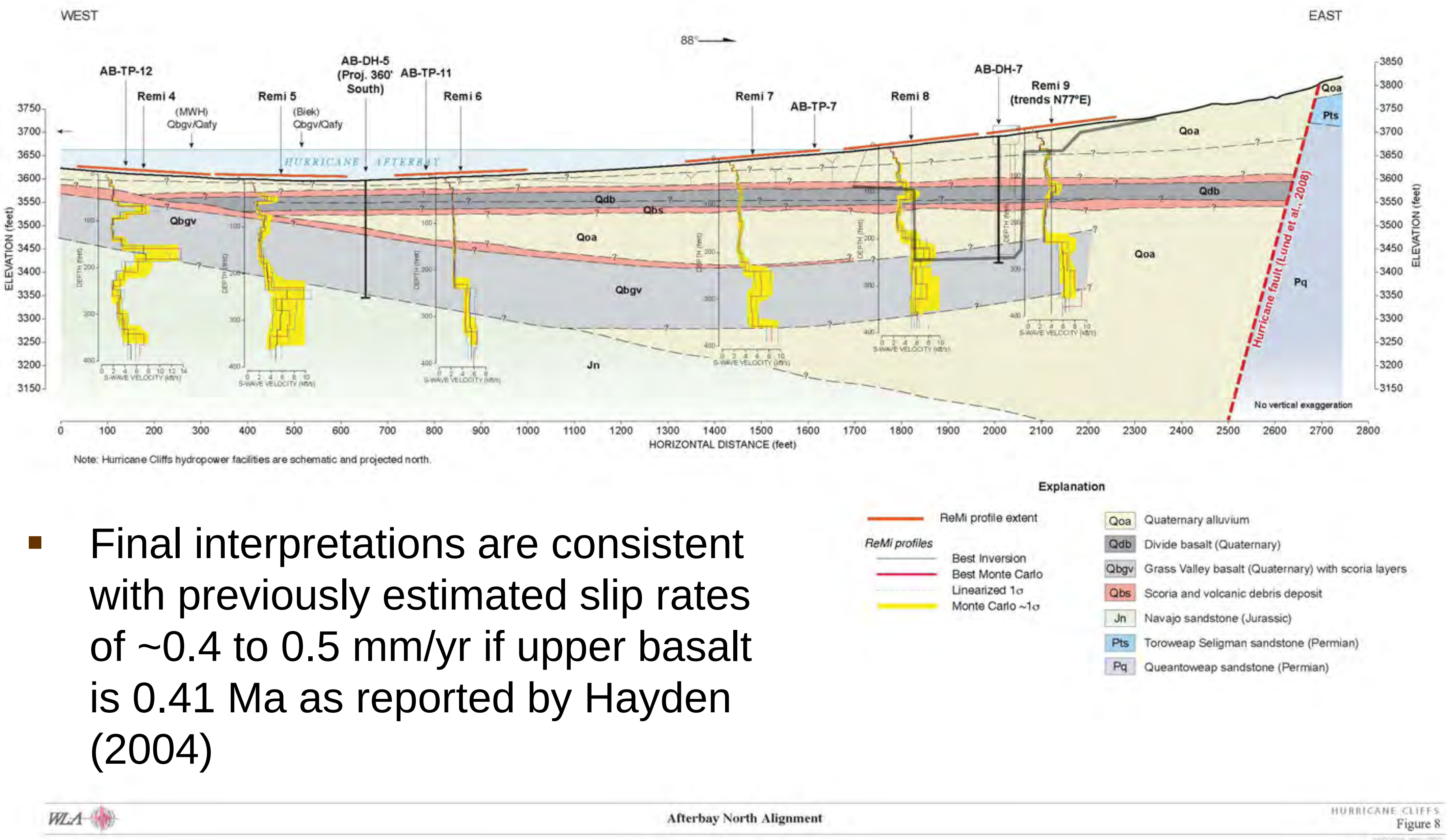


Interpreted Basalt Extent from Geophysics



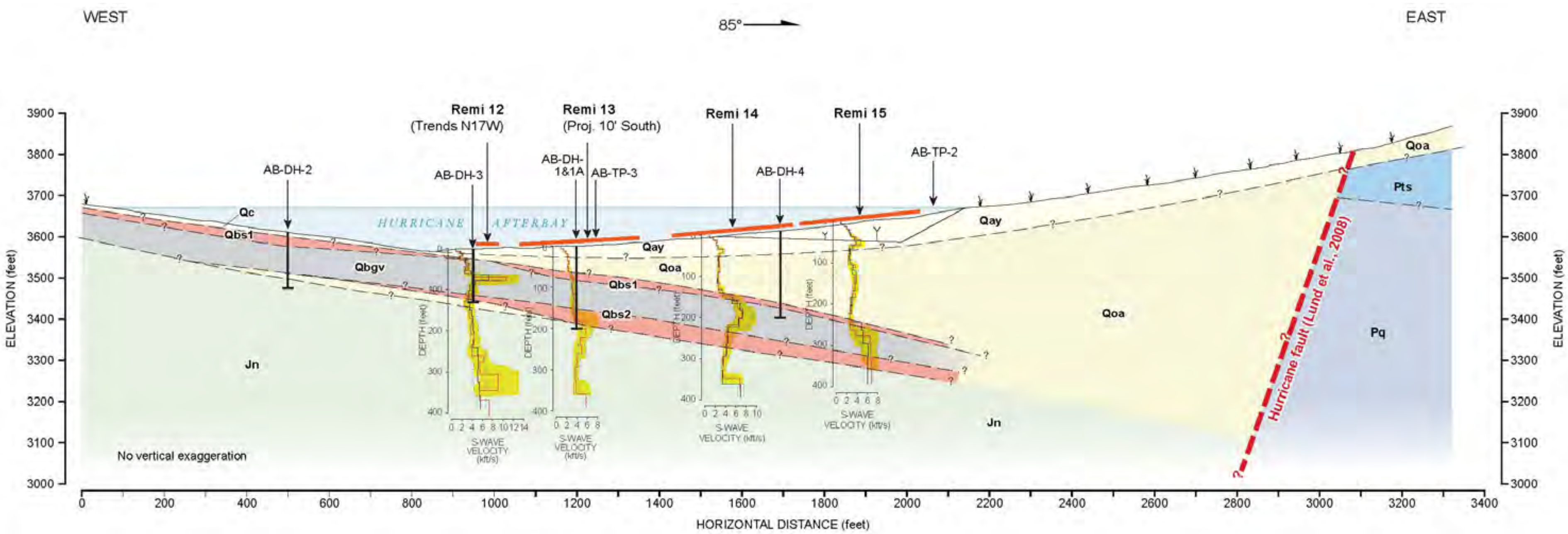


Northern Section – Options 1 & 2



- Final interpretations are consistent with previously estimated slip rates of ~0.4 to 0.5 mm/yr if upper basalt is 0.41 Ma as reported by Hayden (2004)

Southern Section – Options 1 & 2



Notes: Hurricane Cliffs hydropower facilities are schematic and projected south.
Locations of borings are approximate.

Explanation

AB-3 — RG&B boring (2009)

ReMi profile extent

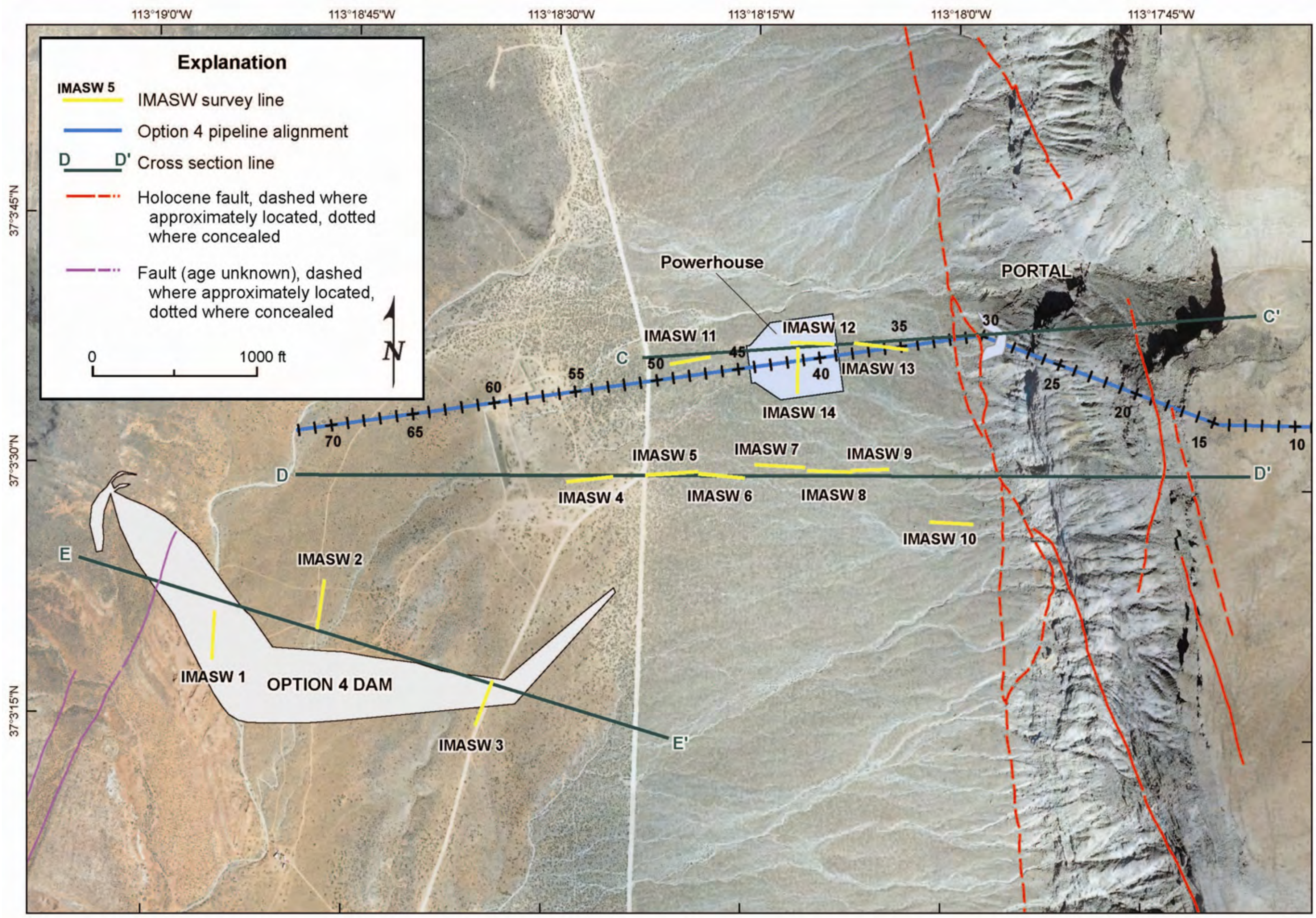
ReMi profiles

- Best Inversion
- Best Monte Carlo
- Linearized 1σ
- Monte Carlo ~1σ

Unit descriptions

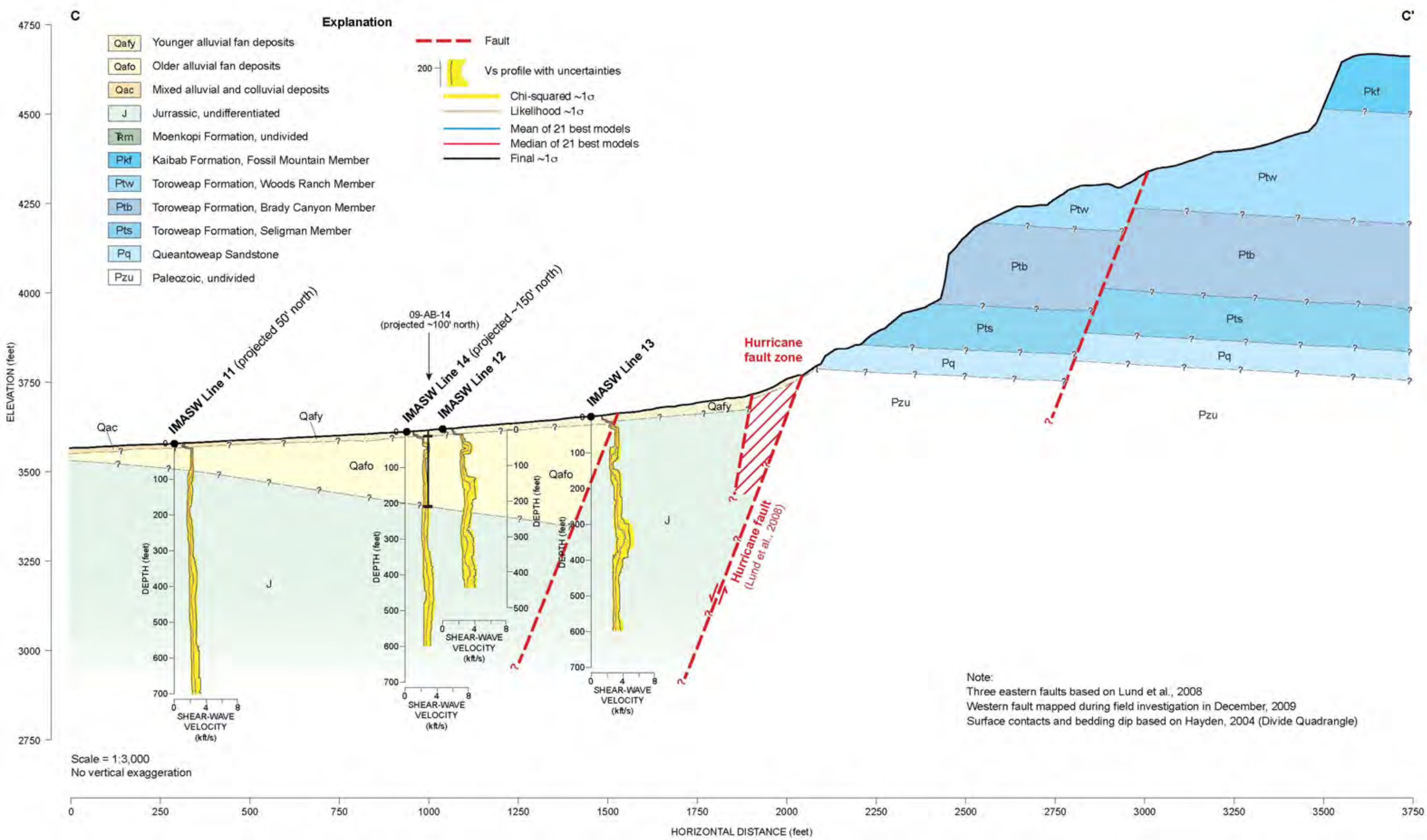
Qc	Colluvium / slope wash
Qay	Late Holocene alluvium
Qoa	Quaternary alluvium
Qbs1	Upper scoria and volcanic debris deposit
Qbgv	Grass Valley basalt (Quaternary)
Qbs2	Lower scoria and volcanic debris deposit
Jn	Navajo sandstone (Jurassic)
Pts	Toroweap Seligman sandstone (Permian)
Pq	Queantoweap sandstone (Permian)

Hurricane Cliffs Geophysical Sites - Option 4

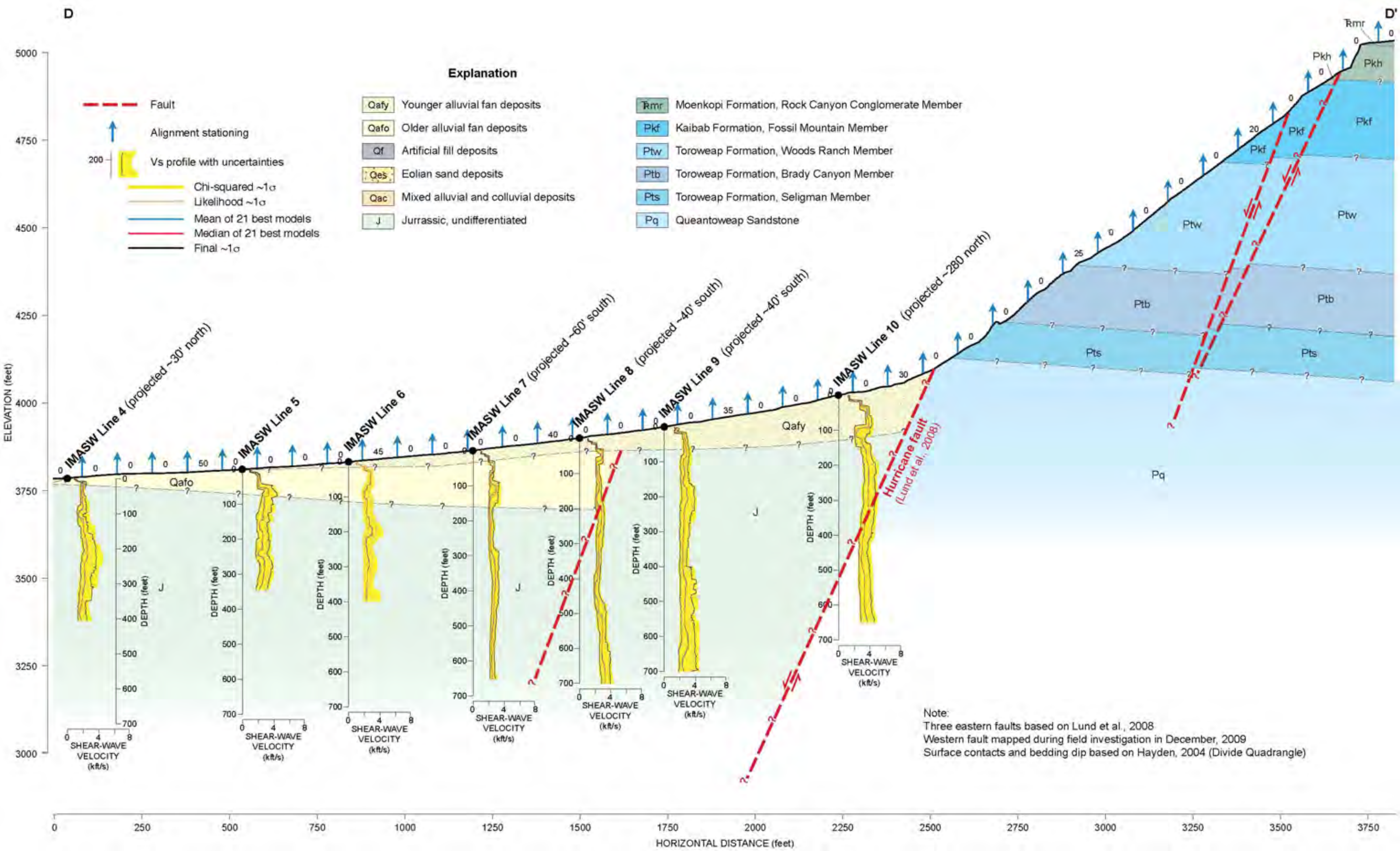


Option 4 Site Area and Hurricane Cliffs

Option 4 - Section C – C'



Option 4 – Section D – D’

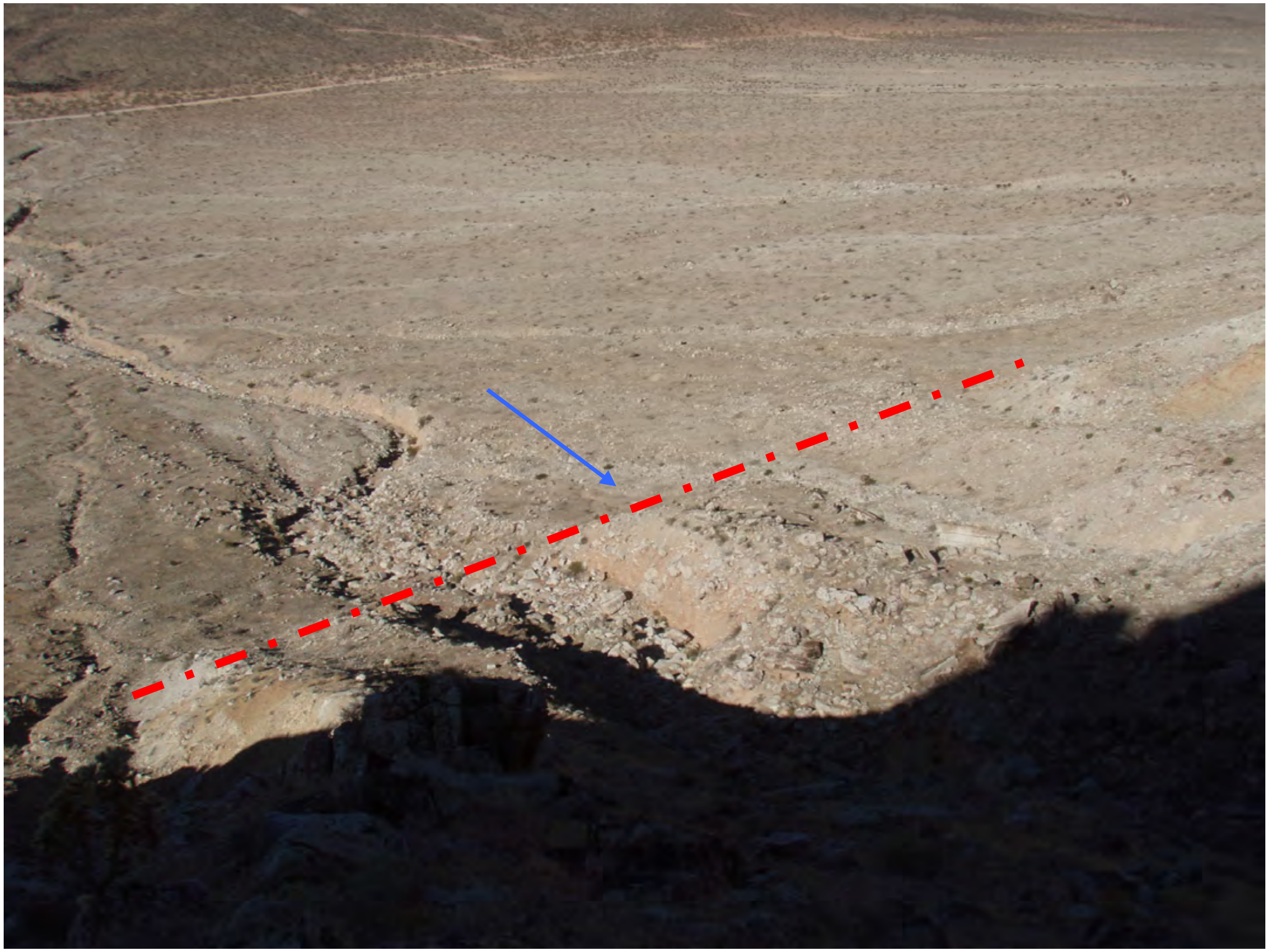


Hurricane Fault

- Steep dipping fault trace juxtaposing Permian bedrock against Quaternary colluvium south of Option 4 alignment

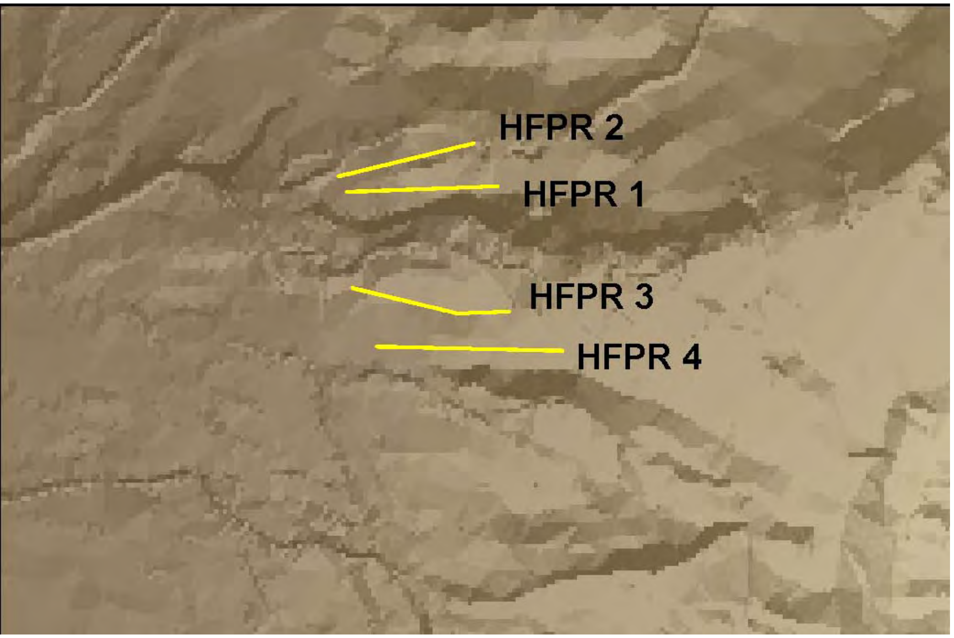
Scarp in Quaternary Alluvium near Option 4

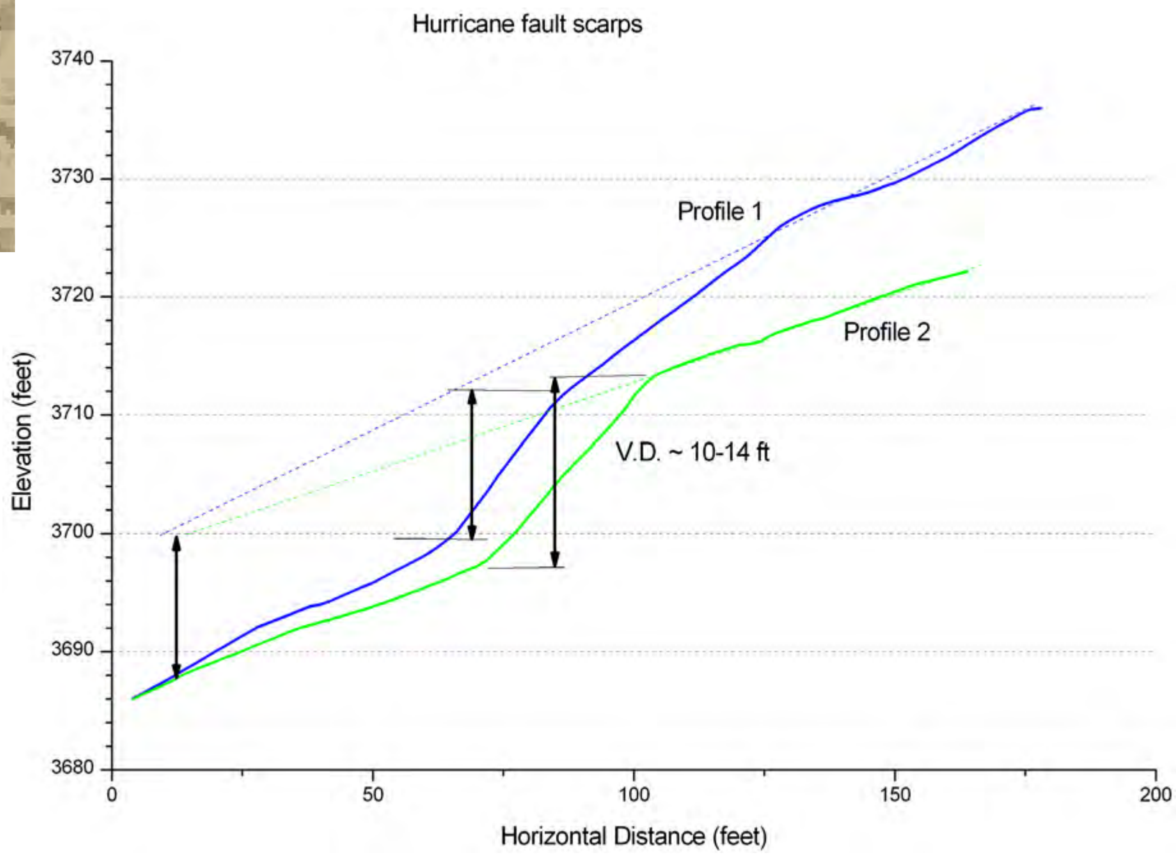
- Profiles 1 and 2 near blue arrow



Hurricane fault near Option 4 alignment

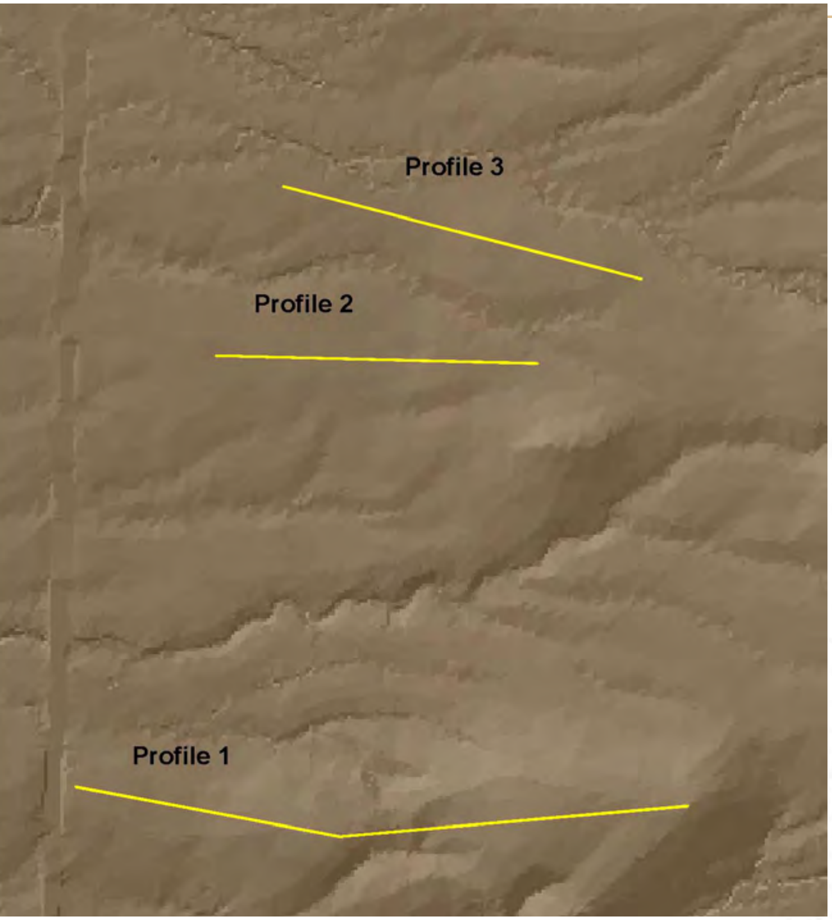
Scarp profiles near Option 4 alignment

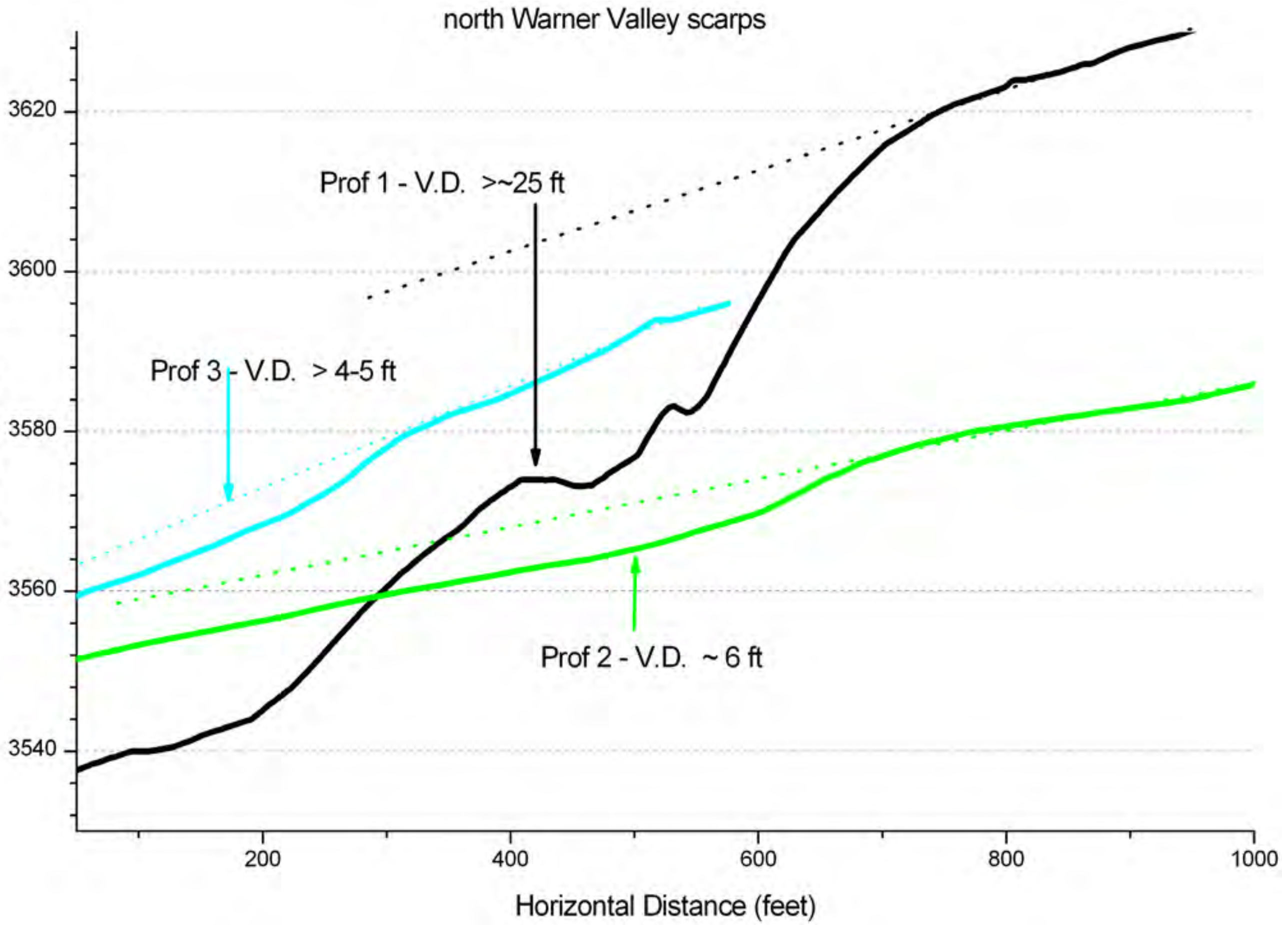




- MRE may have vertical displacement of ~12 ft (3.6 m)
- Profiles 3 and 4 appear to be in older fans, and have vertical displacements 2-3x larger but correlation across the fault is uncertain

Northern extensions of Warner Valley fault





- Isolated remants of older fans (Profile 1) may not correlate

Thank You

BlueCastleProject

Blue Castle Licensing Project

UQFPWG Update

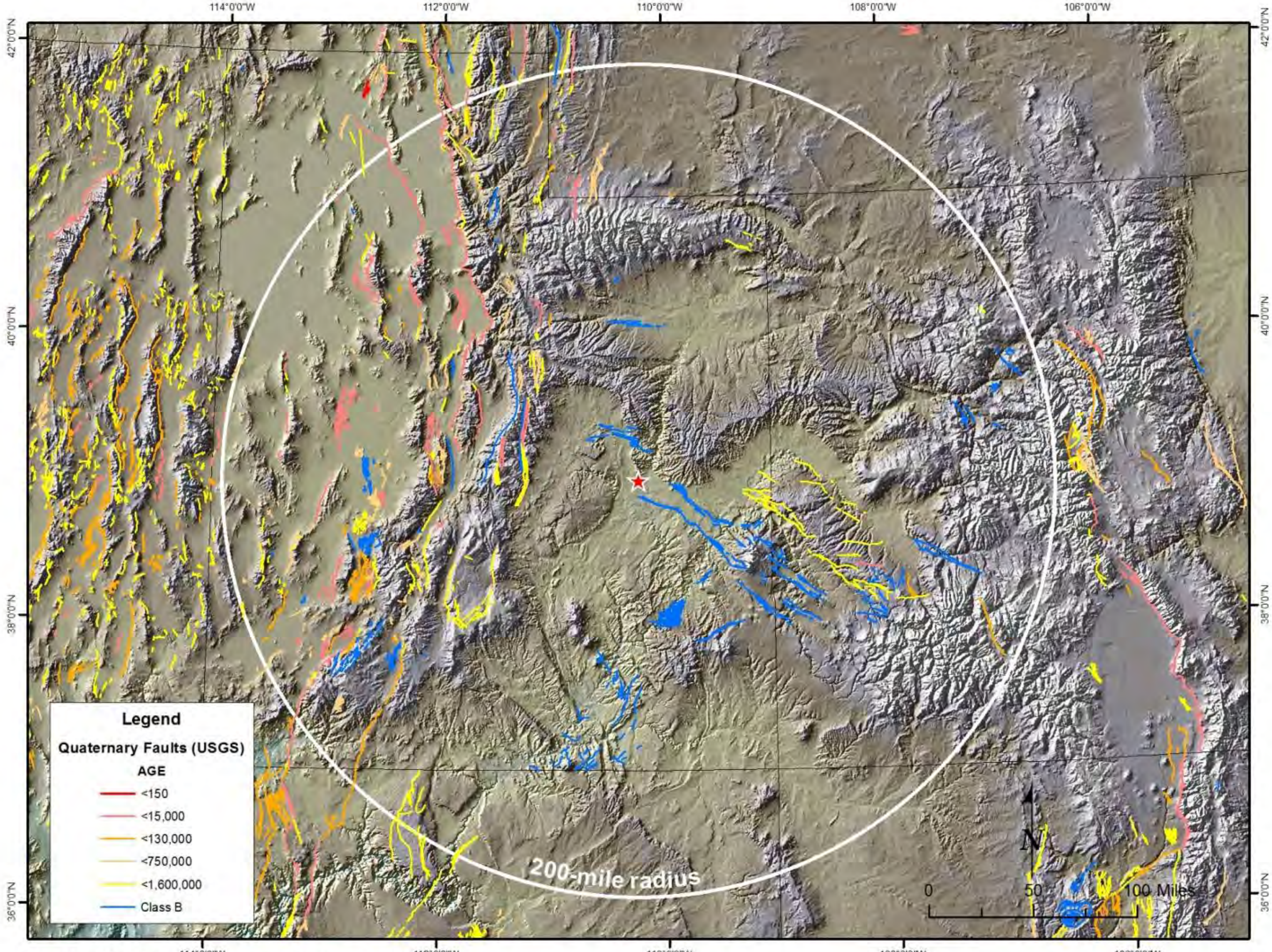
February 15, 2012

Dean Ostenaa – Fugro Consultants, Inc.

Ongoing Geologic and Seismic Hazard Studies

- Ongoing studies to support licensing effort for proposed Nuclear Power facility near Green River, UT
  - Current scope is for Early Site Permit (ESP) submittal to NRC expected in early 2013
    - Many study elements mandated by NRC regulatory process
- Seismic Hazard Characterization following a SSHAC Level 3 Process with formal Peer Review and involvement of outside experts
- Most detailed geologic mapping and investigations are focused in Site Area (25 mile radius of site)

Blue Castle Site Region – USGS Quaternary Faults



Faults - USGS Quaternary Fault and Fold

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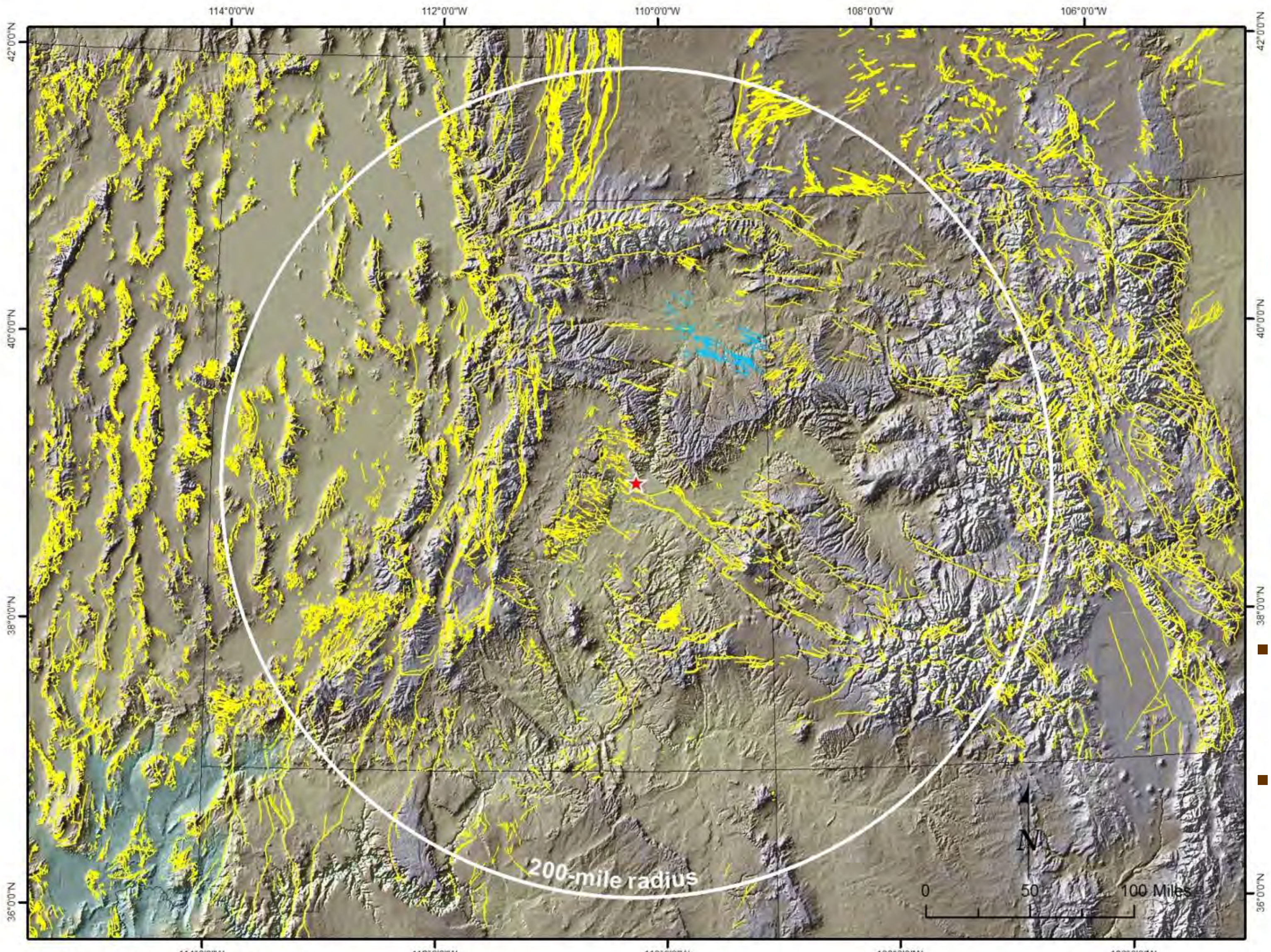
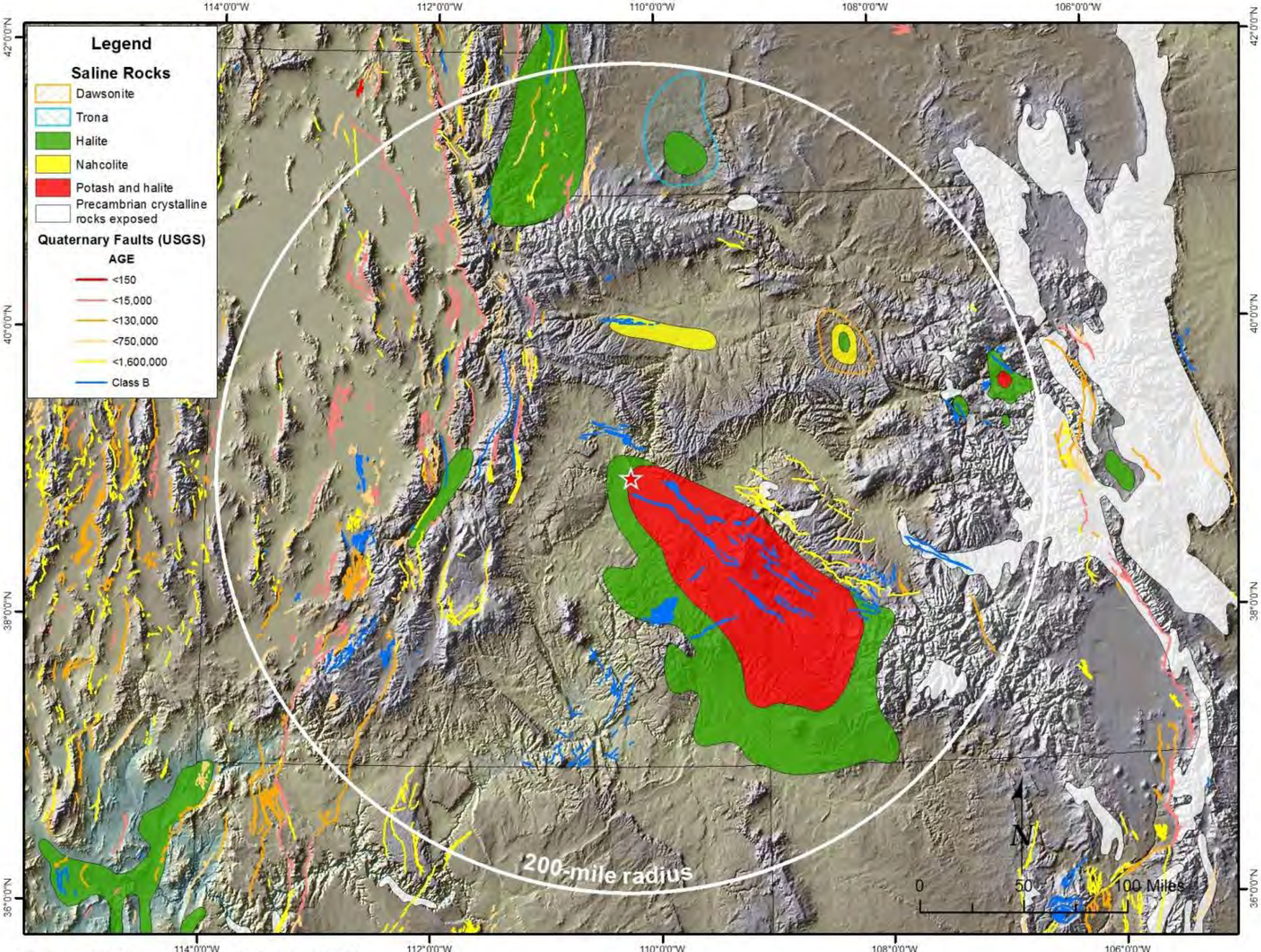
Blue Castle Site Region - Faults from State Geologic Maps



Faults - From state geologic maps

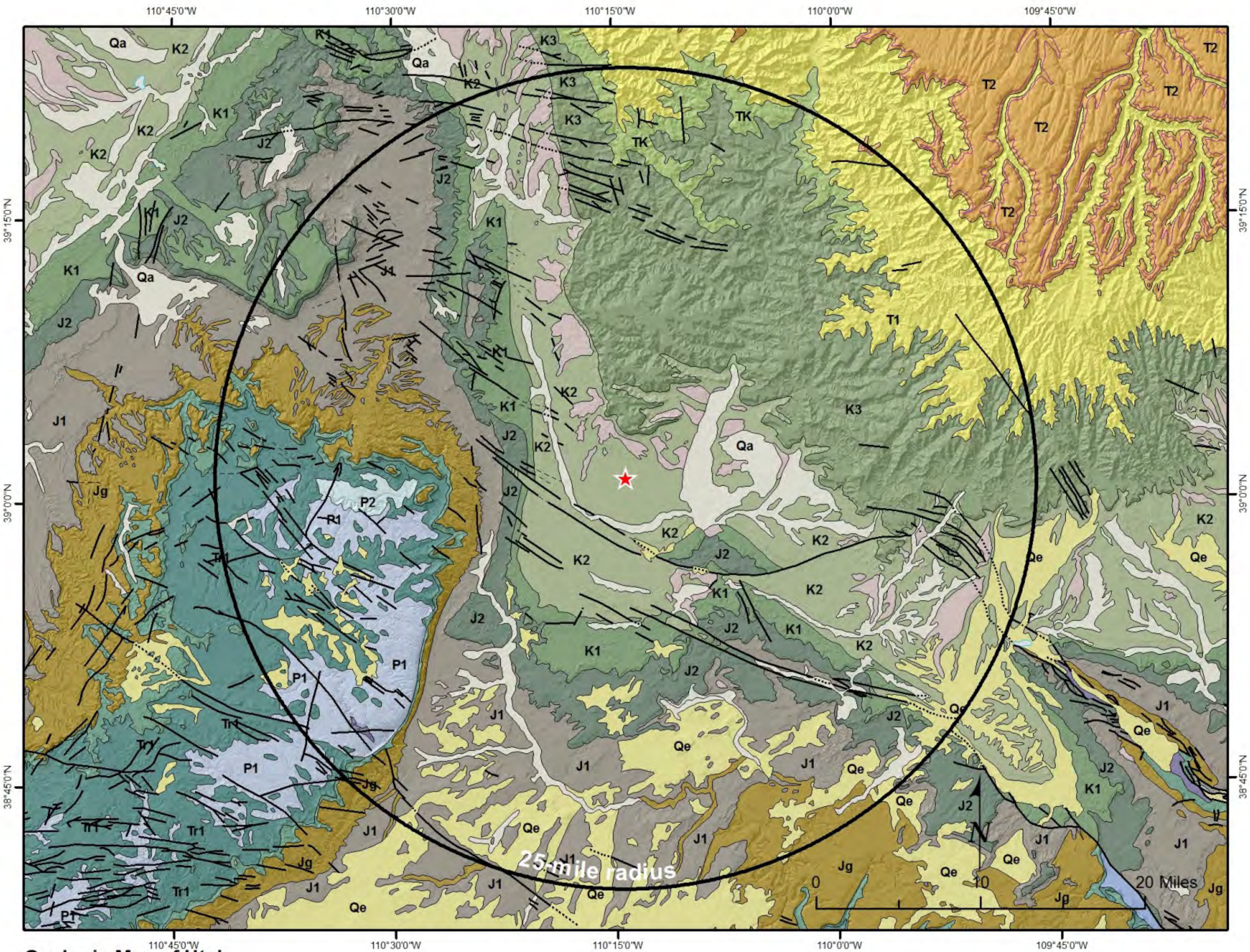
- Compiled from 1:500,000 State maps
- New Mexico faults not included

Saline Rocks and Quaternary Faults



Saline Rocks and Quaternary Faults

Blue Castle Site Area Geologic Map



Geologic Map of Utah

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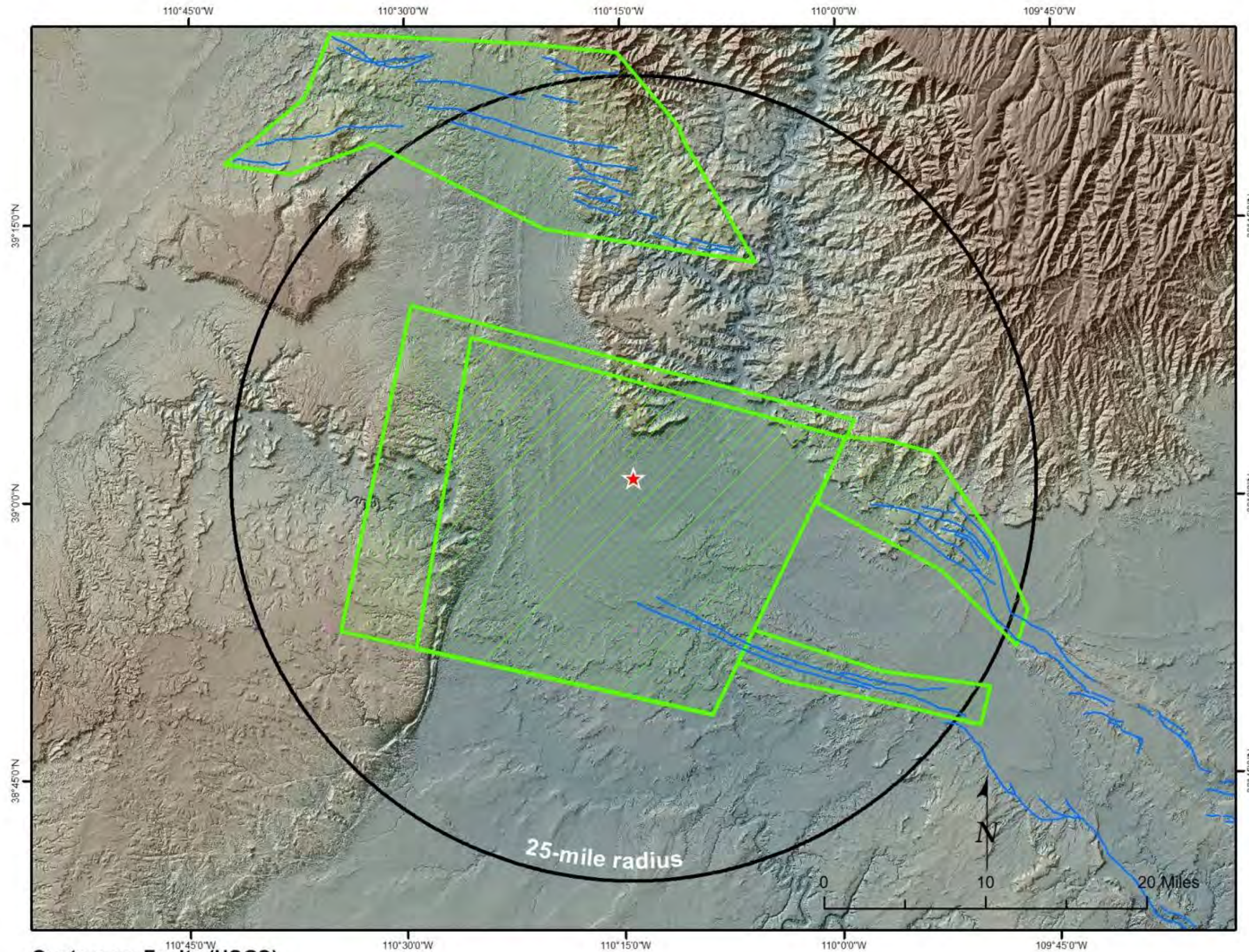
LIDAR Areas and USGS Quaternary Faults



Quaternary Faults (USGS)

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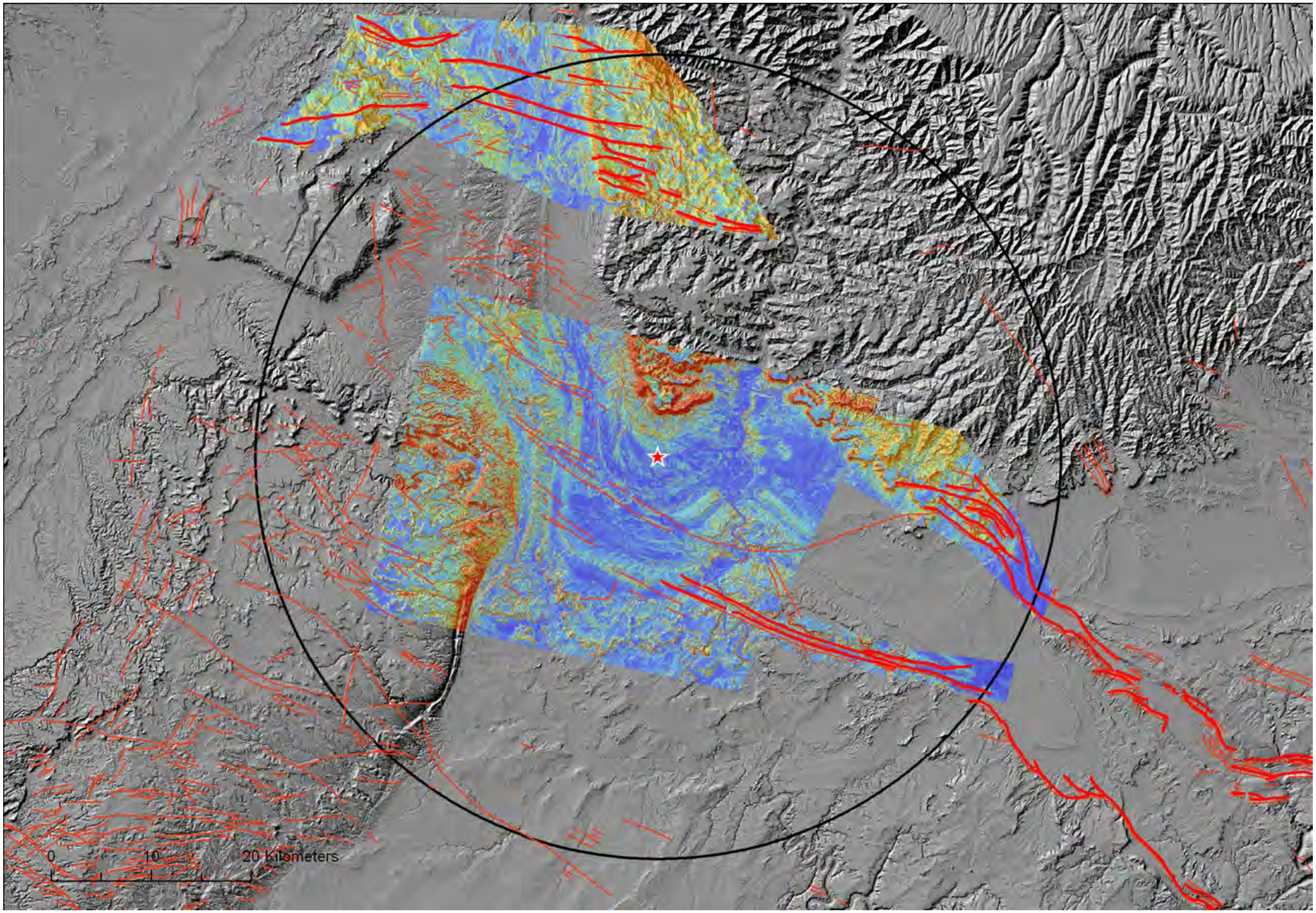
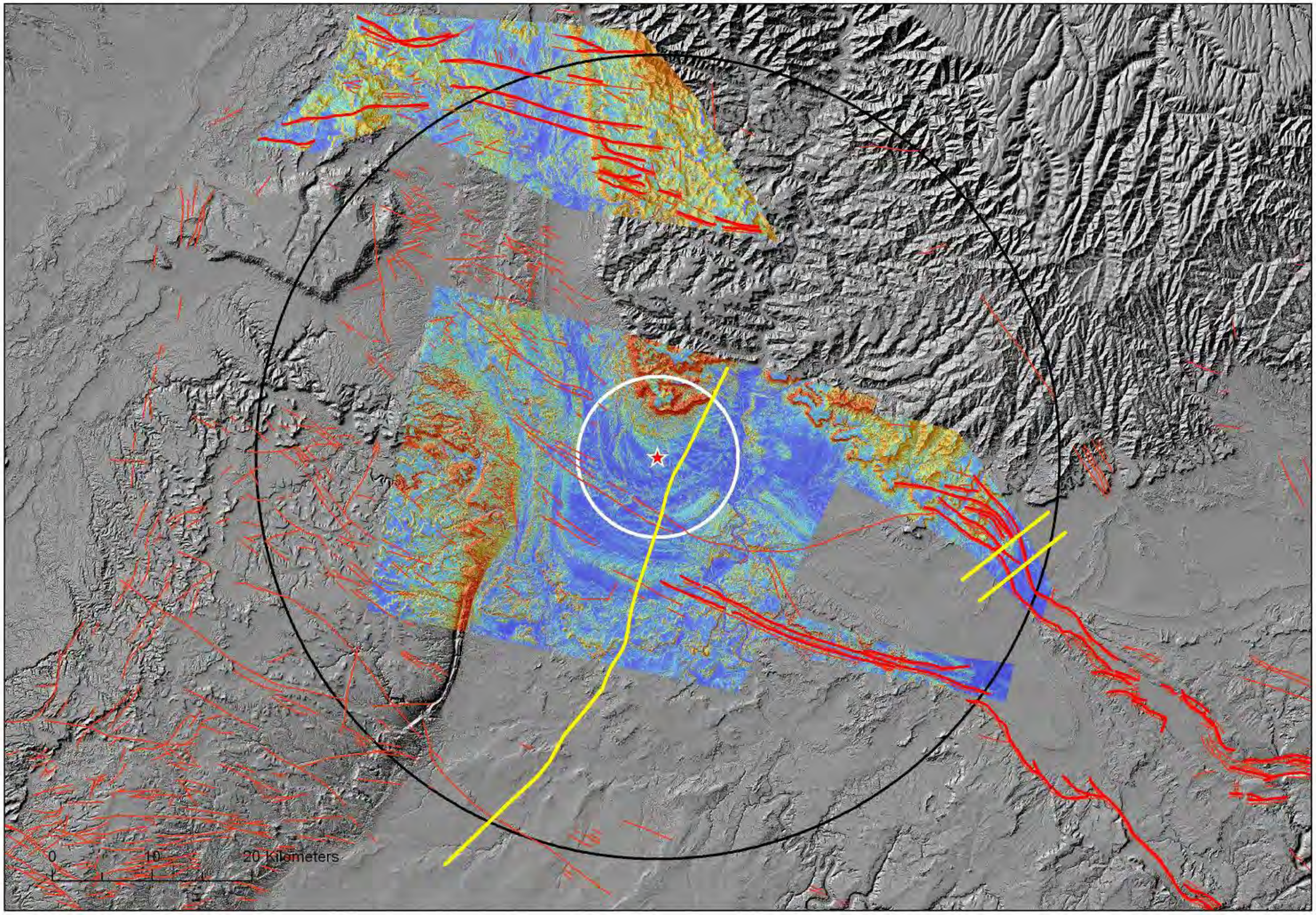
Lidar Extent --- Expanded Site Vicinity, Ten-Mile Graben and Little Grand Wash faults



Proposed Seismic Lines



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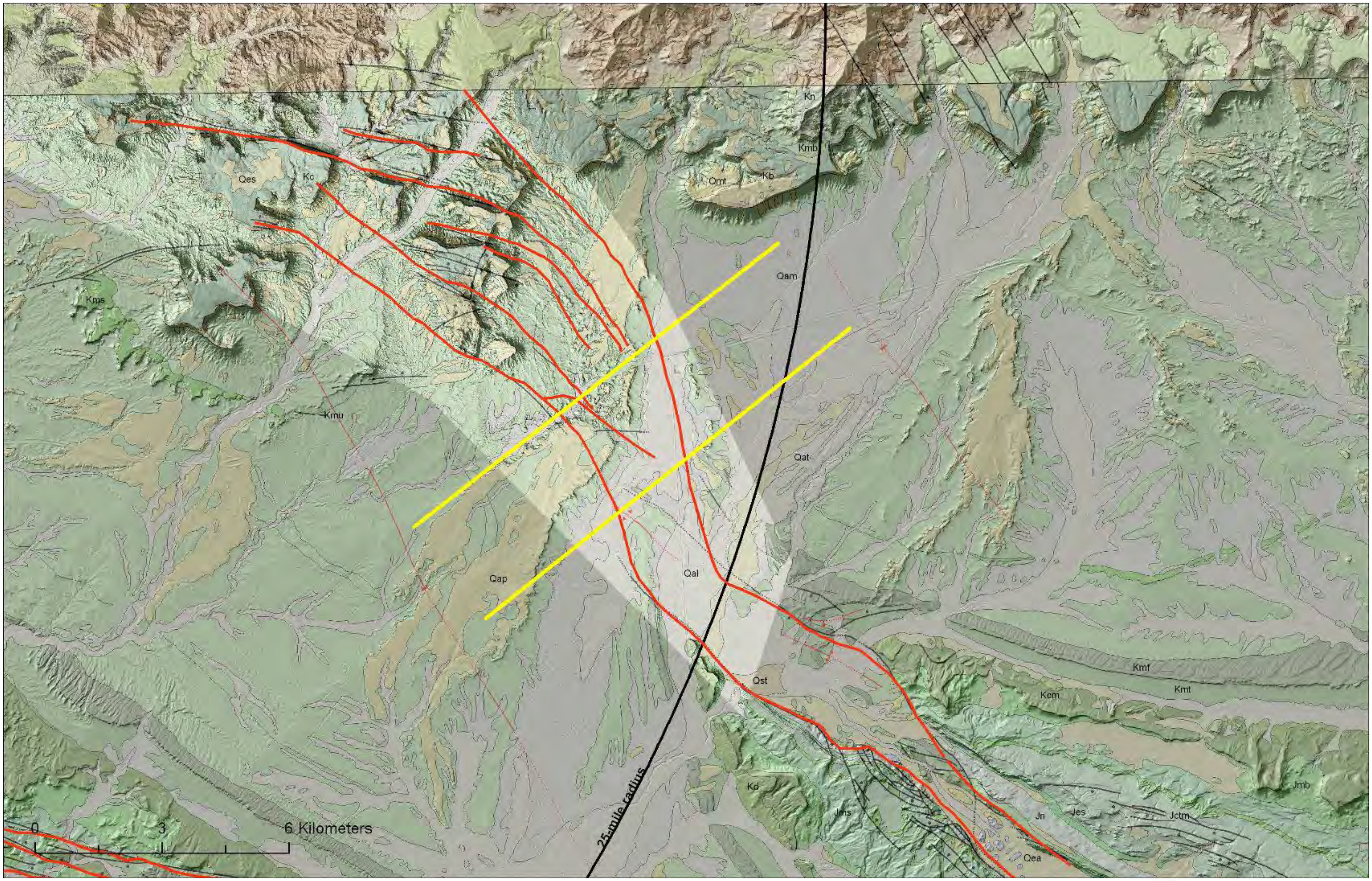
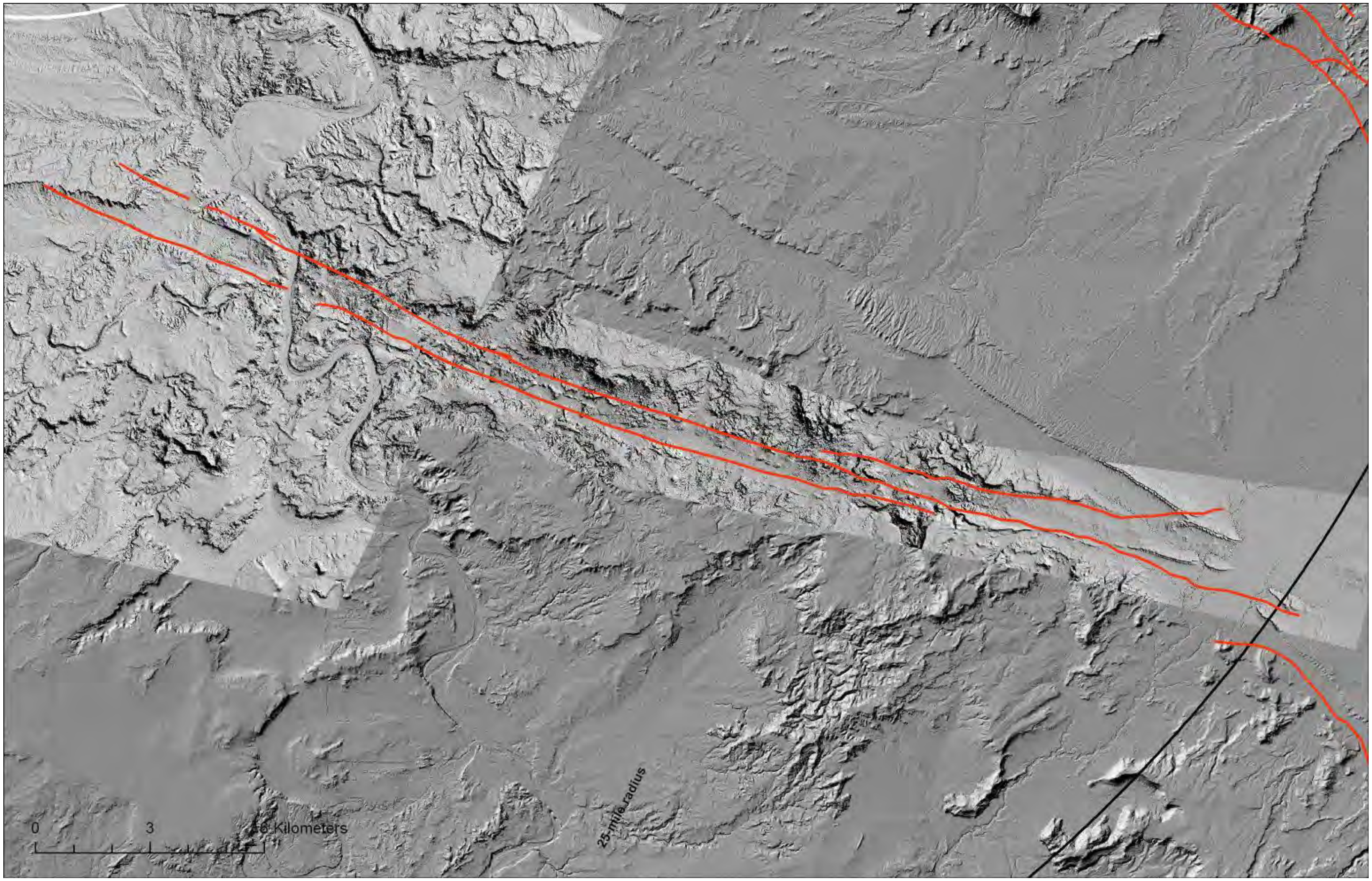
Salt Valley faults – northwest extensions



Ten-Mile Graben Lidar



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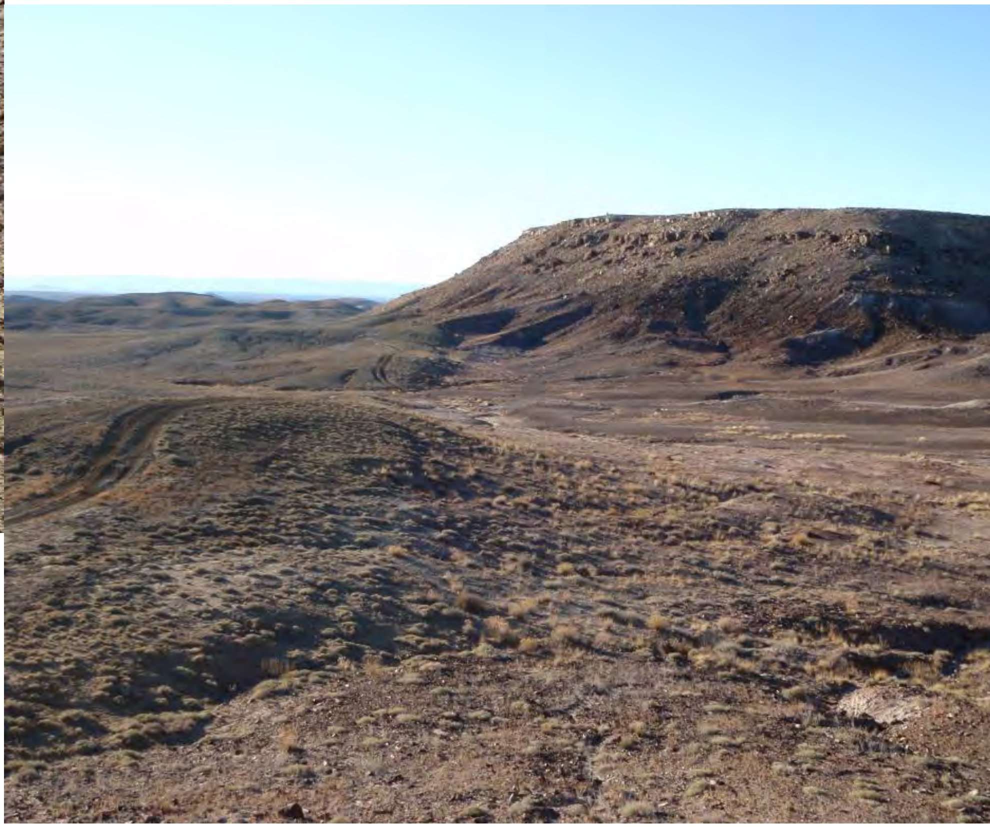
Ten Mile Graben fault

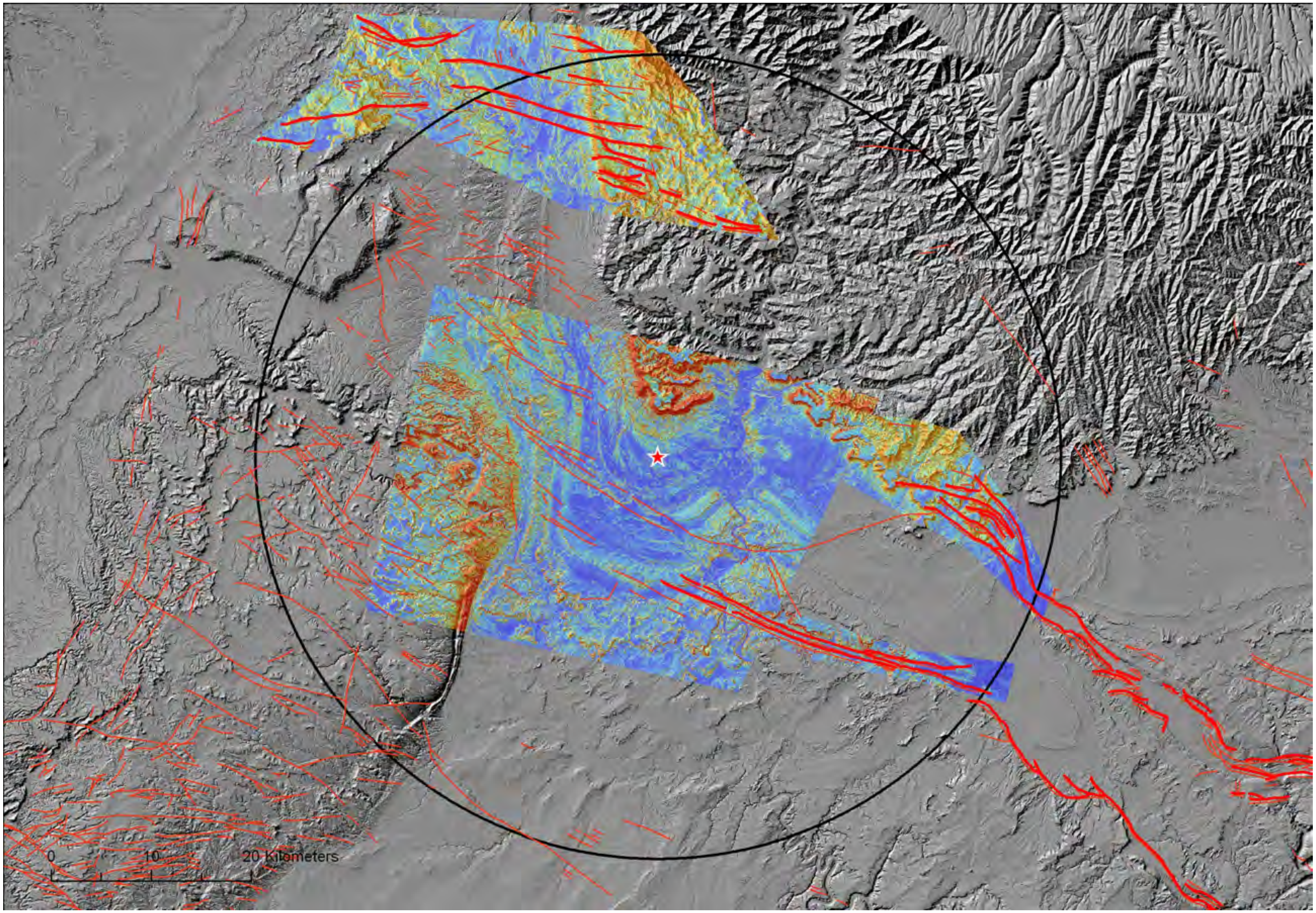


Contrasting geomorphic expression along strike

Green River terraces at Ten-Mile Graben

Green River terraces – Little Grand Wash fault

Lidar Extent and Faults --- Price River faults



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Price River faults

Expression in actively eroding Mancos landscape

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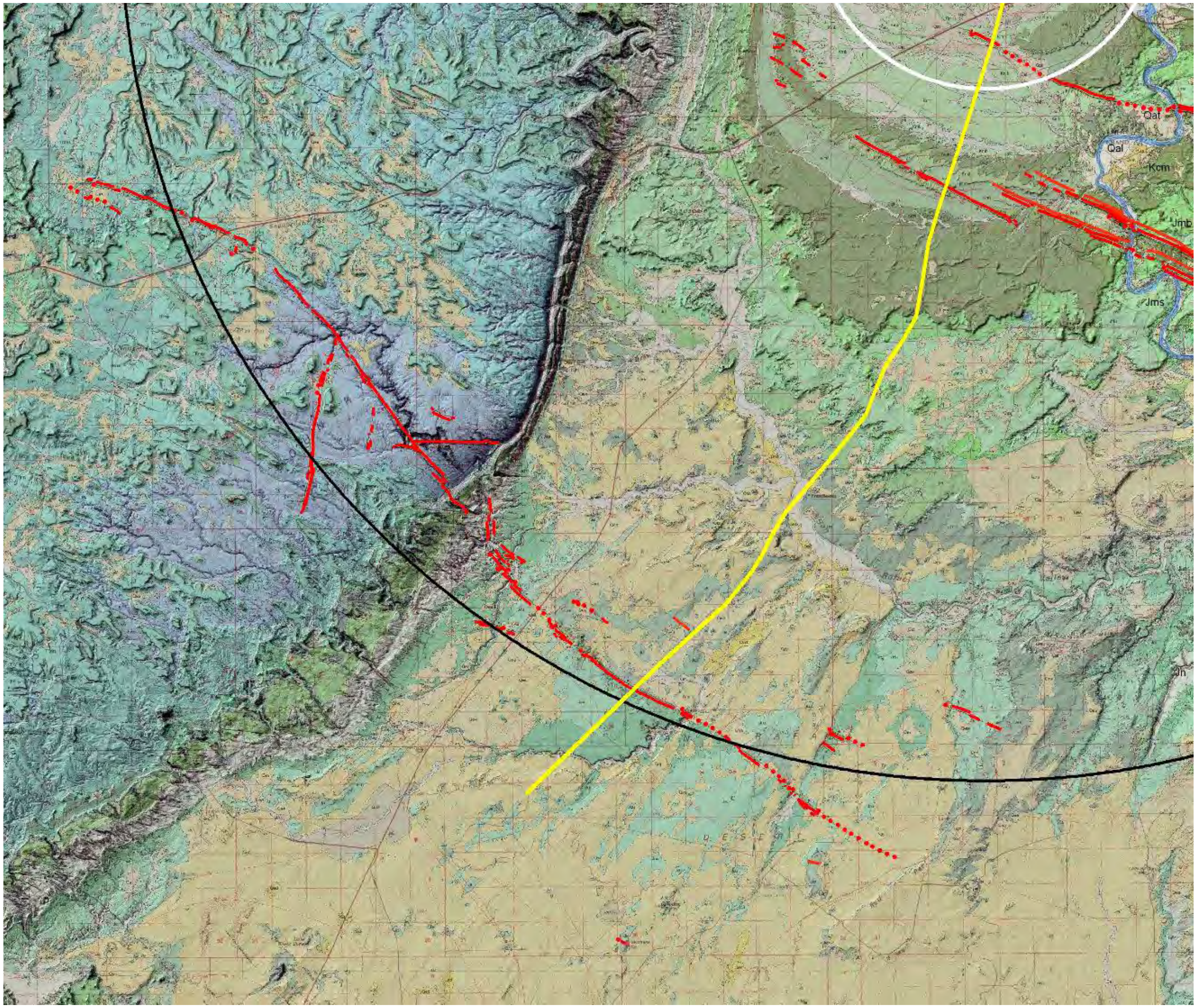
Iron Wash fault



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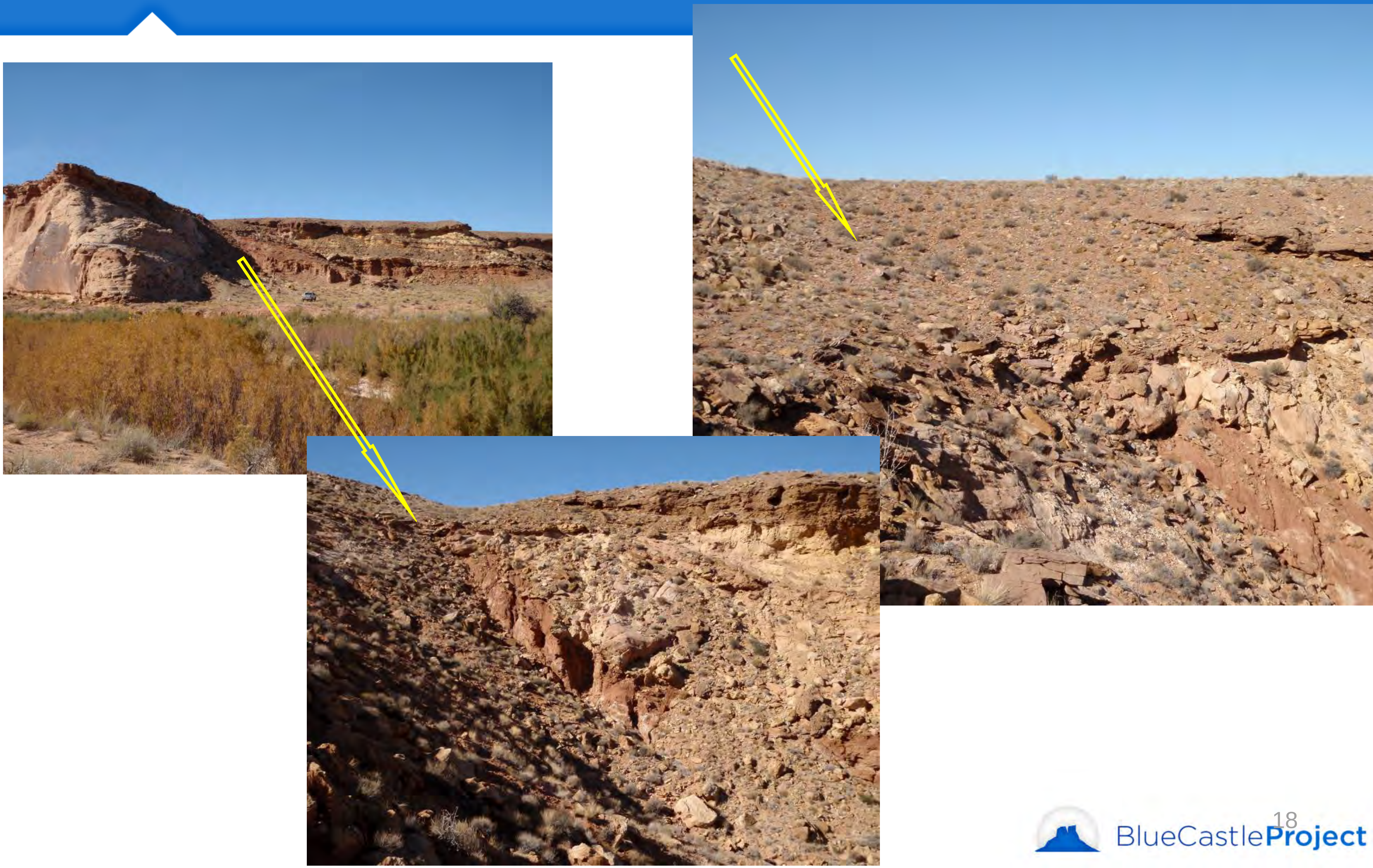
Iron Wash fault at Cottonwood Wash



Project Information

www.bluecastleproject.com

BlueCastle**Project**

SUMMARY OF PRELIMINARY INVESTIGATIONS OF THE PAUNSAUGUNT FAULT, UTAH

prepared for the February 15, 2012 meeting of the Utah Quaternary Fault Parameters Working Group

by

RJH Consultants, Inc., Englewood, Colorado

February 1, 2012

In 2010 RJH Consultants, Inc. (RJH) initiated a paleoseismic hazard study of the Paunsaugunt fault for a proposed pumped storage hydroelectric-generating facility in Grass Valley, Utah. The Paunsaugunt fault is the easternmost fault within the Basin and Range-Colorado Plateau transition zone in southwestern Utah. It is included in the U.S.G.S. and Utah Geological Survey's Quaternary fault databases, where it is described as a "poorly understood Quaternary (?) fault along the western edge of the Aquarius Plateau". Late Tertiary volcanic rocks are downdropped to the west about 500 m by the fault (Rowley and others, 1981).

Although the total length of the structure may exceed 160 km, only the northern ~44 km of the fault is included in the Quaternary fault databases. The fault trace used in the Quaternary fault databases is from the 1^{o} x 2^{o} geologic map of Williams and Hackman (1971). But the rationale for inclusion of only this section of the fault in the databases apparently comes from the mapping by Carpenter and others (1967), who locally show this part of the fault as either a solid or dashed line in Quaternary deposits on their map. The Quaternary fault database also mentions that Bowers (1991) reported low scarps in remnants of Pleistocene deposits at two locations in the vicinity of Bryce Canyon National Park. However, this southern part of the fault trace is not included in the Quaternary fault database.

Investigations by RJH in 2010 focused primarily upon evaluation of the published evidence of Quaternary fault activity that was described in the Quaternary fault databases. RJH reviewed relevant geologic literature, interpreted publically available aerial photography and topographic maps, and conducted reconnaissance-level field work. RJH found no evidence of fault scarps in the Pleistocene fan deposits at locations where Carpenter and others (1967) depicted the fault trace as a solid or dashed line. RJH also concluded that the two scarps reported by Bowers (1991) in the vicinity of Bryce Canyon National Park probably were tectonic scarps along the main trace of the fault. These scarps were in relatively narrow remnants of pediment or piedmont deposits inferred to be middle Pleistocene age or older. A topographic profile across the scarp at the Bulldog Hollow site suggested the surface was offset about 4 ½ m.

Two other locations along the fault trace in the project vicinity were examined in the field during 2010, and no scarps were observed at those locations. Two relatively short, east-facing, antithetic scarps were detected on the aerial photography and examined in the field. The scarps are about ½ mile west of the range front and occur in a small remnant of fan deposits that were estimated to be middle Pleistocene in age.

In 2011 high-resolution LiDAR (4 points/m^2) was acquired for over 310 km^2 (>120 square miles) along the fault in the project vicinity. Color aerial photography at a scale of 1:3,000 also was acquired as part of the LiDAR project. Hillshades and topographic maps were prepared from the LiDAR data. Interpretation of this data, along with additional field work, confirmed the absence of scarps at the locations where Carpenter and others (1967) had mapped the fault as a solid or dashed line in Quaternary deposits. RJH also discovered that large slope failures had occurred at many locations along the range front in the footwall of the fault and that these features often obscure the main trace of the Paunsaugunt fault.

Many linear features suspected to be of possible tectonic origin were identified in the LiDAR imagery and examined in the field during 2011, but nearly all were judged to be non-tectonic in origin. The main trace of the Paunsaugunt fault was located in several areas, but no scarps were observed where the fault projected into adjacent Quaternary deposits. The antithetic scarps detected in 2010 were very apparent on the imagery, and a few other short, but less obvious antithetic scarps in remnants of older fan deposits were detected and examined in the field.

If the project continues, we may excavate and log soil pits in unfaulted deposits along the main trace of the fault. Relative and absolute dating would be used to determine the minimum age of the most recent event on the main trace of the fault. We may also trench the antithetic scarps to determine the minimum age of the most recent event and the slip rates on them.

References Cited

Bowers, W.E., 1991, Geologic map of Bryce Canyon National Park and vicinity, southwestern Utah: U.S. Geological Survey, Miscellaneous Investigations Series Map I-2108, scale 1:24,000.

Carpenter, C.H., Robinson, G.B. Jr., and Bjorklund, L. J., 1967, Ground-water conditions and geologic reconnaissance of the upper Sevier River Basin, Utah: U.S. Geological Survey, Water-Supply Paper 1836, 91 p.

Rowley, P.D., Steven, T.A., and Mehnert, H.H., 1981, Origin and structural implications of upper Miocene rhyolites in Kingston Canyon, Piute County, Utah: Geological Society of America, Bulletin v. 92, no. 8, p. 590-602.

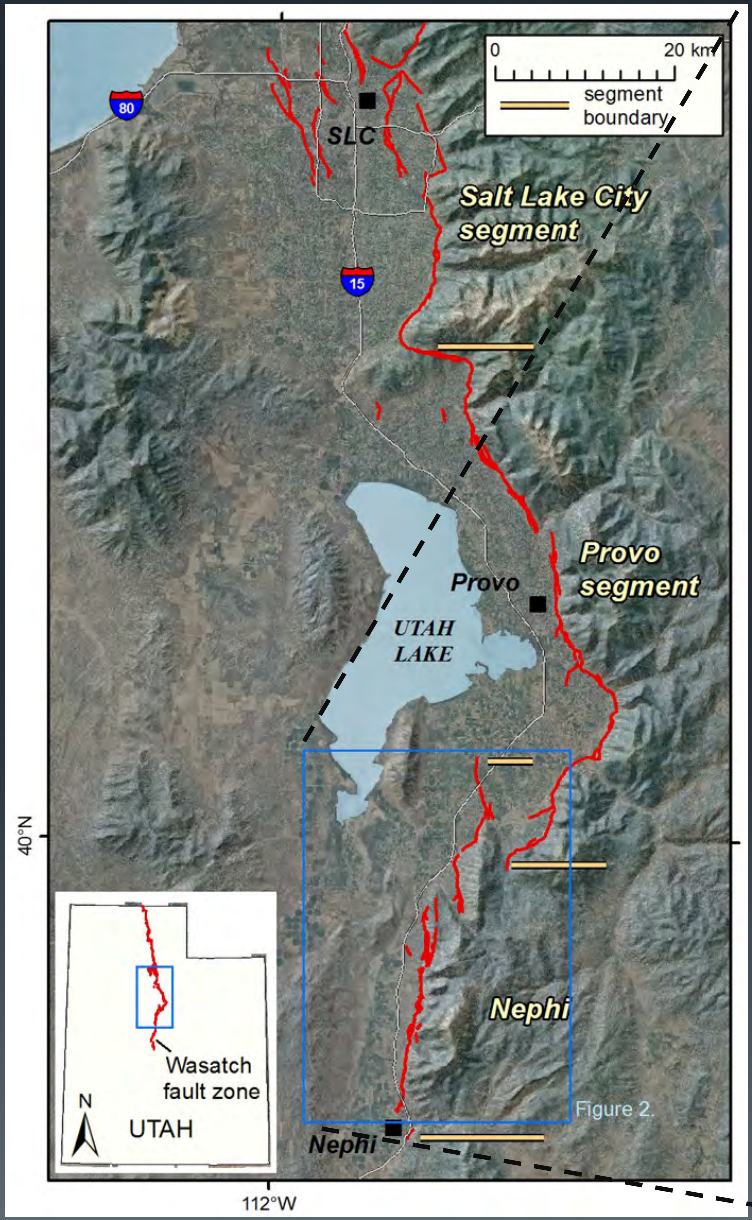
Williams, P.L., and Hackman, R.J., compilers, 1971, Geology, structure, and uranium deposits of the Salina quadrangle, Utah: U.S. Geological Survey, Miscellaneous Geologic Investigations Map I-591, scale 1:250,000.

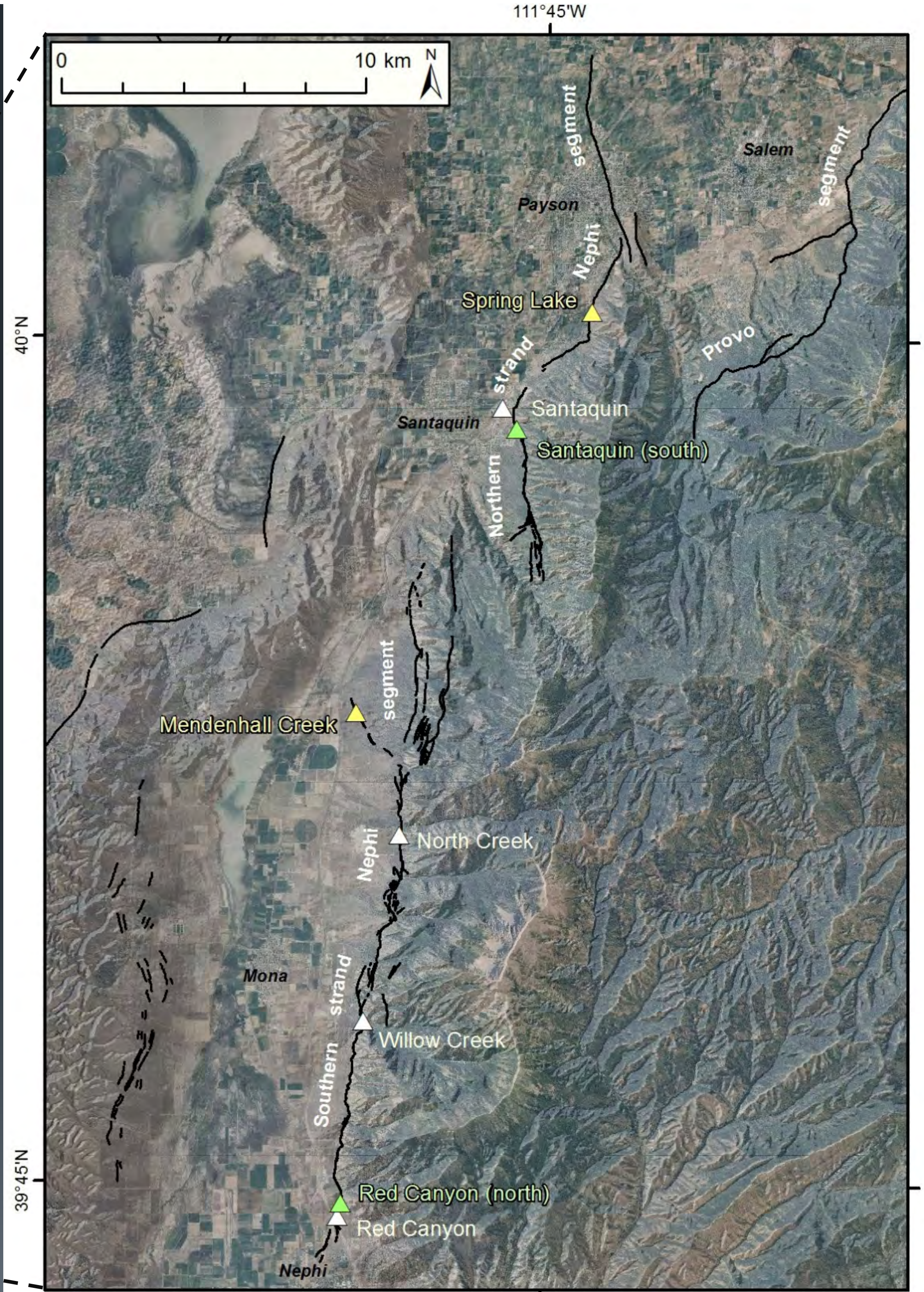
Utah Geological Survey
Nephi Segment Trenching Project
June 2012

Chris DuRoss
[and Mike Hylland, Greg McDonald, and others (UGS);
Tony Crone, Steve Personius, and others (USGS)]

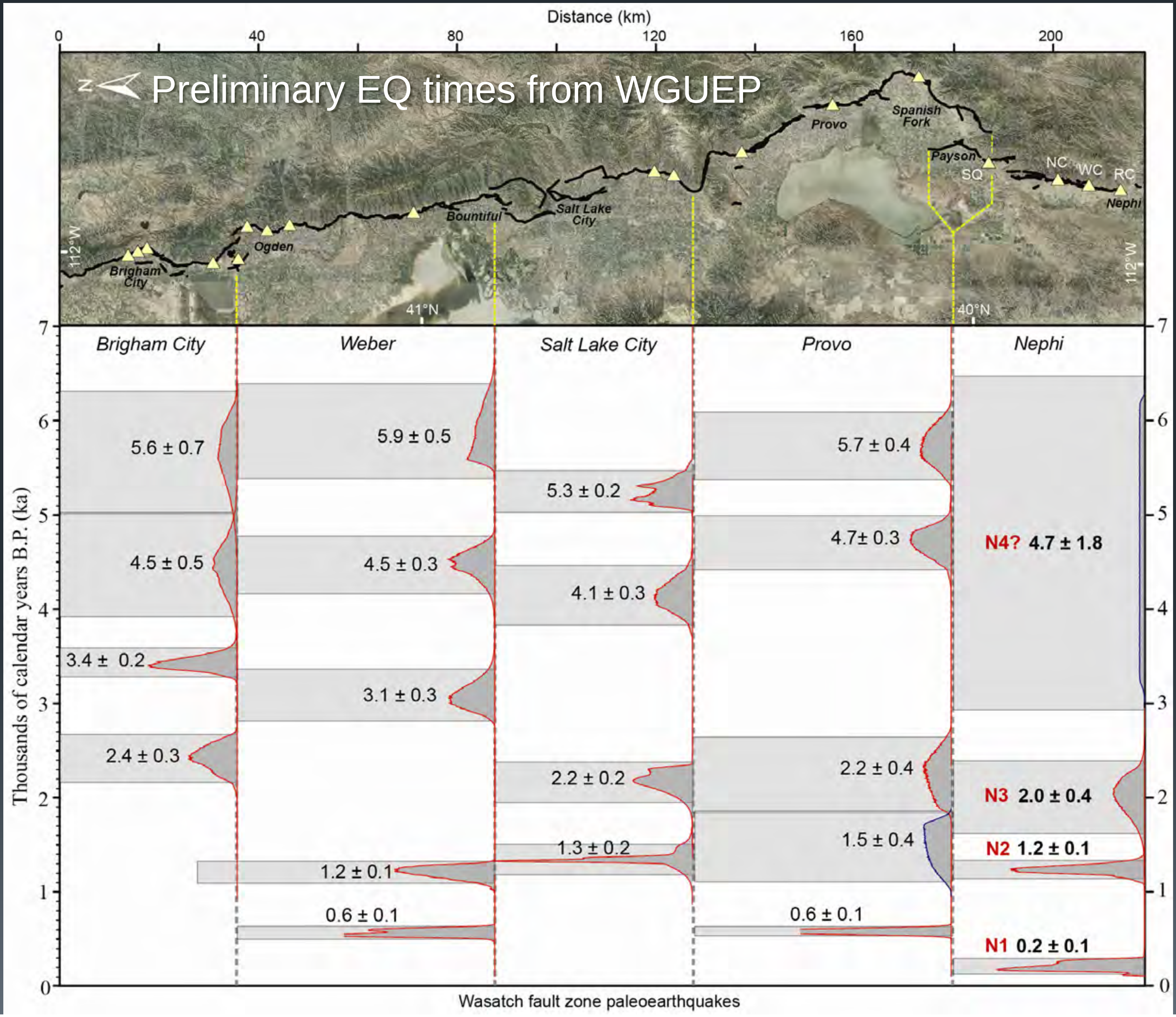
Utah Quaternary Fault Parameters Working Group, February 2012

Nephi Segment

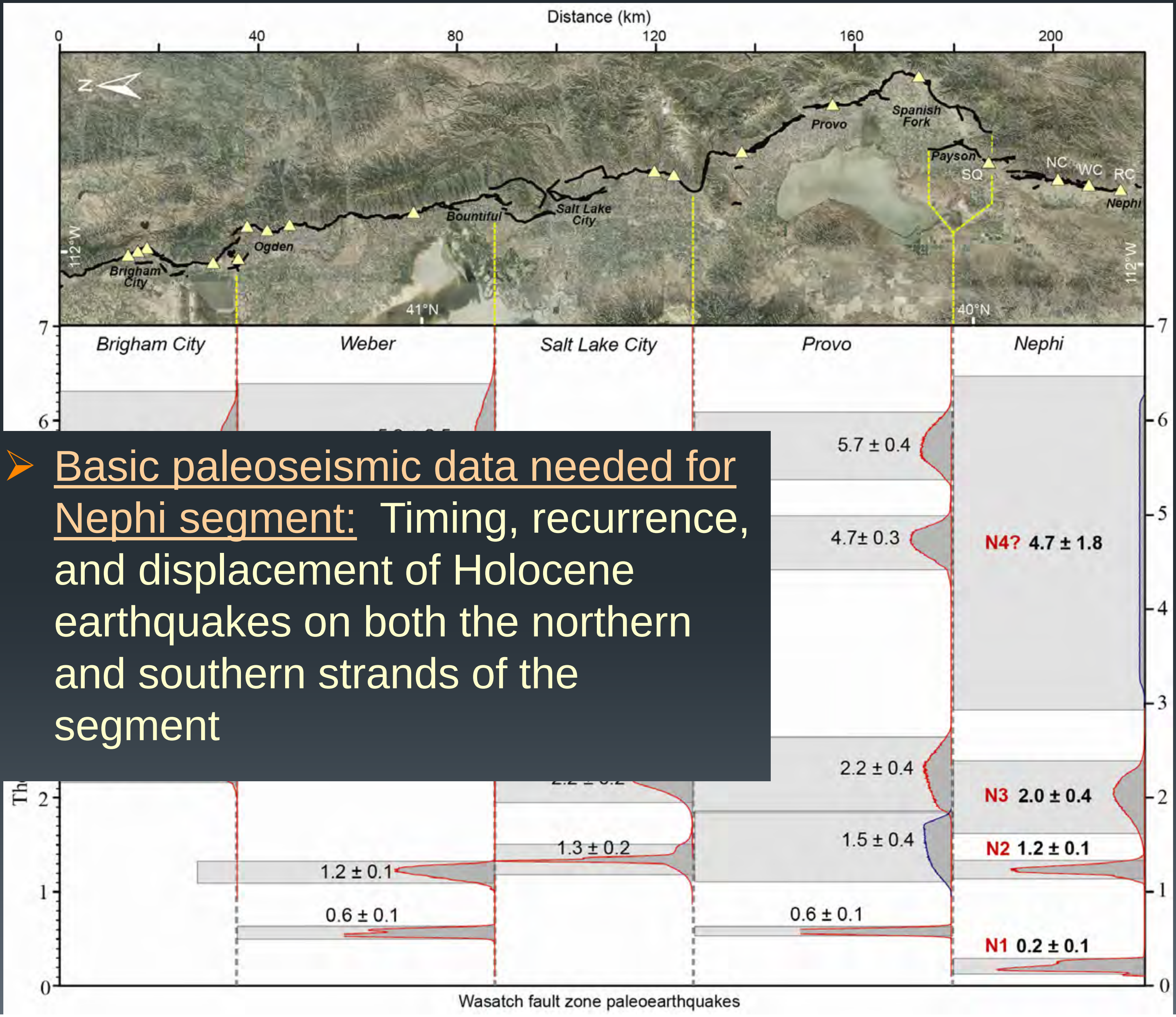




Central Wasatch Fault Earthquakes



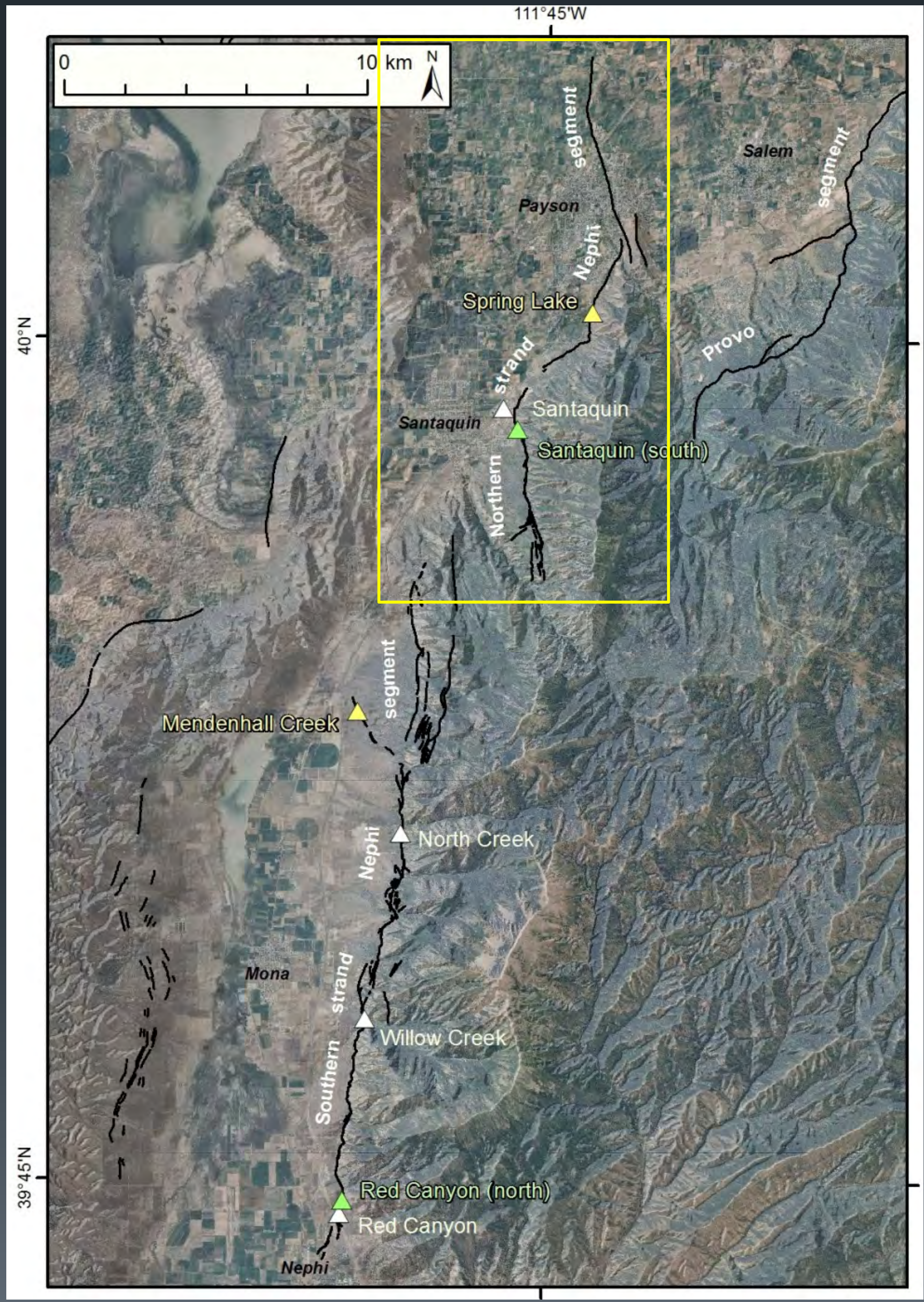
Central Wasatch Fault Earthquakes



- Basic paleoseismic data needed for Nephi segment: Timing, recurrence, and displacement of Holocene earthquakes on both the northern and southern strands of the segment

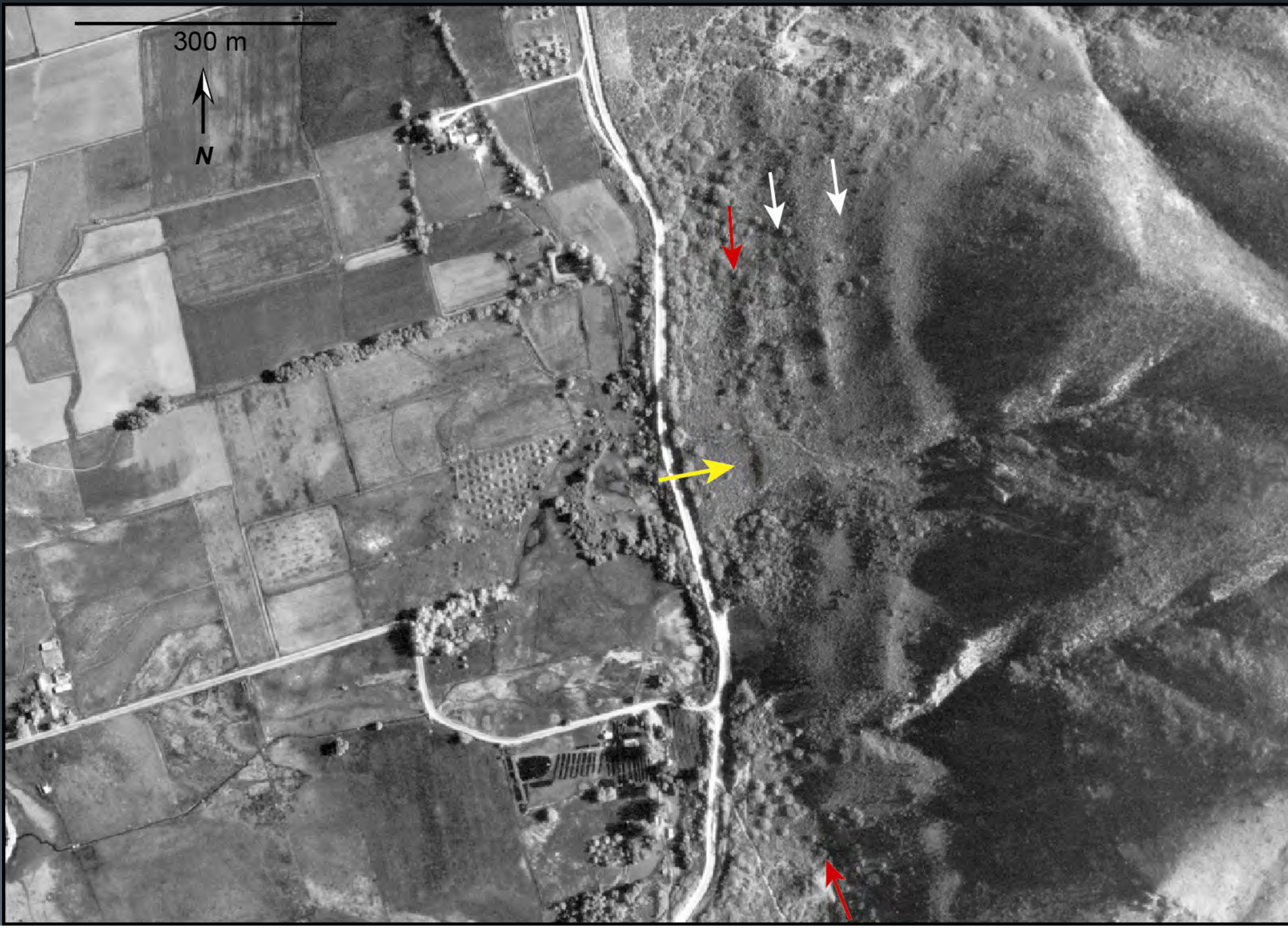
Northern Nephi segment

- What is the timing of late to mid-Holocene ruptures on the northern strand?
  - Does the northern strand rupture with the southern strand of the Nephi segment, the Provo segment, or both? (or can it rupture independently?)
  - What are the rupture lengths and displacements for events involving the northern strand?

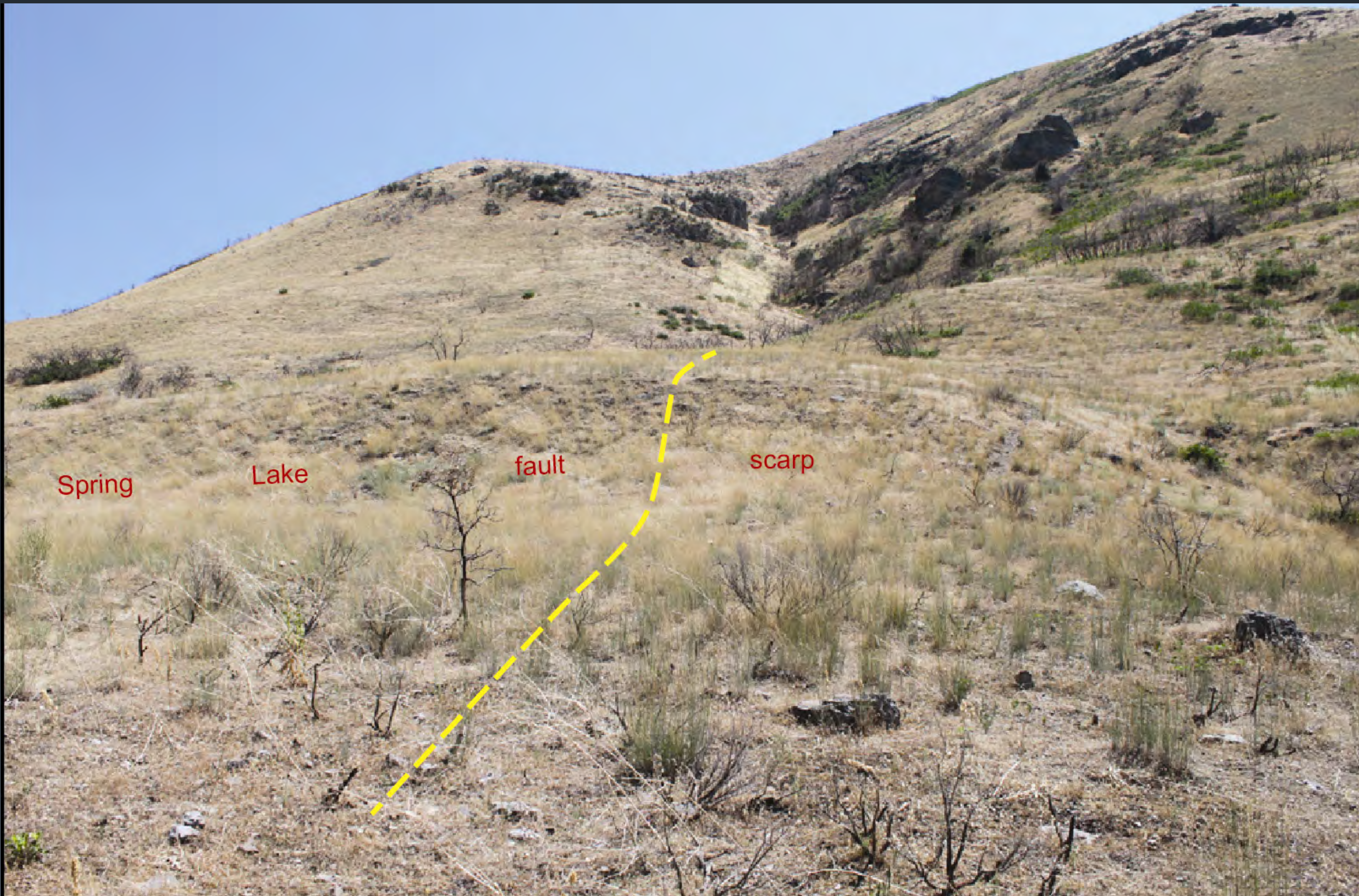


Northern Nephi segment

Northern Nephi segment – Spring Lake

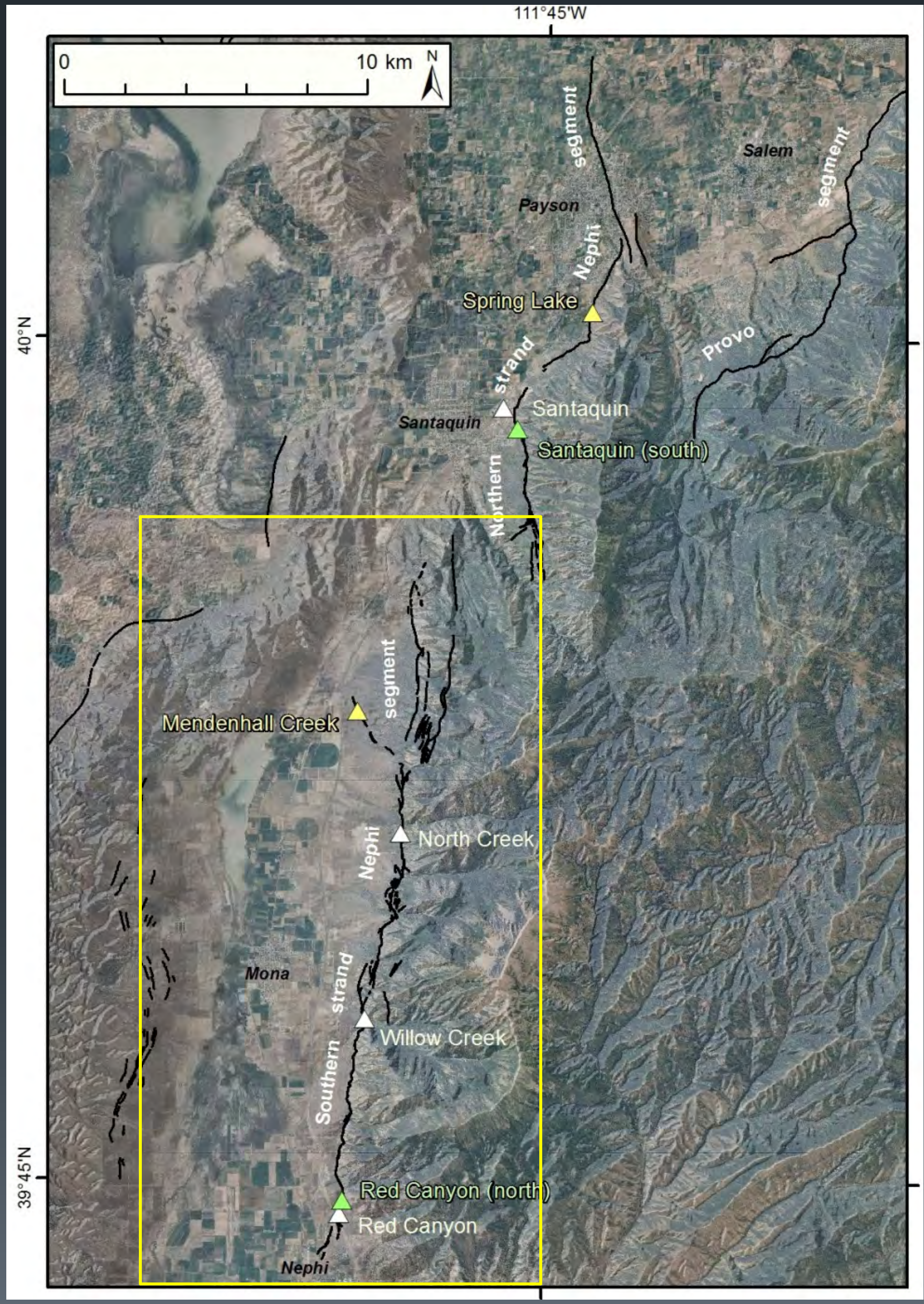


Northern Nephi segment – Spring Lake

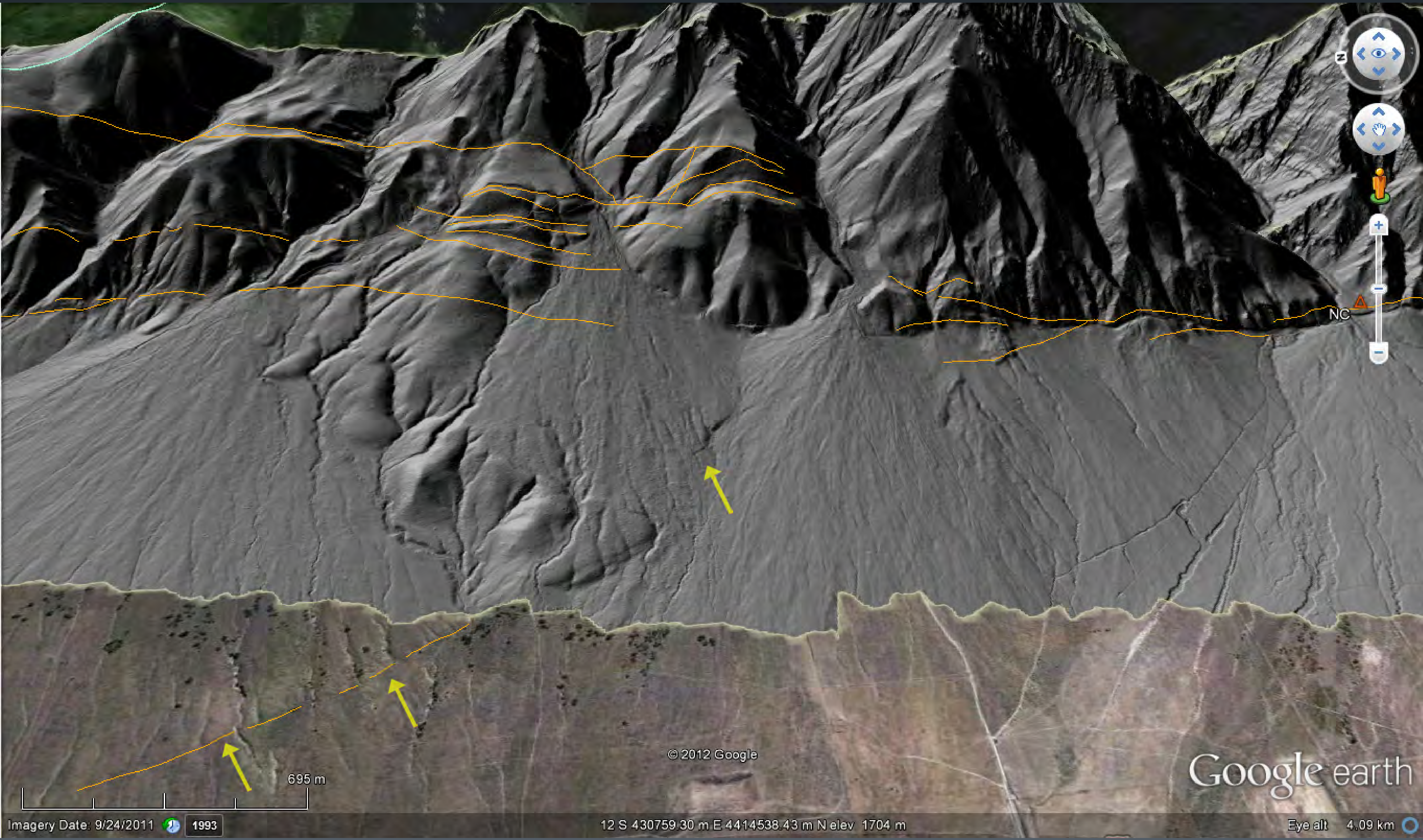


Southern Nephi segment

- What is the timing of mid- to early Holocene ruptures on the southern strand.
  - Need to refine the time of N4 (4.7 ± 1.8 ka), which affects mean recurrence and slip rate estimates.
  - Are events on the southern strand clustered in the late Holocene?
  - How do earthquake times on the southern strand compare to those on the northern strand?



Southern Nephi segment



Southern Nephi segment – Mendenhall Ck.

Southern Nephi segment – Mendenhall Ck.

Characterizing the central Wasatch Fault Zone for the Working Group on Utah Earthquake Probabilities

Paleoseismology Subgroup:

Christopher B. DuRoss

Susan S. Olig

Anthony J. Crone

Stephen F. Personius

William R. Lund

UTAH DNR GEOLOGICAL SURVEY

URS

USGS science for a changing world

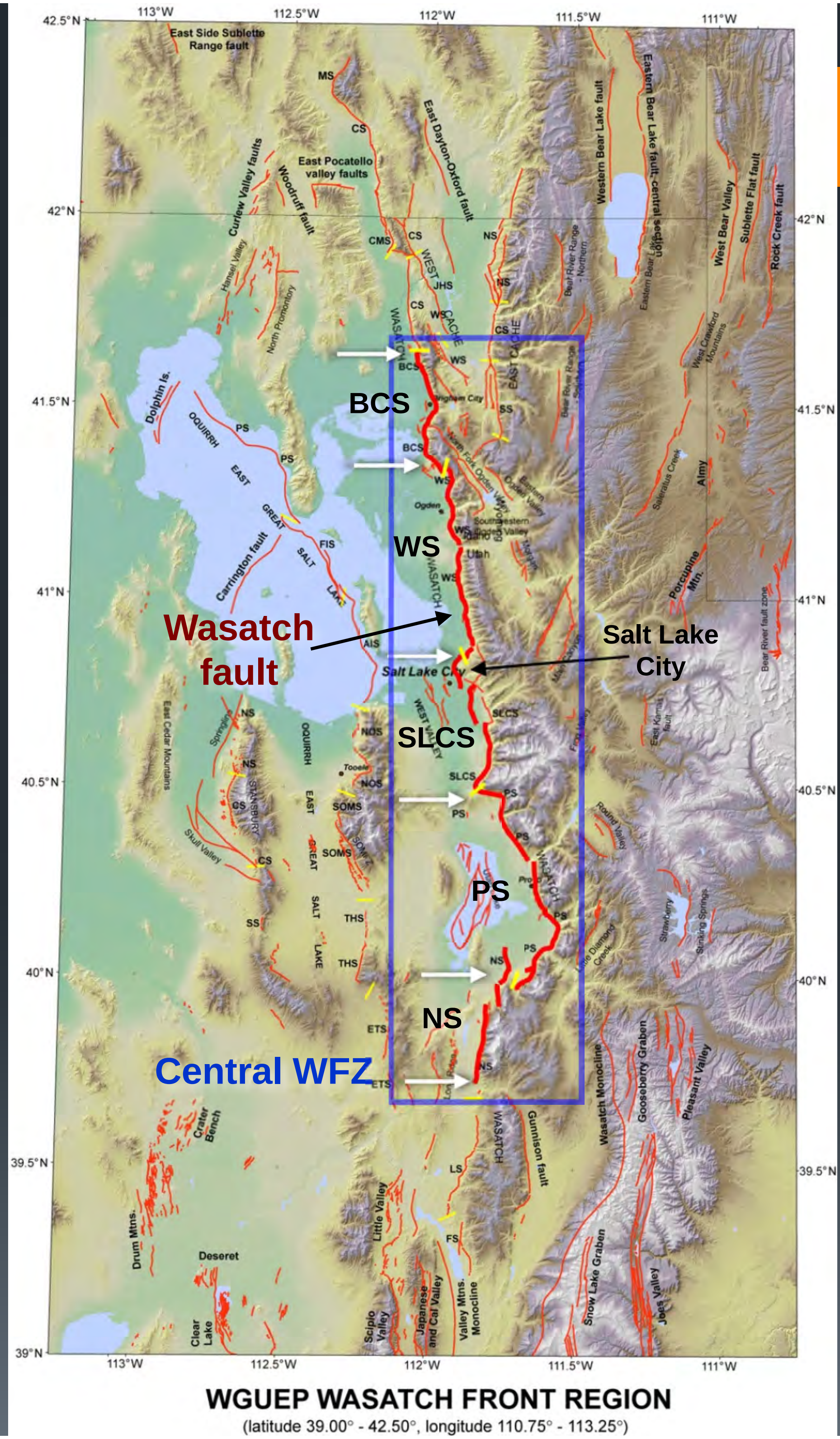
Utah Quaternary Fault Parameters Working Group, February 2012

Introduction

- WGUEP: time-independent and -dependent earthquake forecasts ($M \geq 6.5$) for the central Wasatch fault zone (WFZ)

- Paleoseismic data needed:
  - Surface-faulting earthquake timing
  - Rupture lengths and displacements (M_0 release)
  - Recurrence intervals for segments
  - Vertical slip rates
  - Uncertainties in these values

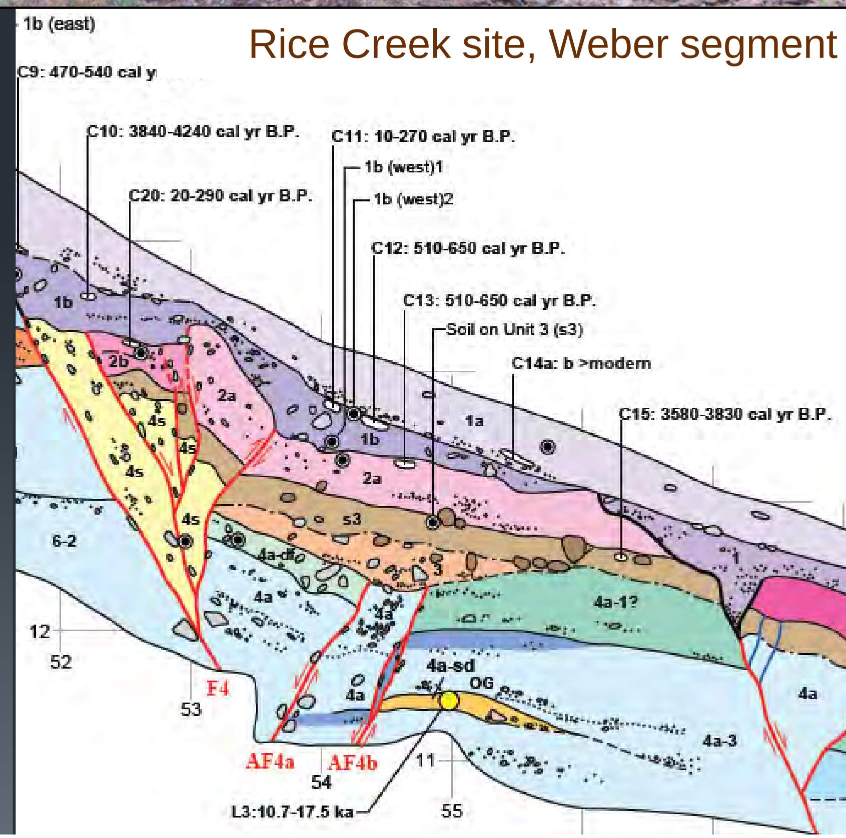
<u>*Central WFZ segments:*</u>
BCS – Brigham City segment
WS – Weber segment
SLCS – Salt Lake City segment
PS – Provo segment
NS – Nephi segment



WFZ Characterization

1. Updated the earthquake chronology for each trench site and segment
2. Used paleoseismic data to develop multi-segment rupture models
3. Calculated recurrence-interval and vertical-slip-rate estimates
4. Reviewed **M** relations and calculated composite earthquake recurrence and periodicity (COV) for the central WFZ

Rice Creek site, Weber segment



<u>Disclaimer</u>: Results presented here are preliminary (have not been reviewed) and are subject to revision

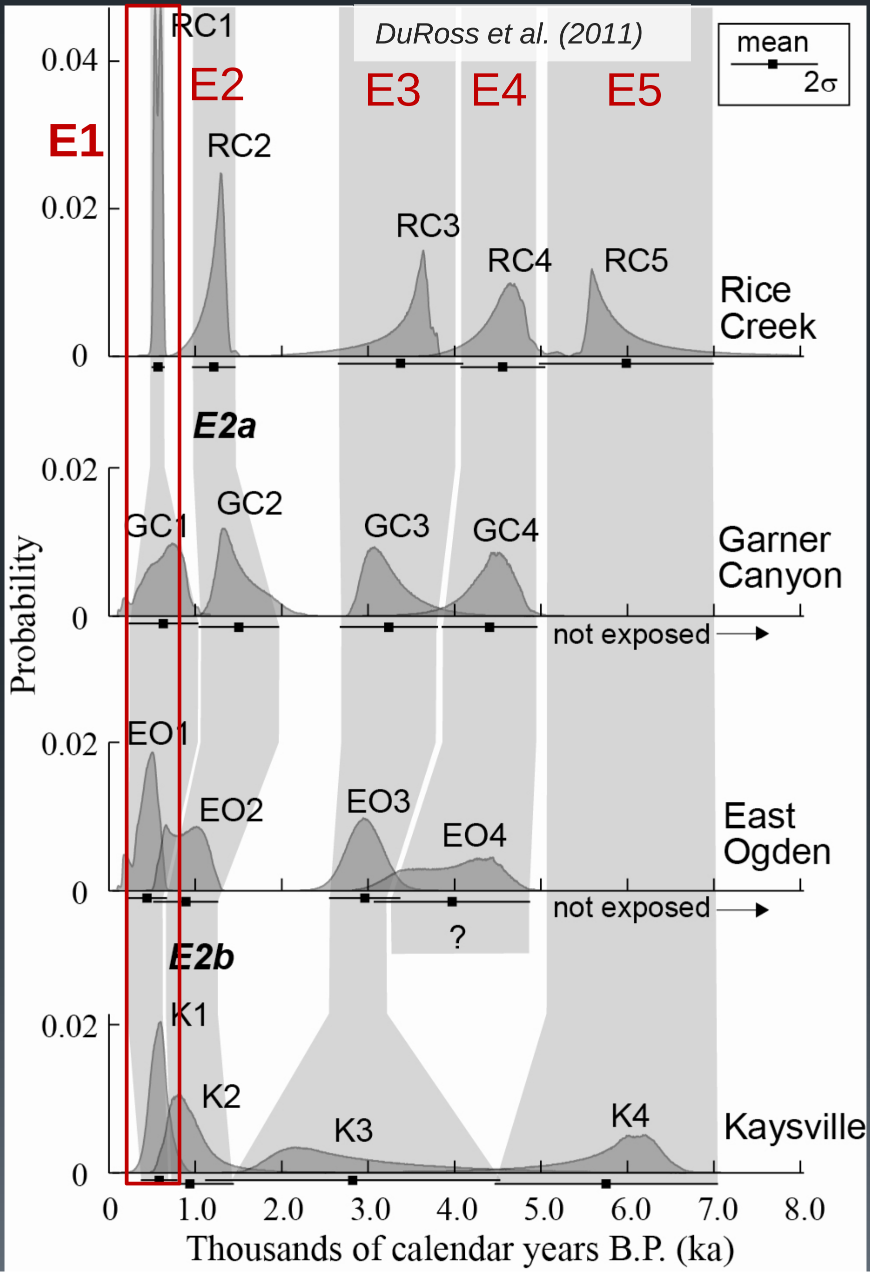
Updated Earthquake Chronologies

- To update WFZ paleoseismic data: *(DuRoss et al., 2011 – BSSA v. 101)*
  1. Considered common limitations in constraining paleoearthquakes
  2. Examined original paleoseismic site reports and evaluated geologic and chronologic evidence for interpreted events
  3. Constructed time-stratigraphic OxCal models for each site
  4. Qualitatively correlated events between sites to develop a segment-wide earthquake history
  5. Computed probability density functions (PDFs) for each segment earthquake
  6. Used the revised earthquake data to calculate mean recurrence

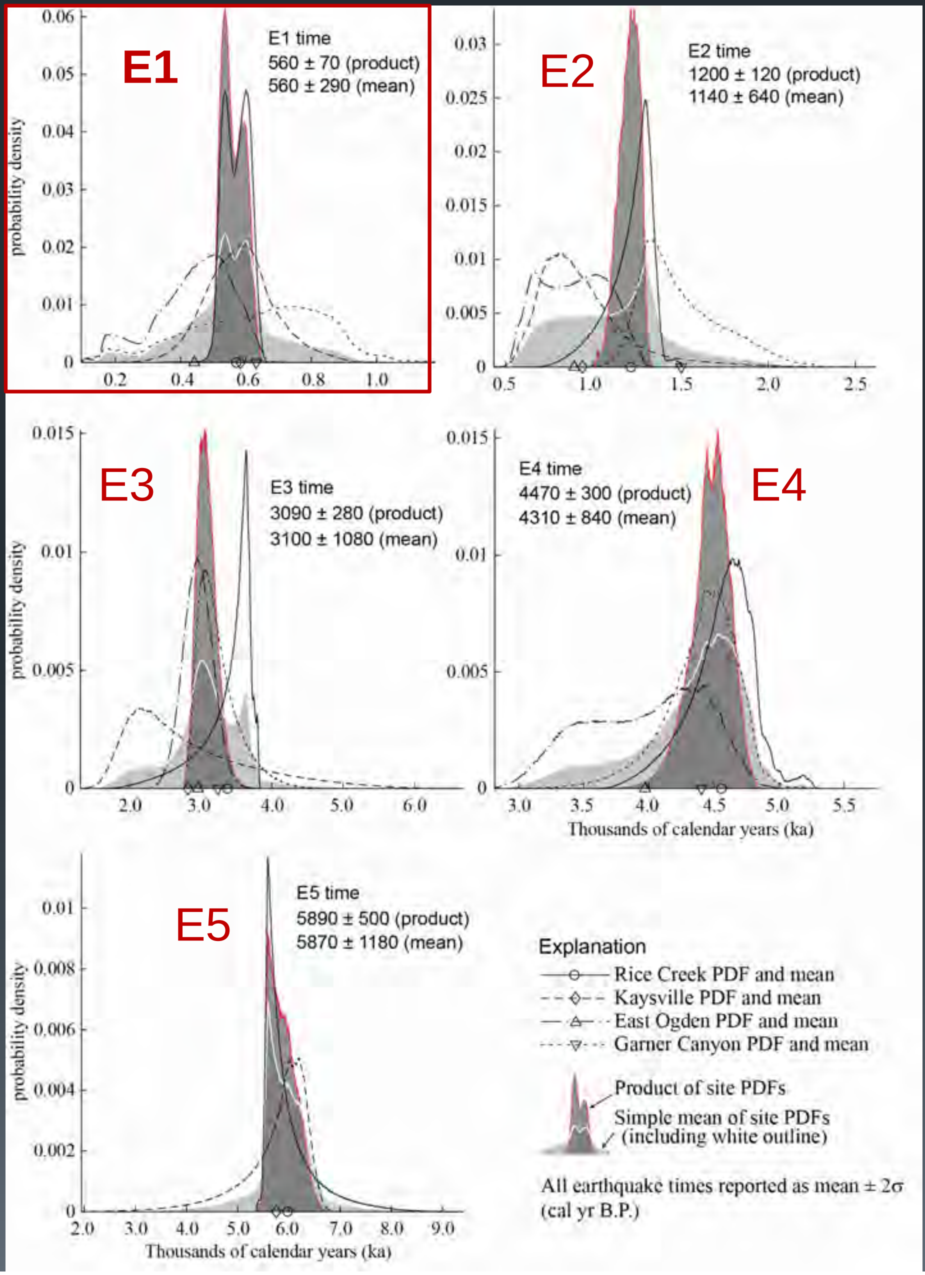
- Key papers
  - Bronk Ramsey (2008). Depositional models for chronological records (Quat. Sci. Rev. v. 27; O*xCal online: c14.arch.ox.ac.uk*)
  - Lienkaemper and Bronk Ramsey (2009). OxCal: Versatile tool for developing paleoearthquake chronologies – A primer (SRL v. 80)
  - Biasi and Weldon (2009). San Andreas fault rupture scenarios from multiple paleoseismic records – Stringing pearls (BSSA v. 99)

Updated Earthquake Chronologies

- Correlation of site earthquakes

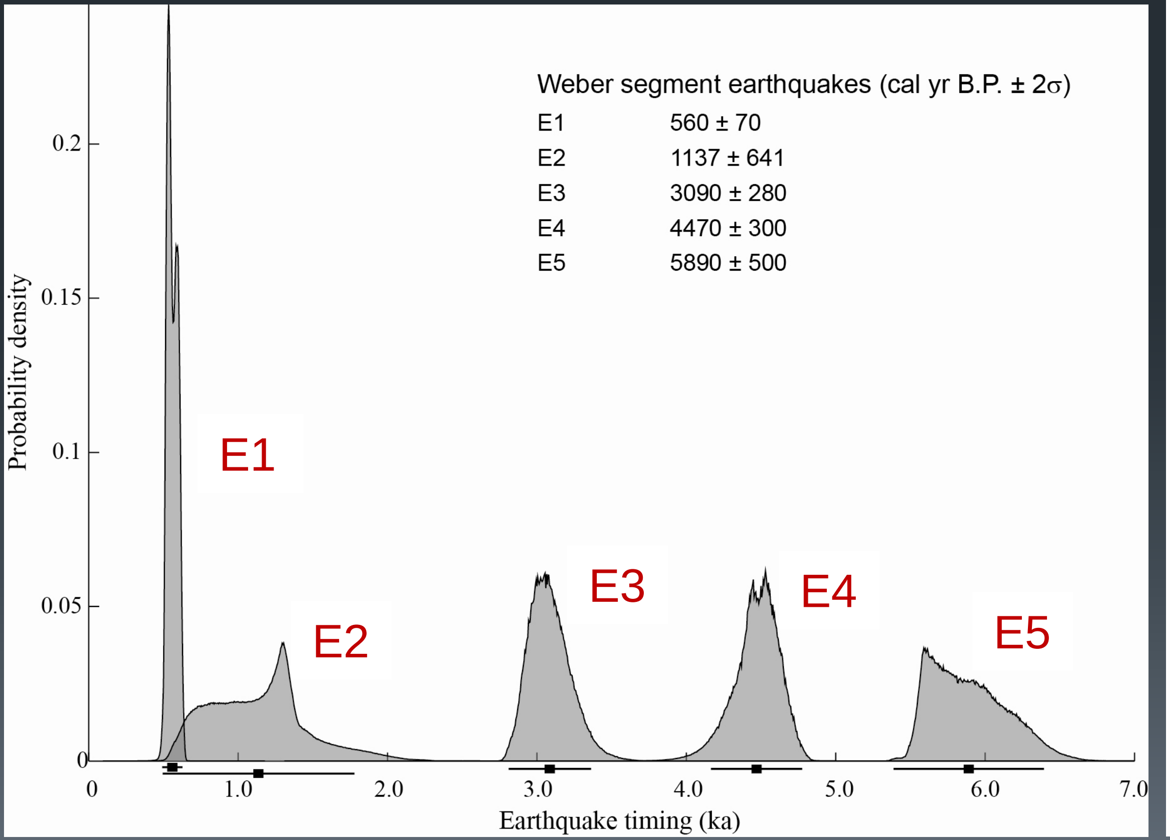


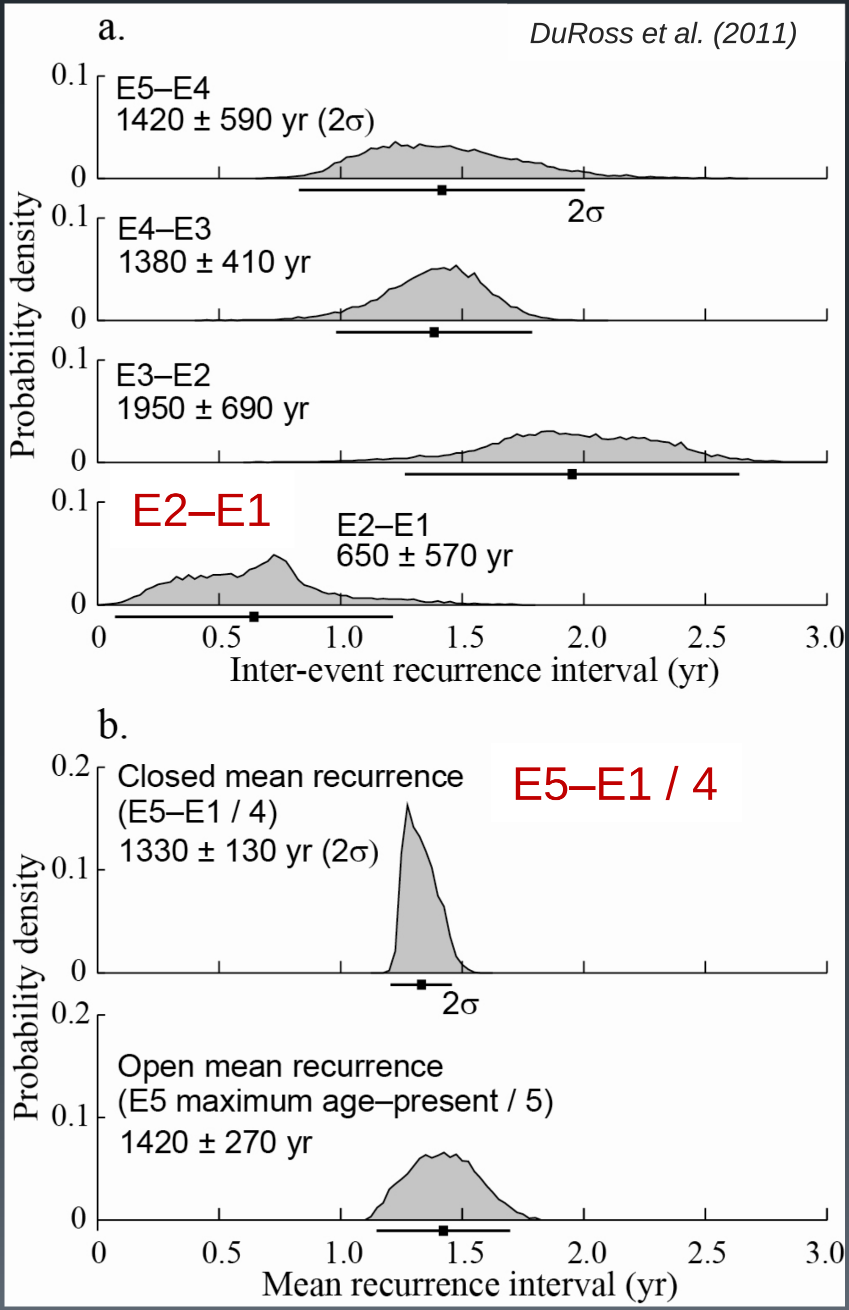
- Segment earthquakes (PDFs)



Updated Earthquake Chronologies

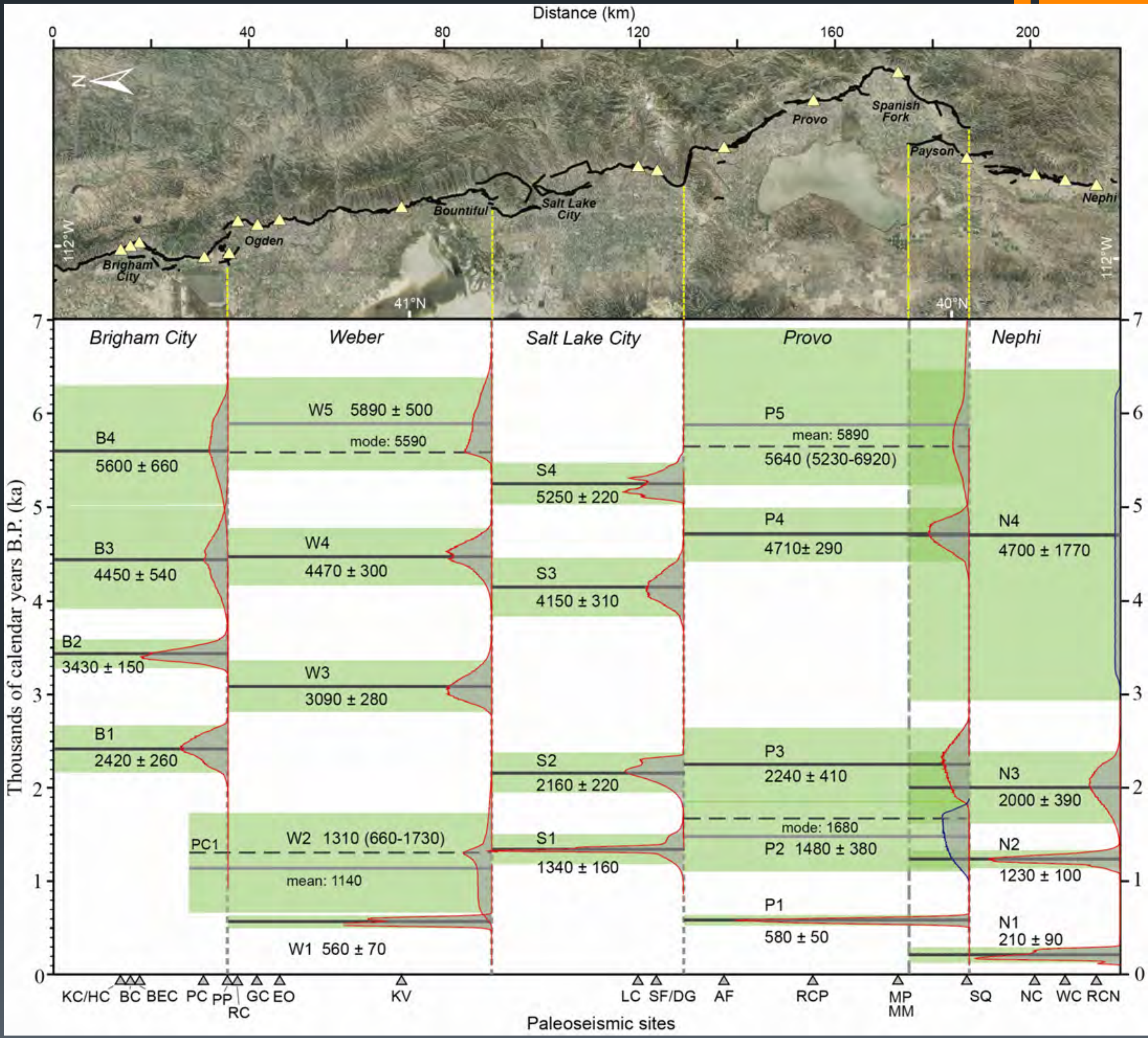
- Timing PDFs for segment earthquakes
- Inter-event (closed), open, and mean recurrence estimates using PDF data





Rupture Models

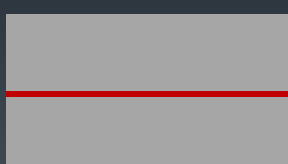
- Single segment earthquakes
  - At least 22 earthquakes since the mid-Holocene
  - Closed mean recurrence intervals per segment: 0.9–1.3 kyr



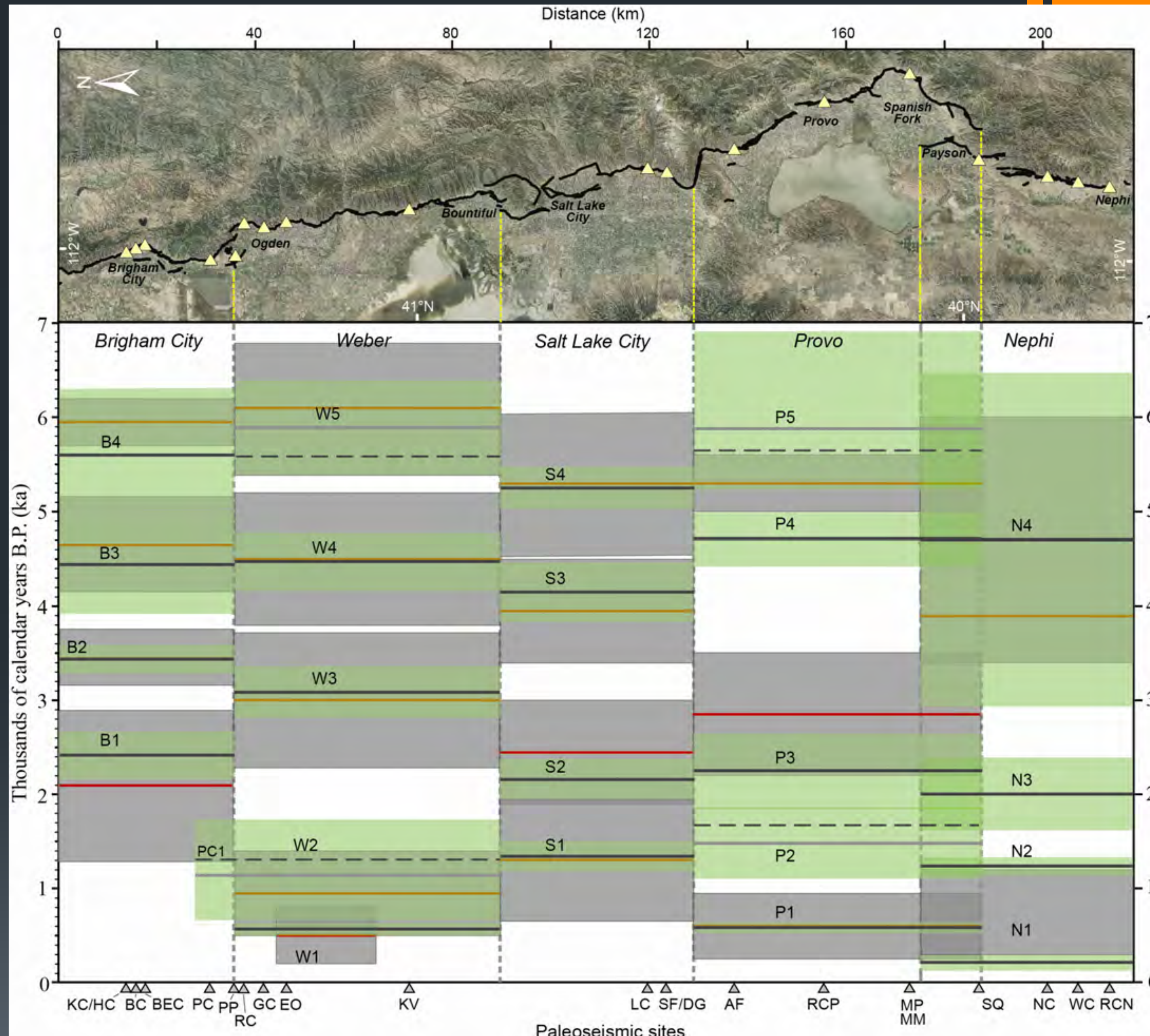
Preliminary data subject to revision

Rupture Models

- Comparison with consensus values of UQFPWG (2005)
  - Refined earthquake times
  - Most significant changes related to Provo and Nephi segments



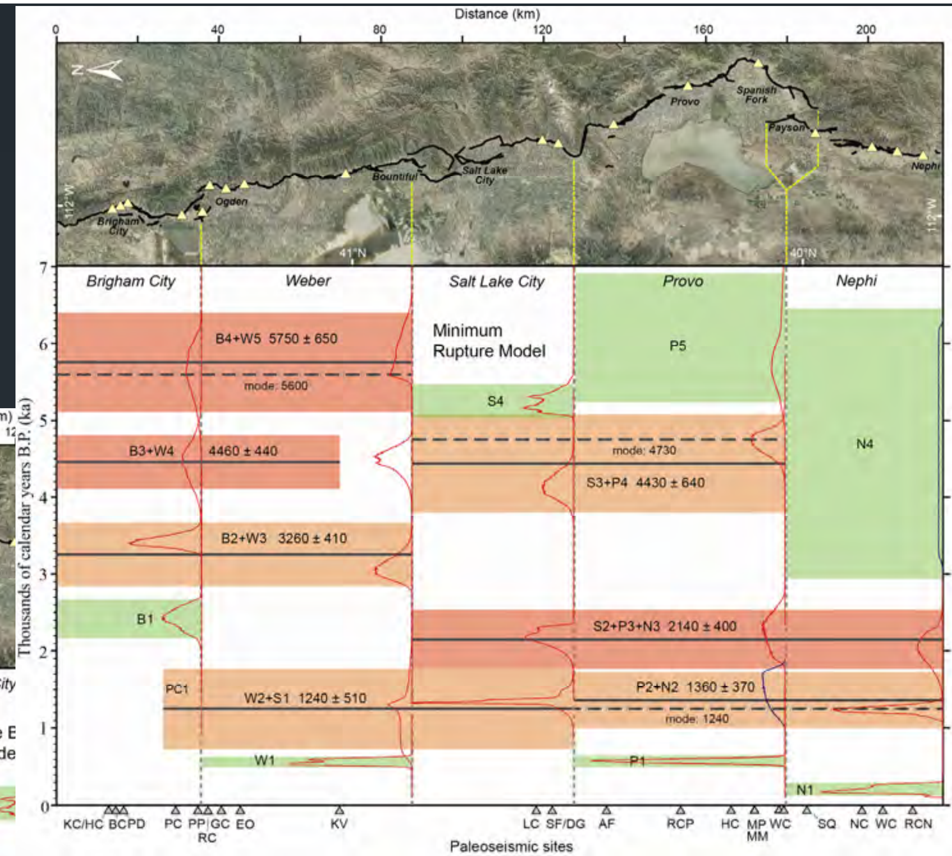
UQFPWG preferred EQ time (red) and estimated 5th–95th percent range (Lund, 2005)



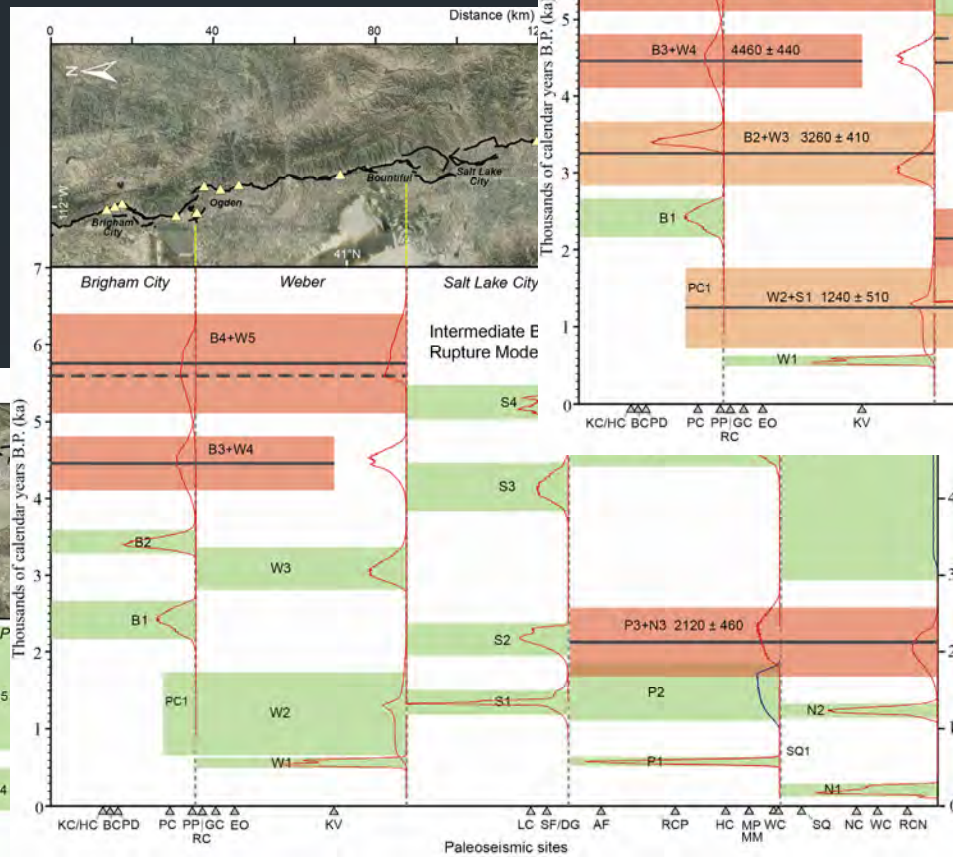
Preliminary data subject to revision

Rupture Models

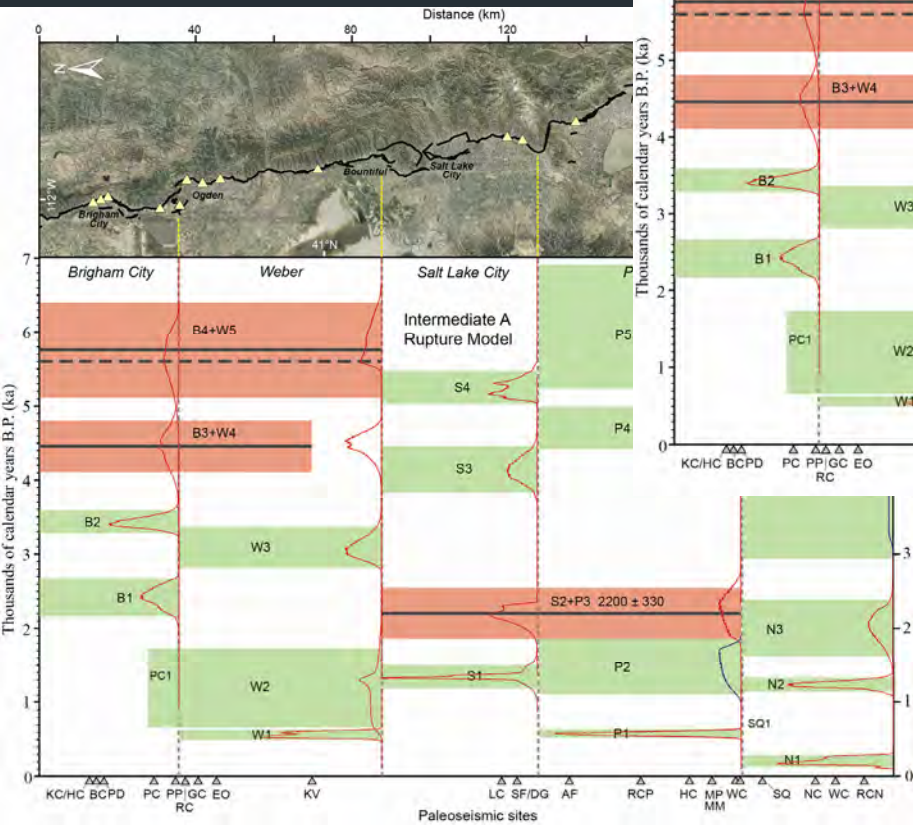
- Multi-segment rupture models
  - Recurrence for rupture that only occur once?



Multi-segment rupture model (fewest earthquakes)



Intermediate B



Intermediate A

Preliminary data subject to revision

Earthquake Recurrence

- Time-independent recurrence intervals
  - N/T = number of events (N) in time window (T) per segment (open mean recurrence)
  - Composite* N/T = sum of all events (N) in sum of time windows (T) for the central WFZ

- Time-dependent recurrence intervals
  - Closed mean = mean closed (inter-event) recurrence interval per segment
  - Composite* closed mean = composite closed mean recurrence interval for central WFZ

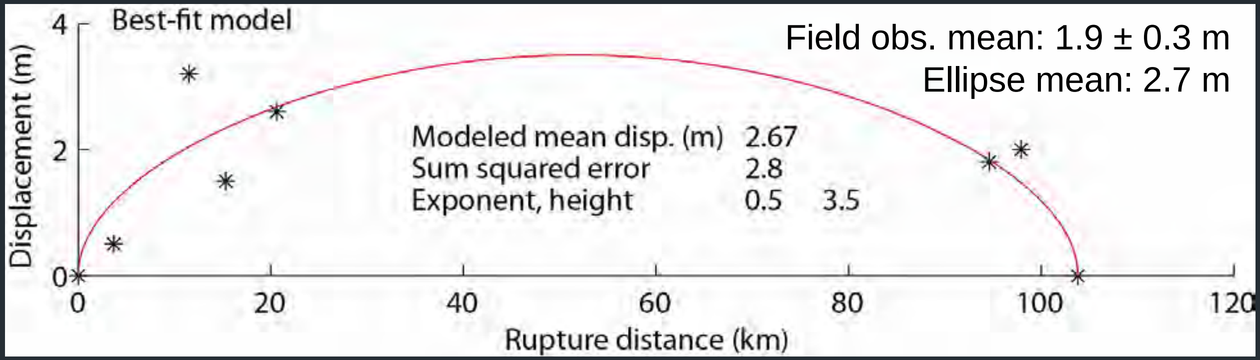
- Composite* COV on recurrence (periodicity)
  - Standard dev. of all inter-event recurrence times divided by mean of all inter-event recurrence times

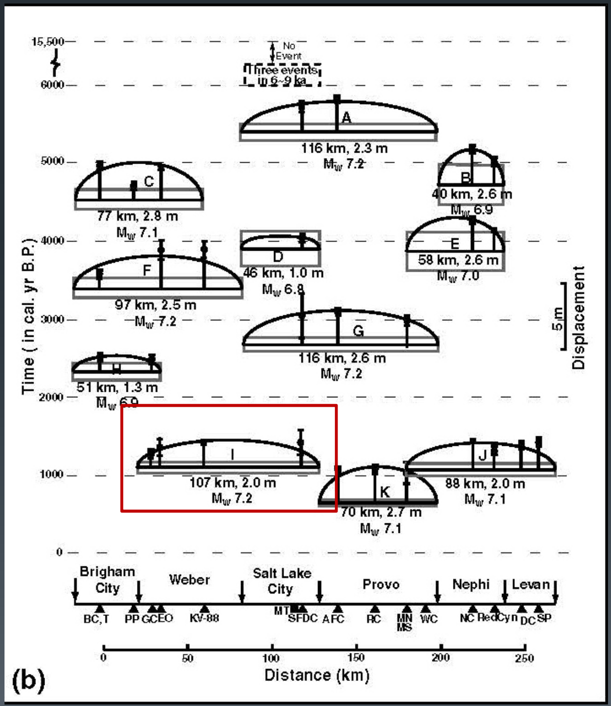
**Assumption:*
The mean recurrence interval and COV are the same for each of the Wasatch Fault segments considered

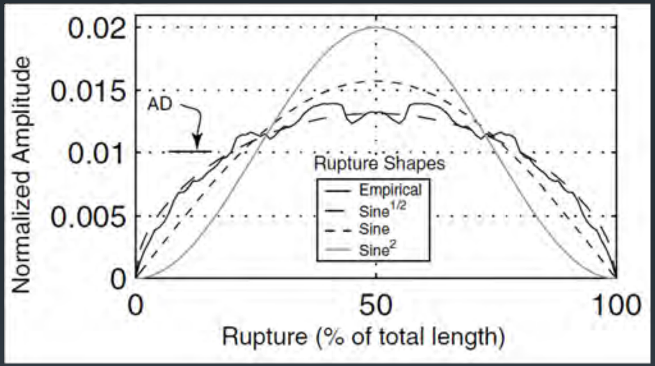
Displacement

- Least-squares best fit of half ellipse to data by varying:
  - <u>Shape (n)</u>: sin(L)^n, where n = 0.1 (~flat) to 0.9 (peaked)
  - <u>Max height (h):</u> 0 to ~2x max displ.
- Similar to methods of Chang and Smith (2002) and Biasi and Weldon (2009)

W2+S1







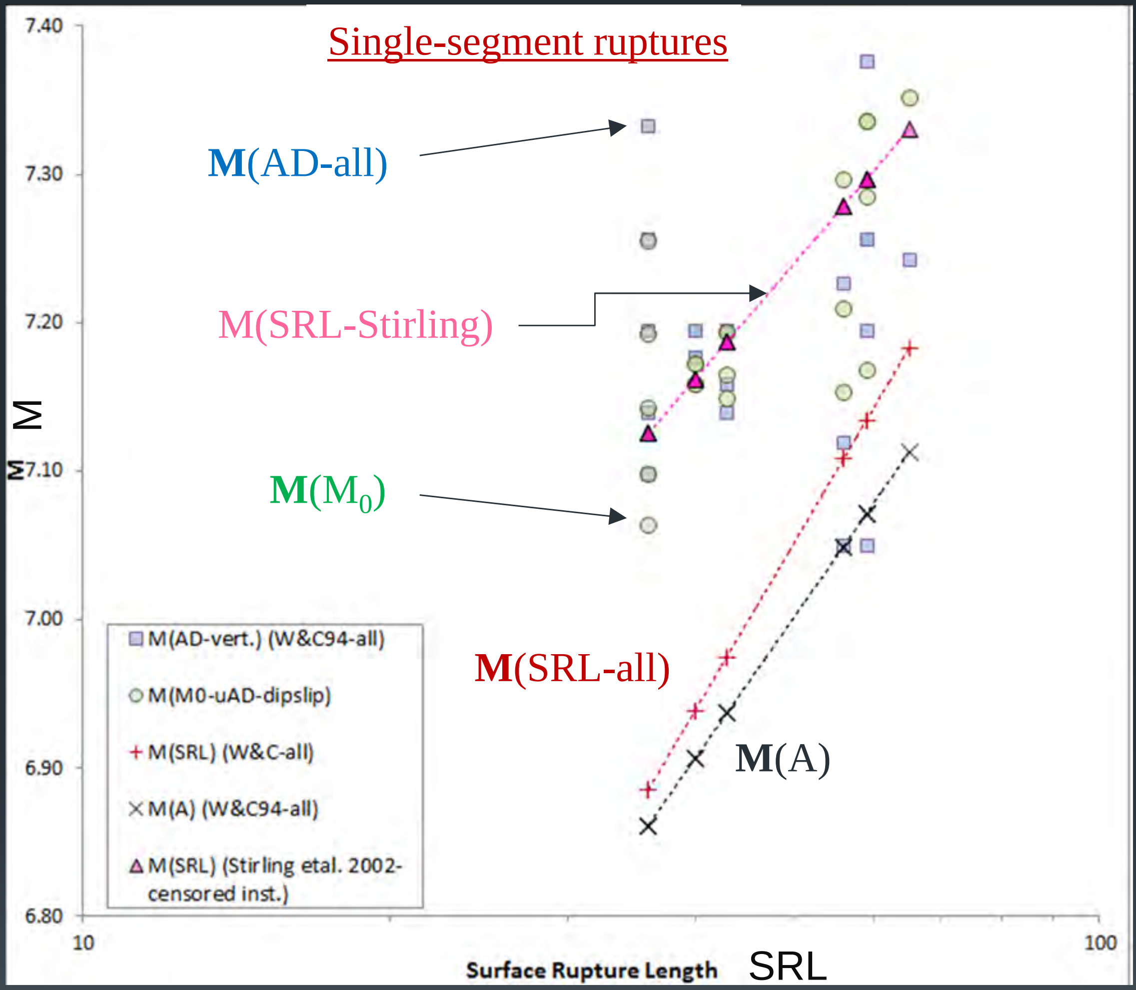
Biasi and Weldon (2009)

Chang and Smith (2002)

Preliminary data subject to revision

Misc. – M Relations

- Magnitude relations for central WFZ
  - Hanks & Kanamori (1979) – M_0
  - Stirling et al. (2002) – SRL (censored instrumental)
  - Wells & Coppersmith (1994) – SRL (all fault types)
  - Wells & Coppersmith (1994) – A (all fault types)
  - Not using W&C(1994) AD and normal-fault-type regressions because of limited data used to define these regression



*M_0 – seismic moment (μ*A*AD)*
SRL – surface rupture length
A – rupture area
AD – average displacement

Preliminary data subject to revision

Summary & Conclusions

- Significant advances:
  - OxCal modeling; objective determination of segment chronologies
  - Recurrence intervals using full earthquake-timing PDFs
  - Composite recurrence and COV for central segments
  - Multiple-segment rupture scenarios (and spill-over rupture)
  - Modeled displacement per event/source and revised slip rates
  - Epistemic uncertainty in magnitude

- Conclusions
  - WFZ paleoseismic data are complex (of variable quality and spanning several decades)
  - We evaluated and interpreted the data as objectively as possible
  - Some subjectivity remains (e.g., correlating events among sites)
  - <u>Final product</u>: full evaluation of WFZ data from individual trench-site data to multi-segment rupture and composite recurrence

Comparison of Moment Rates from GPS Observations and Late Quaternary Earthquakes on the Wasatch Fault, Utah

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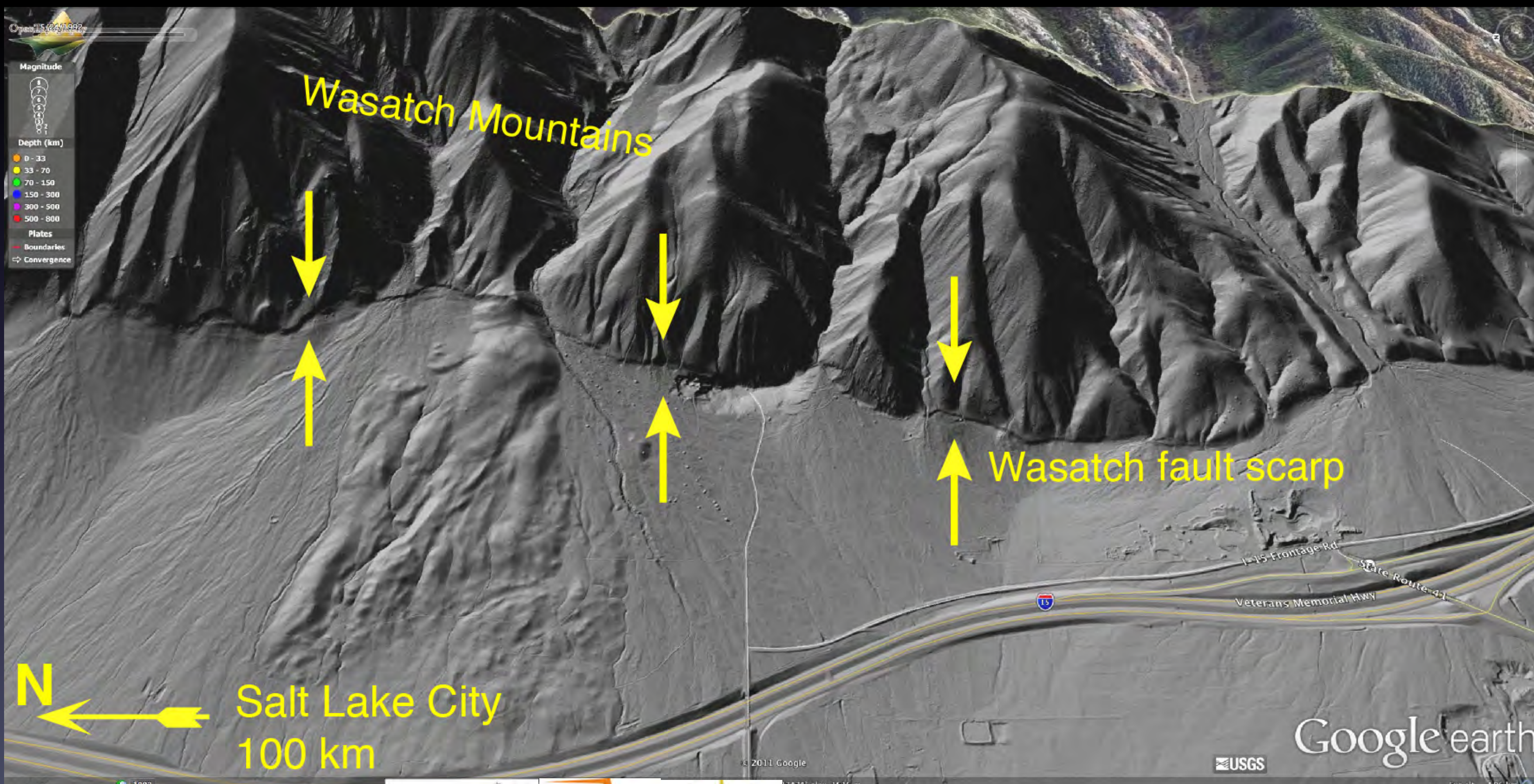
UNAVCO

Robert B. Smith
Univ. of Utah

Wu-Lung Chang
Natl. Central Univ.

Alan Cannaday
Univ. of Utah

Chris DuRoss
Utah Geol. Survey



(Open Topography)

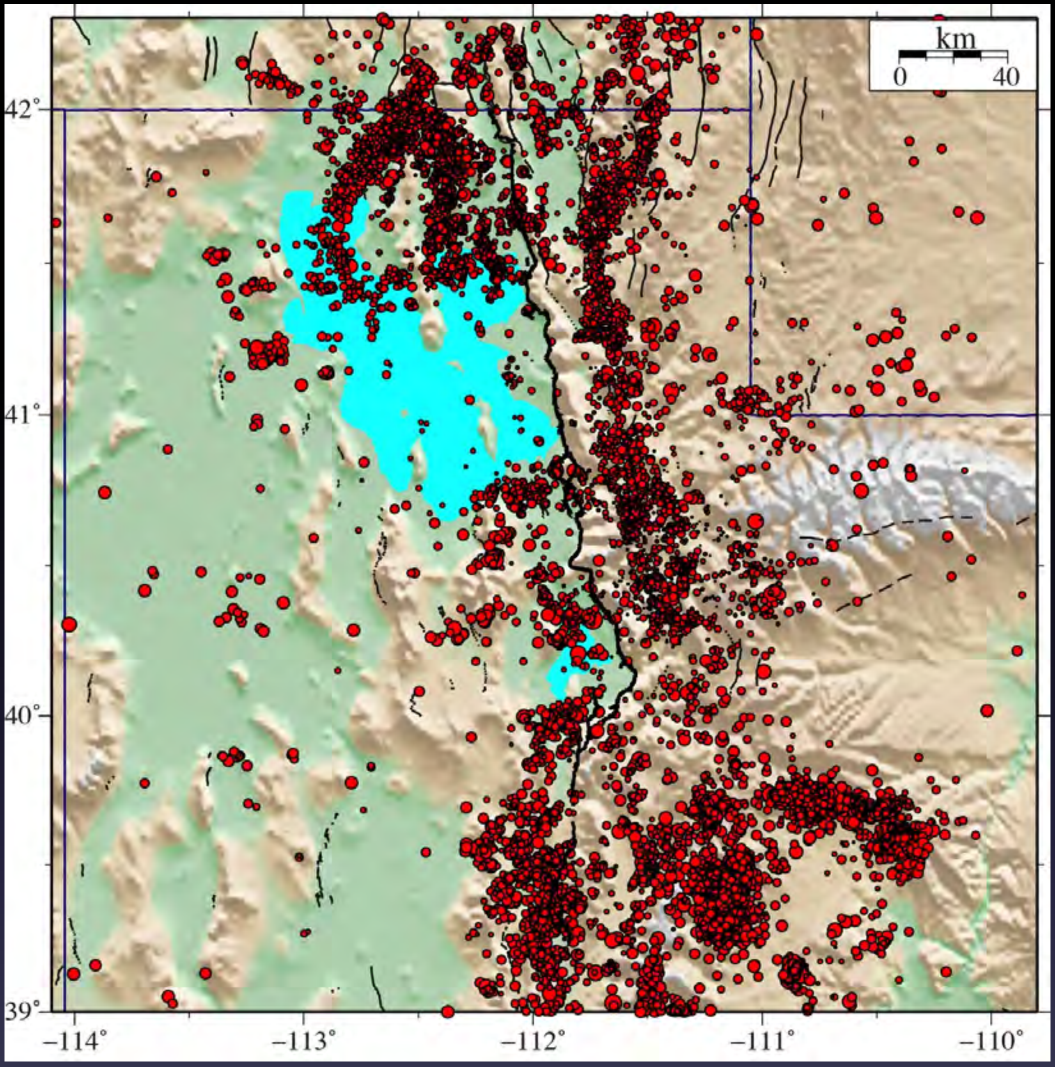
THE UNIVERSITY OF UTAH Seismology and Active Tectonics Research Group

UNAVCO PBO

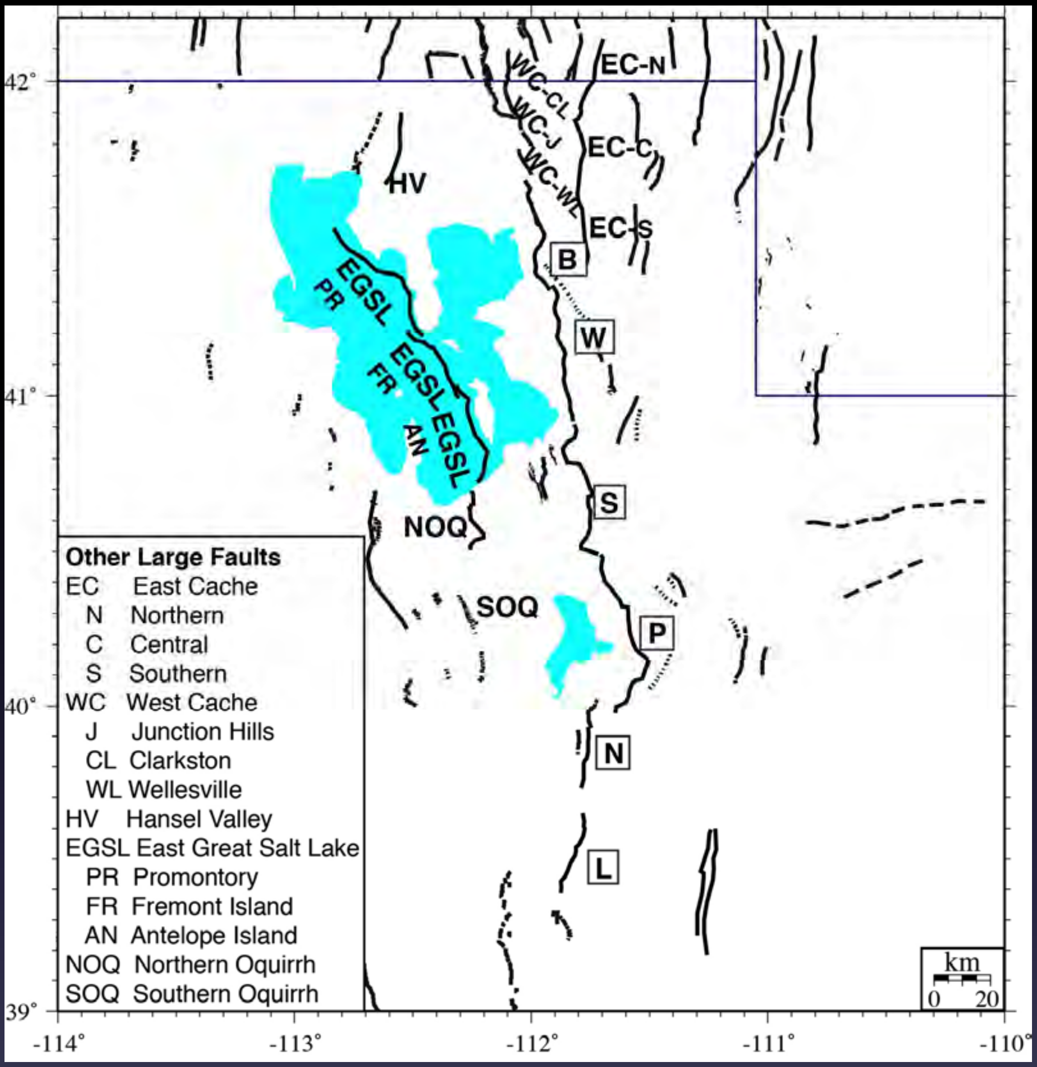
UTAH DNR GEOLOGICAL SURVEY

NSF

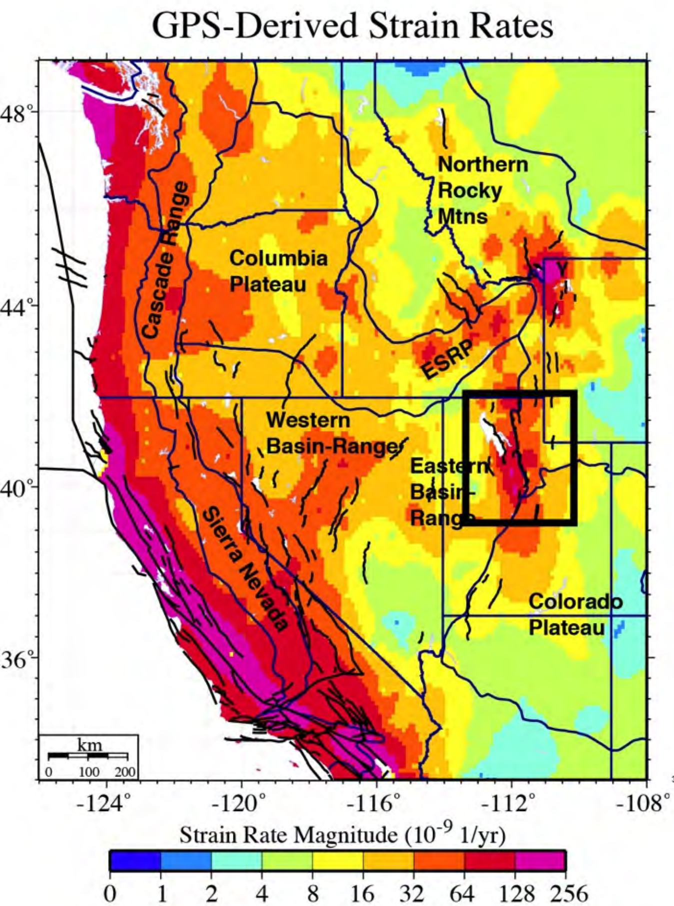
Wasatch Front Earthquakes 1962-2011

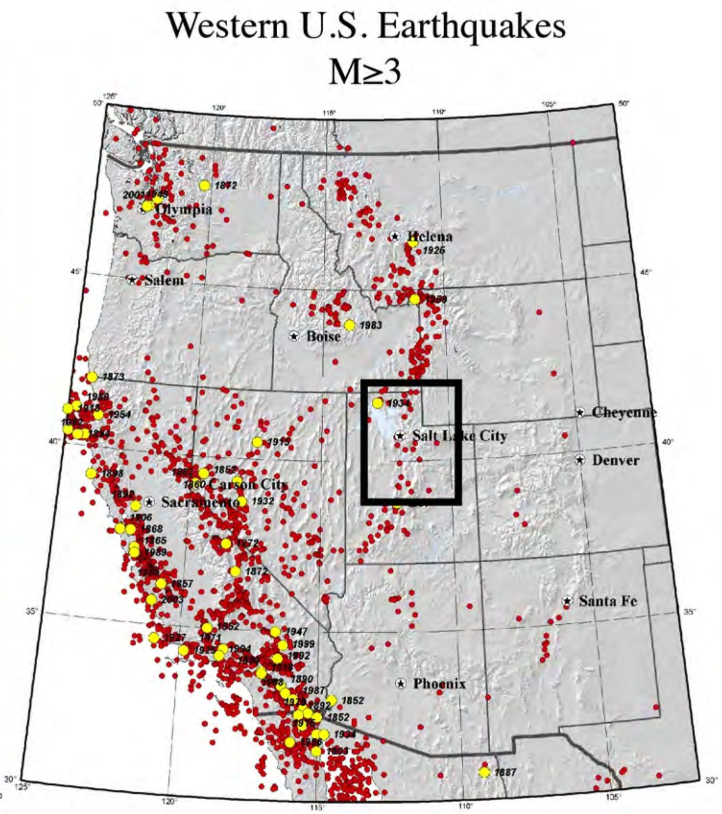


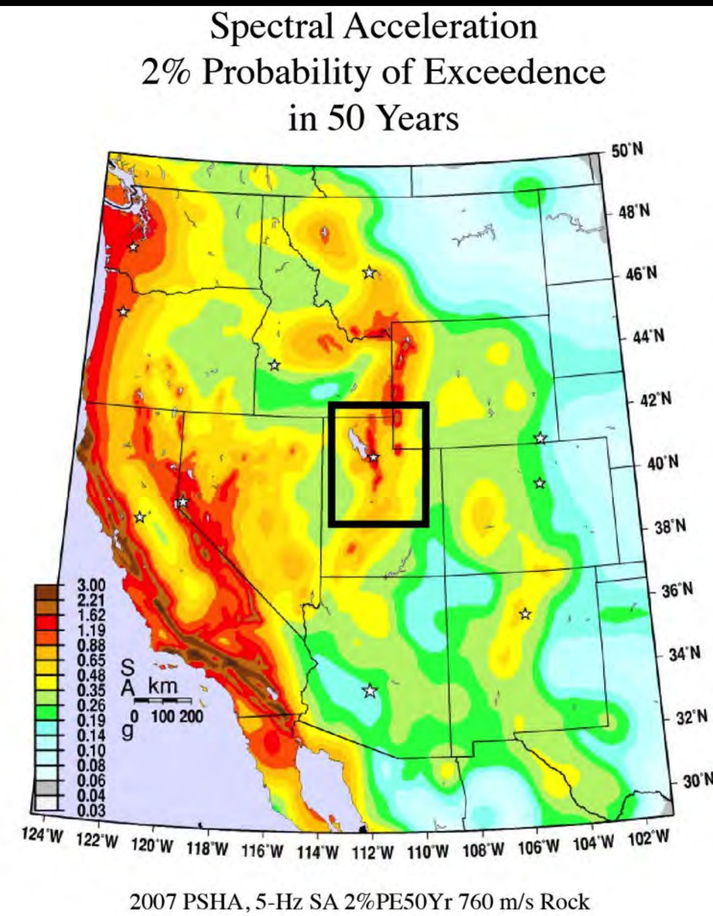
Major Faults in Northern Utah



- Seismic zone with frequent microearthquakes
- Largest historic quake was 1934 M6.6 Hansel Valley
- Trenching studies have dated prehistoric events on Wasatch, other faults

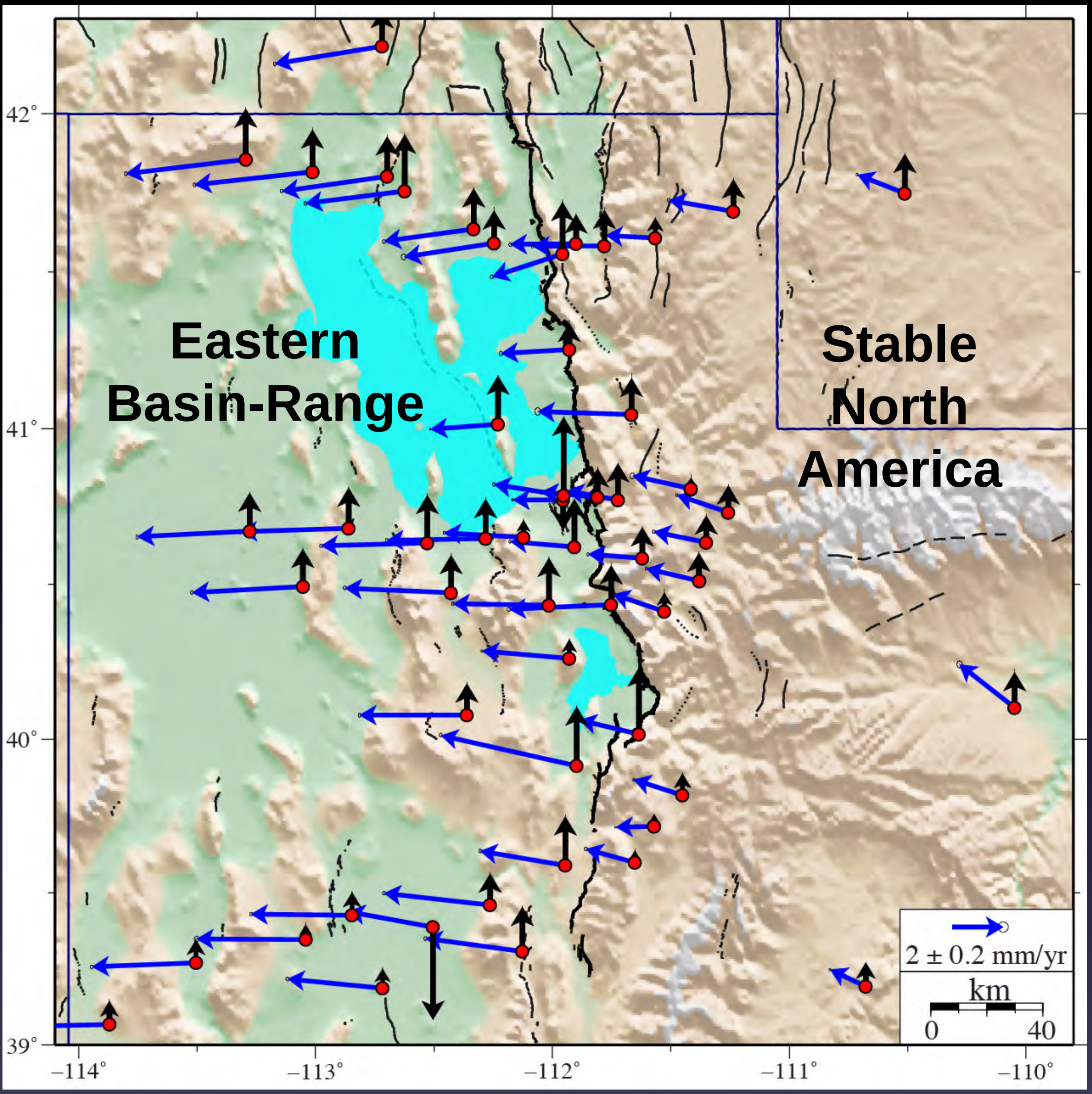






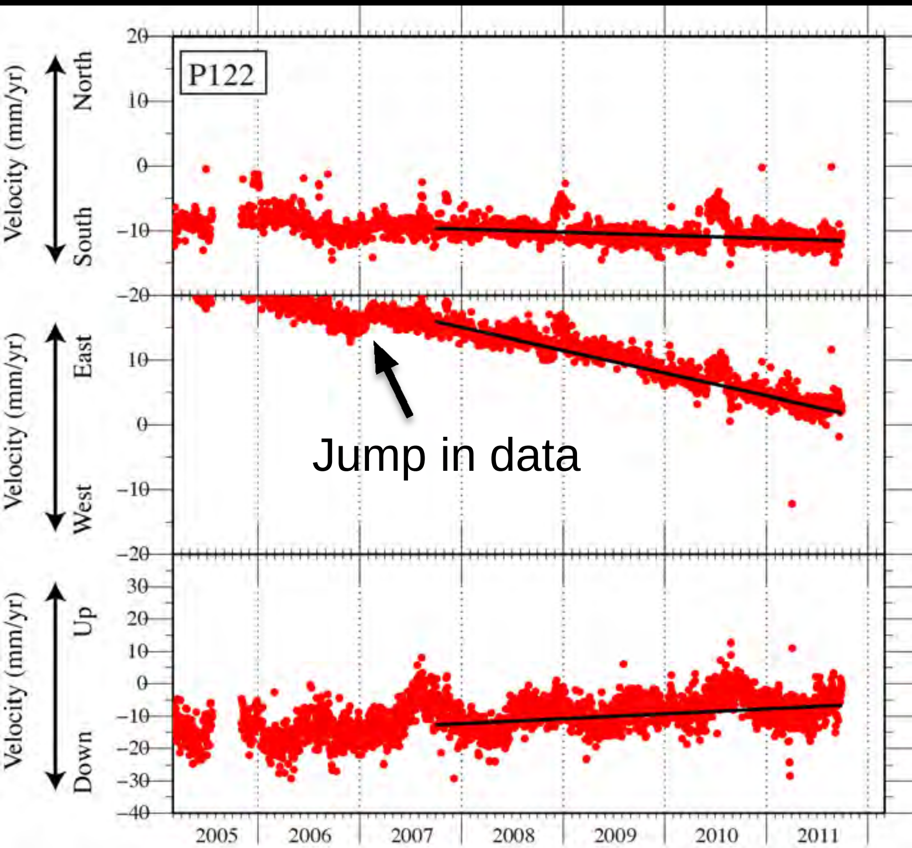
- Regional westward extension at Wasatch Front
- Boundary of eastern Basin and Range and Stable North America
- Earthquakes correlate with deformation
- Compare energy stored through deformation and released in earthquakes

Horizontal and Vertical Velocities



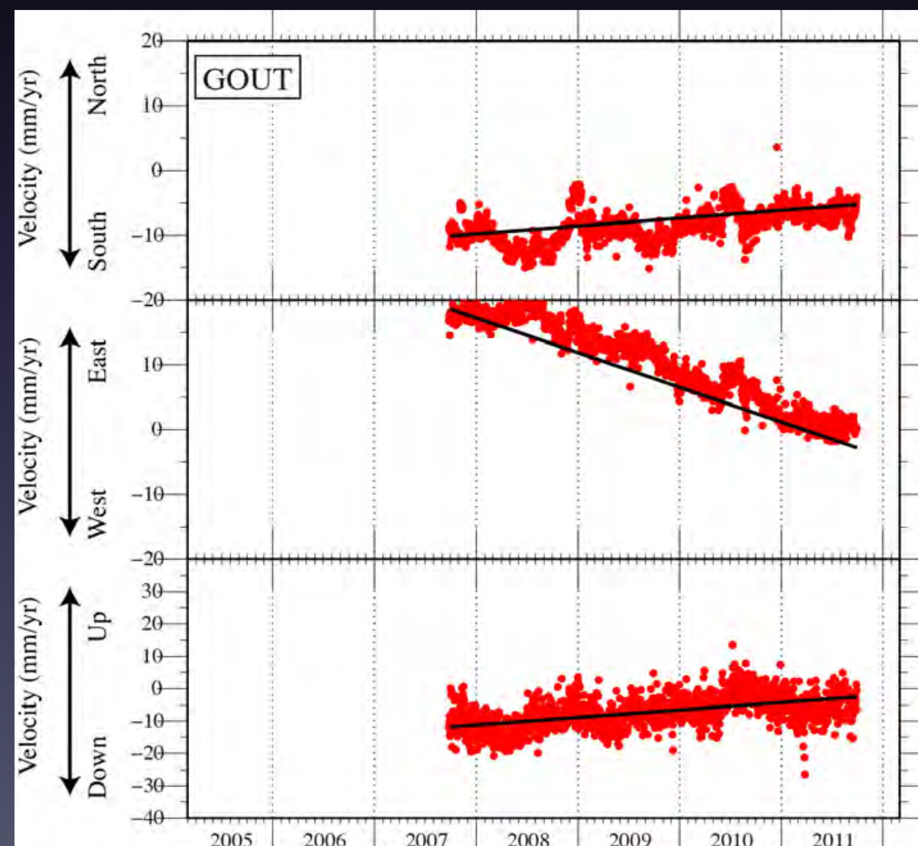
- Plate Boundary Observatory/University of Utah operate GPS stations
- University of Utah processes data and monitors regional deformation
- 55 stations in network across Utah and Wasatch Front
- Updated processing software in 2011
  - Bernese 5 replaced version 4.2
  - Improved station positions
  - Data available at university web site:
    www.uusatrg.utah.edu

Change in Position over Time



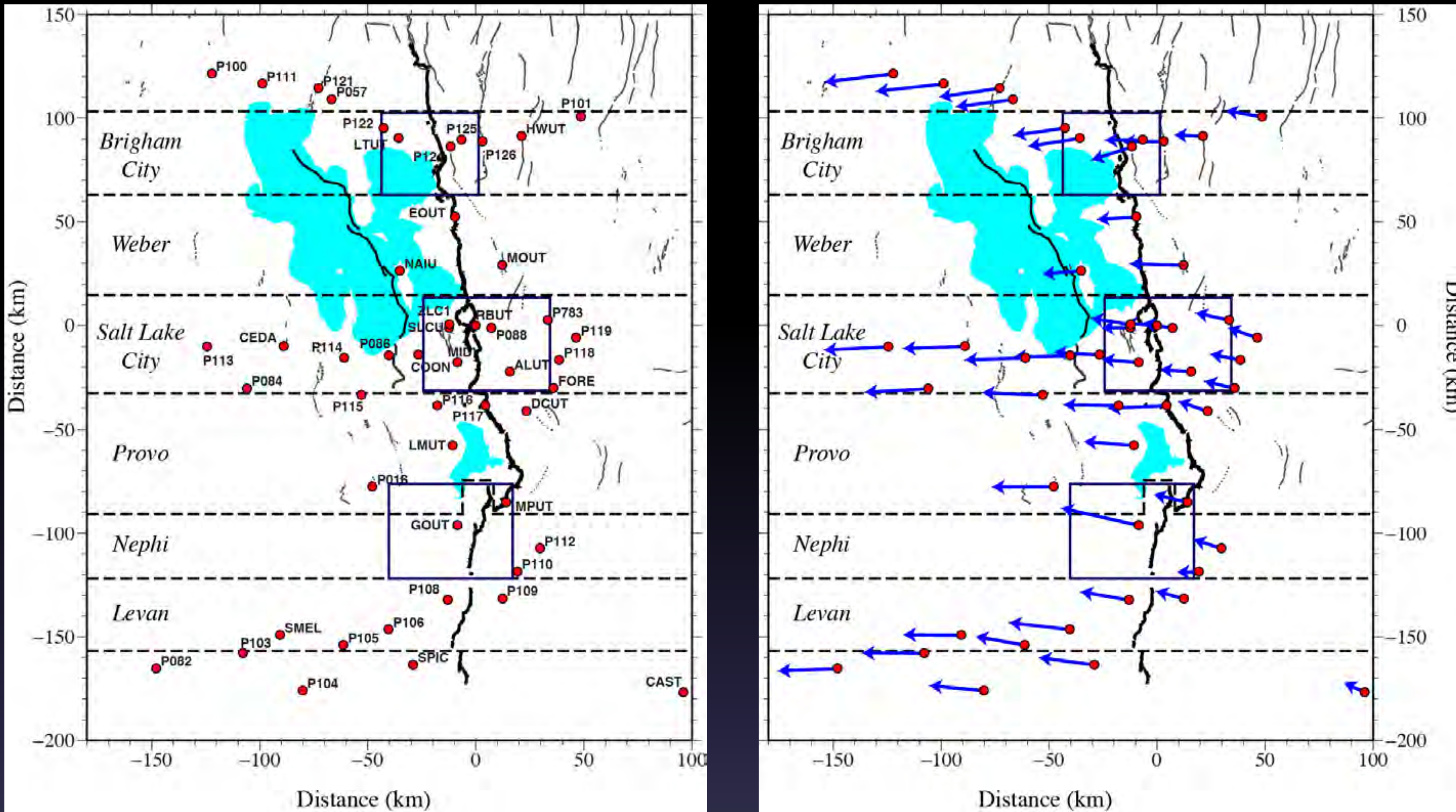
P122 north of Great Salt Lake

- Velocities calculated from time series
    - Linear least-squares fit
- Fit over periods of good quality data
    - Avoid offsets, jumps
    - Maximize time span
    - Requires inspection of time series



GOUT south of Utah Lake

GPS Station Distribution and Wasatch Fault Segments

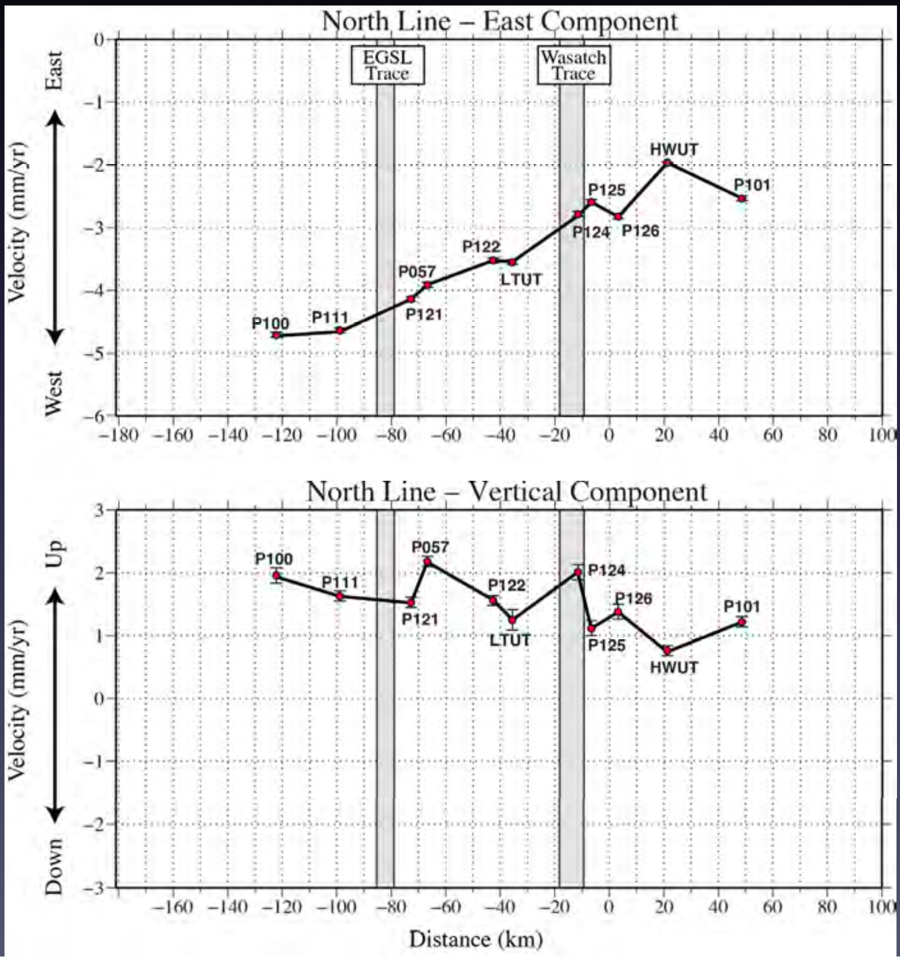


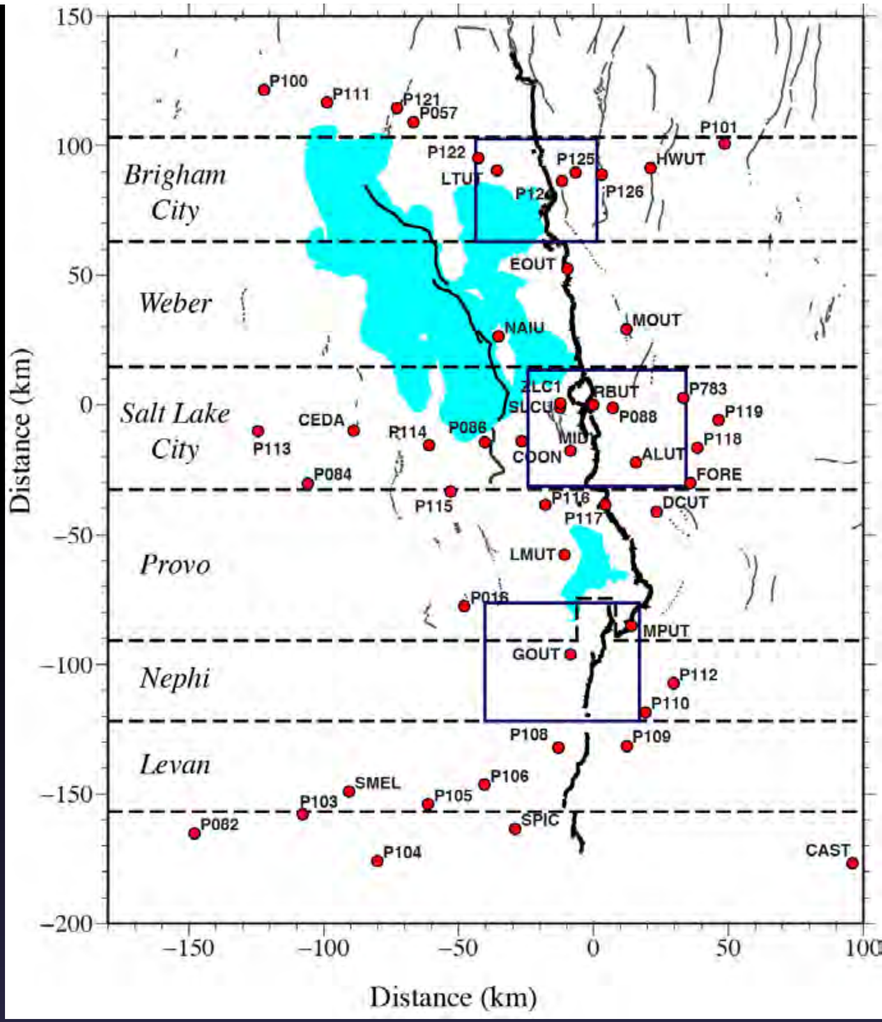
- GPS stations grouped into profiles across northern, central, southern fault zone
  - North = Brigham City segment
  - Center = Salt Lake City segment
  - South = Nephi segment + part of Provo segment

- Define boxes for each segment to use in loading calculations

Brigham City Profile

2.75 mm/yr



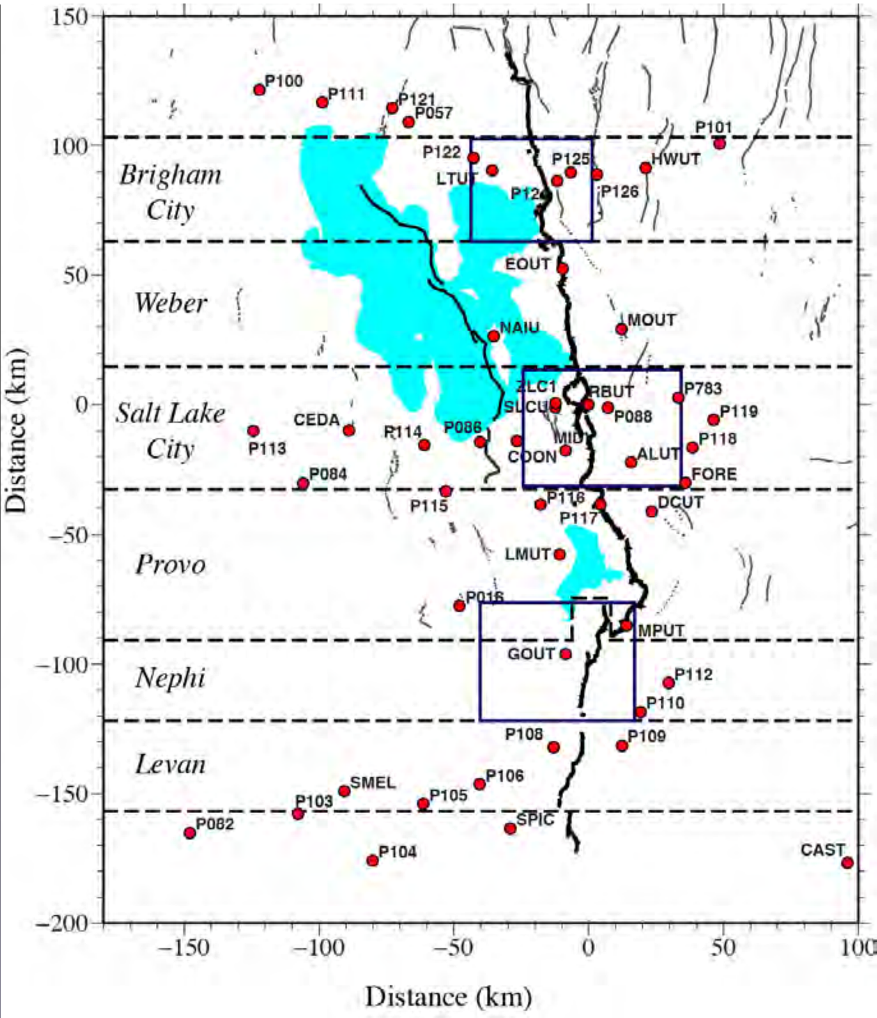


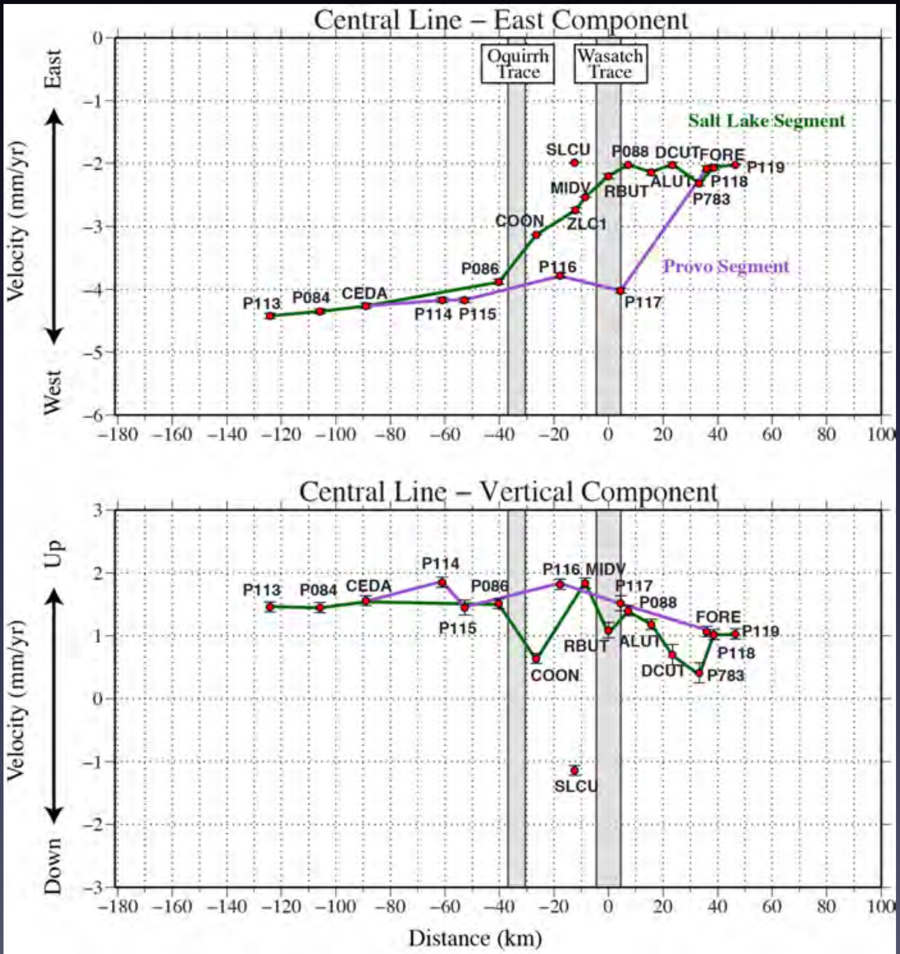
Faults sampled by profile:

- East Cache
- (West Cache)
- Wasatch – Brigham City
- East Great Salt Lake

Salt Lake City Profile

2.35 mm/yr





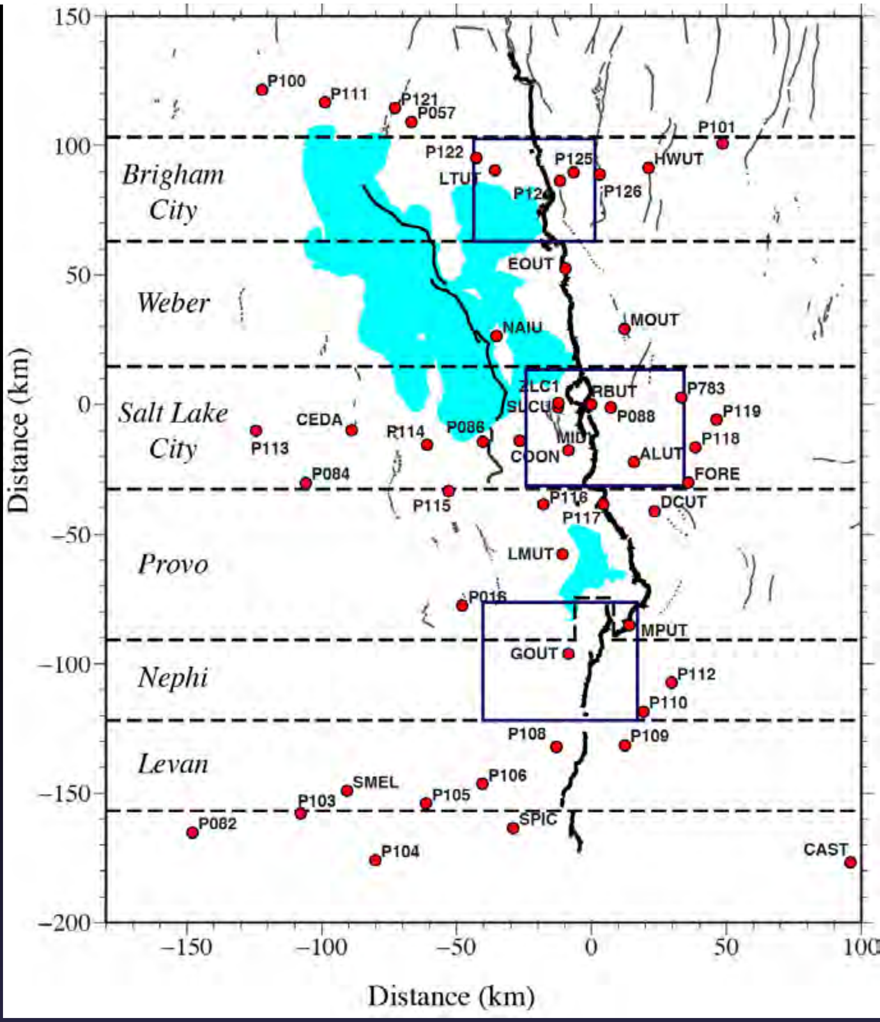
Faults sampled by profile:

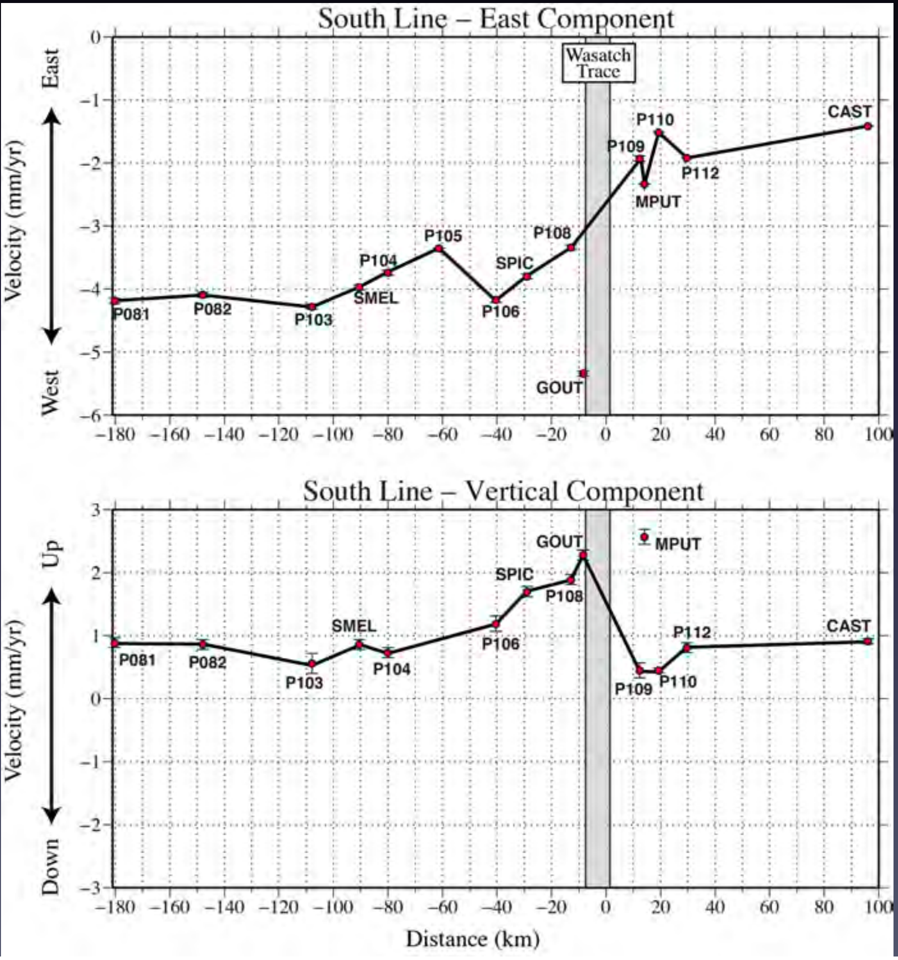
- Wasatch – Salt Lake City
- Wasatch – Provo (?)
- North Oquirrh

Outlier: SLCU

Nephi Profile

2.17 mm/yr

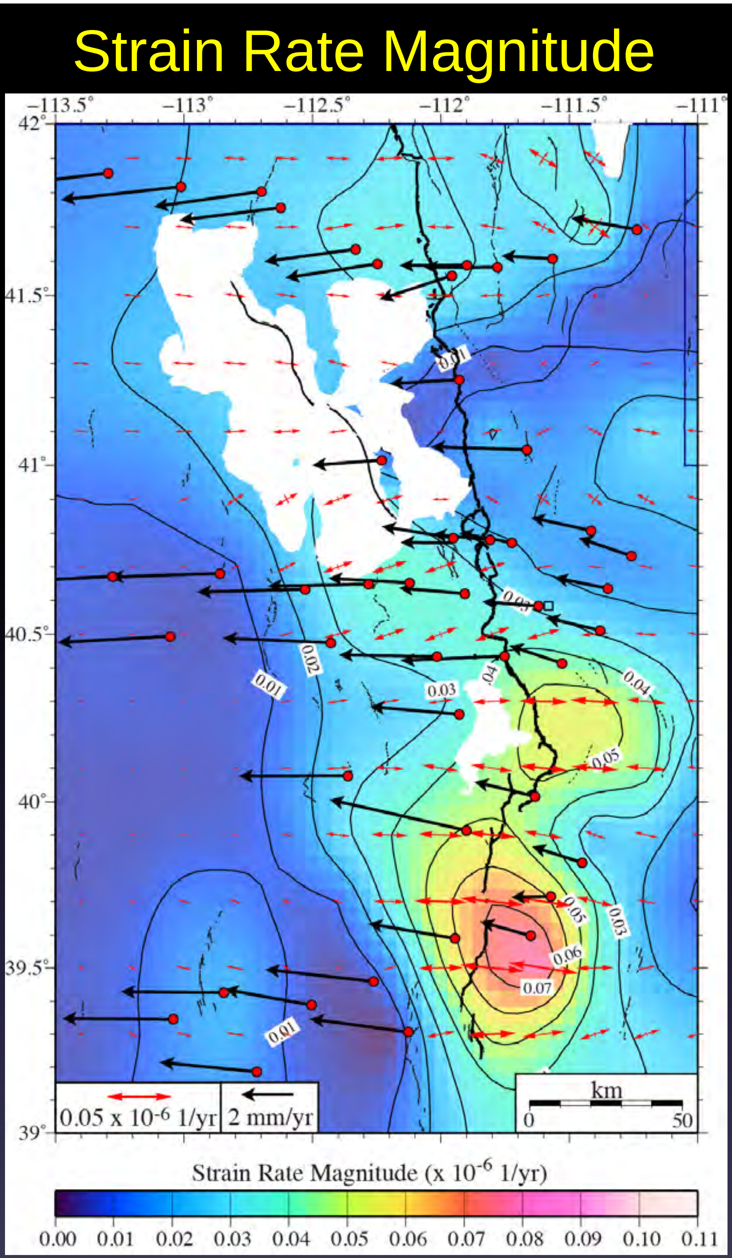


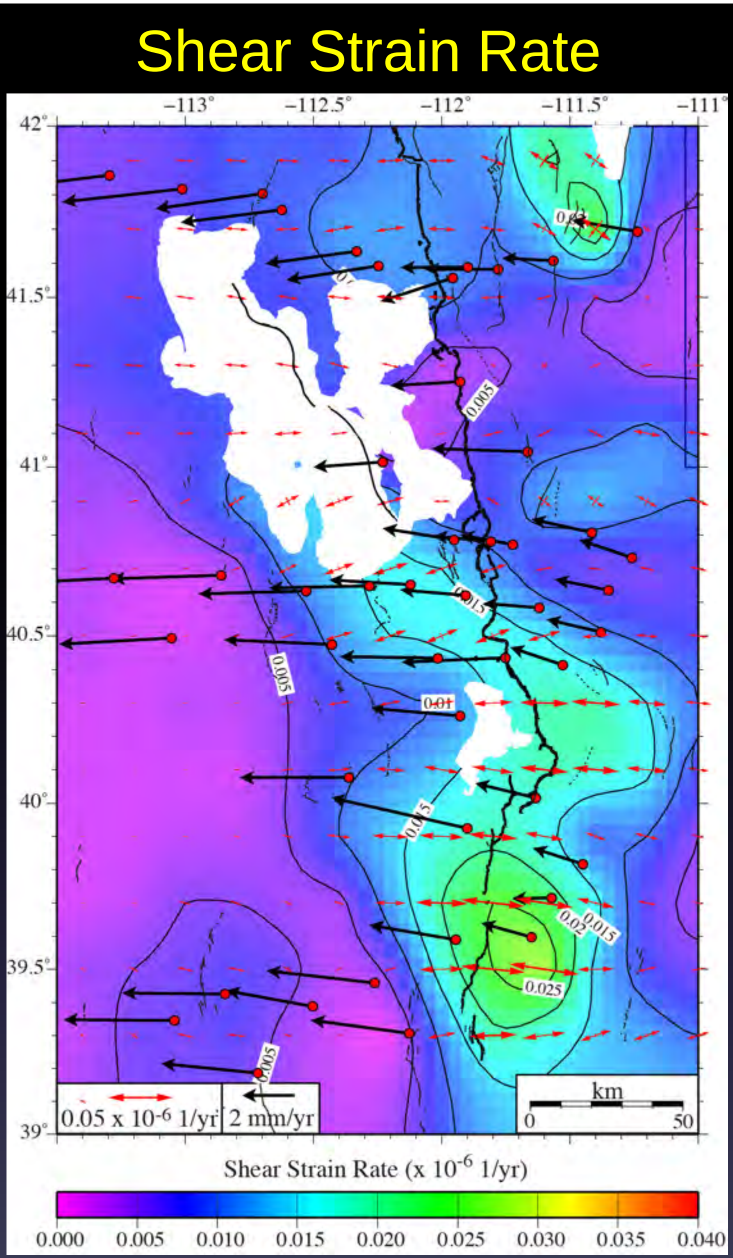


Faults sampled by profile:

- Wasatch – Provo
- Wasatch – Nephi
- Wasatch - Levan

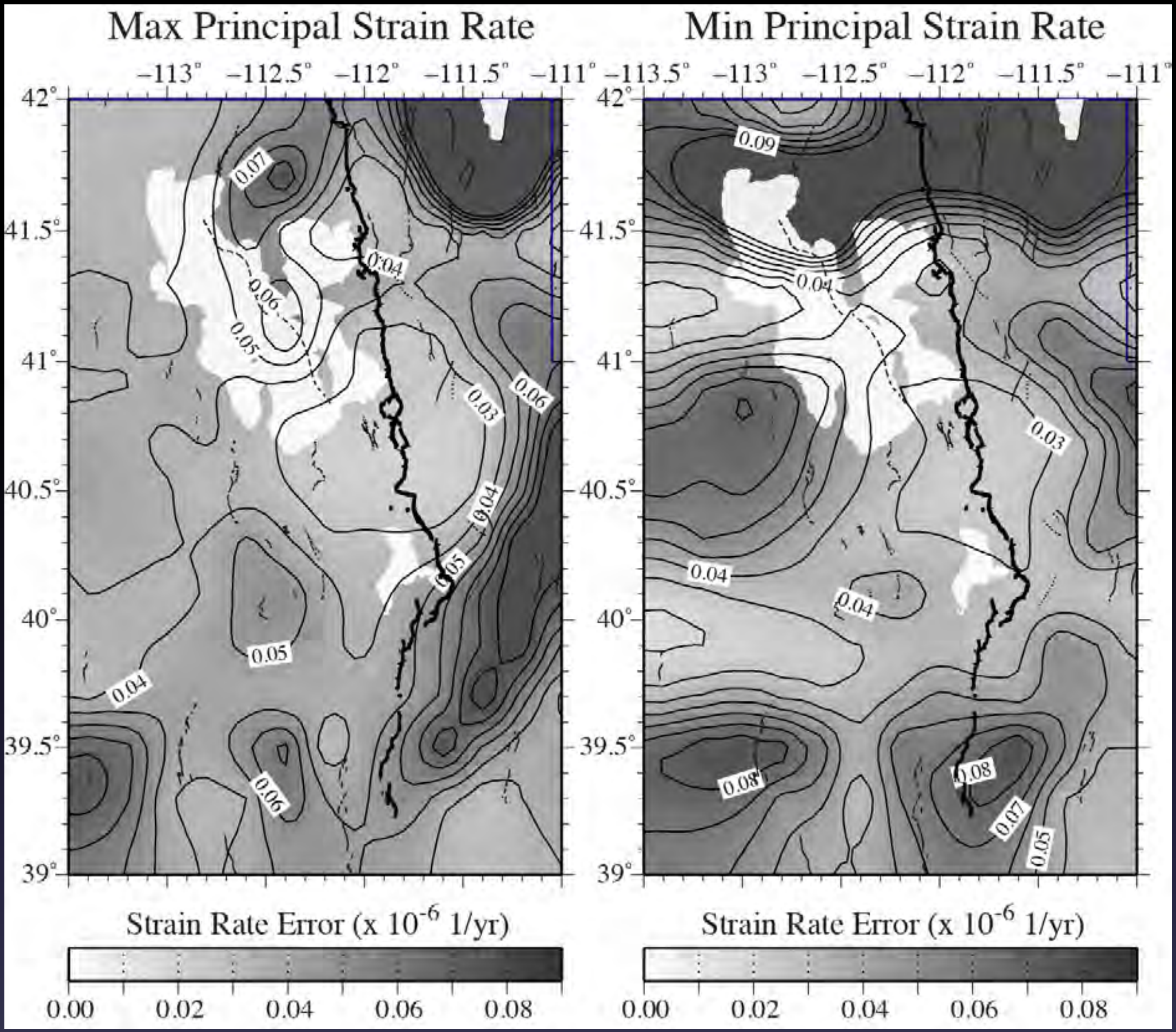
Outlier: GOUT





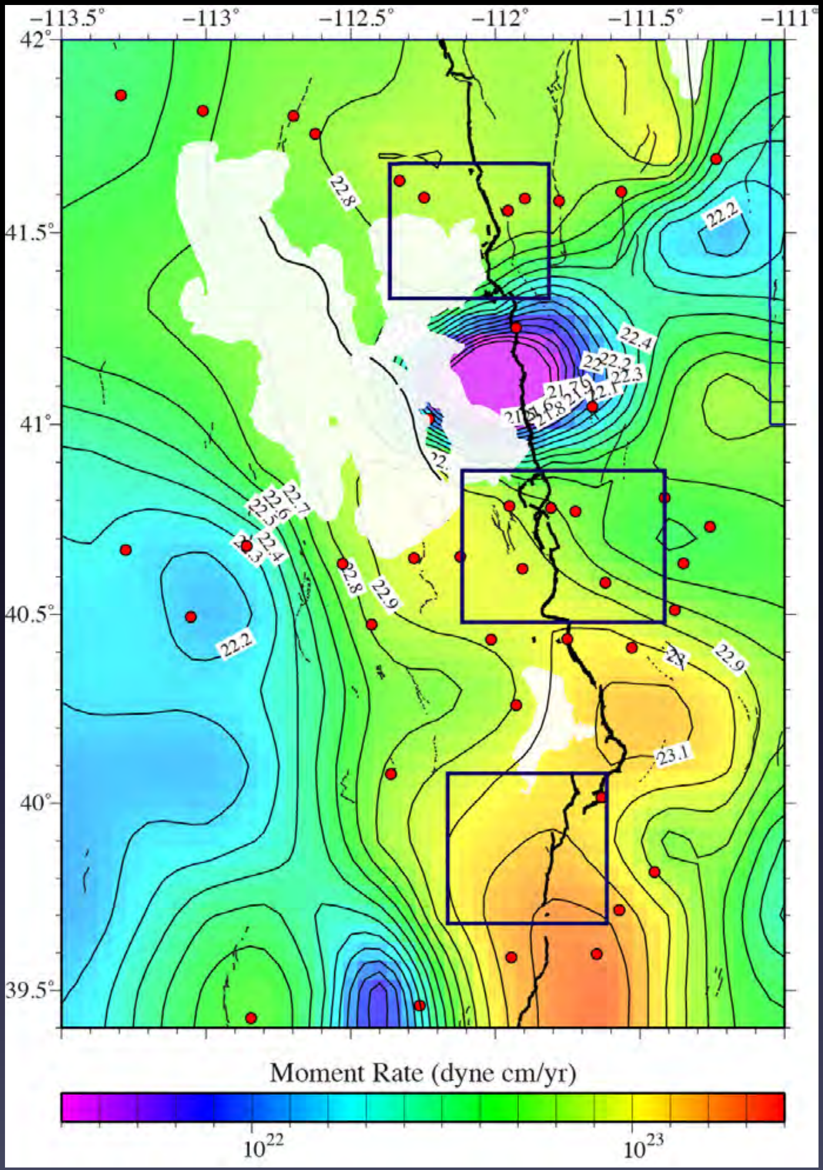
- Interpolate horizontal GPS velocities to strain rates
  - Eliminate outliers SLCU and GOUT
- Higher strain rates reflect larger changes of deformation over smaller areas

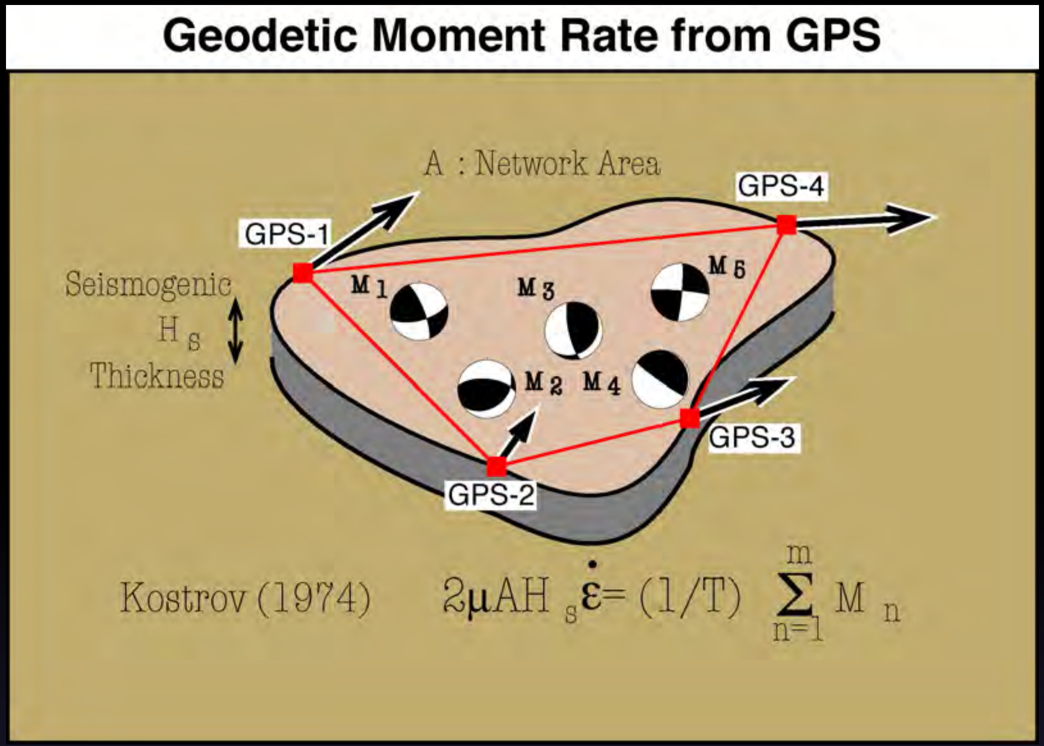
Strain Rate Errors



- Uncertainties depend on geographic distribution, strain component

Geodetic Moment Loading Rate





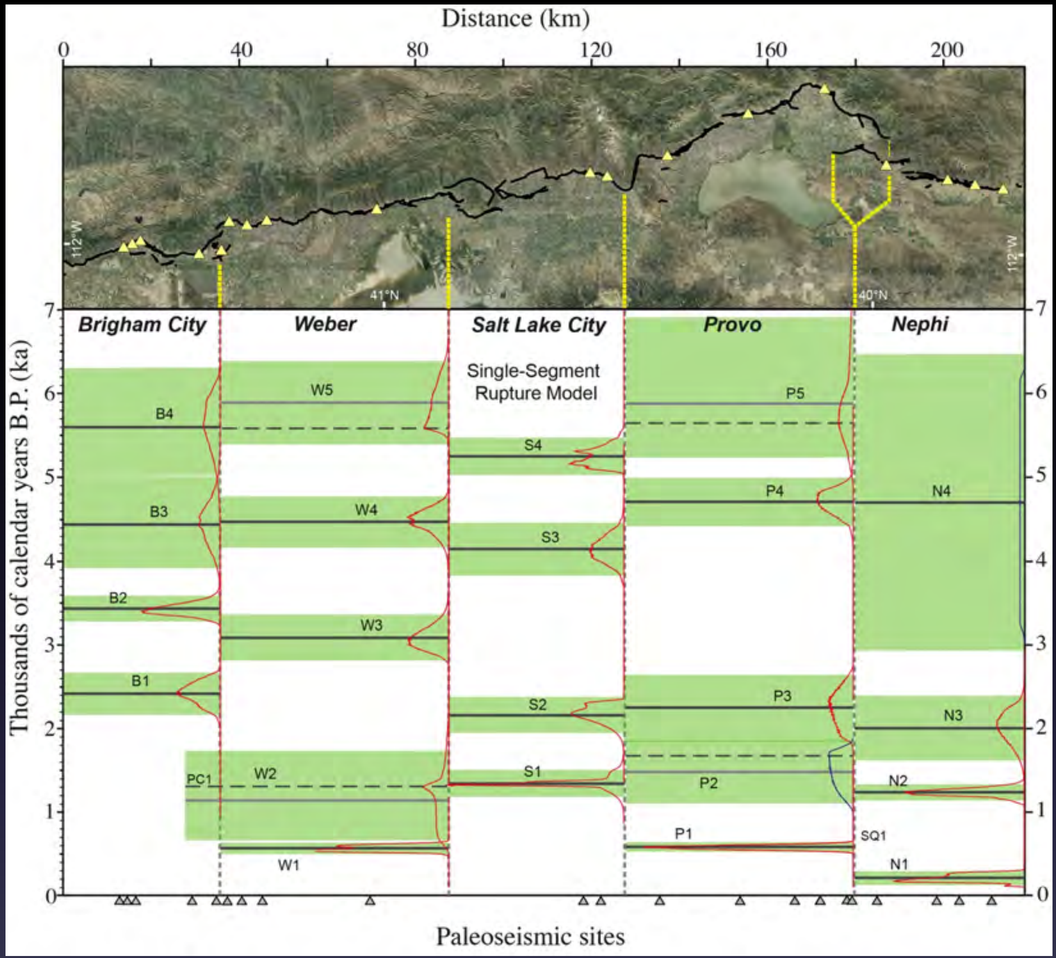
(Ward, 1998)

- Use Kostrov formula to convert deformation rate to geodetic moment rate
  - Moment is measure of energy required for deformation

- Moment available for earthquakes depends on:
  - Seismogenic volume
  - Strain rate for network area

Prehistoric Earthquakes Identified for Wasatch Fault

EQ Ref #	Segment Ref #	Age (yrs)	ΔAge (2-σ)	SRL (km)	ΔSRL (2-σ)
E1	N1	206	86	43	11.5
E2	P1	576	48	59	11.5
E3	W1	561	68	56	6.5
E4	W2	1137	641	65	8.5
E5	N2	1234	96	43	11.5
E6	S1	1343	162	40	6.5
E7	P2	1479	378	59	11.5
E8	N3	2004	388	43	11.5
E9	P3	2240	406	59	11.5
E10	S2	2160	215	40	6.5
E11	B1	2417	256	36	6
E12	W3	3087	275	56	6.5
E13	B2	3430	153	36	6
E14	B3	4452	543	36	6
E15	W4	4471	303	36	13
E16	S3	4147	315	40	6.5
E17	P4	4709	285	59	11.5
E18	N4	4699	1768	43	11.5
E19	S4	5250	221	40	6.5
E20	B4	5603	660	36	6
E21	P5	5888	1002	59	11.5
E22	W5	5891	502	56	6.5

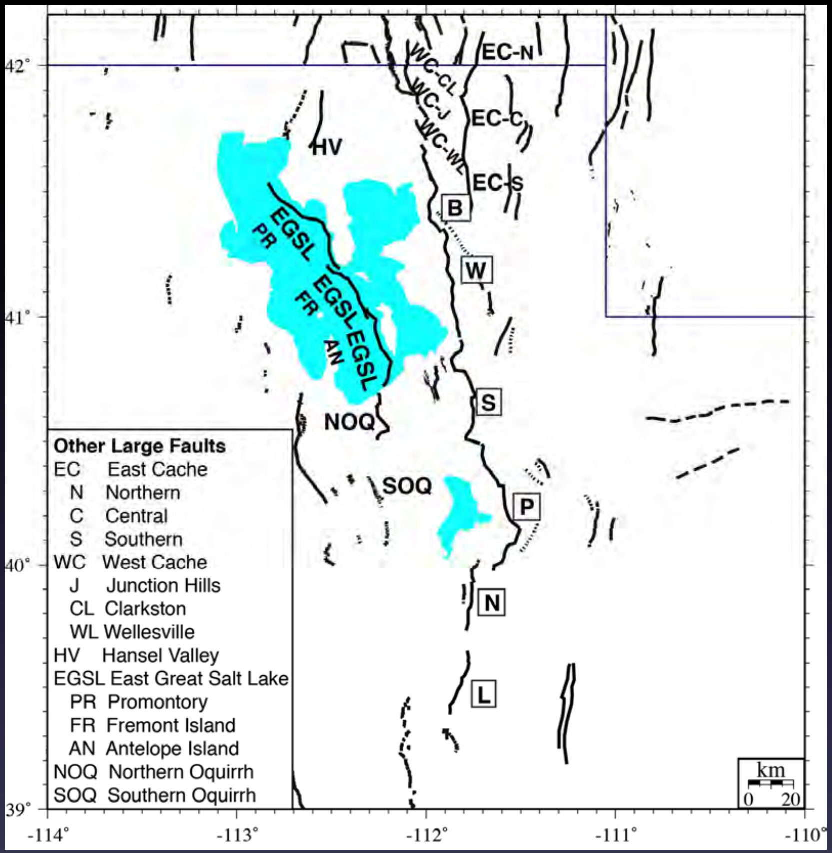


(DuRoss et al., 2011)

- 4-5 earthquake on each segment
- Events dated within last 6000 years

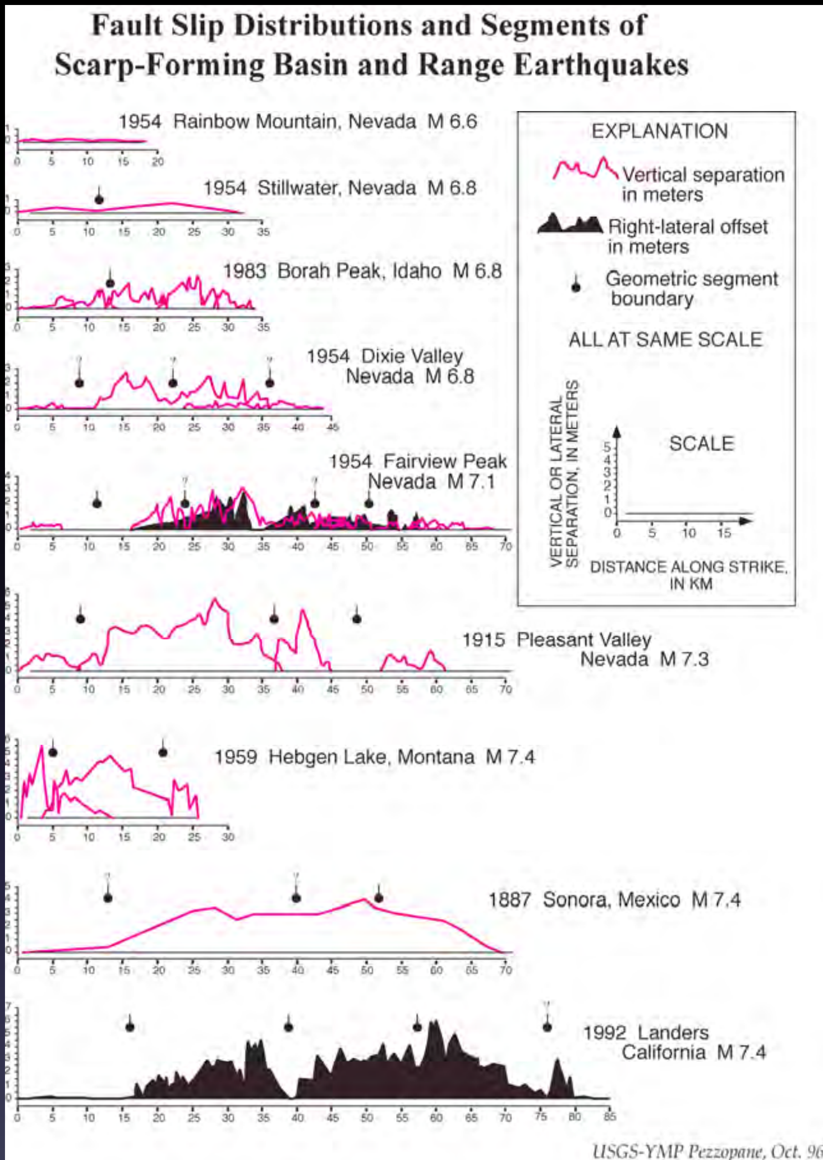
Other Prehistoric Earthquakes

Fault Name	Segment Name	Segment Length (km)	Age Range	Closest Wasatch Segment
Hansel Valley		11	78 (1934 M6.6)	Collinston
EGSL	Promontory	49	355-797	Brigham City
EGSL	Antelope Island	35	5936-6406	Weber
EGSL	Fremont Island	30	2939-3385	Weber
N. Oquirrh		21	4800-7900	Salt Lake City
S. Oquirrh		24	1300-4830	Salt Lake City
West Cache	Clarkston	21	3600-4000	Clarkston
West Cache	Wellsville	20	4400-4800	Brigham City
East Cache	Central	17	4300-4600	Brigham City



(Hansel Valley: Doser, 1989; EGSL: Dinter and Pechmann, 2011; Oquirrh: Olig et al., 2011; West Cache, East Cache: Lund, 2005)

Historic Multi-Segment Earthquakes



(Pezzopane and Dawson, 2010)

- Earthquake magnitude scales with displacement, surface rupture length
- Choose rupture lengths corresponding to segment lengths on Wasatch fault
- Used average magnitudes from multiple magnitude-SRL relations for seismic moment calculation

Moment-Magnitude Relation:
Hanks and Kanamori (1979) $\log(Mo) = 1.5\,M + 16.0$

Magnitude-Earthquake Parameter Relations:

Stirling et al. (2002)	$M = 5.88(0.17) + 0.80(0.10)\log(SRL)$
Wells and Coppersmith (1994)	$M = 5.08(0.10) + 1.16(0.07)\log(SRL)$
Wells and Coppersmith (1994)	$M = 4.07(0.06) + 0.98(0.03)\log(RA)$
Blaser et al. (2011)	$\log(SRL) = -1.91(0.29) + 0.64(0.02)\,M$

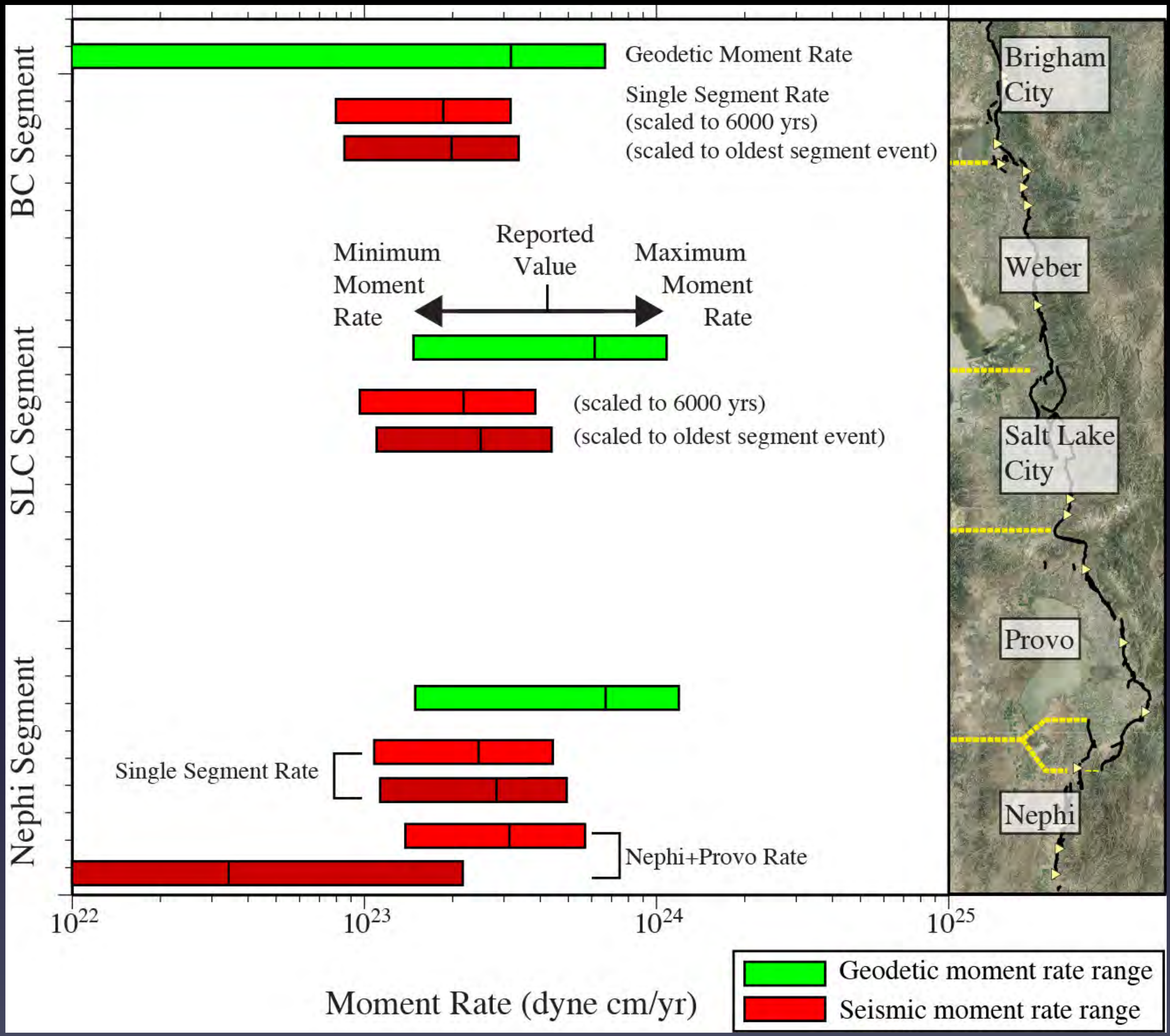
Fault Segment Moment Rates (dyne cm/yr)

GPS-Derived Moment Rates	BC	SLC	Nephi
Interpolated Strain Rates	3.18E23	6.13E23	6.71E23
Direct Calc from GPS Vels	5.61E23	4.46E23	1.10E23

Paleoseismic Moment Rates (scale to 6000 yrs)			
Single Segment Ruptures	1.86E23	2.19E23	2.46E23
Nephi + Provo			2.83E23
Wasatch + Other Known EQs	1.96E23	2.34E23	

Paleoseismic Moment Rates (scale to oldest event on segment)			
Single Segment Ruptures	1.99E23	2.50E23	3.14E23
Nephi + Provo			2.18E23
Wasatch + Other Known EQs	2.10E23	2.68E23	

Fault Segment Moment Rates (dyne cm/yr)

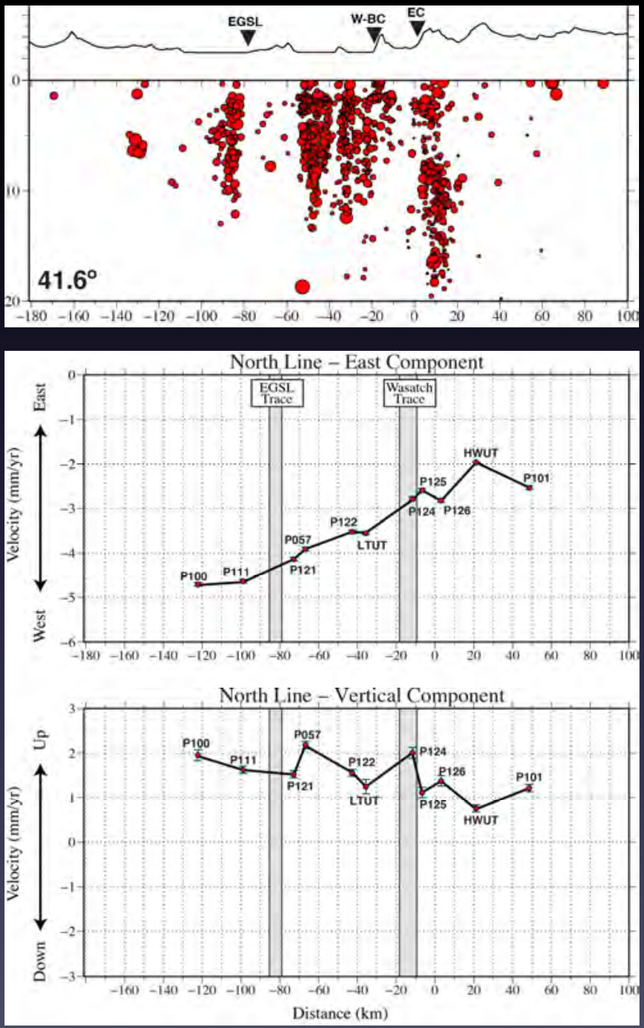


Brigham City Profile

3.18E23 dyne cm/yr geodetic loading (BC only)

2.75 mm/yr net extension rate

110-km wide seismic zone

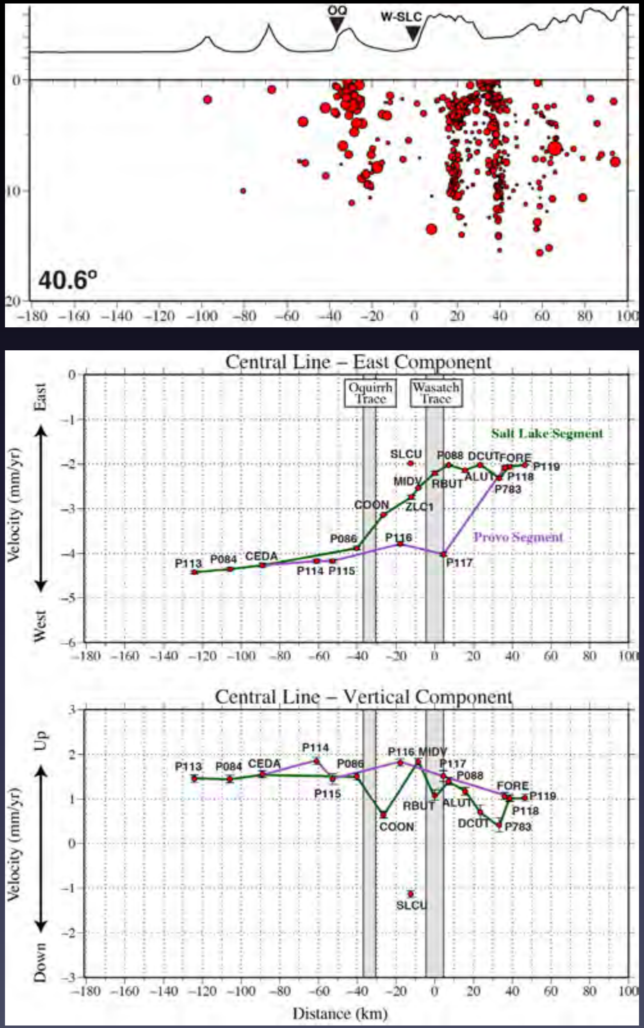


Salt Lake City Profile

6.13E23 dyne cm/yr geodetic loading (SLC only)

2.35 mm/yr net extension rate

80-km wide seismic zone

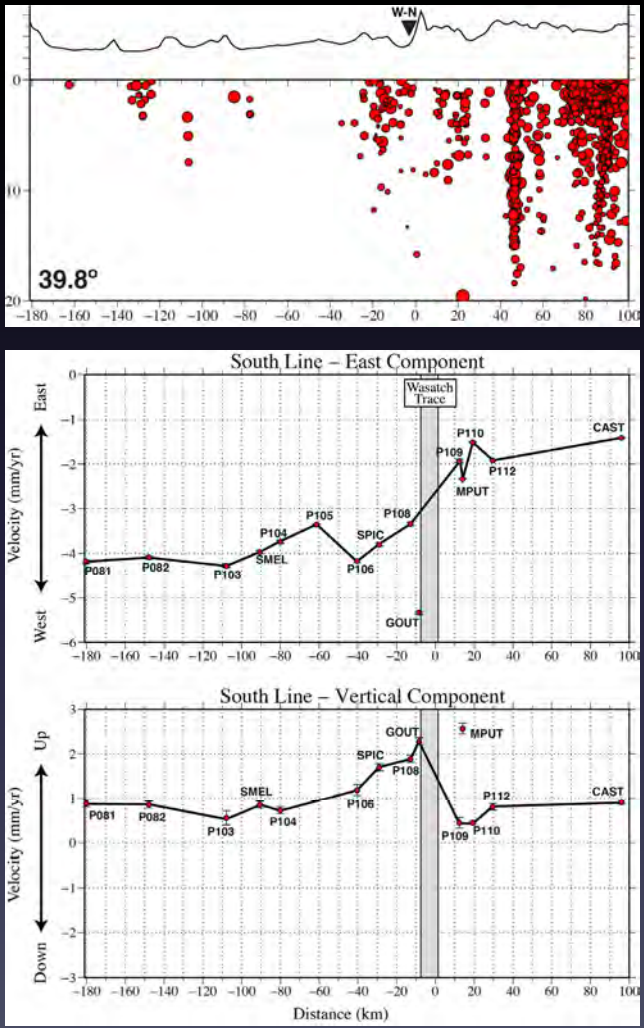


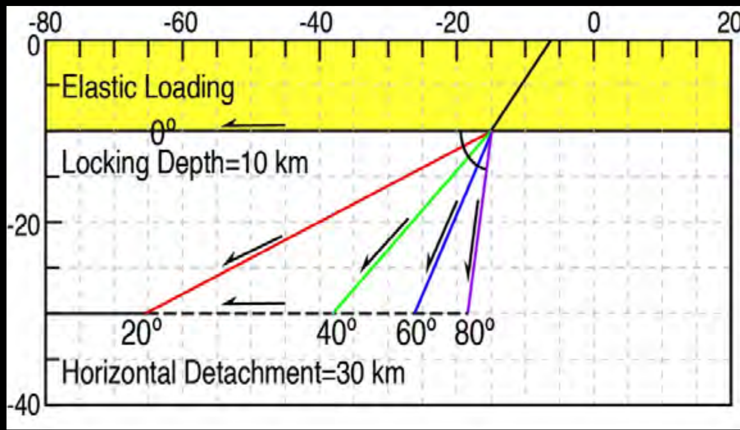
Nephi Profile

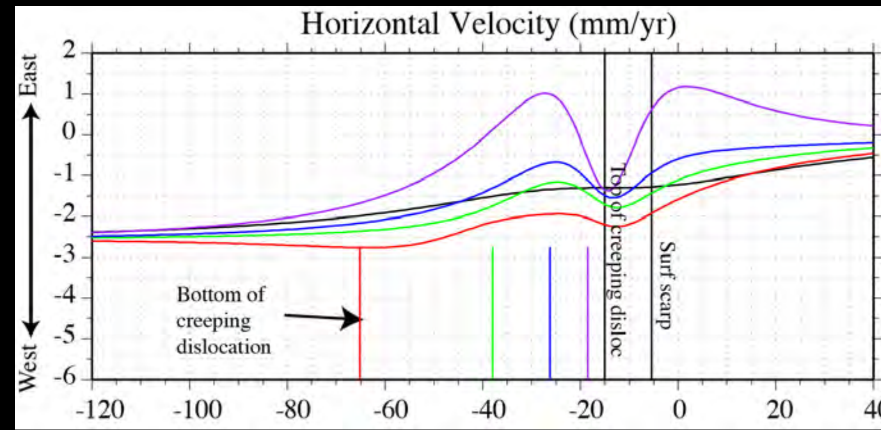
6.71E23 dyne cm/yr geodetic loading (SLC only)

2.17 mm/yr net extension rate

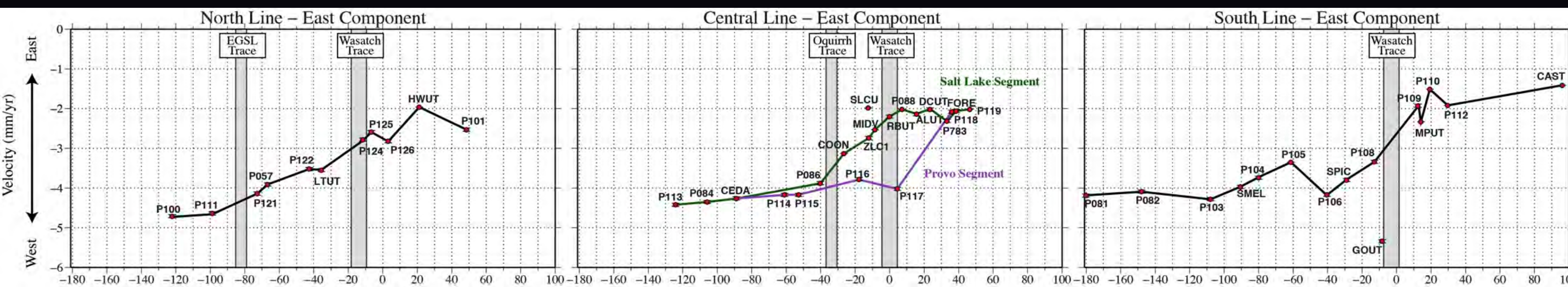
50-km wide seismic zone







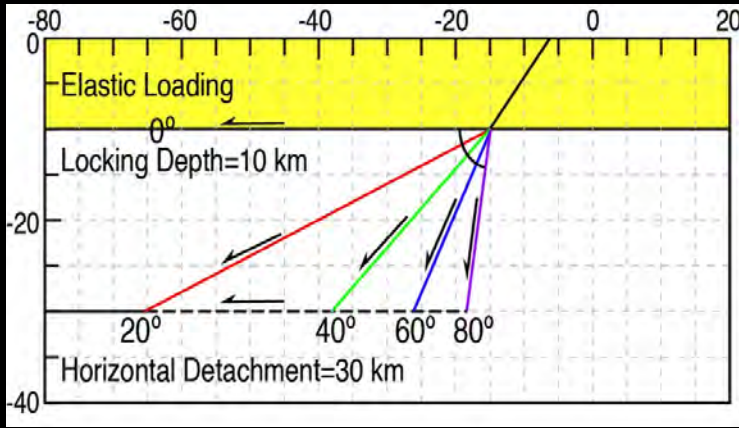
Brigham City Profile | Salt Lake City Profile | Nephi Profile

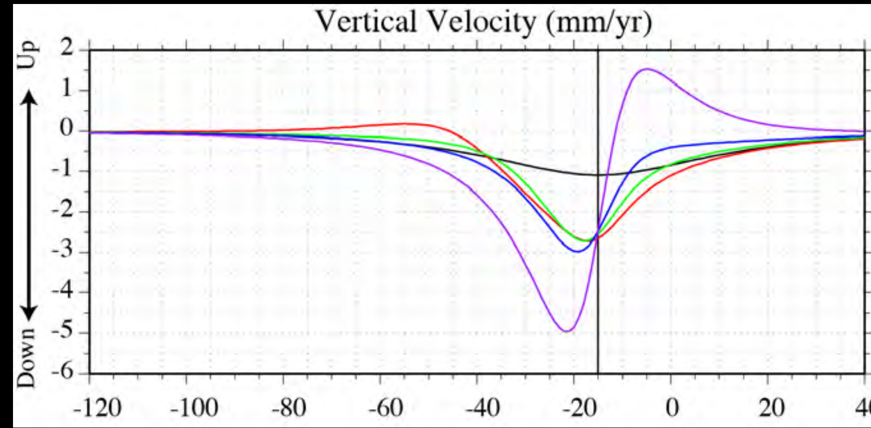


- 1-D horizontal dislocations for fault creeping at depth

- Model predicts smoothly varying surface velocities
    - Width of deformation zone: ~65 km
    - Deformation amplitude depend on dip, slip rate

- Observed GPS velocity profiles
    - 2-D station distribution with more complex deformation
    - Have at least 100-km wide deformation zone

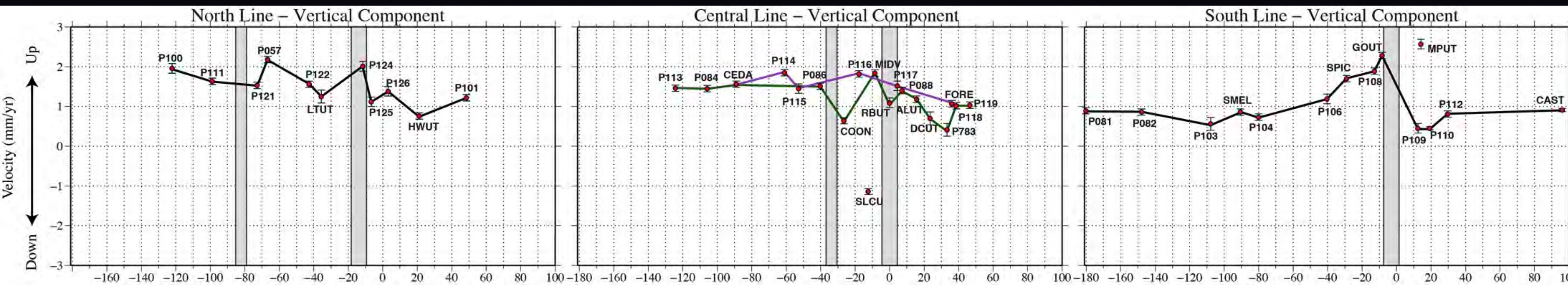




Brigham City Profile

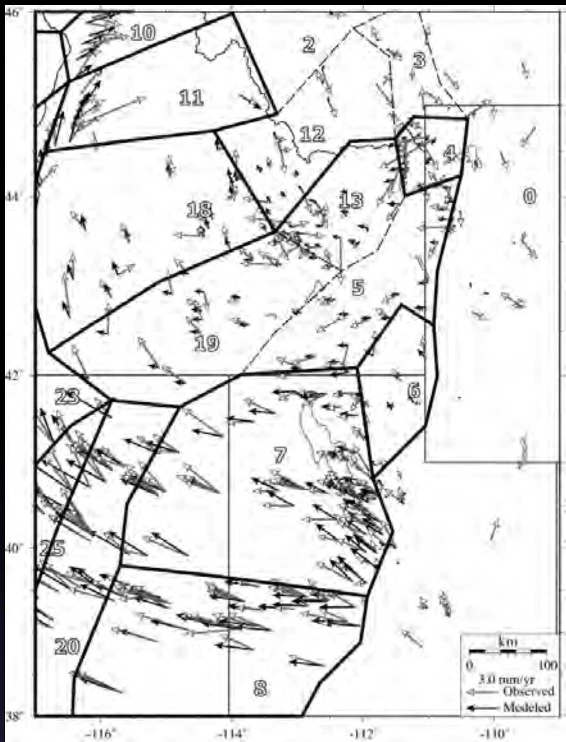
Salt Lake City Profile

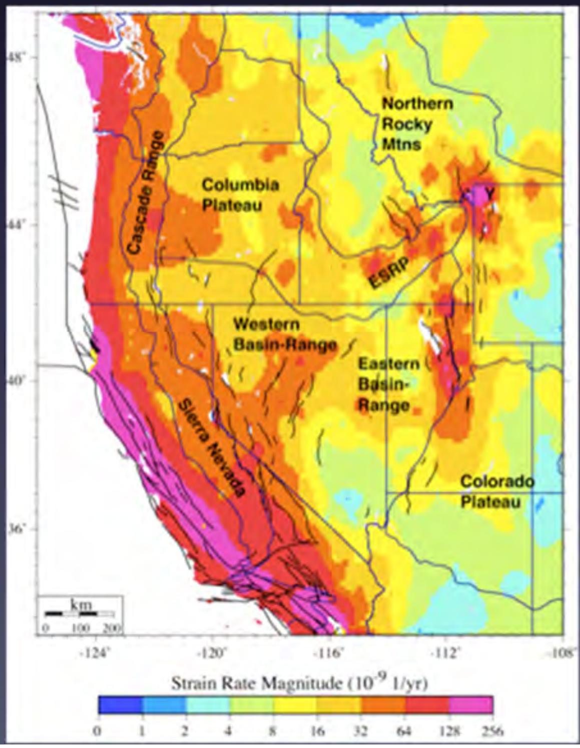
Nephi Profile



- 1-D vertical dislocations for fault creeping at depth
- Model predicts smoothly varying surface velocities
- Observed GPS velocity profiles
  - Do not resemble model profiles
  - More complex, noisy deformation pattern
- Possible multiple dislocations

Older Deformation Models



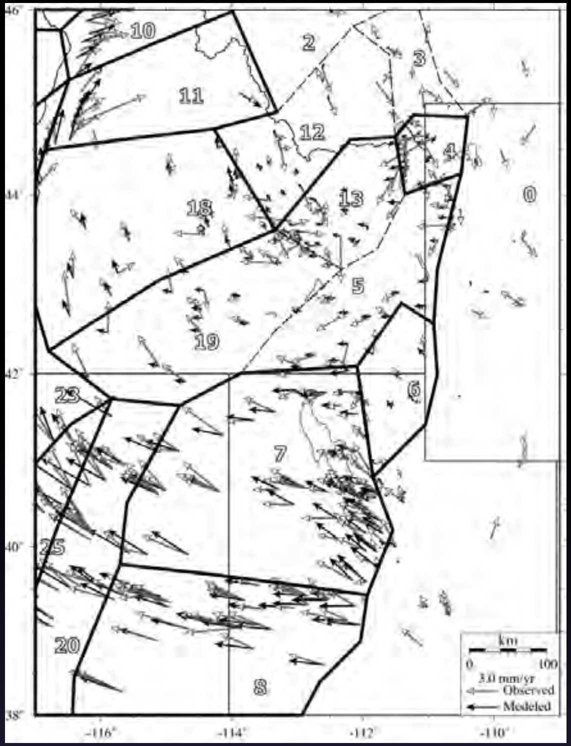


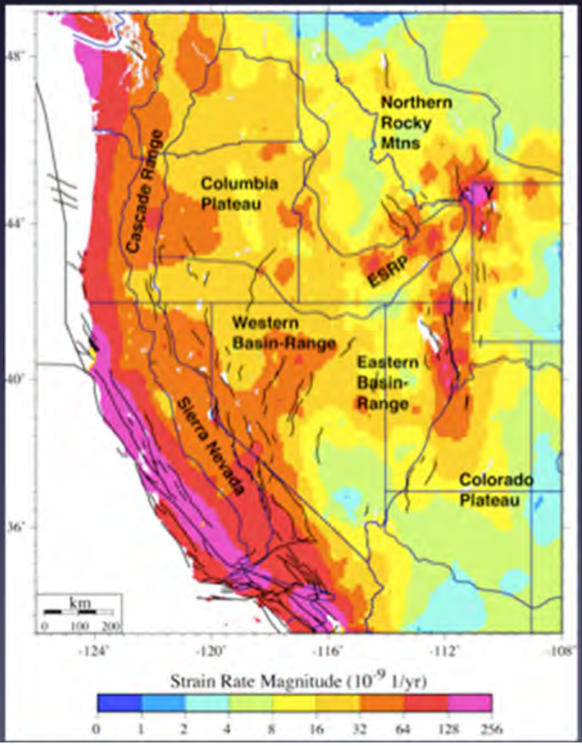
- Previous models treated Eastern Basin-Range as single block with Wasatch Fault as only major boundary fault

- Geodetic analysis suggests multiple faults contributing to extension across Wasatch Front
  - Similar extension rate from north to south
  - Geodetic moment rate decreases from south to north
  - Width of deformation zone decreases from north to south
  - Width of earthquake zone decreases from north to south

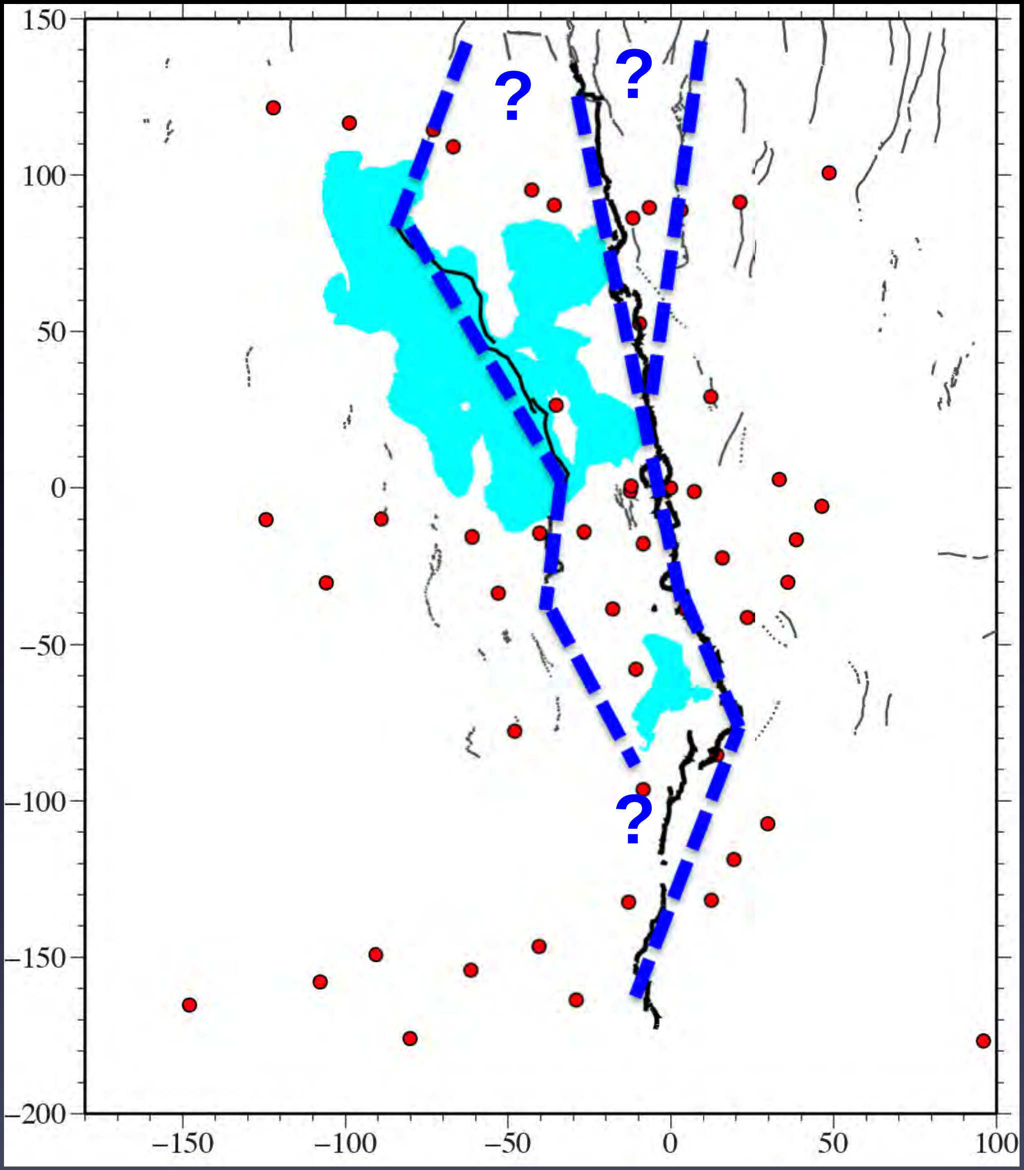
- Candidate faults
  - Brigham City profile: East Cache, EGSL faults
  - Salt Lake City profile: Oquirrh fault
  - Nephi profile: no other faults

Older Deformation Models





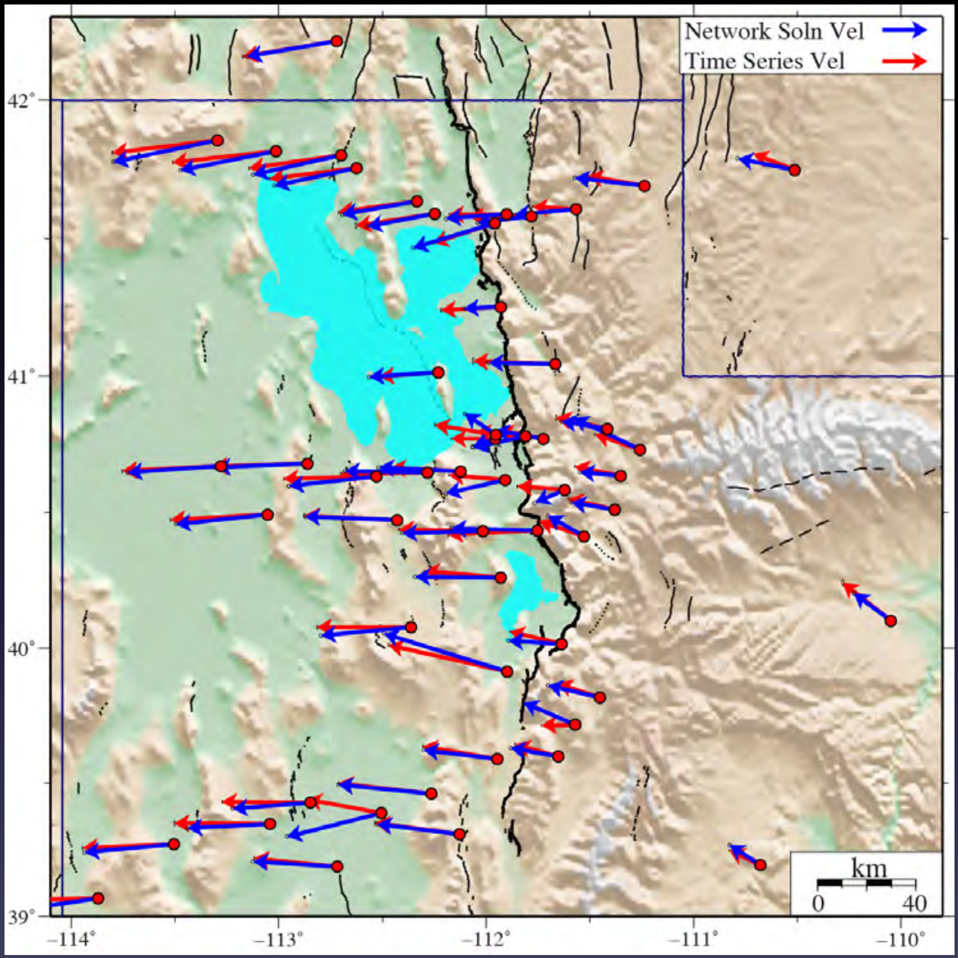
Proposed New Block Model

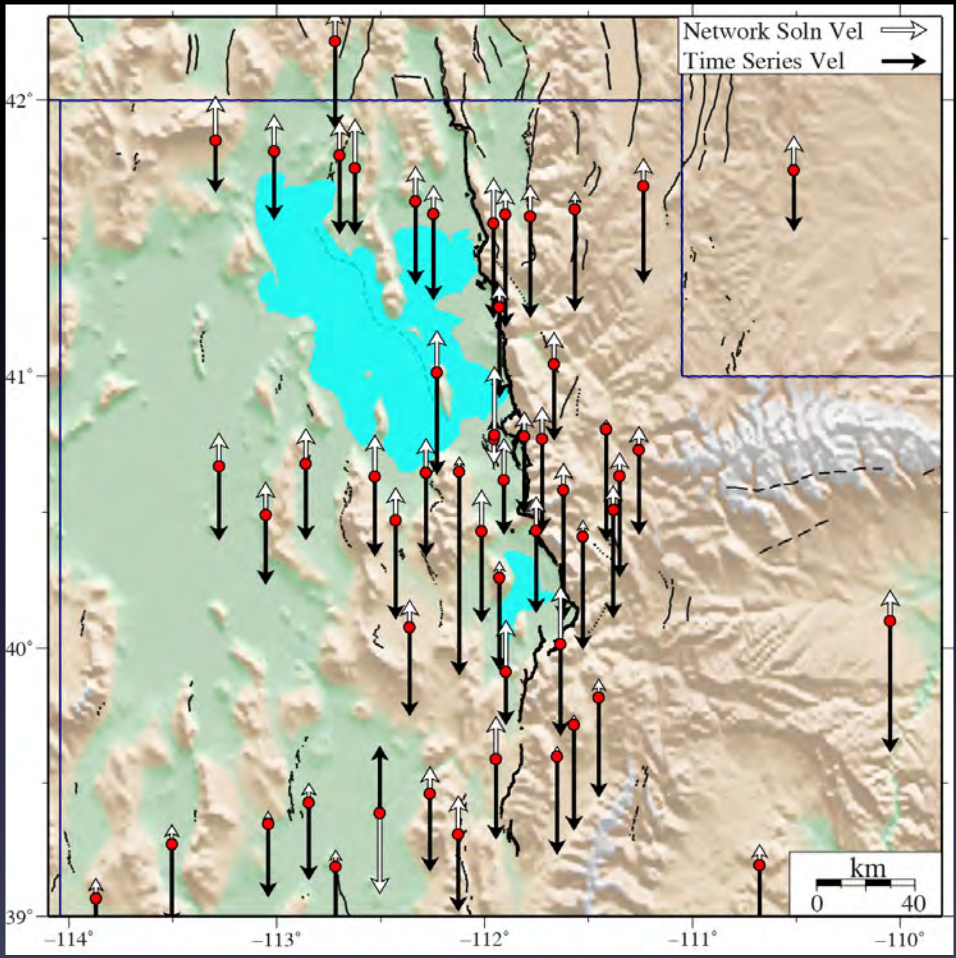


Conclusions

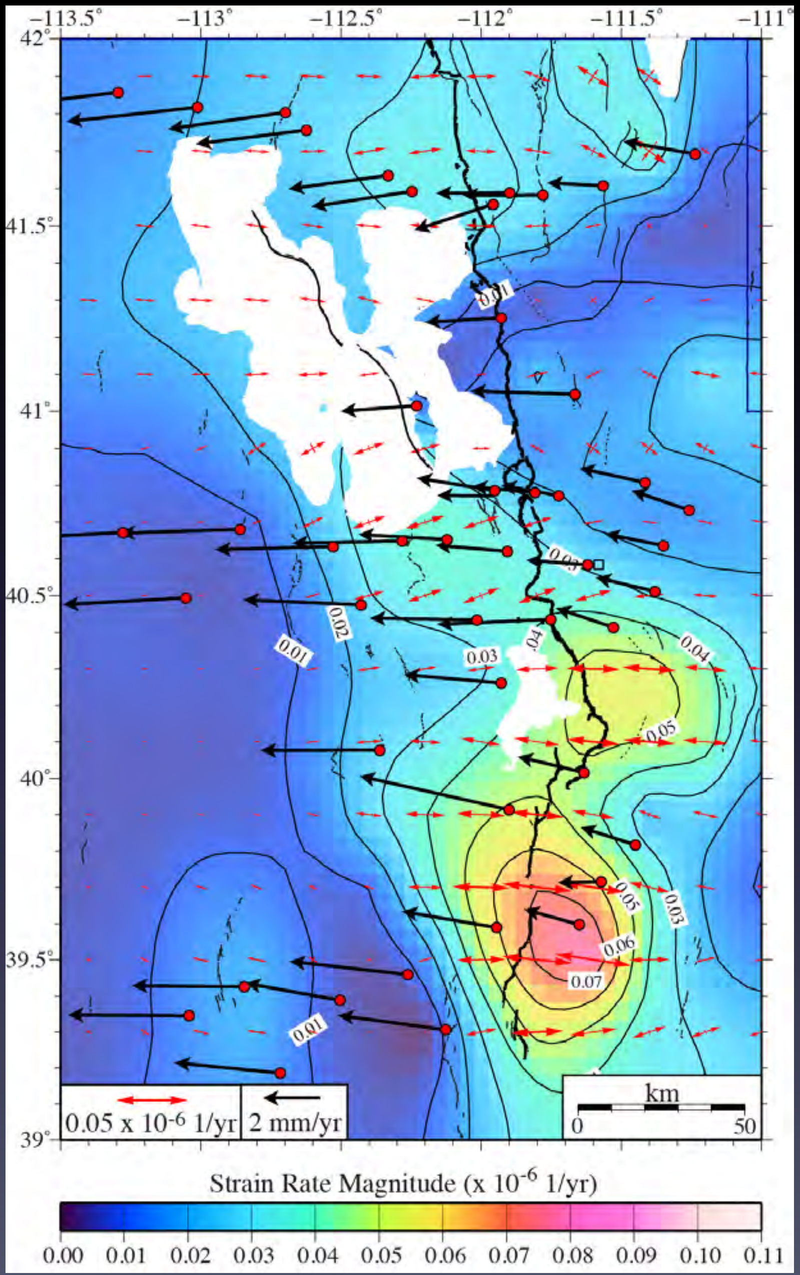
- Improved analysis lead to better match between geodetic moment loading rate and seismic moment release rate
- Geodetic moment rate still exceeds seismic moment rate by up to 2.5X
- Seismic and geodetic moment rates match within ranges of uncertainty
- Wasatch fault is major source of deformation, seismic moment
- Other faults contribute to regional deformation
    - EGSL, East Cache, Oquirrh fault
- Geodetic data consistent with complex block model of Wasatch Front, where regional extension accommodated on multiple faults

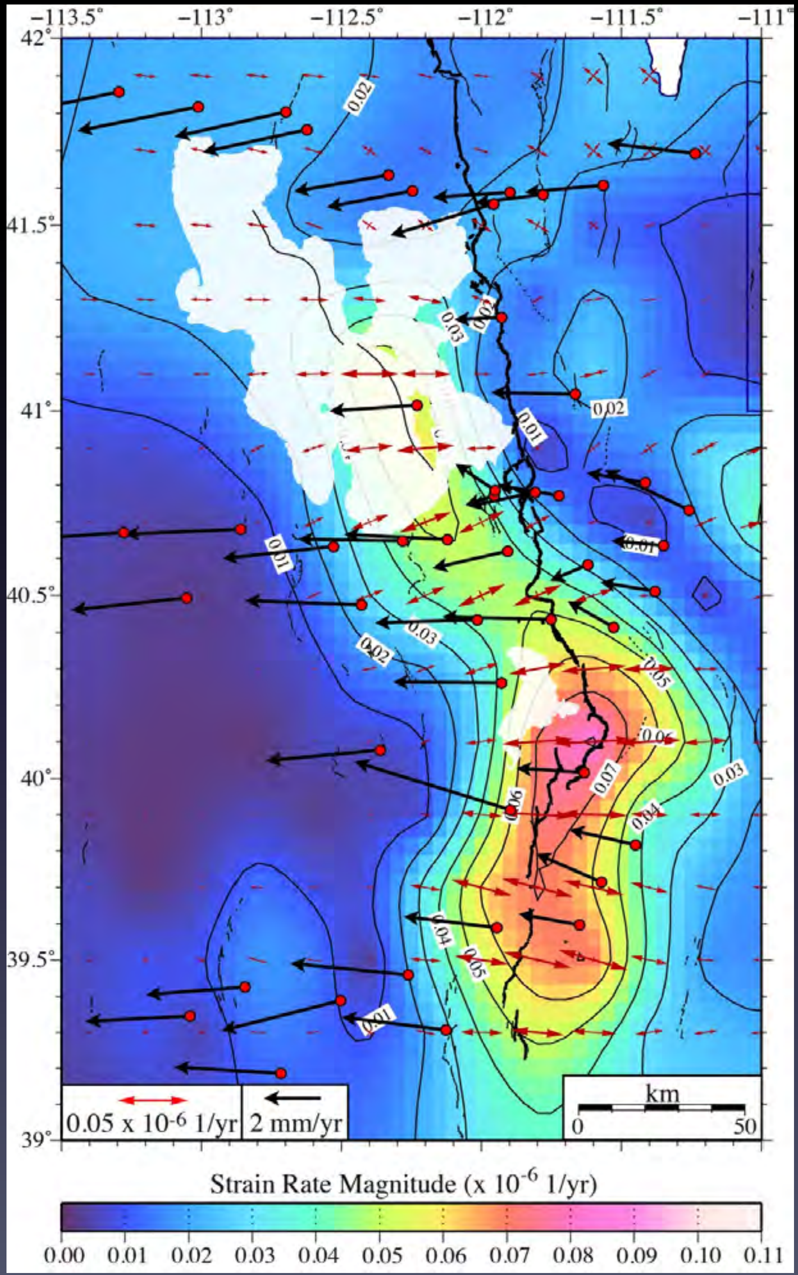
Horizontal and Vertical Velocities
Network Solution vs. Time Series



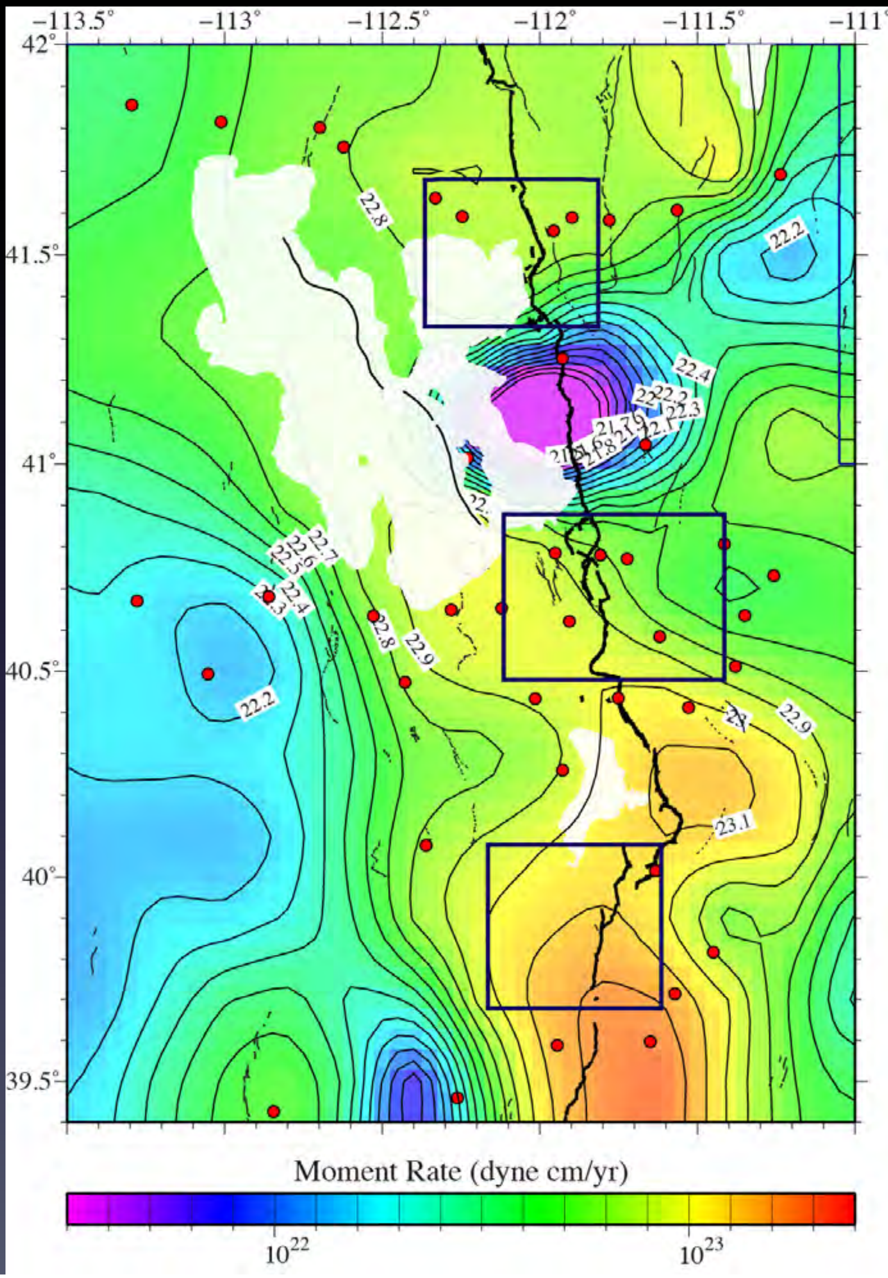


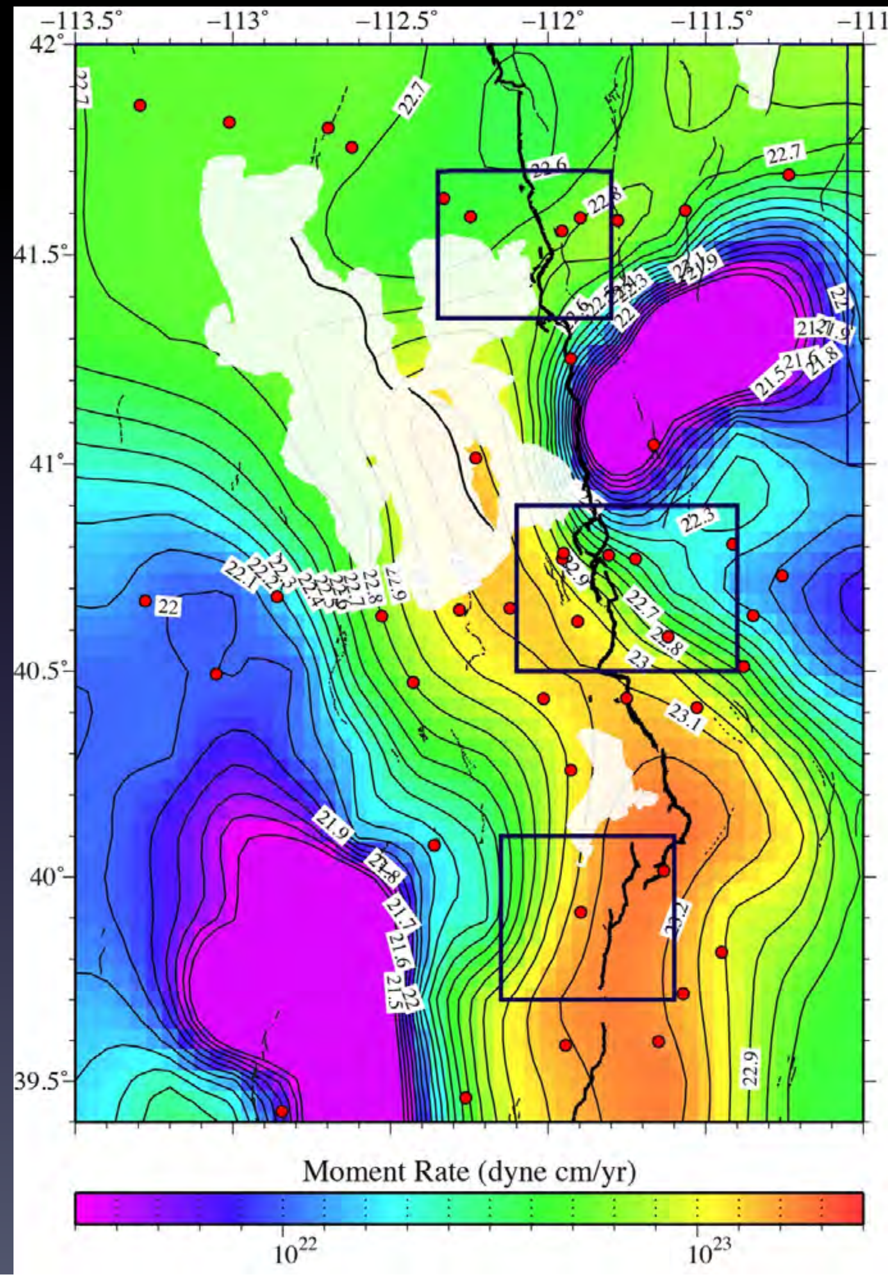
Strain Rates and Magnitudes
Time Series vs. Network Solution
(no GOUT in TS-derived strains



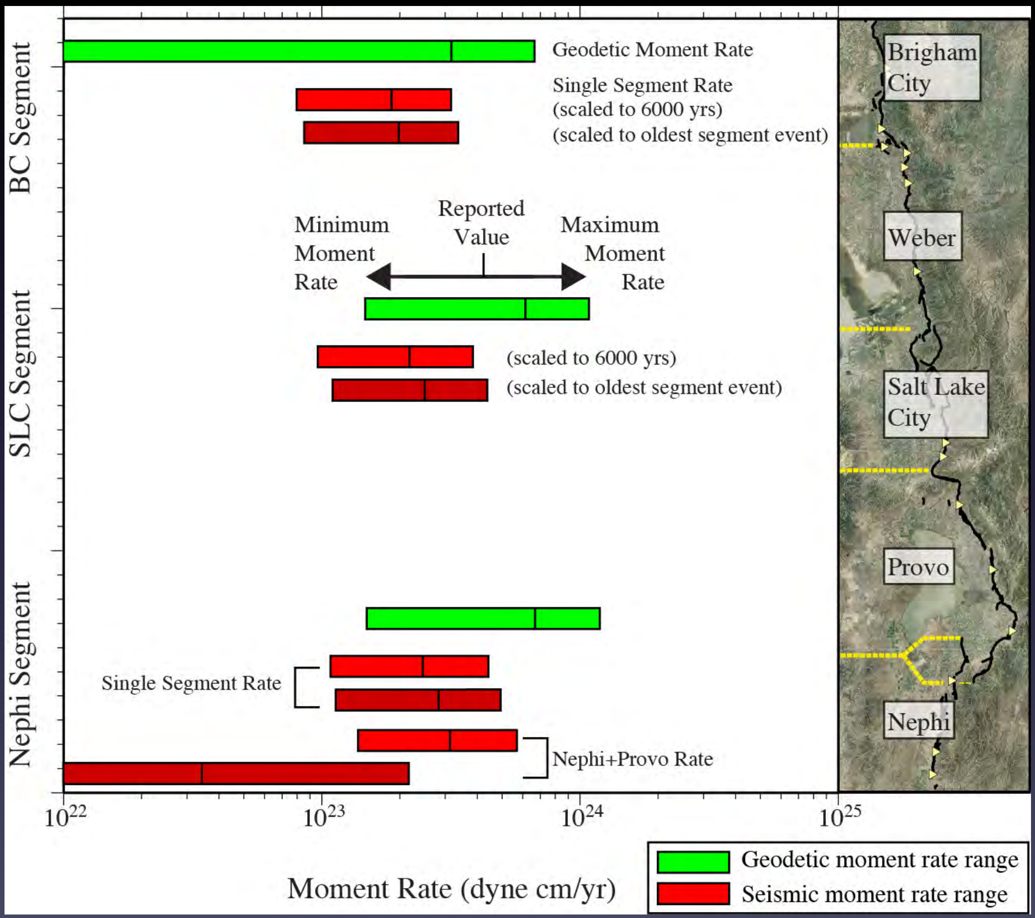


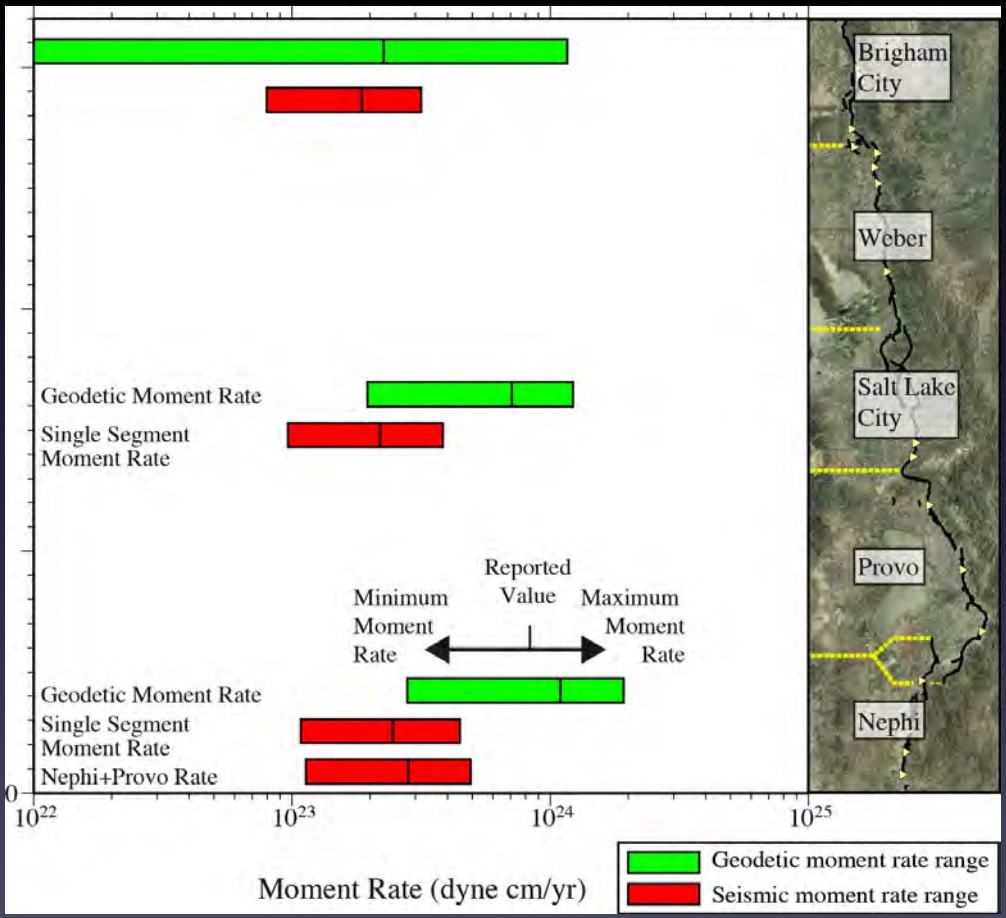
Geodetic Moment Rates
Time Series vs. Network Solution
(no GOUT in TS-derived strains





Seismic and Geodetic Moment Comparisons
Time Series vs. Network Solution
(no GOUT in TS-derived strains





High-resolution dense wide-aperture seismic profiling as a tool for seismic hazard assessment of fault-bounded intramontane basins: application to Vallo di Diano, Southern Italy

Pier Paolo Bruno[1,2], Antonio Castiello[2,3], Fabio Villani[2] and Luigi Improta[2]

(1) THE UNIVERSITY OF UTAH

(2) Istituto Nazionale di Geofisica e Vulcanologia

(3) CGGVERITAS

Seismic hazard in in central Mediteranean

is mostly posed by high-angle normal faults and deep hanging-wall basins that can promote significant ground motion amplifications.

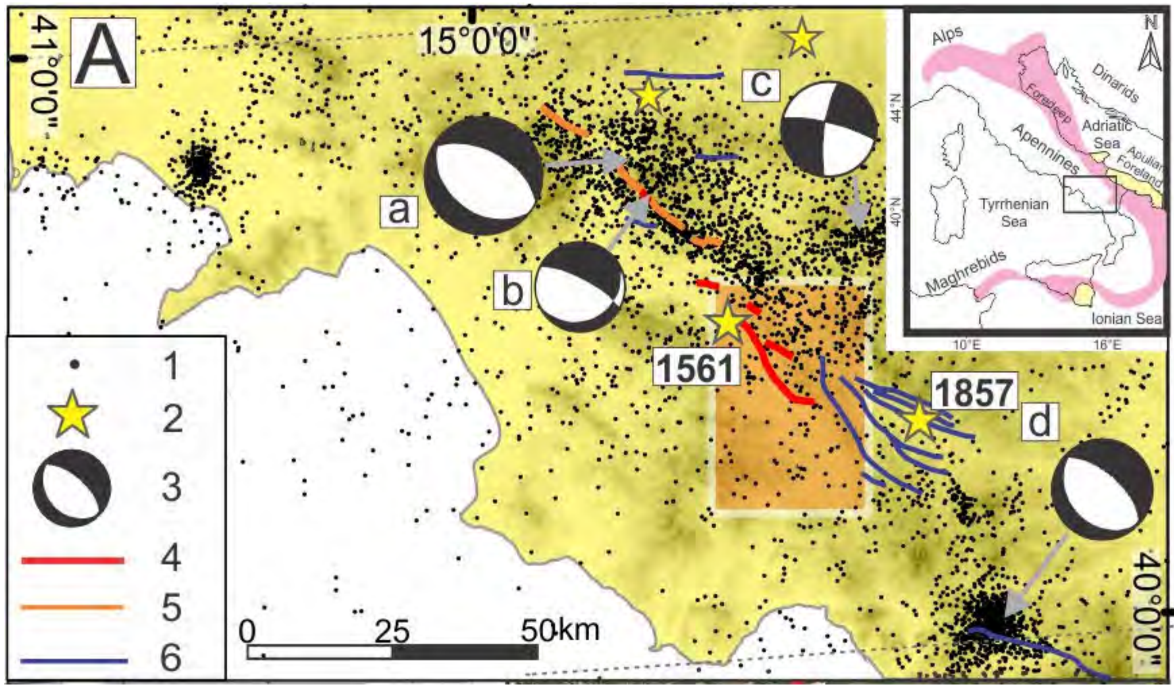
For deterministic assessment of the seismic hazard posed by large normal faults and related basins it is crucial to:

1) locate faults with a high level of confidence;

2) define fault geometry, kinematics and seismogenic potential;

3) constrain geometry and velocity structure of the related basins (in particular, the substratum morphology);

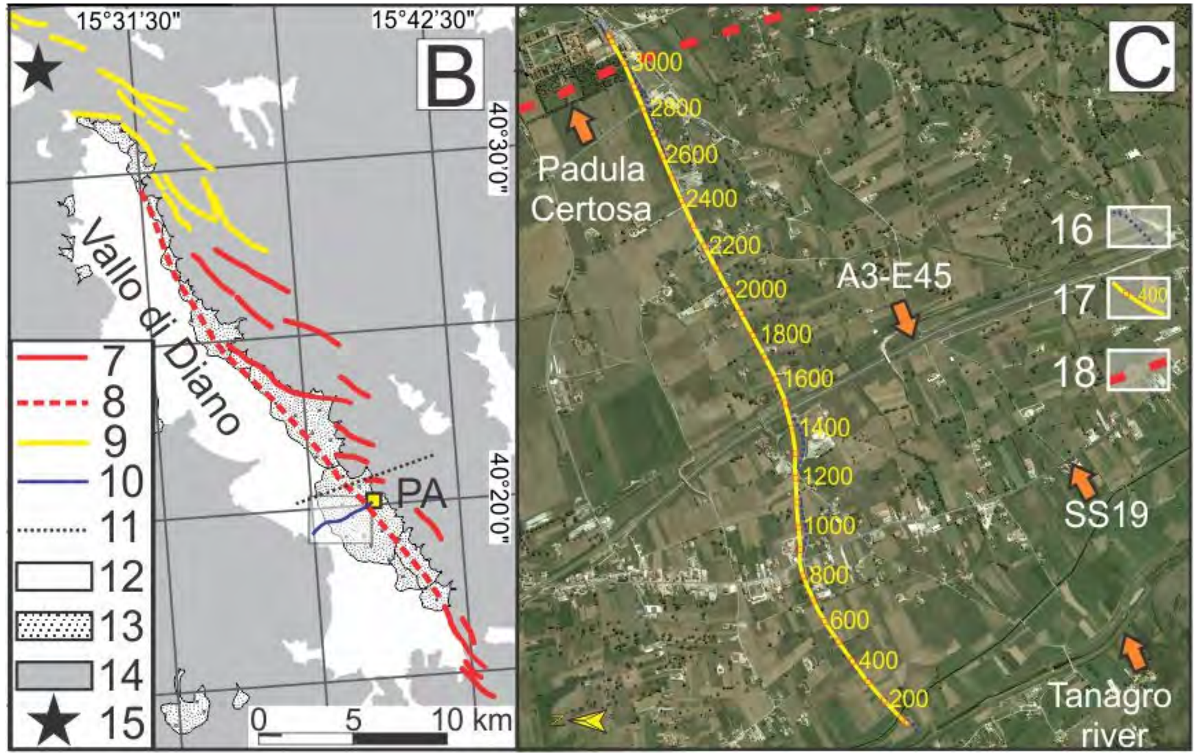
4) define the shallow architecture of fault zones, by focusing on shallow splays which could break the surface.

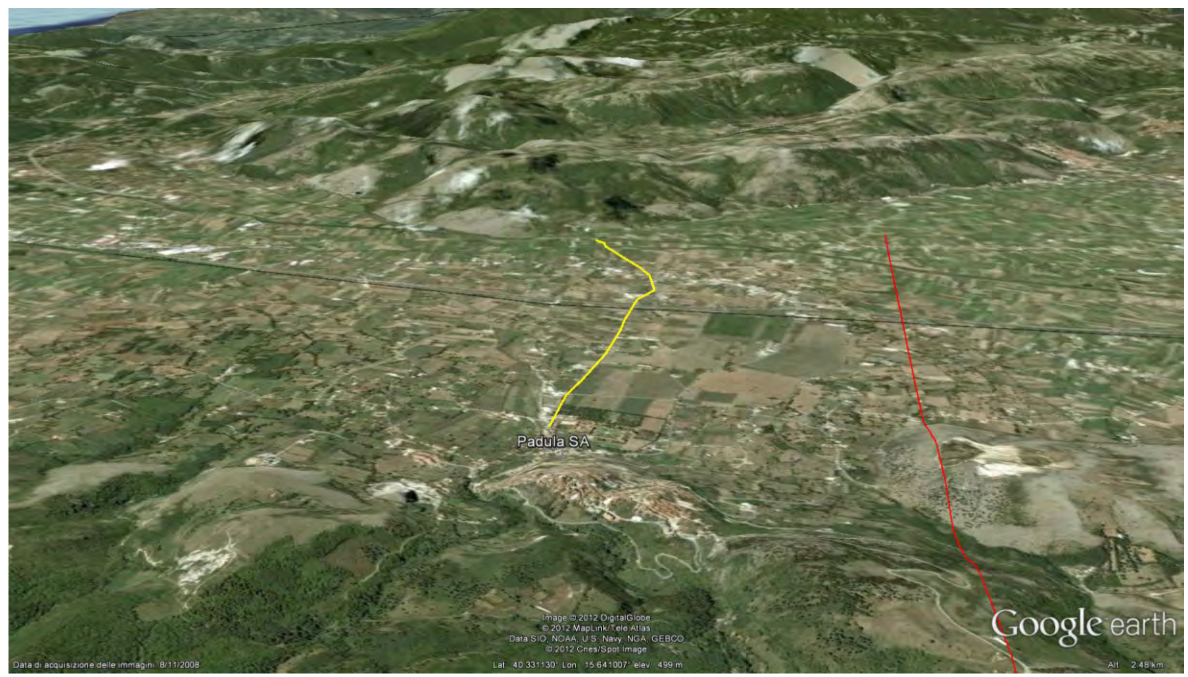


1. Crustal seismicity (1981-2002; depth: 0-30 km);
2. Historical earthquakes (M > 6) with the 1561 and 1857 events outlined;
3. Focal mechanism of M > 5 events (a - 1980 M6.9; b - 1996 M5.1; c - 1990 M5.7; d - 1998 M5.6);
4. Vallo di Diano Fault System (VDFS);
5. Fault scarps of the 1980 Irpinia earthquake;
6. Quaternary faults.

Vallo di Diano Fault System (VDFS)

7. VDFS in bedrock;
8. VDFS buried;
9. VDFS northern segments active during late Pleistocene – Holocene (after Galli *et al.*, 2006);
10. position of our HR profile;
11. position of ENI industry line VD07;
12. Middle Pleistocene - Holocene lacustrine deposits;
13. Alluvial fans and slope breccias (Middle Pleistocene - Holocene);
14. Meso-Cenozoic linestones and dolostones;
15. Epicenter of the 1561 earthquake.
16. Padula survey station crooked line position;
17. Padula line processing position;
18. buried presumed location of VDFS.

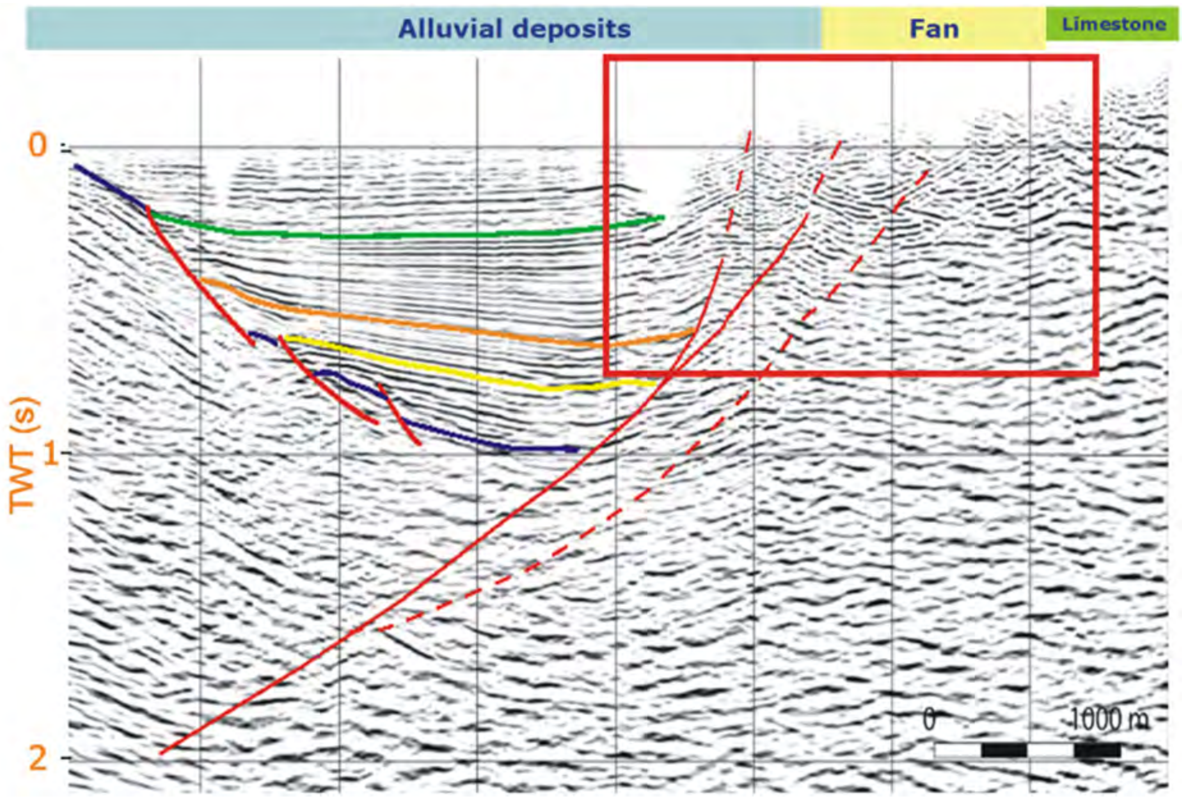




Why reflection seismology often fails in mountain belt environments?

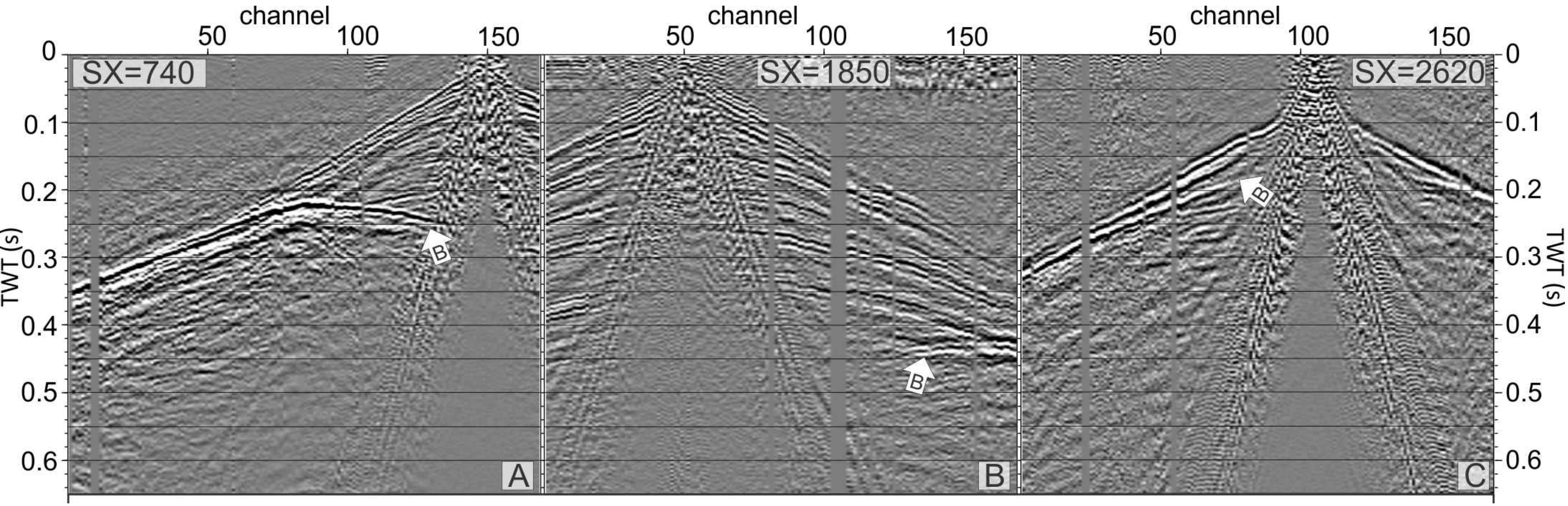
Reflection seismic imaging of active faults is very attractive for the potential benefits in terms of adding valuable information for seismic hazard studies.

However, difficulty in collecting good quality seismic data across the fault-zone, as well as the presence of strong lateral velocity changes and steep-dipping reflectors, often make standard CDP processing inappropriate.

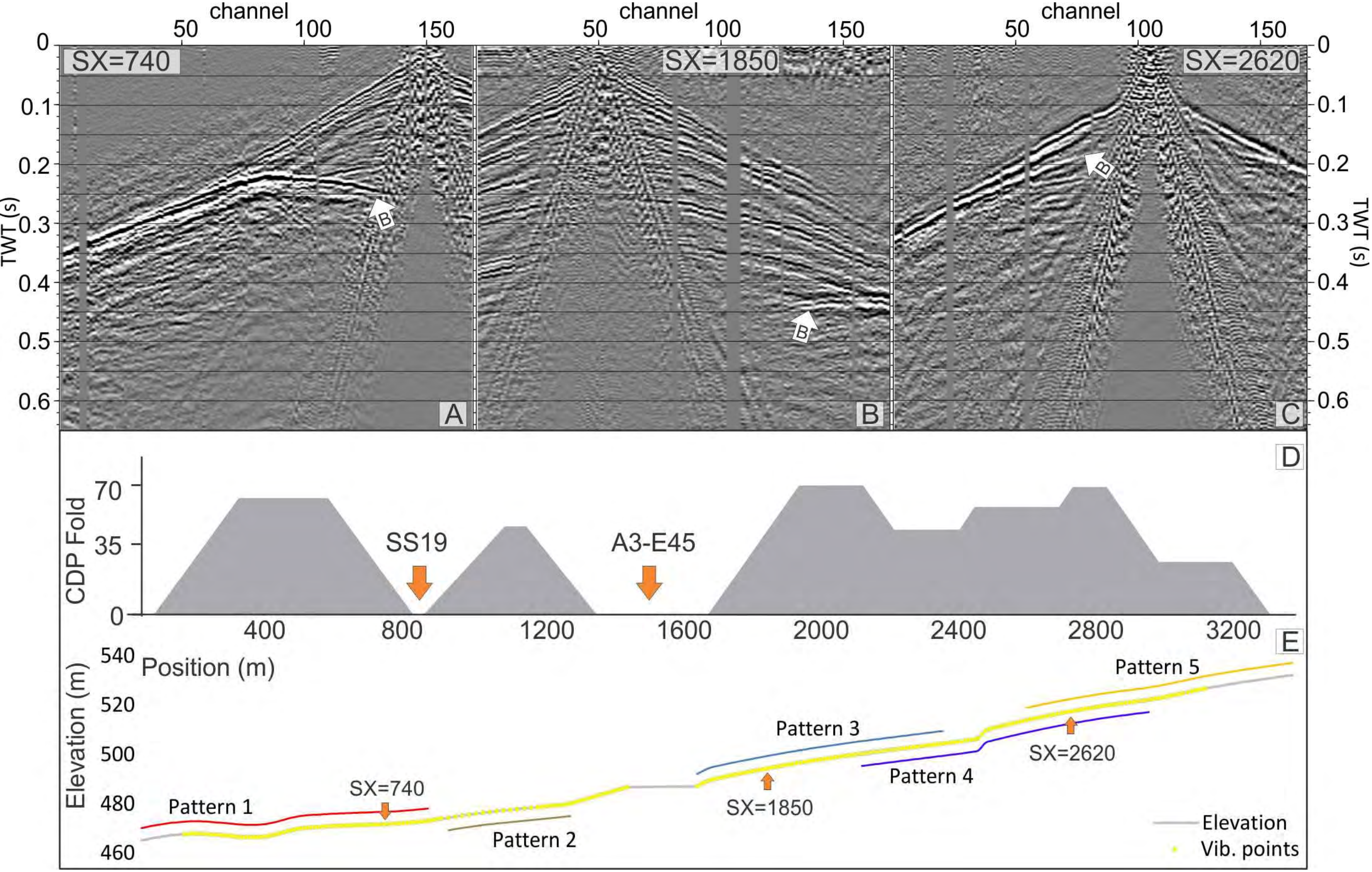


Poor Shallow Imaging on the Eastern Basin border

- scant acquisition geometry
- complex geological environments (statics, sharp 2D Vp variations)

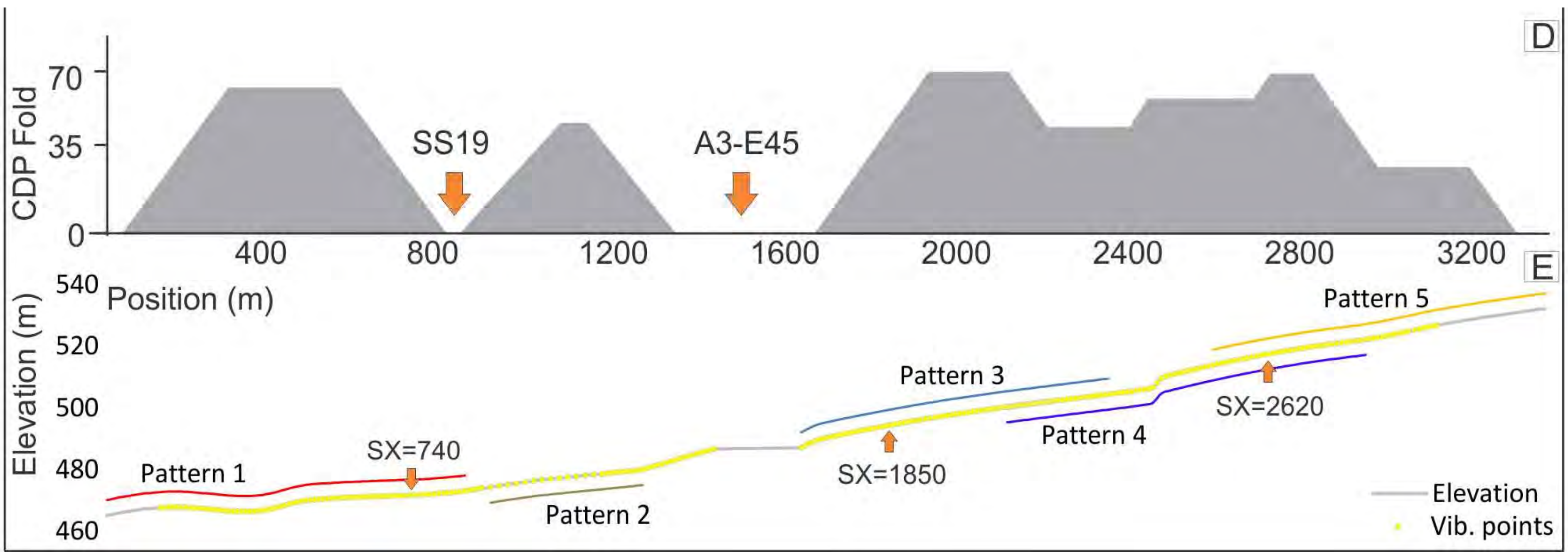


Three processed Common Shot Gathers acquired with source located in the VD basin at 740 m (A), 1850 m (B), and in the eastern margin at 2620 m (C). The arrows outline the reflection “B” generated at the basin substratum. Note the asymmetry of the substratum reflection, compared to the basin filling reflections. This asymmetry is evident in (A) and (B), and suggests a complex morphology of the substratum.



channel
50
100
150
SX=740
SX=1850
SX=2620
TWT (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
B
A
C
D
CDP Fold
70
35
0
SS19
A3-E45
400
800
1200
1600
2000
2400
2800
3200
Position (m)
E
Elevation (m)
540
520
500
480
460
Pattern 1
Pattern 2
Pattern 3
Pattern 4
Pattern 5
SX=740
SX=1850
SX=2620
Elevation
Vib. points

(D) CDP fold coverage along the profile; (E) scheme of the acquisition layout showing the five wide-aperture geophone arrays (pattern 1-5) and source locations (yellow dots) used for this survey. A state road (SS19) and an highway (A3-E45) limited the length of the second and third geophone array and caused two acquisition/source gaps. Using a "target oriented" acquisition layout we were able to illuminate the presumed VDFS zone (i.e. 2000-2800 m) with the maximum folding and data offset range.



Requirements of an effective high-resolution seismic source:

•High frequency

• High energy content
(in the signal bandwidth)

• possibly, generation of
S-waves

IVI Minivib®

Max. Peak Force: 27,000 N

Baseplate Area: 1.16 m^2

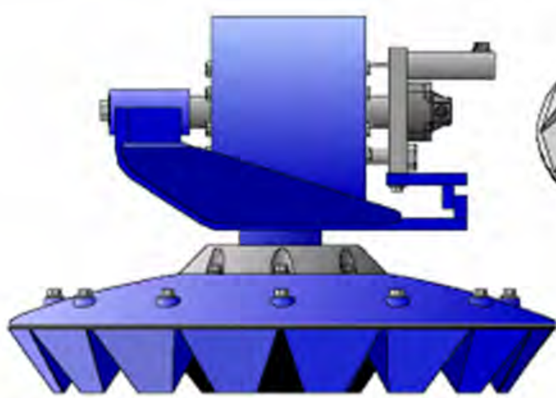
Mass and baseplate weight: 309 Kg

Operable frequency range from 5 to 350 Hz.
(effective: from 6 to 250 Hz)

Pad impression with shear wave waffle plate attachment

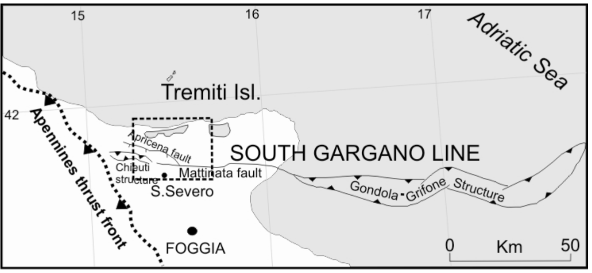
In shear wave mode the base plate couples to the ground with elongated triangle teeth that can penetrate a soft ground surface as much as 4 inches.

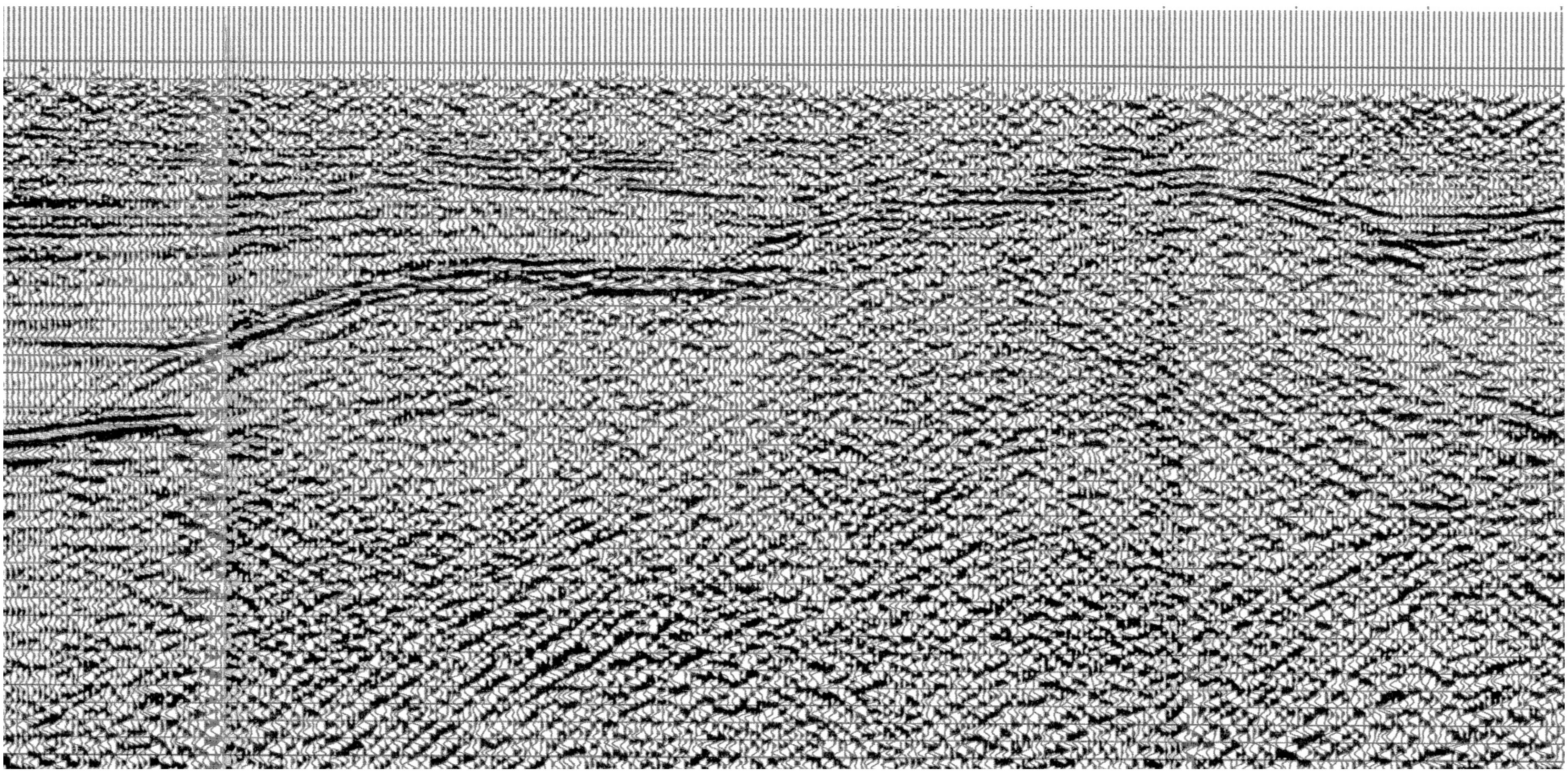
This waffle plate is omni-directional and therefore allows the vibrator to operate in either SH or SV mode by simply rotating the mass.



Bottom view of the shearwave baseplate adapter

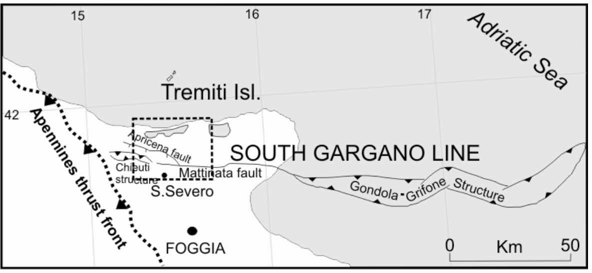
Any difference between High Resolution and Industry seismics?

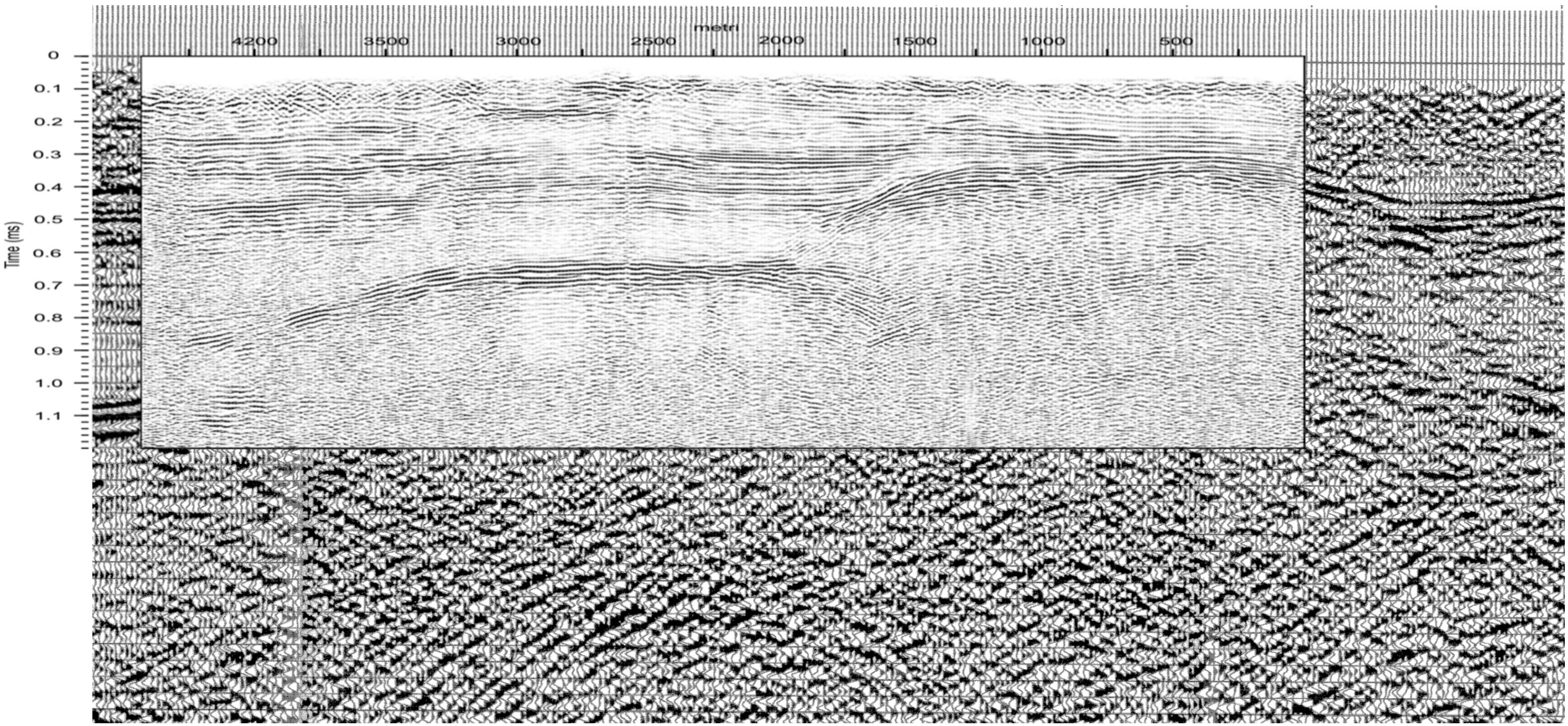




Example 1: seismic reflection exploration in the Apulian Foredip (Apricena fault): Comparison between CDP stacks of industry seismics and High Resolution seismic reflection (IVI minivib source)

Well…yes!





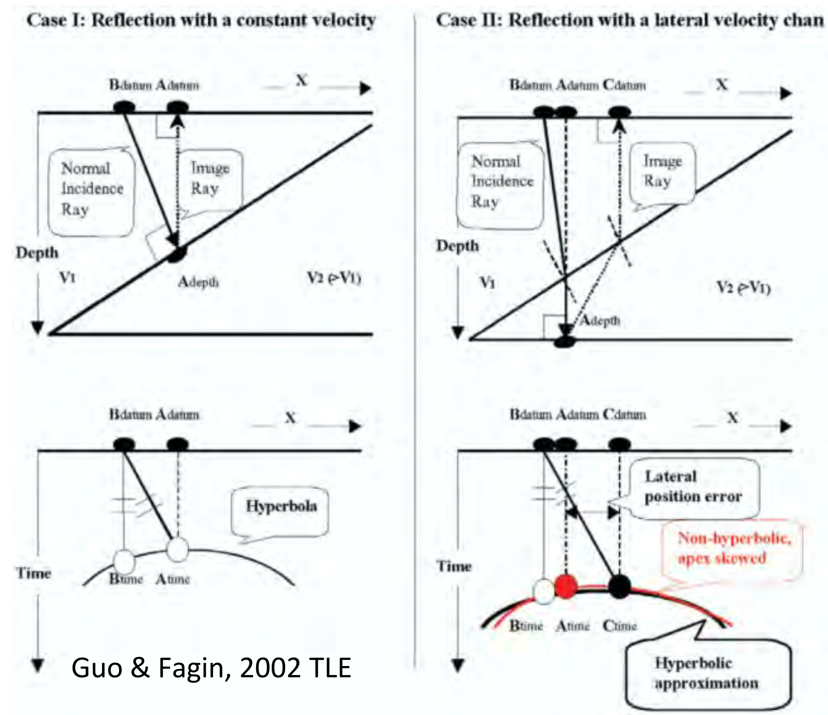
Example 1: seismic reflection exploration in the Apulian Foredip (Apricena fault): Comparison between CDP stacks of industry seismics and High Resolution seismic reflection (IVI minivib source)

Strategy for Improvement of seismic reflection imaging in complex environments

- Field techniques:
  - Dense wide-aperture array geometry
- Processing techniques:
  - first break non linear tomography down to the target depth
  - (tomo) static corrections
  - NMO correction
  - Pre Stack Depth Migration (PSDM)

Migration Strategies

CASE	MIGRATION
Dipping events	Post-stack Time Migration
Conflicting dips with different stacking velocities	Prestack Migration or DMO+Post-Stack Migration
CASE	**MIGRATION**
Smooth lateral velocity variations associated with complex overburden structures	Post-stack Depth Migration
Complex non-hyperbolic moveout due to strong lateral velocity contrasts	Prestack depth Migration



Guo & Fagin, 2002 TLE

time migration fails when there is a lateral velocity change.

It introduces an amplitude error by collecting the data along a hyperbola, and

a lateral positioning error by putting the collected data at the apex of the hyperbola.

Poststack migration is limited by the assumptions of NMO processing that include:

1. Horizontal reflectors
2. Small offset-to-depth ratio
3. Small lateral and vertical velocity gradients

All the point above are commonly violated in shallow reflection surveys and/or in complex geological settings.

Pre Stack Depth Migration (PSDM)

The process of PSDM, coupled with migration velocity analysis, produces both a migrated image and a depth-velocity model that are not subject to the assumption of NMO processing

Advantages

Improved image accurancy

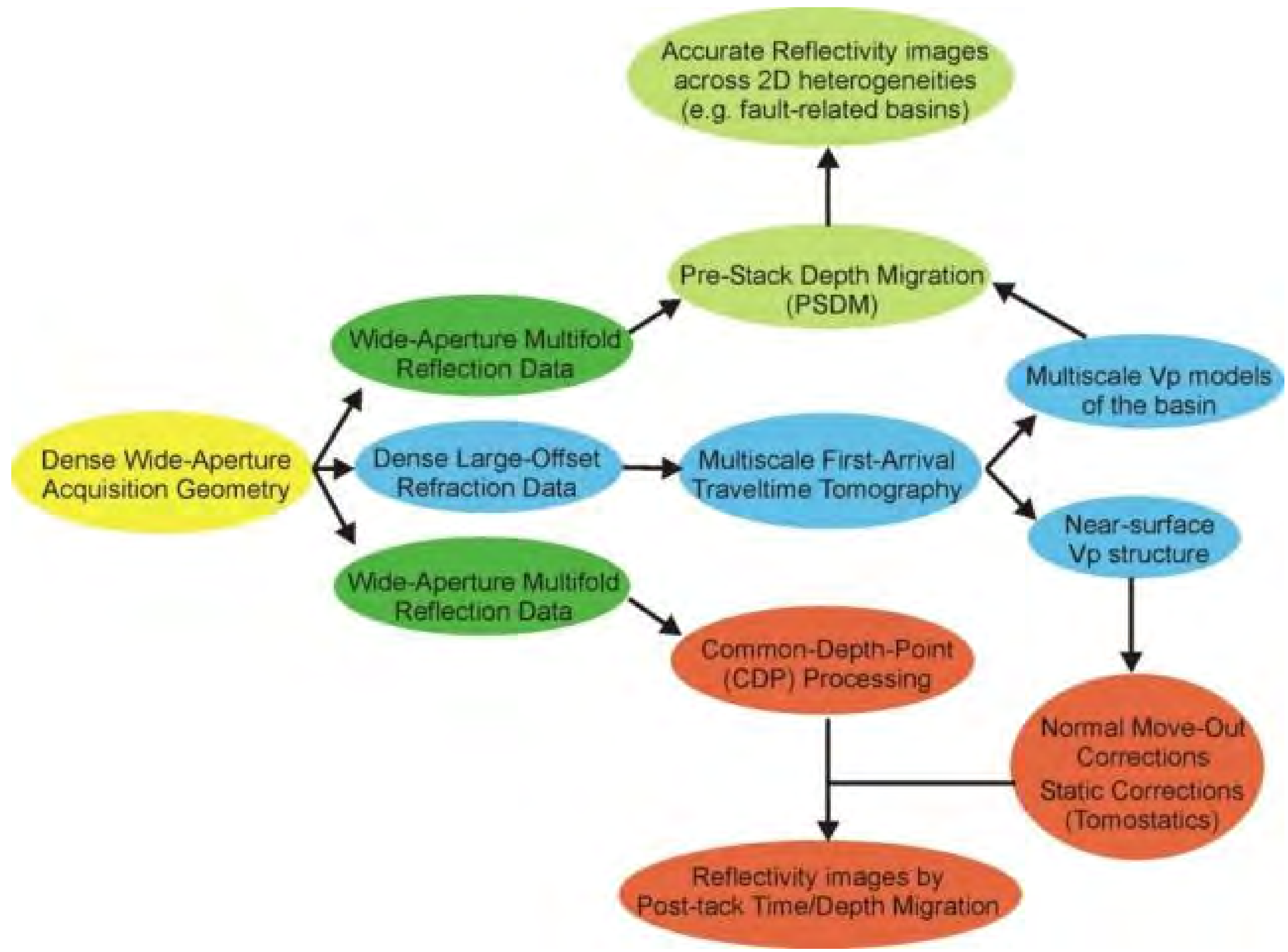
Disadvantages

PSDM needs a detailed background velocity model that cannot always be obtained in complex environments

Why a dense wide-aperture acquisition geometry?

It is an effective strategy to obtain high-resolution images of complex 2D structures :

Seismic imaging flow for dense wide-aperture data

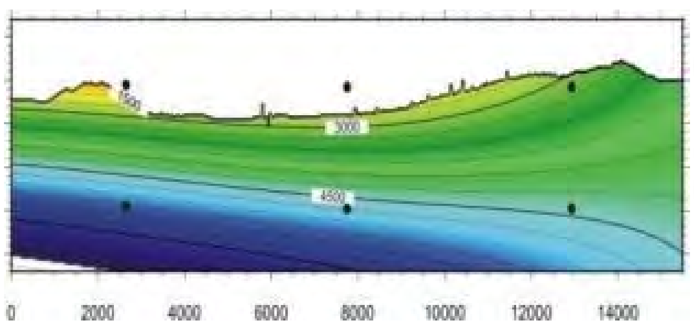


Processing techniques:
1st step: non linear refraction tomography

Non Linear First arrival Tomography

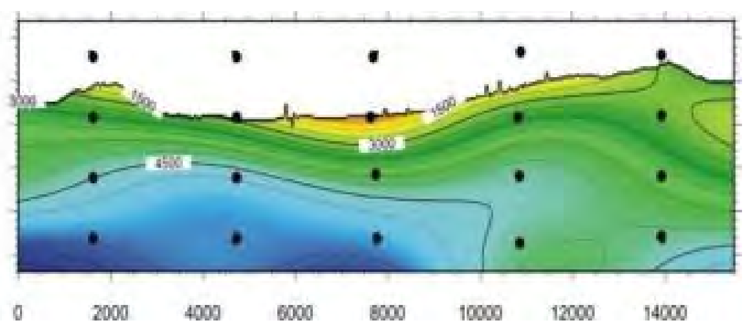
(Herrero et al., 2000, Improta et al., 2002)

- the velocity field along complex geological structures may be extremely heterogeneous, thus making difficult the estimation of an “a priori” reference model sufficiently accurate for linearization purpose.
- Herrero et al. (2000) proposed a nonlinear approach: the computing of the reference model can be seen as a step or few steps of the inversion process. This allows to perform the inversion without any reference model.
- The inversion first resolves the large wave lengths. The number of inversion parameters is increased at each step.
- the multi scale approach is limited to the parameters of the inversion and it is aimed to accelerate the convergence of the inversion process.
- The method is based on a representation of the P-wave velocity variations by a bi-cubic spline (by definition smooth).



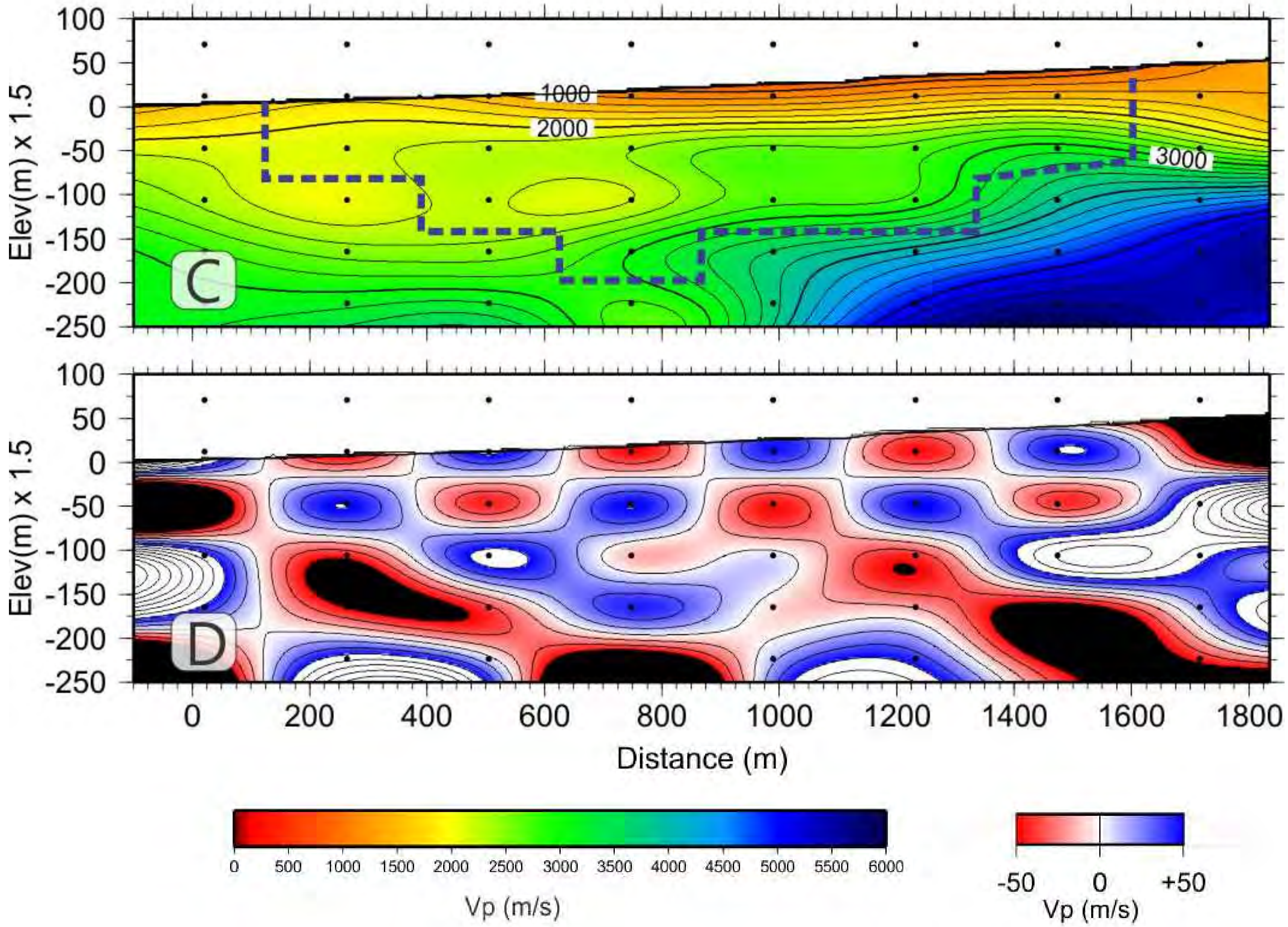
Large wavelength model (3x2 nodes)

Increase of the number of nodes



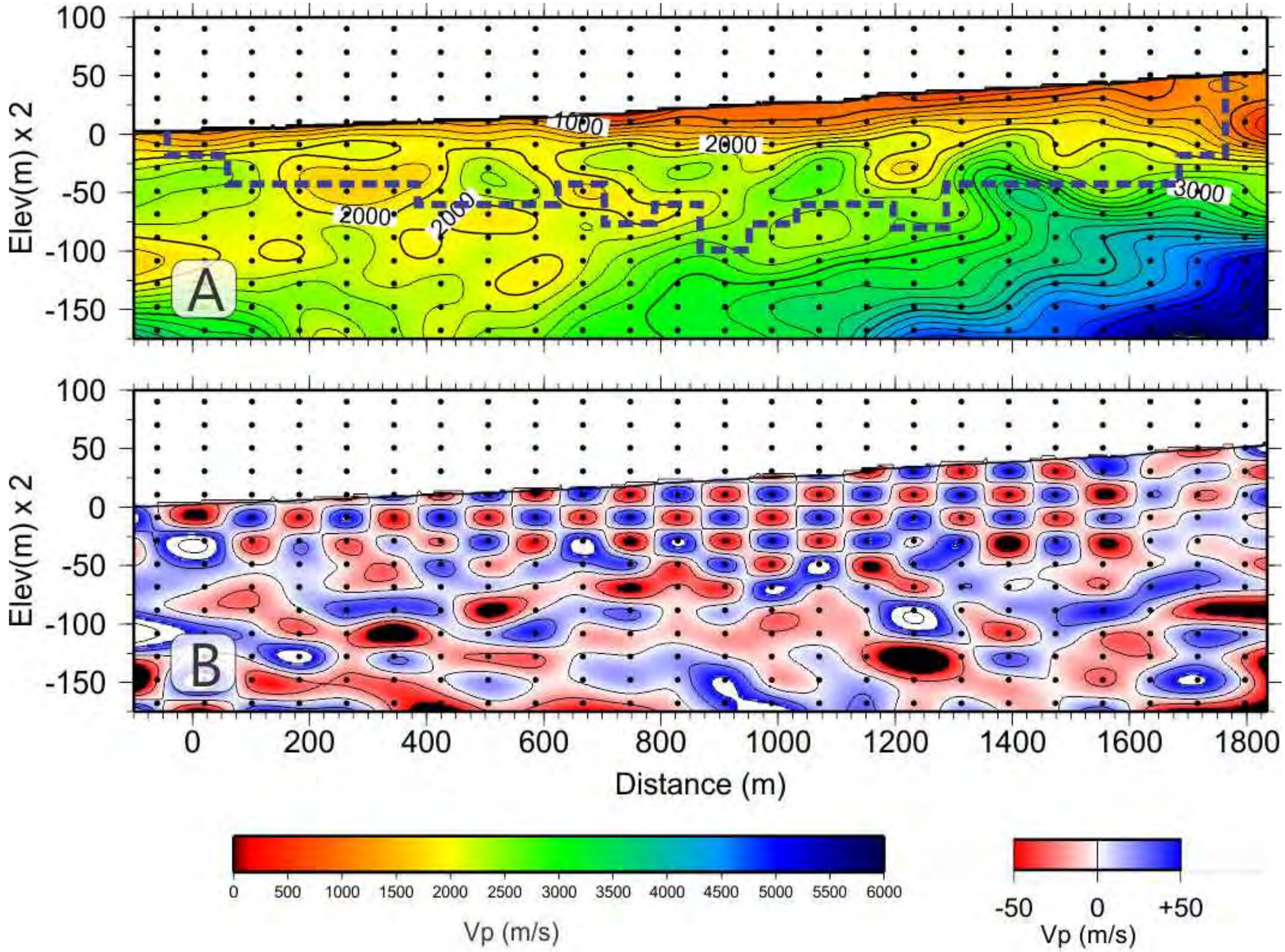
Small wavelength model (5x4 nodes)

Results of multiscale refraction tomography along the eastern portion of the basin



(C) Large-wavelength model (8 horizontal x 6 vertical nodes) with perturbation pattern (D) retrieved after the "*a posteriori*" checkerboard resolution tests.

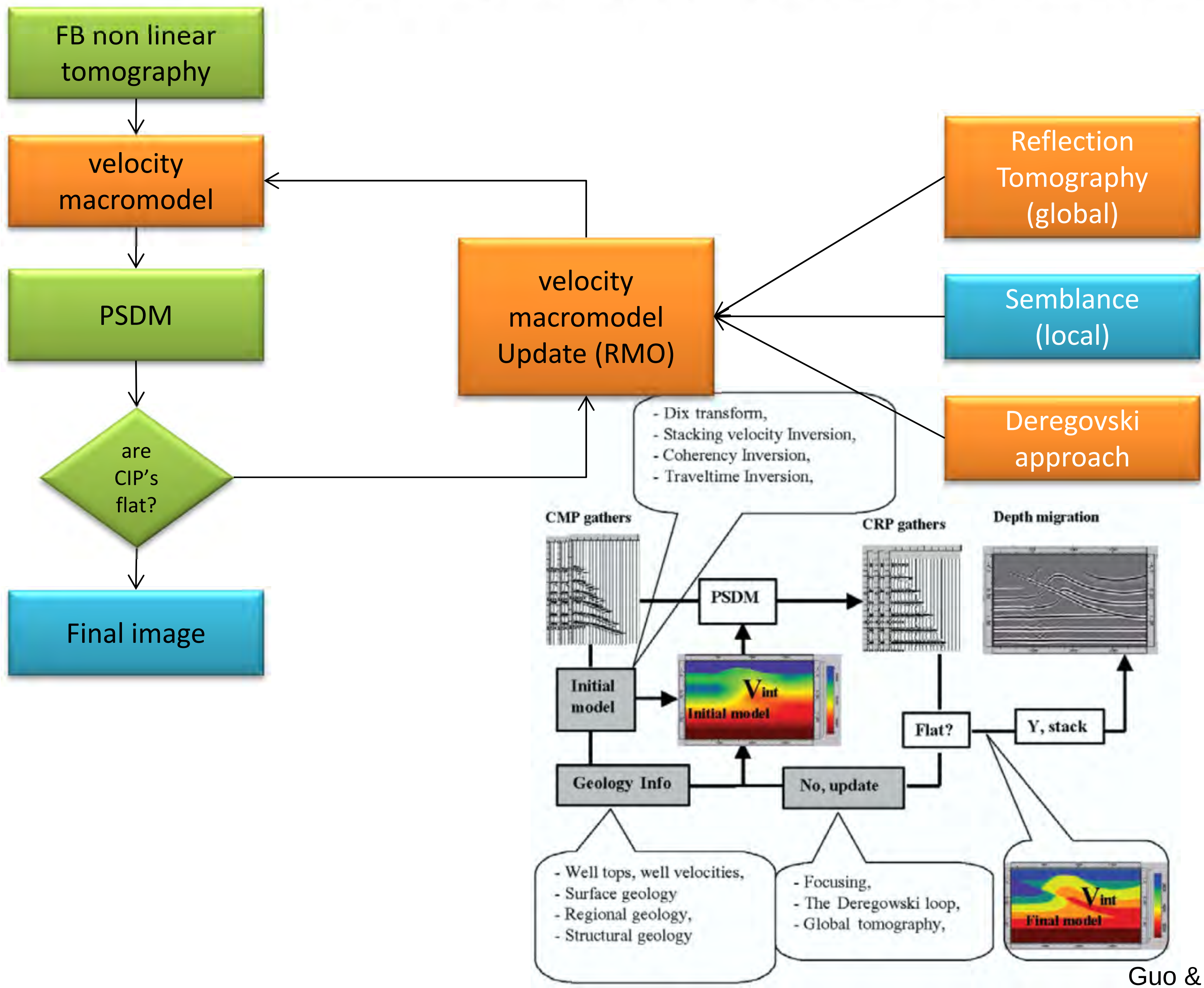
Results of multiscale refraction tomography along the eastern portion of the basin



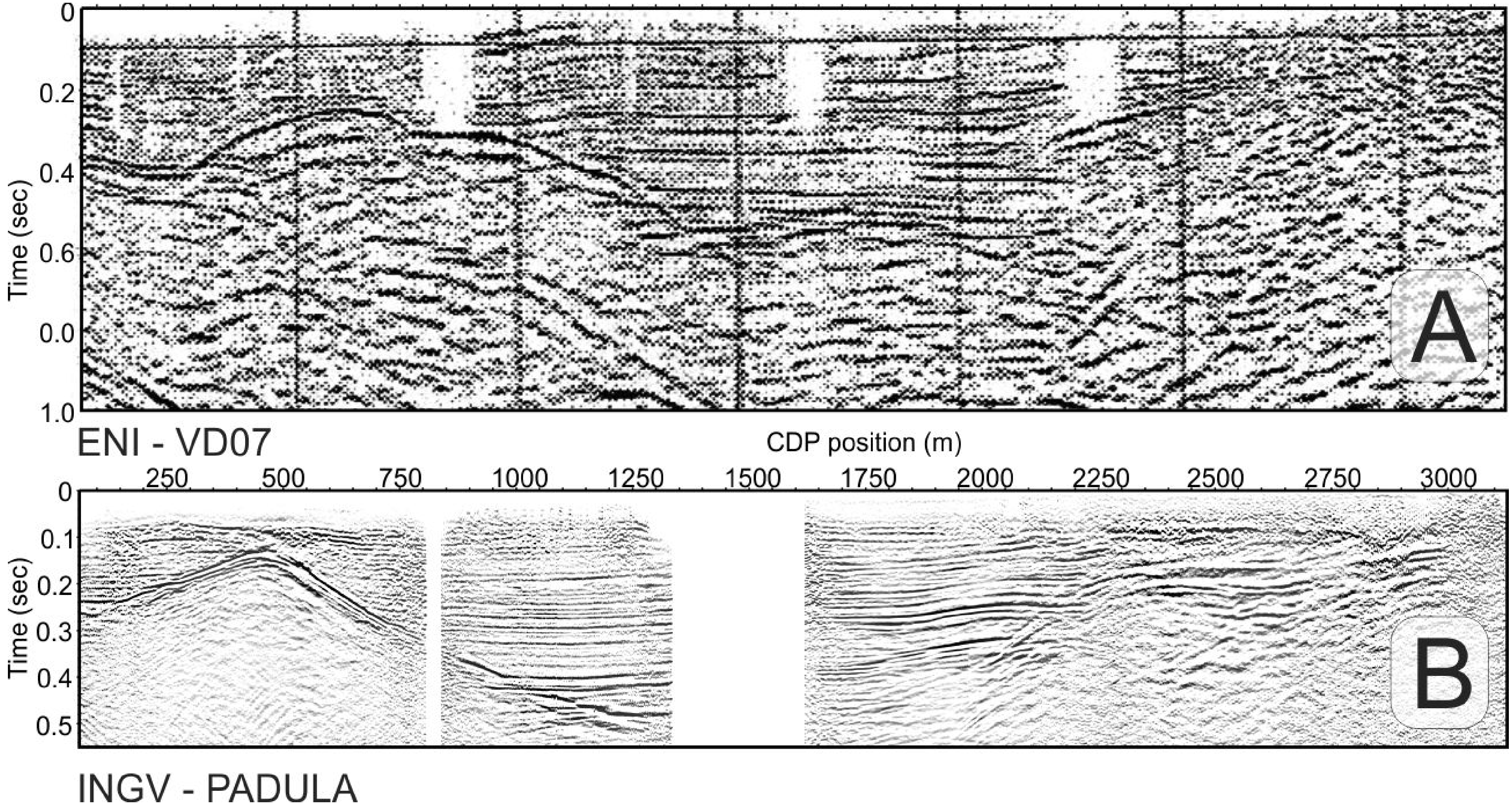
(A) Shallow small-wavelength Vp model (24 horizontal x 14 vertical nodes), with perturbation pattern (B) retrieved after the "*a posteriori*" checkerboard resolution tests.

2° step: estimation of the velocity macromodel:

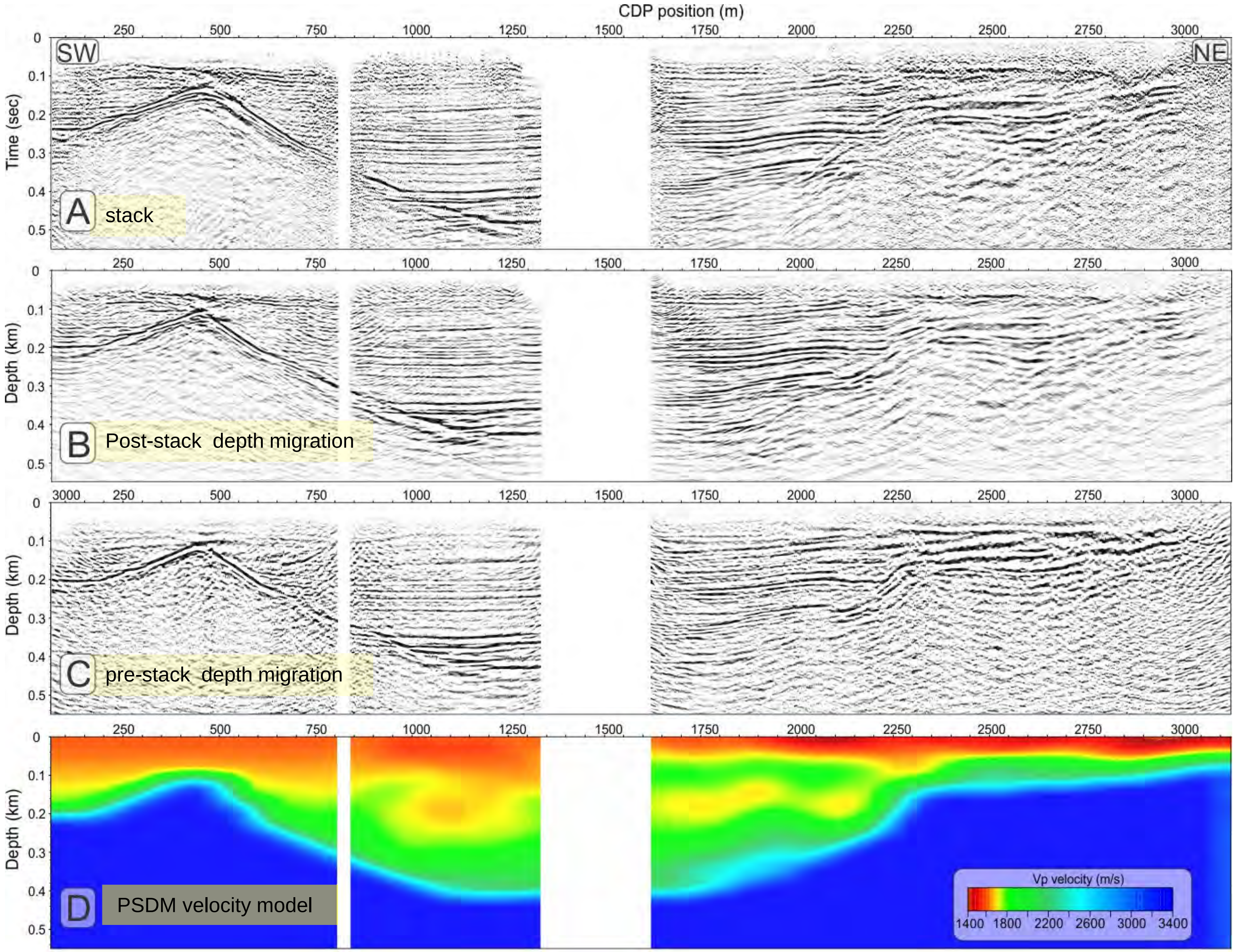
Refraction tomography +Migration Velocity Analysis (MVA)



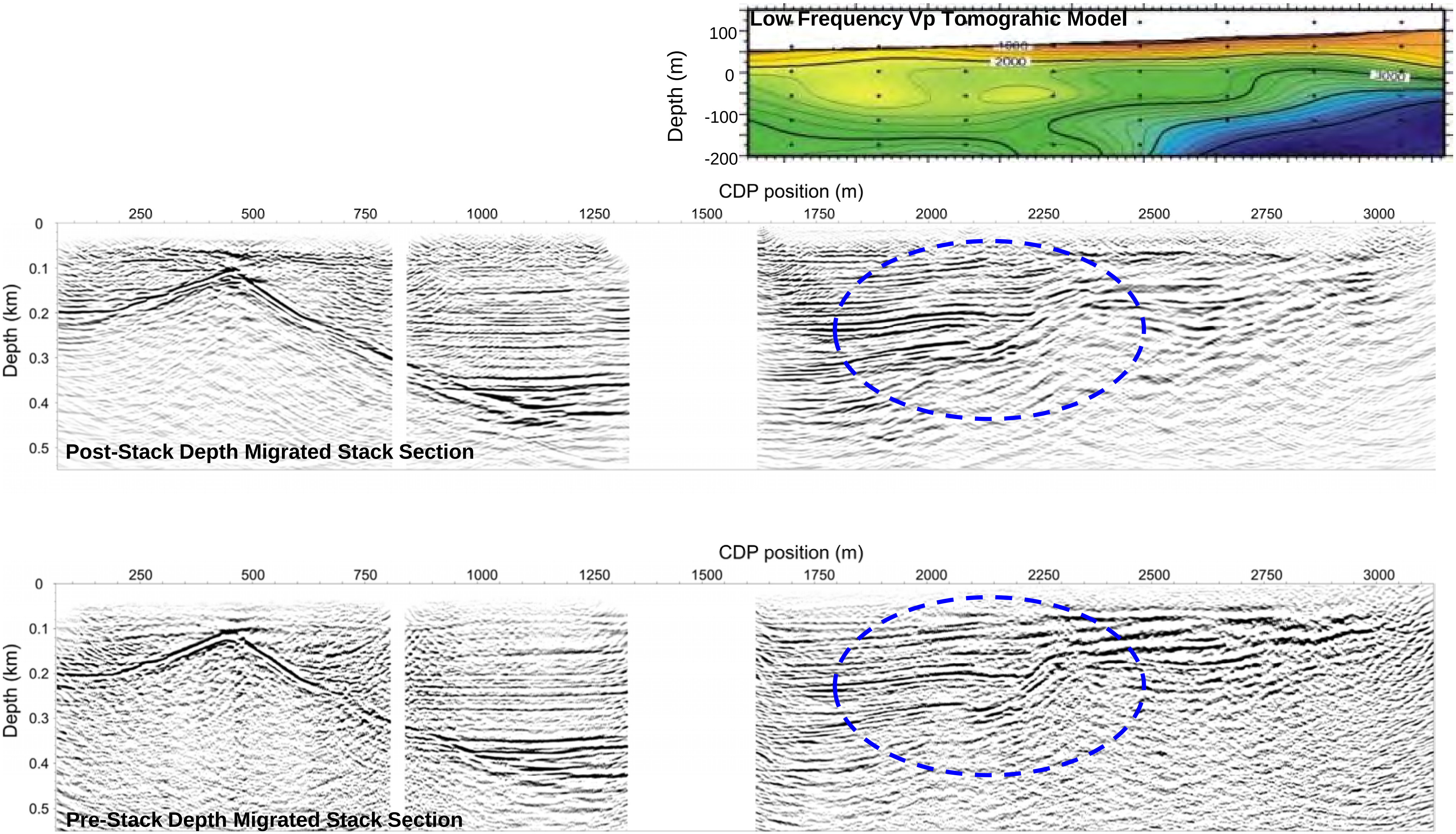
Guo & Fagin, 2002 TLE

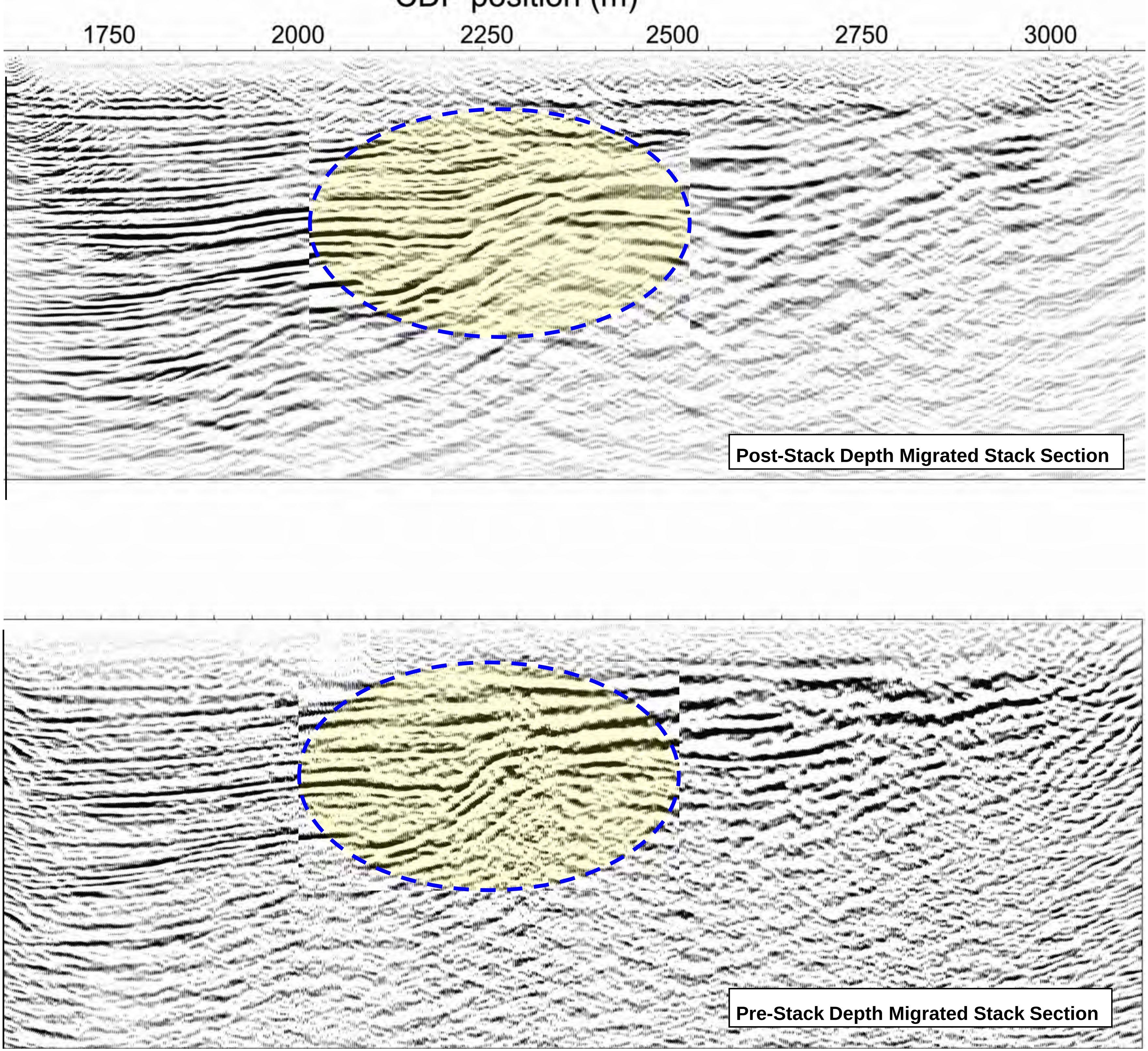


Comparison between industry profile VD07 and line Padula (stack) (B). The two profiles are sub-parallel and about 1.5 apart.

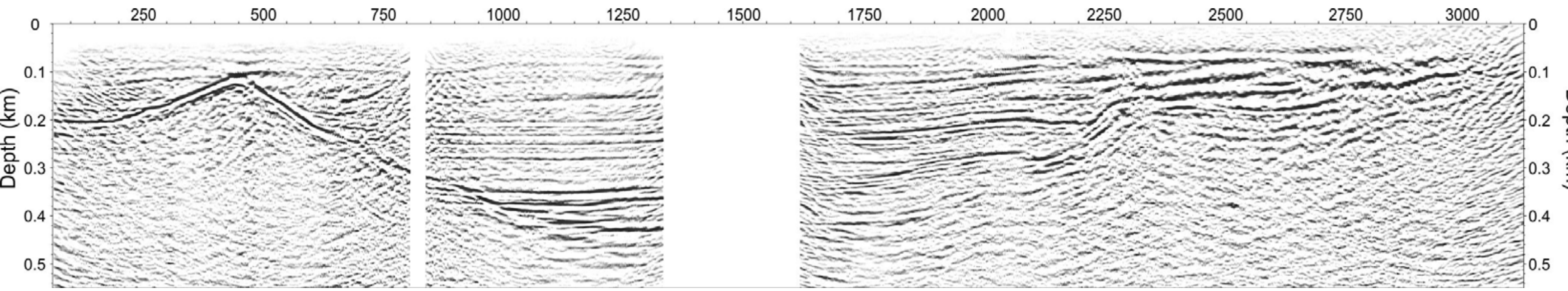

CDP position (m)
SW
NE
Time (sec)
A stack
Depth (km)
B Post-stack depth migration
C pre-stack depth migration
D PSDM velocity model
Vp velocity (m/s)
1400 1800 2200 2600 3000 3400

Comparison between 1st arrivals tomography and seismic reflection for shallow fault imaging



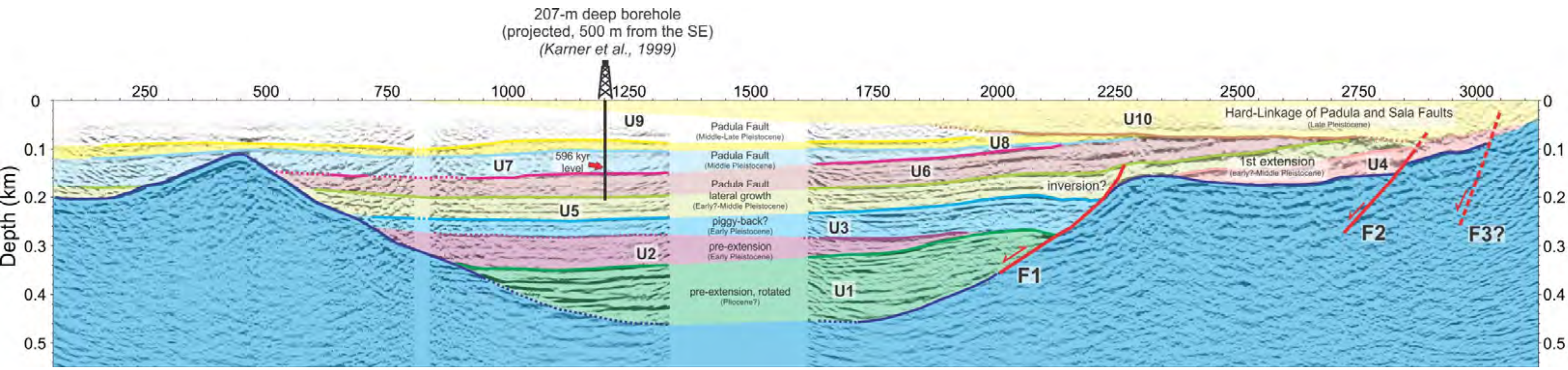

1750
2000
2250
2500
2750
3000
Post-Stack Depth Migrated Stack Section
Pre-Stack Depth Migrated Stack Section

Geo-structural interpretation



seismic reflection images for Seismic hazard:

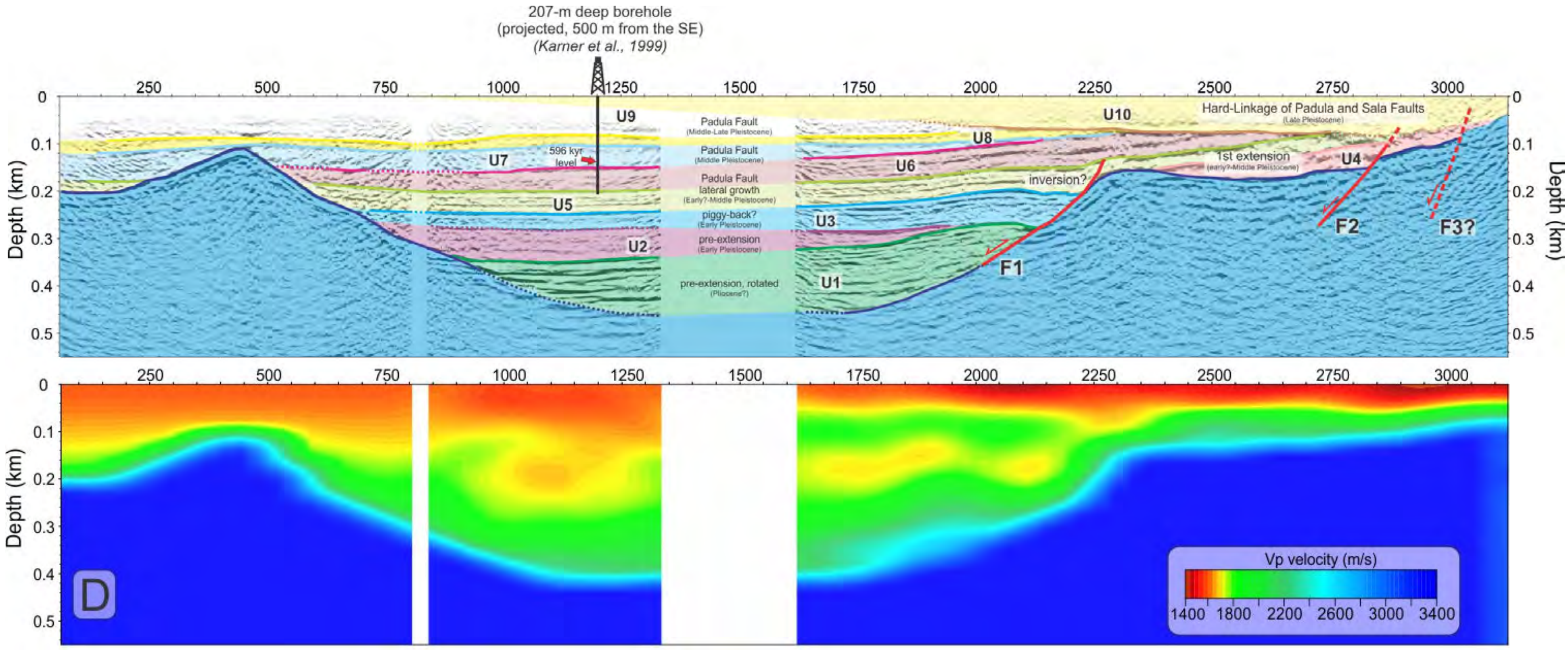
Geo-structural interpretation



seismic reflection images for Seismic hazard:

1. outline the articulated morphology of the basin substratum and the Quaternary filling (tectonic evolution & earthquake scenario studies)

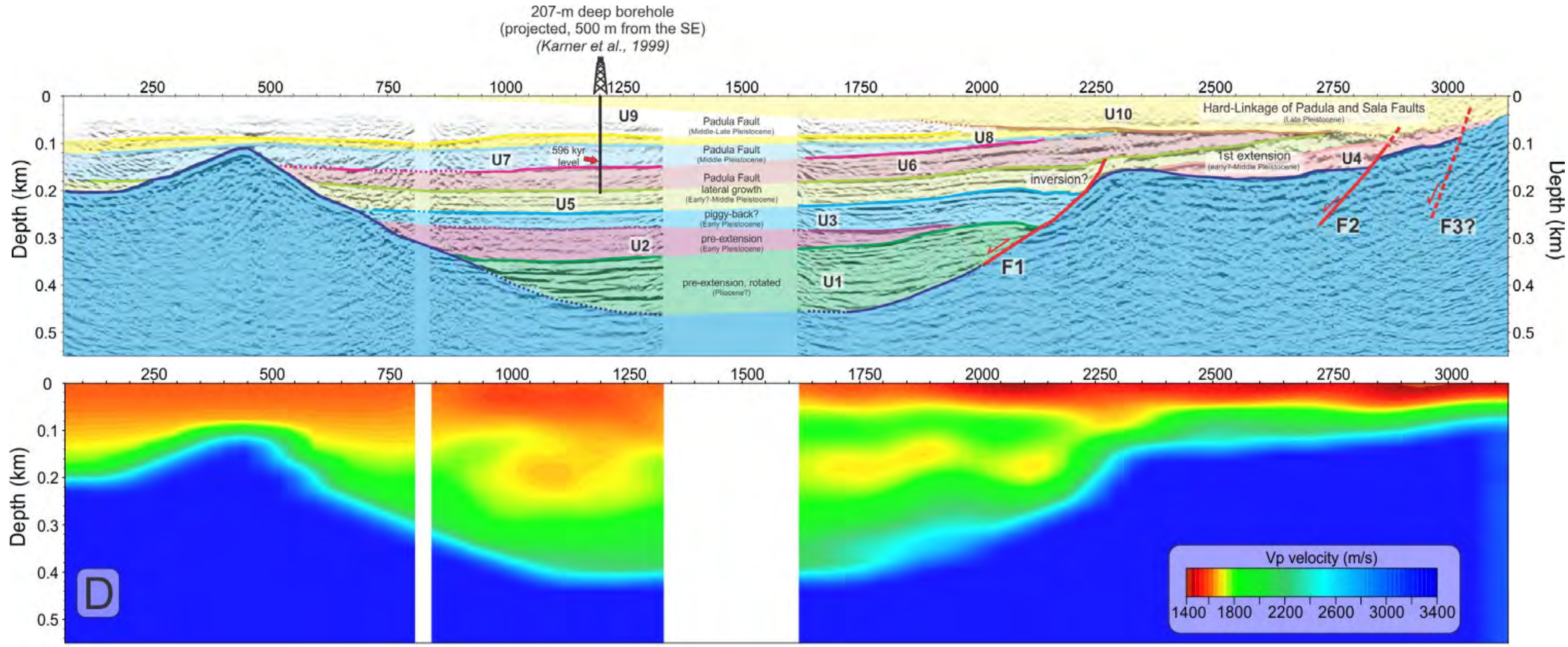
2. identify its bounding normal faults (surface-faulting rupture hazard).

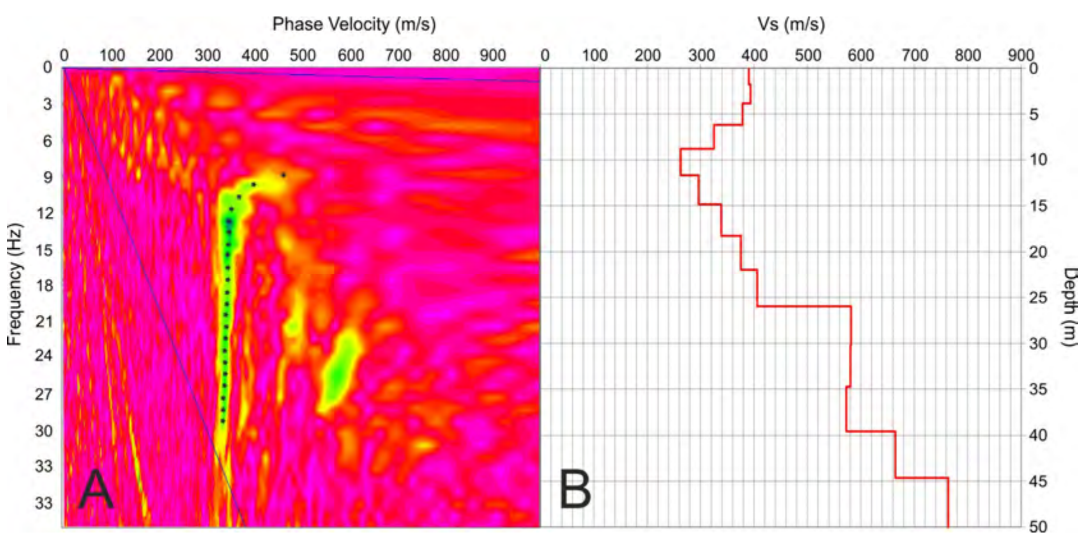


Dense wide aperture arrays allowed to obtain a reliable velocity model in a complex settings which:

1. is functional for PSDM of reflection data,

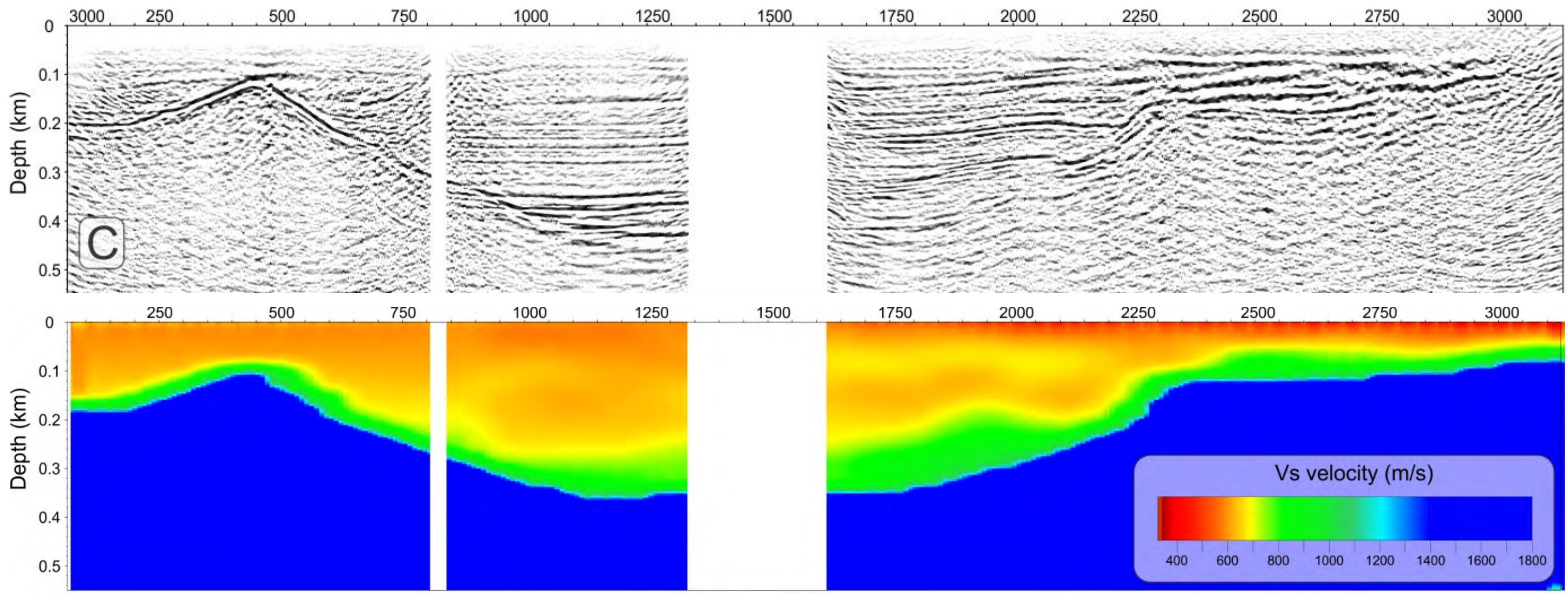
2. provides independent and geologically reliable geometric/velocity constraints for ground motion numerical simulations.





example of dispersion curve (A) and Vs profile (B) obtained by the analysis of the surface wave on Common Shot Gathers

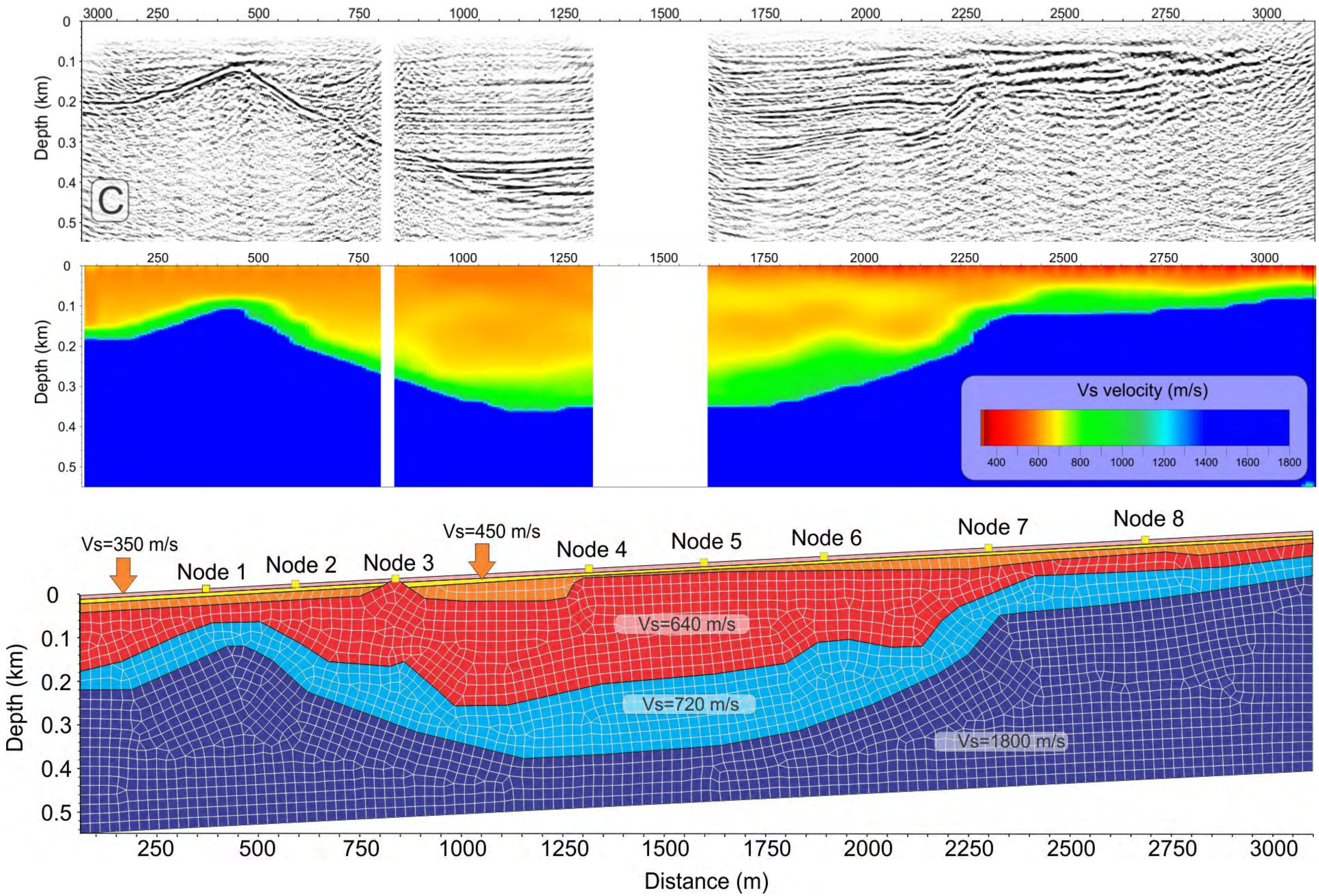
Wide-aperture shot gathers characterized by strong ground roll can be used to estimate Vs profiles along the seismic line from the dispersion curves of Rayleigh waves



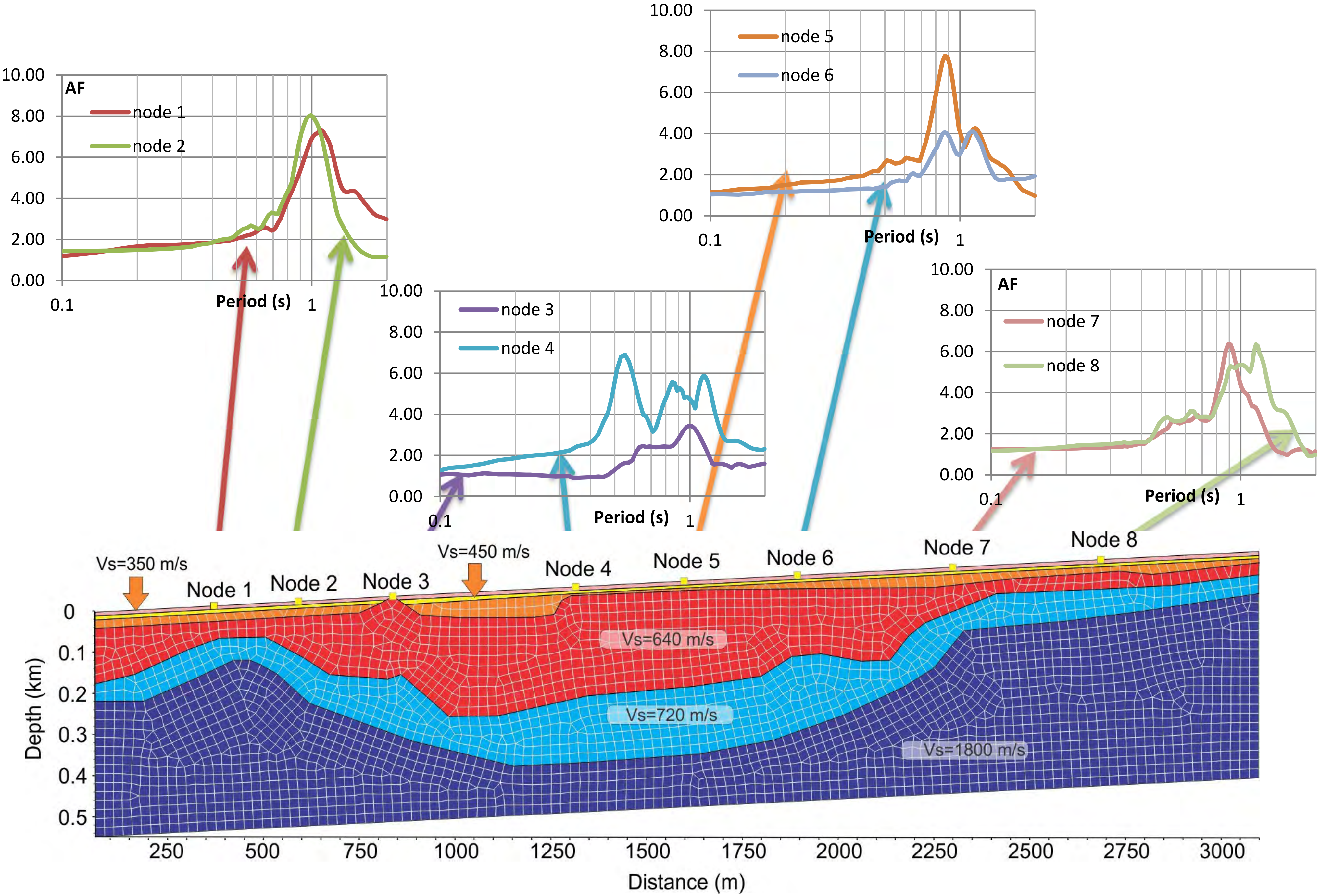
Seismic response of a basin mainly depends on the substratum morphology and on the Vs distribution.

Both can be determined in an elegant and yet cost effective way by integrating seismic reflection and refraction data with surface wave analysis;

all data being recorded simultaneously using a dense wide-aperture acquisition geometry.



Finite element mesh used to simulate ground motion



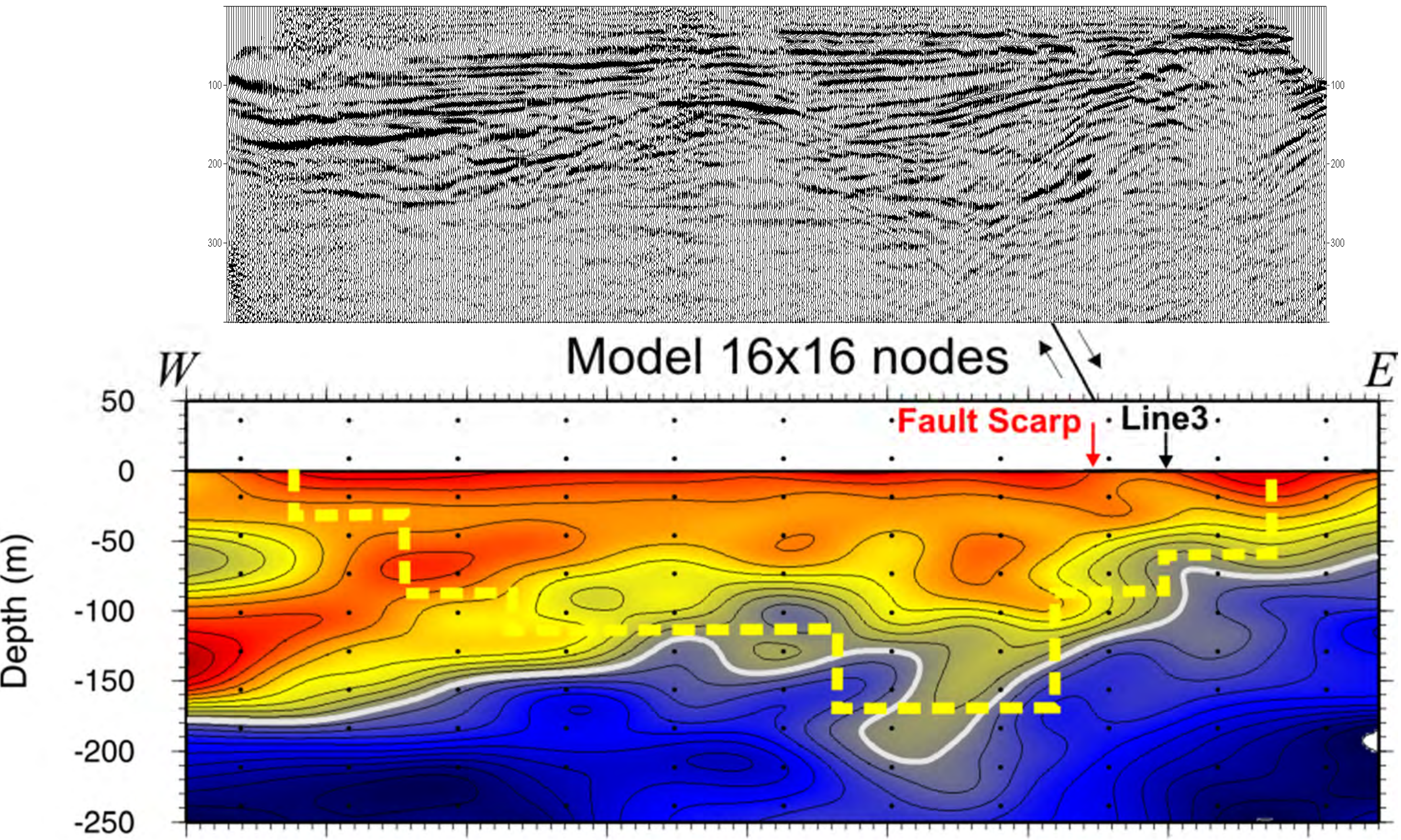
Synthetic seismograms were computed by the finite element code QUAKE/W (Idriss *et al.*, 1994) that is used for equivalent linear dynamic analysis of earth structures subjected to earthquake shaking. The method solves the motion equations at the nodal points of a discrete grid where shear moduli and damping values are defined and it is able to predict the generation of Rayleigh waves in correspondence of strong lateral heterogeneities (e.g. at the basin edges).

HR dense wide aperture seismic profiling can successfully contribute to the definition of many of the factors that concur to build up the seismic hazard in thick intramontane basins.

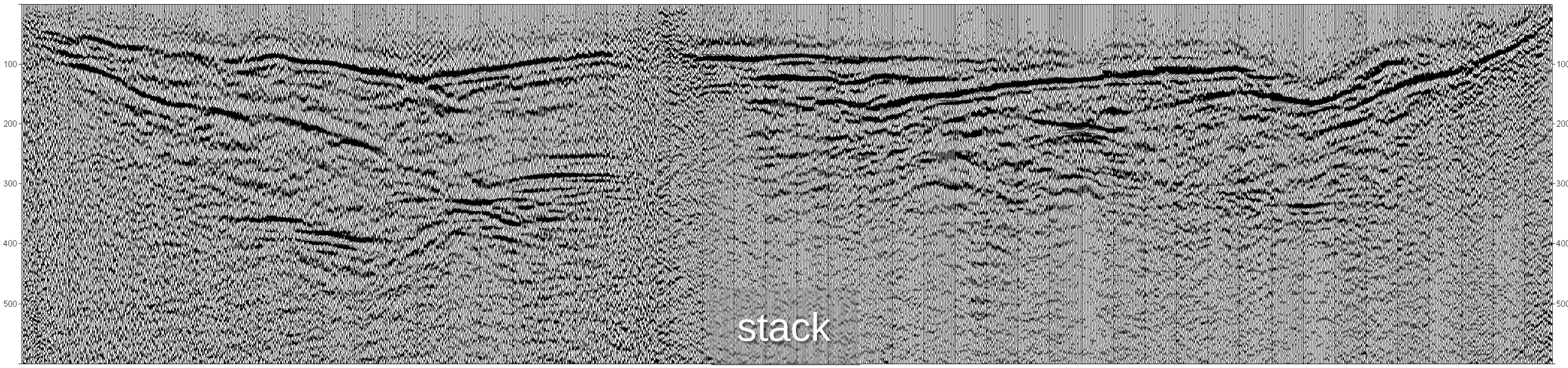
- Dense wide aperture arrays allowed to obtain a reliable velocity model in a complex settings which:
  1. is functional for PSDM of reflection data,
  2. provides independent and geologically reliable geometric/velocity constraints for ground motion numerical simulations.
- seismic reflection images:
  1. outline the articulated morphology of the basin substratum and the Quaternary filling (tectonic evolution & earthquake scenario studies)
  2. identify its bounding normal faults (surface-faulting rupture hazard).

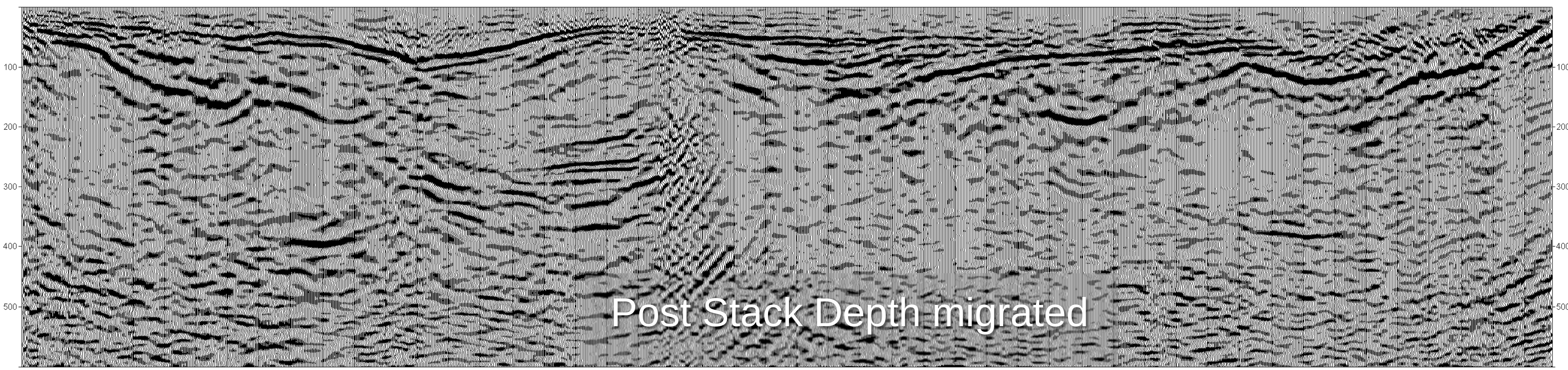
- Seismic response of a basin mainly depends on the substratum morphology and on the Vs distribution. Both can be determined in an elegant and yet cost effective way by integrating seismic reflection and refraction data with surface wave analysis; all data being recorded simultaneously using a dense wide-aperture acquisition geometry.

Example 2: tomograpy vs seismic reflection in a intramontane settings of Southern Apennines with IVI Minivib® source



Example 3: seismic reflection exploration in L'Aquila area with IVI Minivib® source





The Working Group on Utah Earthquake Probabilities (WGUEP): Background, Goals, and Progress

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Seismic Hazards Group, URS Corporation, Oakland, CA

Bill Lund
Utah Geological Survey, Cedar City, UT

Patricia Thomas and Susan Olig
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Walter Arabasz, James Pechmann, and Robert Smith
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Tony Crone, Nico Luco, Steve Personius, and Mark Petersen
U.S. Geological Survey, Denver, CO

David Schwartz
U.S. Geological Survey, Menlo Park, CA

UQFPWG Meeting
Salt Lake City, UT
15 February 2012

URS

Introduction

- The level of information on past earthquakes along the Wasatch fault, along with regional seismicity and geodetic data, is now sufficiently robust to provide the basis for making probabilistic estimates of future large earthquakes within the Wasatch Front.
- The methodologies necessary to estimate probabilities have been developed and refined by the various California Working Groups, and their experience can now be applied to Utah.

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Introduction (cont.)

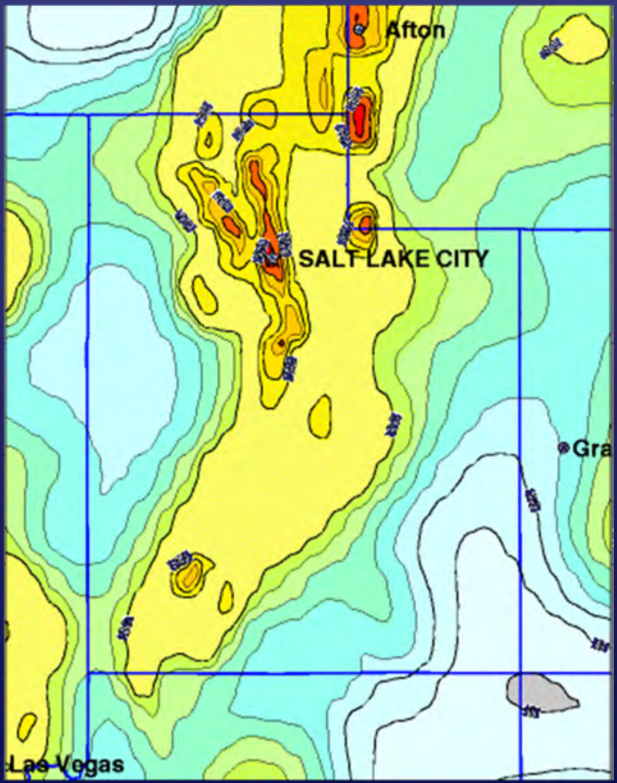
- An earthquake forecast can be can be directly incorporated into site-specific probabilistic seismic hazard analyses (PSHA) for the design and safety evaluation of critical structures and facilities.

URS

Introduction (cont.)

- Wasatch Front urban hazard maps are planned by the U.S. Geological Survey (USGS), and time-dependent probabilities can also be incorporated into the PSHAs that will form the bases of those maps.

- Earthquake probabilities will also eventually be incorporated into the USGS National Hazard Maps and possibly the National Earthquake Hazard Reduction Program (NEHRP) building code provisions.



Background

- Previous estimates of Wasatch Front earthquake probabilities have been made by individual authors using the limited data available at the time. The results of these investigations had little impact on public policy.

- Conversely, the California Working Group probability estimates have found a broad audience, and have been used to heighten public earthquake awareness, as a basis for retrofitting lifeline infrastructure, for adopting unreinforced masonry retrofit ordinances, and for setting earthquake insurance rates.

Objective

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

URS

WGUEP

- A Working Group on Utah Earthquake Probabilities has been formed to develop an earthquake forecast for the Wasatch Front.
- The analyses will include both time-dependent and time-independent probabilities for the Wasatch fault and other faults in the Wasatch Front region.
- Funded by U.S. Geological Survey and Utah Geological Survey.

URS

WGUEP Members

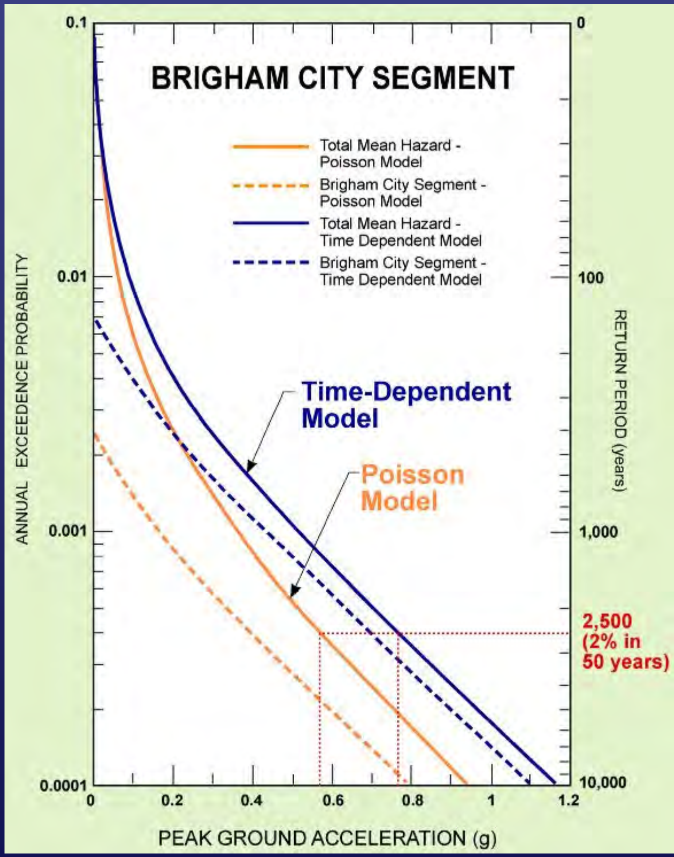
Walter Arabasz, UUSS
Tony Crone, USGS
Chris DuRoss, UGS
Mike Hylland, UGS
Nico Luco, USGS
Bill Lund, UGS (Coordinator)
Susan Olig, URS
Jim Pechmann, UUSS
Steve Personius, USGS
Mark Petersen, USGS
David Schwartz, USGS
Bob Smith, UU
Patricia Thomas, URS
Ivan Wong, URS (Chair)

Assistance from Steve Bowman (UGS)

Time-Independent Versus Time-Dependent Models

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

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



Scope of Work

- Calculate time-dependent probabilities of large earthquakes on major faults where the "requisite" information is available on the expected mean frequency of earthquakes and the elapsed time since the most recent large earthquake.
- Where such information is lacking on less well-studied faults, time-independent probabilities are estimated.
- Epistemic uncertainties in all input parameters are being explicitly addressed by the WGUEP.

URS

Products

- The WGUEP is calculating the probabilities of both moderate and large earthquakes in the Wasatch Front region for a range of intervals varying from annually to 100 years.
- The earthquake probabilities being estimated are:
  - Segment-specific time-dependent and time-independent probabilities of the characteristic earthquakes on the five central segments of the Wasatch fault zone.
  - Time-dependent and time-independent probabilities for the whole Wasatch fault zone for **M** 6.5 and greater and **M** 7.0 and greater events.
  - Segment-specific and fault-specific time-dependent and time-independent probabilities for the Oquirrh Mountains-Great Salt Lake fault zone.

URS

Products

- Time-independent probabilities for each of the other faults in the Wasatch Front.
- Time-dependent and time-independent probabilities for the Wasatch Front for range of magnitudes starting at **M** $\geq$ 5.0.
- Time-independent probability for background earthquakes in the Wasatch Front for range of magnitudes starting at **M** $\geq$ 5.0.
- Maps of time-dependent probabilities for Wasatch Front.

➤ The final forecast will undergo a formal internal USGS review, and will be sent to the National Earthquake Prediction Council for review and comment as well.

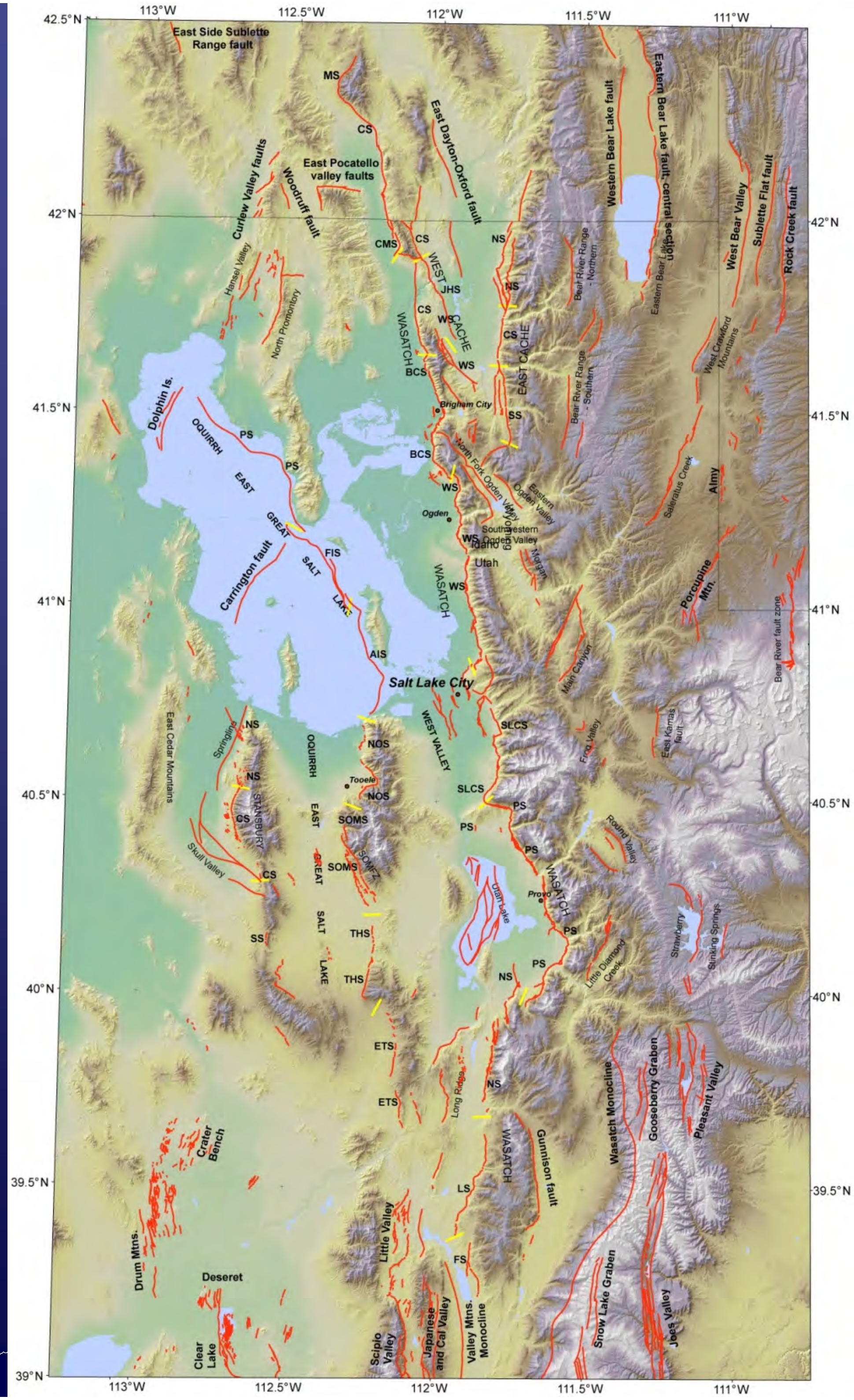
URS

Products (cont.)

- Media release of the WGUEP results will be handled by the UGS. Project results will be presented at meetings for the general public and at professional and scientific society meetings.

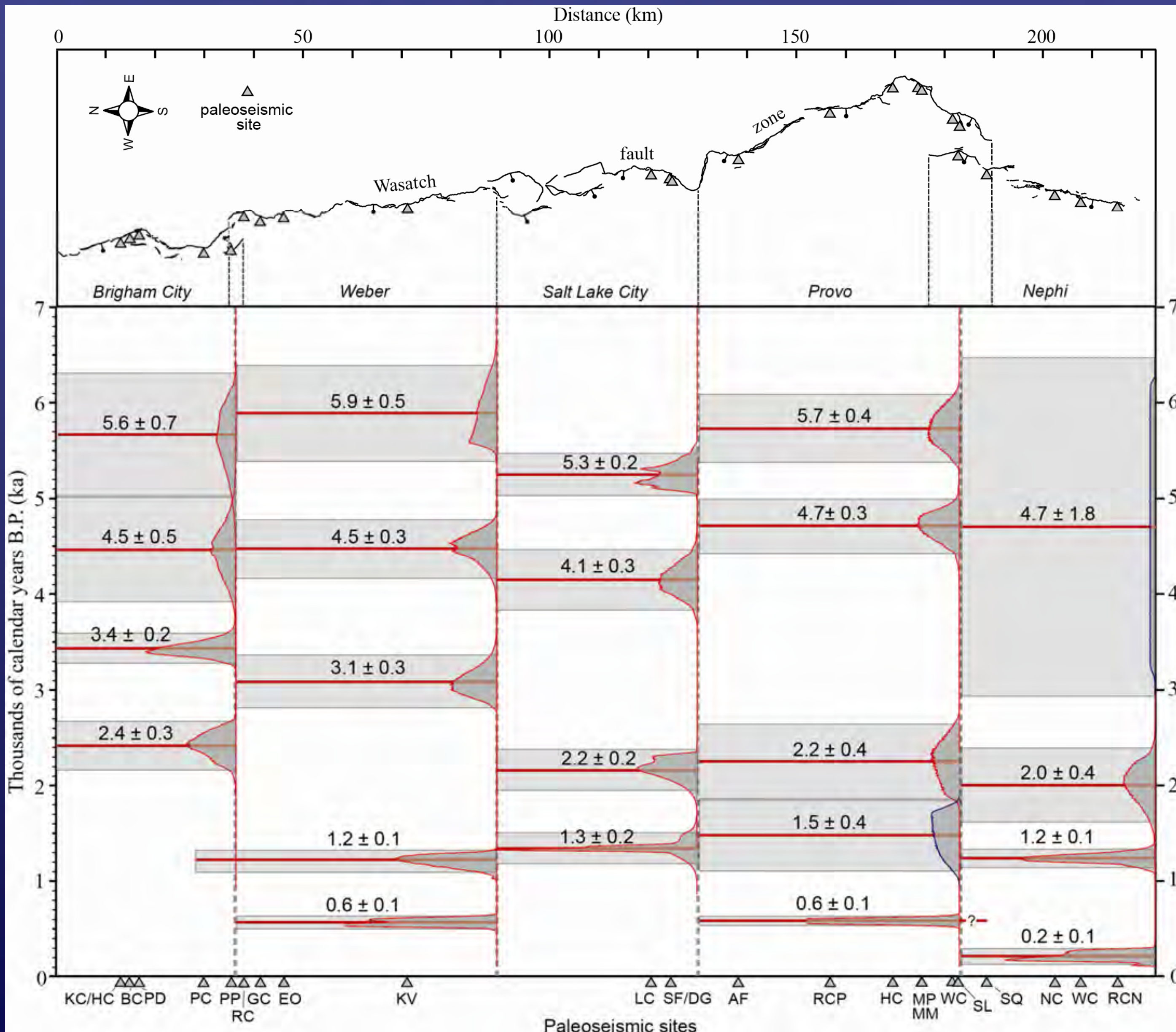
URS

Wasatch Front



URS

Paleoearthquake Space-Time Diagram for the Central Wasatch Fault



URS

Progress to Date

- Finalized earthquake chronology for central segments of the Wasatch fault using Oxcal analysis.
- Selected single and multiple-segment rupture scenarios for Wasatch fault central segments.
- Finalized chronology and rupture scenarios for Great Salt Lake fault.
- Finalized slip rates for end segments of Wasatch fault and other faults in Wasatch Front.
- Characterized coseismic rupture of Salt Lake City segment and West Valley fault.

Next Steps

- Finalize historical catalog and treat if for magnitude bias and incompleteness.
- Compute background earthquake recurrence.
- Finalize time-dependent probabilities for central segments of the Wasatch fault and Great Salt Lake fault and time-independent probabilities for all other faults.
- Constrain geologic horizontal slip rates across Wasatch Front using geodetic rates.
- Produce final report, review by external agencies, and release results in early 2013.

BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP II

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

BACKGROUND

The Basin and Range Province Earthquake Working Group II (BRPEWGII) was convened to consider eight Basin and Range Province (BRP) seismic-hazard issues (four seismologic and four geologic) important to the U.S. Geological Survey's (USGS) 2013 update of the National Seismic Hazard Maps (NSHMs). The eight seismic-hazard issues were formulated by the staff of the USGS National Seismic Hazard Mapping Program (NSHMP). BRPEWGII was jointly convened by the Western States Seismic Policy Council (WSSPC), the USGS, and the Utah Geological Survey (UGS).

BRPEWGII follows BRPEWGI, which was convened in 2006 in response to WSSPC Policy Recommendation 04-5, which advocated creating a broad-based group of technical experts to evaluate five BRP seismic-hazard issues important to the 2007 update of the NSHMs. Those issues were identified at the Basin and Range Province Seismic Hazard Summit II. WSSPC PR 04-5 was subsequently updated, and is currently WSSPC PR 10-5 *Basin and Range Province Working Group(s)*, which formed the basis for convening BRPEWGII.

BRPEWGII GOALS

- Bring together a group of BRP subject-matter experts to discuss evidence, evaluate issues, and define strategies for resolving the eight BRP seismic-hazard issues identified by the NSHMP as important to the 2013 update of the NSHMs.
- Where possible, establish a consensus recommendations to the USGS for each issues.
- Where necessary, outline research programs to resolve outstanding technical issues that the USGS can use when setting future research priorities.

BRPEWGII MEMBERS

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

Issue discussion leader
***Working Group Coordinator** (preceded by **)*

SEISMIC-HAZARD ISSUES

The eight BRP seismic-hazard issues considered by BRPEWGII were:

Seismology Issues

Issue S1—How should the magnitude-frequency relations for a single BRP fault be characterized? Does existing seismological data help define this relationship?

Issue S2 —How should the "smoothing" of seismicity be handled in the NSHMs? The current NSHMs use a radial smoothing process, but recent precarious rock studies in California and western Nevada suggest that anisotropic smoothing (i.e. along faults) might be more appropriate. If anisotropic smoothing is used, should it be applied universally across the entire BRP?

Issue S3—Does the rate of earthquakes represented on the NSHMs need to match the rate of historical earthquakes? If not, what level of mismatch is acceptable?

Issue S4 —What are the sources and levels of uncertainty in the earthquake magnitudes contained in the seismicity catalogs used for the BRP in the NSHMs?

Geology Issues

Issue G1—How should we calculate M_{max} for BRP faults based on rupture lengths, fault areas, and available displacement data (M_{max} of 7.5 currently is used in the NSHMs and is based on the magnitude of the 1959 Hebgen Lake earthquake)? What is the source or explanation of the discrepancy between M calculated using surface-rupture length versus using the average or maximum displacement (site bias, underestimation of surface rupture length, other?)? How should the discrepancy in the magnitude determined from these two measurements be handled in the NSHMs?

Issue G2—How should antithetic fault pairs be modeled in the NSHMs? For example, what is the relation and seismogenic significance of antithetic fault pairs such as the East and West Cache faults, and strands of the Salt Lake City segment of the Wasatch fault and the West Valley fault zone?

Issue G3—The USGS seeks guidance on how to estimate the uncertainty for the slip rates on BRP normal-slip faults, especially for faults that have little or no slip-rate data. The method used in California to estimate the uncertainty has varied the upper and lower bounds of the slip rate by plus-or-minus 50%. Thus the uncertainty bounds for a fault that has a slip rate of 5 mm/yr would be 7.5 mm/yr and 2.5 mm/yr. Do these bounding values encompass the fifth and ninety-fifth percentiles for this fault?

Issue G4—Based on the recommendations from BRPEWGI (Lund, 2006), the current NSHMs use a dip of 50° ± 10° for normal faults in the BRP. Are the 50° dip value and the ± 10° uncertainty range valid and acceptable to cover the probable range of dips for BRP normal faults?

BRPEWGII PROCESS

- To achieve the BRPEWGII goals, two discussion leaders were identified for each seismic-hazard issue. Their job was to frame the issue succinctly for BRPEWGII as a whole, facilitate discussion during their session, and guide the BRPEWGII to consensus.

- Each issue session lasted approximately two and a half hours, followed by a ninth session to review and finalize the recommendations generated during the meeting.

- The issue session format consisted of one to several short (15-20 minute) presentations, either by discussion leaders or by other subject-matter experts to frame the issue and present available relevant data. The presentations were followed by open discussion to further explore the issue and elicit opinions from the BRPEWGII members, and finally the end of the session was used to formulate consensus recommendations.

BRPEWGII RESULTS

YES
WE HAVE RECOMMENDATIONS

- They run to several pages in excruciating detail, and are currently under review.

- The final consensus document will be submitted to the WSSPC Board of Directors for approval at the National Earthquake Meeting in early April and will be given to the USGS NSHMP immediately thereafter.

- The UGS will subsequently publish the consensus document and make it available to the public. It will also be available on the WSSPC Website.

http://geology.utah.gov/ghp/workgroups/pdf/brpewg/BRPEWGII_Presentations.pdf

AGENDA

BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP II (BRPEWGII) MEETING

November 14-16, 2011

Utah Department of Natural Resources Building (1st Floor Meeting Rooms)

` **DuRoss**) [Room 1050]

Tuesday, November 15

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

Wednesday, November 16

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