UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP

Wednesday, February 15, 2006

WELCOME

UTAH GEOLOGICAL SURVEY

UQFPWG HISTORY

- Expert panel convened to evaluated the paleoseismic-trenching data available for Utah’s Quaternary faults.

- Used experience and best professional judgment to assign preferred consensus recurrence-interval and vertical slip-rate estimates, and “best estimate” confidence limits for faults under review.

- Resulting RI and VSR estimates and associated confidence limits represent the best presently available information regarding the faults/fault sections reviewed.

- Recommended additional paleoseismic study of 20 faults/fault sections to characterize Utah’s earthquake hazard to a minimally acceptable level.

UQFPWG TODAY?

- One of four standing committees created to help set and coordinate the earthquake-hazard research agenda for the State of Utah.

- Reviews ongoing paleoseismic research in Utah.

- Provides advice/insight regarding technical issues related to fault behavior in Utah/BRP.

- Identifies & prioritizes future Utah Quaternary fault studies – NEHRP or otherwise

UQFPWG 2006 ACTIVITIE REVIEW

Presentations of work completed

- Latest Provo segment megatrench dating results
- Collinston & Clarkston Mountain segments paleoseismic reconnaissance
- Nephi segment trenching study
- Northern Weber segment paleoseismic study
- Corner Canyon fault trenching study
  Robert Smith discussion items
- Basin and Range Province Earthquake Working Group update

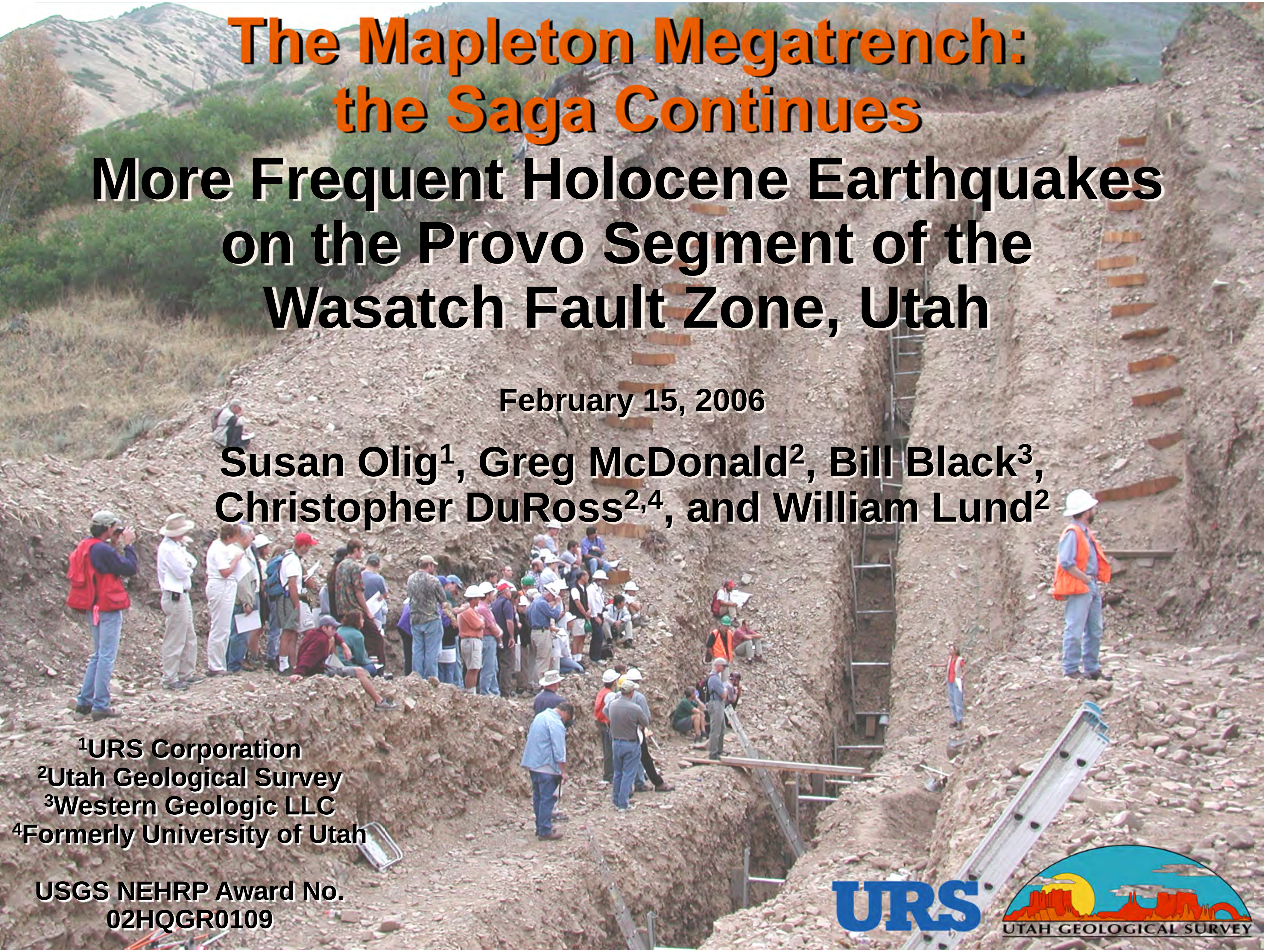
Discussion items

- Updating the UQFPWG consensus slip-rate and recurrence-interval database.
- Wasatch fault multi-segment rupture model.

UQFPWG 2005 PALEOSEISMIC RESEARCH RECOMMENDATIONS

- West Valley fault zone (Salt Lake County)
- Weber segment Wasatch fault zone (Weber & Davis Counties*
- Faults and folds beneath Utah Lake (Utah County)*
- Washington fault (Washington County
- East Cache fault zone (Cache County)
- Classify Utah Quaternary faults as A – D in a manner similar to the USGS Quaternary Fault and Fold Database
- Perform studies to resolve seismogenic vs. non-seismogenic faults

**NEHRP proposals?*



The Mapleton Megatrench: the Saga Continues

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

February 15, 2006

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

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

USGS NEHRP Award No. 02HQGR0109

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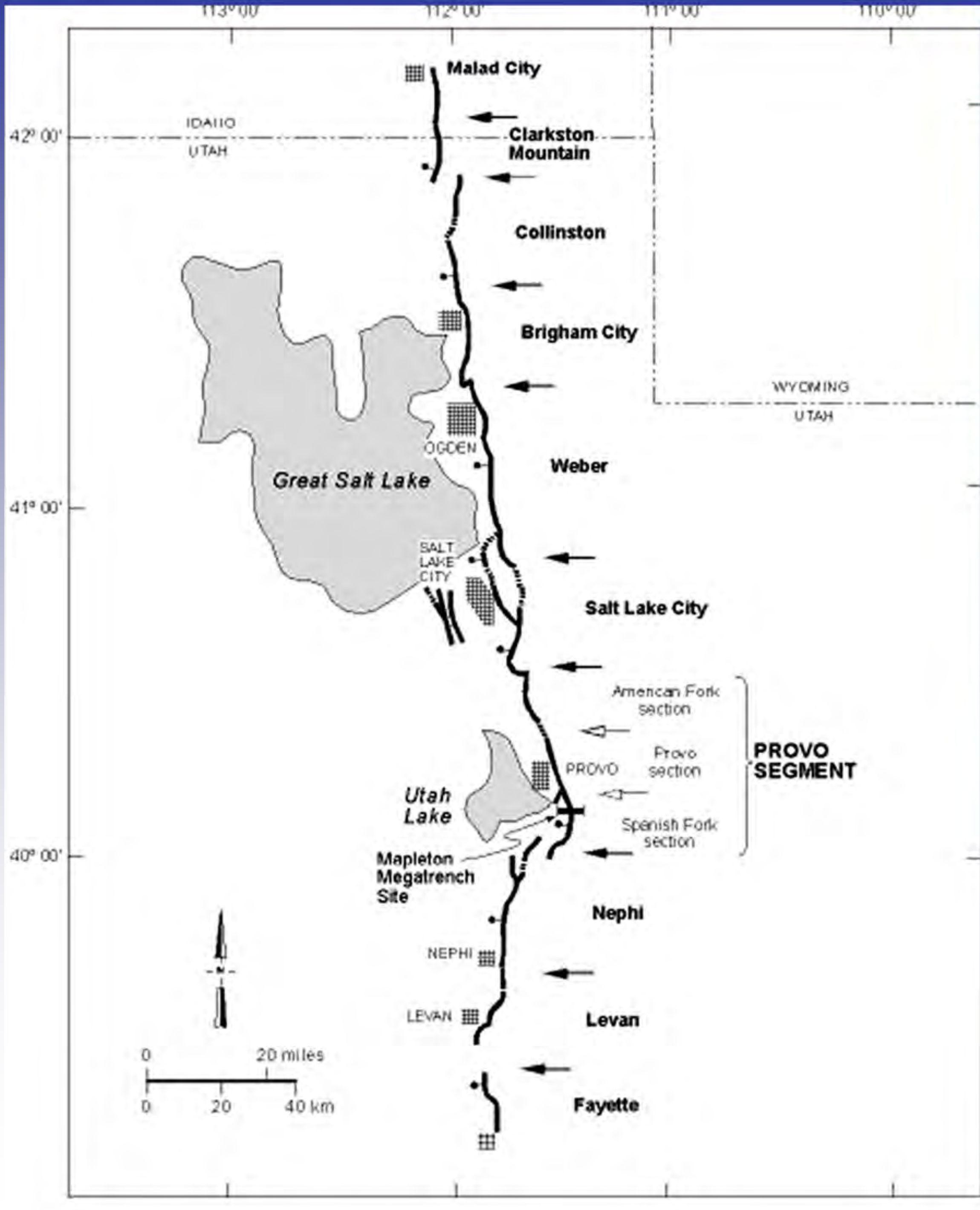
UTAH GEOLOGICAL SURVEY

Wasatch Fault Zone

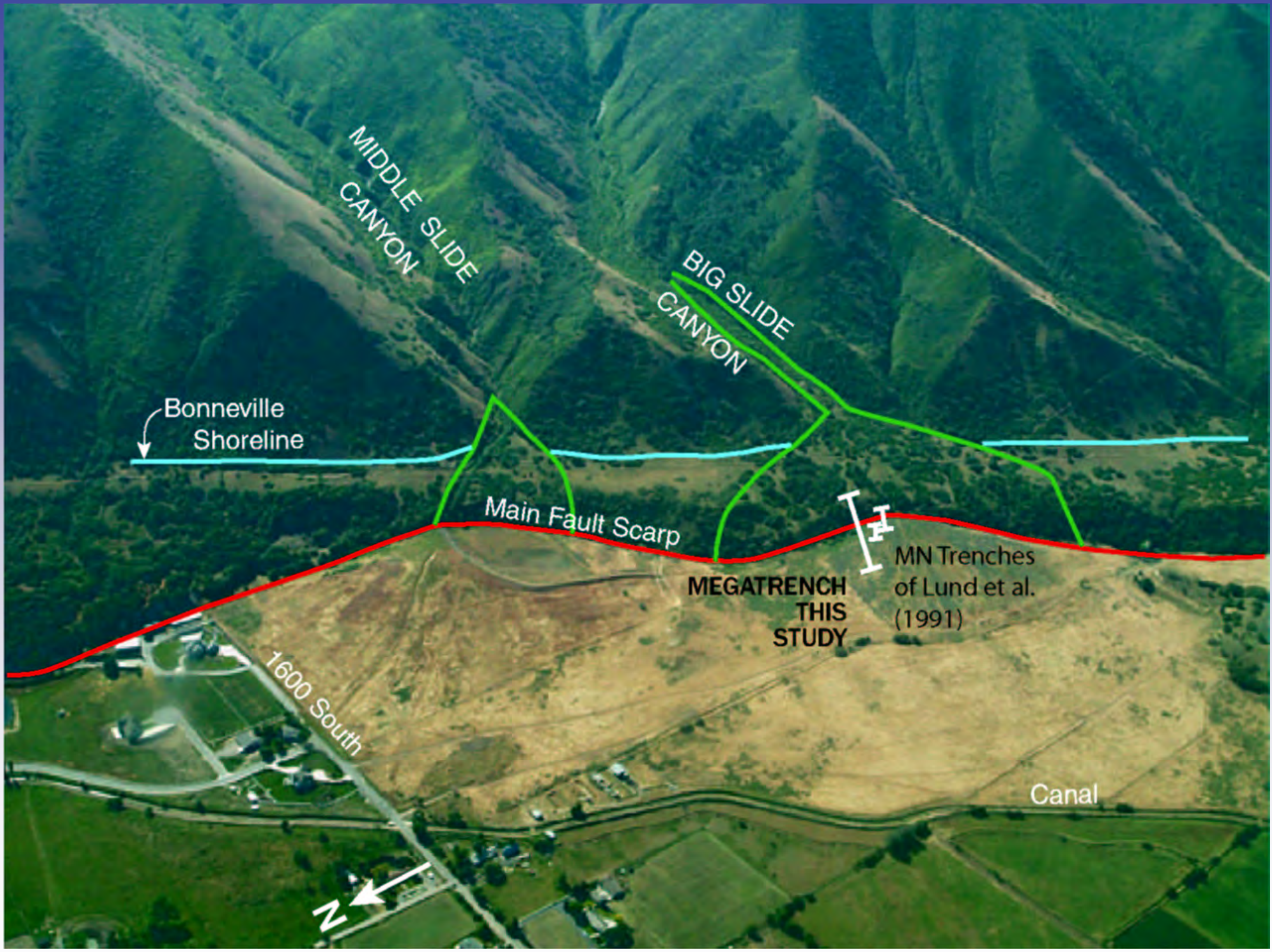


UQFPWG Consensus Recurrence Intervals (years)

Preferred	(5th, 95th)
1300	(500, 2800)
1400	(500, 2400)
1300	(500, 2400)
2400	(1200,3200)
2500	(1200, 4800)

From Lund (2005)

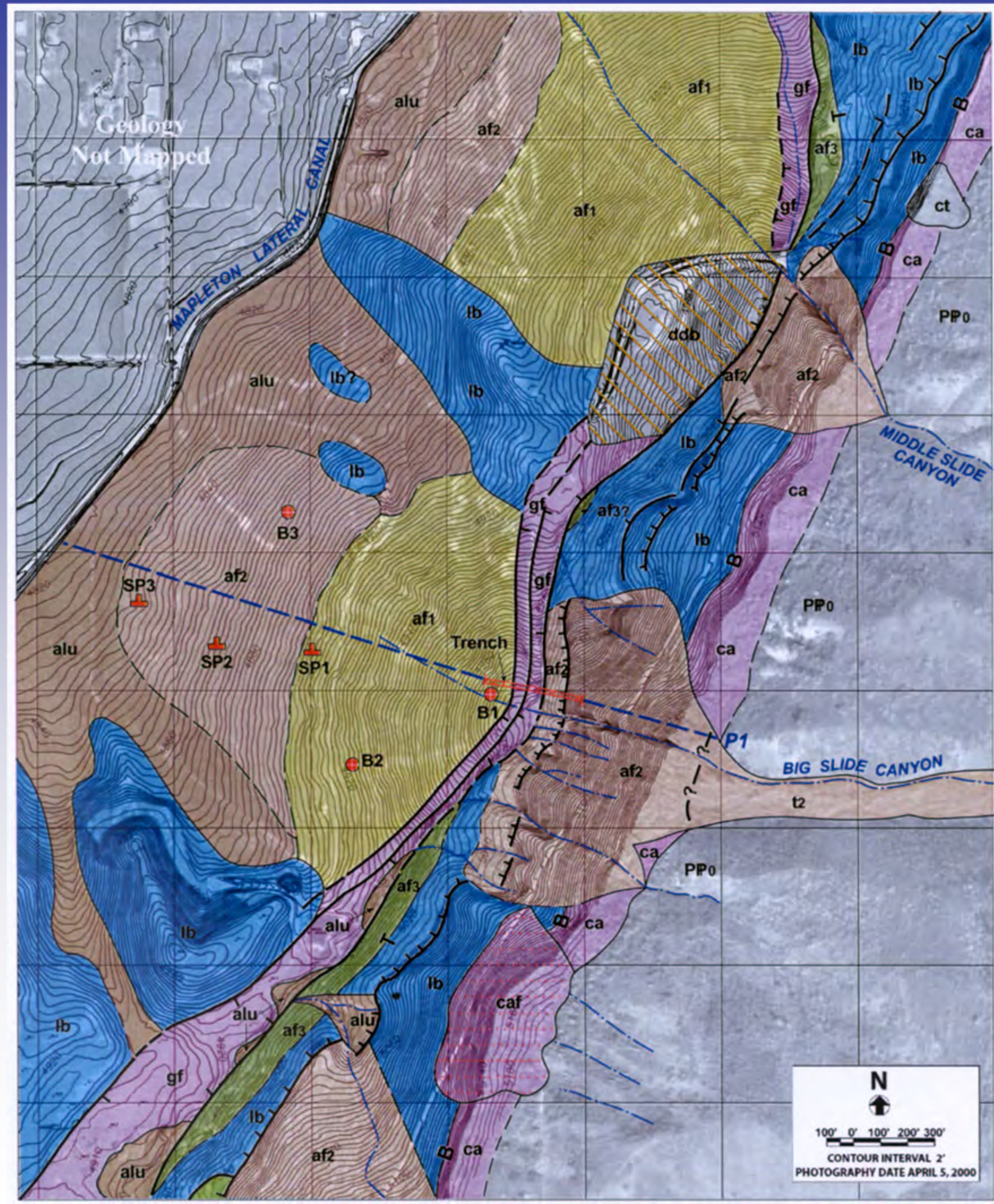
Mapleton Megatrench Site



(Photo from R. Bruhn)

Surficial Geology of the Mapleton Megatrench Site

- **Topographic Profiles (P1)**
- **Boreholes (B1, B2, B3)**
- **Soil Pits (SP1, SP2, SP3)**



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- Evidence for at least 7, possibly as many as 11, separate surface faulting earthquakes
- This talk focuses on events since mid Holocene (~6 ka)

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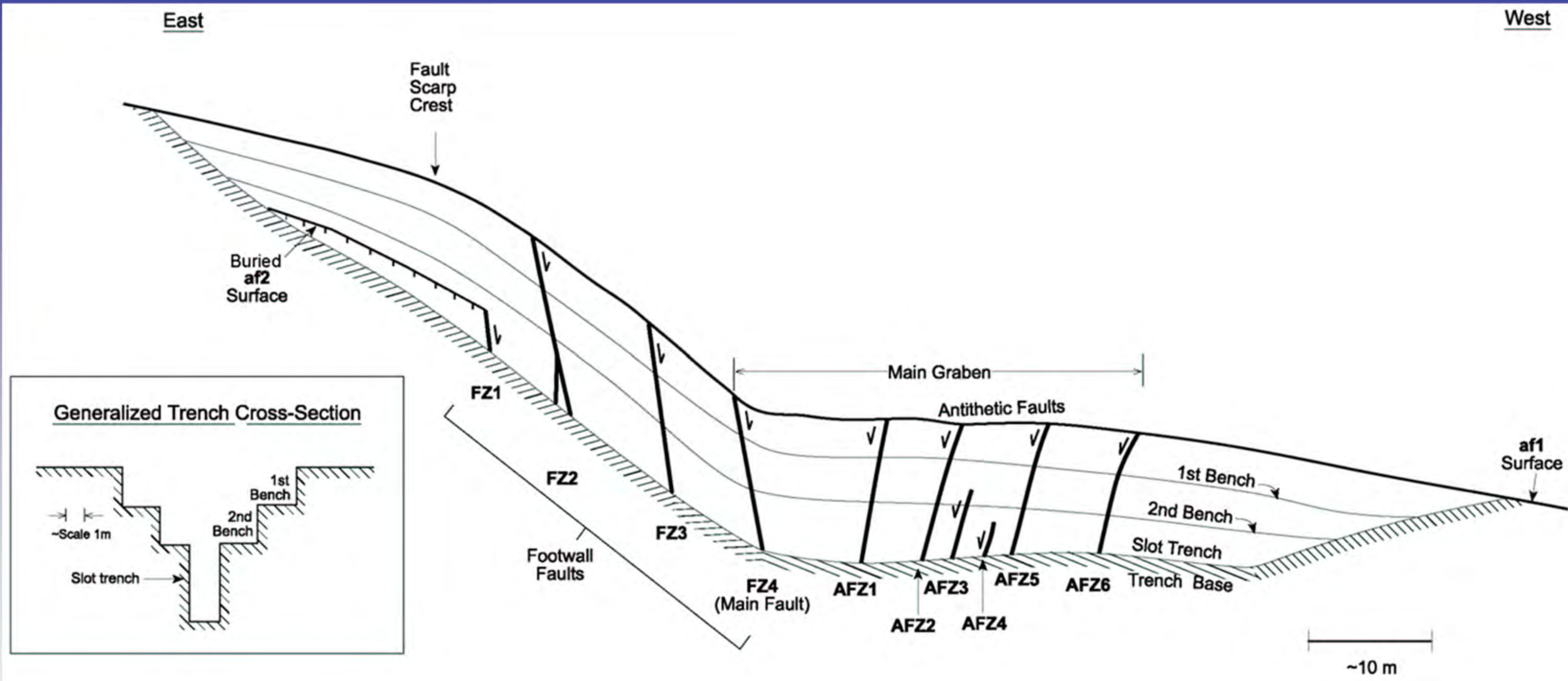
Significant Faults in the Mapleton Megatrench



FOOTWALL:

4 west-dipping fault zones FZ1 through FZ4

HANGING WALL:

6 east-dipping antithetic fault zones AFZ1 through AFZ6

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Hanging Wall Stratigraphy

(Photo from W. Case)

- 35-m-wide graben (from FZ4 to AFZ6)
- Mid to late Holocene debris flows, channel alluvium, and colluvium (7,500 cal BP to historic)
- 27 alluvial fan units (6a through 6za) and 10 fault-scarp colluvium units (FC#Z through FC#V)
- Able to correlate fan stratigraphy across antithetic faults

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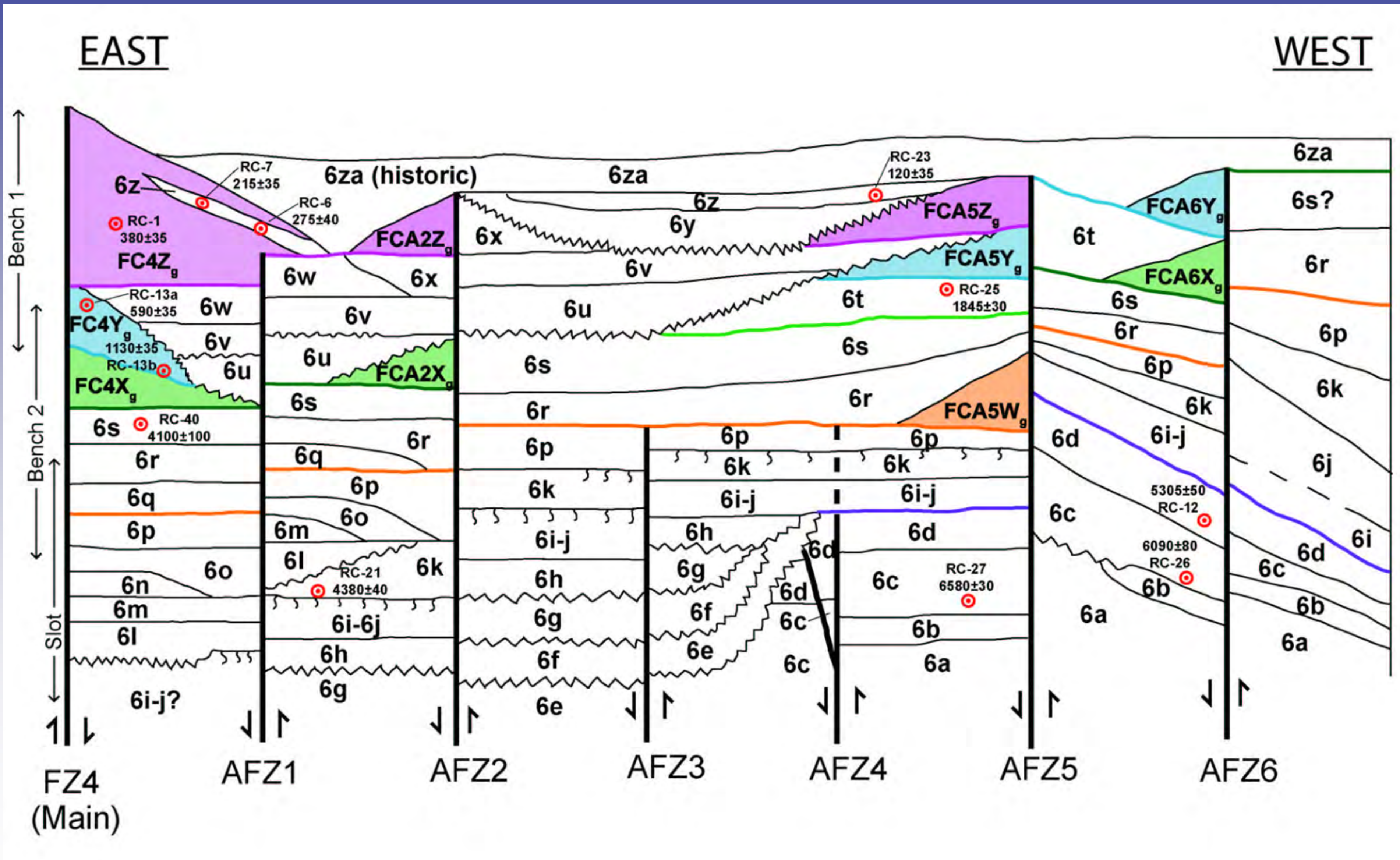
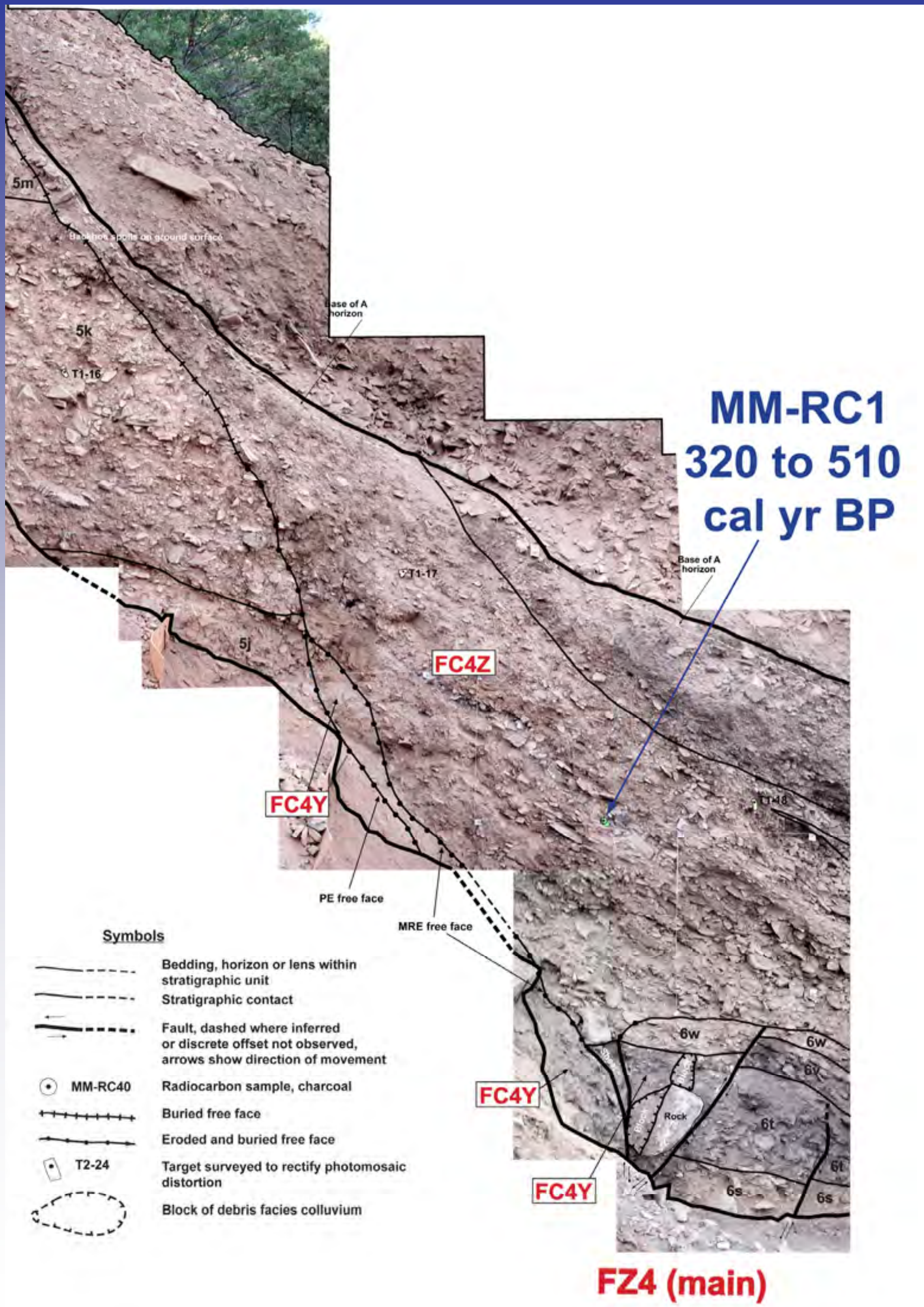
Graben Surface-Faulting Event Horizons
Events Z_g Through V_g (?)



FZ4 Bench 1

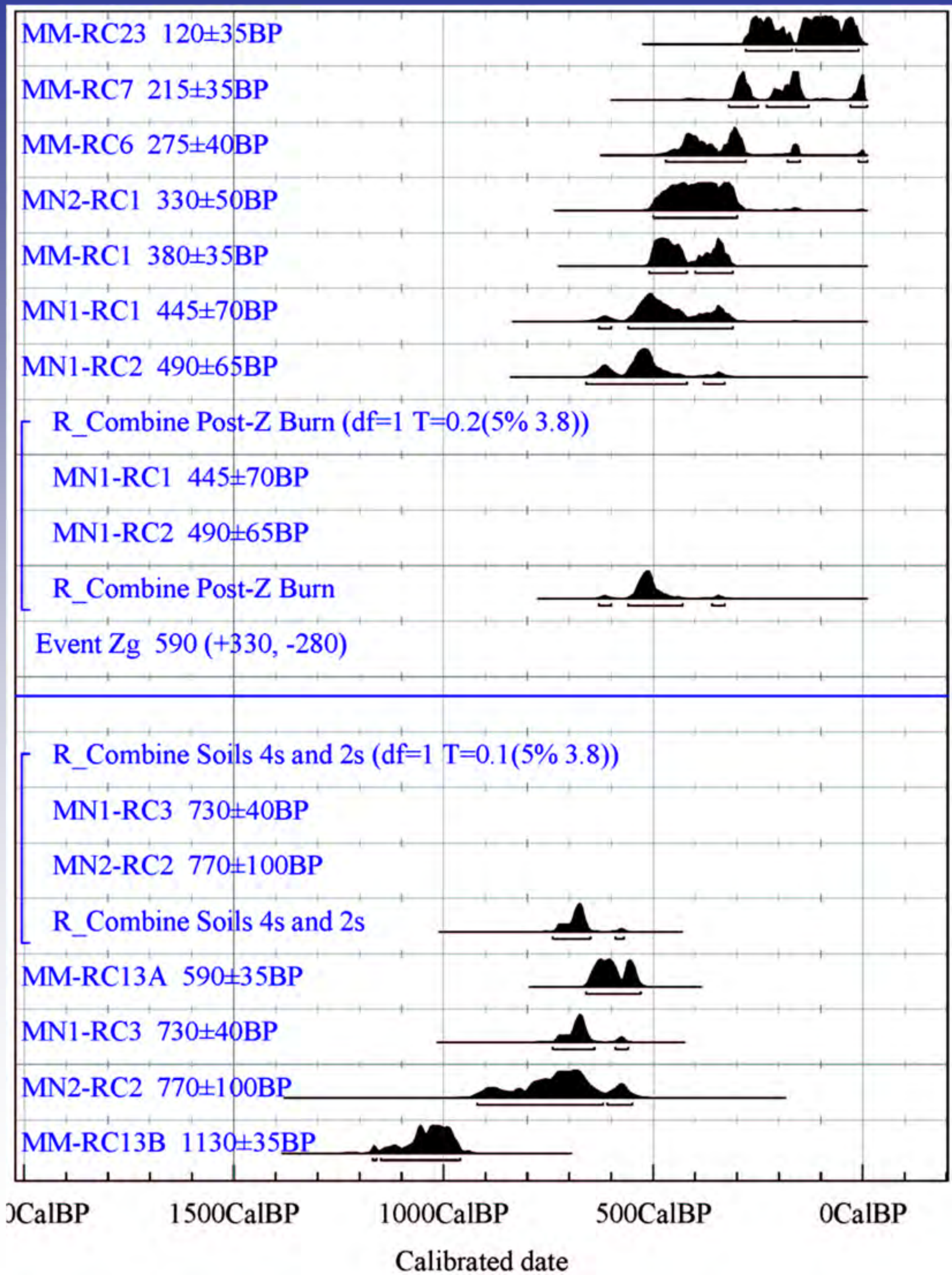


Youngest event (Z_g) created a scarp 8 m high

Event Z_g occurred between 320 and 650 cal BP

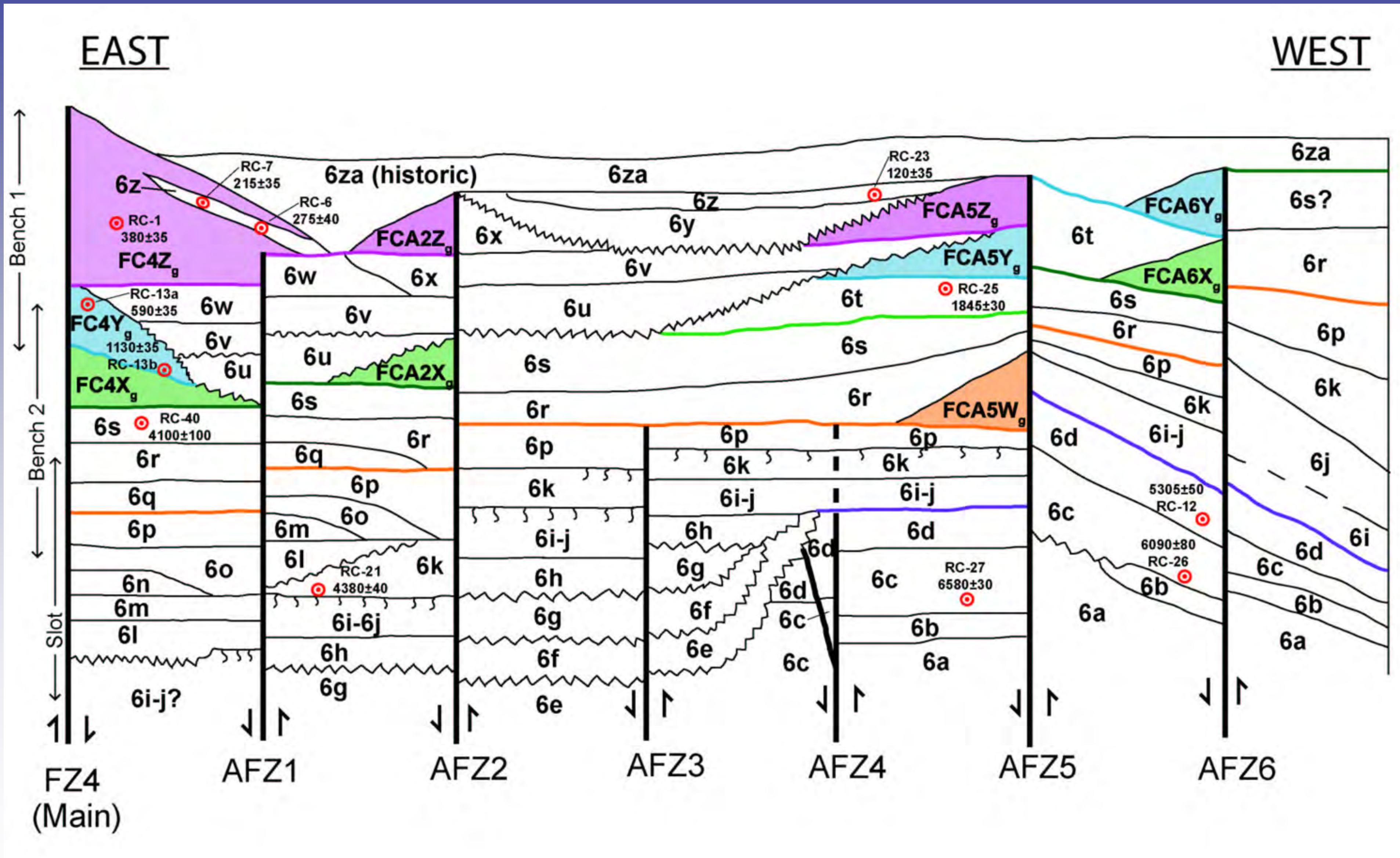
Z_g event correlates to youngest event identified by Lund *et al.* (1991), 600 ± 80 cal BP

Combined Ages for Trenches MM and MN



Event Z_g occurred 600 ± 300 cal BP

Surface-Faulting Event Y_g
Faults FZ4, AFZ1, AFZ5, and AFZ6



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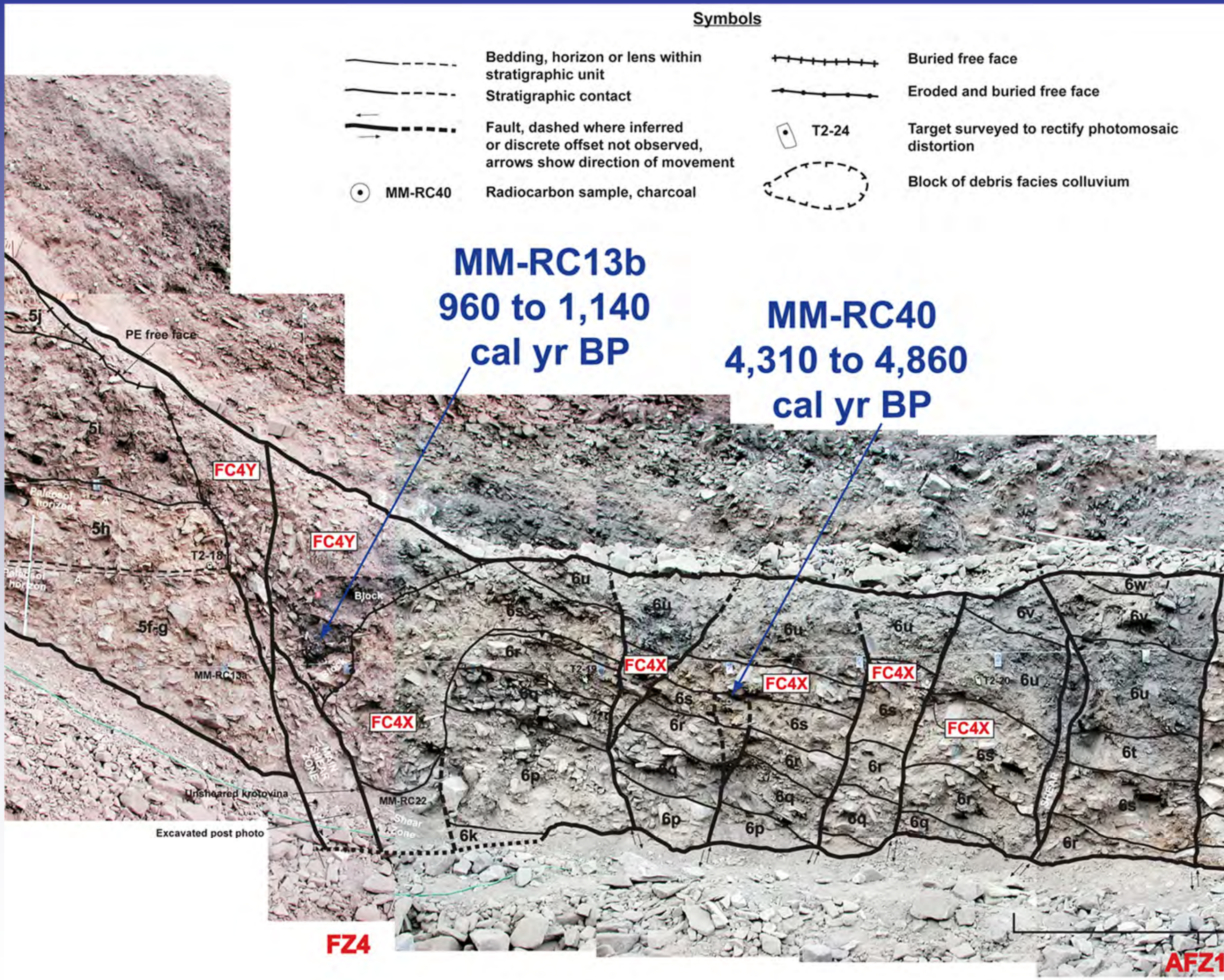
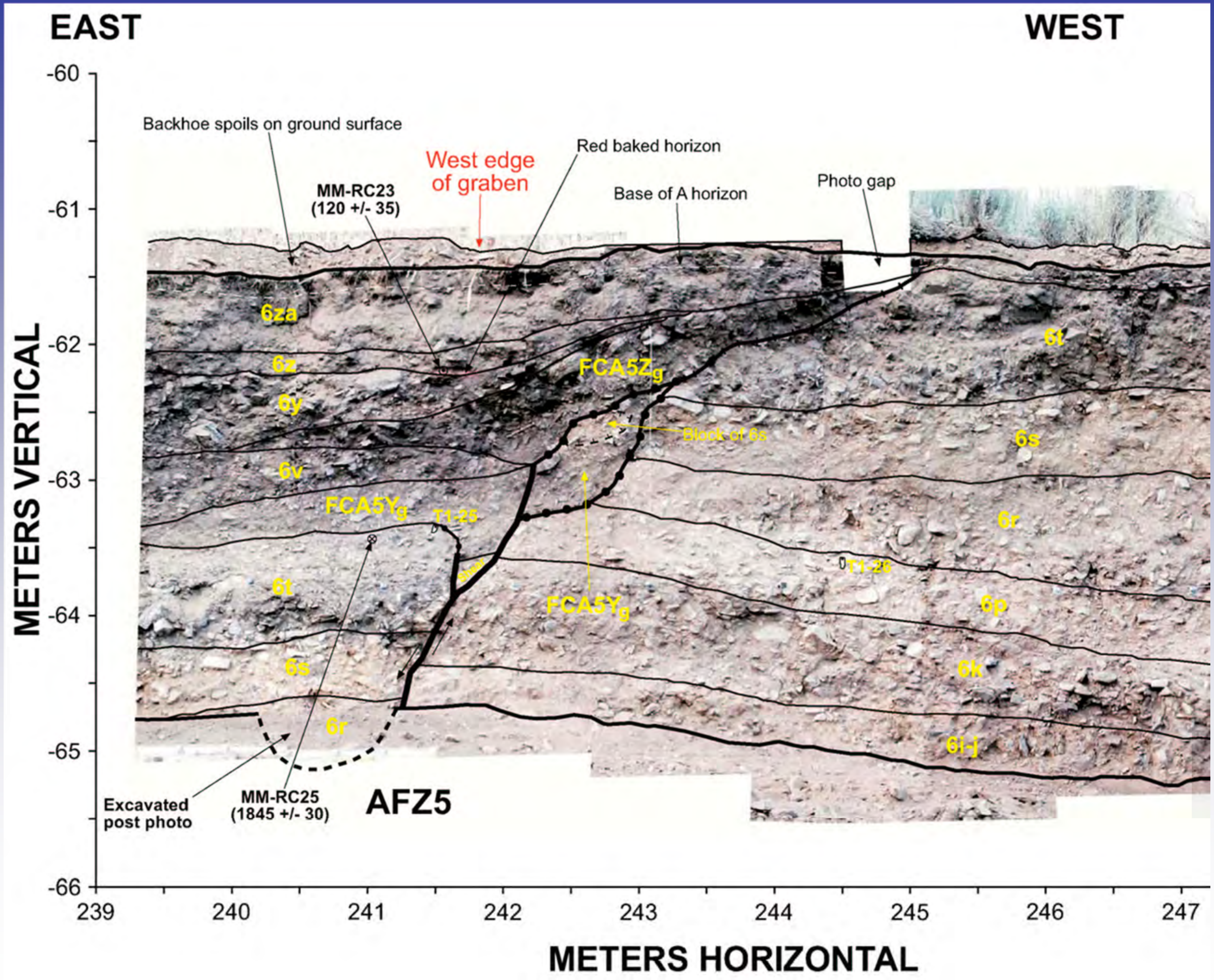
FZ4 Bench 2


Symbols
Bedding, horizon or lens within stratigraphic unit
Stratigraphic contact
Fault, dashed where inferred or discrete offset not observed, arrows show direction of movement
MM-RC40
Radiocarbon sample, charcoal
Buried free face
Eroded and buried free face
T2-24
Target surveyed to rectify photomosaic distortion
Block of debris facies colluvium
MM-RC13b
960 to 1,140
cal yr BP
MM-RC40
4,310 to 4,860
cal yr BP
PE free face
FC4Y
FC4Y
FC4X
FC4X
FC4X
FC4X
FC4X
Block
T2-18
MM-RC13a
MM-RC22
Unsheared krotovina
Excavated post photo
T2-19
T2-20
FZ4
AFZ1

AFZ5 Bench 1



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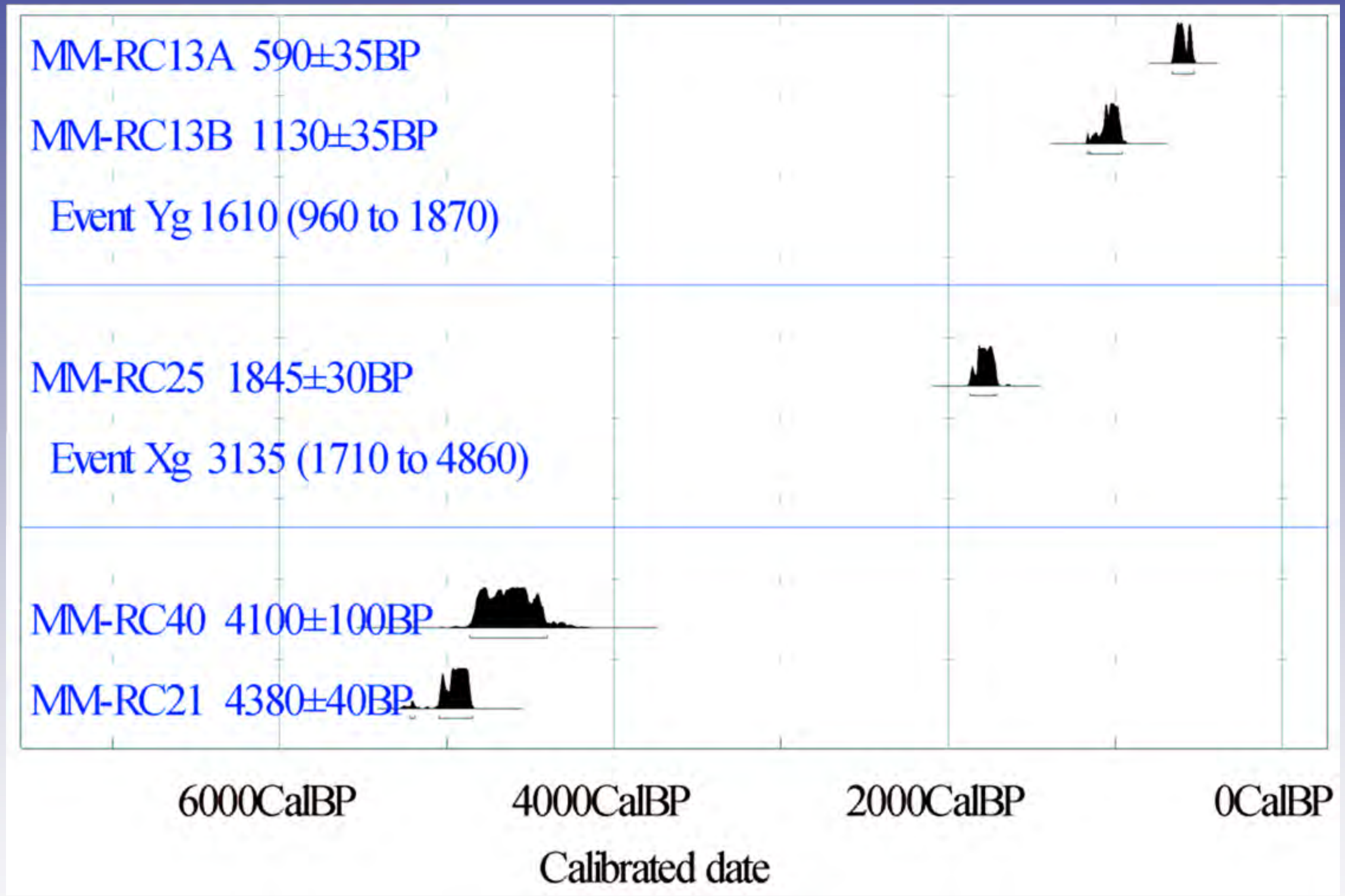
Event Y_g Occurred 1600 (+300, -600) cal BP



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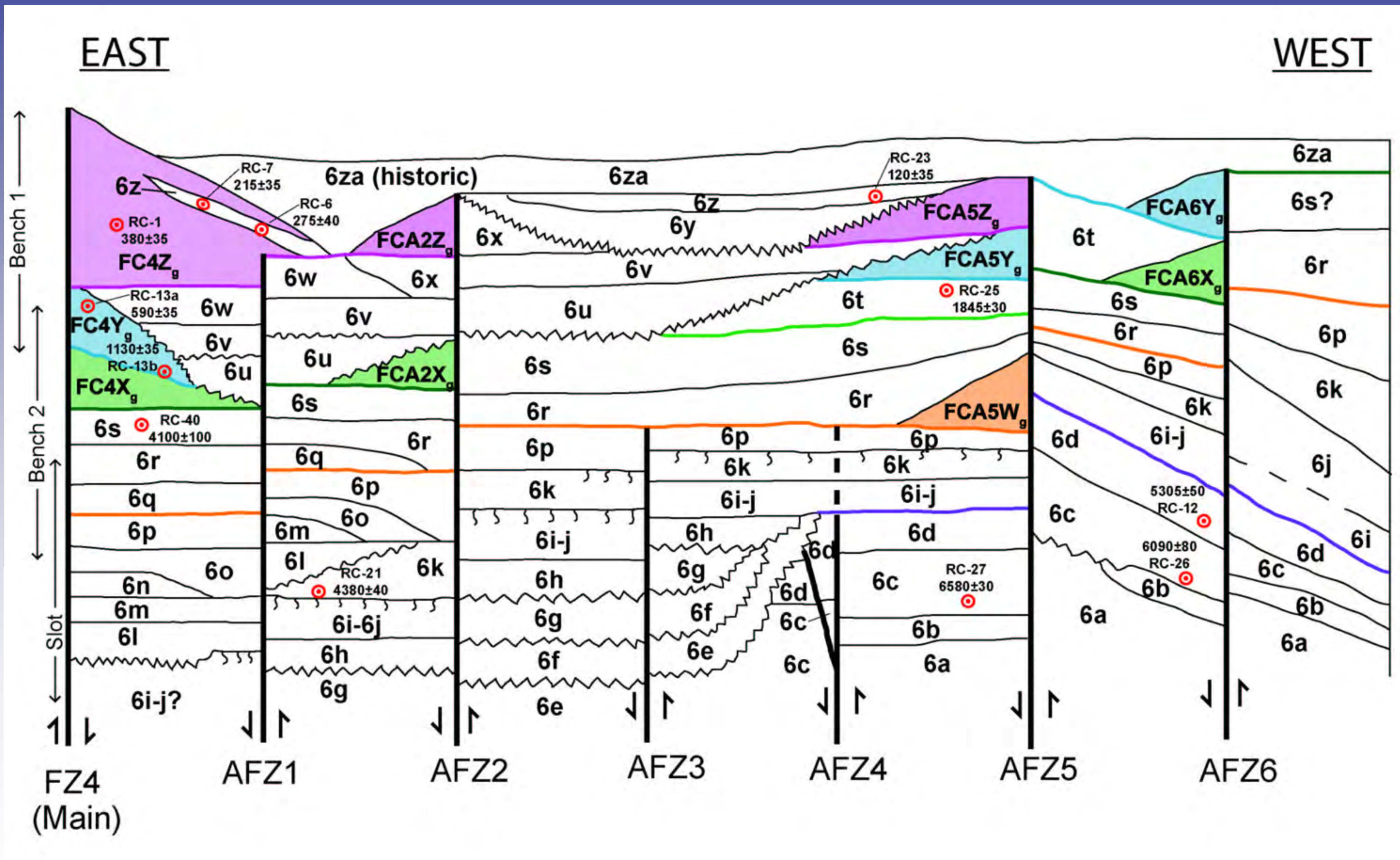
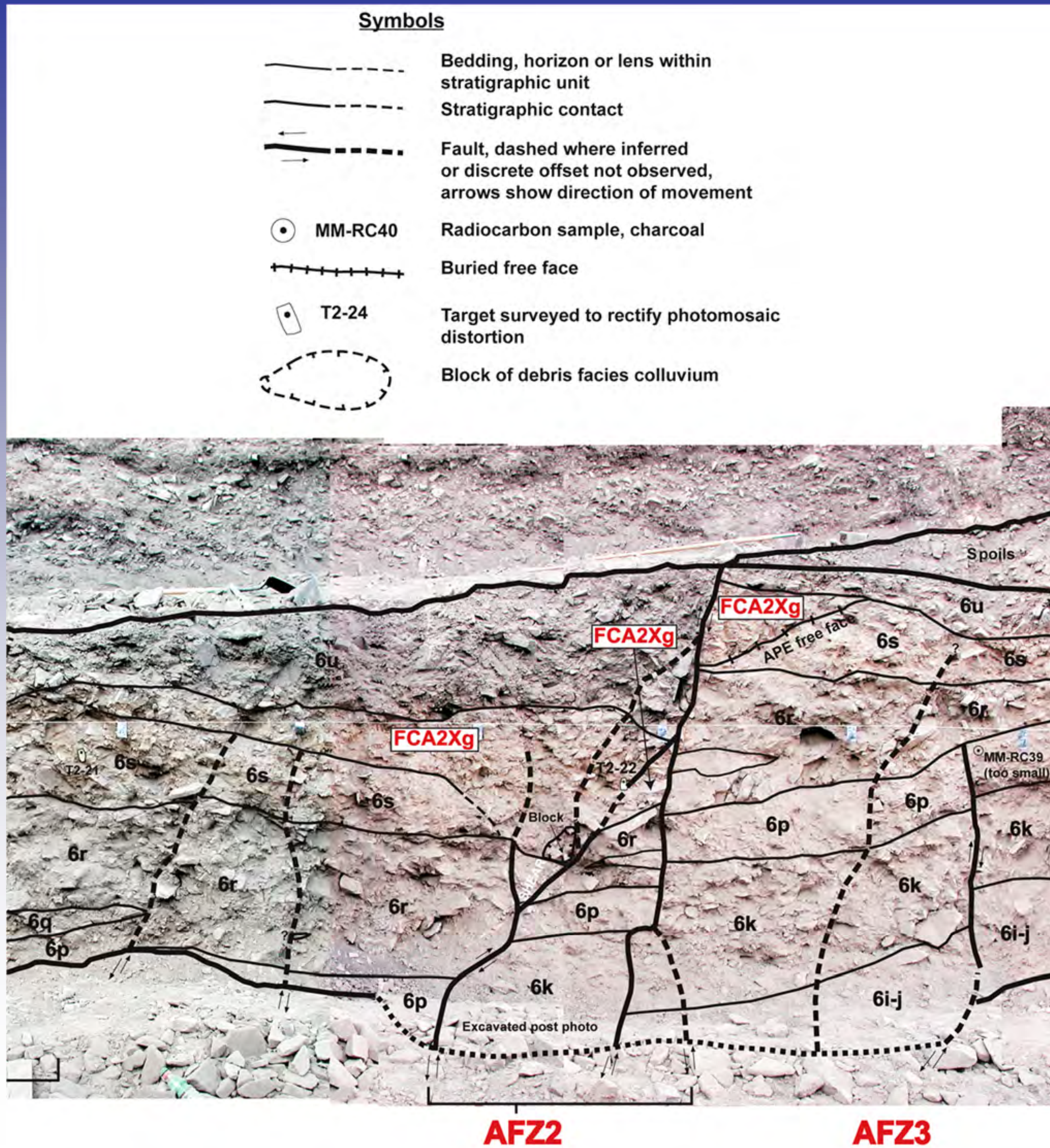
Surface-Faulting Event X_g

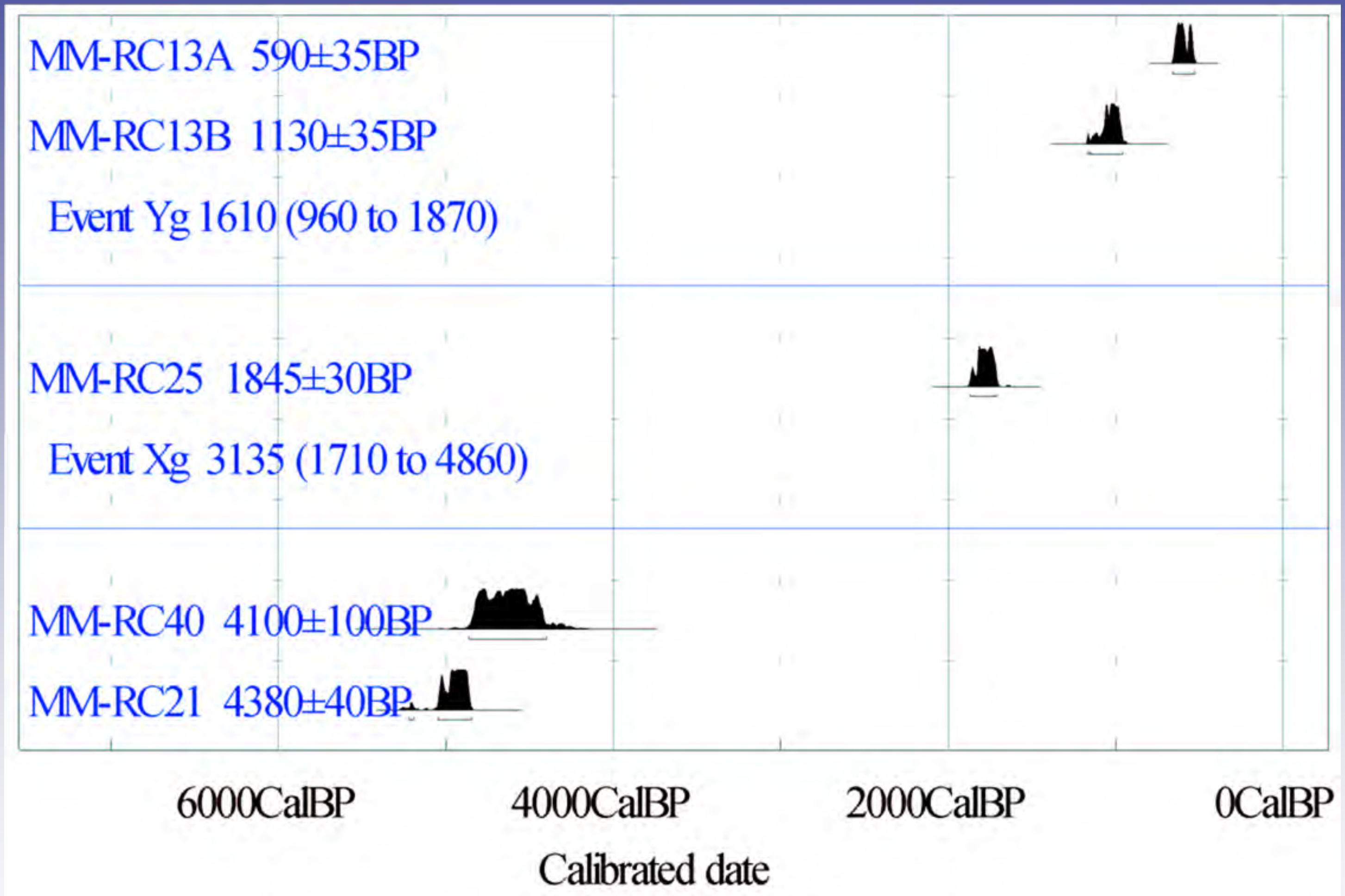
Faults FZ4, AFZ2, and AFZ6



AFZ2 Bench 2


Symbols
Bedding, horizon or lens within stratigraphic unit
Stratigraphic contact
Fault, dashed where inferred or discrete offset not observed, arrows show direction of movement
MM-RC40
Radiocarbon sample, charcoal
Buried free face
T2-24
Target surveyed to rectify photomosaic distortion
Block of debris facies colluvium
Spoils
FCA2Xg
FCA2Xg
FCA2Xg
6u
6u
APE free face
6s
6s
6r
6r
MM-RC39 (too small)
T2-21
6s
6s
6s
T2-22
Block
6p
6p
6k
6r
6r
6r
6r
6k
6p
6k
6q
6p
6k
6i-j
6p
6k
6i-j
Excavated post photo
AFZ2
AFZ3

Event X_g Occurred 3100 (+1900, -1400) cal BP



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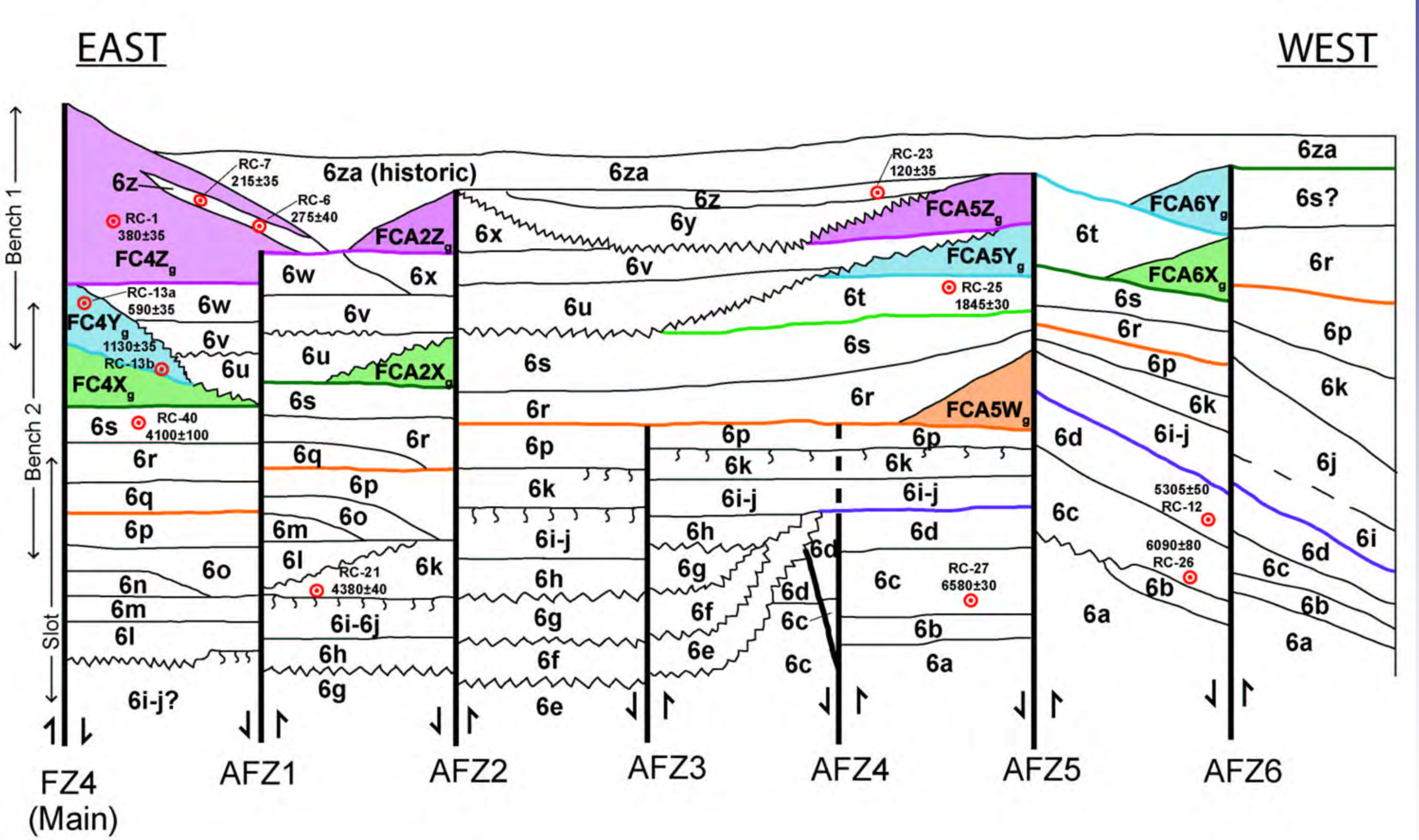
Surface-Faulting Event W_g

Faults AFZ3, AFZ5, FZ2, and/or FZ3 (?) (probably not FZ4)



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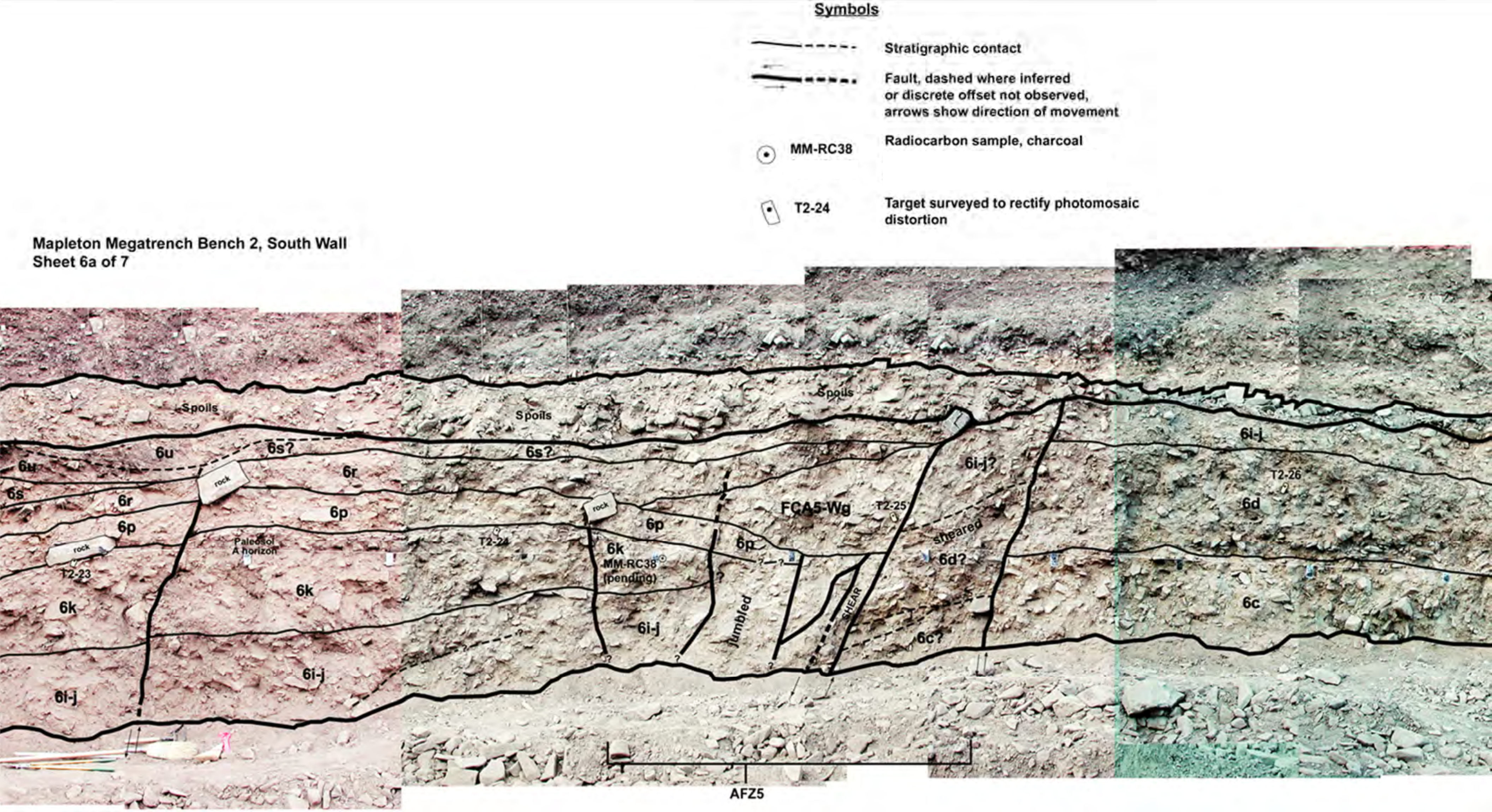
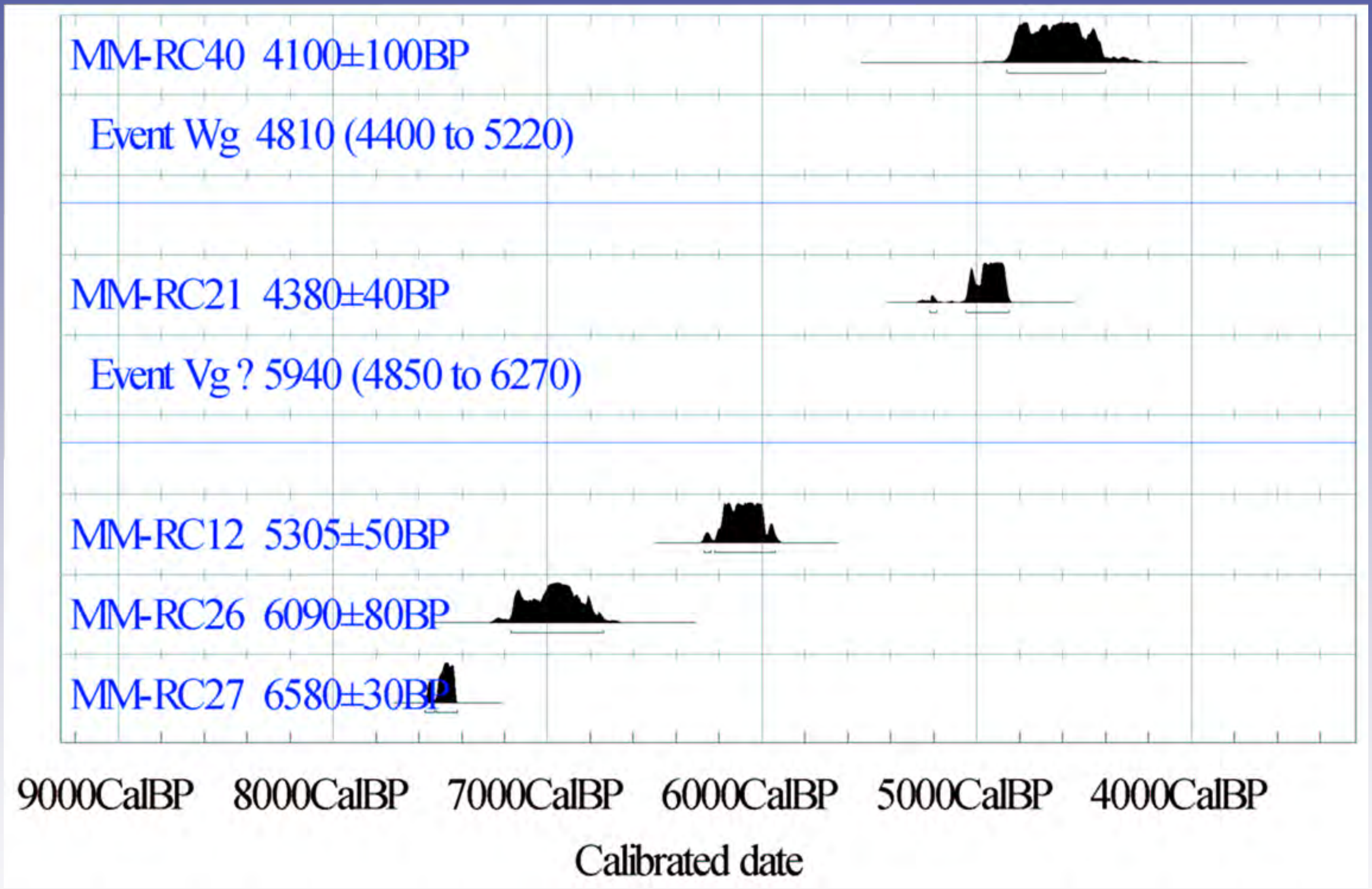
Faulting Event W_g on AFZ5 – Bench 2



Event W_g Occurred 4800 (± 400) cal BP



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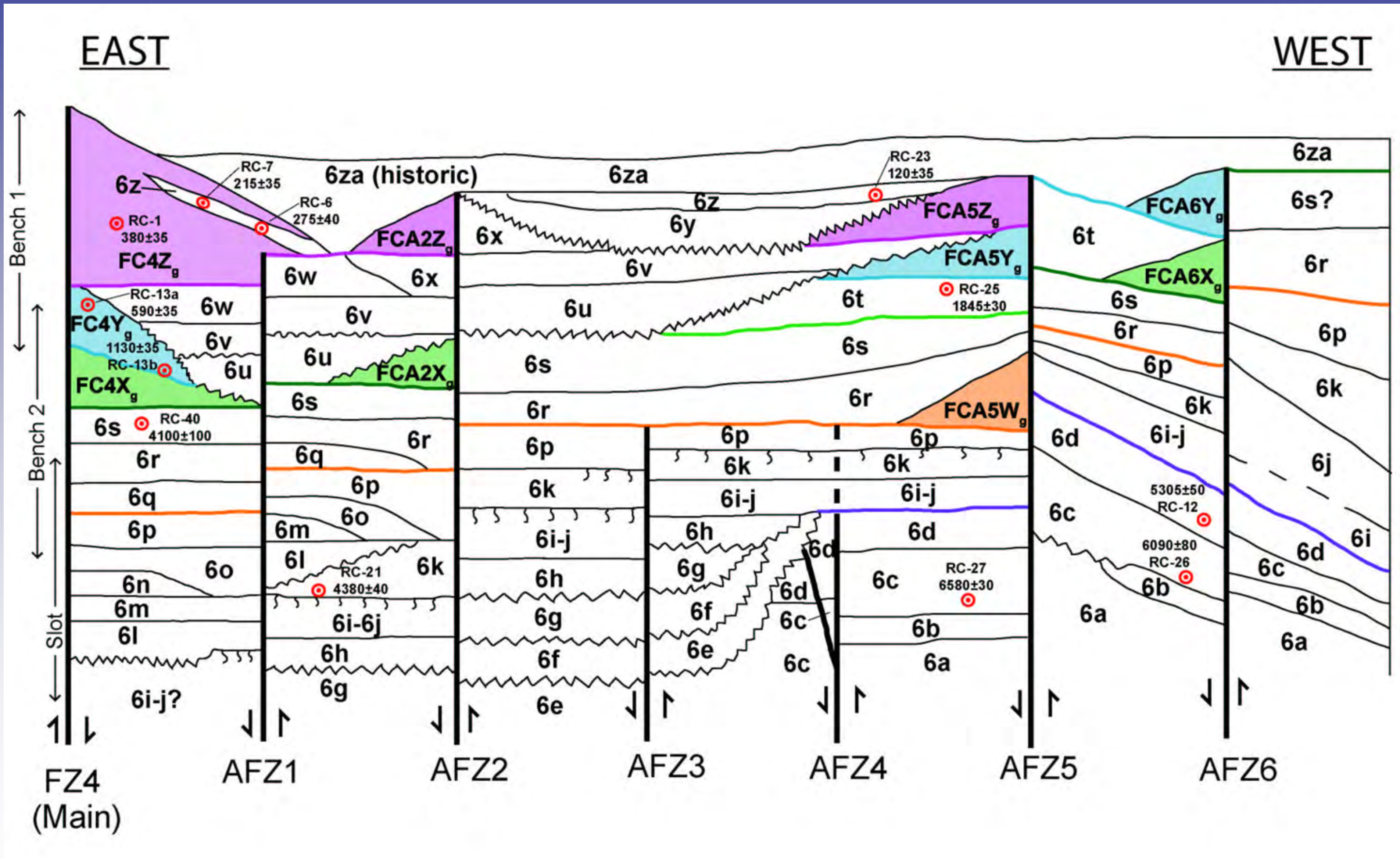
Surface-Faulting Event V_g
Fault AFZ4



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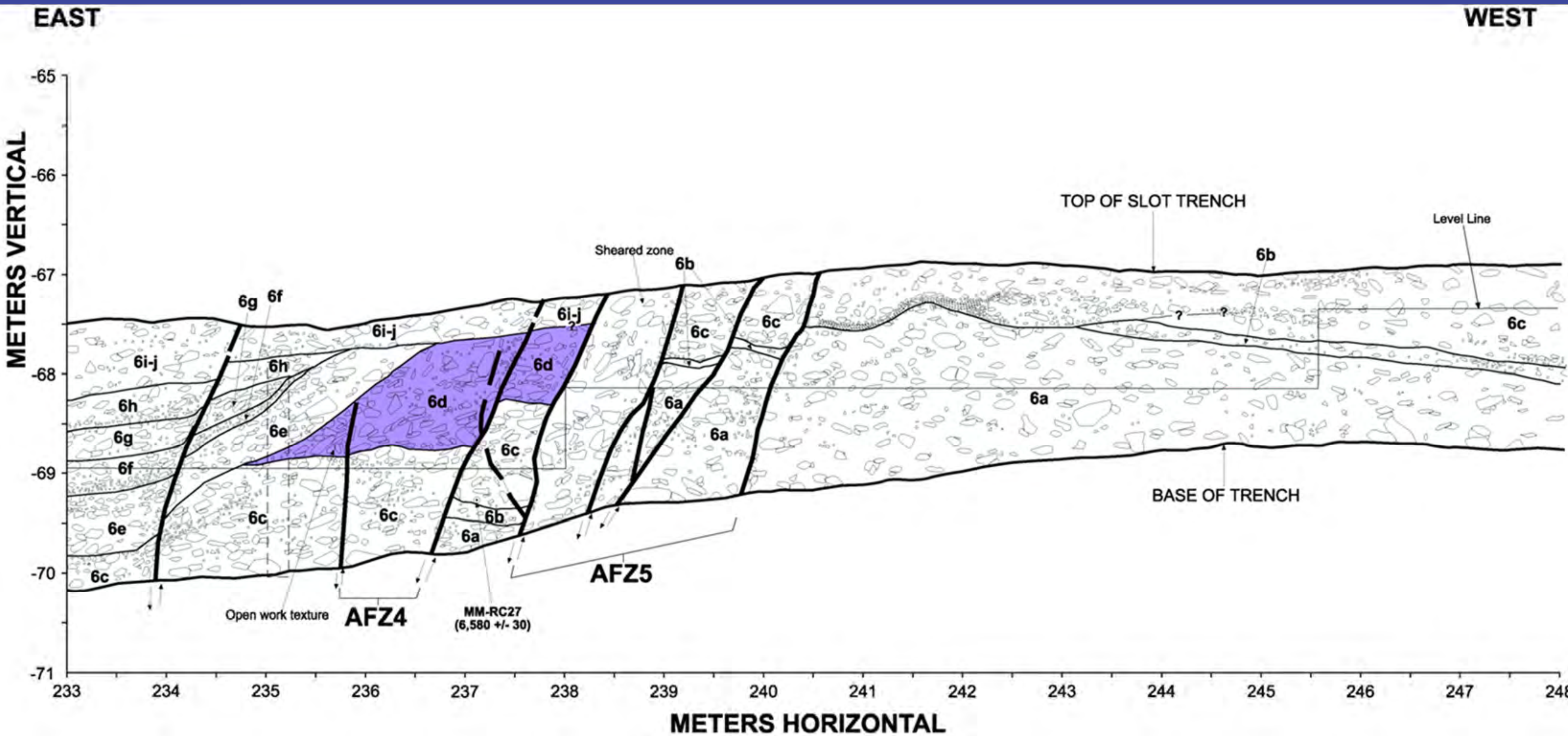
Event V_g (?) on AFZ4



- Differential displacements
  (0.5 m throw on Unit 6d, vs ~0 m throw on Unit 6i-j)
- Fault terminations at top of Unit 6d

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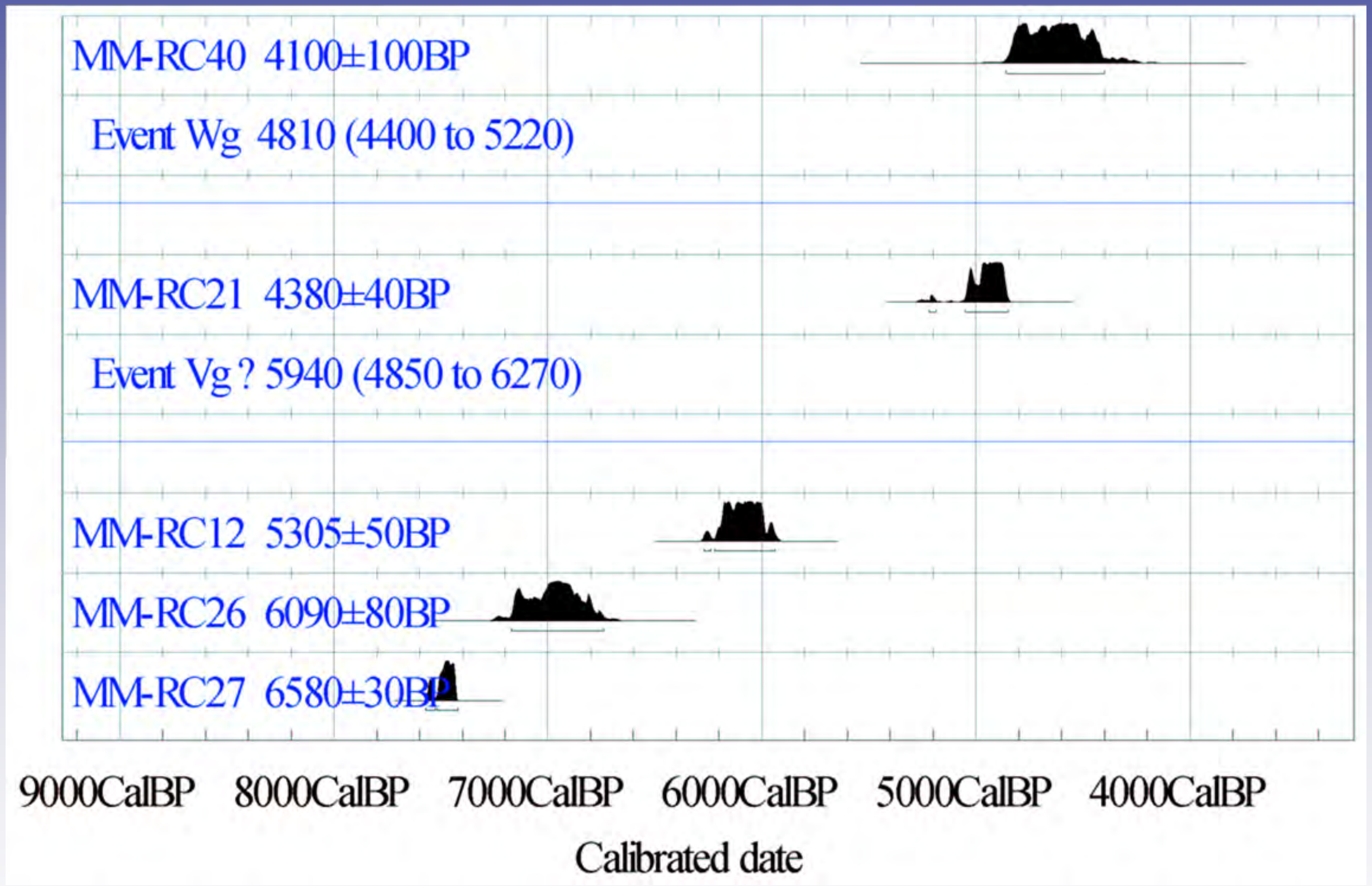
Event V_g (?) Occurred 4900 (+400, -1100) cal BP



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Graben Fault Summary

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

At least 4, Possibly 5 Separate Events

Between ≈ 600 and 6,300 cal BP

NOT ACTIVE

ACTIVE

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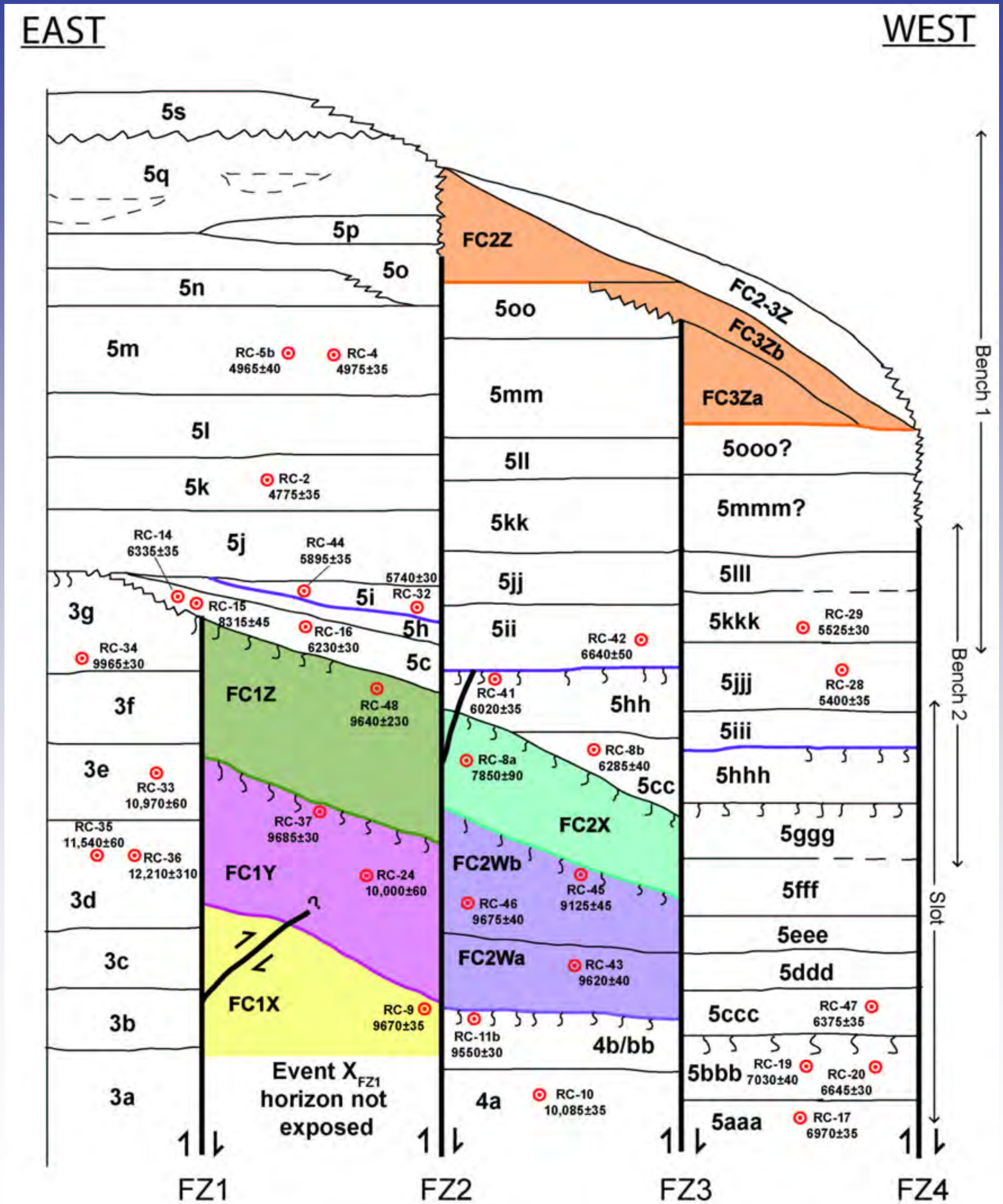
Footwall Surface-Faulting Events Horizons



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FZ2 Uppermost Colluvial Wedge

- Event Z_{FZ2} occurred after 5,350 to 5,590 cal BP
- 2.8 m throw
- May correlate to Event Z_{FZ3}
  (both colluvial wedges overlie Unit 5o)

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Paleoseismic Summary Since Mid Holocene

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

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

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

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

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Comparison With Previous Studies

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

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

Summary and Implications for UQFPWG

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

PALEOSEISMIC (NON-TRENCHING) STUDIES OF THE COLLINSTON AND CLARKSTON MOUNTAIN SEGMENTS OF THE WASATCH FAULT ZONE, BOX ELDER COUNTY, UTAH

Michael D. Hylland

Utah Geological Survey

Research supported through funding from the USGS, contract no. 03HQAG0008.

UTAH GEOLOGICAL SURVEY

Malad City segment: 40 km

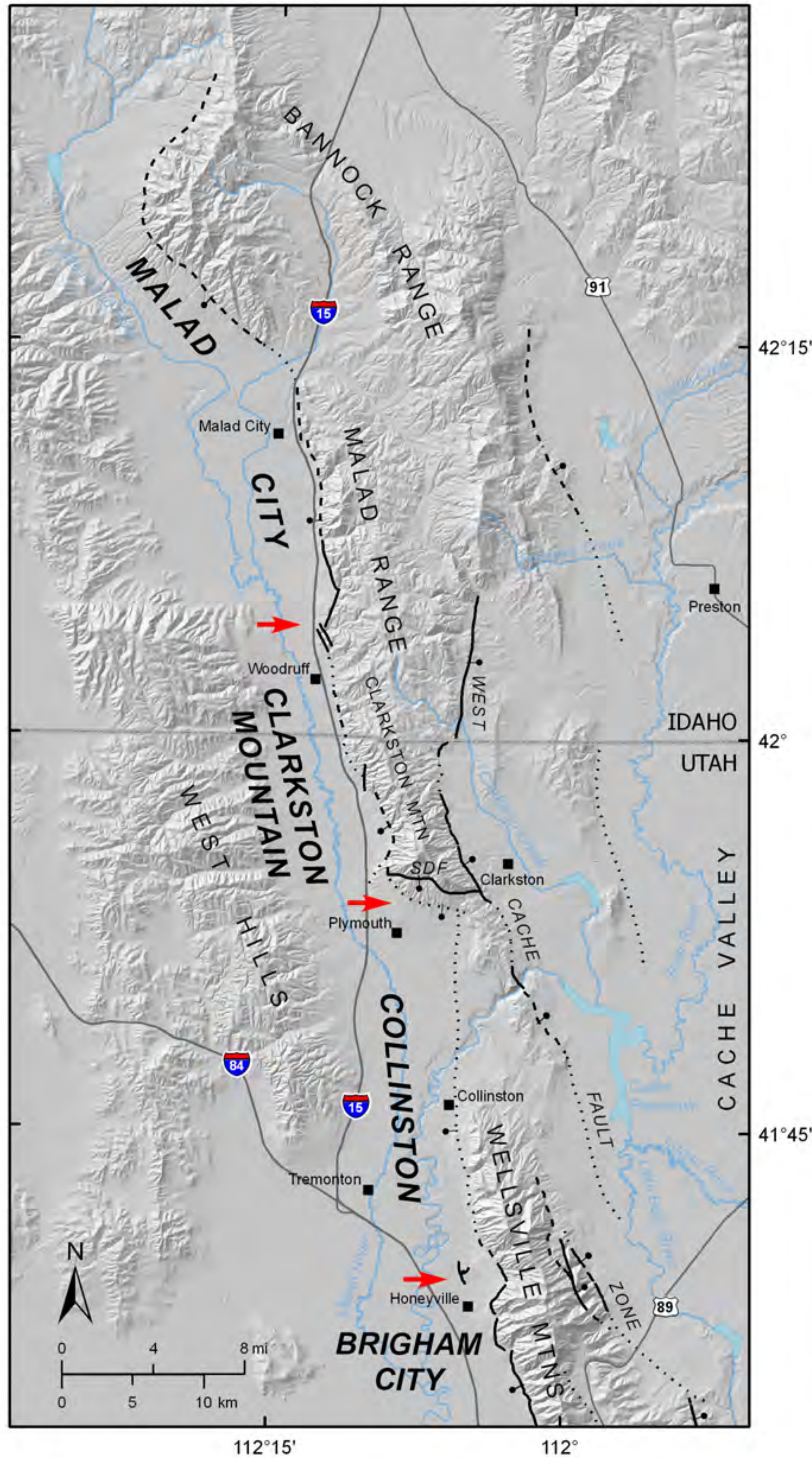
Clarkston Mountain segment: 20 km

(Biek et al., 2003)

Collinston segment: 30 km

(Oviatt, 1986a, 1986b; Personius, 1990)

Brigham City segment: 40 km



Collinston Segment:

- No post-Bonneville surface faulting along most of trace (Personius, 1990)
- Northernmost scarp on Quaternary deposits in Coldwater Canyon reentrant (segment boundary) likely Brigham City-segment rupture (Personius, 1990)
- Mapped two additional multiple-event fault scarps in Coldwater Canyon reentrant

Collinston Segment (cont.):

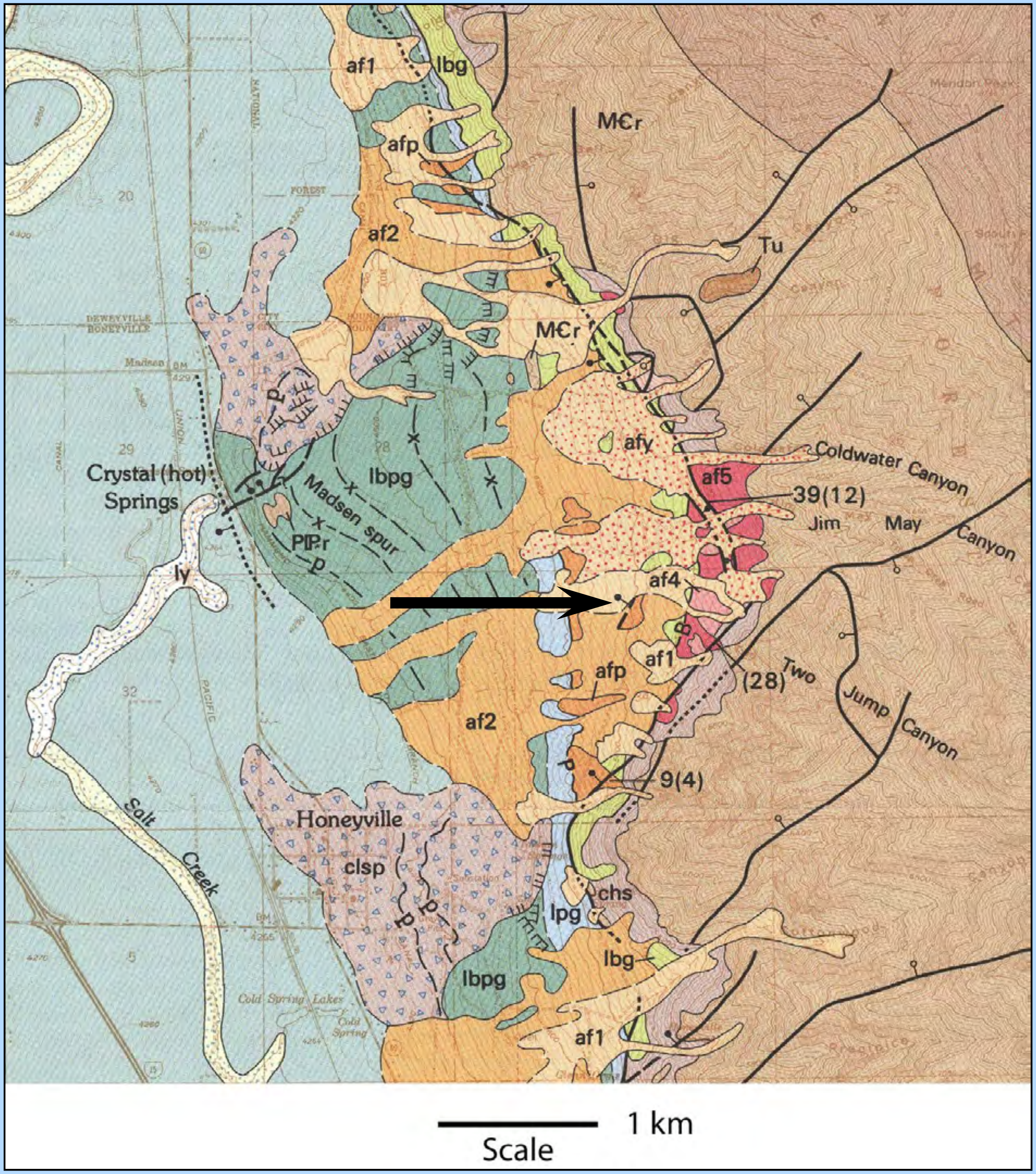
- Linear, steep mountain front indicates late Pleistocene activity
- Holocene strain partitioning (Machette and others, 1992): Collinston segment inactive, West and East Cache fault zones active
- Measured nine fault-scarp profiles and two Bonneville shoreline-scarp profiles to obtain data for diffusion-equation modeling
  - provide insights into spatial and temporal patterns of surface faulting in segment boundary area
  - compare with patterns inferred from trench data to south

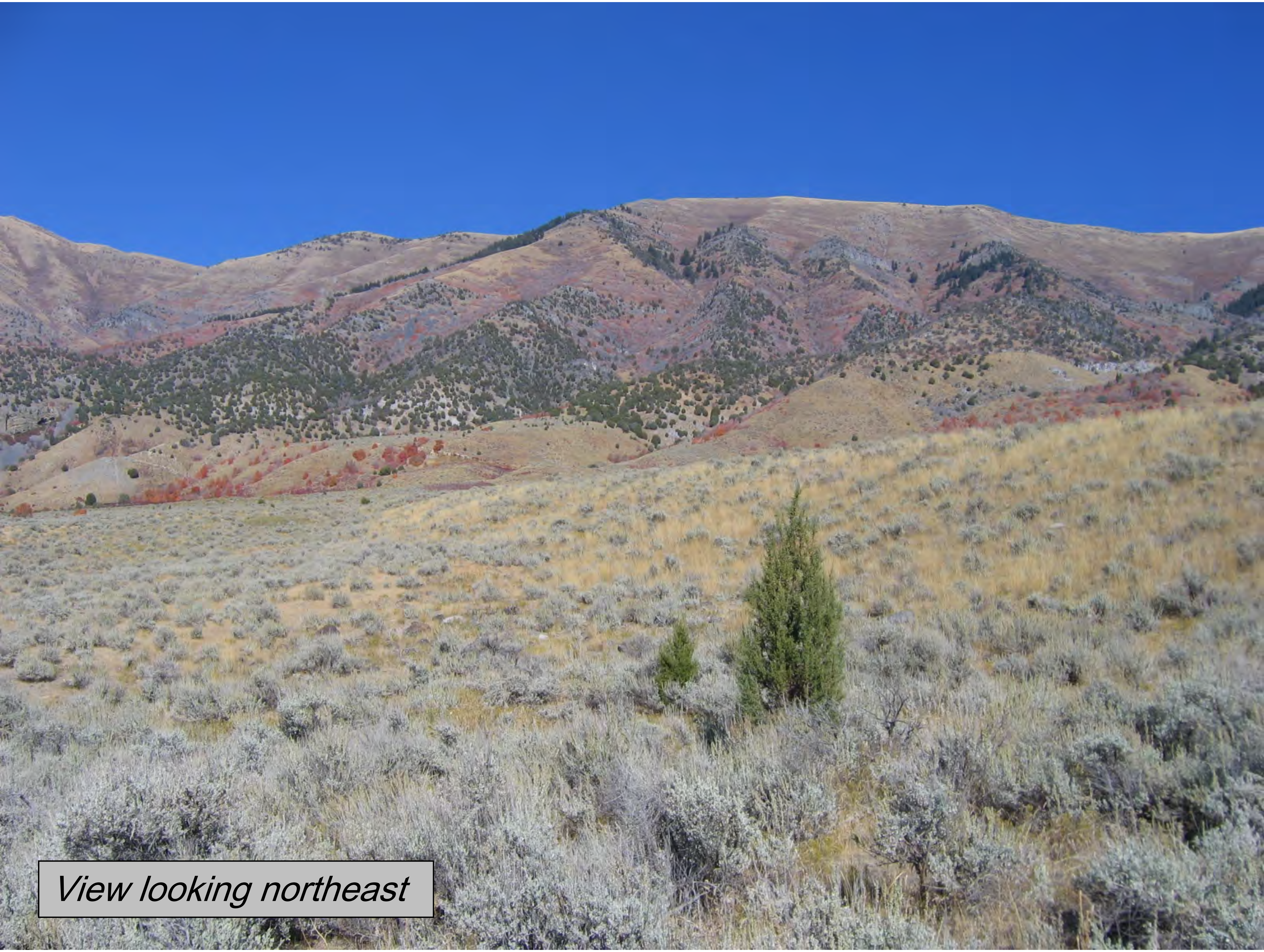
Collinston-Brigham City Segment Boundary

Honeyville Area

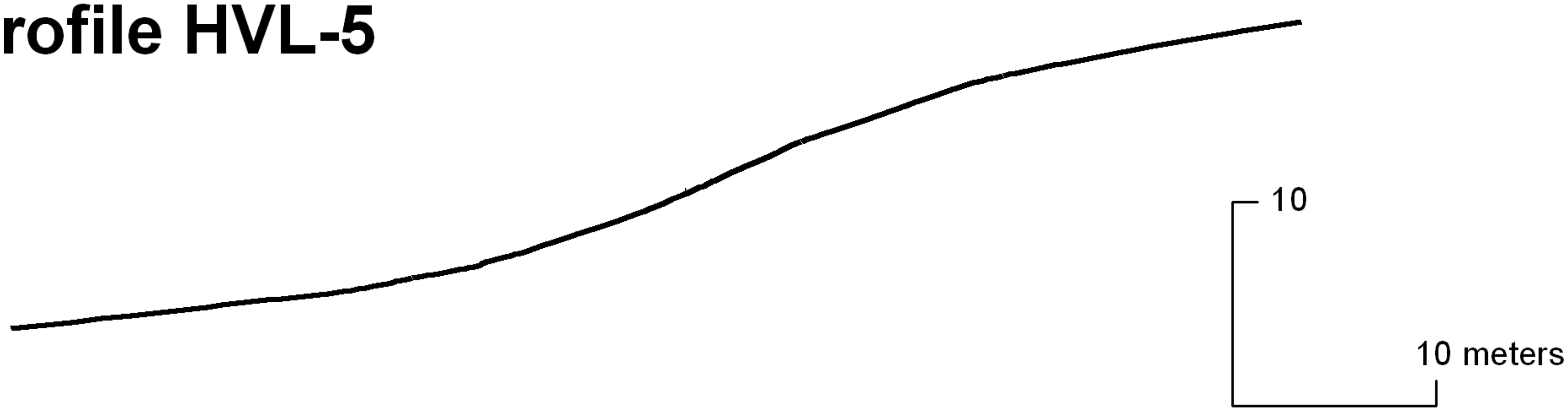
(Coldwater Canyon Reentrant)

(*from Personius, 1990*)



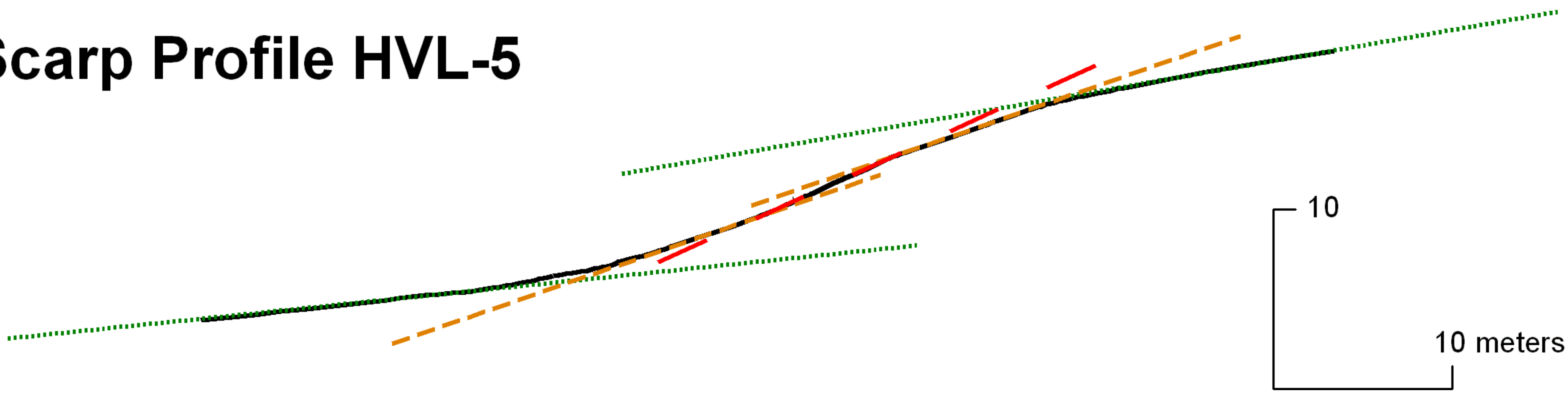

View looking northeast

Scarp Profile HVL-5



Profile	H (m)	SO (m)	θ_{max} (º)	γ (º)
HVL-4	9.4	5.3	24.0	10.0
HVL-5	10.5	6.6	24.0	8.0

Scarp Profile HVL-5

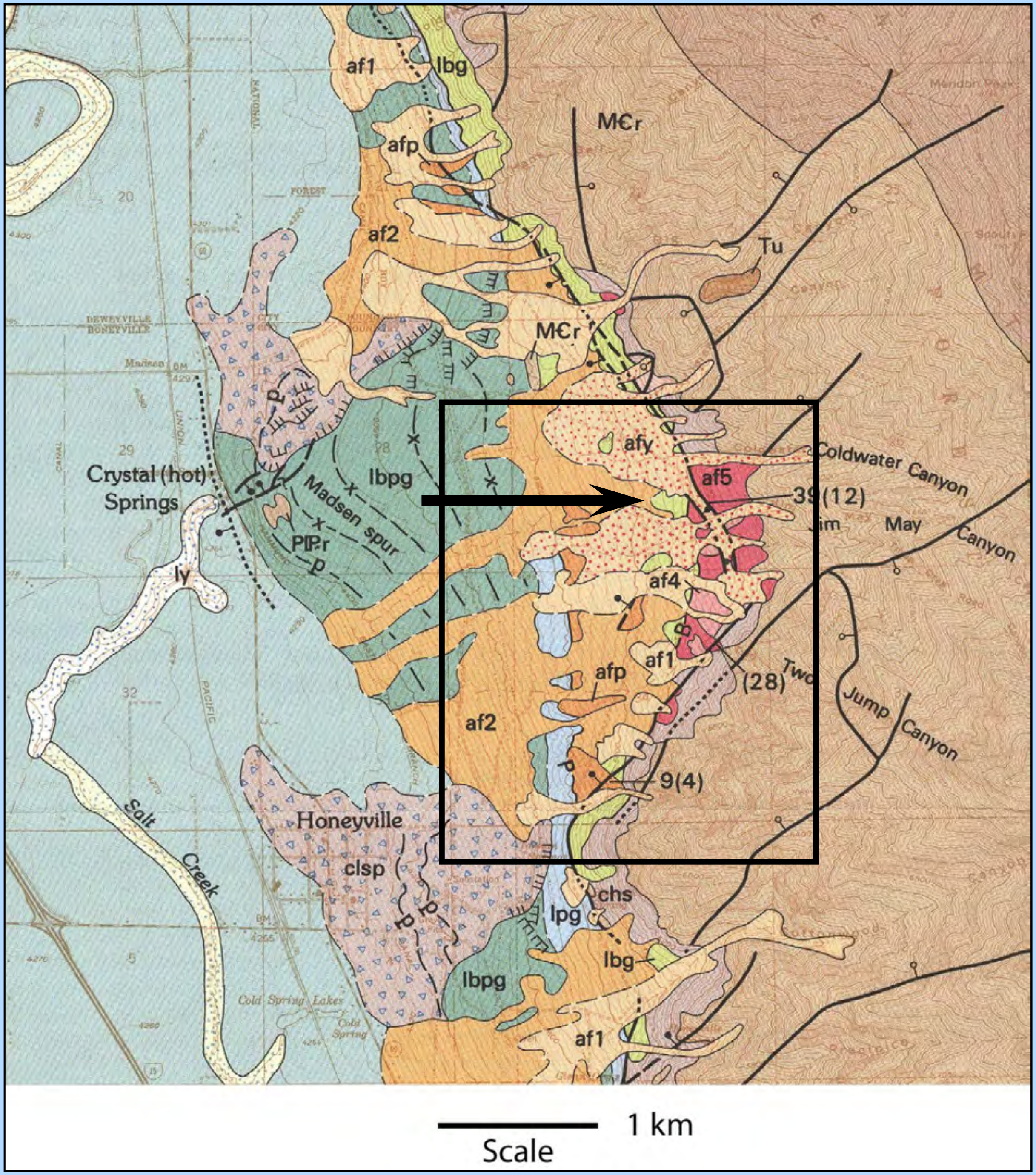


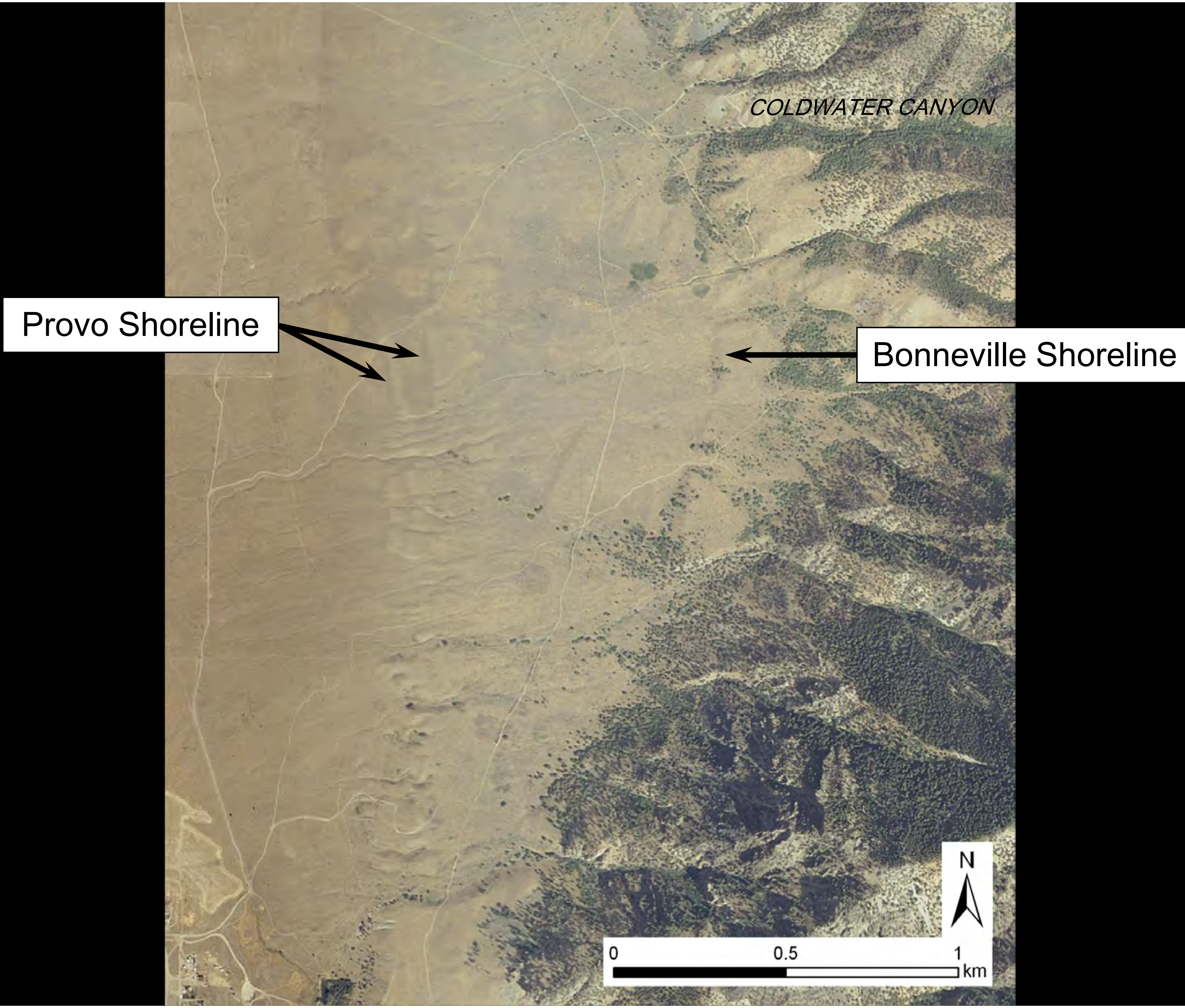
Collinston-Brigham City Segment Boundary

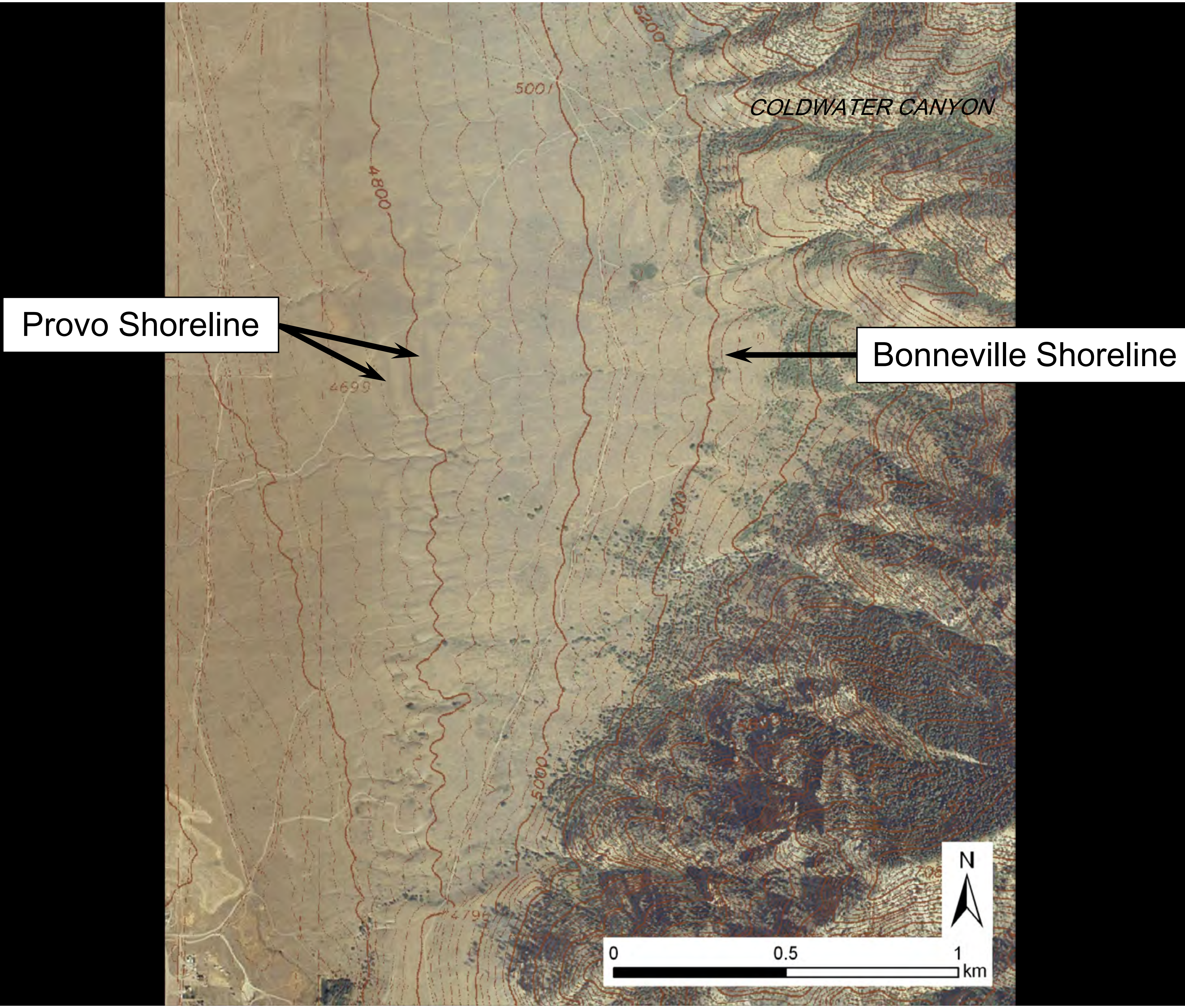
Honeyville Area

(Coldwater Canyon Reentrant)

(*from Personius, 1990*)

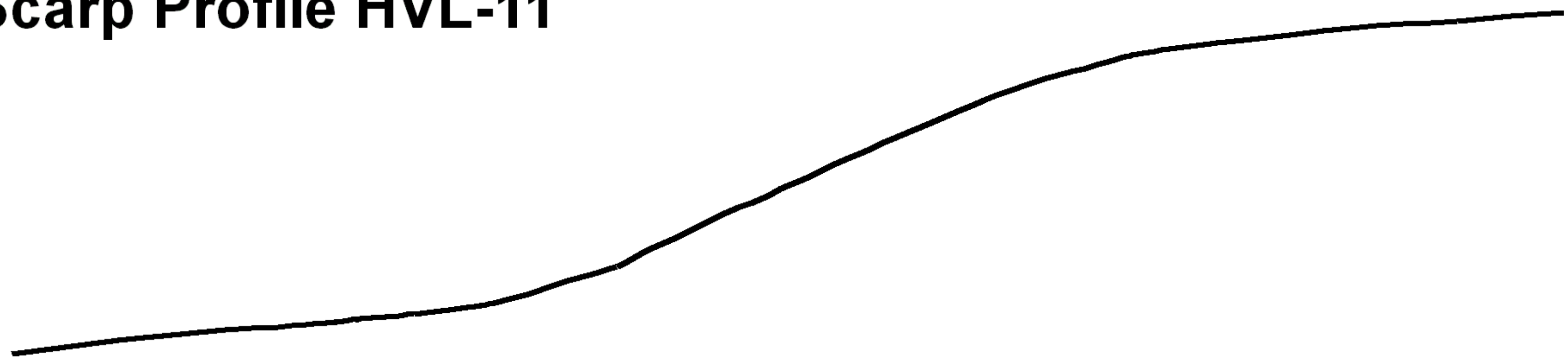



COLDWATER CANYON
Provo Shoreline
Bonneville Shoreline
N
0
0.5
1
km

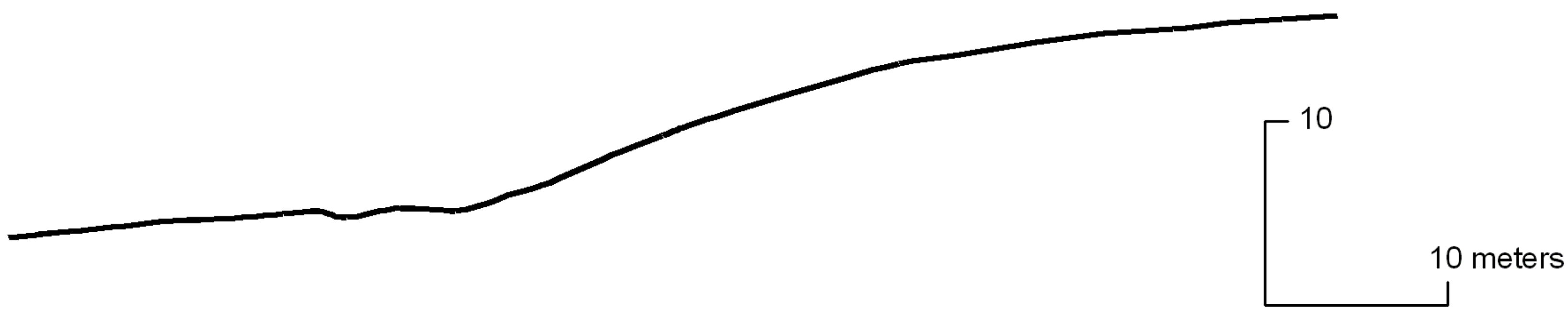

COLDWATER CANYON
Provo Shoreline
Bonneville Shoreline
5200
5001
4800
4699
5200
5000
4796
N
0
0.5
1
km


View looking northeast

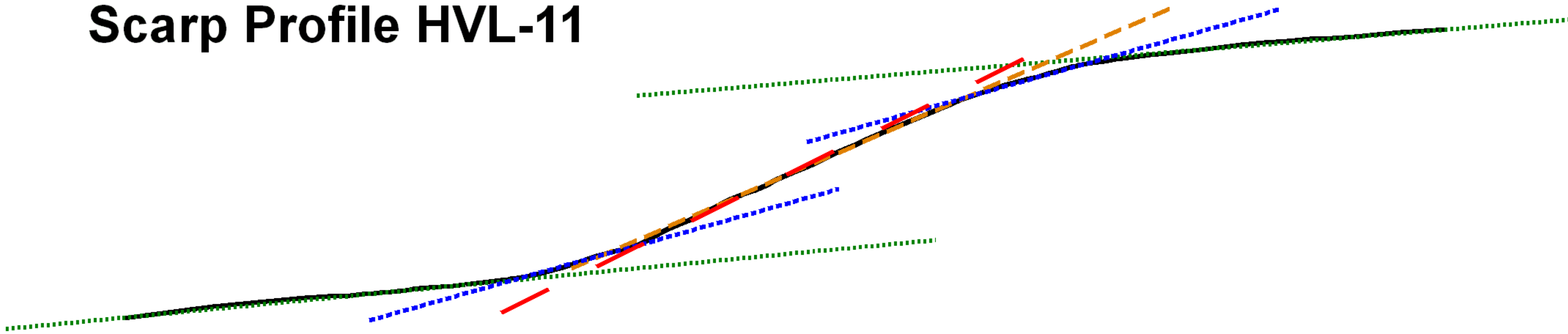
Scarp Profile HVL-11



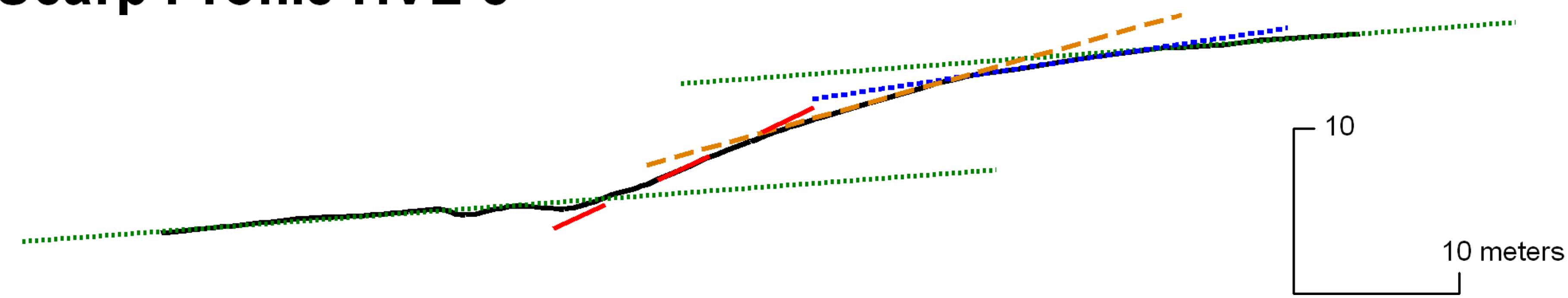
Scarp Profile HVL-8



Scarp Profile HVL-11



Scarp Profile HVL-8



Coldwater Canyon Scarps

Profile	H (m)	SO (m)	θ_{max} (º)	γ (º)
HVL-8	8.9	6.6+	24.5	4.0
HVL-9	7.3	5.7+	22.0	5.0
HVL-10	13.4	9.9	25.0	6.0
HVL-11	14.8	11.2	26.0	5.0

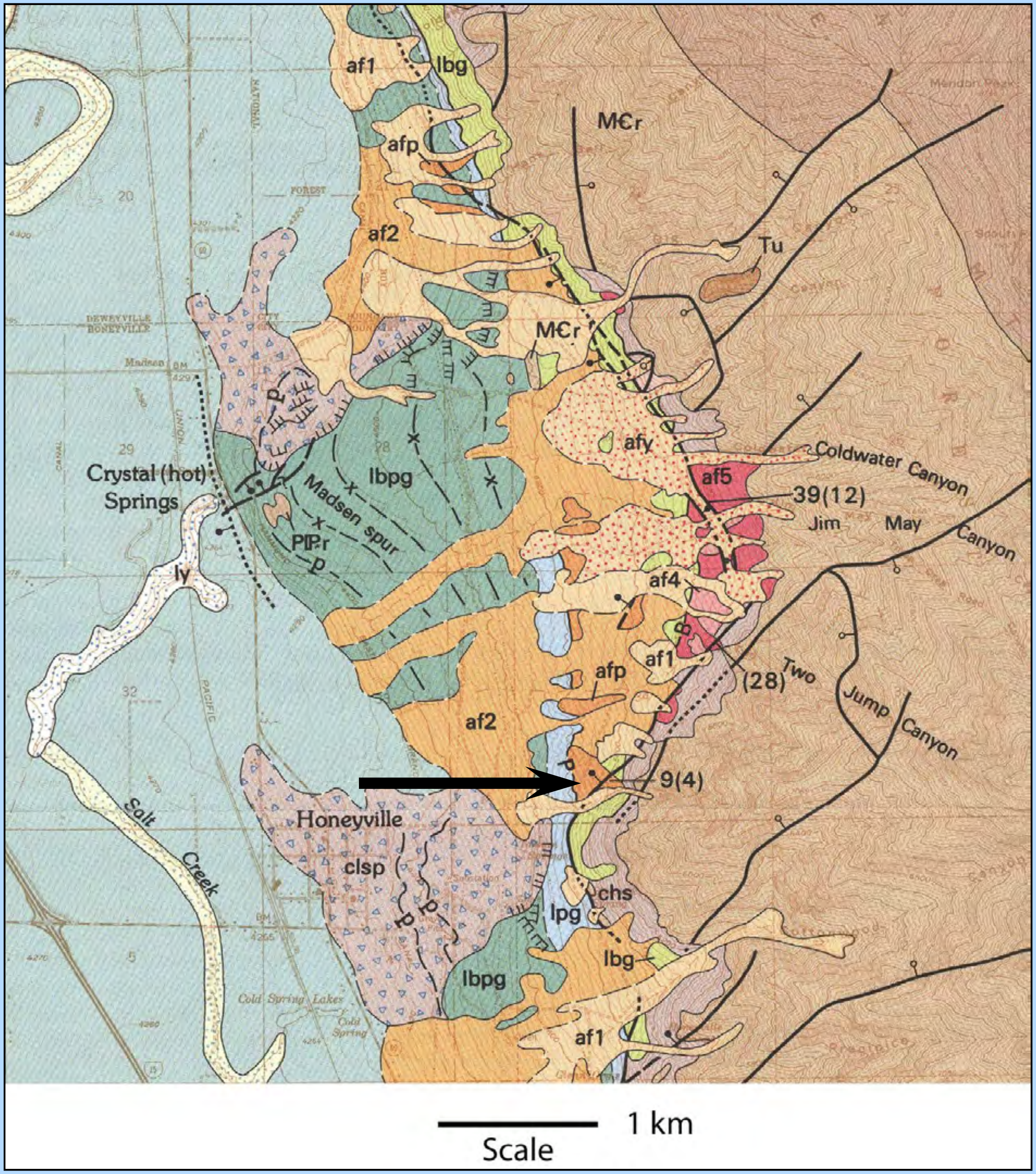
Total SO across scarps ~16.7+ m

Collinston-Brigham City Segment Boundary

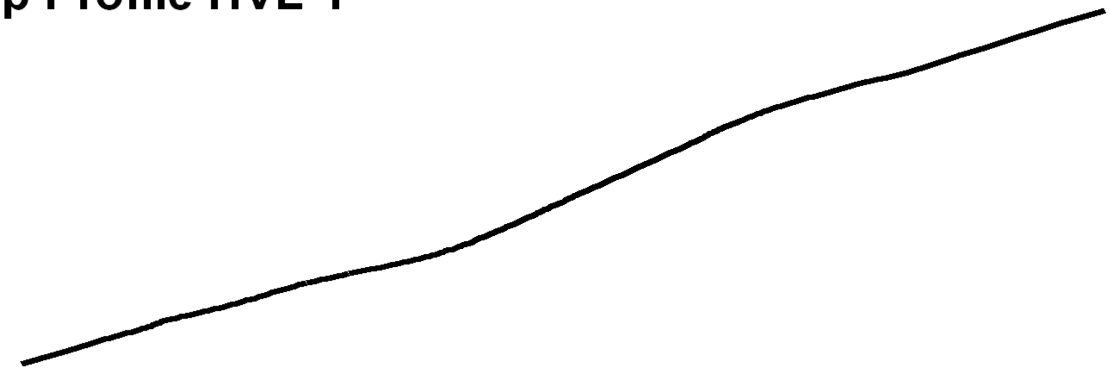
Honeyville Area

(Coldwater Canyon Reentrant)

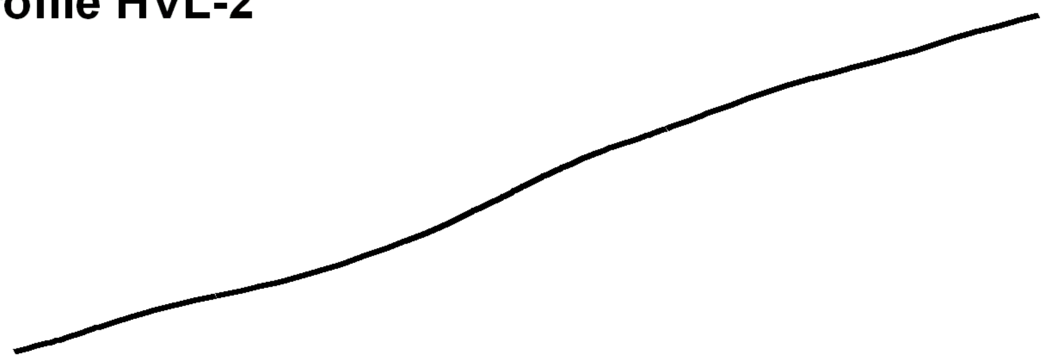
(*from Personius, 1990*)



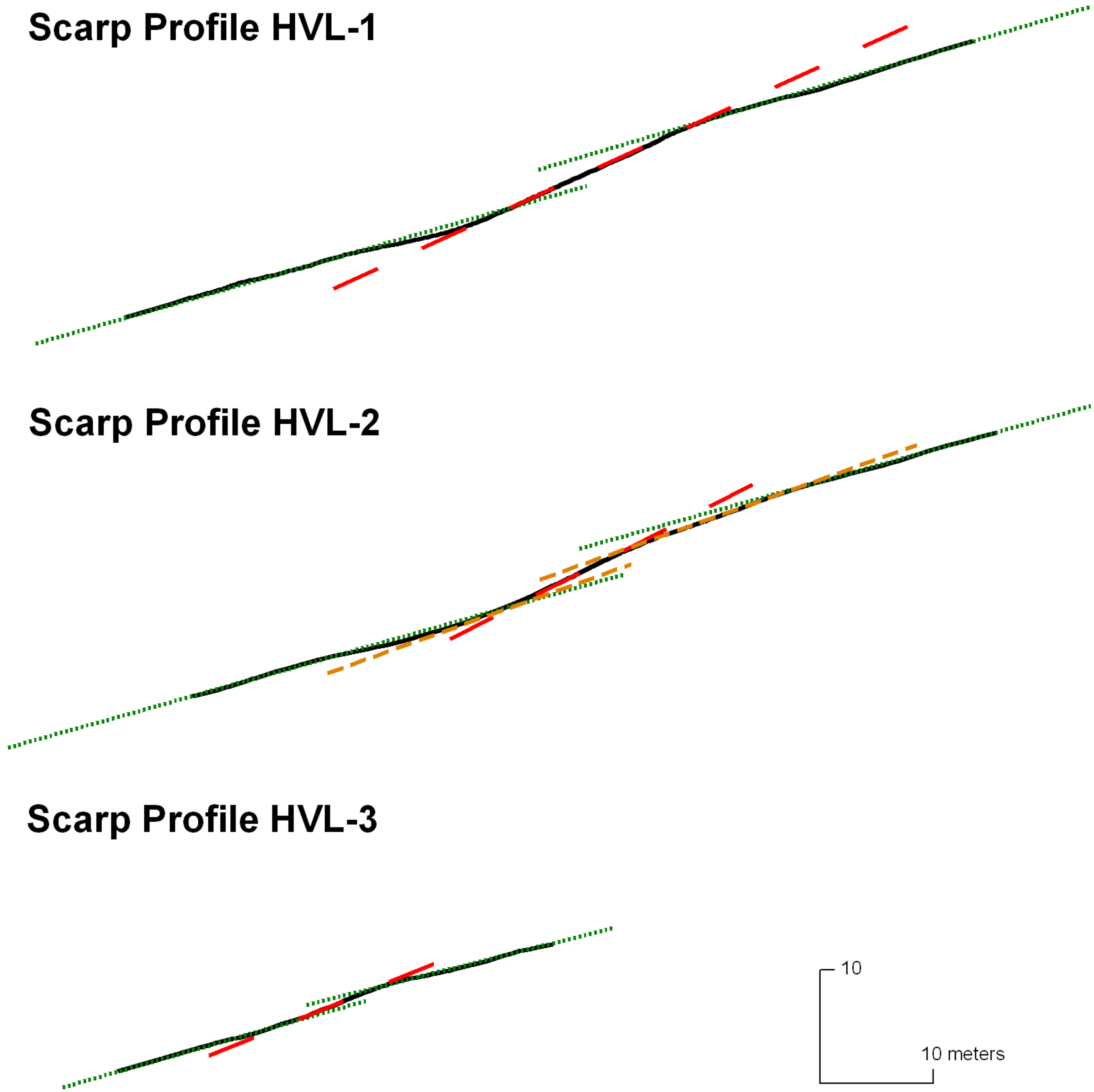
Scarp Profile HVL-1



Scarp Profile HVL-2



Scarp Profile HVL-3



Scarp Profile HVL-1
Scarp Profile HVL-2
Scarp Profile HVL-3
10
10 meters

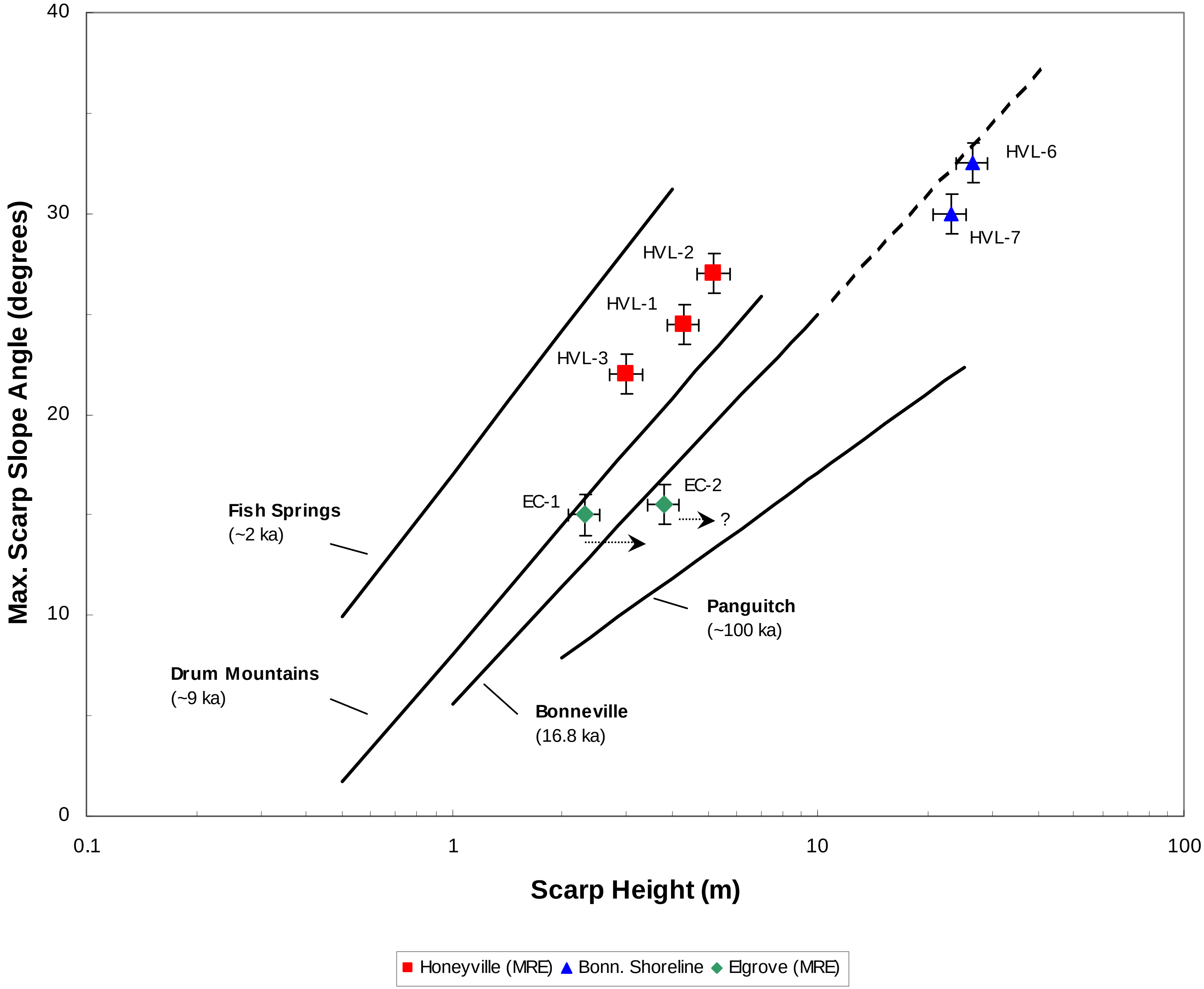
Southern Scarps, Honeyville area

Profile	H (m)	SO (m)	θ_{max} (º)	γ (º)
HVL-1 (full scarp)	9.0	3.4	24.5	16.0
HVL-1 (MRE)	4.3	1.6	24.5	16.0
HVL-1 (PE)	4.7	1.8	24.5	16.0
HVL-2 (full scarp)	11.7	3.7	27.0	16.0
HVL-2 (MRE)	5.2	1.7	27.0	16.0
HVL-2 (PE)	6.5	2.0	20.0	16.0
HVL-3	3.0	1.0	22.0	15.5

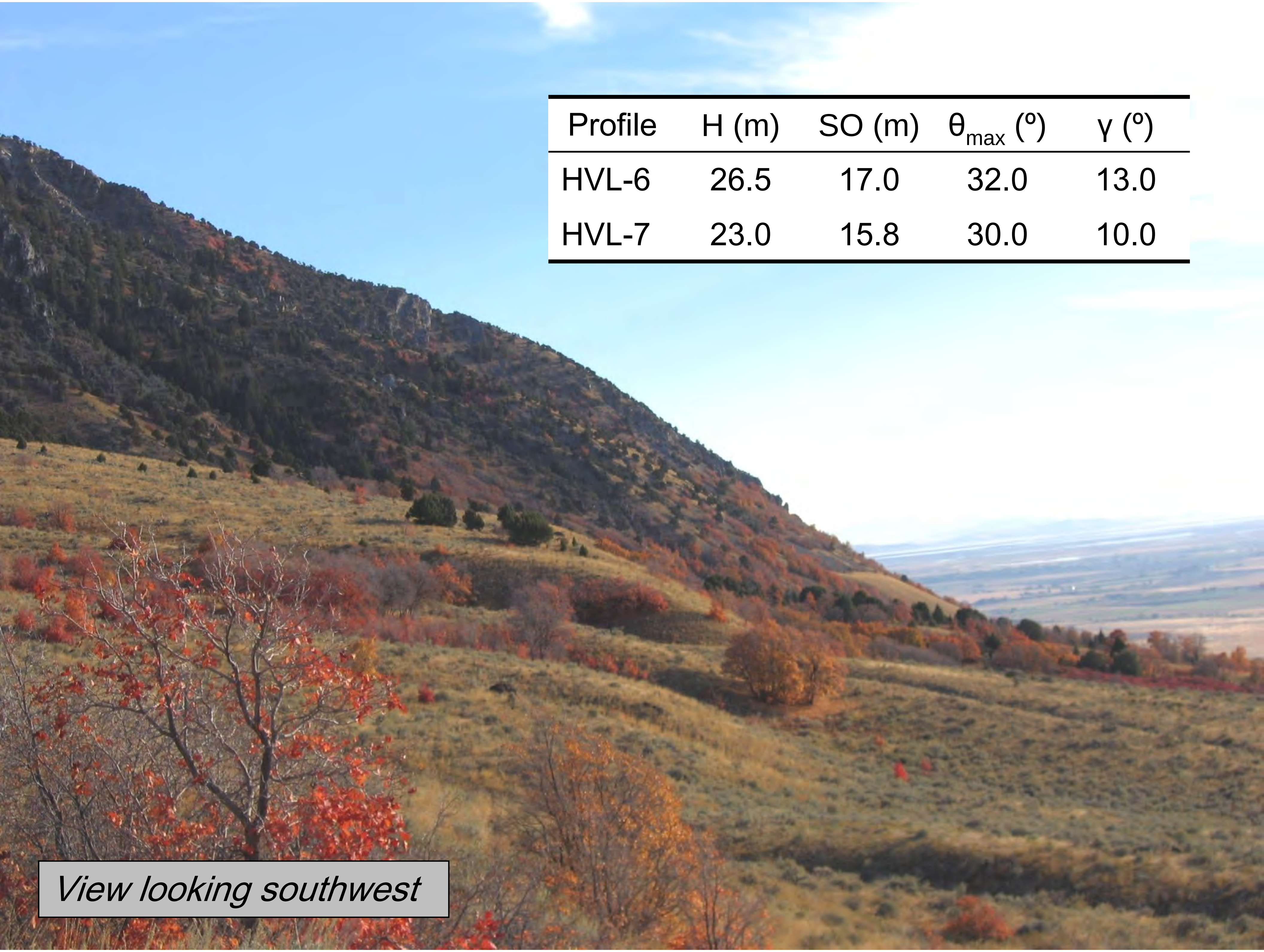
Southern Scarps, Honeyville area

Profile	H (m)	SO (m)	θ_{max} (º)	γ (º)
HVL-1 (full scarp)	9.0	3.4	24.5	16.0
HVL-1 (MRE)	4.3	1.6	24.5	16.0
HVL-1 (PE)	4.7	1.8	24.5	16.0
HVL-2 (full scarp)	11.7	3.7	27.0	16.0
HVL-2 (MRE)	5.2	1.7	27.0	16.0
HVL-2 (PE)	6.5	2.0	20.0	16.0
HVL-3	3.0	1.0	22.0	15.5

Scarp Slope Angle – Scarp Height Diagram

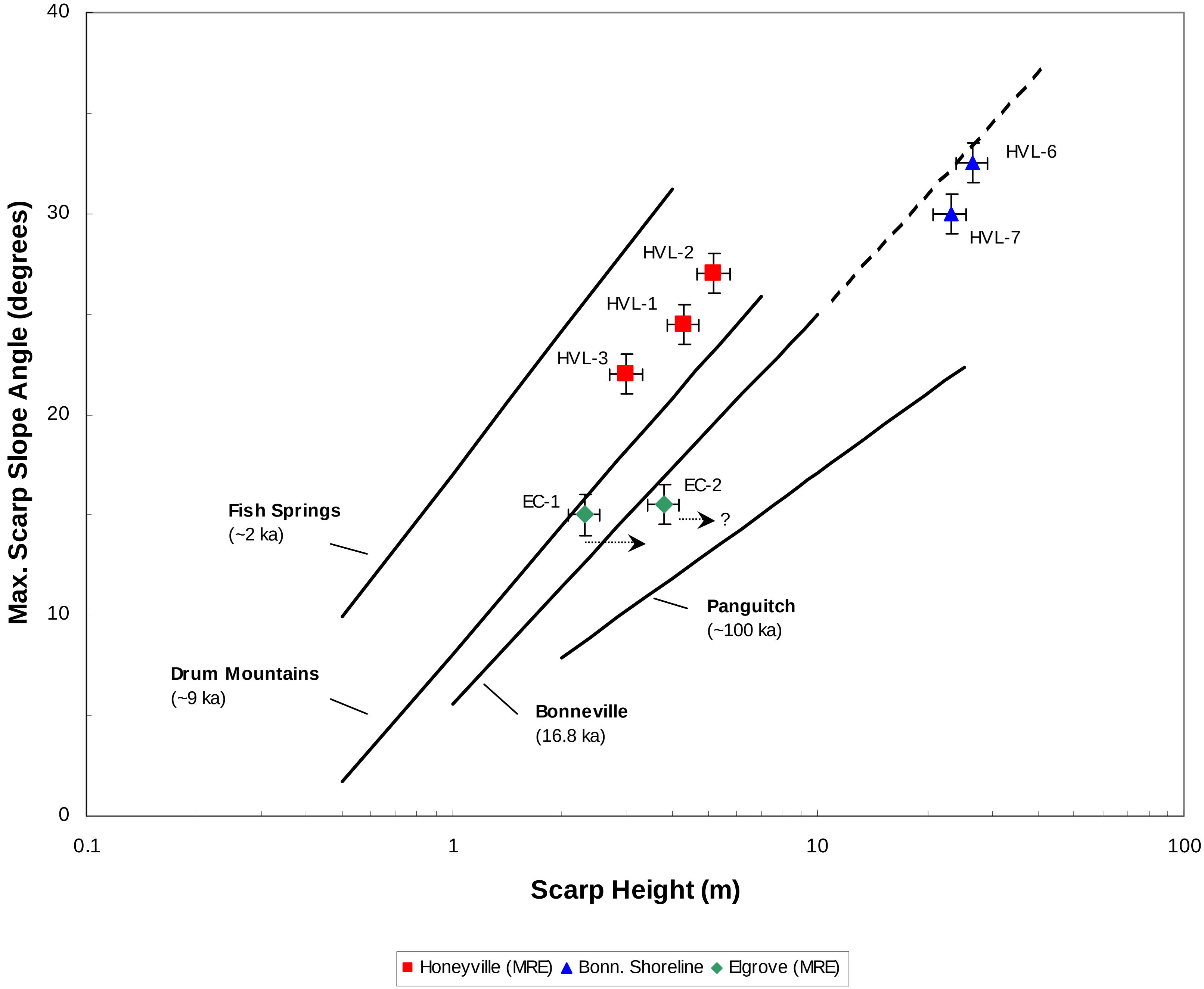


After Bucknam and Anderson (1979)



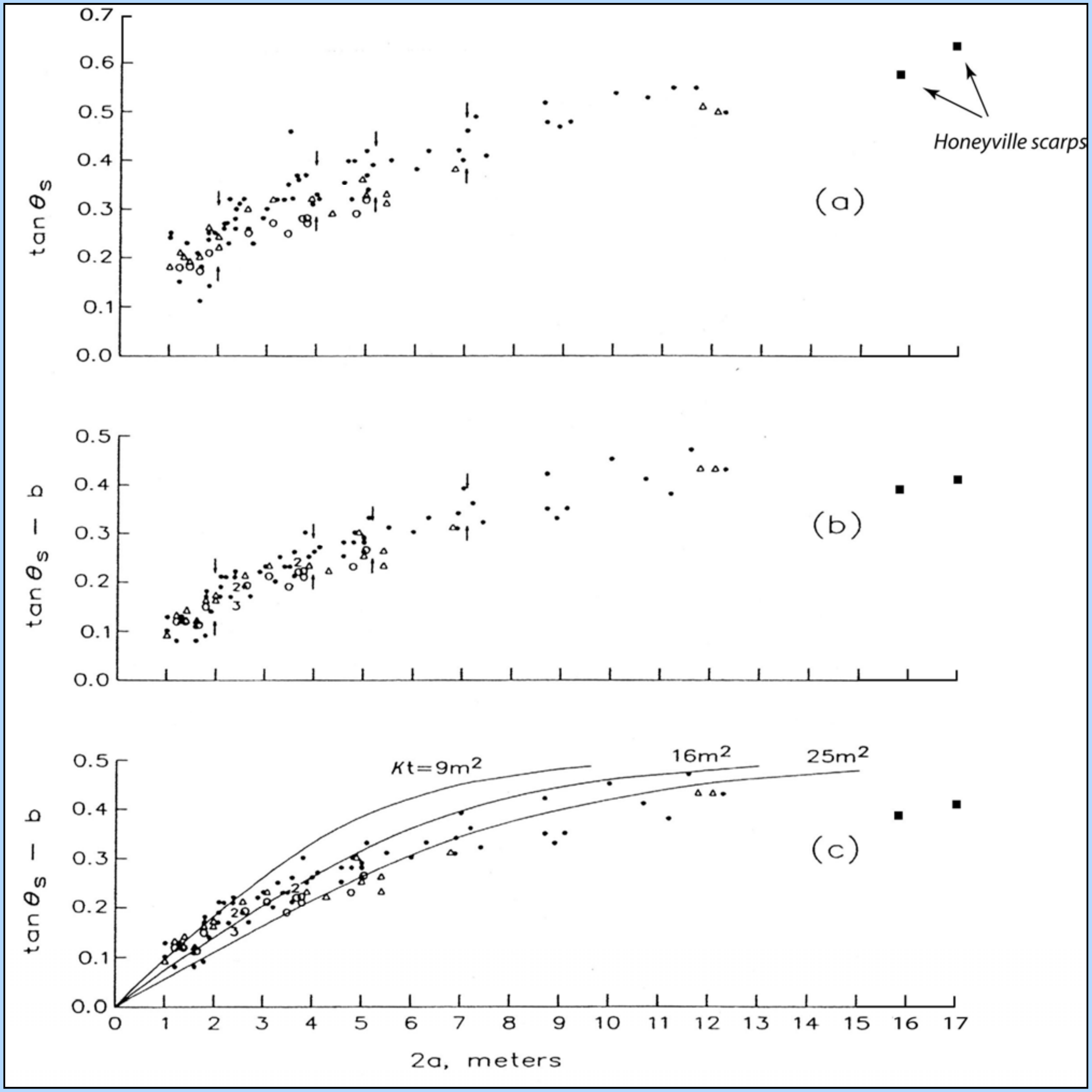
Profile	H (m)	SO (m)	θ_{max} (º)	γ (º)
HVL-6	26.5	17.0	32.0	13.0
HVL-7	23.0	15.8	30.0	10.0

Scarp Slope Angle – Scarp Height Diagram



After Bucknam and Anderson (1979)

Slope-Offset Plots
(Lake Bonneville & Lake Lahontan shoreline scarps)



After Hanks and Andrews (1989)

Lake Bonneville Shoreline Scarps – Diffusivity Estimates

Site	*N*	2a (m)	*K* (m^2/kyr)	K_o (m^2/kyr)	References
W Utah	61	1-12	1.1	-	Hanks et al., 1984
W Utah	61	1-12	-	0.46 (uses t = 14.5 ka)	Andrews & Bucknam, 1987
				0.39 (recalculated using t = 16.8 ka)	This study
N Ogden	3	29±3	12.9±1.7	5.9±0.1	Mattson & Bruhn, 2001
S Willow Cyn	4	10±4	1.9±0.5	1.2±0.3	Mattson & Bruhn, 2001
Tooele	2	23	4.7	1.4	Mattson & Bruhn, 2001
Stansburys	3	4±3	1.8±0.9	1.1±0.4	Mattson & Bruhn, 2001
Honeyville	2	16±1	4.5±0.3 (assumes θ_r = 35° [α = 0.7])	0.55 (model assumes θ_r = 31°)	This study (*K* calculated using equations in Hanks, 2000; K_o calculated using equation in Andrews & Bucknam, 1987, and profile HVL-7)
			7.0±0.3 (uses M&B's α = 0.95 [θ_r = 43°])		

Lake Bonneville Shoreline Scarps – Diffusivity Estimates

Site	N	2a (m)	K (m^2/kyr)	K_o (m^2/kyr)	References
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N Ogden	3	29±3	12.9±1.7	5.9±0.1	Mattson & Bruhn, 2001
S Willow Cyn	4	10±4	1.9±0.5	1.2±0.3	Mattson & Bruhn, 2001
Tooele	2	23	4.7	1.4	Mattson & Bruhn, 2001
Stansburys	3	4±3	1.8±0.9	1.1±0.4	Mattson & Bruhn, 2001
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S Willow Cyn	4	10±4	1.9±0.5	1.2±0.3	Mattson & Bruhn, 2001
Tooele	2	23	4.7	1.4	Mattson & Bruhn, 2001
Stansburys	3	4±3	1.8±0.9	1.1±0.4	Mattson & Bruhn, 2001
Honeyville	2	16±1	4.5±0.3 (assumes θ_r = 35° [α = 0.7])	0.55 (model assumes θ_r = 31°)	This study (K calculated using equations in Hanks, 2000; K_o calculated using equation in Andrews & Bucknam, 1987, and profile HVL-7)
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			7.0±0.3 (uses M&B's α = 0.95 [θ_r = 43°])		

Malad City segment: 40 km

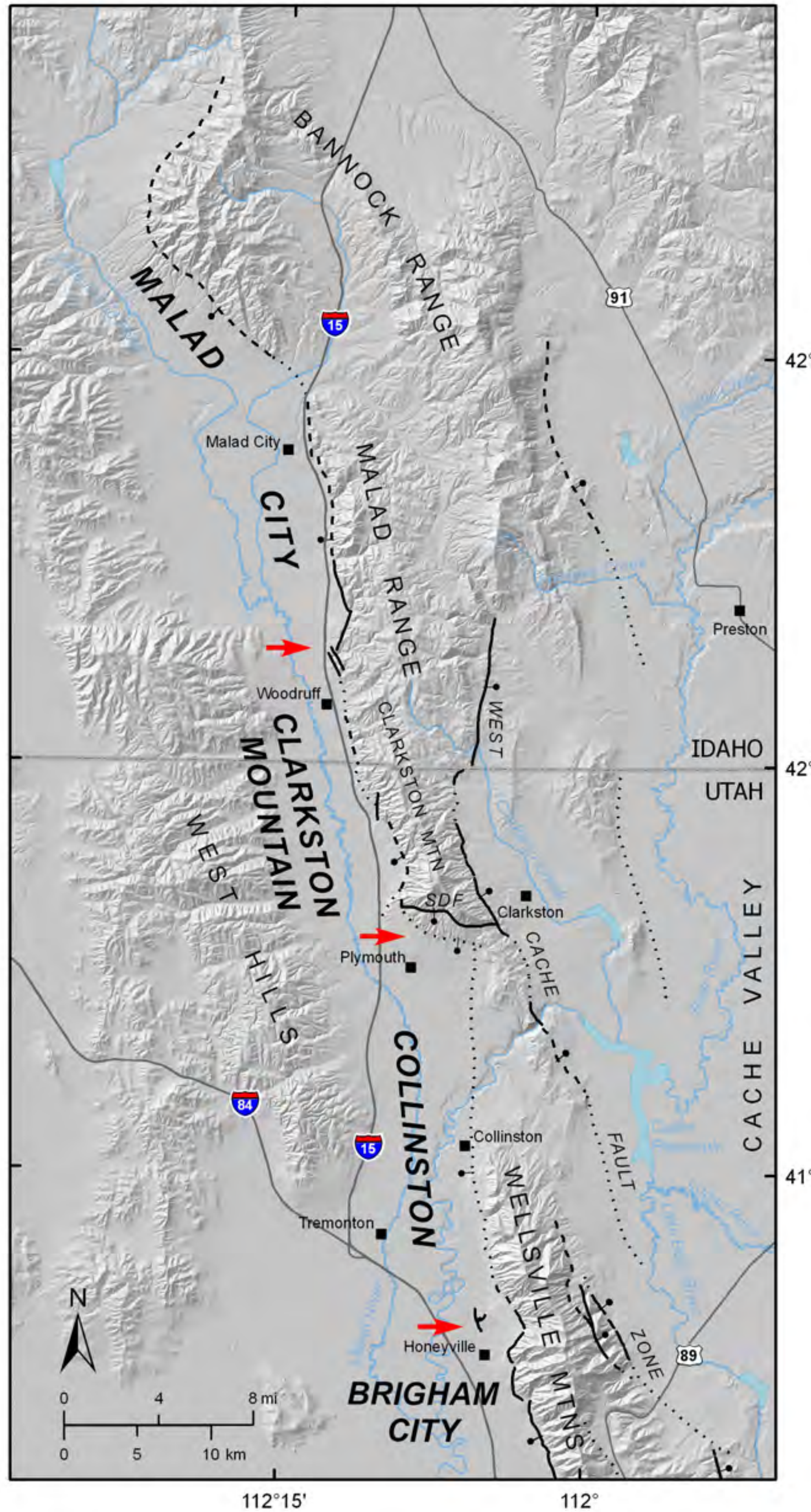
Clarkston Mountain segment: 20 km

(Biek et al., 2003)

Collinston segment: 30 km

(Oviatt, 1986a, 1986b; Personius, 1990)

Brigham City segment: 40 km



Clarkston Mountain Segment

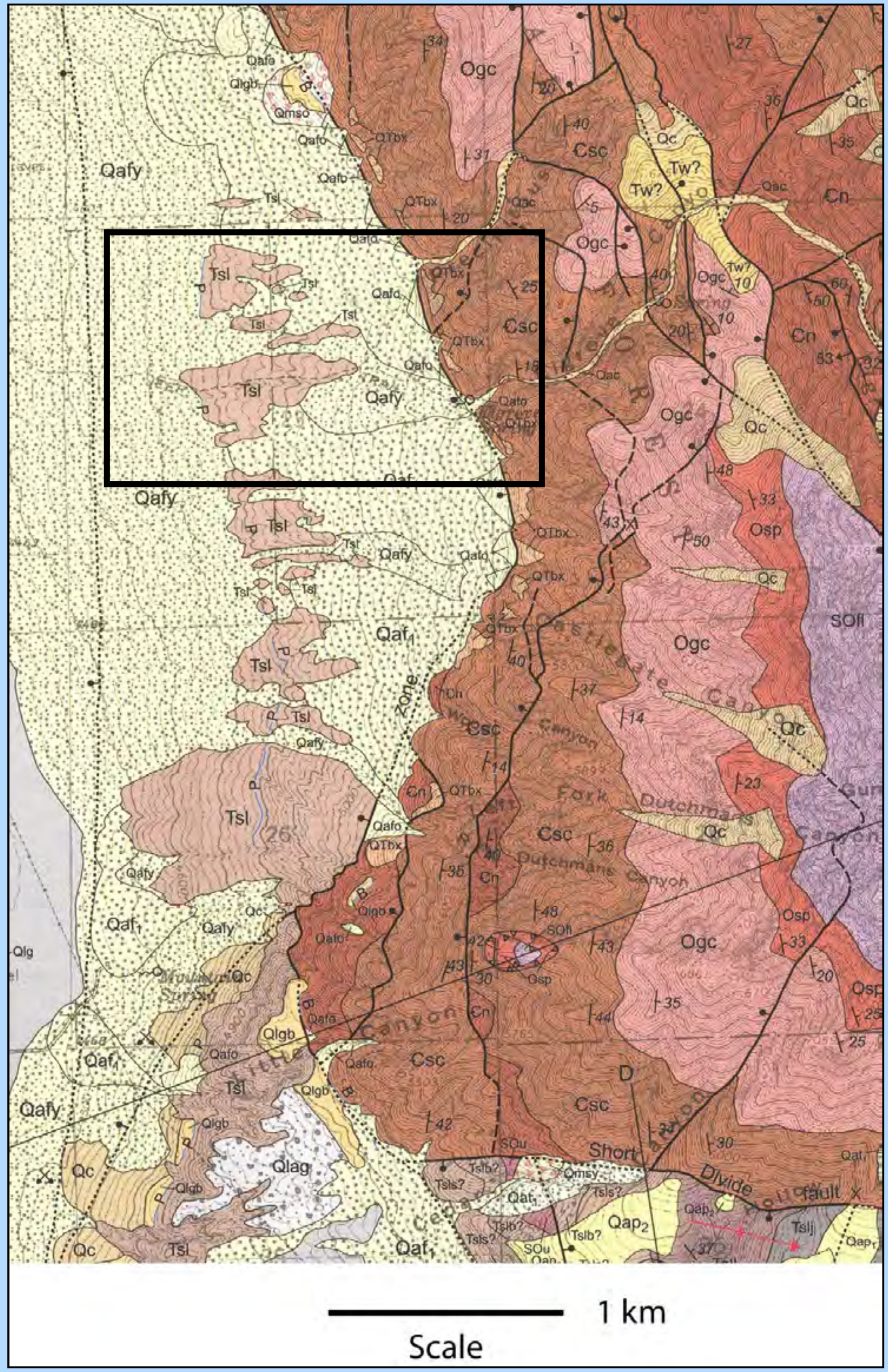
- No evidence of post-Bonneville surface faulting (Machette and others, 1992; Biek and others, 2003)
- Fault scarp (40 m long) at mouth of Elgrove Canyon, cutting late Pleistocene fan alluvium
- Measured two scarp profiles, indicate two pre-Bonneville shoreline surface faulting events
- Linear, steep mountain front and faulted fan alluvium indicate late Pleistocene activity

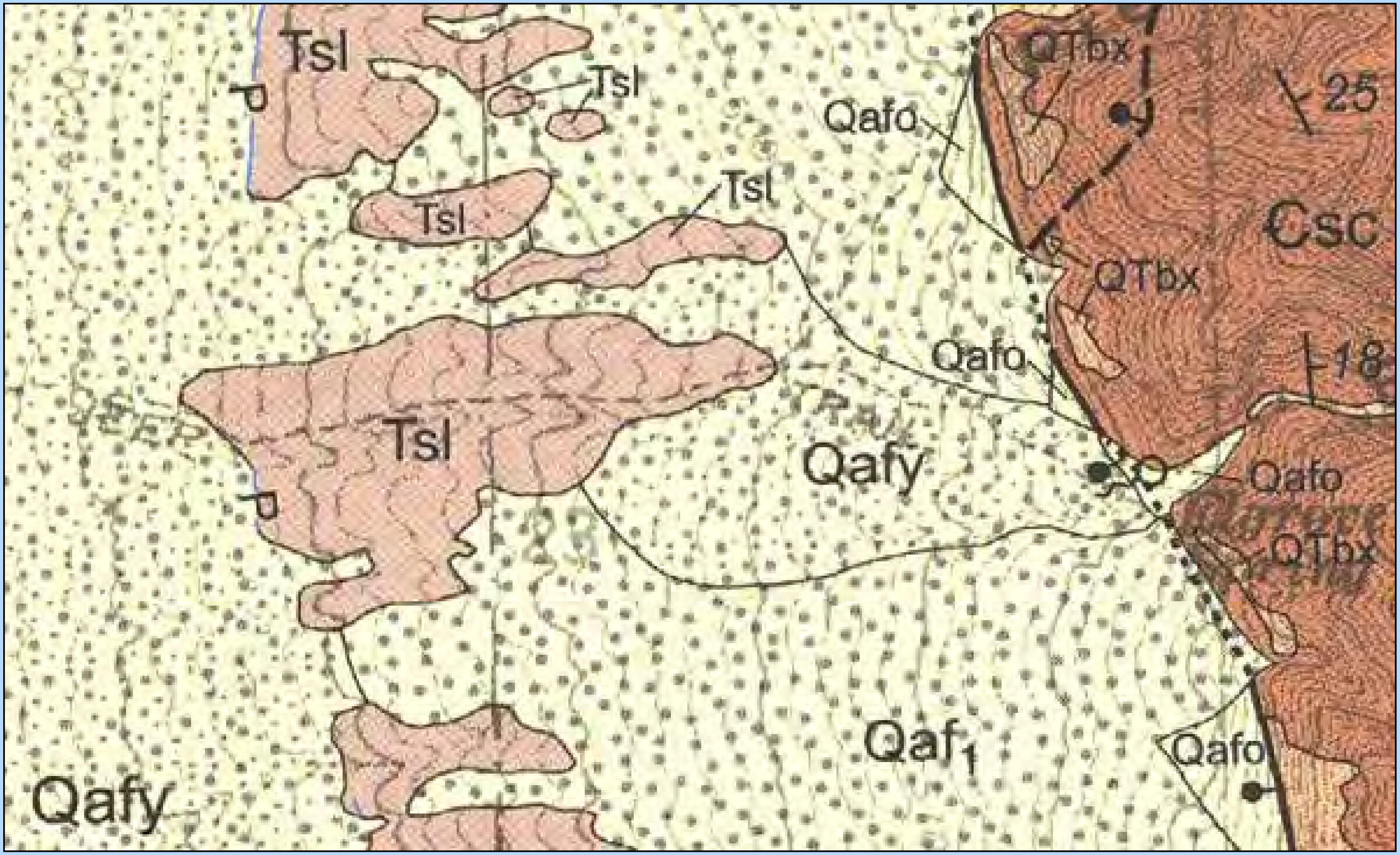
Clarkston Mountain Segment

Elgrove Canyon Area

(*from Biek and others, 2003*)

Fault dip = 44°

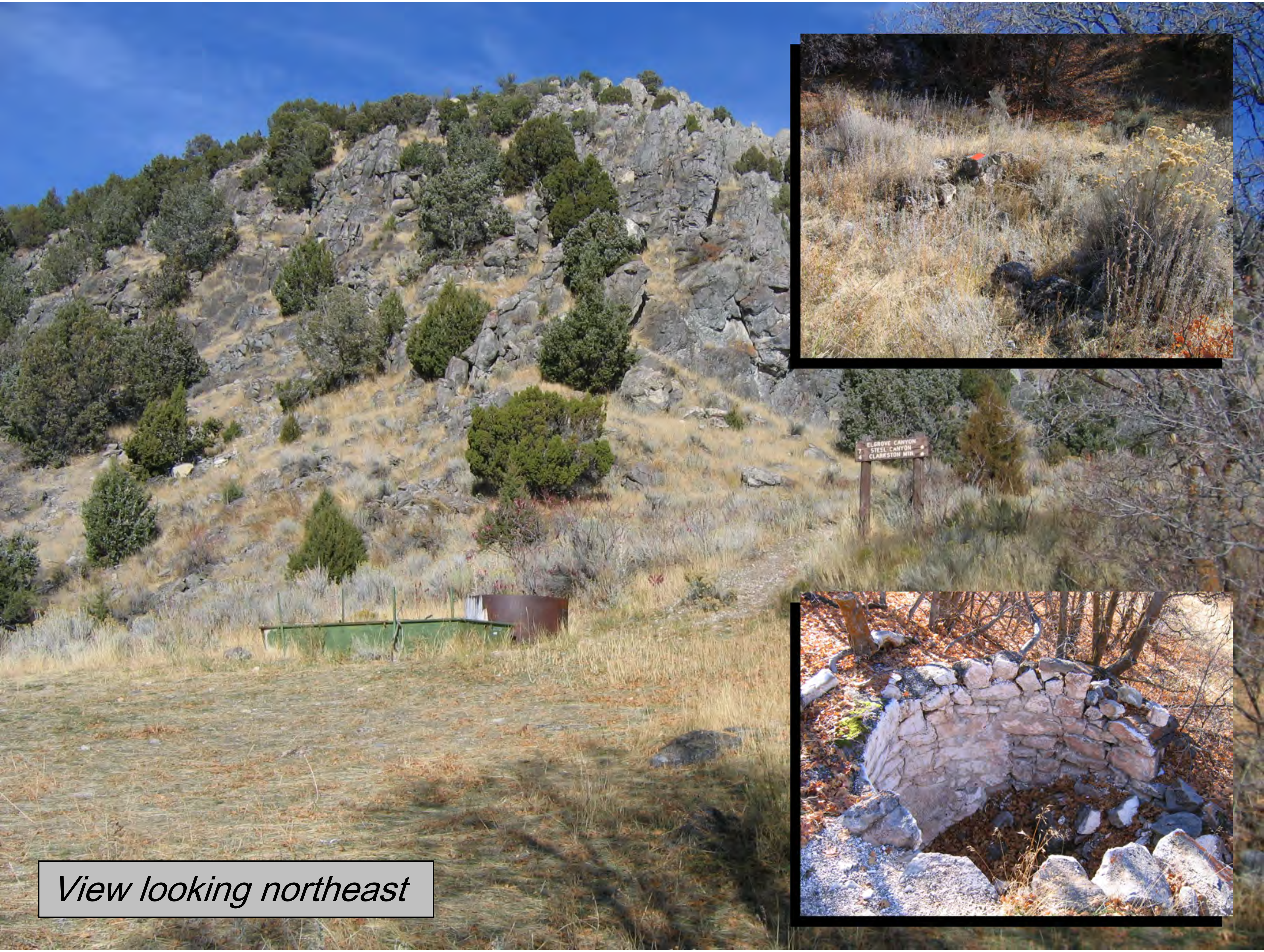




1 km

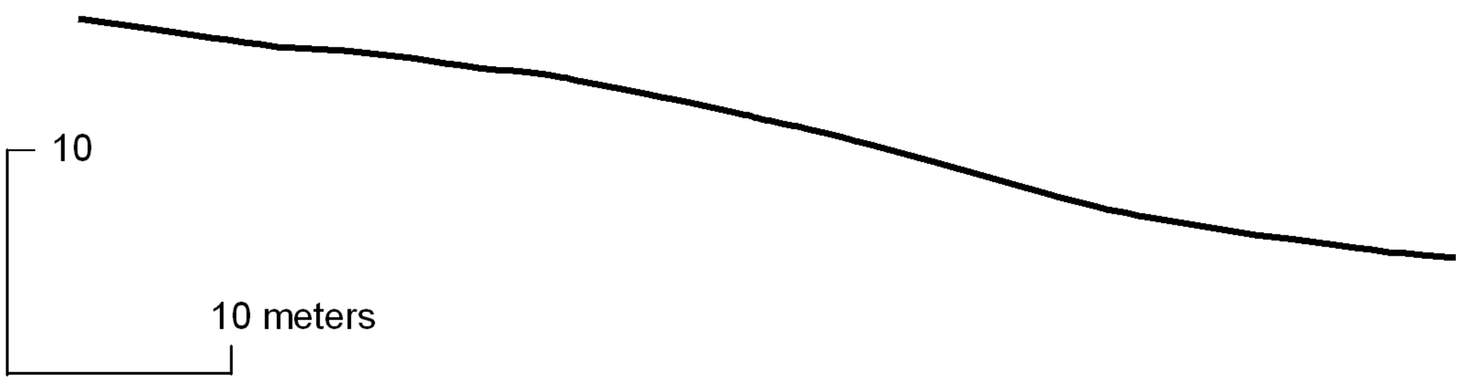
Scale

(*from Biek and others, 2003*)



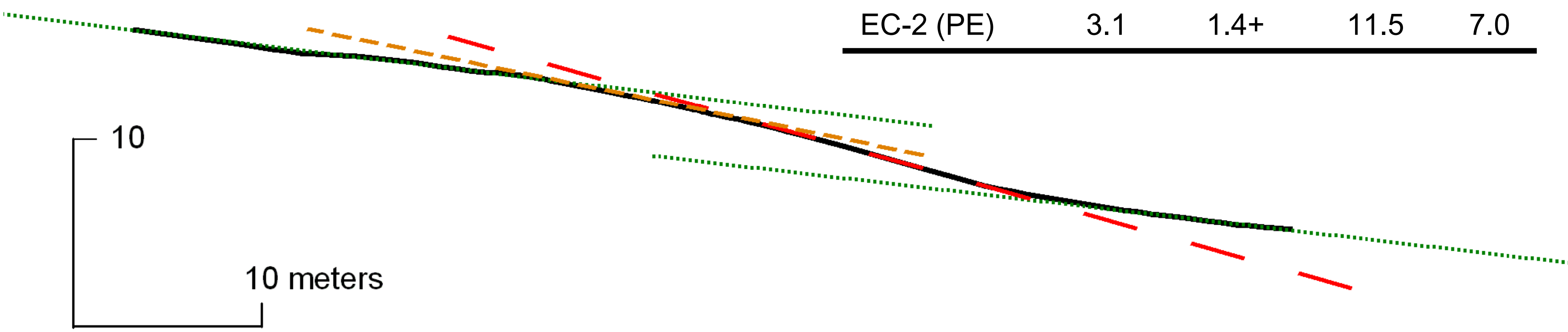
View looking northeast

Scarp Profile EC-2

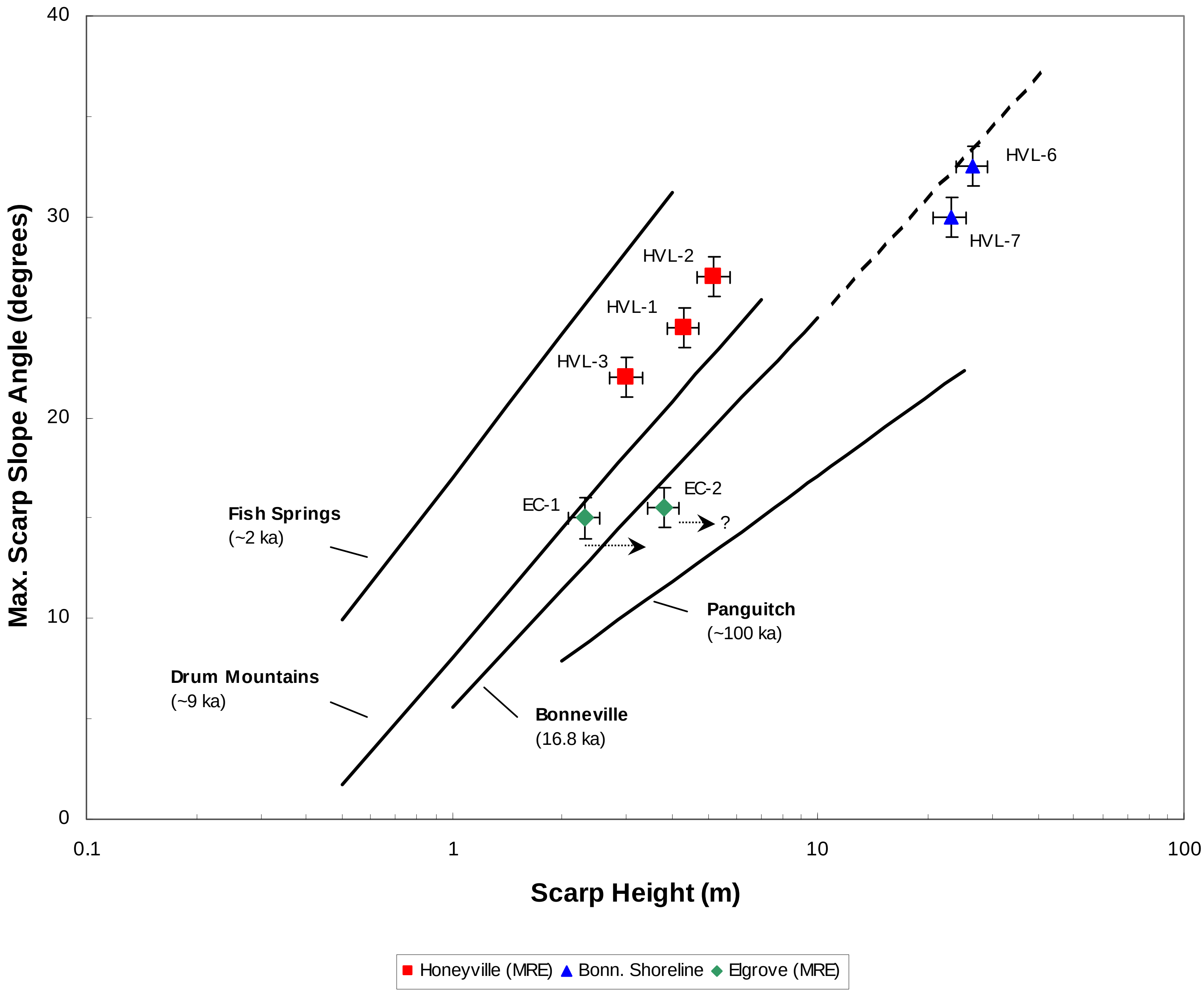


Scarp Profile EC-2

Profile	H (m)	SO (m)	θ_{max} (º)	γ (º)
EC-2 (MRE)	3.8	2.2+?	15.5	7.0
EC-2 (PE)	3.1	1.4+	11.5	7.0



Scarp Slope Angle – Scarp Height Diagram



After Bucknam and Anderson (1979)

Summary of surface offsets at Elgrove Canyon

Profile	Event	SO (m)
EC-1	MRE	0.6+
	PE	0.5+
EC-2	MRE	2.2+?
	PE	1.4+

Wells & Coppersmith (1994) displacements, from surface rupture length (SRL)

SRL = 20 km (**M** 6.6):

Av. Displacement = 0.42 m (N) to 0.52 m (All)

Max. Displacement = 0.88 m (All) to 0.96 m (N)

SRL = 27 km (incl. Short Divide fault):

Av. Displacement = 0.61 m (N) to 0.68 m (All)

Max. Displacement = 1.2 m (All) to 1.5 m (N)

SRL = 34 km (incl. Short Divide fault and concealed, parallel fault to south) (**M** 6.9):

Av. Displacement = 0.81 m (N) to 0.83 m (All)

Max. Displacement = 1.5 m (All) to 2.1 m (N)

W&C datasets: N*, normal faults;* All*, strike-slip, reverse, and normal faults.*

2005 NEPHI SEGMENT FAULT TRENCHING

Utah Geological Survey

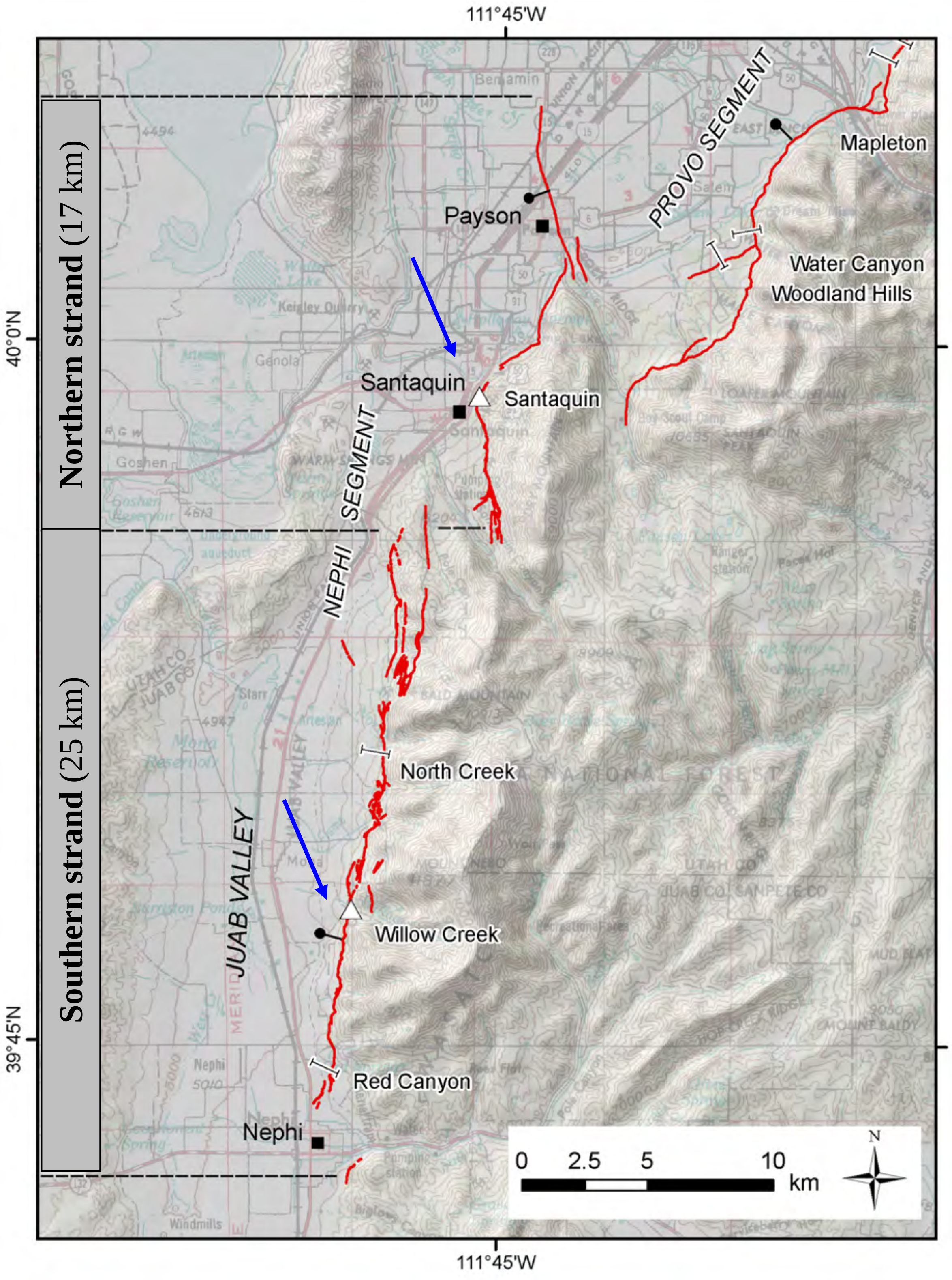
McDonald, Lund, Kirschbaum [NEHRP]

U.S. Geological Survey

Machette, Crone, Personius, Lidke, Dart, Olig

2 new trench sites (USFS)

- Santaquin (UGS)
- Willow Creek (USGS)



Background

Existing trench sites

- North Creek
  (Hanson and others, 1981)
- Red Canyon
  (Jackson, 1991)

EQ timing:

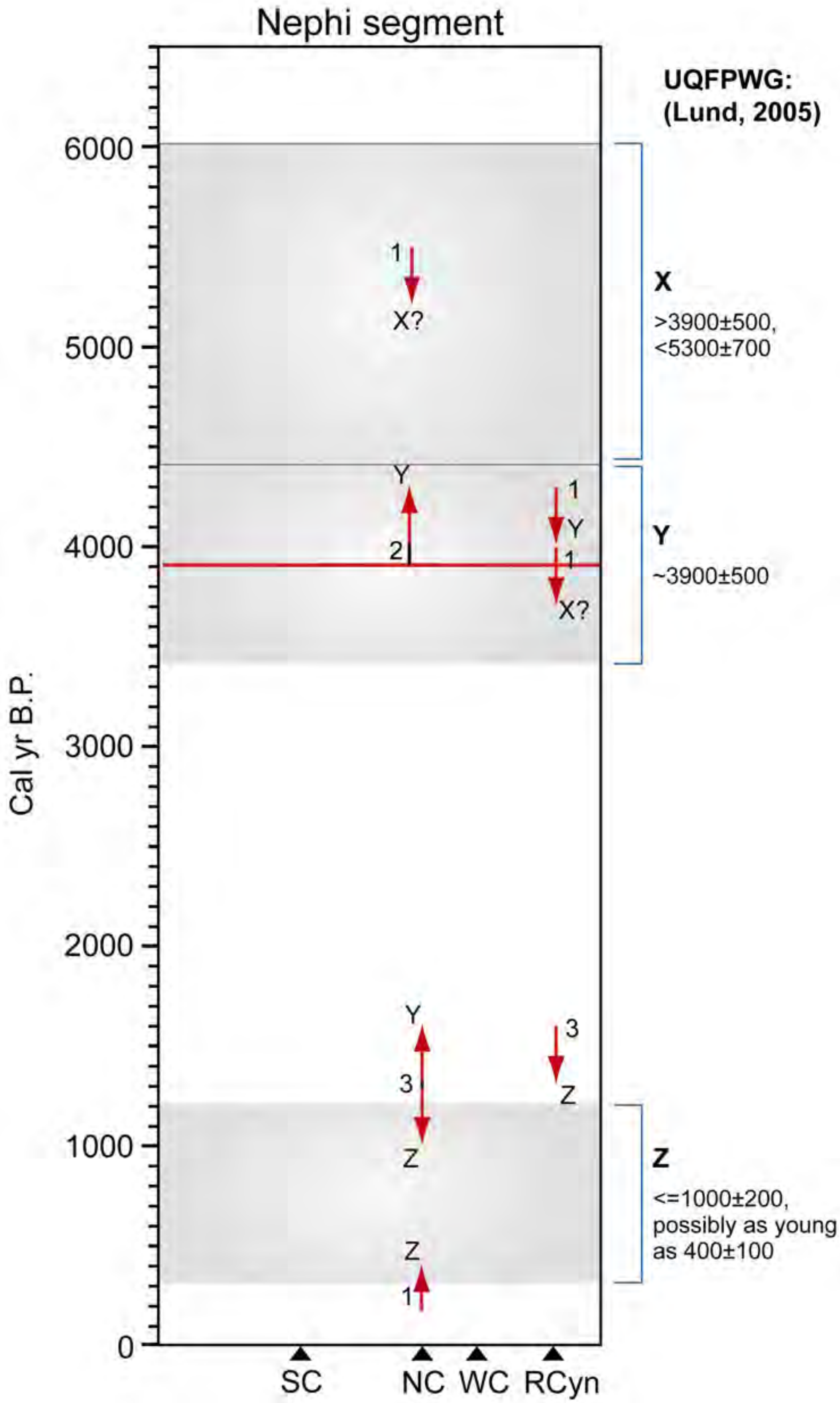
3 earthquakes after ~5300 yr

Recurrence interval:

1200-**2500**-4800 yr

Slip rate:

0.5-**1.1**-3.0 mm/yr



Why trench the northern Nephi segment?

1. **No paleoseismic data for northern 25 km of segment**
   - Northern-strand EQ history**?**

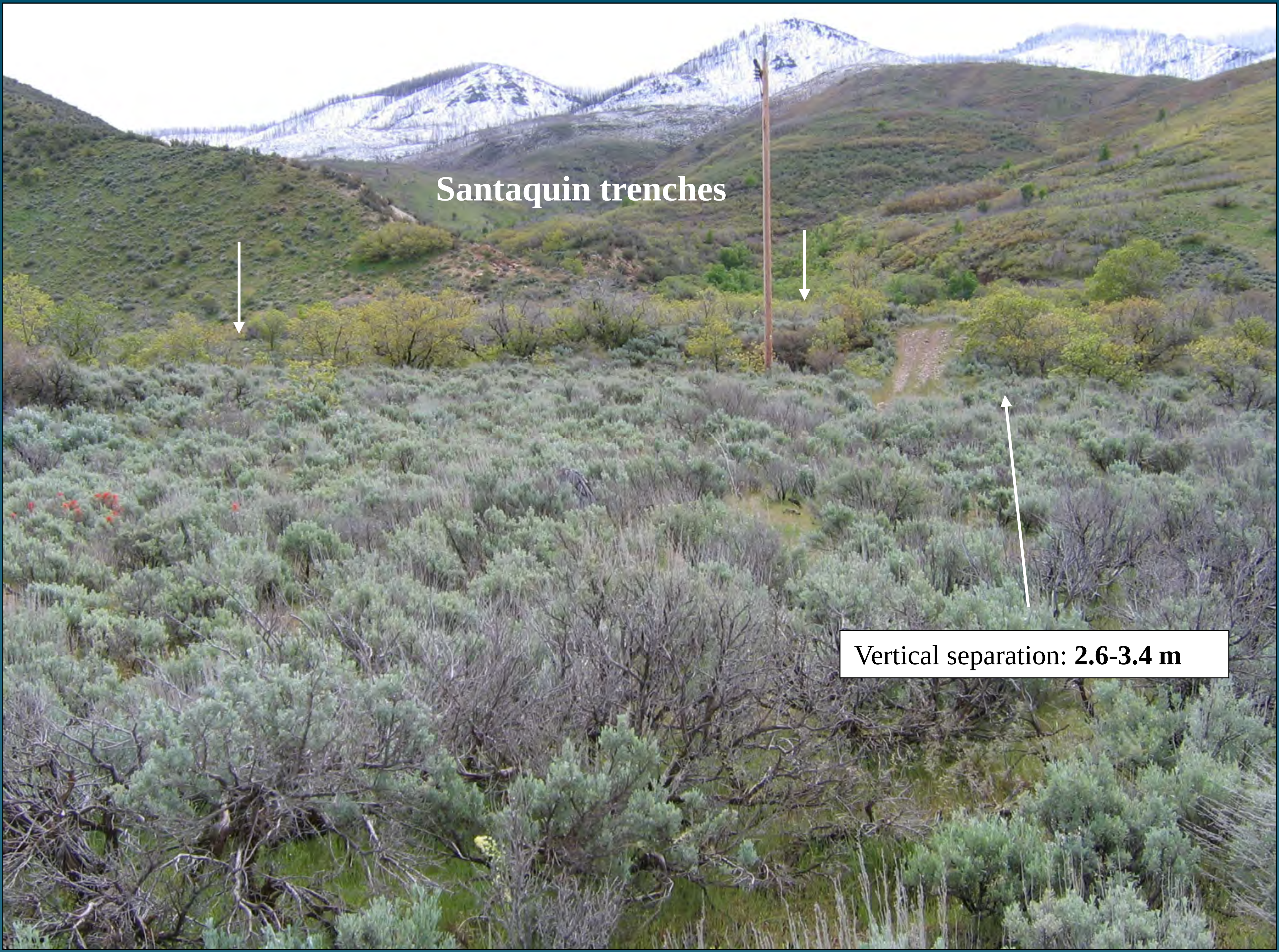
2. **Poor existing paleoseismic data for southern strand**
   - Need to refine Holocene EQ history

3. **Resolve questions regarding potential for:**

   - **Partial segment ruptures** on Nephi segment
     (N and S strands act independently?)
   - **Rupture spill-over**: Provo $\longleftrightarrow$ northern Nephi

4. **Characterize southern WFZ earthquake parameters**

Santaquin site

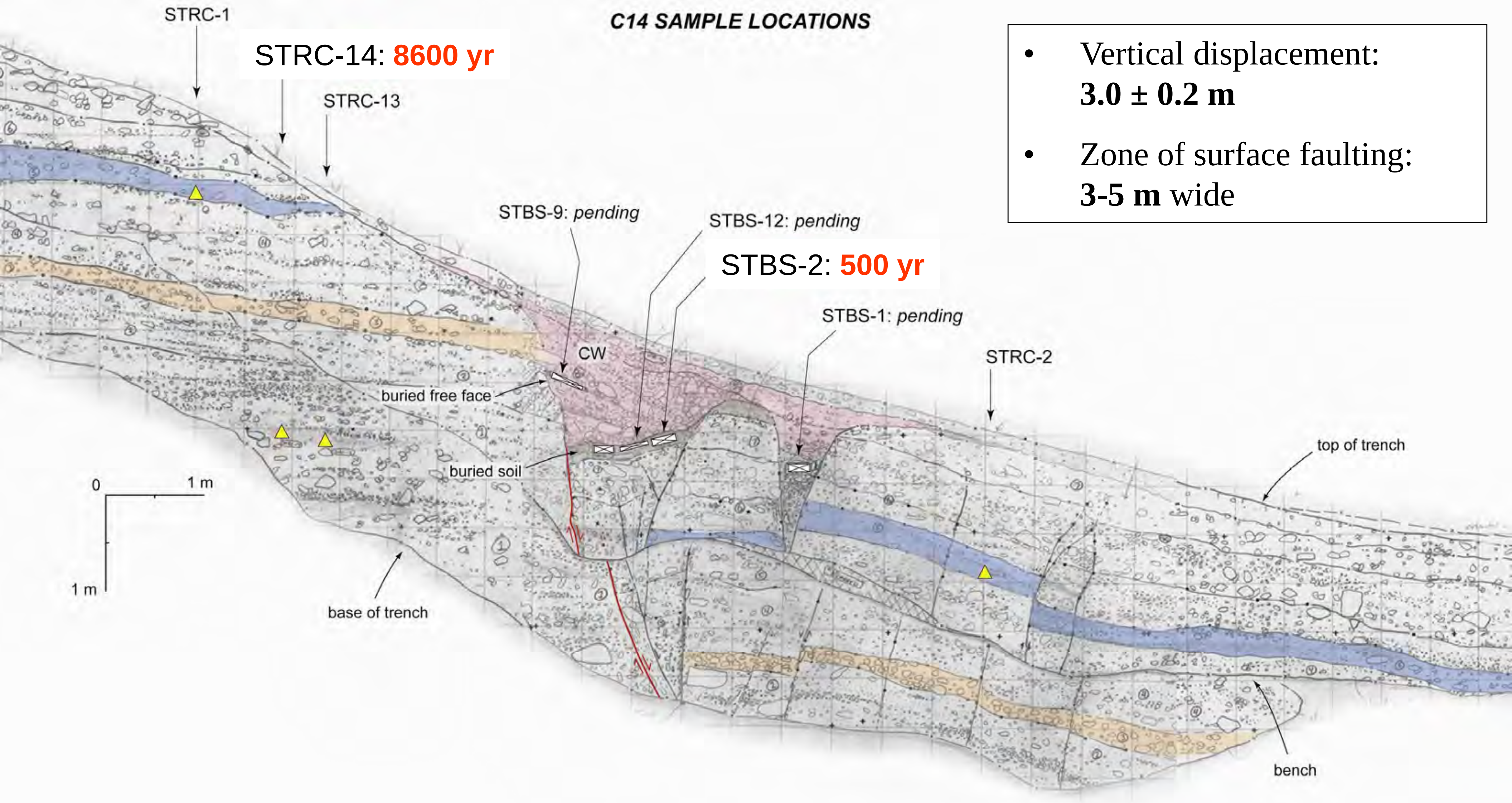


Santaquin site

Trench 2, south wall

Santaquin site

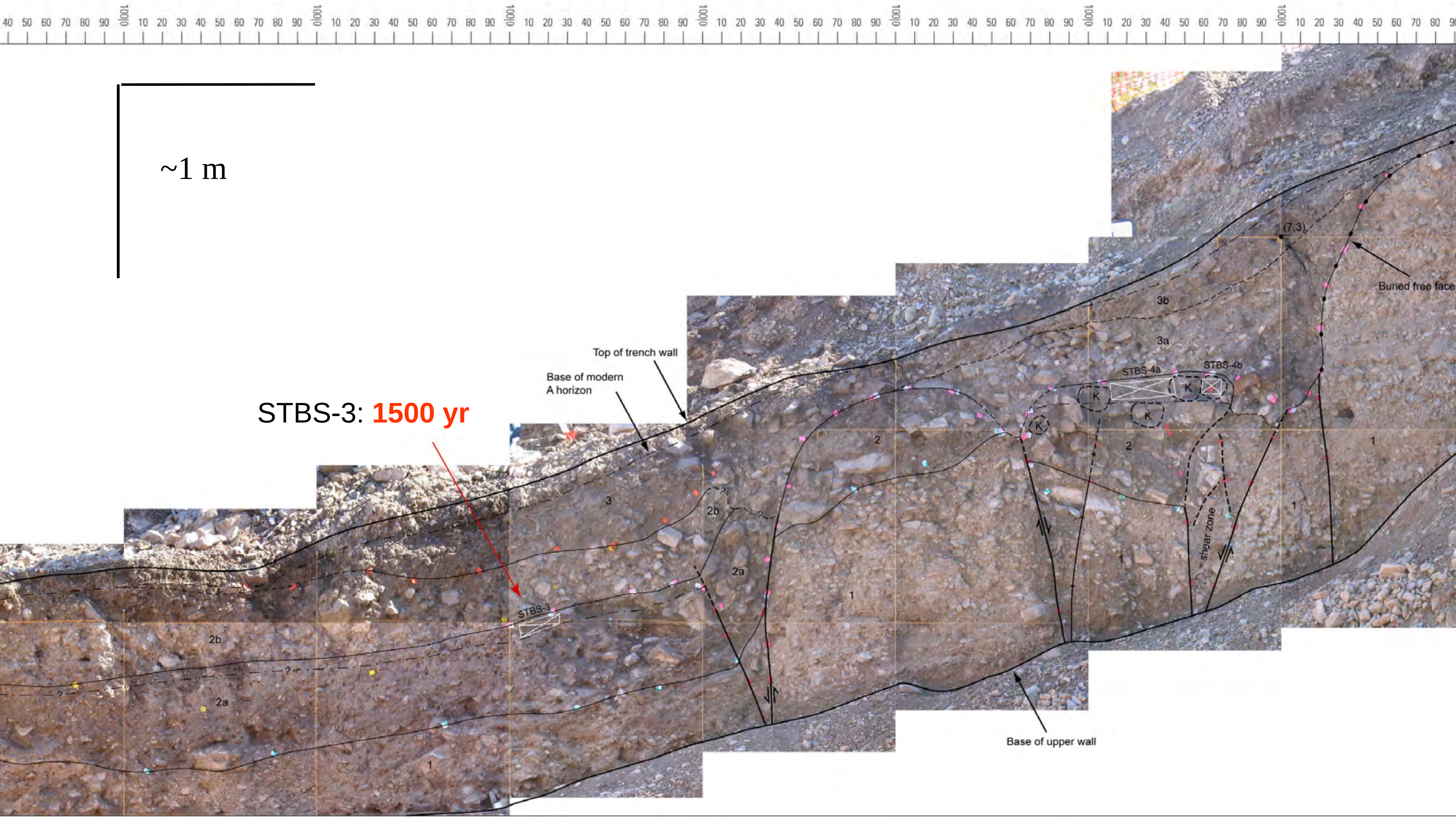
Trench 2, south wall



- Vertical displacement: **3.0 ± 0.2 m**
- Zone of surface faulting: **3-5 m** wide

Santaquin site

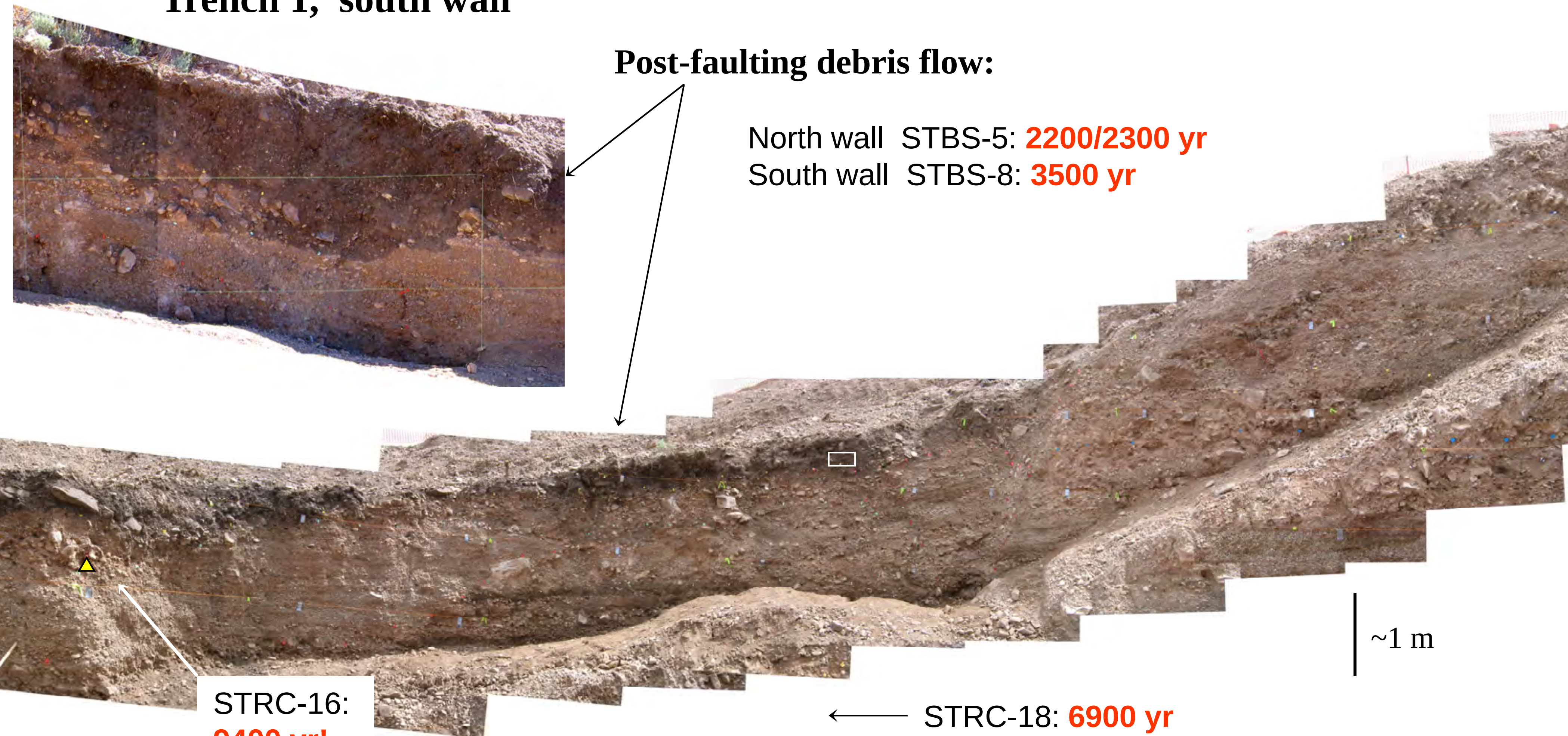
Trench 2, north wall



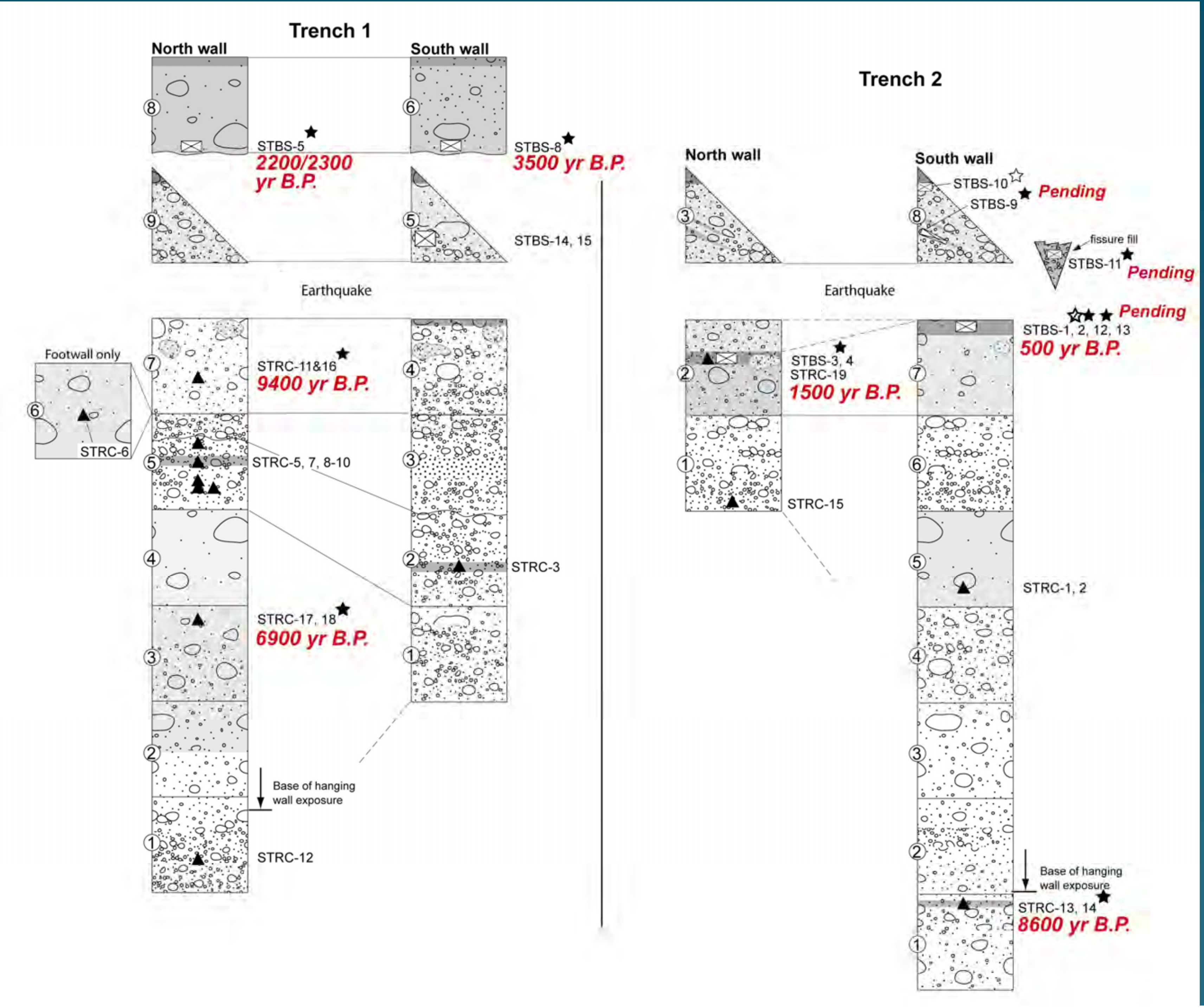
Santaquin site

Trench 1, north wall

Trench 1, south wall



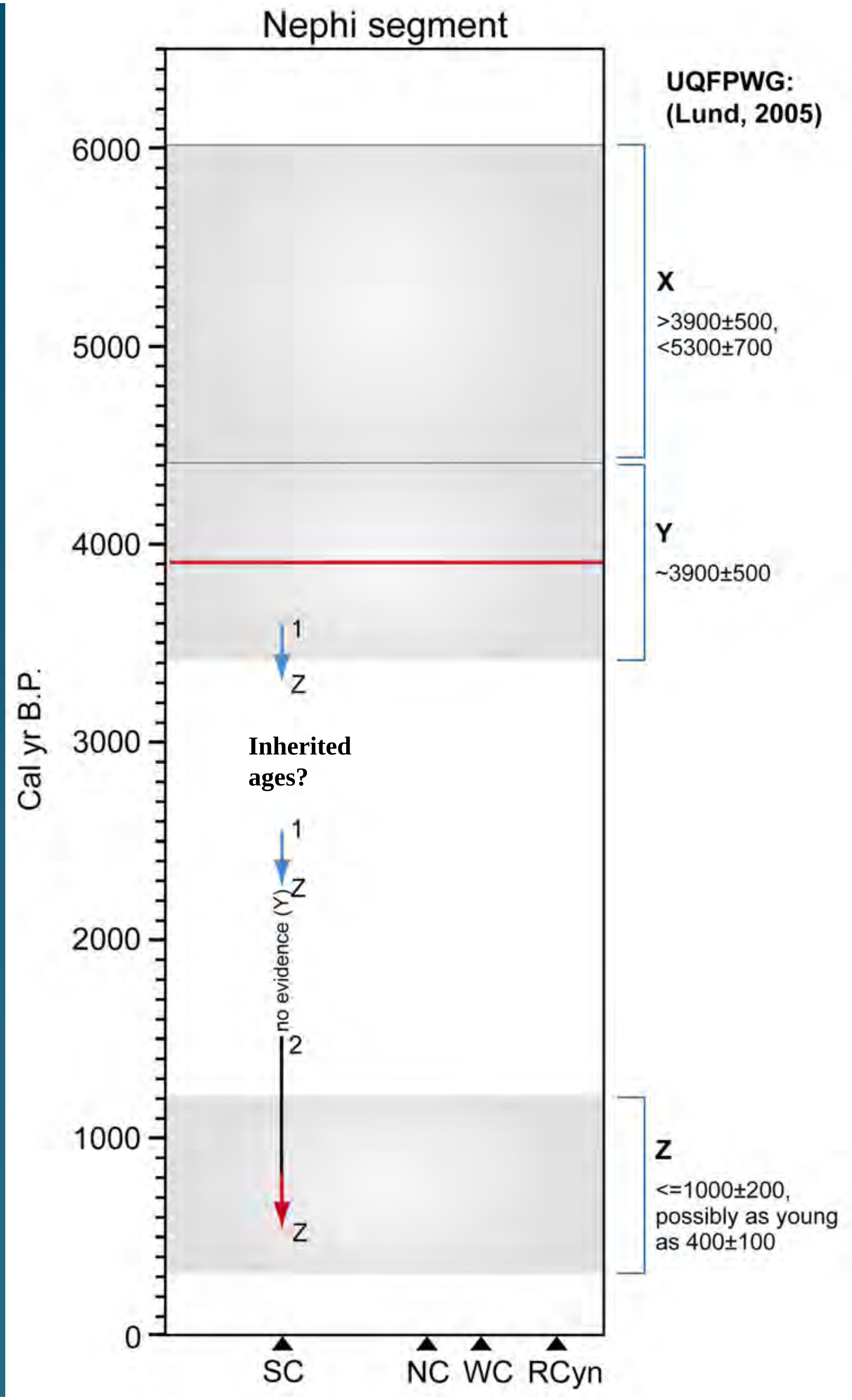
Santaquin site



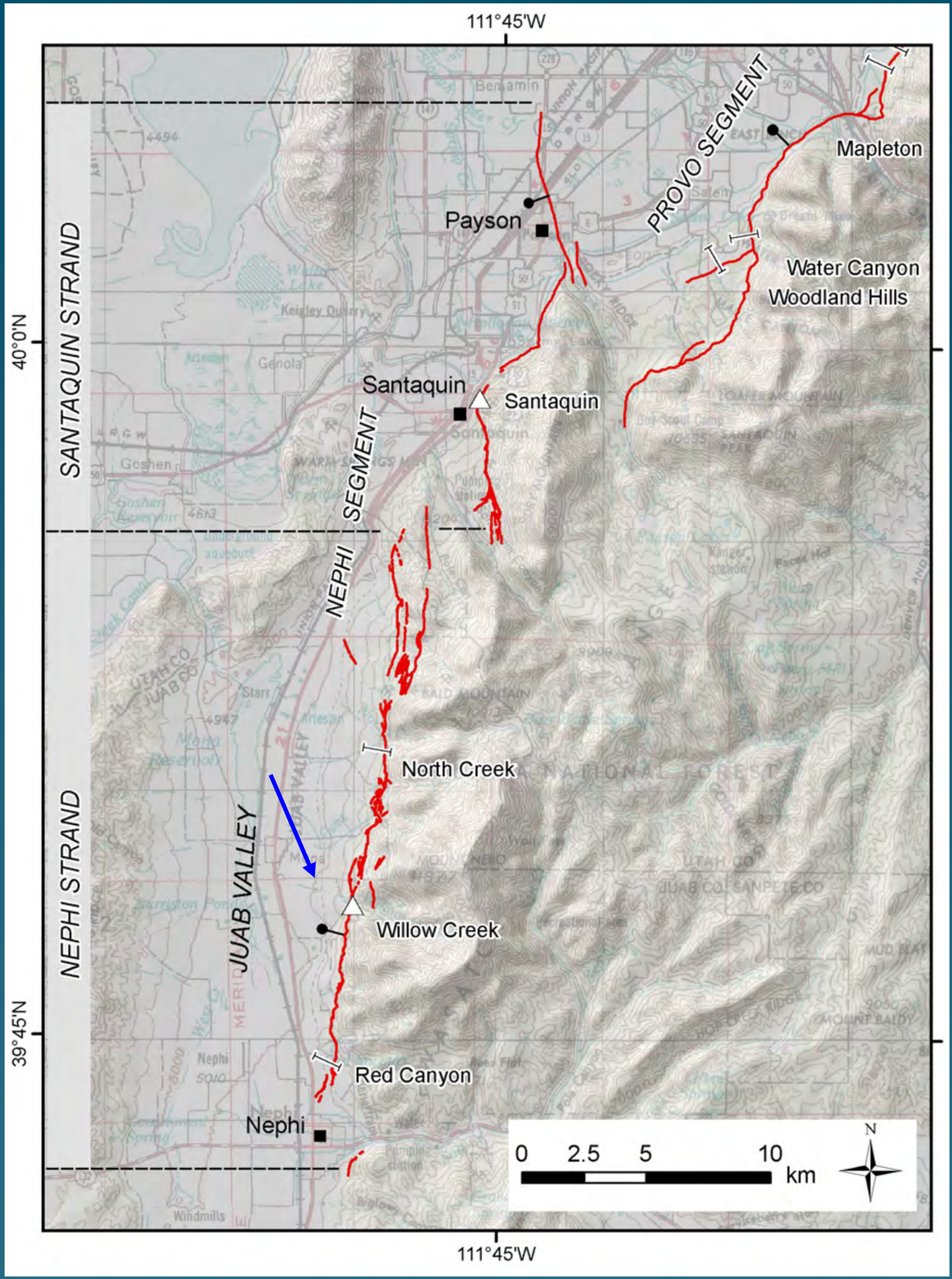
Santaquin site

Santaquin Paleoseismic Data

- Single **3-m**-displacement earthquake during the mid-Holocene.
- ***Preliminary* EQ timing** ~500 yrs
- **Recurrence?** Y(?)-Z: > 5400-6400 yrs



Willow Creek site



Willow Creek Site

Willow Creek Site

3 colluvial wedges:

CW1

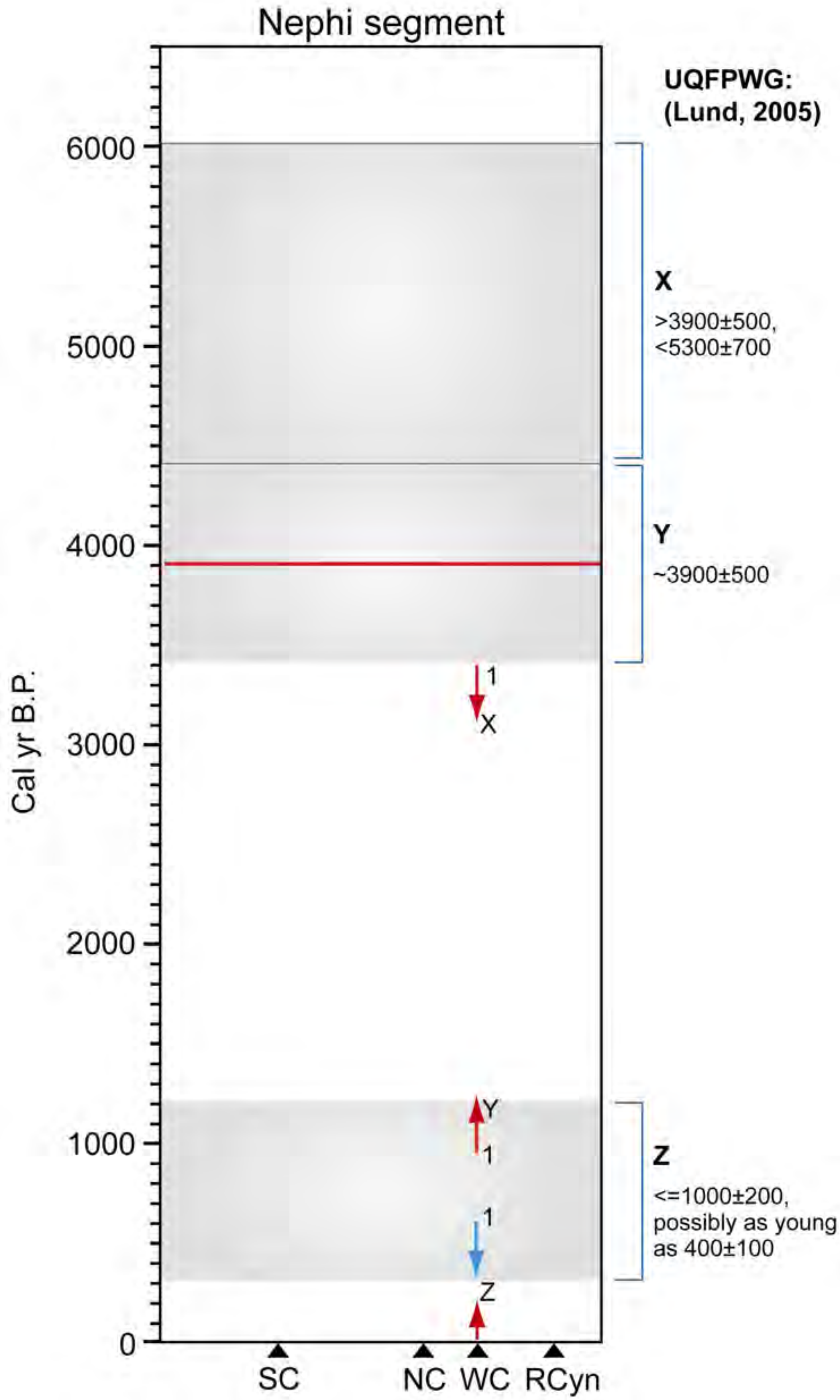
CW2

CW3

Nephi Segment Earthquake Timing

Willow Cr. Paleoseismic Data

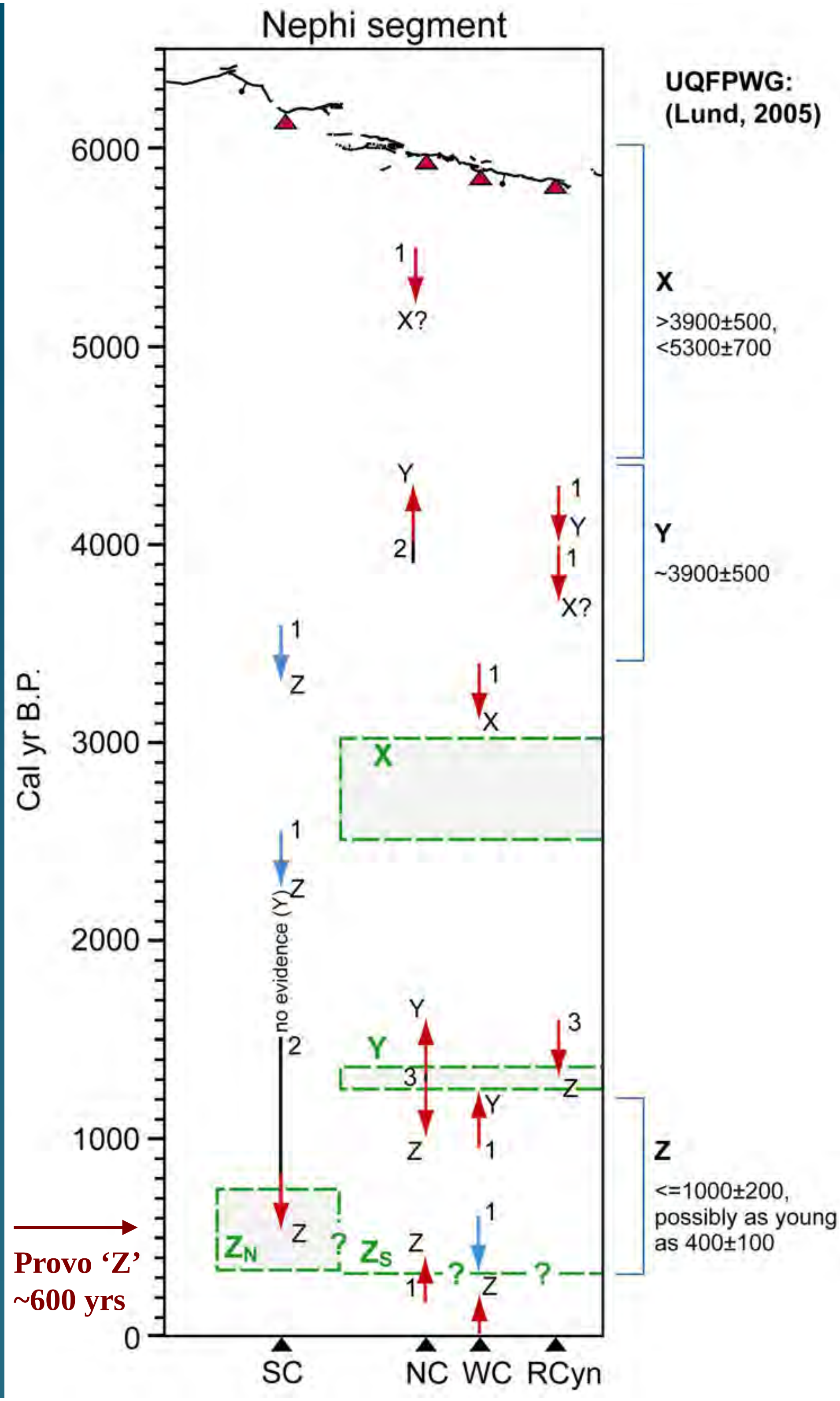
- 3 events after 3100 yrs
- **Recurrence:**
  X-Y: ≤ 1800 yrs
  Y-Z: ≤ 1000 yrs
- **Slip rate:**
  4-5m (Y & Z)/3 ky = 1.3-1.7 mm/yr



Nephi Segment Earthquake Timing

Questions answered

1. Northern-strand EQ history?
   1 mid-Holocene event
2. Southern-strand history?
   3 events after ~3100 yr
3. Partial segment ruptures?
   Yes (mostly)
4. Potential for Provo-segment EQ to influence Santaquin strand?
   High
5. Potential for northern-Nephi to Provo spill-over?
   Low

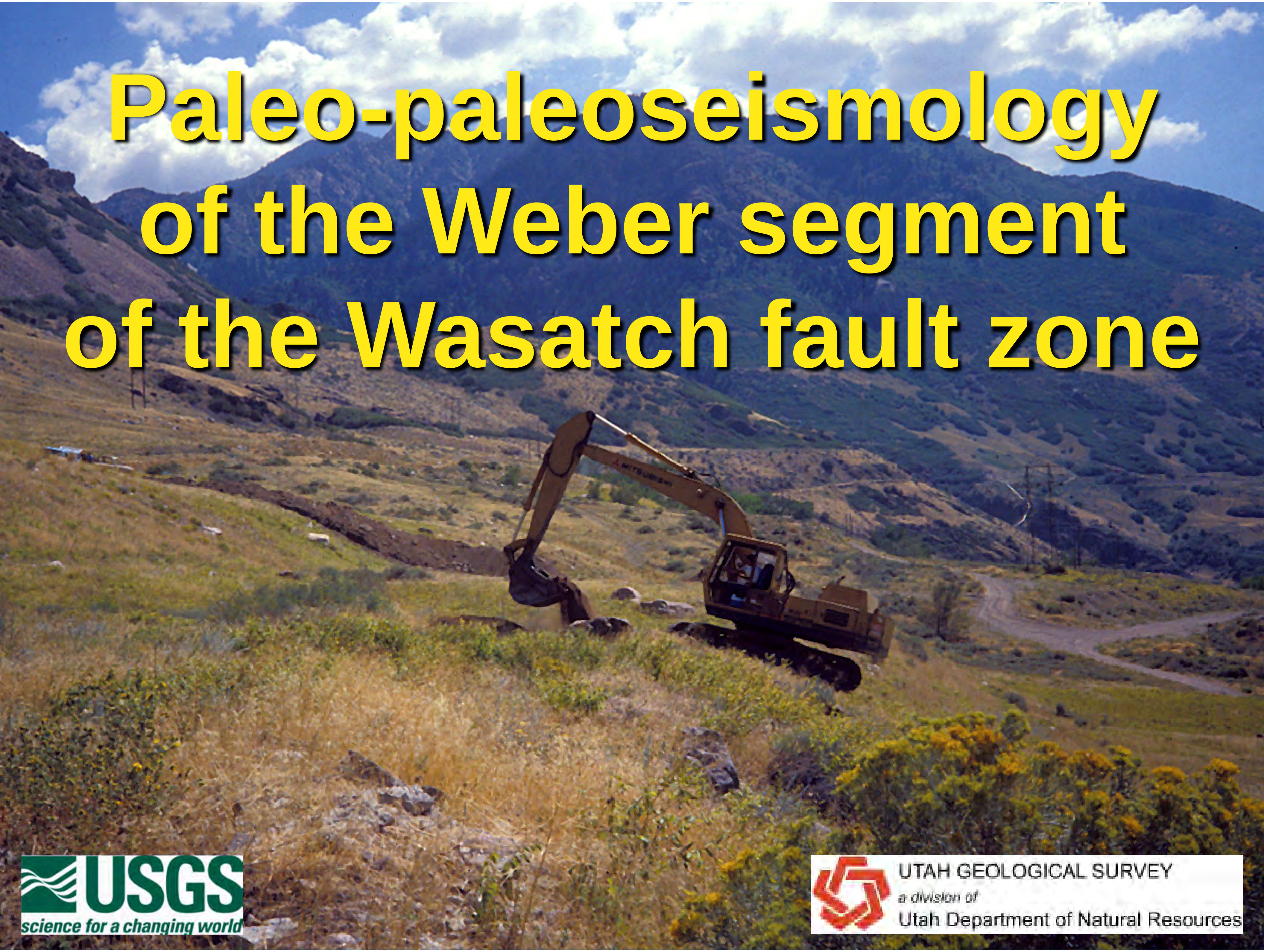


Nephi Segment Earthquake Timing

Remaining work/questions

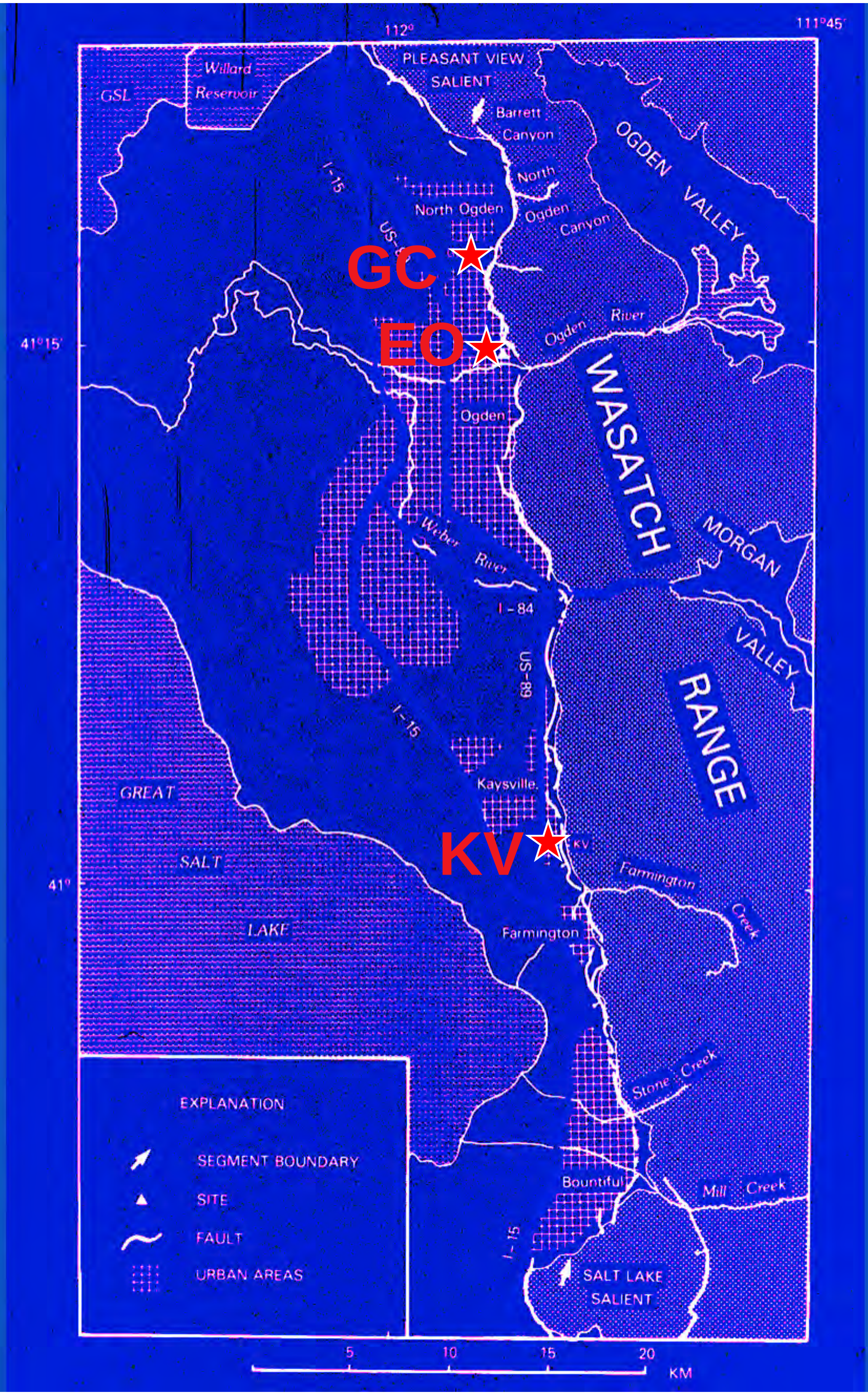
- Refine Santaquin and Willow Creek MREs & PE (WC)
- Southern strand always rupture separately?
- Extent of 3-m Santaquin MRE - northern strand part of large, infrequent MSRs?
- Early Holocene EQ history on both strands?

Paleo-paleoseismology of the Weber segment of the Wasatch fault zone

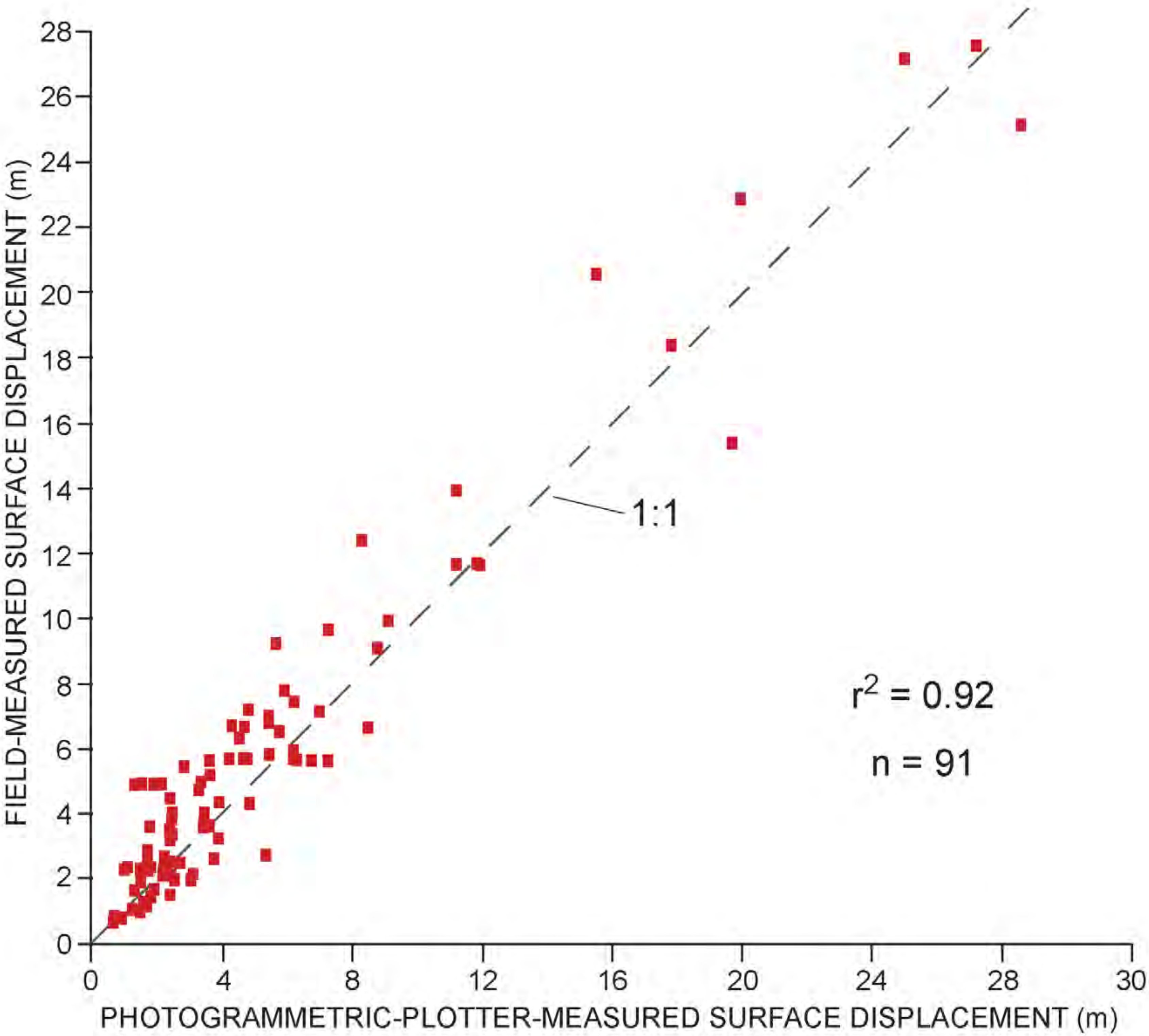


USGS
science for a changing world

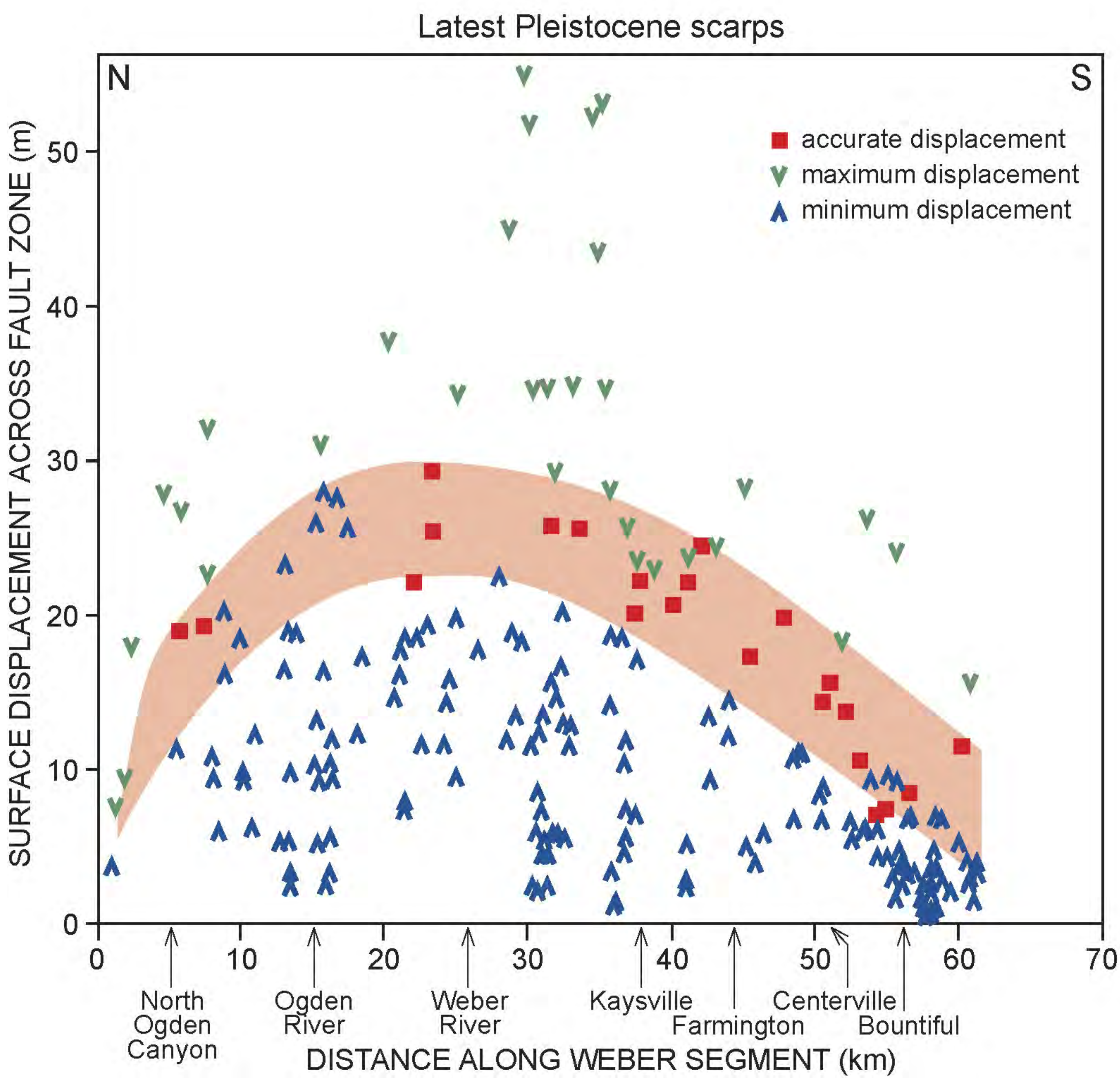
UTAH GEOLOGICAL SURVEY
a division of
Utah Department of Natural Resources



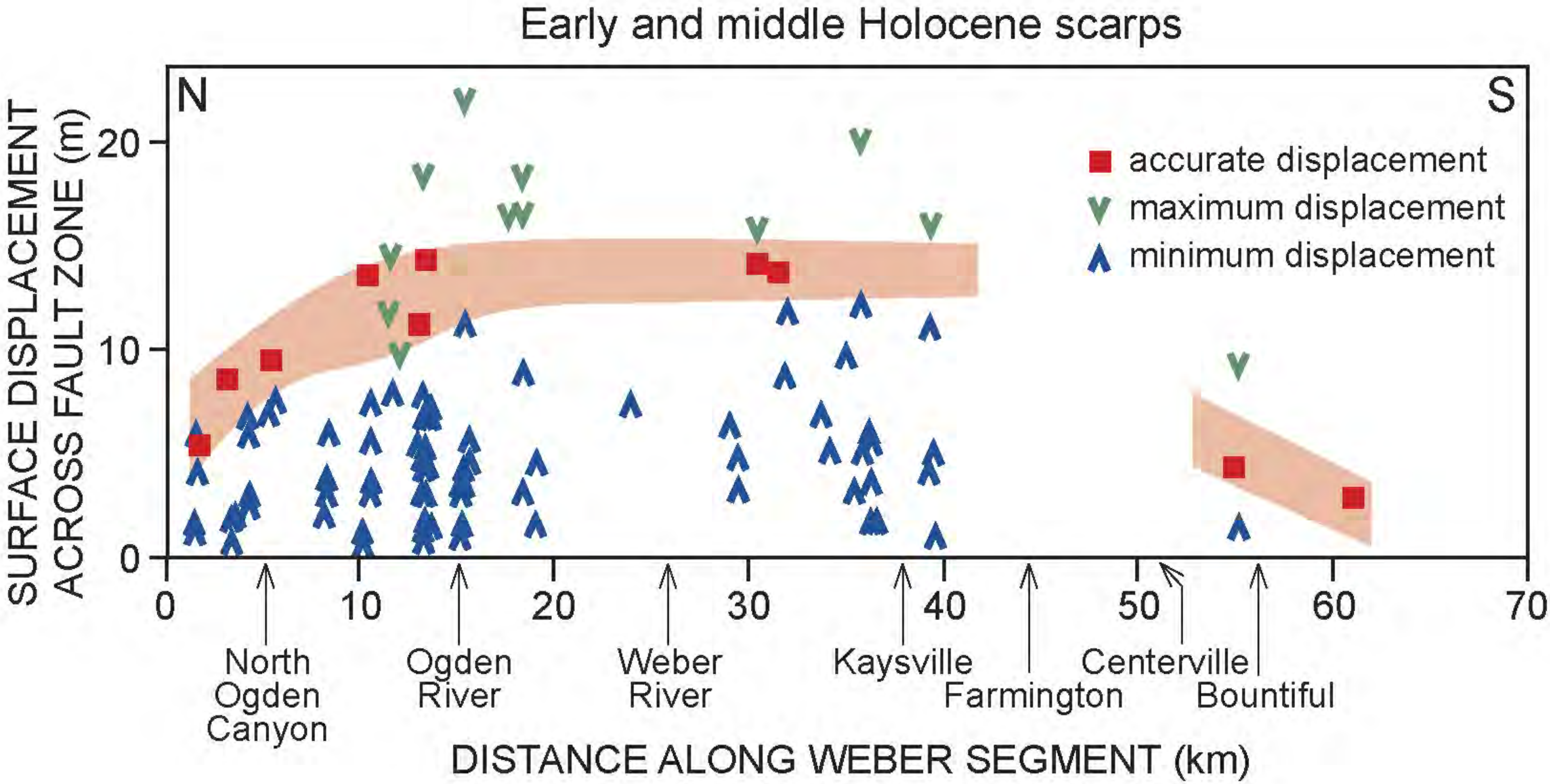
112°
111°45'
41°15'
41°
GSL
Willard Reservoir
PLEASANT VIEW SALIENT
Barrett Canyon
North Ogden Canyon
OGDEN VALLEY
North Ogden
GC
EO
Ogden River
Ogden
WASATCH
RANGE
MORGAN VALLEY
Weber River
I-84
I-15
US-89
Kaysville
KV
Farmington Creek
Farmington
GREAT SALT LAKE
Stone Creek
Mill Creek
Bountiful
SALT LAKE SALIENT
EXPLANATION
SEGMENT BOUNDARY
SITE
FAULT
URBAN AREAS
5
10
15
20
KM

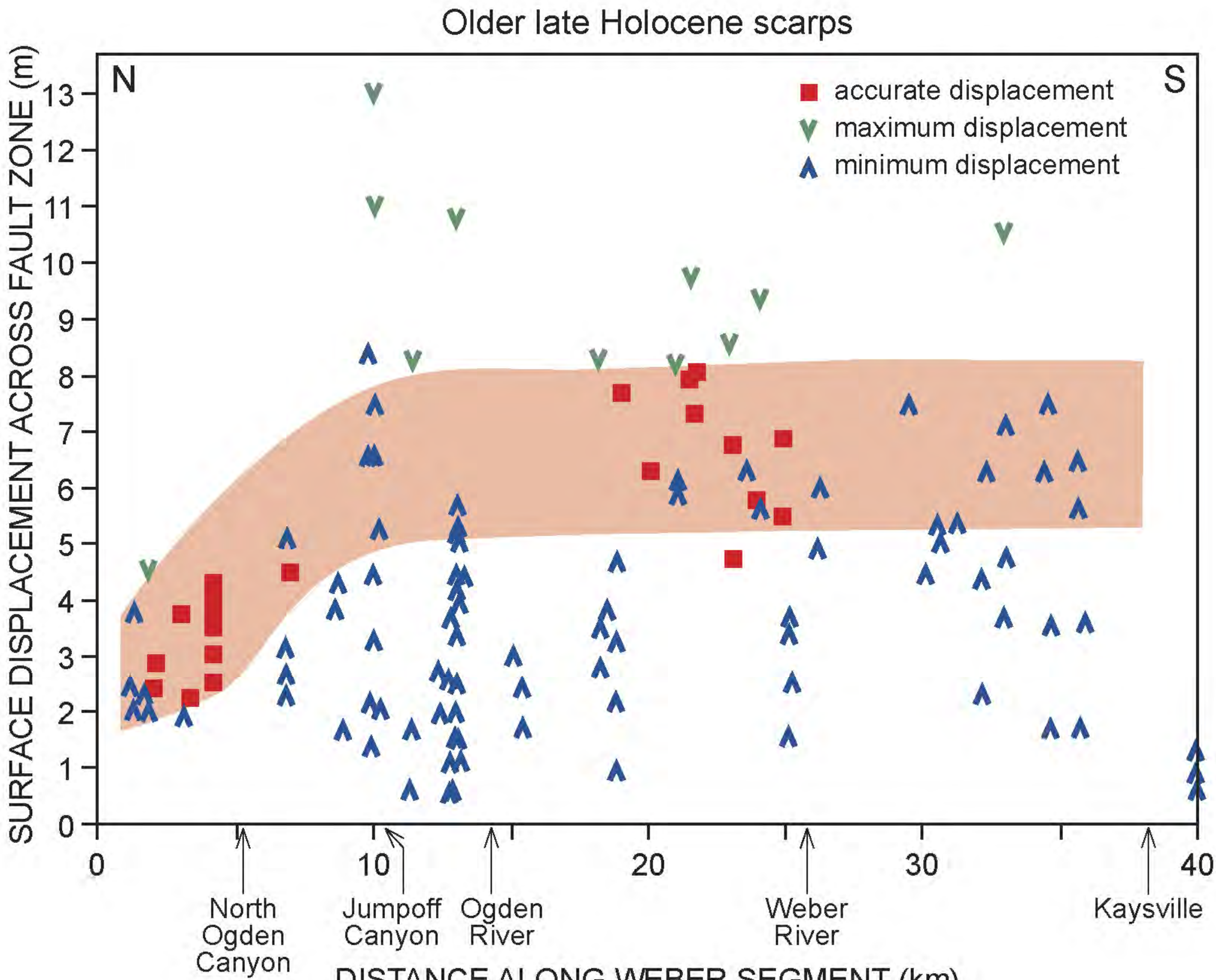


FIELD-MEASURED SURFACE DISPLACEMENT (m)
PHOTOGRAMMETRIC-PLOTTER-MEASURED SURFACE DISPLACEMENT (m)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
4
8
12
16
20
24
28
30
1:1
r2 = 0.92
n = 91

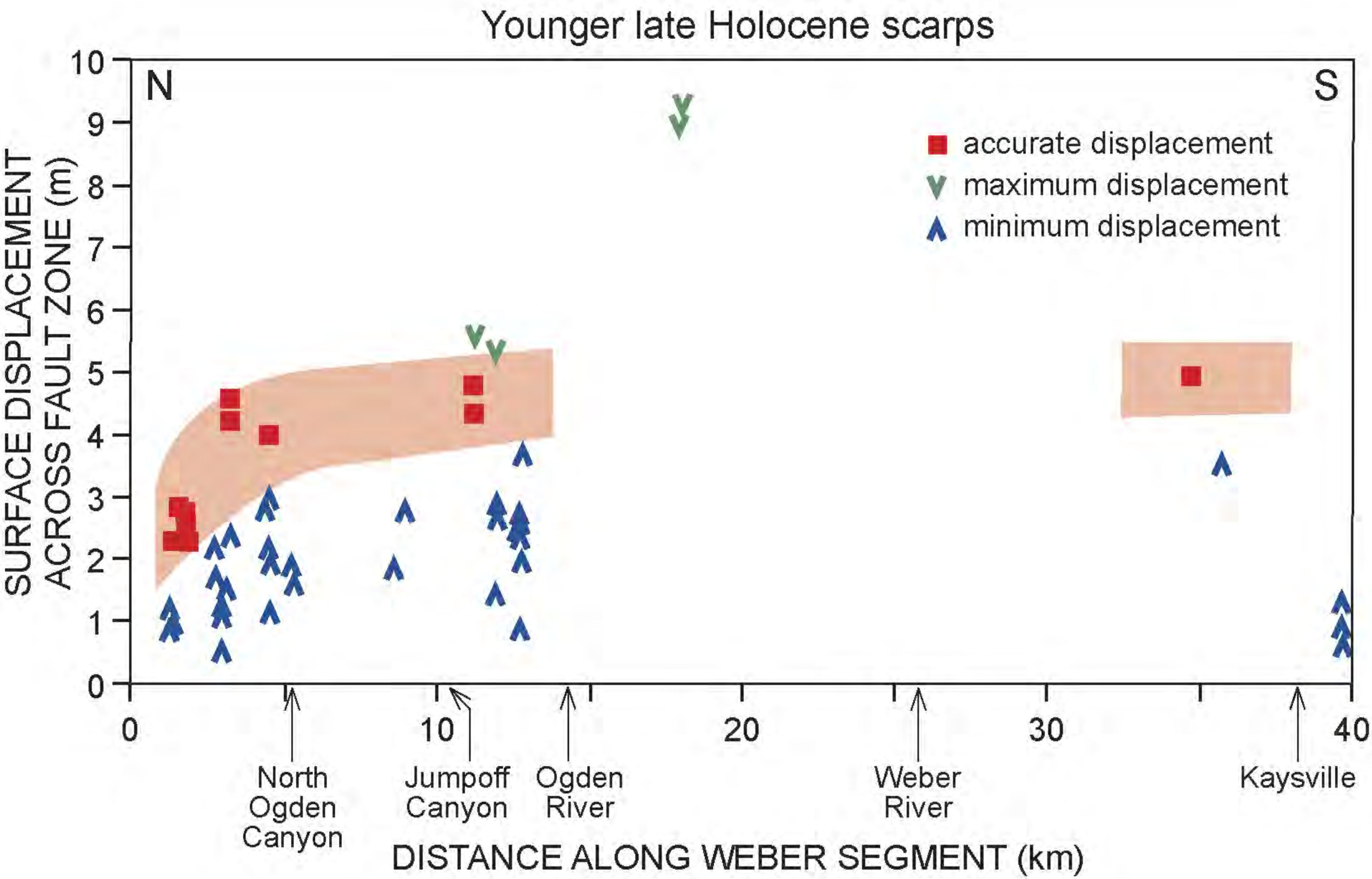


Latest Pleistocene scarps
N
S
accurate displacement
maximum displacement
minimum displacement
SURFACE DISPLACEMENT ACROSS FAULT ZONE (m)
0
10
20
30
40
50
0
10
20
30
40
50
60
70
North Ogden Canyon
Ogden River
Weber River
Kaysville
Farmington
Centerville
Bountiful
DISTANCE ALONG WEBER SEGMENT (km)

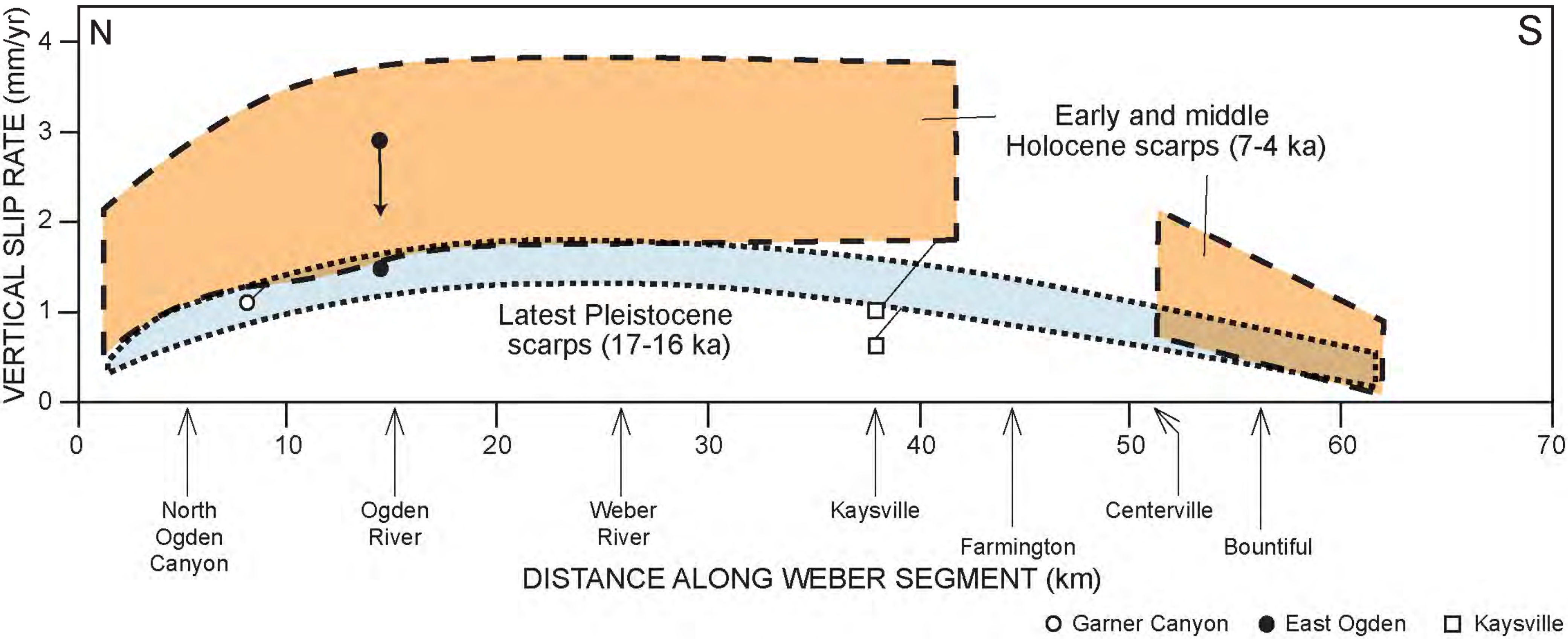

Early and middle Holocene scarps
N
S
accurate displacement
maximum displacement
minimum displacement
SURFACE DISPLACEMENT ACROSS FAULT ZONE (m)
0
10
20
0
10
20
30
40
50
60
70
North Ogden Canyon
Ogden River
Weber River
Kaysville
Farmington
Centerville
Bountiful
DISTANCE ALONG WEBER SEGMENT (km)



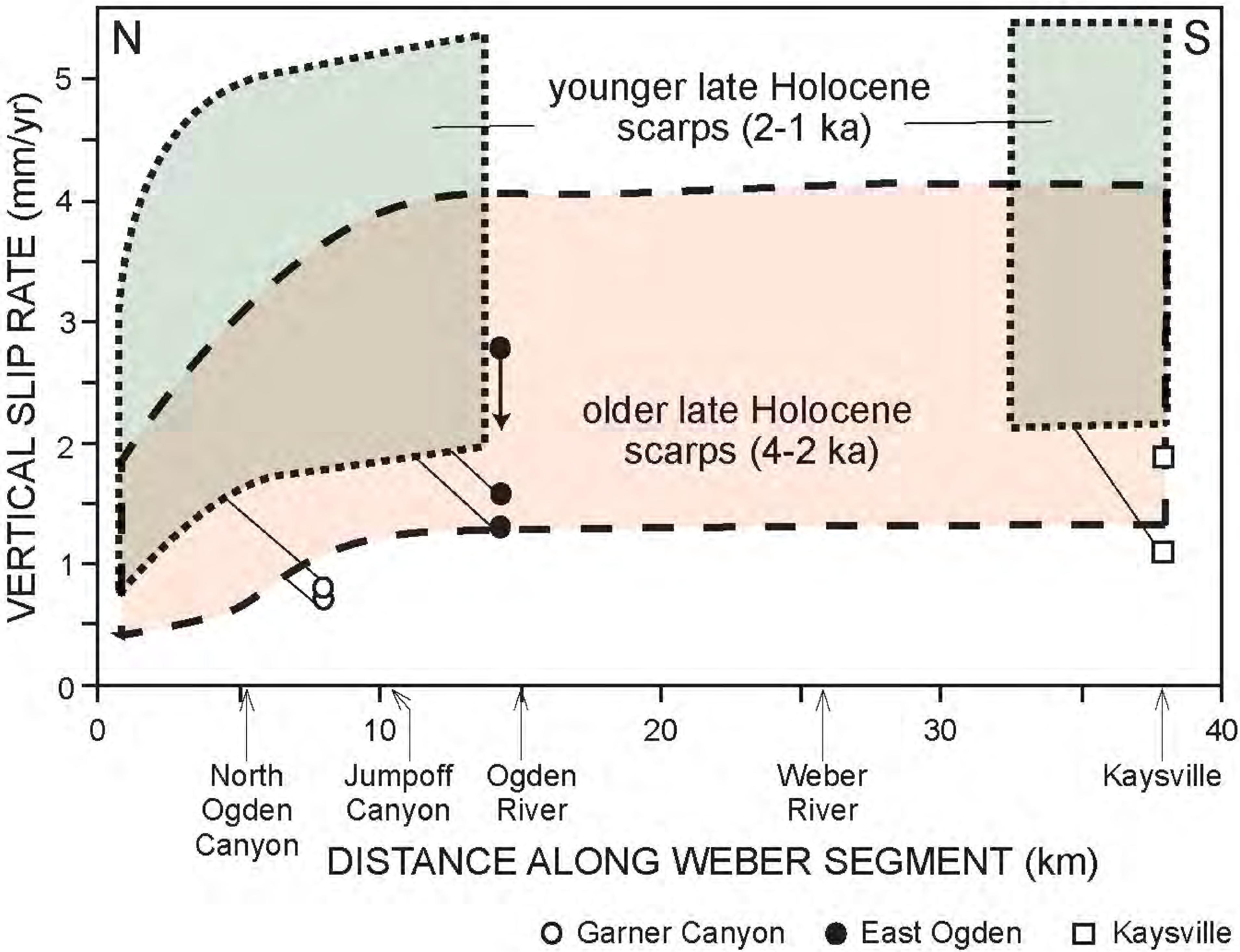
Older late Holocene scarps
N
S
accurate displacement
maximum displacement
minimum displacement
SURFACE DISPLACEMENT ACROSS FAULT ZONE (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
0
10
20
30
40
North Ogden Canyon
Jumpoff Canyon
Ogden River
Weber River
Kaysville
DISTANCE ALONG WEBER SEGMENT (km)



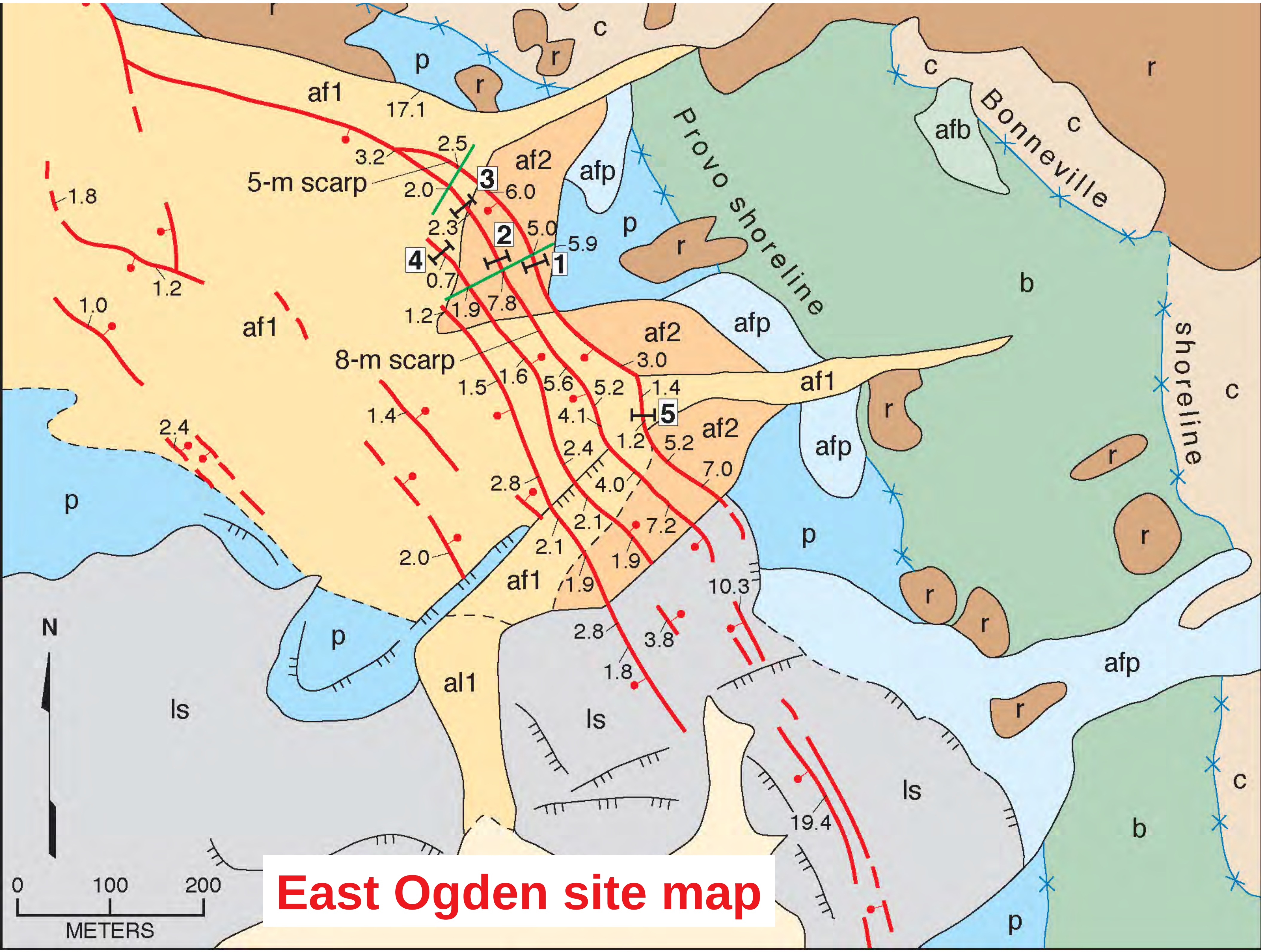
Younger late Holocene scarps
SURFACE DISPLACEMENT ACROSS FAULT ZONE (m)
N
S
accurate displacement
maximum displacement
minimum displacement
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
North Ogden Canyon
Jumpoff Canyon
Ogden River
Weber River
Kaysville
DISTANCE ALONG WEBER SEGMENT (km)



VERTICAL SLIP RATE (mm/yr)
N
S
Early and middle
Holocene scarps (7-4 ka)
Latest Pleistocene
scarps (17-16 ka)
0
1
2
3
4
0
10
20
30
40
50
60
70
North
Ogden
Canyon
Ogden
River
Weber
River
Kaysville
Farmington
Centerville
Bountiful
DISTANCE ALONG WEBER SEGMENT (km)
Garner Canyon
East Ogden
Kaysville



N
S
younger late Holocene scarps (2-1 ka)
older late Holocene scarps (4-2 ka)
VERTICAL SLIP RATE (mm/yr)
0
1
2
3
4
5
0
10
20
30
40
North Ogden Canyon
Jumpoff Canyon
Ogden River
Weber River
Kaysville
DISTANCE ALONG WEBER SEGMENT (km)
Garner Canyon
East Ogden
Kaysville

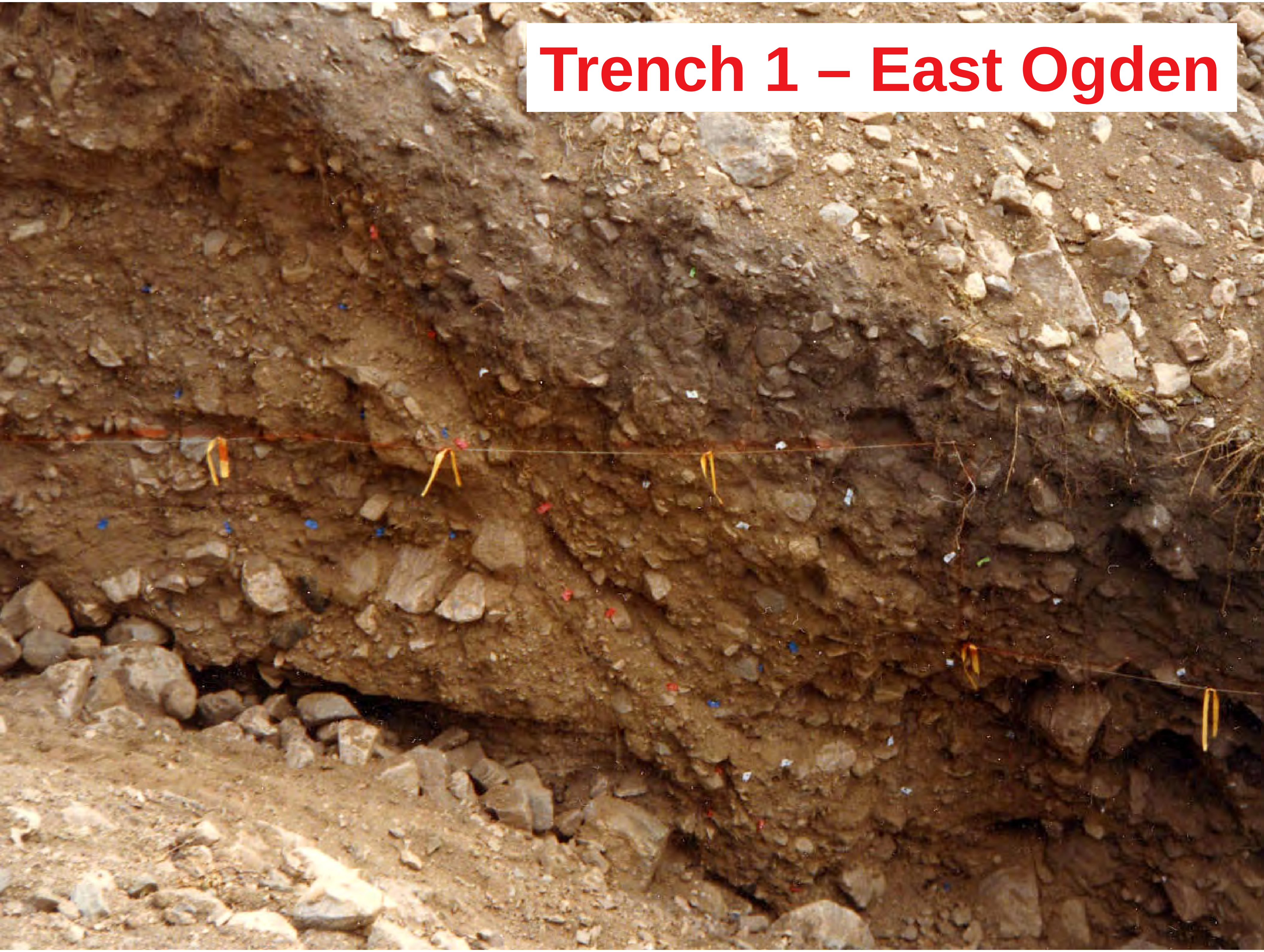


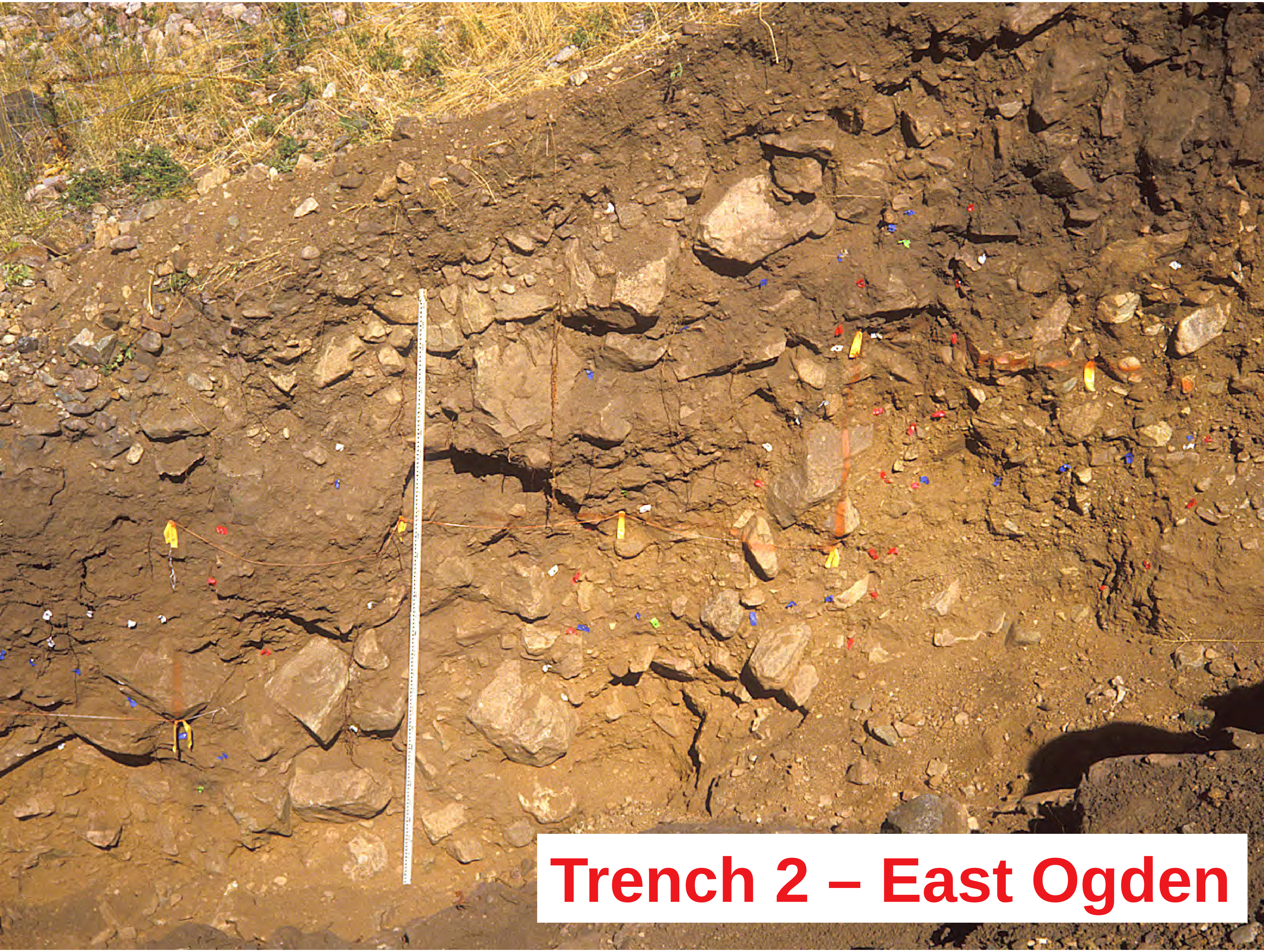
East Ogden site map

Trench 2 – East Ogden

East Ogden site
1
2
3
4
5

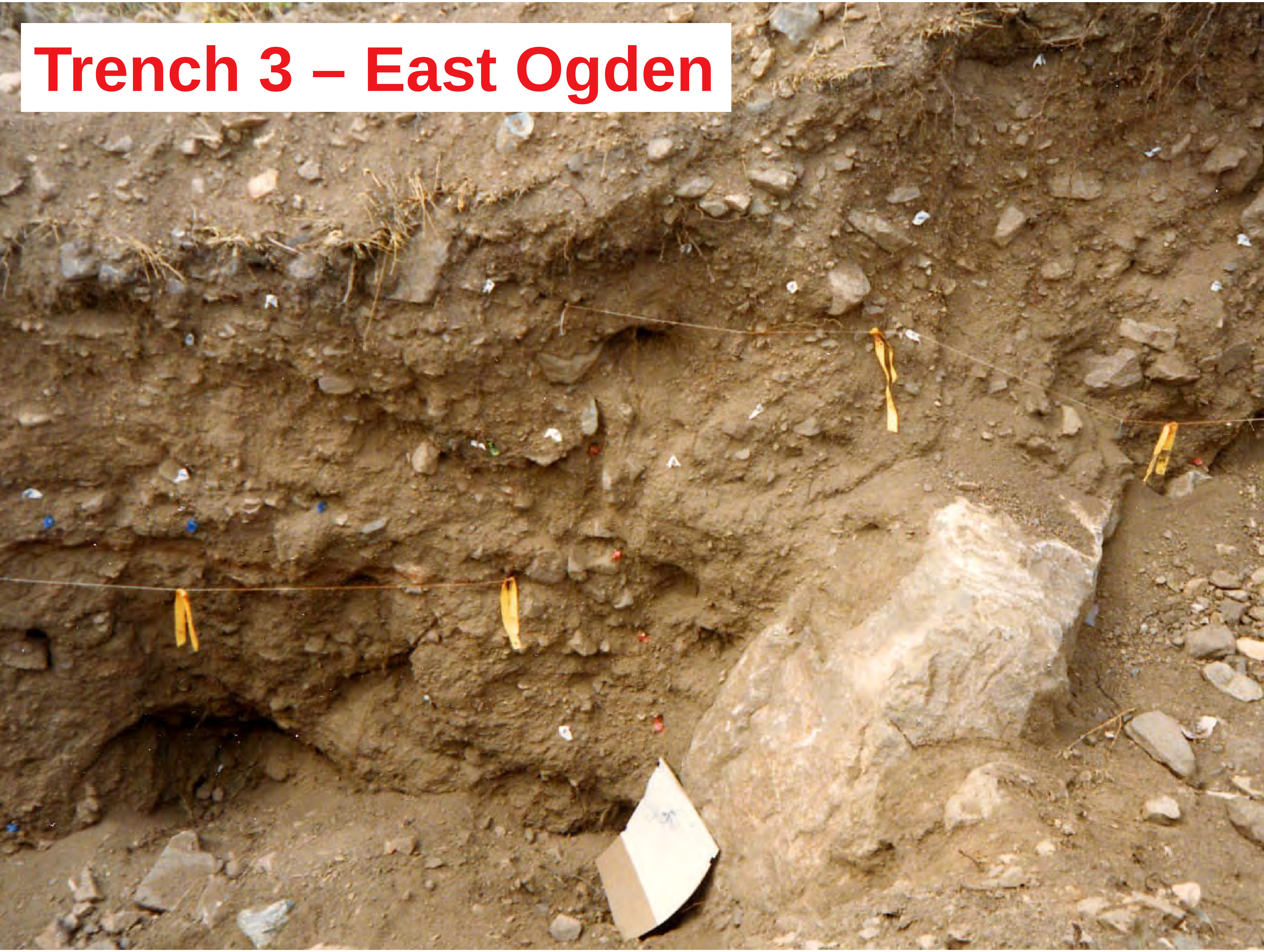

East Ogden site
1
5-m scarp
3
2
4
8-m scarp


Trench 1 – East Ogden

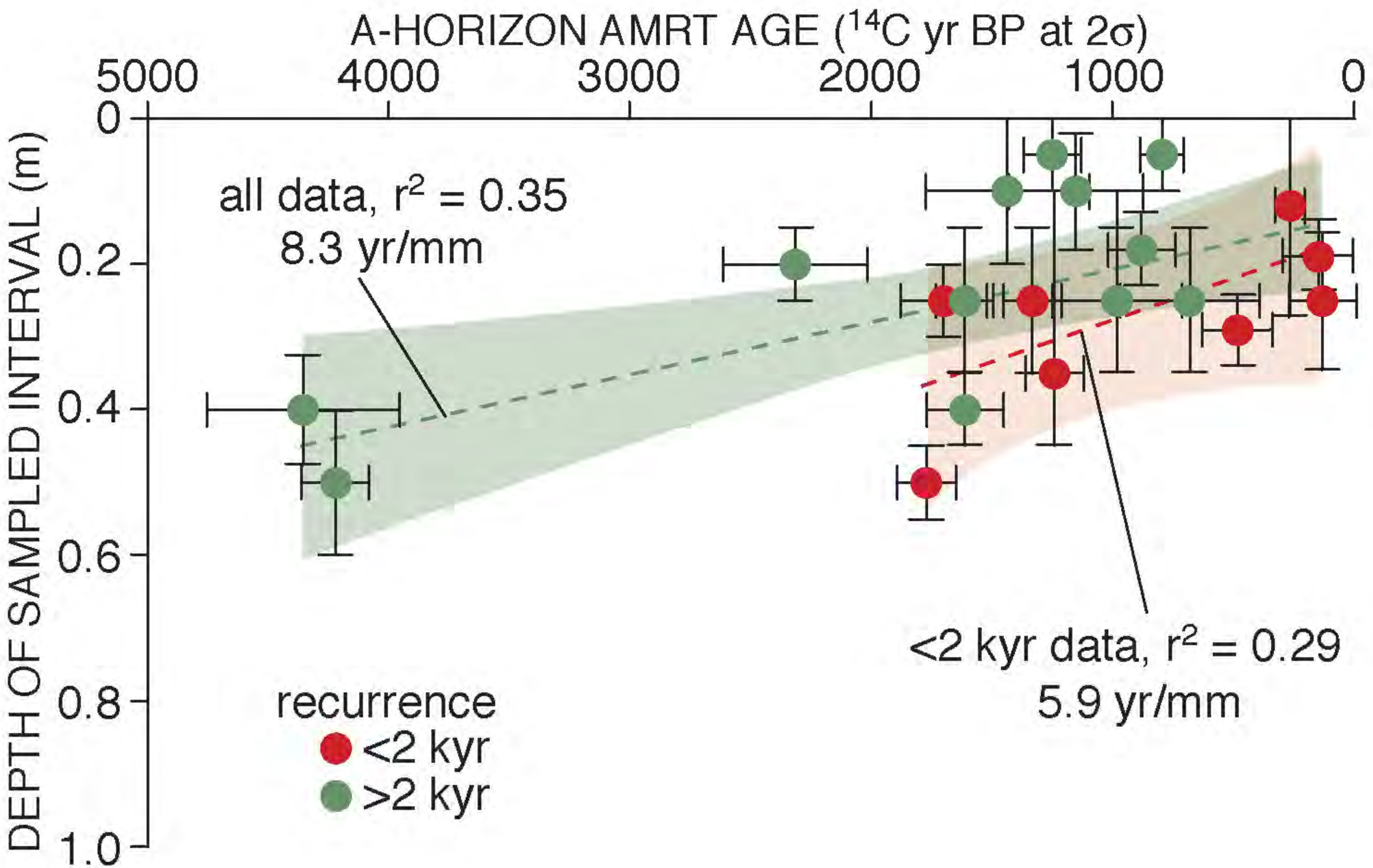


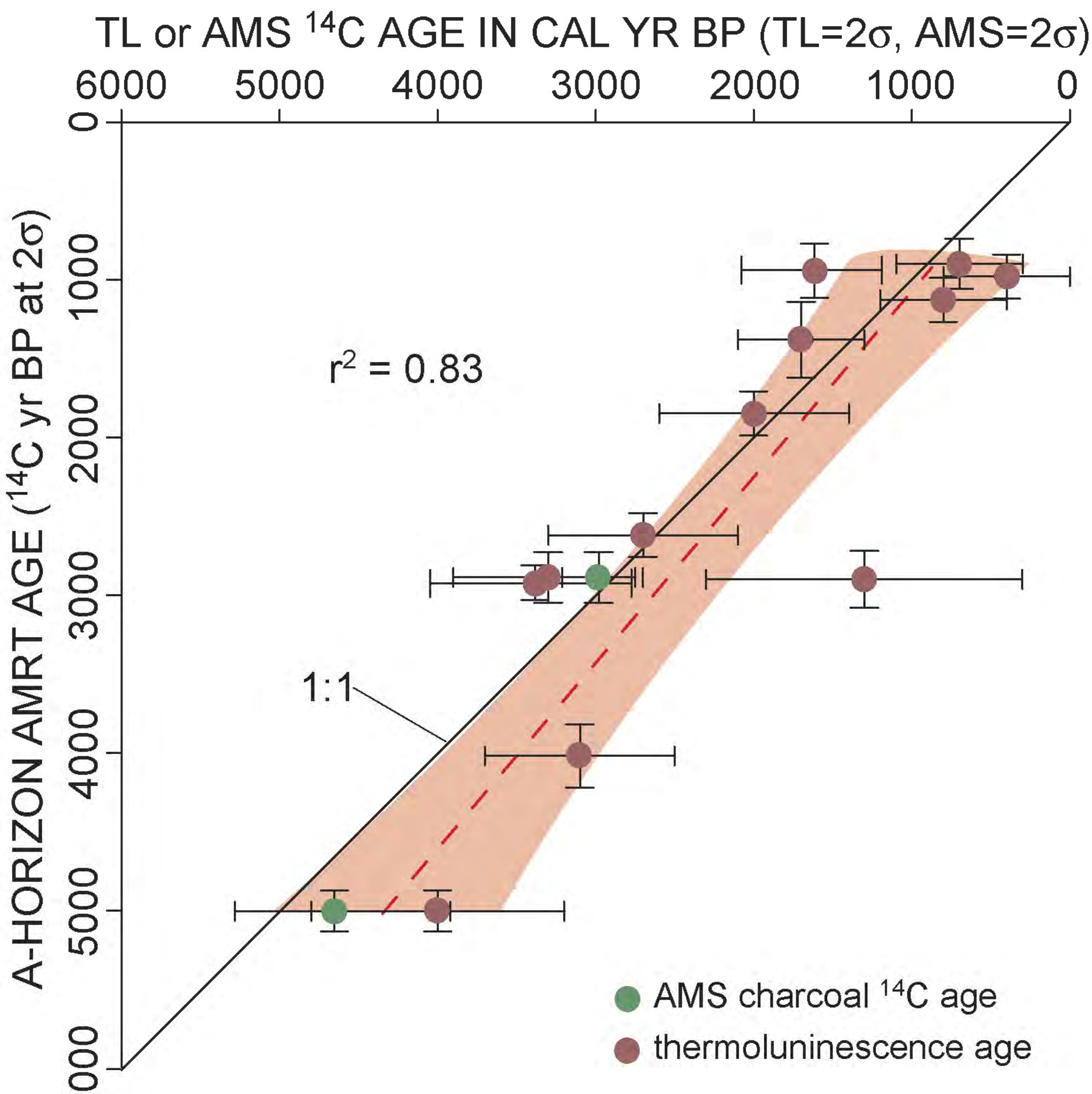
Trench 2 – East Ogden

Trench 3 – East Ogden

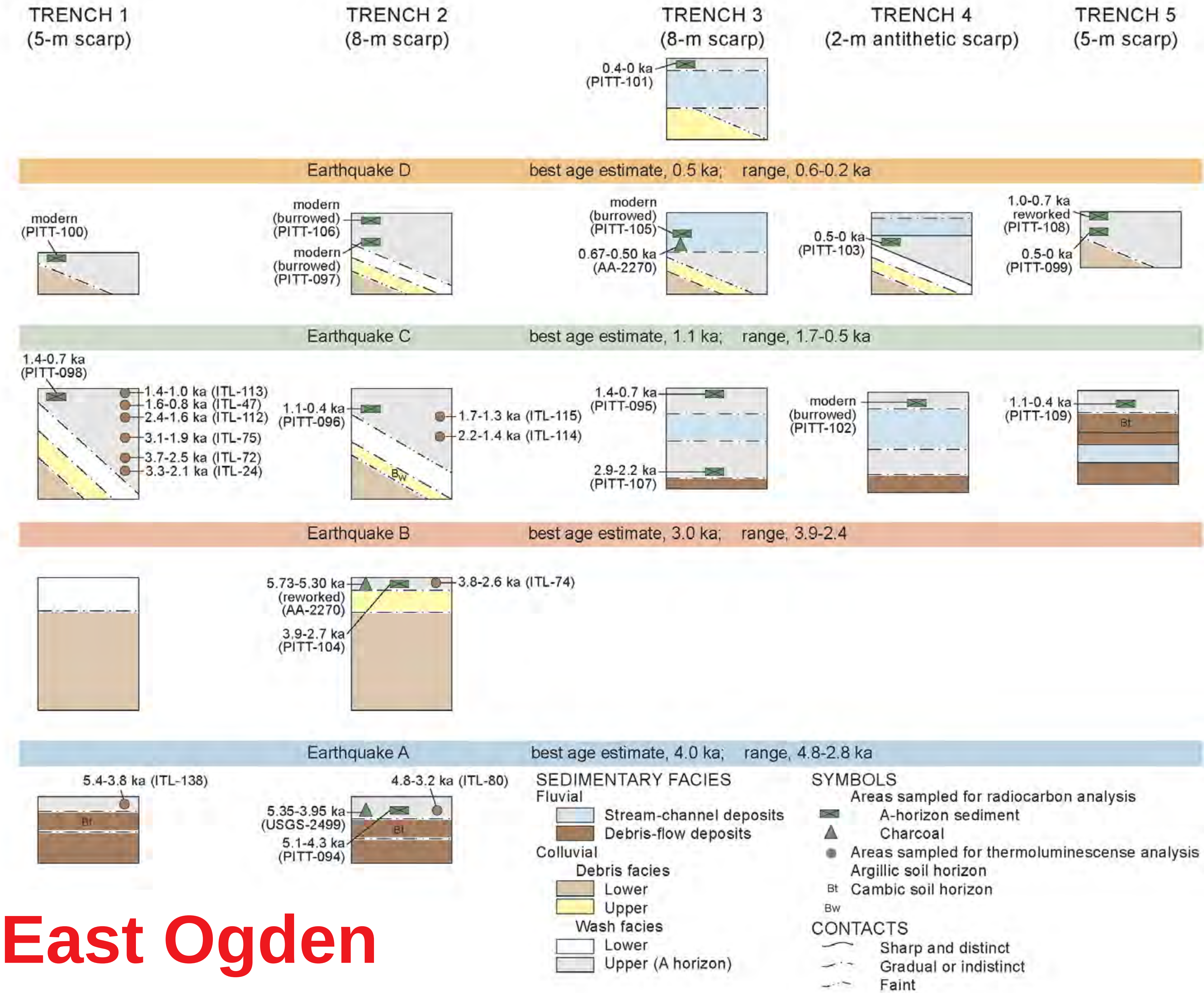


Trench 5 – East Ogden


A-HORIZON AMRT AGE (14C yr BP at 2σ)
5000
4000
3000
2000
1000
0
DEPTH OF SAMPLED INTERVAL (m)
0
0.2
0.4
0.6
0.8
1.0
all data, r2 = 0.35
8.3 yr/mm
<2 kyr data, r2 = 0.29
5.9 yr/mm
recurrence
<2 kyr
>2 kyr



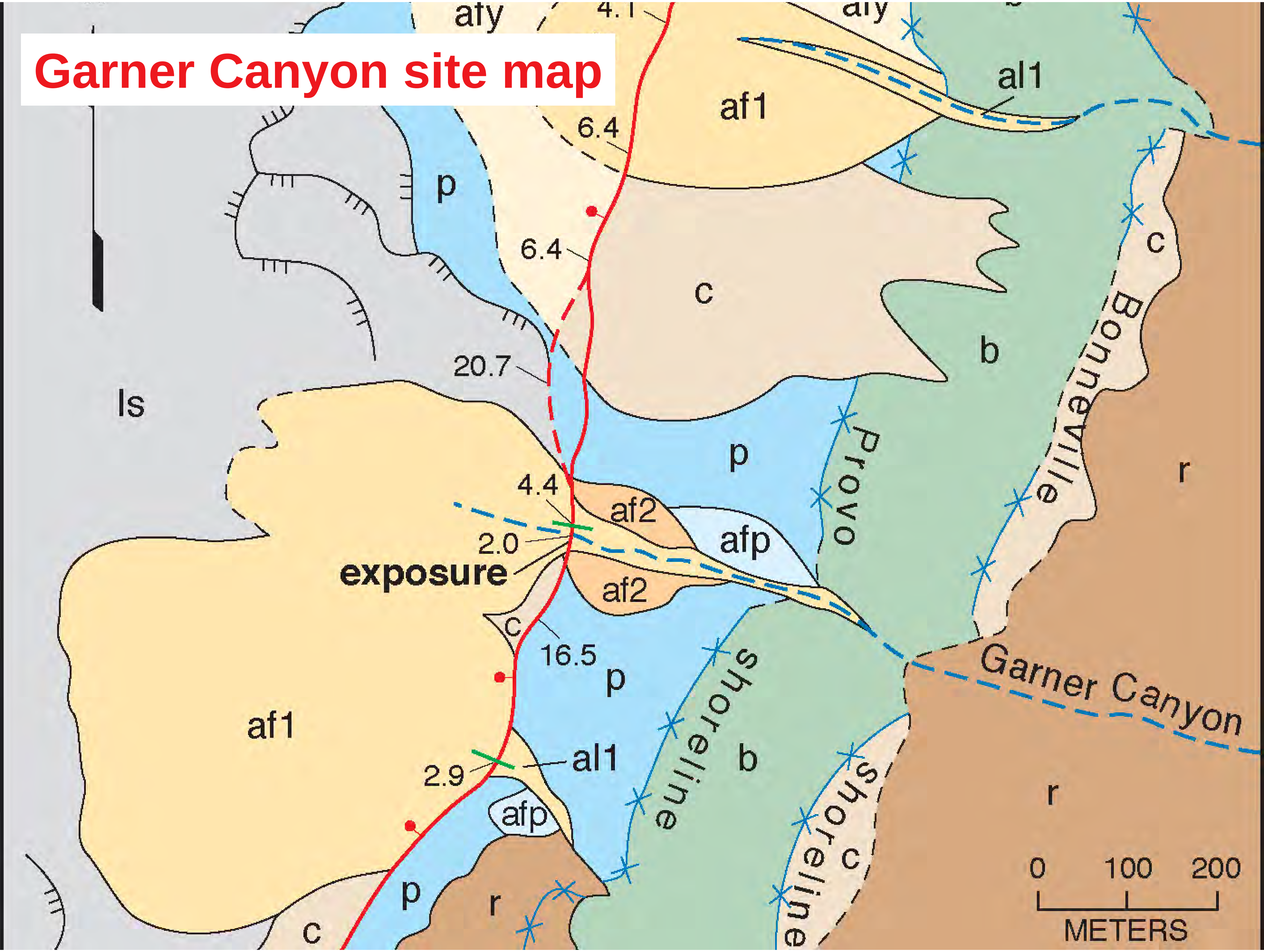
100-500 yr AMRT effect assumed



TRENCH 1
(5-m scarp)
TRENCH 2
(8-m scarp)
TRENCH 3
(8-m scarp)
TRENCH 4
(2-m antithetic scarp)
TRENCH 5
(5-m scarp)
0.4-0 ka
(PITT-101)
Earthquake D
best age estimate, 0.5 ka; range, 0.6-0.2 ka
modern
(PITT-100)
modern
(burrowed)
(PITT-106)
modern
(burrowed)
(PITT-097)
modern
(burrowed)
(PITT-105)
0.67-0.50 ka
(AA-2270)
0.5-0 ka
(PITT-103)
1.0-0.7 ka
reworked
(PITT-108)
0.5-0 ka
(PITT-099)
Earthquake C
best age estimate, 1.1 ka; range, 1.7-0.5 ka
1.4-0.7 ka
(PITT-098)
1.4-1.0 ka (ITL-113)
1.6-0.8 ka (ITL-47)
2.4-1.6 ka (ITL-112)
3.1-1.9 ka (ITL-75)
3.7-2.5 ka (ITL-72)
3.3-2.1 ka (ITL-24)
1.1-0.4 ka
(PITT-096)
Bw
1.7-1.3 ka (ITL-115)
2.2-1.4 ka (ITL-114)
1.4-0.7 ka
(PITT-095)
2.9-2.2 ka
(PITT-107)
modern
(burrowed)
(PITT-102)
1.1-0.4 ka
(PITT-109)
Bt
Earthquake B
best age estimate, 3.0 ka; range, 3.9-2.4
5.73-5.30 ka
(reworked)
(AA-2270)
3.9-2.7 ka
(PITT-104)
3.8-2.6 ka (ITL-74)
Earthquake A
best age estimate, 4.0 ka; range, 4.8-2.8 ka
5.4-3.8 ka (ITL-138)
Bt
4.8-3.2 ka (ITL-80)
5.35-3.95 ka
(USGS-2499)
5.1-4.3 ka
(PITT-094)
Bt
SEDIMENTARY FACIES
Fluvial
Stream-channel deposits
Debris-flow deposits
Colluvial
Debris facies
Lower
Upper
Wash facies
Lower
Upper (A horizon)
SYMBOLS
Areas sampled for radiocarbon analysis
A-horizon sediment
Charcoal
Areas sampled for thermoluminescense analysis
Argillic soil horizon
Bt
Cambic soil horizon
Bw
CONTACTS
Sharp and distinct
Gradual or indistinct
Faint
East Ogden

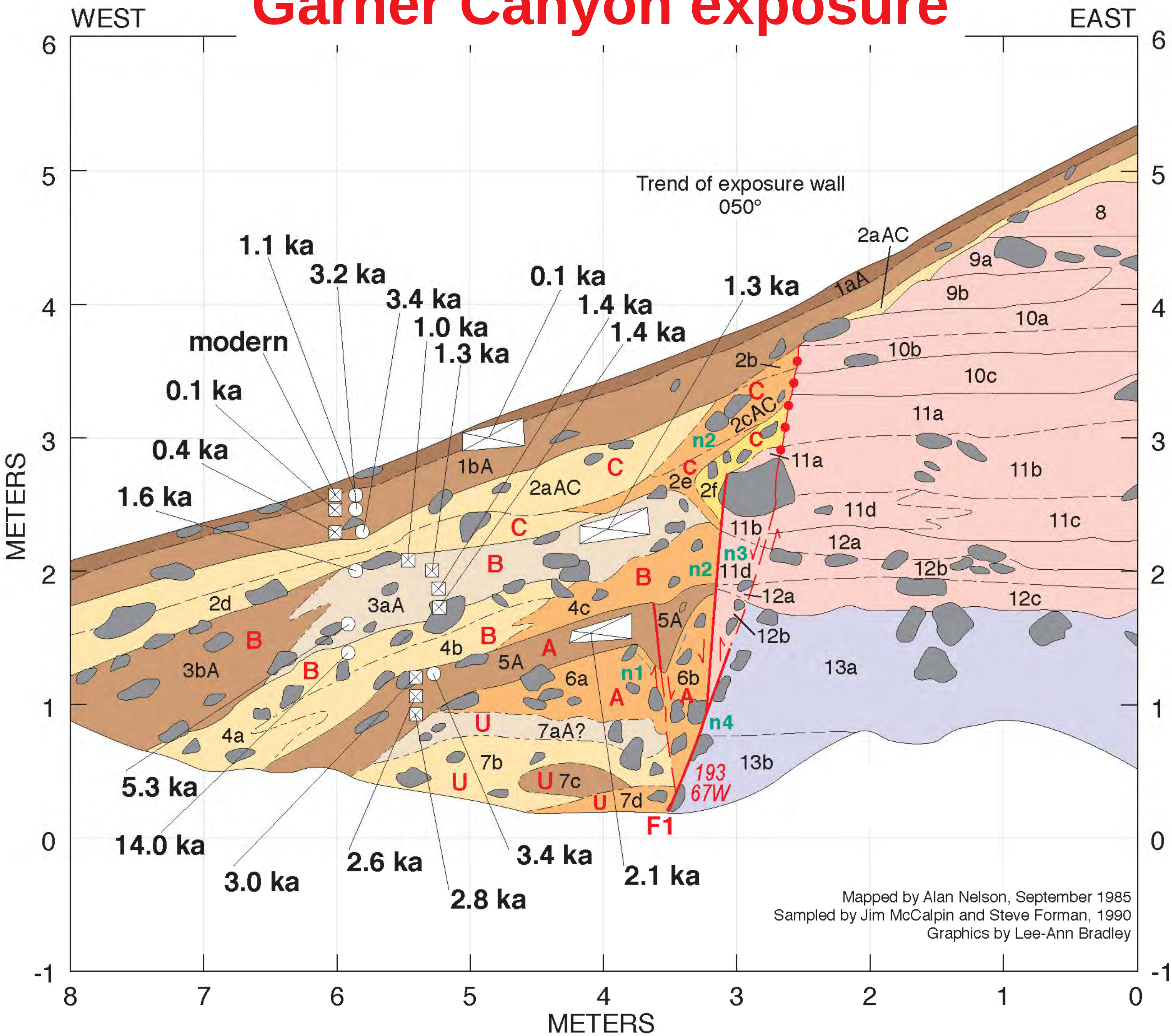

Garner Canyon site

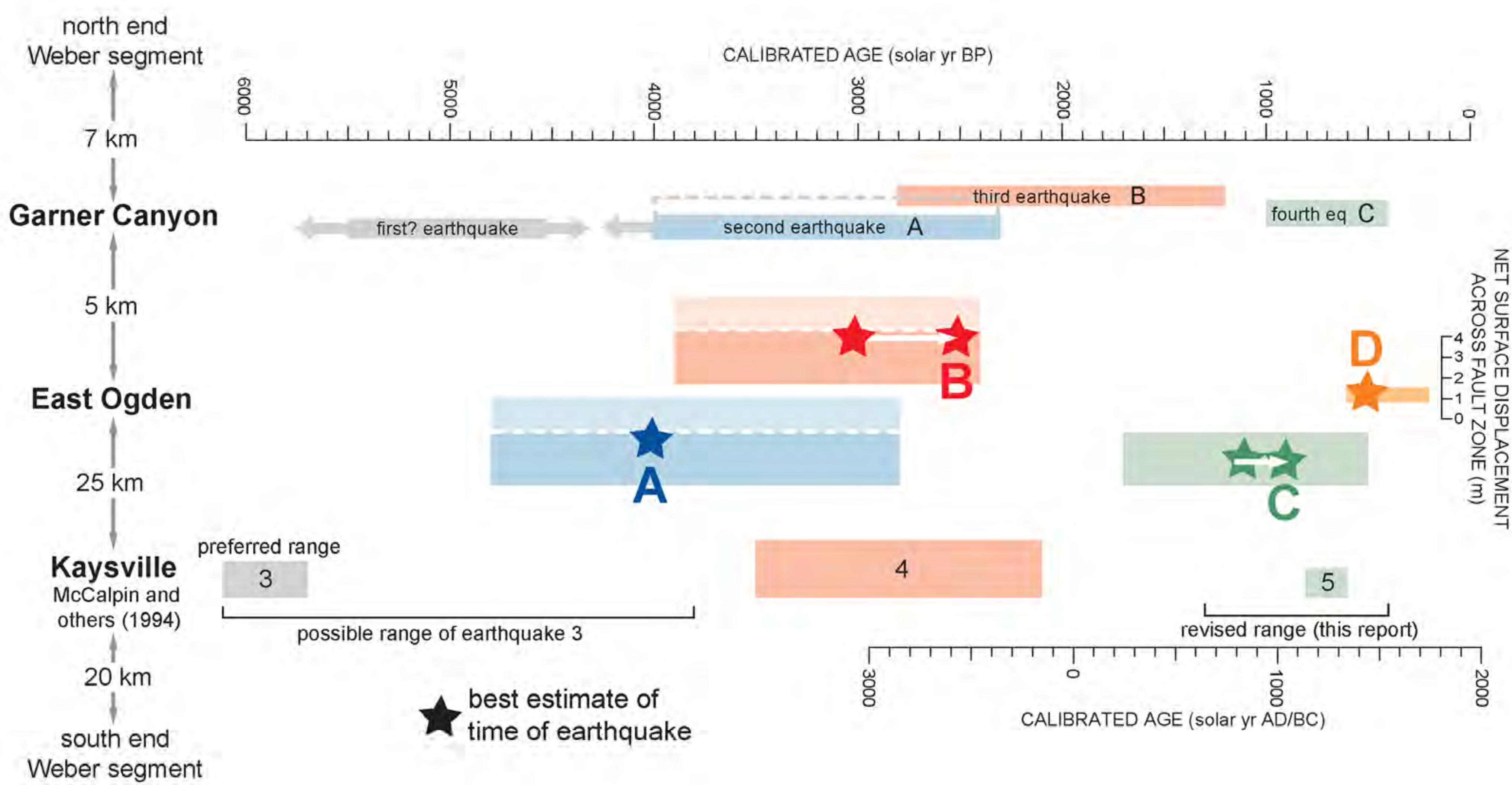
Garner Canyon site map



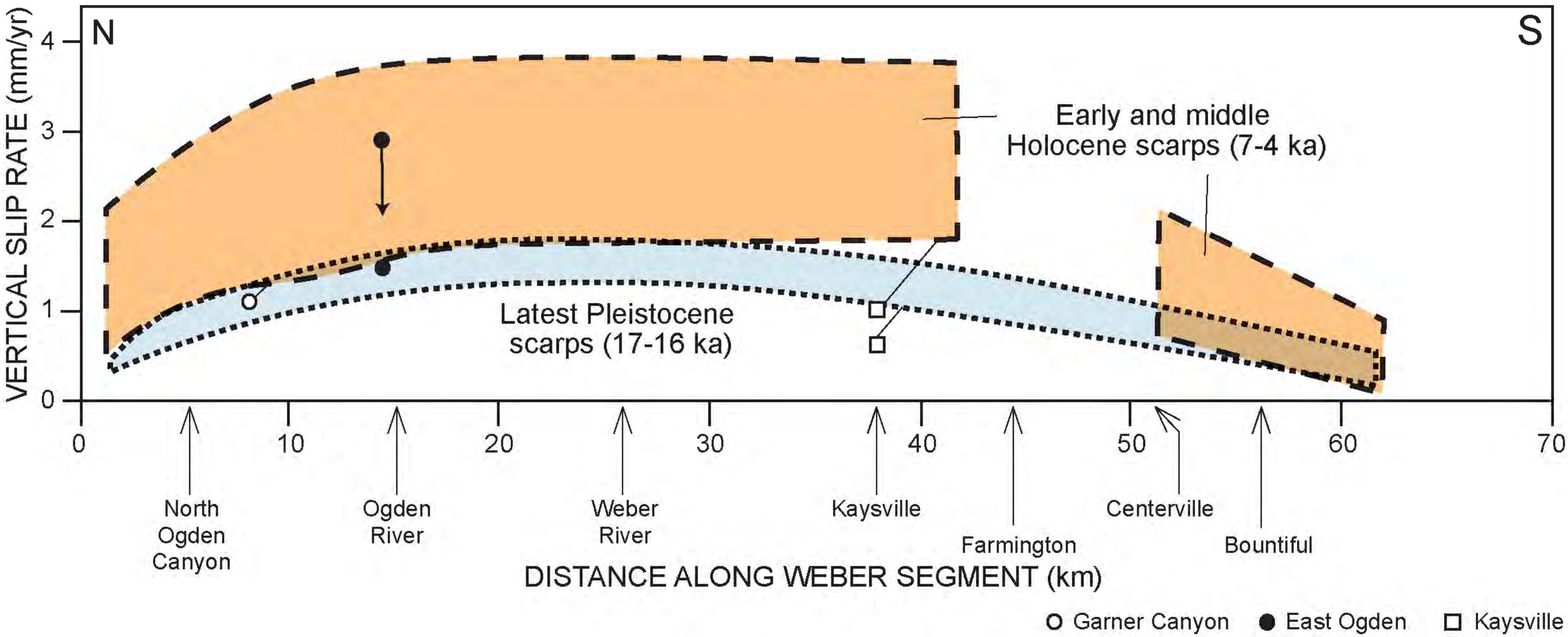

Garner Canyon exposure

Garner Canyon exposure

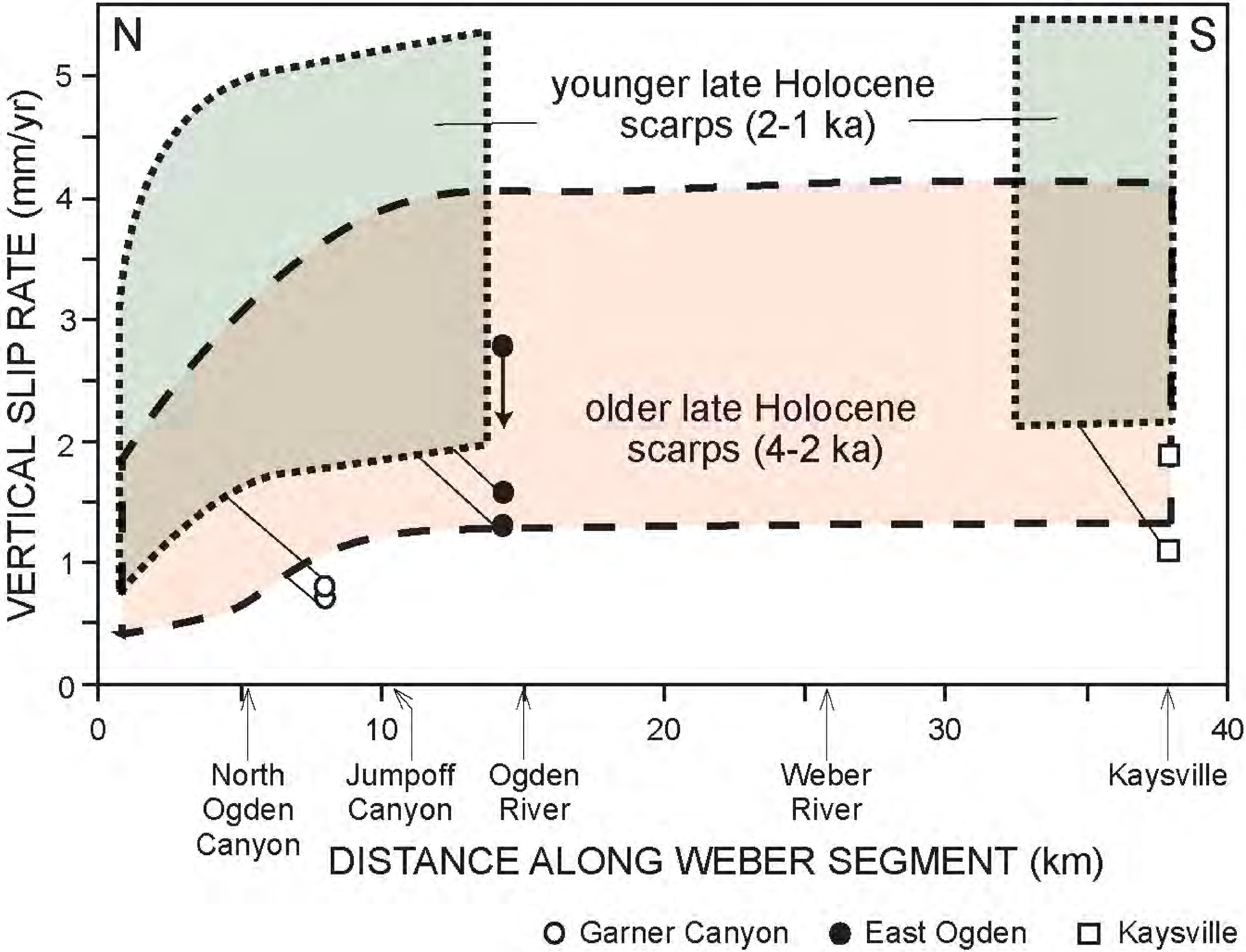




Earthquake history of Weber segment?



N
S
VERTICAL SLIP RATE (mm/yr)
0
1
2
3
4
Early and middle
Holocene scarps (7-4 ka)
Latest Pleistocene
scarps (17-16 ka)
0
10
20
30
40
50
60
70
North
Ogden
Canyon
Ogden
River
Weber
River
Kaysville
Farmington
Centerville
Bountiful
DISTANCE ALONG WEBER SEGMENT (km)
Garner Canyon
East Ogden
Kaysville



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younger late Holocene scarps (2-1 ka)
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Ogden River
Weber River
Kaysville
DISTANCE ALONG WEBER SEGMENT (km)
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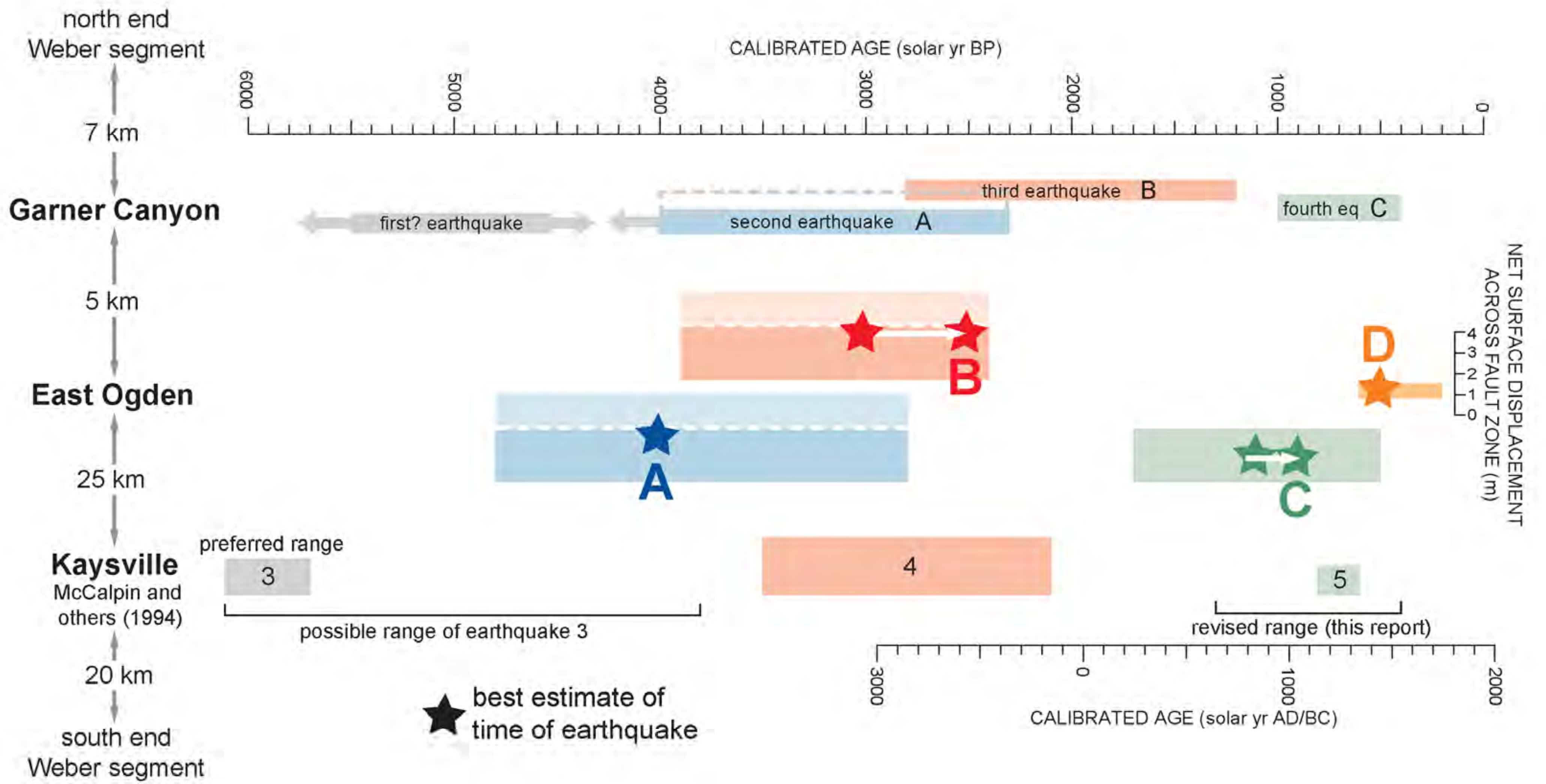
East Ogden
Kaysville



Earthquake history of Weber segment?

Conclusions

East Ogden – 3 large surface-faulting earthquakes (A, B, and C) and a smaller, most recent earthquake (D)

Displacements during earthquakes A and B were probably 1.5 m less than measured (4.2 m) due to unrecognized antithetic faulting

Garner Canyon – 3 large surface-faulting earthquakes with about 1 m of displacement that correlate with earthquakes A, B, and C; plus a probable 4th earlier earthquake

Earthquakes B and C correlate with large earthquakes at Kaysville (McCalpin, 1994); 1-to-3-m displacements suggest ruptures of much of Weber segment

Conclusions

Earthquake A is not (?) recorded at Kaysville, but displacements to north for A are same size as for earthquakes B and C

The small displacement (0.5 m) for earthquake D, and it's identification in only 1 of 7 exposures at the 3 sites, suggest a short rupture

Scarp surface displacements in both Holocene and Pleistocene deposits decrease within 10 km of segment boundaries

Scarp displacements are smaller south of Farmington

Conclusions

Holocene scarp-displacement slip rates are too high using ages inferred during 1985 mapping of Weber segment

Reconciling trench-site and scarp-displacement slip rates suggests Holocene surfaces are 20-100% older than inferred in 1985

Reconciliation yields slip rates of about 1-2 mm/yr, with highest rates between Kaysville and Ogden

Because earthquake (D) was apparently much smaller than older earthquakes, using its age yields recurrence calculations that are not representative of the entire Weber segment (1.5 kyr vs. 1.1 kyr)

Questions

When and how long was the last surface rupture on the Weber segment?

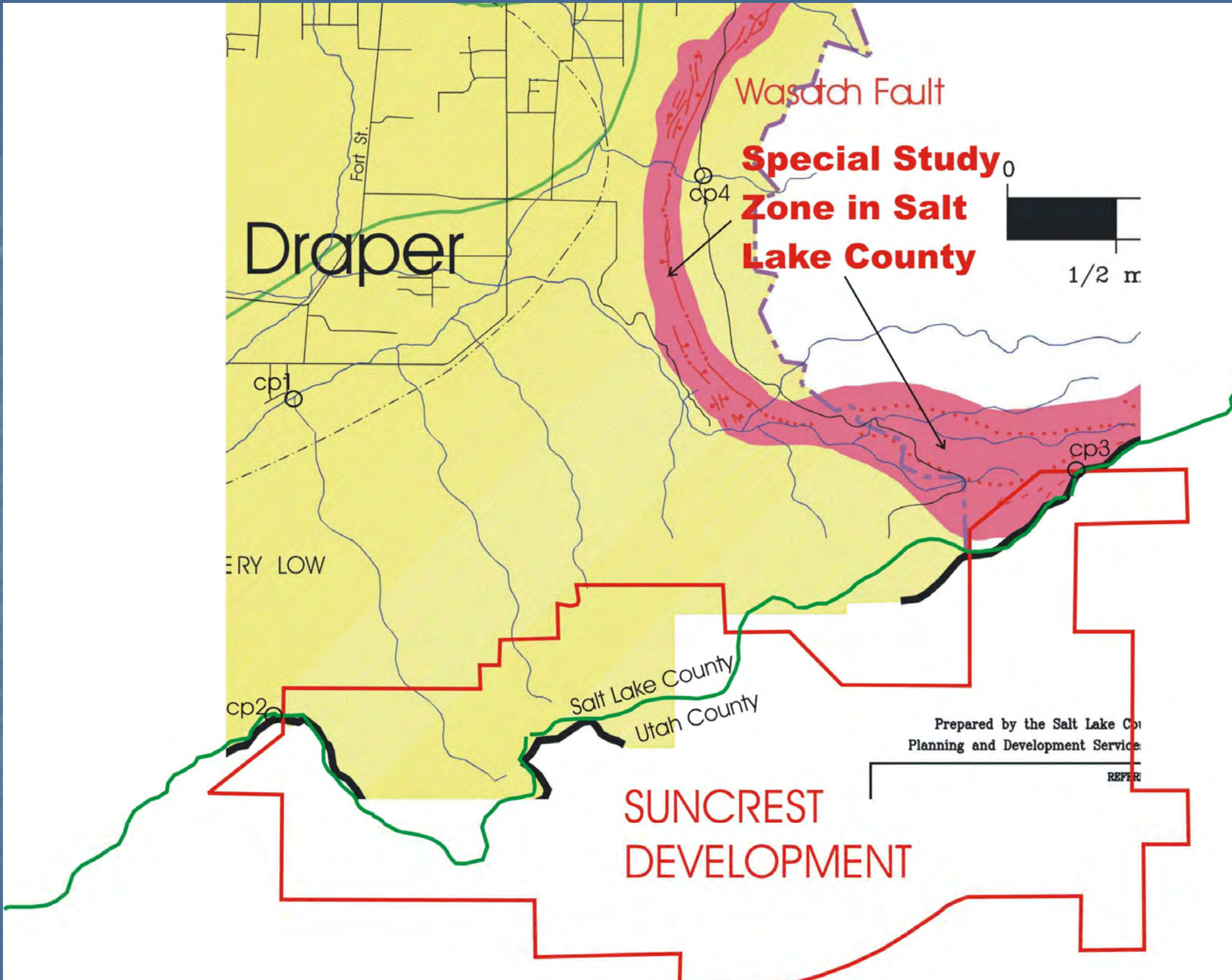
What is magnitude threshold of preservation for surface ruptures on the Weber segment?

How old are middle and late Holocene fans along the Weber segment?

Are apparent north-to-south decreases in slip rate due to differences in earthquake frequency, in amounts of surface displacement and rupture extent, or both?

IN-PROGRESS TRENCHING OF THE CORNER CANYON FAULT, SEGMENT BOUNDARY BETWEEN Salt Lake City segment and Provo segment

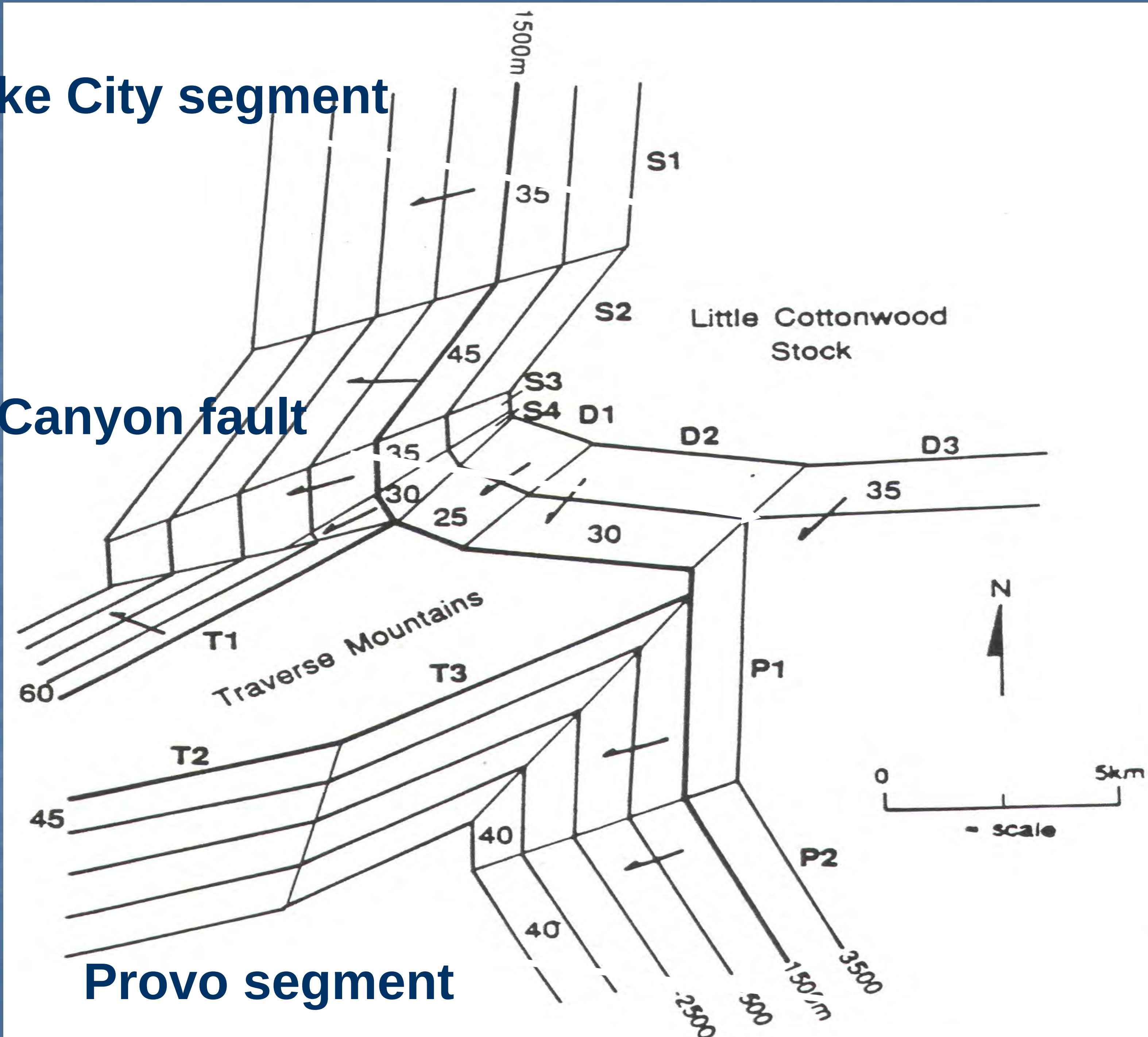
PSI– Jamie Robinson
GEO-HAZ– Jim McCalpin, Al Jones, Deb Green



Wasatch Fault
Special Study Zone in Salt Lake County
0
1/2 m
Fort St.
cp4
Draper
cp1
cp3
ERY LOW
cp2
Salt Lake County
Utah County
Prepared by the Salt Lake Co
Planning and Development Service
SUNCREST DEVELOPMENT

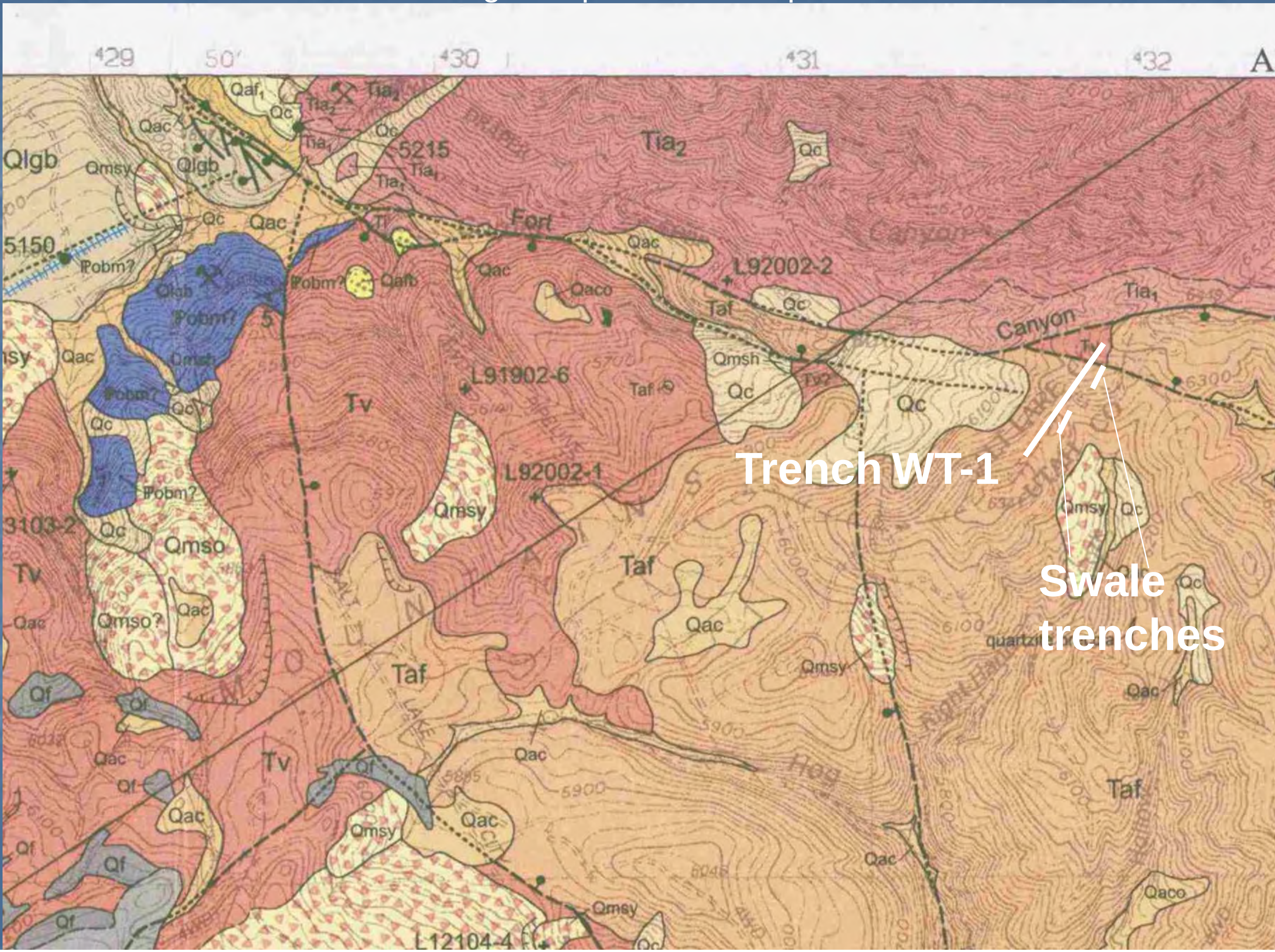
Salt Lake City segment

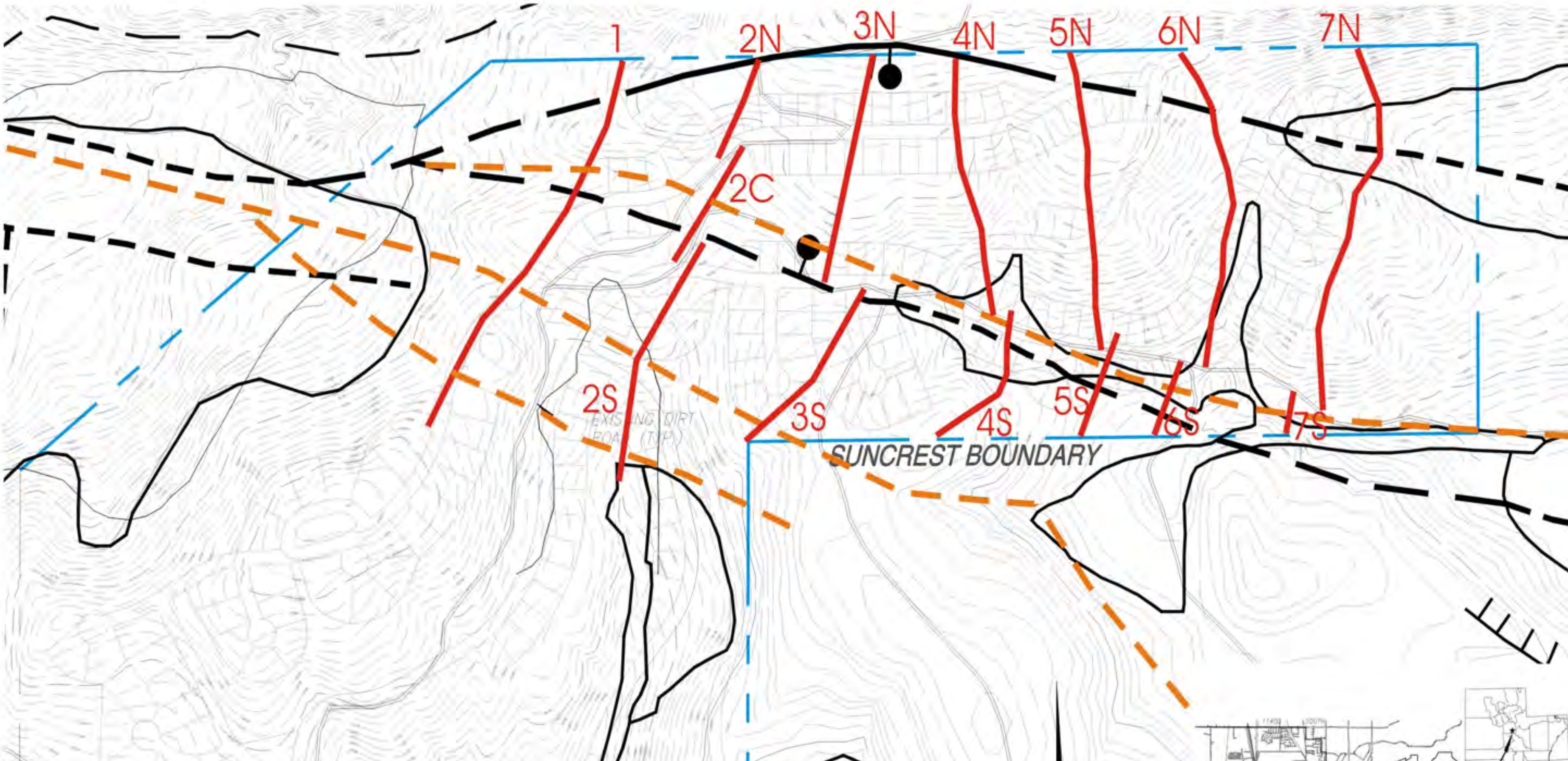
Corner Canyon fault



Provo segment

From Biek, 2005, Geologic map of the Lehi quad





WORK PLAN FOR TRENCHING THE WASATCH FAULT ZONE AT SUNCREST, DRAPER, UTAH

FAULT TRACE, Utah Quat, Fault database

More probable location of fault

Proposed trench

SCALE 1"=400'

0 400 800 1200

SCALE IN FEET

VICINITY MAP

SUNCREST MOUNTAIN • SKY • HOME

REVISIONS
NO. DESCRIPTIONS DATE

LAND DISTURBANCE EXHIBIT

WASATCH FAULT STUDY

STANTEC CONSULTING INC.
960 LEVOY
SUITE 100
SALT LAKE CITY, UT 84123
801 743 0696

Stantec

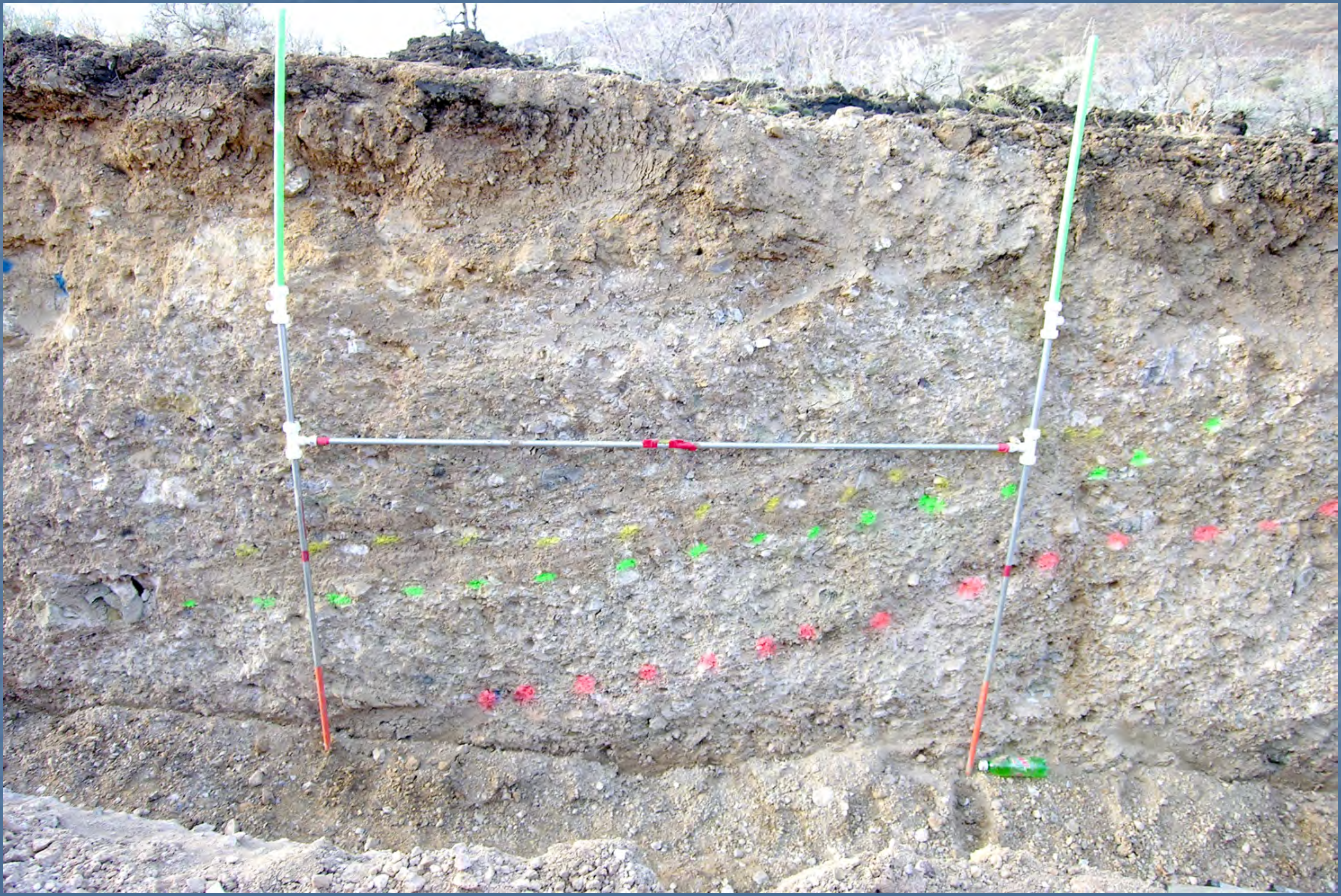
EXHIBIT
A

General Stratigraphy

- Q – Quaternary Swale Deposits and Soils
- Taf - Tertiary Alluvial Fan Conglomerates
- Tvba – Tertiary Andesite Block & Ash Flows
- Tva – Tertiary Andesite

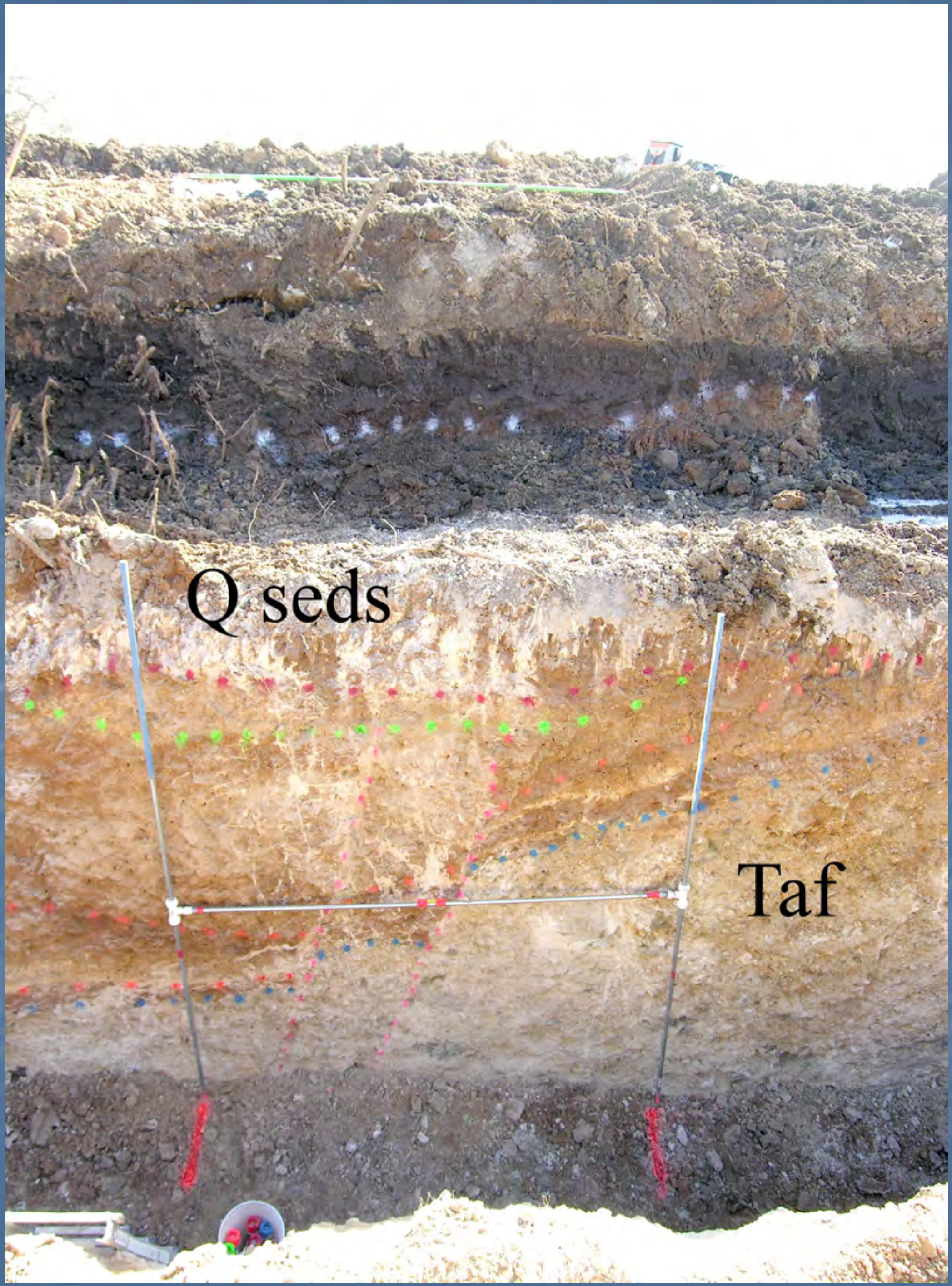
Tertiary Block and Ash Flow

Tertiary Alluvial Fan Deposits – WF-1 South End

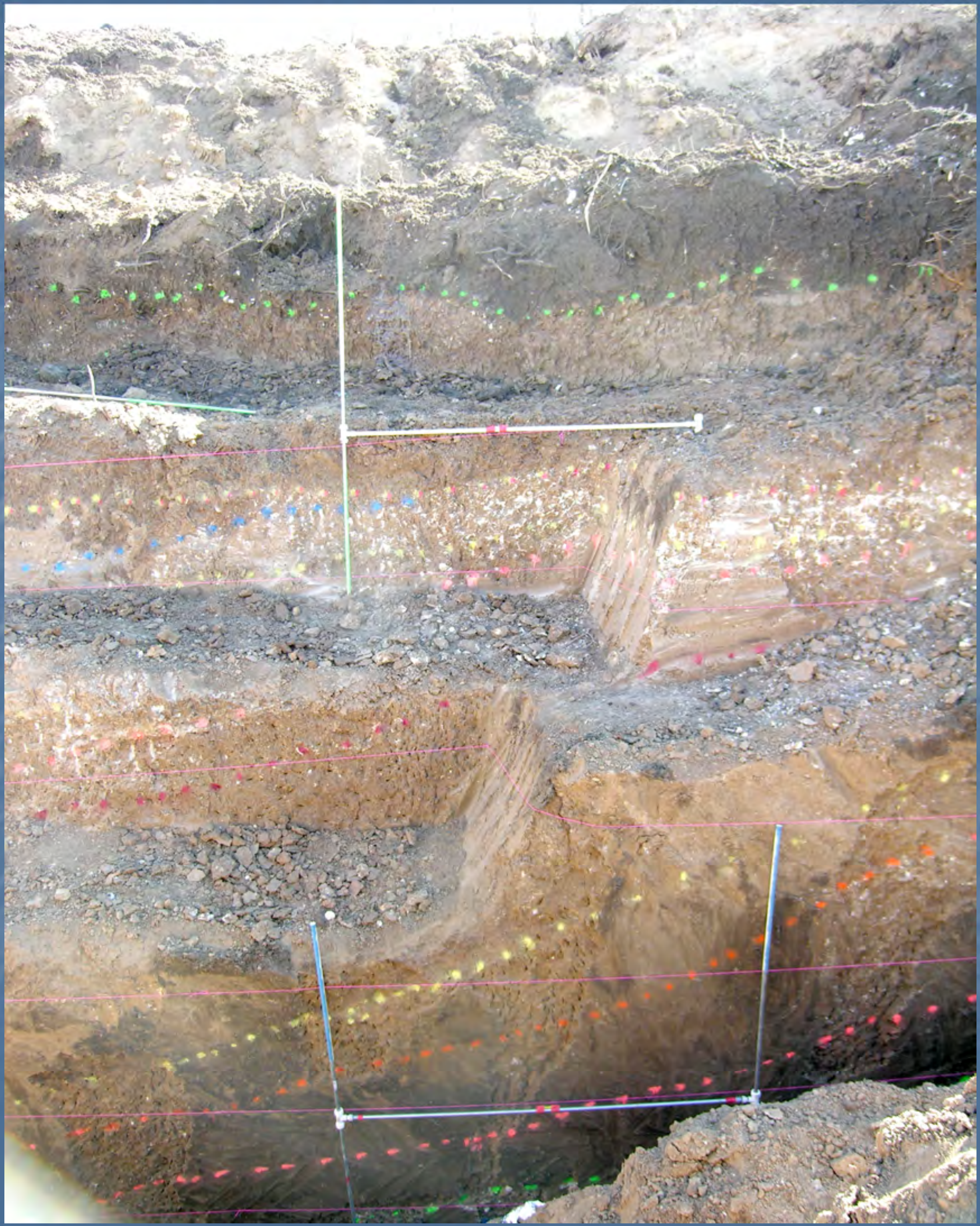


Tertiary Alluvial Fan Deposits – WF-2 North End

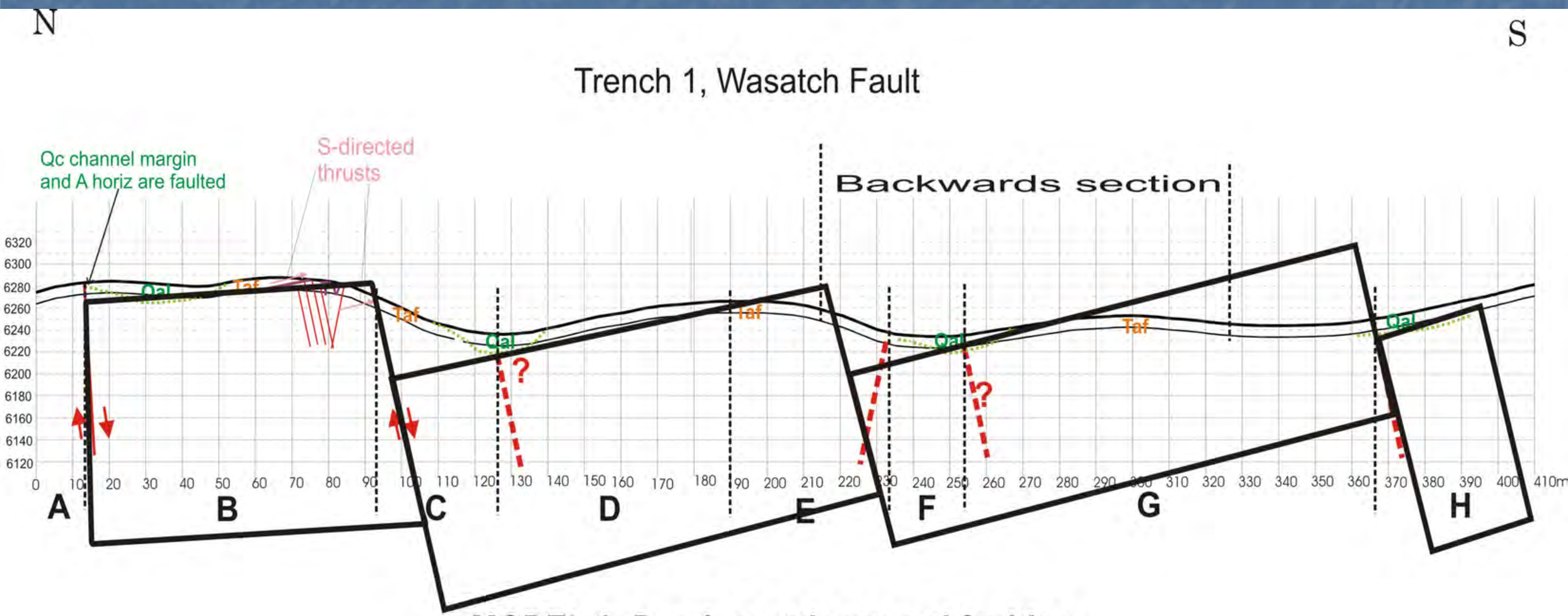
Quaternary Deposits-South Swale Trench



Quaternary Deposits – North Swale Trench



Gravel Lens in Quaternary Silt & Clay – WF-2 North End



MODEL 1: Domino-style normal faulting

General Types of Faults – WF -1

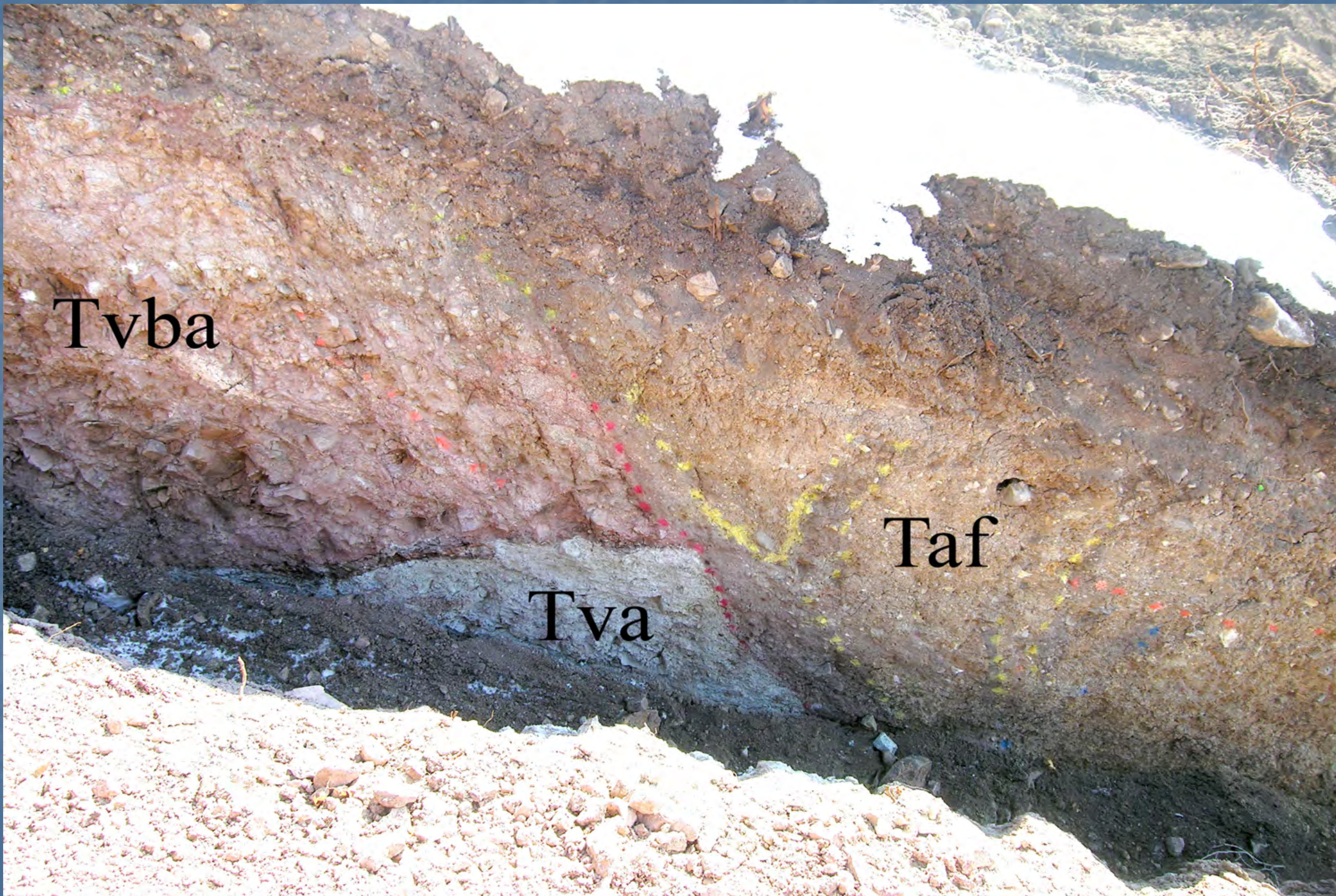
OLDER FAULTS

- Single-strand High-angle Normal Faults
- Domino-style High-angle Normal Faults
- High-angle Normal Faults that form Horsts
- Low-angle Shear Zones

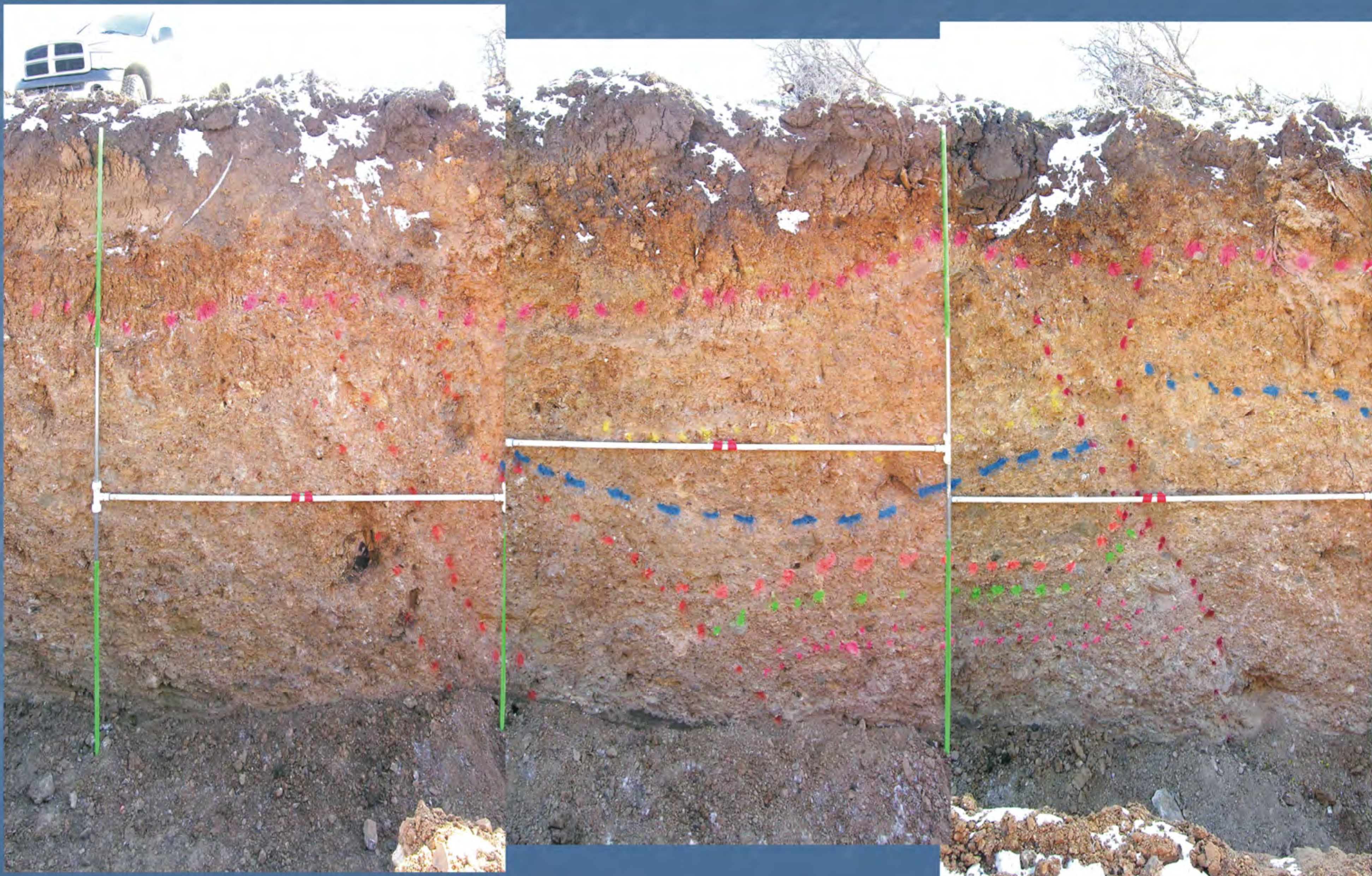
HOLOCENE FAULTS

- High-angle to Vertical Normal Faults

Single-Strand High-Angle Normal Fault

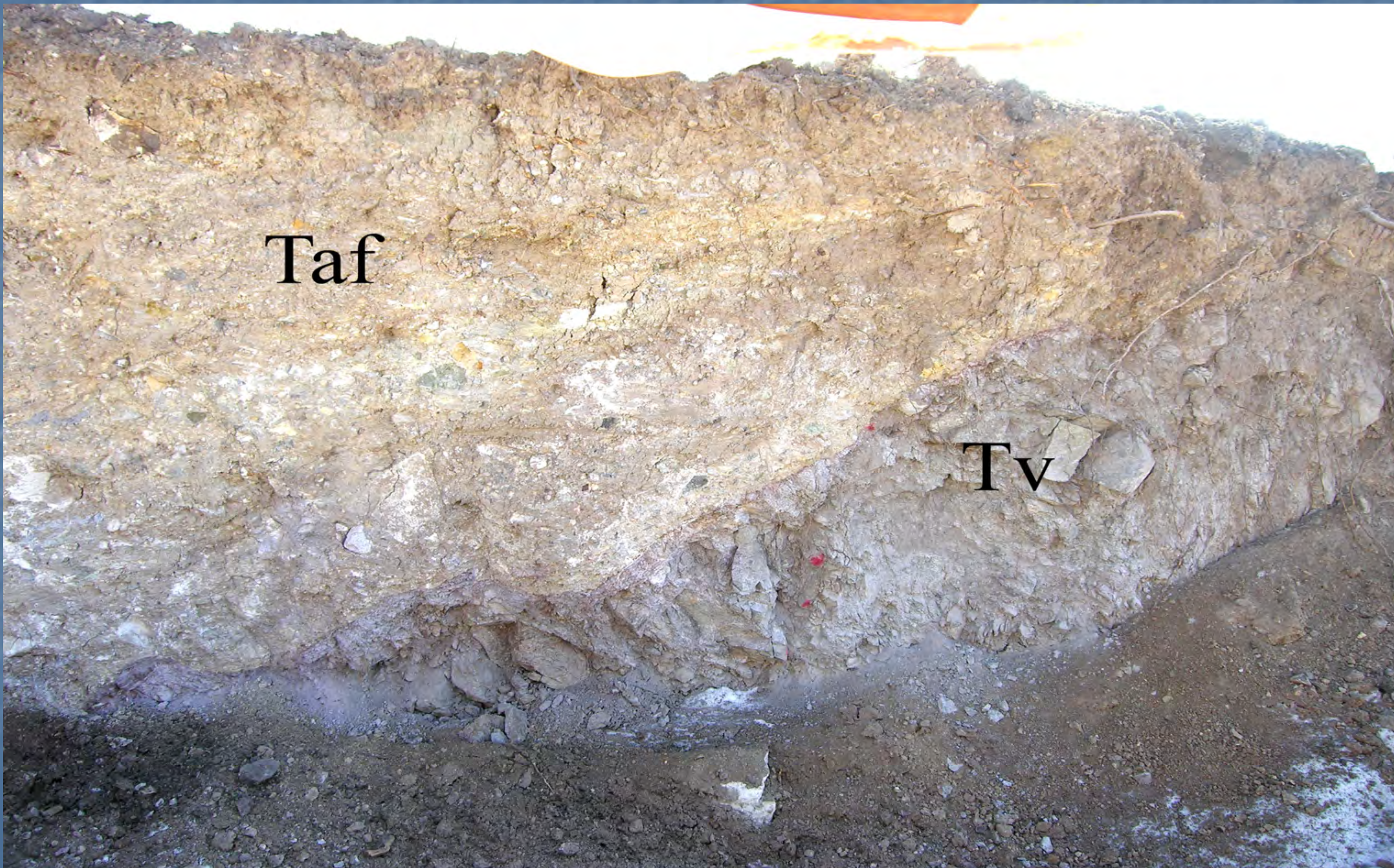


Domino-style High-Angle Normal Faults

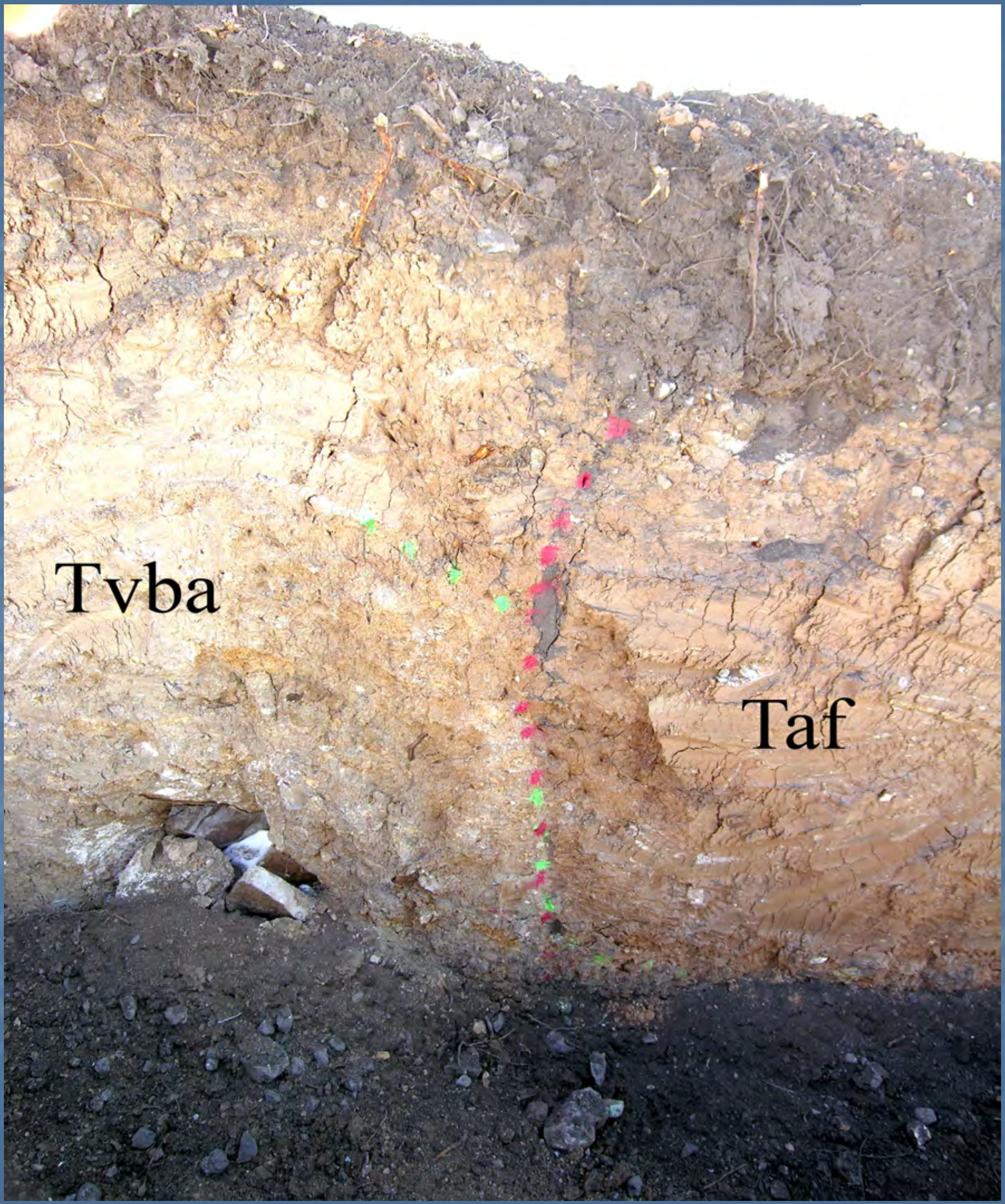


Horst-style High-Angle Normal Faults

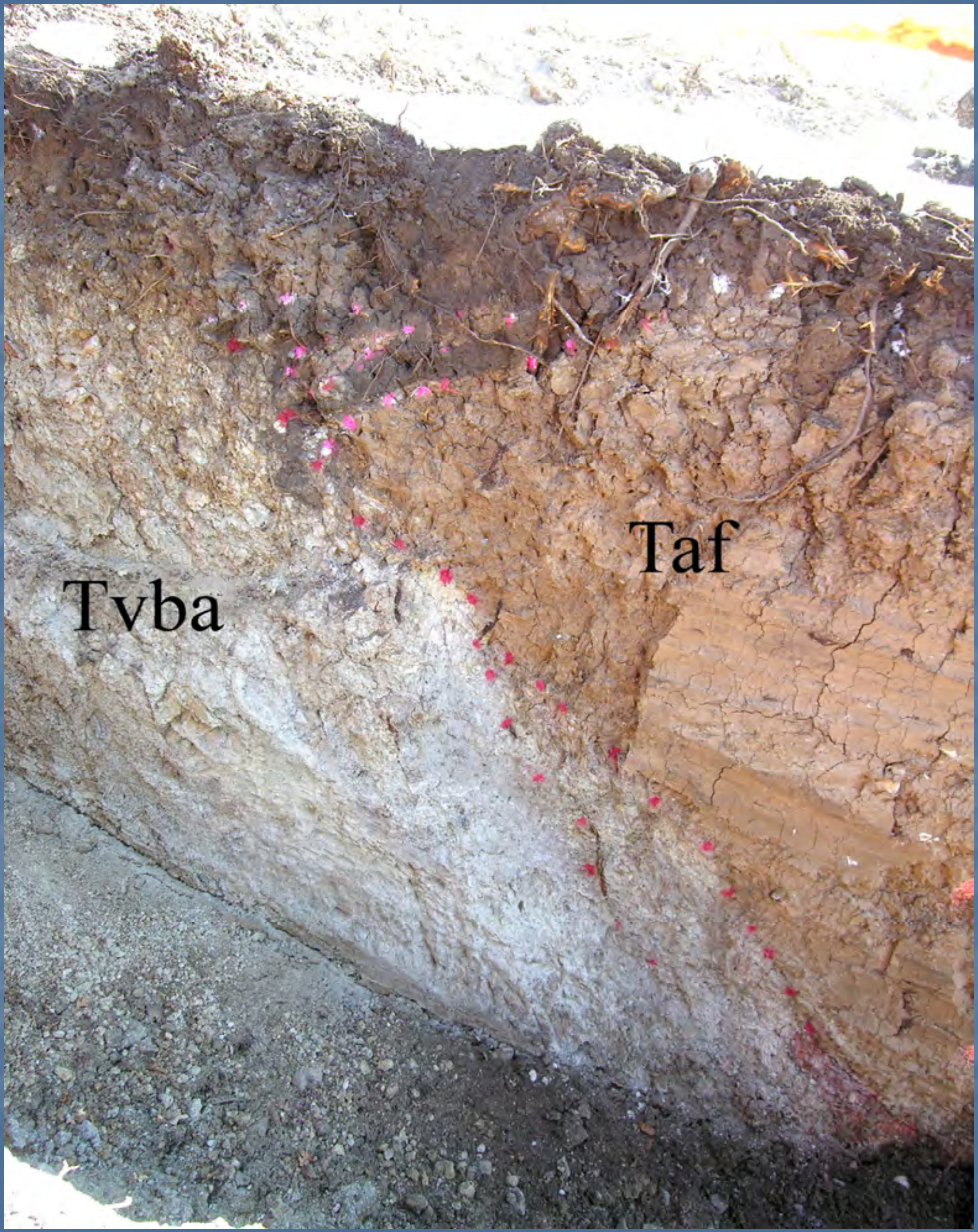
Low-angle Shear Zone



Holocene Fault – WF-1



Holocene Fault – WF-2



Conclusions

- TO BE CONTINUED!
- Several generations of normal faults in Tertiary rocks that do not appear to displace Quaternary strata.
- One fault with Holocene displacement at the northern end of each of the two trenches.

BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP

WESTERN STATES SEISMIC POLICY COUNCIL

UTAH GEOLOGICAL SURVEY

U.S. GEOLOGICAL SURVEY

WESTERN STATES SEISMIC POLICY COUNCIL

UTAH GEOLOGICAL SURVEY

USGS science for a changing world

WESTERN STATES SEISMIC POLICY COUNCIL POLICY RECOMMENDATION 04-5

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

SEISMIC-POLICY ISSUES IDENTIFIED AT BRPSHSII

1. Use and relative weighting of time-dependent, Poisson, and clustering models to characterize BRP fault behavior.

2. Proper magnitude-frequency distributions (Gutenberg-Richter vs. characteristic earthquake models) for BRP faults.

3. Use of length vs. displacement relations to estimate earthquake magnitudes.

4. Probabilities and magnitudes of multi-segment ruptures on BRP faults.

SEISMIC-POLICY ISSUES IDENTIFIED AT BRPSHSII

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

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

BRPEWG GOALS

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

BRPEWG MEMBERS

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

**Issue discussion leader*

BRPEWG SCHEDULE

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

UPDATING THE UQFPWG CONSENSUS SLIP-RATE AND RECURRENCE-INTERVAL DATABASE

UTAH GEOLOGICAL SURVEY

UQFPWG
2005 RECOMMENDATIONS

- UGS perform a detailed review of new paleoseismic-trenching data as it is published.
- Provide a summary of information to UQFPWG members for their review.
- UQFPWG will meet as necessary (at least annually) to evaluate new data and recommend consensus vertical-slip-rate and recurrence-interval values for inclusion in the database.

QUESTIONS

- What constitutes “published?”
- UQFPWG to meet annually, but how often should the database be updated?
- How should the database and documentation be maintained – CDROM, UGS web site, other?

NEW PALEOSEISMIC STUDY RESULTS

- Holocene Earthquake History of the Northern Weber Segment of the Wasatch Fault Zone, Utah – USGS, in press.
- Provo Segment Megatrench – Susan Olig, URS Corp. nearing completion – final publication?
- Nephi Segment Trenching – UGS and USGS.
- Promontory Segment of the Great Salt Lake Fault – University of Utah; when done/when published?
- New age estimates for Little Cottonwood Canyon moraines – could change Woodward-Clyde slip rates, abstract only at this time.

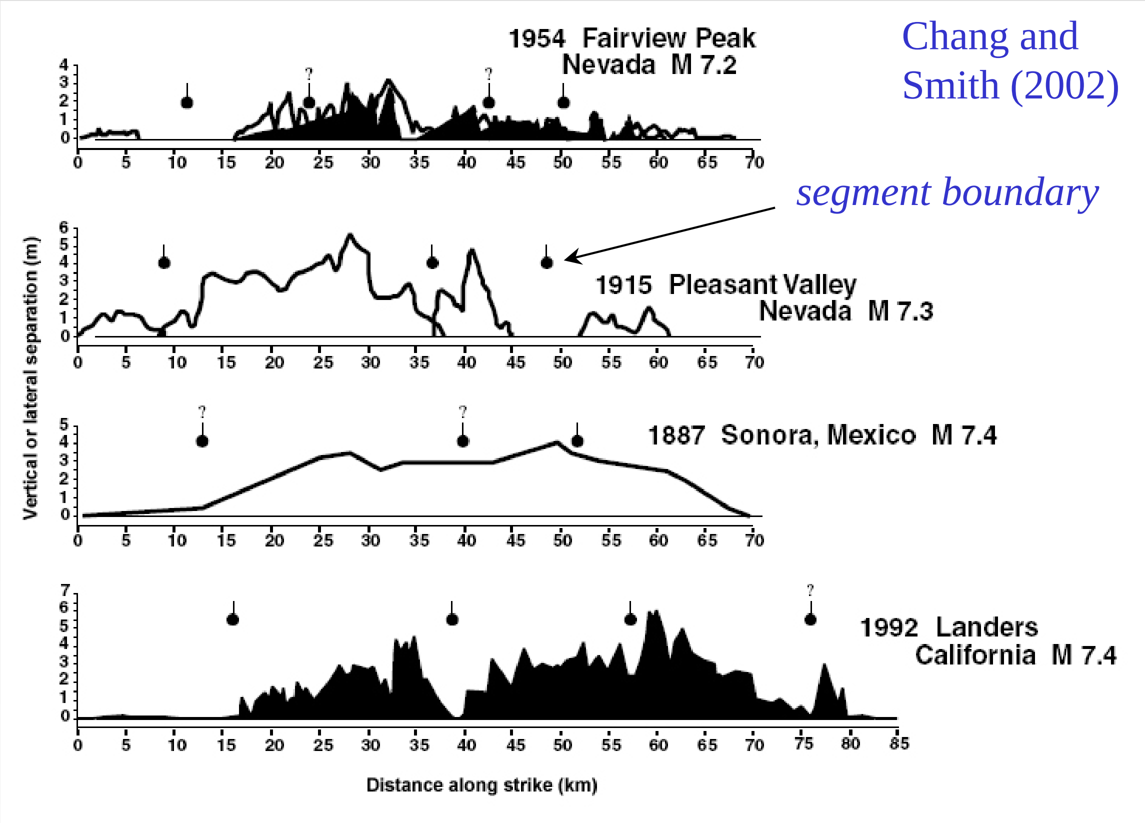
Multi-Segment Ruptures (MSRs)

MSRs - Why Bother?

1. Nonzero probability of segment boundary rupture (Andrews and Schwerer, 2000)

2. BRP EQs: complex and extensive surface faulting (dePolo and others; 1991)

3. 2007 update of NSHMs



4. Directions for future WFZ paleoseismic research

MSR Analyses

Approaches:

Segment Boundary

Probability of SB rupture:

- SB physical characteristics
- EQ sequence & stress change (Harris, Kase, WGCEP, 2002)

EQ Timing

- MSR model based on EQ timing (Chang and Smith, 2002)
- Treat all SBs equally (Andrews and Schwerer, 2000)
- Quality of paleoseismic data?

Strain Analysis

- EQ displacement and strain accumulation important (Weldon and others, 2004)
- Displacement per earthquake

Working Models

- Multiple working models
- Using historical EQ and paleoseismic data
- Expert opinion (WGCEP, 2003)
- Difficult to balance EQ moment

WFZ MSR Analysis

Preferred Method:

Quantitatively combine **EQ Timing** with **Working Models** (WGCEP, 2003)

Qualitatively include **SB** and **Strain Analyses**

- ***Rupture source***: single segment or combination of segments that may produce an earthquake

  Central WFZ: **BC, WB, SLC, PV, BC+WB, WB+SLC, SLC+PV**

- ***Rupture scenario***: combination of rupture sources – possible mode of failure of entire fault zone

WFZ: 5 rupture scenarios

1. BC, WB, SL, PV
2. BC+WB, SL, PV
3. BC, WB+SL, PV
4. BC, WB, SL+PV
5. BC+WB, SL+PV

WFZ MSR Analysis

Preferred Method:

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

	MSR Models:	A	B	C
1.	BC, WB, SL, PV	100%	80%	20%
2.	BC+WB, SL, PV	0%	5%	20%
3.	BC, WB+SL, PV	0%	5%	20%
4.	BC, WB, SL+PV	0%	5%	20%
5.	BC+WB, SL+PV	0%	5%	20%

WFZ MSR Analysis

<u>Limitations:</u>

- ***Worst-case scenario***: **MSRs >90 km**

  1887 M_W 7.4 Sonora, Mexico (Pitaychachi) EQ:
  >100 km (2-3 faults/segments)

  Most other BRP EQs: 20-70 km

- ***Partial-segment ruptures & spill-over*** not accounted for.

  Need a floating **M ~6.5** EQ?

- ***Not all paleoseismic data are equal*:**

  Older studies - fewer limiting ages

  Older earthquakes - more difficult to investigate

WFZ MSR Analysis

Approach:

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

2. Formulate criteria to quantify the **potential for MSRs** along the WFZ

3. Formulate criteria to quantify **confidence in the paleoseismic data**

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

5. **Weight models**, finalize preferred model(s), and reach UQFPWG consensus (?).

1. Space-Time

<u>WFZ Space-Time Diagram</u>:

- Limiting ages: number, type, event
  (McCalpin and Nishenko, 1996; Lund and Black, 1998; McCalpin, 2002; Nelson and others, in press)

- Vertical displacement per event

- Fault-zone complexity

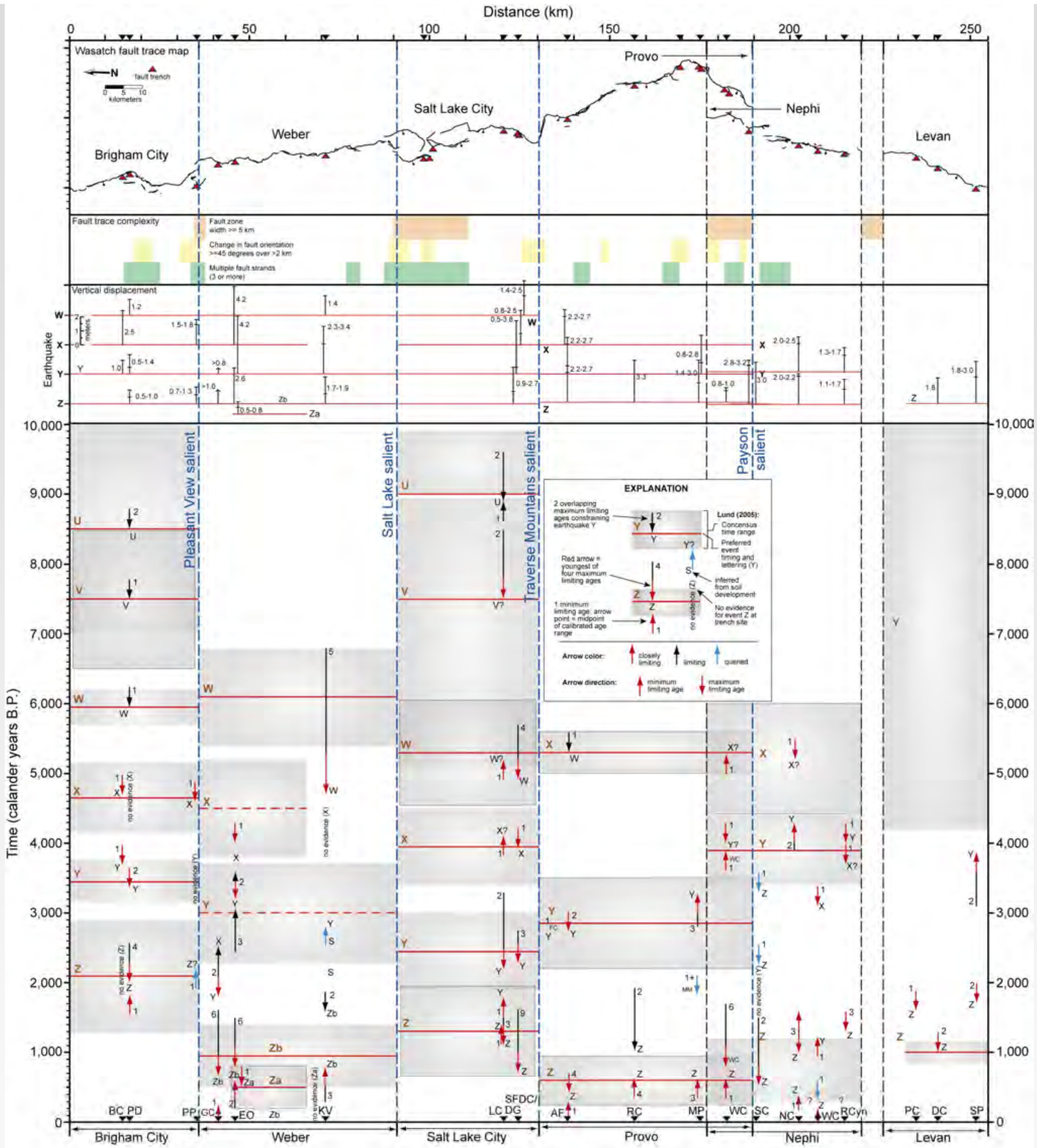


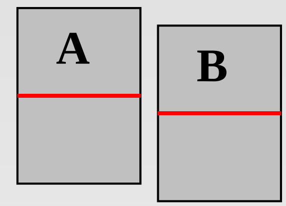
Figure 1. Wasatch fault zone paleoearthquake space-time diagram, based on paleoseismic trench data. Trench-site abbreviations (north to south): BC - Brigham City, PD - Provo delta (Box Elder Canyon), PP - Pole Patch, GC - Garner Canyon (construction-related excavation), EO - East Ogden, KV - Kaysville, LC - Little Cottonwood Canyon (megatrench), SFDC/DG - South Fork Dry Creek/Dry Gulch, AF - American Fork, RC - Rock Creek (stream cut)/Rock Canyon, MP - Mapleton north and south (Mapleton "megatrench" [MM] results pending), WC - Water Canyon, SC - Santaquin Canyon (results pending), NC - North Creek, WC - Willow Creek (results pending), RCyn - Red Canyon, PC - Pidgeon Creek, DC - Deep Creek (stream cut), and SP - Skinner Peaks.

2. MSR Potential

MSR Potential Criteria

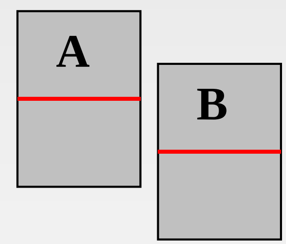
5 (high):

2-sigma time ranges overlap;
A preferred time is within time range of B;
A preferred time – B preferred time = **0-200** yrs.



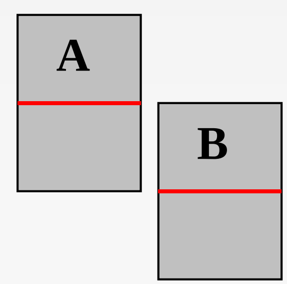
4 (medium-high):

2-sigma time ranges overlap;
A preferred time is within time range of B;
A preferred time – B preferred time = **201-400** yrs.



3 (medium):

2-sigma time ranges overlap;
A preferred time is within time range of B;
A preferred time – B preferred time = >**400** yrs.

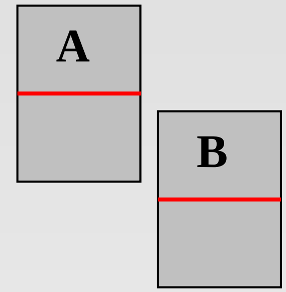


2. MSR Potential

<u>MSR Potential Criteria</u>

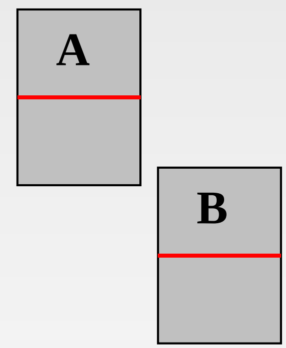
2 (medium-low):

2-sigma time ranges overlap;
A preferred time is <u>outside</u> of time range of B; A
preferred time – B 2-sigma time range = **0-200** yrs.



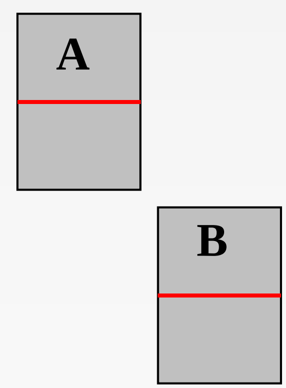
1 (low):

2-sigma time ranges overlap;
A preferred <u>outside</u> of time range of B;
A preferred time – B 2-sigma time range = **201+** yrs.



0 (nonexistent):

2-sigma time ranges <u>**do not**</u> overlap.



3. Data Confidence

Paleoseismic-Data Confidence Criteria

High confidence

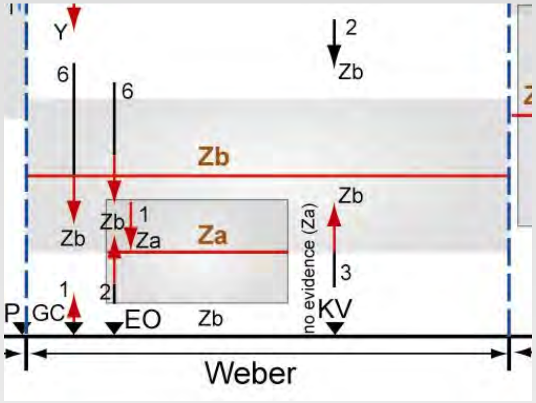
Combination of **minimum and maximum ages** (≥ 3 total) from two or more trench sites

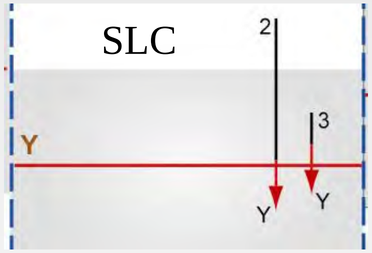
Medium-high

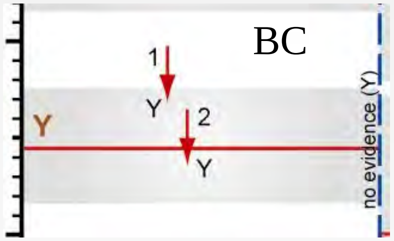
\> **4 close limiting** ages (that overlap) from two or more trench sites

Medium confidence

≥ 2 **maximum** (or ≥ 2 **min**) ages from two or more trench sites







3. Data Confidence

<u>Paleoseismic-Data Confidence Criteria</u>

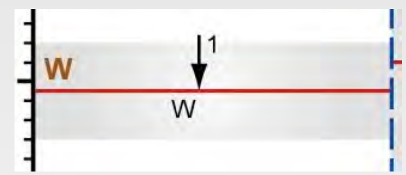
Medium-low

Minimum & **maximum** ages, or $\geq$ **2 overlapping maximum** (or **min**) ages from a <u>single trench site</u>

Low confidence

Only **minimum or maximum** ages from a s<u>ingle trench site</u>

BC



Unknown

No paleoseismic data (numerical ages) constraining earthquake.

4. MSR Models

WASATCH FAULT ZONE MULTI-SEGMENT RUPTURE MODEL SOURCE DATA

WFZ MSR Model earthquake-timing data

INPUT:	BC		WB		SLC		PV		NP	
	EQ timing	± 2σ	EQ timing	± 2σ	EQ timing	± 2σ	EQ timing	± 2σ	EQ timing	± 2σ
W	**5950**	250	**6100**	700	**5300**	750				
X	**4650**	500	**4500**	700	**3950**	550	**5300**	300	**3100**	400
Y	**3450**	300	**3000**	700	**2450**	550	**2850**	650	**1300**	400
Z	**2100**	800	**950**	450	**1300**	650	**600**	350	**1000**	500
		Za	**500**	300						

*yellow indicates values that can be modified

		BC	WB	SLC	PV	NP
W	**Preferred t**	**5950**	**6100**	**5300**	**0**	**0**
	t + 2σ	6200	6800	6050	0	0
	t - 2σ	5700	5400	4550	0	0
X	**Preferred t**	**4650**	**4500**	**3950**	**5300**	**3100**
	t + 2σ	5150	5200	4500	5600	3500
	t - 2σ	4150	3800	3400	5000	2700
Y	**Preferred t**	**3450**	**3000**	**2450**	**2850**	**1300**
	t + 2σ	3750	3700	3000	3500	1700
	t - 2σ	3150	2300	1900	2200	900
Z	**Preferred t**	**2100**	**950**	**1300**	**600**	**1000**
	t + 2σ	2900	1400	1950	950	1500
	t - 2σ	1300	500	650	250	500

MSR Potential		TEST 1	TEST 2	Assignment 1 (difference in preferred t)				Assignment 2 (preferred t - 2σ range)	
highest	**5**	TRUE (1)	TRUE (1)	<=	**200**				
	4	TRUE (1)	TRUE (1)	>	**200**	**and <=**	**400**		
	3	TRUE (1)	TRUE (1)	>	**400**				
	2	TRUE (1)	FALSE (0)					<=	**200**
lowest	**1**	TRUE (1)	FALSE (0)					>	**200**
zero	**0**	FALSE (0)	NA						

*yellow indicates values that can be modified

4. MSR Models

MSR Potential

MSR notation:

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

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

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

MSR Potential	
highest	**5**
	4
	3
	2
lowest	**1**
zero	**0**

4. MSR Models

Model A

- No MSRs. 100% weight given to scenario 1.

MSR scenarios:		Model A
1.	BC, WB, SL, PV	100%
2.	BC+WB, SL, PV	0%
3.	BC, WB+SL, PV	0%
4.	BC, WB, SL+PV	0%
5.	BC+WB, SL+PV	0%

4. MSR Models

Model B

- Conflicting events OK (e.g., SLC[Y] used in two MSRs)
- Only MSR potential ≥ 3
- Relative weighting of scenarios 2-4
- 2/15 (13.3%) single-segment, 13/15 (86.7%) MSR earthquakes

BC-WB			WB-SLC			SLC-PV		
BC[W]	**WB[W]**	**5**	WB[W]	SLC[W]	2.0	SLC[W]	PV[W]	0.0
BC[W]	WB[X]	0.0	WB[W]	SLC[X]	0.0	**SLC[W]**	**PV[X]**	**5**
BC[X]	WB[W]	0.0	WB[X]	SLC[W]	2.0	SLC[X]	PV[W]	0.0
BC[X]	**WB[X]**	**5.0**	**WB[X]**	**SLC[X]**	**3.0**	SLC[X]	PV[X]	0.0
BC[X]	WB[Y]	0.0	WB[X]	SLC[Y]	0.0	SLC[X]	PV[Y]	1.0
BC[Y]	WB[X]	0.0	WB[Y]	SLC[X]	1.0	SLC[Y]	PV[X]	0.0
BC[Y]	**WB[Y]**	**3**	**WB[Y]**	**SLC[Y]**	**3.0**	**SLC[Y]**	**PV[Y]**	**4**
BC[Y]	WB[Z]	0.0	WB[Y]	SLC[Z]	0.0	SLC[Y]	PV[Z]	0.0
BC[Z]	WB[Y]	2.0	WB[Z]	SLC[Y]	0.0	SLC[Z]	PV[Y]	0.0
BC[Z]	WB[Z]	1.0	**WB[Z]**	**SLC[Z]**	**4.0**	SLC[Z]	PV[Z]	2.0
Sum of highest potent:		4.3			3.3			4.5

Sum of averages: 12.2

	Scenario	Relative weight:	Total weight
1)	BC, WB, SLC, PV		**13.3**
2)	BC+WB, SLC, PV	0.36	**30.9**
3)	BC, WB+SLC, PV	0.27	**23.8**
4)	BC, WB, SLC+PV	0.37	**32.1**
5)	BC+WB, SLC+PV		**0.0**
		sum: 1.00	*sum: 100.0*

Total weight for MSR scenarios (2-5):

86.7

4. MSR Models

Model C

- No conflicting events (e.g., WB+SLC[Y] removed)
- Only MSR potential ≥ 3
- Relative weighting of scenarios 2-5
- 3/15 (20%) single-segment, 12/15 (80%) MSR earthquakes

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

Sum of highlighted: 34.5

Total weight for MSR scenarios (2-5):

80.0

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

4. MSR Models

Model D

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

Confidence multipliers:

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

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

um of confidence modified: 28.31

Total weight for MSR scenarios (2-5):

80.0

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

4. MSR Models

Model E

- Based on Chang and Smith (2002)
- Conflicting events OK (WB[Y] used twice)
- Relative weighting of scenarios 2-5
- 2/14 (14.3%) single-segment, 12/14 (85.7%) MSR earthquakes

BC-WB		
BC[W]	WB[W]	
BC[W]	WB[X]	
BC[X]	WB[W]	
BC[X]	**WB[X]**	**1**
BC[X]	WB[Y]	
BC[Y]	WB[X]	
BC[Y]	**WB[Y]**	**1**
BC[Y]	WB[Z]	
BC[Z]	**WB[Y]**	**1**
BC[Z]	WB[Z]	
	sum:	7

spill-over?

WB-SLC		
WB[W]	SLC[W]	
WB[W]	SLC[X]	
WB[X]	SLC[W]	
WB[X]	SLC[X]	
WB[X]	SLC[Y]	
WB[Y]	SLC[X]	
WB[Y]	SLC[Y]	
WB[Y]	SLC[Z]	
WB[Z]	SLC[Y]	
WB[Z]	**SLC[Z]**	**1**

SLC-PV		
SLC[W]	PV[W]	
SLC[W]	**PV[X]**	**1**
SLC[X]	PV[W]	
SLC[X]	PV[X]	
SLC[X]	PV[Y]	
SLC[Y]	PV[X]	
SLC[Y]	**PV[Y]**	**1**
SLC[Y]	PV[Z]	
SLC[Z]	PV[Y]	
SLC[Z]	PV[Z]	

Total weight for MSR scenarios (2-5): **85.7**

	Scenario	**Relative weight:**	**Total weight**
1)	BC, WB, SLC, PV		***14.3***
2)	BC+WB, SLC, PV	***0.43***	***36.7***
3)	BC, WB+SLC, PV	***0.14***	***12.2***
4)	BC, WB, SLC+PV	***0.29***	***24.5***
5)	BC+WB, SLC+PV	***0.14***	***12.2***
	sum:	*1.00*	*100.0*

5. MSR Model Weights

Weighting the models

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

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

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

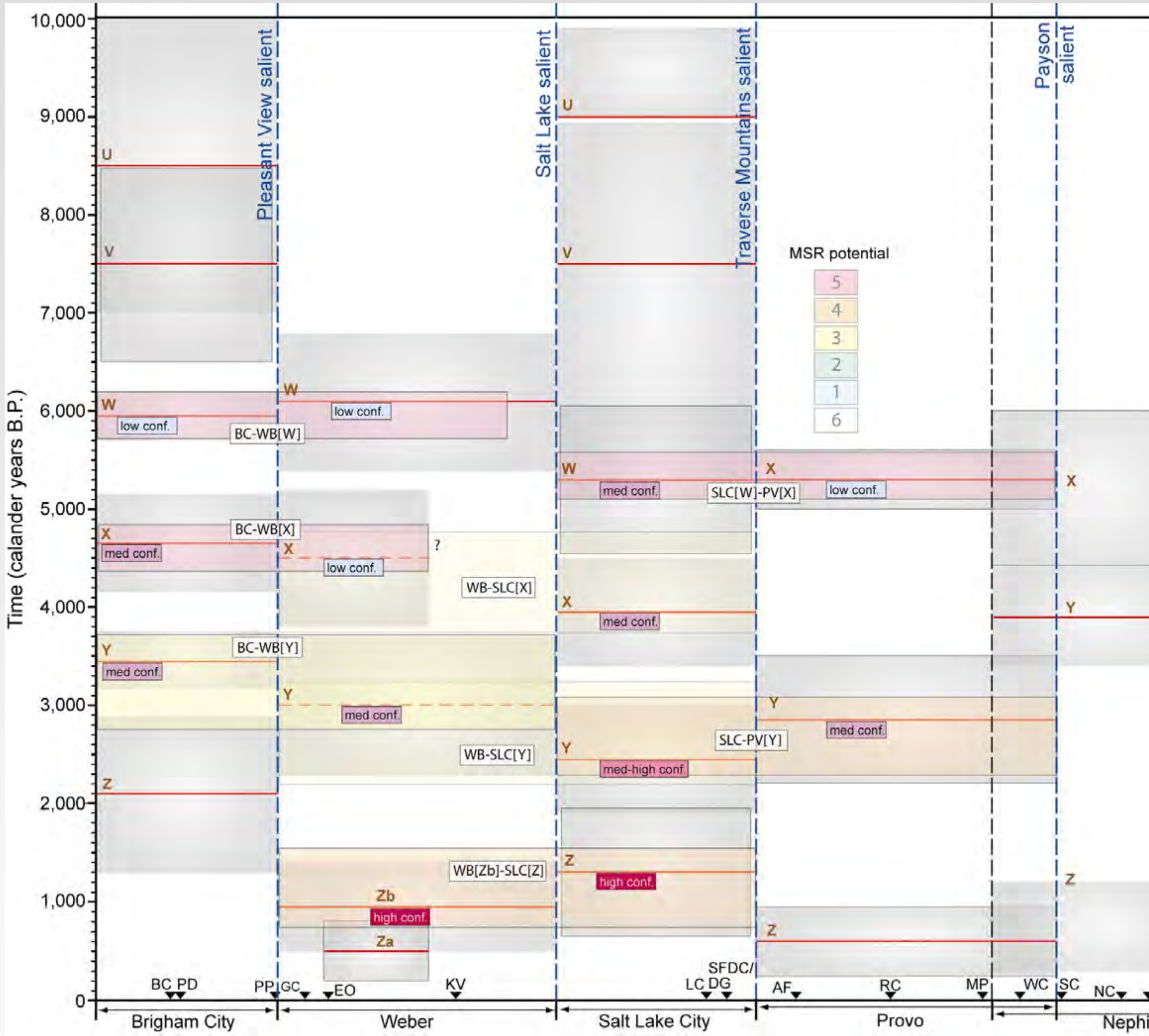
Summary of relative scenario weights

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

Preferred Model

MSR Models B-E:

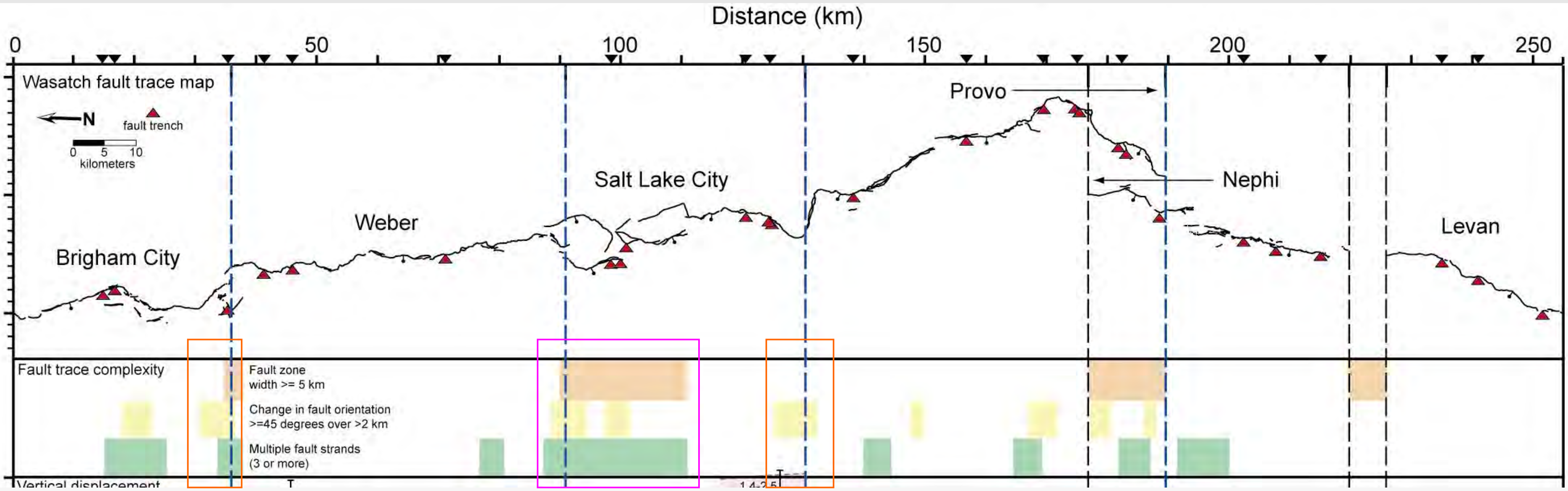
- **6-8 MSRs; 2-3 single-segment EQs**
- Incorporate Fault-zone complexity & strain?
- Relative frequency of rupture sources? Moment balance?



Segment Boundary Analysis

Geometric Complexity

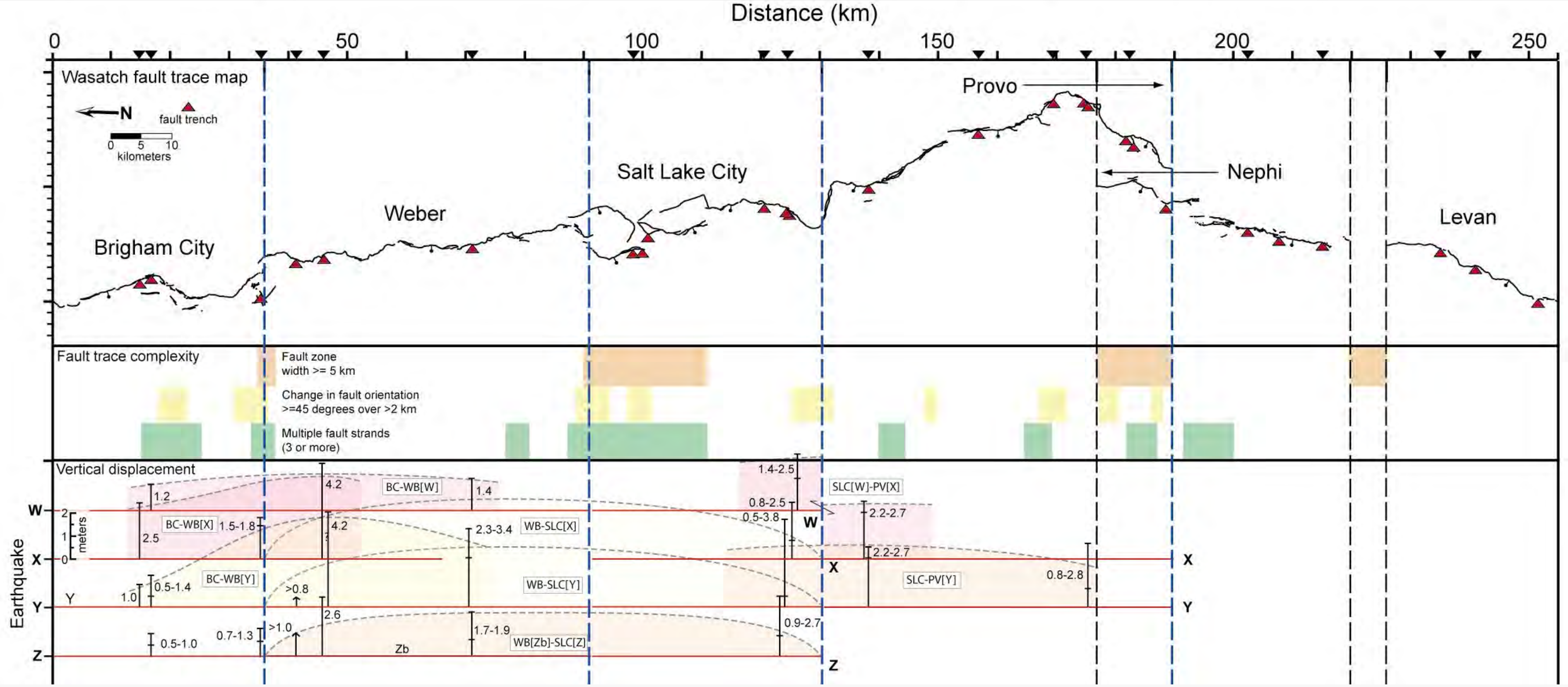
- ***More complex:*** WB+SLC
- ***Less complex:*** BC+WB, SLC+PV
- Supports more frequent **BC+WB** & **SLC+PV** MSRs



Segment Boundary Analysis

EQ displacements

- Large displacements (~4 m) on northern Weber segment, but don't unequivocally support MSRs



Strain Analysis

<u>WFZ Strain Analysis</u>

- **Do MSRs occur during periods of relative strain accumulation?**
  SAF: more frequent/large EQs occur after high strain accumulation
  (Weldon and others, 2004)

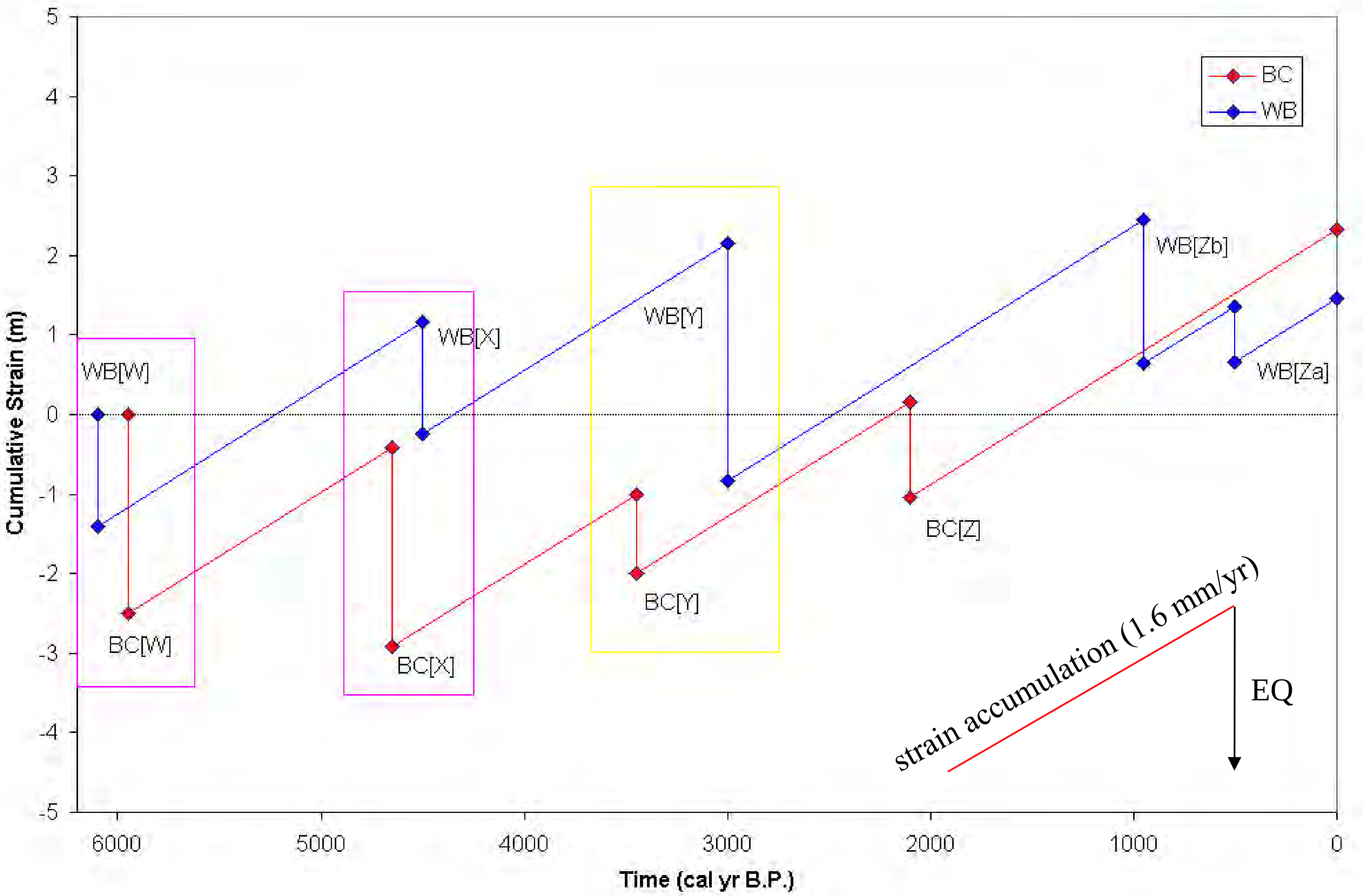
- Strain accumulation rate ≈ geodetic extension rate?

- Quality of displacement-per-event data?

- **BC to PV**: positive accumulation during mid-Holocene.

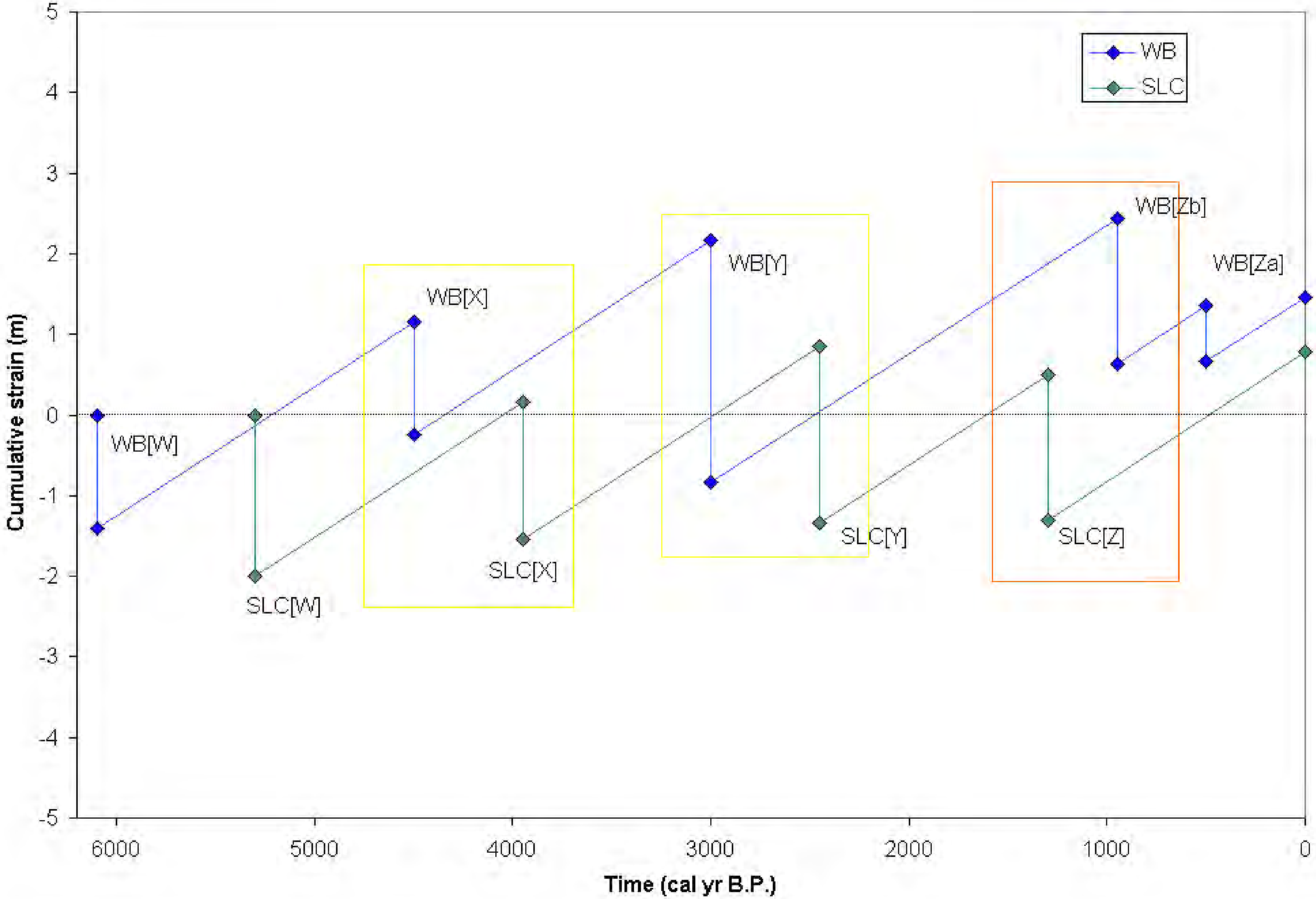
Strain Analysis

BC+WB



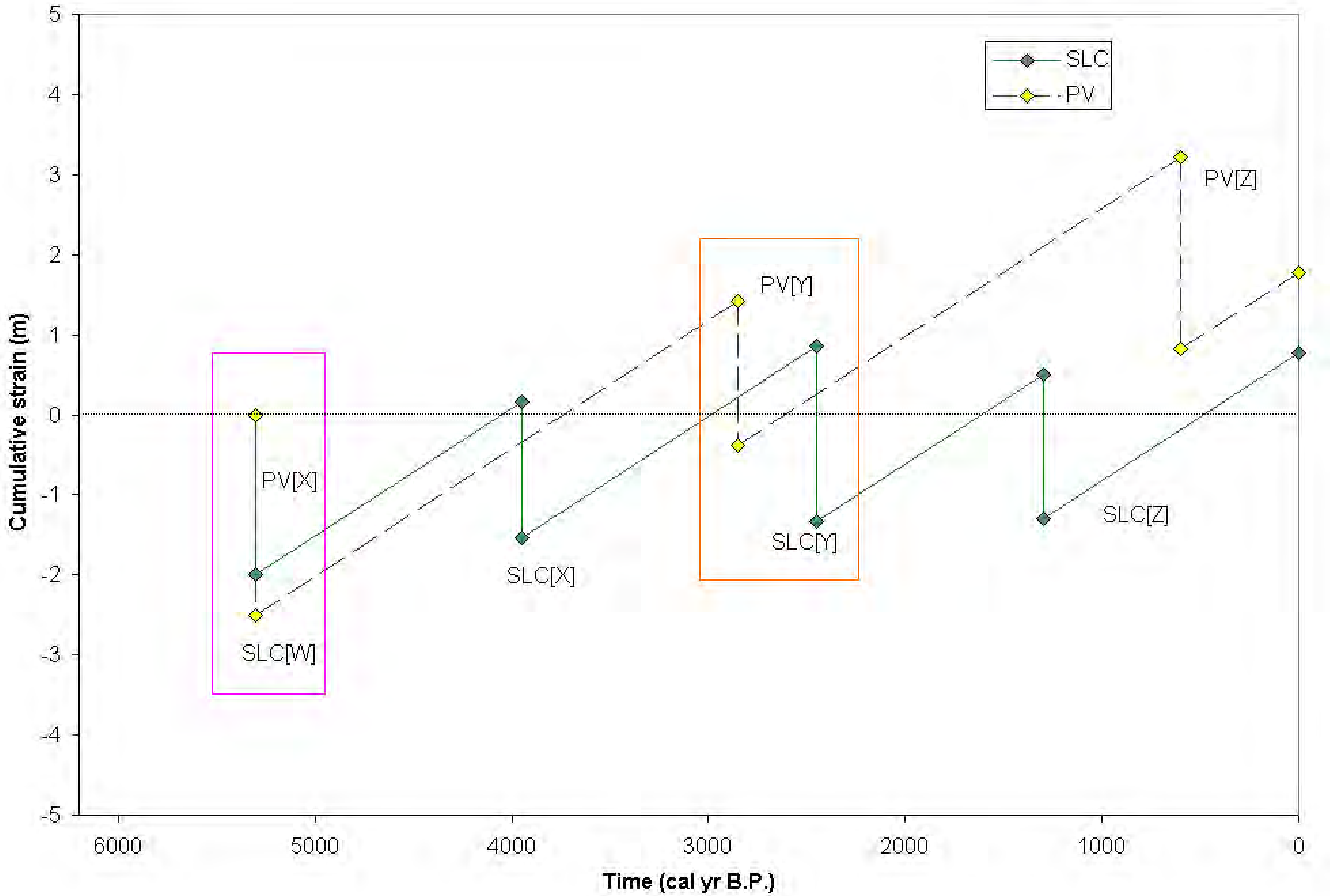
Strain Analysis

WB+SLC



Strain Analysis

SLC+PV



WFZ MSR Analysis

Summary

5 MSR models:

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

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

- **5 MSR models**:
  - Pre-2005 trench data, MSR potential, paleoseismic data confidence, quantitative scenario weights
- **FZ complexity** - weakly supports scenarios 2, 4, 5
- **Displacement** per event & **strain analysis** - inconclusive
- **Future work** - finalize models/weights, occurrence rates, & moment balance

WFZ MSR Analysis

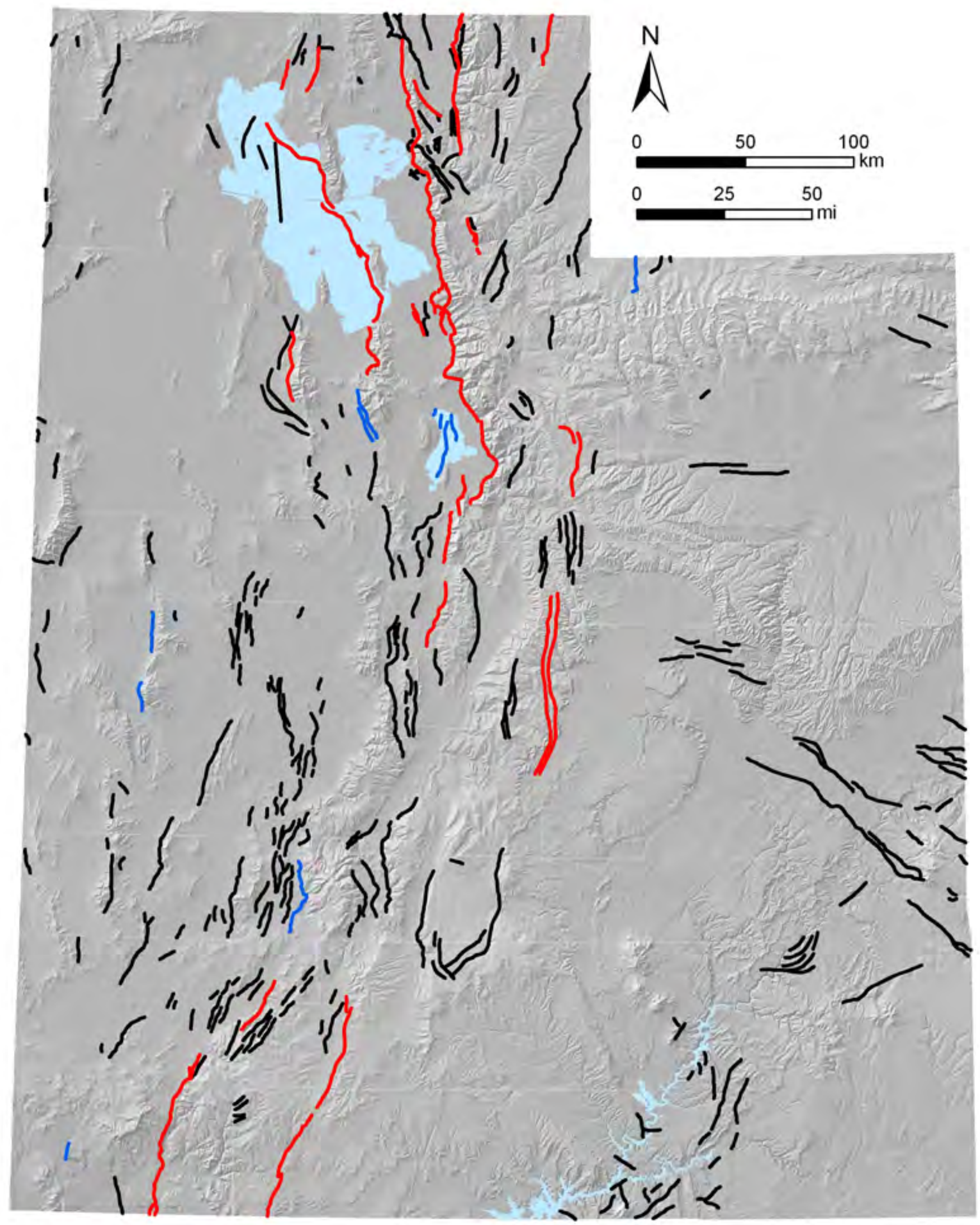
Based on the current WFZ paleoseismic data, do we go ahead with the MSR model?

- Or wait for new WB, PV, NP data and reevaluate?

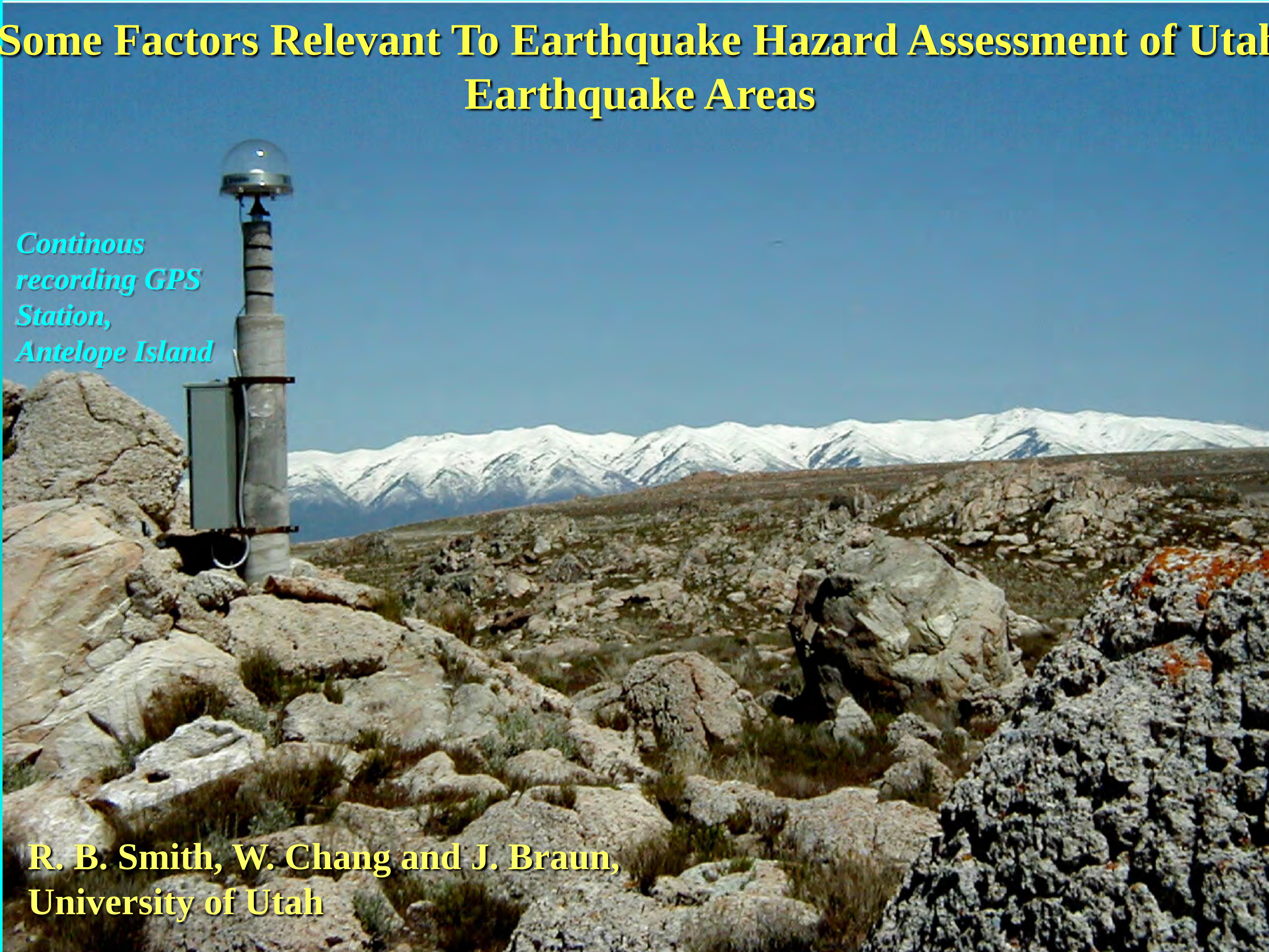
If so, how do we pick appropriate models and weights?

- Are the rupture sources appropriate? (e.g., SLC+PV = 98 km)
- Include additional/fewer models?

- Appropriate weights for all MSR models? (e.g., 20%)
- Appropriate weights for competing MSR models? (e.g., 5% ea.)


N
0 50 100
km
0 25 50
mi

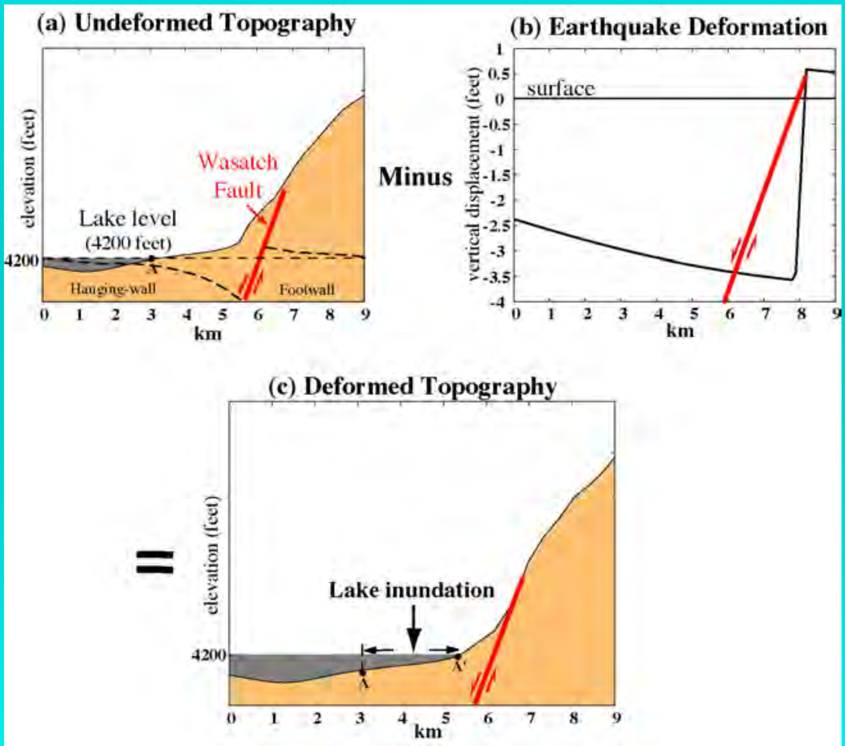
Some Factors Relevant To Earthquake Hazard Assessment of Utah Earthquake Areas

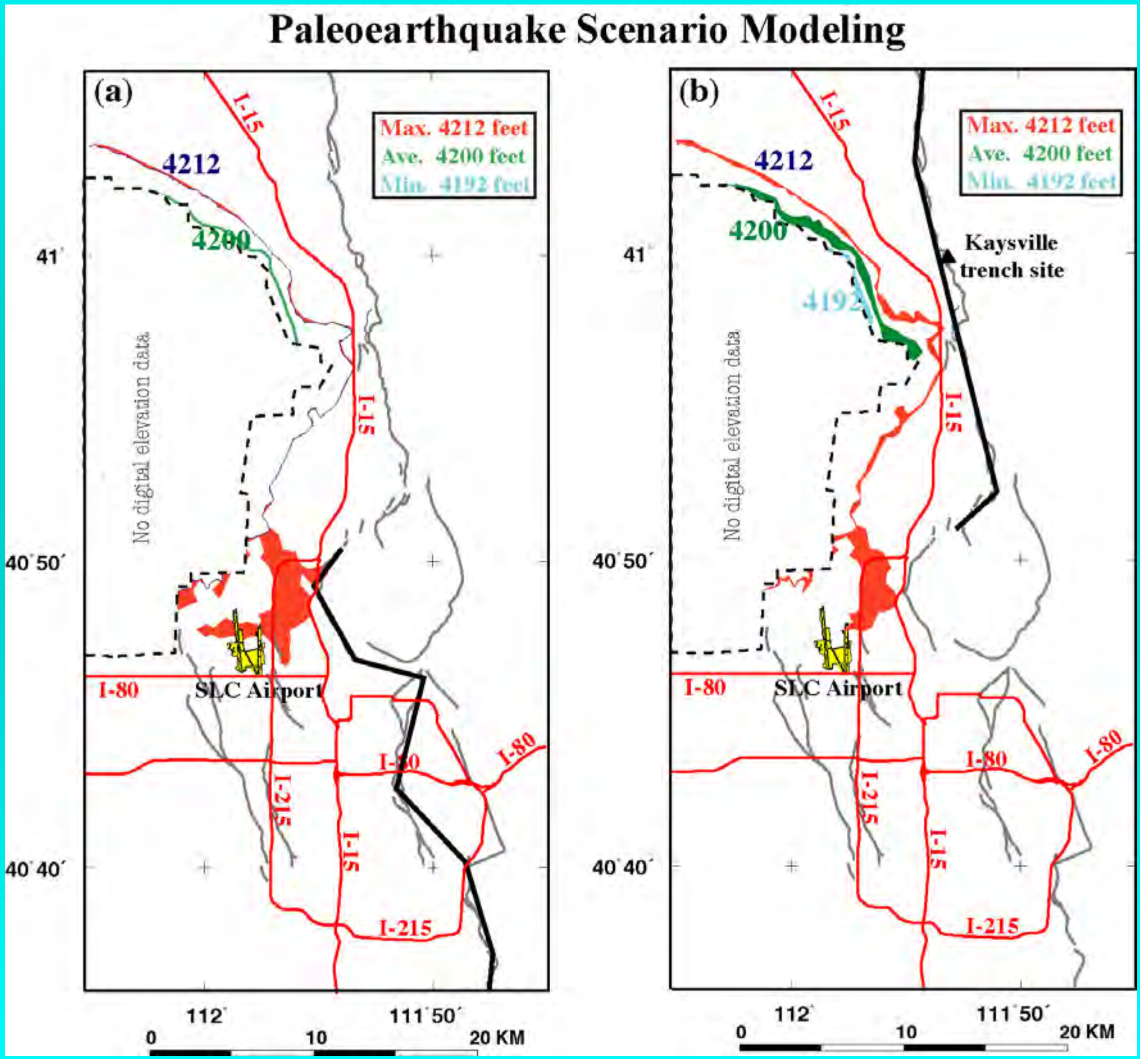


Continous recording GPS Station, Antelope Island

R. B. Smith, W. Chang and J. Braun,
University of Utah

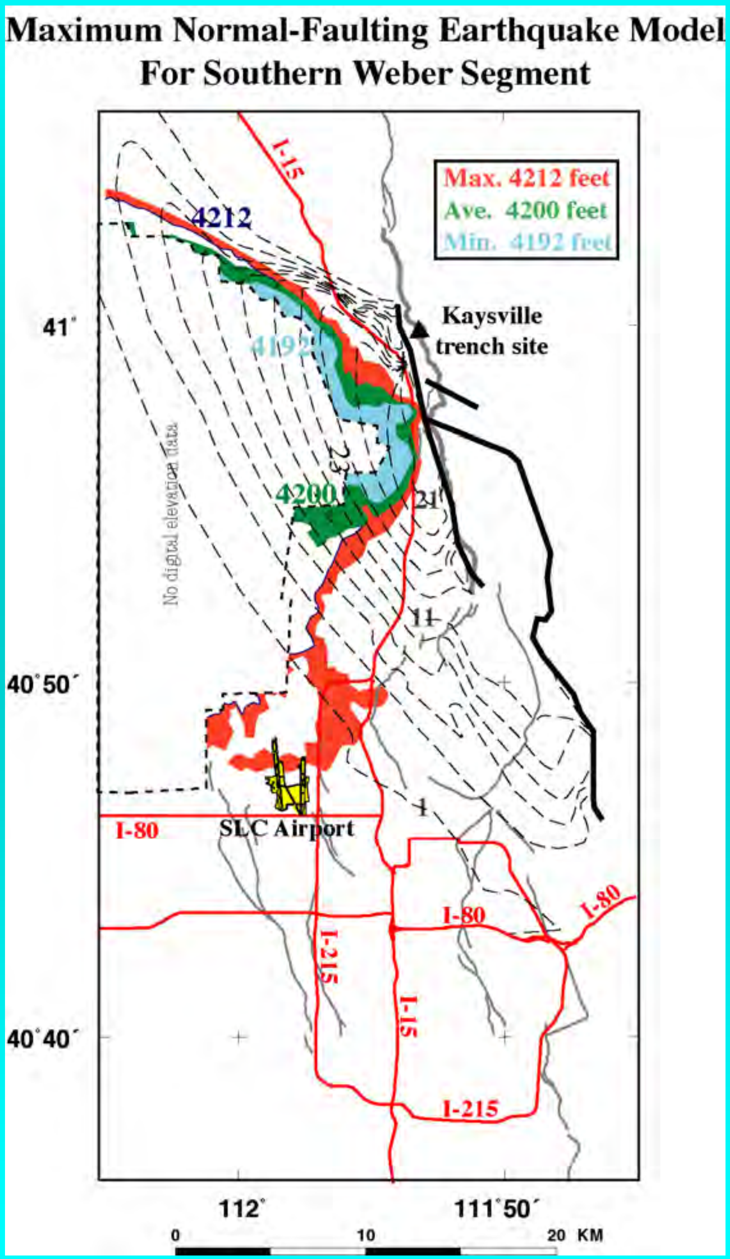
Tectonically Induced Flooding by the Great Salt Lake From Large Earthquakes on the Wasatch Fault

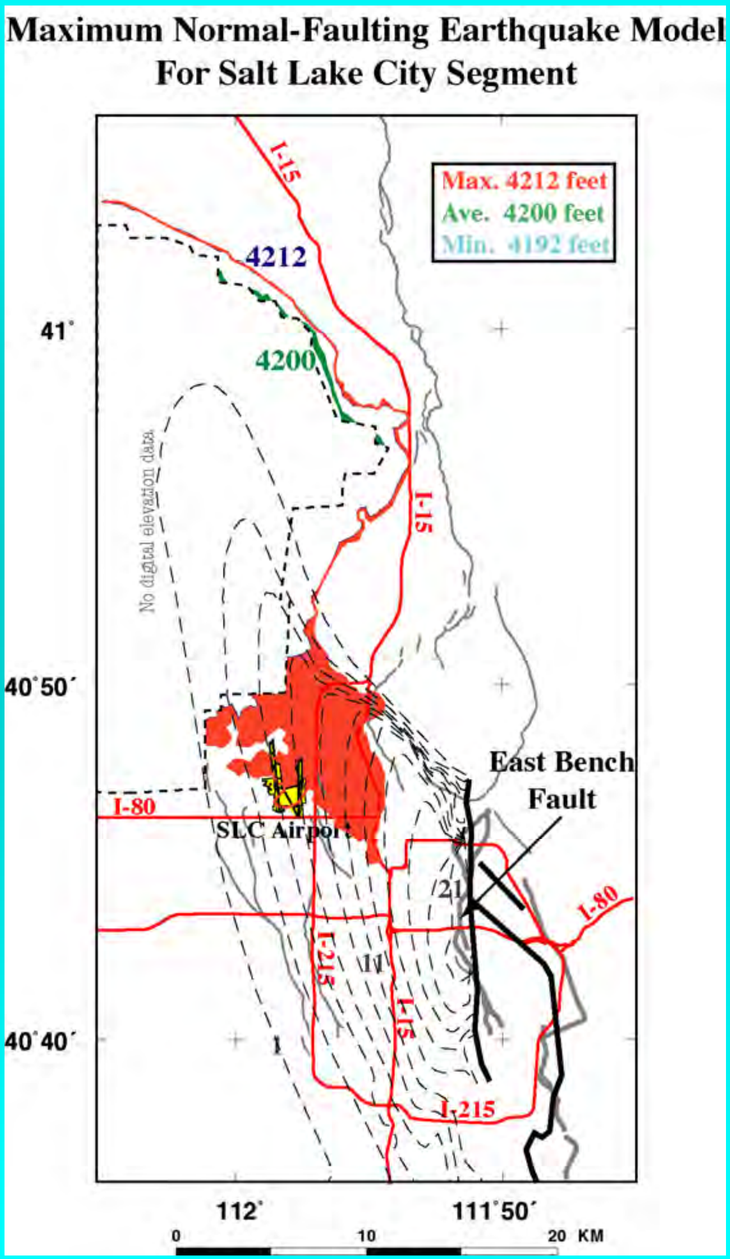




Chang and Smith [1997]

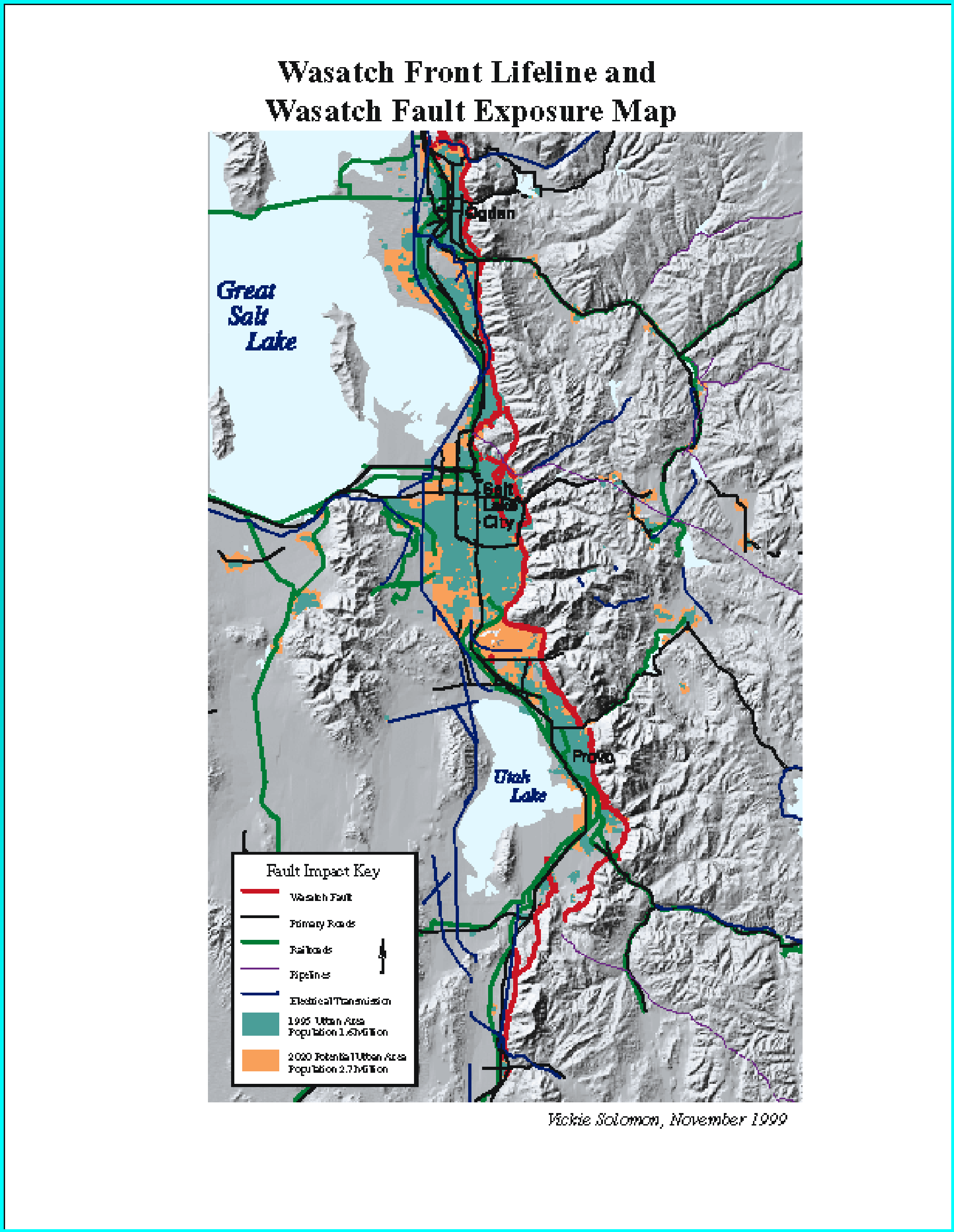
Tectonically Induced Flooding by the Great Salt Lake From Large Earthquakes on the Wasatch Fault





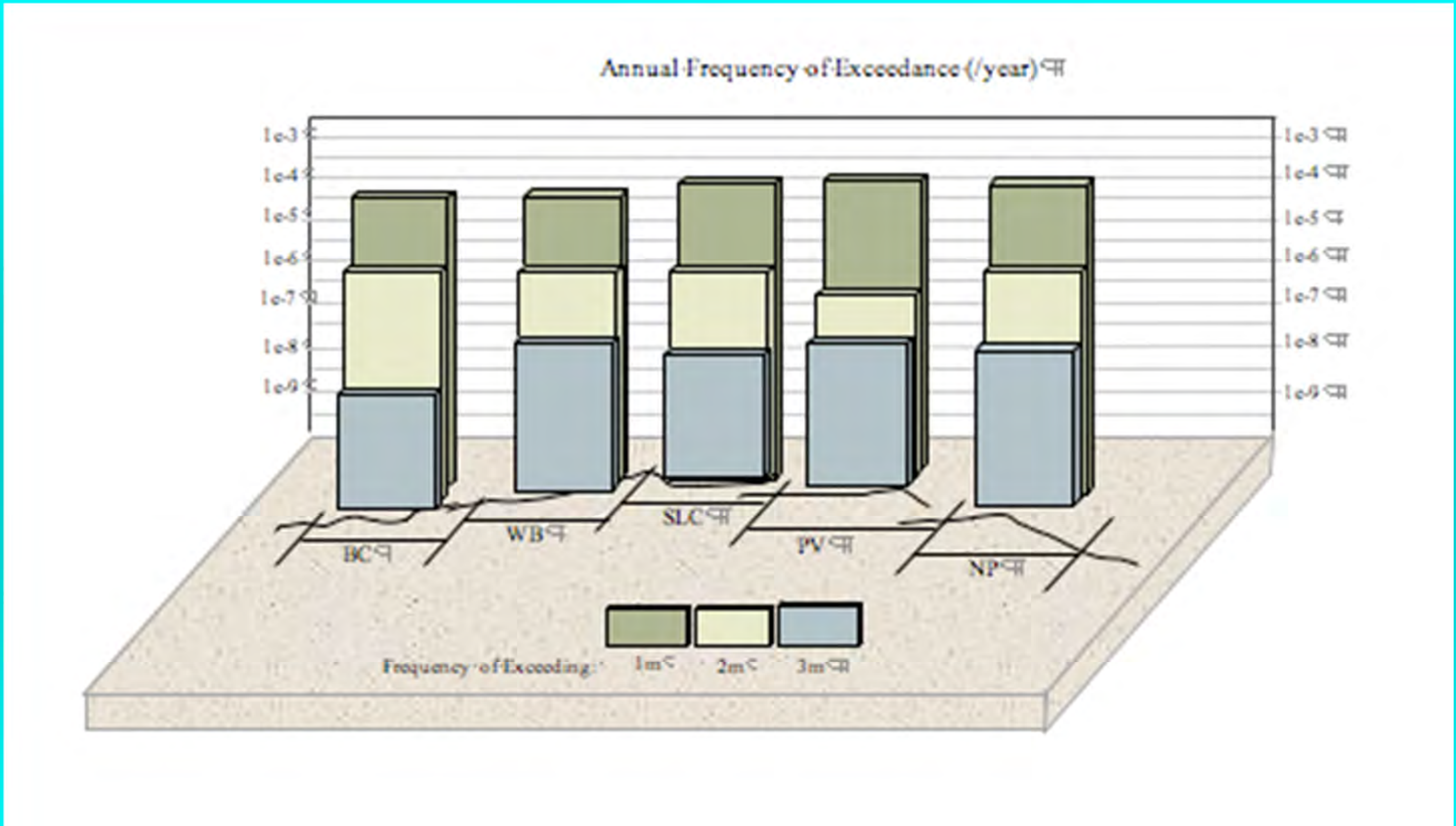
Chang and Smith [1997]

Map of Wasatch fault and Wasatch Front lifelines showing the potential of direct fault-rupture of these critical facilities.



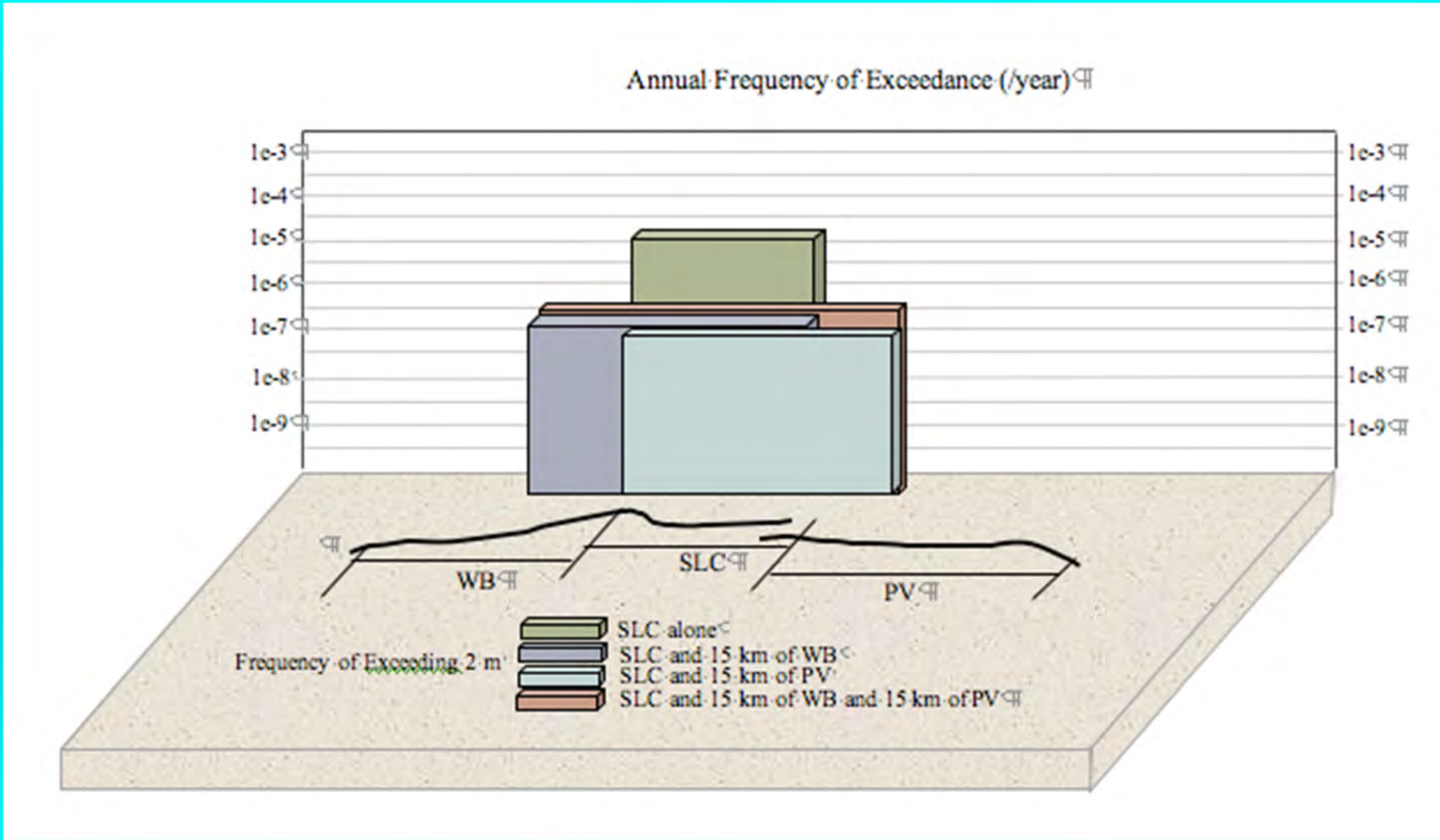
Braun, 2000

Single segment PDHA



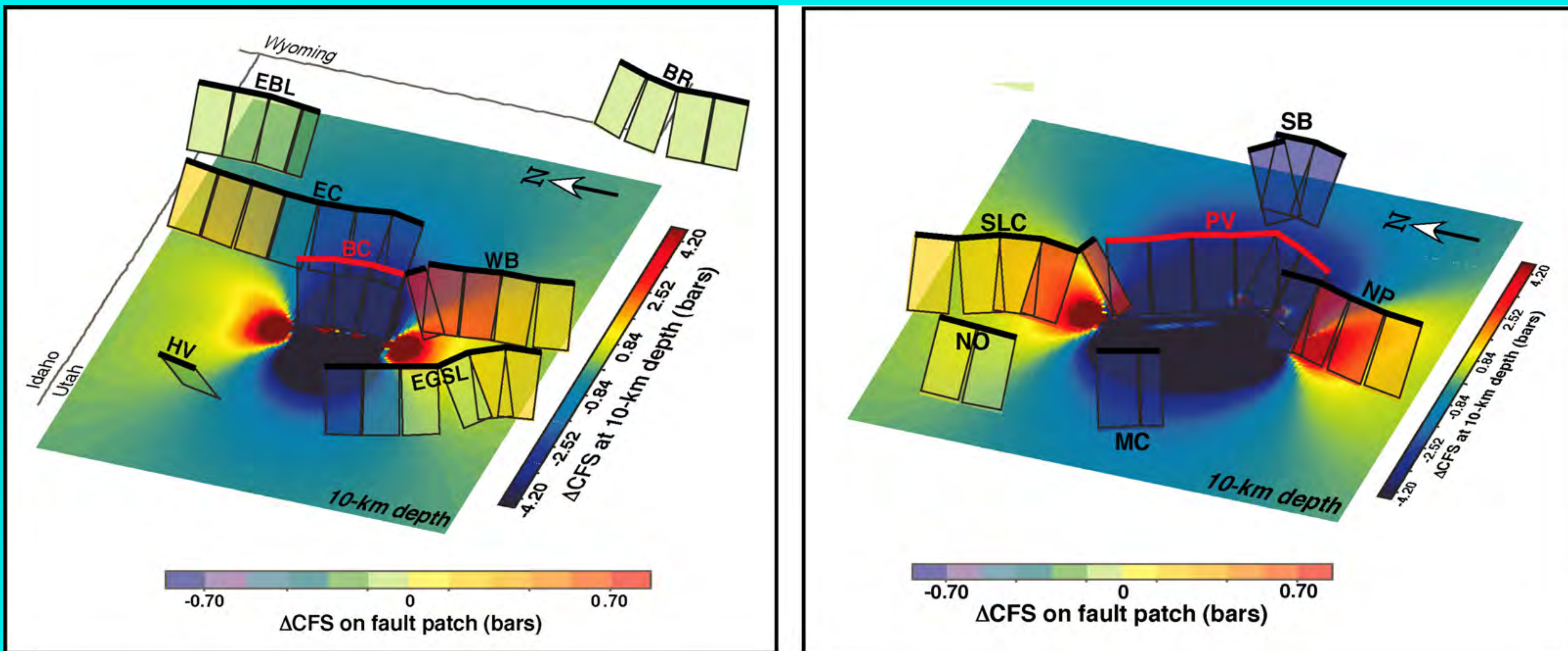
Braun, 2000

Multi segment PDHA



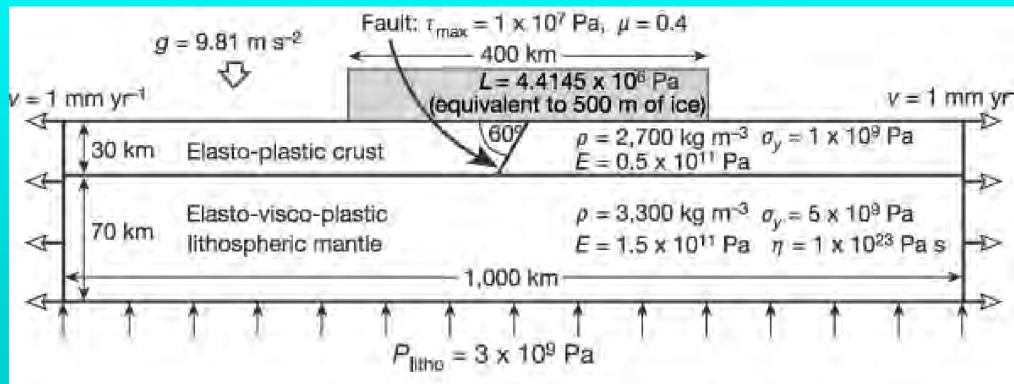
Braun, 2000

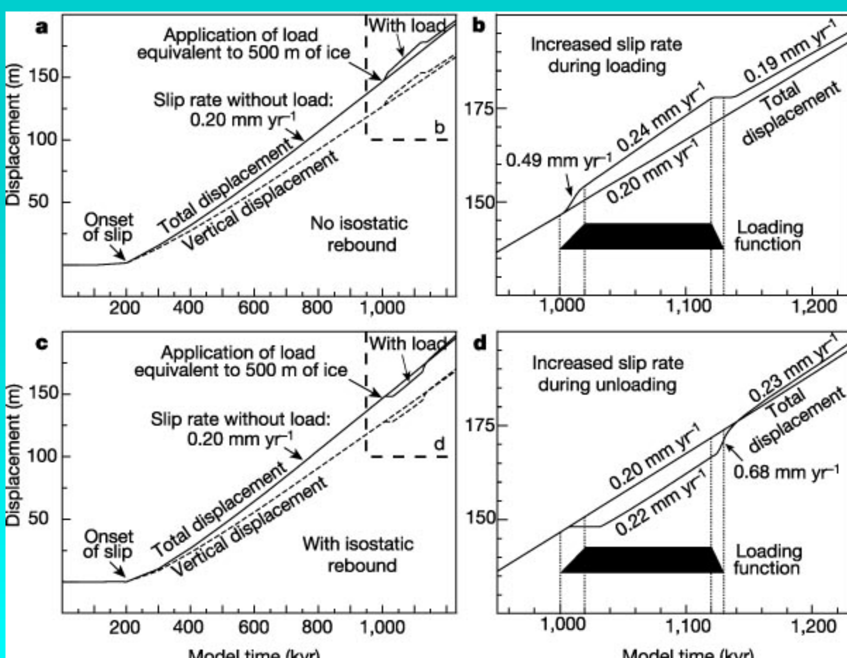
Stress Contagion Model for the Wasatch Fault

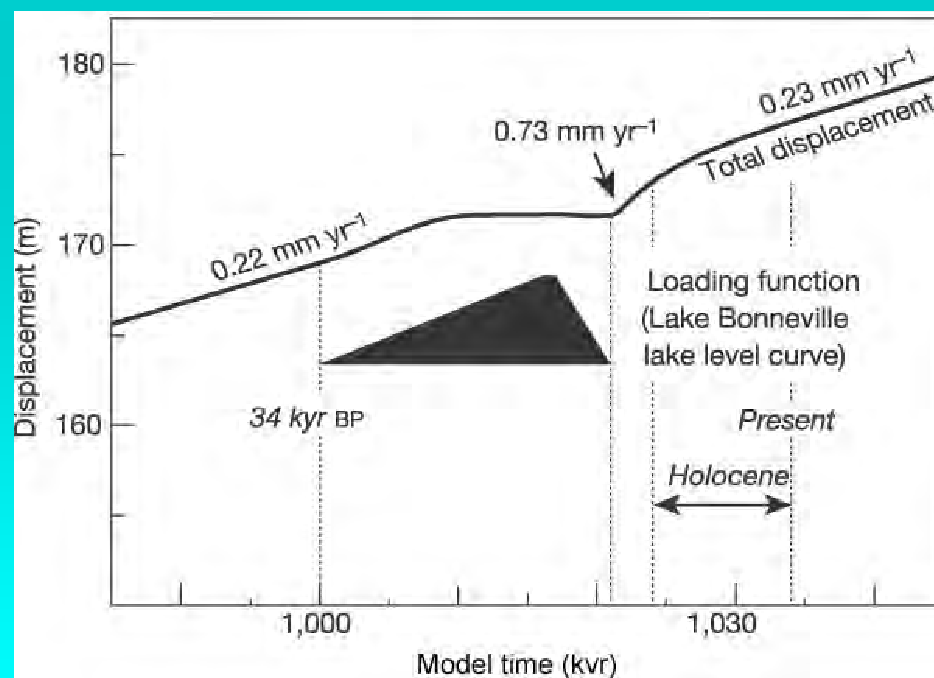


Chang and Smith [2002]

Fault loading from desication of Lake Bonneville and deglaciation of Wasatch Range at ~12-10 ky. produces increased fault slip rates and consequential earthquake clustering

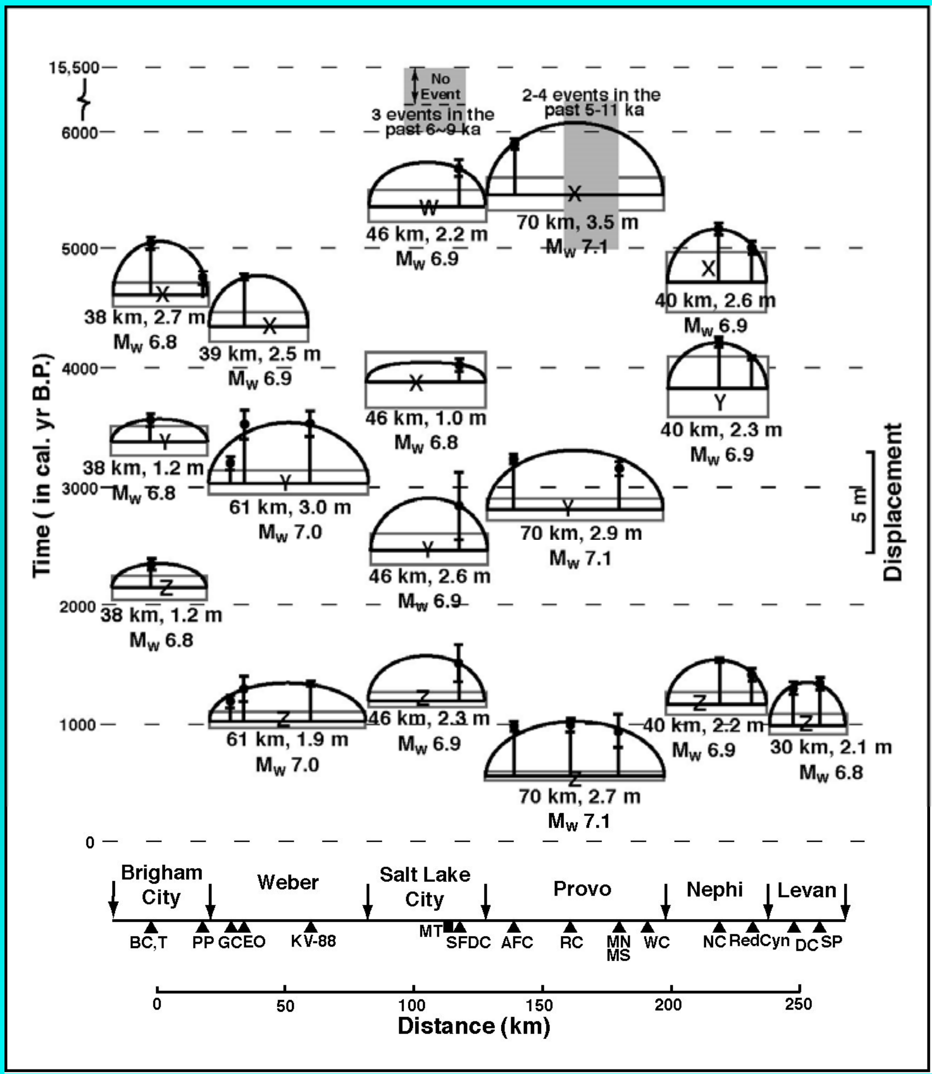




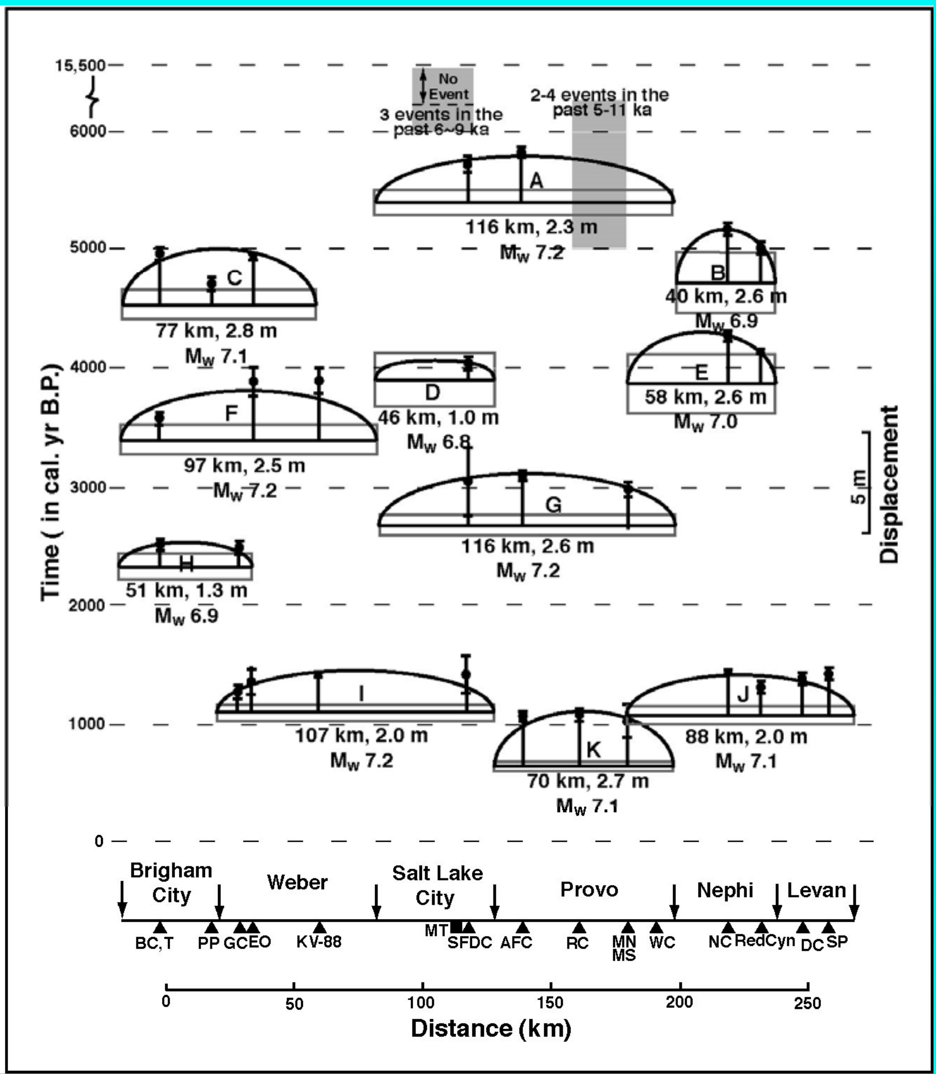


Hetzel, 2005

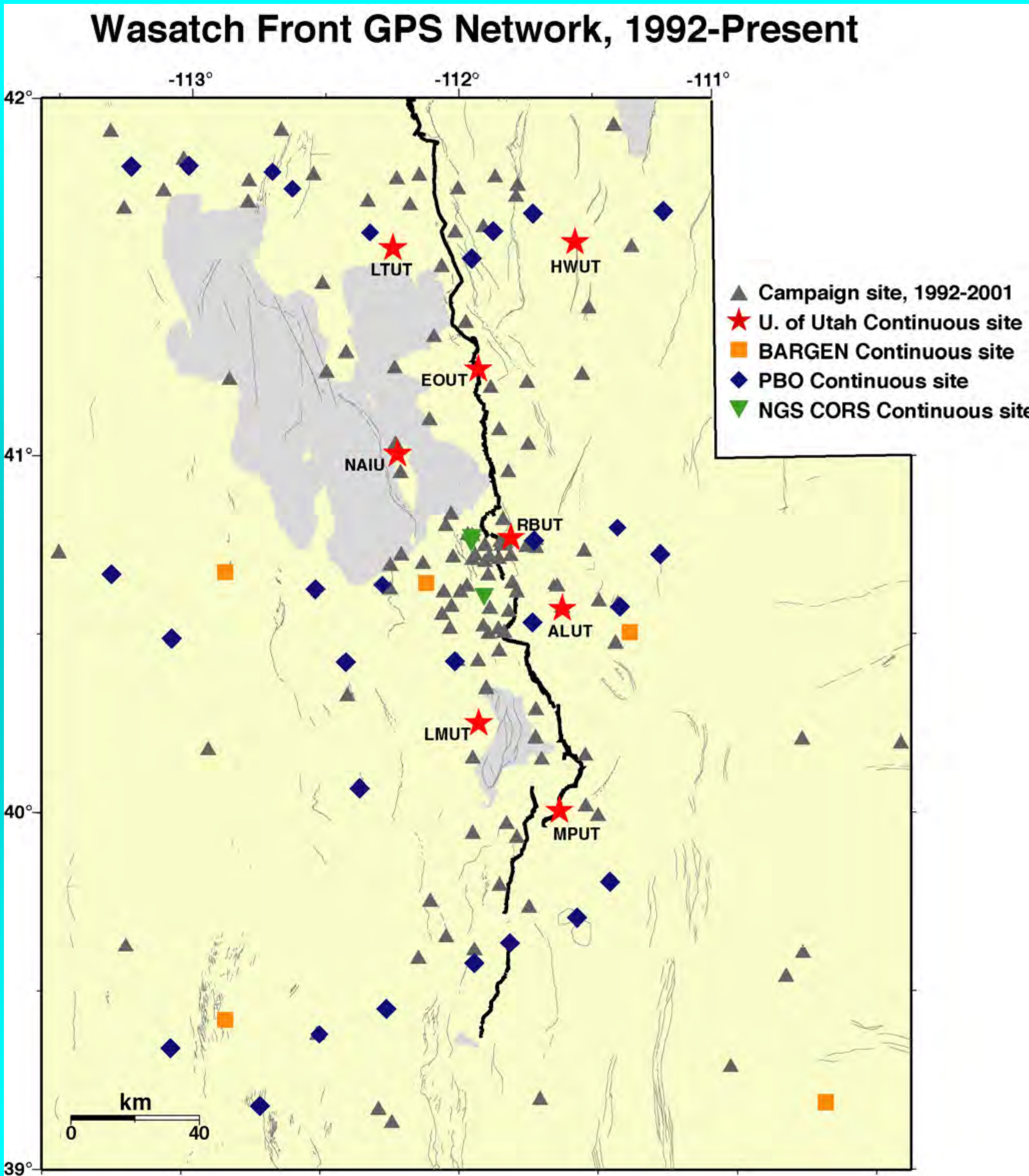
Single- and Multi-segment Model for the Wasatch Paleoearthquakes



after McCalpin and Nishenko [1996]



Chang and Smith [2002]

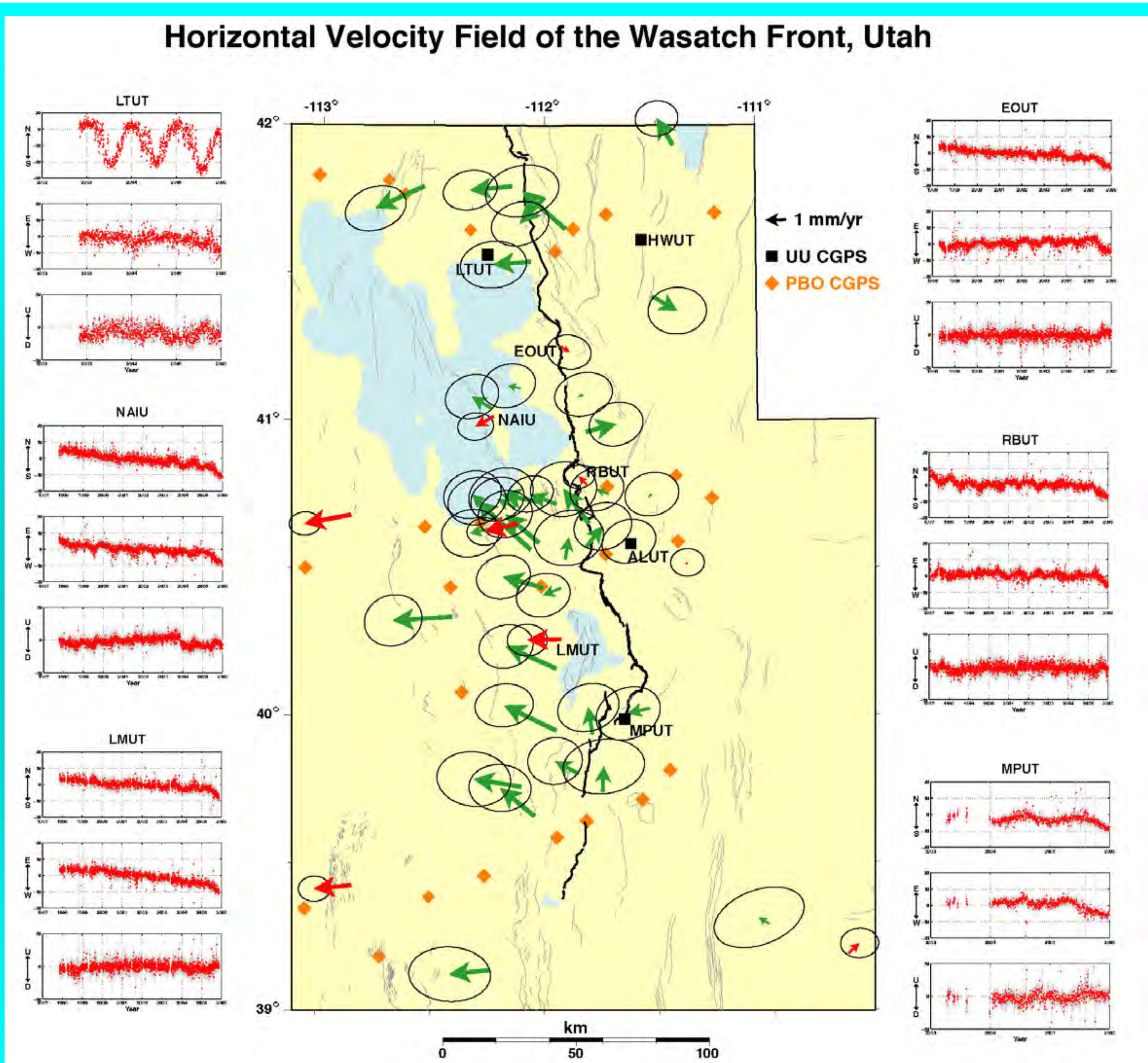


UU and PBO (EarthScope) other agency real-time permanent and campaign Station GPS network

40 real-time permanent stations

60 campaign stations

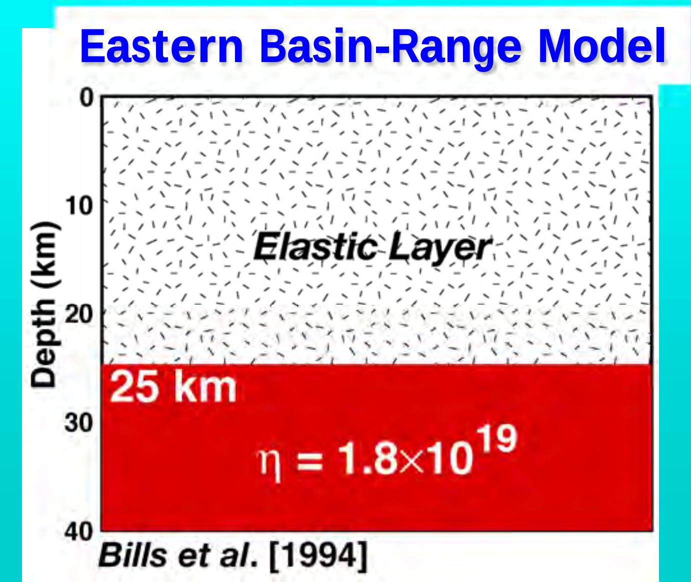

Wasatch Front GPS Network, 1992-Present
-113°
-112°
-111°
42°
41°
40°
39°
LTUT
HWUT
EOUT
NAIU
RBUT
Salt Lake City
ALUT
LMUT
MPUT
Campaign site, 1992-2001
U. of Utah Continuous site
BARGEN Continuous site
PBO Continuous site (current)
NGS CORS Continuous site
km
0
40

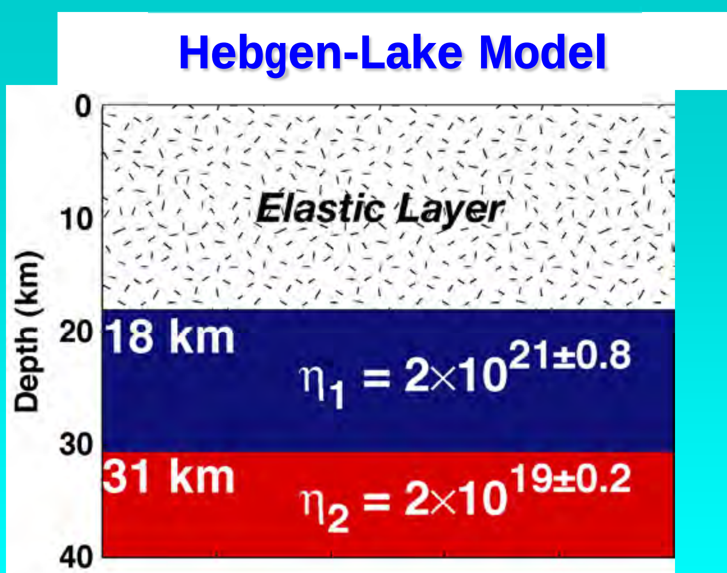


The Wasatch Fault is zone of major strain accumulation

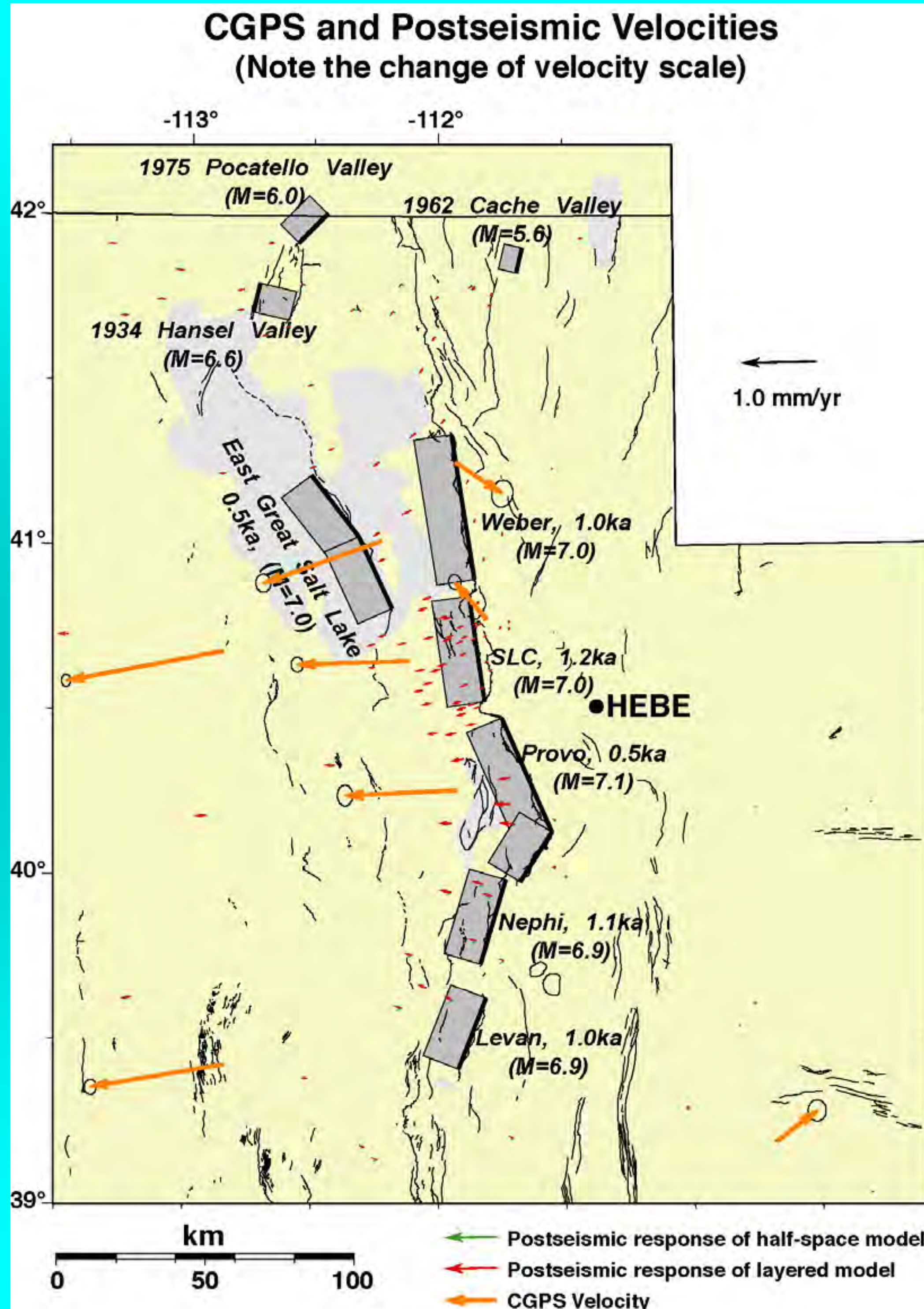
Chang et al. [2006, submitted to JGR]

Rheologic Models for Estimating Postseismic Deformation

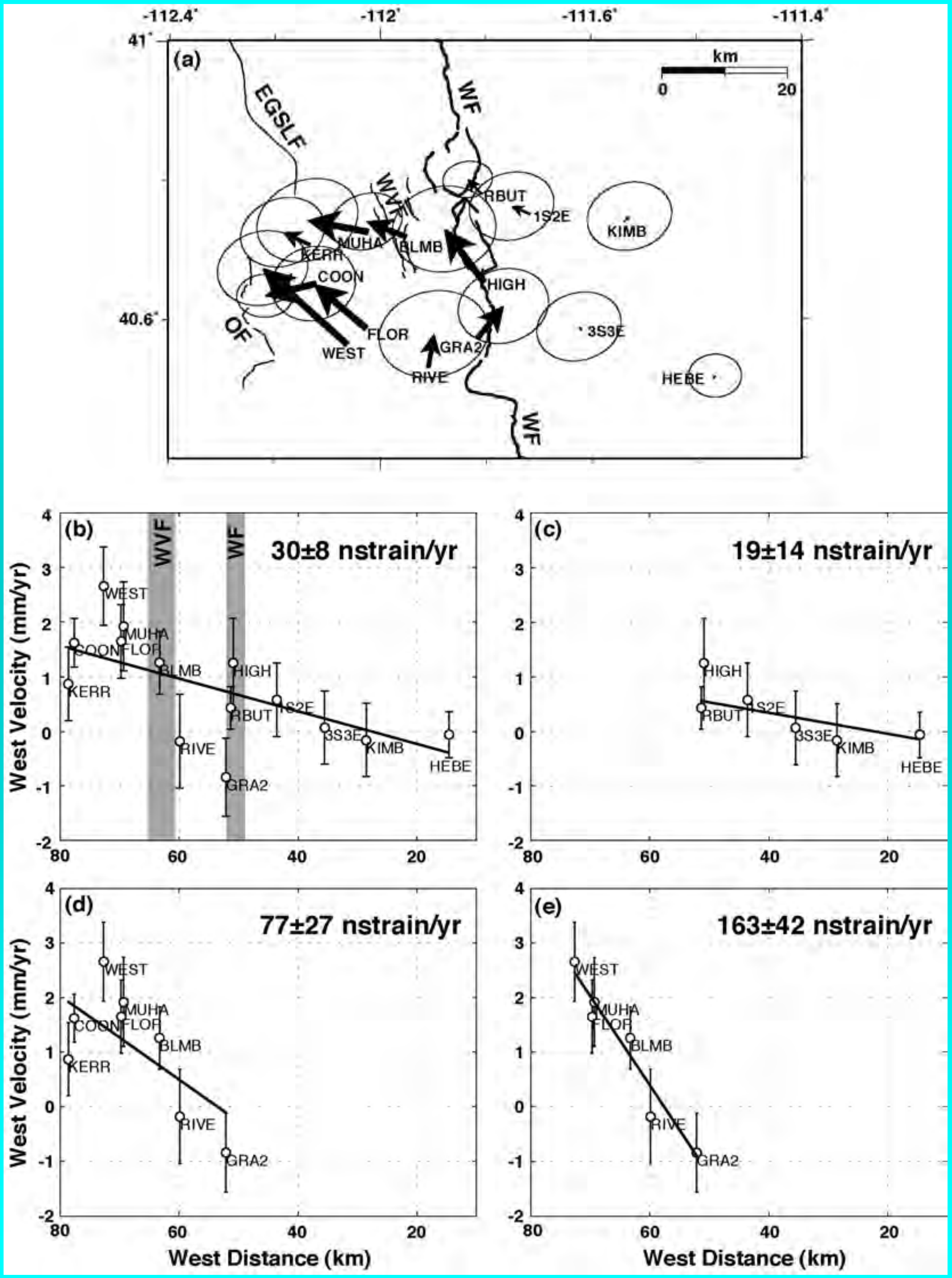


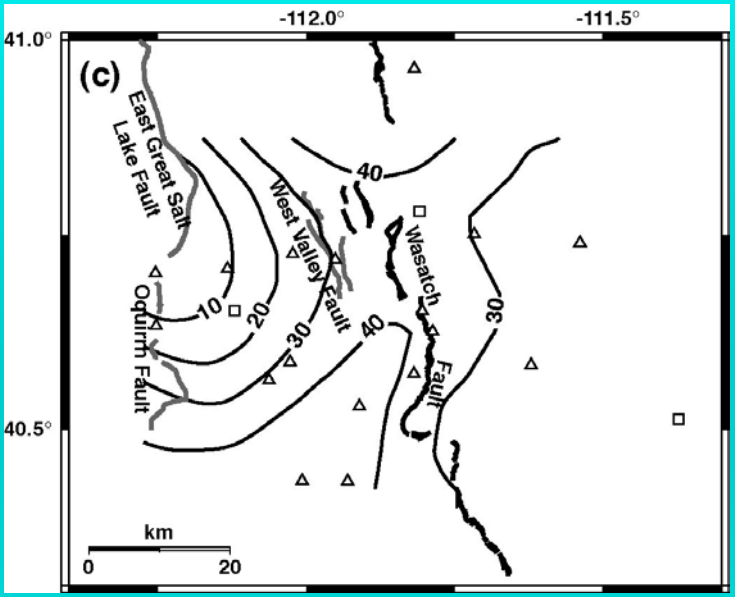


Chang et al. [2006, submitted to JGR]



GPS Velocity and Strain-Rate Field across the Central Wasatch Fault

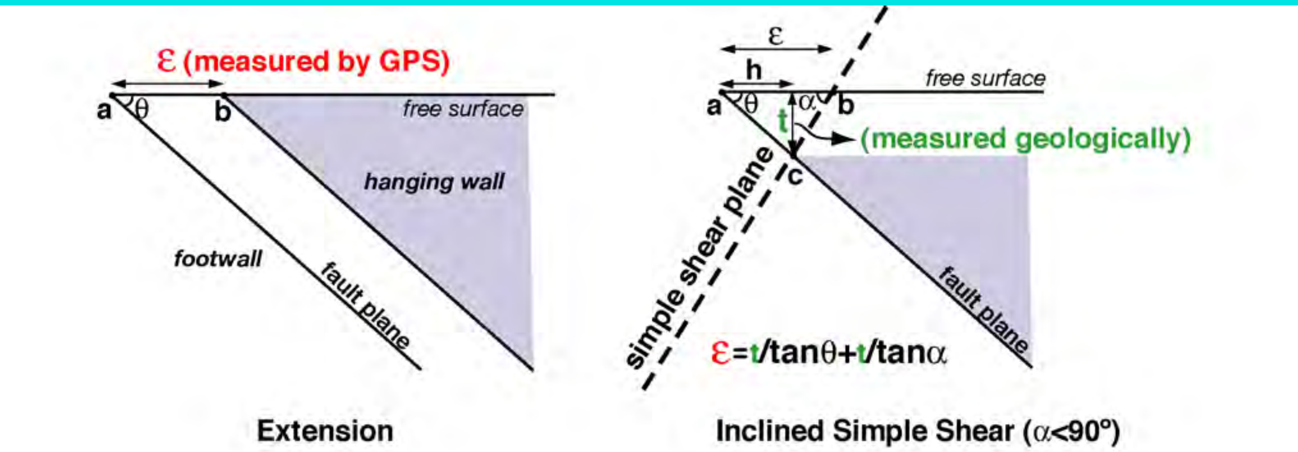




Note the strong strain gradients across the fault zone

Chang et al. [2006, submitted to JGR]

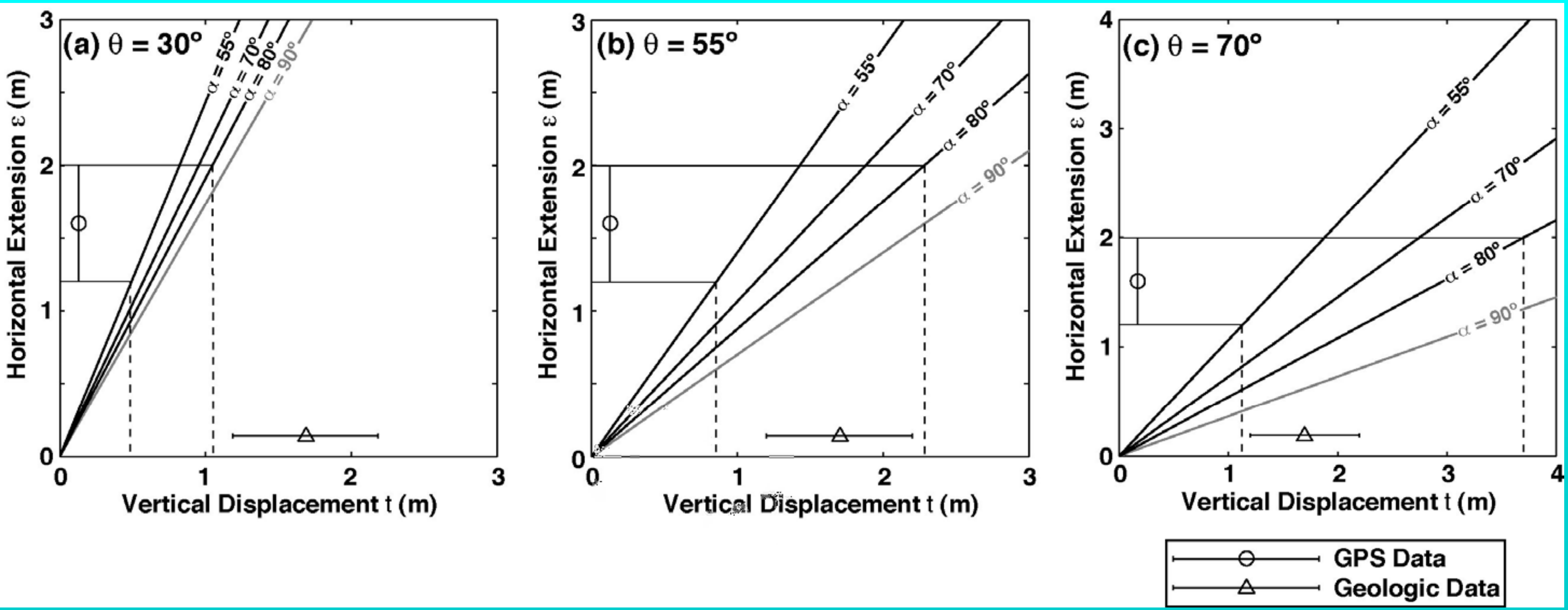
Simple-Shear <u>Finite-Strain</u> Model for Converting Geologic Vertical Displacement To Geodetic Horizontal Extension for Normal Fault



$$\text{Horizontal Extension} = \text{Vertical Displacement} \times (1/\tan\theta + \tan\alpha)$$

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

Chang et al. [2006, submitted to JGR]

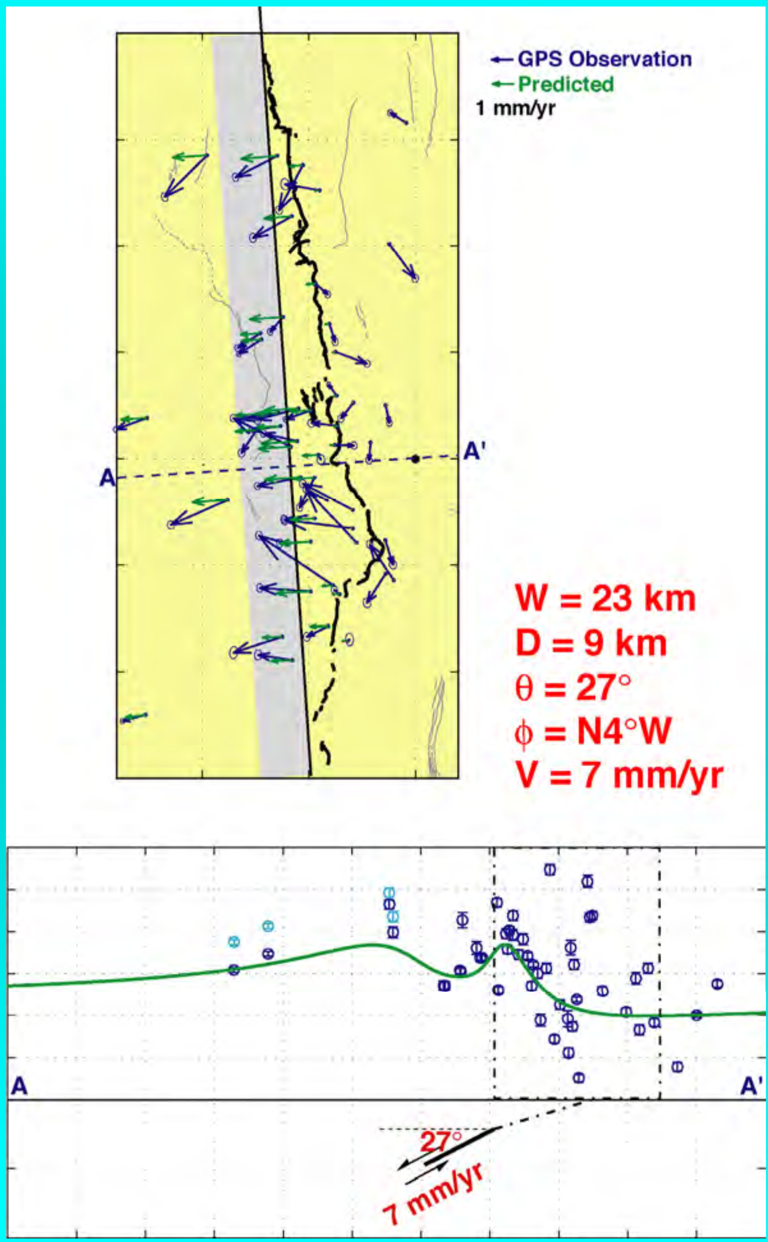


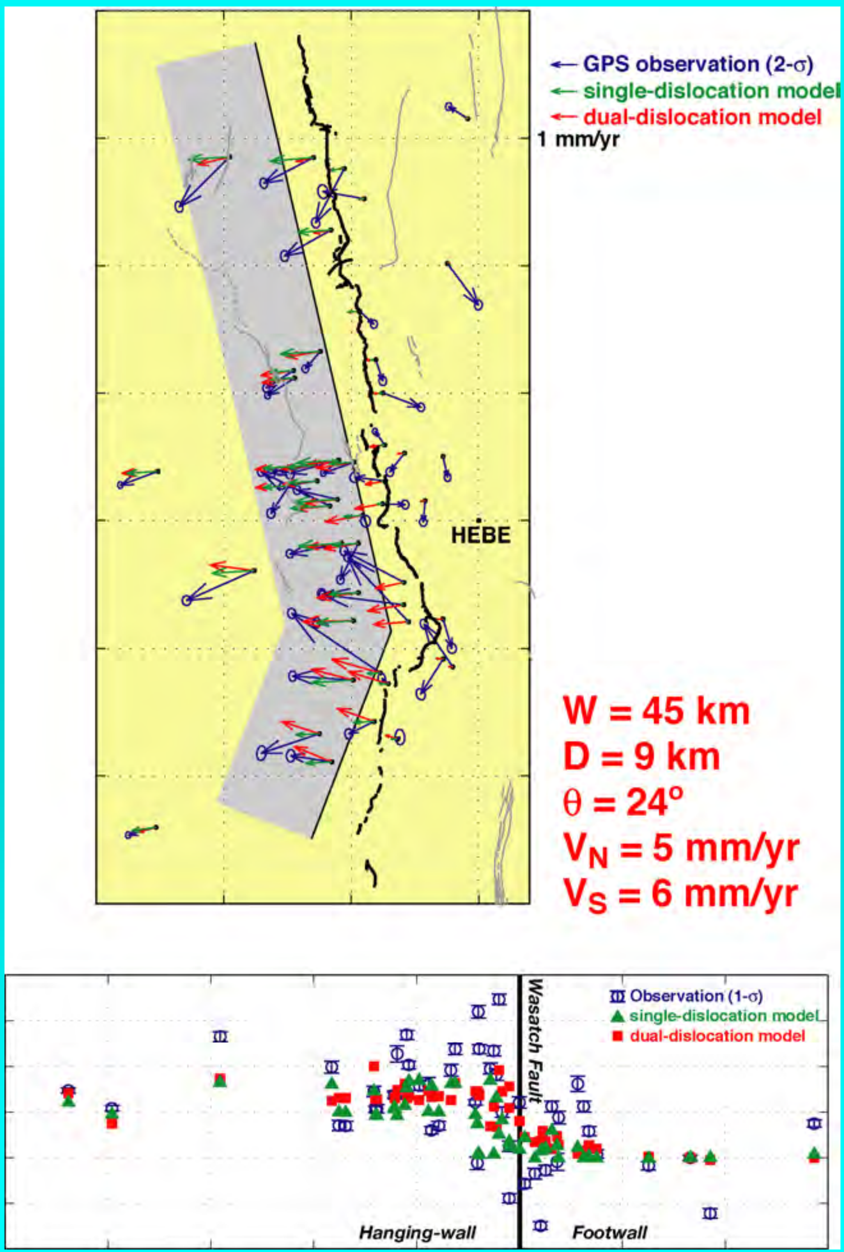
Comparison of Deformation Rates Across the Wasatch Fault From GPS and Geologic Determinations

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

Chang et al. [2006, submitted to JGR]

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



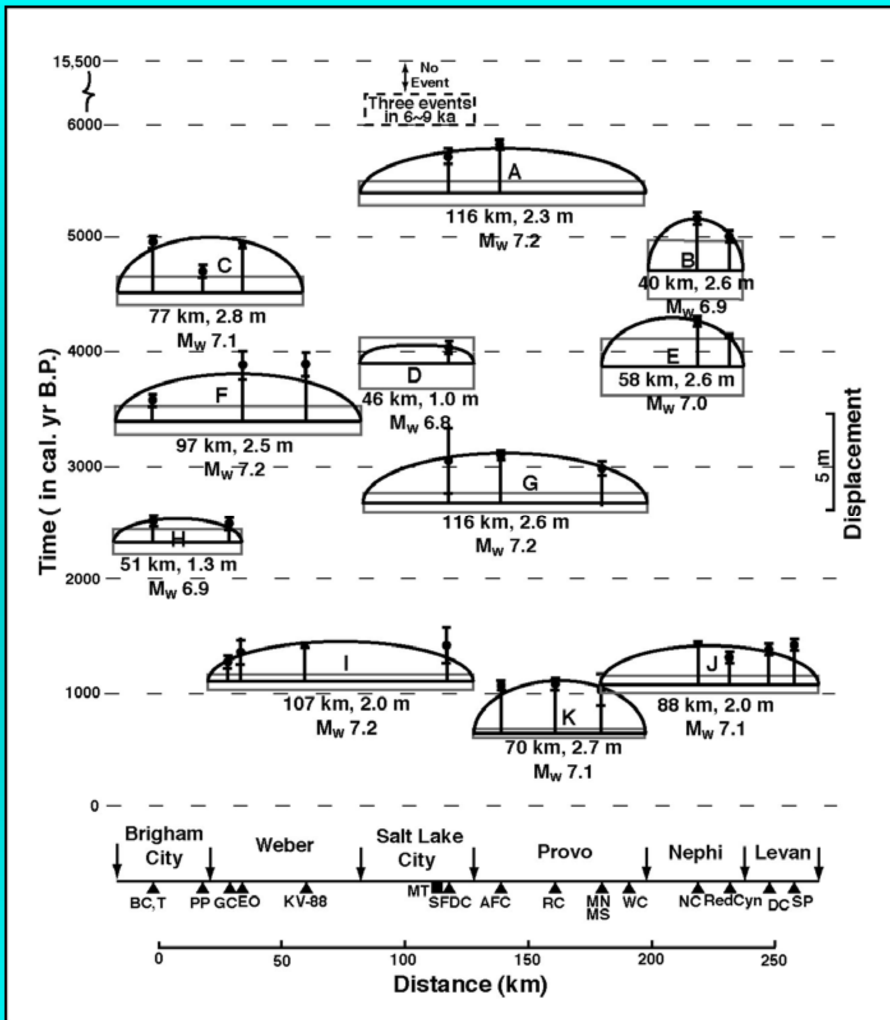


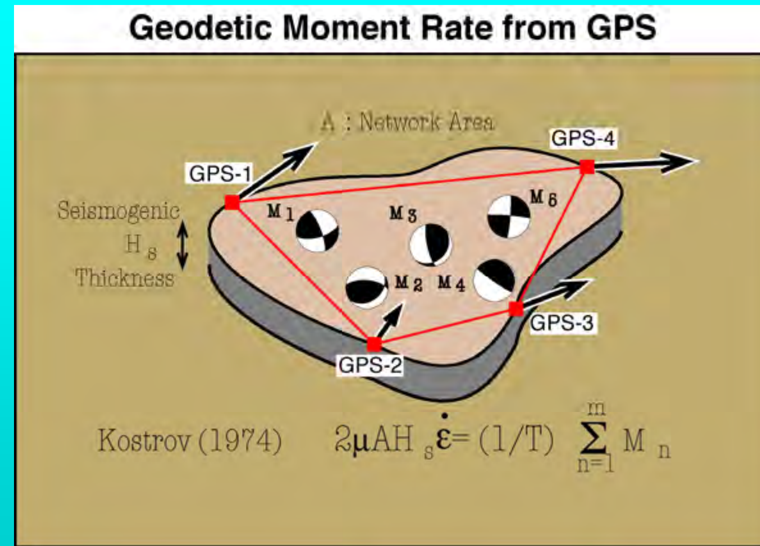
Again note the strong strain gradients across the fault zone

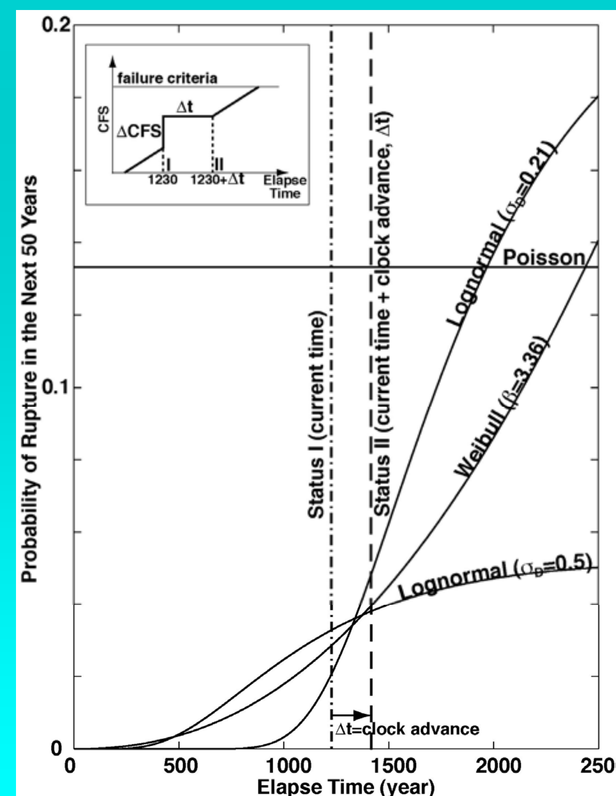
Chang et al. [2006, in preparation]

Contributions to PSHA

Multi-segment Model

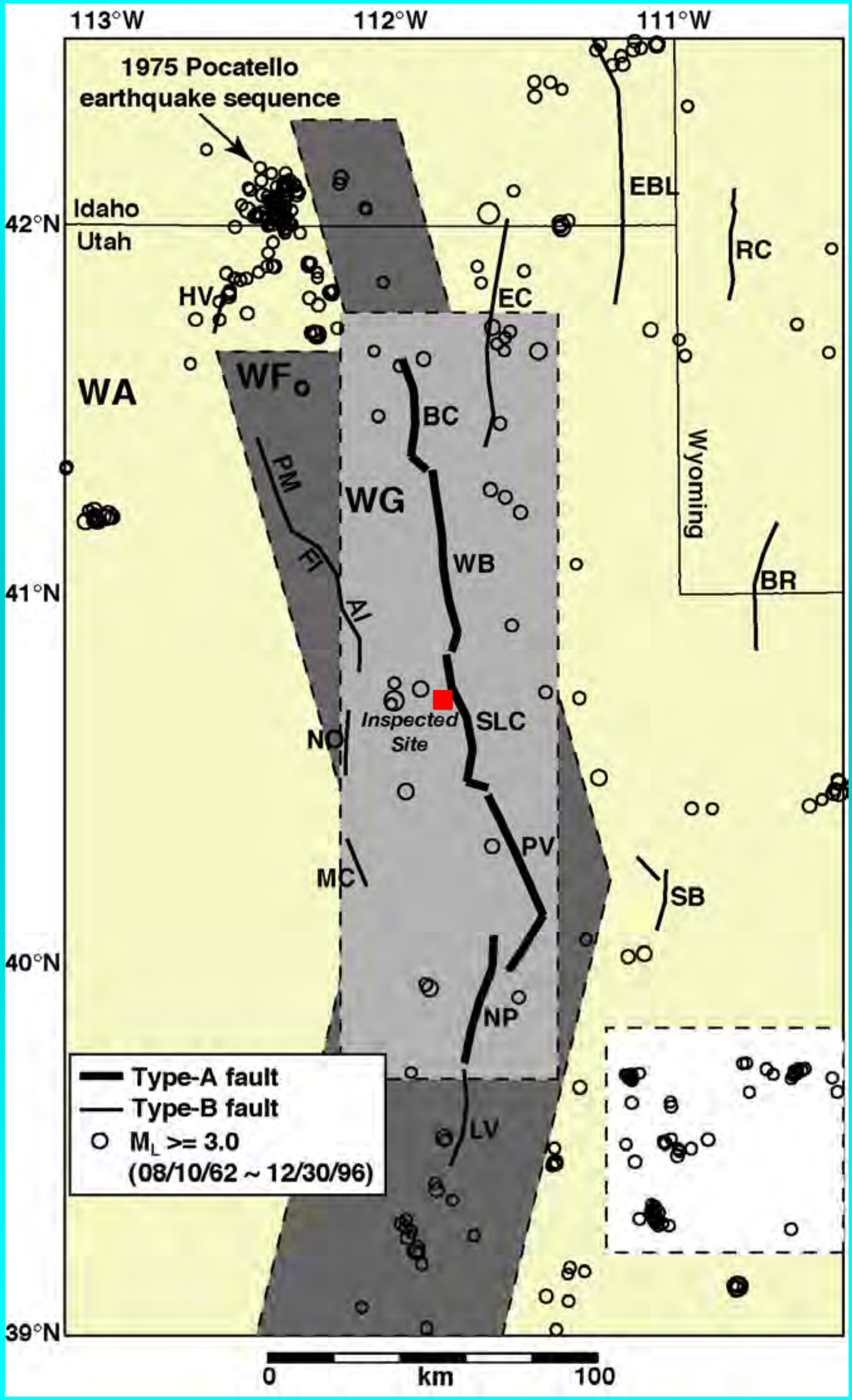




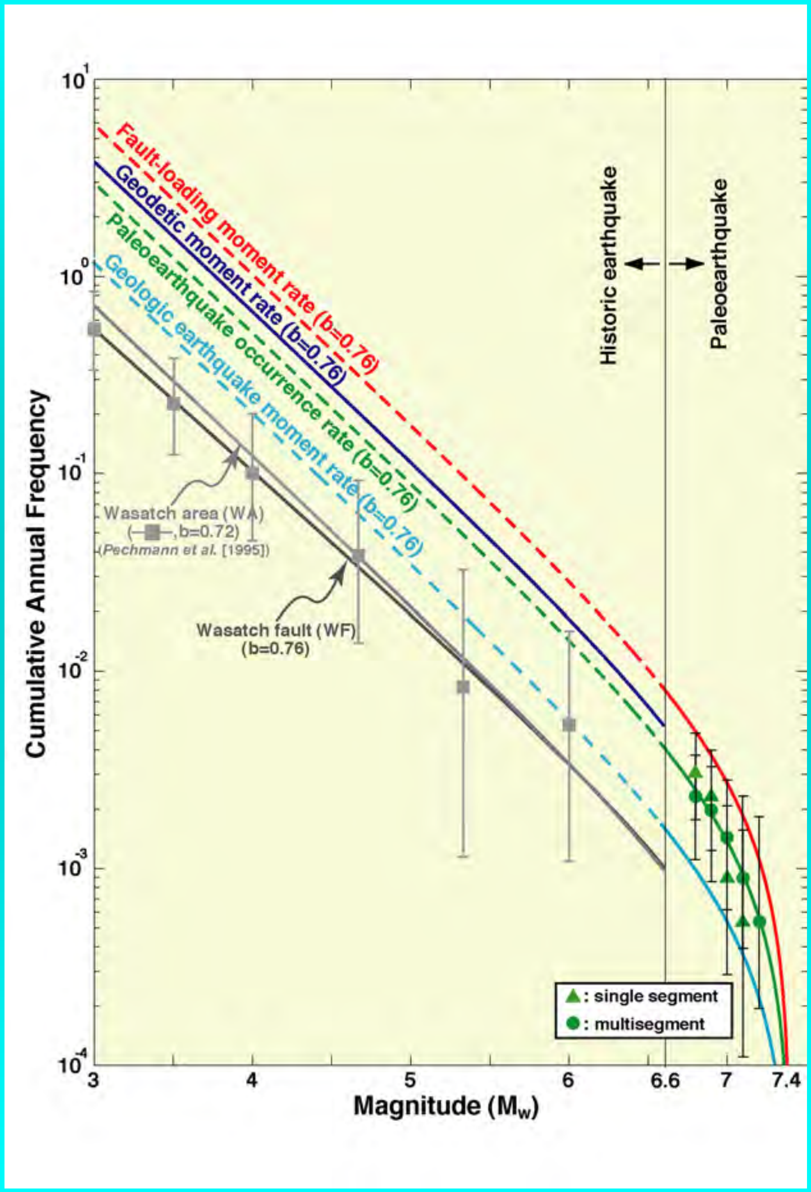


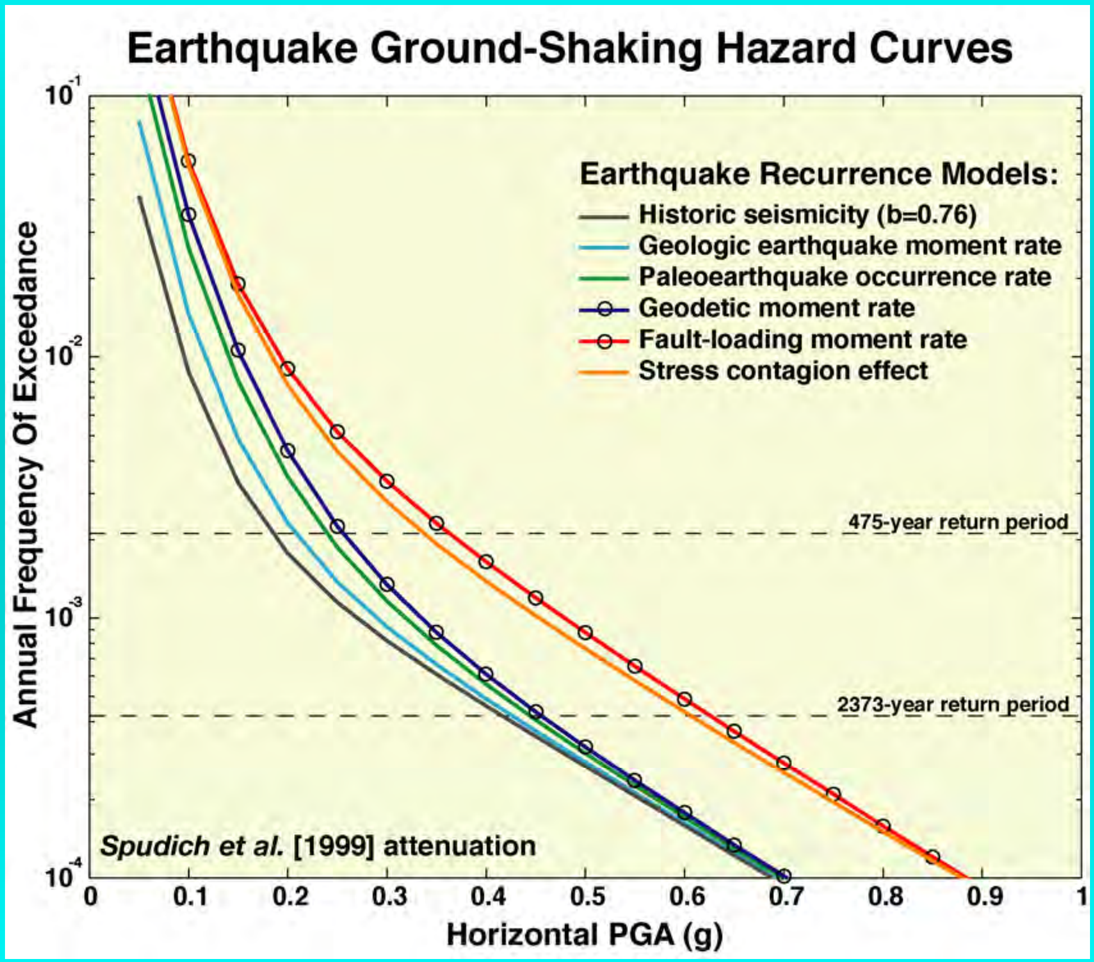
Chang and Smith [2002]

Wasatch Front Historic Seismicity



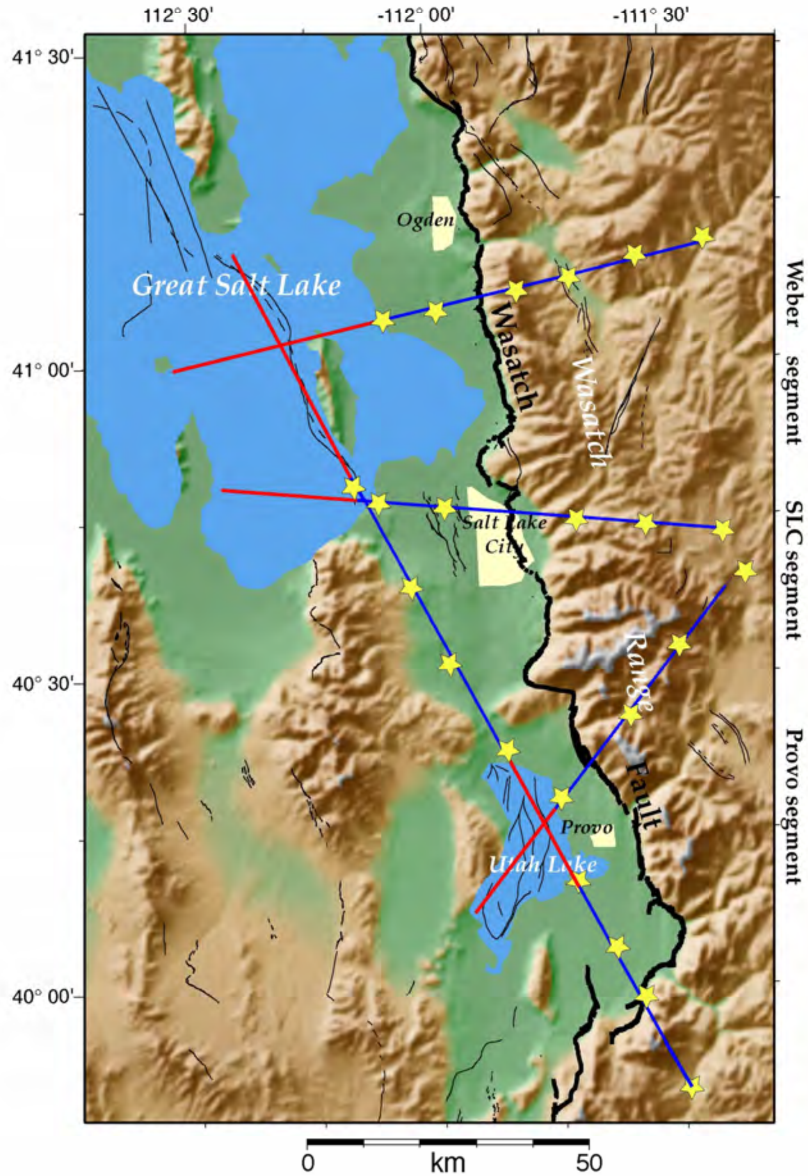
Frequency of earthquake occurrence





Chang and Smith [2002]

Proposed High Seismic Refraction Profiles For Imaging the Wasatch Fault and Wasatch Front Basins



Red lines = airgun source profiles, stars are 0.5 to 1 ton drilled shot points,
Blue = profiles of data loggers (0.5 km spacing decreased to 0.1 km for fault focusing)
= locations of explosive shots (permitted and done by USGS).

Possible NEHRP-NSF proposal

Upcoming Utah Earthquake Hazards Seminars and Workshops

1. Ralph Archuleta, UCSB, GG Earthquake Seismology/Hazard Assessment class workshop and UU Geology and Geophysics Distinguished Lecture, Mar. 2
   Normal fault mechanics, liquefaction and basin amplification effects.

2. Shaky Wasatch, Leonardo-Utah Science Center, Mar. 2, 7PM, Salt Lake City Auditorium, Panel (Arabasz, Archuleta, Bartlett, Carey, Lund, Smith) with community discussions.

3. Ed Field, USGS/SCEC, OpenSource Sesismic Hazard Analysis (online PSHA), GG Earthquake Seismology/Hazard Assessment class workshop and UU Geology and Geophysics Distinguished Lecture, Mar. 21-23.

4. Mary Lou Zoback, USGS and SSA Lecture, Overview of the 1906 San Francisco earthquake, SSC, lecture, Evening, Mar. 22

Considered Utah Earthquake Hazards Topics

Shaky Wasatch, March 2, Utah Science Center, SL Library

- **Are Utah normal faults normal? Paradigm and Paradox**
- **Stress drops: normal or not.**
- **Fault and footwall geometry and effects on PGAs**
- **Valley amplification with basin effects.**
- **Effects of low velocity layers and inter basin reflections of surface waves on energy focusing.**
- **Can Wasatch fault produce PGA's be > 2 g.**
- **How to incorporate ANSS and EarthScope data into Utah earthquake research (seismic and GPS)**
- **Contemporary loading and interseismic rates from GPS and how they are used in PSHA**
- **Rheology and time dependent fault loading from GPS and geologic rates**
- **Implications and updates on real-time emergency response, communication, broadcast alerts, state and HS issues.**
- **Wasatch fault paleohistory, geometry, directivity, footwall amplification, and enhanced PGA**
- **Early Holocene earthquake clustering with Bonneville and glacial unloading effects on fault slip rates.**
- **Footwall flood inundation from GSL and Utah Lakes accompanying large earthquakes.**
- **Fault displacement PDHA and lifelines.**
- **Multi - segment models and stress contagion models, with rheology.**
- **Time dependent PSHA with stress interaction**
- **Integrated PSHA, PDHA and PLHA**