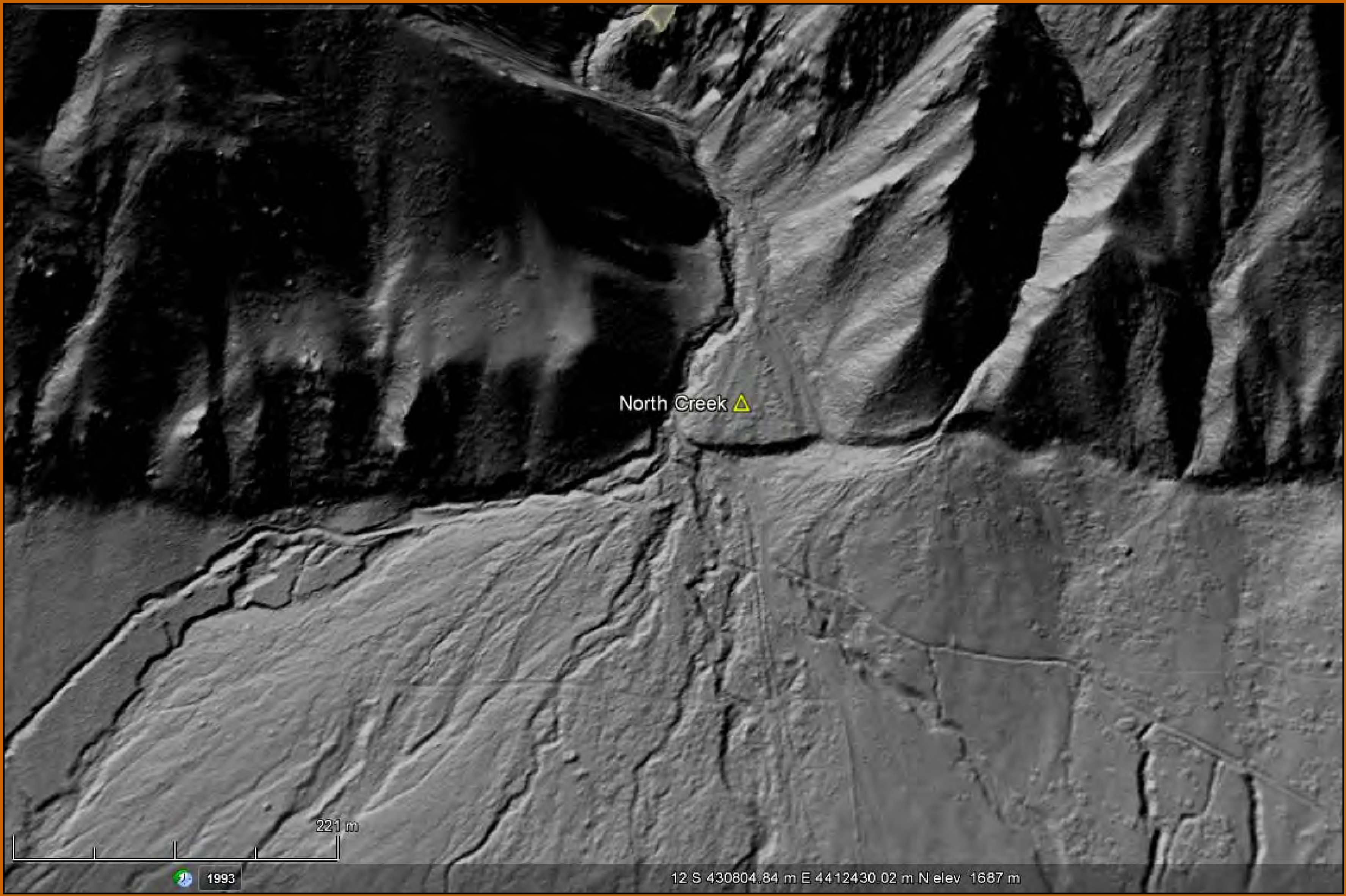
UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP



Wednesday, February 5, 2014

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.

2013 MEETING REVIEW

Presentations on Paleoseismic Work Completed or in Progress

- **Utah Lake fault investigation**
- **Automated fault scarp offset analysis of the Nephi segment**
- **Nephi segment paleoseismic trenching**
- **Penrose Drive/Baileys Lake paleoseismic studies final results**
- **New information for the Taylorsville fault from Orange Street consultant's trench**
- **Does fault segmentation limit earthquake magnitude on the Wasatch fault**
- **Bear River fault behavior–clues provided by LiDAR**
- **Update on U.S. Bureau of Reclamation Joes Valley fault study**
- **GPS Monitoring of the Wasatch Fault**

2013 MEETING REVIEW

Presentations on Paleoseismic Work Completed or in Progress

- **Large liquefaction features and evidence for earthquakes induced by Lake Bonneville in Cache Valley**
- **Preliminary results high resolution seismic reflection profiling in Hansel Valley**
- **Update Blue Castle nuclear facility licensing project**
- **Paleoseismic-related NEHRP FTR reports for Utah; Steve Bowman**
- **WGUEP update; Ivan Wong, URS Corp.**
- **Re-examination of trenches for early-mid Holocene climatic events and redefining "Active" faults**

AGENDA
QUATERNARY FAULT PARAMETERS WORKING GROUP
Wednesday, February 5, 2014
Utah Department of Natural Resources Building, Room 2000 (2nd floor)
1594 West North Temple, Salt Lake City

8:00 Continental breakfast

8:20 Welcome, overview of meeting, and review of last year's activities

8:30 Technical presentations of work completed or in progress

8:30 – Update on Nephi segment paleoseismic studies; Chris DuRoss, UGS
8:50 – Preliminary results from the Flat Canyon paleoseismic trench site, southern Provo segment, Wasatch fault—potential implications for Holocene fault segmentation along the Wasatch fault; Scott Bennett, USGS
9:10 – Geomorphic and paleoseismic evidence for multiple surface ruptures along structures between the Salt Lake City and Provo segments of the Wasatch fault; Nathan Toke, UVU
9:30 – Newly discovered Holocene-active basin floor fault in Goshen Valley, Utah County, Utah; Adam McKean, UGS
9:50 – U.S. Bureau of Reclamation Joes Valley fault study; Jim McCalpin, GEO-HAZ Consulting CANCELLED

10:10 Break

10:40 Technical presentations of work completed or in progress

10:40 – New observations from the Bear River fault zone; Dave Schwartz, USGS
11:00 – Clustered earthquakes during the Bonneville high stand–an update; Susanne Janecke, USU
11:20 – Contemporary deformation of the Wasatch Front, Utah, and its implication for the interseismic loading of the Wasatch Fault Zone; Wu-Lung Chang, UUGG
11:40 – New high-resolution LiDAR data for the Wasatch fault zone, and Salt Lake and Utah Counties, and hazard mapping; Steve Bowman, UGS

12:00 Lunch

AGENDA
QUATERNARY FAULT PARAMETERS WORKING GROUP
Wednesday, February 5, 2014
Utah Department of Natural Resources Building, Room 2000 (2nd floor)
1594 West North Temple, Salt Lake City

1:00 **Technical presentations of work completed or in progress**

- 1:00 – Working Group on Utah Earthquake Probabilities, an update; Ivan Wong, URS Corporation
- 1:20 – Update on planned UGS & USGS trenching on the Salt Lake City and Provo segments of the Wasatch fault; Chris DuRoss, UGS and Scott Bennett, USGS
- 1:40 – Basin and Range Province Seismic Hazard Summit III; Bill Lund, UGS

2:00 **UQFPWG 2014 fault study priorities**

3:30 **Adjourn**

UPDATE ON PALEOSEISMIC TRENCHING OF THE NEPHI SEGMENT

Utah Geological Survey

Chris DuRoss

Mike Hylland

Adam Hiscock

Gregg Beukelman

Greg McDonald

Ben Erickson

Adam McKean

U.S. Geological Survey

Steve Personius

Rich Briggs

Ryan Gold

Tony Crone

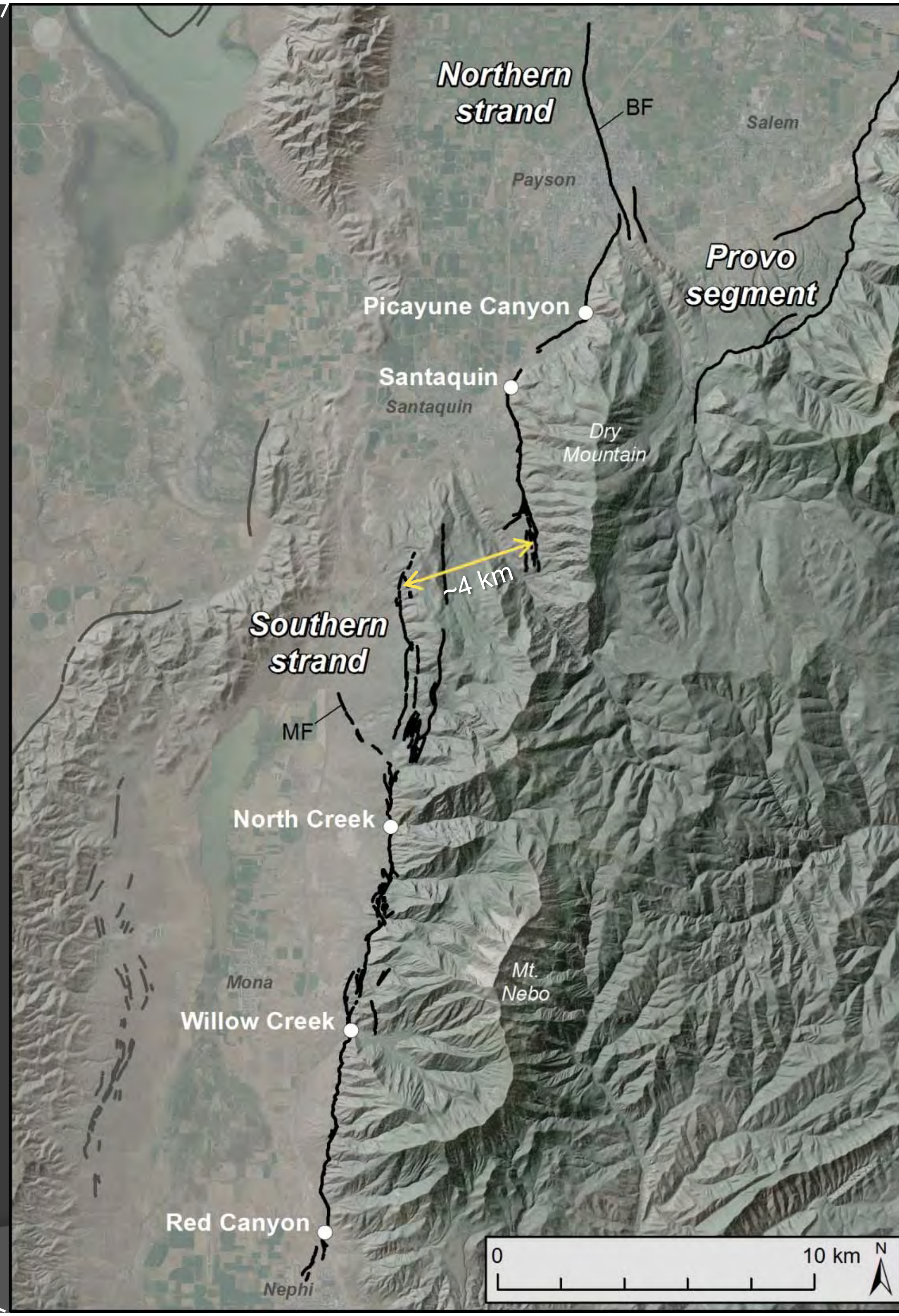
Steve Angster *(University of Nevada, Reno)*

Roselyn King *(Colorado School of Mines)*

Shannon Mahan

Partially funded by the National Earthquake Hazards Reduction Program

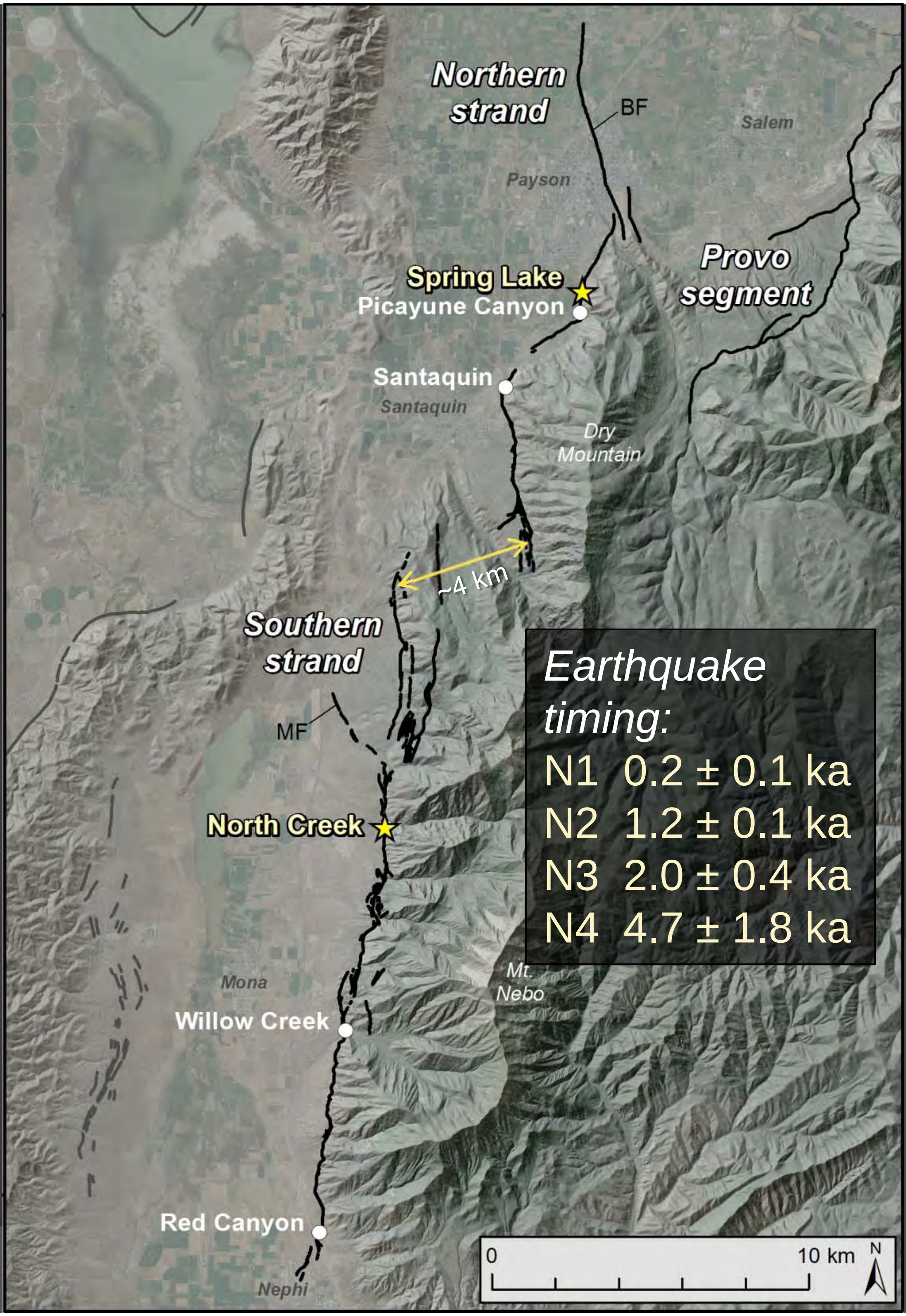
Nephi Segment



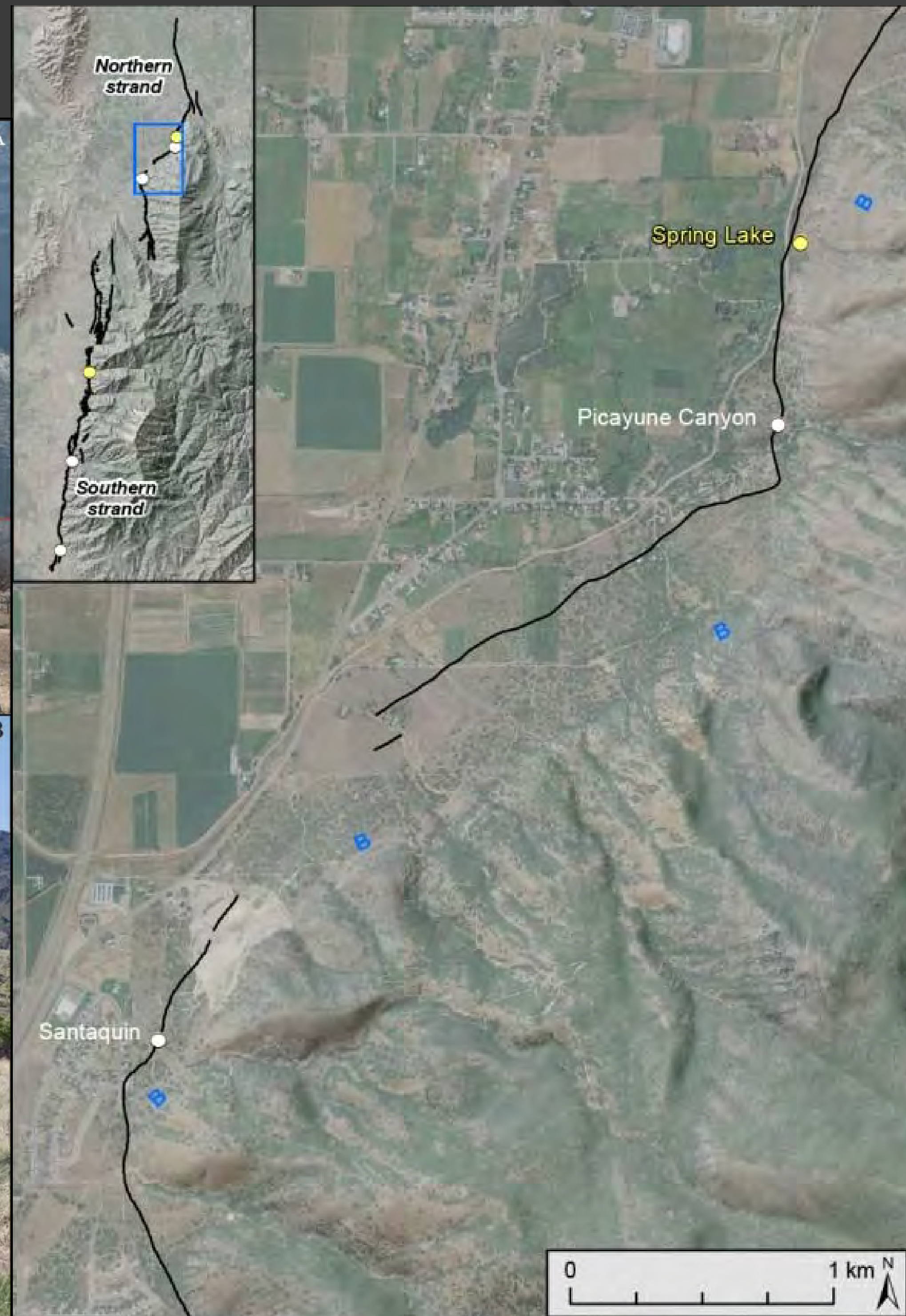
Nephi Segment

- **Important questions**
  1. Timing and recurrence of mid-Holocene surface-faulting earthquakes?
  2. Rupture behavior of the northern and southern strands?
  3. Relation between the northern strand and Provo segment?

- **2012 Trenching:**
  - Spring Lake and North Creek sites

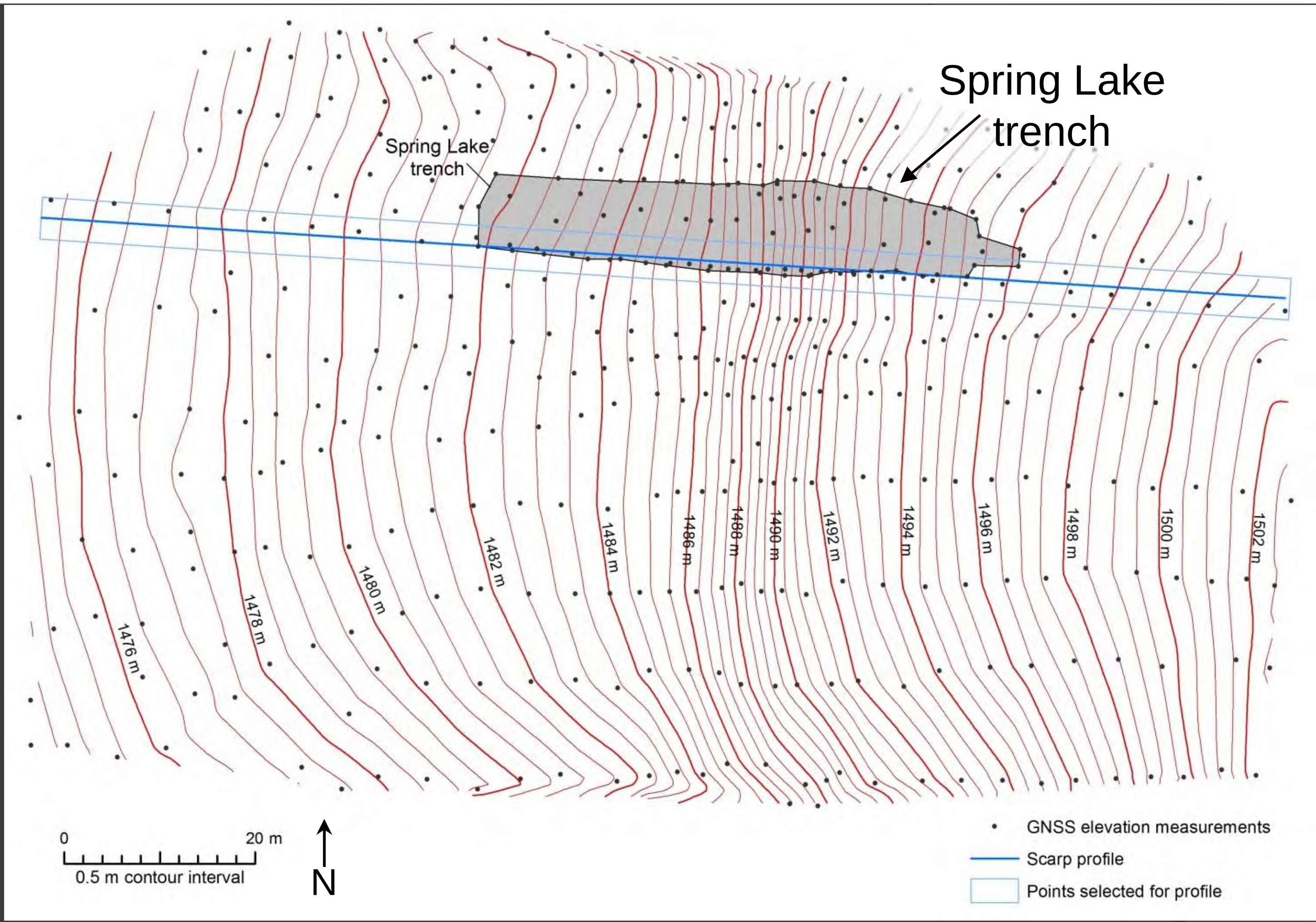


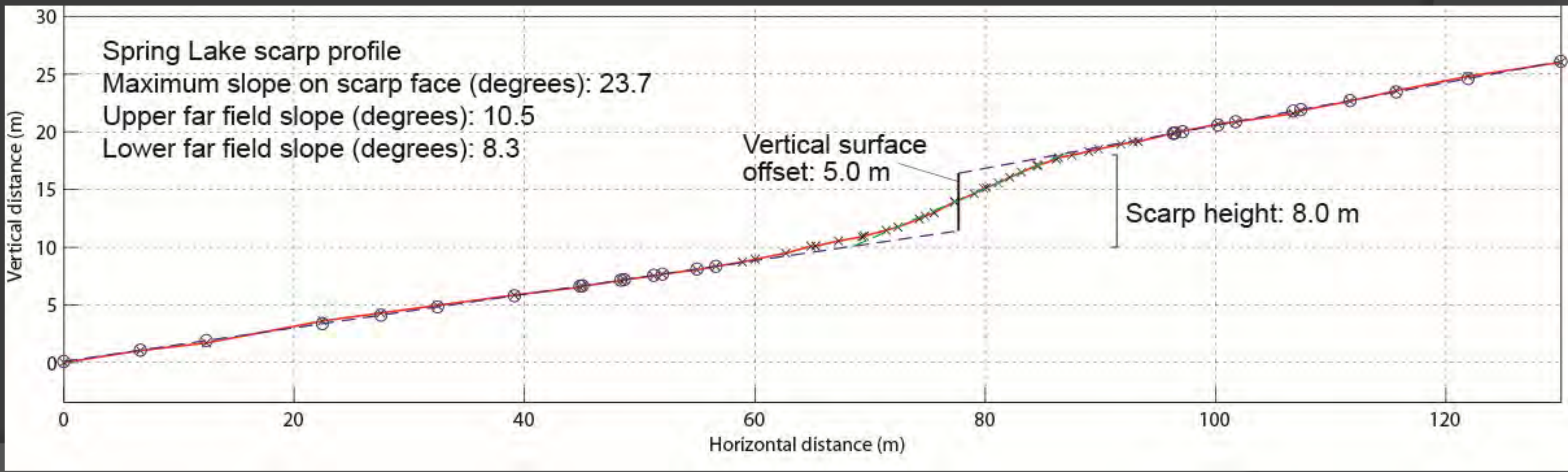
Spring Lake Site



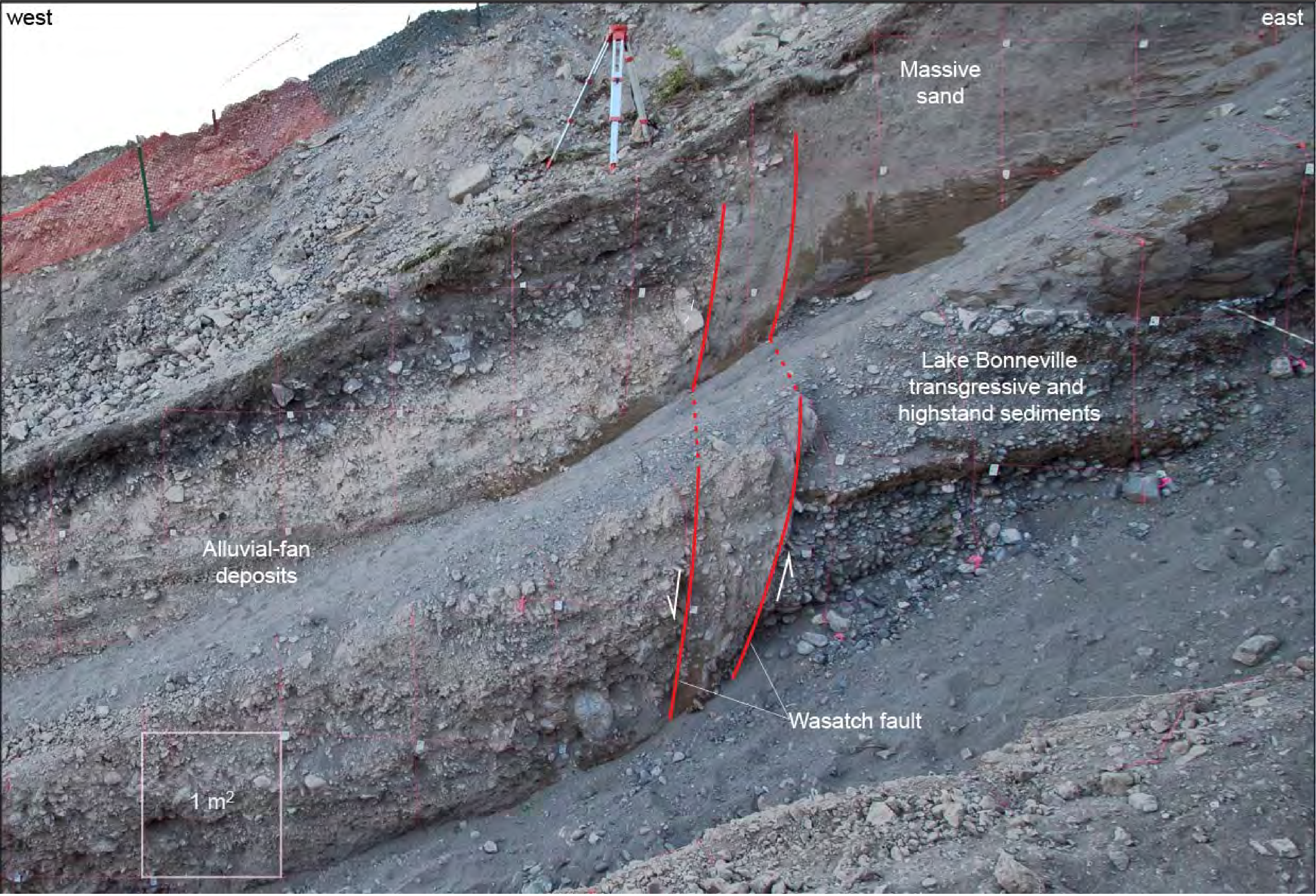
Spring Lake Site

- West-sloping alluvial-fan set below the highstand shoreline
- 36-m long trench across an ~8-m high scarp



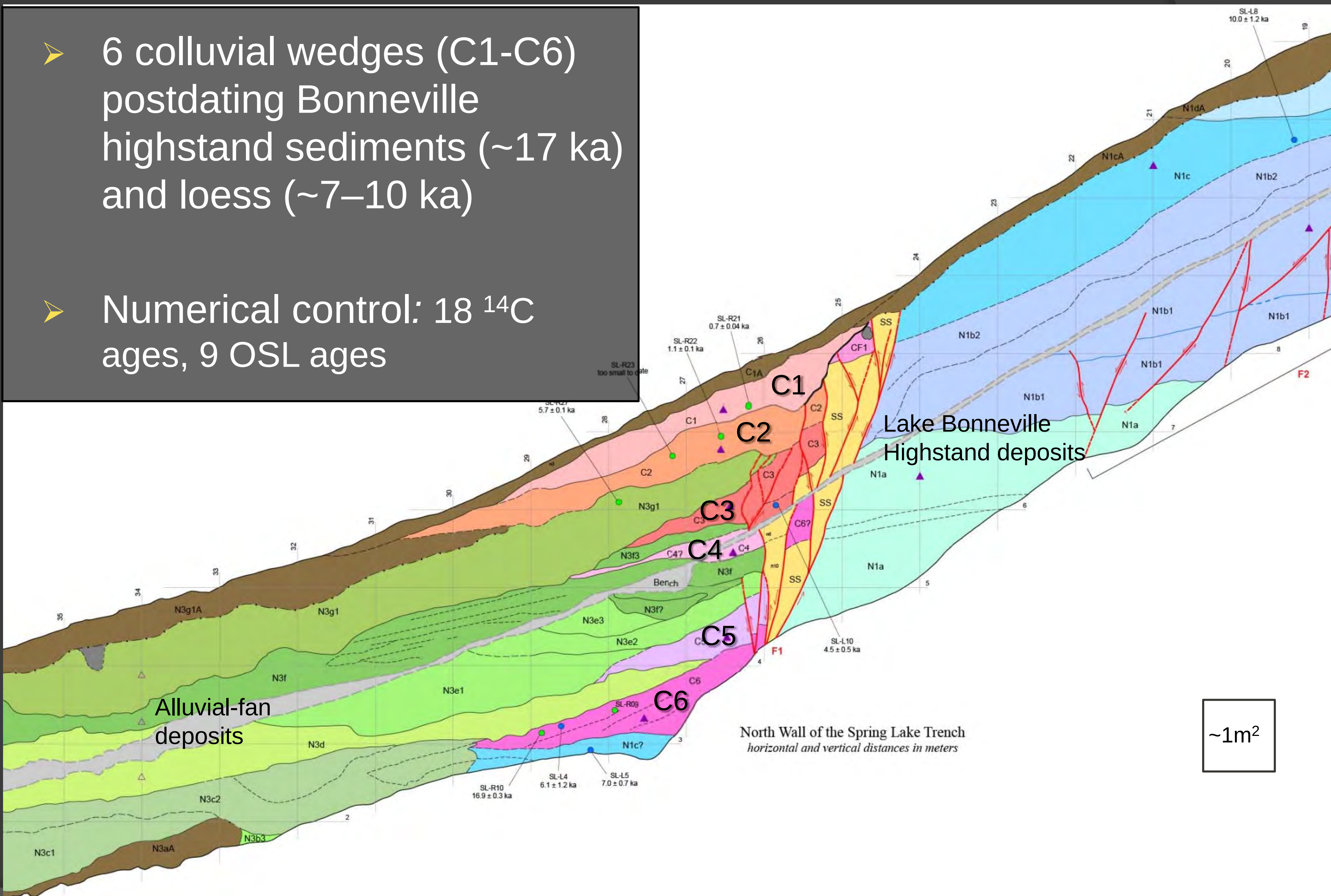


Spring Lake Trench

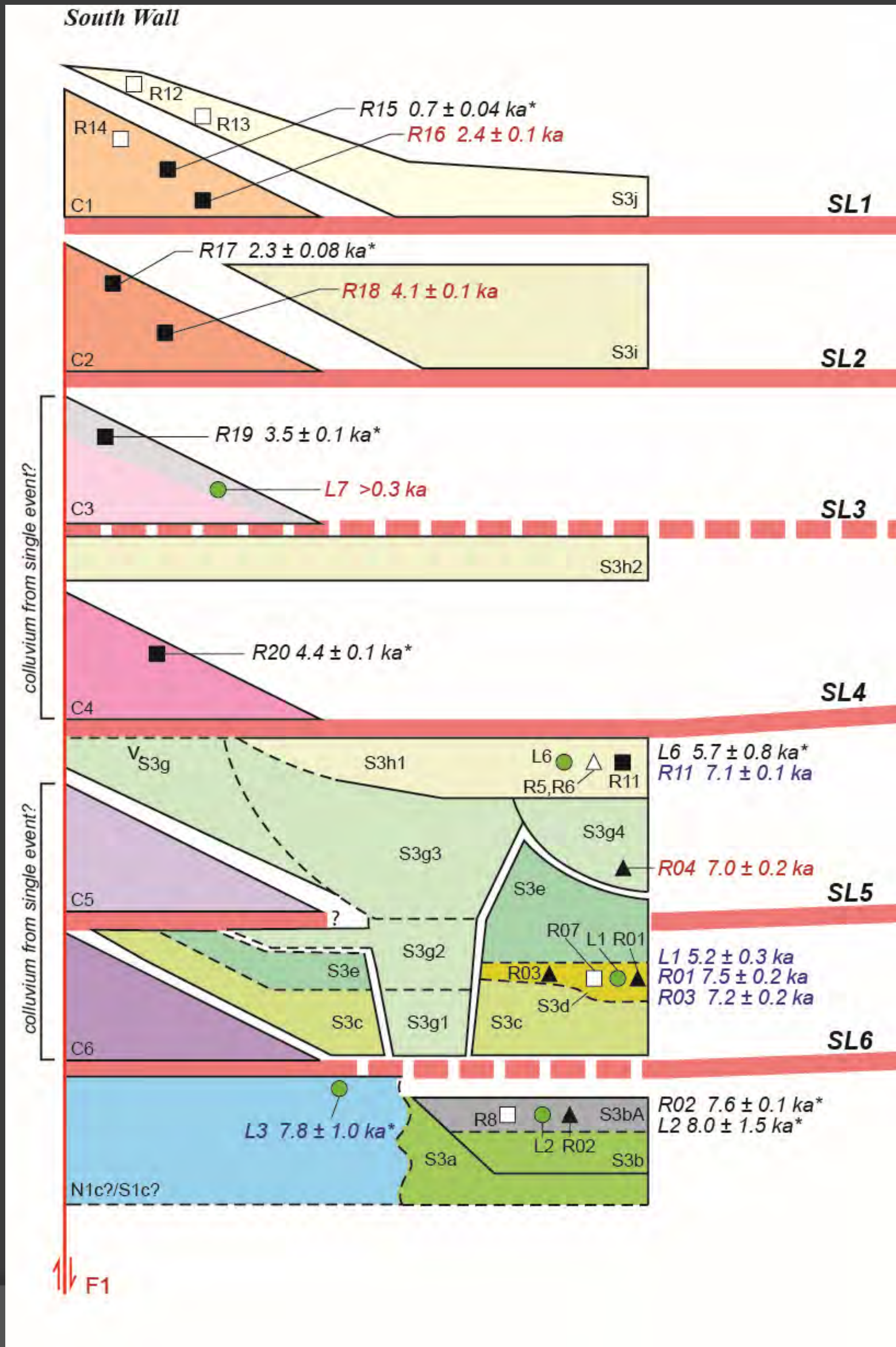


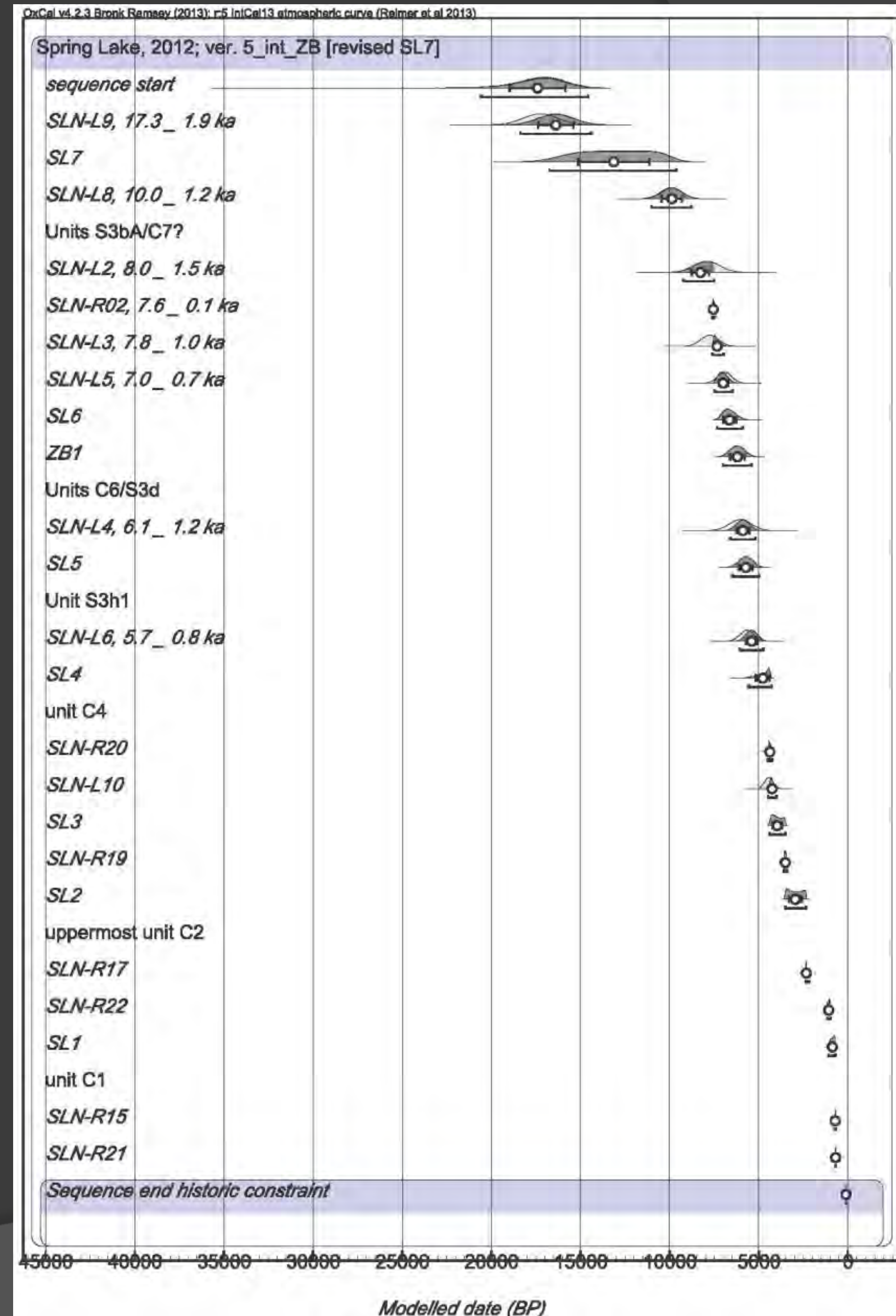
Spring Lake Trench

- 6 colluvial wedges (C1-C6) postdating Bonneville highstand sediments (~17 ka) and loess (~7–10 ka)
- Numerical control*:* 18 ^{14}C ages, 9 OSL ages



Interpretation of Surface-Faulting Earthquakes





Spring Lake Earthquake Chronology

- 5–7 earthquakes postdating Bonneville highstand
  - 4–6 since ~6.6 ka
- Mean recurrence:
  - ~2.0 kyr (incl. SL7)
  - ~1.2–1.5 kyr (excl. SL7)
- Vertical displacement per event:
  - 1.0 ± 0.3 m
- Slip rate:
  - ~0.6-0.8 (~0.4–1.2) mm/yr (since ~mid-Holocene)

Earthquake timing and recurrence at the Spring Lake site

	Earthquake timing		**Earthquake recurrence**	
Event[1]	**Mean ± 2σ** (ka)	**Central 95%** (ka)	**Inter-event** (kyr)	**Mean** (kyr)
SL7	**13.1** ± **4.0**	9.6–16.8	SL7–SL6: 6.5	SL7–SL1: 2.0
SL6	**6.6** ± **0.7**	5.9–7.3	SL6–SL5: 0.9	SL6–SL1: 1.2
SL5	**5.7** ± **0.8**	5.0–6.5	SL5–SL4: 1.0	SL5–SL1: 1.2
SL4	**4.8** ± **0.8**	4.3–5.6	SL4–SL3: 0.8	SL4–SL1: 1.3
SL3	**4.0** ± **0.5**	3.5–4.4	SL3–SL2: 1.0	SL3–SL1: 1.5
SL2	**2.9** ± **0.7**	2.3–3.5	SL2–SL1: 2.1	-
SL1	**0.9** ± **0.2**	0.7–1.1	-	-

[1] Spring Lake earthquakes; color shading indicates events that could possibly be grouped (e.g., SL6 and SL5 could be related to single earthquake)

Northern Strand Earthquake History

- 2 Spring Lake earthquakes correspond well with previous data:
  - SL3 and SL2 correspond well with PC2 and PC1 *(likely evidence that SL3 is a separate earthquake from SL4)*
- Northern strand MRE only identified at Santaquin

Summary of earthquake timing data for the northern strand

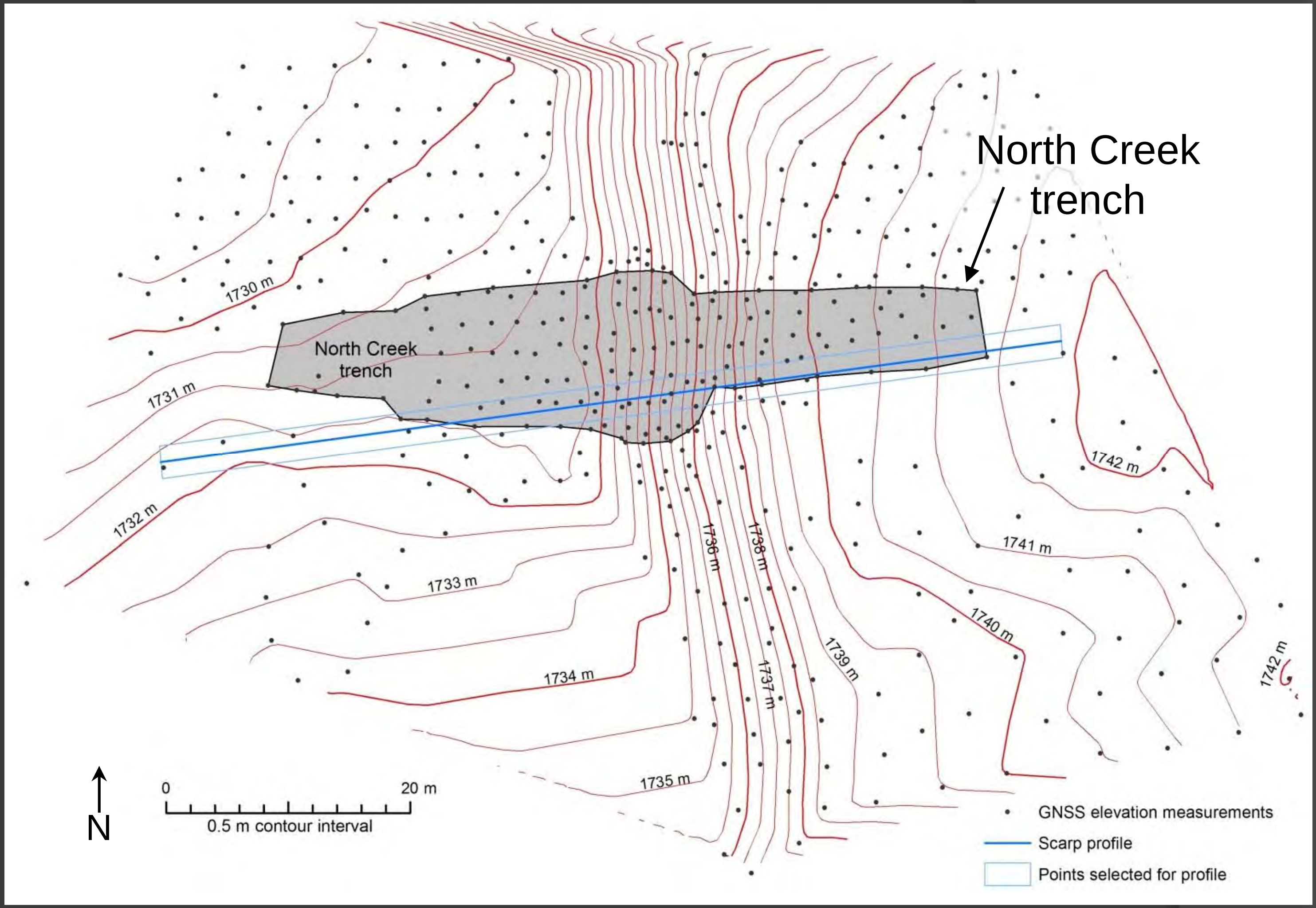
Spring Lake (ka)	Picayune Canyon (ka)	Santaquin (ka)
13.1 ± 4.0 (SL7)	-	-
6.6 ± 0.7 (SL6)	-	-
5.7 ± 0.8 (SL5)	-	-
4.8 ± 0.8 (SL4)	*not exposed*	-
4.0 ± 0.5 (SL3)	~3.5 (PC2)	*not exposed*
2.9 ± 0.7 (SL2)	~2.5 (PC1)	*not exposed?*
0.9 ± 0.2 (SL1)	*no evidence*	*no evidence*
no evidence	*no evidence*	~0.3–0.5 (S1)

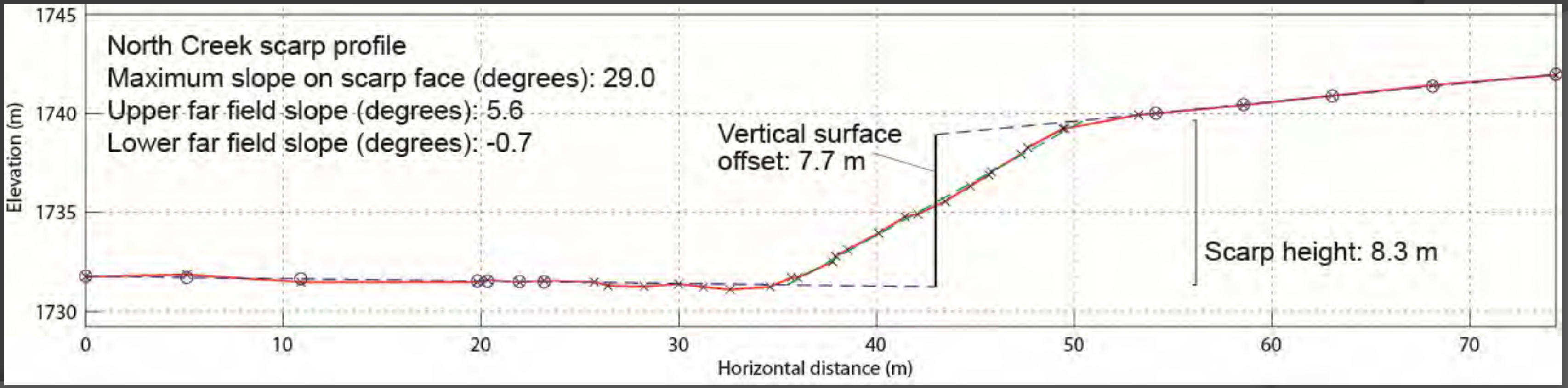
- Mean recurrence:
  - ~1.0 kyr (7 earthquakes since 6.6 ka)
  - ~1.2 kyr (6 earthquakes since 6.6 ka—excl. SL5)
  - ~1.1 kyr (5 earthquakes since ~5 ka)
  - *Previously undefined*

North Creek Site

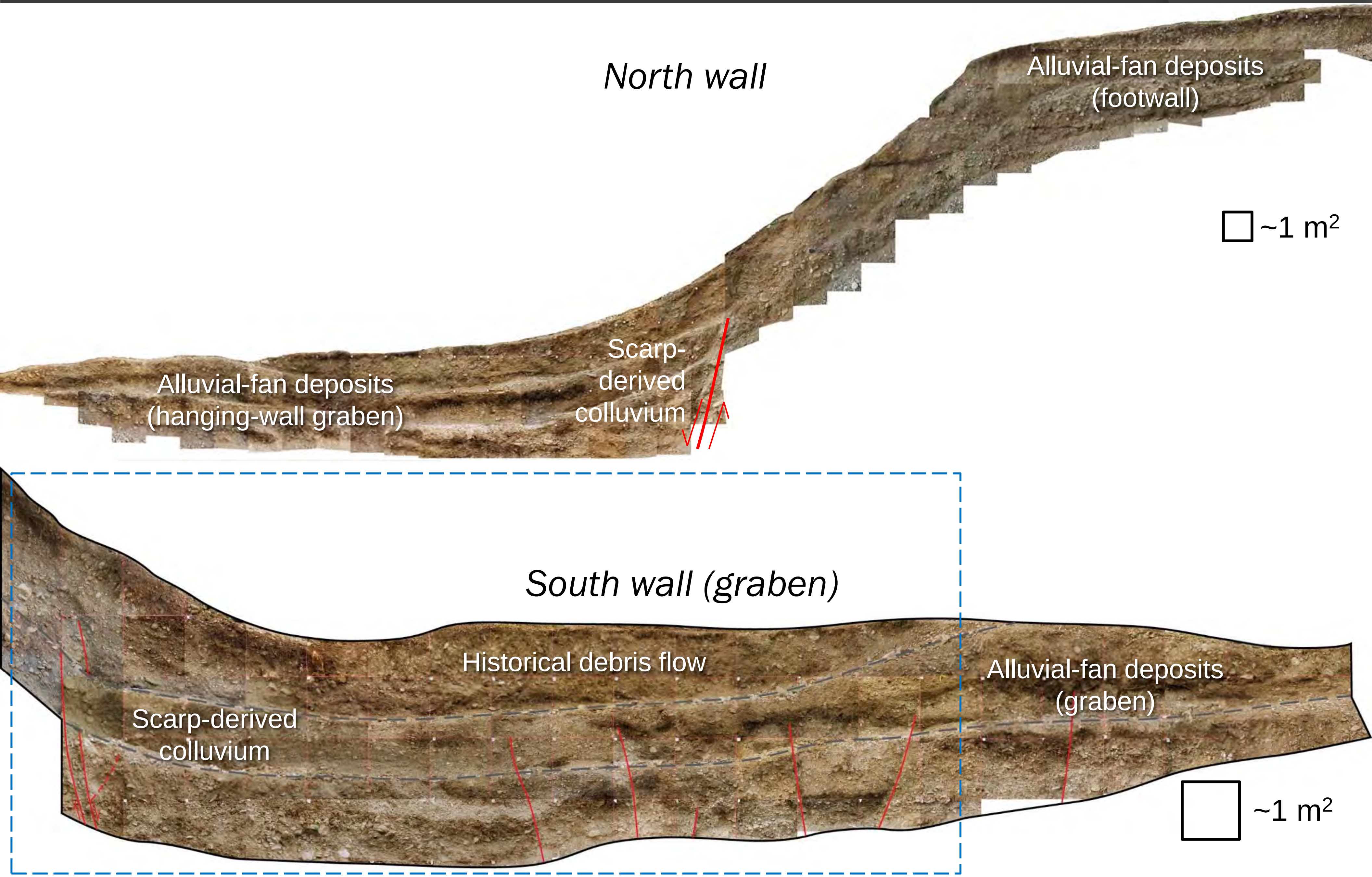
North Creek Site

- Alluvial fan at the head of a large drainage (above the Bonneville shoreline)
- ~40-m long trench across an ~8-m high scarp



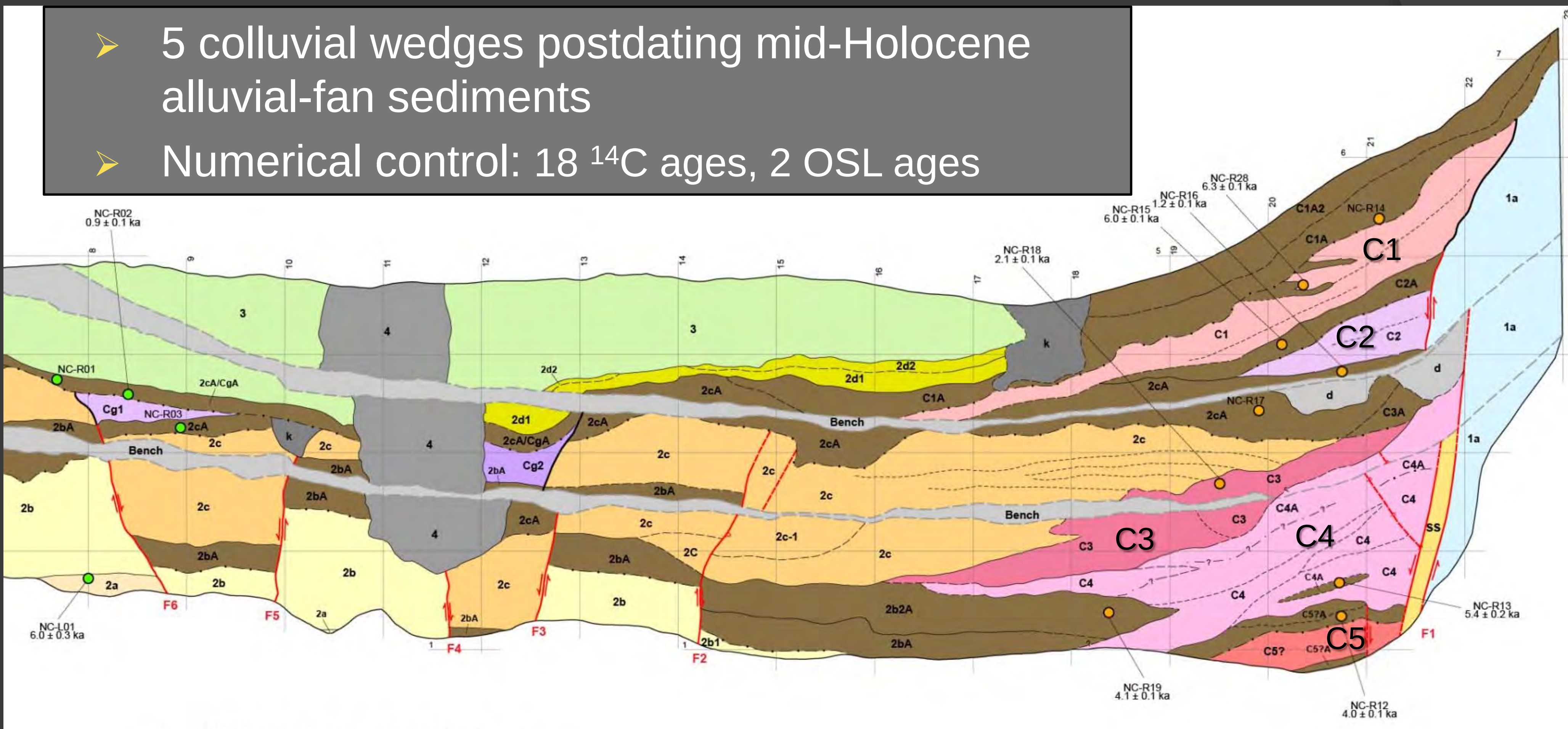


Southern Nephi segment – North Creek site



North Creek Trench

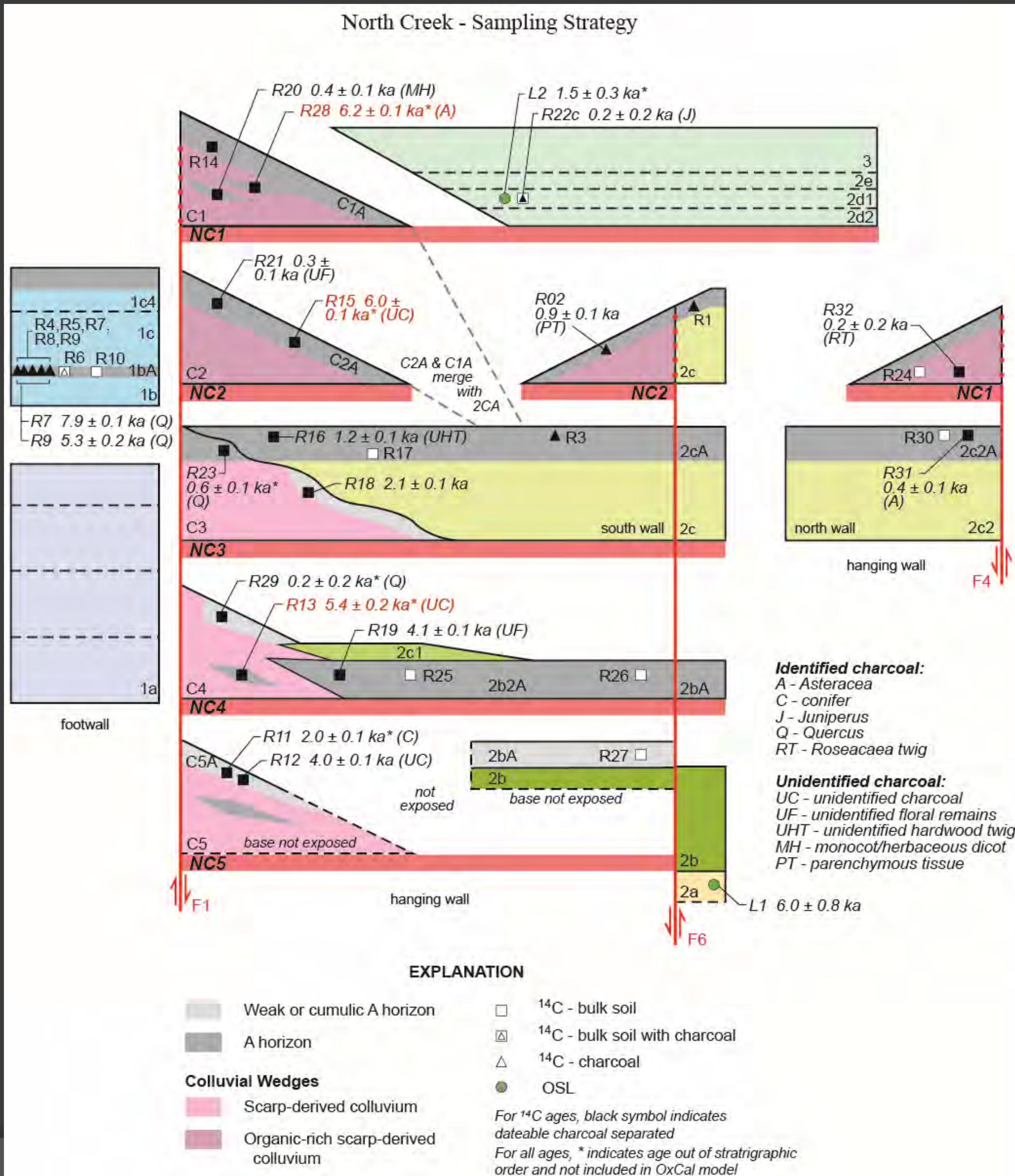
- 5 colluvial wedges postdating mid-Holocene alluvial-fan sediments
- Numerical control: 18 ^{14}C ages, 2 OSL ages

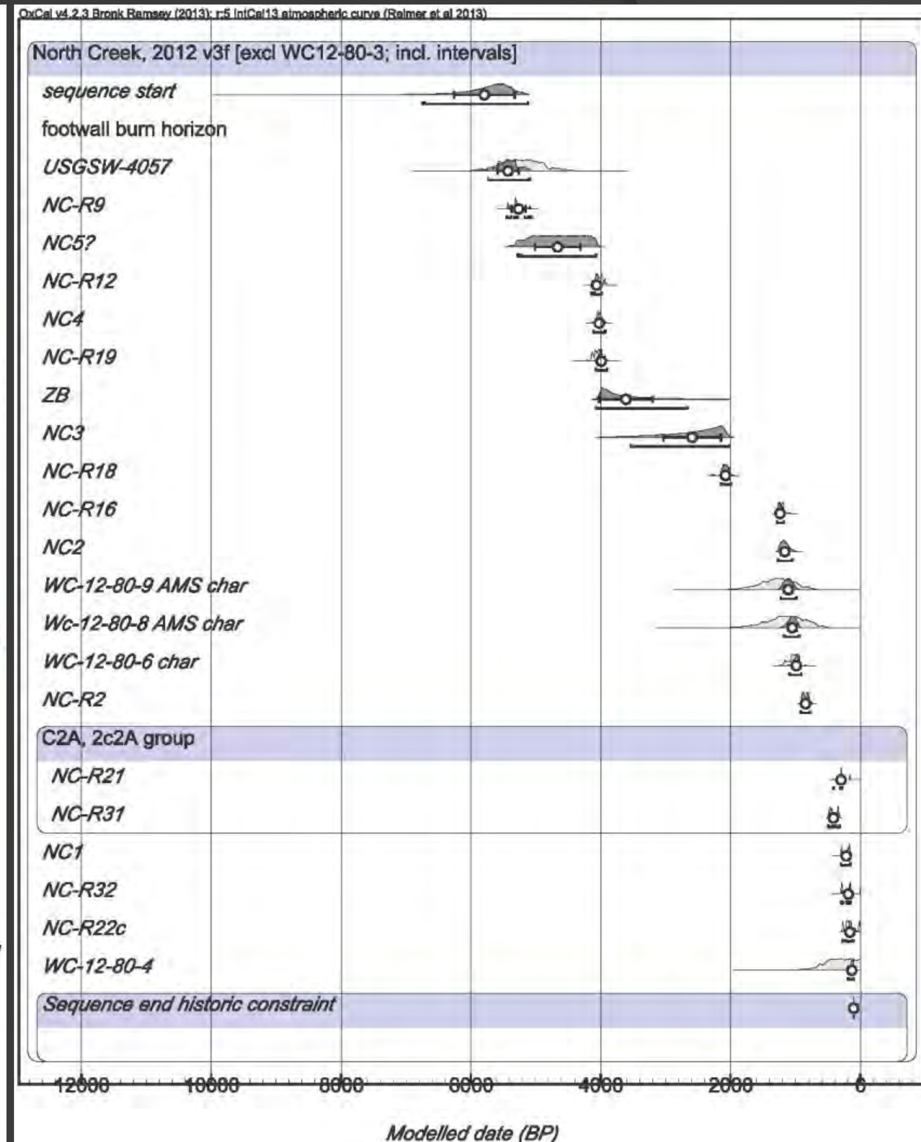


South Wall of the North Creek Trench (Mirror Image)

horizontal and vertical distances in meters

Interpretation of Surface-Faulting Earthquakes





North Creek Earthquake Chronology

- 4–5 earthquakes since ~mid Holocene
- Mean recurrence:
  - ~1.1–1.3 kyr
- Per-event displacement: poorly resolved

Earthquake timing and recurrence at the North Creek site

	Earthquake timing		Earthquake recurrence	
Event	**Mean** ± **2σ** *[mode]* (ka)	**Central 95%** (ka)	**Inter-event** *[mode]* (kyr)	**Mean** *[mode]* (kyr)
NC5?	**4.7** ± **0.7**	4.1–5.3	NC5–NC4: 0.6	NC5–NC1: 1.1
NC4	**4.0** ± **0.1**	3.9–4.1	NC4–NC3: 1.4 *[1.8]*	NC4–NC1: 1.3
NC3	**2.6** ± **0.9** ***[2.2]***	2.0–2.5	NC3–NC2: 1.4 *[1.0]*	NC3–NC1: 1.2 *[1.0]*
NC2	**1.2** ± **0.1**	1.0–1.3	NC2–NC1: 0.9	-
NC1	**0.2** ± **0.1**	0.2–0.3	-	-

- Slip rate:
  - 2.0 (1.1–2.9) mm/yr (total displacement/footwall soil age)
  - 1.9 (0.8–3.3) mm/yr (NC4–NC1 displacement/NC5–NC1 time)

Southern Strand Earthquake History

- 4 of 5 North Creek earthquakes correspond well with previous data
- Young MRE identified at Willow Creek confirmed at North Creek
- Additional earthquake at ~4.0 ka identified
- Mean recurrence:
  - ~1.1 kyr (5 earthquakes since ~ 5 ka)
  - *Previously ~0.9–1.5 kyr*

Summary of earthquake timing data for the southern strand

Southern Strand		
North Creek (ka)	Willow Creek (ka)	Red Canyon (ka)
-	-	-
-	-	-
not exposed	*not exposed*	*not exposed*
4.7 ± 0.7 (NC5?)	4.7 ± 1.8 (WC4)	4.7 ± 2.7 (RC3)
4.0 ± 0.1 (NC4)	*no evidence*	*no evidence*
2.2 (2.0–2.5) (NC3)	1.9 ± 0.6 (WC3)	*no evidence*
1.2 ± 0.1 (NC2)	1.2 ± 0.1 (WC2)	1.2 ± 0.3 (RC2)
0.2 ± 0.1 (NC1)	0.2 ± 0.1 (WC1)	0.5 ± 0.5 (RC1)

Rupture Behavior of the Nephi Segment?

Northern Strand			Southern Strand		
Spring Lake (ka)	Picayune Canyon (ka)	Santaquin (ka)	North Creek (ka)	Willow Creek (ka)	Red Canyon (ka)
4.8 ± 0.8 (SL4)	*not exposed*	-	4.7 ± 0.7 (NC5?)	4.7 ± 1.8 (WC4)	4.7 ± 2.7 (RC3)
4.0 ± 0.5 (SL3)	~3.5 (PC2)	*not exposed*	4.0 ± 0.1 (NC4)	*no evidence*	*no evidence*
2.9 ± 0.7 (SL2)	~2.5 (PC1)	*not exposed?*	2.2 (2.0–2.5) (NC3)	1.9 ± 0.6 (WC3)	*no evidence*
0.9 ± 0.2 (SL1)	*no evidence*	*no evidence*	1.2 ± 0.1 (NC2)	1.2 ± 0.1 (WC2)	1.2 ± 0.3 (RC2)
no evidence	*no evidence*	~0.3–0.5 (S1)	0.2 ± 0.1 (NC1)	0.2 ± 0.1 (WC1)	0.5 ± 0.5 (RC1)

- Complex patterns of rupture have occurred on the Nephi segment during the late Holocene.

- Using possible correlations of individual earthquakes along the segment, we developed three rupture scenarios

Rupture Behavior of the Nephi Segment

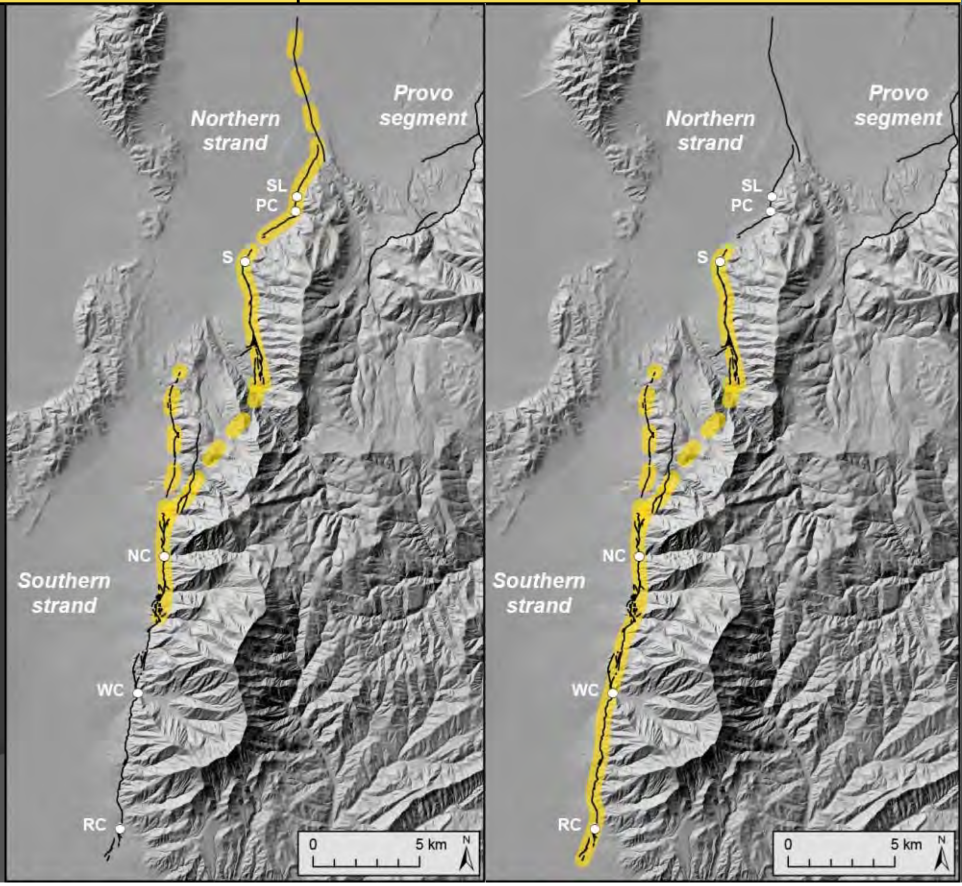
Northern Strand[1]			Southern Strand[1]		
Spring Lake (ka)	Picayune Canyon (ka)	Santaquin (ka)	North Creek (ka)	Willow Creek (ka)	Red Canyon (ka)
4.8 ± 0.8 (SL4)	*not exposed*	-	4.7 ± 0.7 (NC5?)	4.7 ± 1.8 (WC4)	4.7 ± 2.7 (RC3)
4.0 ± 0.5 (SL3)	~3.5 (PC2)	*not exposed*	4.0 ± 0.1 (NC4)	*no evidence*	*no evidence*
2.9 ± 0.7 (SL2)	~2.5 (PC1)	*not exposed?*	2.2 (2.0–2.5) (NC3)	1.9 ± 0.6 (WC3)	*no evidence*
0.9 ± 0.2 (SL1)	*no evidence*	*no evidence*	1.2 ± 0.1 (NC2)	1.2 ± 0.1 (WC2)	1.2 ± 0.3 (RC2)
no evidence	*no evidence*	~0.3–0.5 (S1)	0.2 ± 0.1 (NC1)	0.2 ± 0.1 (WC1)	0.5 ± 0.5 (RC1)

1. Simultaneous rupture of both strands (the entire Nephi segment)

Rupture Behavior of the Nephi Segment

Northern Strand[1]			Southern Strand[1]		
Spring Lake (ka)	Picayune Canyon (ka)	Santaquin (ka)	North Creek (ka)	Willow Creek (ka)	Red Canyon (ka)
4.8 ± 0.8 (SL4)	*not exposed*	-	4.7 ± 0.7 (NC5?)	4.7 ± 1.8 (WC4)	4.7 ± 2.7 (RC3)
4.0 ± 0.5 (SL3)	~3.5 (PC2)	*not exposed*	4.0 ± 0.1 (NC4)	*no evidence*	*no evidence*
2.9 ± 0.7 (SL2)	~2.5 (PC1)	*not exposed?*	2.2 (2.0–2.5) (NC3)	1.9 ± 0.6 (WC3)	*no evidence*
0.9 ± 0.2 (SL1)	*no evidence*	*no evidence*	1.2 ± 0.1 (NC2)	1.2 ± 0.1 (WC2)	1.2 ± 0.3 (RC2)
no evidence	*no evidence*	~0.3–0.5 (S1)	0.2 ± 0.1 (NC1)	0.2 ± 0.1 (WC1)	0.5 ± 0.5 (RC1)

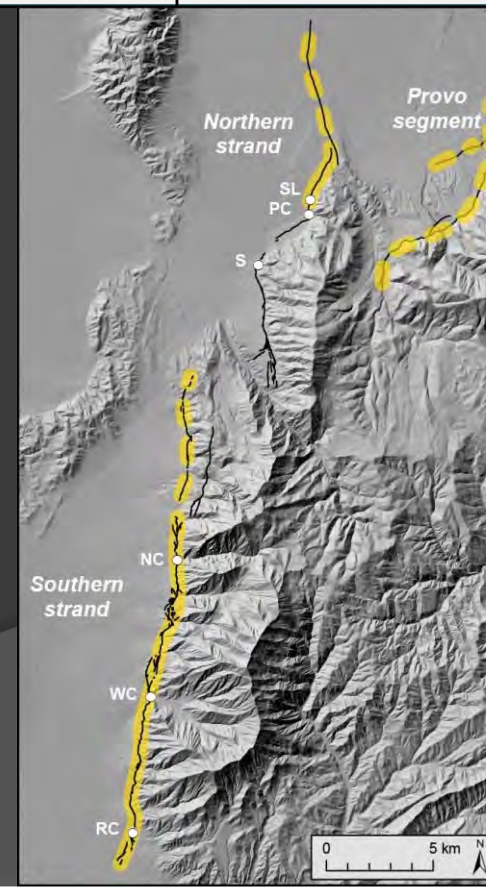
2. Rupture of one strand and partial rupture of the other strand



Rupture Behavior of the Nephi Segment

Northern Strand[1]			Southern Strand[1]		
Spring Lake (ka)	Picayune Canyon (ka)	Santaquin (ka)	North Creek (ka)	Willow Creek (ka)	Red Canyon (ka)
4.8 ± 0.8 (SL4)	*not exposed*	-	4.7 ± 0.7 (NC5?)	4.7 ± 1.8 (WC4)	4.7 ± 2.7 (RC3)
4.0 ± 0.5 (SL3)	~3.5 (PC2)	*not exposed*	4.0 ± 0.1 (NC4)	*no evidence*	*no evidence*
2.9 ± 0.7 (SL2)	~2.5 (PC1)	*not exposed?*	2.2 (2.0–2.5) (NC3)	1.9 ± 0.6 (WC3)	*no evidence*
0.9 ± 0.2 (SL1)	*no evidence*	*no evidence*	1.2 ± 0.1 (NC2)	1.2 ± 0.1 (WC2)	1.2 ± 0.3 (RC2)
no evidence	*no evidence*	~0.3–0.5 (S1)	0.2 ± 0.1 (NC1)	0.2 ± 0.1 (WC1)	0.5 ± 0.5 (RC1)

3. Independent rupture of the strands (northern strand with the Provo segment?)



Conclusions

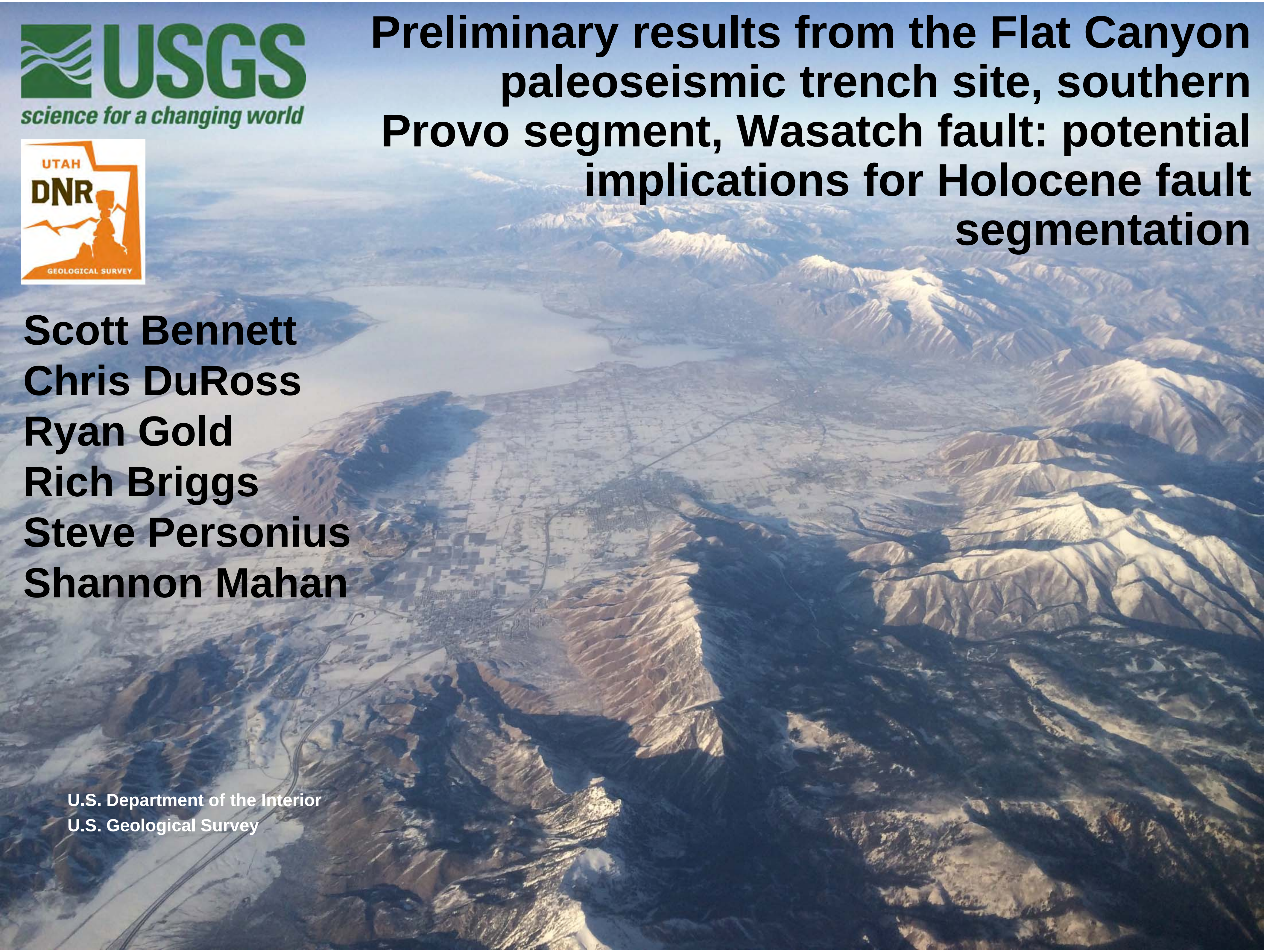
1. Our data indicate similar late Holocene earthquake histories and mean recurrence rates for the northern and southern strands:
   - Mean recurrence ~1.1 kyr since ~5 ka
   - Other central segments: ~1.1–1.3 kyr since ~7 ka

2. Based on our earthquake data and interpretation:
   - We have the most confidence in ***simultaneous rupture of the strands*** and ***rupture of one strand and part of the other***.
   - ***Independent rupture*** of the strands does not appear as likely.
   - Thus, the 4-km step between the strands is likely not a significant barrier to rupture propagation.

3. Uncertainty in rupture behavior of the Nephi segment remains because of the limitations of earthquake dating (timing resolution). Future work: per-event and along strike displacement.

Questions?

Final Technical Report:
http://earthquake.usgs.gov/research/external/research.php
http://geology.utah.gov/ghp/consultants/pubs/utah.htm



Preliminary results from the Flat Canyon paleoseismic trench site, southern Provo segment, Wasatch fault: potential implications for Holocene fault segmentation

Scott Bennett
Chris DuRoss
Ryan Gold
Rich Briggs
Steve Personius
Shannon Mahan

U.S. Department of the Interior
U.S. Geological Survey

Wasatch Fault Zone

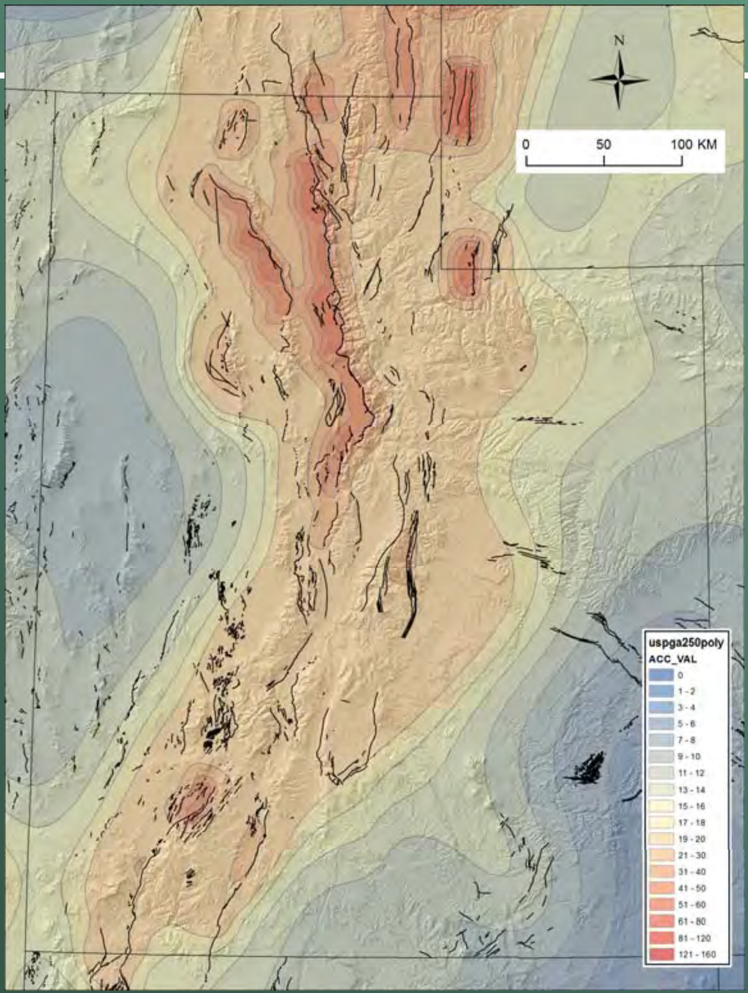
- 1st-order structure at eastern edge of Basin and Range province
- W-dipping normal fault zone
- 10 structural segments
  - fault step-over (relay ramp)
  - transfer structure (strike-slip fault)

Scientific Questions

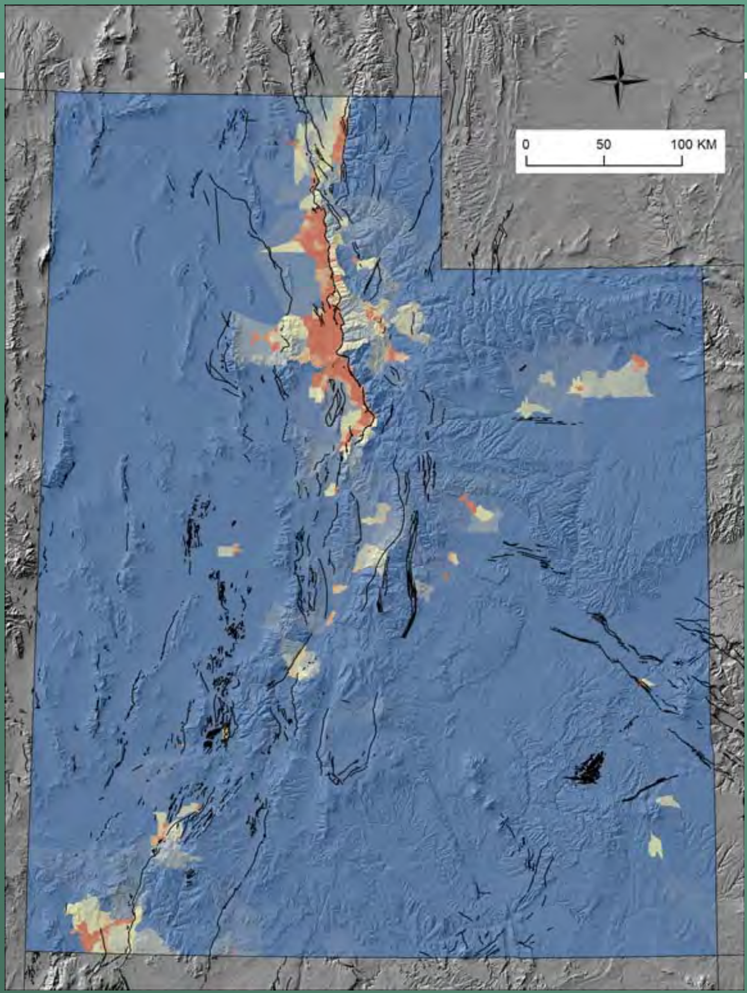
- Are surface-rupturing earthquakes restricted to one fault segment or do they involve multiple fault segments?
- If the latter occurs, how frequent?
- Do ruptures tend to break full or partial segments?
- How do these findings impact seismic hazard analysis along the Wasatch Front urban corridor?

USGS

Scientific Questions



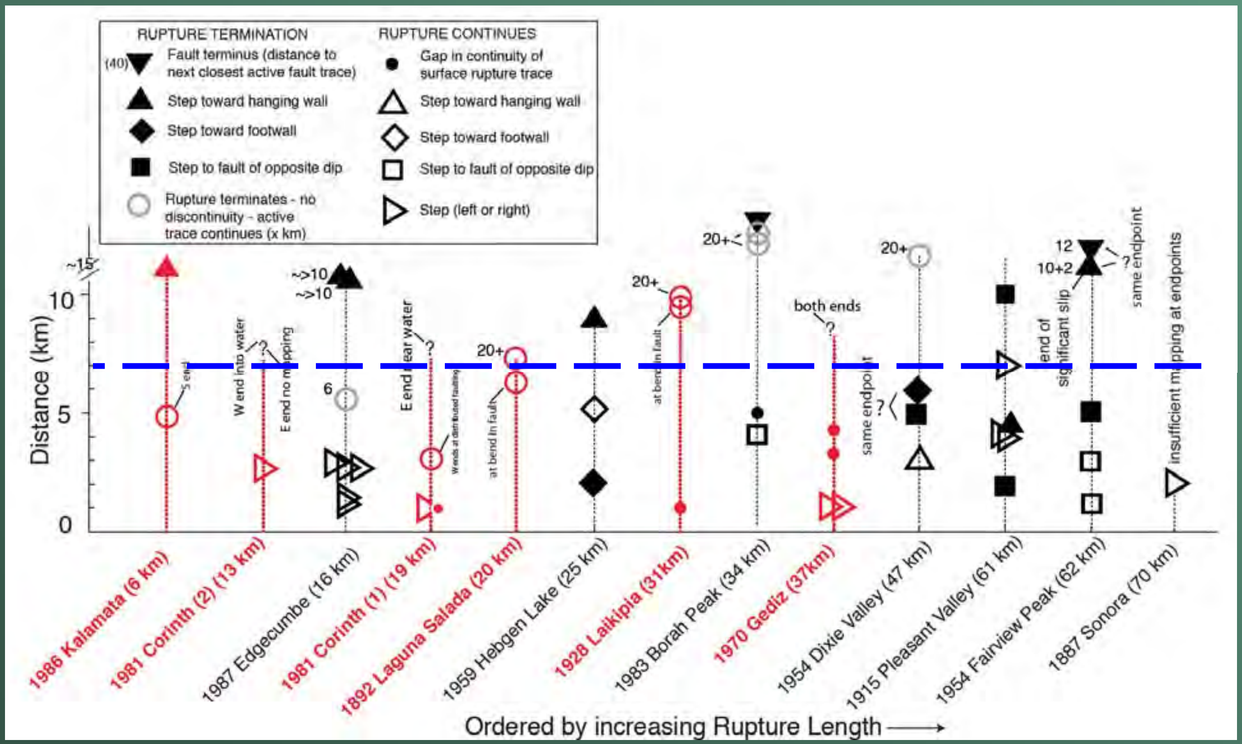
Seismic Hazard



Population Density

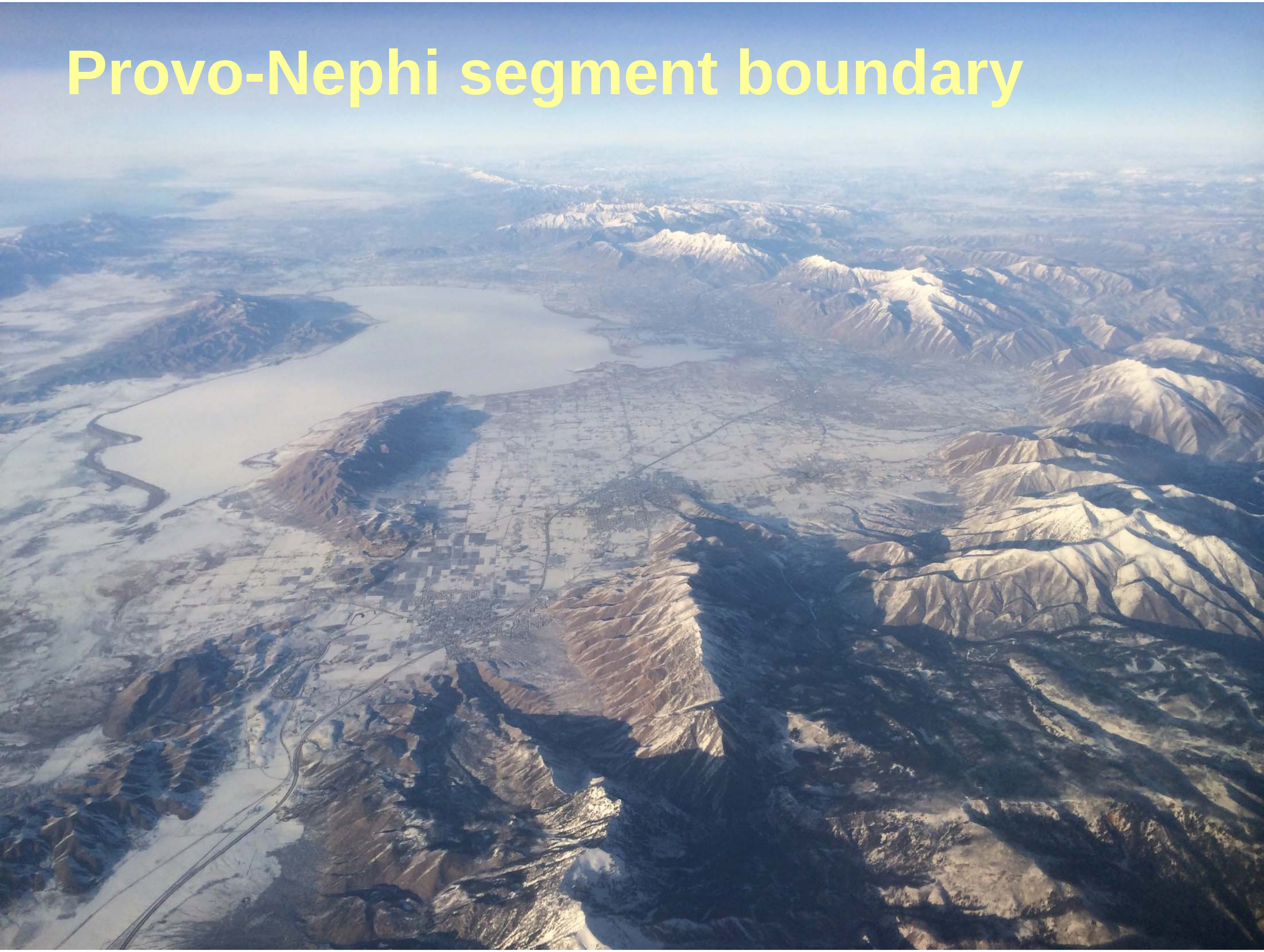
Scientific Questions

- **All WFZ stepovers are within empirical limit (7km) for historic normal fault ruptures**

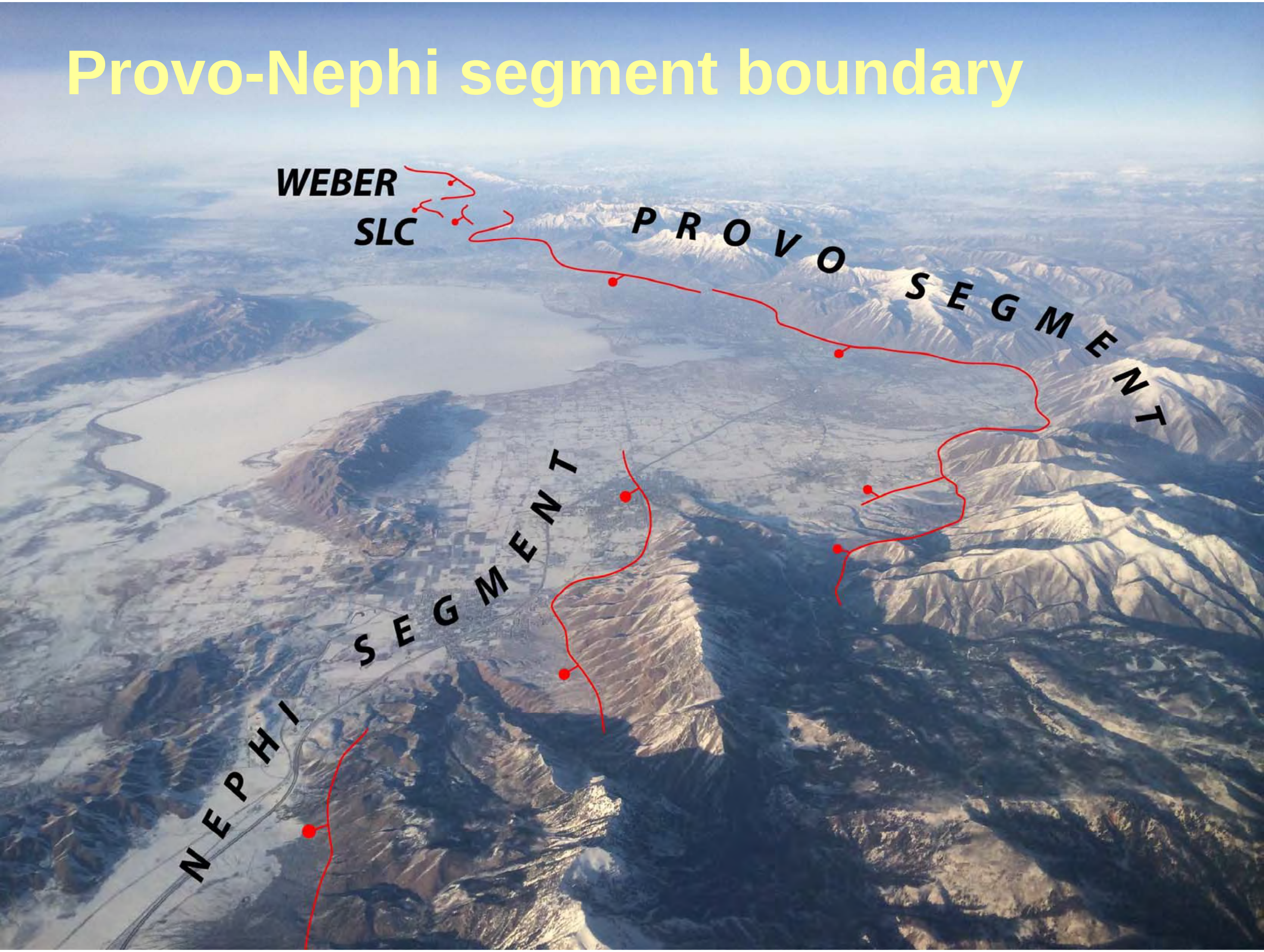


Morelan & Wesnousky (2012)

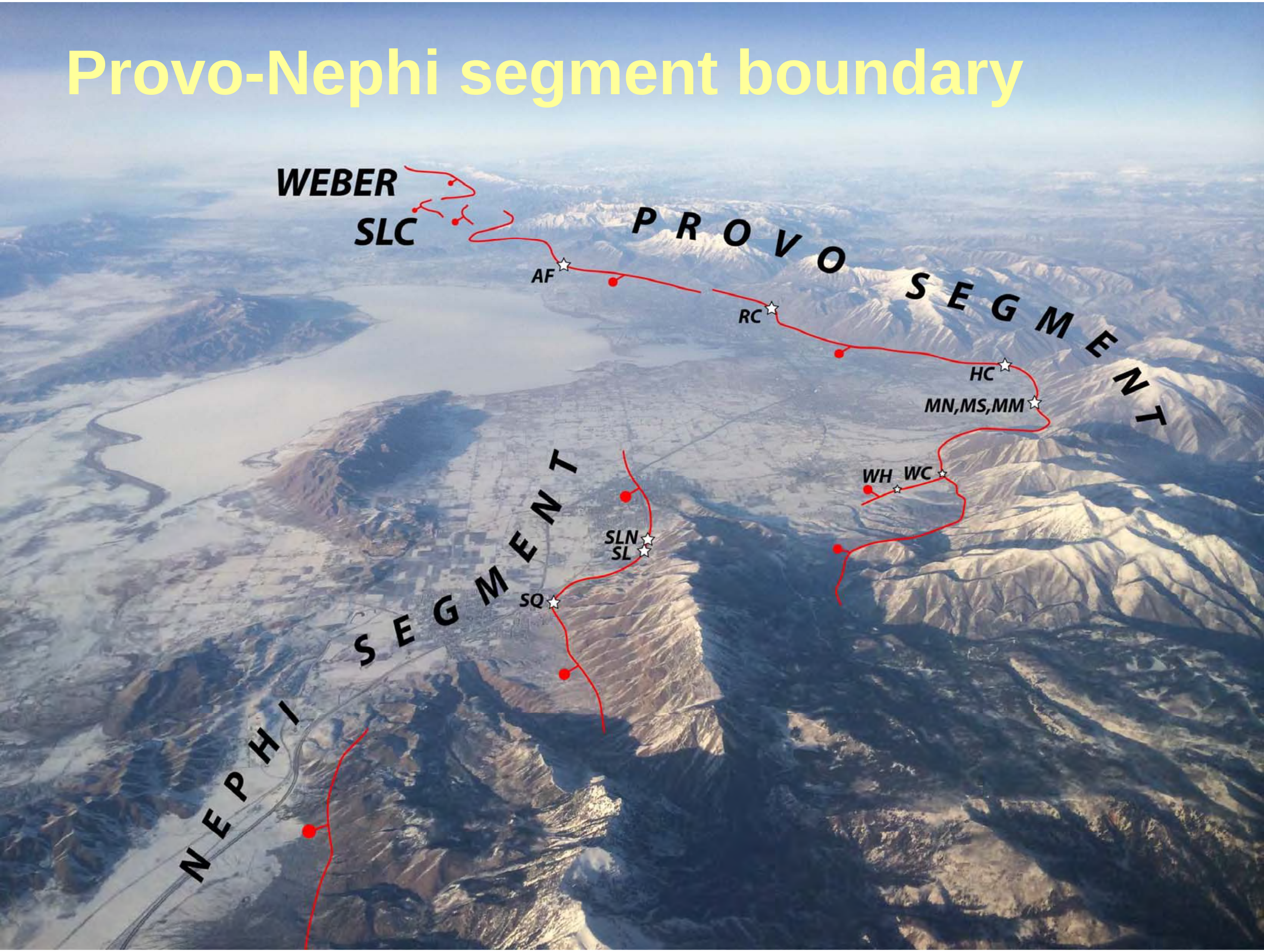
USGS


Provo-Nephi segment boundary

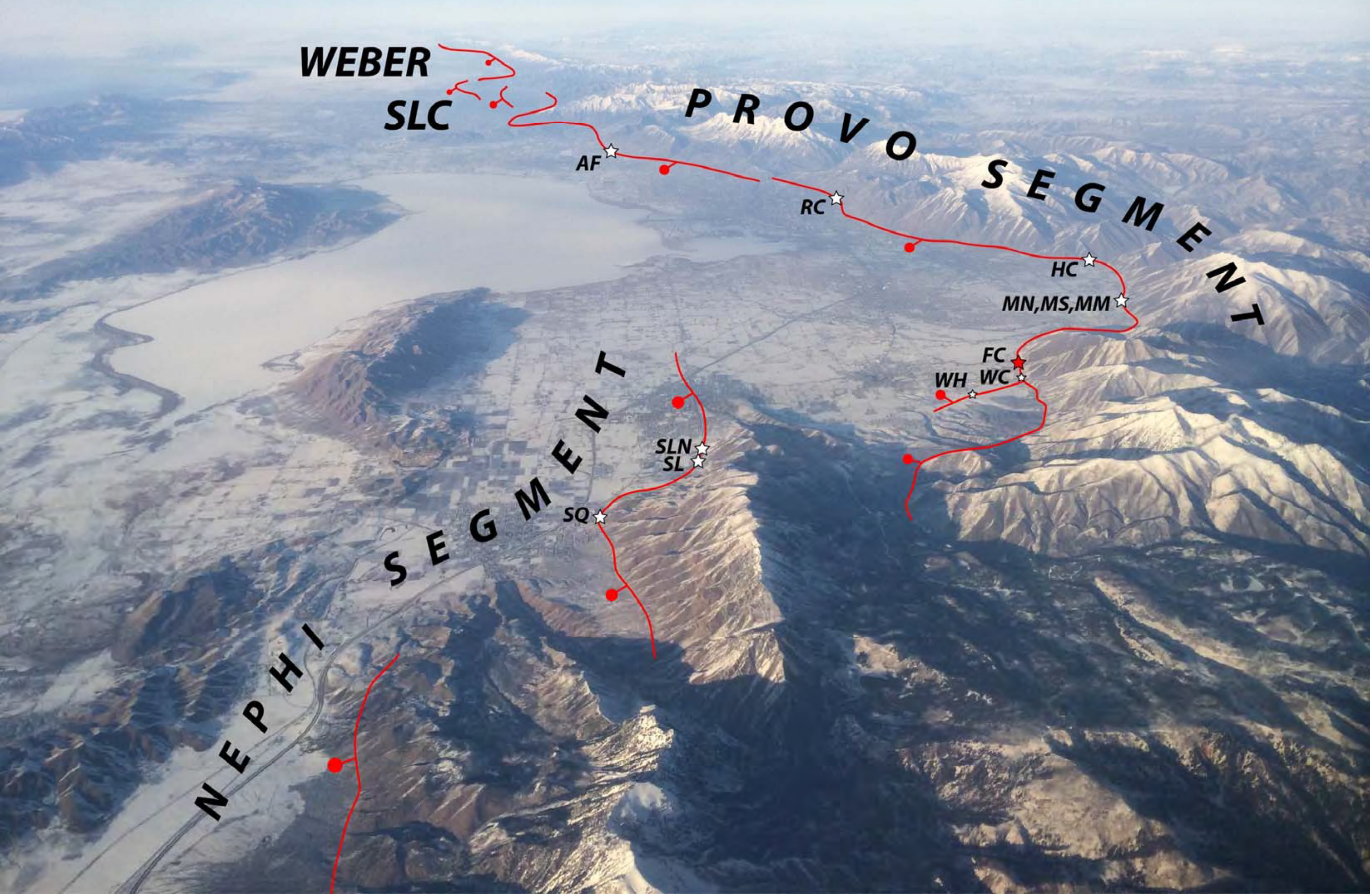
Provo-Nephi segment boundary



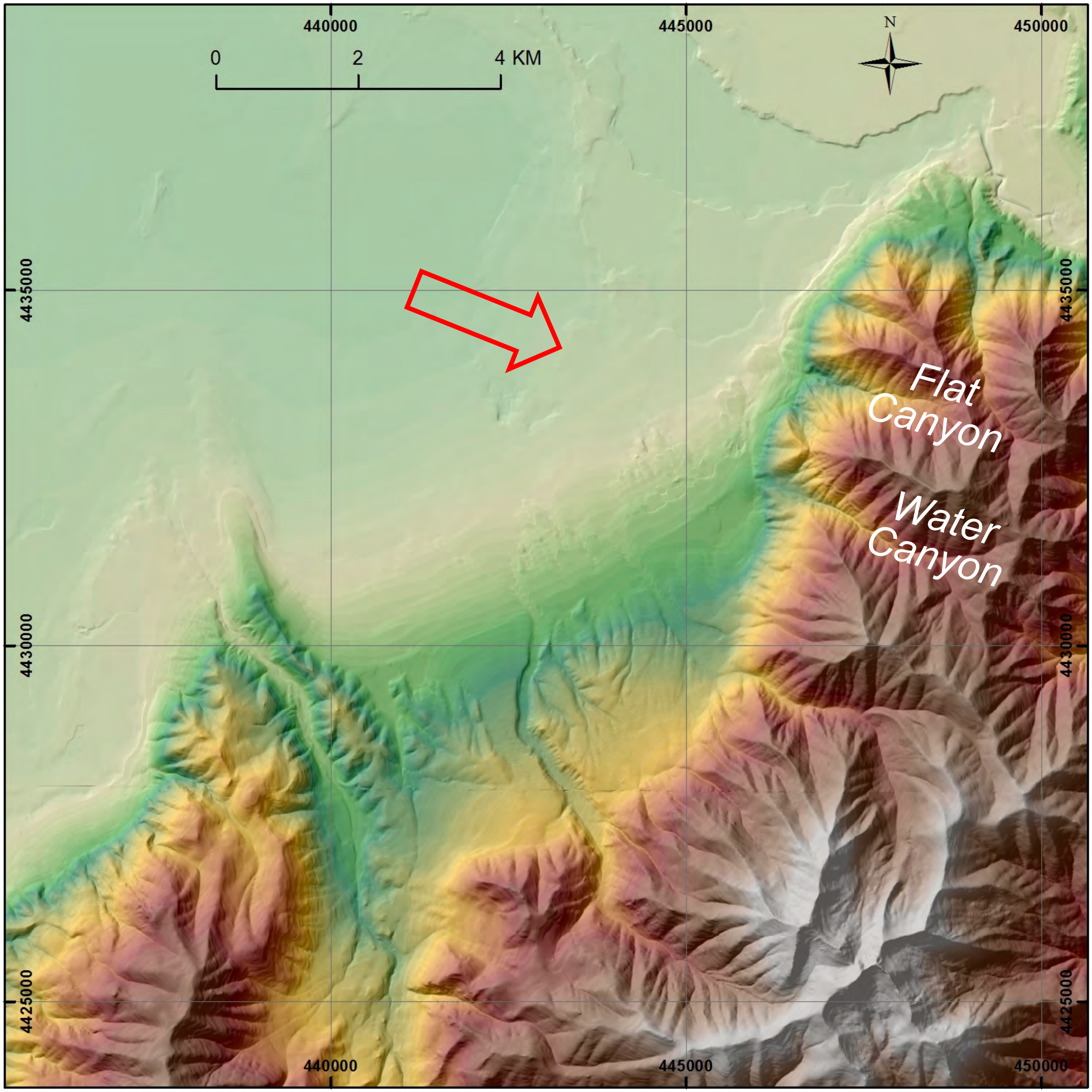
Provo-Nephi segment boundary



Provo-Nephi segment boundary



Flat Canyon

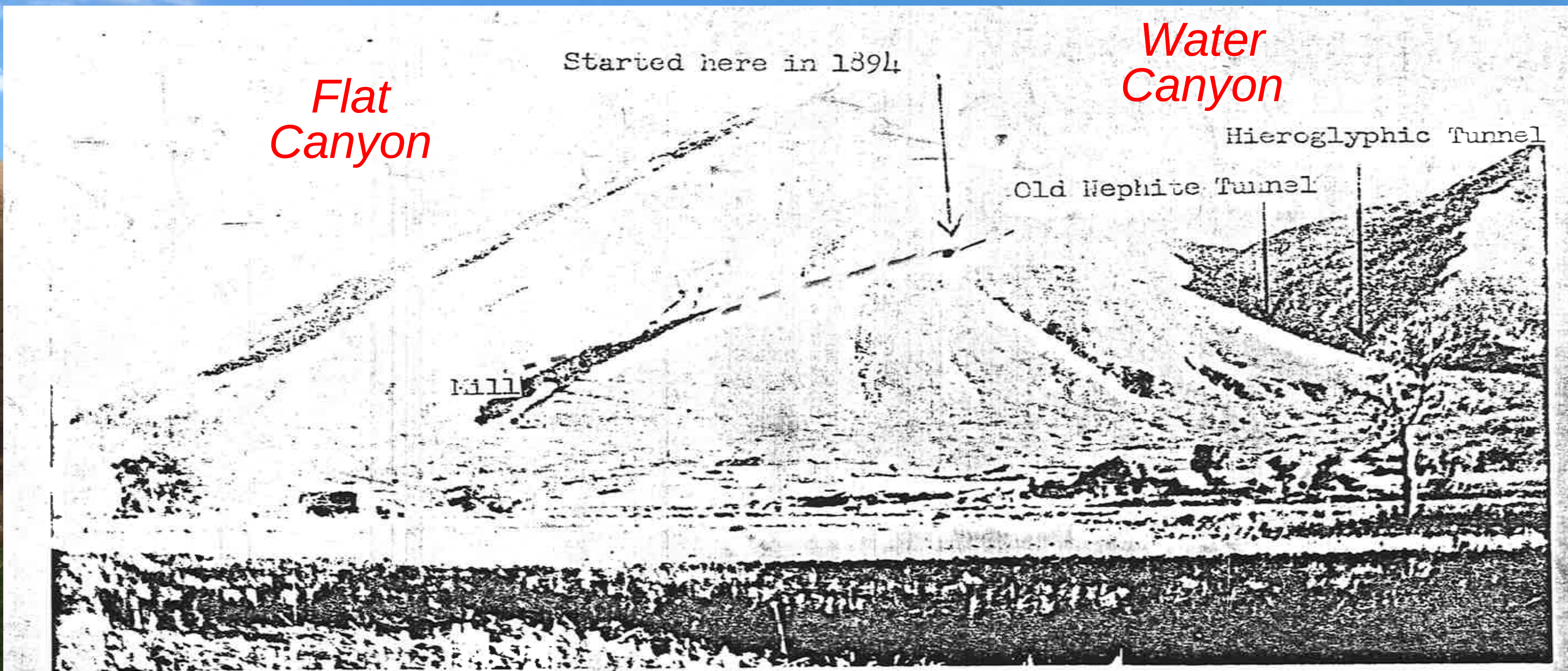


10m NED

USGS

Flat Canyon site

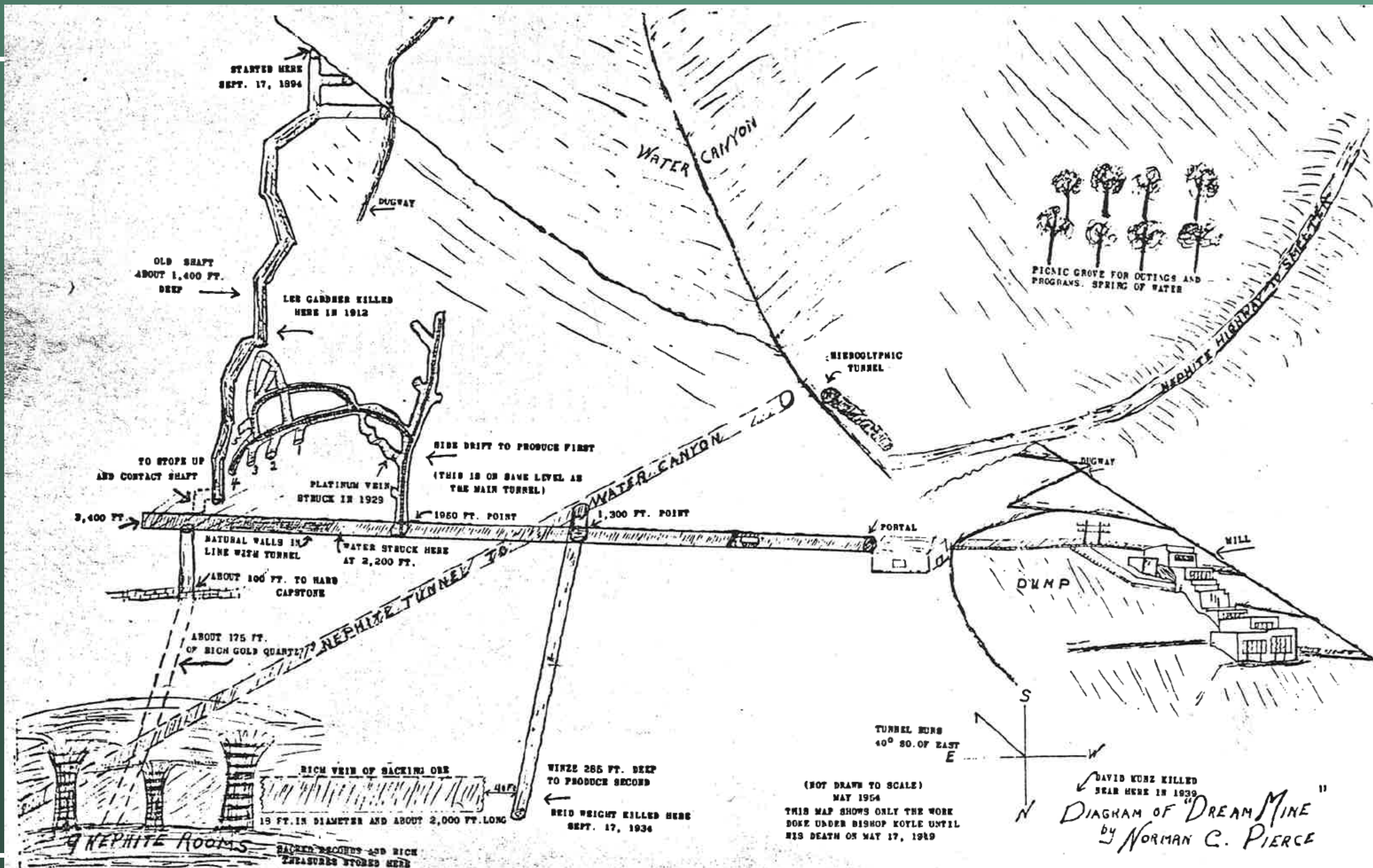
- Relief “Dream” Mine property

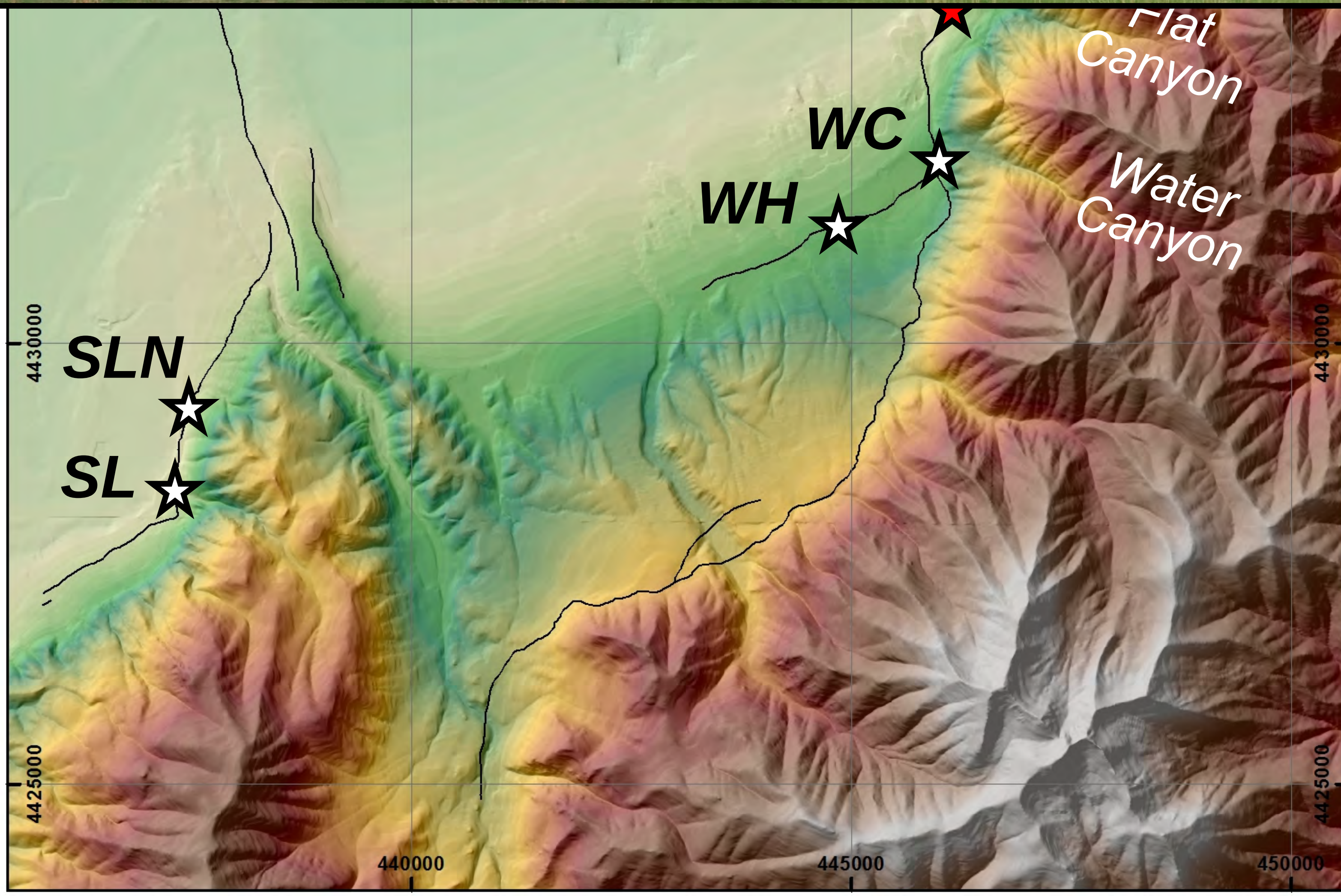


"THE RELIEF MINE"

The white building near left center is the mill. The dugway may be seen winding up the hill. It passes over a saddle back of Knob Hill into Water Canyon on the right and extends to the top of the mountain linking many mines together. The Nephite Tunnel will be opened near the mouth of Water Canyon where the Nephite Highway begins. "White City" is to be built on the foothill in the foreground.

Flat Canyon site

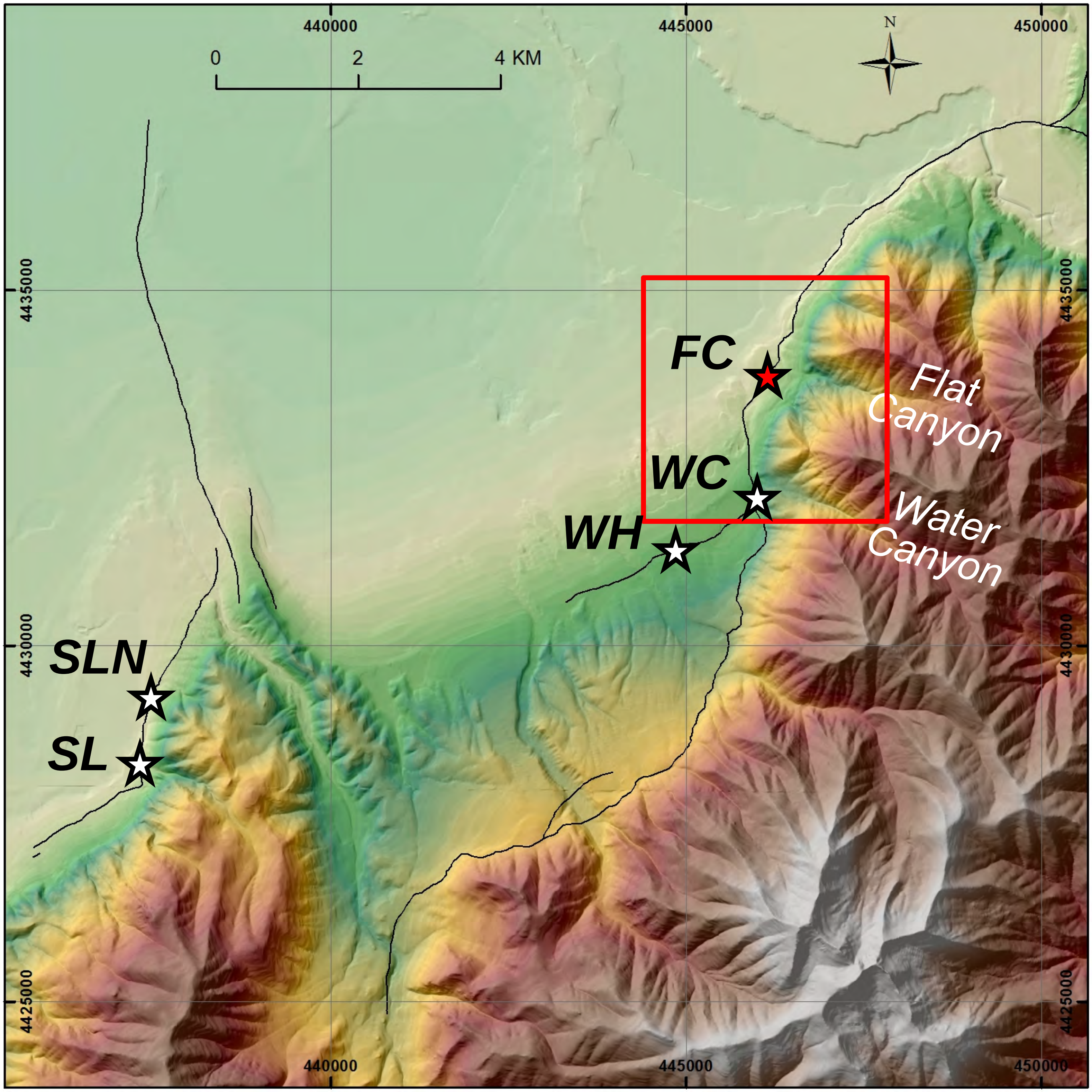




Flat Canyon
WC
WH
Water Canyon
SLN
SL
4430000
4425000
440000
445000
450000

10m NED

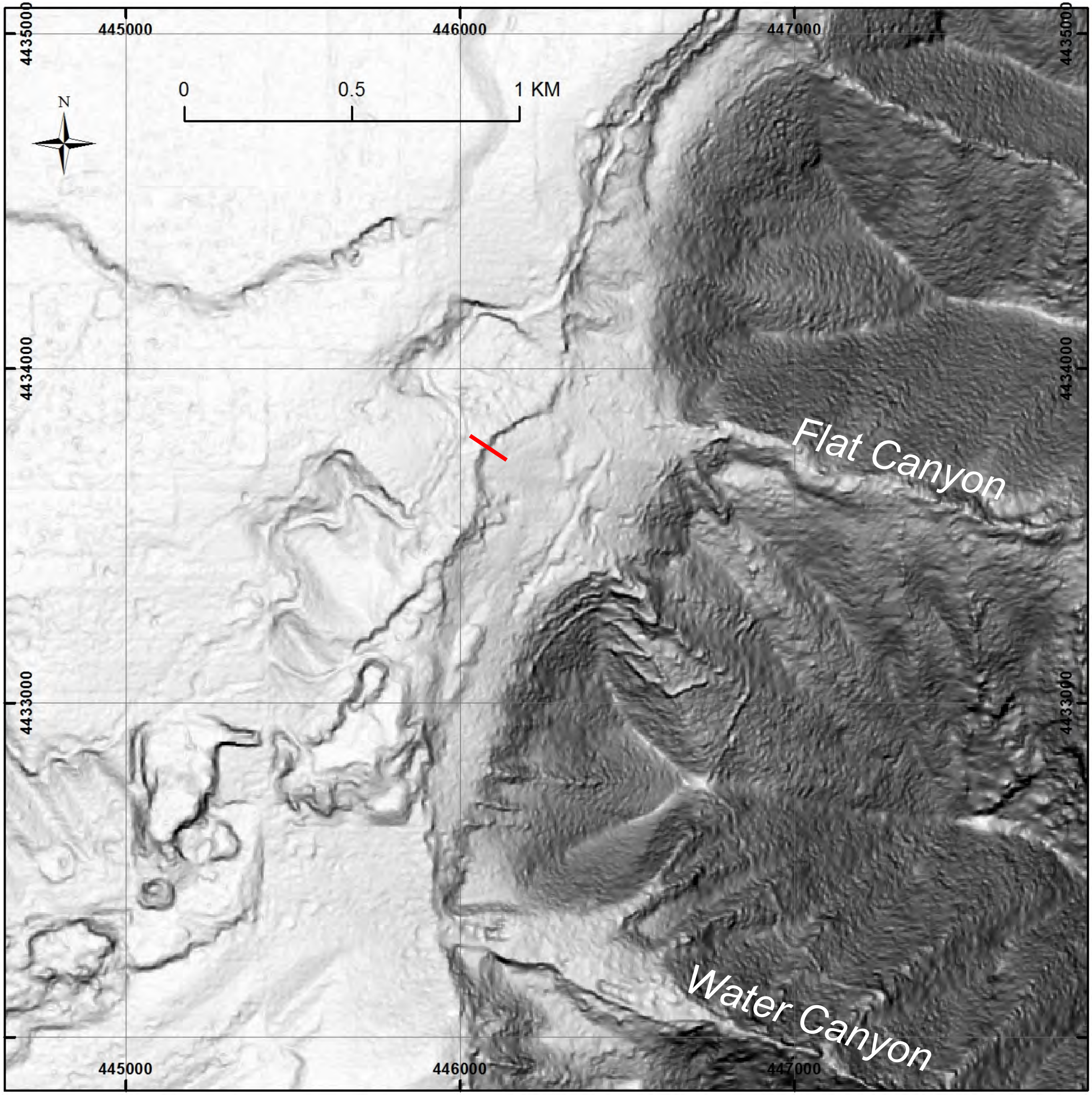
Flat Canyon



10m NED

USGS

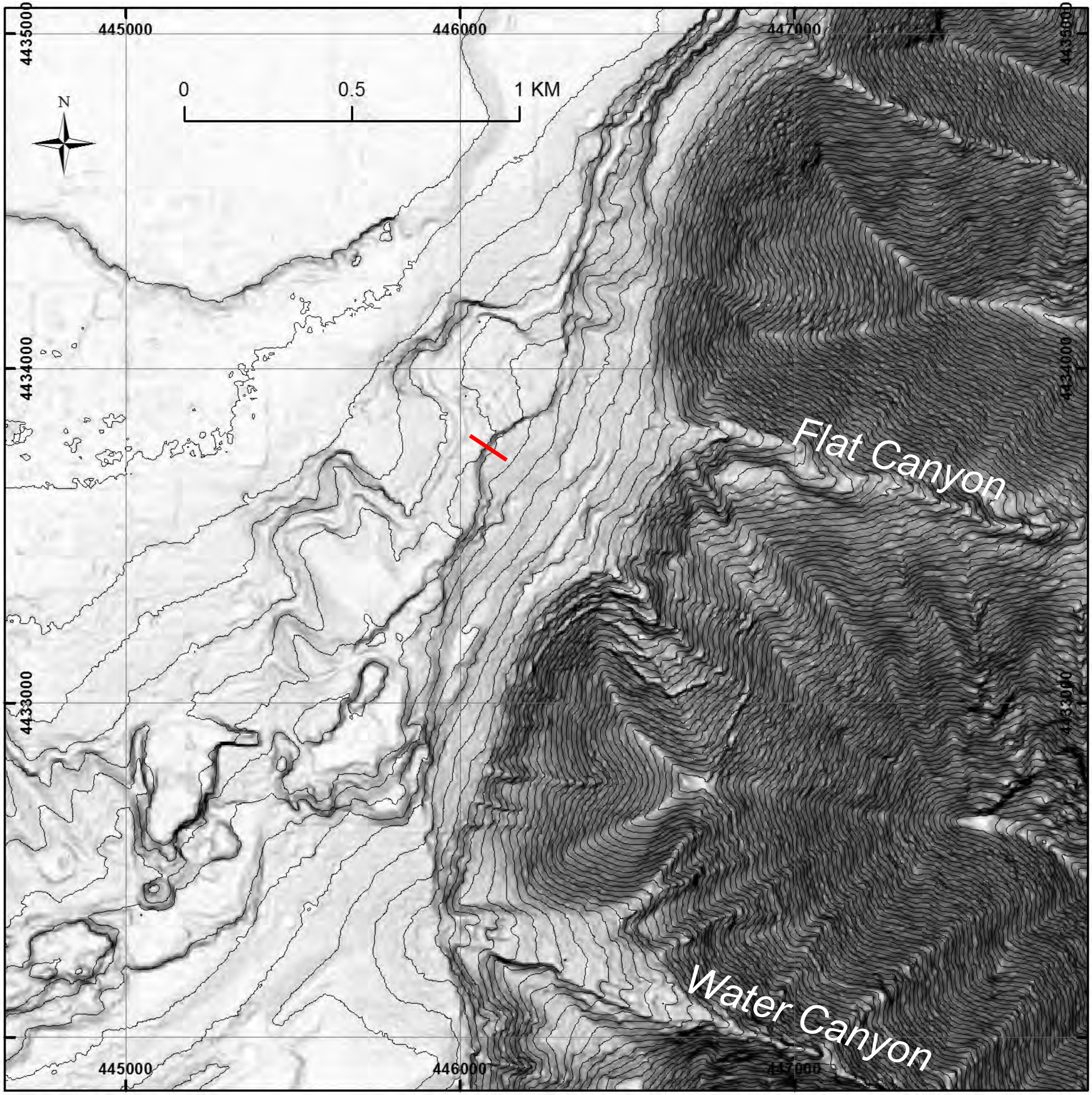
Flat Canyon



Slope-shade from 5m Auto-Correlated DEM

USGS

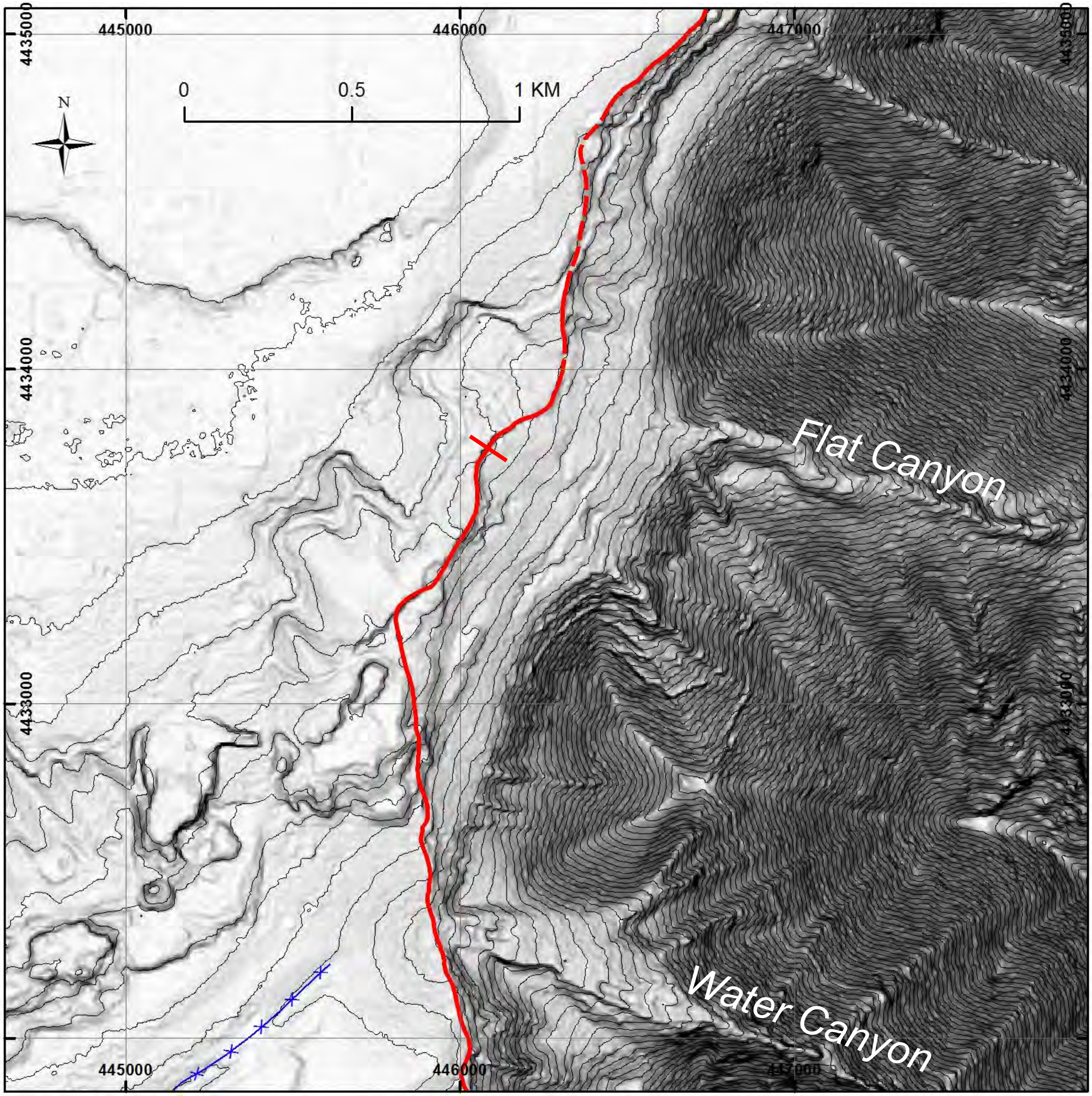
Flat Canyon



Slope-shade from 5m Auto-Correlated DEM

USGS

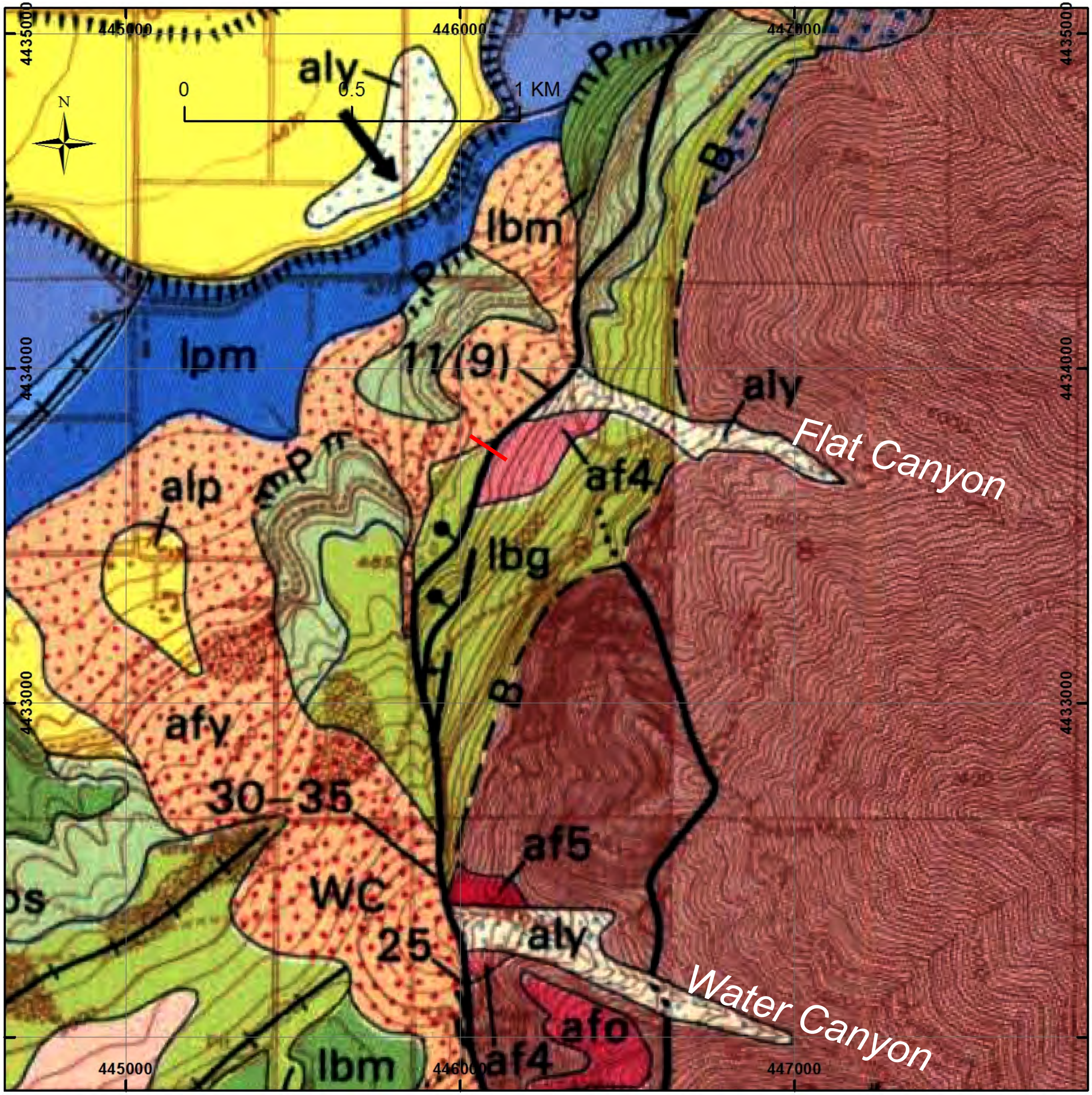
Flat Canyon



Slope-shade from 5m Auto-Correlated DEM

USGS

Flat Canyon

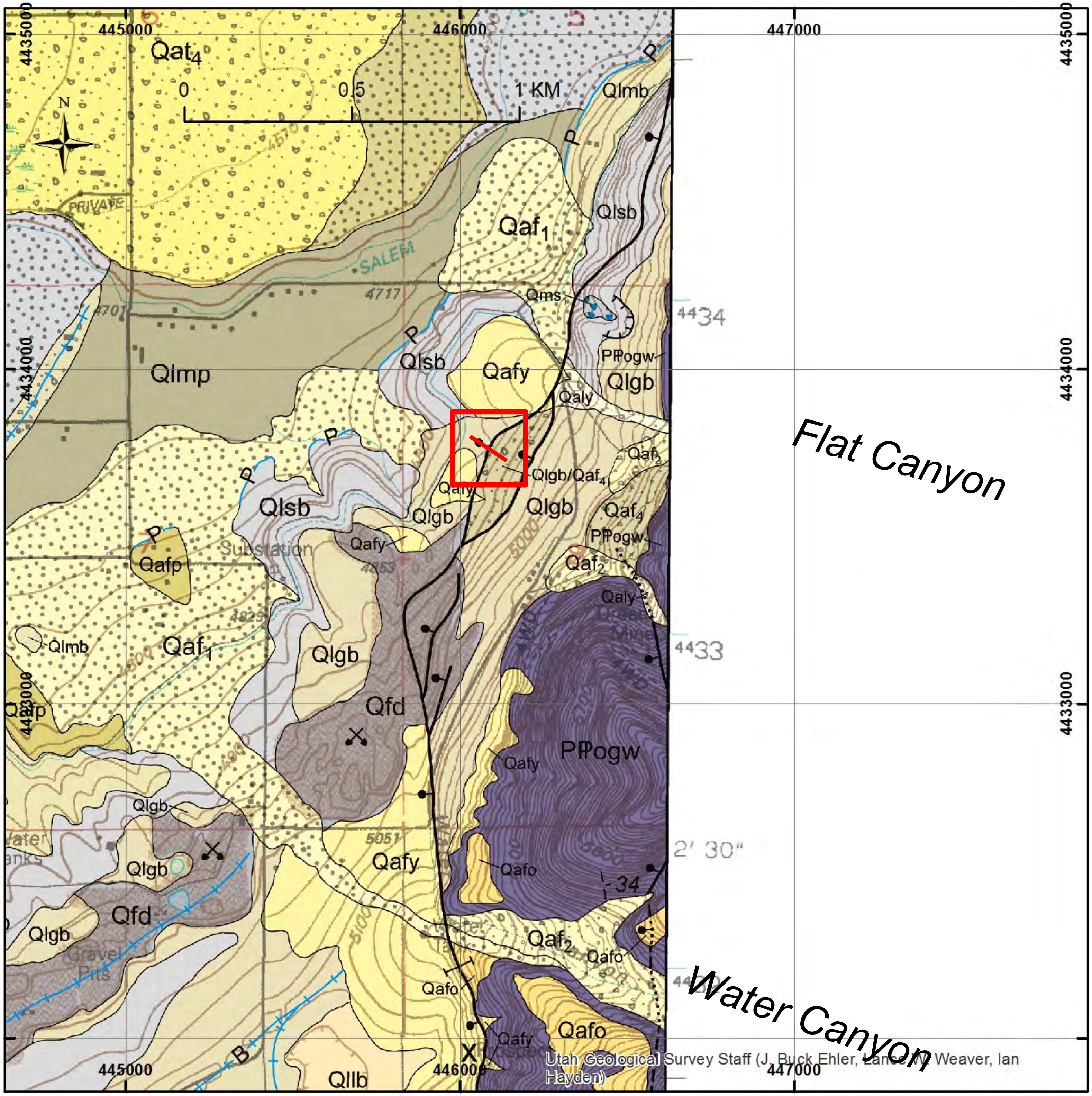


Machette (1992)

USGS

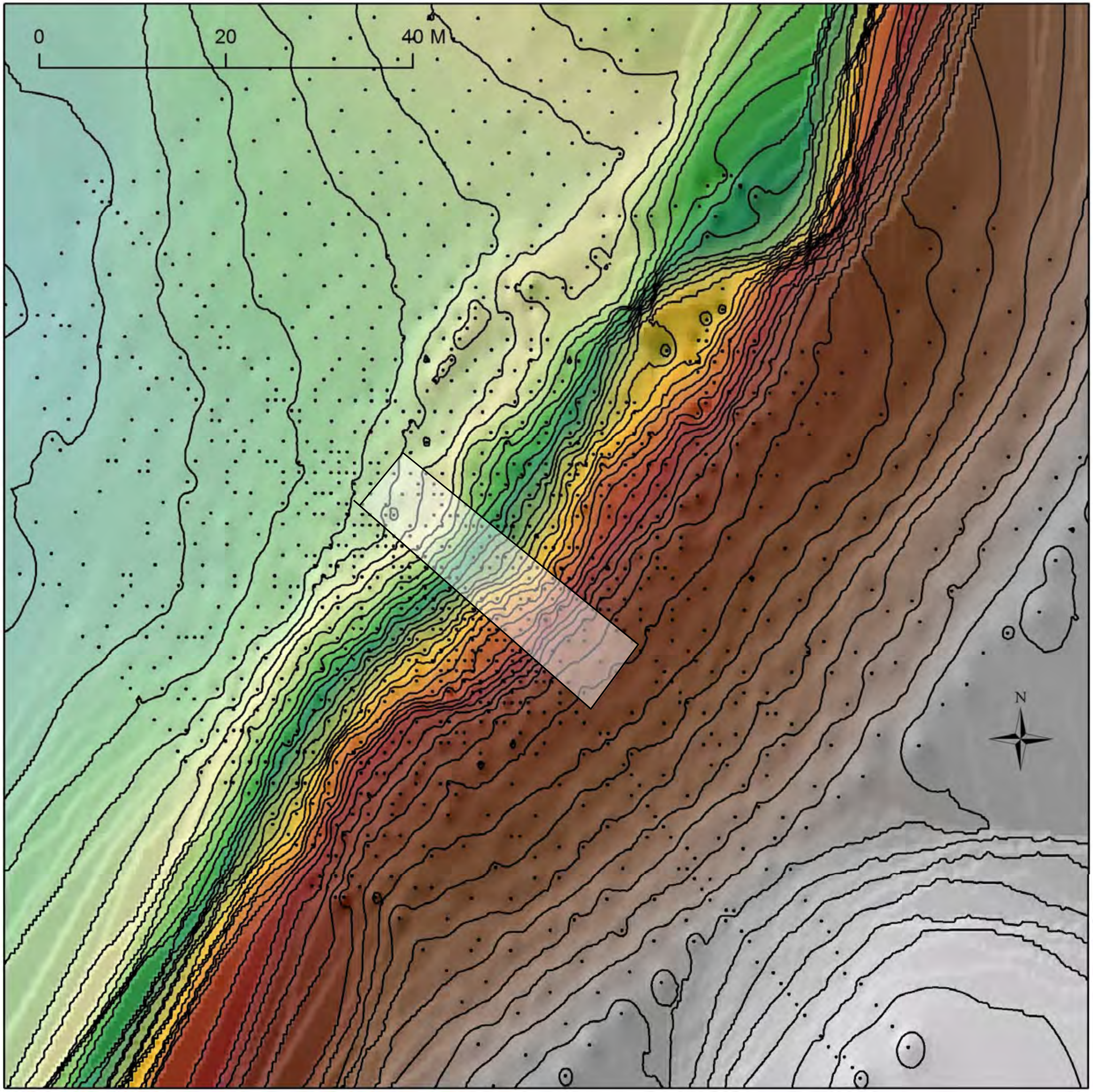
Flat Canyon

Solomon et al. (2007)



Flat Can

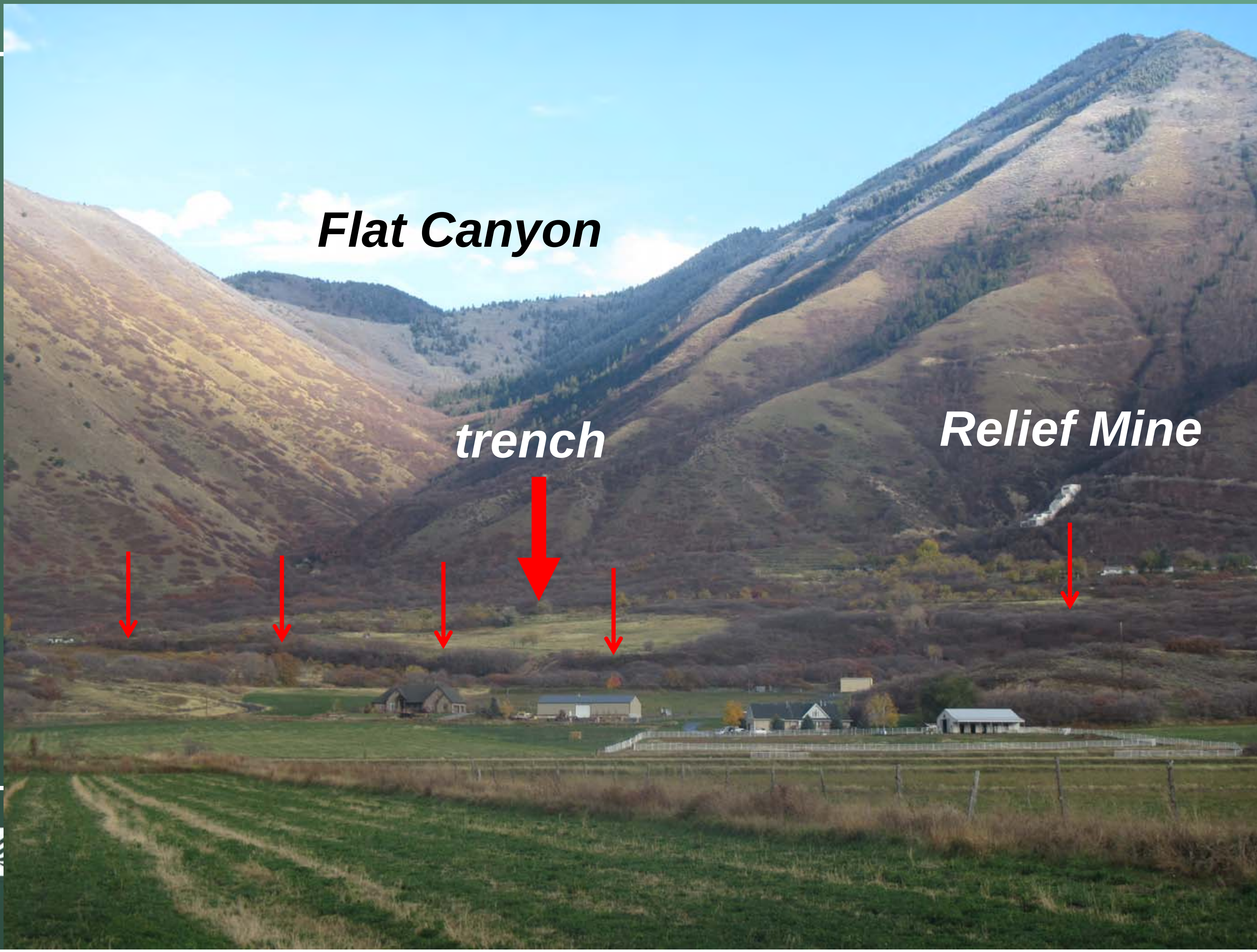
- detailed



USGS

0.5 m contours

Flat Canyon site



Flat Canyon site

Hanging Wall

Footwall

LOOKING NORTH

Trench Excavation (Oct 18-19)

USGS

Evidence for multiple surface ruptures along structures between the Salt Lake City and Provo segments of the Wasatch Fault

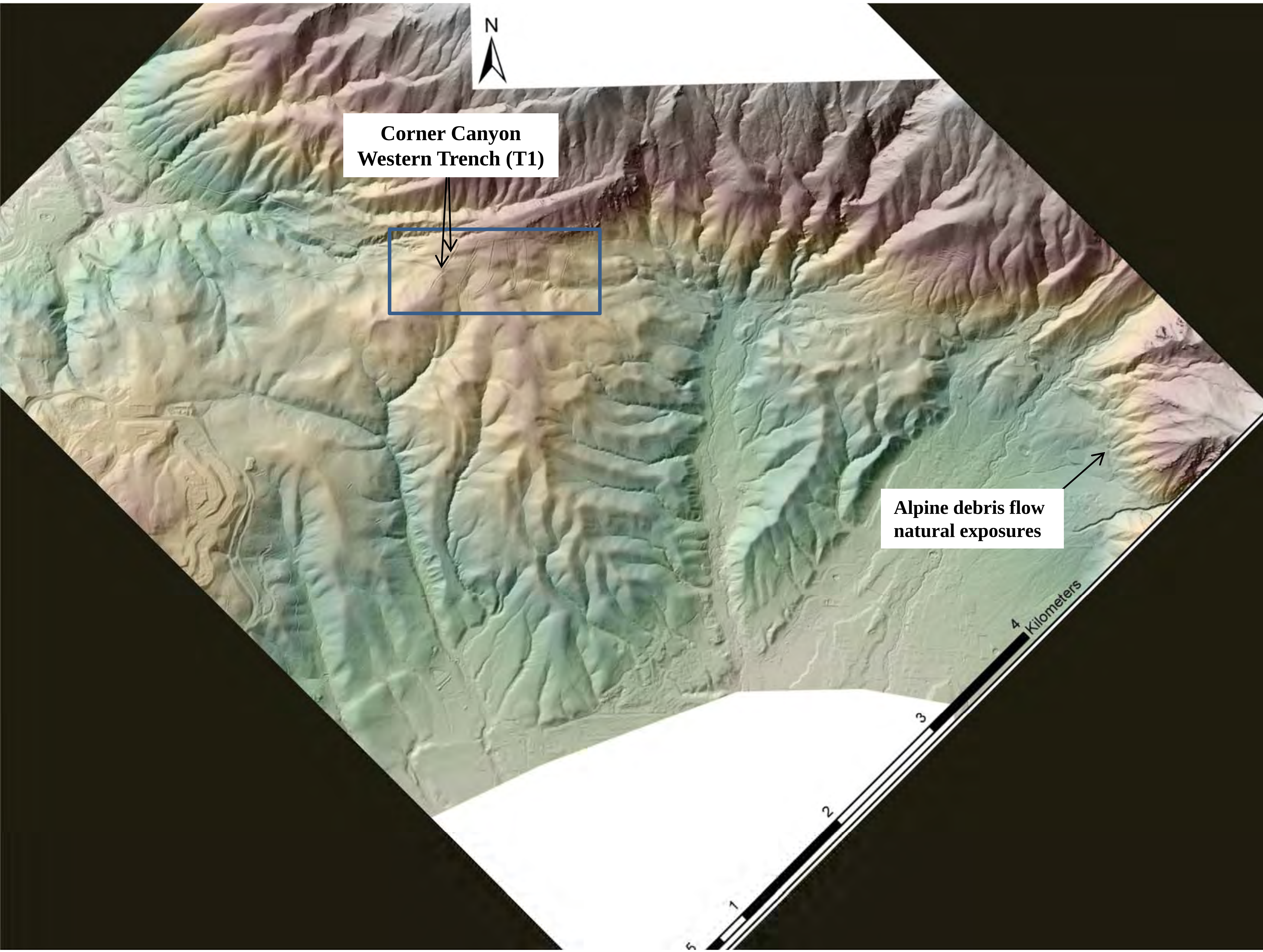
Kade Carlson

Mike Arnoff

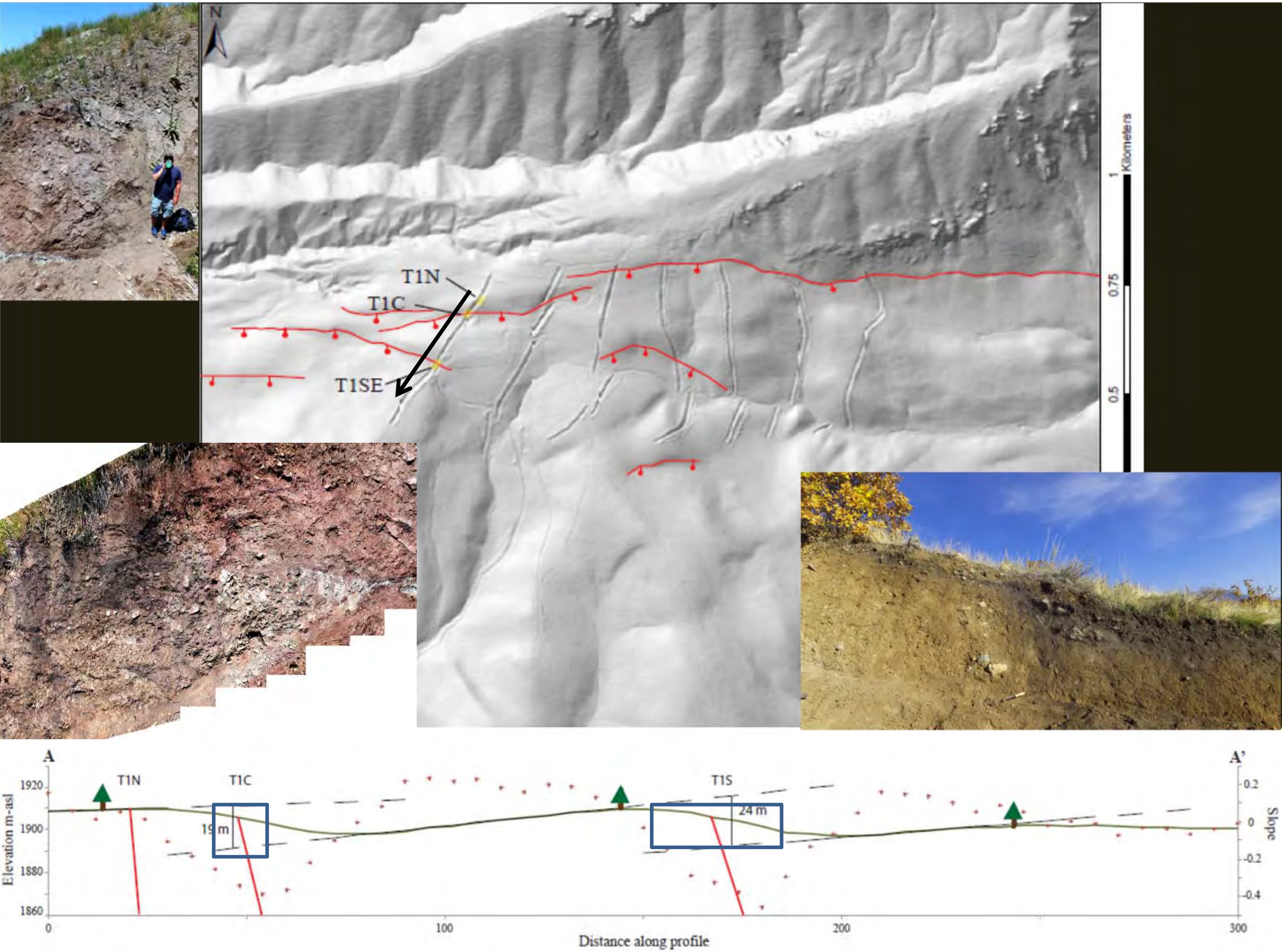
Quaternary Fault Parameters Working Group

Wednesday February 5th, 2014, 9:10-9:30 am

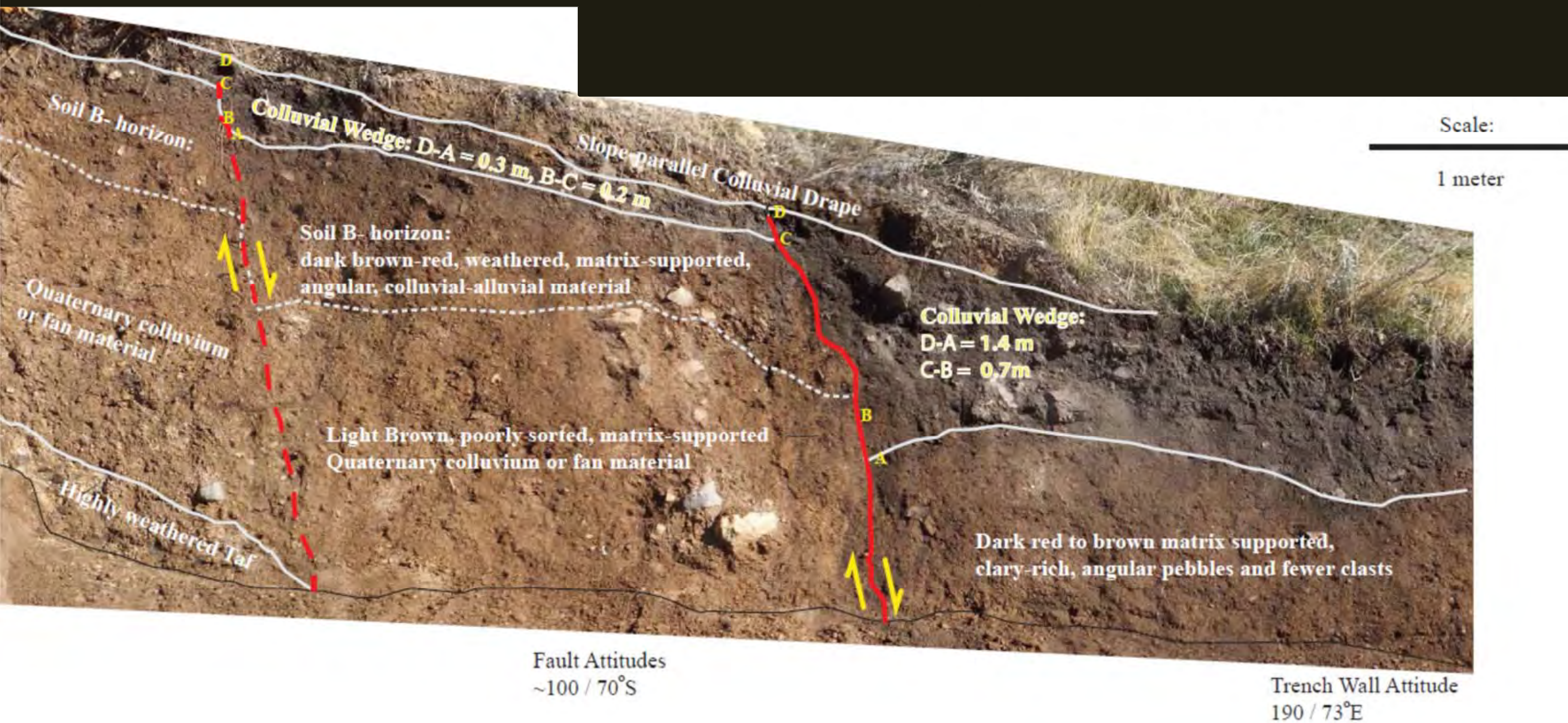
Dr. Nathan A. Toké and UTAH VALLEY UVU UNIVERSITY Department of EARTH SCIENCE Students


N
Corner Canyon
Western Trench (T1)
Alpine debris flow
natural exposures
0
1
2
3
4
Kilometers

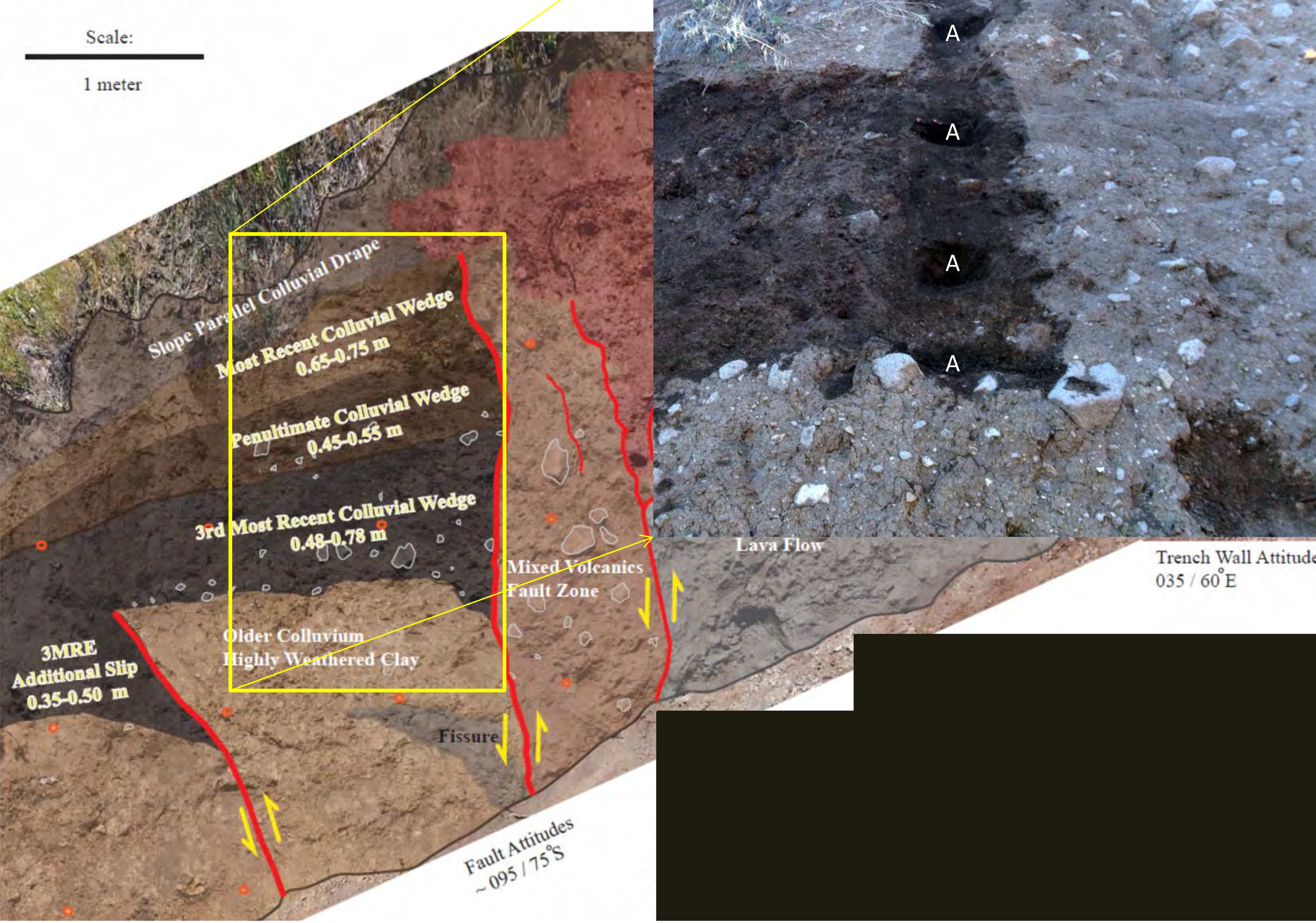

A'
A
Trench Site Map (1:8,000K)
Hillshade over 2m LiDAR
Kilometers
0 0.1 0.2 0.4 0.6 0.8
N


N
Kilometers
1
0.75
0.5
T1N
T1C
T1SE
A
A'
T1N
T1C
T1S
19 m
24 m
1920
1900
1880
1860
Elevation m-asl
0.2
0
-0.2
-0.4
Slope
0
100
200
300
Distance along profile

Trench 1 South
(east wall)



- Trench 1 Center (west wall)

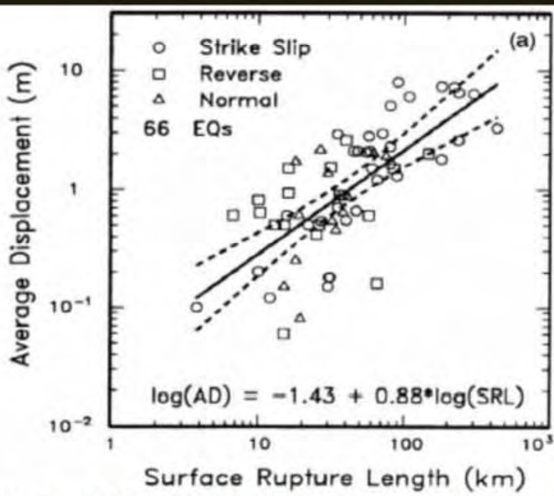


Wells and Coppersmith,1994:

Empirical relationships between mean displacement and surface rupture length

0.5-1.5 m displacement
~25-55 km ruptures

C



Empirical relationships between average displacements and surface rupture length (Wells and Coppersmith, 1994) indicate that the 0.5 - 1.4 meter displacements observed at this site may correspond to rupture lengths of 24-54 km (Figures A, E, and Table 1).

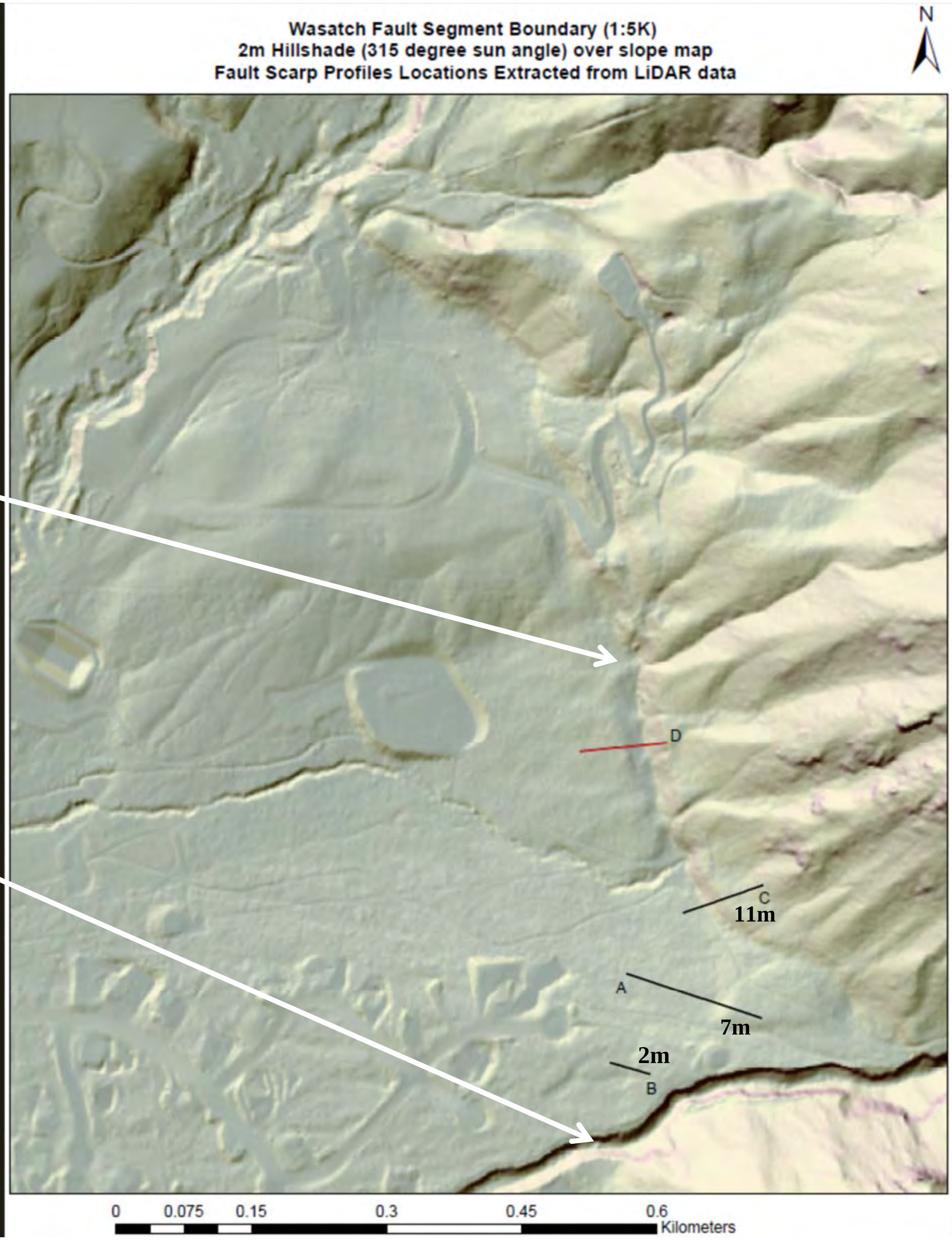
September 2013, Alpine Debris Flows

Northernmost Provo Segment

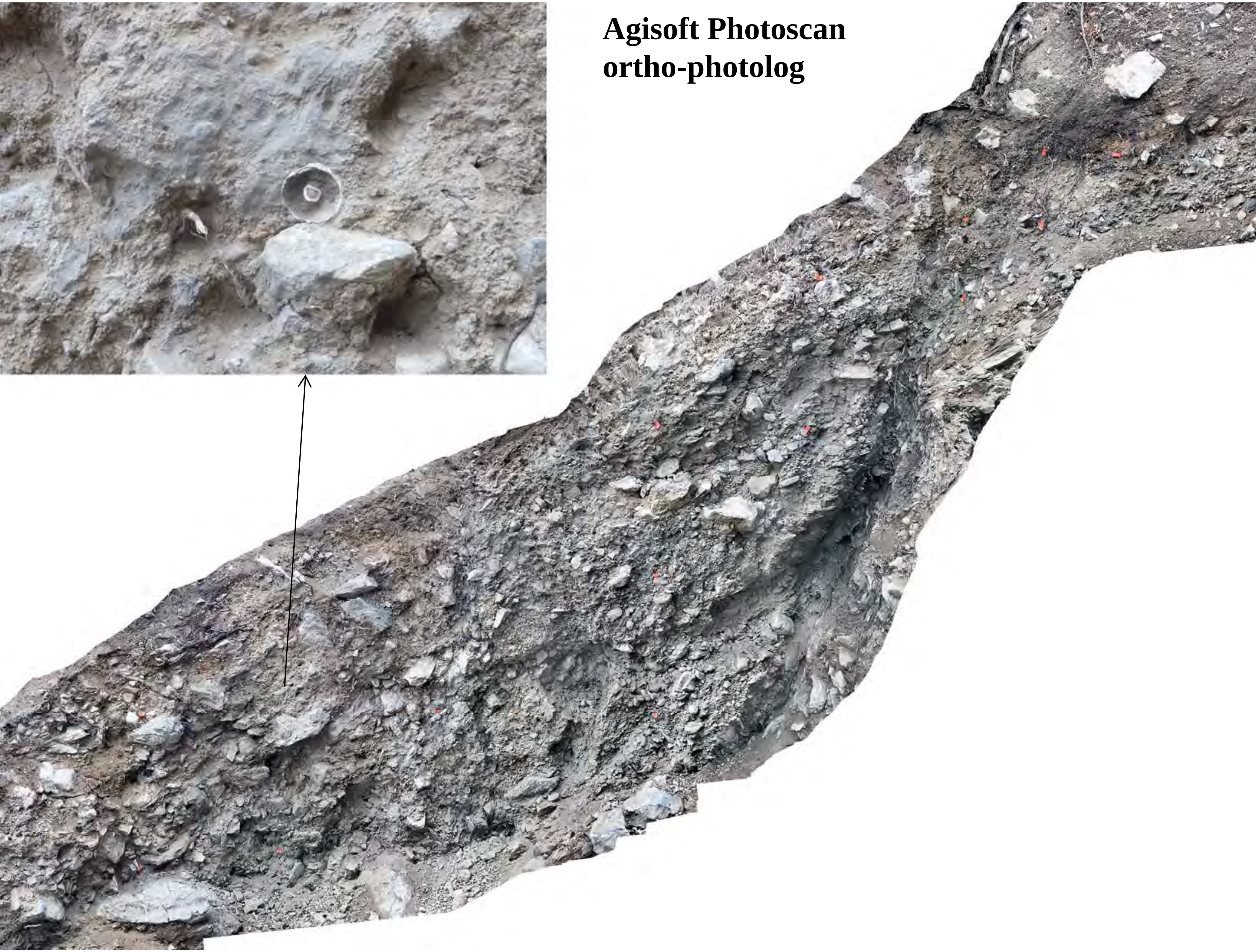
Two Natural Fault Exposures

1) Debris flow channel
   - September 2013
   - Incision of hanging wall
   - Evidence for at least one recent event, probably several.

2) Post-Bonneville Arroyo
   - Large exposure
   - Inaccessible
   - Agisoft possibilities?



Agisoft Photoscan ortho-photolog



Continued Work Plan

- NEHRP proposal for dates and continued trenching

Ongoing UVU Undergraduate Student Work:

- LiDAR Fault Mapping
- Refined Alpine Trench logging/Agisoft
- Coulomb 3 modeling.

- Future Collaborations – Jim McCalpin, UGS? USGS?

Trench 1 Center
(west wall)

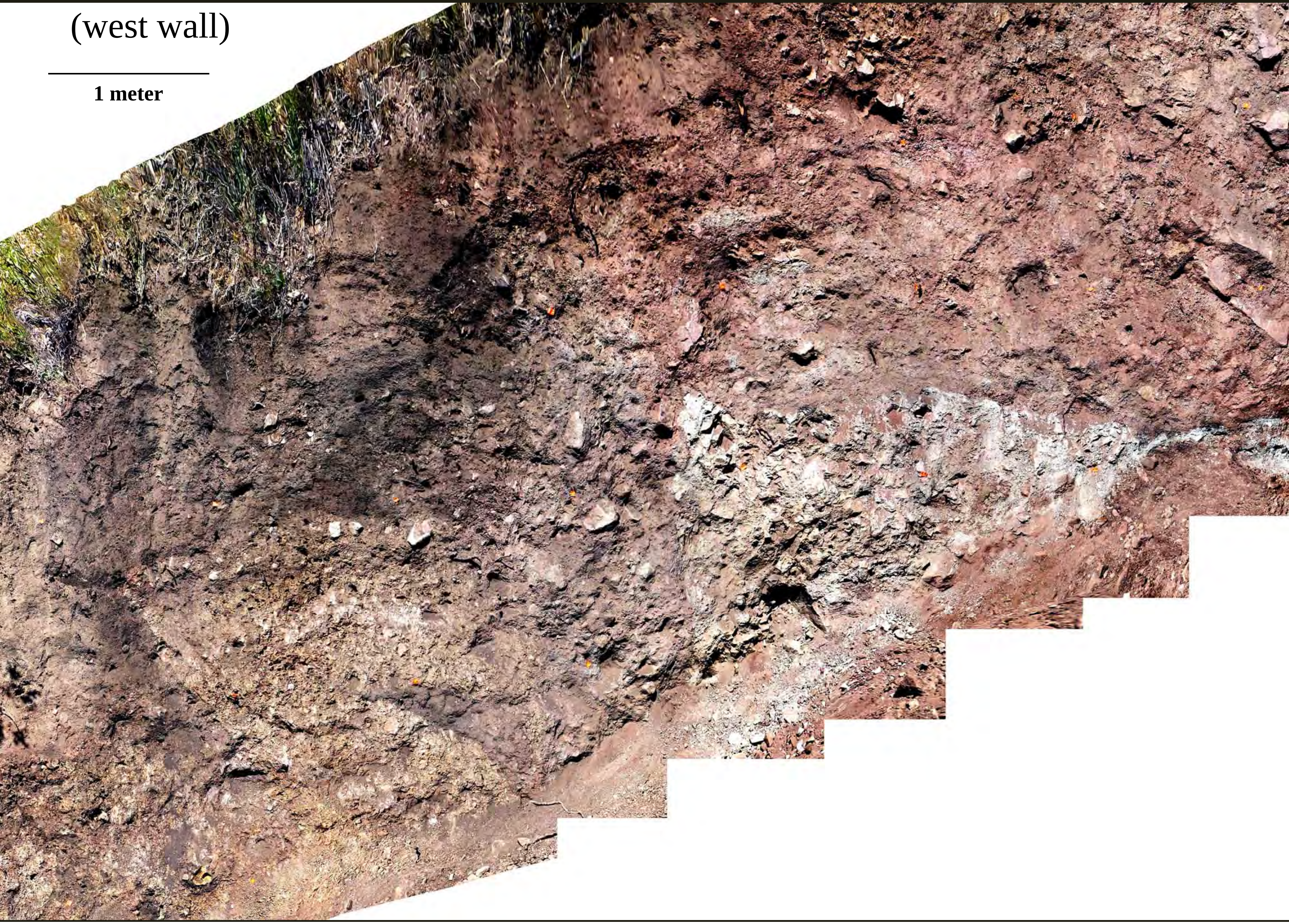


Table 1. Colluvial Wedge Heights, Displacement Magnitudes, and Estimated Rupture Length, Salt Lake City and Provo Segment Boundary along the Wasatch Fault - Traverse Ridge, Utah.

Location	Measurement	Apparent Height[1]	True Height[2]	Fault	Wall	*Est. Fault Slip*[3]	*Est. Rupture Length*[4]
South Exp.[5]	*South Scarp height*[6]	-	-	-	-	24 m	-
Trench-1S[7]	**Most Recent Event South Exp.**	**Min = 0.90 m Max = 1.40 m**	**0.80 m 1.25 m**	**100/70 s**	**190/73 w**	***1.4 m***	***54 km***
Central Exp.	*Central Scarp height*[6]	-	-	-	-	19 m	-
Trench-1C	**Most Recent Event Central Exp.**	**Min = 0.65 m Max = 0.75 m**	**0.50 m 0.57 m**	**095/75 s**	**035/60 e**	***0.8 m***	***32 km***
Trench-1C	**Penultimate Event Central Exp.**	**Min = 0.45 m Max = 0.55 m**	**0.34 m 0.42 m**	**095/75 s**	**035/60 e**	***0.5 m***	***24 km***
Trench-1C	**3rd Most Recent Event Central Exp.**	**Min = 0.83 m Max = 1.28 m**	**0.64 m 0.98 m**	**095/75 s**	**035/60 e**	***1.1 m***	***44 km***
North Exp.	*North Scarp Height*	Total Offset = 0 m	-	264/80 s	-	***0.0 m***	-
Trench -1N	V. Old Single Event[8]	Min = 0.60 m Max = 0.50 m	0.34 m 0.41 m	264/80 s	218/53 e	***0.5 m***	***24 km***

1 – Apparent colluvial wedge height was measured along the plane of the trench wall exposures. Trenches were sloping for safety.

2 – True colluvial wedge height was calculated by projecting the apparent wedge height (measured along the laid back trench wall exposures) into a vertical exposure.

3 – Estimated Fault slip was calculated presuming that colluvial wedge height represents ~60% of total fault slip in an earthquake due to scarp erosion.

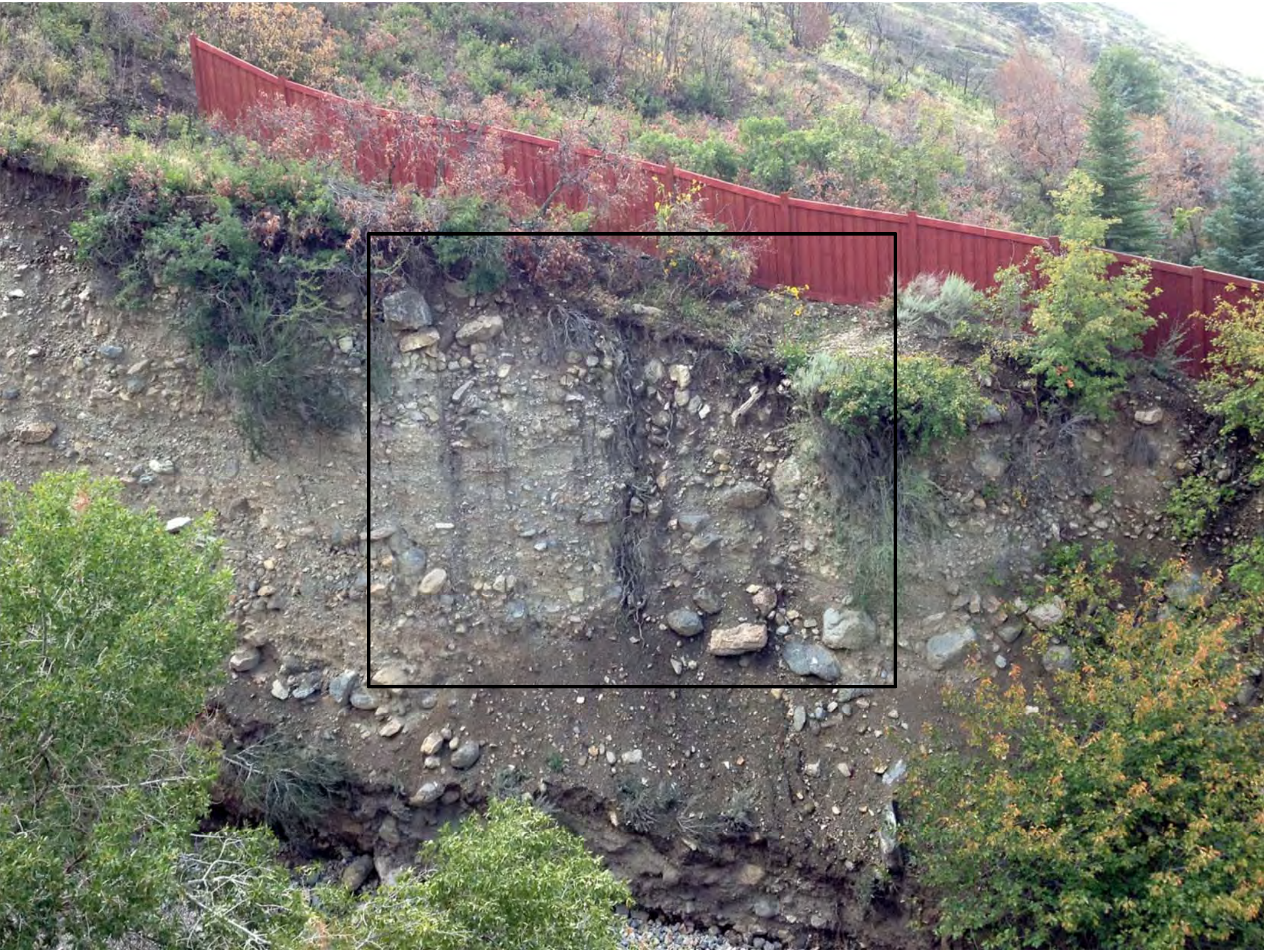
4 – Rupture lengths were estimated using the empirical equation: **Log (average displacement) = -1.99 + 1.24 Log (Surface Rupture Length)** from Wells and Coppersmith, 1994.

5 – See Site map for each trench exposure location.

6 – Scarp Heights were extracted from 2m LiDAR data (http://gis.utah.gov/data/elevation-terrain-data/2-meter-lidar/)

7 – Trench logging is shown in the middle panel of the poster.

8 – Because there is no surface scarp this event is likely Pleistocene (preBonneville) age or older.

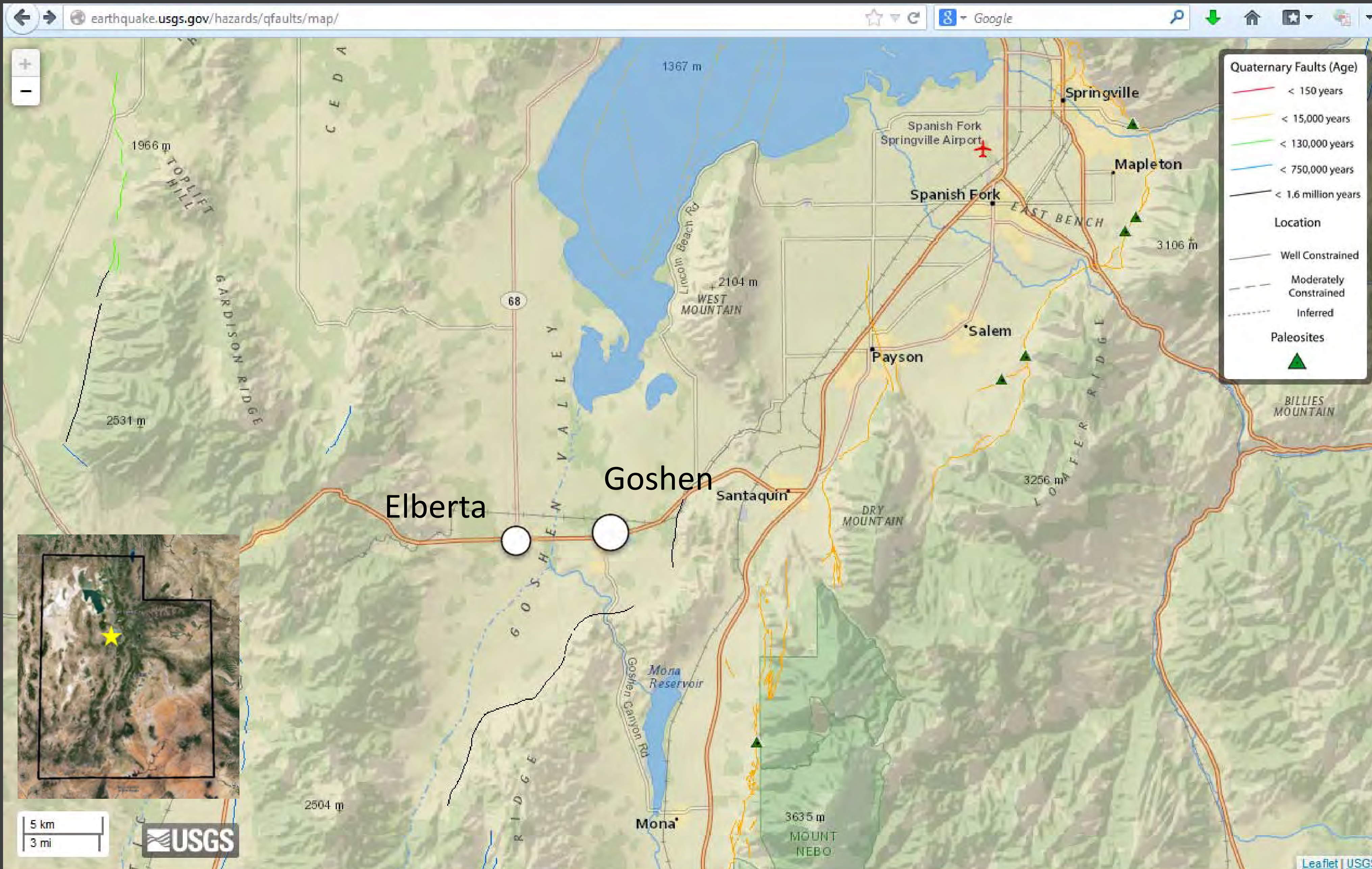


Newly discovered Holocene-active basin floor fault in Goshen Valley, Utah County, Utah

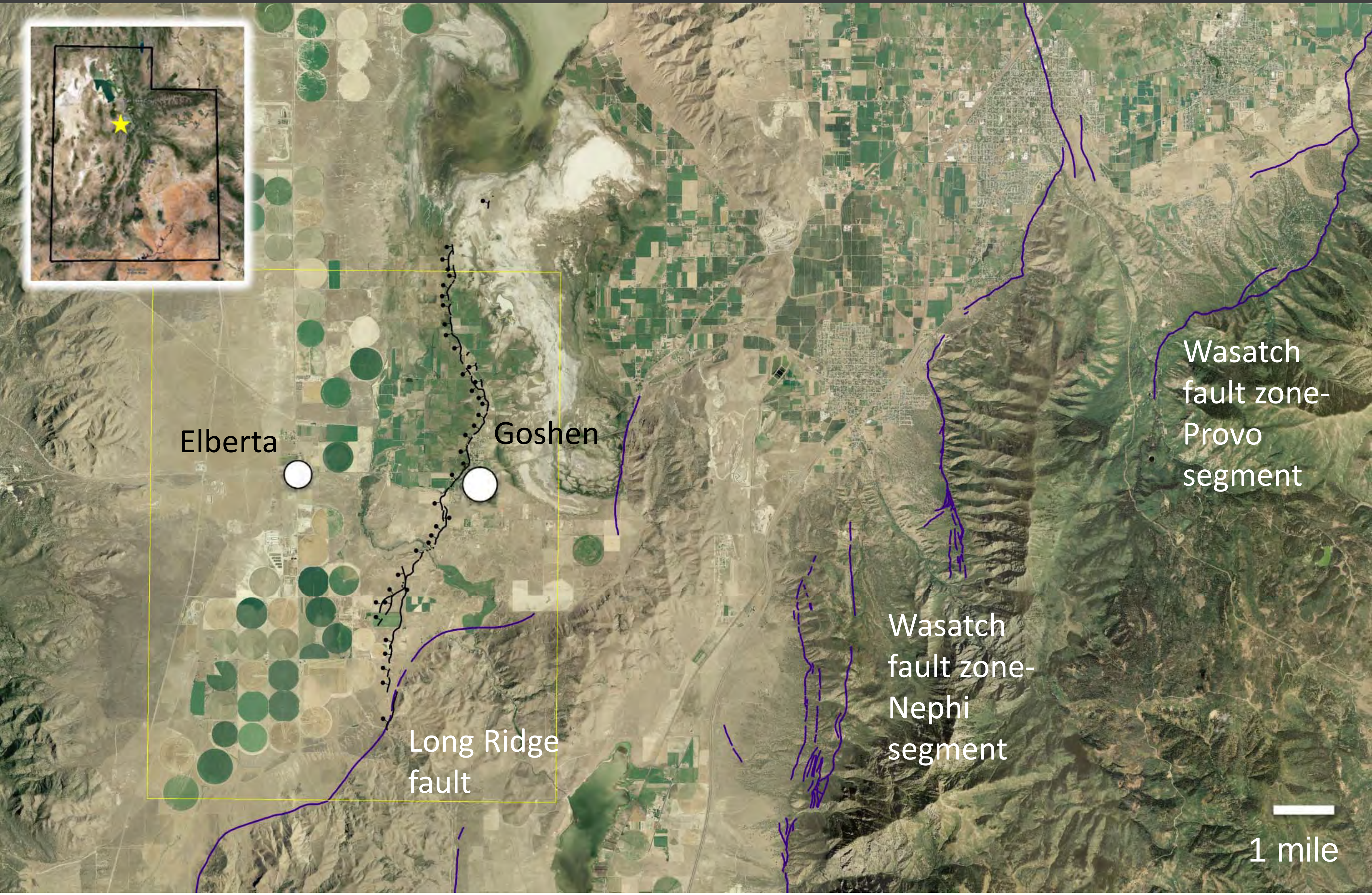
Adam McKean

Stefan Kirby

Location of Goshen Valley

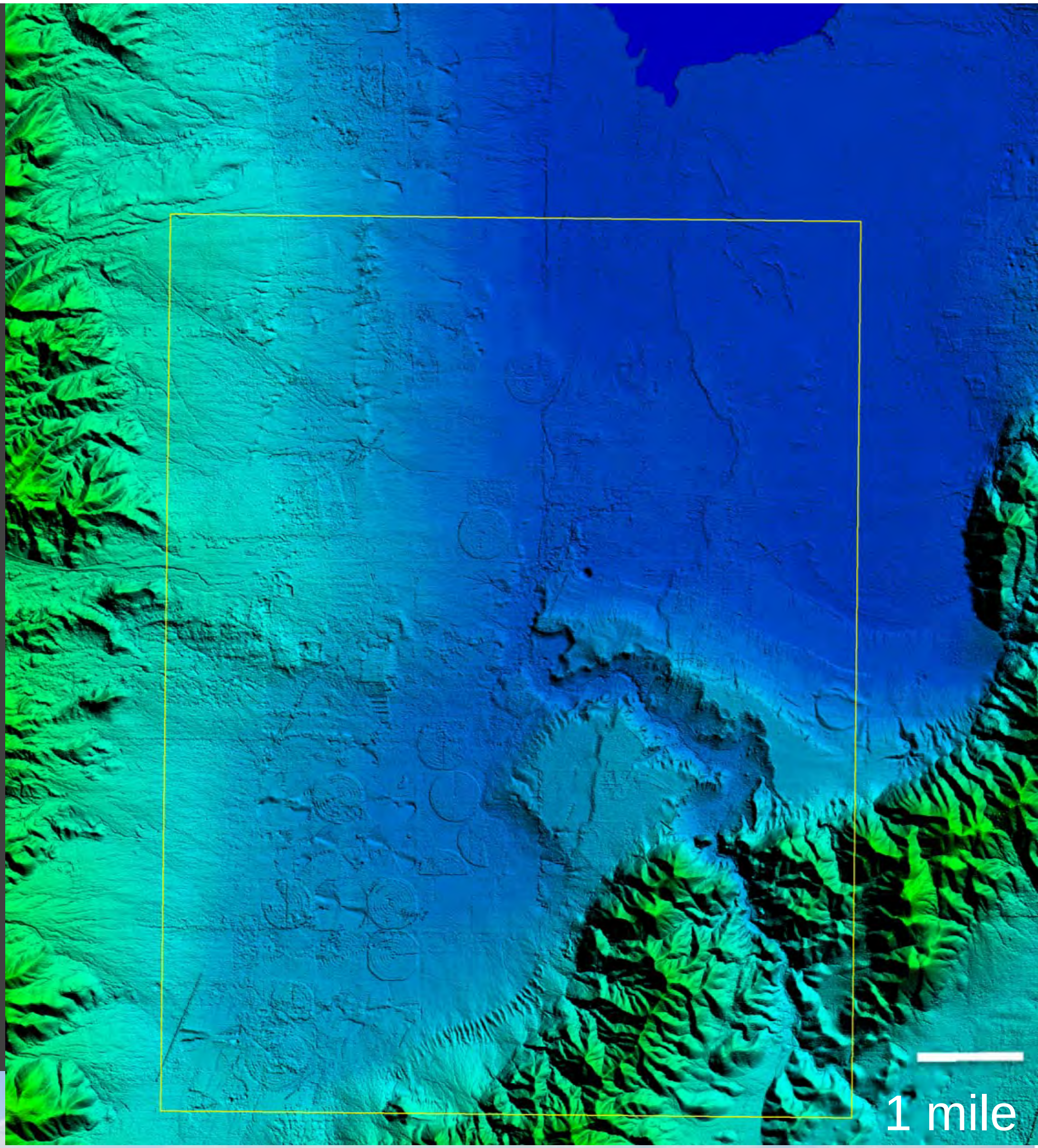


Newly discovered fault

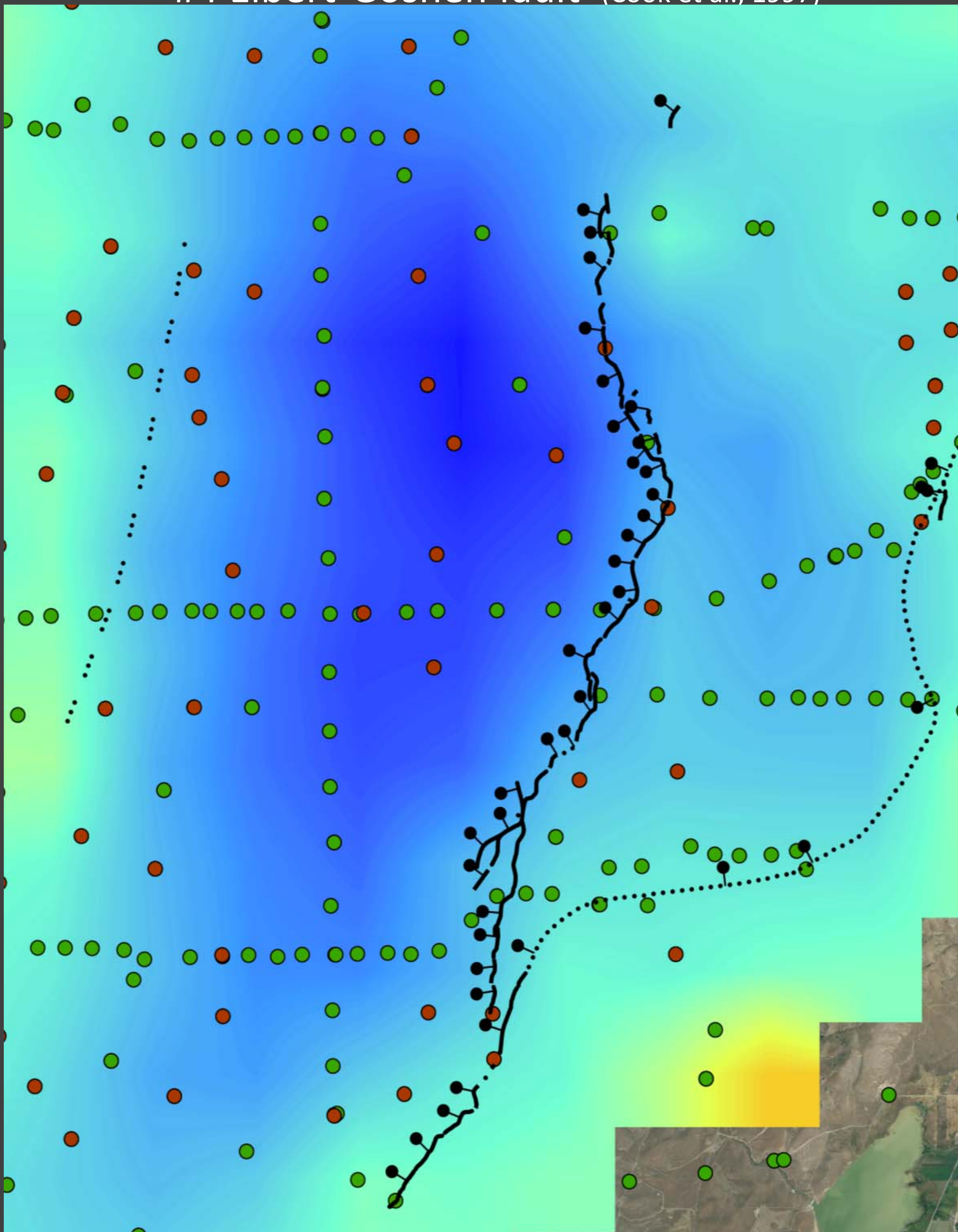


Background

- Previous mapping:
  - Nephi 30′x60′ (Witkind and Wiess, 1991)
  - Goshen 7.5′ (McKean and Solomon, 2012)
- Fault discovered during a hydrogeologic study of Goshen Valley (Kirby)
- 1st recognized on 5 meter auto correlated DEM

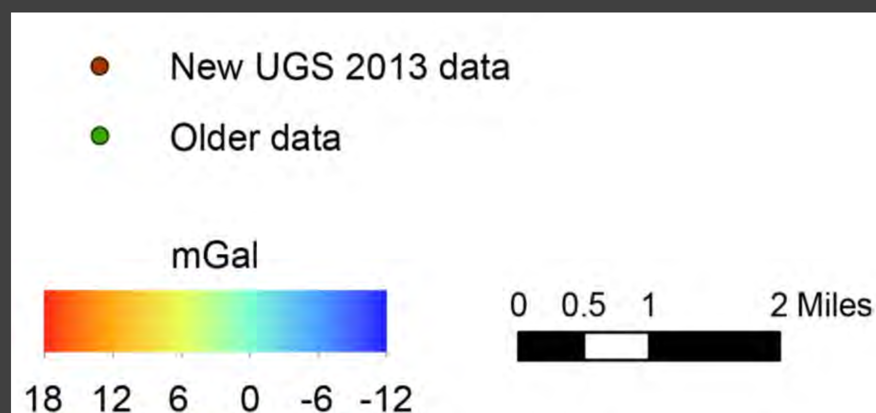


#4 Elbert-Goshen fault (Cook et al., 1997)



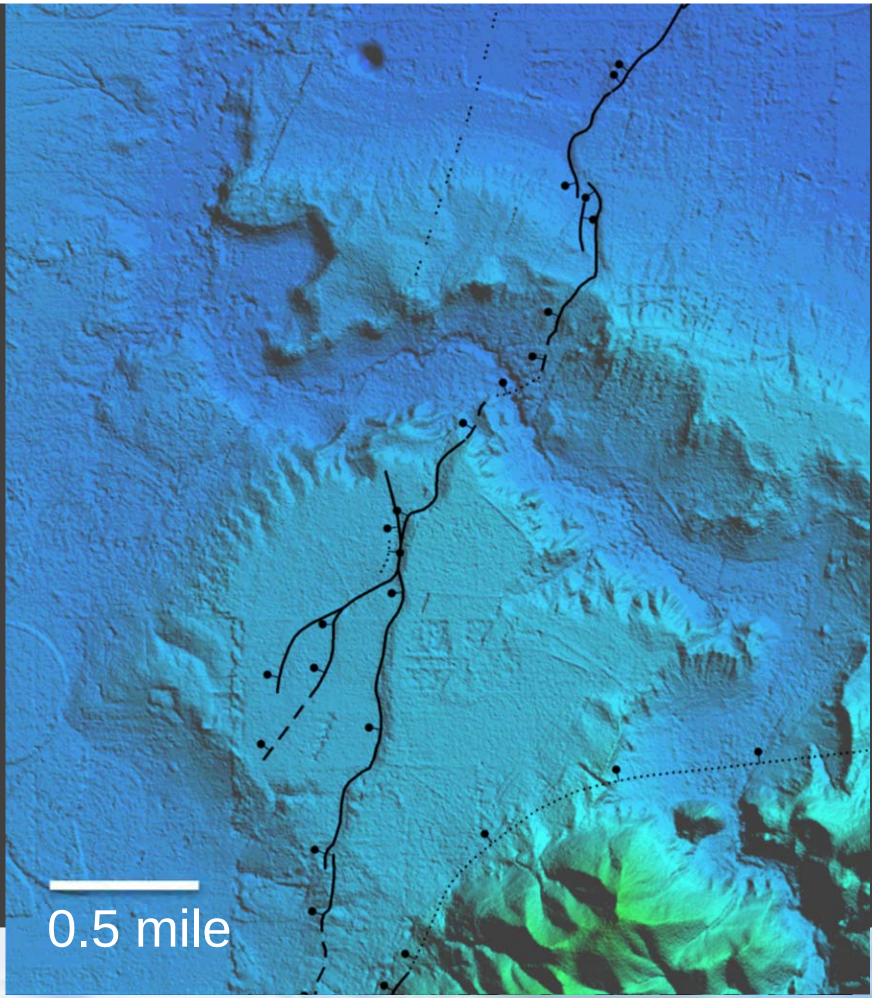
Evidence of faulting (Gravity)

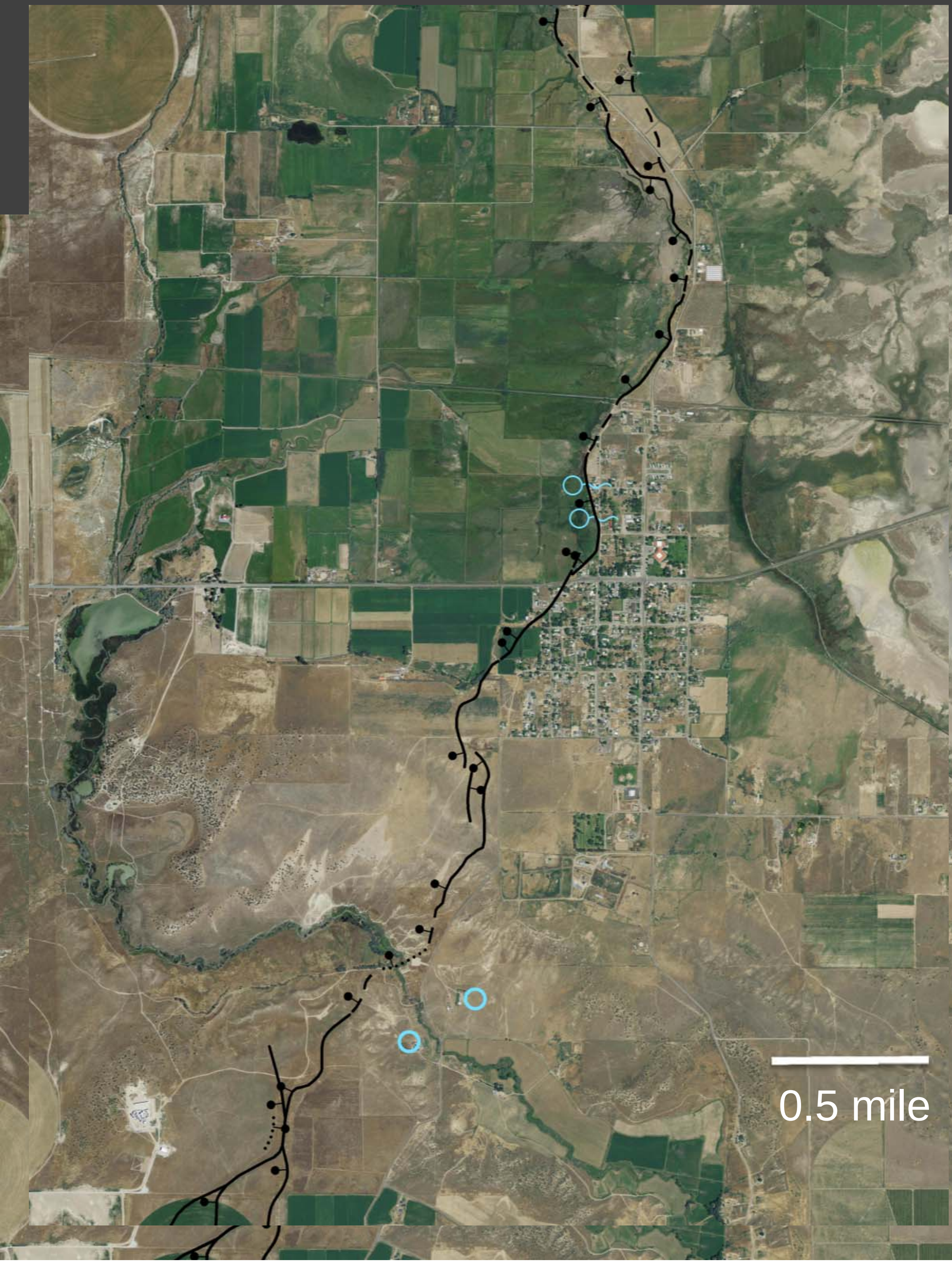
- Older gravity data
  - Elberta-Goshen normal fault, concealed, inferred from gravity data
- New gravity data (UGS, in progress) for Goshen Valley hydrologic study
  - (CBGA residual shown)



Evidence of faulting (Geomorphology)

- Faults cuts across Provo and Bonneville delta at Goshen Canyon
- Faults cuts across topography

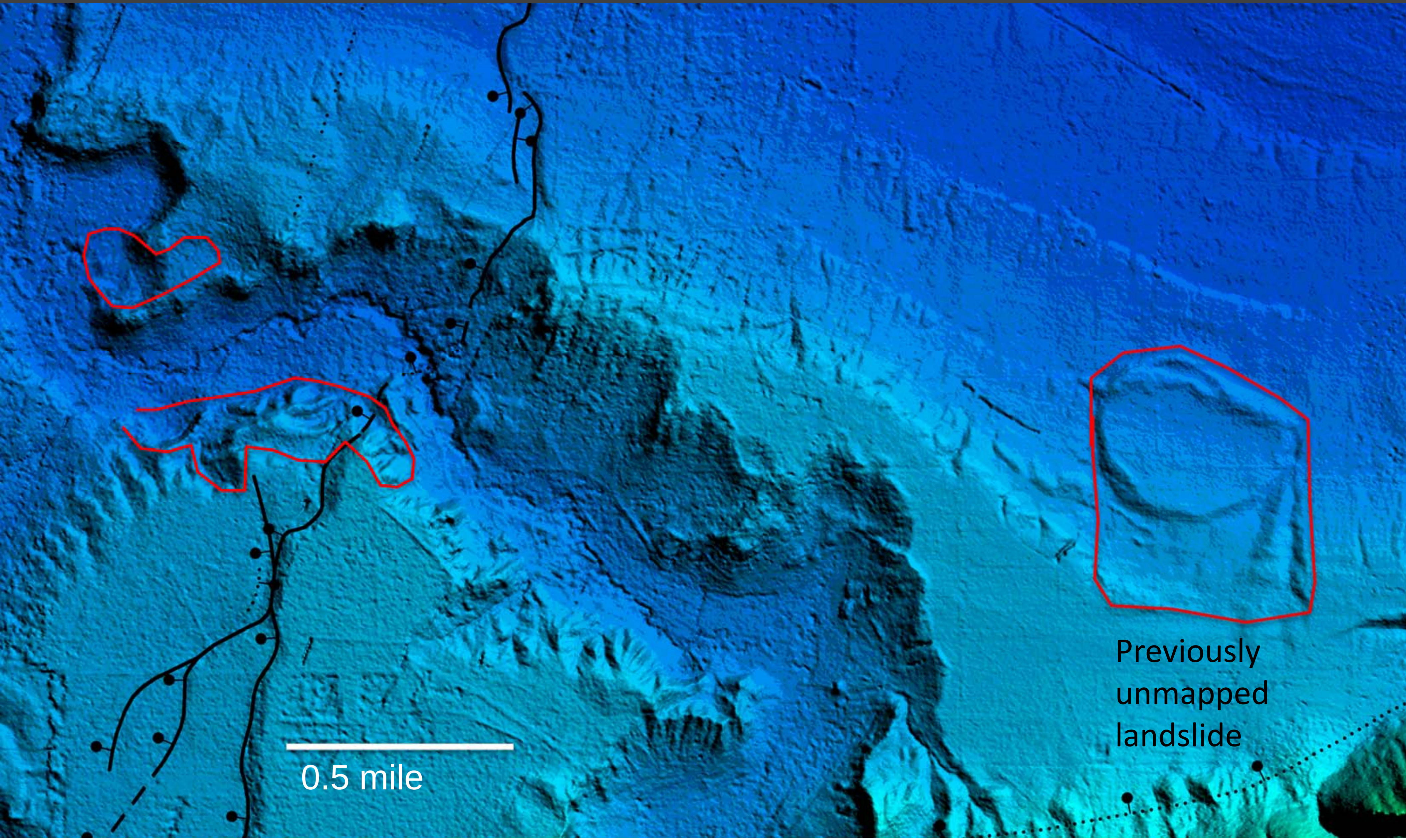




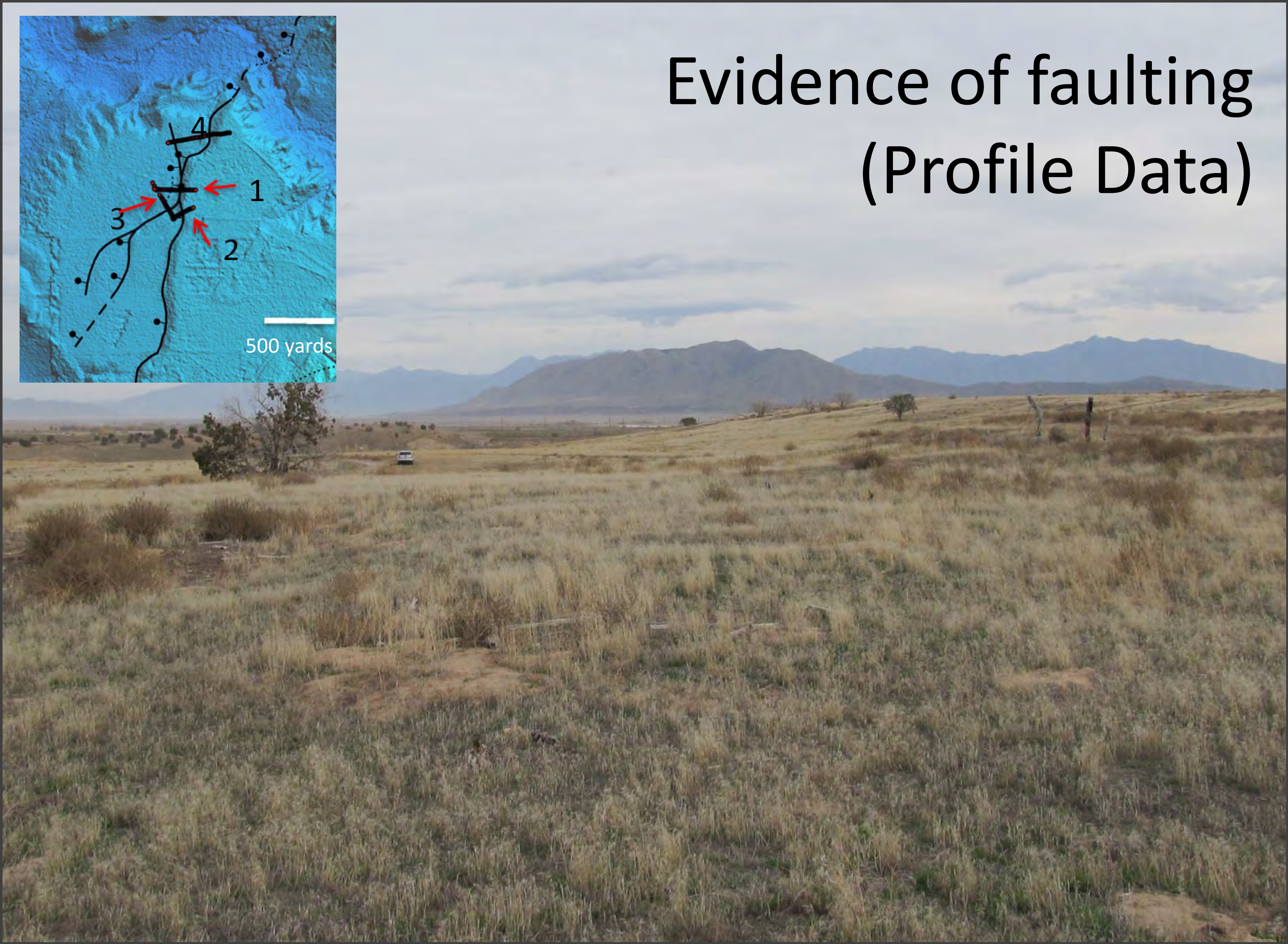
Evidence of faulting (Indirect)

- Springs associated with the fault trace
- Water well data shows offset
  - TD in fractured limestone at 150 ft.
  - Fractured volcanics at 192 ft. to TD
  - Wells directly west of the fault have ~200 ft. to <300 ft. of young basin fill

Evidence of faulting (Indirect-Landslides)



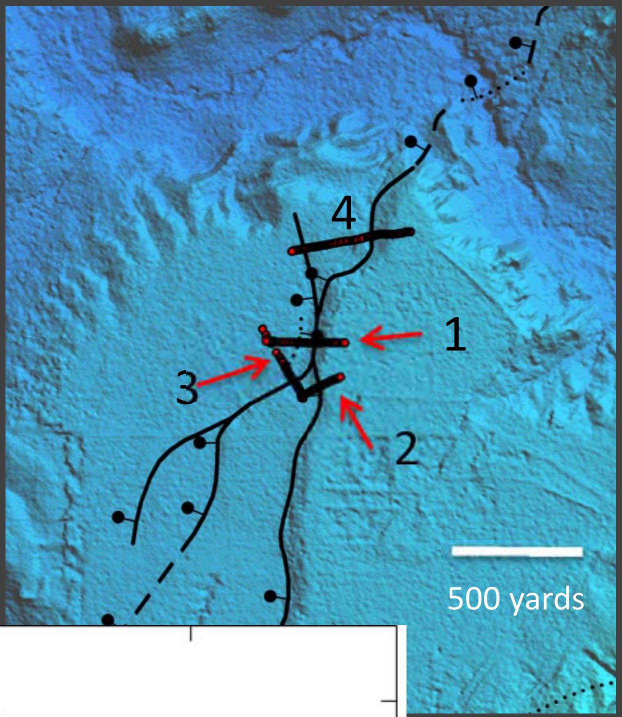
Evidence of faulting (Profile Data)

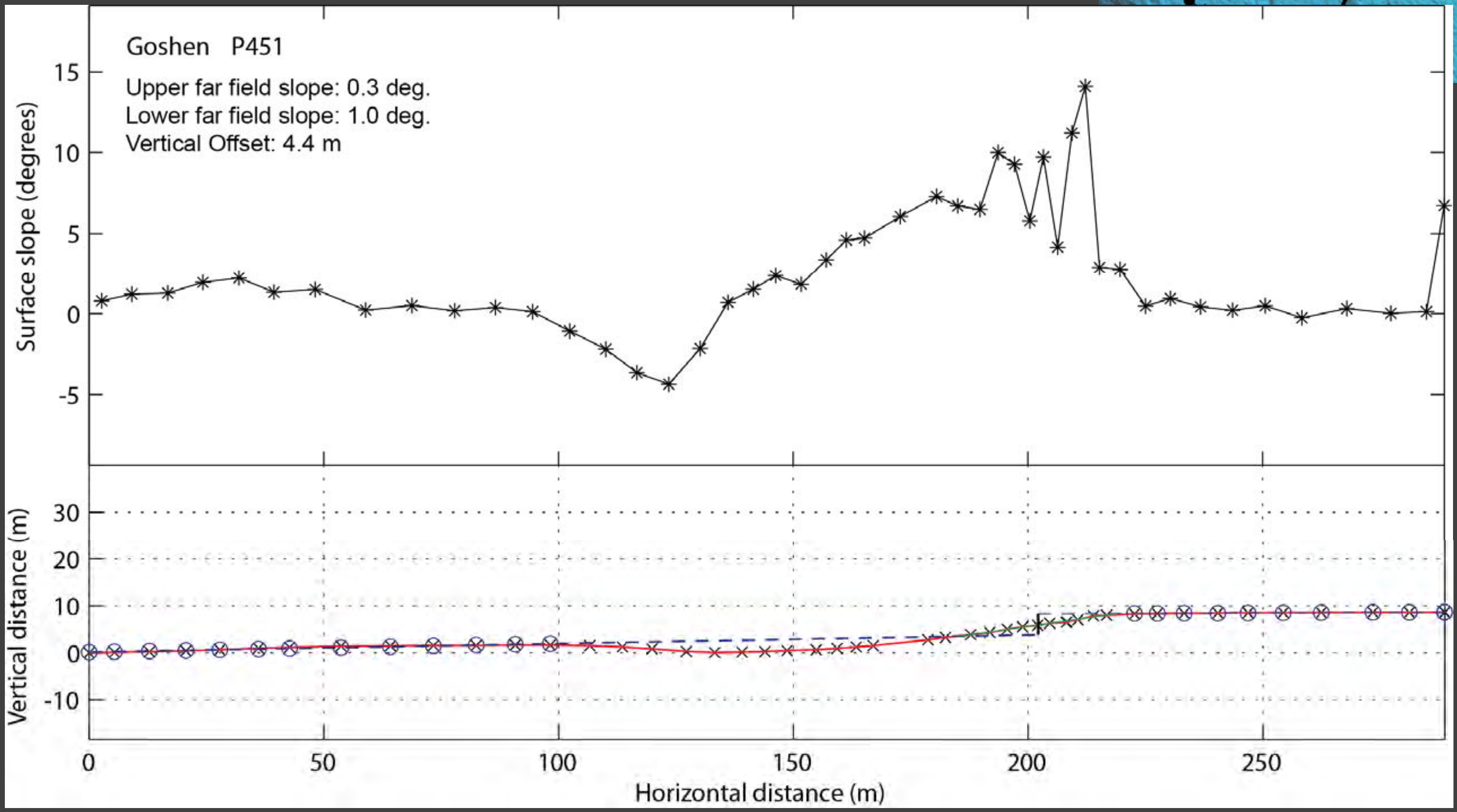


Evidence of faulting (Profile data)

- Fault scarp data (Vertical displacement calculations)

Profile 1 = 4.2 to 4.8 m





Evidence of faulting (Profile data)

- Fault scarp data (Vertical displacement calculations)

Profile 1 = 4.2 to 4.8 m

Profile 2 = 2.8 m

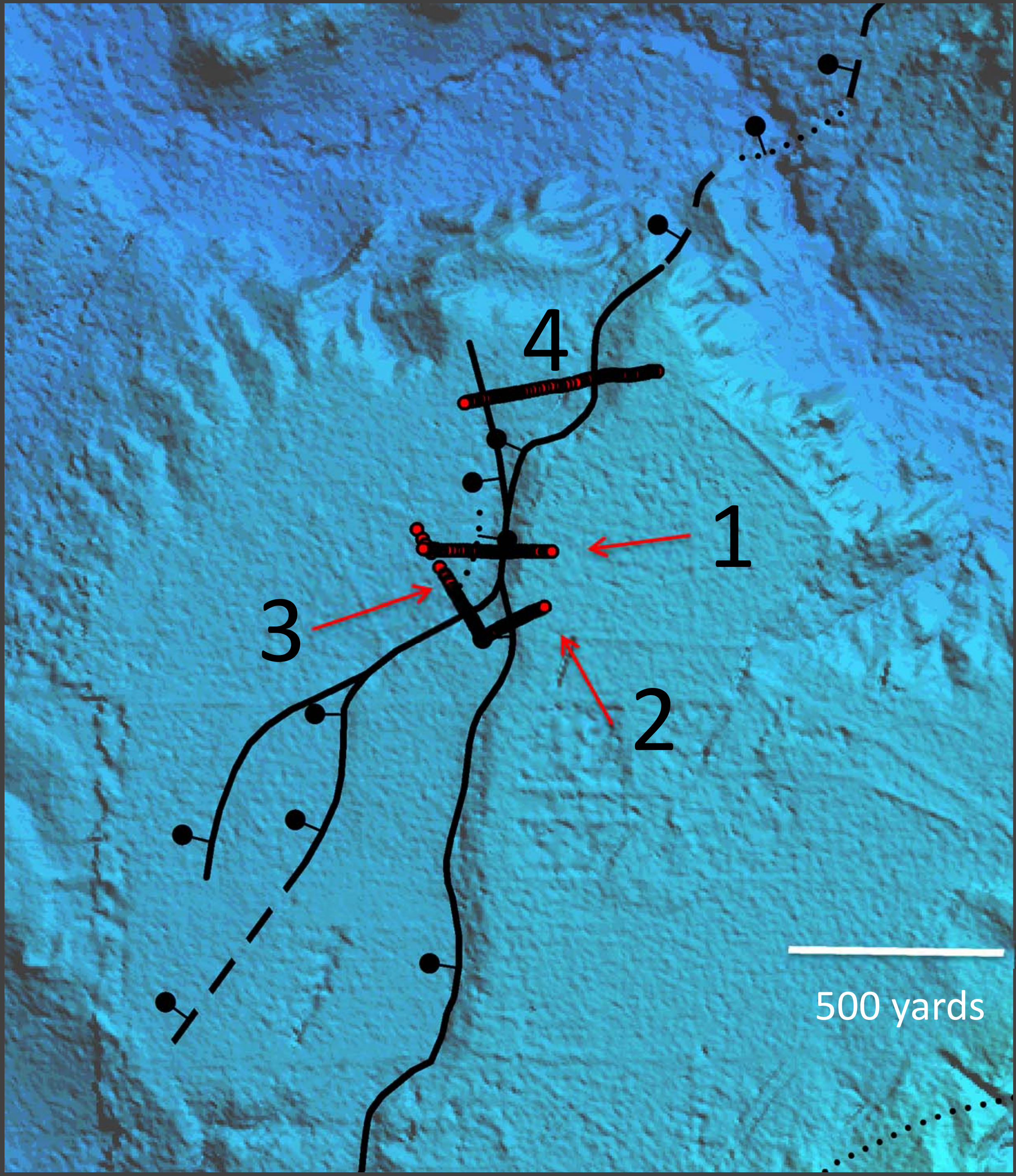
Profile 3 = 1.9 m

Profile 4 west = 2.1 m

Profile 4 east = 6.2 m

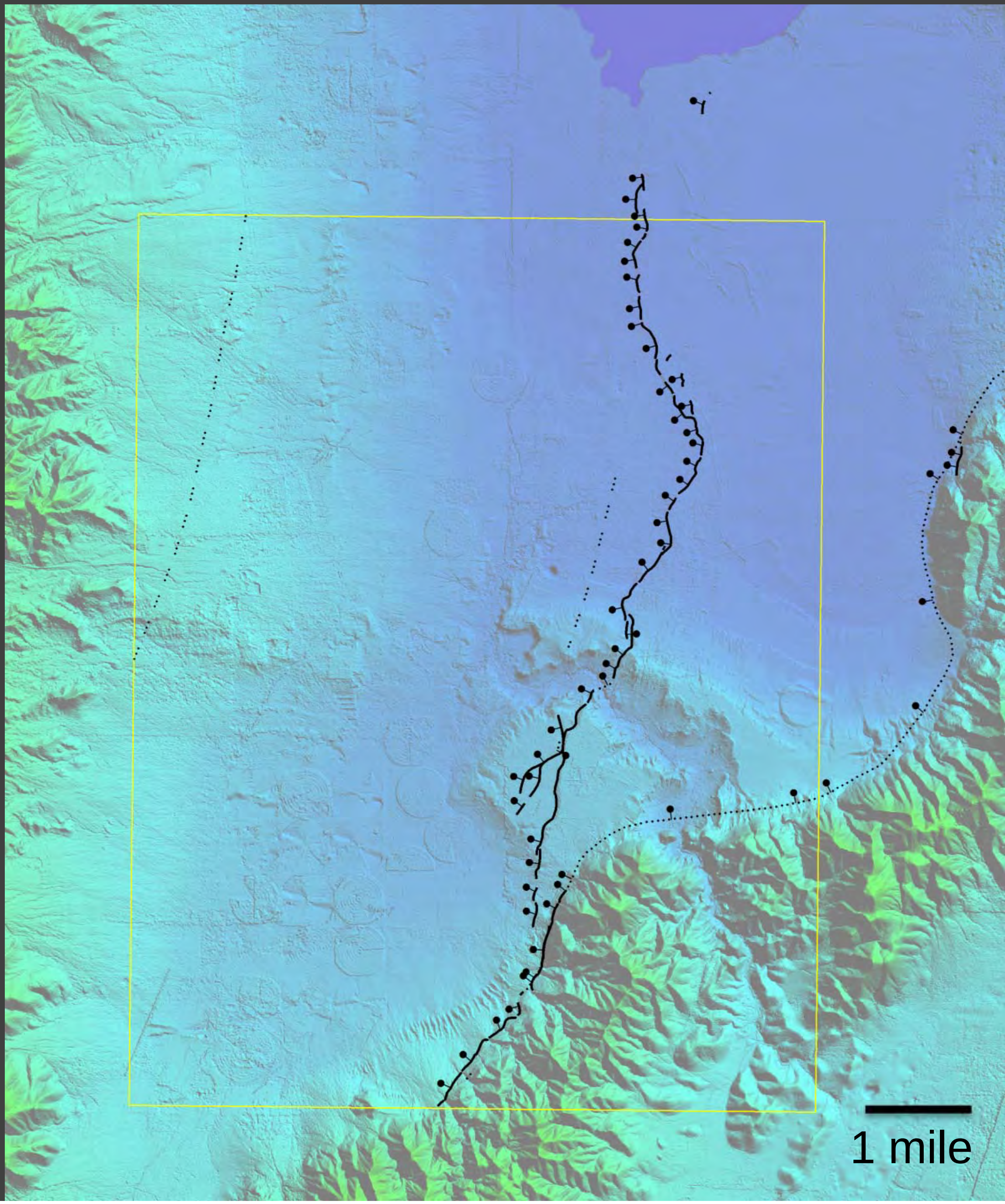
Profile 5 = 2.4 m

(to the north)

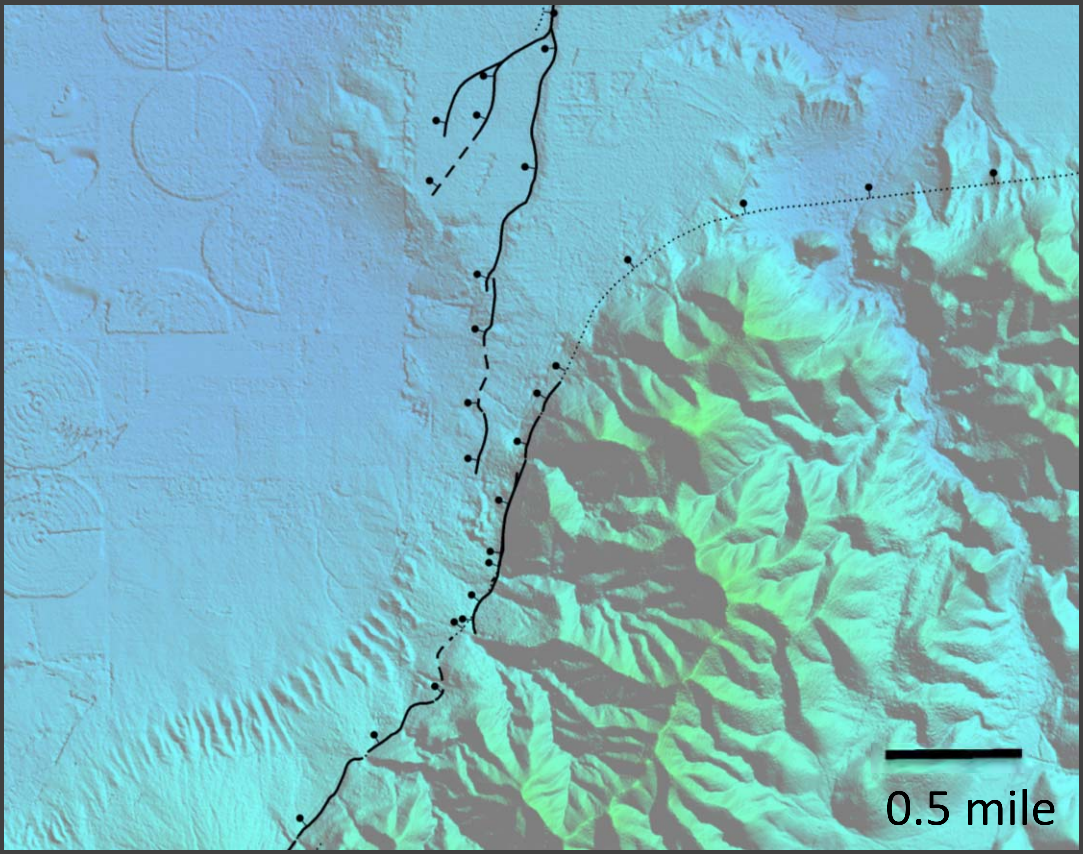


Surface fault rupture length

- Fault located at a bend in Long Ridge
- Long Ridge fault (Holocene active <15,000 years)
- Length 7.3 miles (maybe up to 8.3 miles)



Does the Goshen Fault connect with the Long Ridge fault?



- Similar post-Bonneville age (Currently listed age of faulting in USGS database <1.6 Ma)
- Lack of Long Ridge fault trace east of Current Creek
- Do the two faults share a same surface fault rupture event?

Does the Goshen fault connect with Utah Lake faults?

- Draft 0.5 m 2013 LiDAR along Utah lake
- Fault scarps strike towards lake, but are concealed by Utah Lake highstand sediments
- Approximately 4 to 5 miles separate the Goshen and Utah Lake faults

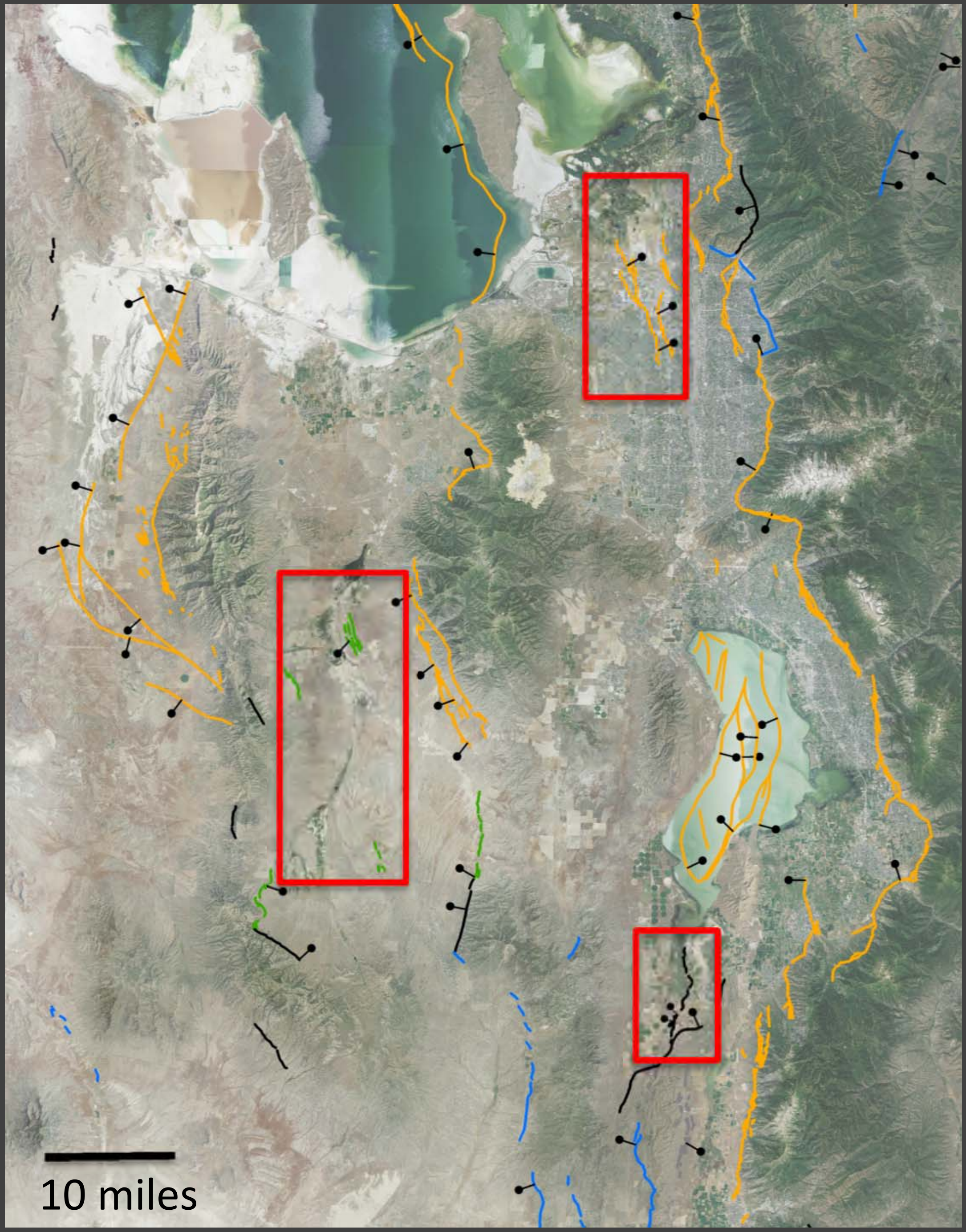
Summary of evidence

- Age = post-Bonneville and pre-Utah Lake highstands
- Length = 7.3 miles (up to 8.3 miles)
- Vertical displacement = between 1.9 to 6.2 m
- Other evidence = gravity data, springs, well data, landslides

- Potential moment magnitude (M) calculation from surface fault rupture length
  – Wells and Coppersmith (1994), M= 6.3 to 6. 4
  – Wesnousky (2008), M = 6.4 to 6.6
  – Stirling et al. (2002), M= 6.7 to 6.8

How common are basin floor faults?

- Other examples
  - Rush Valley basin floor faults (Kirby, 2012, 2013a, 2013b, and 2013c)
  - West Valley fault zone (Granger and Taylorsville) (Keaton and others, 1987; Keaton and Currey, 1989; DuRoss and Hylland, 2012; Hylland and others, in press; and McKean and Hylland, 2013)
- More work needs to be done to understand and map these type of faults
- How many more are out there ready to be discovered?

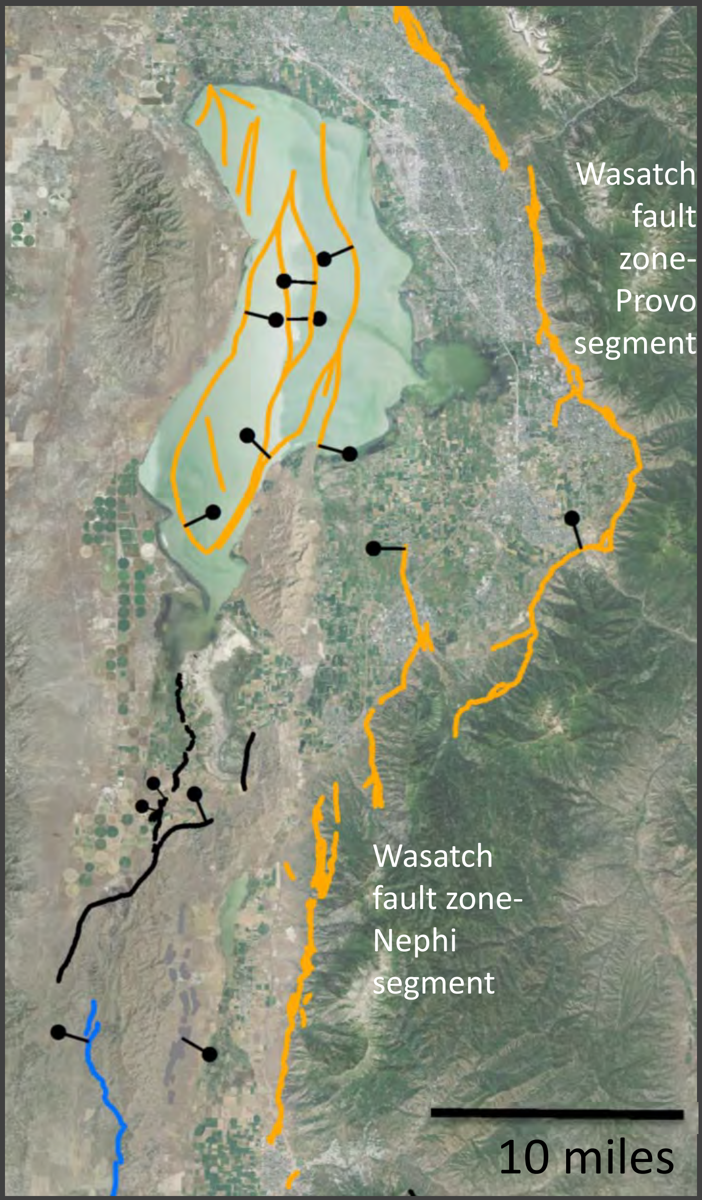


Conclusion: Local Goshen Impacts

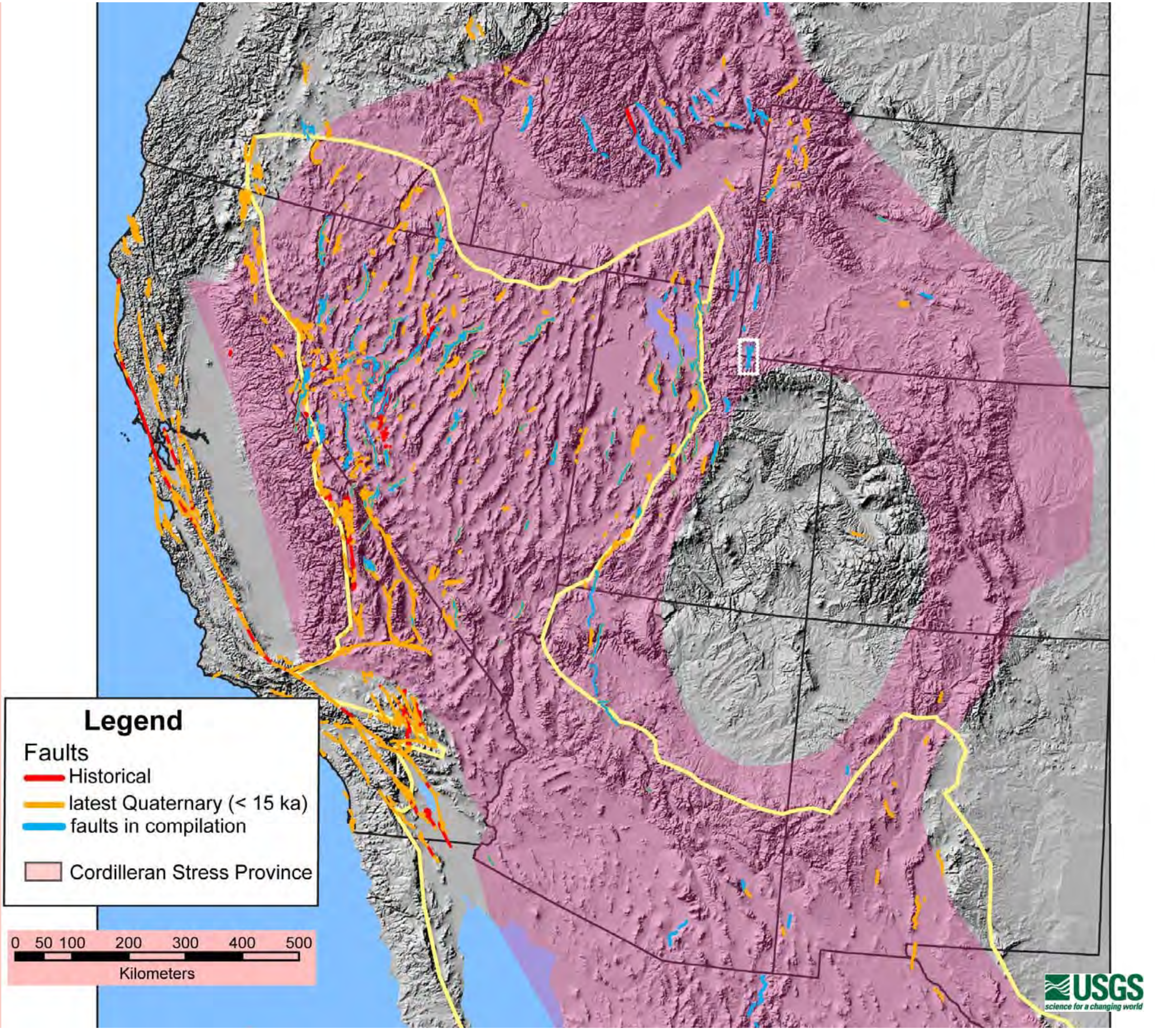
- Geologic hazards awareness and mapping:
  - Surface fault rupture potential
  - Ground shaking potential
  - Liquefaction potential
  - Landslide potential
  - Building code/City planning adjustments needed?
- Development and infrastructure
  - West Utah Lake highway plan
  - Residential or commercial development
  - Natural gas pipeline and power line corridor

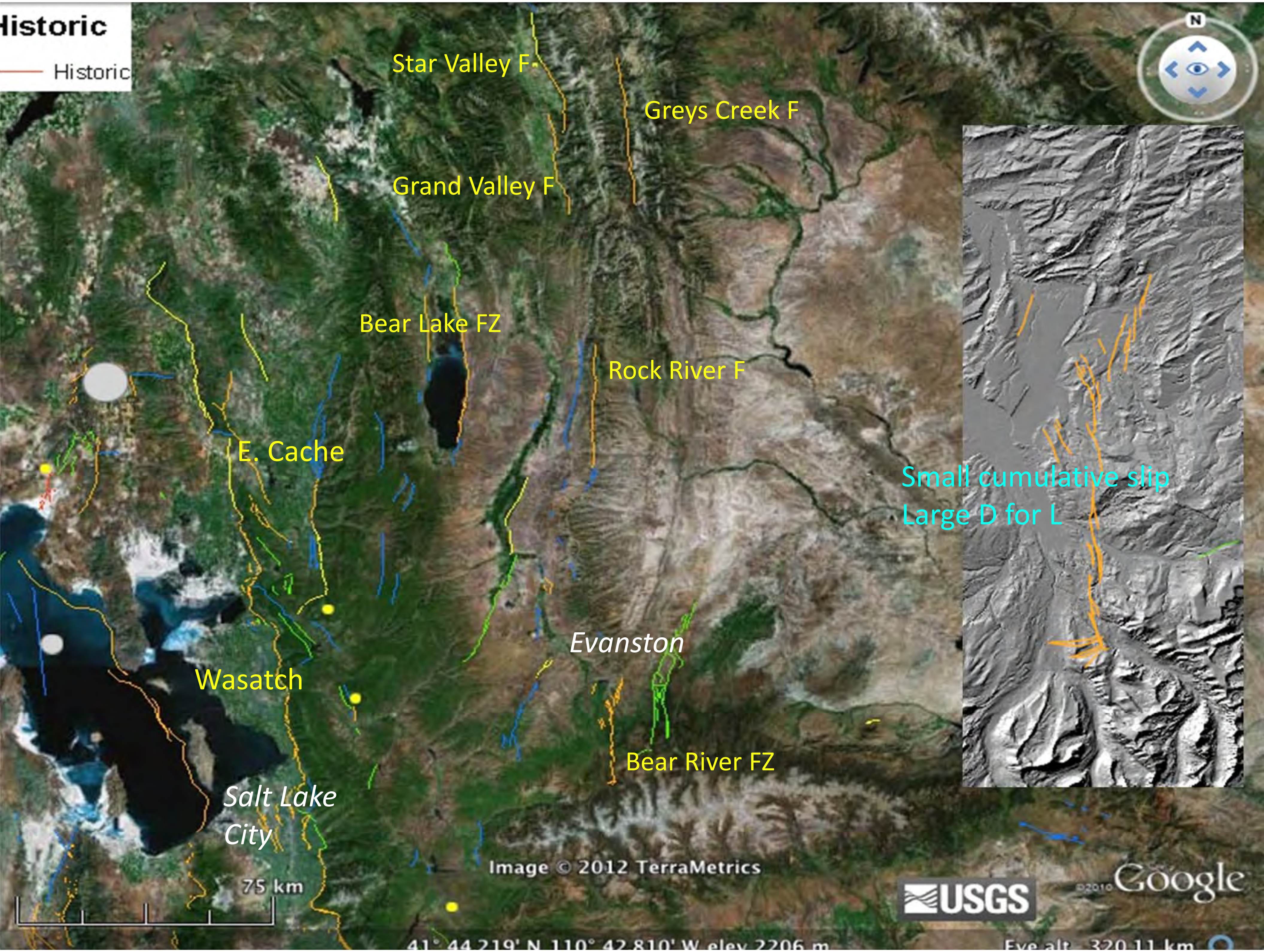
Conclusion

- Implication of new Goshen basin floor fault for modeling
  - How do GPS horizontal loading rates compare with measured vertical displacement ?
  - Is there a gap that this fault could help explain?

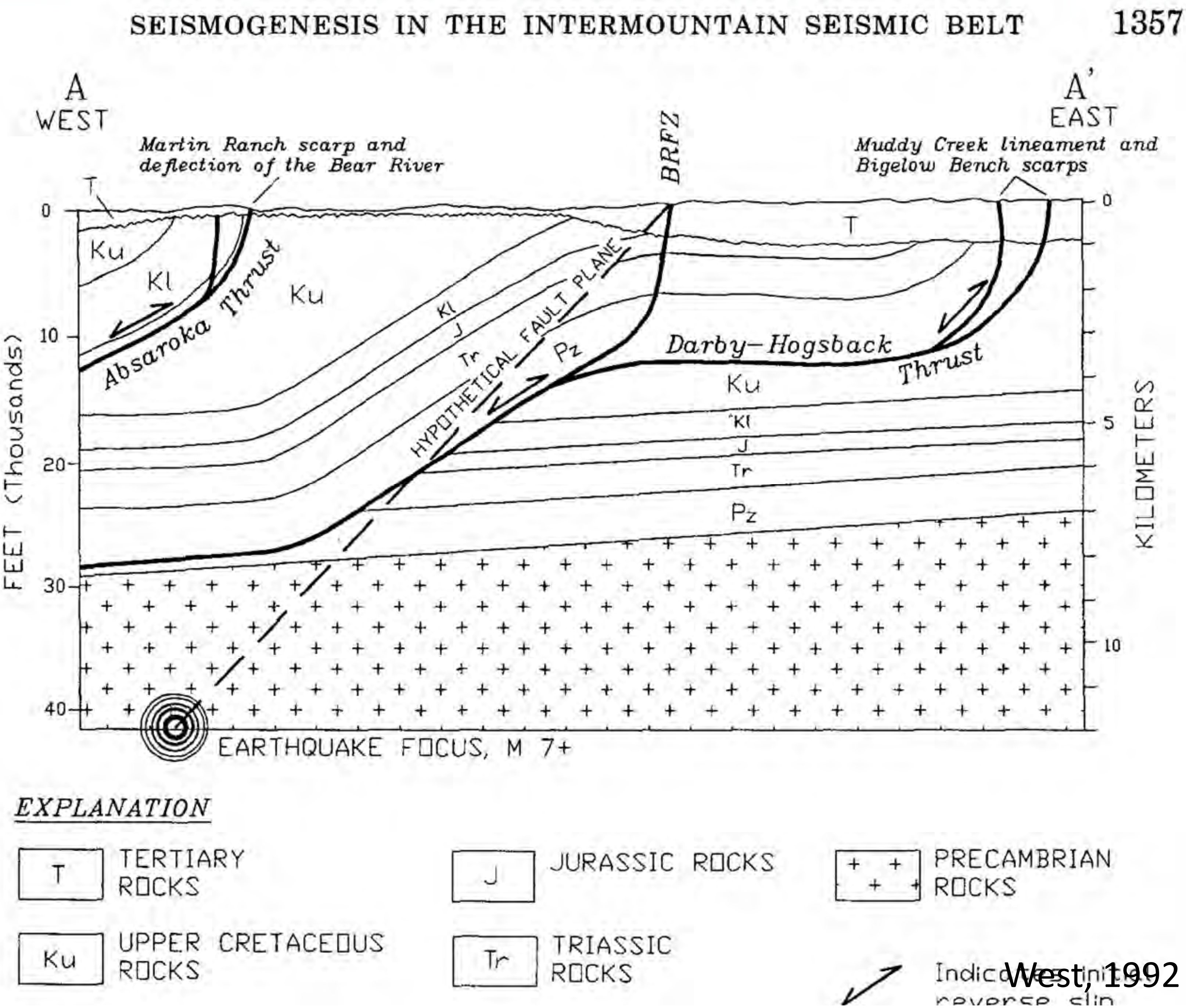



The Bear River Fault Zone, Wyoming and Utah:
Complex Ruptures on a Young Normal Fault
U.S. Geological Survey
Utah Geological Survey
Reactivation
Recurrence
Rupture complexity
Future behavior

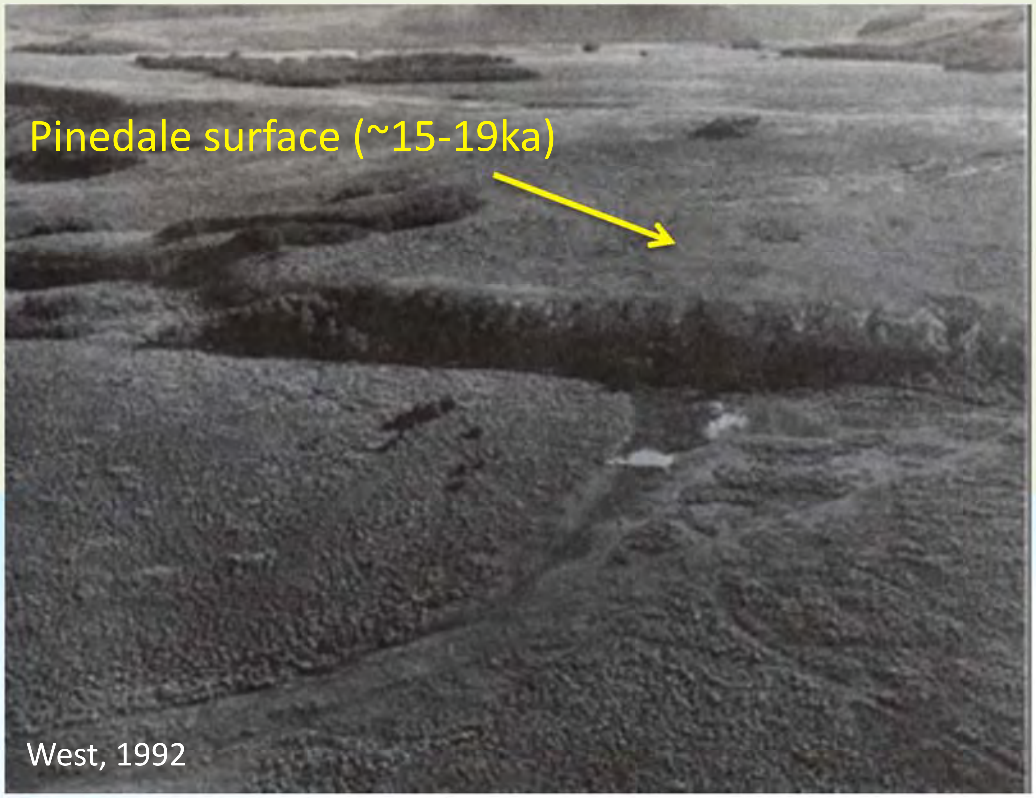

Legend
Faults
Historical
latest Quaternary (< 15 ka)
faults in compilation
Cordilleran Stress Province
0 50 100 200 300 400 500
Kilometers
USGS
science for a changing world


Historic
Historic
Star Valley F
Greys Creek F
Grand Valley F
Bear Lake FZ
Rock River F
E. Cache
Small cumulative slip
Large D for L
Evanston
Wasatch
Bear River FZ
Salt Lake
City
Image © 2012 TerraMetrics
75 km
USGS
©2010 Google
41° 44.219' N 110° 42.810' W elev 2206 m
Eye alt 320.11 km

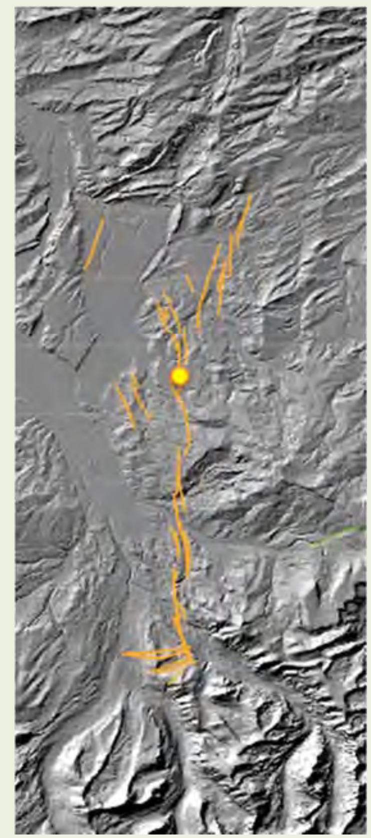
Reactivation of Laramide thrust faults



West, 1992


Pinedale surface (~15-19ka)
West, 1992


Eocene Wasatch Fm.



USGS
science for a changing world

Bear River Fault Zone: Lester Ranch (West, 1973)

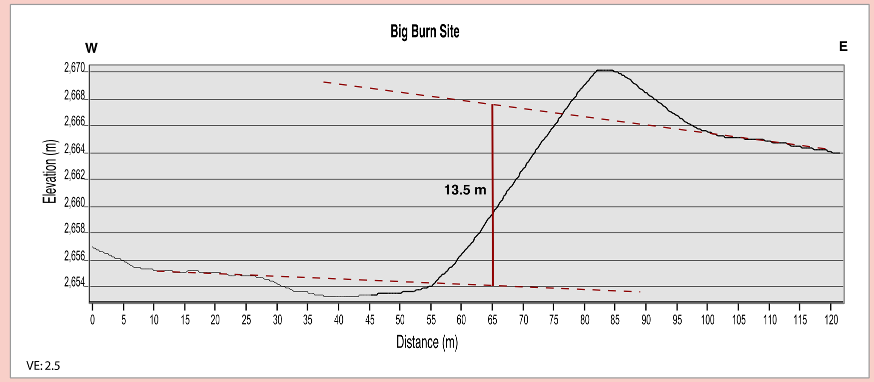
2 surface ruptures:

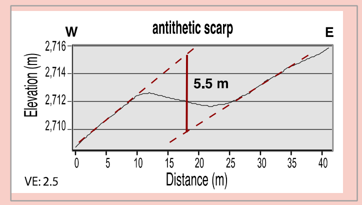
2.4 ± 1.1 ka

4.6 ± 0.7 ka

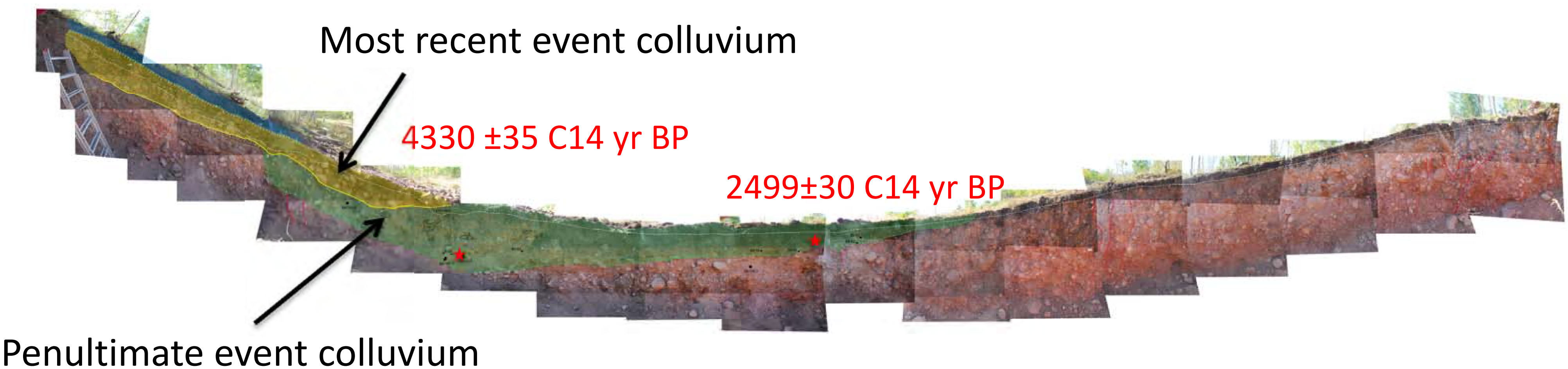
Bear River Fault Zone

Big Burn Site



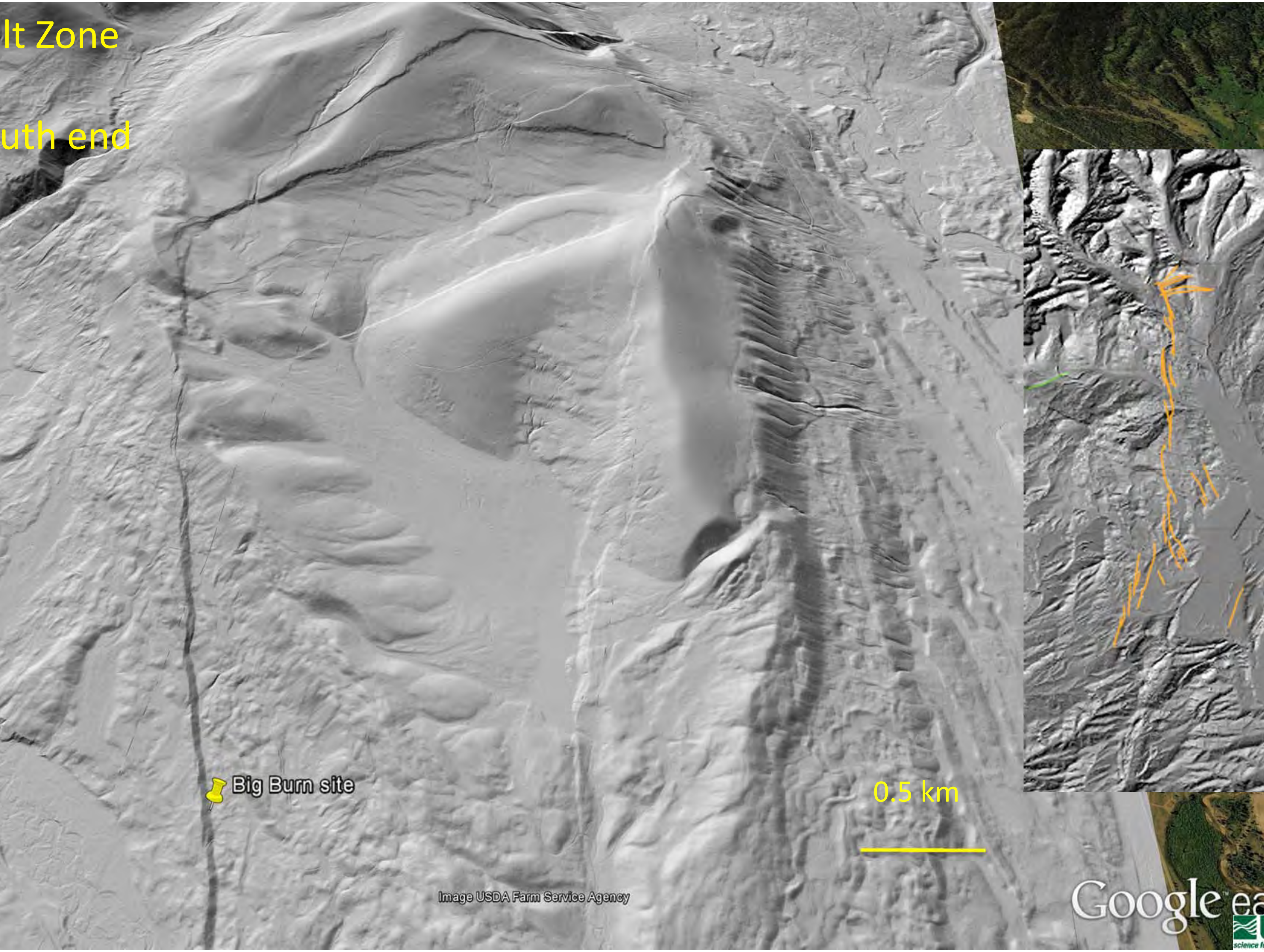


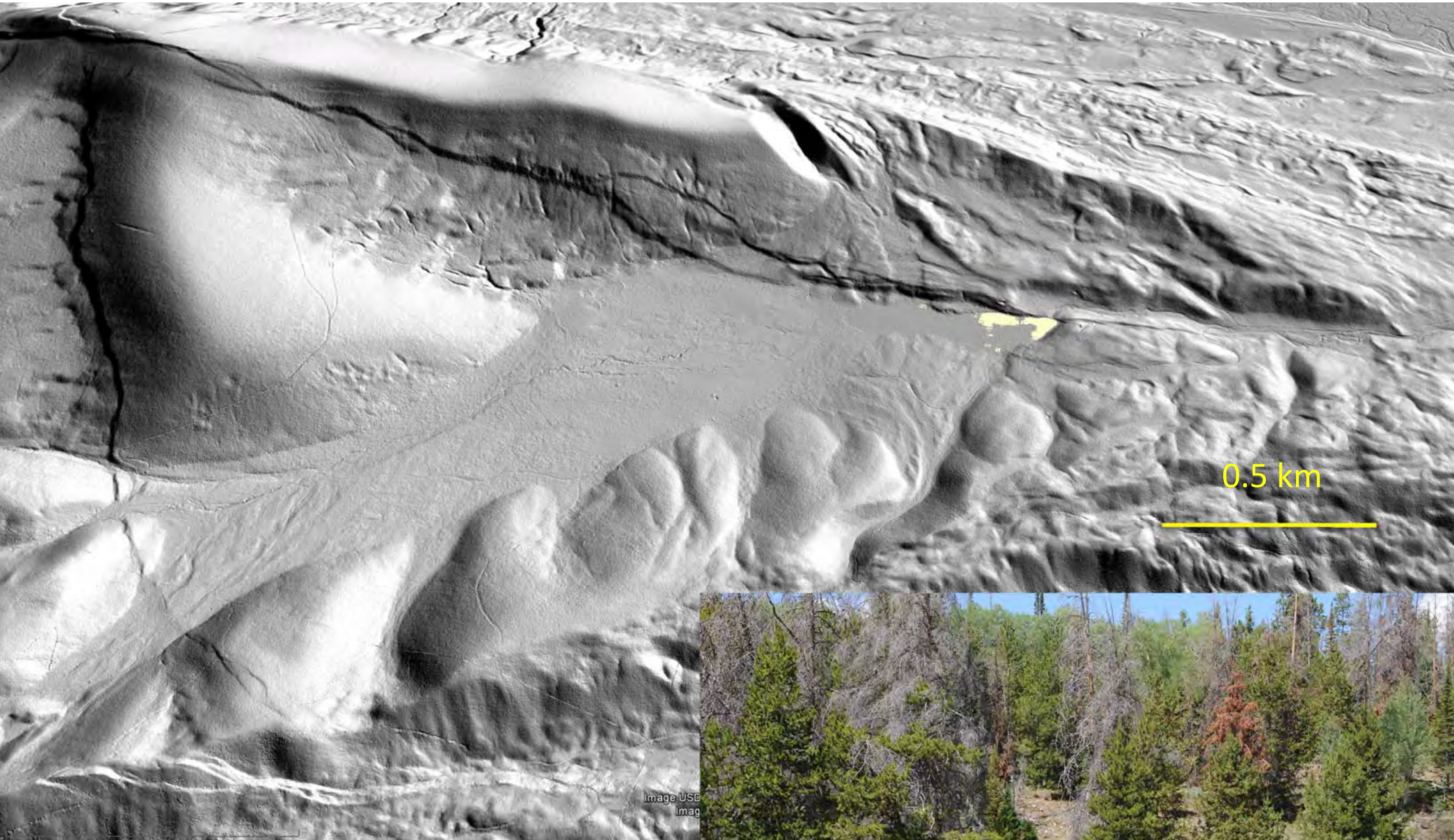
NTVD ~ 8 m (max)



lt Zone

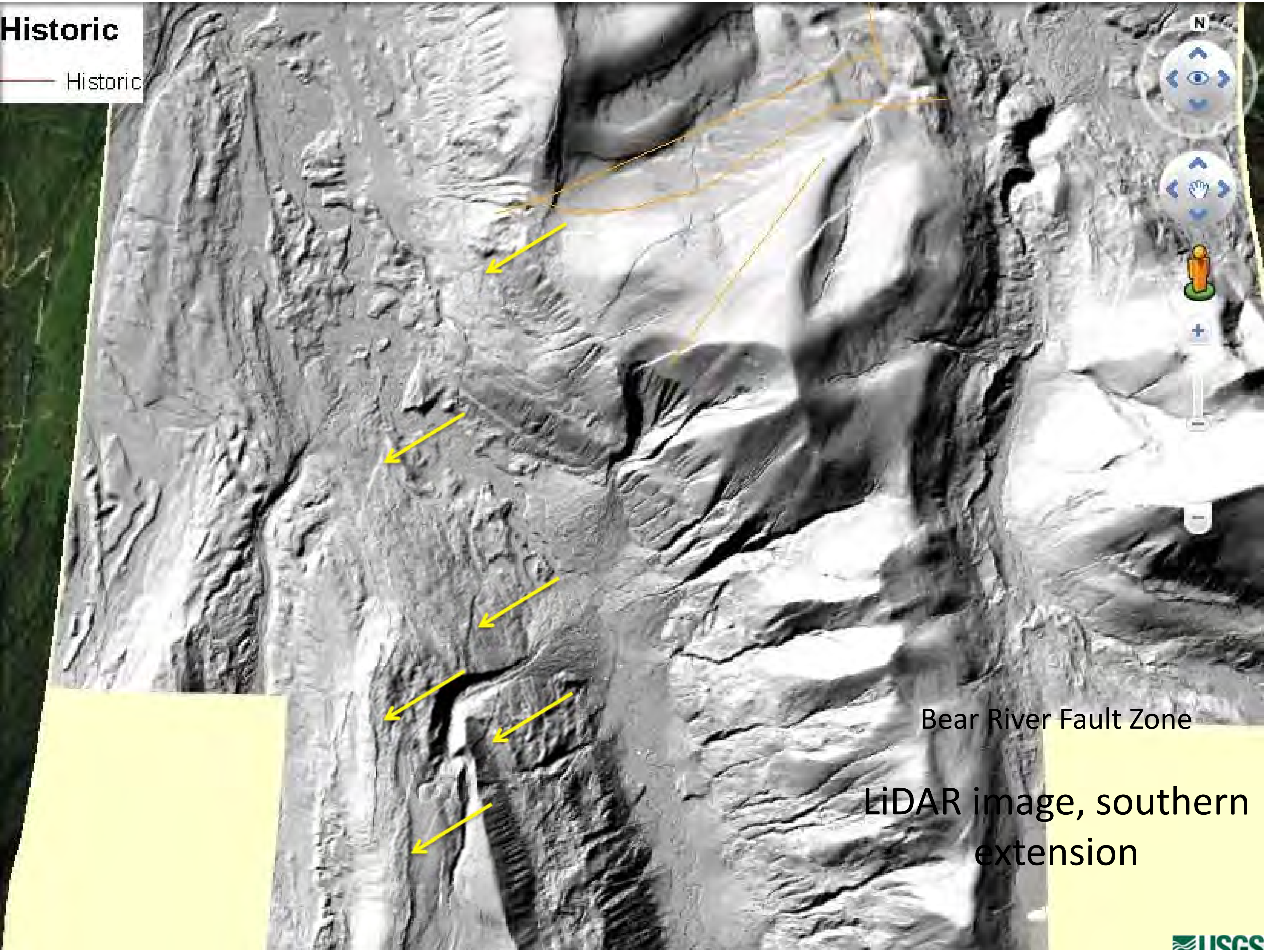
uth end

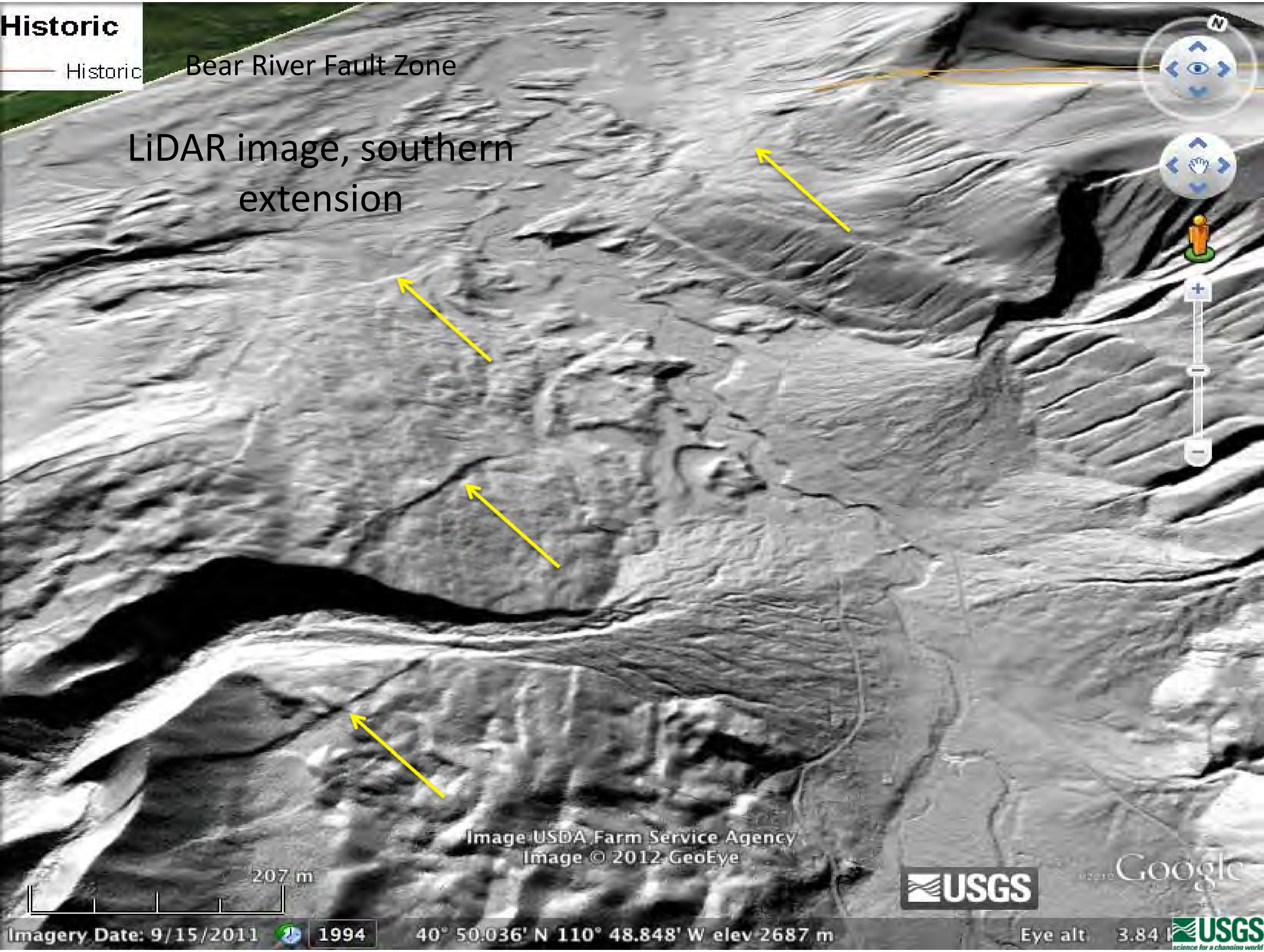


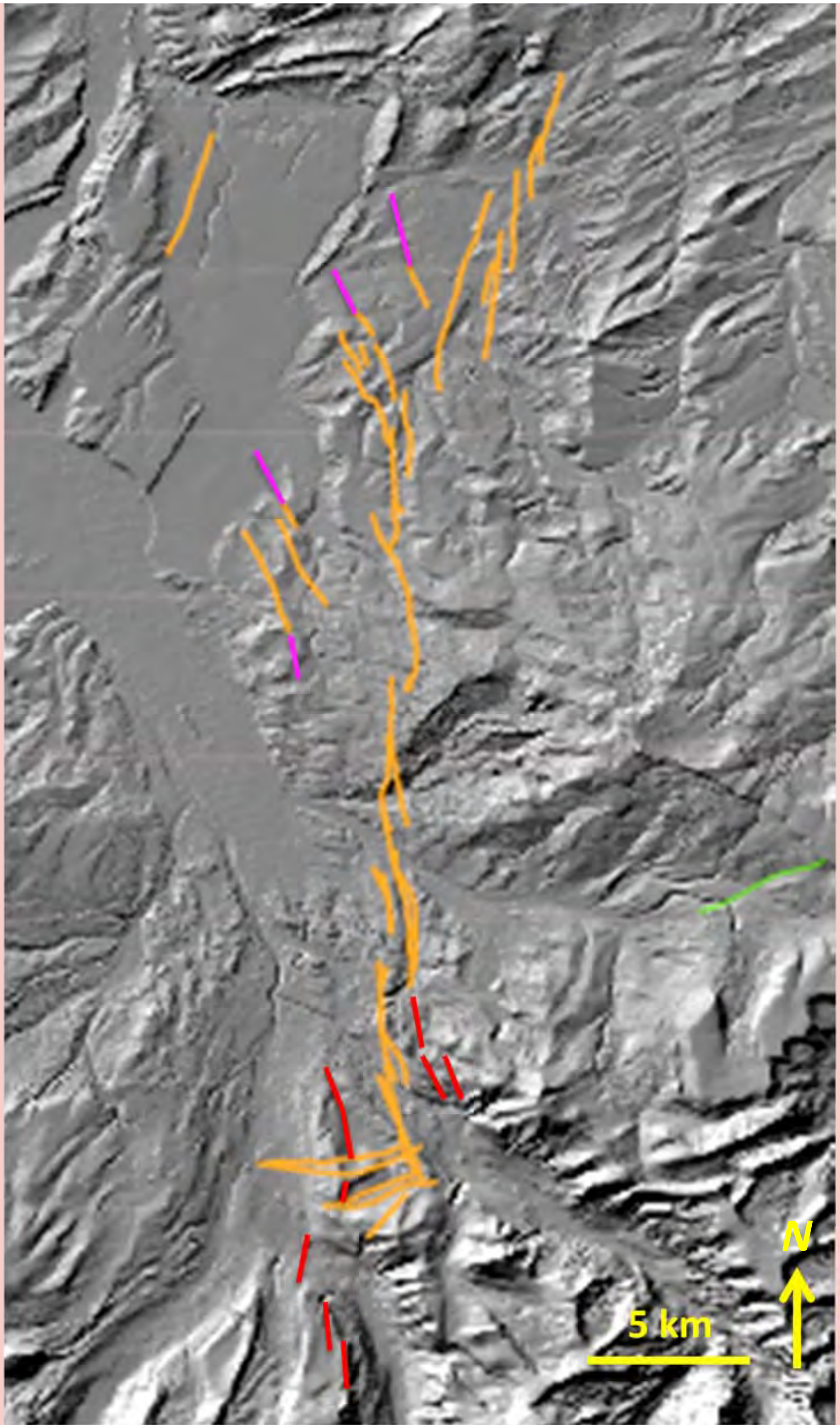


Bear River Fault Zone

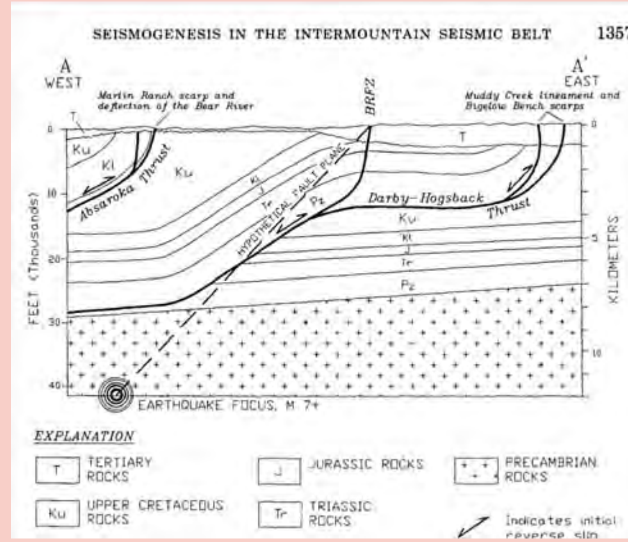
LiDAR view, antithetic scarps


Historic
Historic
N
Bear River Fault Zone
LiDAR image, southern extension


Historic
Historic
Bear River Fault Zone
LiDAR image, southern extension
Image USDA Farm Service Agency
Image © 2012 GeoEye
207 m
USGS
Google
Imagery Date: 9/15/2011
1994
40° 50.036' N 110° 48.848' W elev 2687 m
Eye alt
USGS
science for a changing world



BEAR RIVER FAULT ZONE



Extensional reactivation of thrust faults

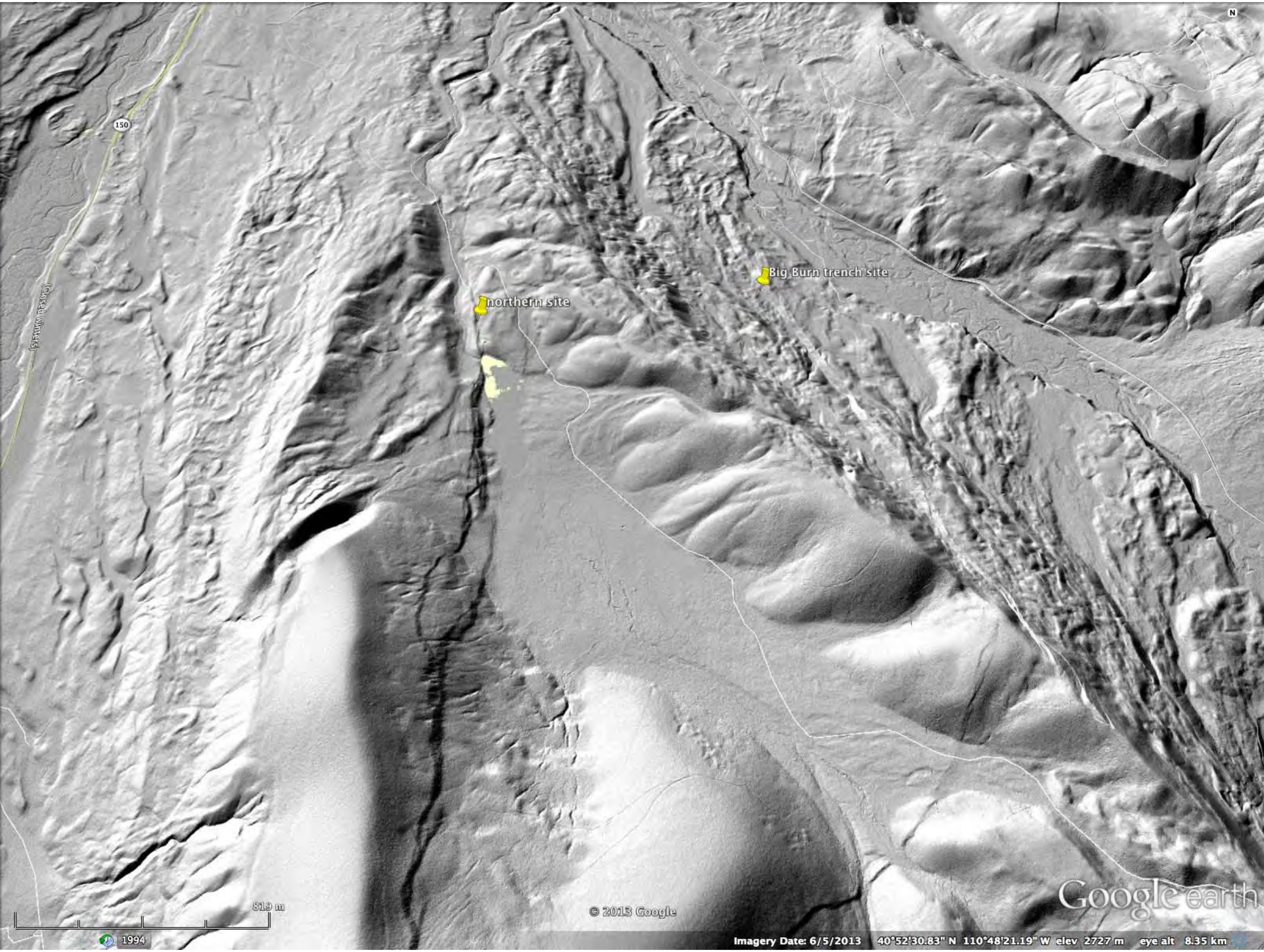
Total surface rupture length 40 Km

Large displacement, high stress drop; near-fault distortion, antithetic faulting complicate net slip

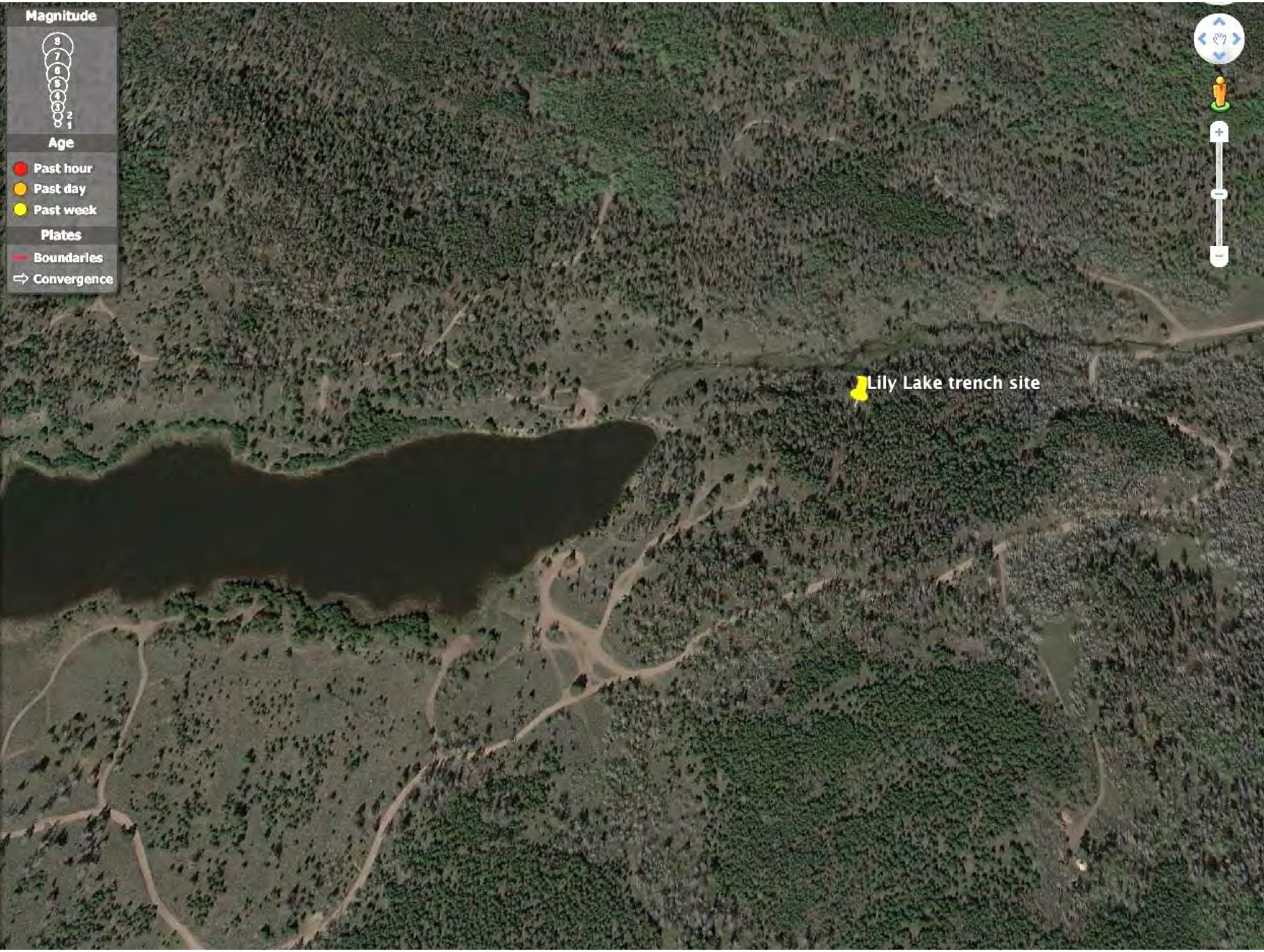
Complex rupture pattern that has largely repeated across zone up to 5km wide

No geomorphic expression pre-Holocene

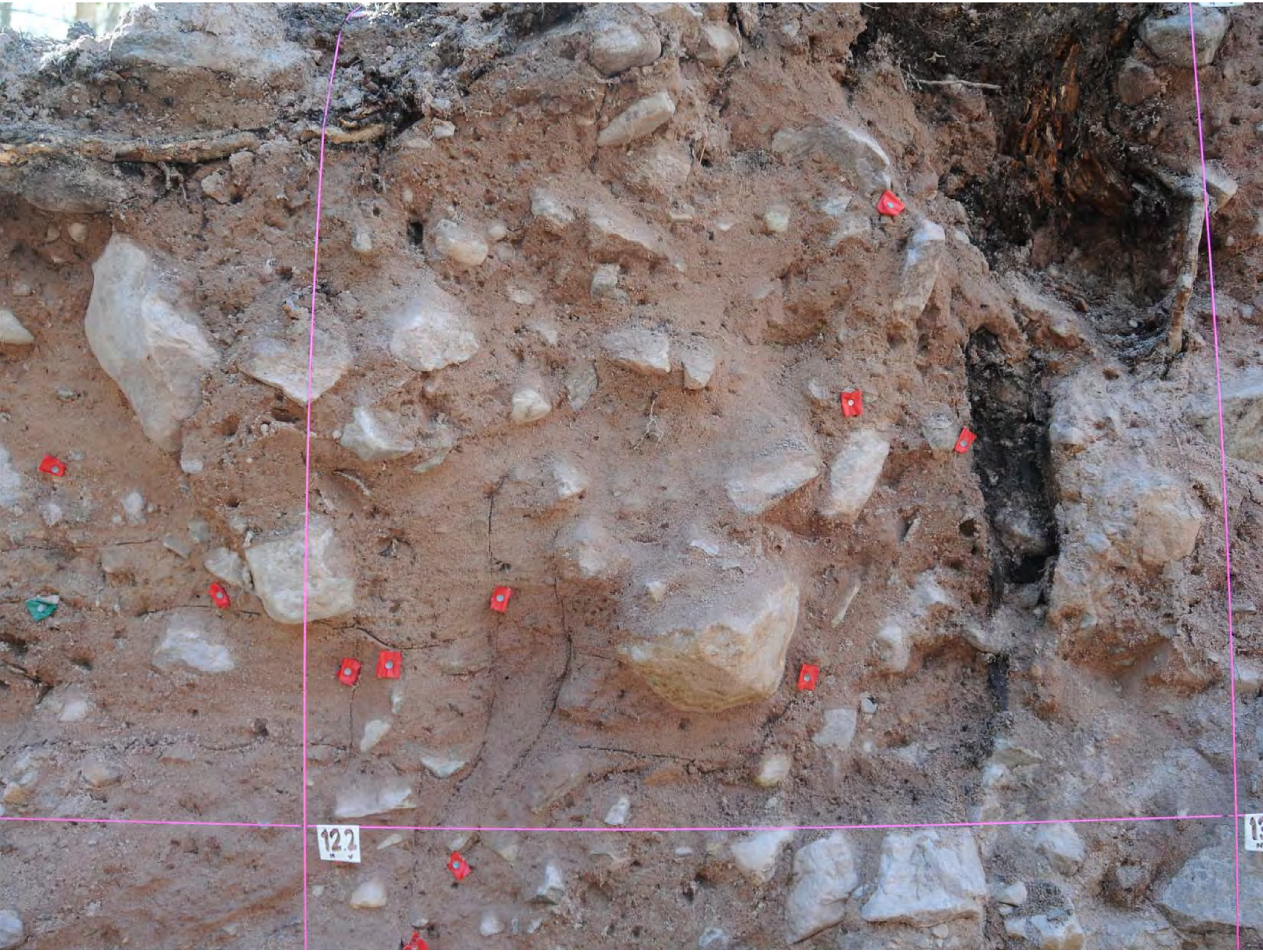
Two ruptures in past ~ 5ka



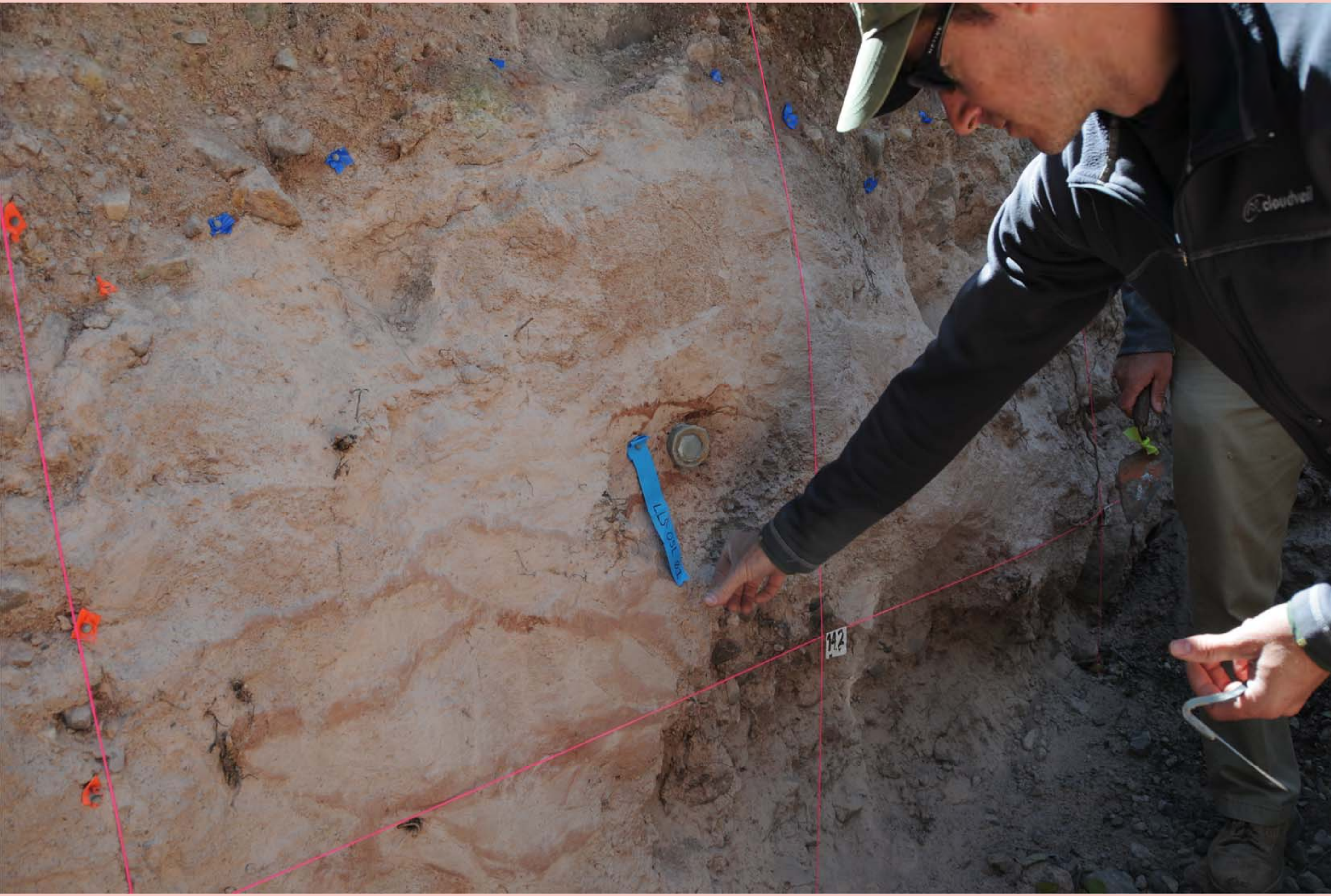
150
(closed winters)
northern site
Big Burn trench site
819 m
© 2013 Google
Google earth
1994
Imagery Date: 6/5/2013 40°52'30.83" N 110°48'21.19" W elev 2727 m eye alt 8.35 km

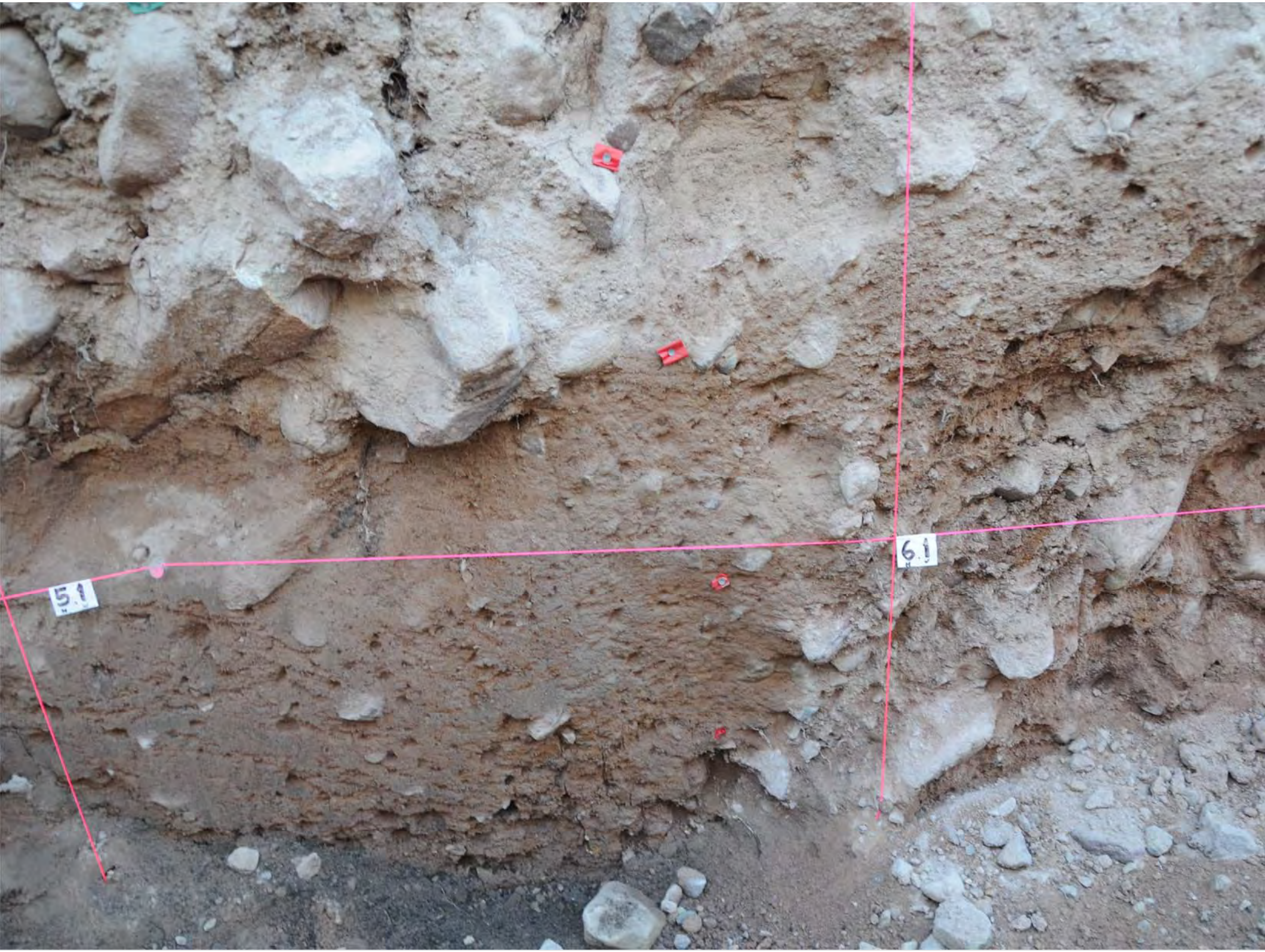

Magnitude
8
7
6
5
4
3
2
1
Age
Past hour
Past day
Past week
Plates
Boundaries
Convergence
Lily Lake trench site


CAT
308D

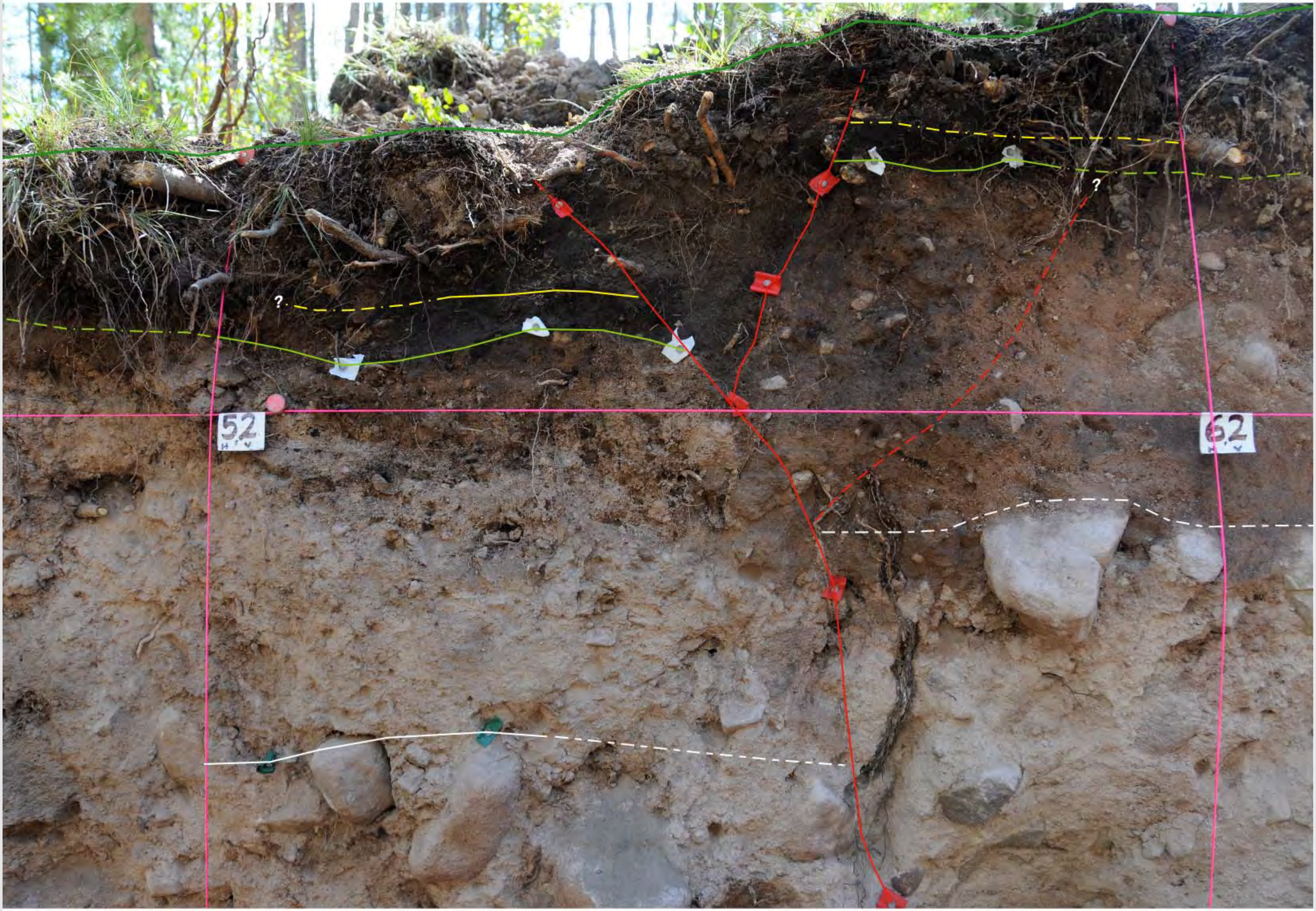

12.2


112
122

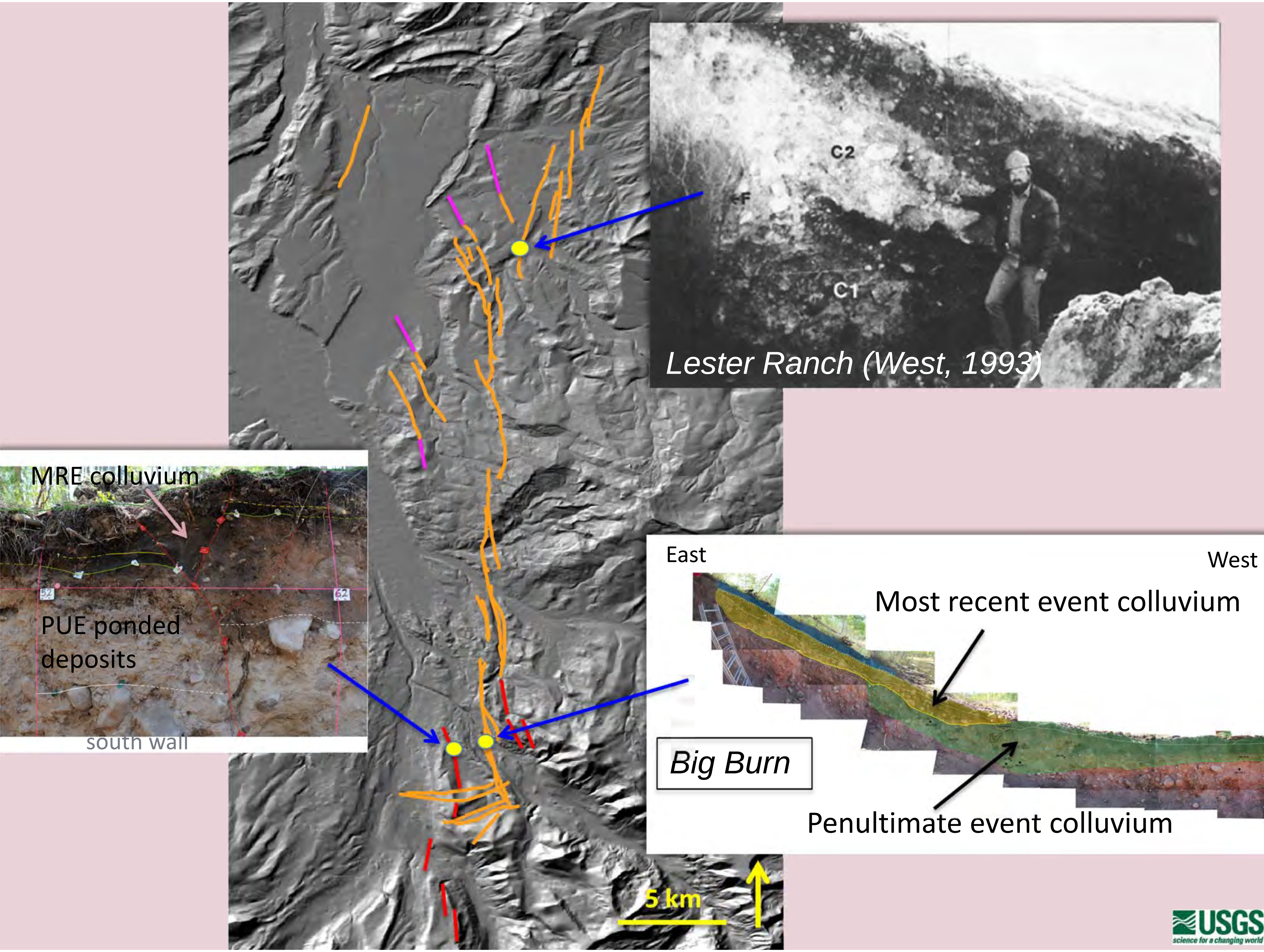

142


5.1
6.1

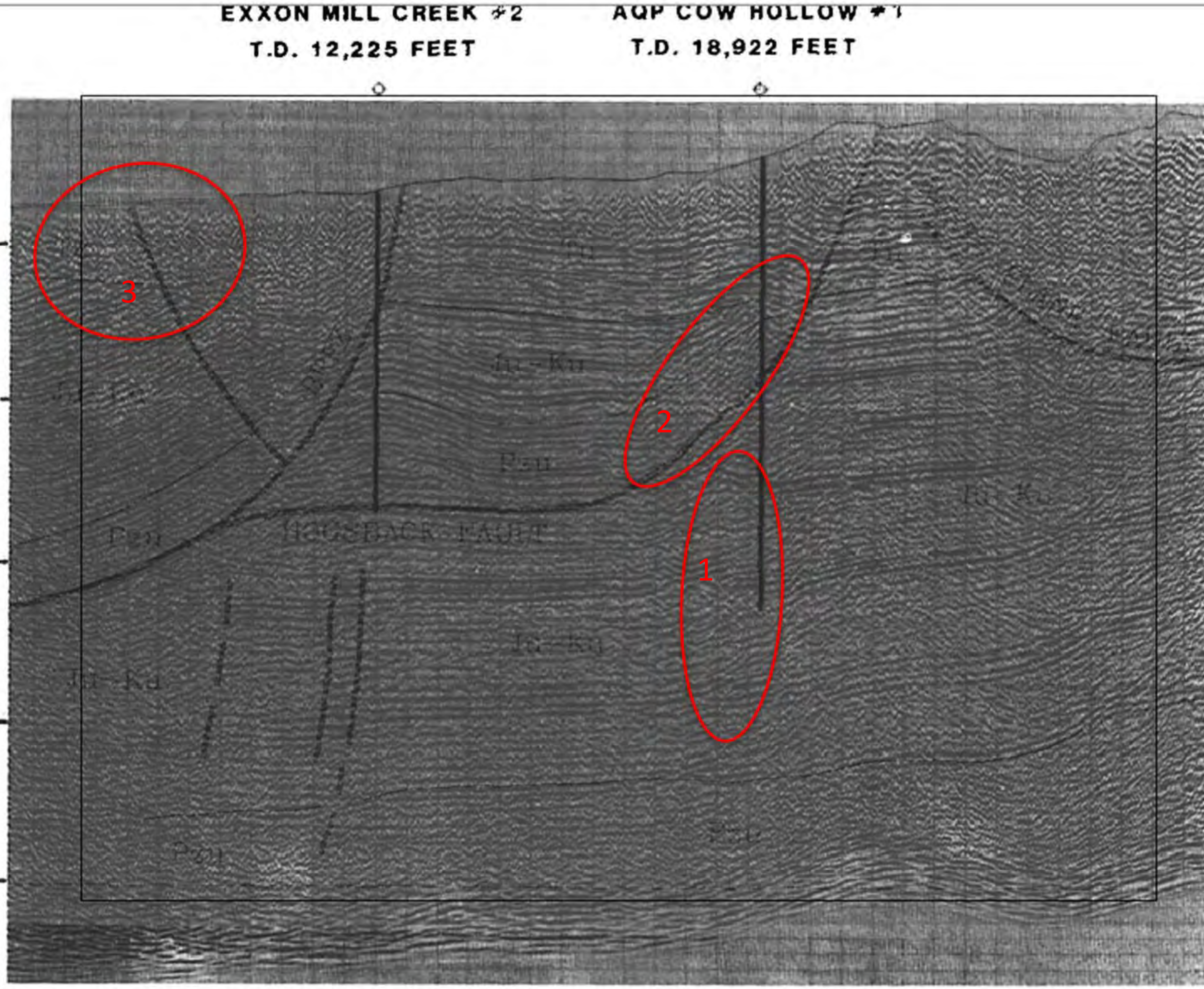
52
H V
62
H V



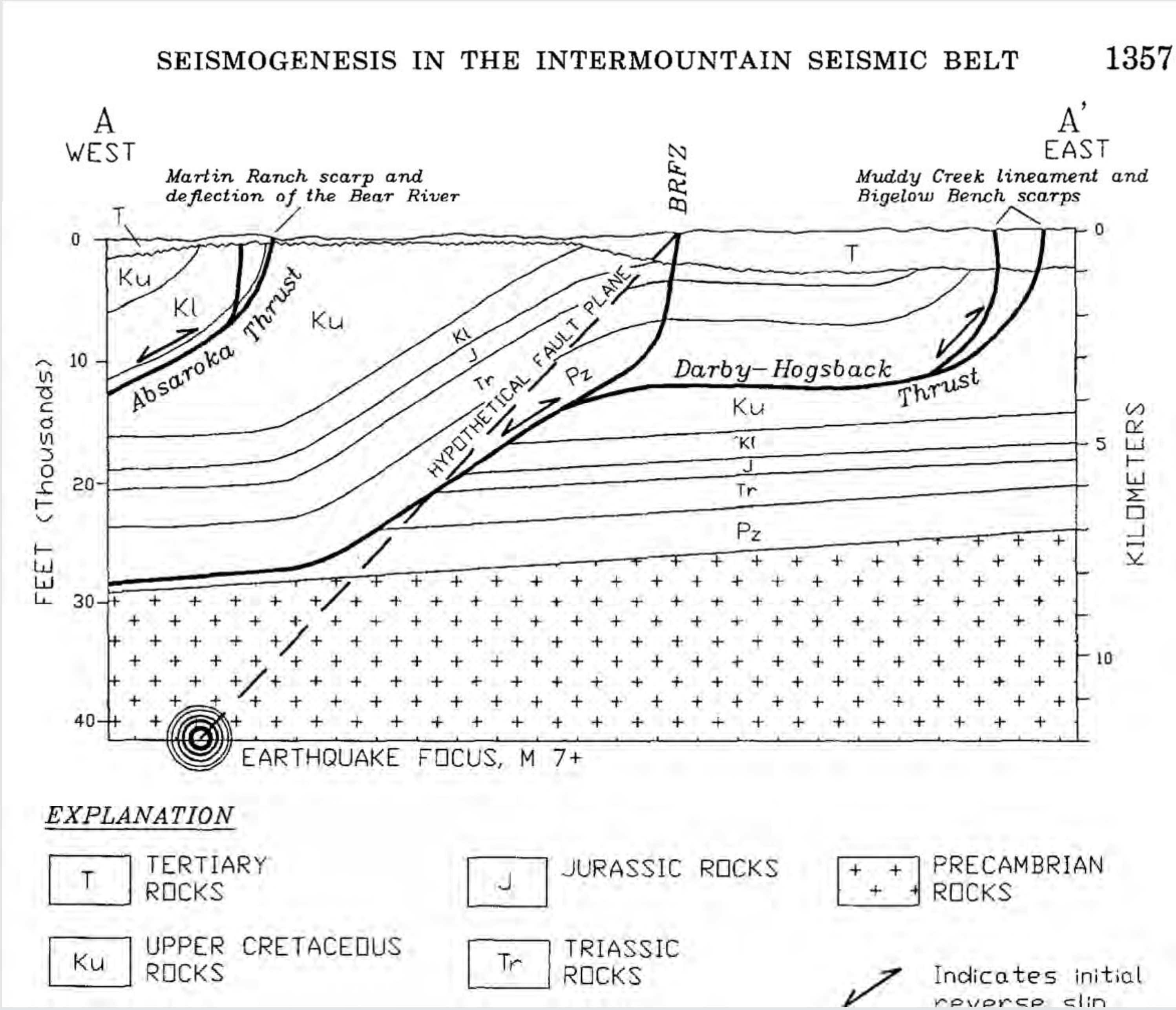
?
?
52
62



C2
F
C1
Lester Ranch (West, 1993)
MRE colluvium
52
62
PUE ponded deposits
south wall
East
West
Most recent event colluvium
Big Burn
Penultimate event colluvium
5 km
USGS
science for a changing world


EXXON MILL CREEK #2
T.D. 12,225 FEET
AQP COW HOLLOW #1
T.D. 18,922 FEET
0
1
2
3
4
HOGSBACK FAULT
1
2
3

Reactivation of Laramide thrust faults

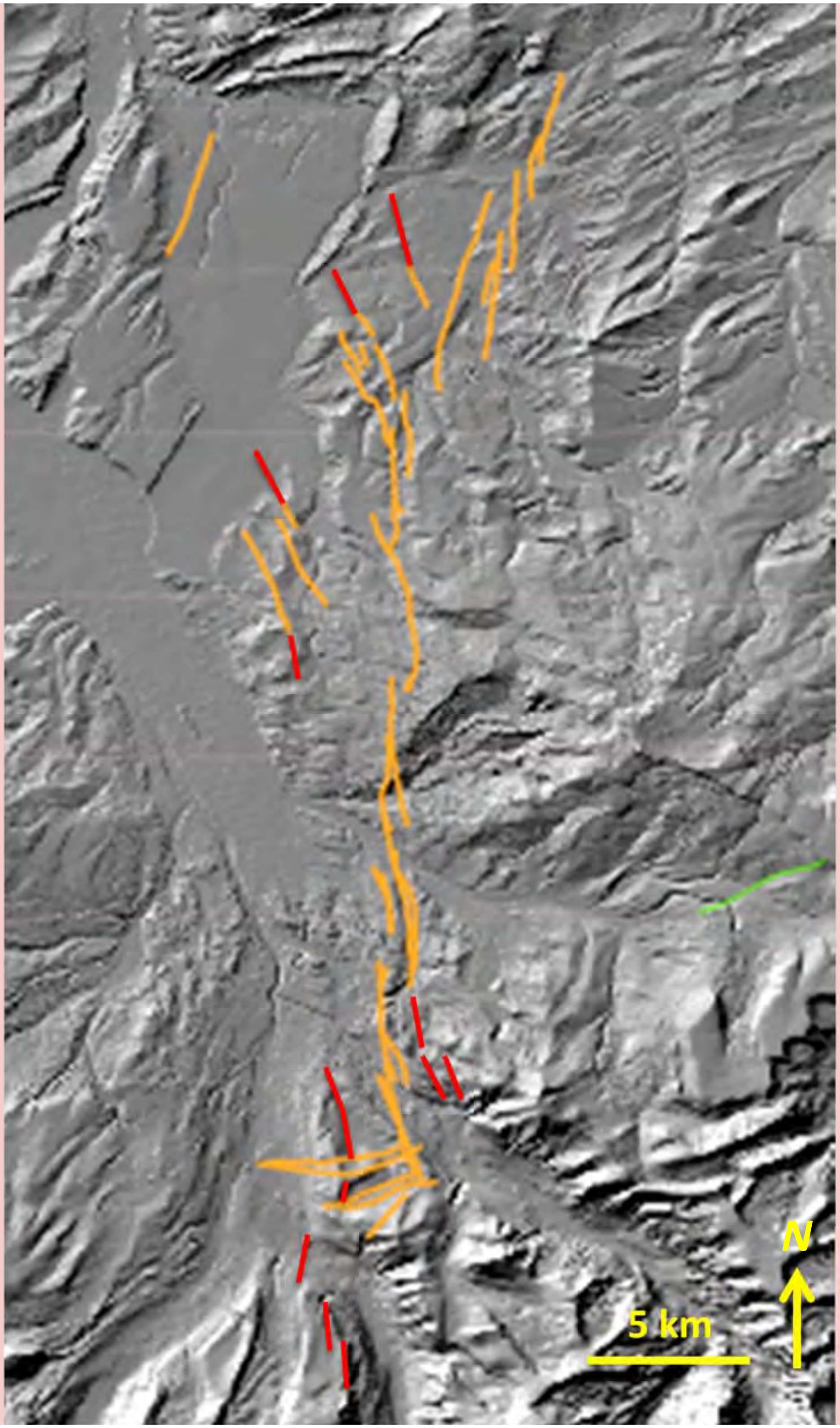


West, 1992

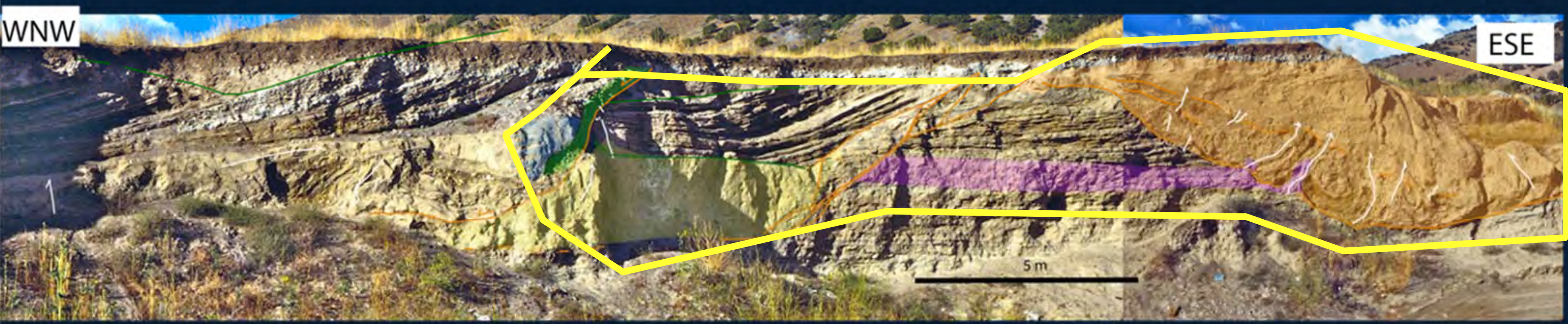
?????

How would the hazard have been interpreted 6ka ago?

What will happen in the future? Semi-regular recurrence interval? Long interval until next event? Rupture sequence has terminated?


N
5 km

Updates about Pleistocene earthquakes in East Cache Valley, Utah



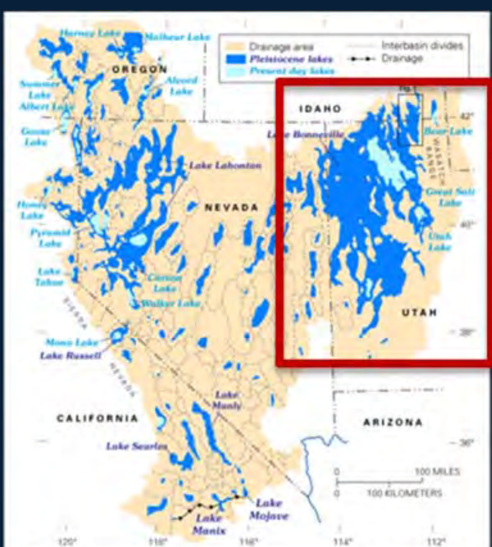
Susanne Janecke
Robert Q. Oaks, Jr.
Tammy Rittenour

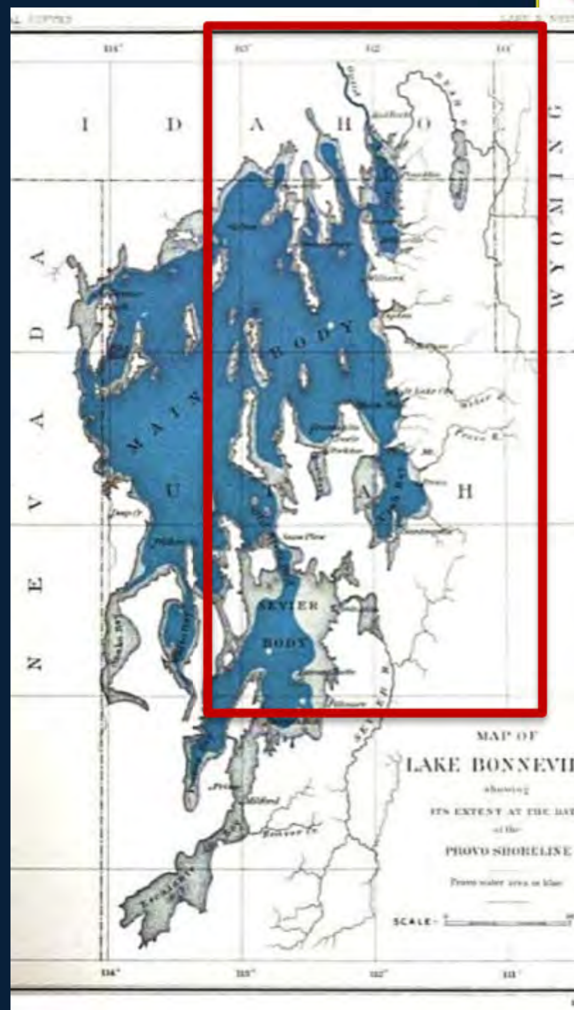
Each colored unit is liquefied

UtahState UNIVERSITY Geology

Our topic today is how the filling of a pluvial lake Bonneville by climate forcing may have produced a tectonic signature in the Basin and Range province. Cache Valley, Utah.

Hansel Valley eq, 1934, M6.6, is analogue





Maps from Reheis, Gilbert and DuRoss 2005

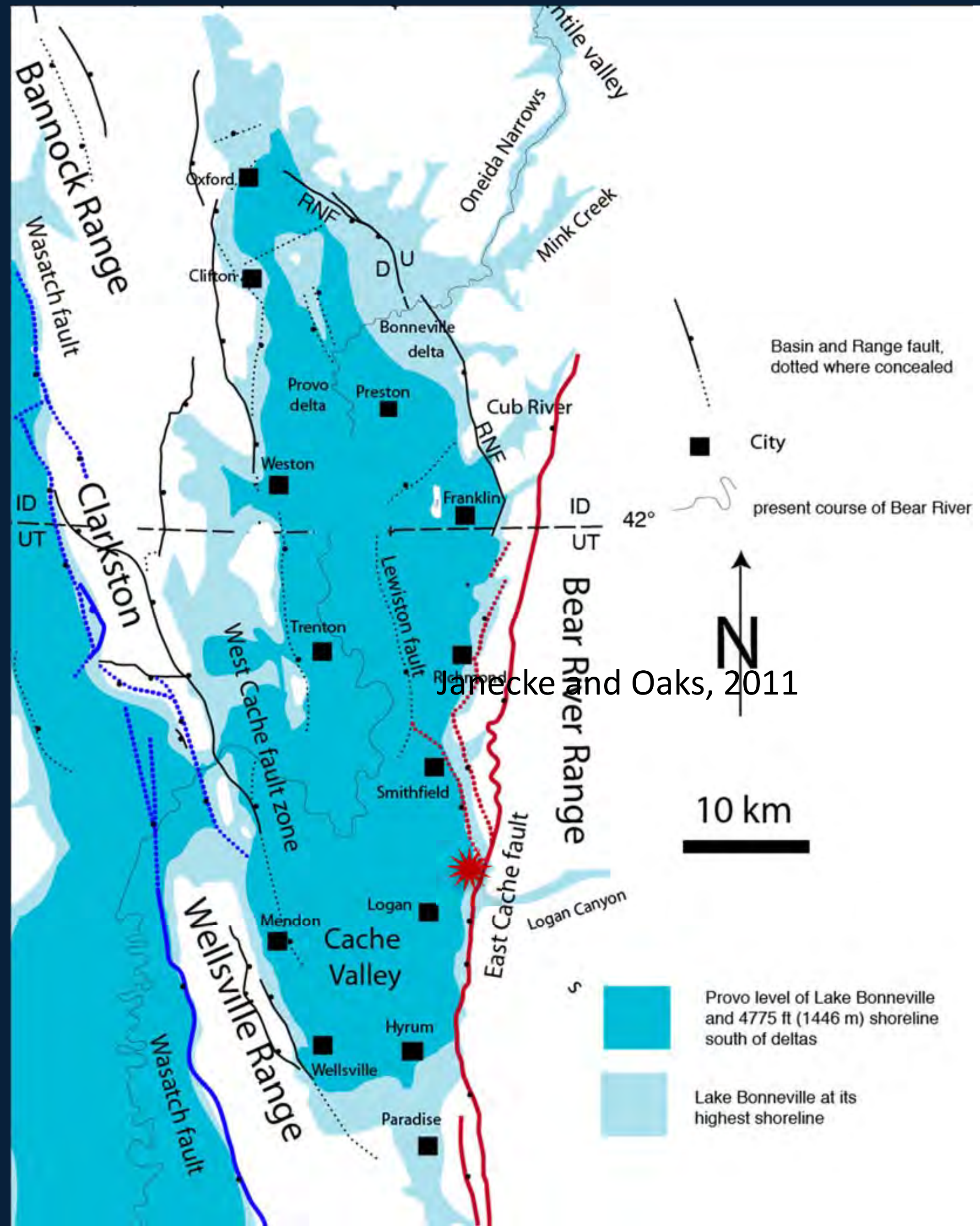
A. Since Lake Bonneville, normal faults in Cache Valley slipped at low rates with long recurrence intervals.

B. The depth of the basement suggests higher rates in the past

- Site is at a segment boundary, where several faults branch

Central segment of ECF:
MRE 4.5 ka
Penultimate event was 15.6 to 18.5 ka during Provo time

Northern segment:
No evidence of latest Quaternary slip except for a lateral spread
(McCalpin, 1987, 1994)



Janecke and Oaks, 2011

Gravity data show that the main range-front fault bends and steps about 5 km west at the Green Canyon segment boundary

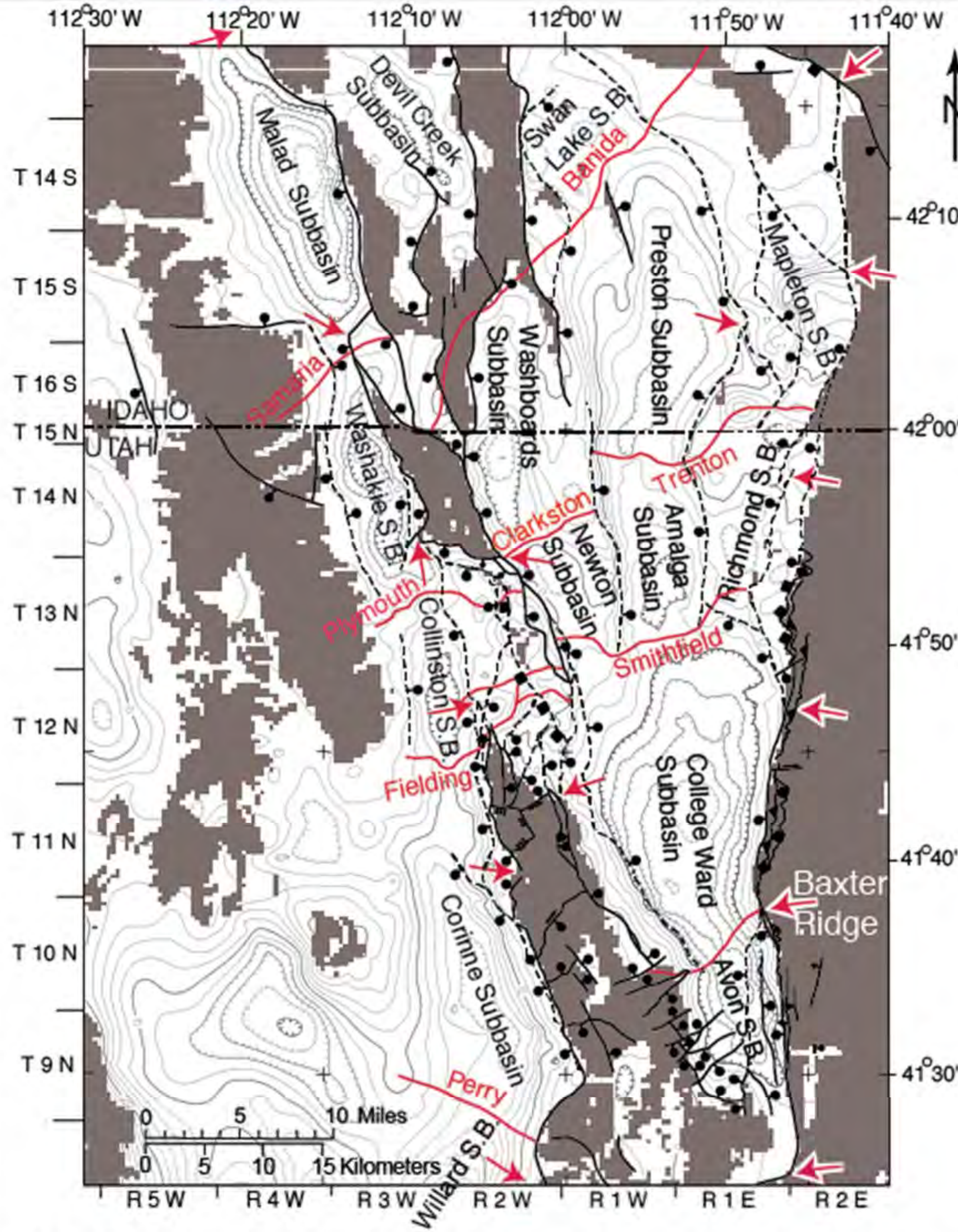
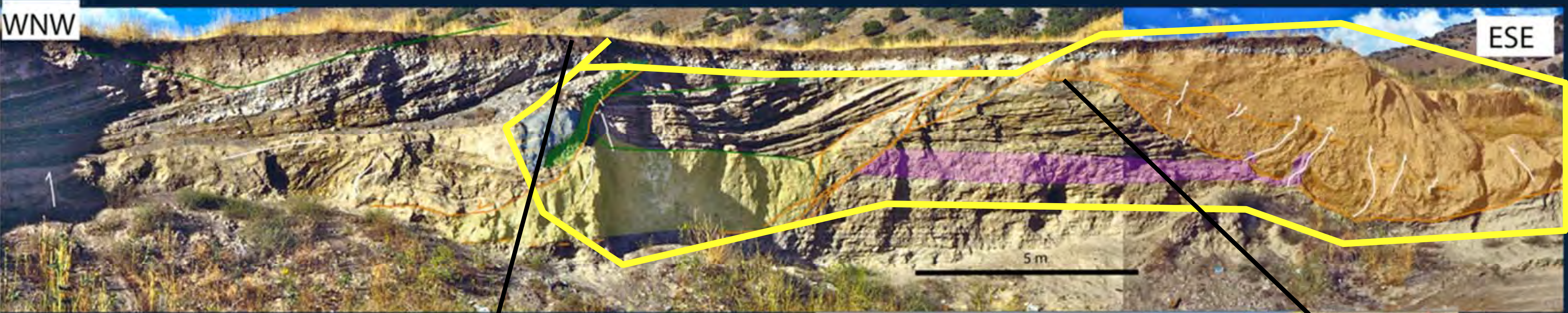


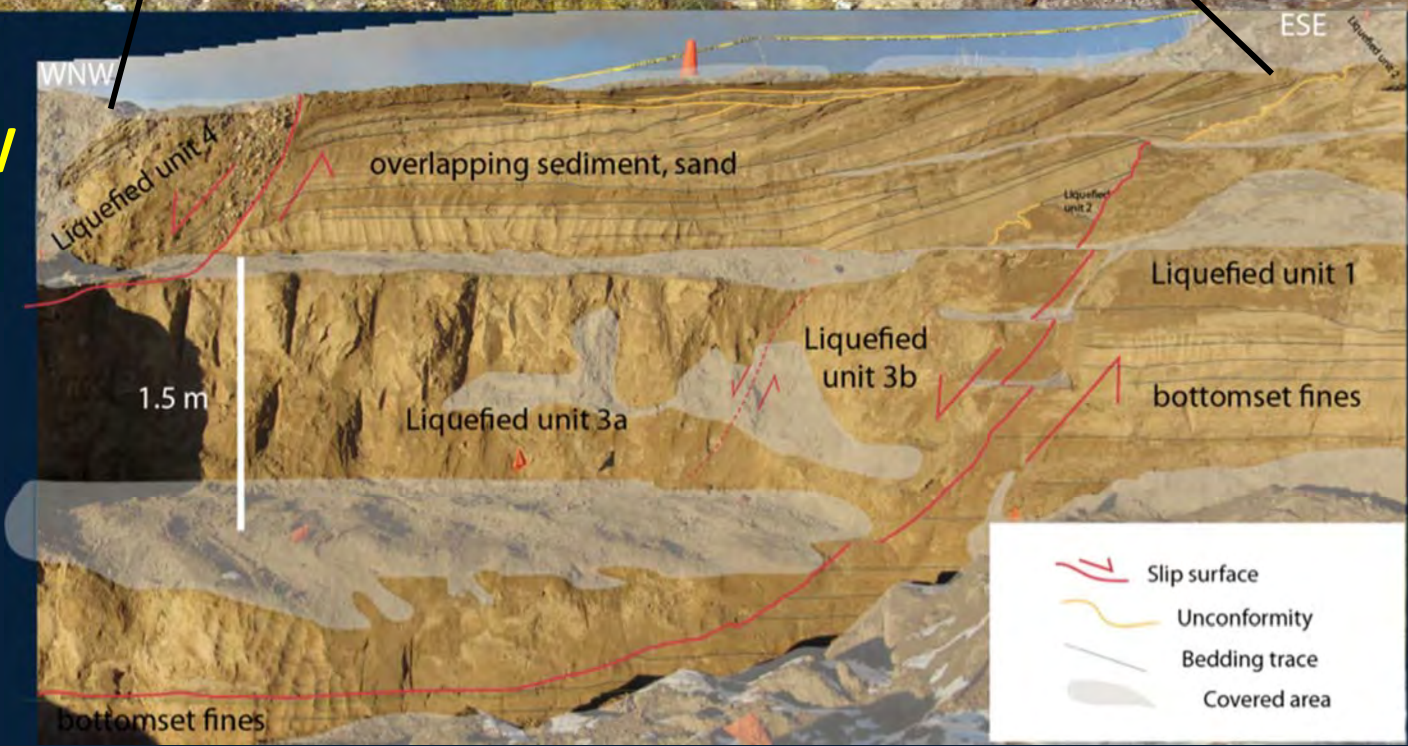
Figure 7. Map showing faults (dashed where covered), segment boundaries (red arrows), and transverse zones (red lines) that separate subbasins in Cache Valley and the Northern Wasatch Fault Zone. Isostatic residual-anomaly countours, interval 4 mGals. Oaks in prep.

Backhoe restored ~ a quarter(?) of original outcrop

Then



Now



*40 m below Bonneville Shoreline

*Colors denote liquefied units

Research questions

3. Did large earthquakes trigger the liquefaction (and the associated slumps)?

4. How many liquefaction events are there?

5. Does the Bonneville hydrograph need revision?

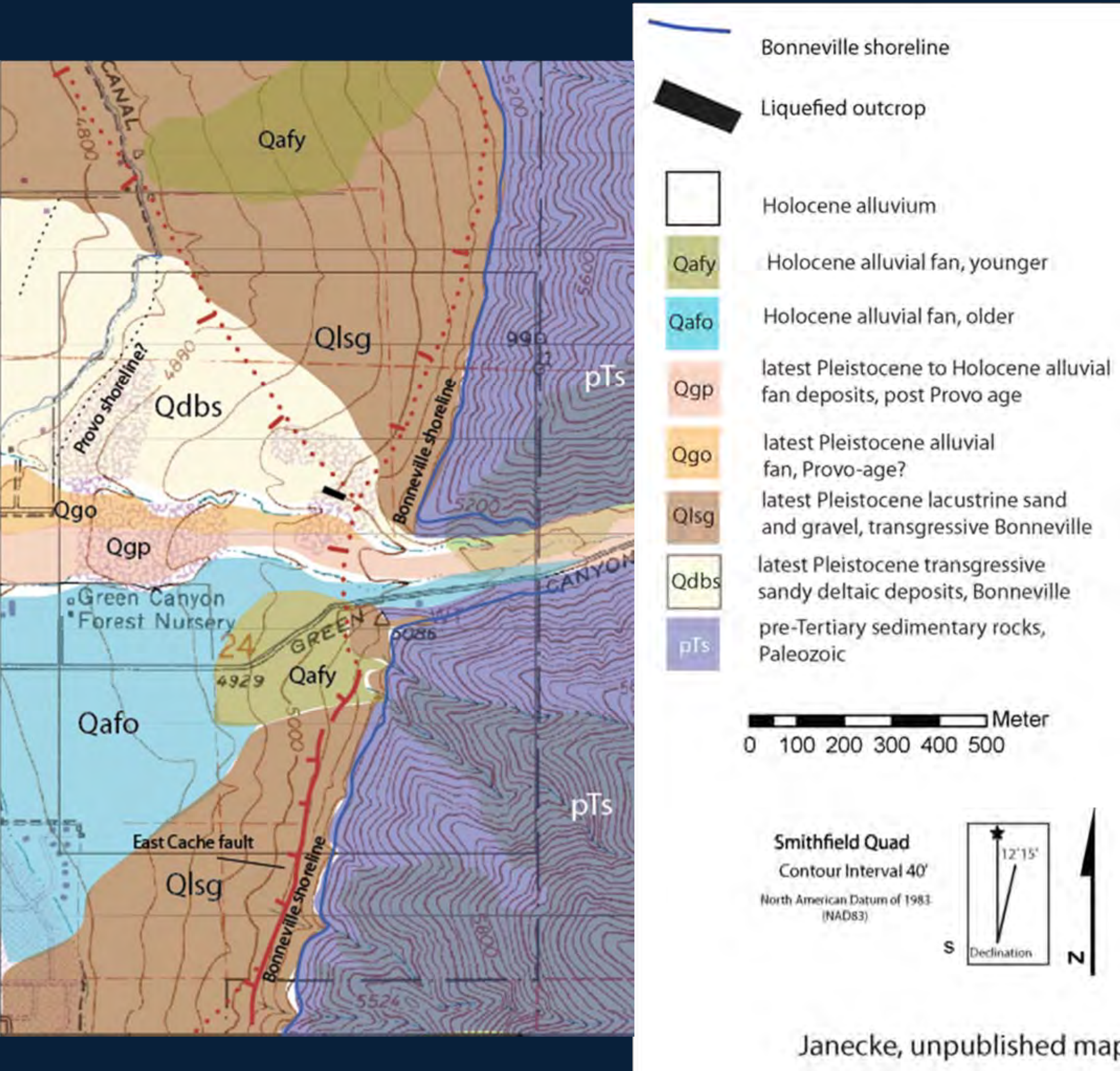
6. Why were earthquakes so clustered under L. Bonneville?

Updates

- Geochronology: Several new ages, more aliquots of OSL, 4 radiocarbon in progress
- Aerial photos from 1937 reveal unmapped faults and scarps
- Outcrop photos from 1980's document extent of liquefaction near range front
- We considered post-Bonneville earthquakes to compare Holocene and Pleistocene frequencies of earthquakes
- We examine the distribution of the significant liquefaction farther west in the gravel pit

Plus exposures of East Cache fault under power line, sld. 51

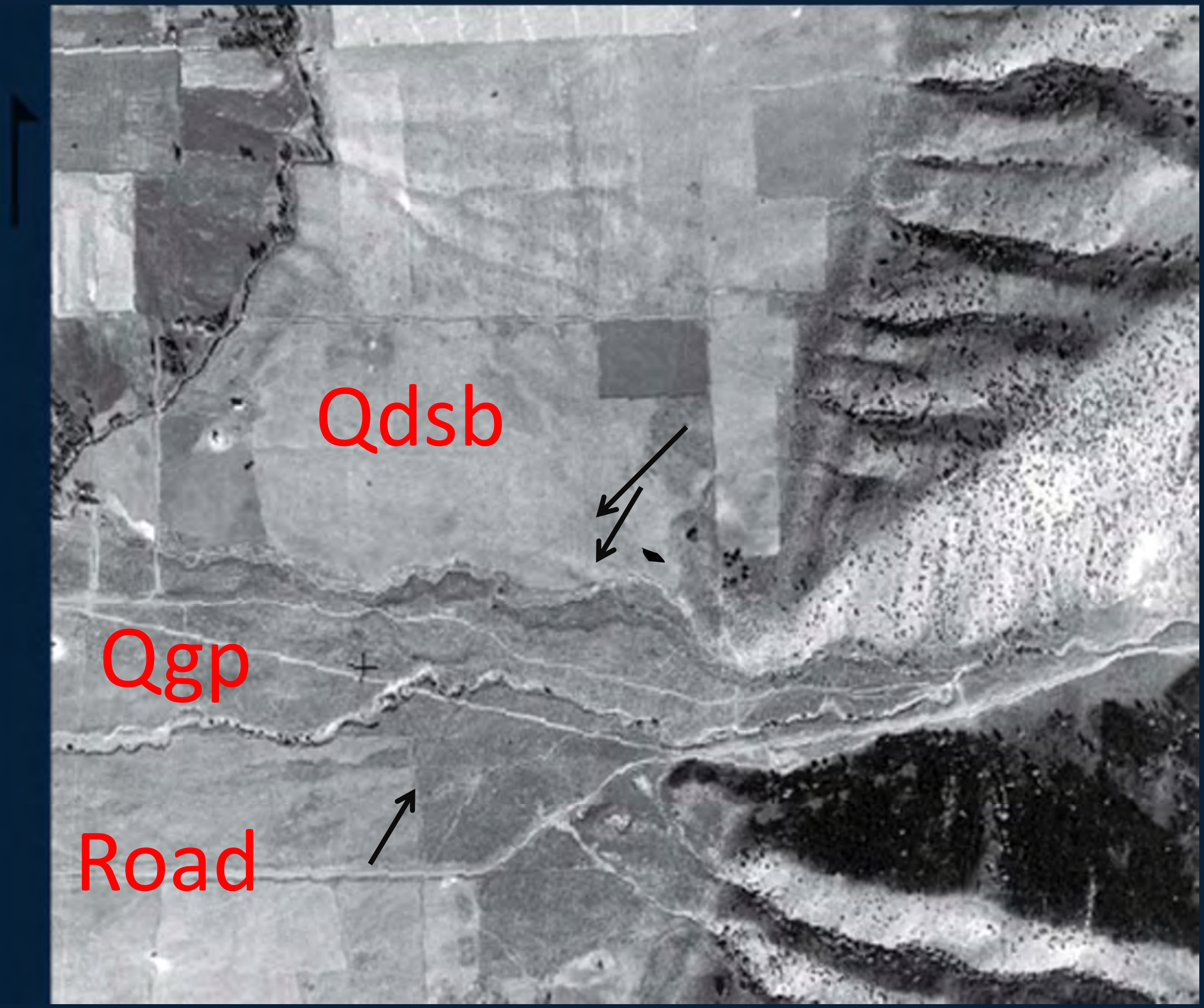
2013 map



Methods:

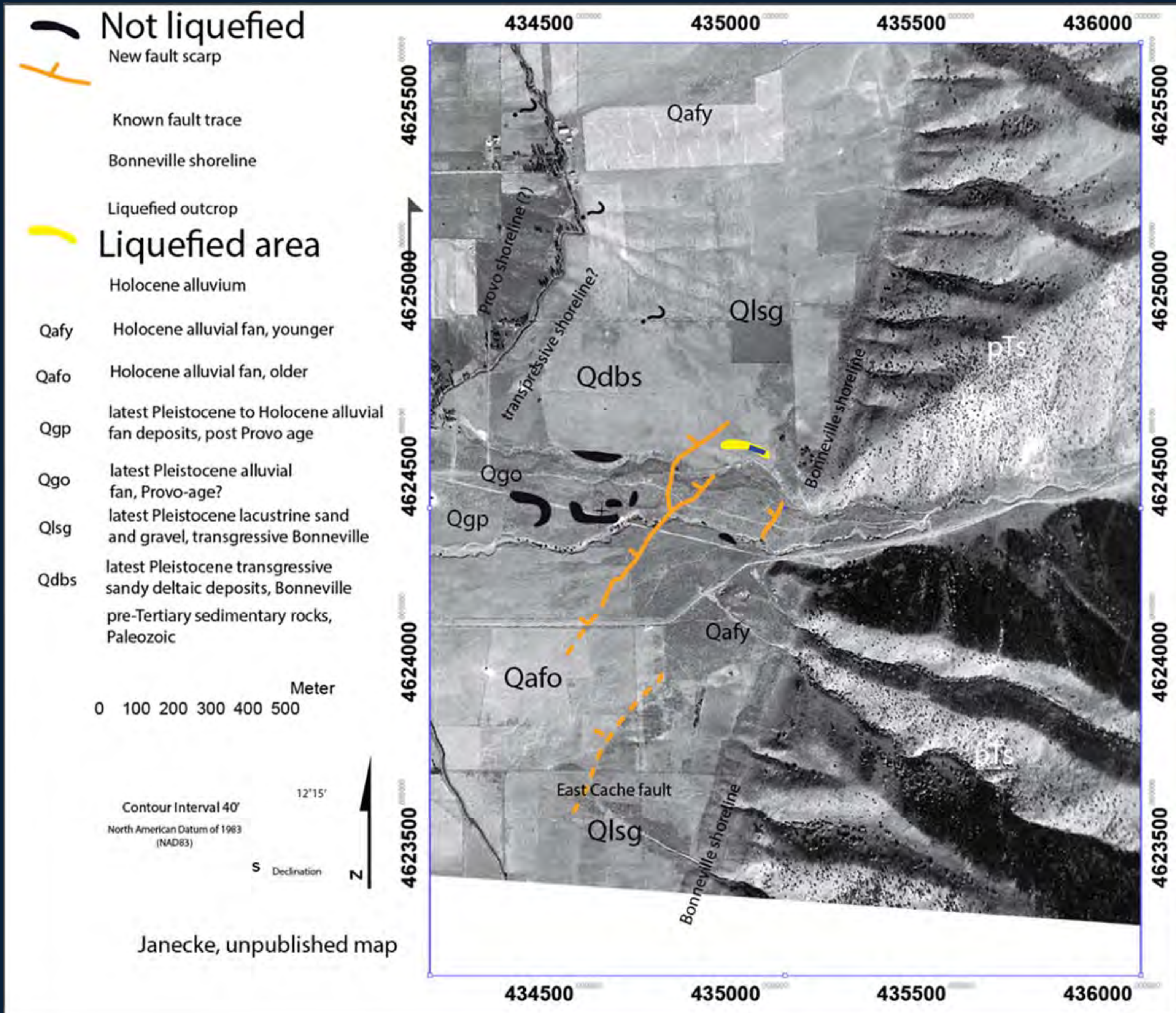
- Geologic mapping, analysis of outcrops in the gravel pit
- Digging, cleaning and logging at main outcrop.
- Use of backhoe to restore the main outcrop
- Radiocarbon and OSL dating of beds below and above deformed layers
- Stereo-analysis of 1980's photos of outcrop
- Stereo-analysis of several sets of aerial photos

1937 Aerial photo reveal unmapped fault scarps in post-Bonneville alluvium



Fault scarps may be 5-20 m west of current exposure

New faults are orange

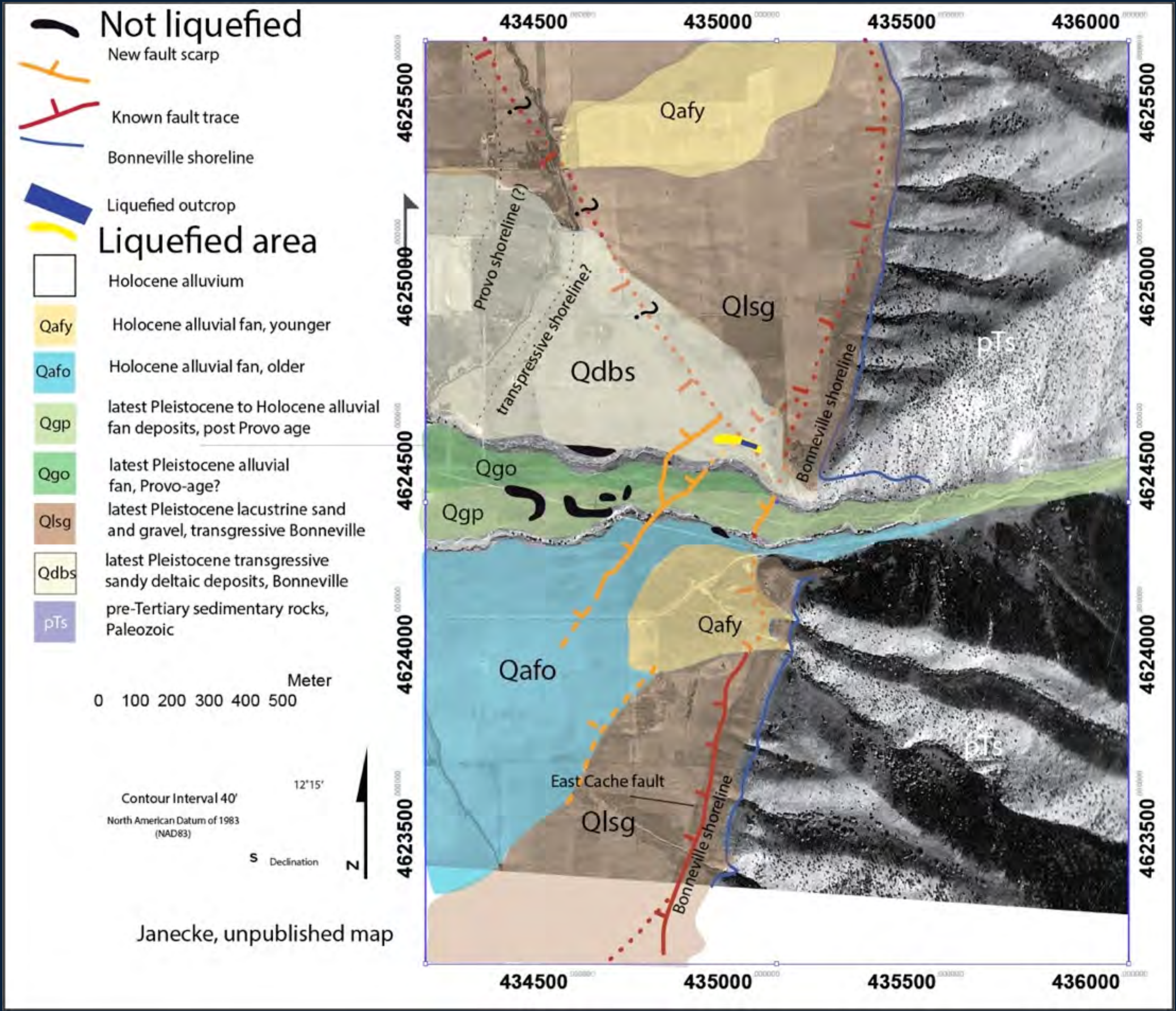


East Cache fault is more complex

There are strands of East Cache fault all around the site

One inactive strand is ~200 m to E along mountain front (McCalpin, 1989)

New mapping show additional scarps nearby



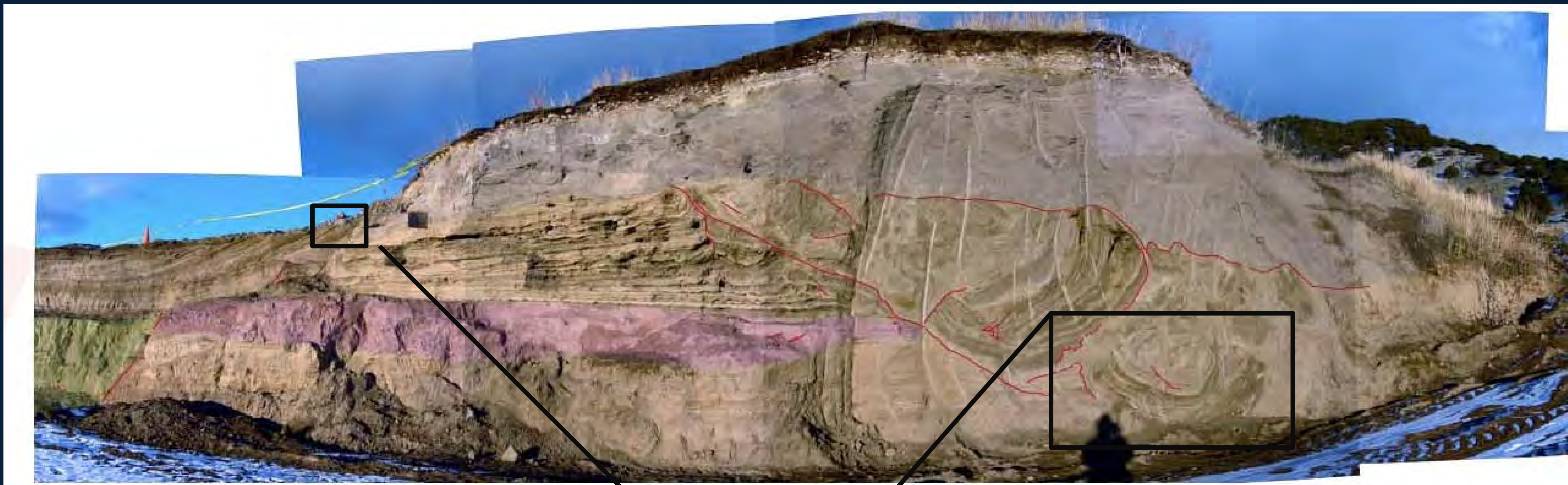
Stratigraphy

1980's photo of ~half of outcrop:

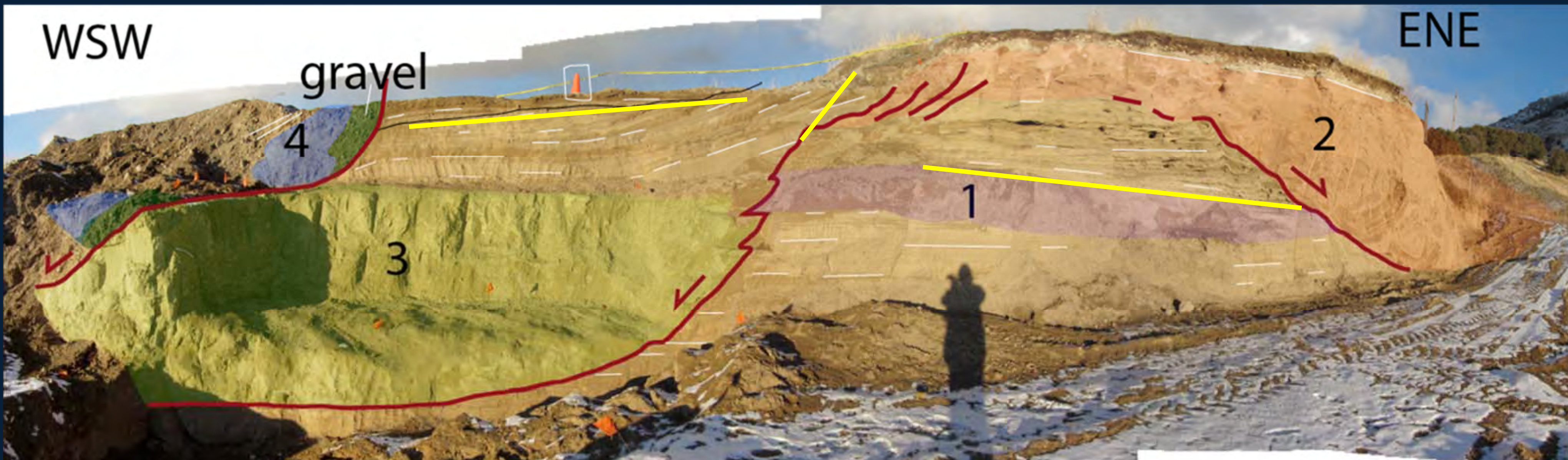
WNW ESE

- Soil
- Provo-age(?) cap of alluvial gravel,
- over Bonneville deltaic sand (s)
- over Bonneville prodelta fine sand, silt and clay (f, fines)
- Bonneville deltaic gravel in foresets (g)

Today.~ 5 m high:



The 4 THICK liquefied intervals: numbered and colored from oldest to youngest

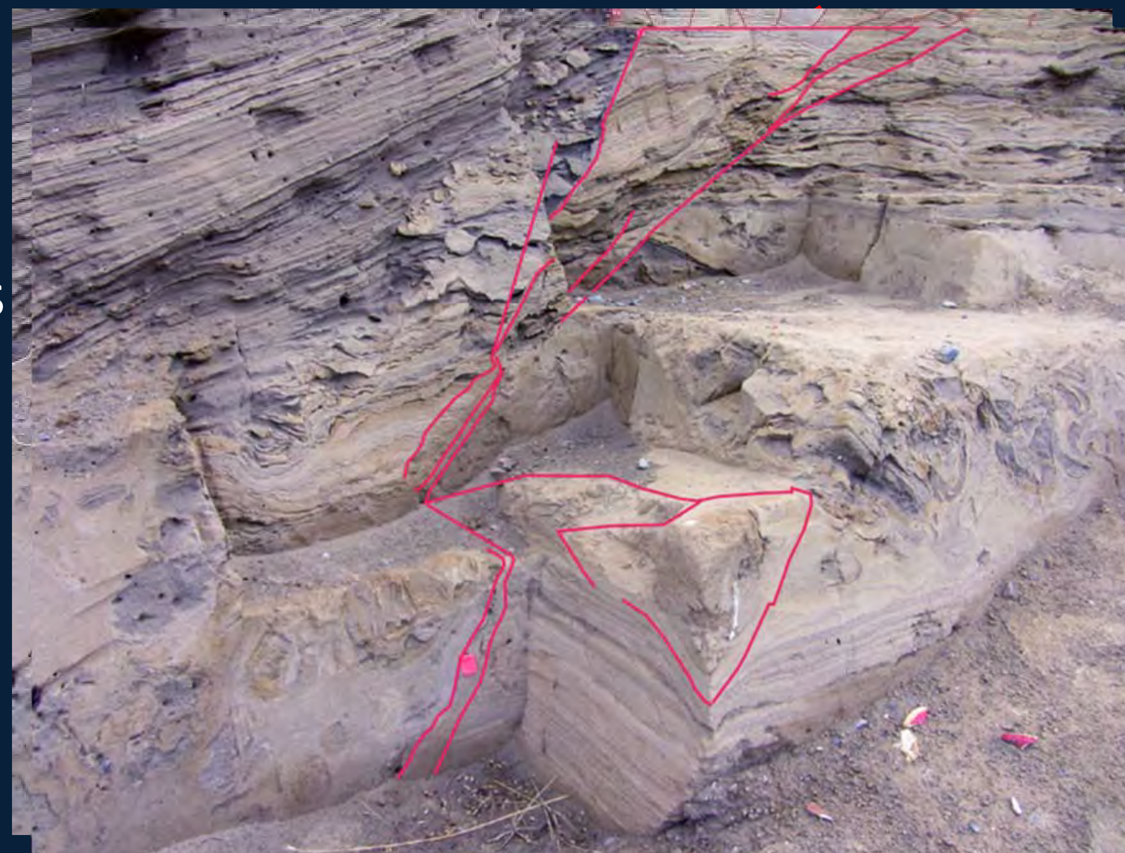


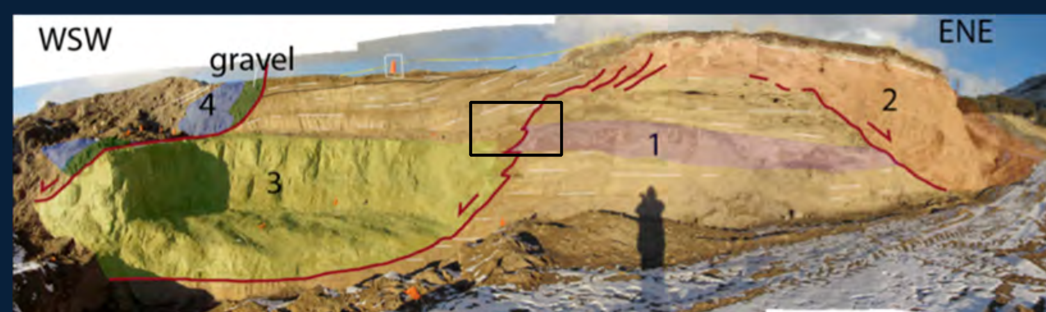
Each bench is 1.5 m high

Cross-cutting relationships
between these beds and
show that each is a different age,
from 1 to 4
Unconformities,
slip surfaces and
overlapping beds

Summary

- Deltaic transgressive sand of Lake Bonneville
- Contain 4 thick liquefied units
- That formed sequentially
- Outcrop is cut by 3 listric slip surfaces of slumps or lateral-spread complex
- Those slip surfaces were active at least 4 times under Lake Bonneville.

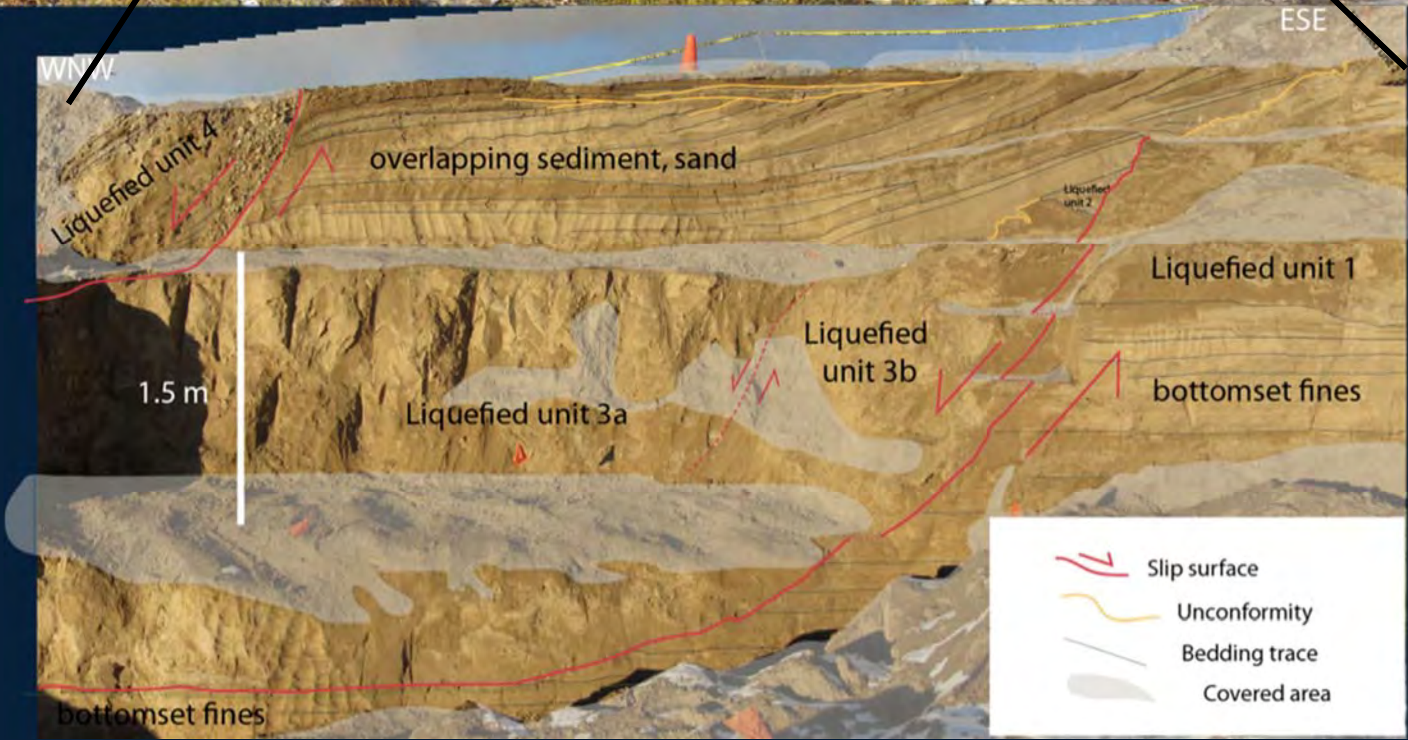




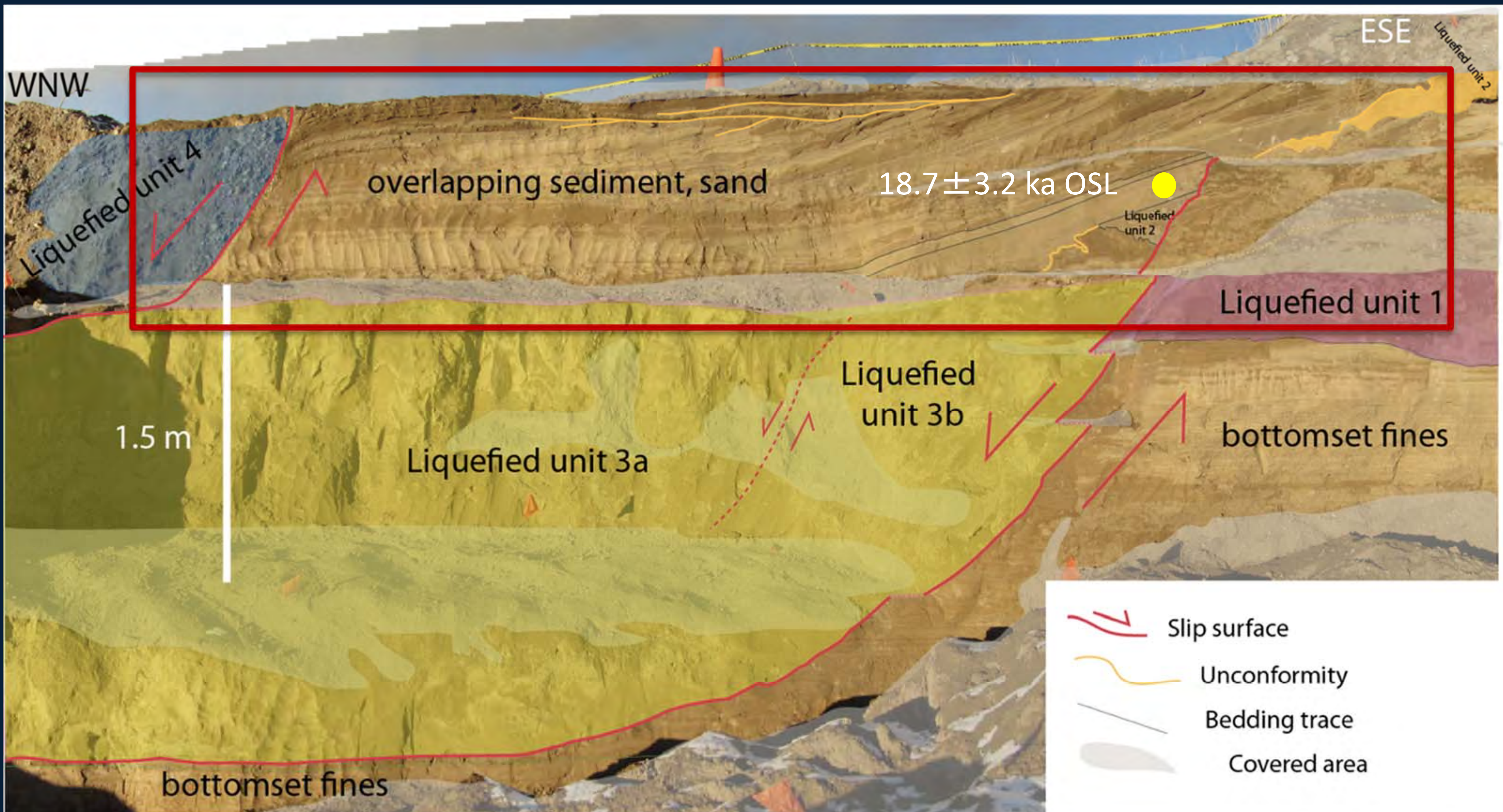
Liquefaction and slumping were associated

Then

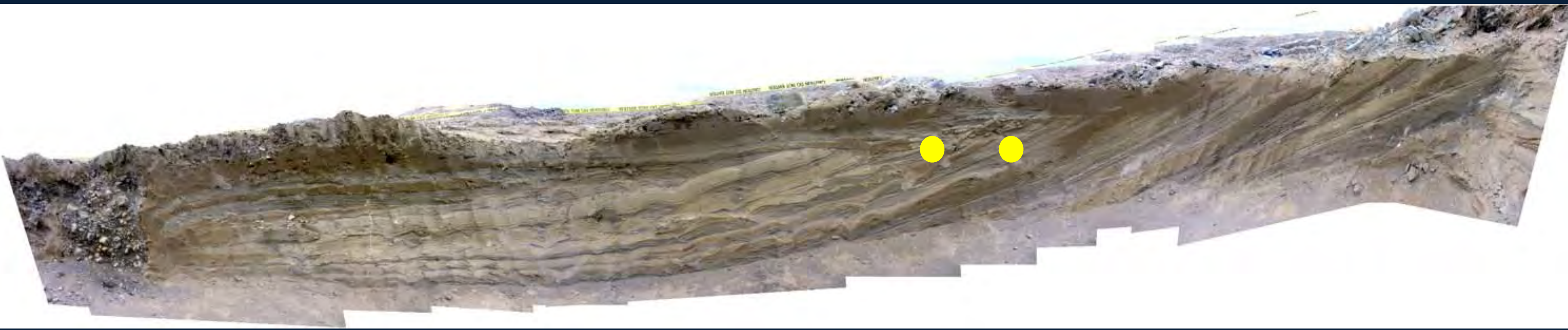
Now



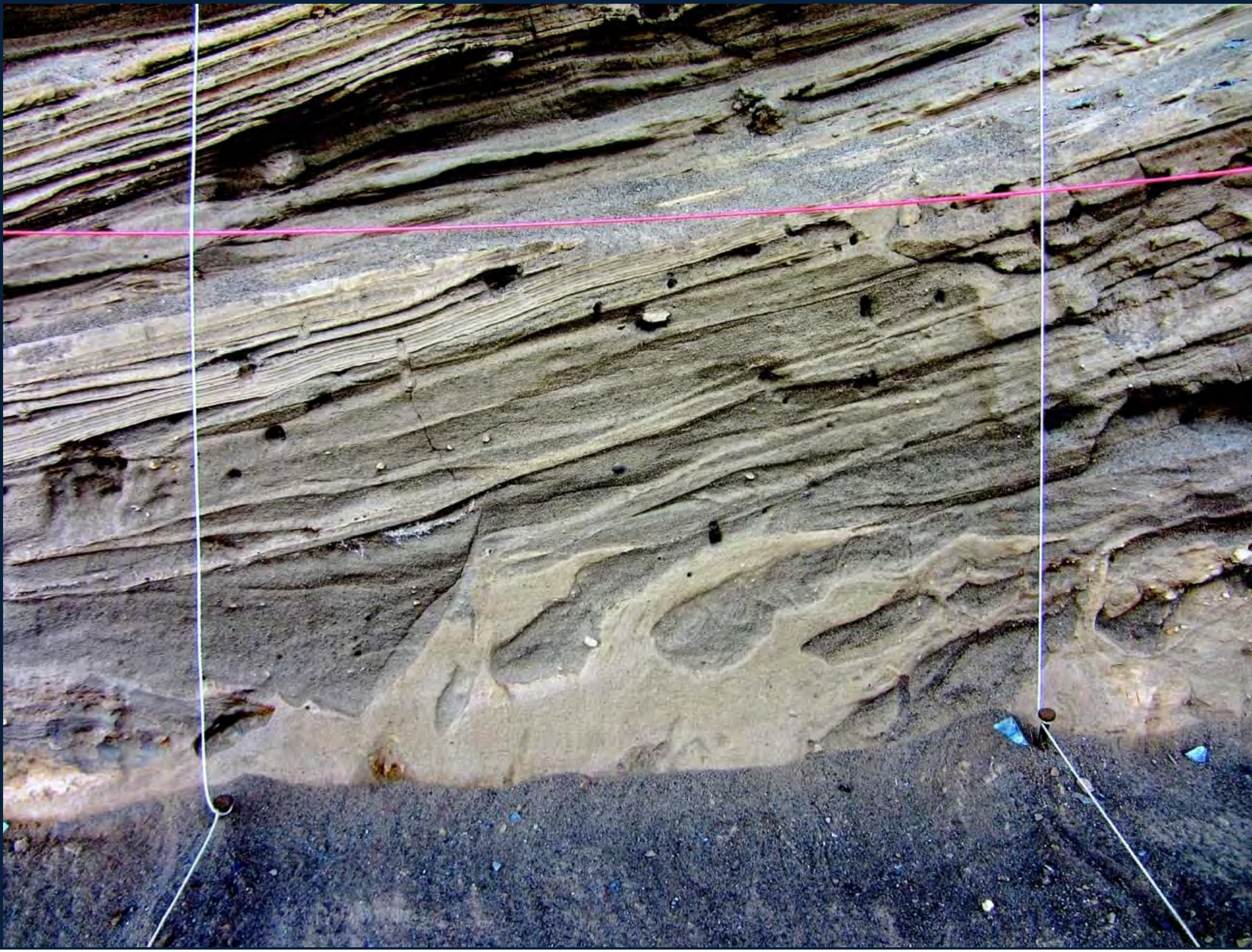
Examples of cross-cutting relationships



22.3±3.2 ka OSL

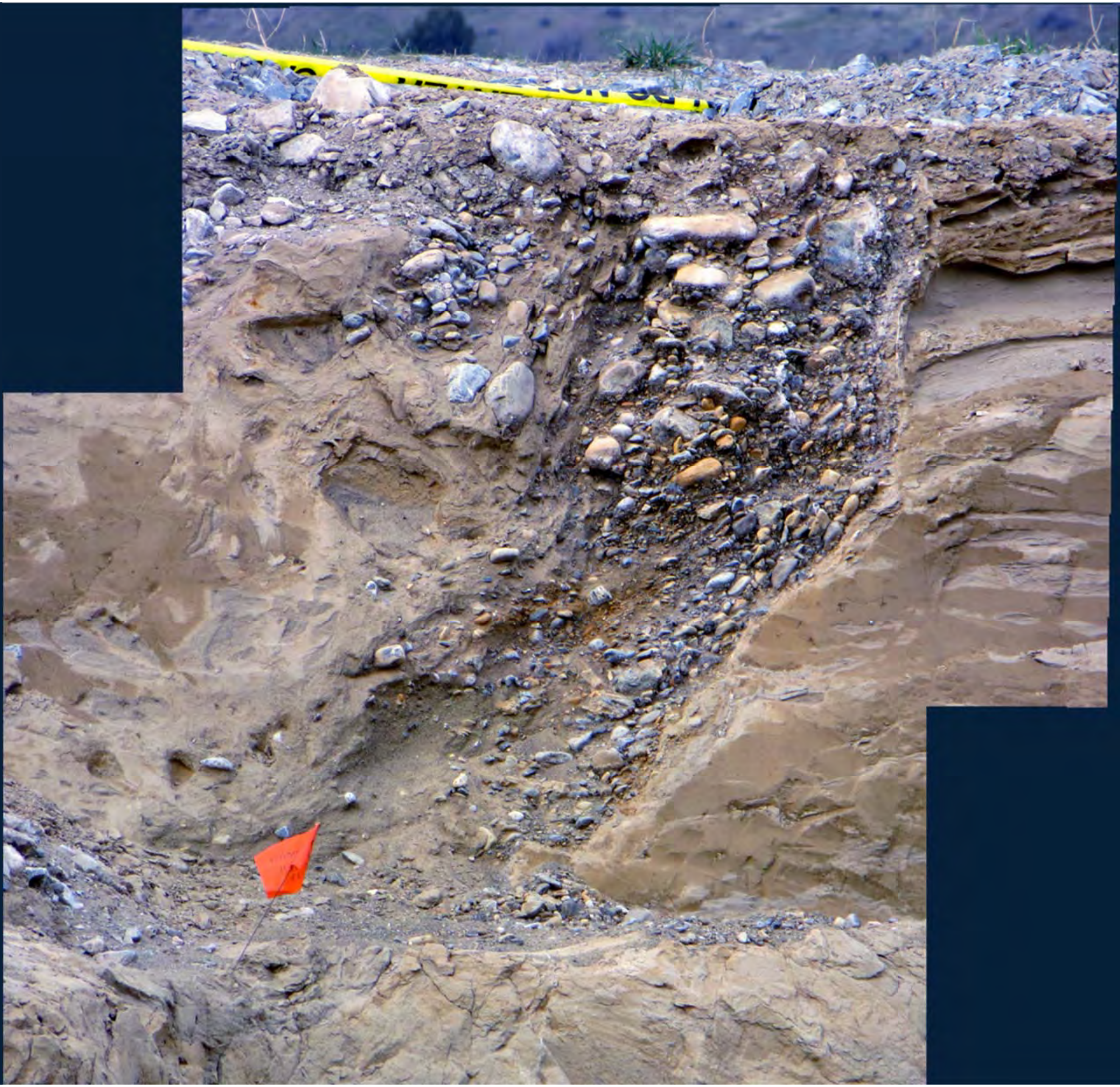


18.7±3.2 ka OSL



More angular unconformities

Notice the self-loaded ripples



Onlap, slump+liquefaction, deposition of inclined beds

Soft sediment deformation or seismite?

Or some of each?

- Features consistent with loading processes

  -Delta fronts are known to fail in lateral spreads and slumps

  -Possible association of deformational events and regressions in Paola et al's lab experiments

Soft sediment deformation or seismite?

Or some of each?

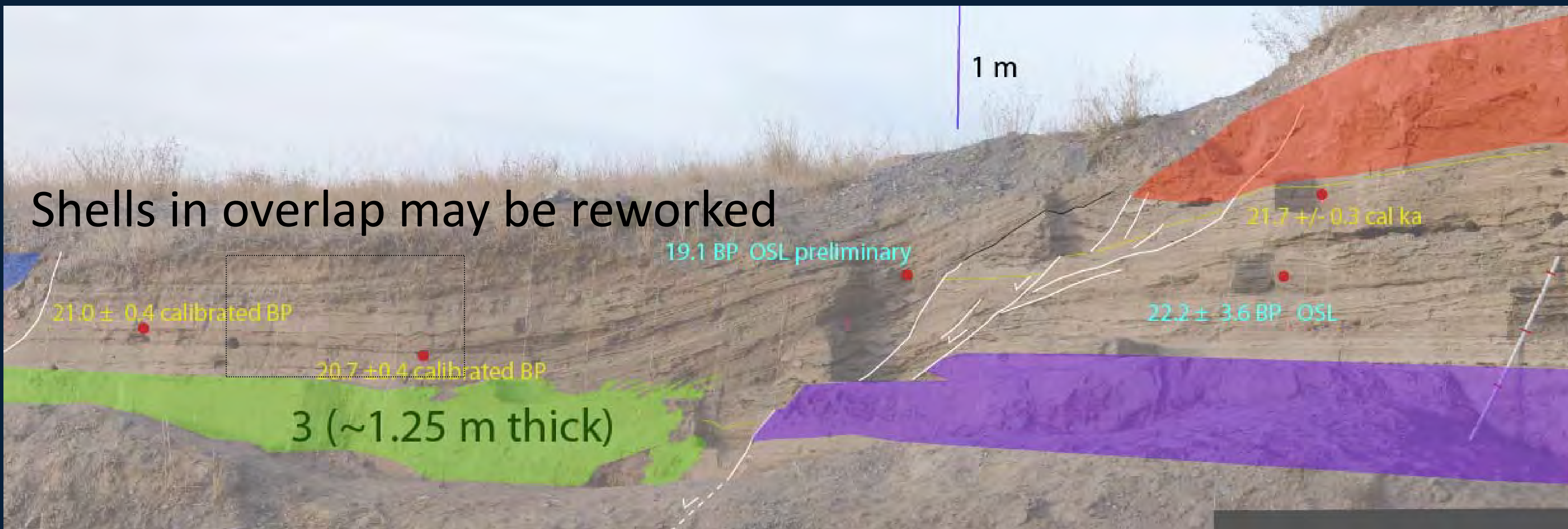
- Features consistent with loading processes

  -Delta fronts are known to fail in lateral spreads and slumps

  -Possible association of deformational events and regressions in Paola et al's lab experiments

- Features consistent with seismite interpretation
  - Location near E Cache Flt.
  - Great thickness of structureless, liquefied beds
  - Injections, sand dikes and sills
  - The delta seems too small and gentle for such massive and repeated collapses
  - Structures are "fault graded bedding"
  - Brittle faults require high strain rates, > loading
  - Fluid escape across brittle faults from oscillatory conditions
  - Hansel Valley earthquake produced similar liquefaction, slumping and lateral spreads (Robison, McCalpin)

Age of deformation was based on 3 radiocarbon and 3 OSL ages: all Bonneville ages



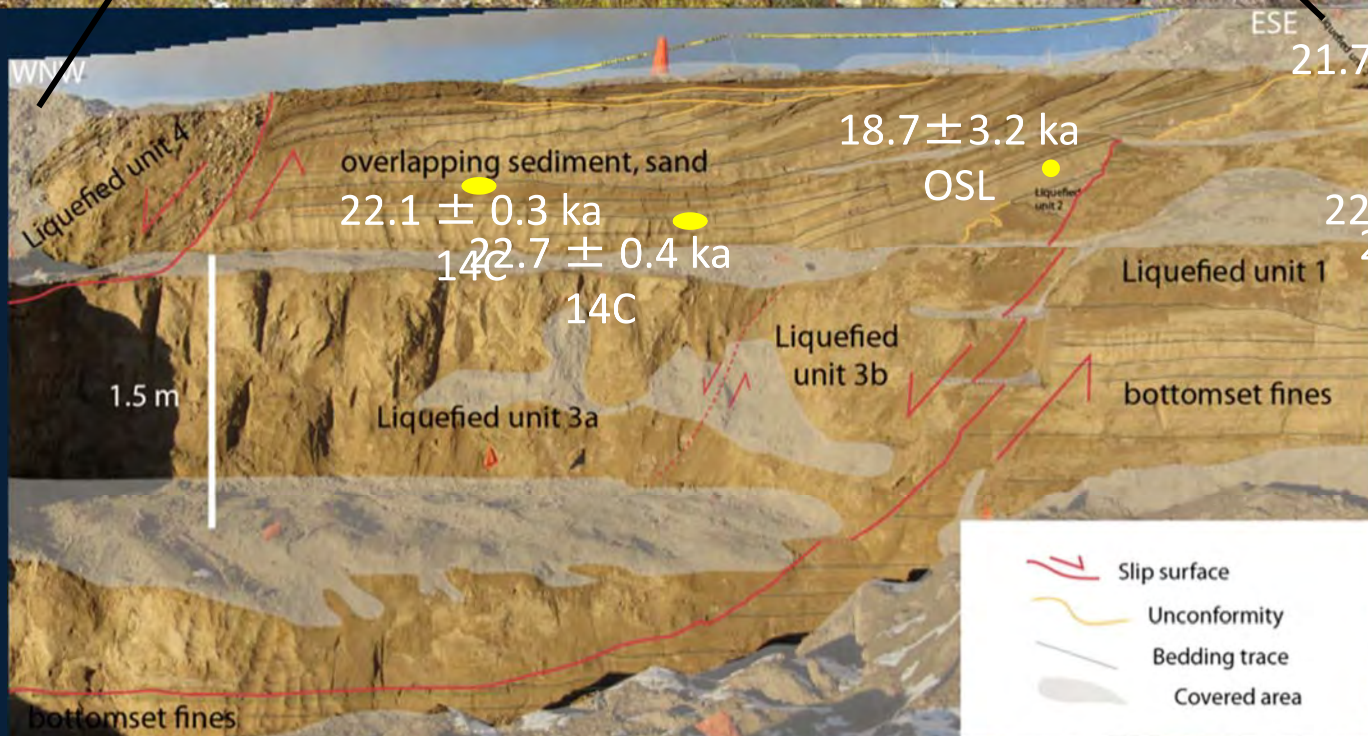
Logging string is spaced 50 cm apart

Janecke et al., 2013 UQFPWG

Age of deformation more certain
8 ages, 4 pending:

Then

Now

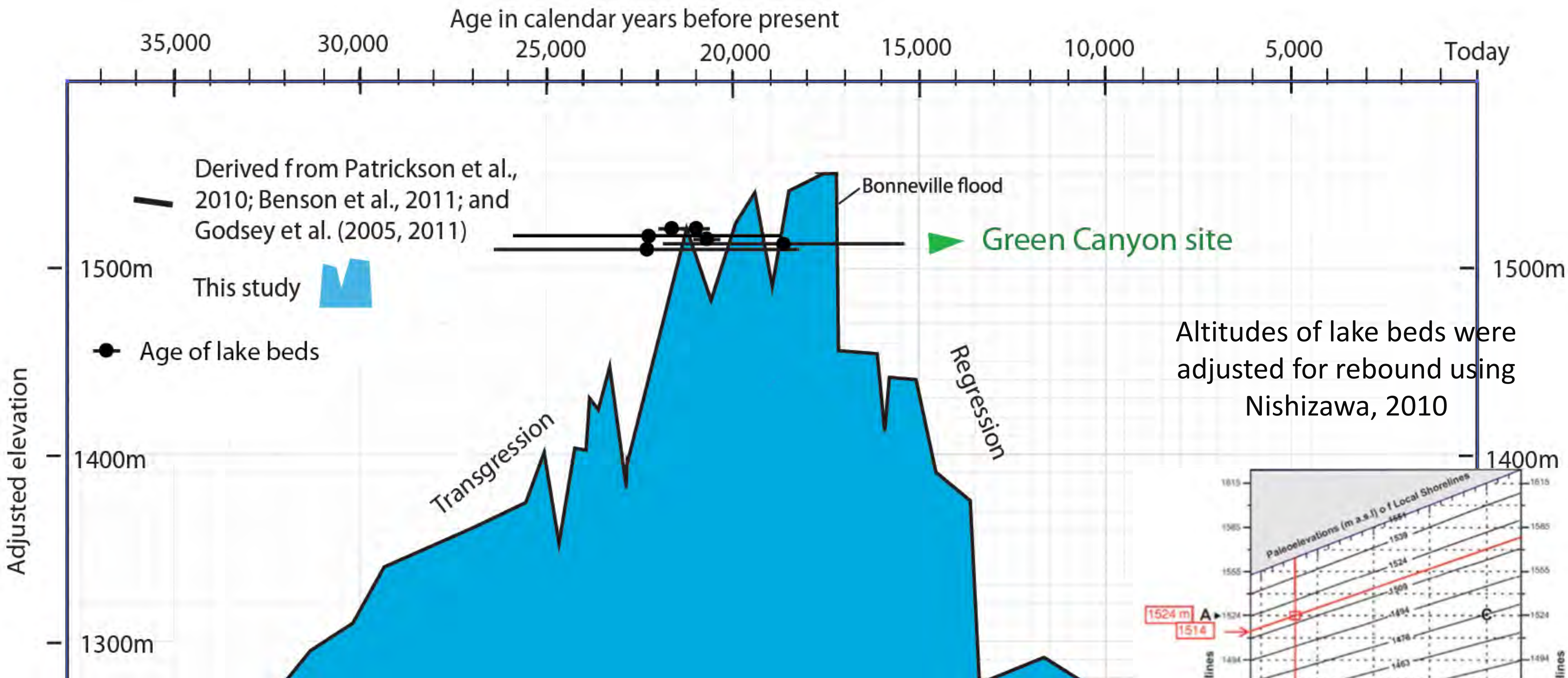


21.7 ± 0.3 cal ka
14C
18.4 ± 2.8 ka
OSL
22.2 ± 3.6 ka
OSL
22.2 ± 3.6 ka
OSL

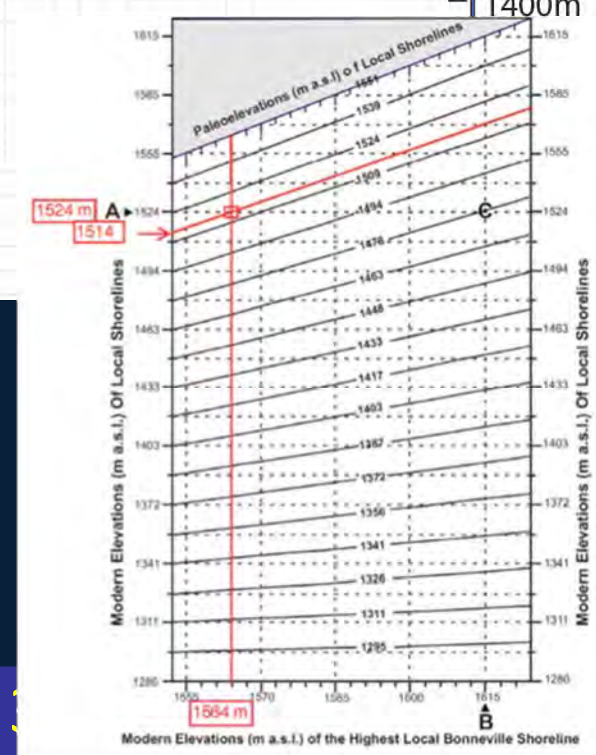
22.3±4.1 ka
OSL

One v. young age in a soil was omitted

When did earthquakes occur?



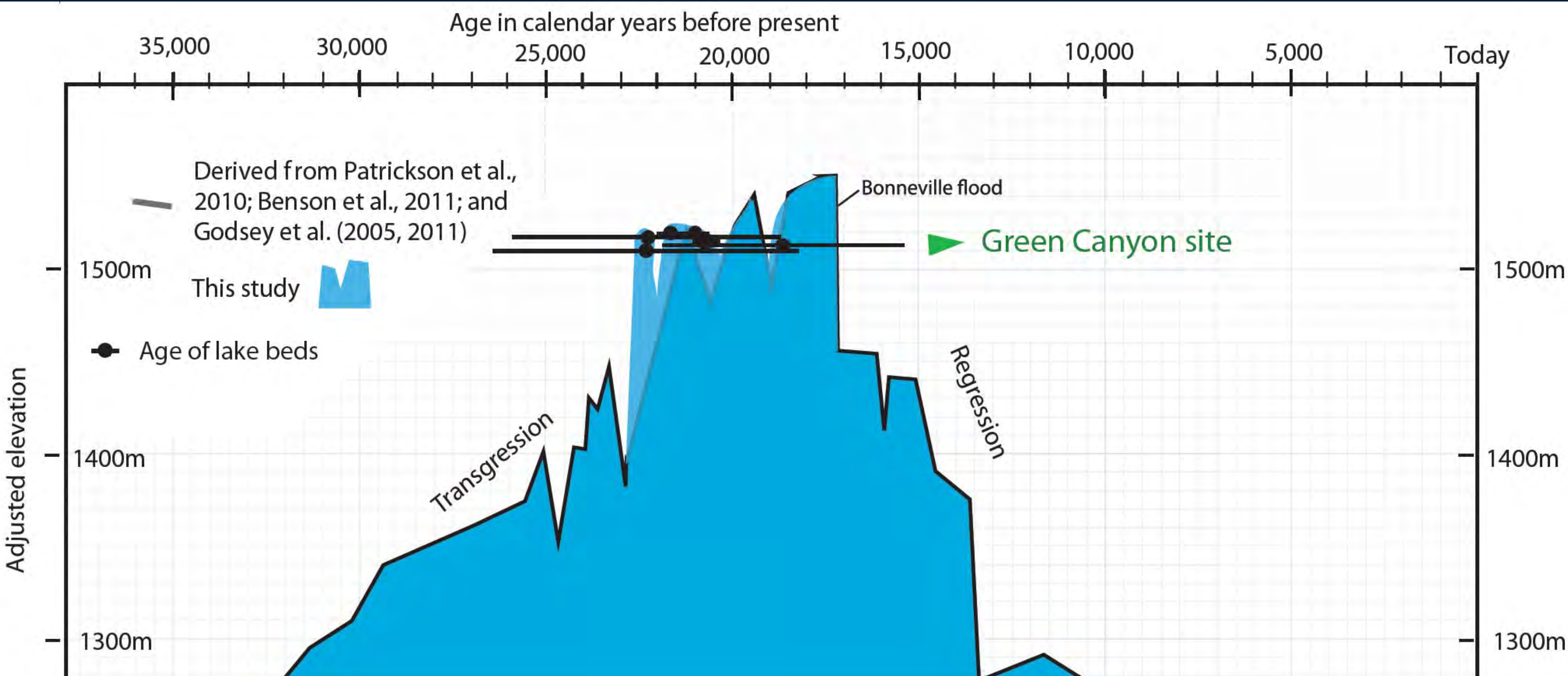
Altitudes of lake beds were adjusted for rebound using Nishizawa, 2010



- Note, only one age agrees with current hydrograph
- although errors of OSL ages overlap

Nishizawa, 2010 fig

Possible updates to hydrograph?



- OSL and radiocarbon dating confirm the short time period of deposition-5-6 ky
  - <22.3 to Bonneville flood at ~17.4 ka(?).
- Rise to this altitude was earlier than expected
- Hydrograph may need tweaking

What is age of the flood?

Table 4
Timing of Lake Bonneville hydrologic events.

Lake Bonneville Hydrologic Event	Blue Lake Core BL04-4	Outcrop-Based Lake-Level Record
	PSV-Based age model (ka)	0 ka Reservoir effect (ka)
Stansbury Oscillation(s)	26.0–23.0	25.8–24.3
Initiation of Lake Bonneville overflow	18.5	≤18.6
Fall from the Bonneville highstand	17.0	17.5
Beginning of the Provo event	17.0	17.4
Fall from Provo level	15.2	13.8 (Godsey)[a] or 17.0 (Oviatt)[b]
Gilbert event	13.1–11.6	12.9–11.2

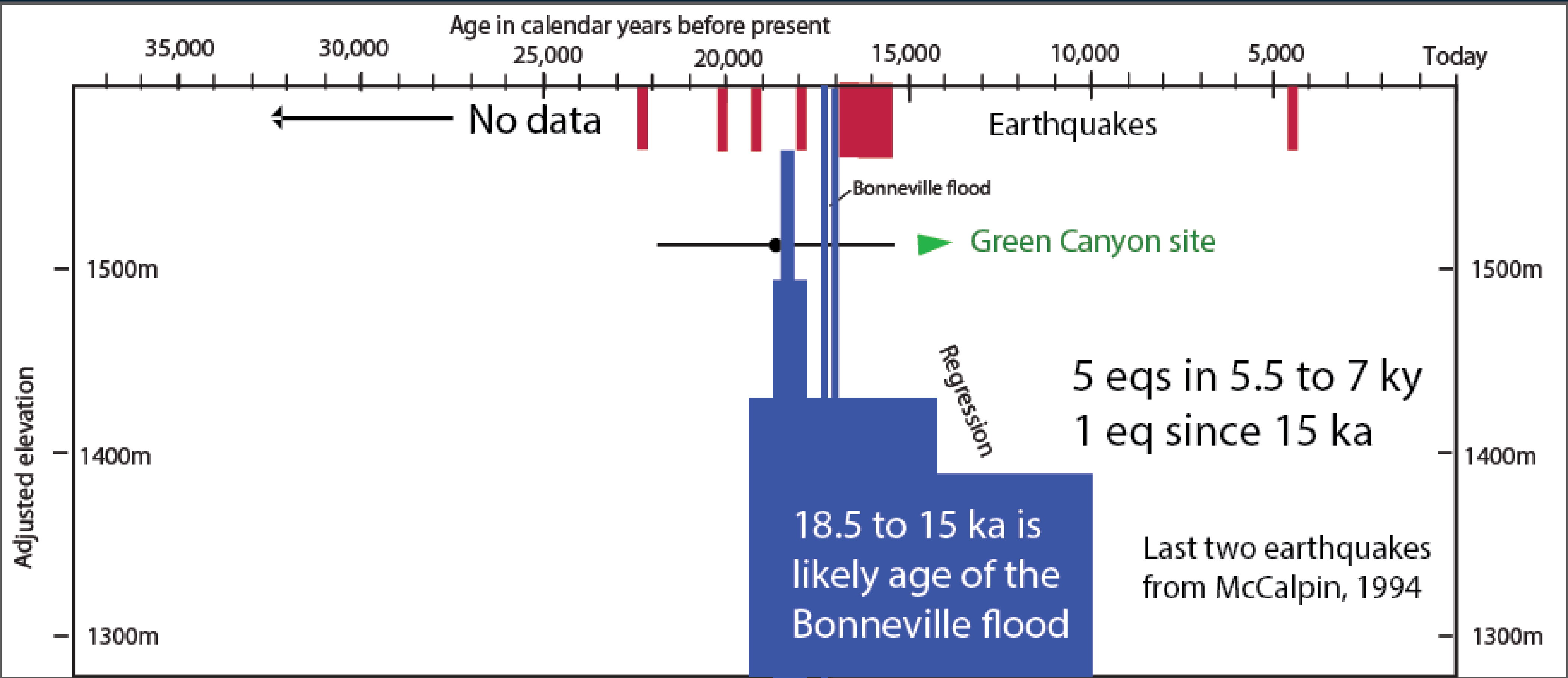
[a] Godsey refers to Godsey et al. (2005).
[b] Oviatt refers to Oviatt (1997).

Age of Bonneville flood is uncertain

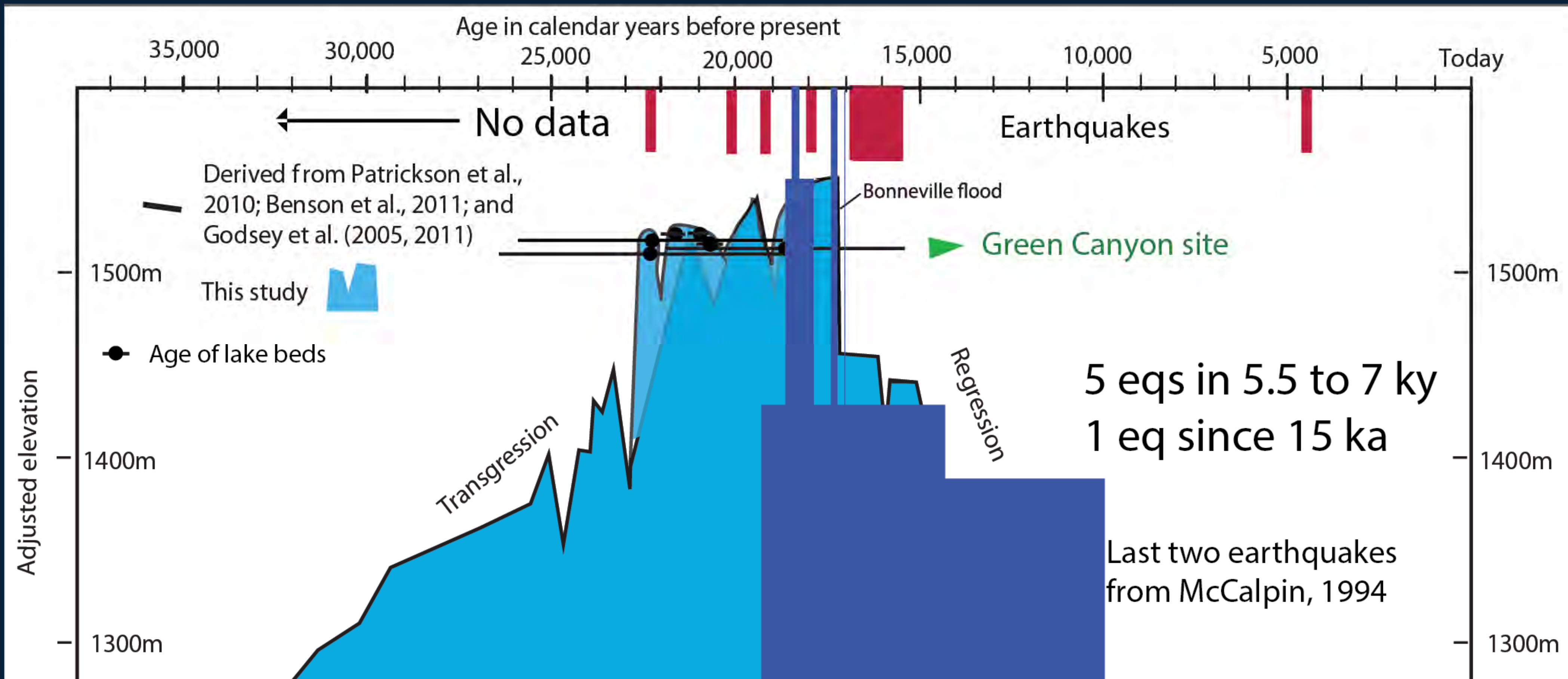
Authors	Ages of youngest transgresive sediment	Ages of oldest Provo sediment	Age of flood	Notes
Benson et al. , 2011			17.0 ka	Based on oxygen isotope, carbonate mineralogy stratigraphy.
Miller et al. 2012 Boreas	Model A	18.1±0.4 is oldest Provo age	18.1±0.4 ka is oldest Provo age	Gastropod shells, snails
	Model B	18.1±0.4 is oldest Provo age	17.7 - 17.8 is youngest possible in error bars	All ages are ok, put flood at youngest possible in error bars
DuRoss and Hylland, 2013: Bailey's Lake	*After OSL dated lacustrine silt and fine sand at 19. 3± 0.38 ka*	*Before OSL dated sediment 14.07± 0.82*	*19.1 to 14.1 ka*	
DuRoss and Hylland, 2013: Penrose Drive	After 17.8+/-0.7 ka and 17.0+/-1.4 ka radiocarbon	10,000+/-75 ka 9,940+/-65 ka 9,390+/-45 ka 9,550+/-55 ka	After 17.0 ka and before 10 ka	
McGee et al., 2012 EPSL	18.2±0.3 ka	16.5 ka	18.2± 0.3 ka based on end of deposition	U series and xx
Nishizawa 2010 uu dissertation	8 ages,		17.3 ka	Radiocarbon on shells
Oviatt unpublished compilation	After ~18.3 ka		After 18 ka	Radiocarbon on wood
Janecke et al. this study	After 18.7 ka OSL			There is considerable sediment on top of the dated sample

Compilation of some recent studies

Age of Bonneville flood is dark blue

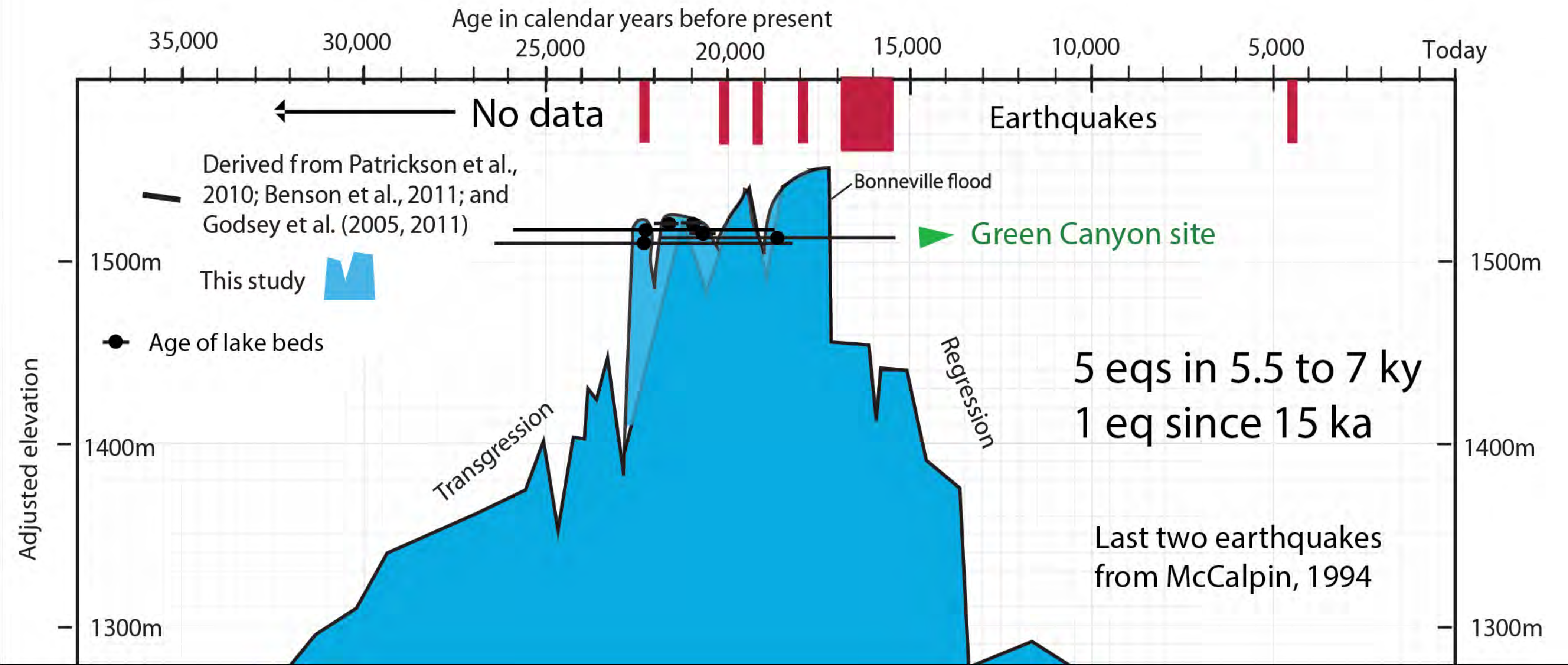


Age of Bonneville flood is dark blue



- Clustering of earthquakes might be tighter if flood is older than 17.4 ka

Implications for earthquake hazards?

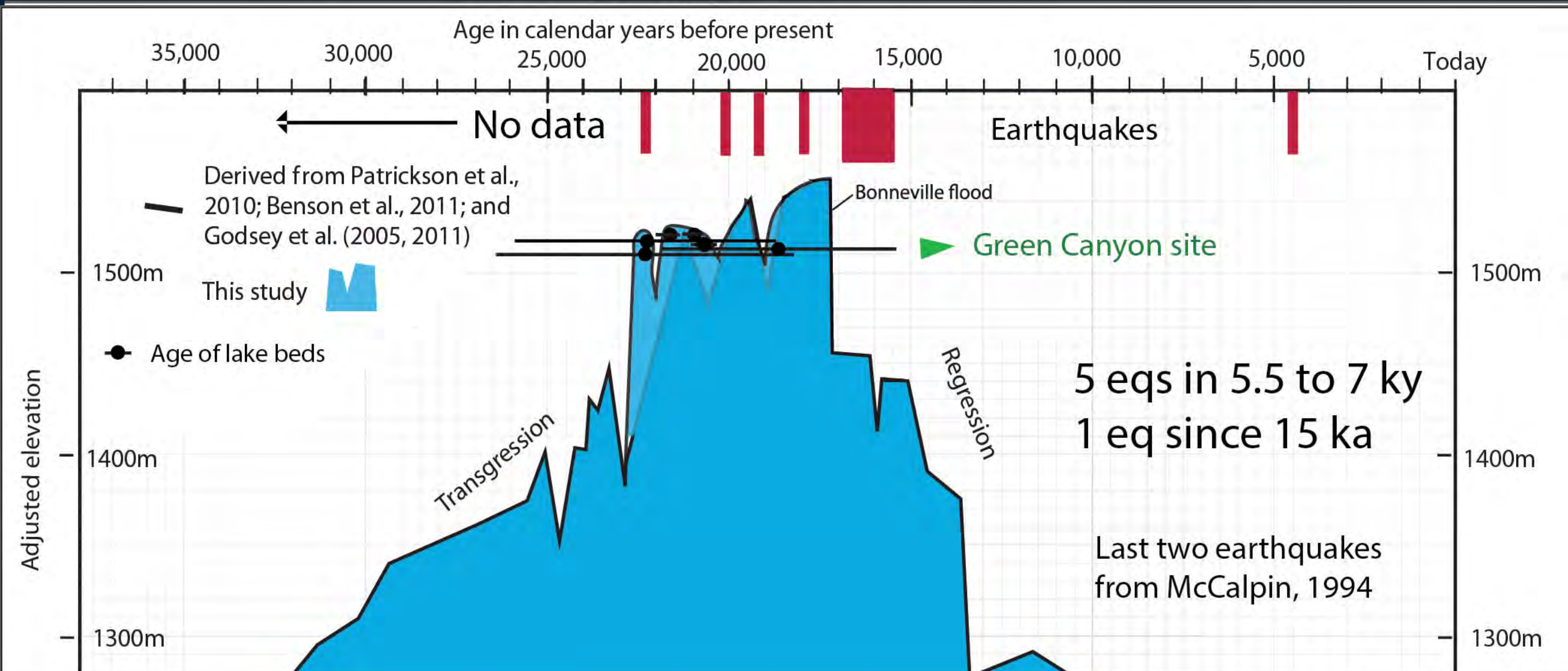


- Episodic slip and loading-induced seismicity
- On north and central segments of E. Cache fault
- During deep water phases of Lake Bonneville.
- Decline in earthquake frequency on adjacent segments of the East Cache fault after the Bonneville flood,

In contrast to the Wasatch fault,

- which increased its slip rate markedly at the same time (Karow and Hampel, 2010)

Regardless, earthquakes clustered when lake was high

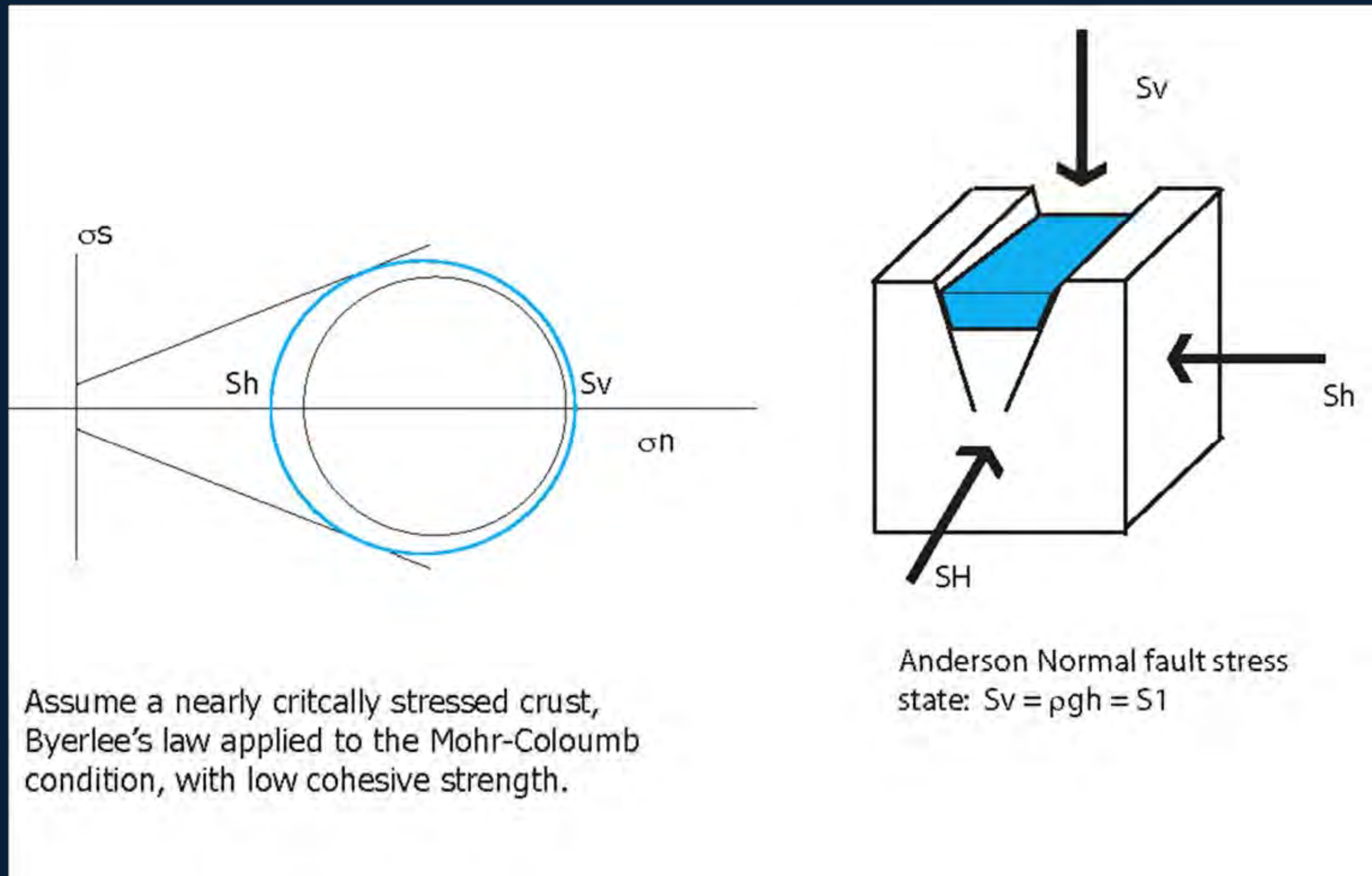


Induced seismicity is due to 3 factors

- Increased pore pressure
- (Mohr circle moves left)

- Loading
- (Circle grows)

- Flexure at upper monoclinal hinge
- (Circle grows even more)



Conclusions

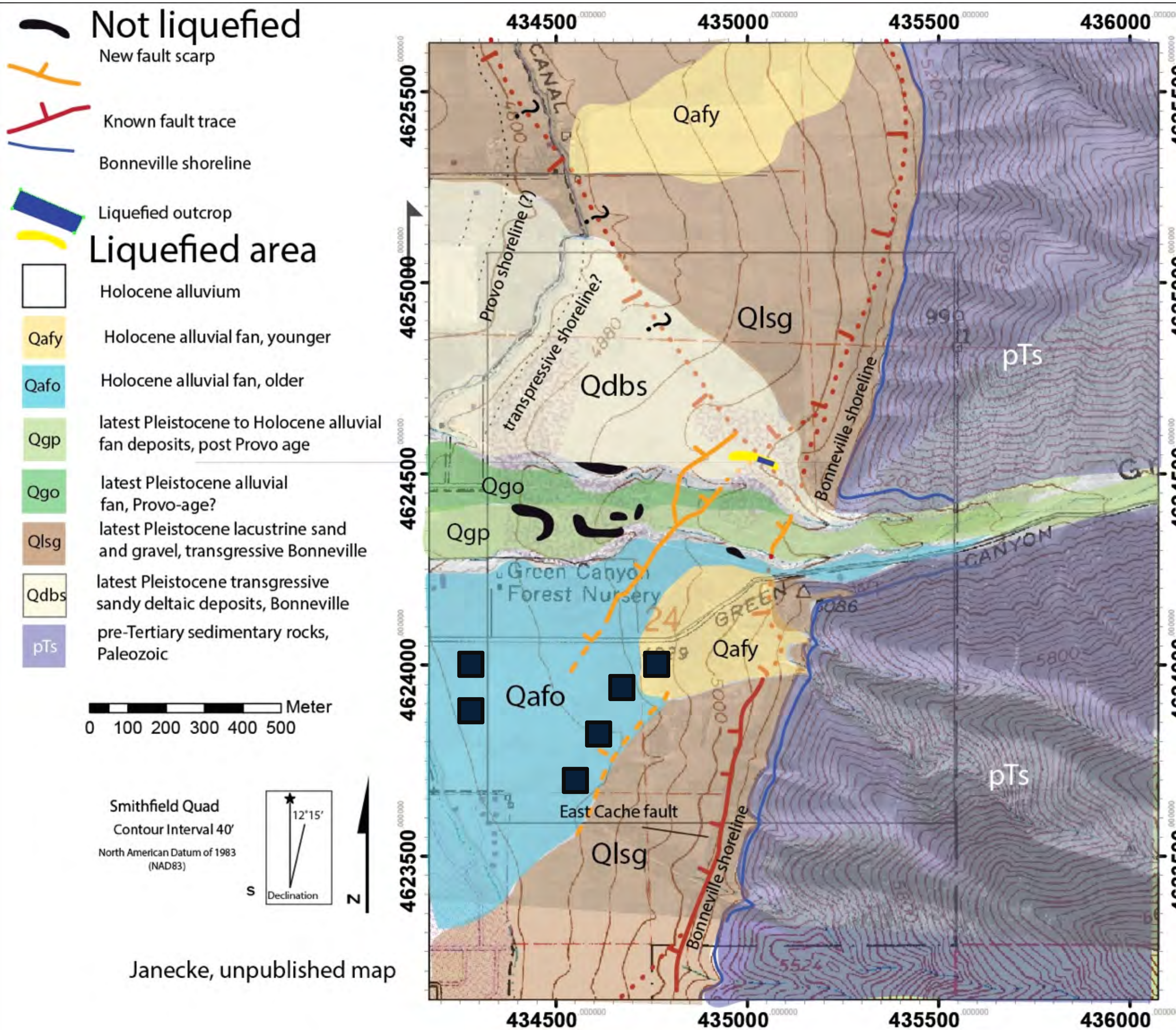
- Liquefaction suggests a change in the frequency of moderate to large(?) earthquakes on the East Cache fault

  -by increasing earthquakes when lake was high

  -or by suppressing earthquakes since the lake receded.

  -Loading, pore pressure and flexure all explain this (Karow and Hampel, 2010)

- Where does the strong deformation end?

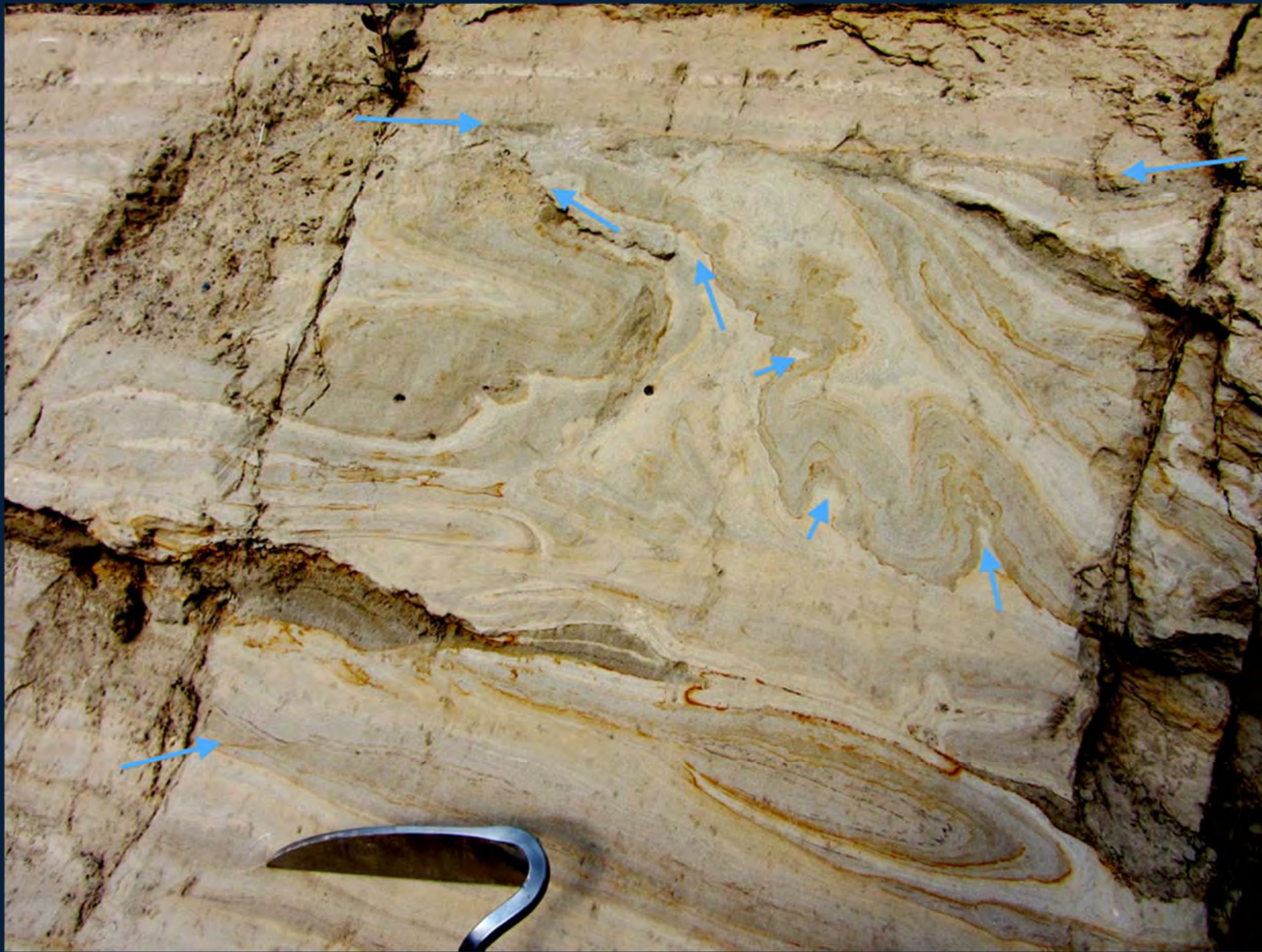


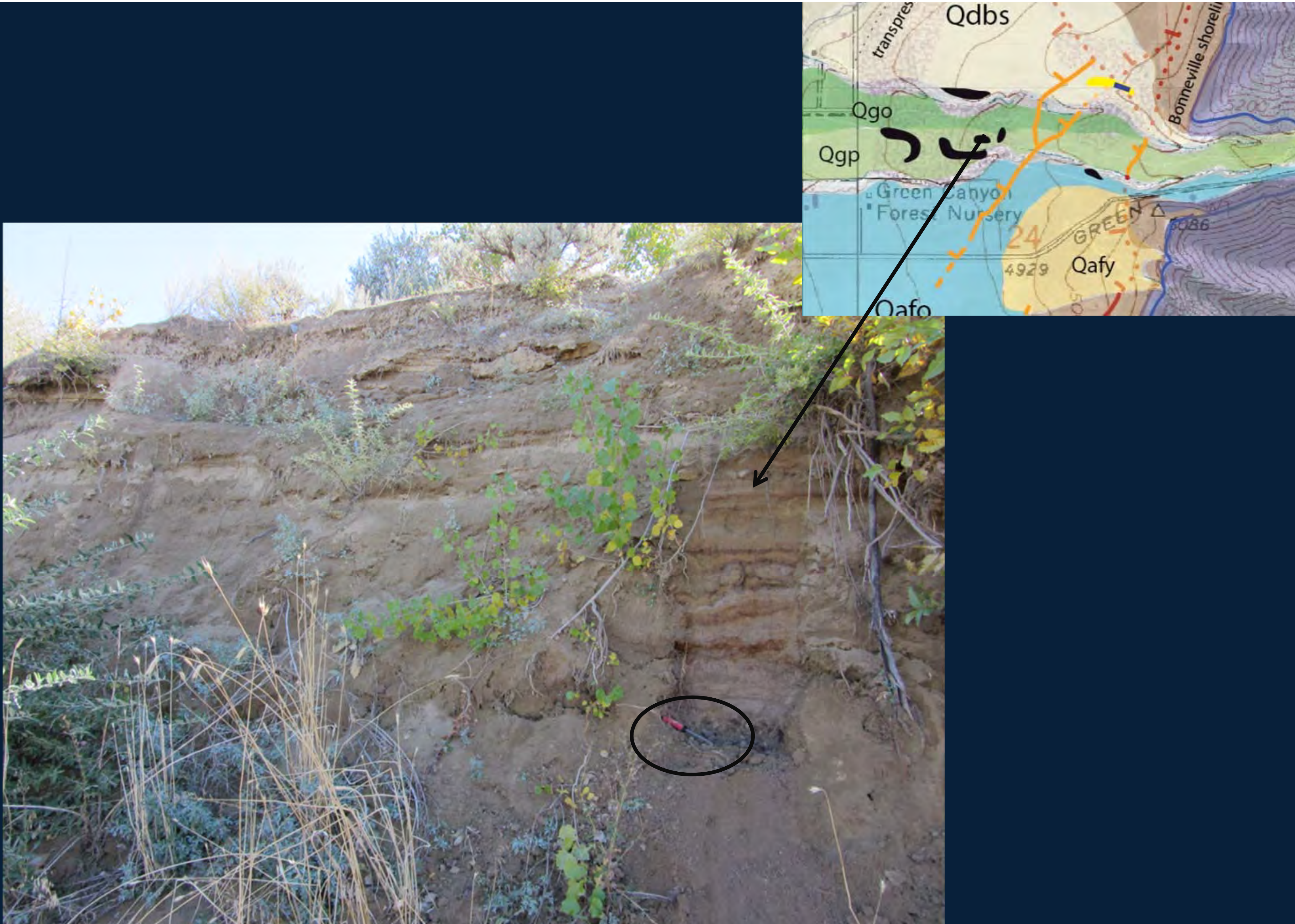
Not liquefied
New fault scarp
Known fault trace
Bonneville shoreline
Liquefied outcrop
Liquefied area
Holocene alluvium
Qafy
Holocene alluvial fan, younger
Qafo
Holocene alluvial fan, older
Qgp
latest Pleistocene to Holocene alluvial fan deposits, post Provo age
Qgo
latest Pleistocene alluvial fan, Provo-age?
Qlsg
latest Pleistocene lacustrine sand and gravel, transgressive Bonneville
Qdbs
latest Pleistocene transgressive sandy deltaic deposits, Bonneville
pTs
pre-Tertiary sedimentary rocks, Paleozoic
Meter
0 100 200 300 400 500
Smithfield Quad
Contour Interval 40'
North American Datum of 1983 (NAD83)
12°15'
Declination
S
N
Janecke, unpublished map
434500
435000
435500
436000
4625500
4625000
4624500
4624000
4623500
Provo shoreline (?)
transpressive shoreline?
Bonneville shoreline
East Cache fault
Green Canyon Forest Nursery
GREEN
CANYON
CANAL

How is deformation distributed?

Our tour will be from near to far, westward

Look north

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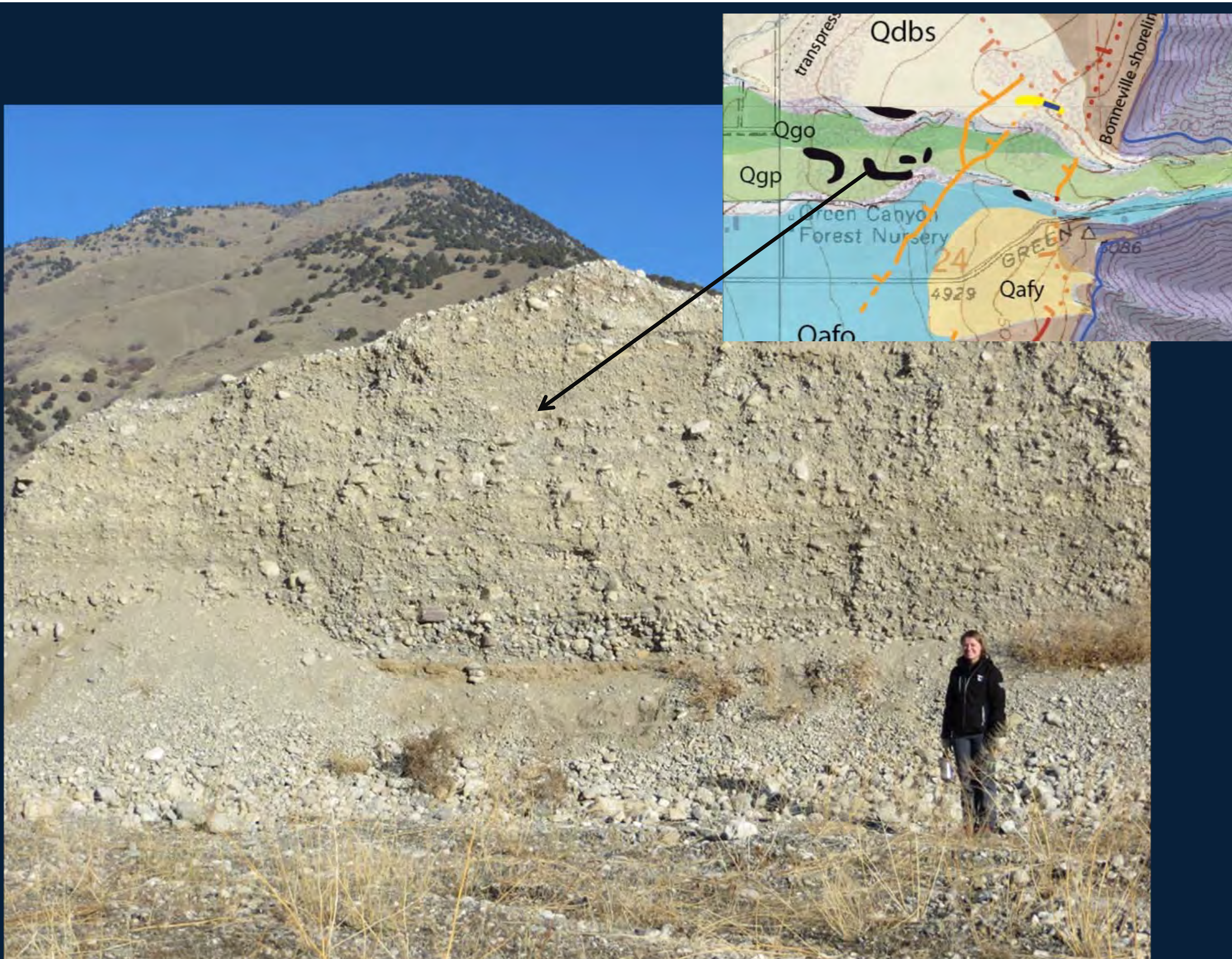
Bonneville shoreline
Qgo
Qgp
Green Canyon
Forest Nursery
24
GREEN
5086
4929
Qafy
Qafo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Bonneville shoreli
Qgo
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Green Canyon
Forest Nursery
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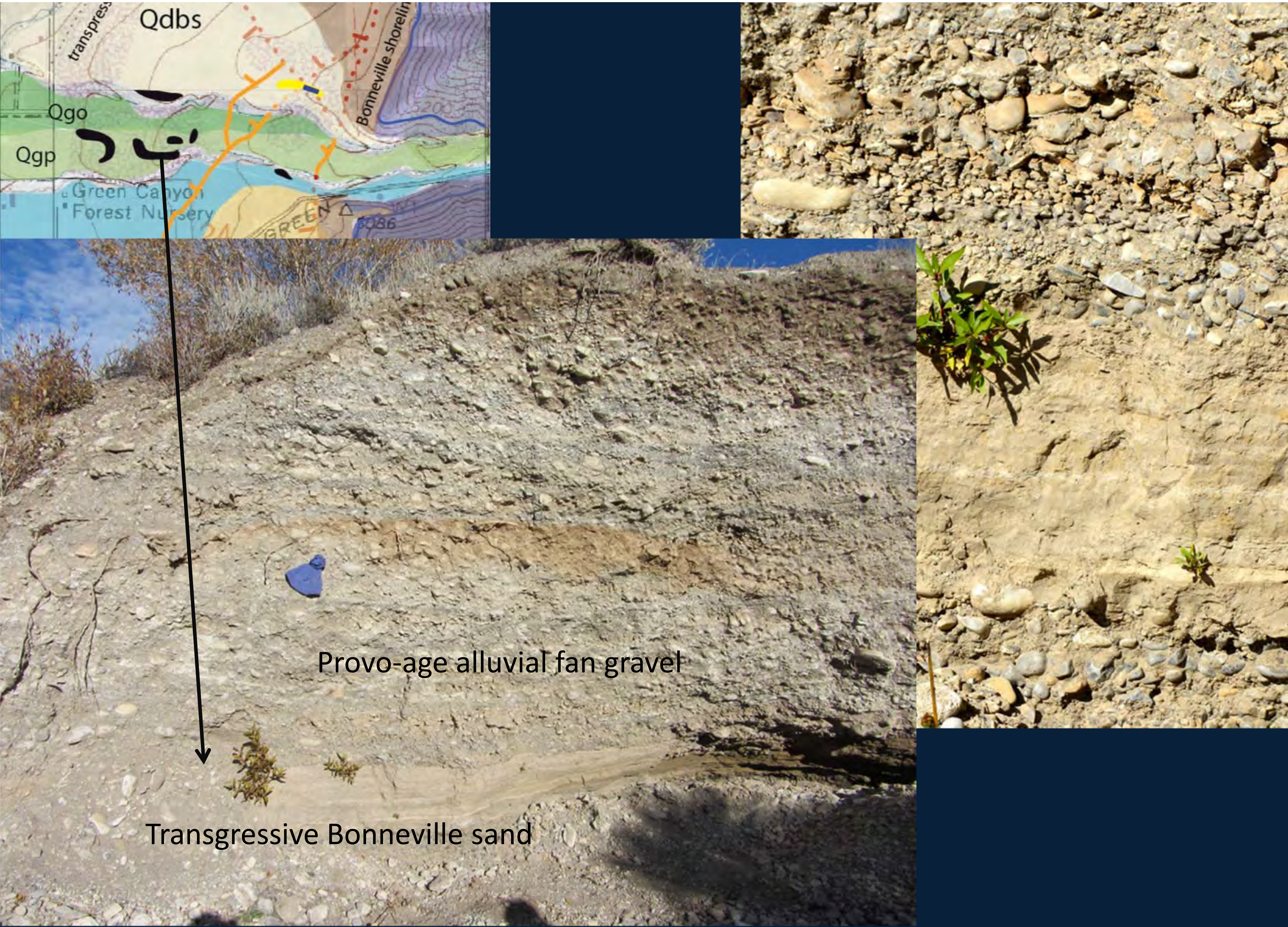
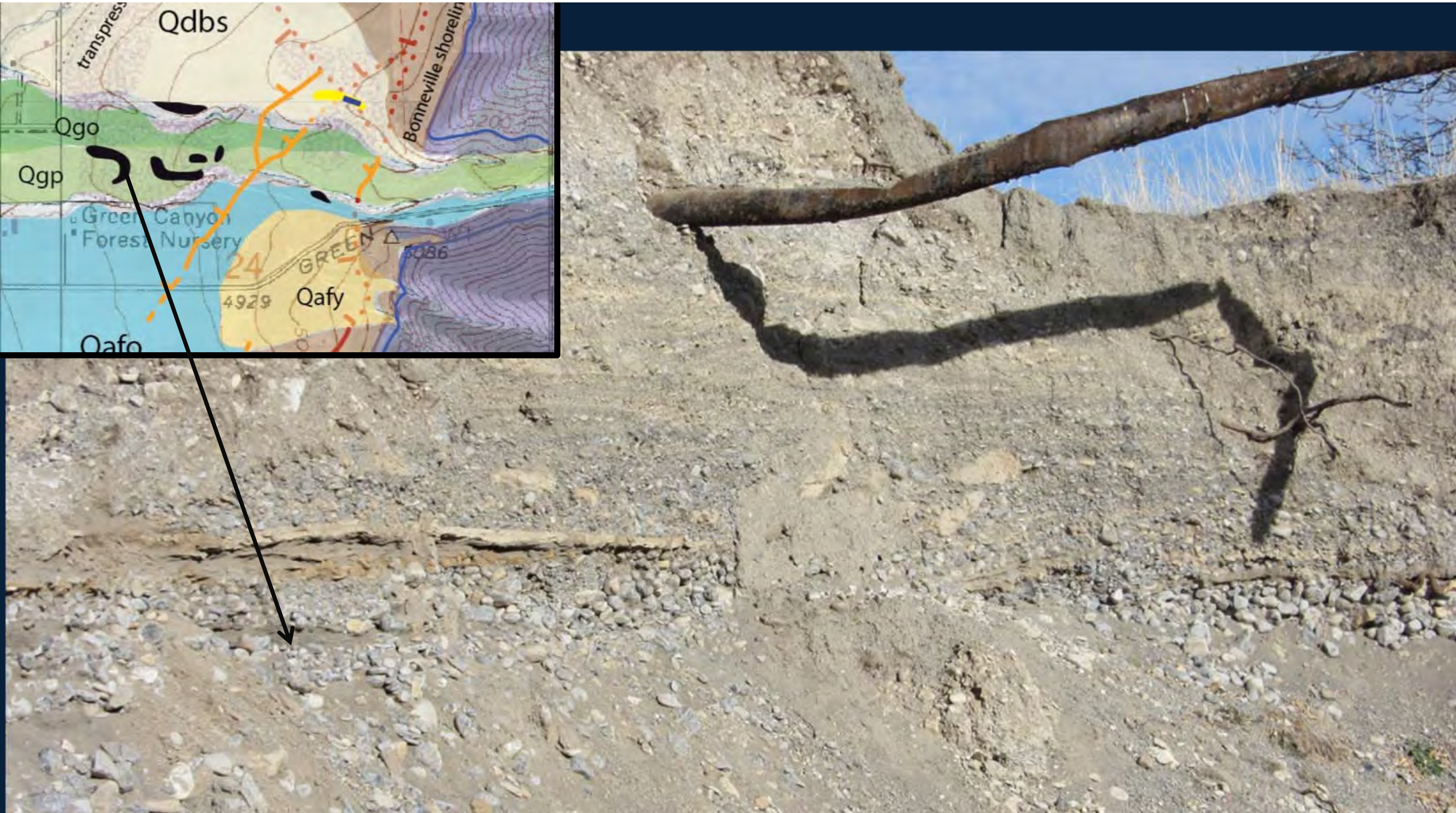


Qdbs
Qgo
Qgp
5086
Provo-age alluvial fan gravel
Transgressive Bonneville sand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Green Canyon
Forest Nursery
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Qdbs
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Green Canyon
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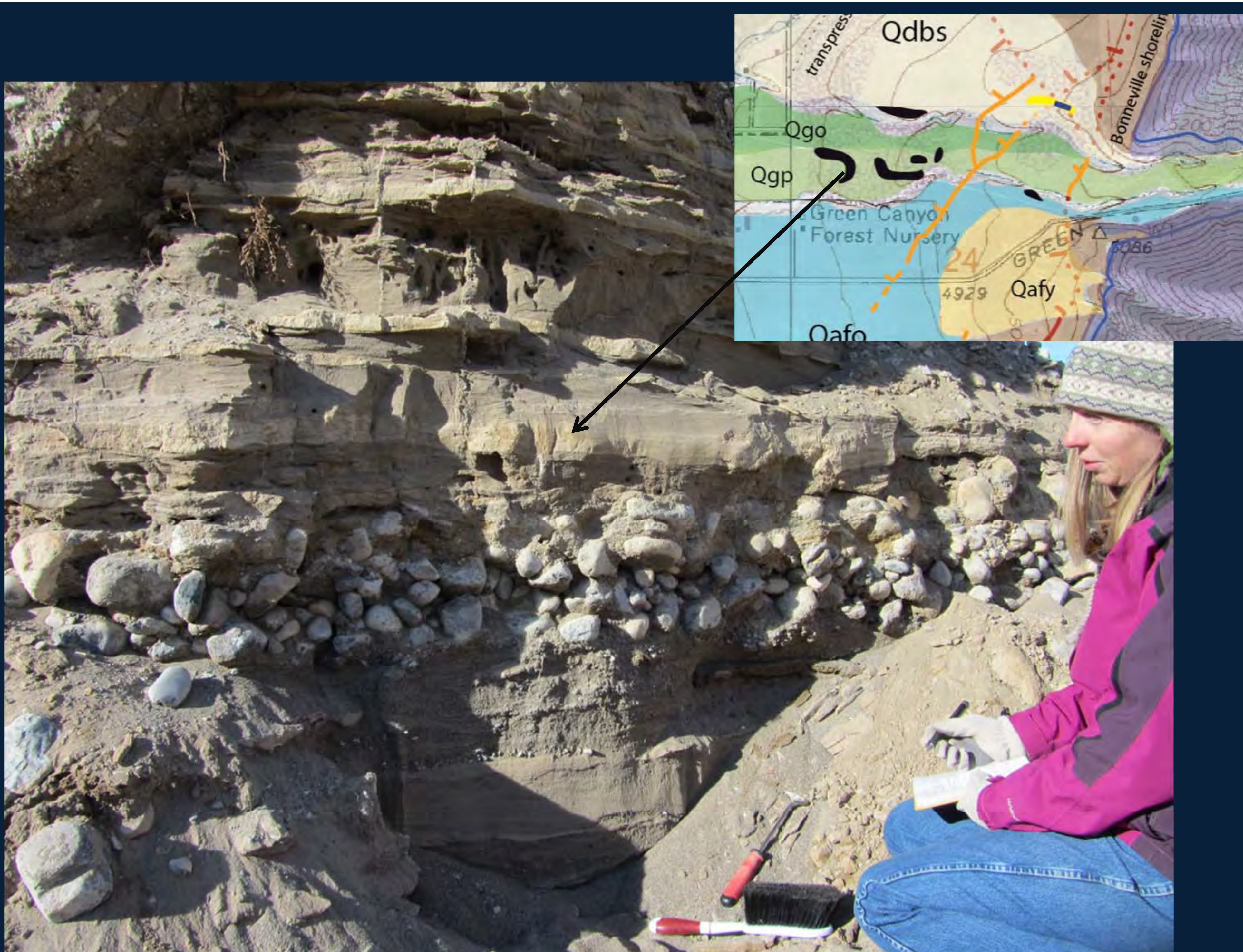

Qdbs
Qgo
Qgp
Green Canyon
Forest Nursery
24
GREEN
5086
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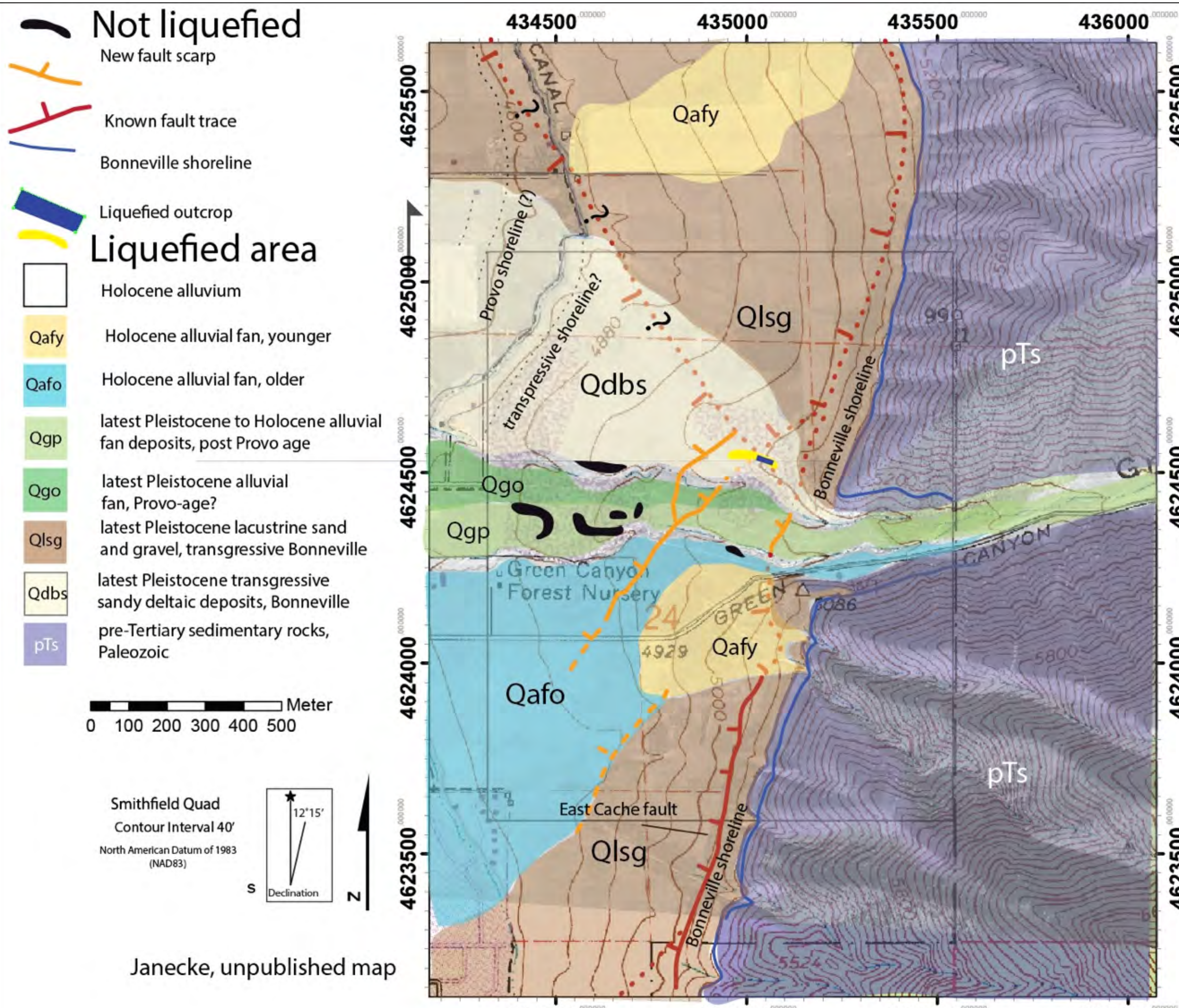
Qafy
Qafo



Janecke, unpublished map

Hansel Valley earthquake

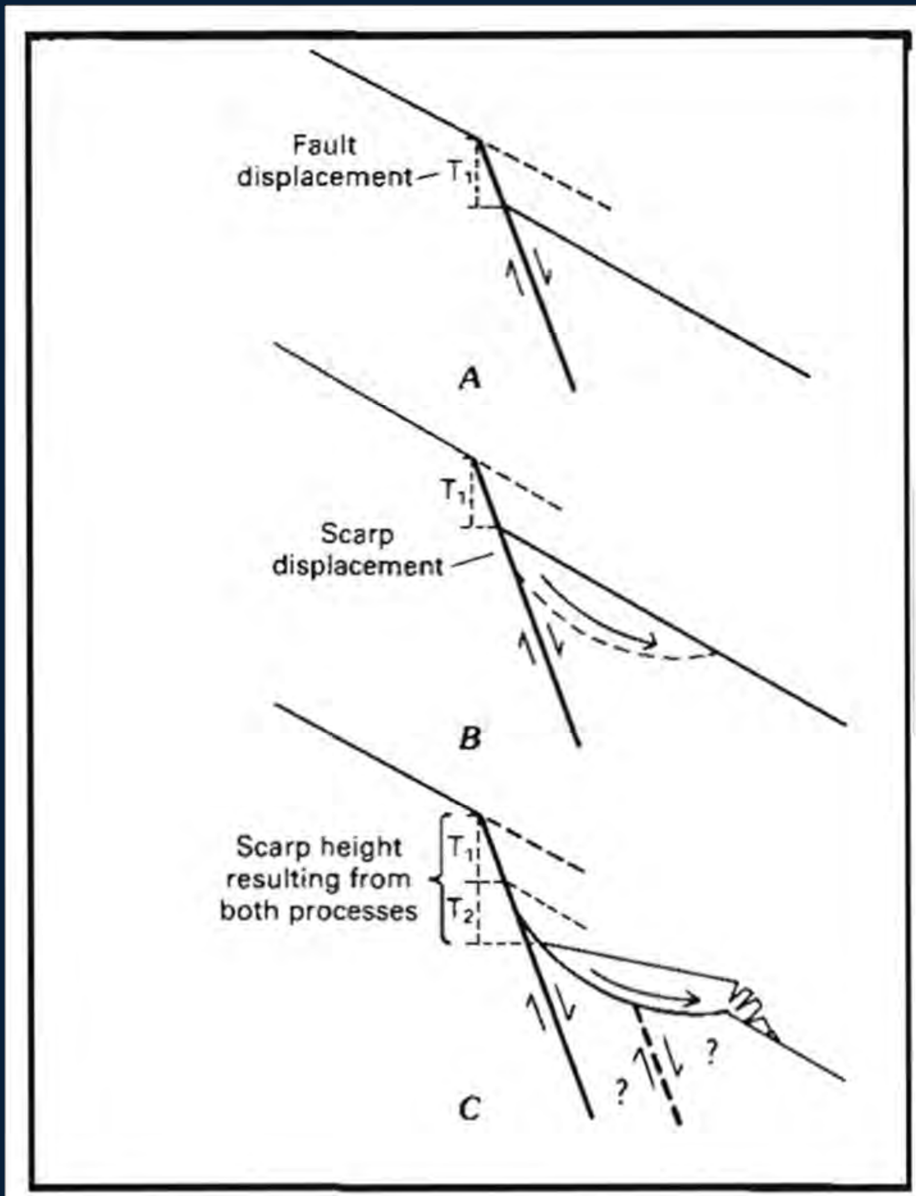


FIGURE 13.—Conceptual model showing how fault scarps on the southwestern margin might be heightened by a coseismic rotational slump. *A*, Initial fault displacement creates a scarp of height T_1. *B*, During seismic shaking, a rotational slump begins to form on the downthrown block. Slumping would be likely if surface materials were saturated (see text). *C*, After slumping, the total scarp height includes components from fault displacement (T_1) and from the slump headscarp (T_2). The dashed and queried fault in *C* indicates that the causative fault may actually underlie the slump, in which case the scarp preserved today is entirely of slump origin. Because slumps were large and slump toes indistinct, profiles used to calculate surface offsets in figure 12 were not extended downslope to include the entire slump deposit.

McCalpin et al, 1992

Hansel Valley has ~7 liquefaction events in West Gully

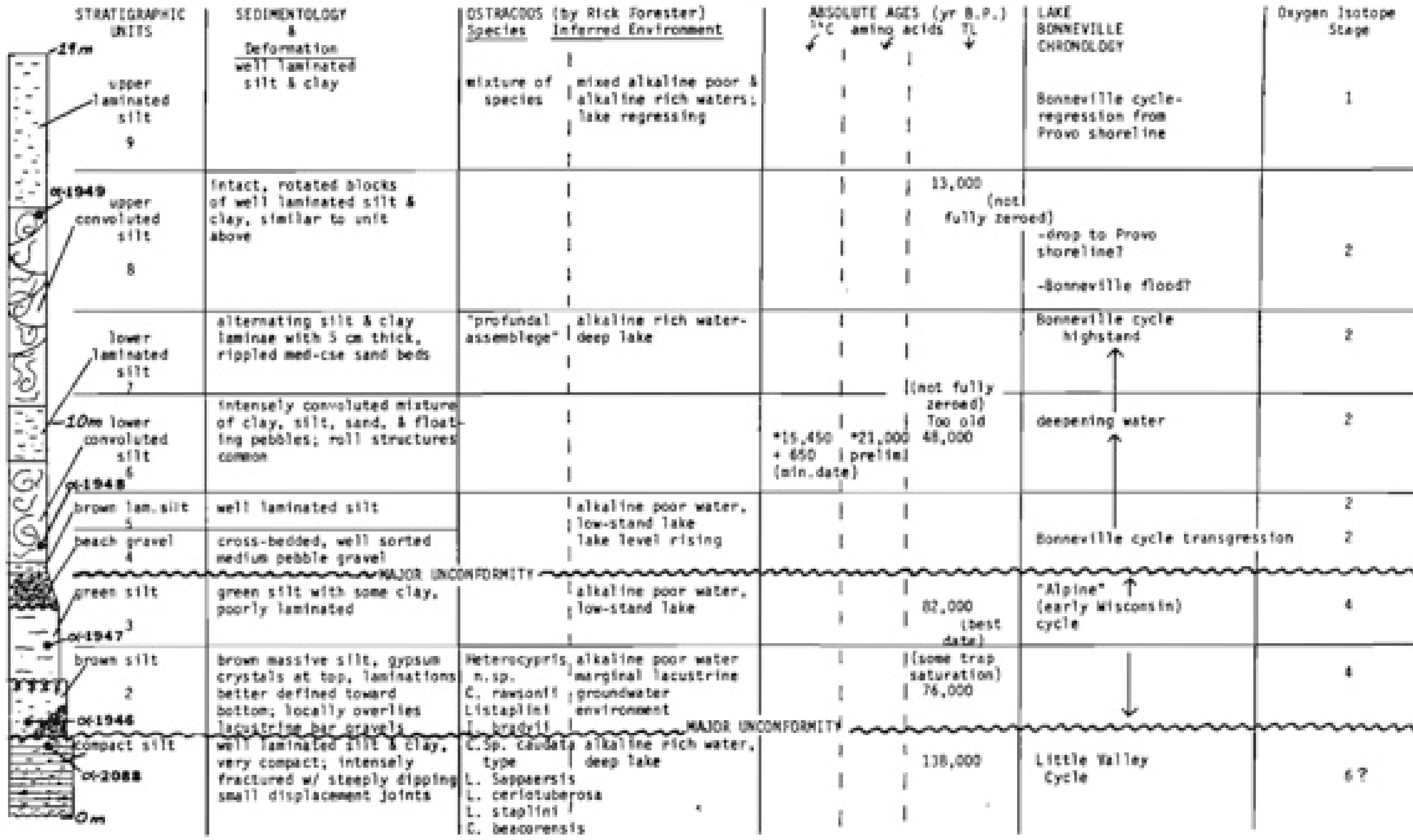
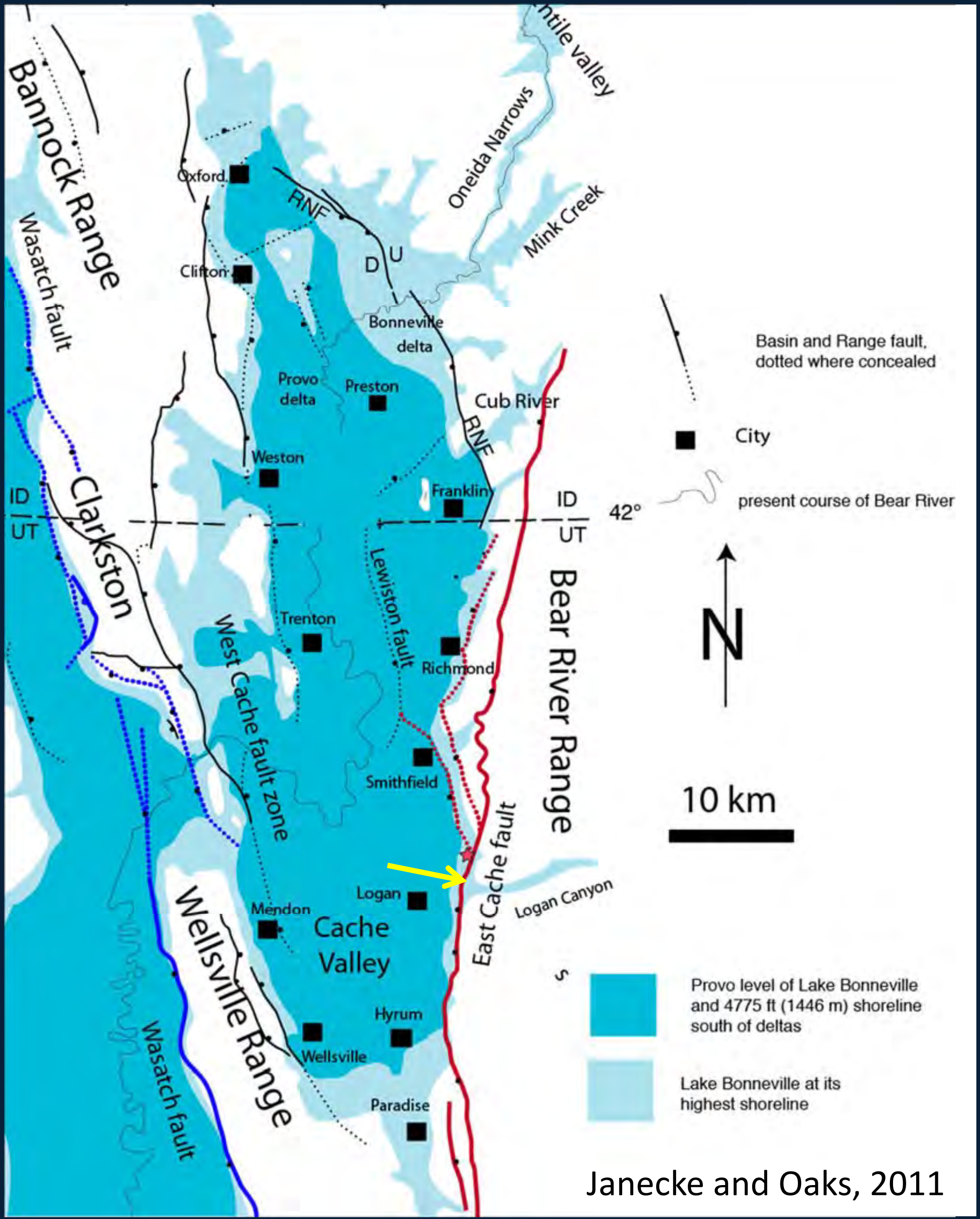


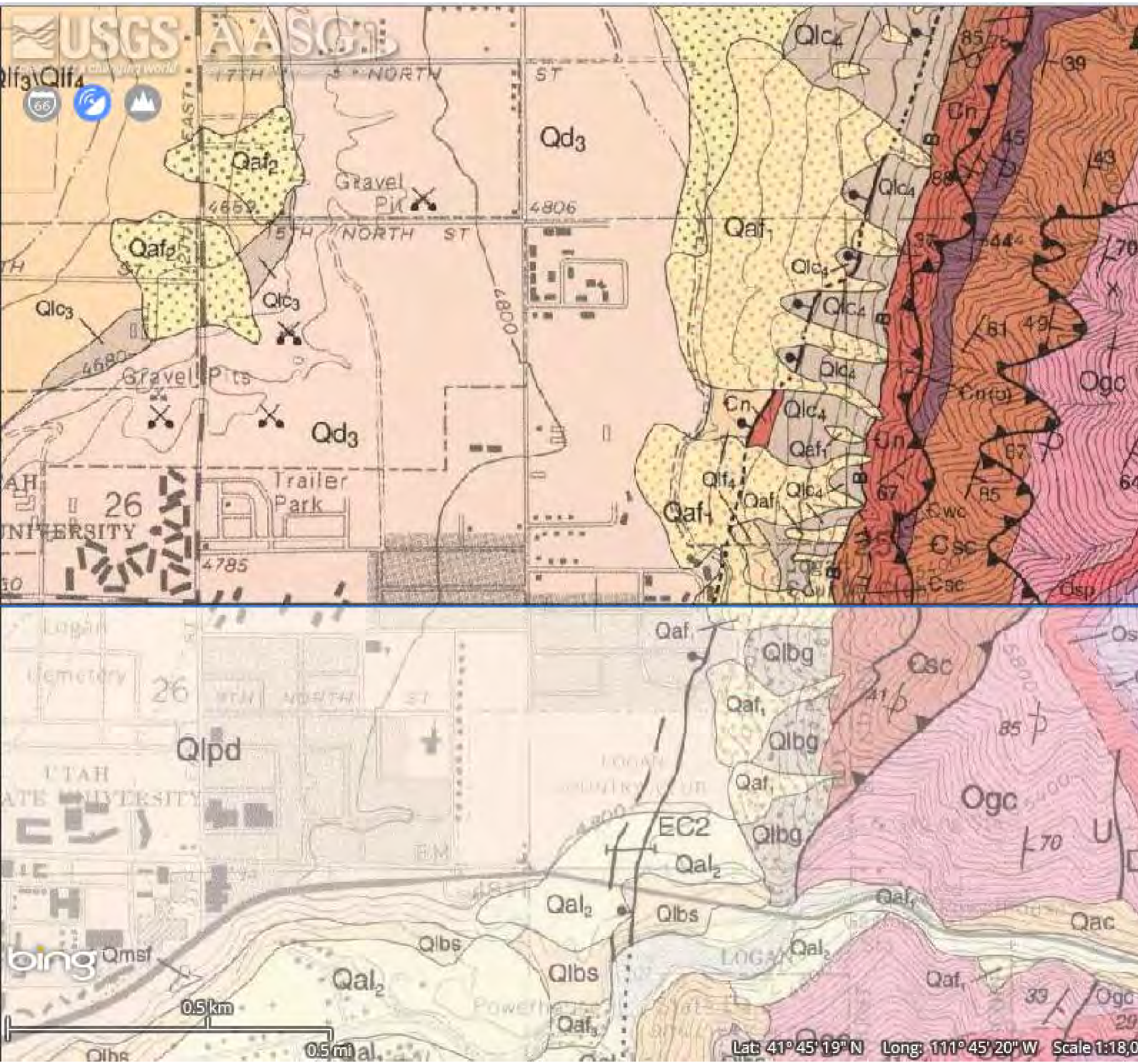
Fig. 5

Composite stratigraphic section from the West Gully. Evidence from sedimentology and ostracod assemblages (interpreted by R. Forester, USGS) is compatible with TL, ^{14}C, and amino-acid dates.

Thermoluminescence (TL) Dating in Seismic Hazard Evaluations: An Example From The Bonneville Basin, Utah
By James McCalpin
Page 18

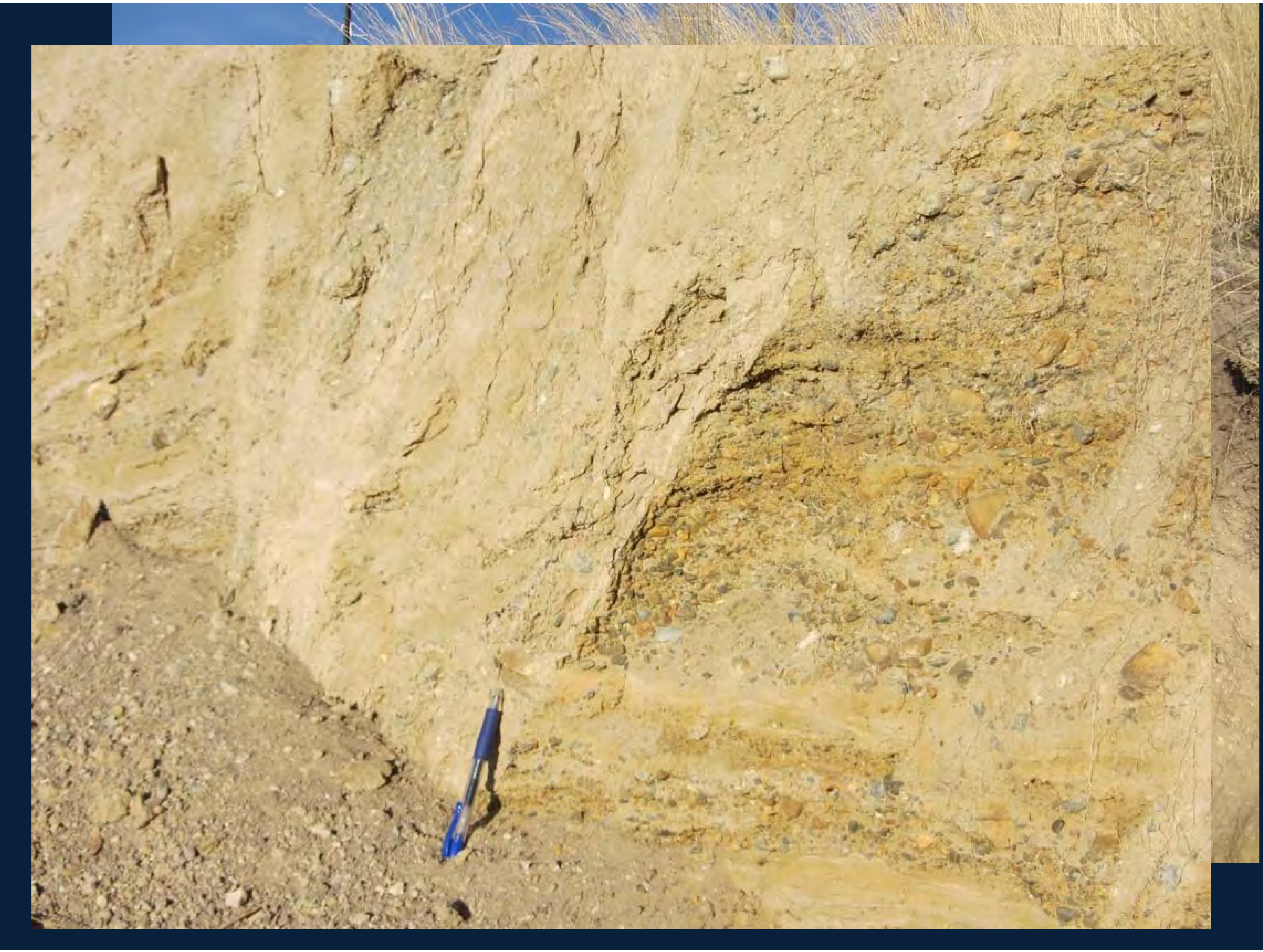
Farther south, East Cache fault was temporarily exhumed by Rocky Mtn power company





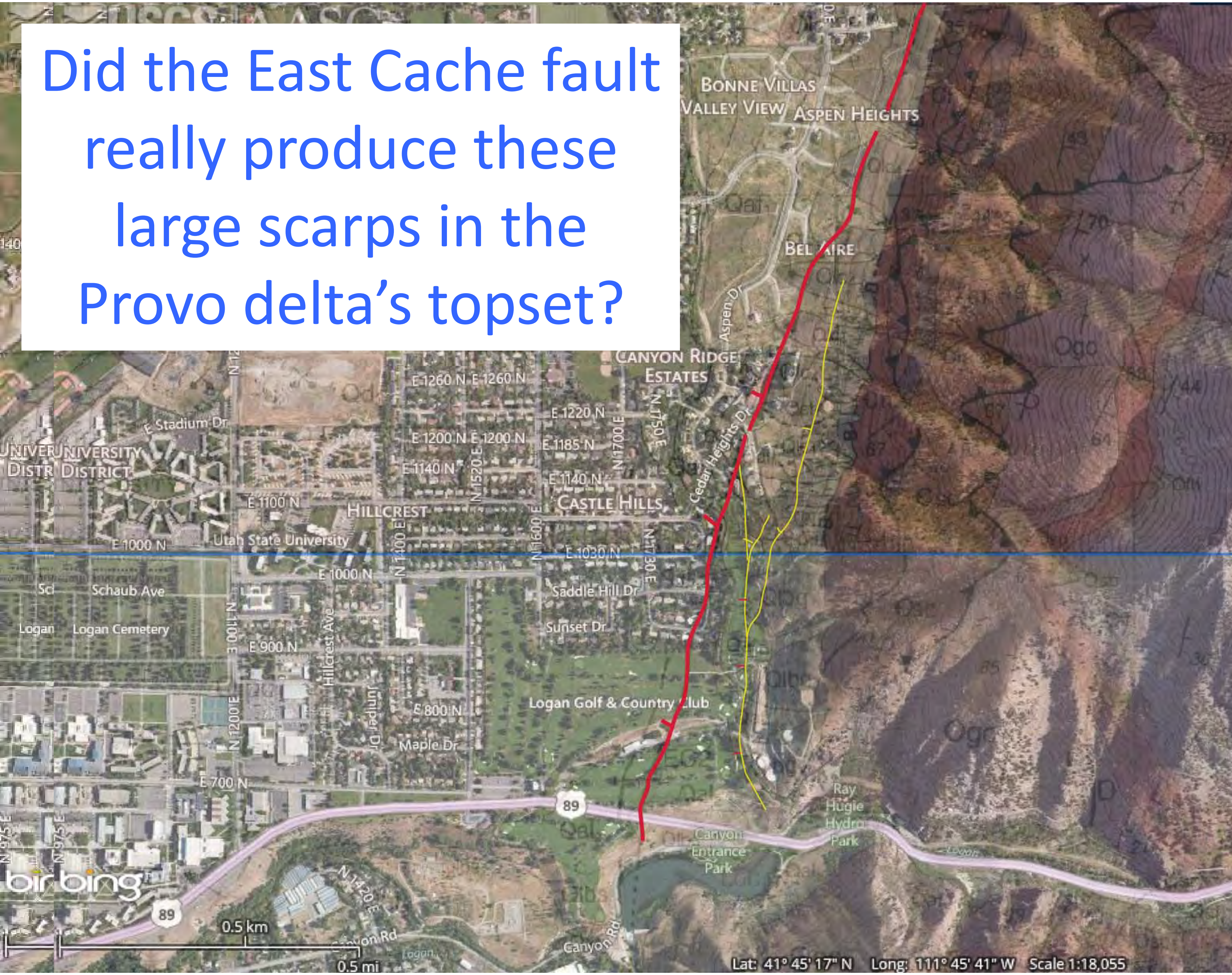
USGS
AASG
Qlf4
Qd3
Qaf2
Gravel Pit
4806
4659
15TH NORTH ST
Qaf1
Qlc4
Qlc3
4680
Gravel Pits
Qd3
Trailer Park
26
4785
Cn
Csc
Ogc
Qlbg
Qlpd
26
EC2
Qal2
Qlbs
Qmsf
Qac
bing
0.5 km
0.5 mi
Lat: 41° 45' 19" N
Long: 111° 45' 20" W

Figure 126 Oblique aerial photo of the East Cache fault looking south along the base of the Bear F
scarp, marked on our main panoramic view as a red line that crosses the golf course, can be seen on this pic



E 1700 N
Country Lane Estates
E 1625 N
E 1590 N
E 1550 N
E 1630 N
Deer Crest
Bonne Villas
Valley View
Aspen Heights
E 1600 N
E 1550 N
N 1770 E
N 1640 E
N 1600 E
N 1515 E
Bristol Rd
E 1500 N
E 1500 N
E 1460 N
1400 N
Bel Aire
E 1425 N
E 1425 N
E 1400 N
E 1385 N
N 1720 E
E 1350 N
Aspen Dr
Jack B Parson Dr
N 1400 E
N 1200 E
Lundstrom Park
Canyon Ridge Estates
E 1260 N
E 1260 N
E 1220 N
N 1750 E
E Stadium Dr
E 1200 N
E 1200 N
E 1185 N
N 1700 E
Cedar Heights Dr
University District
E 1140 N
N 1520 E
E 1140 N
E 1100 N
Hillcrest
Castle Hills
E 1000 N
Utah State University
E 1030 N
N 1730 E
E 1000 N
Schaub Ave
Saddle Hill Dr
Logan Cemetery
N 1100 E
Hillcrest Ave
Sunset Dr
E 900 N
Logan Golf & Country Club
E 800 N
Juniper Dr
Maple Dr
E 700 N
89
Ray Hugie Hydro Park
Canyon Entrance Park
N 975 E
N 1420 E
89
0.5 km
0.5 mi
Canyon Rd
Canyon Rd
Lat: 41° 45' 19" N
Long: 111° 45' 49" W
Scale 1:18,055

Did the East Cache fault really produce these large scarps in the Provo delta’s topset?



Contemporary Deformation of the Wasatch Front, Utah, and its Implication for the Interseismic Loading of the Wasatch Fault Zone

Christine M. Puskas
UNAVCO

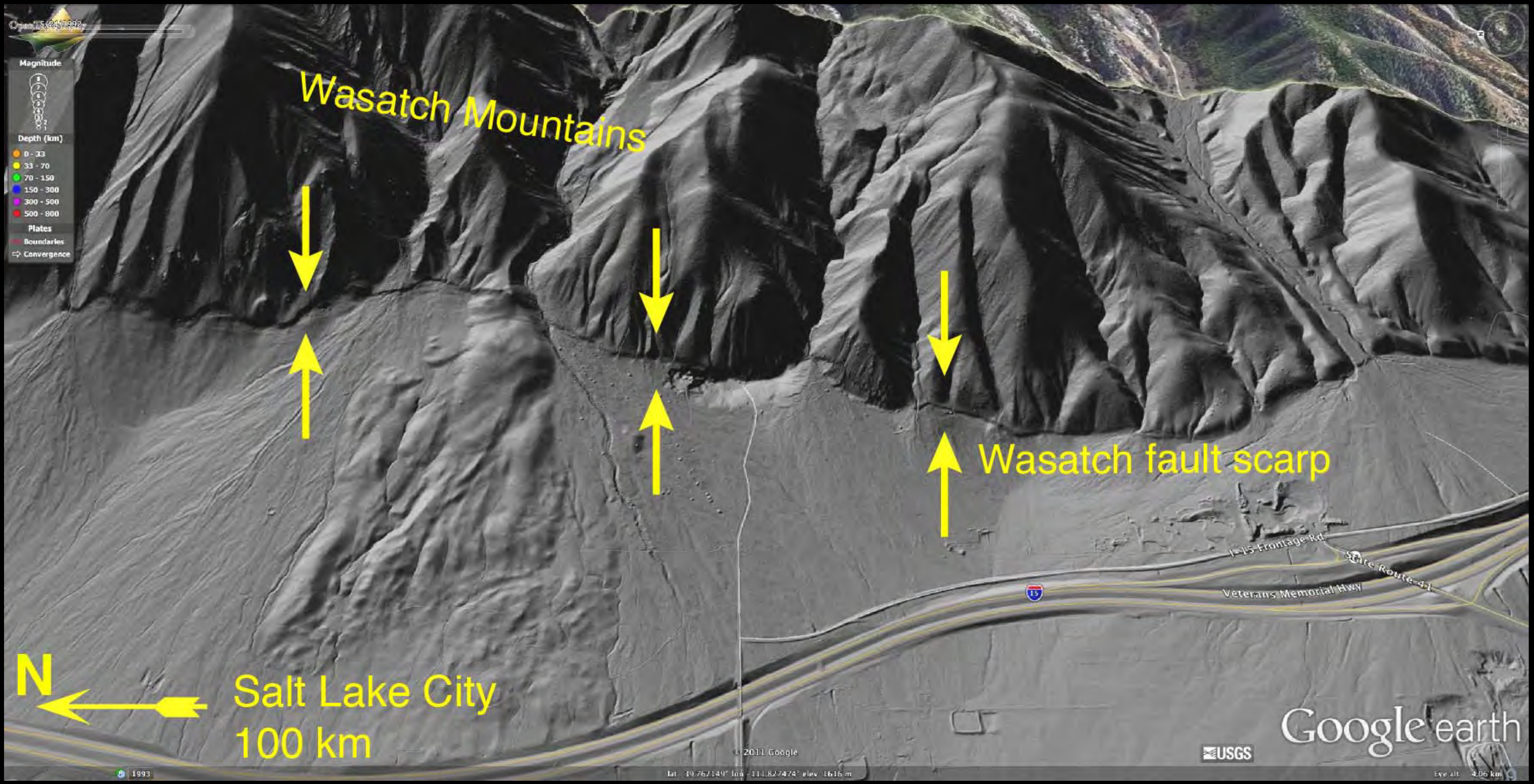
Wu-Lung Chang
National Central Univ.

Robert B. Smith
Univ. of Utah

- How fast is Wasatch Front extension?
  - GPS measurements
- How is deformation distributed?
  - Block rotation models
- Can GPS be used to constrain fault models?
  - Contributions of block motions
  - Dislocation models

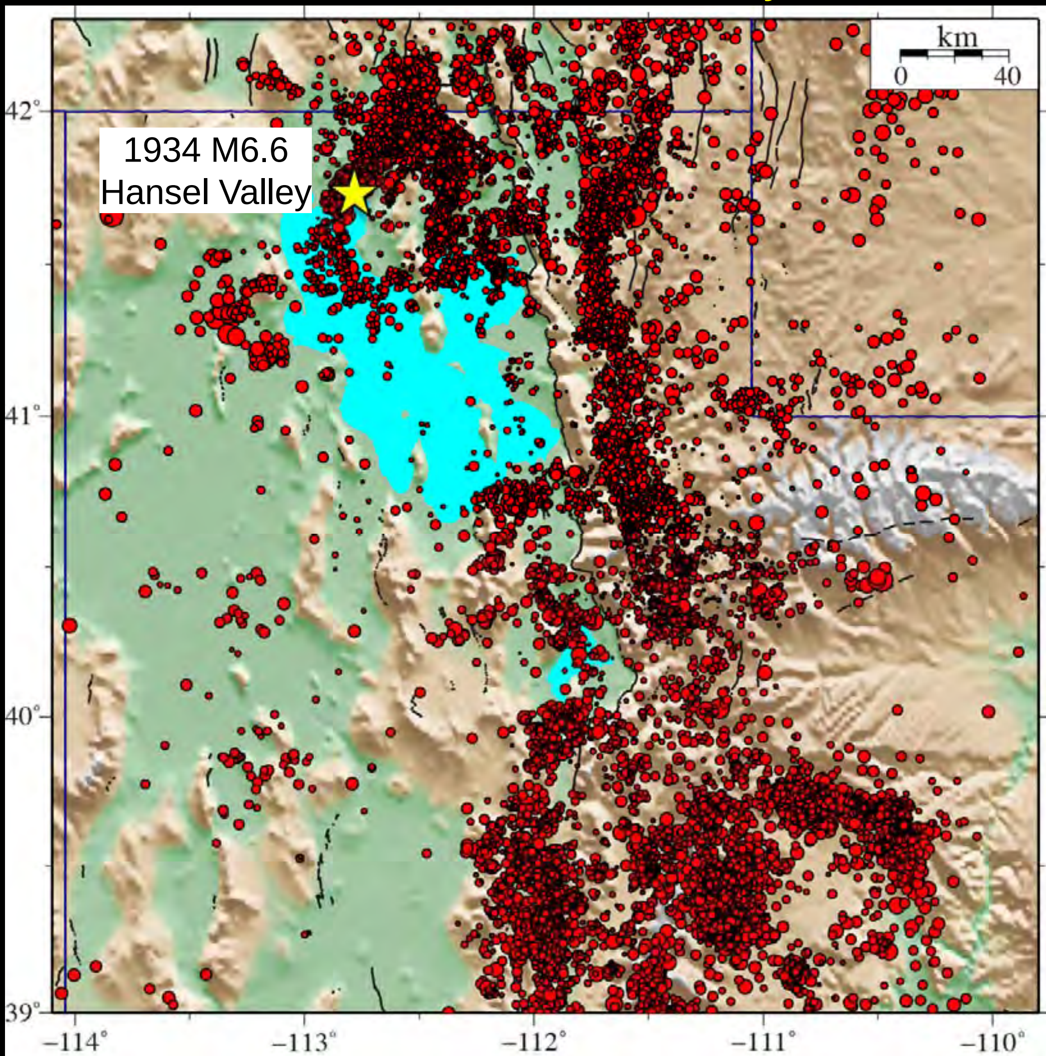
THE UNIVERSITY OF UTAH Seismology Research Group
UNAVCO PBO
UTAH DNR GEOLOGICAL SURVEY
USGS science for a changing world

Wasatch Fault, Nephi Segment, Utah

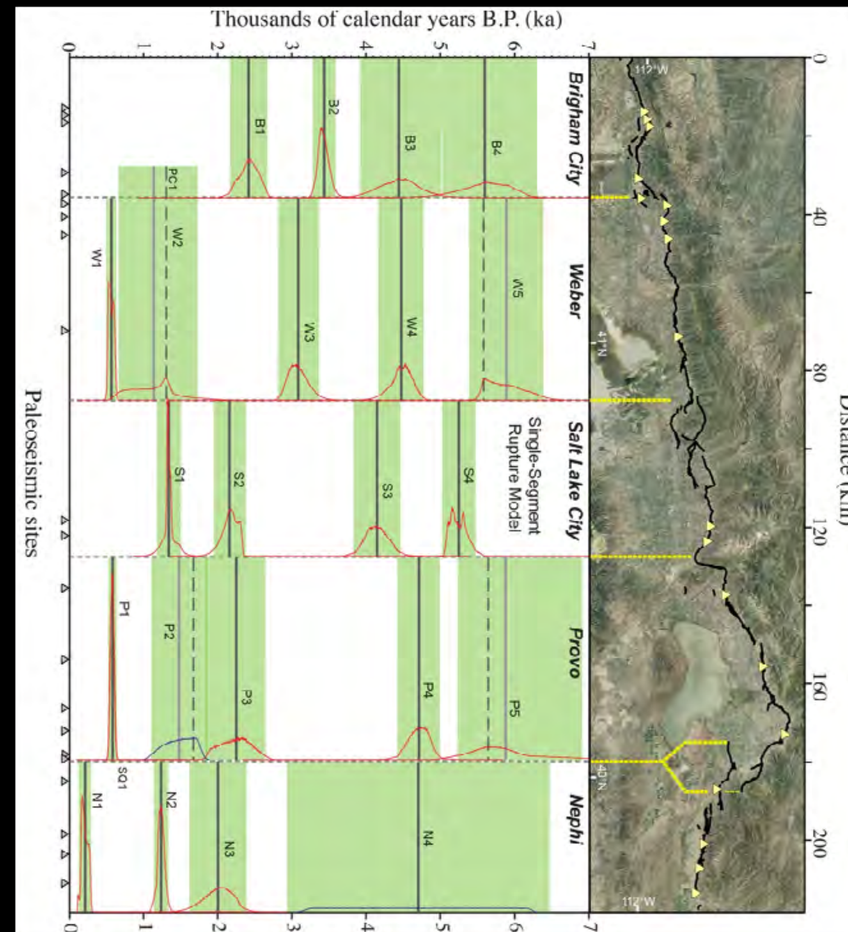


(Open Topography)

Wasatch Front Seismicity



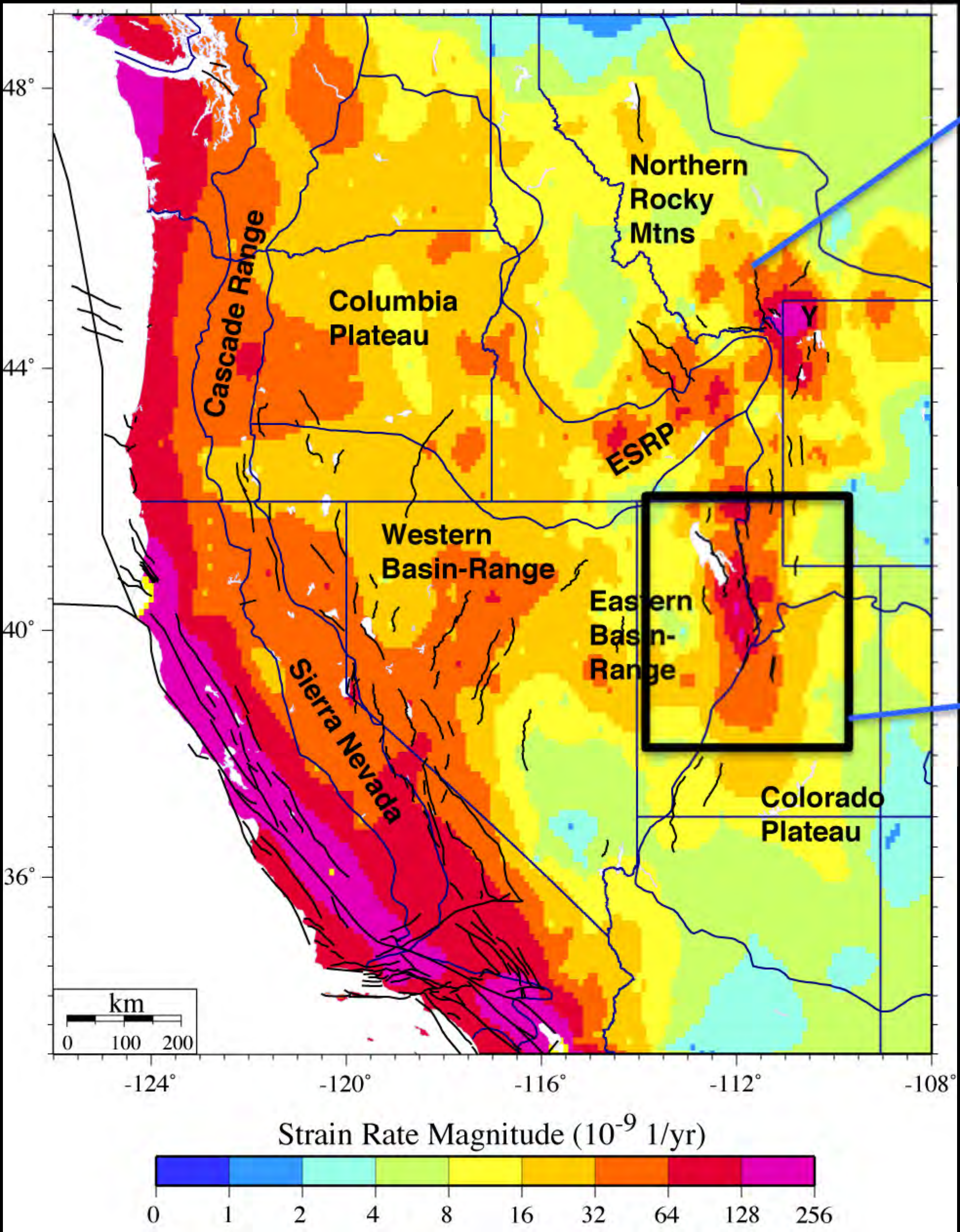
Wasatch Paleoearthquake History



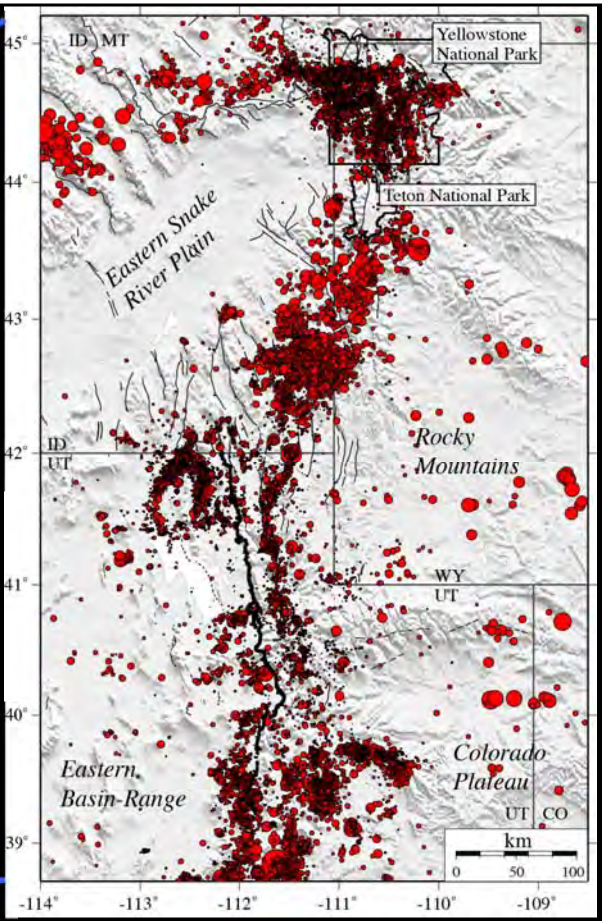
DuRoss et al. [2011]

- Wasatch Front is currently seismically active
  - Largest historic event: M6.6 March 12, 1934 Hansel Valley earthquake
  - Over 38,000 earthquakes in UUSS catalog
- Wasatch fault has been prehistorically active
  - 4-5 events identified for each segment in last 6000 years
  - Estimate M6.7-7.3 for each paleoearthquake

Western US Strain Distribution

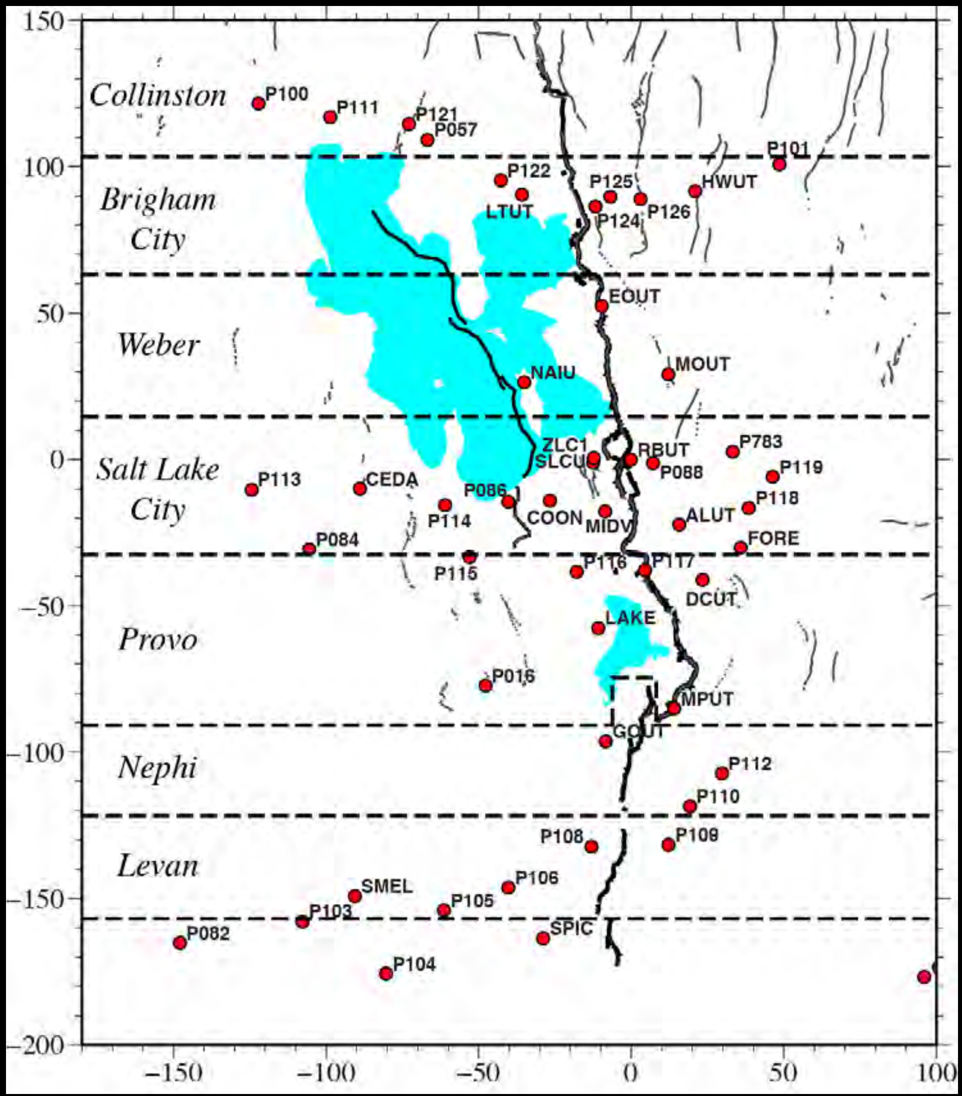


Puskas [2009]

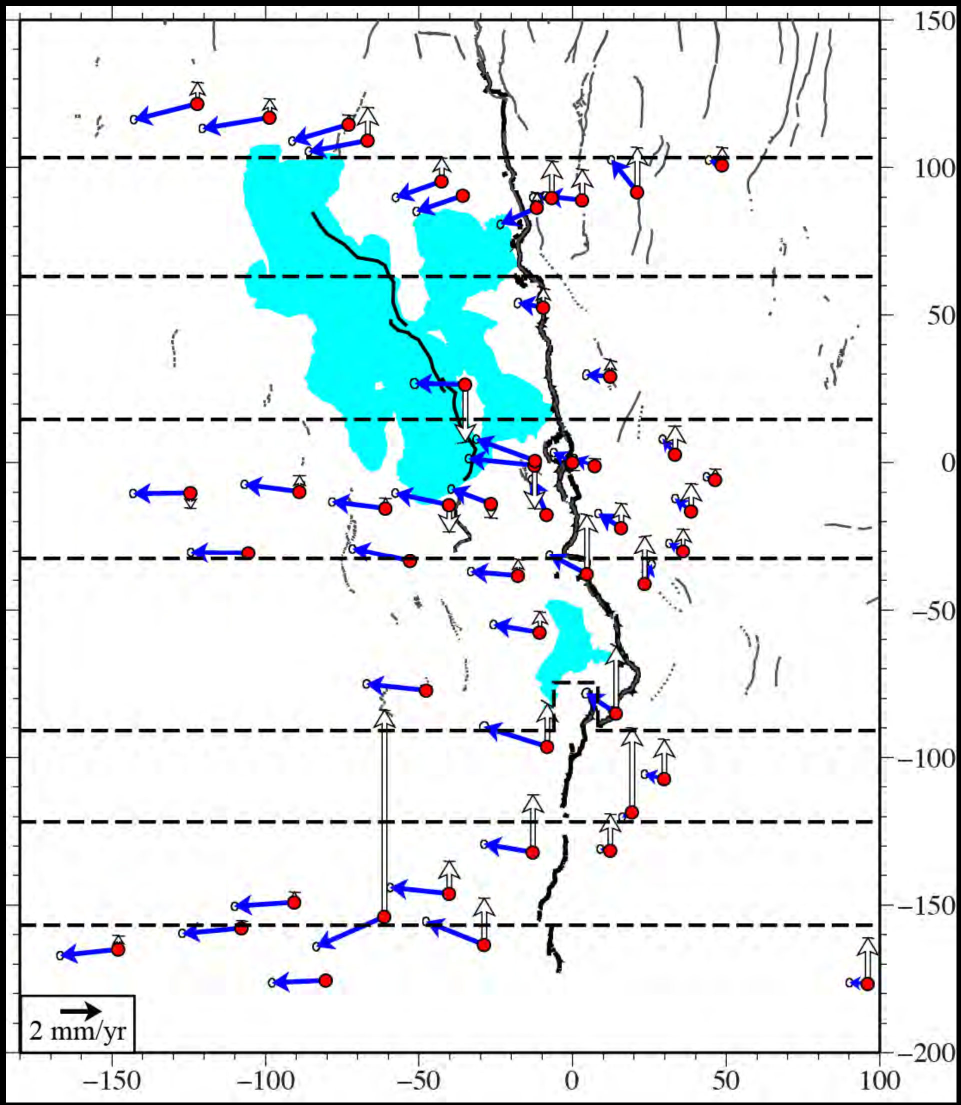


- Wasatch Front extension zone
    - Associated with Intermountain Seismic Belt
    - Largest deformation rates east of California
- How fast is Wasatch extension?
    - GPS measurements
- How is deformation distributed?
- Can GPS be used to constrain fault models?
    - Contributions of block motions
    - Dislocation models*

Wasatch Front GPS Network
Wasatch Fault Segments



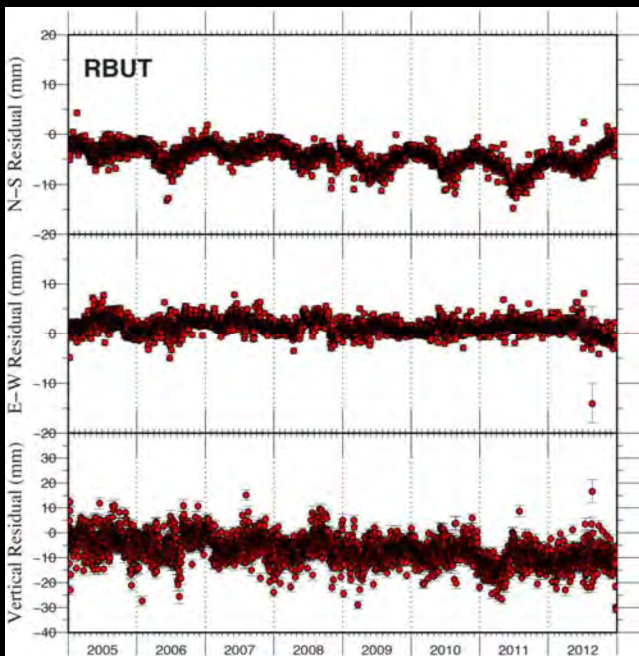
2010-2012 GPS Velocities



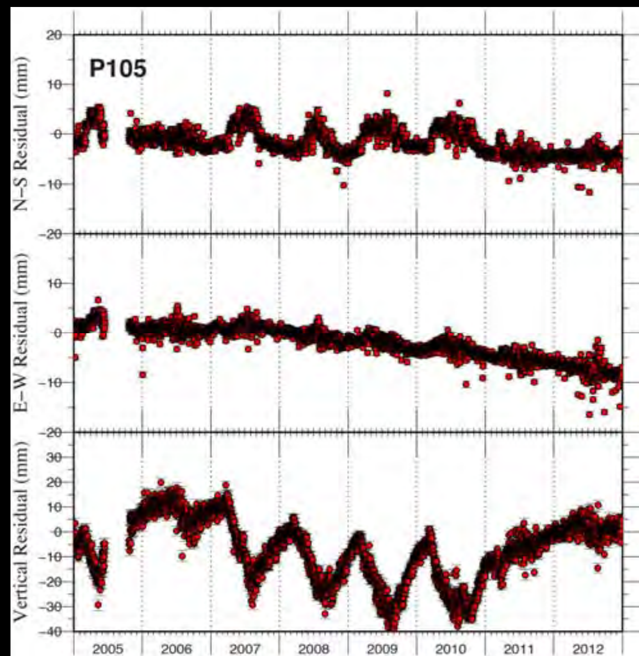
- University of Utah processes data from 55 permanent GPS stations
  - Plate Boundary Observatory (PBO) Network
  - University of Utah
  - National Geodetic Survey Continuously Operated Reference Stations (NGS-CORS)

- Stations distributed across north/central/southern sections of Wasatch fault

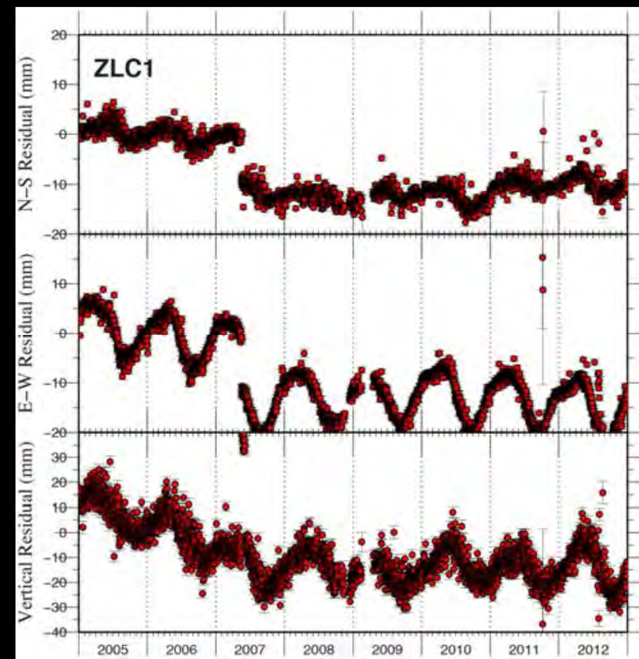
Station Time Series



Good

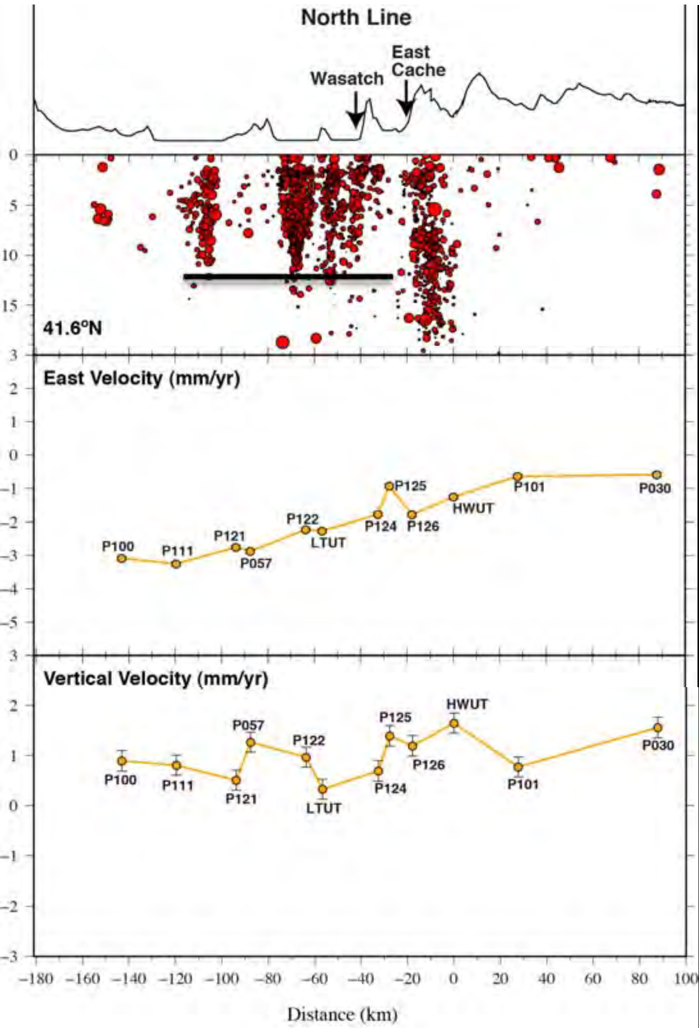


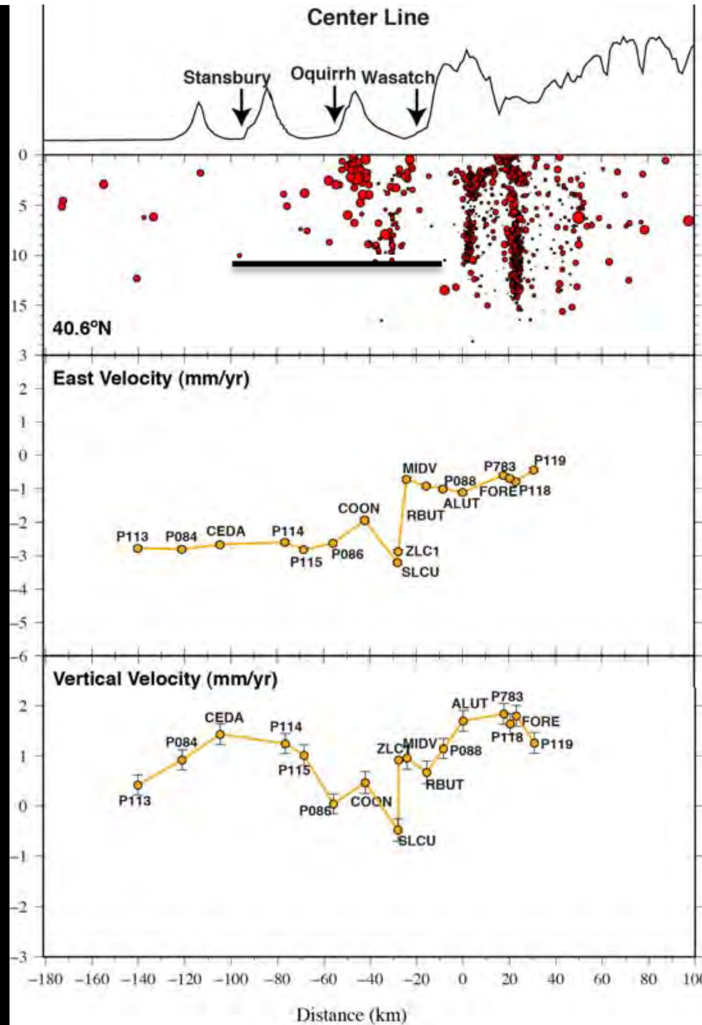
Groundwater Pumping

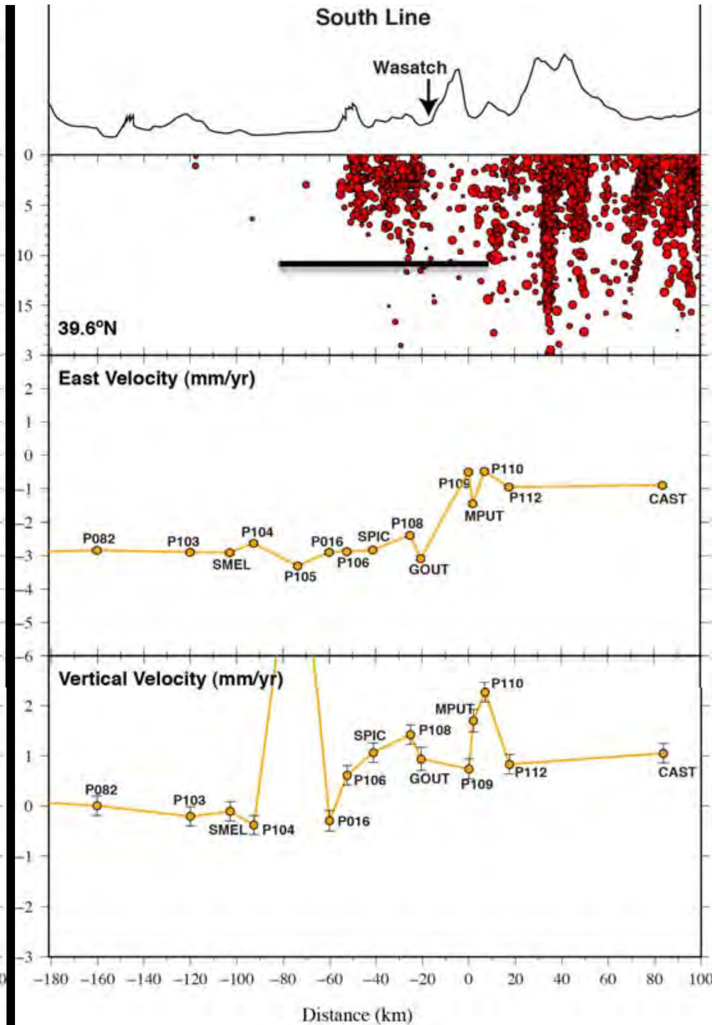


Probably bad

- Use time series to check station quality
- Identify problematic stations





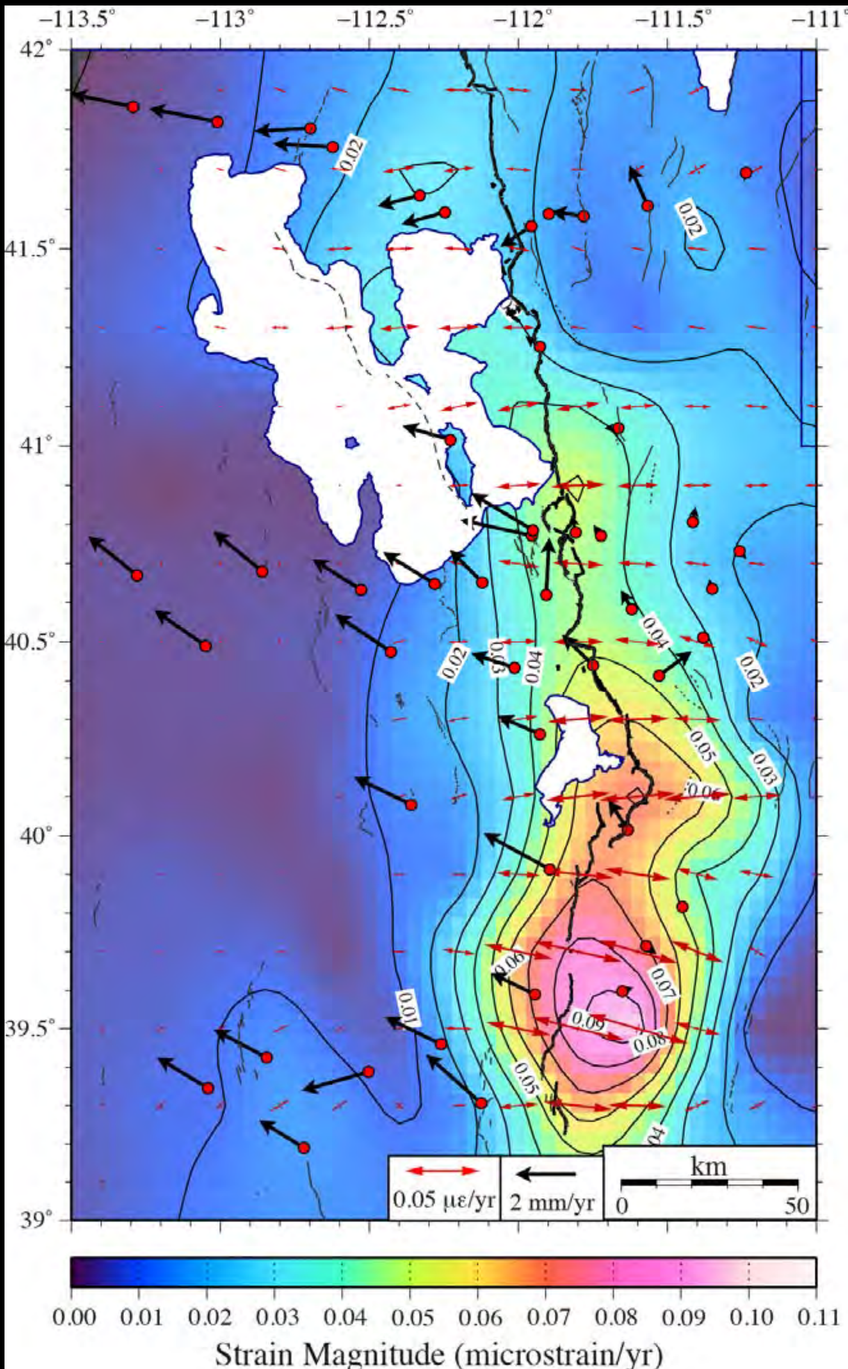


Brigham City Profile
(North Line)
2.1 mm/yr net extension rate

Salt Lake City Profile
(Center Line)
1.9 mm/yr net extension rate

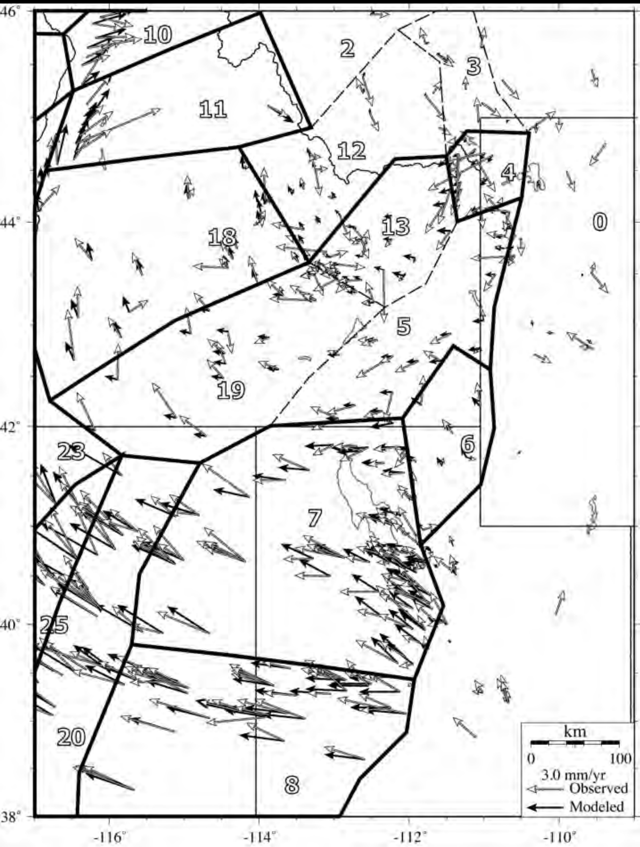
Nephi Profile
(South Line)
1.5 mm/yr net extension rate

Distribution of Deformation



- Use GPS velocities to calculate strain rates
  - Use strain rate tensor to calculate magnitude
- Low strain rates (< 0.02×10^{-6} yr^{-1}) in Basin-Range
- Highest strain rates in southern segments
  - Max strain 0.09×10^{-6} yr^{-1}
- Broad moderate strain rates in northern segments

Regional Block Model

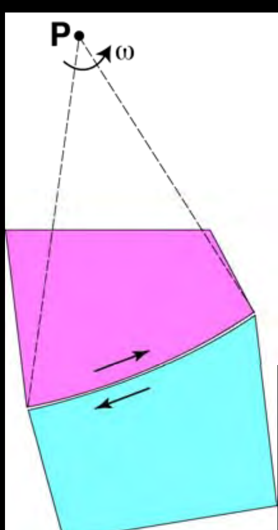


Puskas and Smith [2009]

- Block modeling inverts for block motion and fault slip
  - Total deformation = block rotation + backslip (slip deficit)

- Over long-term, all motion is block rotation
  - Faults are locked in upper crust
  - Interseismic deformation is from creep in lower crust

- Traditional block models assume blocks are well-defined



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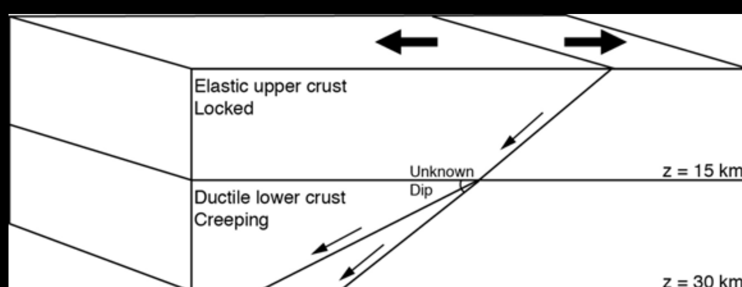

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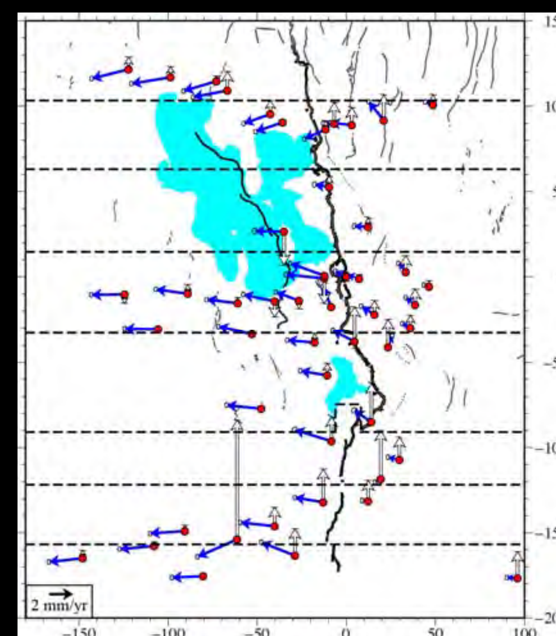
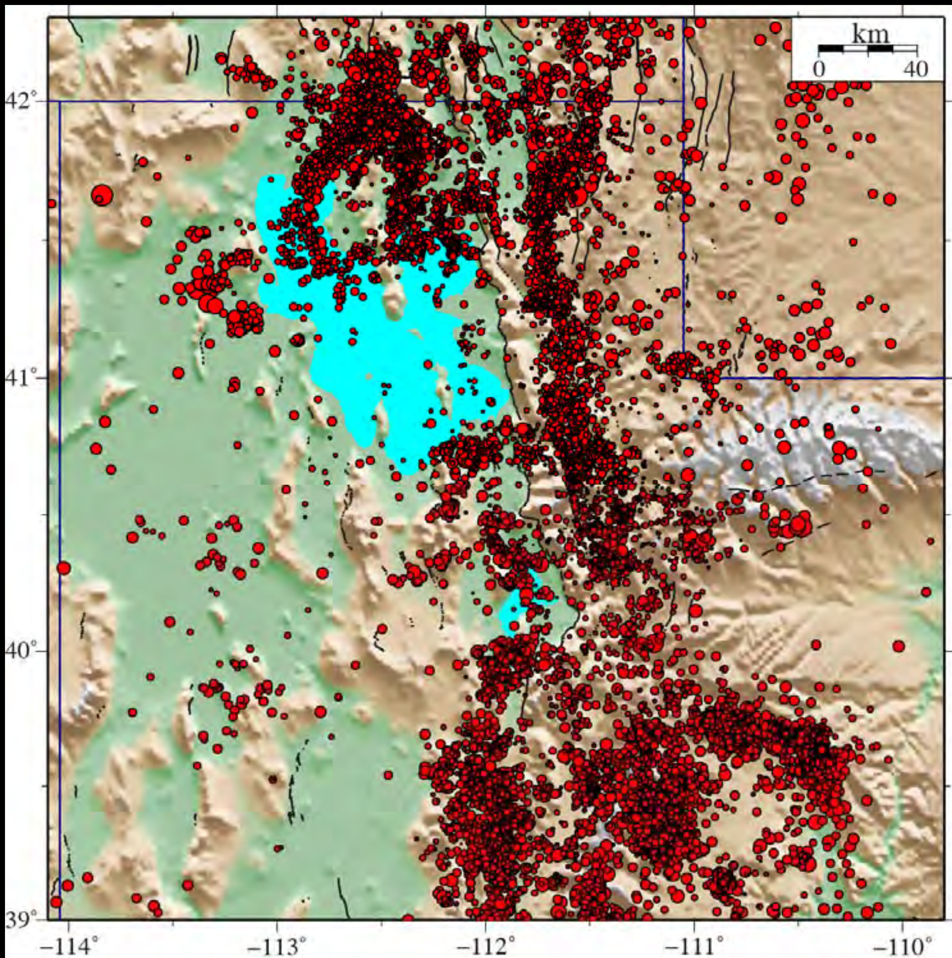
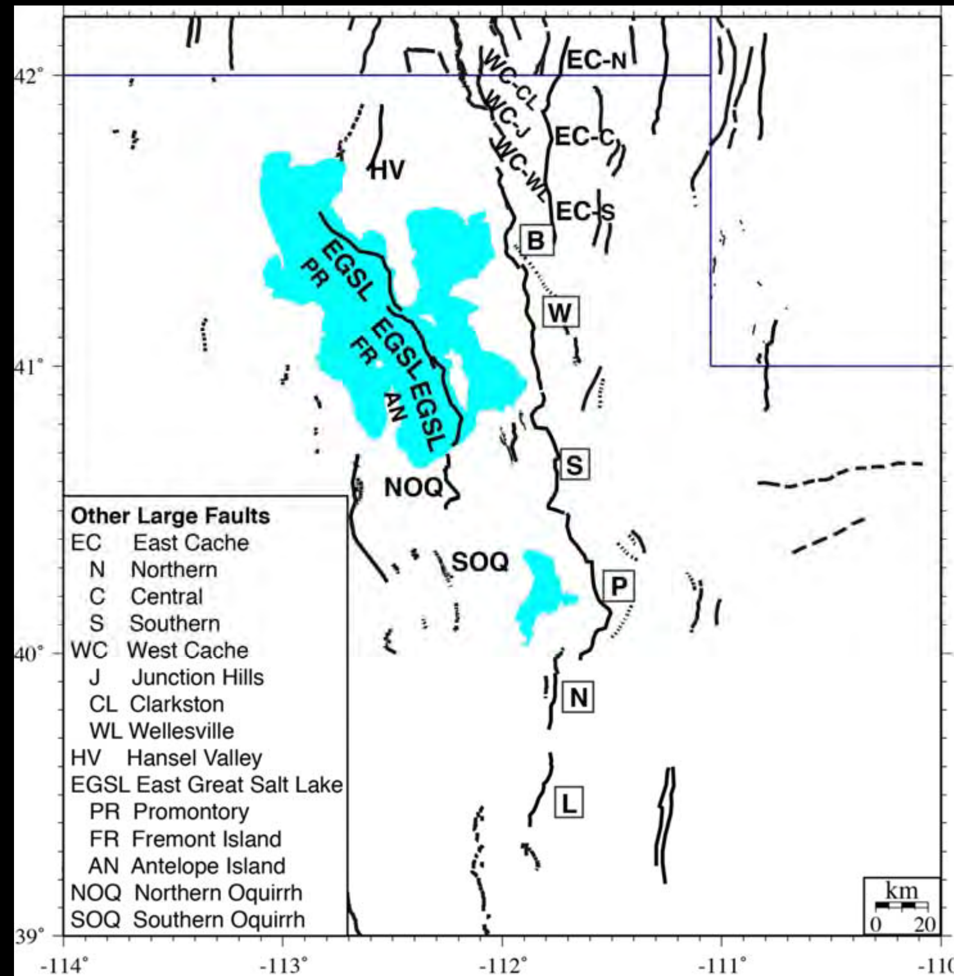


Wasatch Front Earthquakes



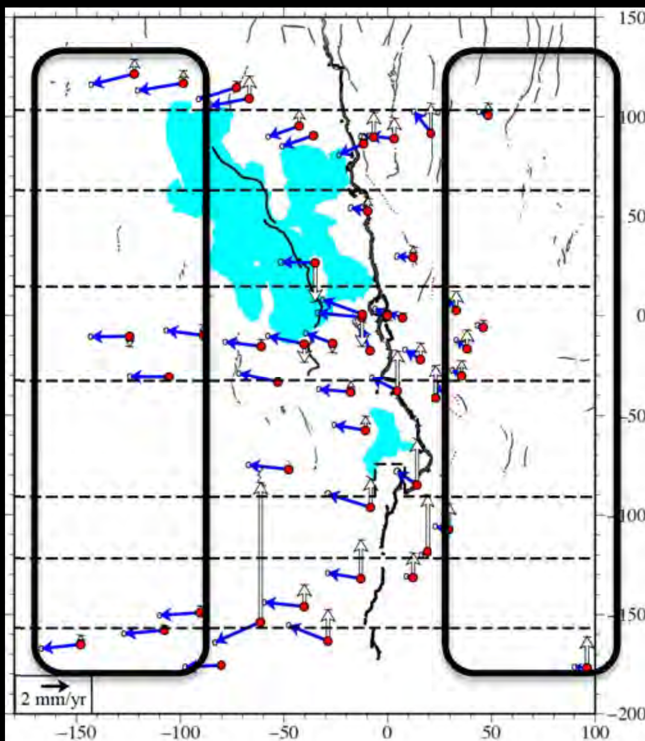
Major Normal Faults



- Picking blocks
  - Examine earthquake distribution
  - Examine faults from USGS fault database
  - Examine change in deformation rates from GPS

- Block modeling the Wasatch Front
    - Solve for block motion based on GPS and fault geometry

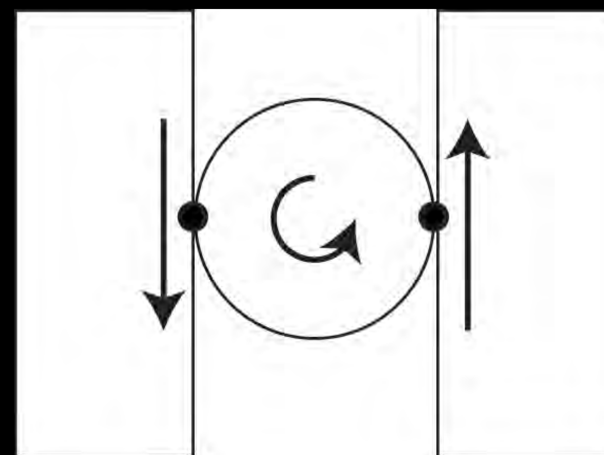
- Solve pole of rotation and rotation rate
    - Direct calculation of pole for large blocks
    - Small blocks strongly affected by fault loading



- Large block interiors unaffected by fault loading

- Equations exist to directly calculate pole coordinates, rotations from station velocities and coordinates

- Can calculate velocity at any point on block, given pole



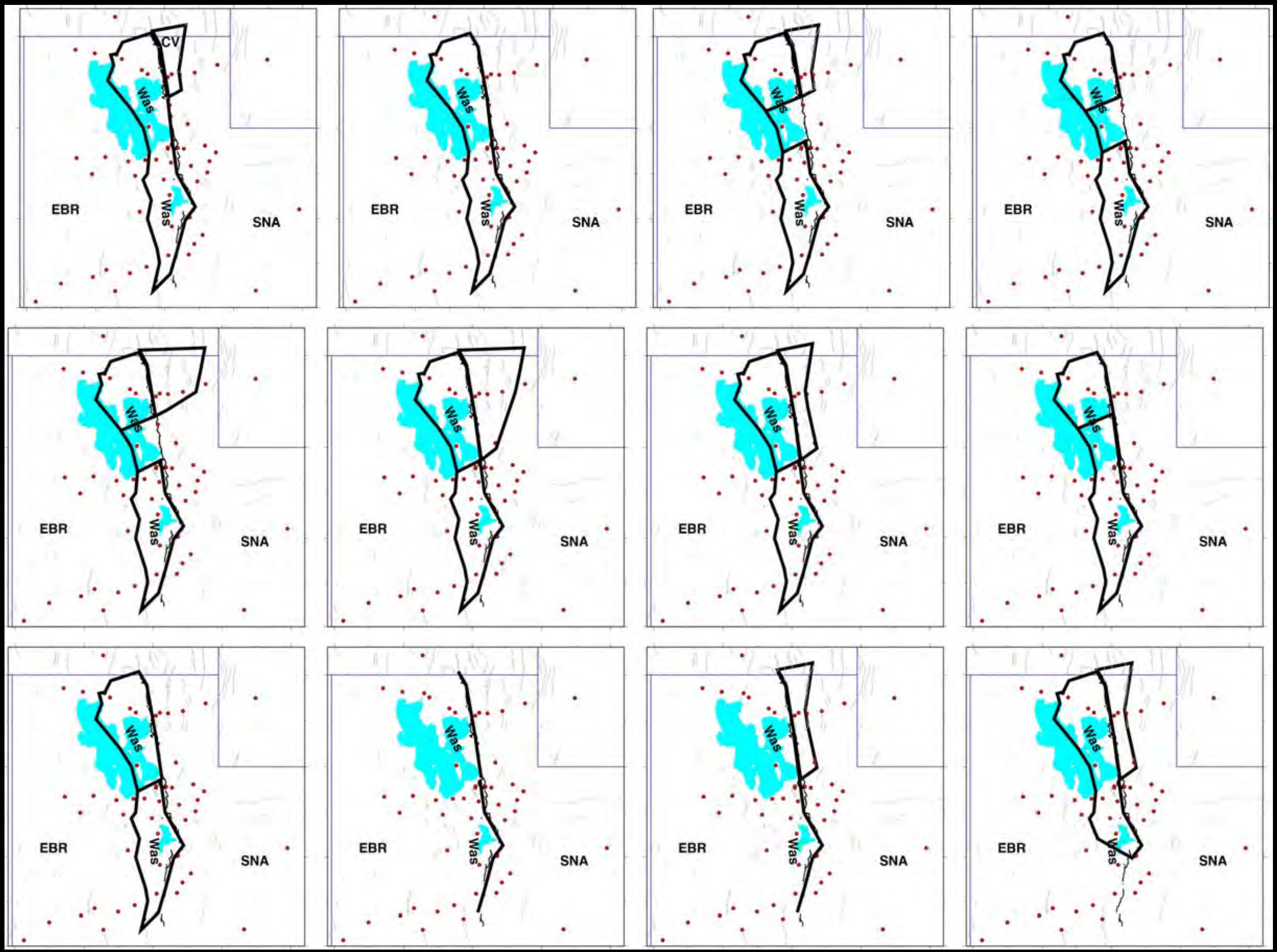
- Small blocks entirely affected by fault zones

- Assume small block accommodates relative motion of larger blocks

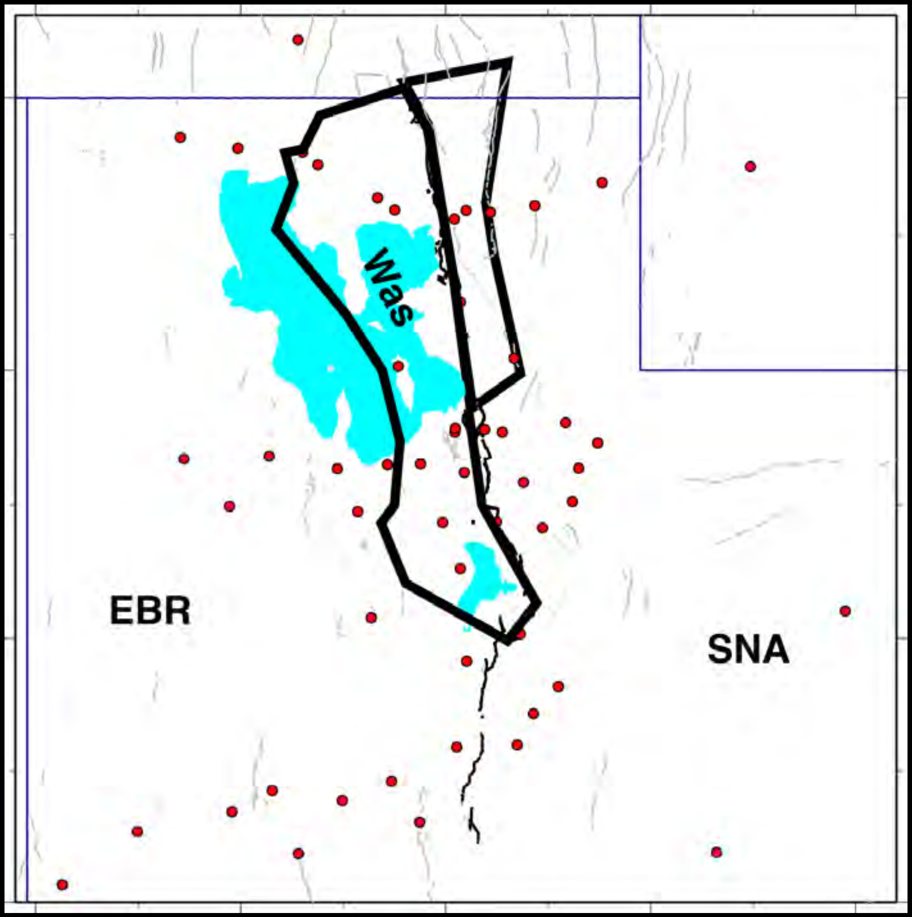
- Use velocities from neighboring block boundaries to calculate small block poles

- Experiment with multiple combinations
  - Subtract block velocities from GPS velocities

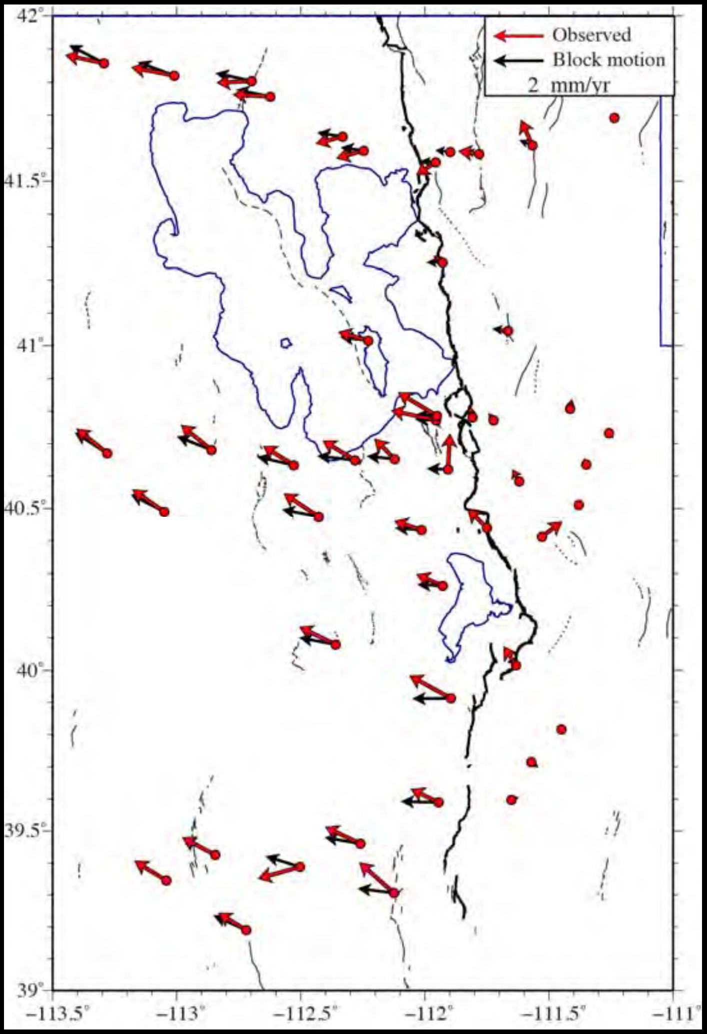
- Evaluate results
  - χ^2 comparison
  - Visual inspection



Best-fit Block Model

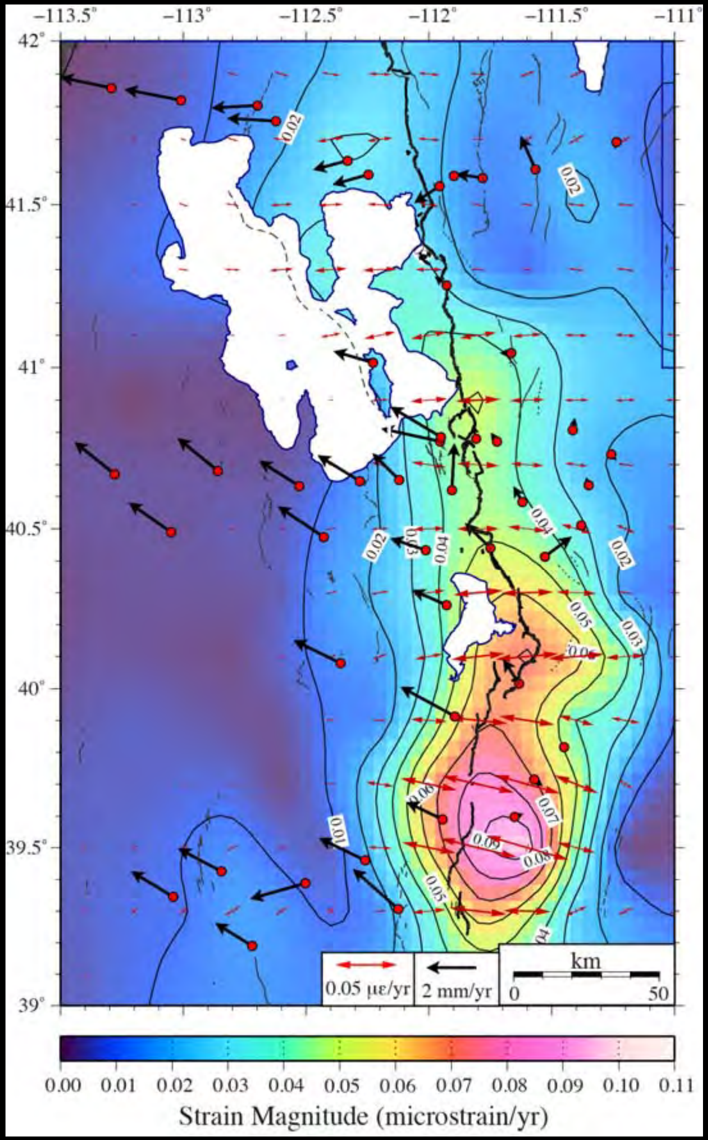


Observed – Modeled Velocities

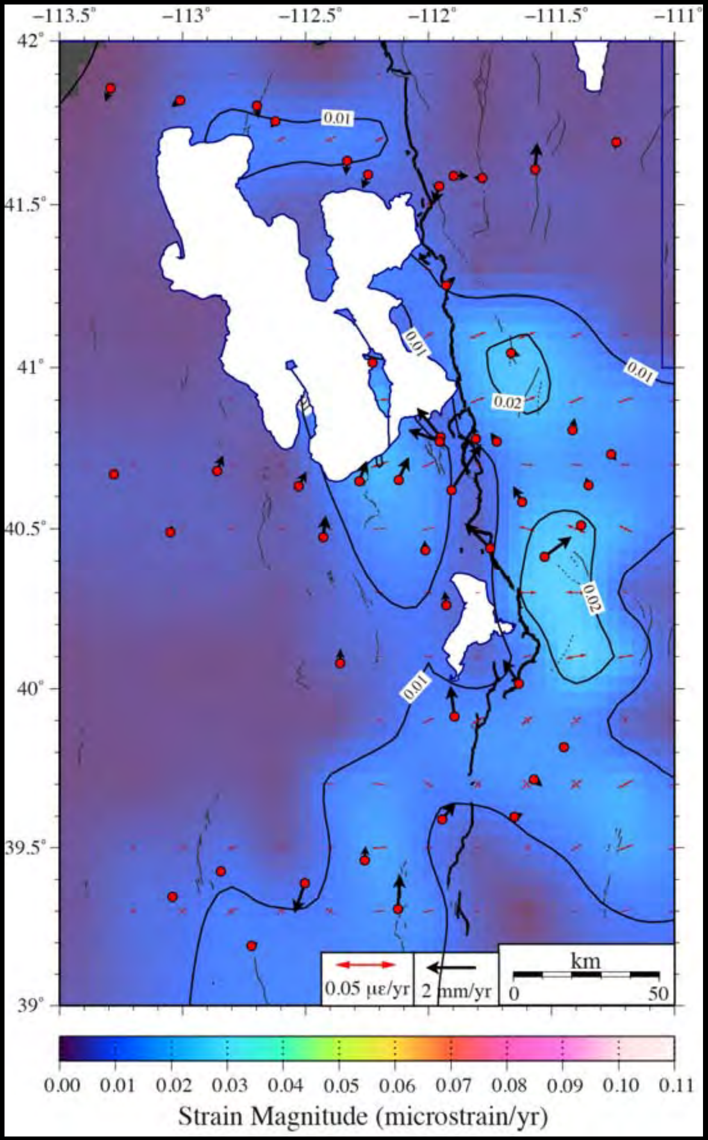


- Wasatch block between Basin-Range and stable North America
- Wasatch block extends from north to central but not southern segments
- Cache Valley block to the northeast of Wasatch fault

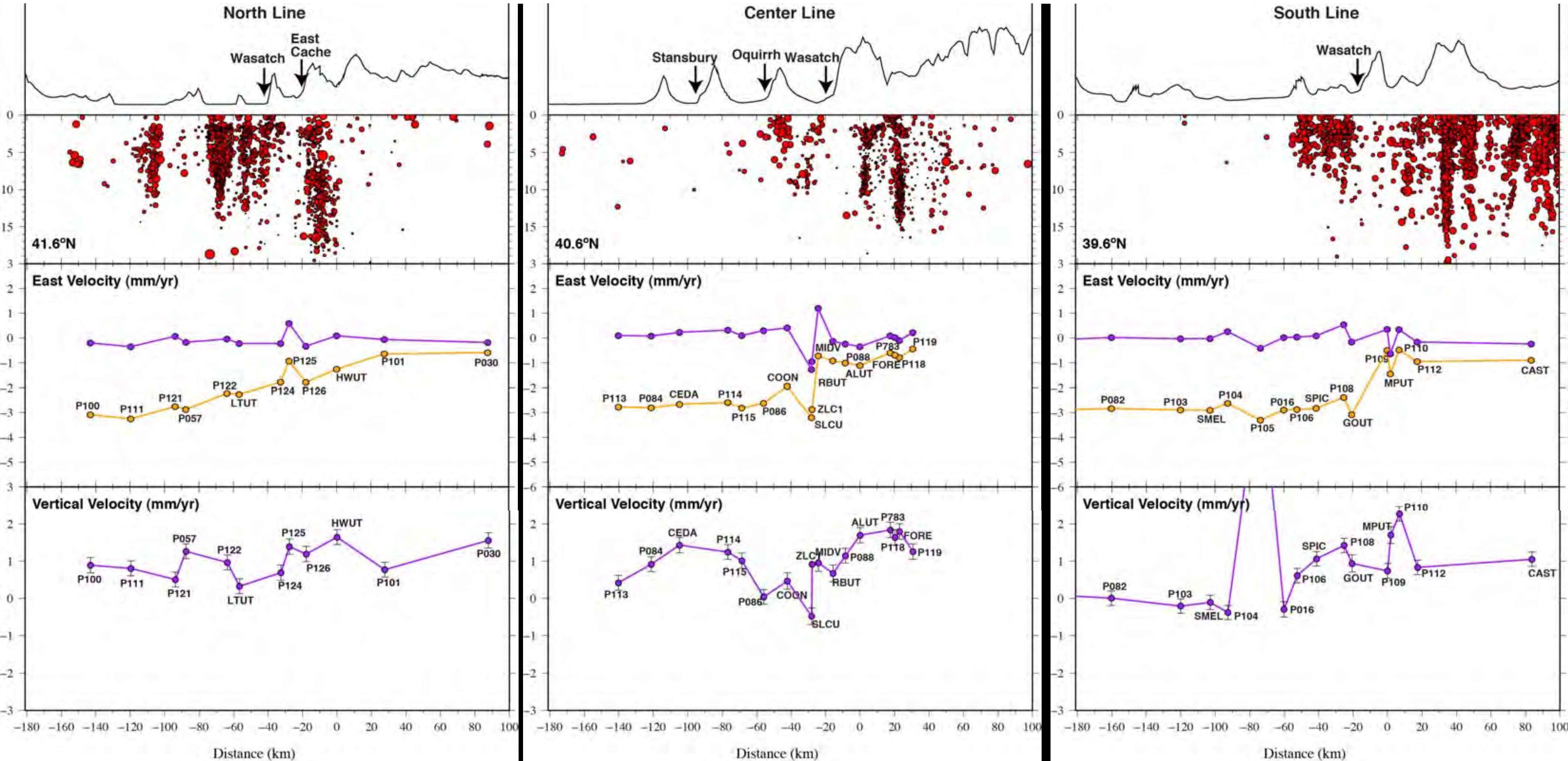
Observed Deformation Rates



Best-Fit Model Residuals after Block Motion Removed

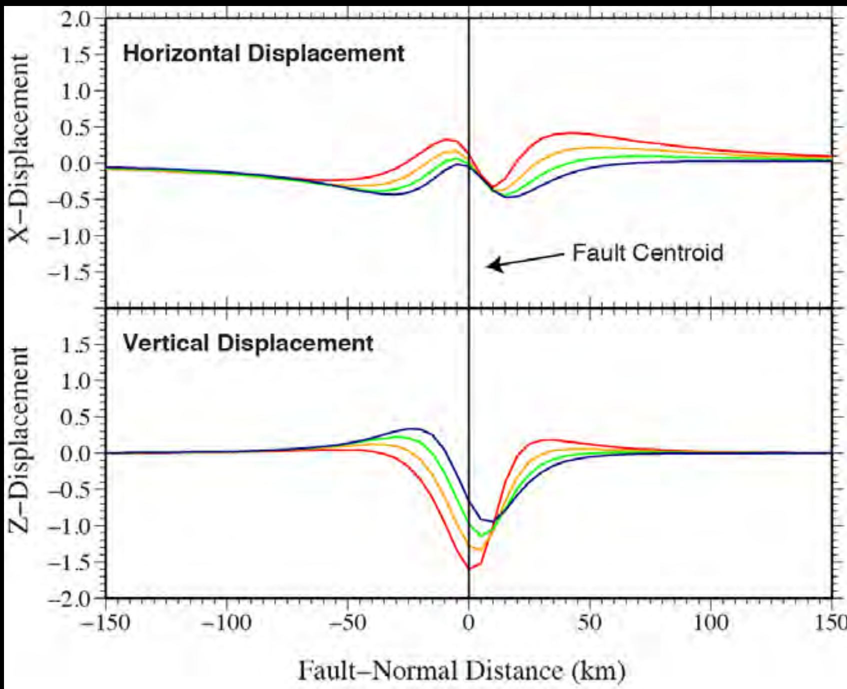


- Greatly reduced strain rates
- Residuals largest in north-south component



- Block modeling applies to horizontal deformation only
- Block-corrected profiles go to zero away from fault zone
- Horizontal surface displacements < 1 mm/yr

Okada Dislocations
Creeping Fault at Depth



• Dislocation models solve for surface displacements from fault creep at depth

• Okada dislocation models must solve for or specify:
  - Slip - Fault position (depth, coordinates)
  - Dip - Strike
  - Rake - Length

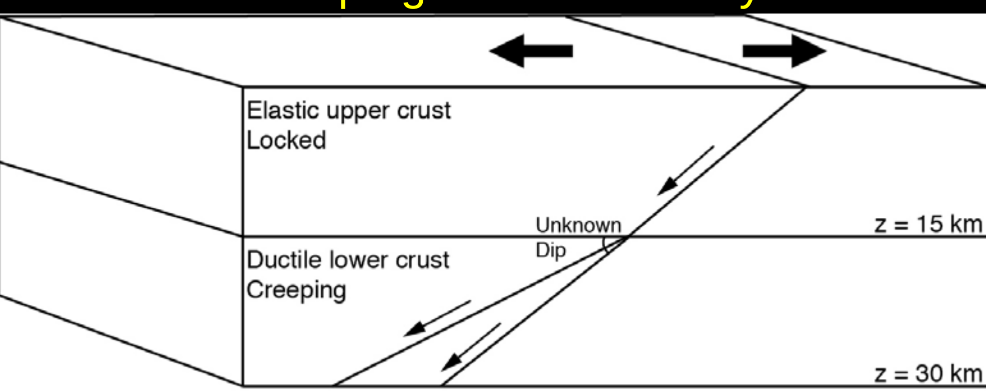
• Slip rates ~1-3 mm/yr from paleoseismic studies

• Creeping segment from ~13-30 km depths from seismic profiles and earthquake distributions

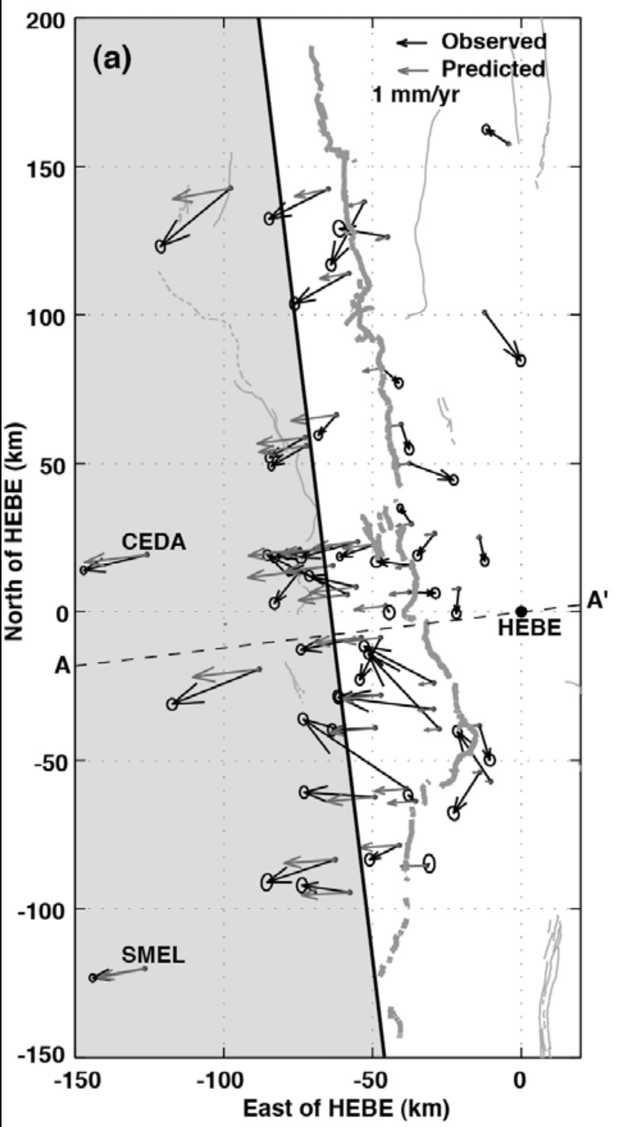
• Strike and segment length from mapping

• Can GPS be used to corroborate seismic slip rates?

Creeping Fault Geometry

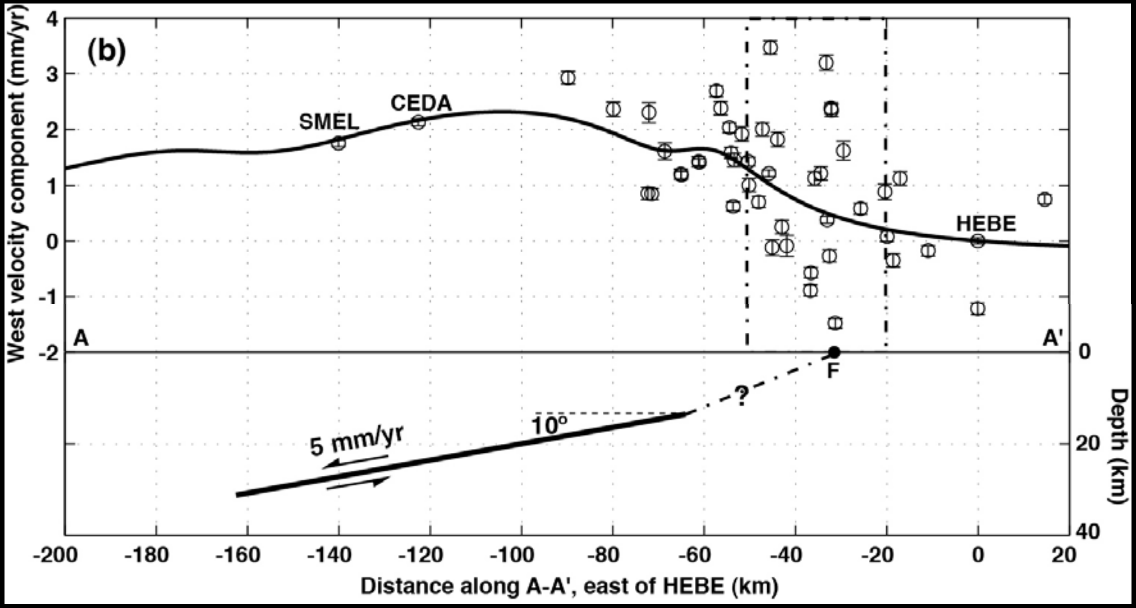


Prior Dislocation Models of Wasatch Fault



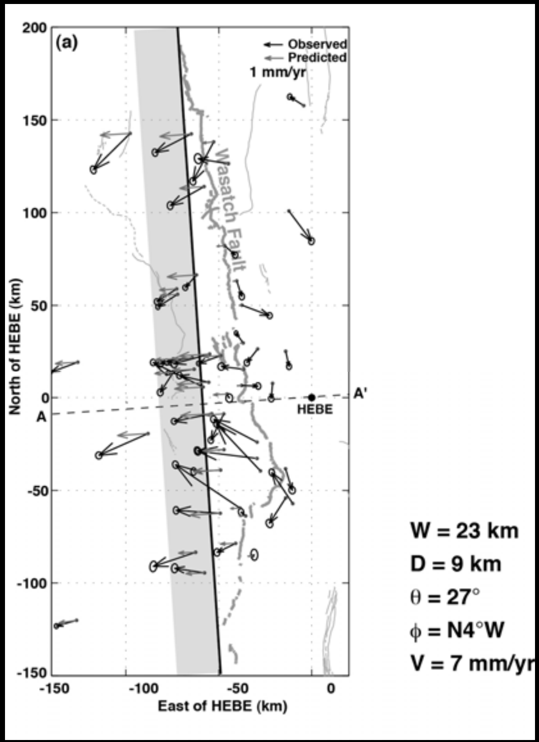
W = 100 km
D = 13 km
$\theta = 10^o$
$\phi = N7^oW$
V = 5 mm/yr

Broad, Shallow-dipping Dislocation

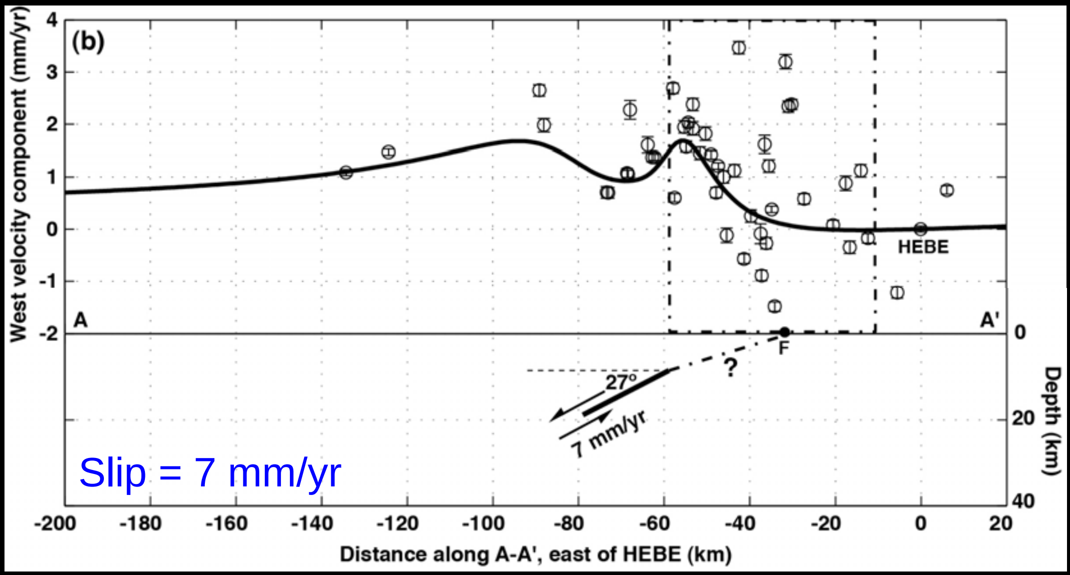


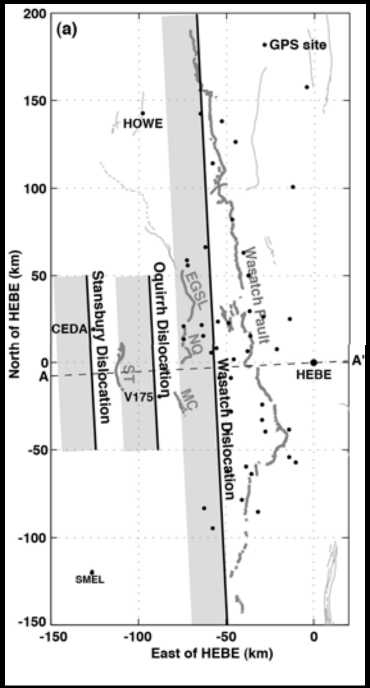
Slip = 5 mm/yr

Prior Dislocation Models of Wasatch Fault

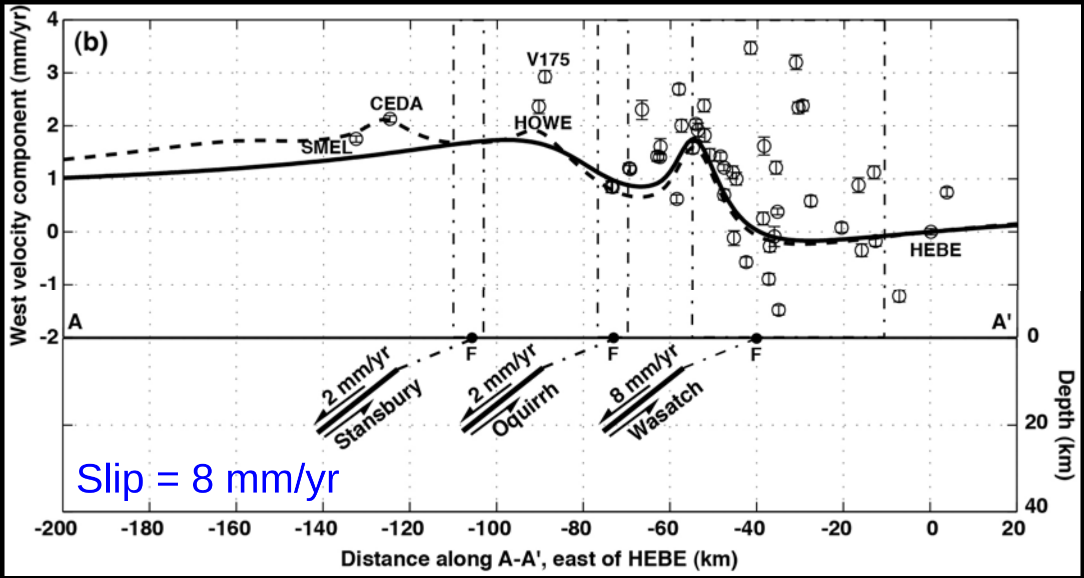


Dislocation with Background Extension Removed





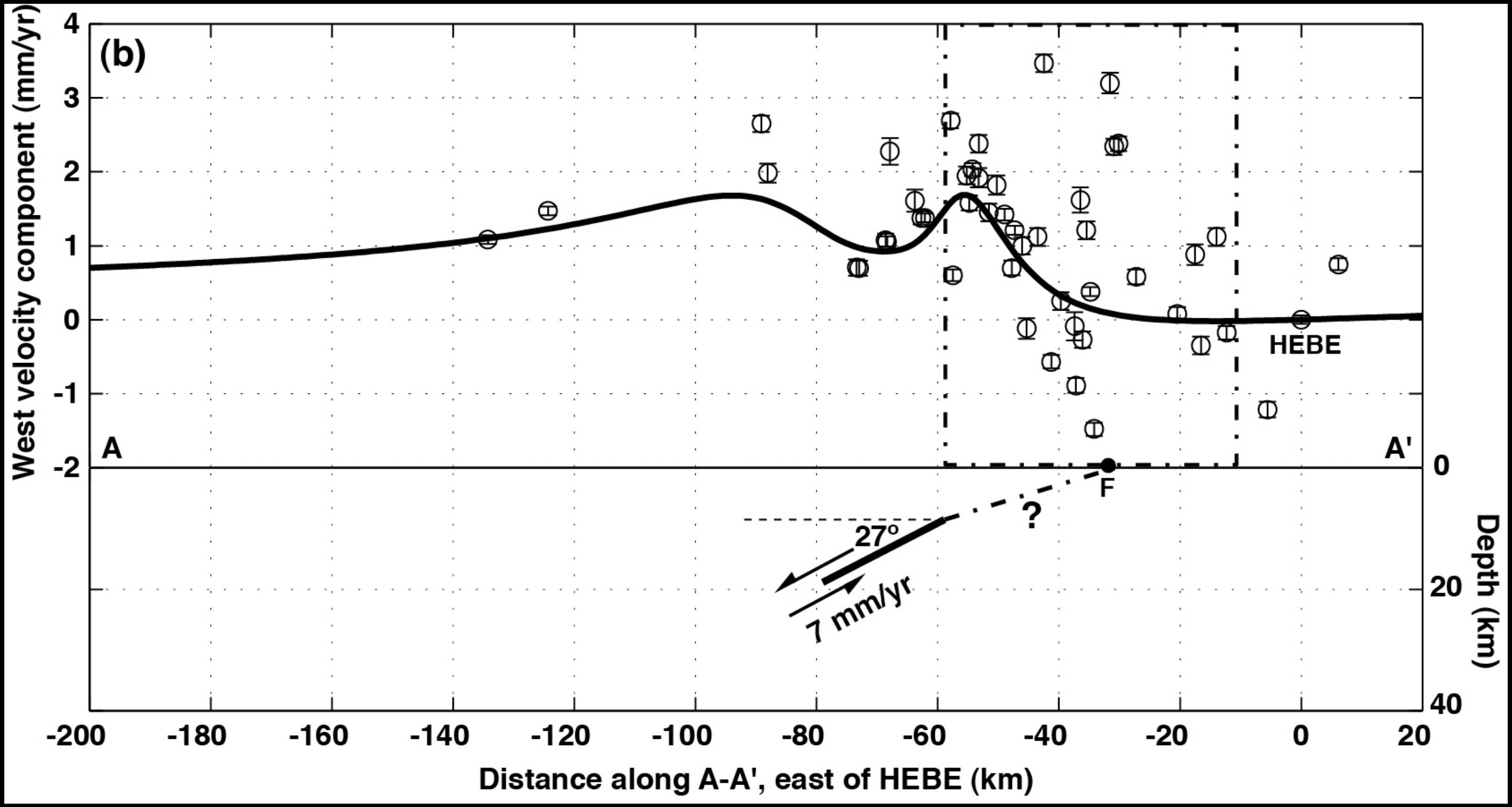
Multiple Dislocations



• Previous dislocation models did not correct for block motions

• Models used campaign data obtained between 1993 and 2001

• Produced large slip rates of 5-8 mm/yr

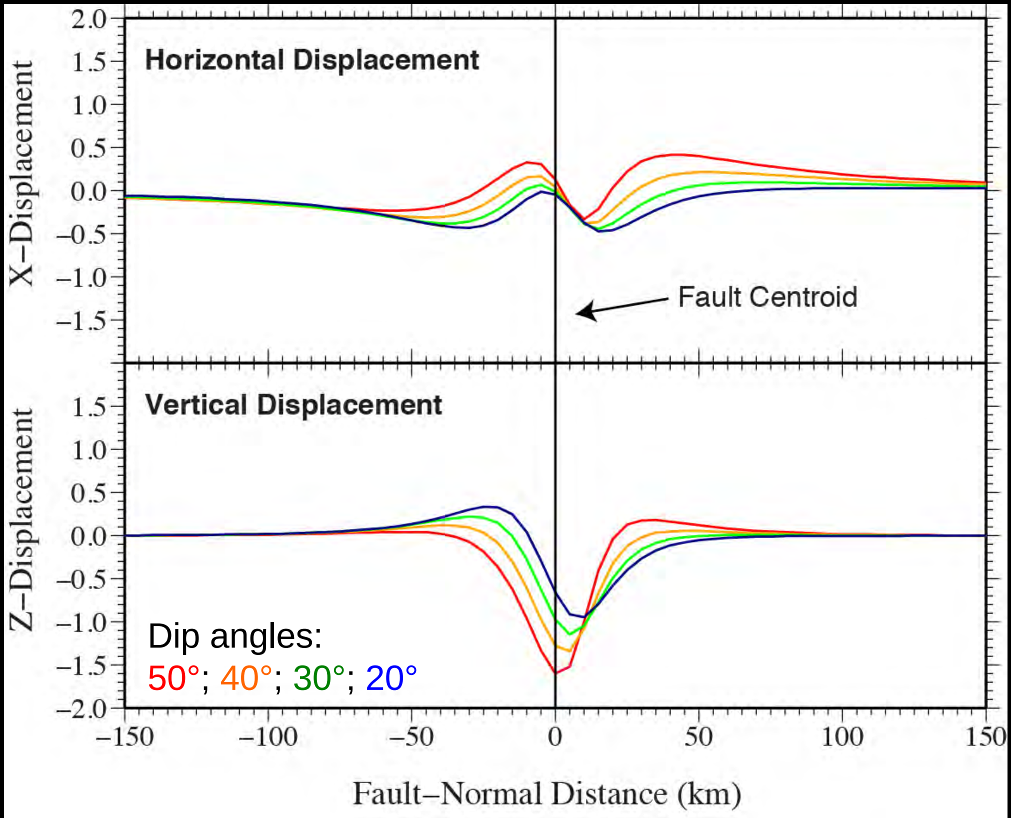


- Previous dislocation models did not correct for block motions
- Models used campaign data obtained between 1993 and 2001
- Produced large slip rates of 5-8 mm/yr

Paleoseismic slip rates are ~1-3 mm/yr – why the discrepancy?

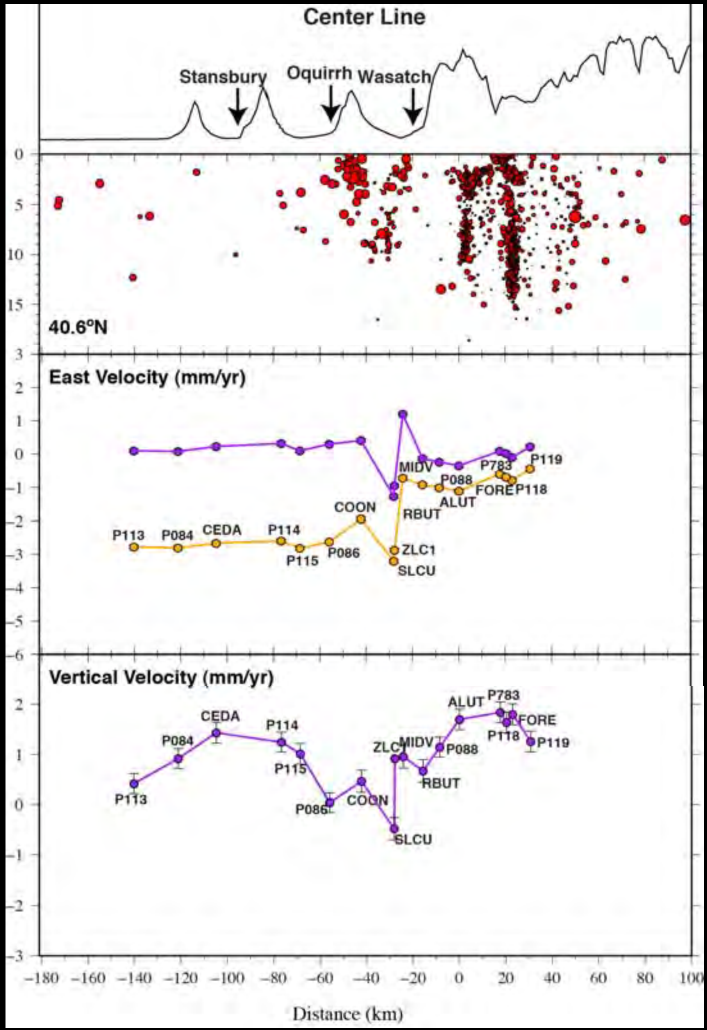
- Improperly removed block rotations
- Viscous flow in lower crust (creep model may not be adequate)
- Noisy campaign data (contaminated by large outliers)
- Other??

Idealized Normal-faulting Surface Deformation



Locking depth=5 km; slip rate=5 mm/yr

Observed Surface Deformation

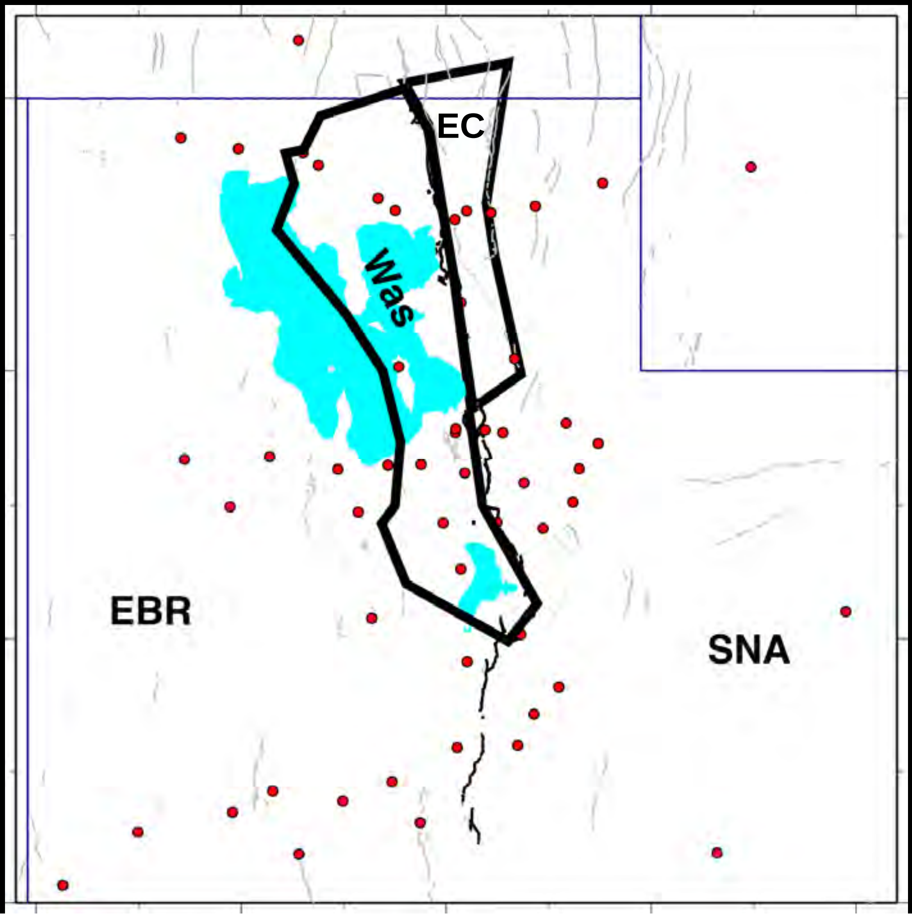


- Use Okada dislocation code to generate sample velocity profiles
    - West-dipping normal fault with 180º strike
- Corrected horizontal GPS velocities are < 1mm/yr
    - Sensitive to outliers, non-tectonic signals
- Vertical GPS profile does not resemble model profile

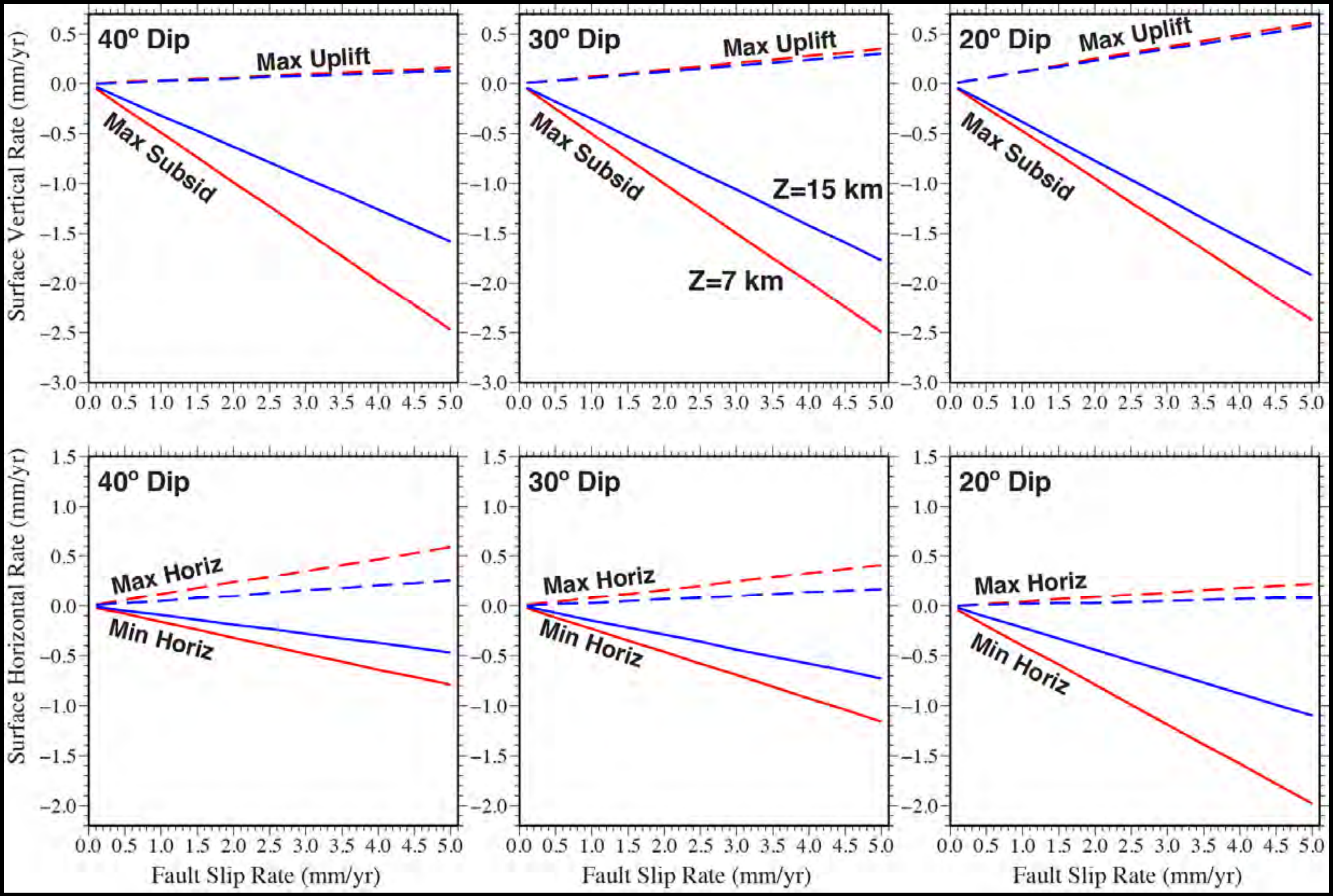
• Block modeling predicts a Wasatch block and a Cache Valley block between the Basin-Range and stable North America

• Block models eliminate background deformation, leaving contribution from fault dislocations (backslips)

• Joint inversion for block rotation and fault backslip rate, and possibly block internal strain rate, will improve models

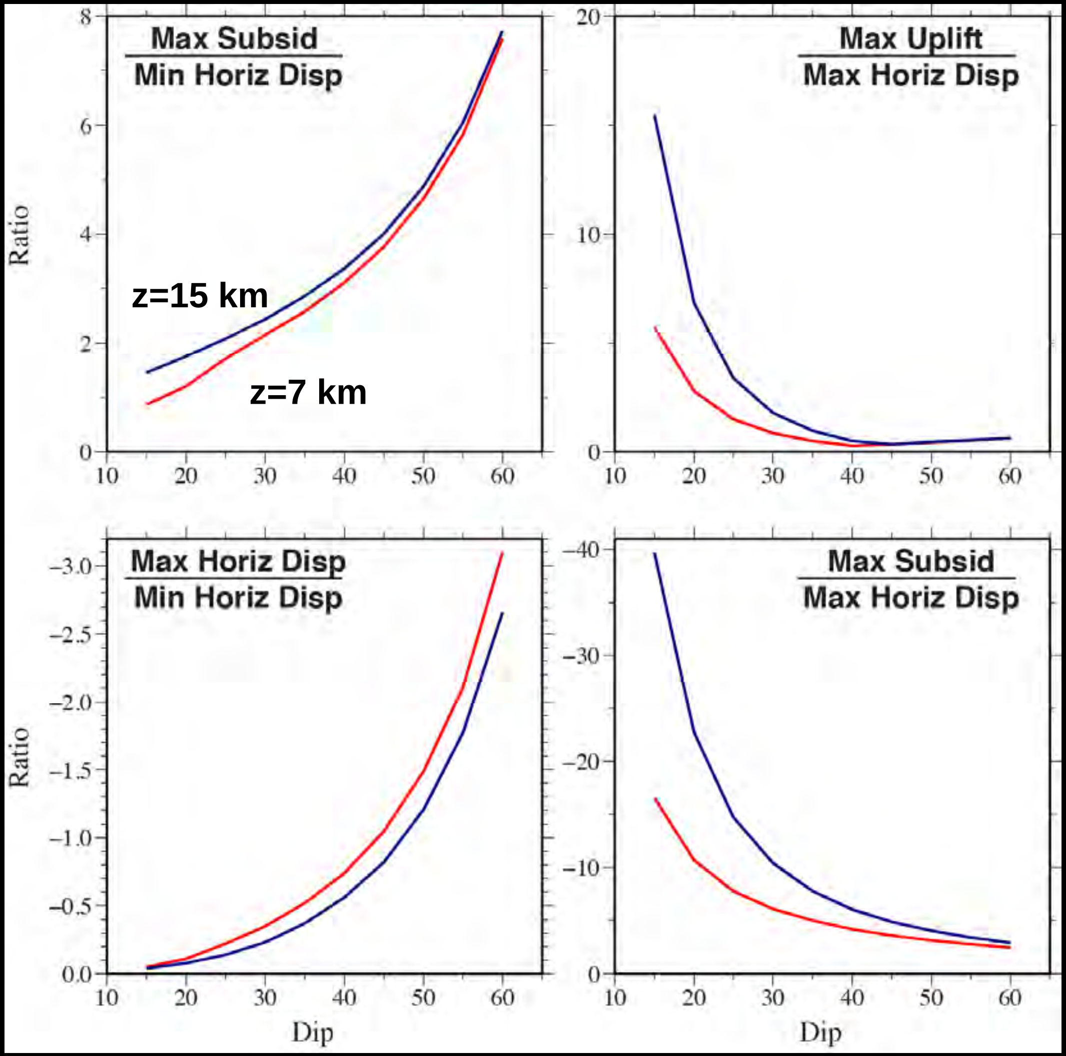


Fault Slip vs. Surface Deformation Examples



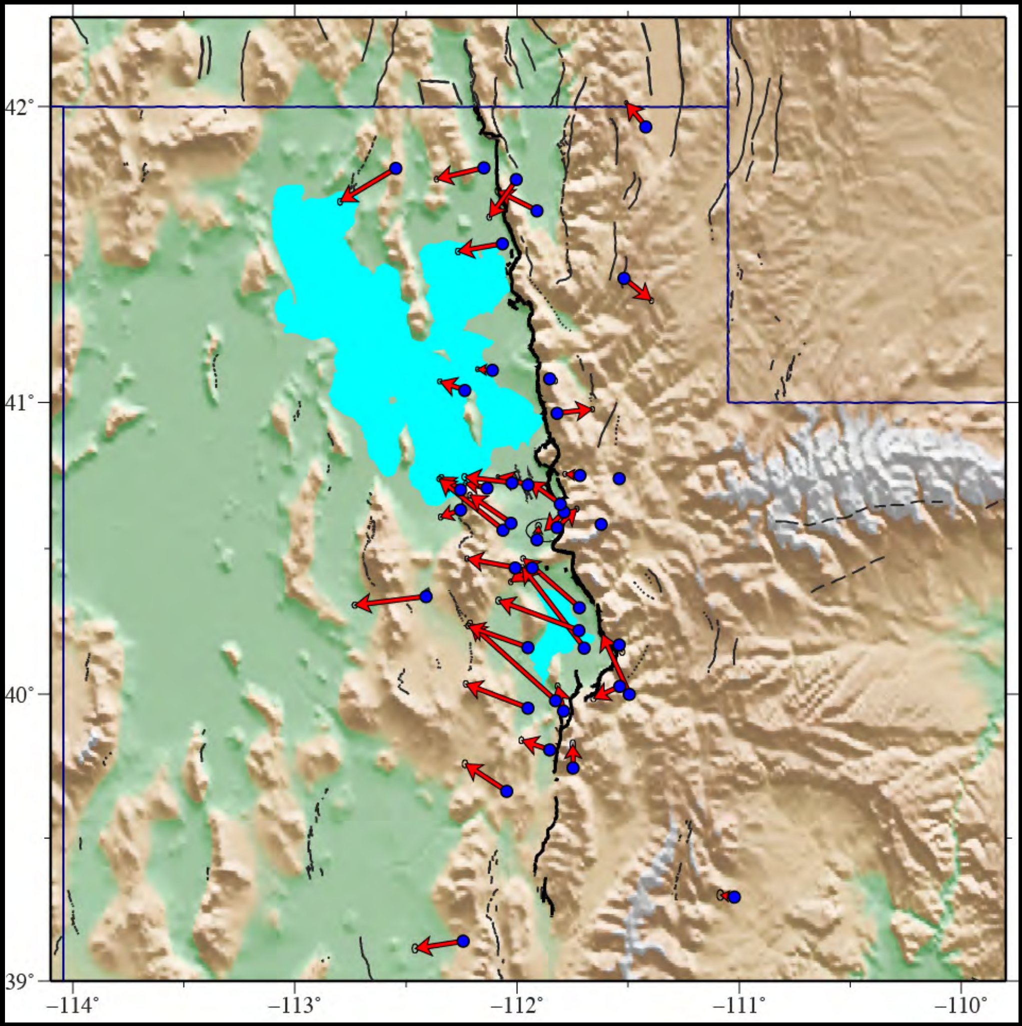
- Fault slip rates, dip, depth to dislocation all determine surface deformation
- Depth effect at surface < ~1 mm/yr

Ratios of Surface Deformation Maxima

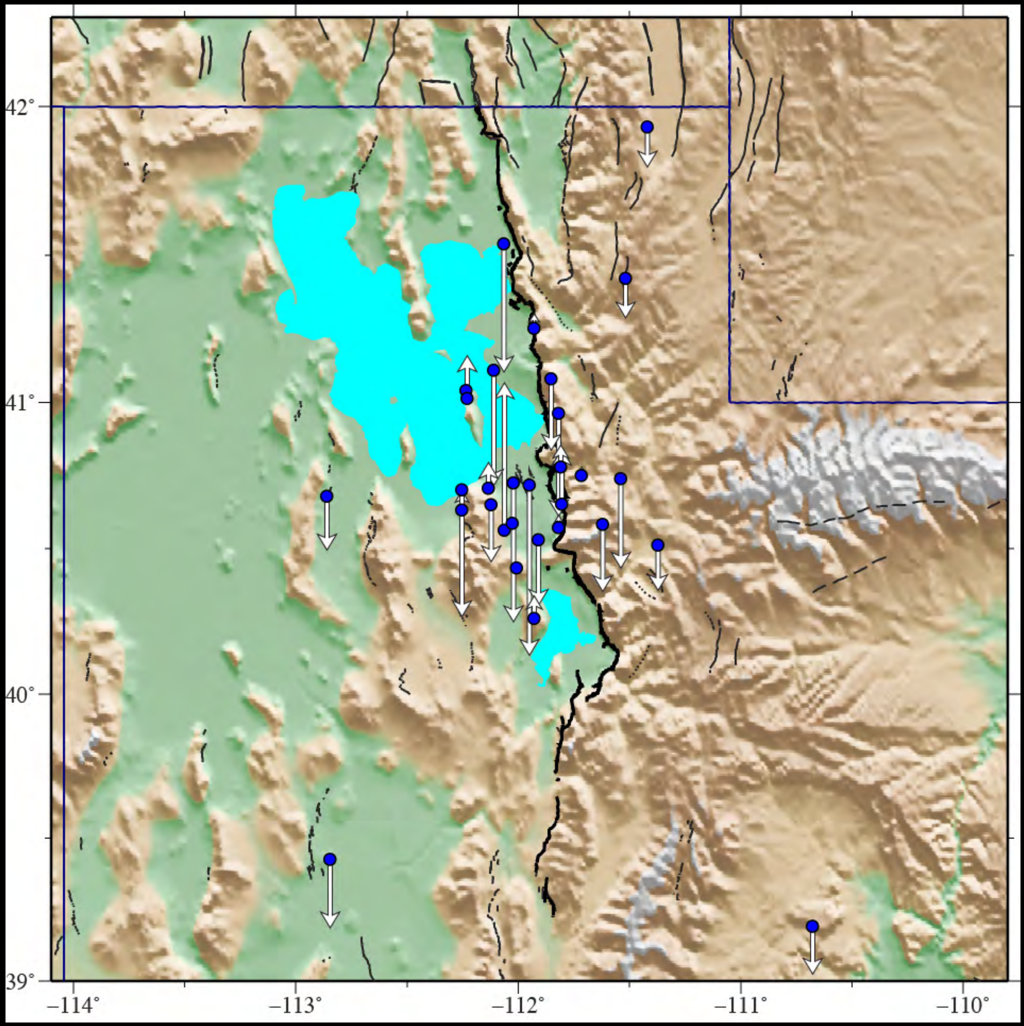


- Ratios of minima to maxima at surface dependent on dip
- Uncertainties in min/max values

1993-2001 Campaign GPS
Horizontal Velocities

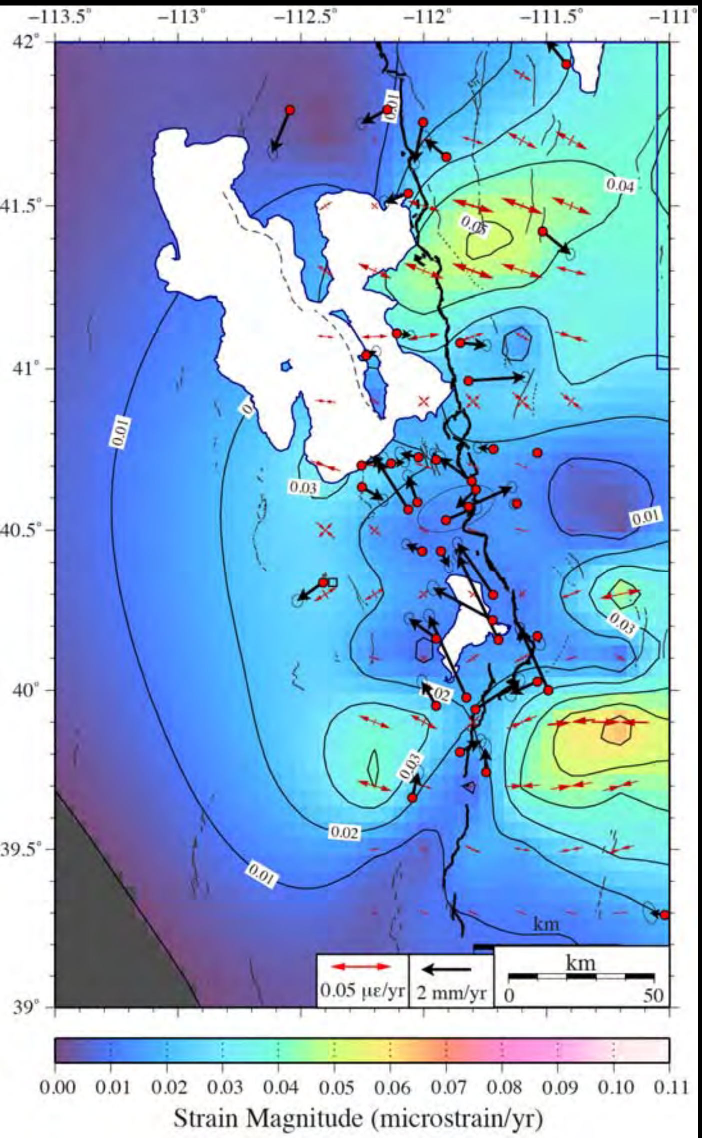


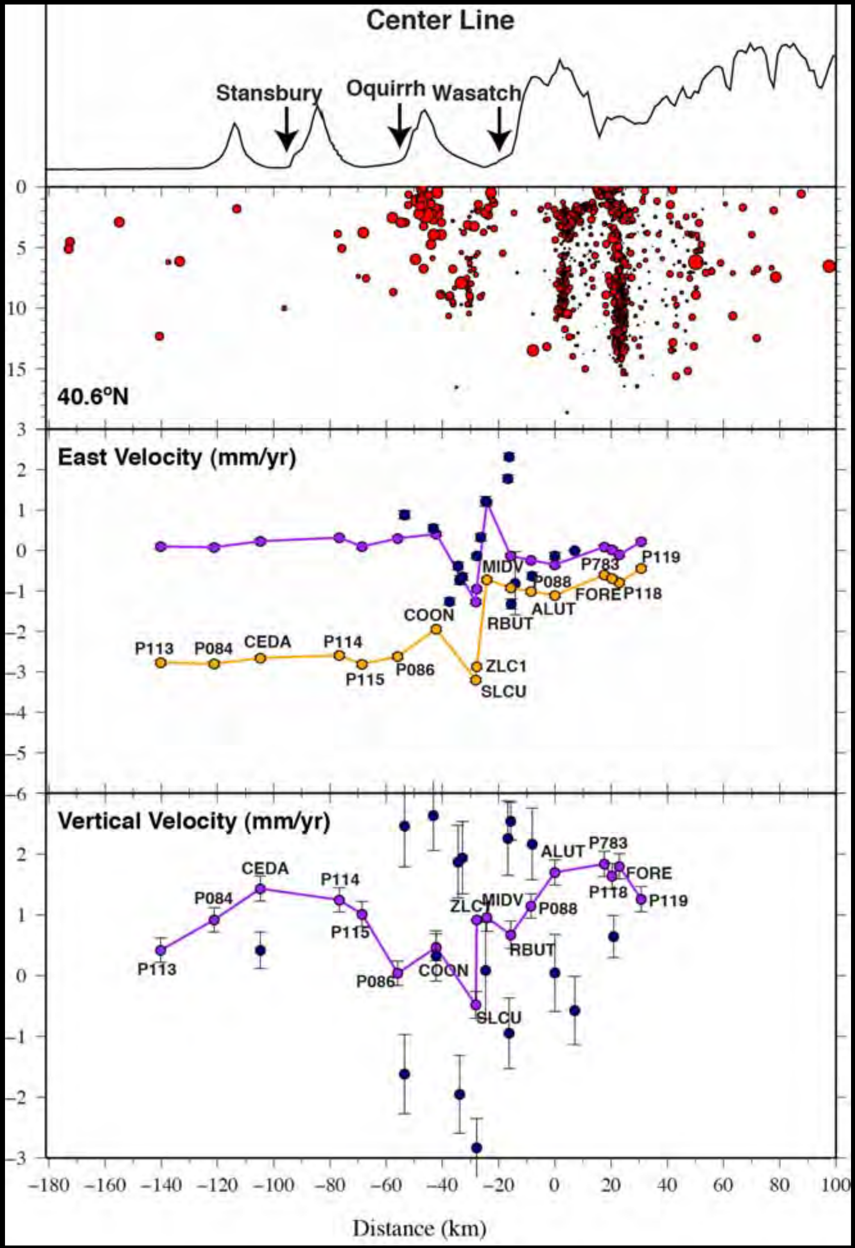
1993-2001 Campaign GPS
Vertical Velocities



- 1993-2001 campaign GPS data available
- Campaign stations concentrated at central segments of Wasatch Fault

1993-2001 Campaign GPS Residuals and Strain Rates

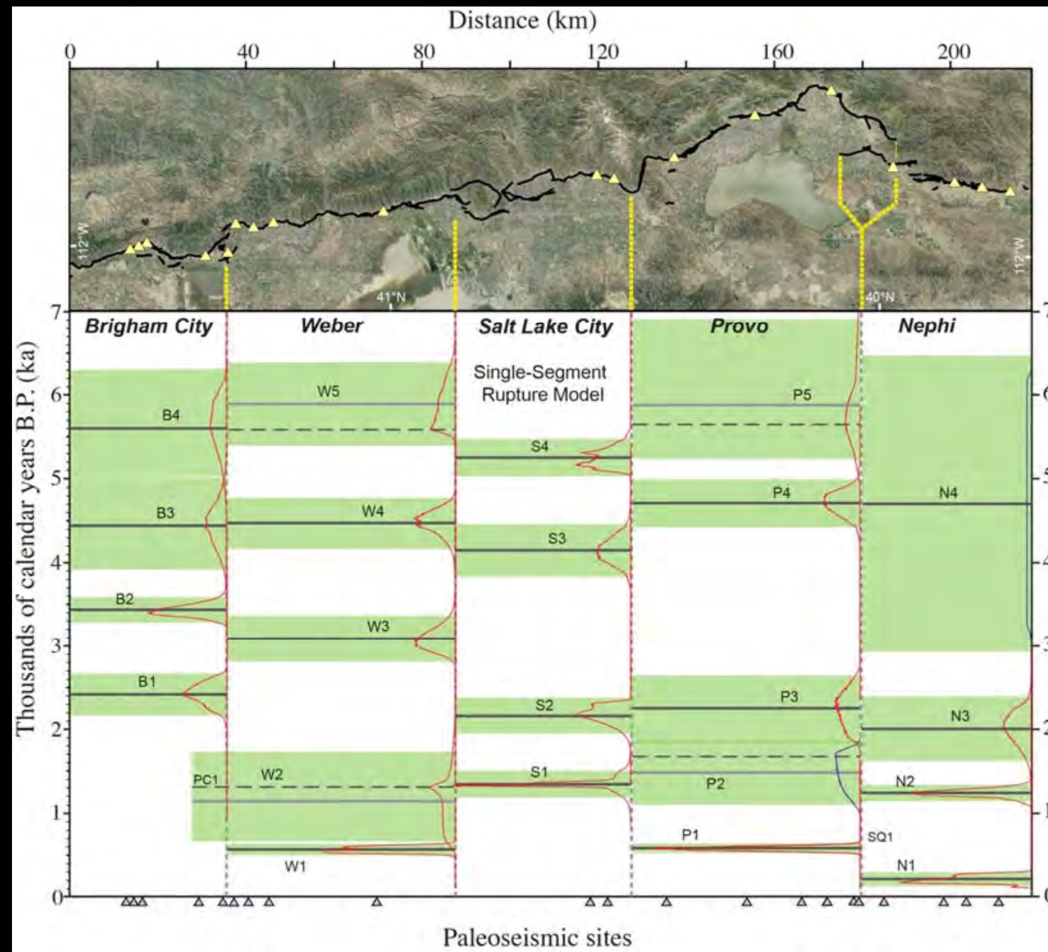




- Applying block rotations to campaign velocities leaves large outliers
- Adding campaign stations will increase noise in profiles

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

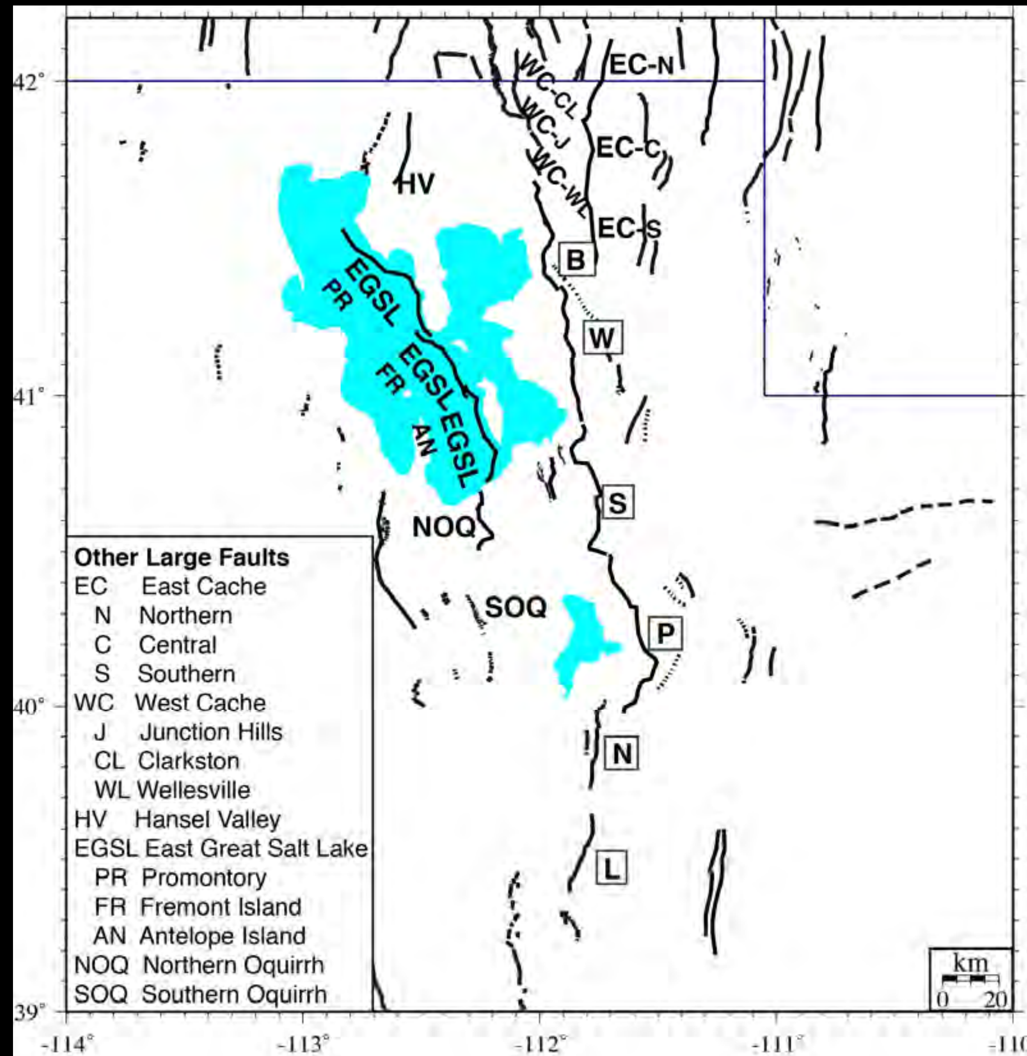


(DuRoss et al., 2011)

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

Wasatch Front Geography

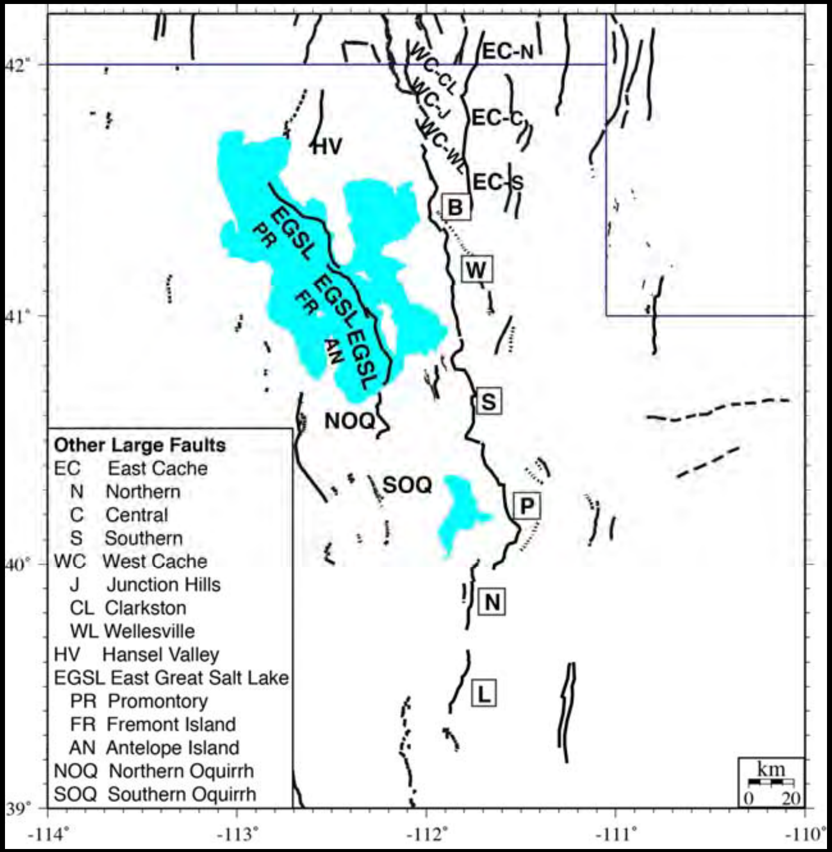
Major Normal Faults

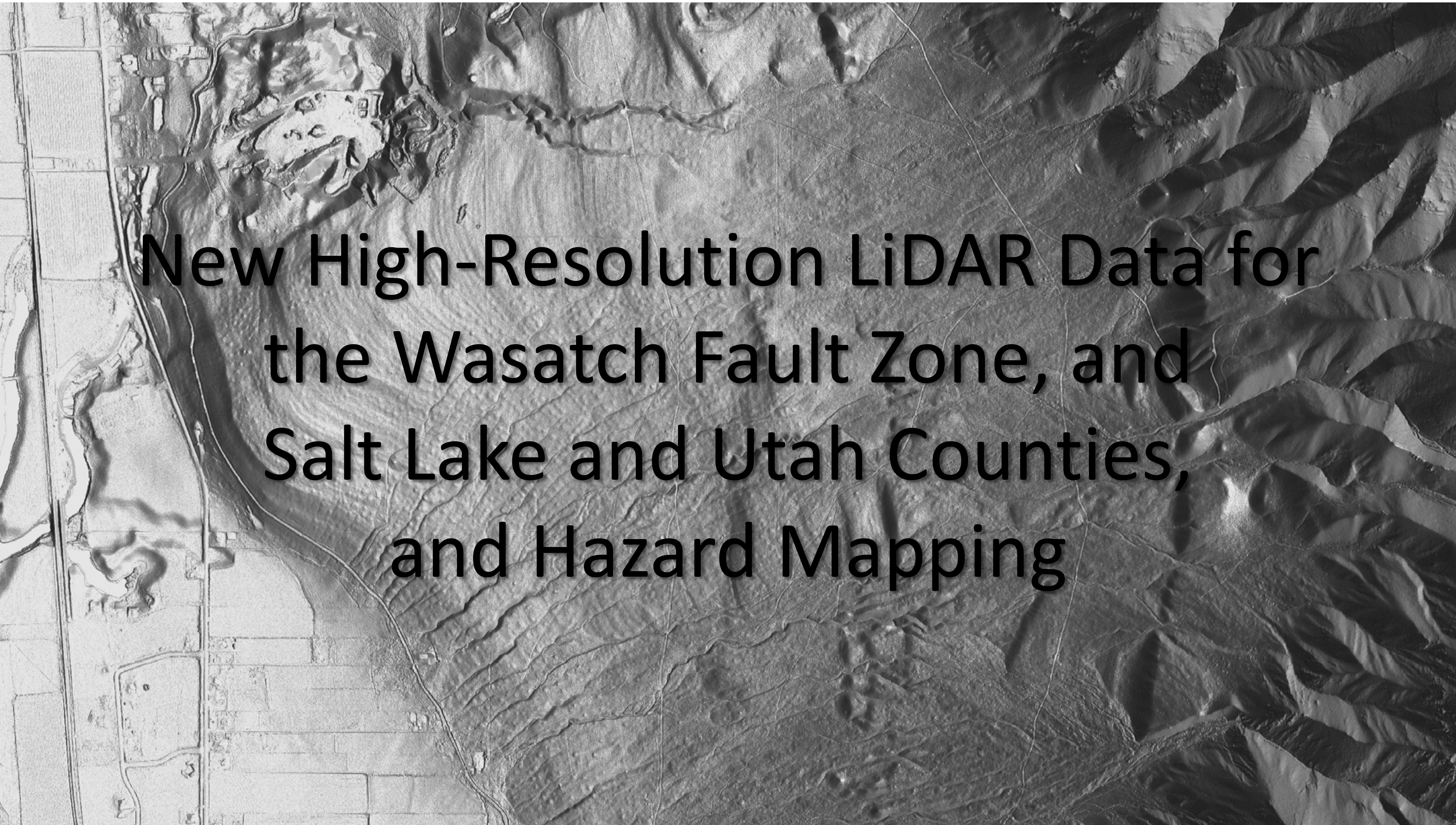


Other Prehistoric Earthquakes

Fault Name	Segment Name	Segment Length (km)	Age Range	Closest Wasatch Segment
Hansel Valley		11	78 (1934 M6.6)	Collinston
EGSL	Antelope Island	35	355-797	Weber
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)





New High-Resolution LiDAR Data for the Wasatch Fault Zone, and Salt Lake and Utah Counties, and Hazard Mapping

Steve Bowman and Adam McKean
Geologic Hazards Program

UTAH DNR GEOLOGICAL SURVEY

UGS LiDAR Acquisition

The UGS is acquiring LiDAR data to support detailed geologic and geologic hazard (active fault traces, ground subsidence, etc.) mapping. All data collected is in the public domain and free to distribute.

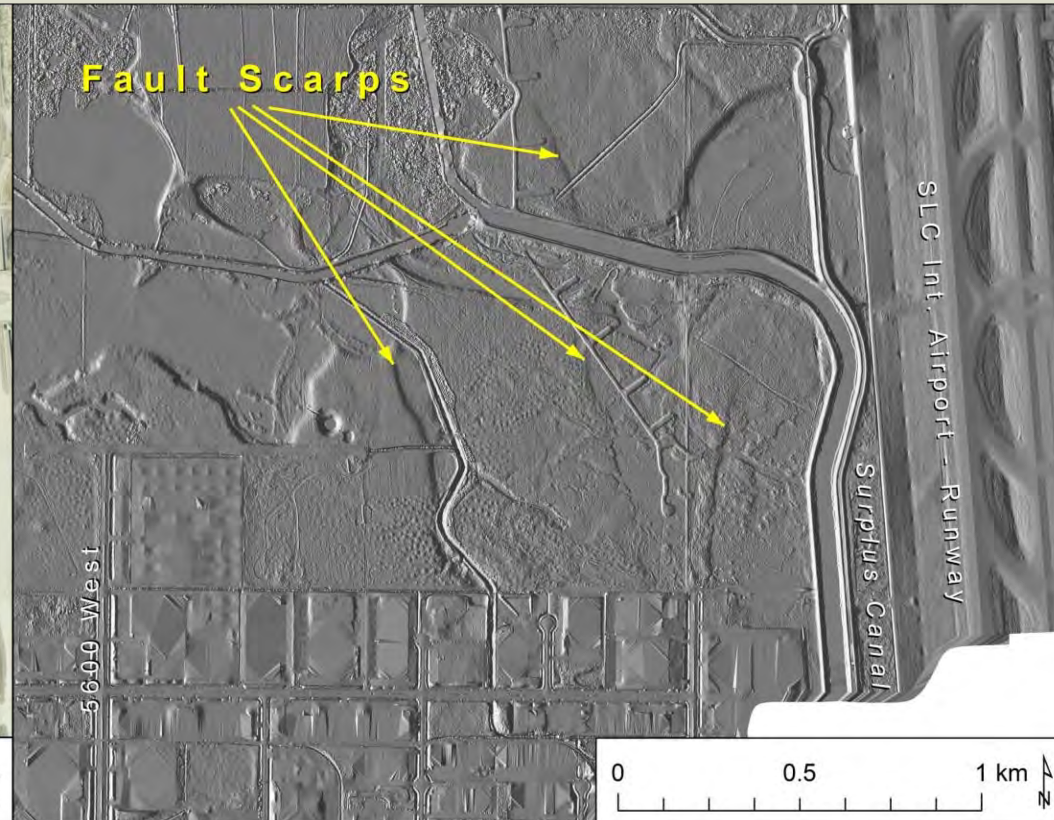
- 2011 Acquisition (1902 square miles, 1 meter data)
  - Partnership with Utah Division of Emergency Management (UDEM), Federal Emergency Management Agency (FEMA), and the Utah Automated Geographic Reference Center (AGRC).
  - Data currently available from the UGS (metadata), AGRC (metadata and DEM data), and OpenTopography (all data).

- 2013 Acquisition (1352 square miles, 0.5 meter data)
  - Partnership with the UDEM, FEMA, U.S. Geological Survey, Salt Lake County, and the AGRC.
    - Data will be available to the public summer 2014.

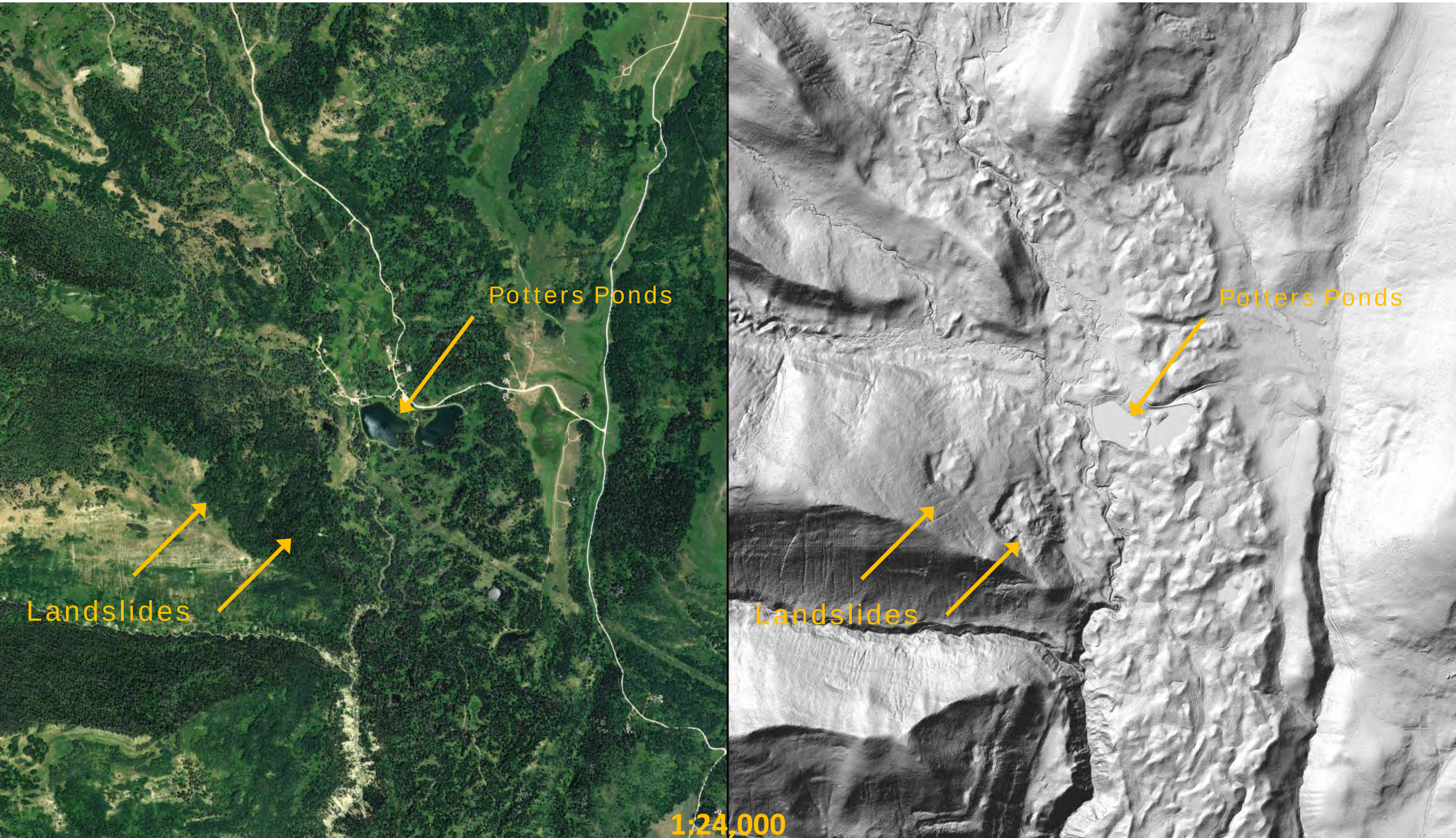
More Faults Than Previously Mapped on the Grainger Fault, West Valley Fault Zone

2006 NAIP

2011 1-Meter LiDAR



Mapping for the Baileys Lake and Salt Lake City North 7-1/2 min. quadrangles.



2011 1 Meter NAIP

2011 1 Meter LiDAR

Lowry Waters Area (Wasatch Plateau) Landslide Mapping
Difficulty of Landslide Detection in Vegetated Areas

USGS Topo Map 40 Foot Contours

2011 LiDAR Derived 6.6 Feet Contours

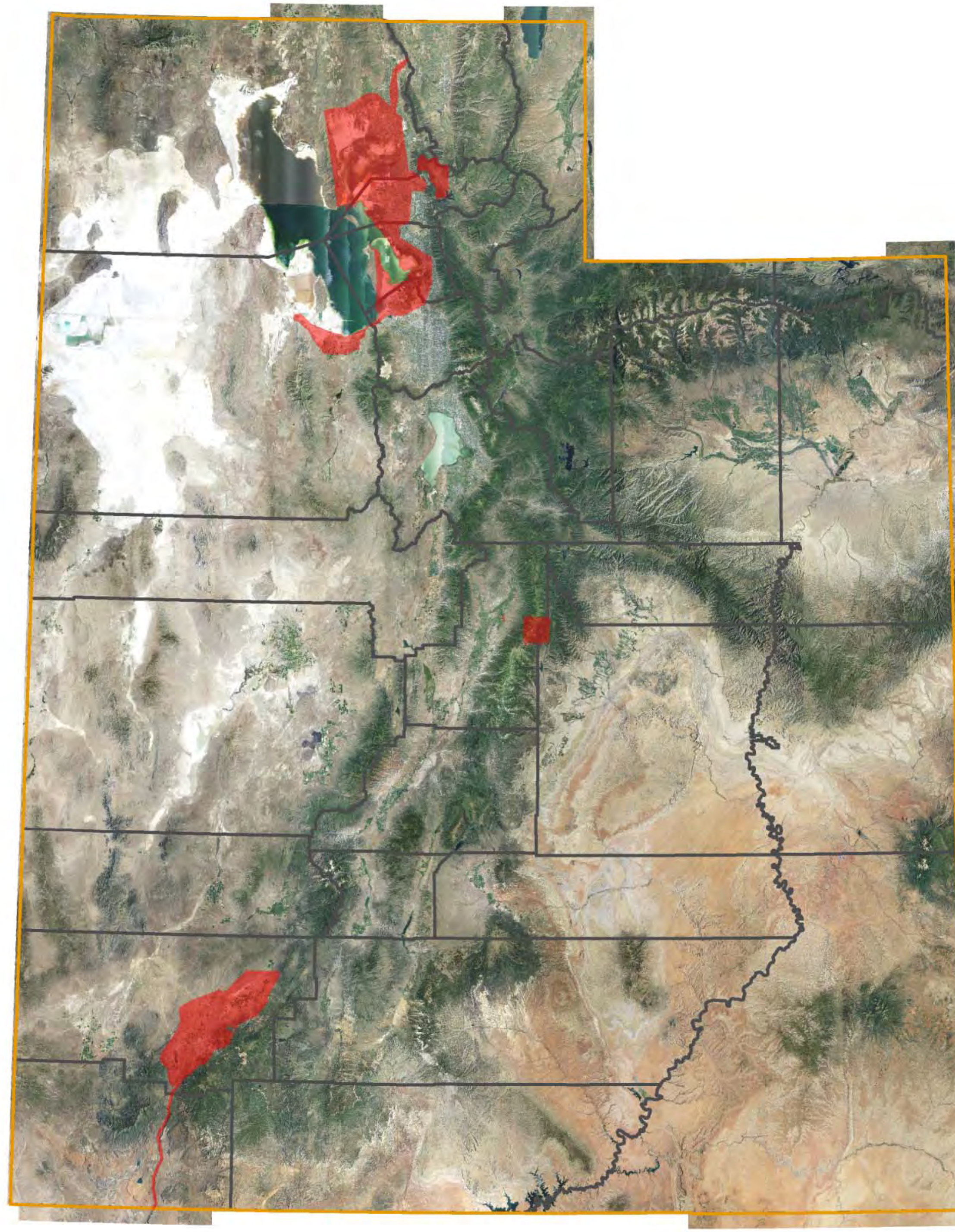
Lowry Waters Area (Wasatch Plateau) Landslide Mapping
Enhanced Topographic Contours from 2011 LiDAR Data

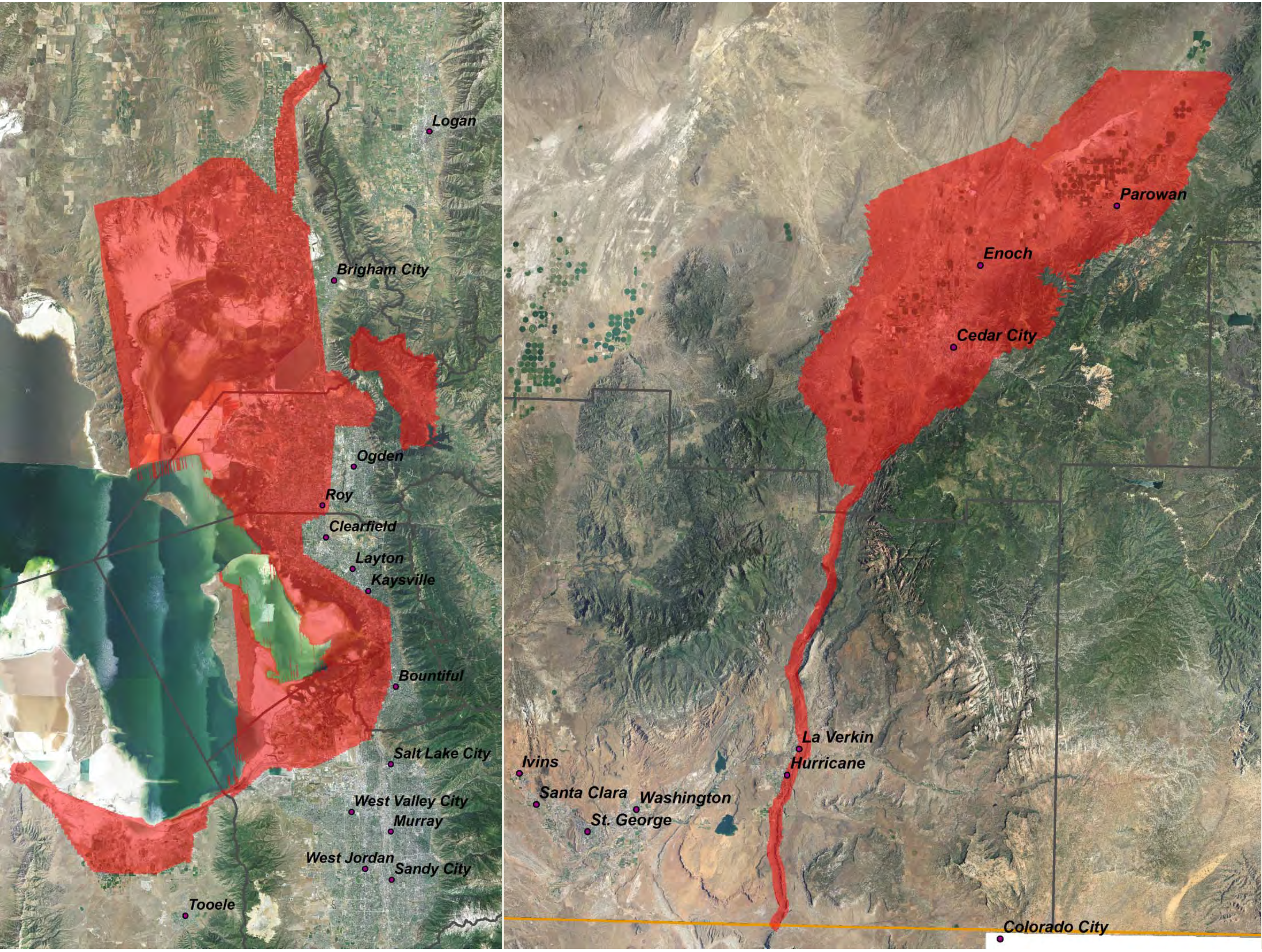
2011 UGS 1 m LiDAR Acquisition

- Hurricane Fault
- East Great Salt Lake
- West Half of Ogden Valley
- Southern Great Salt Lake
- Cedar & Parowan Valleys
- North Odgen (FEMA/UDEM)
- Wasatch Plateau (Lowry Water area)

1902 square miles

Raw, DEM, and DSM data available.





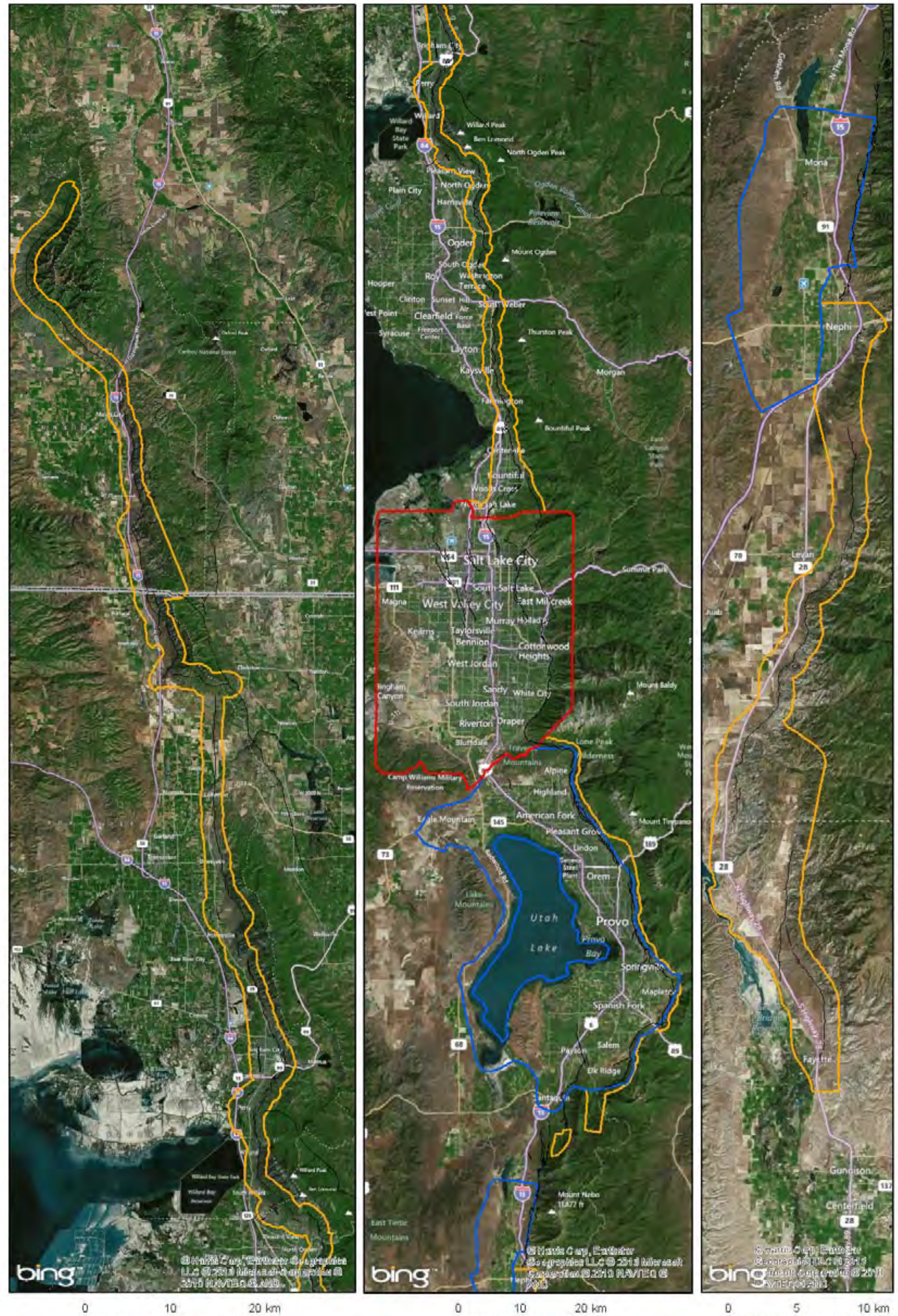
Logan
Brigham City
Ogden
Roy
Clearfield
Layton
Kaysville
Bountiful
Salt Lake City
West Valley City
Murray
West Jordan
Sandy City
Tooele
Parowan
Enoch
Cedar City
La Verkin
Hurricane
Ivins
Santa Clara
Washington
St. George
Colorado City

2013 UGS High-Resolution 0.5 m LiDAR Acquisition

- Salt Lake Valley
- Utah Valley
- Wasatch Fault Zone

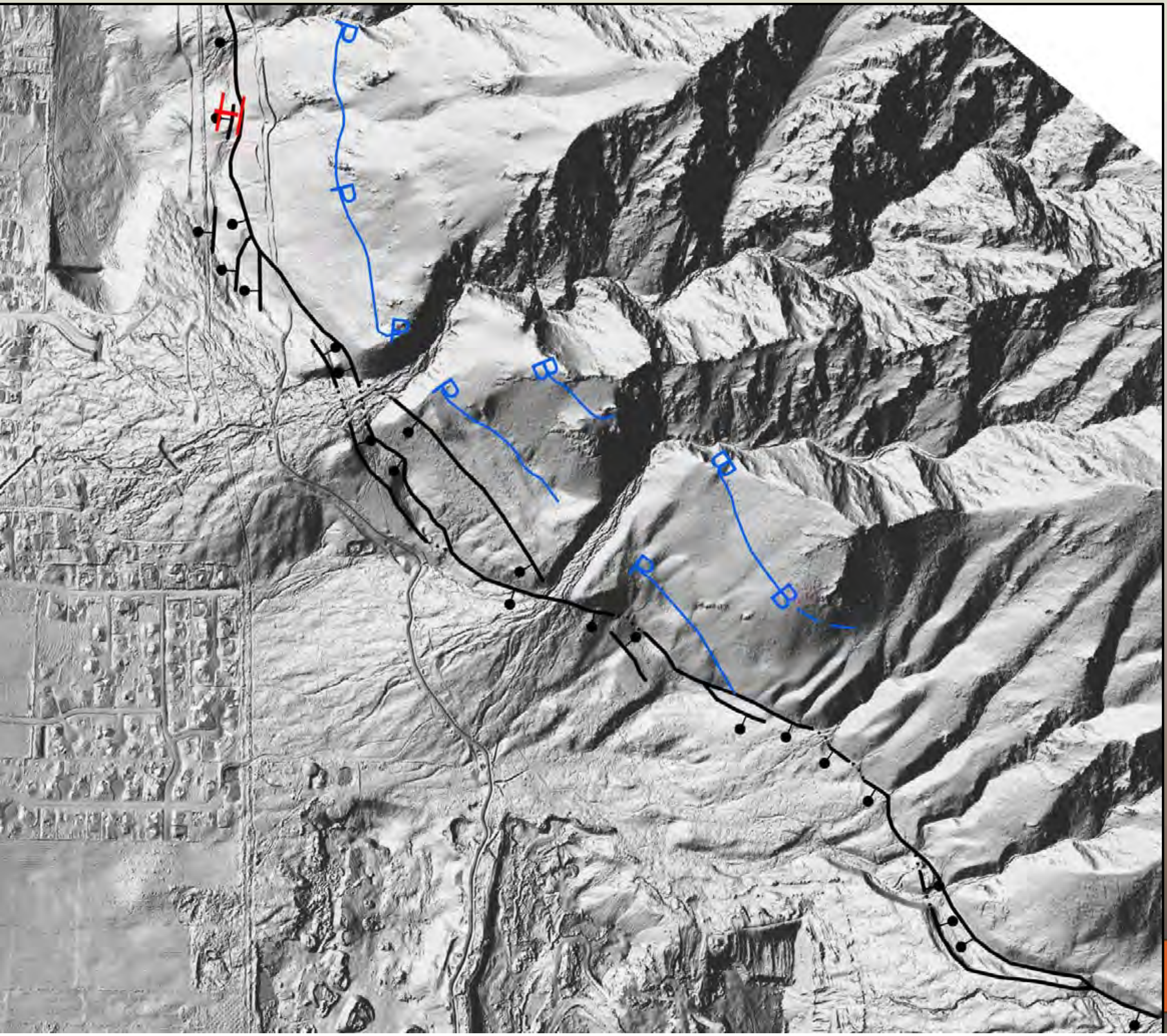
1352 square miles

Raw, DEM, and DSM data will be available to all summer 2014.



UTAH GEOLOGICAL SURVEY

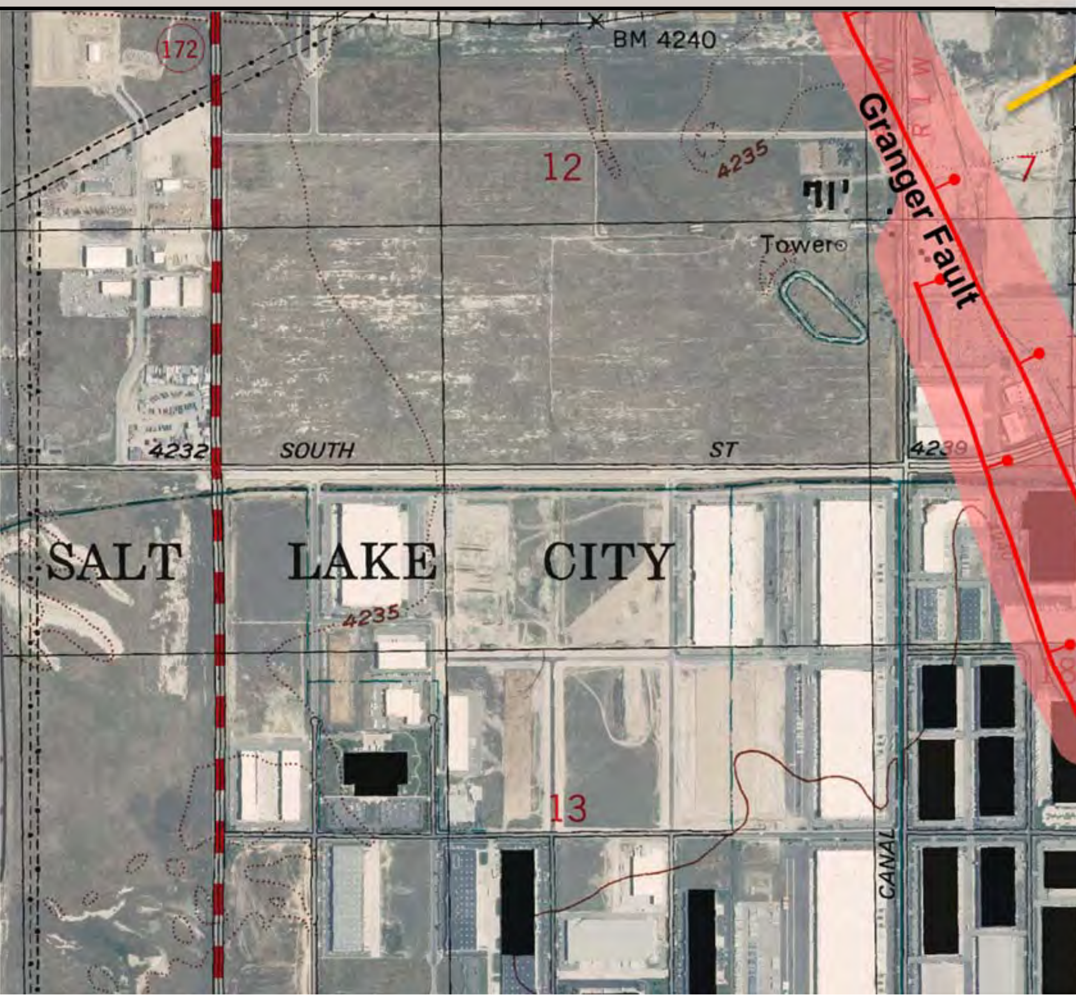
Detailed Re-Mapping of the Wasatch Fault Zone (WFZ) using new 0.5 meter LiDAR



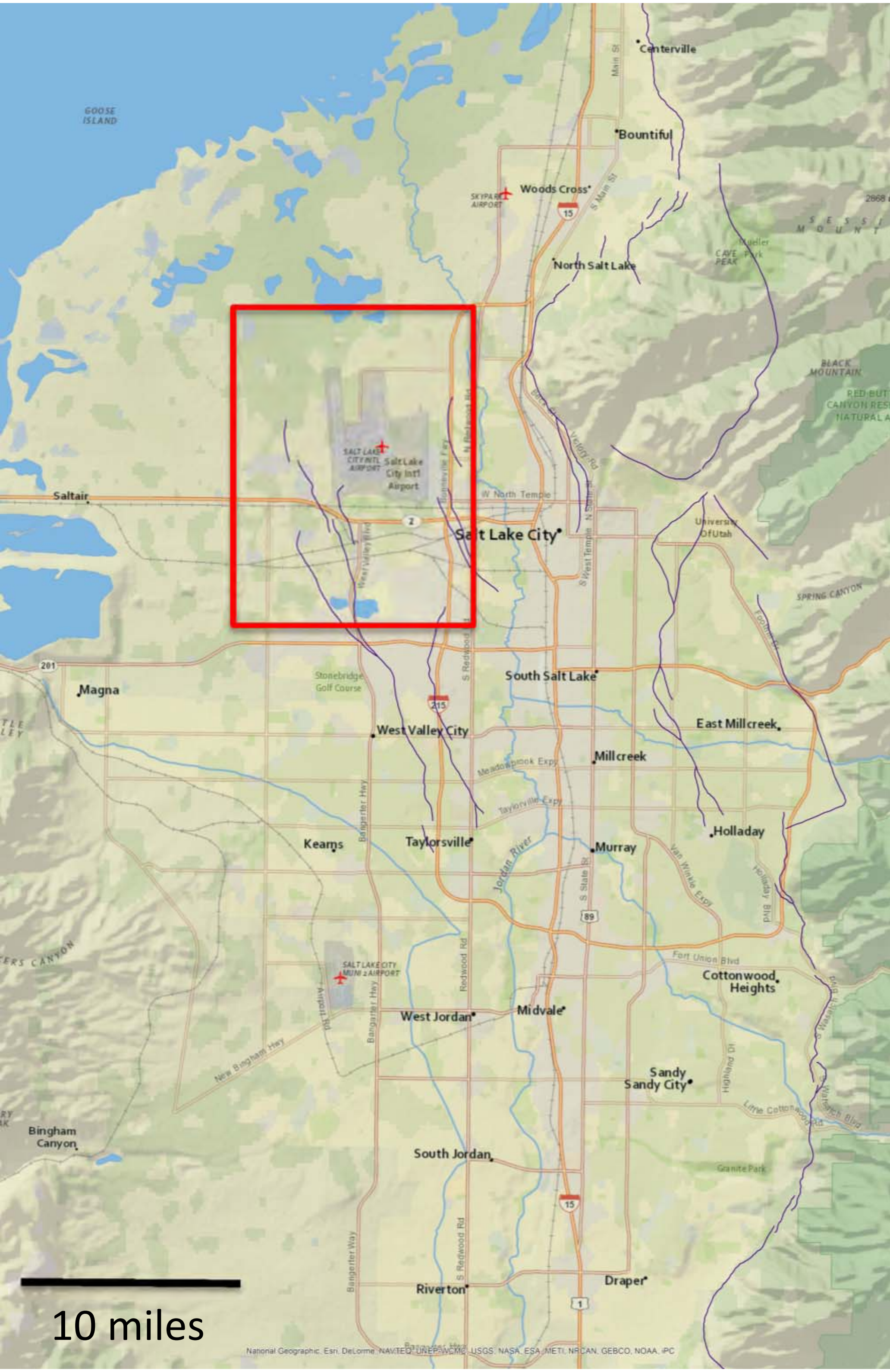
- Salt Lake City segment (Adam McKean)
- Southern Half of the Collinston segment (Kimm Harty)
- Malad City and Clarkston Mountain segments (Kimm Harty)
- Levan and Fayette segments (Mike Hylland)
- Various segment boundaries (Chris DuRoss and Scott Bennett [USGS])
- Landslides along the WFZ (Gregg Beukelman)

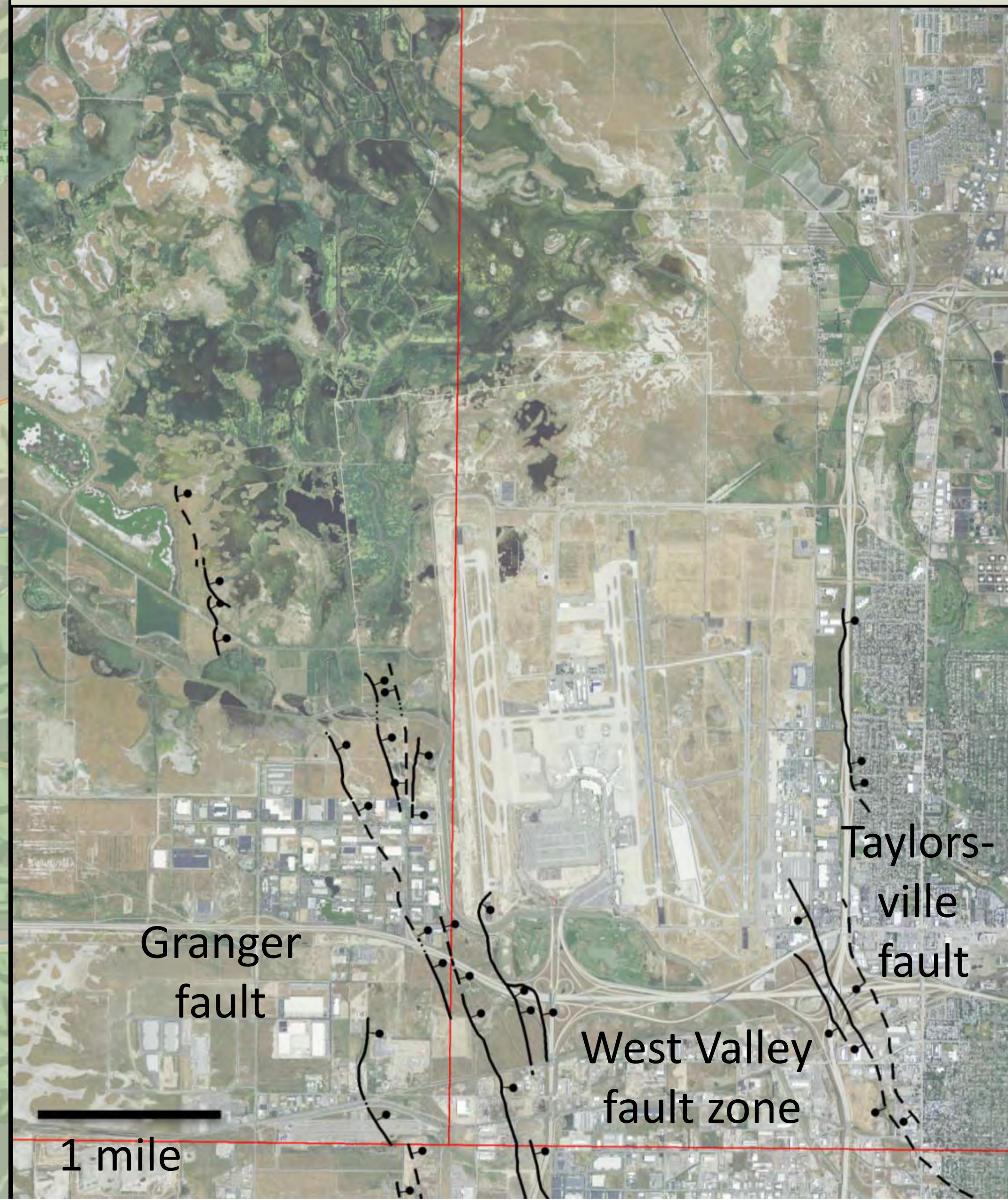
New Surface-Fault-Rupture Hazard Maps for the Wasatch Fault Zone (WFZ) to be Created Using New 0.5 meter LiDAR

Sample from 2011 Magna quadrangle map set.

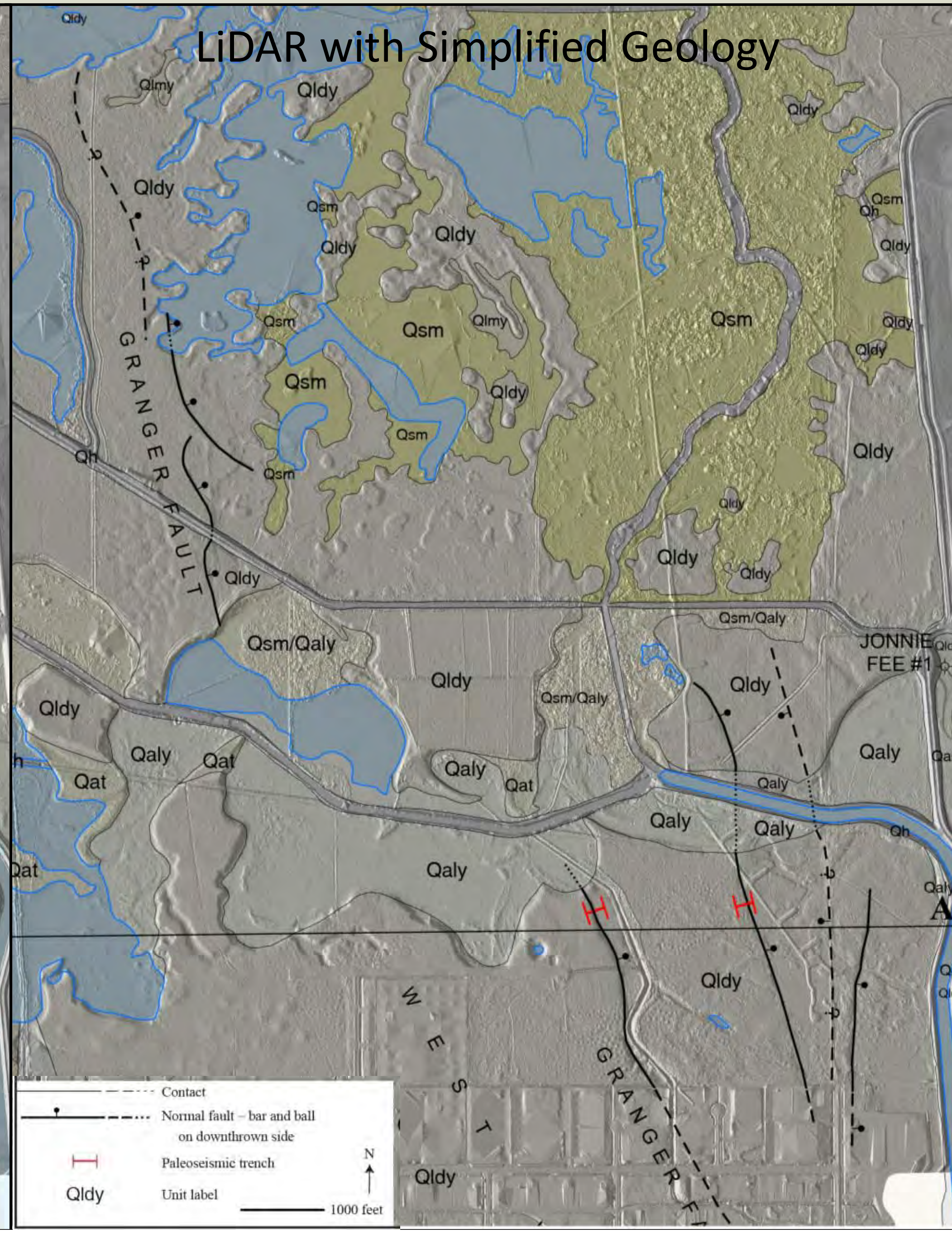


STATEMAP Geologic Mapping of the Baileys Lake and Salt Lake City North 7.5-min Quadrangles



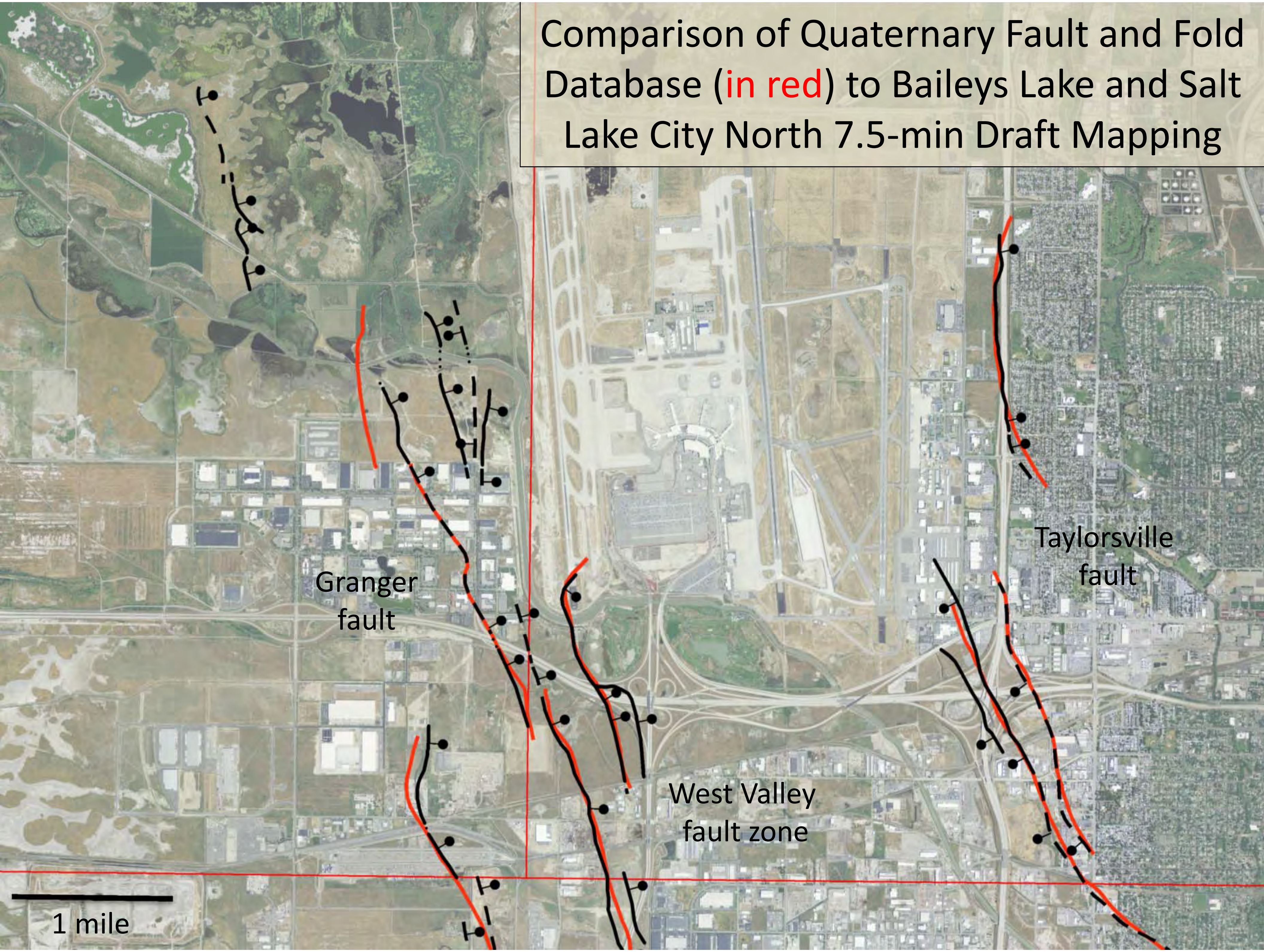


LiDAR Mapping of the Granger Fault (Baileys Lake 7.5-min Quadrangle)



- Extension of Granger fault with LiDAR
  - From about 9.5 miles
  - To between 10.9 or 11.5 miles
  - New strand is 0.7 to 1.2 miles long

- Measured vertical displacement of new surface fault ruptures:
  - Most new traces are in the 0.2 to 0.6 m range
  - As small as 0.1 to 0.2 m vertical displacement



Comparison of Quaternary Fault and Fold Database (in red) to Baileys Lake and Salt Lake City North 7.5-min Draft Mapping
Granger fault
West Valley fault zone
Taylorsville fault
1 mile

Forecasting Large Earthquakes Along the Wasatch Front

Ivan Wong
Seismic Hazards Group, URS Corporation, Oakland, CA

Bill Lund
Utah Geological Survey, Cedar City, UT

Patricia Thomas and Susan Olig
Seismic Hazards Group, URS Corporation, Oakland, CA

Chris DuRoss and Mike Hylland
Utah Geological Survey, Salt Lake City, UT

Walter Arabasz, James Pechmann, and Robert Smith
Department of Geology and Geophysics, University of Utah, Salt Lake City, UT

Tony Crone, Nico Luco, Steve Personius, and Mark Petersen
U.S. Geological Survey, Denver, CO

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

Utah Quaternary Fault Parameters Working Group
Salt Lake City, UT

5 February 2014

URS

WGUEP

- The Working Group on Utah Earthquake Probabilities was formed in late 2009.
- Funded by the USGS through the NEHRP external grants program for 3 years and the Utah Geological Survey.
- The final report and results will be released by end of ~~2013~~ 2014.

WGUEP Members

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

Assistance from Steve Bowman, UGS

Introduction

- The WGUEP calculated the probability of moderate to large earthquakes (M $\geq$ 5.0) in the Wasatch Front region for a range of intervals varying from annually to 100 years.

- Time-dependent and time-independent earthquake probabilities that were estimated are:

1. Segment-specific for the 5 central segments of the Wasatch fault.
2. Total for the Wasatch fault central segments and the whole fault including the end segments.
3. Segment-specific and fault-specific for the Oquirrh-Great Salt Lake fault.
4. Time-independent fault-specific for all other faults in the Wasatch Front.
5. Time-independent for background earthquakes (M 5.0 to 6.75).
6. Total for the Wasatch Front region.

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Introduction (cont.)

- The final forecast will be reviewed by the UGS, USGS, and NEPEC.
- There will be a media release of the WGUEP results. Project results will also be presented at meetings for the general public and at professional and scientific society meetings.

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Scope of Work

- Time-dependent probabilities were calculated for Wasatch and the Great Salt Lake fault zones where the data is available on the expected mean frequency of earthquakes and the elapsed time since the most recent large earthquake.
- Even for these faults, significant weight was given to the time-independent model.
- Where such information is lacking on less well-studied faults, time-independent probabilities were calculated.
- Epistemic uncertainties in all input parameters were explicitly addressed by the WGUEP using logic trees.

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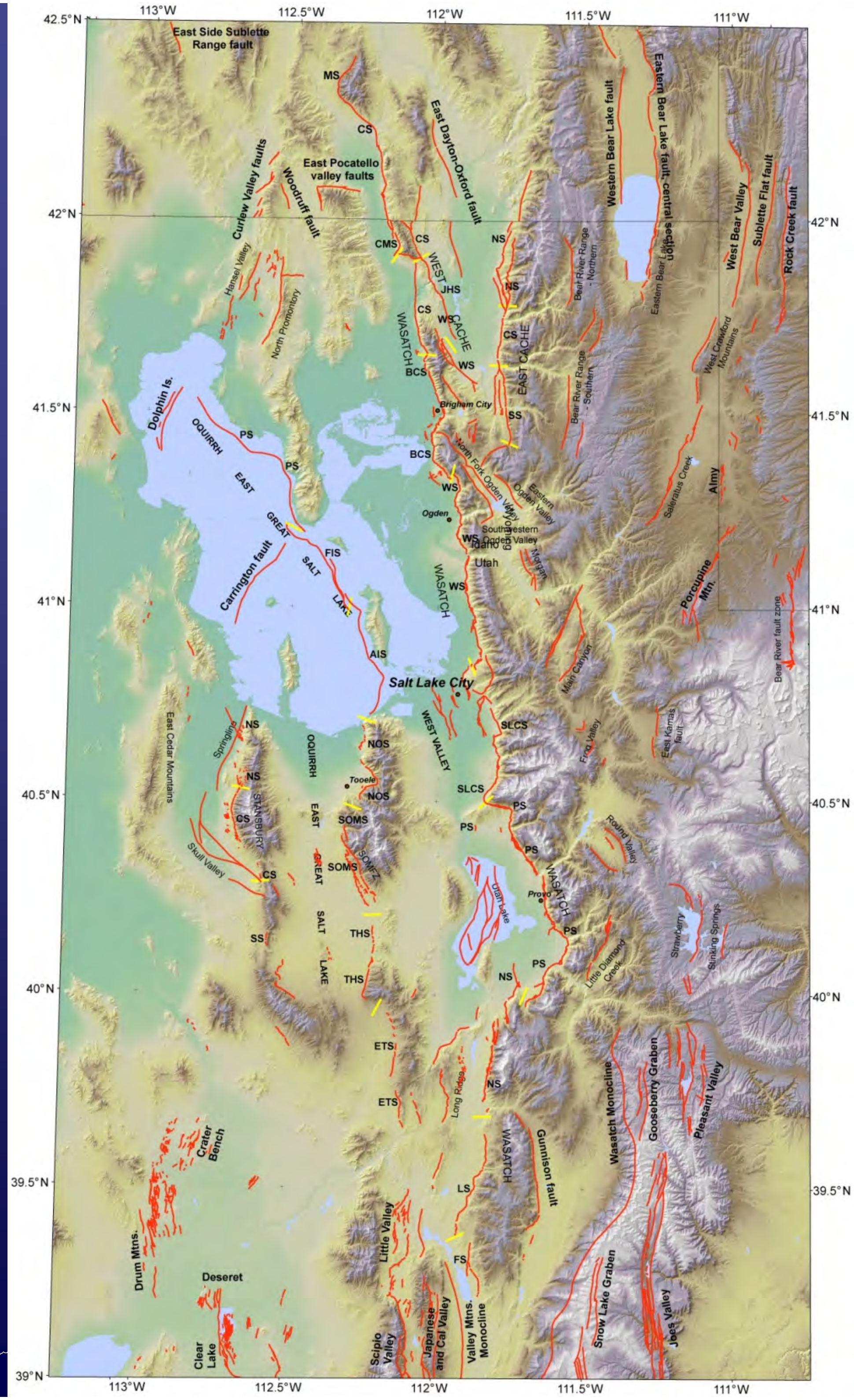
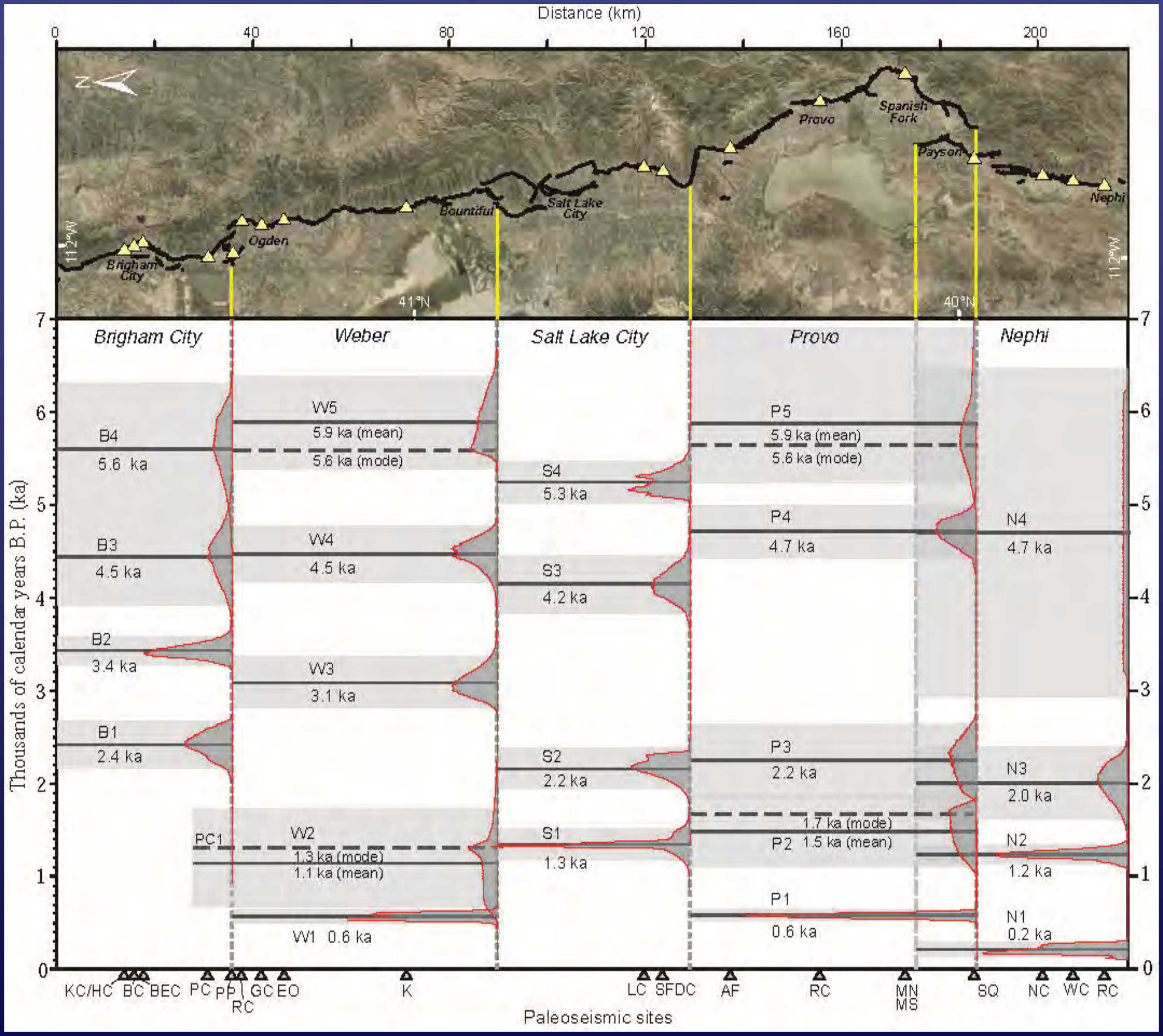
WGUEP Wasatch Front



Segments of the Wasatch Fault Zone (WFZ) in Southern Idaho and Northern Utah

URS

Single-Segment Rupture Model for the Central WFZ

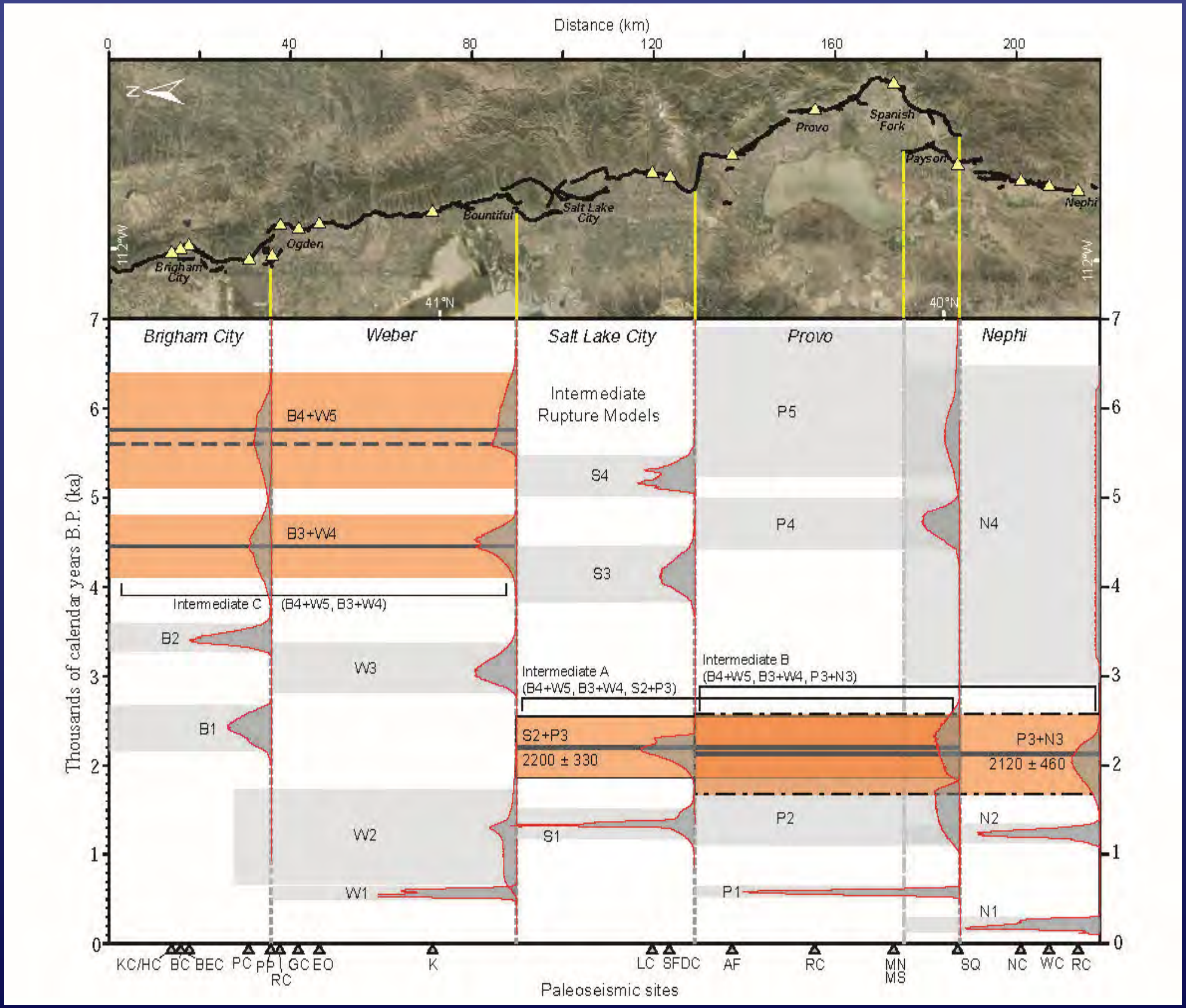


Intermediate Rupture Models for the Central WFZ

A – B4+W5, B3+W4 and S2+P3

B – P3+N3 in place of S2+P3

C – B4+W5 and B3+W4



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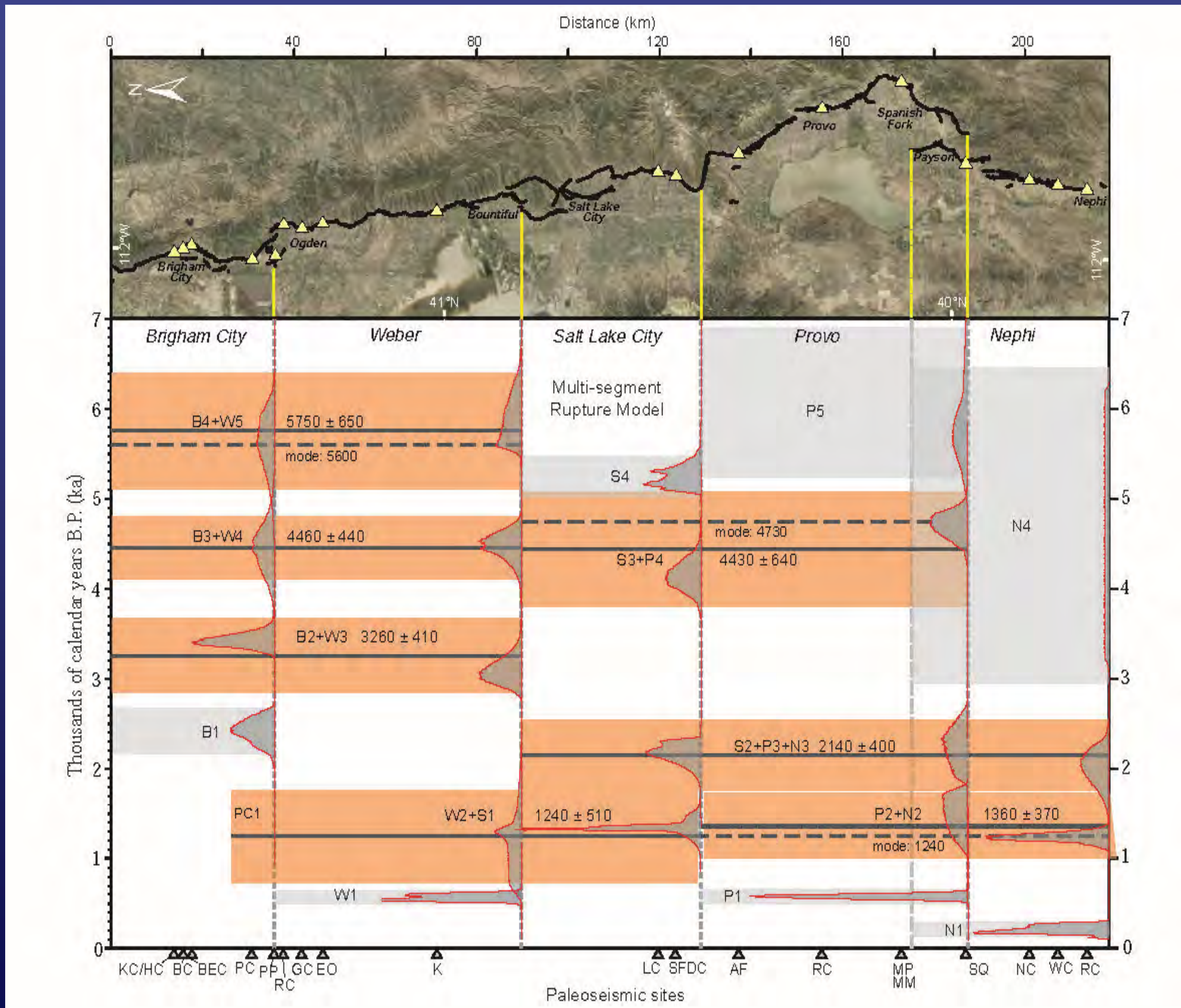
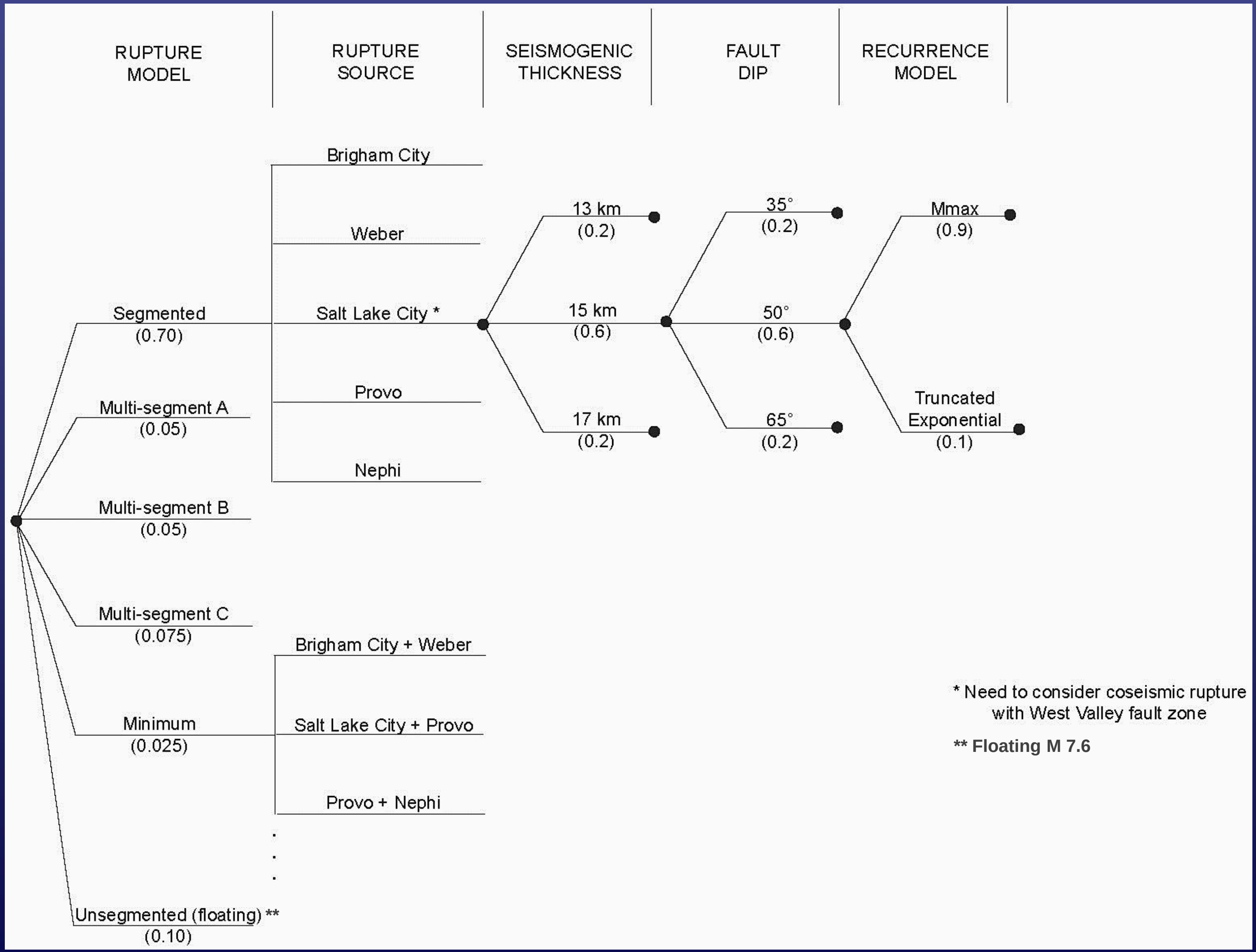
Multi-Segment Rupture Models for the Central WFZ



Generalized Logic Tree for Calculating the Recurrence of the Central Segments of WFZ



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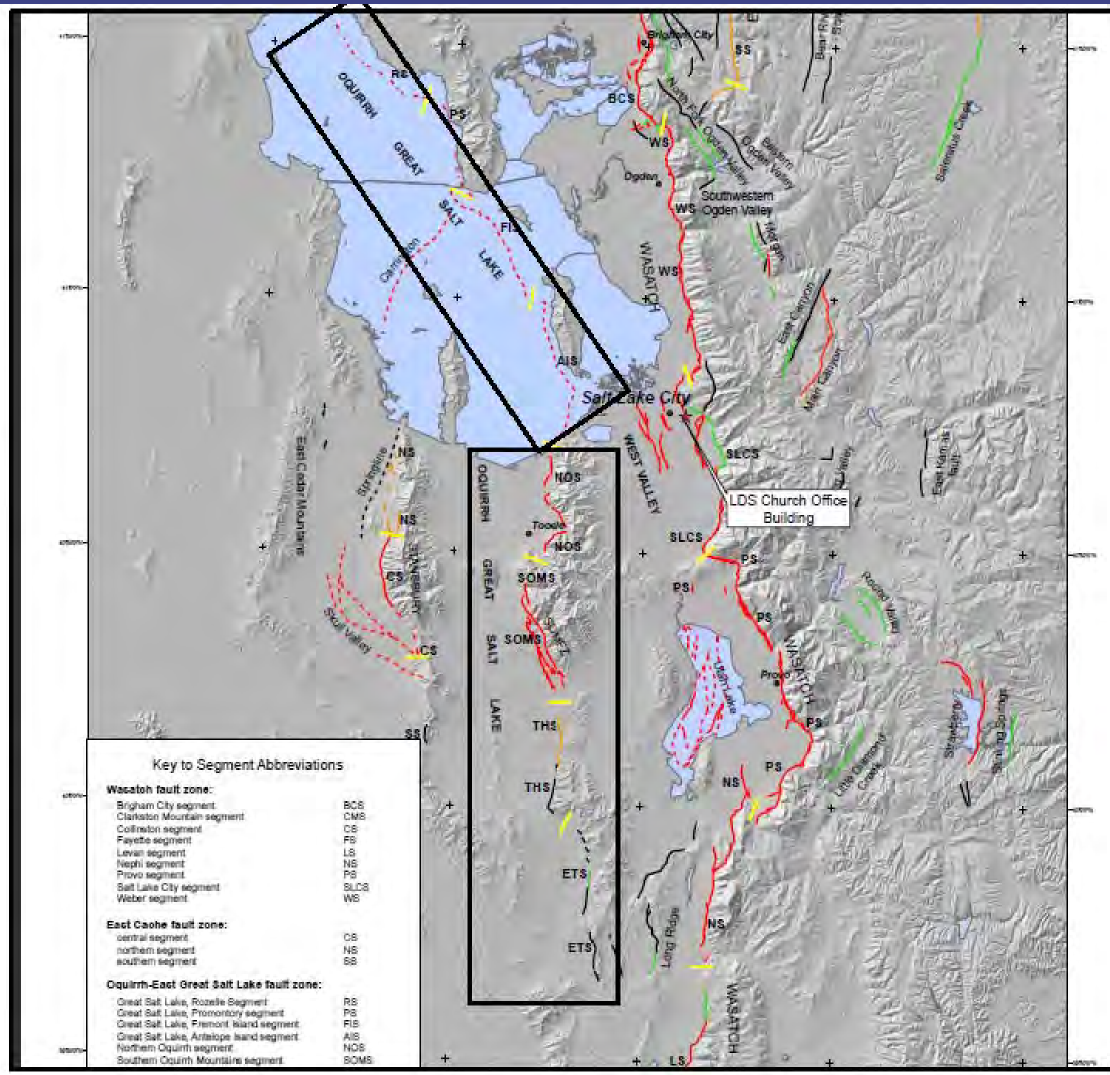
Segments of the Oquirrh-Great Salt Lake Fault Zone

O-GSLFZ SEGMENTS

Rozelle (RZ) – 25 km
Promontory (PY) – 25 km
Fremont Is. (FI) – 25 km
Antelope Is. (AI) – 35 km
No. Oquirrh (NO) – 30 km
So. Oquirrh (SO) – 31 km
Topliff Hills (TH) – 26 km
East Tintic (ET) – 35 km



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Proposed Rupture Models and Weights for the Oquirrh-Great Salt Lake Fault Zone

	Rupture Scenarios	Weights
1	RZ, PY, FI, AI, NO+S0, TH, ET	0.15
2	RZ, PY, FI, AI NO, SO, TH, ET	0.4
3	RZ, PY, FI+AI, NO, SO, TH, ET	0.15
4	RZ, PY, FI, AI, NO, SO+TH, ET	0.1
5	Unsegmented (floating)	0.2

"Other" Faults/Fault Segments in the Wasatch Front Region Retained in the WGUEP Probabilistic Earthquake Forecast

Bear River fault zone
Broadmouth Canyon faults[1]
Carrington fault
Crater Bench fault[2]
Crawford Mountains (west side) fault
Curlew Valley faults
Drum Mountains fault zone[2]
East Cache fault zone
- Northern segment
- Central segment
- Southern segment[1]

East Dayton – Oxford faults
Eastern Bear Lake fault
- Northern segment
- Central segment
- Southern segment

Gunnison fault
Hansel Valley fault[3]
Hansel Valley (east side) faults[3]
Hansel Valley (valley floor) faults[3]
James Peak fault[1]
Joes Valley faults
Little Valley faults
Main Canyon fault
Maple Grove faults[4]
Morgan fault
- Northern section[5]
- Central section[5]
- Southern section[5]

North Promontory fault
Porcupine fault
Pavant Range fault[4]
Reactivated section Absaroka thrust fault
Red Canyon faults[4]
Rock Creek fault
Scipio fault zone[4]
Scipio Valley faults[4]
Skull Valley (mid valley) faults
Snow Lake graben
Stansbury fault
Stinking Springs fault
Strawberry fault
Utah Lake faults
West Cache fault zone
- Clarkston fault
- Junction Hills fault
- Wellsville fault

West Valley fault zone
- Granger fault
- Taylorsville fault

Western Bear Lake fault

URS

Accomplishments

- Characterized end segments of Wasatch fault and other faults in Wasatch Front.
- Characterized all other “significant” faults in the Wasatch Front.
- Developed model for coseismic rupture of antithetic faults
  - SLC Segment/West Valley (0.75/0.25)
  - Provo Segment/Utah Lake (0.5/0.5)
  - Hansel Valley/North Promontory (0.4/0.6)
  - Western/Eastern Bear Lake (0.5)/0.5)
- Compiled new consensus historical catalog through 2012 for the Wasatch Front.

Accomplishments (cont.)

- Developed a methodology to estimate Mmax.

  A faults (segmented with 2+ paleoseismic sites):
  45% Mo (Hanks and Kanamori)
  45% SRL-c (Stirling)
  5% SRL (W&C-all)
  5% W-SRL (Wesnousky)

  B faults (segmented, but limited D data):
  60% SRL-c (Stirling)
  40% SRL (W&C-all)

  C faults (not segmented, limited D data):
  50% SRL-c (Stirling)
  50% SRL (W&C-all)

- We have adopted a background earthquake Mmax of M 6.75 $\pm$ 0.25. USGS recurrence approach (e.g., recurrence models) is being used.

- Fault dip uncertainty adopted is 50 $\pm$ 15 degrees.

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Accomplishments (cont.)

- Seismogenic crustal depths (km):
  - East of WFZ 12 (0.1), 15 (0.7), 18 (0.2)
  - West of WFZ 12 (0.2), 15 (0.7), 18 (0.1)
- Considerable effort has been expended comparing moment rates derived from available geodetic, historical seismicity, and paleoseismic data. A discrepancy remains between geodetic rates and the paleoseismic and historical seismicity-based rates that is difficult to reconcile; the geodetic rates are at least 50% higher. The WGUEP will use the geodetic data as a constraint on regional moment rates. (Smith, Puskas, Petersen)

Results

- Stay Tuned.

UPCOMING INVESTIGATION OF THE SALT LAKE CITY SEGMENT OF THE WASATCH FAULT NEAR CORNER CANYON

Chris DuRoss
Utah Geological Survey

UTAH DNR GEOLOGICAL SURVEY

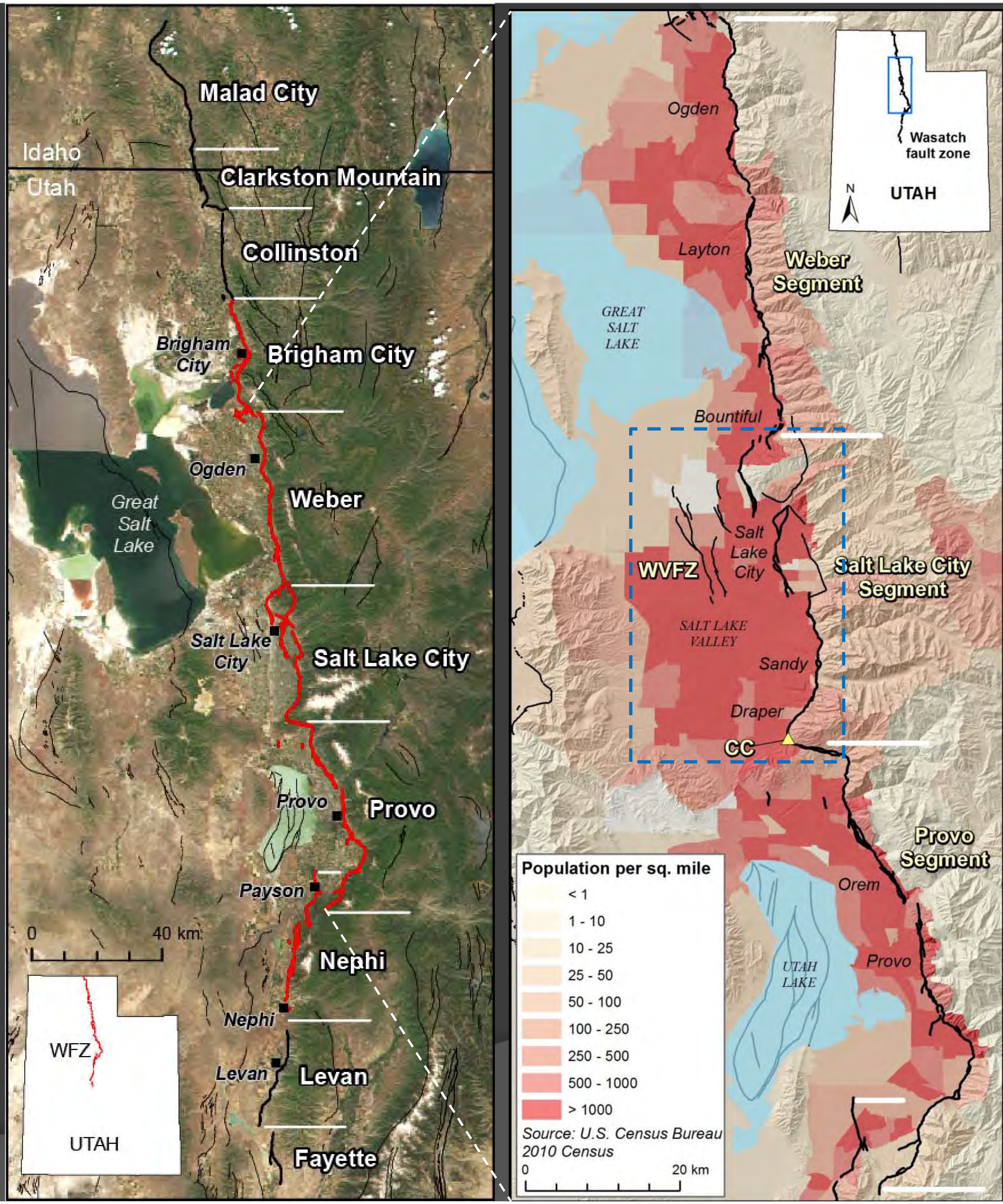
Utah Geological Survey

USGS science for a changing world

U.S. Geological Survey

Introduction

- **Salt Lake City segment (SLCS)**
  - Central of the central Wasatch fault zone segments
  - Adjacent to the most populous part of the Wasatch Front



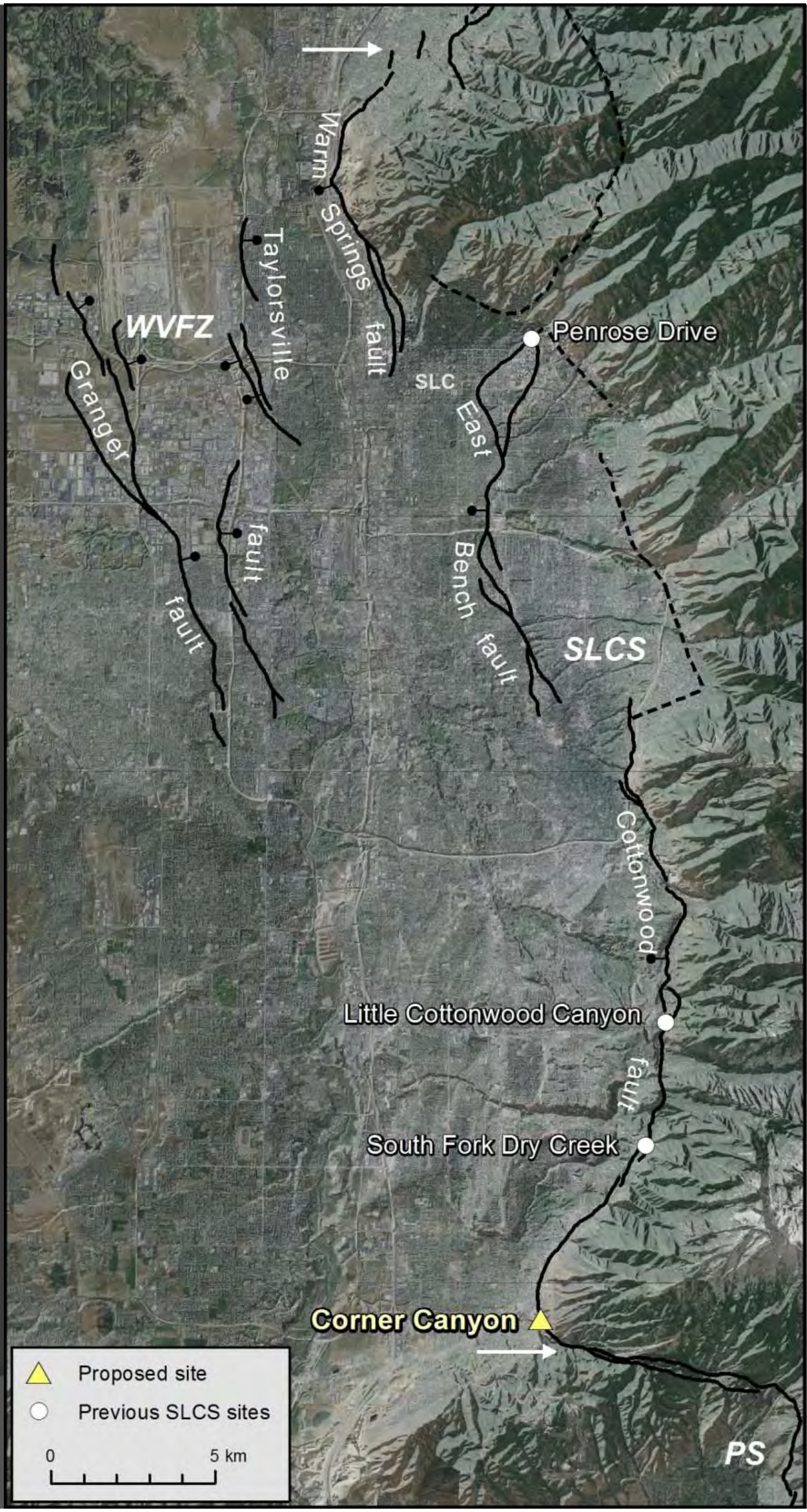
Introduction

- **Previous Data for the SLCS**

Earthquake timing on the SLCS

EQ	East Bench fault	Cottonwood fault		SLCS Chronology
	PD (ka)	LCC (ka)	SFDC (ka)	(ka)
S1	-	1.3 ± 0.04	1.3 ± 0.2	1.3 ± 0.2
S2	-	2.1 ± 0.3	2.2 ± 0.4	2.2 ± 0.2
S3	4.0 ± 0.5	4.4 ± 0.5	3.8 ± 0.6	4.1 ± 0.2
S4	5.9 ± 0.7	5.5 ± 0.8	5.0 ± 0.5	5.3 ± 0.2
S5	7.5 ± 0.8	7.8 ± 0.7	-	7.7 ± 0.4
S6	9.7 ± 1.1	9.5 ± 0.2	-	9.5 ± 0.3
S7	10.9 ± 0.2	-	-	10.9 ± 0.2
S8	12.1 ± 1.6	-	-	11.4–13.8
S9	16.5 ± 1.9	16.5 ± 2.7	-	14.6–17.9

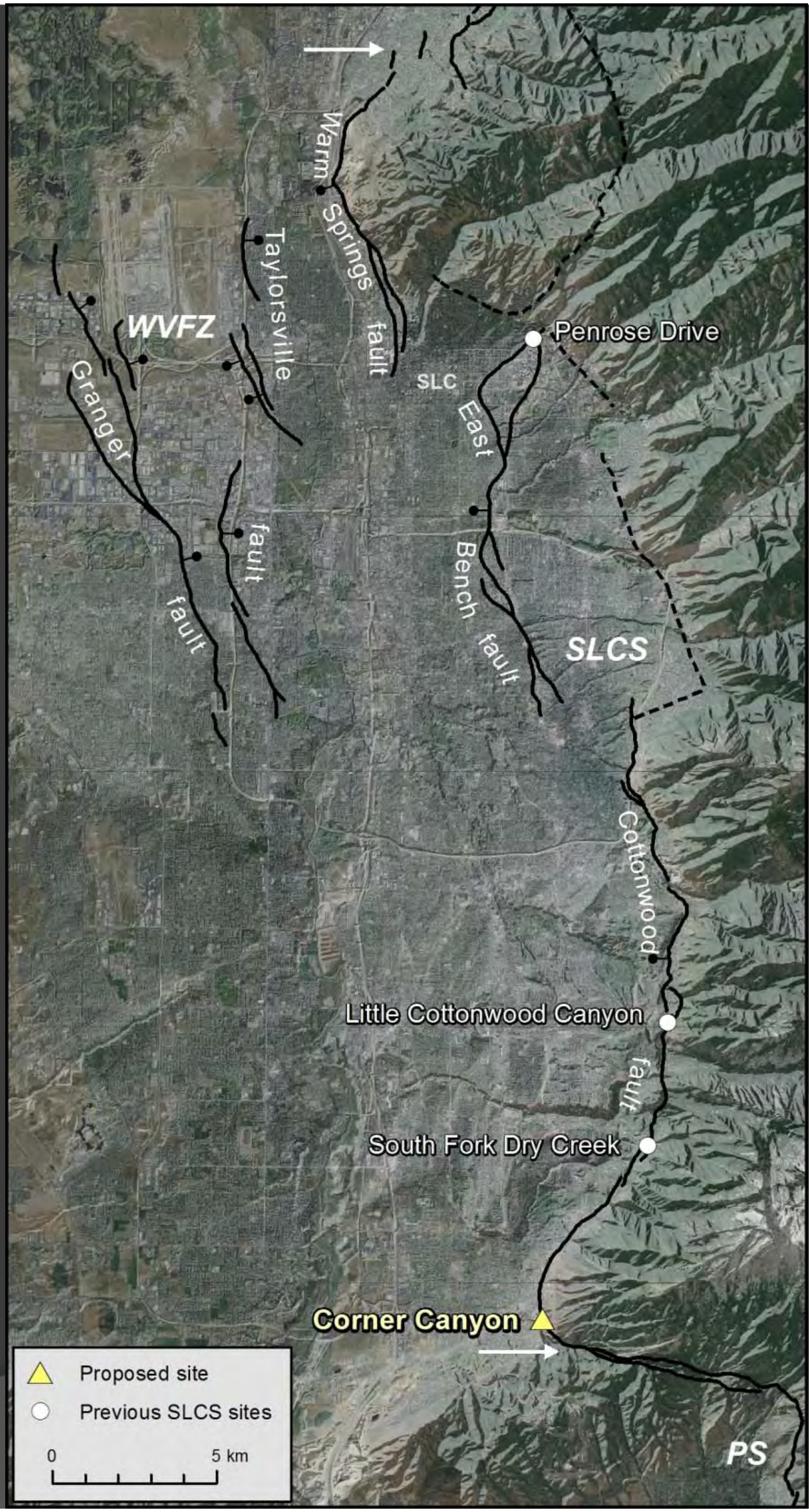
- **LCC: Little Cottonwood Canyon**
  (Swan and others, 1981, McCalpin, 2002)
- **SFDC: South Fork Dry Creek**
  (Schwartz and Lund, 1988; Black and others, 1996)
- **PD: Penrose Drive**
  (DuRoss and Hylland, 2012; DuRoss and others, in press)



Introduction

➢ **Important Questions:**

- What is the early Holocene earthquake chronology of the southernmost SLCS?
- What is the extent of surface-faulting earthquakes on the SLCS (rupture behavior of the fault strands)?
- Have recent (~late Holocene) ruptures crossed the Salt Lake City–Provo segment boundary?



Introduction

- **Important Questions:**
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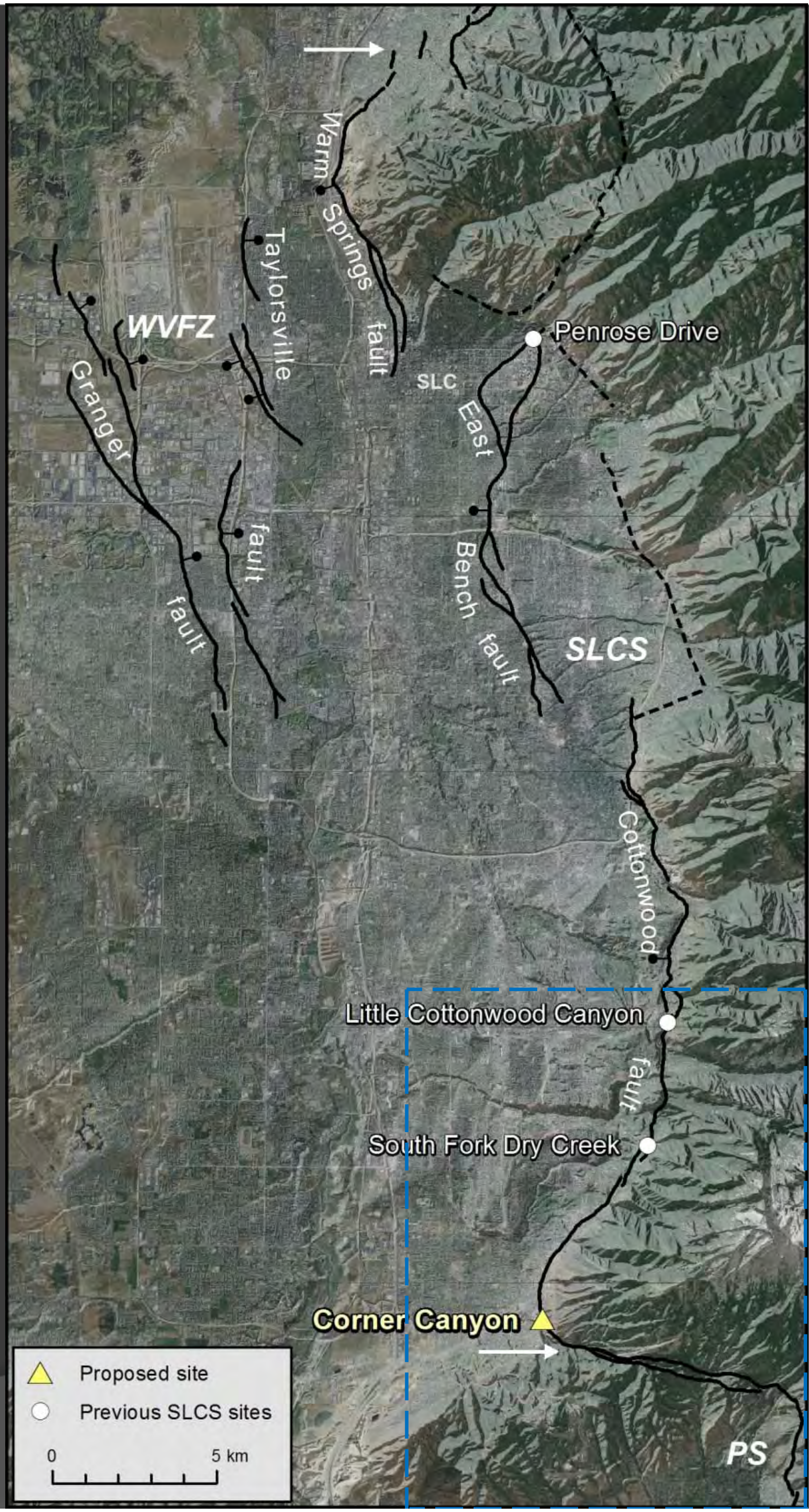
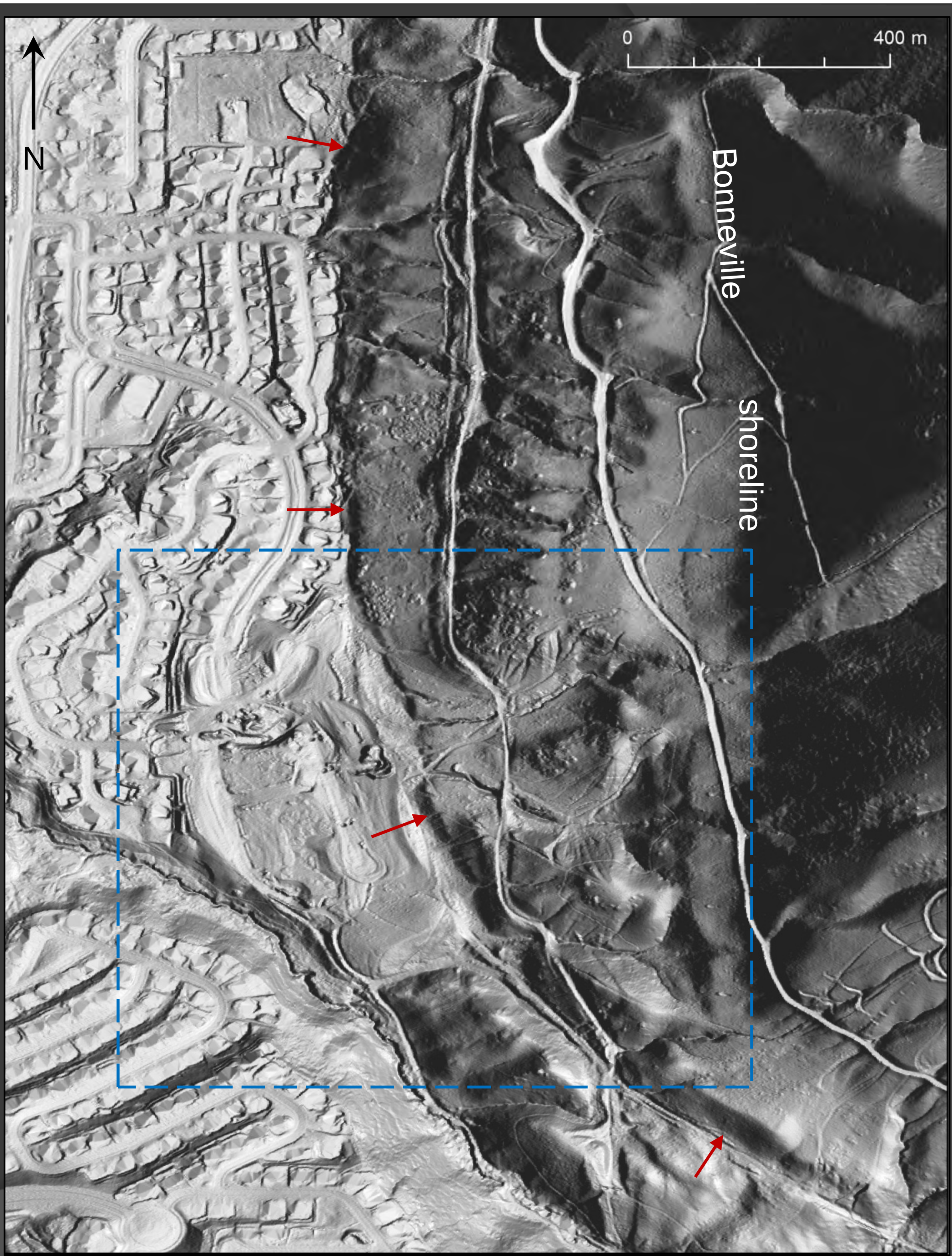


Salt Lake City – Provo Segment Boundary

Southern SLCS

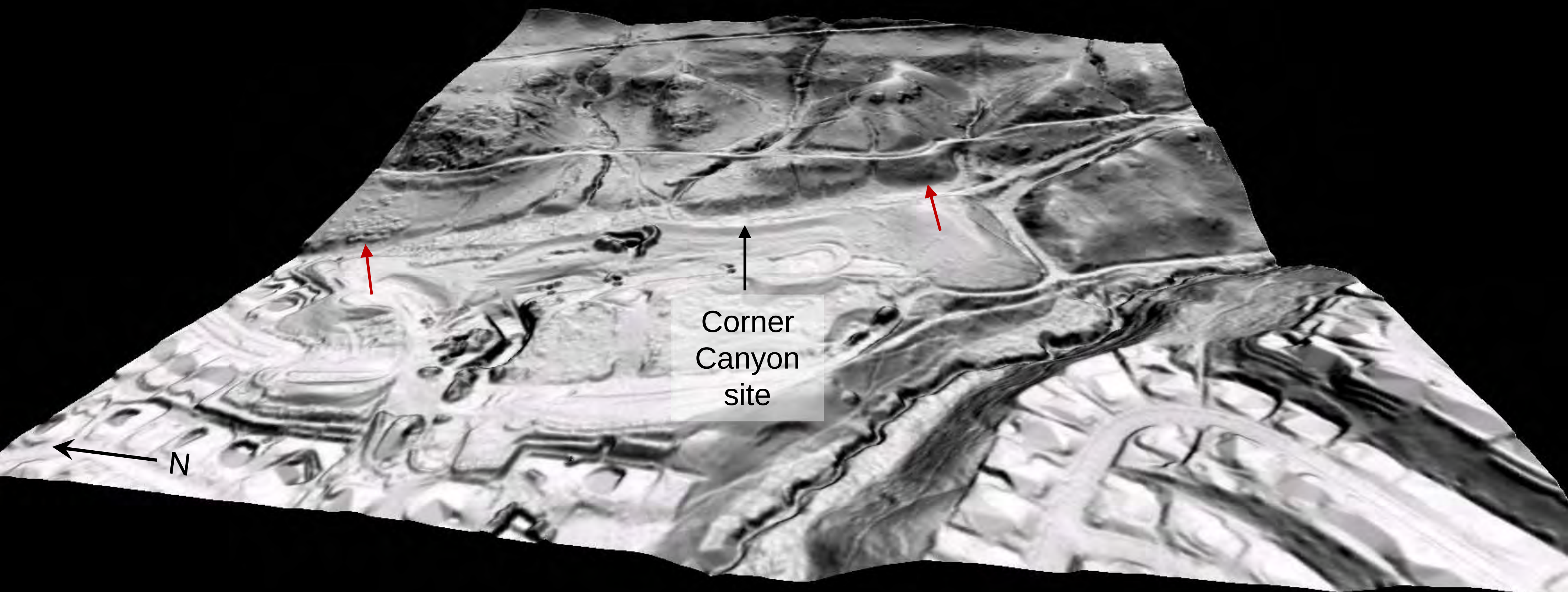
- Large (~20-m+ high) scarps on Bonneville highstand sediments
- Moderate to large (~8 – 12-m high) scarps on post-Bonneville alluvial fan surfaces



65/090 Hillshade map made from 1.25-m Lidar data for Salt Lake County (2006)

Corner Canyon Site

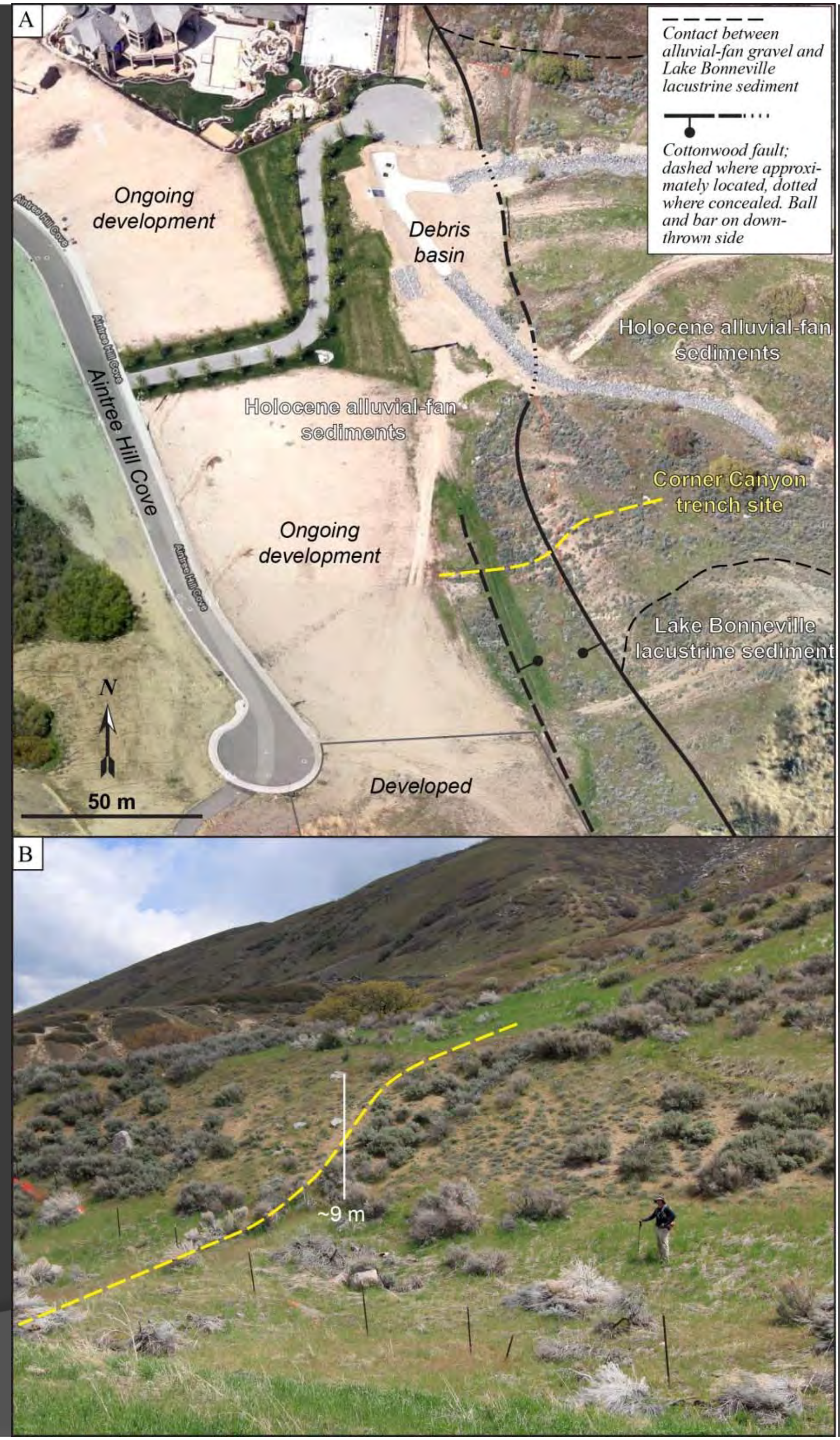
- Corner Canyon: ~9-m high scarp on post-Bonneville fan surface



Slope-shade map made from 1.25-m Lidar data for Salt Lake County (2006)

Corner Canyon Site

- **Trench Plans:**
  - One large trench (~June 16, 2014)
  - Goal: obtain Holocene record for the southernmost SLCS, adjacent to the segment boundary
  - Challenges: ongoing development in the area



UPCOMING INVESTIGATION OF THE PROVO SEGMENT OF THE WASATCH FAULT NEAR DRY CREEK AND MAPLE CANYON

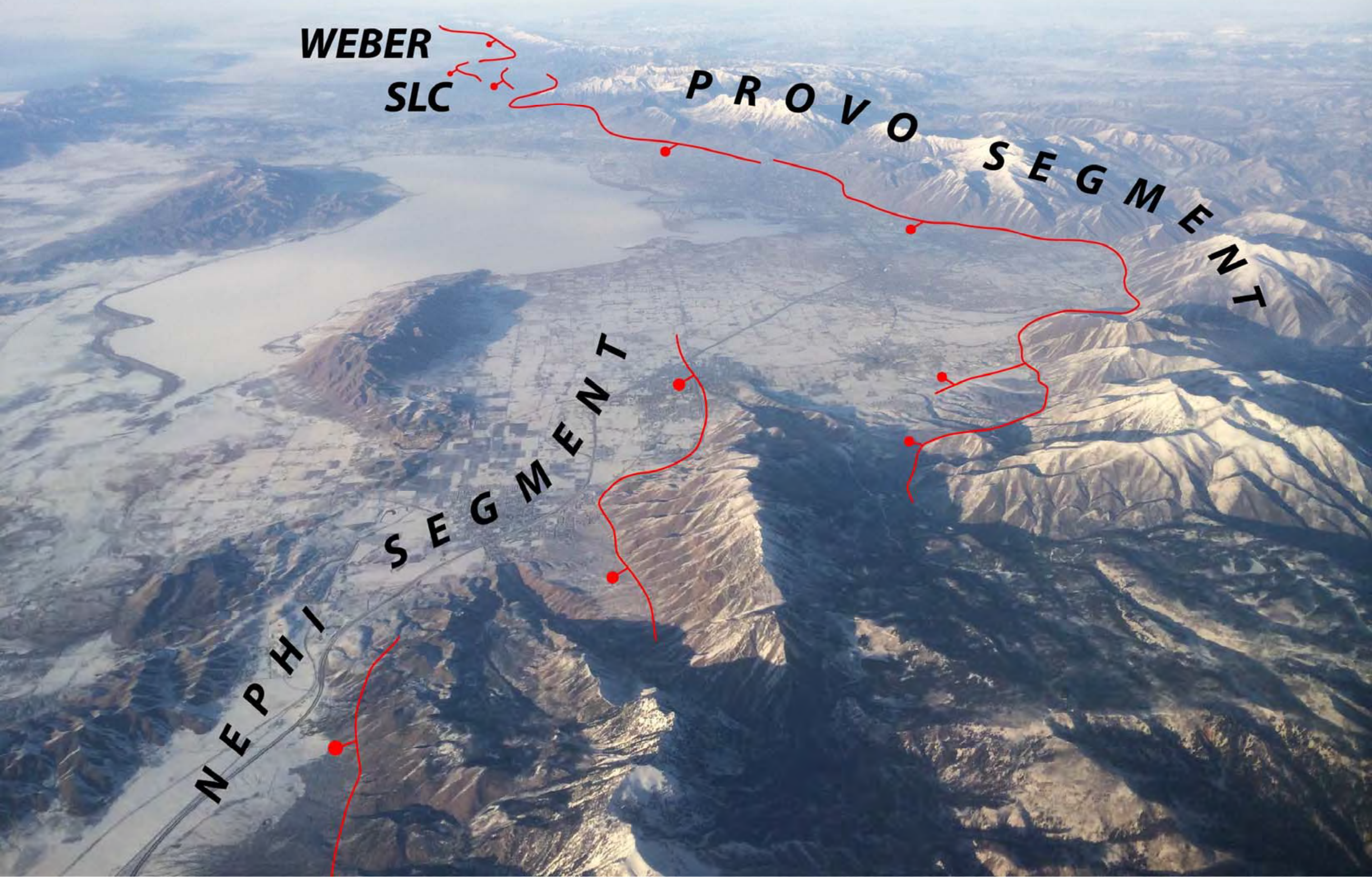
Scott Bennett

US Geological Survey

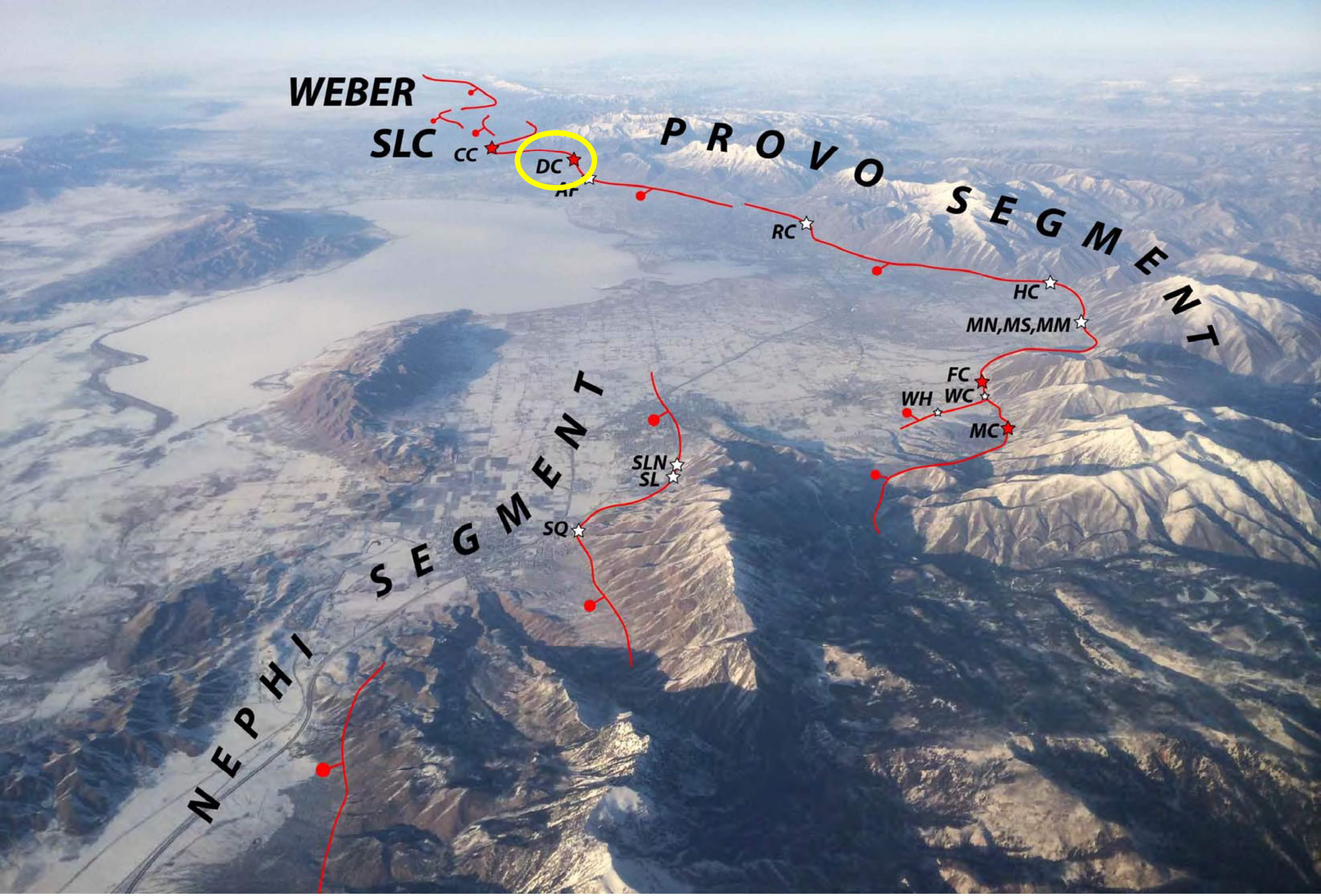
U.S. Geological Survey

Utah Geological Survey

Salt Lake City – Provo Segment Boundary



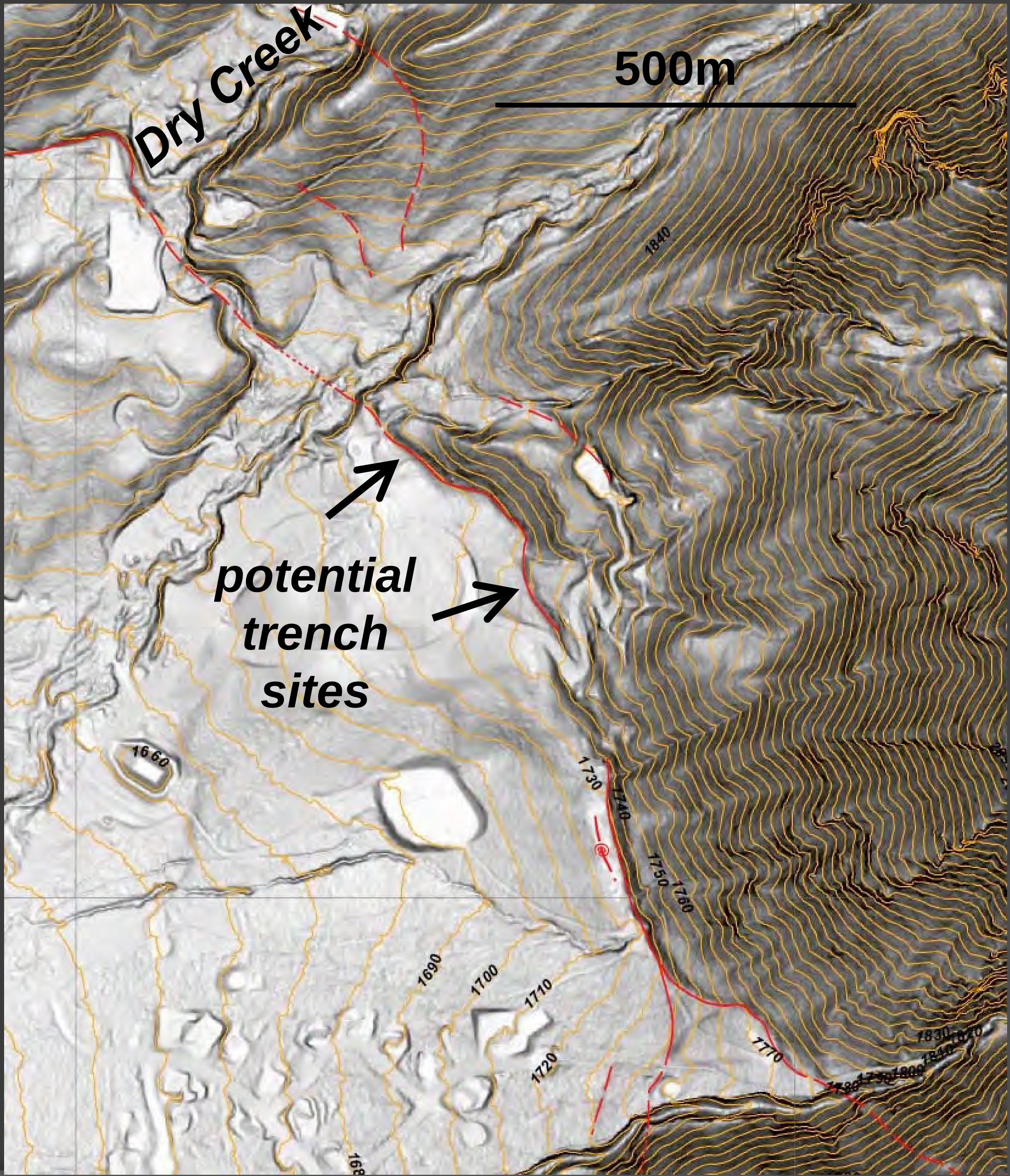
Salt Lake City – Provo Segment Boundary



Salt Lake City – Provo Segment Boundary

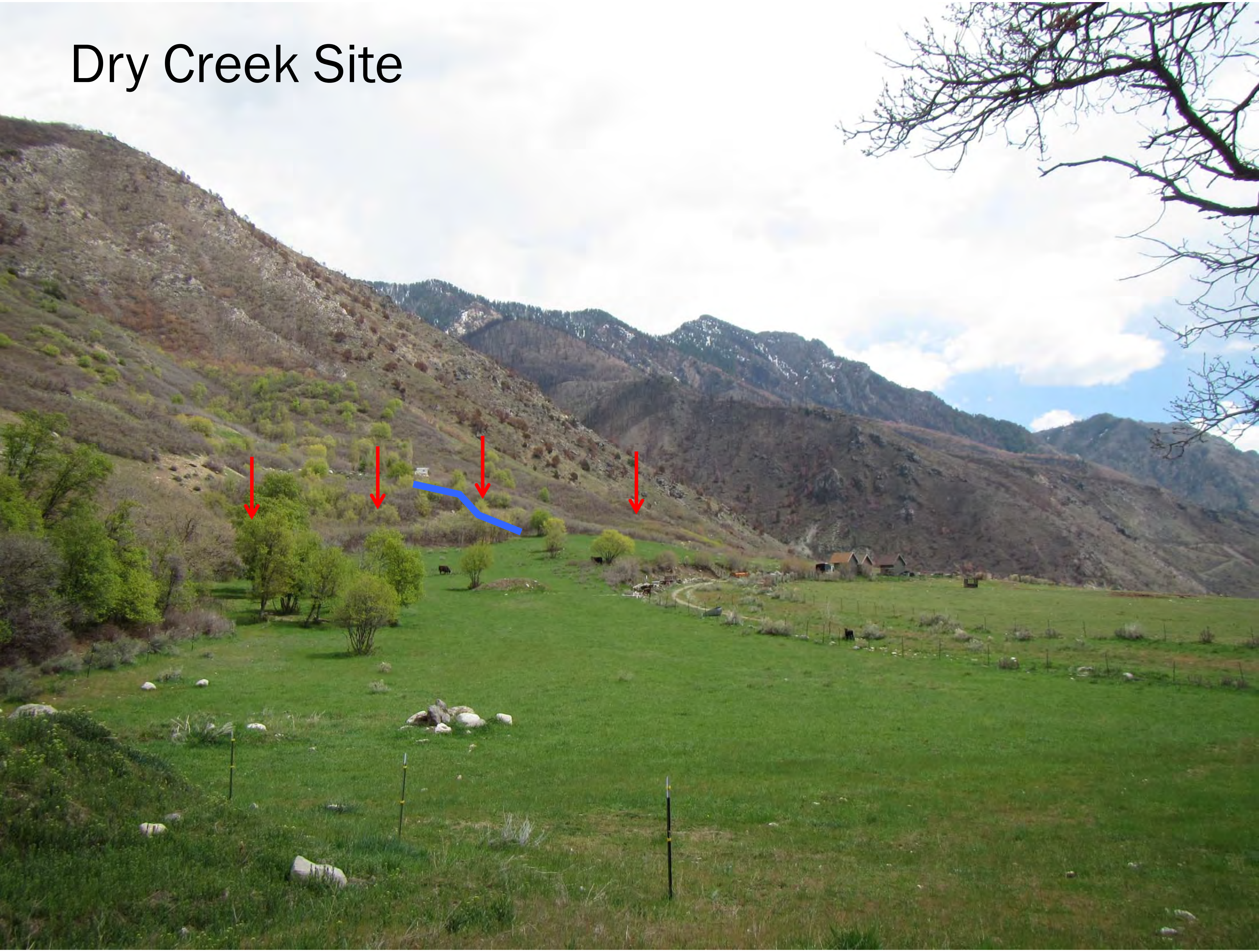
Dry Creek Site

- Evaluate if events observed at southern SLC segment (CC, TM) also ruptured northern Provo segment
- Evaluate if events observed on Provo segment to south (AF, RC, etc.) ruptured entire segment
- verbal landowner permission acquired to open trench late May 2014

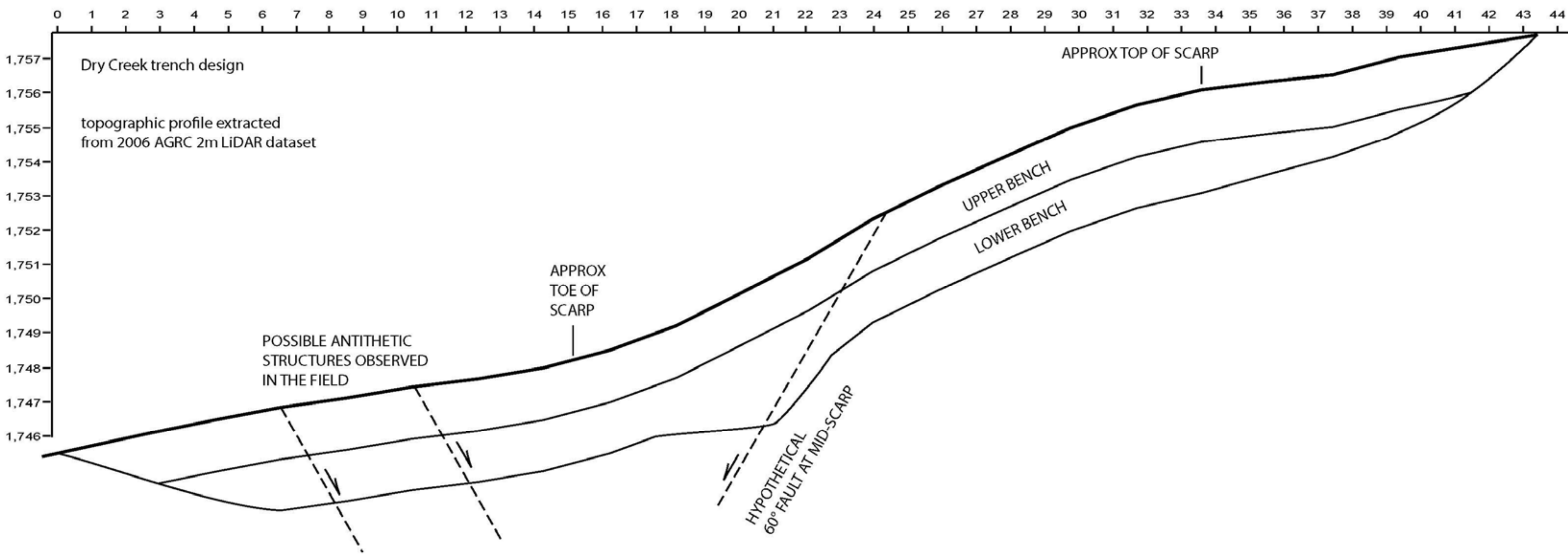


slope-shade from 1.25-m Lidar data for Salt Lake County (2006)

Dry Creek Site

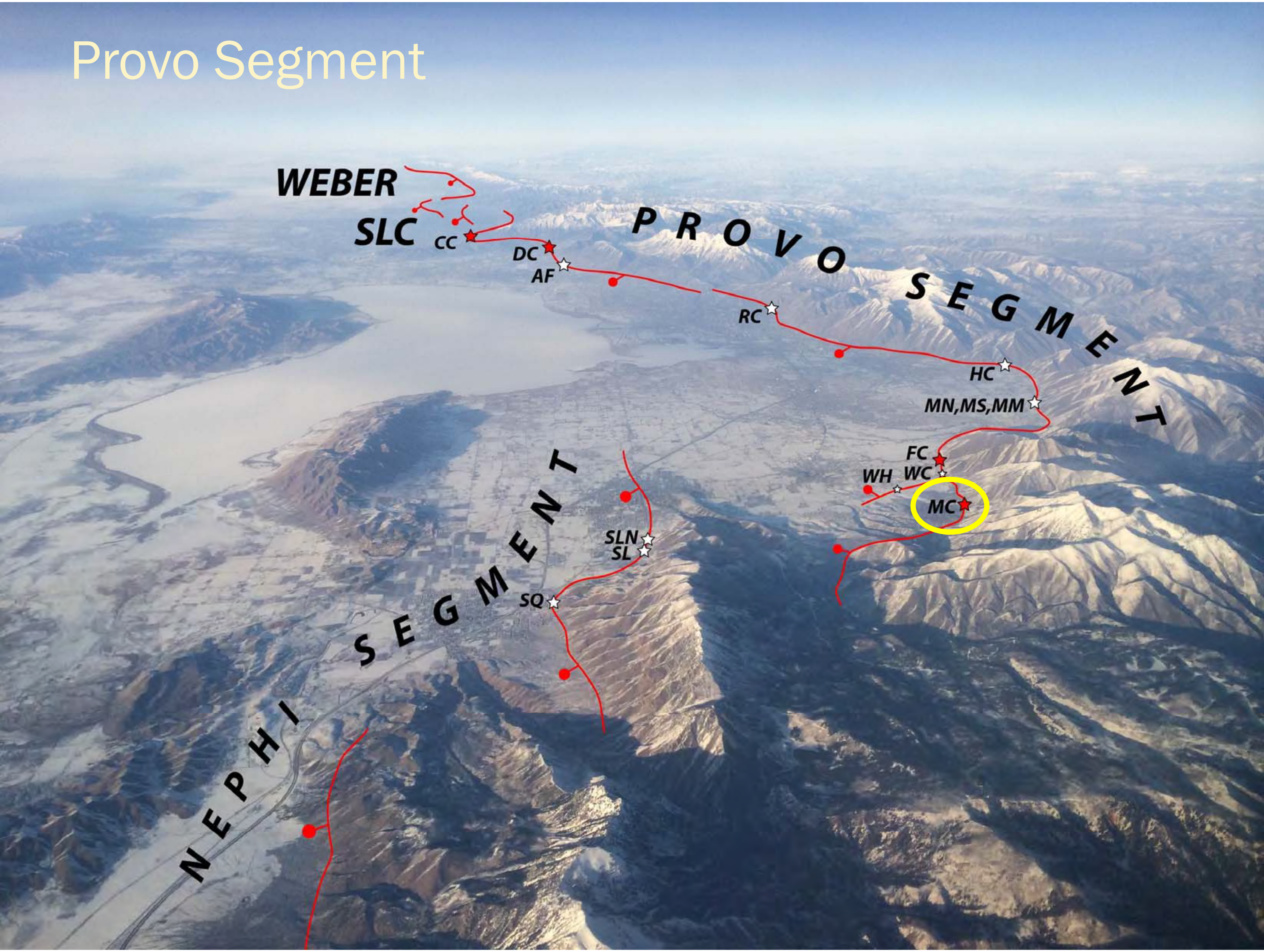


Dry Creek Site



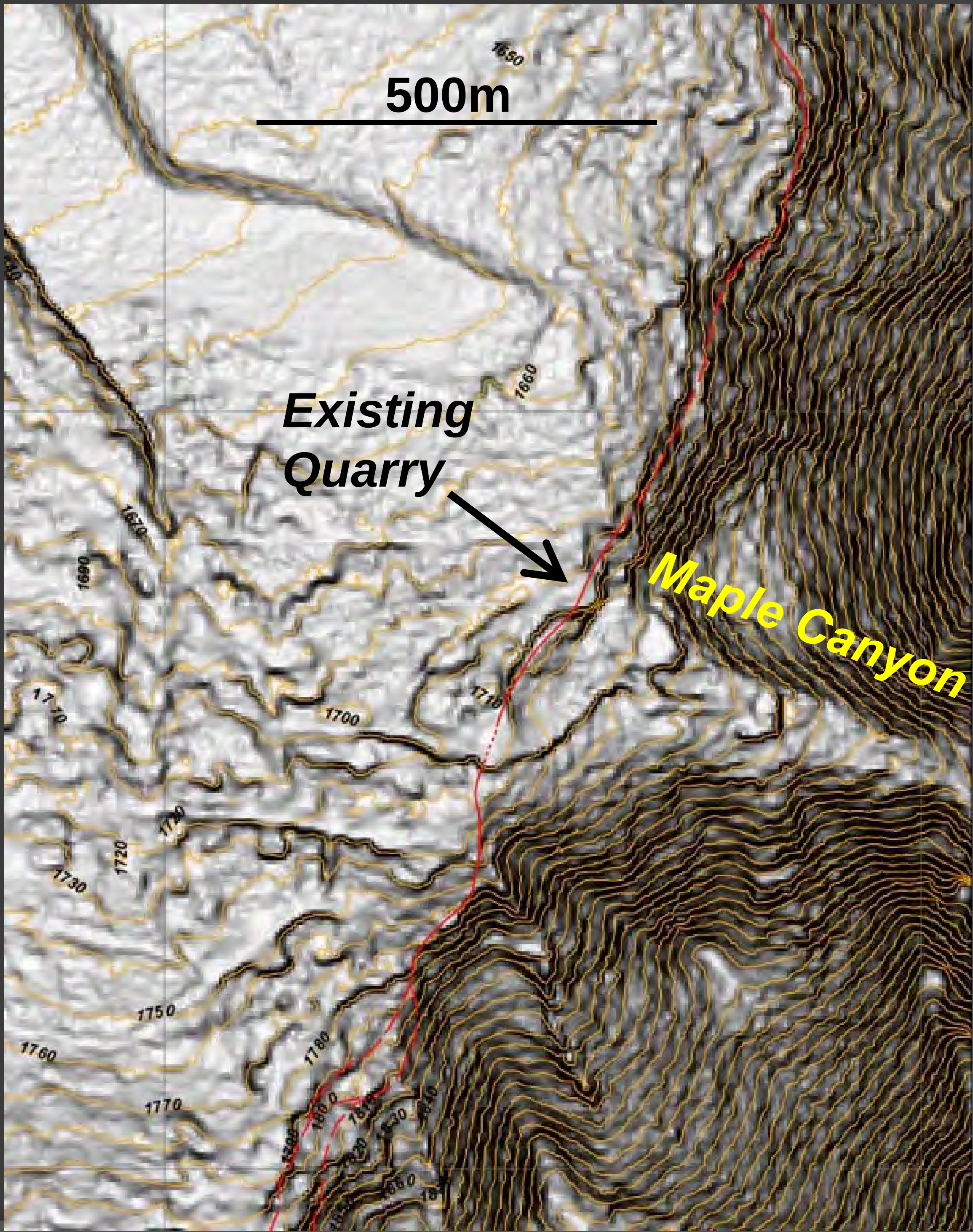
- ~8-m scarp
- designed as a two-bench trench
- potential antithetic structures

Provo Segment

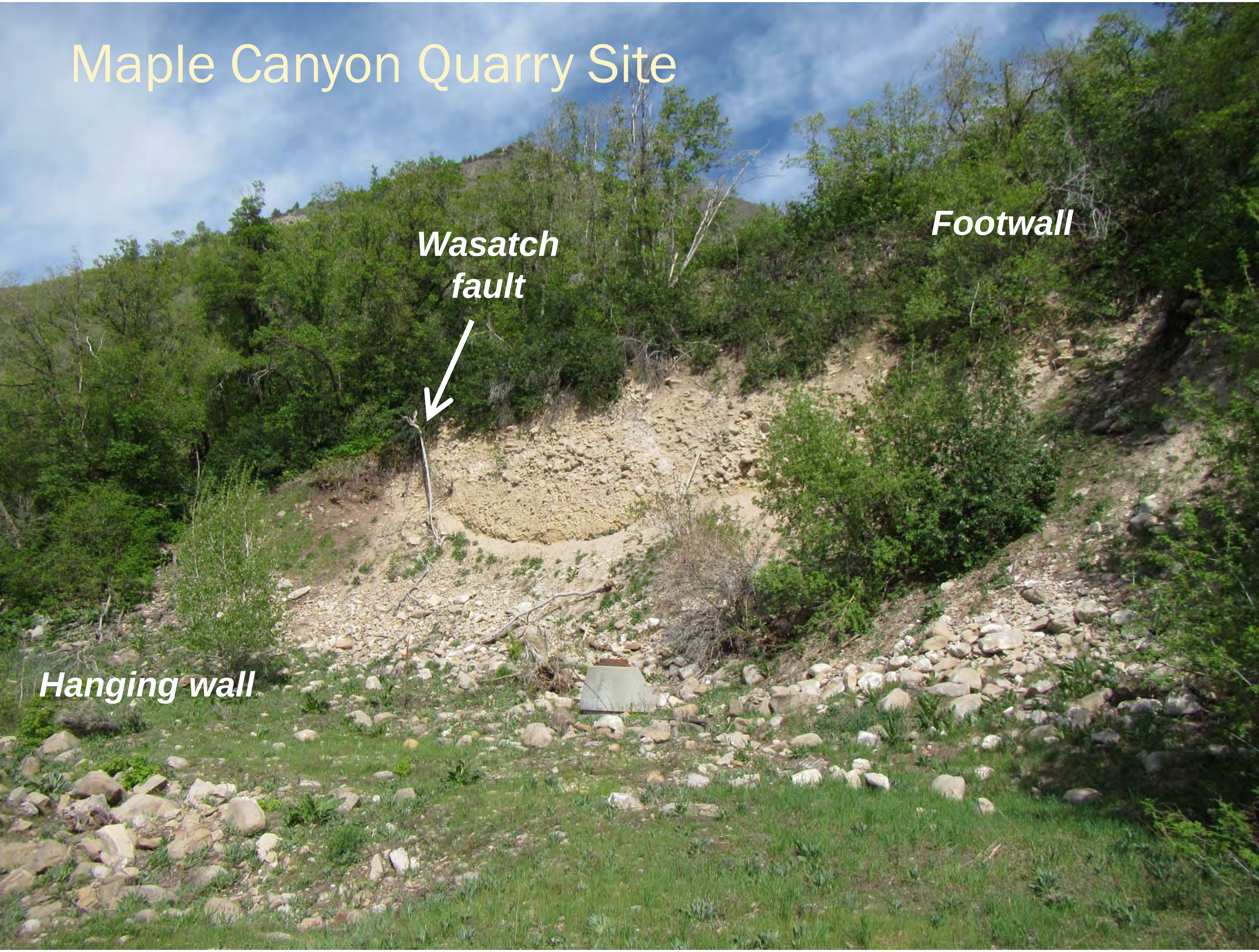


Maple Canyon Quarry Site

- Existing Quarry exposure of Wasatch fault
- potential record of MRE and penultimate events
- written landowner permission acquired to study quarry wall in mid-June 2014



slope-shade from 5-m Auto-Correlated DEM (2006)


Maple Canyon Quarry Site
Wasatch fault
Footwall
Hanging wall

UQFPWG 2014 Fault Study Priorities

Fault/Fault Segment	Original UQFPWG Priority (2005)
Nephi segment WFZ	1
West Valley fault zone	2
Weber segment WFZ – most recent event	3
Weber segment WFZ – multiple events	4
Utah Lake faults and folds	5
Great Salt Lake fault zone	6
Collinston & Clarkston Mountain segments WFZ	7
Sevier/Toroweap fault	8
Washington fault	9
Cedar City-Parowan monocline/ Paragonah fault	10
Enoch graben	11
East Cache fault zone	12
Clarkston fault	13
Wasatch Range back-valley faults	14
Hurricane fault	15
Levan segment WFZ	16
Gunnison fault	17
Scipio Valley faults	18
Faults beneath Bear Lake	19
Eastern Bear Lake fault	20
Bear River fault zone	2007
Brigham City segment WFZ – most recent event	2007
Carrington fault (Great Salt Lake)	2007
Provo segment WFZ – penultimate event	2007
Rozelle section – East Great Salt Lake Fault	2007
Salt Lake City segment WFZ – northern part	2009
Warm Springs fault/East Bench fault subsurface geometry and connection	2010
Brigham City segment WFZ rupture extent (north and south ends)	2011
Long-term earthquake record northern Provo segment WFZ	2011
West Valley fault zone – Taylorsville fault	2011
Hansel Valley fault	2011
Acquire new paleoseismic information in data gaps along the five central segments of the WFZ	2012

Current Status Quaternary Fault Investigations In Utah

2013 Highest Priority Faults/Fault Sections For Study

Fault/Fault Section[1]	Investigation Status	Investigating Institution[2]
Acquire new paleoseismic information for the five central segments of the Wasatch fault zone to address data gaps – e.g., (a) the rupture extent of earthquakes on the Brigham City and Salt Lake City segments, (b) long-term earthquake records for the northern Provo, southern Weber, and Salt Lake City segments, and (c) the subsurface geometry and connection of the Warm Springs and East Bench faults on the Salt Lake City segment	UGS/USGS trenching (see below) BYU Utah Lake sediment study	UGS/USGS BYU
Acquire long-term earthquake record for the West Valley fault zone – Taylorsville fault	Consultant's trench of opportunity	UGS
Improve the long-term earthquake record for Cache Valley (East and West Cache fault zones)	No activity	

Other Priority Faults/Fault Sections Requiring Further Study

Fault/Fault Section	Original UQFPWG Priority	Investigation Status	Investigating Institution[2]
Cedar City-Parowan monocline/Paragonah fault[3]	10	No activity	
Enoch graben	11	No activity	
Clarkston fault[3] (West Cache fault zone)	13	Black and others (2000)	
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[4]	2007	No activity	

Faults/Fault Sections Studies Complete or Ongoing

Fault/Fault Section	UQFPWG Priority	Investigation Status	Investigating Institution[2]
Nephi segment WFZ	1	UGS Special Study 124 USGS Map 2966	UGS/USGS
West Valley fault zone (Granger fault)	2	Contract deliverable FTR[5]	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	Ongoing	UUGG/BYU
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
Washington fault zone	9	Contract deliverable FTR[5]	UGS
East Cache fault zone	12	UGS Miscellaneous Publication 13-3	USU
Wasatch Range back-valley (Main Canyon fault)	14	UGS Miscellaneous Publication 10-5	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	UGS Special Study 142	UGS/USGS
Bear River fault zone	2007	Ongoing	USGS
Salt Lake City segment WFZ – north part	2009	Contract deliverable FTR[5]	UGS/USGS
Hansel Valley fault[3]	2011	McCalpin, (1985), Robinson (1986), McCalpin and others (1992), UUGG ongoing	UUGG
Long-term earthquake record Nephi segment WFZ	2012	Contract deliverable FTR[5]	UGS/USGS
Provo segment Holocene fault segmentation	2012	Ongoing	USGS/UGS

EVALUATION OF THE QUATERNARY HISTORY OF THE JOES VALLEY FAULT ZONE, HUNTINGTON NORTH DAM, UTAH

FINAL REPORT, v. 1: 30-APRIL-2013

Submitted to:
Geophysics and Seismotectonics Group (86-68330)
U.S. Bureau of Reclamation
Denver, CO 80225-0007

Prepared by:
GEO-HAZ Consulting, Inc.
Crestone, CO 81131
Job. No. 2143

EXECUTIVE SUMMARY

This re-evaluation of the Joes Valley fault zone was performed to support the revised probabilistic seismic hazard analysis (PSHA) of Huntington North Dam. The author reviewed all previous published and unpublished reports and then performed a 7-day field reconnaissance of the faults from Oct. 2-8, 2012. A field review with Reclamation personnel was held Oct. 17-18, 2012.

Previous publications had proposed four structural models for the origin of the Joes Valley faults, but only one of the models assumed the faults penetrated deeply into the crust and could generate large earthquakes. The other three models (and a fourth added here) assume that the faults do not penetrate deeper than about 3 km below the surface, or are evaporite dissolution-collapse faults; in either case, the faults could not generate large earthquakes. I collected field data and performed a literature review to determine which model was most likely, given the field evidence how they compared with the typical characteristics of tectonic vs. non-tectonic faults. The small-scale geomorphic features such as fault scarps and fluvial terraces are essentially similar whether produced by tectonic or non-tectonic faulting, so were not diagnostic. The map pattern of faults and fault-zone slickensides indicate that the East Joes Valley fault and intragraben faults are accommodating a component of right-lateral motion, making them normal-oblique faults. This sense of slip is more typical of tectonic than of nontectonic faults.

A key piece of evidence about fault origin lies in the deep seismic reflection profiles that cross Joes Valley, acquired by oil companies and interpreted by this report, and by previous studies. All investigators except Coogan interpret the Joes Valley faults to extend beneath the regional detachment fault (Gunnison Detachment) and to penetrate the Paleozoic section beneath, if not the Precambrian basement. This interpretation is powerful evidence that the Joes Valley faults are tectonic and seismogenic. Based on the evidence assessed, I would weight the tectonic-seismogenic model of the Joes Valley faults as the most likely one (i.e., at least 60%).

Recommendations:

1- The PSHA should continue to include the Joes Valley faults as seismogenic faults, either as separate sources, or with the EJVF as an active master fault and the WJVF and intragraben faults as passive antithetic faults.

2- The possible salt detachment origin for the Joes Valley graben should be formally tested by constructing an analog or numerical deformation model based on the subsurface geometry interpreted from seismic reflection surveys, plus rheological parameters from core samples. The model should be run with various imposed stress fields, to see under what geometric, rheological, and stress parameters the model creates a narrow, detached footwall graben such as Joes Valley. If no model produces such a graben, or if the parameters required to produce a graben contradict known conditions, then this would be powerful evidence that the graben was not produced by an extensional salt detachment.

3- Perform an updated seismic source characterization of the Joes Valley faults. This would include LiDAR data, and excavating trenches to obtain more precise age control on faulting events, using AMS radiocarbon dating, luminescence dating, and perhaps cosmogenic surface-exposure dating. New dating would permit refining recurrence interval and slip rate, and estimating their uncertainties, and might also permit testing whether the graben-bounding faults (EJVF and WJVF) and the intragraben faults rupture simultaneously, which bear on the behavioral models of the faults (segmentation and rupture scenarios).

TABLE OF CONTENTS

1.0 INTRODUCTION

Huntington North Dam is located off Huntington Creek in the Castle Valley, 2 km northeast of the town of Huntington, Utah (see cover photo). The dam consists of two sections and a dike composed of zoned earthfill embankment materials which total about 1.8 km in length with a maximum height of 20 m. The reservoir impounded by Huntington North Dam (Huntington Lake) has a capacity of 6.7×10^6 m^3 at an elevation of 1780 m.

The most-recent seismic hazard analysis (PSHA) for Huntington North Dam, completed in 2002, shows that the Joes Valley fault zone significantly contributes to the potential seismic loadings at the dam. Scarps and other geomorphic features described in an earlier study (Foley et al., 1986) were interpreted to have formed during recurring, large-magnitude earthquakes. However, results of subsequent work on similar geomorphic features, related seismicity, and subsurface geology in this area of Utah and elsewhere have caused questioning of the earlier conclusions. Because of the geologic units in the area, and the surface and subsurface geometry of the faults within the Joes Valley fault zone, a non-tectonic origin for the geomorphic features needs to be considered. The geomorphic features, surface and subsurface geology, and seismicity in this area have not been evaluated together in any detail, and questions remain about the tectonic origin of the Joes Valley fault zone and its potential as a seismic source. Changes in the characterization of the Joes Valley fault zone could significantly change the seismic hazard considered for Huntington North Dam. A recommendation to better define the seismic loadings and to revise the seismic hazard analysis for the dam was proposed in 2008 (2008-SOD-A). This re-evaluation report for the Joes Valley fault zone was made to support the revised seismic hazard analysis.

1.1 THE STRATEGY OF THE RE-EVALUATION

The goal of this seismic re-evaluation is to determine the origin of faults and geomorphic features (e.g., scarps, terraces) in the Joes Valley graben that may be the result of large-magnitude earthquakes , but might also have formed by non-tectonic processes, such as mass movement (e.g., landslides) or deformation due to salt flowage. The re-evaluation was performed in three stages.

<u>Stage 1, Field Reconnaissance</u>: During a field reconnaissance, I examined possible tectonic and nontectonic geomorphic features along and near the Joes Valley fault zone (Fig. 1). Specifically, I examined fault exposures, scarps and other geomorphic features along the Joes Valley fault zone on the ground; reviewed previous geologic and geomorphic mapping; and augmented the existing geologic/geomorphic mapping if needed. This stage occupied October 2-8, 2012 and was performed by the author (Dr. James P. McCalpin of GEO-HAZ Consulting).

<u>Stage 2, Field Review</u>: I conducted a 2-day field review with Reclamation personnel Lucille Piety and Sarah Derouin on October 17-18, 2012. During the review we discussed the methods and results of the re-evaluation, and visited the primary sites that formed the basis for interpretations of the origin and history of possible tectonic or nontectonic geomorphic features along the fault zone.

<u>Stage 3, Report</u>: In October and November of 2012 I prepared a Draft report, which summarizes the studies conducted, findings, and recommendations for additional work. The report included findings about the origin and seismic potential of the Joes Valley fault zone. After review comments were provided by Reclamation in February 2013, this Final Report was written in March and April 2013.

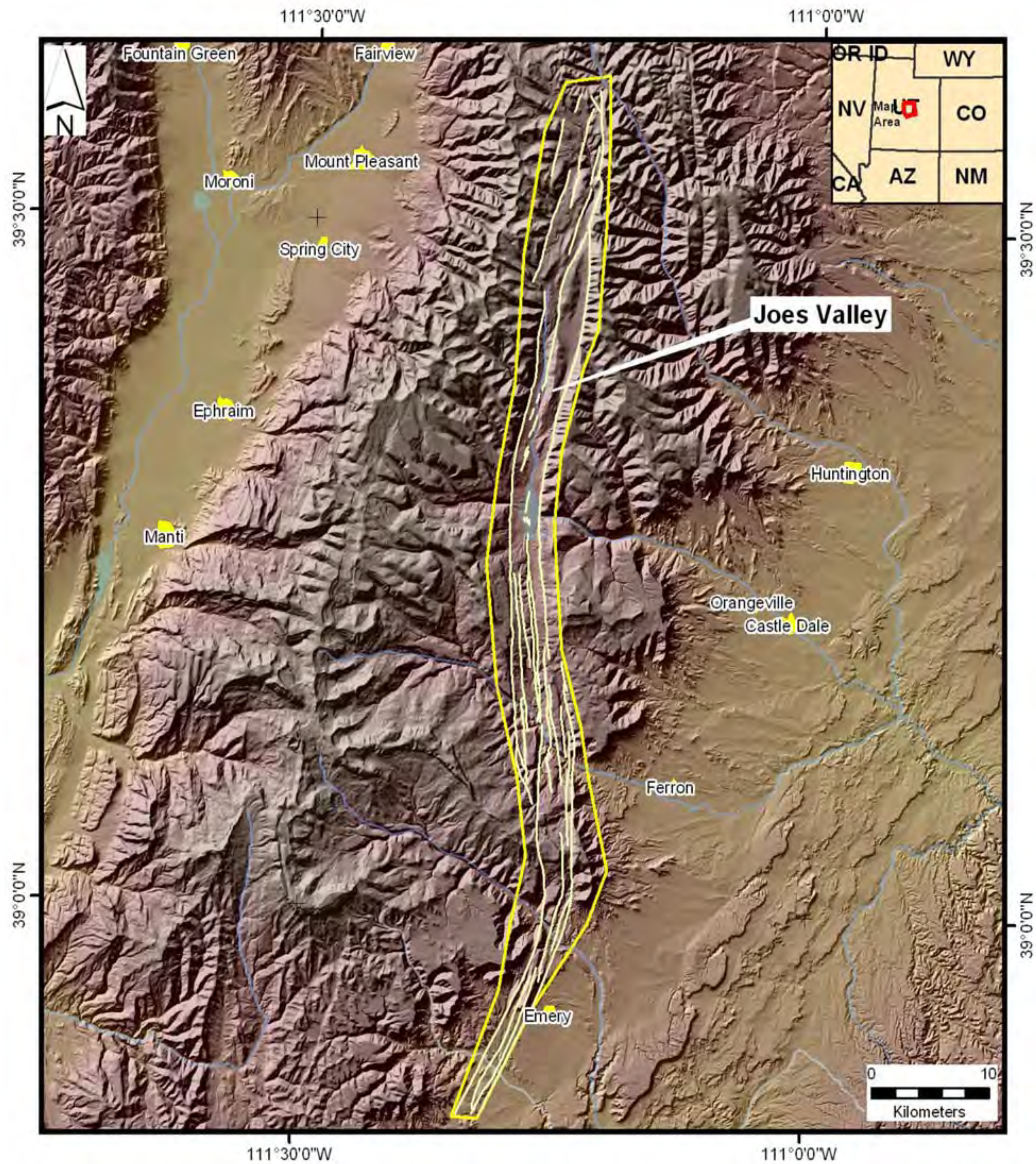


Fig. 1. Location map showing the Joes Valley graben (outlined in yellow) relative to the town of Huntington, Utah and Huntington North Dam (not shown, but only 2 km NE of town). White lines show faults from the USGS Quaternary Fault and Fold Database of the United States. The field reconnaissance performed in this study was limited to the northern 2/3 of the graben, covering it from its northern end, to roughly a latitude line halfway between that of Castle Dale and Ferron. The southern 1/3 of the graben contained very few landforms related to late Quaternary faulting.

1.2 METHODS

Literature Review: I examined the following reports and maps provided by Reclamation: Foley et al., 1986; Hecker, 1993; O'Connell et al, 2005; Schelling et al., 2007; Anderson, 2008; and the USGS Quaternary Fault and Fold Database of the United States, accessed in 2012. In addition I re-examined some classic publications on seismotectonics of the Basin and Range/Colorado Plateau transition zone, including: Arabasz and Julander, 1986; and Witkind et al., 1987.

To develop criteria to distinguish tectonic surface faulting from non-tectonic surface faulting, I reviewed many published papers concerning non-tectonic faulting related to salt dissolution, collapse, and flowage. I also reviewed many datasets on tectonic faulting that related fault displacement to fault length, and to width of the fault damage zone. To understand the significance of near surface structure of the East Joes Valley fault, I reviewed many papers on normal faults and monoclines that displaced flat-lying, vertically jointed sedimentary (or volcanic) rocks. All of these papers are cited in the appropriate sections of this report.

Interviews: I conducted telephone and email interviews with several subject matter experts to increase our knowledge of topics such as fault structure. Dr. James P. Evans (Dept. of Geology, Utah State University, Logan, UT) and Dr. Zoe Shipton (Dept. of Civil Engineering, University of Strathclyde, Scotland) shared their knowledge of the literature concerning fault displacement, fault length, and damage zone width, as well as the typical near-surface architecture of normal faults in sandstones of the Colorado Plateau. Dr. Daniel Schelling (Structural Geology International, Salt Lake City, UT) discussed his 2007 publication (see references) and specifically his interpretation of the subsurface geology beneath Joes Valley.

Office Phase: Before beginning the field reconnaissance, I created a geographical information system (GIS) Workspace that contained various topographic and geologic data. For topography I downloaded the USGS 7.5' topographic base maps (DRGs) and the 10m digital elevation models (DEMs) of the National Elevation Dataset (NED) for all eight 7.5' topographic quadrangles that partially cover the Joes Valley graben. In addition, I downloaded a 2m bare-earth DEM made from LiDAR (light detection and ranging) from the Utah Automated Geographic Reference System (AGRS) website, which covered a small area (10 km N-S by 2.2 km E-W) in Upper Joes Valley. For geology, I manually georeferenced the PDF version of the geologic map in Foley et al., 1986 (provided by Reclamation), which is the most detailed mapping work on the faults and Quaternary deposits of the Joes Valley graben. I also imported the geologic map of the Joes Valley 7.5' quadrangle (the only of the eight quads to be mapped at this scale; Kitzmiller, 1982), as well as the 1:100,000-scale geologic map (Witkind et al., 1987) for the remainder of the study area. I also downloaded the 1 m orthophoto-mosaics of Emery and Sanpete Counties, which show up-to-date cultural features.

Next I manually digitized the faults and selected Quaternary deposits from Foley et al, 1986, as vector lines and polygons, respectively. I also downloaded the digital version of the USGS Quaternary Fault and Fold Database of the United States, in Shapefile and KML formats from the USGS website.

My working maps for the field reconnaissance were comprised of two sets of hard-copy prints at 11"x17" size. The first set showed the orthophoto base in color, with the faults, geology polygons, and trench sites of Foley et al. (1986) superimposed; there were 20 of these sheets to cover the area between Dragon Ridge (on the south) and the north end of Joes Valley. The second set covered only the area of the 2 m LiDAR DEM and was at a larger scale, and comprised 13 sheets. All navigating in the field was performed using these maps, and new feature mapping was done in pen or pencil on these maps, then transferred to the digital Workspace.

Field Reconnaissance (Oct. 2-8, 2012): The days of Oct. 1 and 9 were spent driving from Crestone, CO to Castle Dale, UT, our base of operations. I then spent Oct. 2-8 (7 days) performing the field reconnaissance. Targets visited included: (1) the trench sites of Foley et al., 1986; (2) any place where roads crossed or came near to a mapped Quaternary fault; (3) selected alluvial fans on the valley margin that crossed the fault, and alluvial fans crossed by interior faults; (4) all natural exposures such as roadcuts and quarries. In all, 107 GPS (global positioning system) waypoints were measured at various stops over the 7 days; these are keyed to descriptions in Field Notebook No. 39 of J.P. McCalpin, pages 0-74. Digital versions of the waypoints can be provided upon request.

2.0 STRUCTURAL MODELS AND INTERPRETATIONS OF SUBSURFACE GEOLOGY FOR JOES VALLEY

Previous studies of the Joes Valley graben had proposed four structural models for its origin and seismic potential, described below. Of these models, only Model 1 described below indicates that faults of the Joes Valley graben can generate significant (M>5.5) earthquakes, because they penetrate into basement rocks to the base of the brittle crust at depths of ca. 15 km. The other three models, plus an additional fifth model proposed herein, assume that the faults are “rootless” and do not penetrate downward more than about 3 km below the earth’s surface, and thus cannot generate large earthquakes.

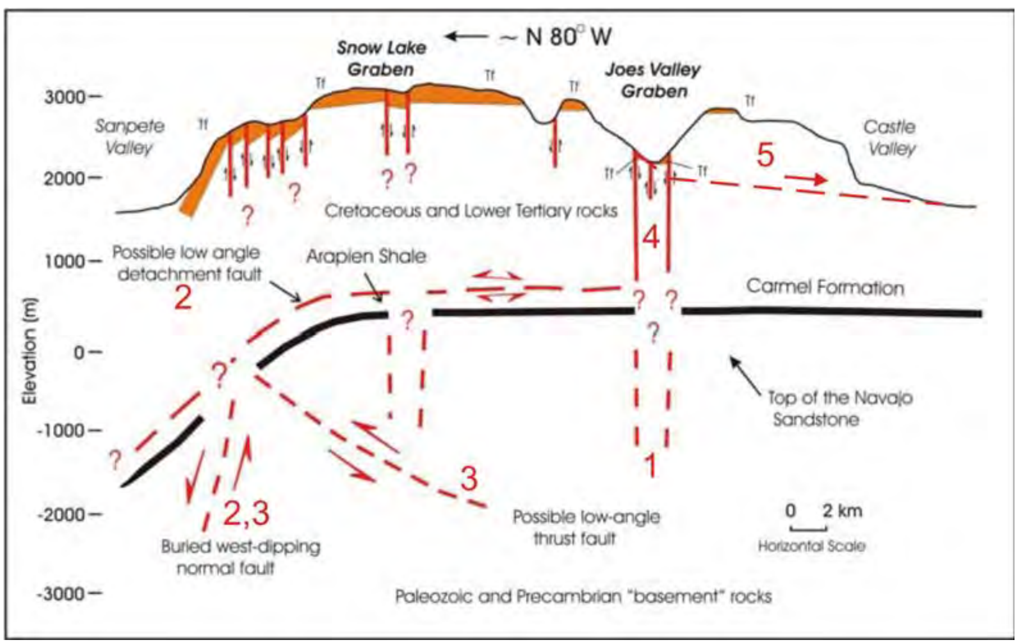


Fig. 2. Diagrammatic cross-section across the Wasatch Plateau and the Joes Valley graben illustrating five alternative structural models for the origin of the graben. Large red numbers indicate structures required in each model. 1) Penetration of the Navajo Sandstone by high angle faults that go to seismogenic depths; 2) Movement on a low-angle, west-dipping detachment fault above the Navajo Sandstone; 3) reactivation of back-thrusts off of a low-angle, east dipping thrust fault associated with buried west-dipping normal fault, near the location of the Wasatch Monocline, (4) Flowage and collapse of the Arapien Shale, and 5) huge eastward gravity slide of the eastern margin of the Wasatch Plateau. Adapted from Anderson, 2008. Tf (orange) is the Eocene-Paleocene Flagstaff Limestone. Cross-section modified from Foley and others (1986) with the geology from Witkind and others (1987). Vertical exaggeration shown is approximately 3X.

2.1 EXPLANATION OF EACH MODEL

Model 1- Fault(s) dip steeply, penetrate the Navajo Sandstone and subjacent units, and extend to seismogenic depths (10-15 km)
Foley et al. (1986) chose this model as their preferred one, based on evidence such as local microearthquakes and interpretation of deep geophysics, and on analogy to the recent (1983) Borah Peak earthquake which occurred on a steeply dipping plane despite rupturing through a former fold-and-thrust belt. An expanded discussion of the seismic reflection data is given in Section 2.2.

Model 2- Faults extend downward to a gently-west-dipping décollement (extensional detachment fault) that lies in the Arapien Shale/Carmel Formation. This model was considered by Foley et al. (1986), based on the seismotectonic model proposed by Arabasz (1986) (Fig. 3) for the Wasatch Plateau and by Arabasz and Julander (1986) for parts of the Intermountain Seismic Belt in previously folded-and-thrusted terrain. In this model graben faults do not continue downward below the top of the Navajo Sandstone, but merge with a gently west-dipping detachment in the overlying, evaporite-rich Arapien Shale.

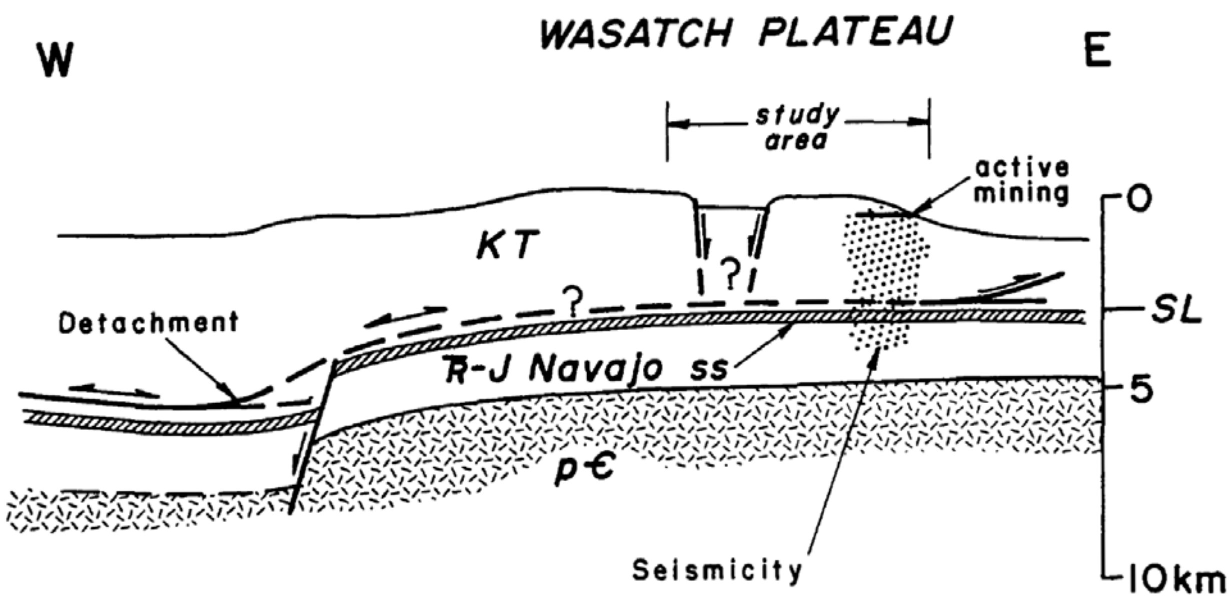


Fig. 3. Schematic geologic cross section illustrating hypothetical interpretation of "thin-skinned" horizontal extension in the Wasatch Plateau (from Arabasz, 1986).

Hecker (1993) agreed with this interpretation, stating: "*The graben structures on the plateau (for example, the Joes Valley fault zone…) are unlike late Cenozoic basins to the west in that they are relatively narrow, are bounded by faults with near-vertical dips, and are associated with little or no net vertical displacement. The nature of these faults suggests they may have formed in response to uplift across the Wasatch monocline (Foley and others, 1986). A blind, steeply dipping normal fault (the "ancient Ephraim fault") lies subparallel to and just east of the Wasatch monocline and cuts upsection as high as the structurally thickened and synclinally folded Arapien Shale (… Standlee, 1982; Allmendinger and others, 1986). Possible basin-range extension across this fault may be transferred along the detachment horizon to the faults on the Wasatch Plateau (Allmendinger and others, 1986). If this blind fault is active, it may be capable of producing large-magnitude earthquakes.*" Similar speculations were made by Willis et al. (2007, p. 17): "*In fact, it appears that it is a combination of both extensional* *reactivation of the basement-rooted Ephraim fault system and the presence of a thick Arapien Shale section that has allowed the eastern deformation front to the Basin and Range extensional province to migrate east of the Wasatch fault and the Sevier Desert detachment along the Gunnison and Salina sectors of the thrust belt."*

There are three variants of Model 2, which explain the source of the westward movement of the 3 km-thick portion of the crust above the detachment. Model 2A would attribute this westward movement to low-angle normal faulting on the Gunnison Detachment, due to regional extension. That such extension is continuing today is documented by GPS surveys across the Wasatch Front (Chang et al., 2006; also discussed in Section 4.3.3). Model 2B was proposed by Hecker (1993) and Willis et al. (2007) and proposes that the westward movement of the crust above the detachment is ultimately caused by normal fault slip on the blind Ancient Ephraim fault that lies beneath the detachment. This normal fault slip somehow propagates upward along the Ephraim normal fault, and then turns 45° when it reaches the Arapien Shale to become near-horizontal extension, apparently "losing" all of the vertical component of displacement that it had below. Model 2C proposes that the entire crustal slab above the Arapien Shale is "sinking" or gravity sliding into the Sanpete Valley, due to dissolution and collapse of the overthickened section of Arapien evaporites there (1600 m thick), as shown on cross-sections by Schelling et al. (2007, section C-C') and Coogan (2008). Such sinking would allow the 3 km of crust above the detachment to gravity slide into the void space left by evaporite dissolution.

Model 3- Faults sole into reactivated west-dipping backthrusts…
This model was proposed by Anderson and Mahrer (2002). Their figure (repeated in O'Connell et al., 2005; Anderson, 2008, same as Fig. 2 of the present report) shows only one thrust fault, an east-dipping "possible low angle thrust fault", but it does not show the backthrust off of this thrust that is central to their model. Because all Sevier-age thrusts dip west, a Sevier backthrust must dip east (see Schelling et al., 2007, p. 14). At the latitude of Joes Valley (roughly 39°N to 39.6°N), east-west crustal cross-sections of Schelling et al. (2007, their Figs. 7 and 8) show several east-dipping backthrusts, coming off of (from east to west) the Gunnison Detachment, the Long Ridge Thrust, and the Sage Valley Thrust. However, they do not show any backthrusts in the vicinity of Joes Valley. Coogan (2008a, his Fig. 6) did interpret a small east-dipping fault to underlie the Joes Valley graben and to sole into the Jurassic Arapien Shale. He thus interpreted this fault as a Sevier backthrust.

Model 4- Faults are passive collapse structures created by dissolution of the Arapien Shale and formation of large void spaces. Faults do not extend below the Arapien Shale.
This model presumes that large volumes of evaporites, perhaps in diapirs, have dissolved in the Quaternary and created a chimney-like void space that has collapsed, creating the Joes Valley graben. The process would be similar to that inferred for the salt valleys of eastern Utah and western Colorado.

Model 5- Joes Valley Graben is the headscarp of a crustal-scale gravity slide to the east.
This assumes that an east-dipping glide plane has developed between Joes Valley and the 600 m-high east-facing escarpment of the Wasatch Plateau that faces Castle Valley. Such a slide would dip opposite to the regional westward dip, so would have to inhabit a weak enough and thick enough unit that it could cut downsection without leaving the weak unit. Because the Mancos Shale forms the lower part of the escarpment and is composed of two shale members 500m and 250 m thick, separated by a sandstone unit, it would be the likely host unit for such a glide plane.

2.2 EVALUATION OF EACH MODEL

Model 1- Fault(s) dip steeply, penetrate the Navajo Sandstone and subjacent units, and extend to seismogenic depths (10-15 km)

Foley et al. (1986) chose this model as their preferred one, based on evidence such as local microearthquakes and interpretation of deep geophysics. For the microearthquake evidence, they state: "*Microearthquake foci have been documented to depths of about 16 km across the Wasatch Plateau, the approximate base of the seismogenic layer of the crust. In Joes Valley, one well recorded microearthquake was located at a depth of 4.4 km placing this earthquake below the Navajo Sandstone and the inferred low-angle detachment* [in the Jurassic Arapien Shale; see next paragraph]. *Without evidence to the contrary, it must be assumed that there exists some rupture pathway connecting the surface scarps in Joes Valley with seismogenic depths. The available seismicity data do not confirm the nature of this rupture pathway, but the nodal planes of the focal mechanism solutions computed for the two microearthquakes that occurred beneath Joes Valley are moderate- to high-angle suggesting that the causative faults are not low-dipping structures. The spatial relationship of the epicenters to the Joes Valley faults, the northerly trend and moderate-to steep dips of the computed nodal planes, and the normal-type focal mechanisms all suggest that these earthquakes could have occurred on the Joes Valley faults*."

For the deep geophysical evidence available at the time (1984-86), they interpreted the following: "*Normal faulting on the Wasatch Plateau has been inferred to be related to westward displacement on a reactivated, formerly east-directed blind thrust in the Arapien Shale above the Jurassic Nugget Sandstone.* [This is Model 2 of this report]. *This inferred low-angle detachment would occur at a depth of 4-5 km below the western Wasatch Plateau and at a depth of about 3 km below Joes Valley (Standlee, 1982; Royse, 1983) implying that these faults do not extend to mid-crustal, seismogenic depths. As verification of this hypothesis would have significant effect on the conclusions of this hazard study, I requested and received permission to review proprietary seismic reflection records across Joes Valley. These data were acquired by CGG (Compagnie Generale de Geophysique) for speculation purposes in the early 1980's and are of very good quality. On the time sections the reflectors are all gently west-dipping including the prominent reflector inferred to be the top of the Navajo Sandstone that is evident on all the lines. The normal faults bounding Joes Valley appear near-vertical on all the sections and <u>clearly interrupt this prominent reflector as well as the rest of the sedimentary section down to a depth of about 5 to 6 km</u> below datum (1.7 km above sea level). Data below these reflectors correspond to the basement and are incoherent both below Joes Valley and away from the graben to the east and west. On the more recent, clearer seismic lines, coherent fault blocks can be defined within the Joes Valley graben. Thus the <u>reflection lines provide no evidence that the Joes Valley fault zone is terminated by a horizontal detachment</u> and they indicate that the faults are near-vertical to a depth of at least 5-6 km. Though the faults cannot be traced into the basement, their continuation to depths consistent with that required to generate large, surface-faulting earthquakes (12-15 km) cannot be precluded.* [underlining added]

Some of the evidence cited above does not uniquely support Model 1. For example, "*The spatial relationship of the epicenters to the Joes Valley faults, the northerly trend and moderate-to steep dips of the computed nodal planes, and the normal-type focal mechanisms all suggest that these earthquakes could have occurred on the Joes Valley faults"* would also be true in Model 2. However, Foley et al. interpret the seismic reflection profile to show that Joes Valley faults penetrate the horizontal detachment, which is critical. A later study by Schelling et al. (2007, balanced cross-section B-B') also shows the East Joes Valley fault dipping west and cutting the Navajo Sandstone, plus all other crustal units (Fig. 4). This is the same crustal-penetrating geometry shown by the other well-known Jurassic normal fault beneath the Wasatch Monocline, the Ancient Ephraim fault system.

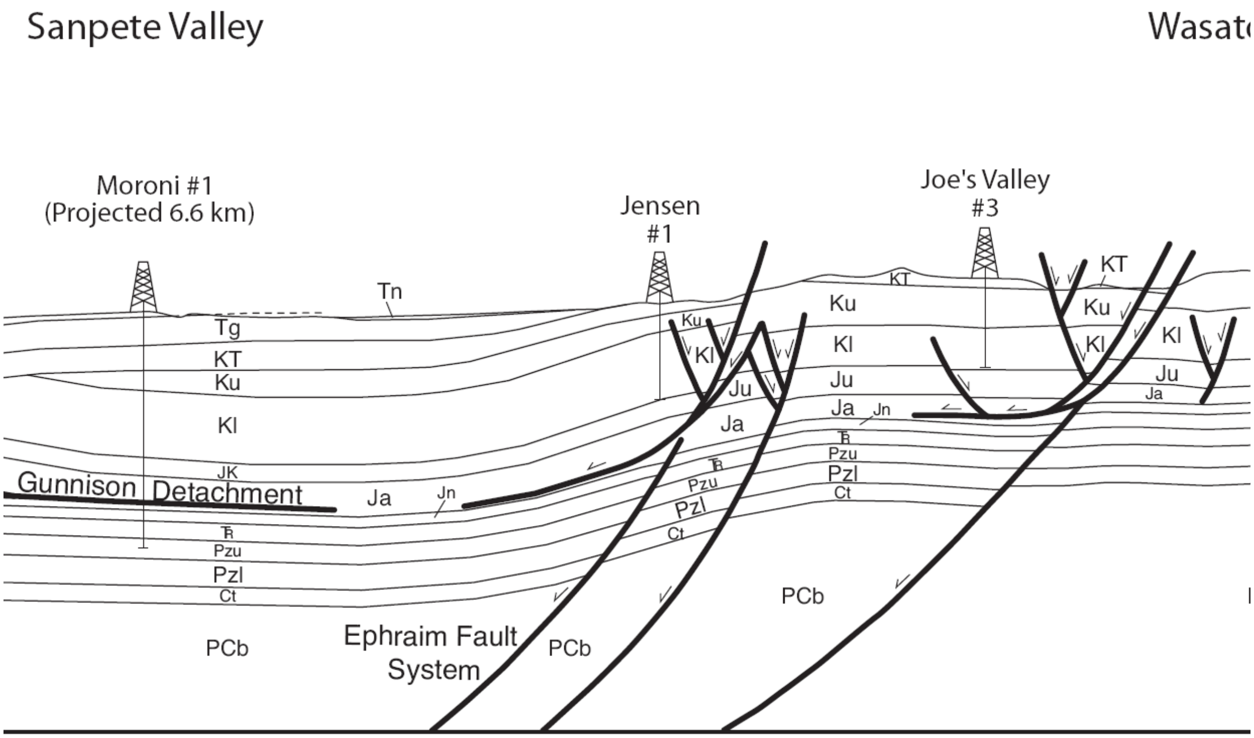


Fig. 4. The far eastern part of cross-section B-B' of Schelling et al. (2007) which crosses the northern part of Joes Valley. West is to the left. The Joes Valley graben lies east of well Joes Valley #3. This balanced cross-section interprets the East Joes Valley fault to both become listric in the Arapien Shale (Ja), AND to connect with a deeper, planar fault which offsets the Paleozoic rocks and continues deep into Precambrian basement (PCb). In this regard it is similar to the Ancient Ephraim fault farther west, except that the listric normal fault there is shown as not quite connecting to the deeper, slightly curved fault that penetrates basement.

In contrast, the study commissioned by Reclamation of the latest seismic reflection data (Coogan, 2008a) concludes that the Joes Valley faults do not penetrate the Navajo Sandstone and terminate in the Arapien Shale. Although I am not an expert in seismic reflection interpretation, it seems clear to me that reflectors are disturbed beneath Joes Valley to a depth well below that of the Arapien Shale/Navajo Sandstone contact (Fig. 5). In both lines the Paleozoic section appears to be downthrown into a graben structure, and there are hints that this deeper graben merges with a west-dipping fault in basement. Such an interpretation agrees with that shown in Fig. 4.

An indirect line of evidence also suggests that Joes Valley graben is underlain by a crustal-penetrating fault. There is geologic evidence that both the Snow Lake graben (Spieker and Billings, 1940) and the Joes Valley graben (this study) are relatively young geologic features. That is, they do not date from the early Miocene inception of Basin and Range extension, but are Pliocene or Quaternary in age. According to the evolutionary seismotectonic model of West

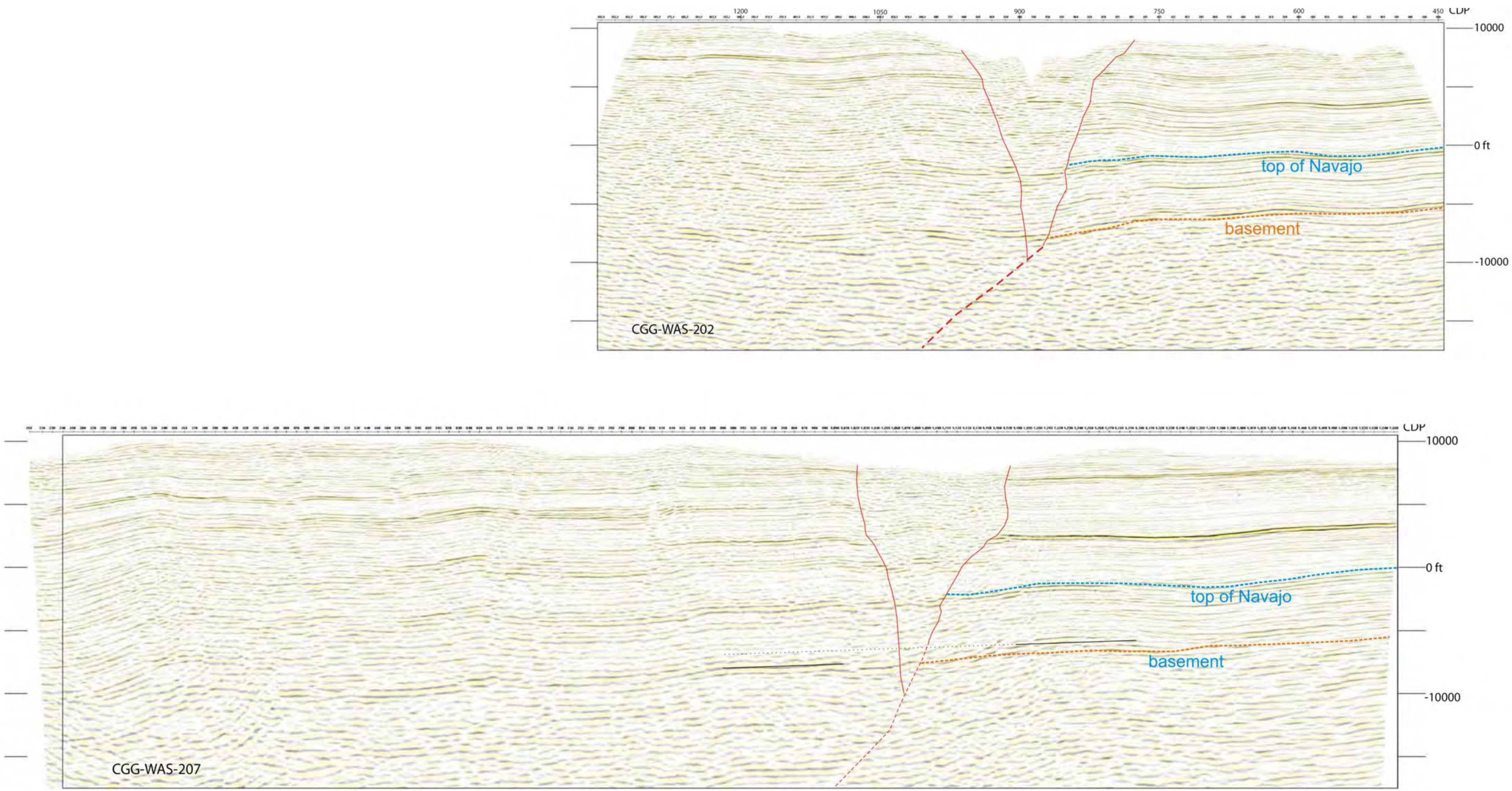


Fig. 5. My interpretation (in red) of the seismic reflection lines shown in Coogan, 2008 (his Figure 5, with his picks for top of Navajo and top of basement/bottom of Tintic shown at right). In both sections it appears clear that reflectors are disrupted below the level of the top of Navajo Sandstone. The definition of the edges of the graben is slightly more distinct in the shorter line at top, whereas the disruption in basement reflectors is easier to see in the longer line at bottom. Dashed lines in basement are more speculative than solid lines above.

(1992; discussed more in the following section), the latest extensional structures to develop at the surface are the high-angle extensions of crustal-penetrating faults. Grabens formed by backslip on low-angle detachments (Model 2) are the first structures to develop, and are tectonically beheaded in the intermediate phases of extension. This topic and its ramifications are discussed in more detail for Model 2, below.

Model 2- Faults extend downward to a gently-west-dipping décollement (extensional detachment fault) that lies in the Arapien Shale/Carmel Formation.
Model 2 was originally proposed by Arabasz and expanded upon in Appendix 4 of Foley et al., 1986, with important caveats: "*It would take extraordinary data to establish that the bounding faults of the Joes Valley graben were truncated by a horizontal detachment and hence not adequately penetrative into the crust to generate a large earthquake. Even if it can be shown by seismic-reflection data that such detachment faulting truncates surficial normal faults elsewhere in the Wasatch Plateau, I cannot conclude that such a detachment is everywhere coherent and undisturbed by younger normal faulting. The question simply is, What are the subsurface relations beneath Joes Valley? Existing seismicity data are equivocal and cannot be relied upon to support any hypothesis that would preclude future surface-faulting earthquakes of large size (say, magnitude 6-1/2 to 7-1/2) along the Joes Valley fault zone*." From this summary, and from Fig. 6, we can see that Arabasz did not think that high-angle normal faults such as the Ephraim fault crossed and displaced the detachment. However, the cross-sections of Schelling et al. (2007) make it clear that the Arapien Shale and most overlying Cretaceous strata are displaced by the Ephraim fault, and if the detachment is restricted to the Arapien, then the detachment is likewise displaced.

According to the evolutionary model of West (1992) (Fig. 7a), once a high-angle normal fault in basement propagates upward and displaces the subhorizontal detachment, that part of the detachment updip of the cutoff is tectonically beheaded and becomes inactive (outlined by red ellipse in Fig. 5). This occurs between West's Stages 3 and 4 (see Fig. 7a). Comparing the cross-sections of Schelling et al. (2007) to the diagrams of West, 1992 (Fig. 7a) it is apparent that extension in the Sanpete Valley-Wasatch Plateau area has reached a stage between Stage 5 and Stage 6, but closer to the latter, because the basement-penetrating Ephraim Fault has reached or nearly reached the ground surface. West's model predicts that by Stage 5, and certainly by Stage 6, faults that had accommodated extension updip (east) of the Ephraim Fault (such as the low-angle detachment) will have been tectonically beheaded and gone inactive. However, geologic evidence (Foley et al., 1986) shows that faults of the Joes Valley graben have continued to move up through the Holocene. This suggests that the observed late Quaternary and Holocene movement on Joes Valley faults cannot be the result of westward sliding on the detachment.

In fact, if the detachment has continued to accommodate extensional slip to the west in the Quaternary, it should have bent or displaced the Ephraim Fault above the detachment in a top-to-the-west manner. But interpretations of seismic reflection lines by Schelling et al. (2007) and Coogan (2008) do not show that to have happened. So, either West's model is wrong, or the extension that created Joes Valley has nothing to do with continued westward slip on the detachment. I favor the latter explanation, which means I think the field evidence argues against Model 2.

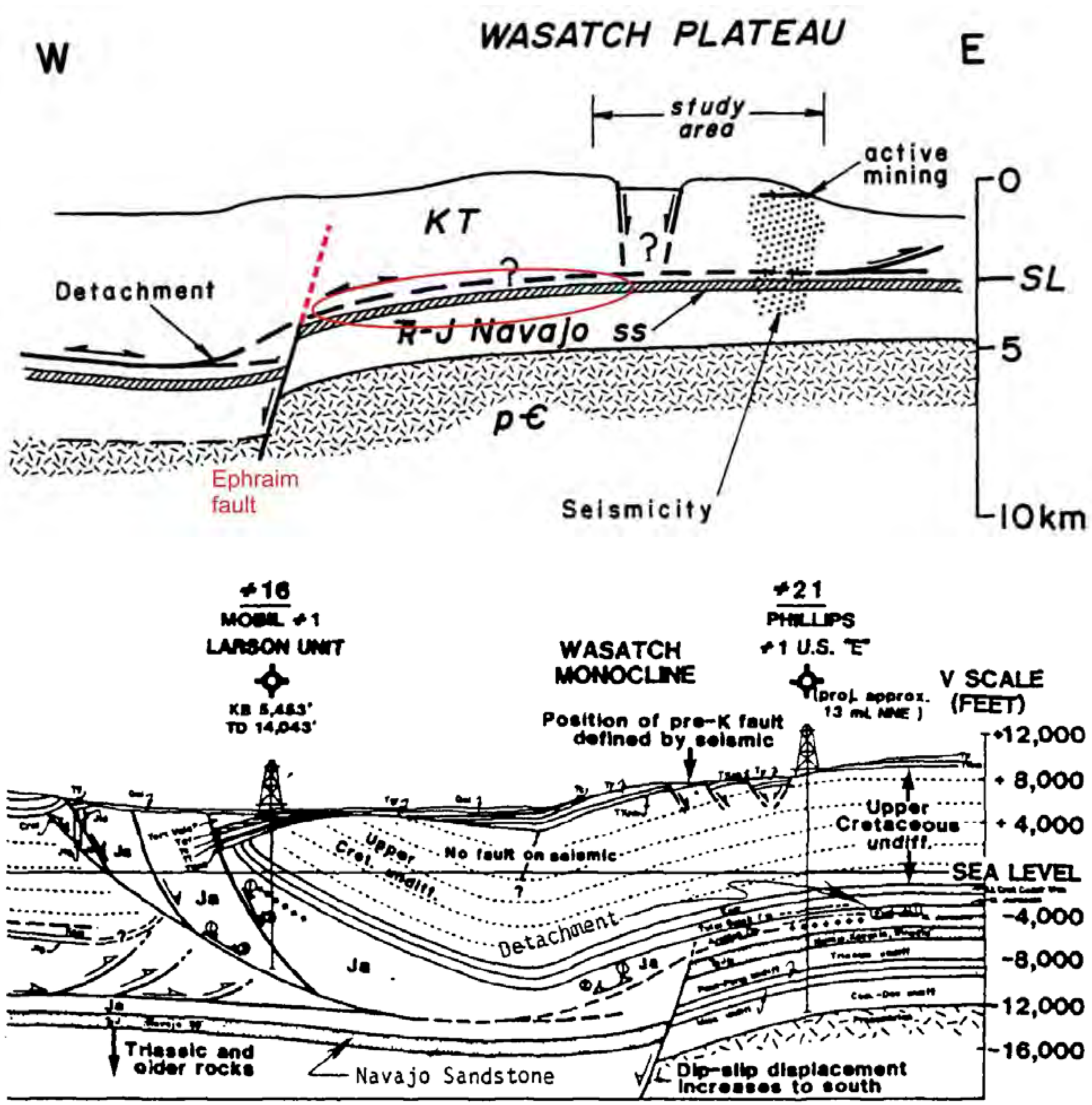


Fig. 6. Upper part, annotated version of cross section from Arabasz, 1986. According to cross-sections B-B' and C-C' of Schelling et al. (2007), the Ephraim Fault has been reactivated in the Neogene and now extends nearly to the surface (section B-B') or all the way to the surface (section C'C'), displacing the detachment and most of the hanging wall strata (red dashed line). Lower part, the crustal cross-section of Standlee (1982) interprets surface normal faults on the Wasatch monocline as not connected to the Ephraim Fault at depth, and none of the strata above the detachment as faulted. This was the most up-to-date cross-section when Arabasz wrote his 1986 paper, and when Foley et al. (1986) was written.

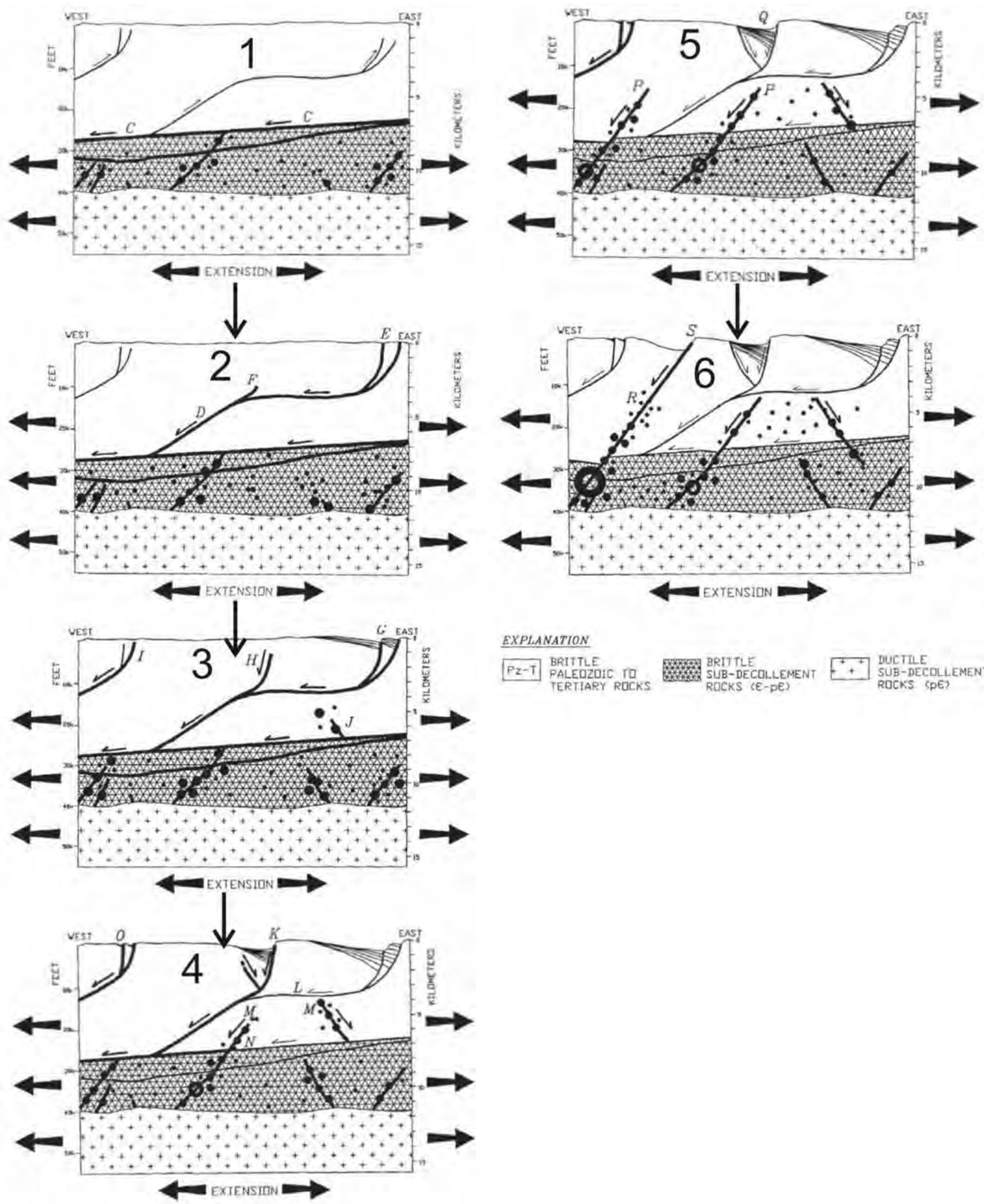


Fig. 7a. Conceptual model of how extensional faults develop and evolve when an older thrust belt is subjected to regional extension. Stage 1 is the earliest. From West, 1992.

Model 3- Faults sole into reactivated west-dipping backthrusts…
The only positive evidence to support this model is Coogan's (2008) interpretation of a small east-dipping fault underlying the Joes Valley graben and soling into the detachment of the Arapien Shale (Fig. 7b). He thus interpreted this fault as a Sevier backthrust. However, Coogan (2008) shows the graben faults to continue downward past their intersection with this backthrust, so it does not seem possible that slip on the backthrust could have created those faults, especially the parts that are lower than the backthrust. In addition, getting significant down-to-the-east normal fault movement on this east-dipping backthrust would require eastward slip on the Arapien detachment horizon, which: (1) would be in opposition to the westward regional dip, and (2) would pass mostly through limestone facies rock rather than evaporite facies. For these reasons, I do not consider Model 3 a very viable option.

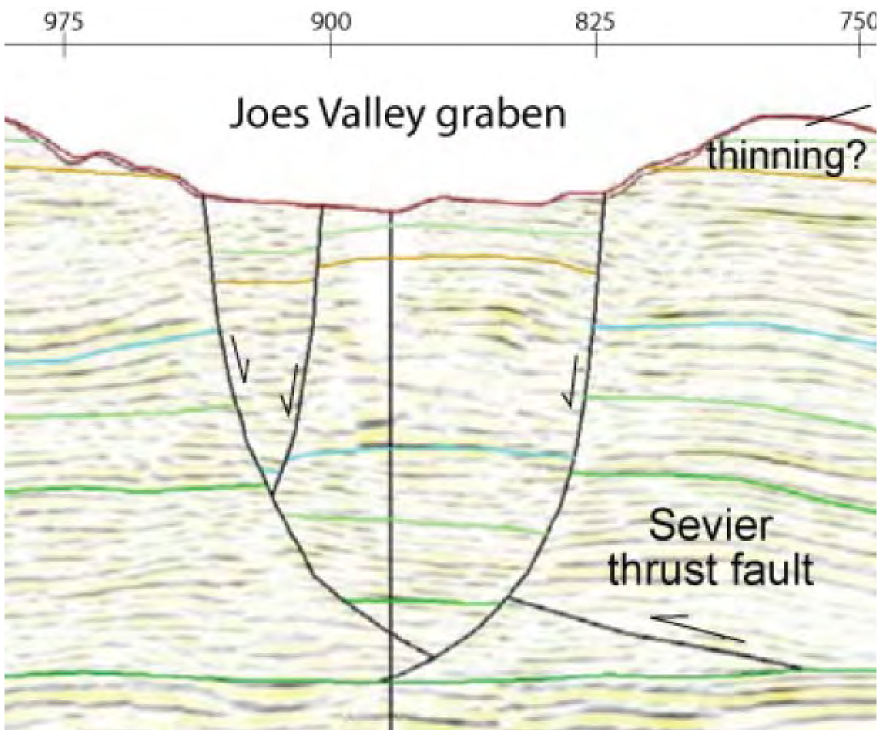


Fig. 7b. Part of the upper central part of seismic line

Model 4- Faults are passive collapse structures created by dissolution of the Arapien Shale and formation of large void spaces. Faults do not extend below the Arapien Shale. Deep seismic reflection profiles (Schelling et al., 2007; Coogan, 2008) show no evidence whatsoever for the existence of diapiric salt or other evaporites beneath Joes Valley.

Model 5- Joes Valley Graben is the headscarp of a crustal-scale gravity slide to the east. I were not able to find any positive evidence for the existence of a giant eastward gravity slide of the Wasatch Plateau between Joes Valley and Castle Valley. Most gravity slide headscarps are concave in the direction of sliding, and the Joes Valley graben shows no such concavity. Nor did I observe any sackung-like features on the eastern Plateau, or bulging or oversteepening of the Plateau escarpment facing Castle Valley.

3.0 RE-EVALUATION OF THE TECTONIC GEOMORPHOLOGY OF THE JOES VALLEY GRABEN AND THE SEISMOTECTONIC STUDY OF FOLEY ET AL., 1986

The initial charge of this investigation was to re-examine the Quaternary fault scarps and other geomorphic features described in an earlier study (Foley et al., 1986), which had been interpreted to have formed during recurring, large-magnitude earthquakes. Because of the geologic units in the area, and the surface and subsurface geometry of the faults within the Joes Valley fault zone, a non-tectonic origin for the geomorphic features (e.g., Models 2-5) needs to be formally considered and weighted for the next PSHA for Reclamation dams. It was hoped that re-examination of these landforms in the field might reveal characteristics that were incompatible with a tectonic or non-tectonic origin, in light of published work since 1986 on the differences in surface expression between tectonic and non-tectonic faulting. Such published works include the overview by Hanson et al. (1999), the comparisons throughout the 2nd edition of *Paleoseismology* (McCalpin, 2009), and journal articles such as Gutierrez et al. (2012a, 2012b).

As this study progressed through the office and field reconnaissance stages, the author slowly came to believe that small-scale Quaternary landforms produced by faulting in Joes Valley were in general not diagnostic of a particular origin for the graben. The surface landforms such as fault scarps in unconsolidated Quaternary deposits represent how these deposits have deformed due to normal surface faulting and then degraded under a semi-arid to sub-humid climate. Their morphology is more determined by the rheology of the faulted deposits, the depth to underlying bedrock, and the dip of the fault in bedrock just below the unconsolidated deposits, than by the deep structural processes occurring 3 km to 15 km beneath the graben. Because of this, the morphology of scarps and terraces is not a good discriminator between Models 1 through 5, all of which induce extensional faults at depths of 3 km or more that would look very similar when they reached the ground surface. A more direct line of evidence that might discriminate between Models 1-5 would be the structural characteristics of the bedrock faults zones, macro-scale patterns of faulting, and kinematic indicators. These topics are address in Section 4 of this report.

However, during the field reconnaissance the author had the opportunity to examine the surface landforms and tectonic geomorphic evidence from which Foley et al. (1986) derived the seismic source characteristics for the Joes Valley faults. Because the Foley report is still the most detailed study of Joes Valley faults, despite being 26 years old, these seismic source characteristics still provide the basis for seismic hazard assessments involving Joes Valley faults. The author thus had the opportunity to examine and evaluate the tectonic geomorphology evidence in light of 26 more years of research, and the development of new analytical tools such as LiDAR and new dating techniques. This Section 3.0 describes relevant observations made on landforms that relate to the seismic source characterization of the faults, in case the PSHA for Huntington North dam contains a branch with nonzero weight that the faults are seismogenic and deeply-penetrating.

3.1 NEW OBSERVATIONS FROM THIS STUDY

3.1.1 Examination of bedrock fault zone exposures

Foley et al. (1986) did not describe any exposures of Joes Valley faults in bedrock, nor have subsequent reports. However, these exposures do exist and may yield relevant information on the kinematic behavior of the graben that would be relevant to discriminating between Models 1-5. Perhaps a more sophisticated interpretation could be made by a structural geologist familiar with extensional faulting, than by this author who is basically a geomorphologist.

(a) Fault-zone exposures of the East Joes Valley Fault
The East Joes Valley fault is poorly characterized in the Foley et al (1986) report, which has a strong emphasis on studying Quaternary scarps in unconsolidated deposits rather than bedrock faults. My field reconnaissance confirmed that there are very few easily-visible fault scarps in Quaternary deposits along the EJVF. This lack is caused by two factors: (1) most of the EJVF fault trace is forested and thus hard to see from a distance, and (2) the range-front geomorphology is not conducive to alluvial fan development.

Much of the EJVF trace is at (or is mapped at) the base of a steep cliff of Castlegate Sandstone up to 60 m high. Tributary streams flowing from the fault footwall into the graben have difficulty forming "normal" alluvial fans at the range front due to this cliff at the valley margin, and in many cases the streams form a waterfall up to 30 m high. At the base of the waterfall is a plunge pool eroded into bedrock. [In contrast, on the WJVF escarpment the Castlegate Sandstone rarely outcrops right at the range front, so the alluvial fans are more "normal", having lower gradients, and extending headward a bit into the mouths of the tributary canyons]. As a result, Foley et al. (1986) were able to find several multiple-event fault scarps and terraces on the WJVF at sites like Littles Creek and Black Creek (Fig. 8a), from which they derived paleoseismic parameters such as number of displacement events, ages of events, vertical displacement per event, and recurrence interval. But they found no corresponding sites on the EJVFZ. As a result their seismic source characteristics for the EJVF, supposedly the master fault of the graben, come either from the WJVF, or from a single trench in Scad Valley which I interpret not to be on the EJVF.

As a slight compensation, the exposures of the bedrock fault are better on the EJVF than on the WJVF. The waterfalls on the Castlegate Cliff have created exposures of the EJVF footwall damage zone (generally) up to 30 m high. No corresponding exposures were noted by this author on the WJVF. I visited several exposures of the EJVF incised by streams at the range front, and saw a few more from a distance (but did not visit them). Good exposures are located:
(1) 6.2 km south of the Dam; a jeep road leads to this spot (477142 m E, 4342957 m N, UTM Zone 12, WGS 84)
(2) 650 m north of the Dam, in a small gully at the south end of the SR29 roadcut (476631 m E, 4349229 m N, UTM Zone 12, WGS84)
(3) 2.9 km north of the Dam, at the head of an alluvial fan that has a jeep road going to its head (see Fig. 8b; 476887 m E, 4351775 m N, UTM Zone 12, WGS84)

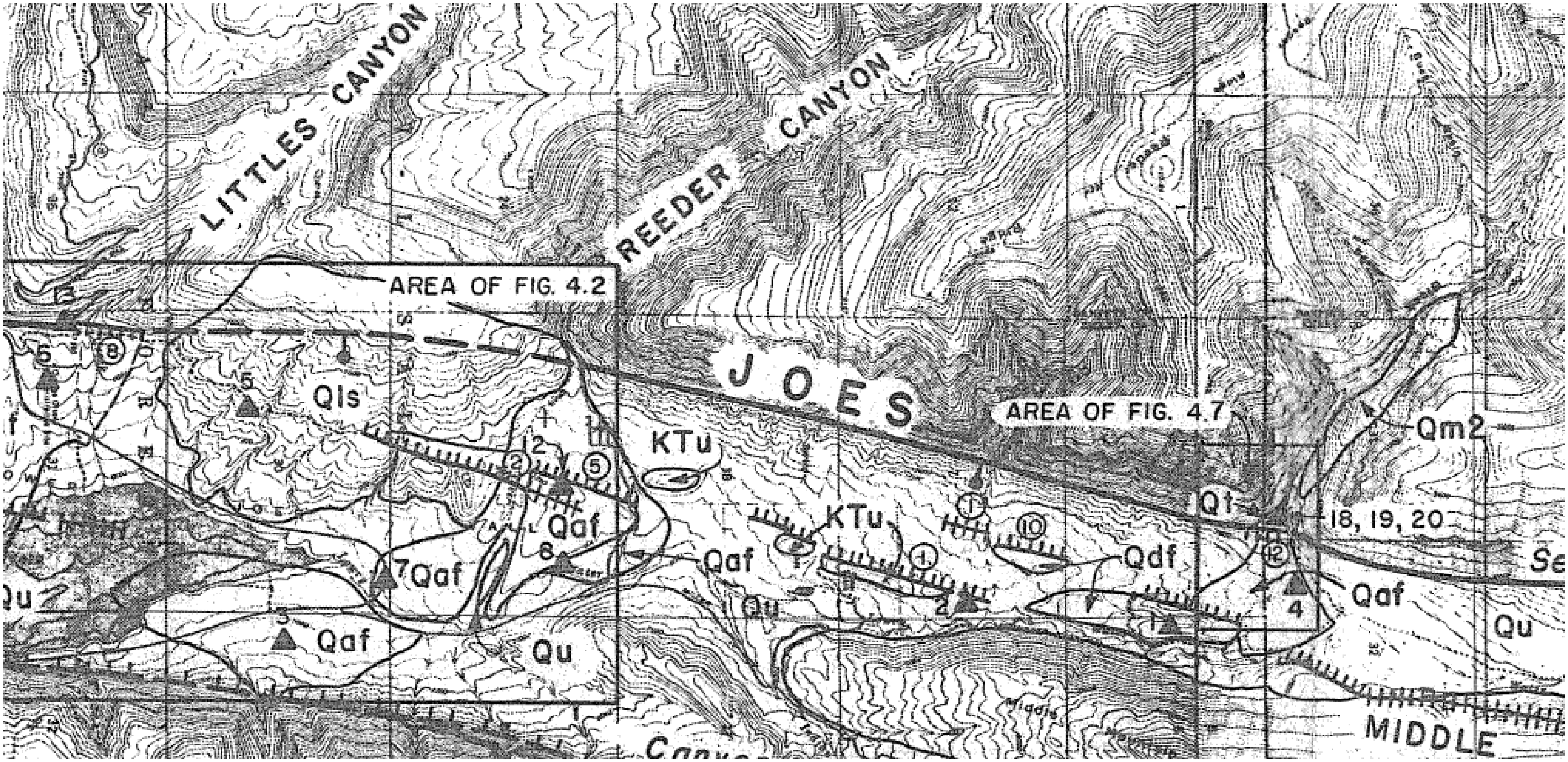


Fig. 8a. Part of the 48,000-scale map of Foley et al. (1986) north of Joes Valley Reservoir; north is to right. The WJVF is shown as a thick black line labeled JOES that crosses the entire width of the figure. The fault scarps at Littles Creek are shown by a hachured pattern at far left on the WJVF, near the circled label 8. Fault scarps at the mouth of Black Creek lie at right, in a rectangle labeled "AREA OF FIG. 4.7."

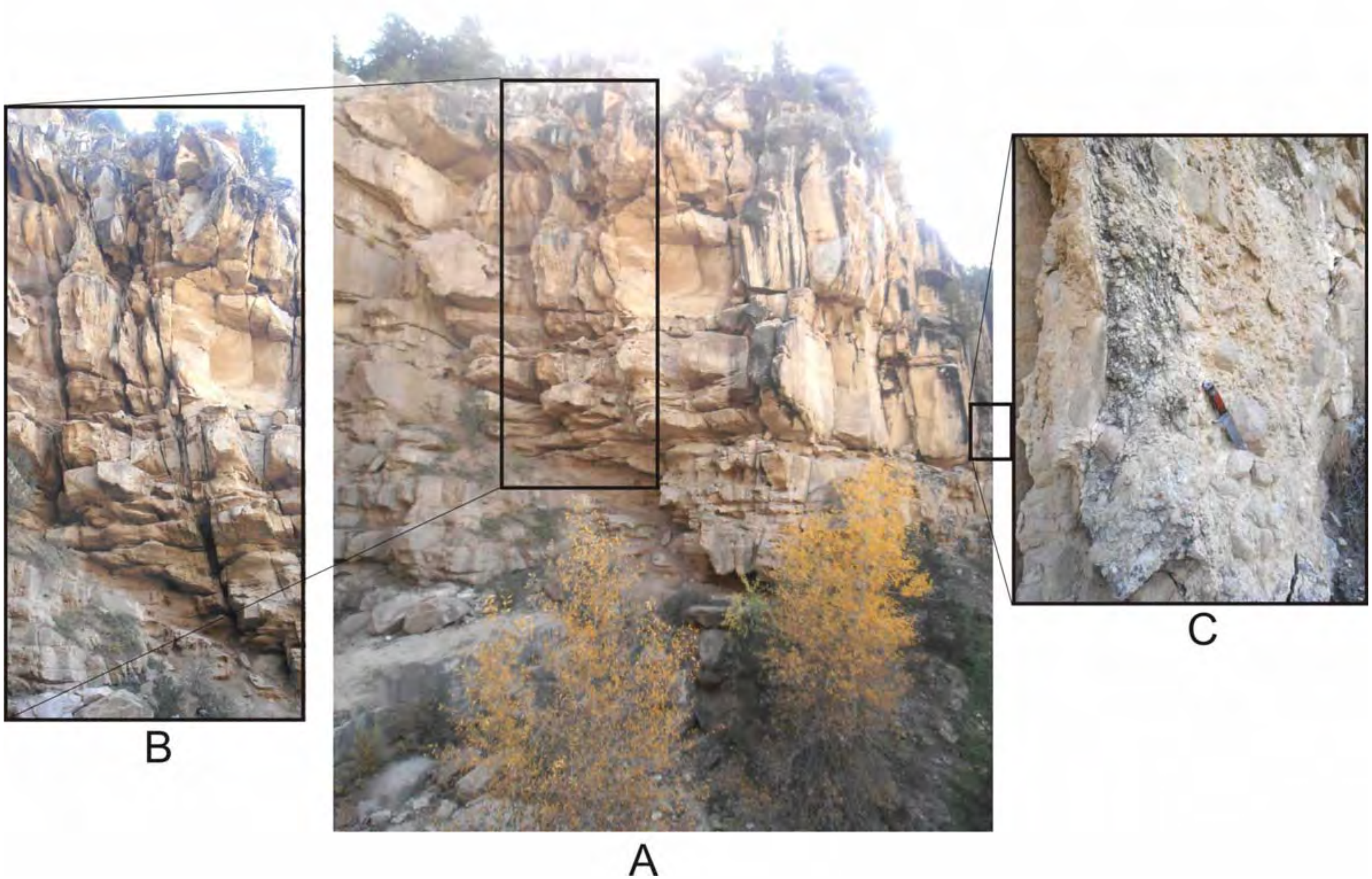


Fig. 8b. (A) Exposure of faults in the footwall of the EJVF at the head of the alluvial fan north of Trail Mountain Resort. Location is 476887 m E, 4351775 m N, UTM Zone 12, WGS84). The rock is the Castlegate Sandstone. The planar face at far right is inferred to be the contact between the footwall and the fault core; (B) Perpendicular view of normal faults in the footwall; (C) Fault breccia at the contact between the footwall and inferred fault core (covered by colluvium here).

3.1.2 Miscellaneous Geomorphic Observations

In this section I summarize some geomorphic observations that may be indirectly related to the origin of the graben.

a-Late Quaternary Fault Scarps on the Graben-Bounding Faults Are Discontinuous

Normally in a Quaternary graben of seismogenic origin, the late Pleistocene/Holocene fault scarps are better preserved and more continuous on the graben-bounding faults, than they are on secondary, intragraben faults. In the Joes Valley graben we see the opposite, which is possibly evidence supporting a nonseismogenic origin.

The graben-bounding faults in Joes Valley exhibit short fault scarps only across selected canyon mouths. Where preserved, these scarps are quite high, but it is not possible to trace them between the canyon mouths along the graben margins. The absence of scarps between the canyon mouths suggests the scarps have been destroyed by erosion since the Most Recent Event (MRE), and further, that the MRE was at least mid-Holocene or older, which accords with the MRE ages cited by Foley et al. (1983) for the West Joes Valley fault. [A similar situation exists on the Star Valley fault, Wyoming, studied by Reclamation in the 1980s (McCalpin et al., 1990), where intra-canyon scarps have (presumably) been destroyed since the MRE dated at 5540 C14 yr BP]. In contrast, the intragraben faults in Joes Valley appear to be more continuous, despite having smaller displacements than the graben-bounding faults. This includes the newly-discovered fault in Indian Creek (described in section b, below).

At the mouth of Littles Canyon there is a 2 m-high scarp on the West Joes Valley fault displacing the youngest terrace on the south side of the creek. Foley et al. (1986) do not show this scarp on their detailed map. This bedrock scarp looks to me like a single-event scarp representing the youngest displacement event (MRE) at this fanhead. If so, that MRE could be dated by either trenching the scarp, or a minimum age for faulting could be determined by cosmogenically dating the offset terrace.

b-Newly-Discovered Intragraben Fault in Indian Creek Valley

Fortuitously for this study, the State of Utah had acquired a publicly-available bare-earth LiDAR DEM with 2m pixels on the eastern edge of Upper Joes Valley, in an area 10 km by 10 km. The western ¼ of the DEM covered upper Indian Creek in Joes Valley including a 10 km-long section of the range front of the East Joes Valley fault (west margin of the Rilka Canyon 7.5' quadrangle).

Examination of the LiDAR imagery prior to the field reconnaissance revealed a 7 km-long, previously unmapped late Quaternary fault that trends N-S up the valley axis (Fig. 9a). The fault scarp faces east (upslope) and is as high as 1.8 m (Fig. 9b). The fault is marked by a line of phreatophytes (mainly willows, but some aspens) along most of its length. A beheaded stream channel is preserved on the footwall of the highest scarp (Fig. 9b, upper) indicating at least two late Quaternary displacement events that total 1.8 m of vertical displacement. This scarp goes through the entire length of the USFS Indian Creek Campground and is responsible for its flat camping sites. The remainder of the scarp is occupied by informal campsites that take advantage of the flat ground at the base of the upslope-facing scarp.

This fault was not recognized or mapped by Foley et al. (1986), despite its 7 km length and proximity to a heavily-traveled road and numerous campsites. I doubt if I would have recognized the significance of this relatively low ridge and trough if I had not acquired the LiDAR DEM and noticed the continuity of the scarp during the office phase. The discovery suggests that there

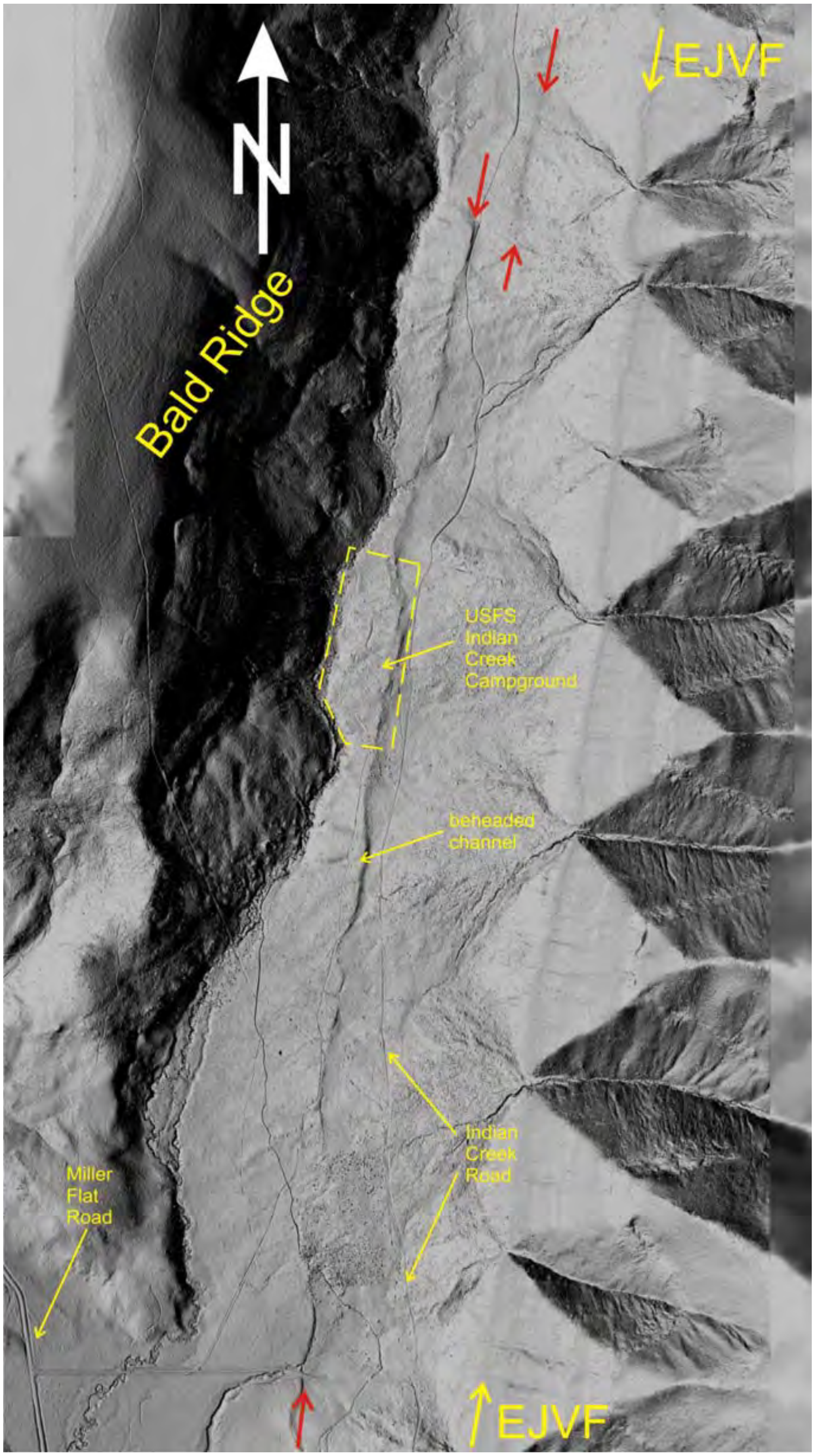


Fig. 9a. 2 m LiDAR DEM of upper Indian Creek showing the trace of the range-front East Joes Valley fault (crossing the bases of faceted spurs, between yellow arrows) and the newly-discovered antithetic fault on the valley floor (between red arrows). Sun azimuth is 270°, sun elevation is 40°, so the east-facing scarp casts a thin shadow on its east face. Mountain at left is Bald Ridge, an intragraben horst.

are probably more undiscovered fault scarps in Joes Valley, particularly in the northern half where forests are abundant.

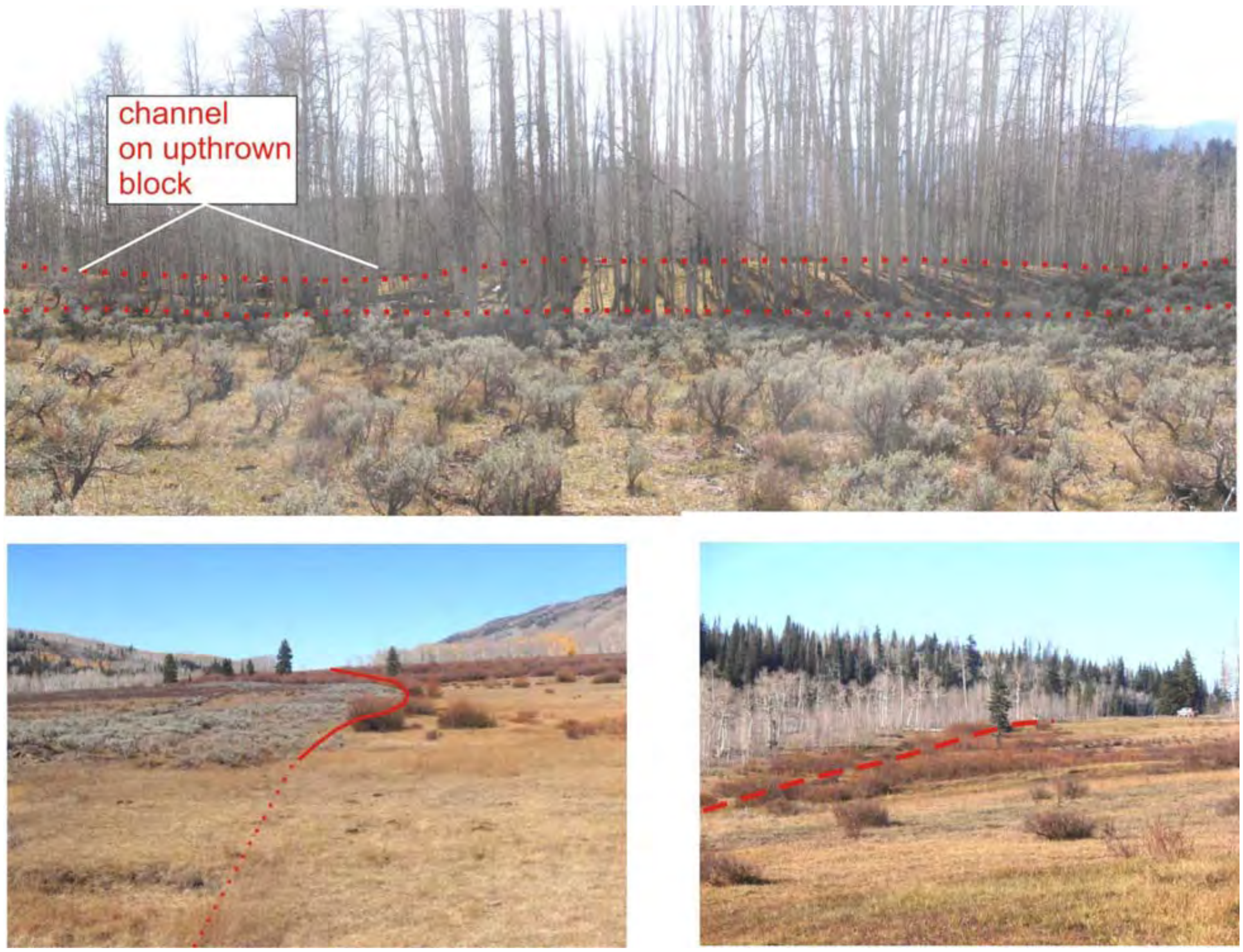


Fig. 9b. Ground photographs of various parts of the upslope-facing scarp in Indian Creek valley. Top, beheaded channel on upthrown block (see location in Fig. 9a). A correlative channel on the downthrown block could not be identified, perhaps due to graben development during the second faulting event.

<u>c- The Fault Scarp in Scad Valley</u>

I re-examined the fault scarp in Scad Valley trenched by Foley et al (1986) (Fig. 10a). This fault scarp and trench are important because they provided the only seismic source parameters attributed to the East Joes Valley fault. However, the scarp can be traced southward away from the East Joes Valley fault, so I conclude that the scarp is not on the East Joes Valley fault, but is actually on a separate intragraben fault that bounds the west side of Bald Ridge (Fig. 10b).

The fault scarp was impressively high (vertical surface offset of 4.0 m) and steep, but the well-developed part of the scarp was anomalously short (330 m long; most of which is shown in Fig. 11). The short length of the scarp can be explained on the south side because it crosses a small stream and then begins ascending a hillslope where erosional processes have subdued its appearance. On the north side that same explanation cannot explain why the 2-4 m-high scarp cannot be traced across the flat valley floor. There is an area of anomalous landforms north of the scarp (isolated hills and antislope scarps) that do not appear to be erosional features, but there was insufficient field time to map these features carefully and to determine their origin.

Fig. 10a. Telephoto view looking east, of the well-developed part of the Scad Valley fault scarp (between red arrows) and the 1985 trench site.

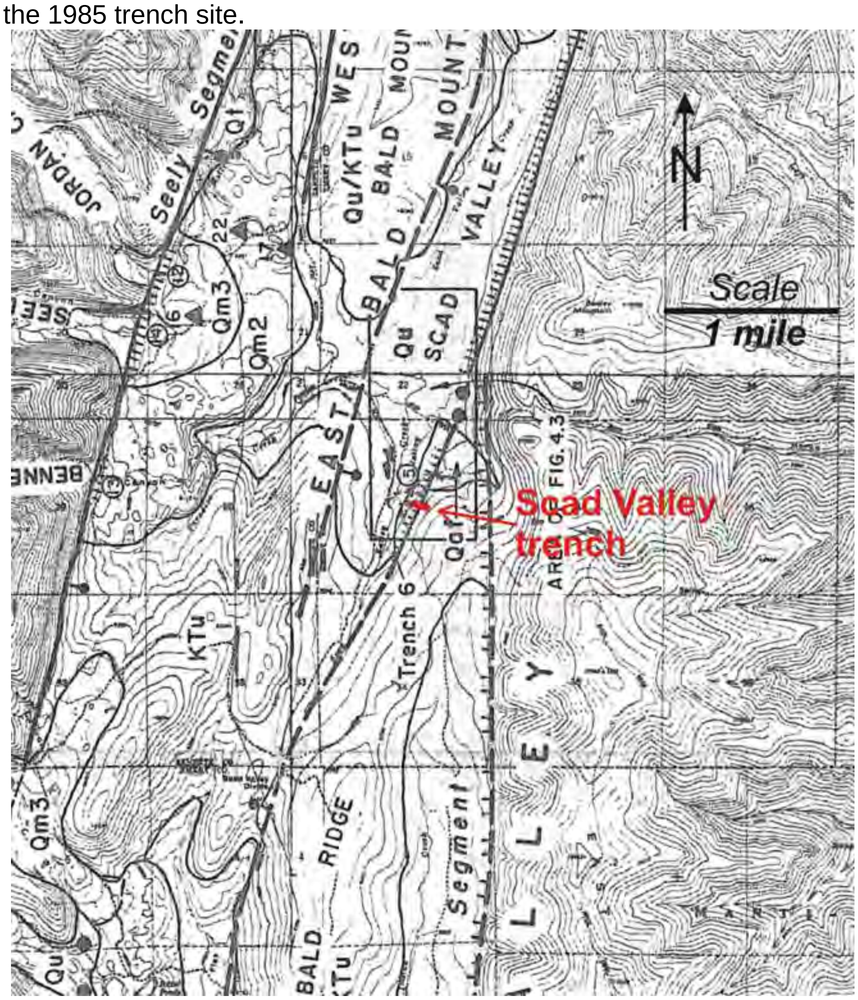


Fig. 10b. Map of the Quaternary faults (thick lines) in the Scad Valley area, from Foley et al. 1986 (Plate 2). The 1985 trench was not on the main range-front trace of the EJVF, but on a splay fault that diverged southward away from the EJVF and bounds the west side of Bald Ridge, an intragraben horst. Thus, it is uncertain if any of the faulting events interpreted in this trench ruptured the main trace of the EJVF.

Therefore, I do not know if the anomalous shortness of the scarp compared to its length is simply due to erosional truncation, or to an originally short length that might be supportive evidence for a nonseismogenic origin (the short, fat fault phenomenon).

In that regard, LiDAR DEMs of the entire Joes Valley graben would make detailed mapping of such features easy and fast. The reconnaissance mapping of Foley et al. (1986) was not done on a scale that would identify or interpret such relatively small fault-related features, which often hold the key to fault interpretation.

d-The Mega-Geomorphology of Seeley Creek
The large-scale geomorphology of the Seeley Creek drainage suggests that it was flowing on a valley floor at about 7880 ft elevation when the graben first began to develop (or accelerated its development). If this inference is correct, then the creek had already cut down from ca. 10,000 ft (the Plateau surface) to 7880 ft before the graben developed. At that time the WJVF began to downdrop the Seeley Creek within the graben, from 7880 ft to its present elevation in the graben of 7100 ft (i.e., 780 ft of tectonic downdropping). This means 2/3 of Seeley Creek incision into the rocks of the Plateau occurred before the graben developed. If uplift of Wasatch Plateau began 25 Ma, then 2/3 of 25 Ma= 16 Ma and 1/3= 8 Ma, which implies that the graben began developing at ca. 8 Ma. This is relatively late for a Basin-and-Range extensional graben, many of which have basal graben fills dating back to the early Miocene. Again, this is weak possible evidence for a nonseismogenic origin of the Joes Valley graben.

However, if this is correct, where is the 8 Ma worth of graben-fill sediments that should have been deposited in the graben? There are only a few possible explanation for the lack of thick Neogene, post-graben deposits in Joes Valley: 1- graben-fill sediments were never deposited, because (a) the graben is much younger than 8 Ma, or (b) streams flushed sediments out into Castle Valley, or 2- sediments were deposited but then later removed by erosion, prior to Bull Lake time.

3.2 EVALUATION OF FOLEY ET AL 1986 STUDY, AS VIEWED FROM A 2012 PERSPECTIVE

Fault Mapping:
Fault scarp mapping was good for larger scarps in open areas, but they missed several large scarps in the trees, such as the 8 m-high fault scarp on the EJVF in Upper Joes Valley in the first drainage north of the Cottonwood Creek Road (UTM coordinates 479766 m E, 4363484 m N, UTM Zone 12, WGS84). They also missed smaller scarps such as the LiDAR scarp mapped in Indian Creek, most of which is in open rather than in forested areas.

Fault Trenching:
(1) Trenches were too shallow;
(2) logging was too cartoon-like;
(3) On logs, deposits that appear to be colluvial wedges are labeled “debris flows”. This makes it hard for a reviewer to interpret the logs;
(4) Event horizons are not labeled, nor are there any retrodeformation sequences made by the trench loggers;

(5) There is very poor dating control on displacement events. Only a few C14 samples, but most of those are not located close to Event Horizons. Most displacement events are not bracketed by dates, due to the unpredictable locations of datable charcoal;
(6) The only non-charcoal dating methods used were soil development and amino acids. The latter method has generally been abandoned by geochronologists, and they never had much confidence in the precision of the former method. Nowadays we use single-grain optically-stimulated luminescence to date trench deposits and cosmogenic isotopes (surface exposure ages) to date geomorphic surfaces. Using luminescence permits one to take samples much closer to Event Horizons and to bracket horizons tightly. Neither of these methods existed in 1986.
(7) The imprecision in dating displacement events has several effects on our ability to interpret seismic source characteristics. First, the recurrence intervals, elapsed time, and slip rates cited by Foley should be seen as very imprecise, given the dates used to compute them. Second, the recurrence intervals are too few and too imprecise to make a meaningful estimate of the variability in recurrence through time, another requirement of the logic tree. Third, no slip rates are cited. Fourth, we cannot test even the most basic behavioral models using imprecise event dates. For example, I cannot confidently test whether displacement events on the EJVF, WJVF, and intragraben faults occurred at the same time. Finally, the estimates of elapsed time and average recurrence times are not good enough to compute the conditional probability of future rupture, in either a deterministic or probabilistic sense.

4.0 COMPARISON OF CHARACTERISTICS OF THE FAULTS IN JOES VALLEY TO PARAMETERS OF FAULTS ASSOCIATED WITH GRABENS FORMED BY TECTONIC AND SALT DEFORMATION PROCESSES

Anderson (2008, p. 7) listed five morphologic characteristics of the Joes Valley fault zone that seemed to differ from other Quaternary fault zones in Utah and the Basin and Range Province. In this section I expand on his list, and compare the dimensions and ratios morphologic features associated with tectonic and non-tectonic grabens.

4.1 MORPHOLOGIC PARAMETERS

4.1.1- Fault sinuousity (trace length/end-to-end length)

It was suggested by Anderson (2008, p. 7) that the Joes Valley graben is abnormally straight compared to other normal faults such as the Wasatch Fault. "*In detail, most of the Basin and Range faults are actually quite arcuate with several salients and embayments [and] which apparently reflect changes in dip and preexisting bedrock relationships.*"

Without performing any type of quantitative analysis, I agree with Anderson's observation. In map view the bounding faults of Joes Valley resemble those of the narrower salt-related grabens of the western Colorado Plateau, more so than B&R faults such as the Wasatch, Cache, Bear Lake, etc. However, those latter faults are within the highly folded and faulted part of the Sevier fold and thrust belt. In contrast, Joes Valley and the salt grabens are east of the thrust belt in domains of flat-lying, vertically-jointed sandstones. So the straightness of the latter faults may be a result of the lack of complicating subsurface thrust structures like ramps and tear faults, and the controlling effect of preexisting vertical joint sets on graben faults. Due to this ambiguity, it is difficult to use fault sinuosity to distinguish between Models 1-5.

4.1.2—Narrowness (graben Length:graben Width)

It was suggested by Anderson (2008, p. 7) that the Joes Valley graben was abnormally narrow (length is more than 80 times width) compared to other Neogene grabens. In other extensional regions of the world, the Length:Width ratio of mature grabens or half-grabens tends to be 3:1 or 4:1 (Delvaux, 1991).

For opposing graben faults with an average 60° dip, the faults come 1.15 km closer together for every 1 km of depth. Thus in order for the two faults to intersect at a depth of 12-15 km (base of the seismogenic crust), they would have to be a minimum of 13.8-17.3 km apart. As can be seen in Fig. 11, many of the tectonic grabens in the B&R-CP transition zone are about this wide. The salt-related grabens, in contrast, are much narrower as a group, ranging from 1-7 km wide and averaging 2-3 km wide. According to the dip model above, opposing faults only 3 km apart would intersect at a depth of 2.6 km, far above the base of the seismogenic crust. This depth, however, is within the range of depths to the bottom of evaporite beds and to Sevier-age detachment faults in the transition zone.

Joes Valley averages 2.5-3 km wide and clearly belongs to the narrow group of grabens. This fact suggests that the cause of graben extension lies at a depth more like 3 km than 12-15 km. Models 2-4 all suggest that the origin of Joes Valley lies near 3 km depth.

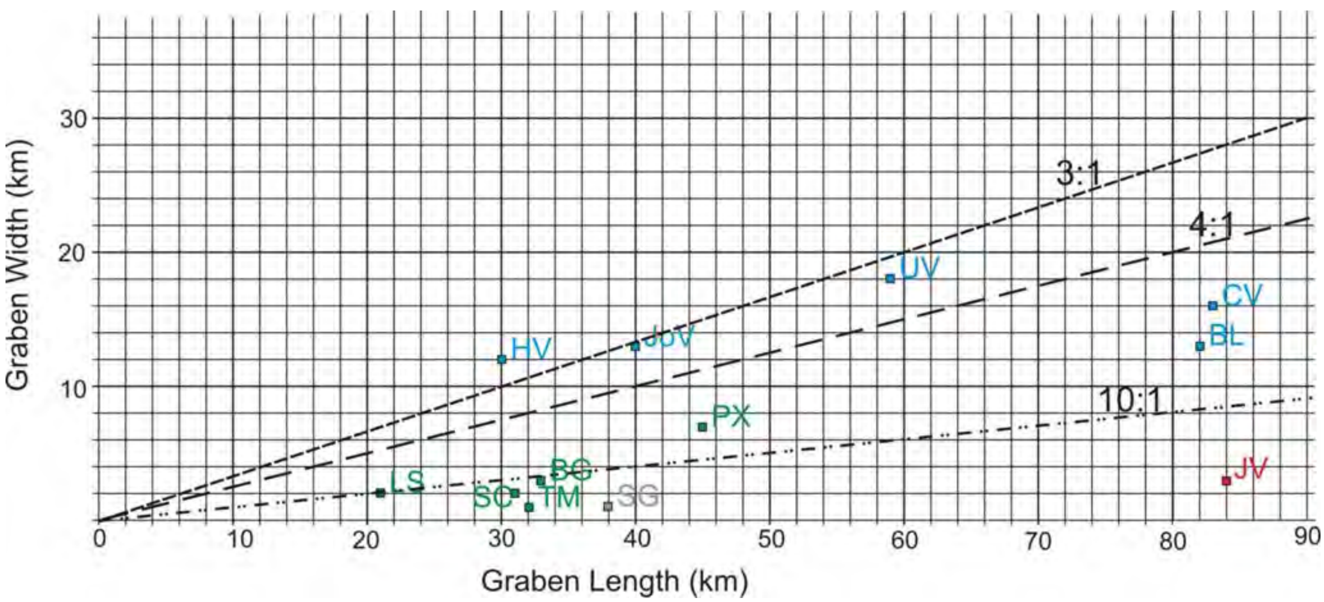


Fig. 11. Length:Width ratios of grabens in the Basin and Range-Colorado Plateau transition area. Joes Valley (JV) in red; tectonic grabens in blue, HV=Hansel Valley, JoV=Jordan Valley, UV=Utah Valley, CV=Cache Valley, BL=Bear Lake Valley; salt-related grabens in green, LS=Lisbon Valley, SC=Salt and Cache Valleys, BG=Big Gypsum Valley, TM=Ten Mile Valley, PX=Paradox Valley; grabens of unknown origin in gray, SG=Shay Graben. Gray lines show the typical ratios for rift tectonic grabens (3:1 and 4:1), plus the reference line for 10:1.

4.2 Structural Parameters

4.2.1- Lack of Net Vertical Displacement Across Graben

Kitzmiller (1982) constructed a geologic cross-section across Joes Valley and concluded that there was negligible vertical displacement across the graben (Fig. 12). I checked this conclusion by determining the strike of two geologic units (Castlegate Sandstone, Kc; lower Price River Formation, Kpl) on the eastern side of Joes Valley in the same location as Kitzmiller's cross-section, which it turns out is oblique to both the strike of beds east of the graben, and to the graben boundaries. The strike lines all trend E-W±5°, and confirm field observations (Fig. 13) that the dip of strata on the flanks of Joes Valley north of the Reservoir is 3-3.5° to the south, not to the west.

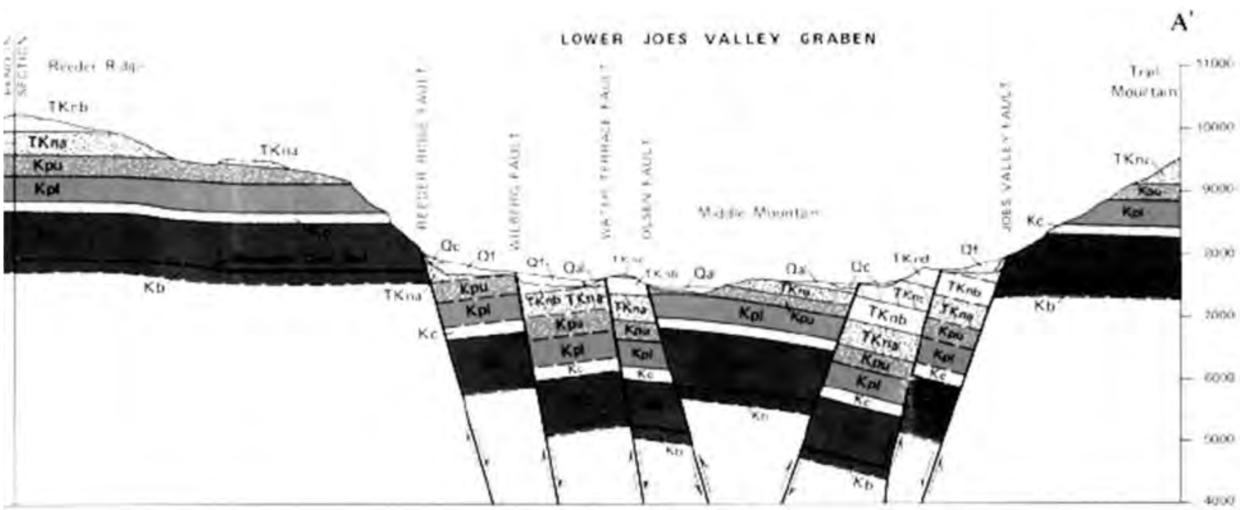
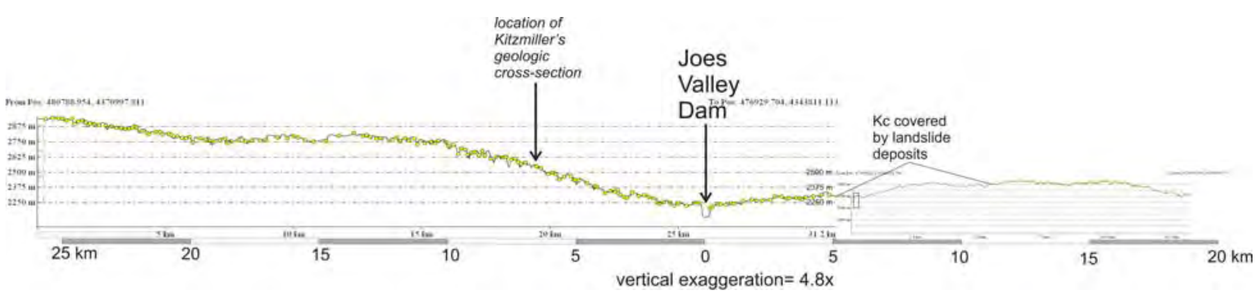


Fig. 12. Cross-section across Joes Valley north of Reeder Canyon, from Kitzmiller (1982). Note the lack of thick Quaternary deposits on the graben floor. The south dips shown in following figures cannot be seen in this section, because it was drawn nearly parallel to strike.



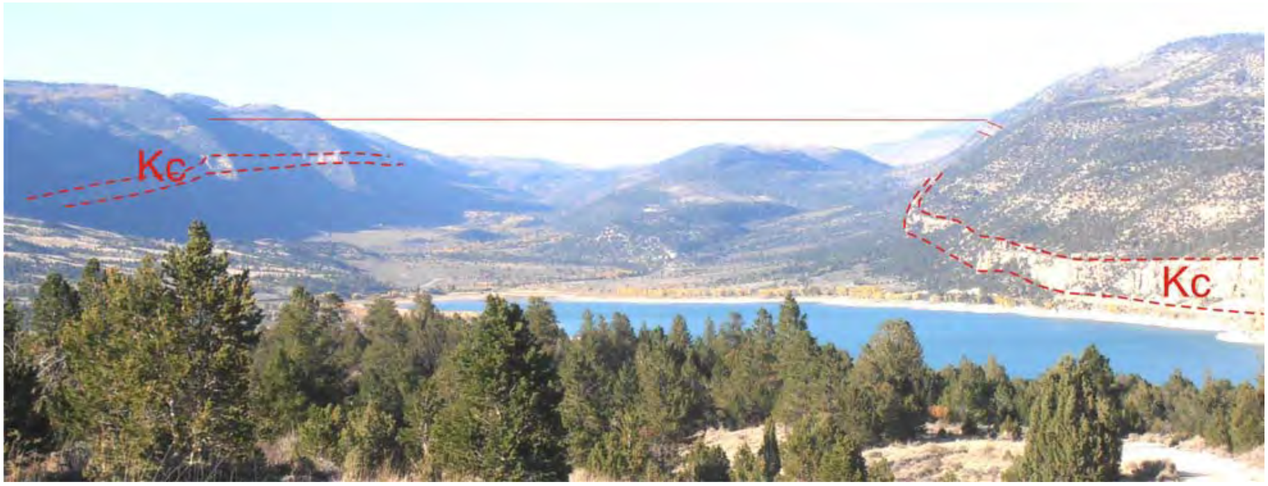


Fig. 13. Upper part: North-south topographic profile on the top of the Castlegate Sandstone (Kc) on the east side of Joes Valley. North is at left. Kitzmiller's geologic section crosses the valley where south dips are the steepest, on the north limb of a broad syncline, the axis of which is at Joes Valley Dam. Lower part: View north up the graben from just south of Joes Valley Reservoir. The cliff of Castlegate Sandstone (Kc) is outlined in red, and dips south toward the camera on both sides of the graben. The horizontal red line also shows that, at the location of Kitzmiller's cross-section, the Castlegate (and Price River) formations are ca. 400 ft lower than they should be on the west side of the graben.

First, three strike lines were drawn 200 vertical ft apart on the formation tops of Kc and Kpl exposed on the east and west sides of Trail Mountain (Fig. 14; Trail Mountain is the ridge between Joes Valley and Cottonwood Creek). Lines connecting the same elevations on the formation tops constitute strike lines. These strike lines were then projected west across the graben, and the elevation of the formation tops there was compared with the elevation of the strike line. The formation tops will yield the same elevation on both sides of the graben along the strike lines, unless: (1) there has been vertical displacement across the graben, or (2) there has been a regional change of strike or dip across the graben.

As shown in Table 1, the formation tops on the west side along strike are all hundreds of feet lower than the same tops on the east side. The larger elevation differences are associated with strike lines that trend slightly SW of due W. As the strike lines trend more NW, the elevation differences become smaller (217 ft, 220 ft). The average misfit of elevations across the graben is 403 ft (123 m). I interpret this misfit as a result of down-to-the-west vertical offset across the graben, rather than a result of a westward component of dip, because the elevation of mapped contacts here show no westward component of dip.

Table 1. Elevation differences between formation tops on the eastern escarpment of the Joes Valley graben, and the elevations where they should be on the western escarpment. In all cases, the unit tops are lower than they should be along strike-line projections on the western escarpment. This geometry indicates there has been roughly 220-540 ft of down-to-the-west displacement across the graben.

Formation Top Elevation, E side	Formation Top Elevation, On projected strike line, W side	Elevation Difference (W side down)
Kc- 8800 ft	Kc- 8583 ft	217 ft
Kc- 8600 ft	Kc- 8222 ft	378 ft
Kc- 8400 ft	Kc- 7990 ft	410 ft
Kpl- 9200 ft	Kpl- 8980 ft	220 ft
Kpl- 9000 ft	Kpl- 8348 ft	652 ft
Kpl- 8800 ft	Kpl- 8260 ft	540 ft

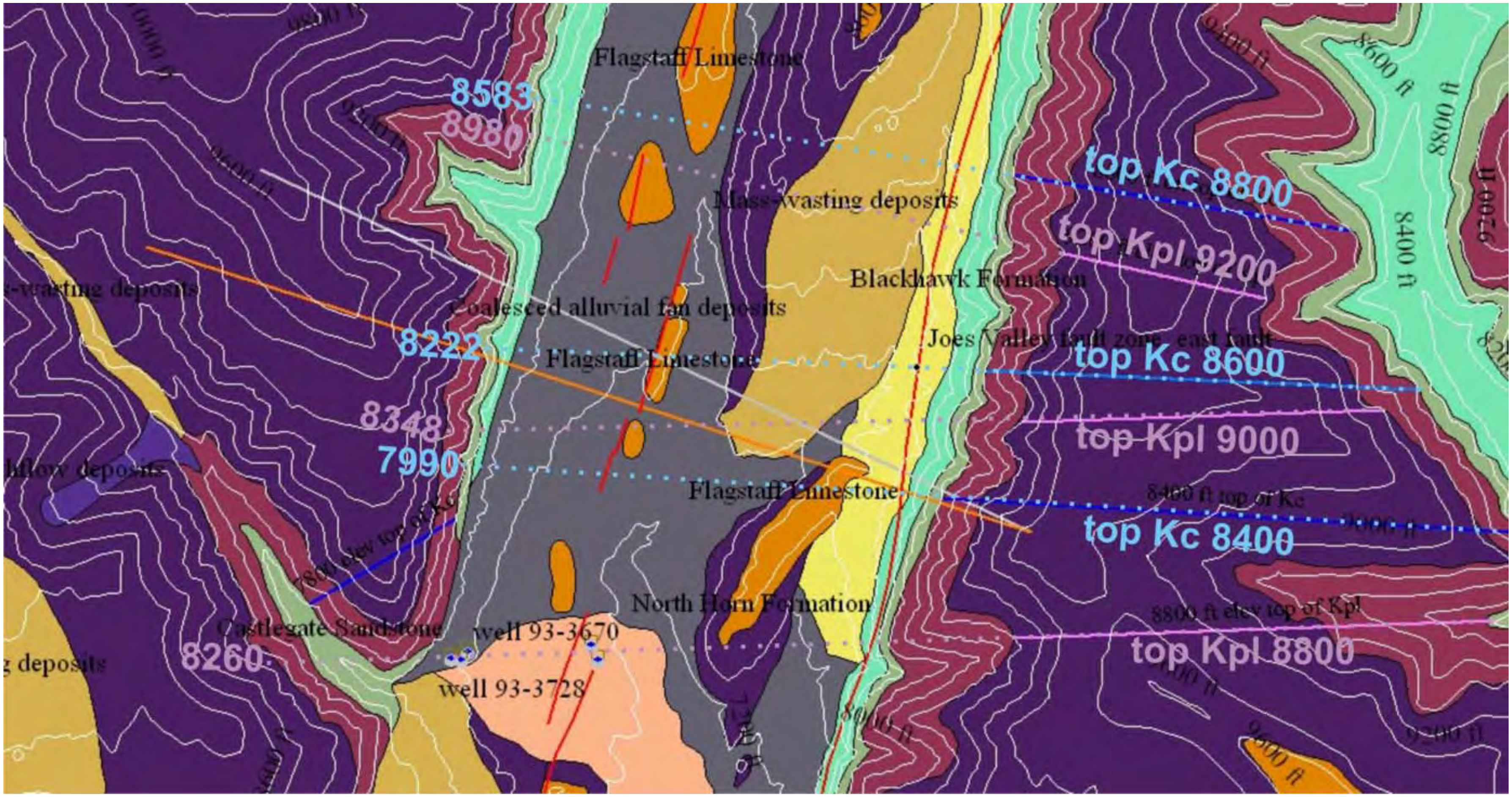


Fig. 14. Strike lines defined on the east side of the Joes Valley graben (graben at center) on the top of geologic units Kc (blue) and top of Kpl (purple), and then projected to the west side (dotted lines). Blue and purple numbers at left show the elevations of the formation tops on the west side along each strike line. In all cases, the formation tops are hundreds of feet lower than they should be for a constant strike and dip across the graben (see Table 1).

Foley et al. (1986), Hecker (1993) and Anderson (2008) all used the fact that there is no vertical offset across the Joes Valley graben as support that the graben is not tectonic or seismogenic. However, our analysis shows that there is an average 400 ft down-to-the-west vertical separation of beds across the graben. This sense of vertical separation is in the correct sense for a graben that had a master, west-dipping normal fault on the east (East Joes Valley fault) and an antithetic fault on the west (West Joes Valley fault). All of the workers cited above inferred that same structural geometry for the graben, but based on the belief that the graben faults soled into a west-dipping detachment.

4.2.2 Elevations of the Hanging Wall and the Footwall

In most tectonic grabens I have worked on, the elevation of the HW (valley floor) is constant, while the elevation of the FW (mountain crest) varies along strike. But in Joes Valley it is the reverse; the elevation of the valley floor varies, but the elevation of the mountain crest is constant. This is a pattern that one would expect if the absolute sense of displacement was 100% graben side down (subsidence), and the FW had not been raised in elevation at all by tectonic forces. In other words, the valley floor has simply collapsed, as would occur in Model 4, the evaporite dissolution-collapse model (Section 2.1, Model 4).

4.2.3 Presence of Evaporites at Shallow Crustal Depths (3 km)

This criterion is merely suggestive, because there are many regions underlain by evaporites that do not have grabens like the Joes Valley graben. Cross-sections by Schelling et al. (2007) and Coogan (2008) show that the Arapien Shale beneath Joes Valley is not particularly thick, such that dissolution of a small part of it would create a large enough void space to account for the Joes Valley graben. In addition, Sprinkel (1996) stated that the Arapien evaporite facies basically ends at the boundary between Sanpete and Emery Counties, beneath Joes Valley, and farther east limestone facies (Twin Creek Fm., Windsor Member) predominate.

Another way that evaporites can create void spaces is by dissolution in a dissolution front that migrates down-dip (in our case, westward). This process forms a migrating monocline over the dissolution front (e.g., Gutierrez et al., 2012a) However, I don't see any such monoclinal features on the Wasatch Plateau near Joes Valley, nor in the subsurface beneath Joes Valley.

4.2.4- Presence of Many Intra-Graben Horsts and Blocks and Apparent Absence of Tertiary or Early-Mid Quaternary Deposits in the Graben

Although not listed by Anderson (2008), Joes Valley has many intra-graben horsts and blocks and little unconsolidated sediment within the graben. The presence of bedrock horsts and ridges in the valley floor, particularly in Upper Joes Valley, suggests that there are not very thick or old graben-fill deposits in the graben. I examined all the water well logs from Joes Valley on file with the Utah Division of water Rights (http://waterrights.utah.gov) and found useful/detailed well logs only in the Reeder Subdivision and in Upper Joes Valley at the large private ranch. In the former area, well 93-3728 was located in the center of Joes Valley on the distal part of the Reeder Creek alluvial fan at about 7240 ft elevation, and 1000 ft south of the entrance road to the Reeder Subdivision. The well was 214 ft deep and encountered suspected bedrock at a depth of 66 ft (Fig. 15). The multicolored clay deposits at that depth resembled the multicolored clay deposits farther down in the well (181-214 ft deep) where the color was reported as "stratified." Green and red shales are common in the Flagstaff Member of the Green River Formation and in the uppermost part of the North Horn Formation (Fouch et al., 1987). So I think that the 102 ft of "tan, gray, brown, and purple" clay reported at 64-166 ft in the well, and the sandstone found beneath it, are more likely to be a shale bedrock unit than a Quaternary alluvial deposit. If so, then Quaternary deposits are only 64 ft thick in the center of Joes Valley at this location. This is surprisingly thin, considering that Reeder Canyon is a major sediment source to Joes Valley and

WL1

W_LL DRILLER'S REPO_T

State of Utah
Division of Water Rights

For additional space, use "Additional Well Data Form" and attach

RECEIVED
NOV 29 1999
WATER RIGHTS

Well Identification
CHANGE APPLICATION: a23022(93-3728)

Owner *Note any changes*
Johnson, Hal E. or Kolleen
P.O. Box 1071
Castle Dale, UT 84513

Contact Person/Engineer:

Well Location *Note any changes*
COUNTY: Emery
SOUTH 685 feet EAST 1140 feet from the N4 Corner of
SECTION 19, TOWNSHIP 17S, RANGE 6E, SLB&M.

Location Description: (address, proximity to buildings, landmarks, ground elevation, local well #) Rex Fillmore Subdivision

Drillers Activity Start Date: Oct 22 1999 Completion Date: Nov 2 99

Check all that apply:
☑ New ☐ Repair ☐ Deepen ☐ Abandon ☐ Replace ☐ Public Nature of Use:

DEPTH (feet) FROM	TO	BOREHOLE DIAMETER (in)	DRILLING METHOD	DRILLING FLUID
0	144	7 7/8	Mud Rotory	Water
144	214	6"	Air Rotory	Water

Well Log

DEPTH (feet) FROM	TO	WATER	PERMEABLE high	PERMEABLE low	UNCONSOLIDATED CLAY	SILT	SAND	GRAVEL	COBBLES	BOULDER	OTHER	CONSOLIDATED ROCK TYPE	COLOR	DESCRIPTIONS AND REMARKS (include comments on *water quality* if known.)
0	30					✓	✓	✓	✓			Sedementy	Brown + tan	
30	35											Solid + fractured	tan	
35	43					✓	✓		✓					
43	46	*	✓											
46	64					✓	✓		✓					
64	166				✓								tan to 72', grey to 81, Brown + grey to 92'; Brown grey	+ Purple to 102, grey w/some Sand + Purple + Brown to 16
166	168											Sandstone		
168	175				✓									
175	181				✓				✓					
181	214				✓								Stratified Color	Brown grey + Purple as before

Static Water Level
Date Nov 16 99 Water Level 23' feet Flowing? ☐ Yes ☑ No
Method of Water Level Measurement Dry String If Flowing, Capped Pressure ______ PSI
Point to Which Water Level Measurement was Referenced ground Surface
Height of Water Level reference point above ground surface 0 feet Temperature 50° ☐ °C ☑ °F

[redacted] *Well Log* [redacted]

Fig. 15. Driller's log of water well 93-3728 on the Reeder Creek alluvial fan. Top of bedrock is inferred at 64 ft below surface. Downloaded from http://waterrights.utah.gov

has deposited one of the largest alluvial fans here in the late Pleistocene (Foley et al., 1986), a fan that has pushed the axial stream (Lowry Water) against bedrock hills on the eastern side of the valley. The implication is that the Reeder Creek fan is not underlain by a thick sequence of similar middle and early Quaternary fan deposits, not to mention Pliocene or Miocene graben fill.

In Upper Joes Valley a single well (0891005M00) was located on a small alluvial fan located on the eastern margin of the valley, 0.5 mile north of where the Cottonwood Creek Road enters Upper Joes Valley. The well is located 1000 ft west (basinward) of the East Joes Valley fault. The well log shows only tan and brown cobbles through clay, which sounds like alluvial fan gravels, indicating that the alluvial fan deposits are at least 186 ft deep. Thus the graben fill in Upper Joes Valley, at least close to the bounding master fault, is deeper than in the valley center at Reeder Creek. This greater depth is probably because the well lies near the depocenter of Upper Joes Valley, which must be a short (3 mi) but deep sub-graben within the overall Joes Valley graben. In this respect Upper Joes Valley resembles the valley at Joes Valley Reservoir, another ca. 3 mi-long depocenter. In contrast, the Reeder Creek alluvial fan is deposited at the north end of the latter depocenter, where the southward-plunging Middle Mountain horst would be expected to keep bedrock relatively near the surface. The inferred thin Quaternary deposits in Joes Valley contrast with the reported 900 m of maximum vertical displacement on the EJVF, and with the thick graben deposits (on the order of thousands of meters thick) found in many tectonic grabens in the Transition Zone such as Cache Valley, UT, Bear Lake Valley, UT-ID, and Star Valley, WY.

These thin deposits and multiple intragraben horsts differ from those of most major Basin and Range normal fault basins, and could have two possible explanations.

EXPLANATION 1: The lack of graben sediment could result from this graben being developed on a plateau, and not having an axial drainage (except for Dragon Creek; Lowry Water; Indian Creek). Instead, the largest streams draining the Wasatch Plateau cut across the graben (Seeley Creek, creek at N end) and deliver their sediment far to the east in Castle Valley.

EXPLANATION 2: The lack of sediments may imply that the graben is very young; an immature/evolving fault system.

NOTE: Seely Creek looks like it was established (deeply incised, at least down from the Plateau top at 10,000 ft to a prominent bench [old valley floor] at 7880 ft) before the graben was there. The creek flows right across the graben with no deflection. If it had not been incised when the graben began to form, it should have been diverted to flow along the graben axis. The same concept applies to Ferron Canyon.

4.2.5 Map pattern of oblique intragraben faults; left-stepping en-echelon arrangement, implies right-lateral component of shear.

From Seeley Creek and Joes Valley Reservoir northward, the intragraben faults trend more northeasterly than the graben-bounding faults, and form a left-stepping en-echelon pattern. Such a pattern suggests a right-lateral component of shear across the graben. Such a shear direction agrees with slickensides on the main fault plane in the EJVF Big Gully exposure (discussed later). In addition, all the trenches excavated across intragraben faults by Foley et al. (1986) expose subvertical faults and flower structures that that look like the result of strike-slip or oblique-slip faulting rather than extensional faulting (Trenches 1-3 on the Reeder Creek fan af1); Trench 5 in the big debris fan of Seeley Creek). [In fact, only the log of Trench 4 across the WJVF exposes a fault that looks like a typical normal fault].

GPS surveys in southern Utah are inconclusive about the existence of a component of right-lateral shear across Joes Valley, because the surveys concentrate on measuring movement across the Wasatch fault. For example, GPS slip vectors E and W of Joes Valley imply left-lateral shear across 180 km line that extends across Wasatch Fault (see Section 4.3.3).

4.2.6 Fault Architecture in Joes Valley

The fortuitous exposure of the EJVF along Highway 29 north of Joes Valley Dam permits us a look inside one of the graben boundary faults. The fault zone is completely transected by the highway in a near-fault-parallel cut (Figs. 16a, 17), but the fault zone is also transected by a gully (Big Gully) trending east from the highway at a more perpendicular angle to fault strike.

4.2.6.1 Shear Zone Properties

The roadcut and gully expose a 44 m-wide damage zone that is comprised of a fault core of highly sheared and crushed clay gouge on its eastern margin, and a series of lenses or panels of highly fractured rock separated by thin (5-20 cm-thick) shear zones (Fig. 16a).

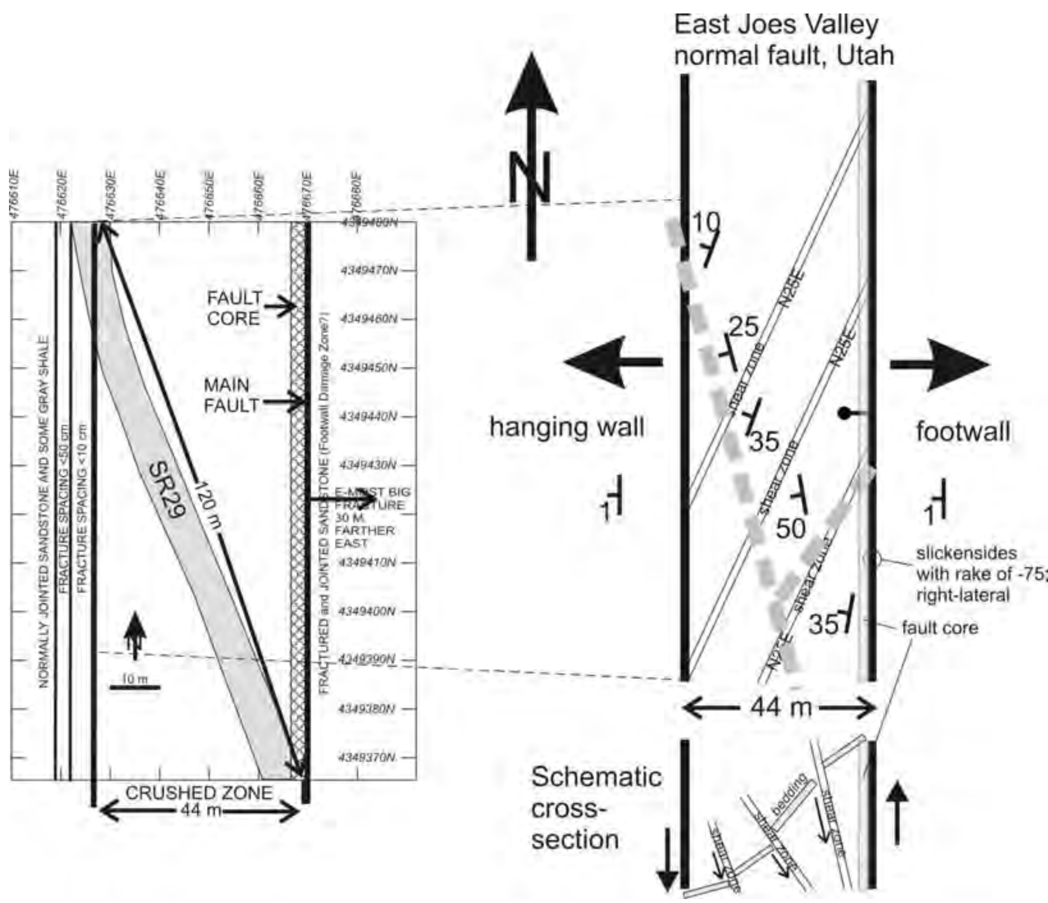


Fig. 16a. Schematic map view (left) and structural interpretation (right) of the East Joes Valley fault zone exposed in the 120 m-long roadcut on SR29 north of Joes Valley Dam. The cross-section (lower right) most resembles drawing "C" in Fig. 20 showing types of faults beneath Colorado Plateau monoclines. However, that drawing does not show if the multiple shear zones within the fault zone trend parallel to the boundaries of the fault zone, or obliquely as on the EJVF.

Fig. 16b. Slickensides preserved on the footwall surface (Castlegate Sandstone) in contact with the east side of the fault core of the EJVF, at the head of the Big Gully. The red surveyors flagging is hanging vertically. Fault plane is slightly overhanging (N07W, 87°E) here, and rake of slickenlines is about 15°, indicating a right-lateral component of about 25% compared to the dip-slip component.

Although the rock within the panels is highly fractured, more so toward the east, it is possible to determine bedding in at least one place in each panel. Bedding dips are all westward, toward the downthrown block, and are generally more steeply inclined in the eastern panels (up to 50°W). I observed slickensides only on the fault footwall on the eastern margin of the shear zone (Fig. 16b). The rake of slickenlines is about 15°, indicating a right-lateral component of about 25% compared to the dip-slip component.

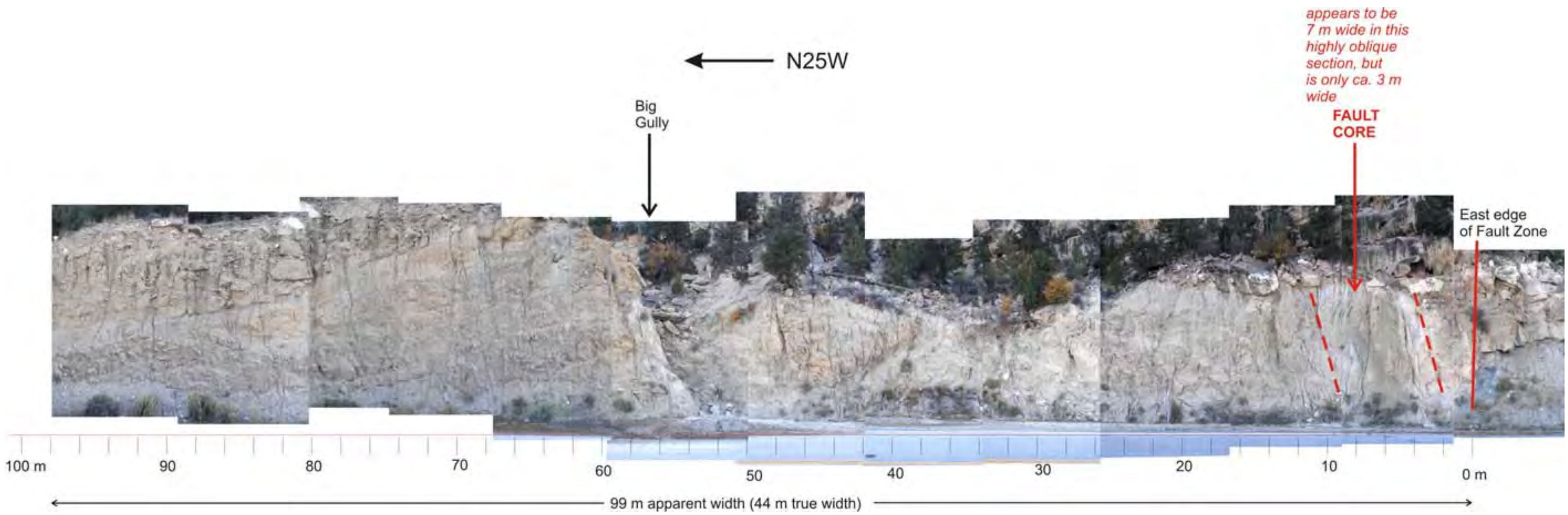


Fig. 17. Semi-controlled photomosaic of the roadcut on SR29 650 m north of Joes Valley dam, which crosses the East Joes Valley fault. The cut trends N25W, only 25 degrees more westerly than the strike of the fault zone (N-S), so it presents a highly oblique section through the fault zone. Horizontal dimensions of fault zone elements appear about 2.5 times wider in the cut than their true width. The fault core lies only 1-2 m from the eastern edge of the fault zone, and is composed of clayey fault gouge ranging in color from white to gray to gray-green to green. A secondary gouge zone lies at 54-56 m on the horizontal scale, and has been partly eroded out by the Big Gully, which follows the gouge zone NE (into the plane of the photograph) about 40 m to the eastern edge of the fault zone, creating another section through the fault zone more perpendicular to strike. Note the complex cataclastic deformation in the fault zone and the fact that it changes between larger domains bounded by thin (8-20 cm) shear zones that trend obliquely into the cut.

Interestingly, the thin shear zones that separate the panels of fractured and crushed rock in the fault zone are not parallel to the fault zone boundaries or to the strike of the beds within the panels. Instead, the shear zones strike N20-25°E whereas the fault zone boundaries are roughly N-S. This orientation suggests the shear zones are Riedel shears (Fig. 18).

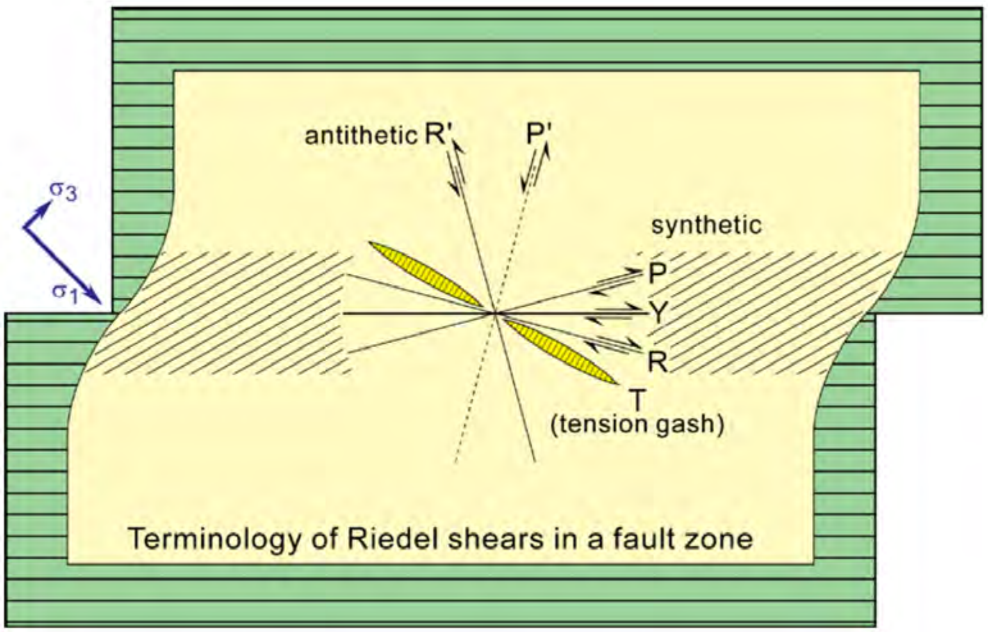


Fig. 18. Schematic diagram showing the orientation of Riedel shears and associated tension gashes in a dextral fault system. Note that if north were to the left, as in the East Joes Valley fault, then the subsidiary shear zones within the 40 m-wide fault zone have the same orientation with respect to the fault as Riedel shears (R) and tension gashes. Source: Strike-slip and oblique-slip tectonics: www.files.ethz.ch/structuralgeology/JPB/files/Emglish/5wrench.pdf

In Fig. 18, Riedel shears (R) are generally the first subsidiary fractures to occur and generally build the most prominent set. They develop at an acute angle, typically 10-20° clockwise to a dextral main fault, anticlockwise to a sinistral strike-slip fault. They often form an en échelon and overstepping array synthetic to the main fault; they evolve as a sequence of linked displacement surfaces. Their acute angle with the fault points in the direction of the relative sense of movement on the main fault. This angle is equal to 2φ, where φ is the material internal friction angle.

4.2.6.2 Possible Tectonic Folding and Block Toppling

Our field reconnaissance revealed several localities where strata had been strongly tilted toward the downthrown block. One location was the northern tip of the North Dragon fault, 1.8 km SW of Joes Valley Dam, where cuts along the main road showed eastward dips of 32-38°. 700 m farther south at the entrance to the North Dragon Reseeding Area, and road diagonally ascends to the top of the fault scarp. Strata exposed in roadcuts dip east but decrease in dip angle as one ascends the scarp, becoming horizontal at the top of the scarp.

Where SR 29 switchbacks up the escarpment of the WJVF, strata dip east as steeply as 60-65° toward the downthrown block (Fig. 19). This area is one of extreme toppling. Perpendicular joints that were once vertical now dip 25° into the slope, and are dilated to an opening of 30 cm or more, and filled with matrix-supported debris that looks like it fell into the fissure).

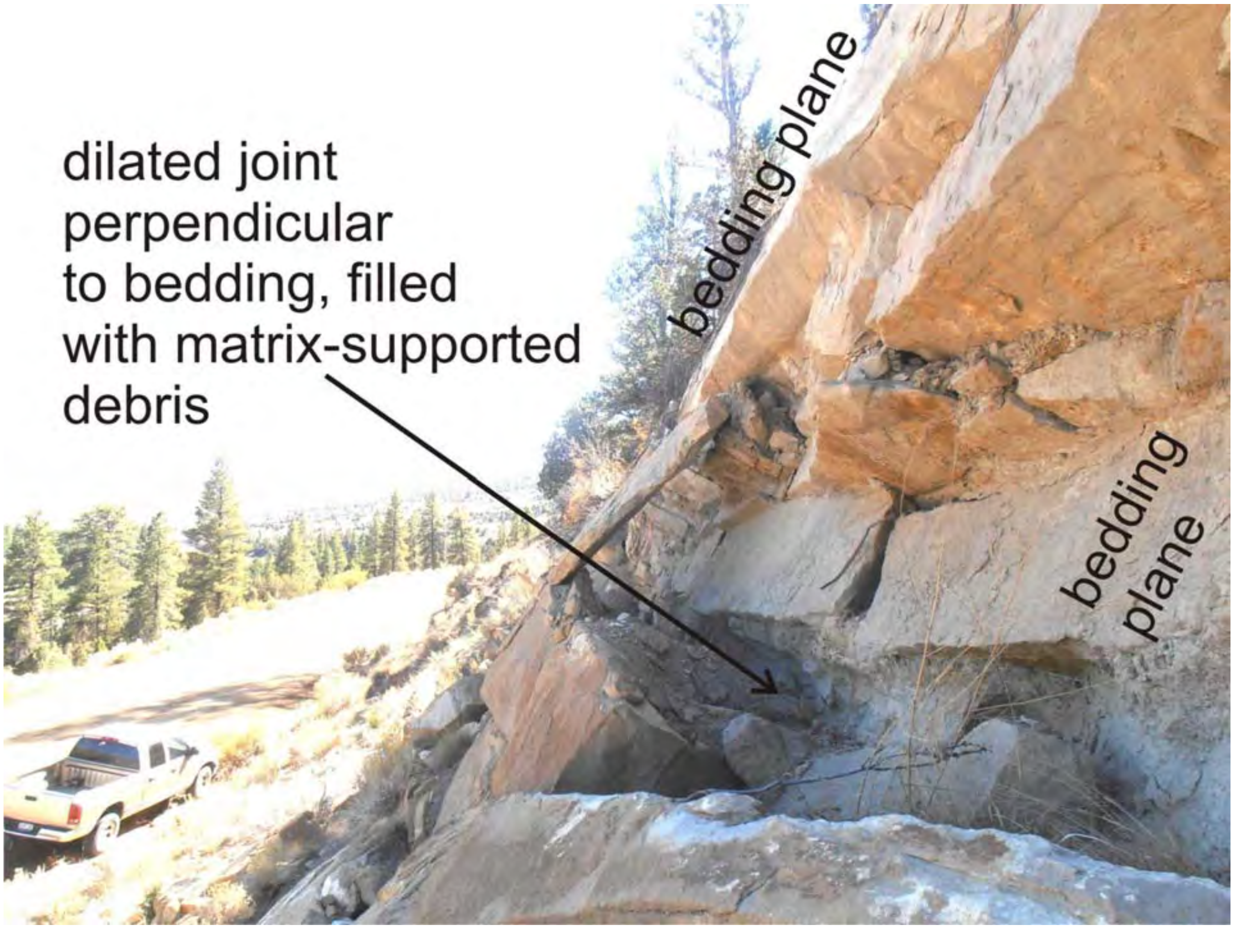


Fig. 19. Photograph of a roadcut on SR29 as it switchbacks to ascend the West Joes Valley fault escarpment. Bedding planes in the fault zone have been rotated from the gentle westward regional dip, to an eastward dip of 60-65° east toward the downthrown block. At the same time, bedding-perpendicular joints that were once vertical now dip 25° into the slope and have become dilated to widths of 30 cm or more, and then infilled with debris. This geometry represents an extreme case of toppling in the fault zone.

The only exposure large enough to place the toppling in context is the 100 m-long roadcut on the EJVF, described above. In that cut it is clear that the forward-toppled strata occupy discrete rock panels bounded by secondary shear zones. This type of faulting and folding/toppling has been described before where high-angle fault have displaced horizontal sequences of sedimentary rocks:

1- Colorado Plateau monoclines (Fig. 20). These monoclines were shown by Powell (1873) to be underlain by reverse faults, so the phenomenon is not restricted to normal faults. Possibly the control is flat-lying sedimentary rocks.

2- Robideau Creek fault, CO and associated faults on the Uncompahgre Plateau; see reports to Colorado Geological Survey (McCalpin, 2003) and Reclamation (McCalpin, 2006)

3- Pajarito fault, NM (McCalpin, 2005)

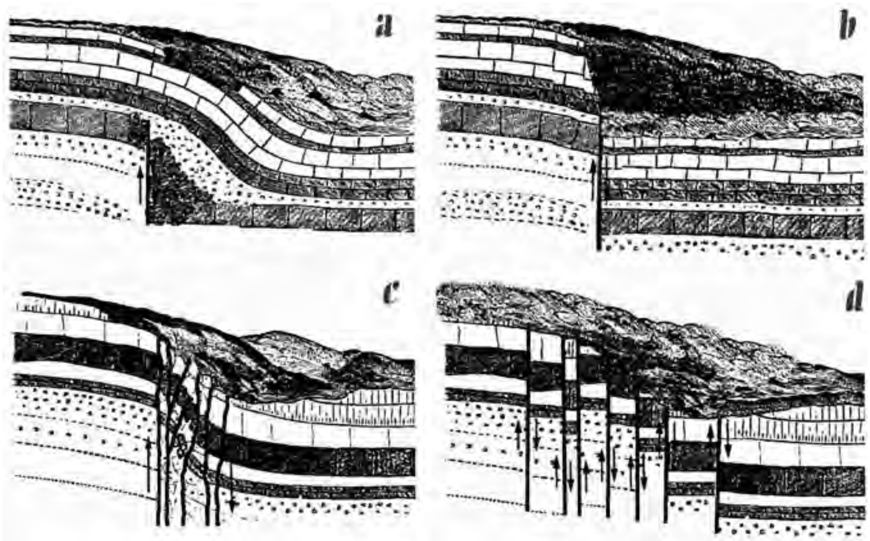


Fig. 20. Schematic cross-sections of faults and monoclines on the Colorado Plateau, from Powell (1873). (a) monoclinal (drape) fold overlying a vertical fault at depth; (b) single vertical fault; (c) faulted monocline with 5 major fault strands. *Note the tilting of strata toward the downthrown block in discrete blocks bounded by faults that dip steeply toward the footwall (toppling?)*; (d) multiple vertical faults with no block rotation. The EJVF exposure most resembles diagram (c).

Generally in Joes Valley there is no evidence for strong folding outside of the fault zone, such as is shown in Fig. 20a. Therefore the normal sequence of developing a fault-propagation monocline over the fault which later gets ruptured may not apply to Joes Valley faults. The sequence is described by Grant and Kattenhorn (2004) for Quaternary faults offsetting vertically-jointed basalts in Iceland: "*Based on these field observations and the results of numerical models, I propose that 60–75° dipping normal faults in the subsurface propagated to the surface from below. Vertical fractures formed at the upper tips of the faults at depths of between 250 and 500 m (25–50% of the fault length) in response to stress concentrations along the tip line. Model results indicate that narrow monoclinal folds develop at the surface above these vertical fractures, which subsequently breach the monoclines along the upper hinge line, forming vertical fault scarps and open fissures at the surface. If vertical fractures utilize pre-existing cooling joints in basalt to connect directly to the surface, the hanging wall is able to pull apart from the footwall without the development of a surface monocline along the fault trace*." The underlined sentence suggests that the presence of preexisting vertical joints in the sedimentary rocks such as the Castlegate Sandstone is responsible for the very steep fault dips observed on the margins of Joes Valley.

Grant and Kattenhorn (2004) also propose an explanation for oblique faults within the fault zone, as exposed in the EJVF roadcut: "*Fracture zones containing echelon fault or fracture segments rotated out of the general trend of the fault zone are indicative of oblique-normal slip on an underlying fault. The resultant rotation of the principal stresses above the fault tip produces echelon fracture segments that propagate upwards to the surface. Such fracture patterns are particularly common in oblique spreading areas such as the Reykjanes Peninsula, but only occur along fault bends where spreading is perpendicular to fracture zones, such as at Thingvellir.*" (p. 556)

Closer to Joes Valley, oblique, en echelon faults have been described associated with Colorado Plateau monoclines (Tindall and Davis, 1999). They describe the faults as follows: "*Fault* *relationships along a 50-km stretch of the East Kaibab monocline in southern Utah suggest that Late Cretaceous/early Tertiary development of the structure involved a significant component of right-lateral strike-slip displacement, accommodated by basement-rooted faulting and fault-propagation folding. Evidence of oblique slip is provided mainly by pervasive map-scale and outcrop-scale faults that define a shear zone occupying the steep east-dipping limb of the monocline for at least its northernmost 50 km. Dominant fault orientations are synthetic and antithetic to the shear zone, and accommodate reverse-right-lateral and reverse-left-lateral slip, respectively".* See Fig. 21.

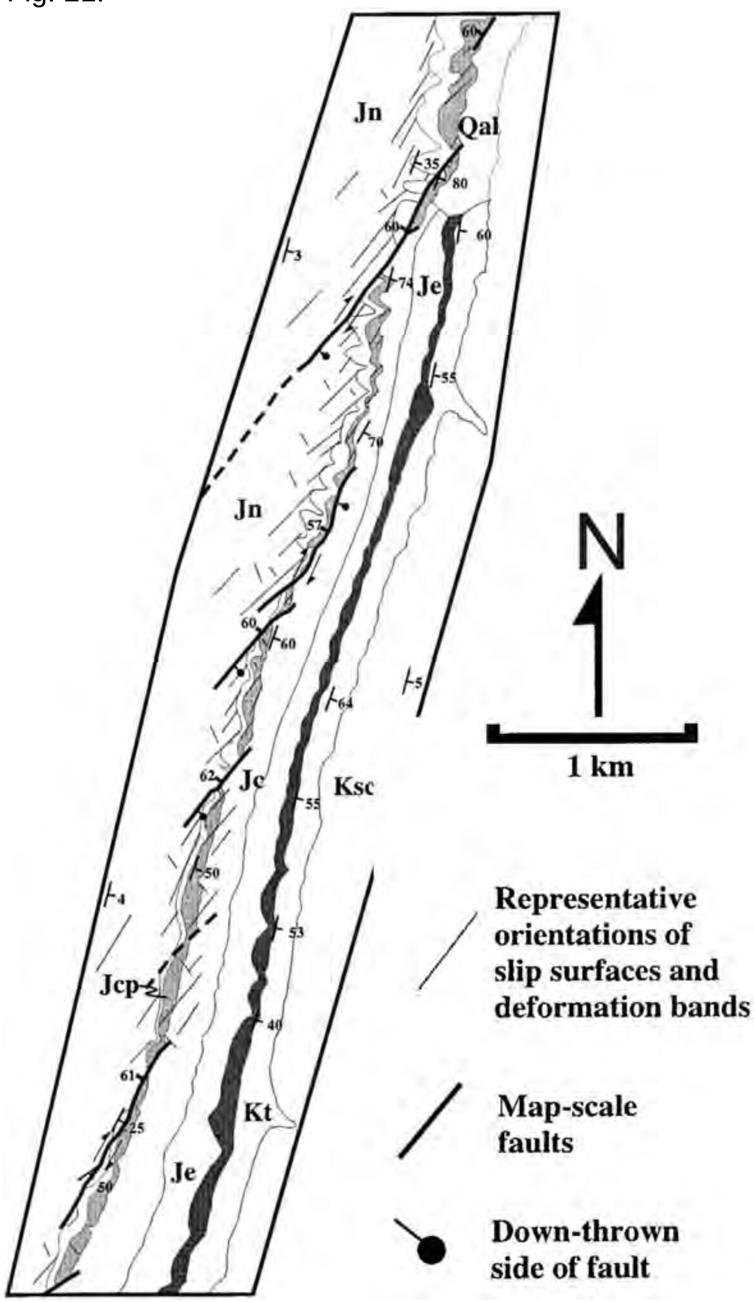


Fig. 21. Example of multiple oblique-trending faults beneath a monocline in the Colorado Plateau. Map of faults, slip surfaces, and deformation bands in the East Kaibab Monocline, interpreted by Tindall and Davis (1999) to result from a component of right-lateral slip on the underlying fault. Note the left-stepping pattern of the many NE-trending faults, the same pattern observed in the damage zone of the East Joes Valley fault exposed in the roadcut.

4.2.7 Fault Architecture of Salt-Deformation Grabens

Two of the five models for Joes Valley involve salt tectonics, but with different mechanisms. Model 2 proposes that Joes Valley formed by westward gliding of the Wasatch Plateau on an extensional salt detachment in the Arapien Shale. Model 4 proposes that the Joes Valley formed by dissolution/collapse of evaporites. Therefore, it would be helpful to compare the fault architecture of the Joes Valley faults with that of faults known to be caused by these two salt tectonics processes.

4.2.7.1 Extensional Salt Detachments

Extensional salt detachments form where the crust is under horizontal extension and salt layers exist. Horizontal extension will be accommodated by normal faults in the subsalt (basement) rocks, as well as by normal faults in the suprasalt section that flatten into the salt layer (Hudec and Jackson, 2012, p. 121). The salt typically thins by stretching and downdip flow during regional extension. Initially, extensional salt detachments consist of salt-detached normal faults, most of which dip basinward. Continued offset may eventually result in raft tectonics, in which fault hanging walls separate completely from their footwalls along the detachment as extension pulls the fault blocks apart. With large amounts of extension the salt thins to zero and the suprasalt section then comes to lie directly on the subsalt section, and condition known as a welded fault.

In the Wasatch Plateau the Gunnison Detachment lies in the evaporite-rich Arapien Shale and is interpreted as a shallow west-dipping extensional salt detachment (Fig. 22a). Beneath the detachment is the Ancient Ephraim Fault, a Jurassic normal fault. Above the Ancient Ephraim fault is the Wasatch Monocline, a drape fold that forms the western boundary of the Wasatch Plateau.

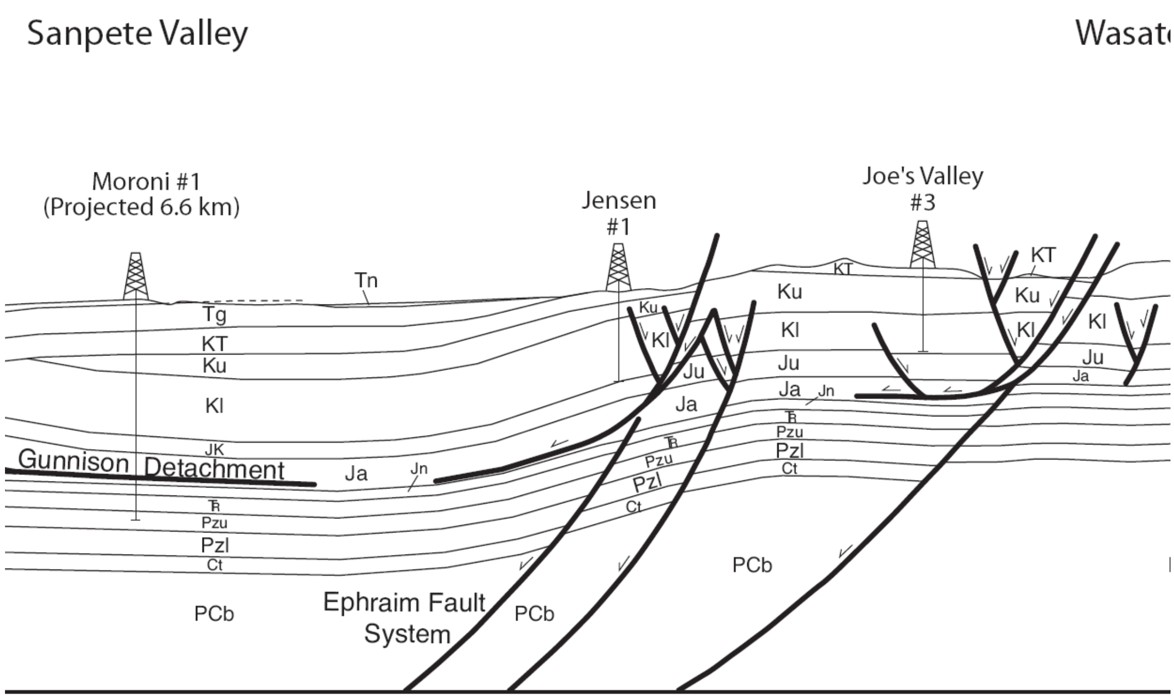


Fig. 22a The far eastern part of cross-section B-B' of Schelling et al. (2007) which crosses the northern part of Joes Valley. West is to the left. The Joes Valley graben lies east of well Joes Valley #3. Compare the structures in this figure to those in Fig. 22b, stage 4.

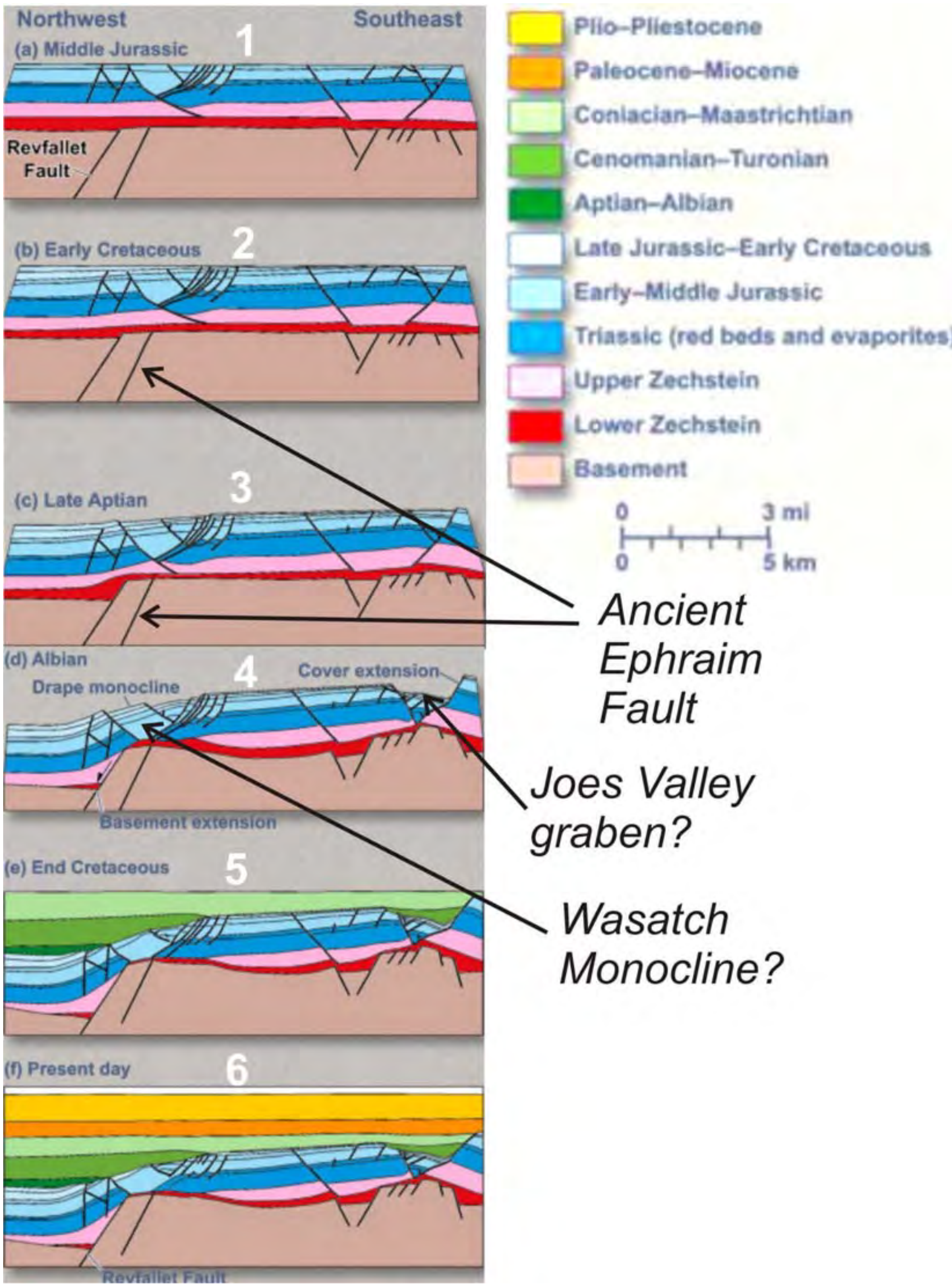


Fig. 22b. Example of an extensional salt detachment (in red) formed above a sub-salt, basement normal fault (in brown unit). The sequence begins with 1 and proceeds to 6. Although this example is from the Revfallet fault in the North Sea off Norway, it has several structures similar to those in the Wasatch Plateau: (1) a sub-salt basement fault like the Ancient Ephraim Fault; (2) a drape monocline over the basement fault, like the Wasatch Monocline, and (3) a graben that formed in the footwall above the salt detachment and affects all the strata above the salt, like the Joes Valley graben. From Hudec and Jackson, 2012.

Model 2 for Joes Valley proposes that the graben formed by extensional gliding of the western Wasatch Plateau on the Gunnison Detachment, pulling it away from the eastern Wasatch Plateau. All the major structures observed in the Wasatch Plateau can be found in other areas of salt tectonics, such as the Revfallet fault in the North Sea (Fig. 22b). Regional extension led to formation of a drape fold over the basement fault (like the Wasatch Monocline), and development of a detached suprasalt graben in the footwall (like the Joes Valley graben).

Withjack and Calloway (2000) made sand-box models to investigate the effects of varying the following "geological" parameters: thickness of the viscous (evaporite) layer, thickness of the suprasalt (overburden) section, ductility of the overburden, displacement on the subsalt fault, and displacement rate (see Fig. 22c). Their standard model had a suprasalt thickness of 3 cm (dry sand), a salt thickness of 1 cm, displacement on the subsalt fault of 1.4 cm, and a displacement rate of 0.03 cm/hr. Evaporite thickness was 33% of overburden thickness, and 71% of fault displacement.

In the Wasatch Plateau we have: (1) a thin evaporite layer (Arapien Shale, <300 m); (2) a relatively thin overburden section (3000 m); (3) a ductile overburden section that contains more than 50% shale and coal by thickness (see Fig. 22d); (4) low (?) displacements on the Ancient Ephraim Fault during the Neogene (only a fraction of the 2200 m amplitude of the Wasatch Monocline); and (5) low tectonic displacement rate/high viscosity of the gypsum-dominated evaporite layer. Evaporite thickness is only 10% of overburden thickness (low in their model), and an unknown percentage of Neogene fault displacement. The detached Joes Valley graben occurs in the footwall 15 km from the Ancient Ephraim Fault, or 5 times the overburden thickness.

Given the geologic parameters in the Wasatch Plateau, we should expect the following effects of Neogene normal-fault slip on the Ancient Ephraim Fault:
1- Effect of Thickness of the Viscous Layer: Due to the great thickness of salt above the Ancient Ephraim Fault, we would expect a broad monocline to form there, and that is observed (the Wasatch Monocline). In the footwall the salt is much thinner, so we would expect more coupling and the development of a footwall detached graben (Fig. 22c, middle diagram in top panel). However, this detached graben is much closer to the basement fault (< 1 times the overburden thickness) compared to the Joes Valley graben (5 times the overburden thickness).

2- Effect of Thickness of Overburden: The thinner the overburden, the more distributed is deformation in the suprasalt section (Fig. 22c, second panel from top). Withjack and Calloway (2000) induced a detached graben to form far into the footwall by decreasing the overburden thickness so it was equal to the salt thickness. Although this location for a graben matches Joes Valley the best, the model parameters (overburden thickness=evaporite thickness) do not seem to match the parameters beneath the Wasatch Plateau (overburden thickness= 10 times evaporite thickness).

3- Effect of Ductility of the Overburden: Having high ductility and cohesion in the overburden section induces more distributed deformation (Fig. 22c, middle panel), including step faults and graben in the footwall. As shown in Fig. 22d, more than half of the overburden section is composed of ductile Cretaceous shales and weak coals. Thus, having the observed ductile suprasalt section is compatible with the observed Snow Lake and Joes Valley grabens.

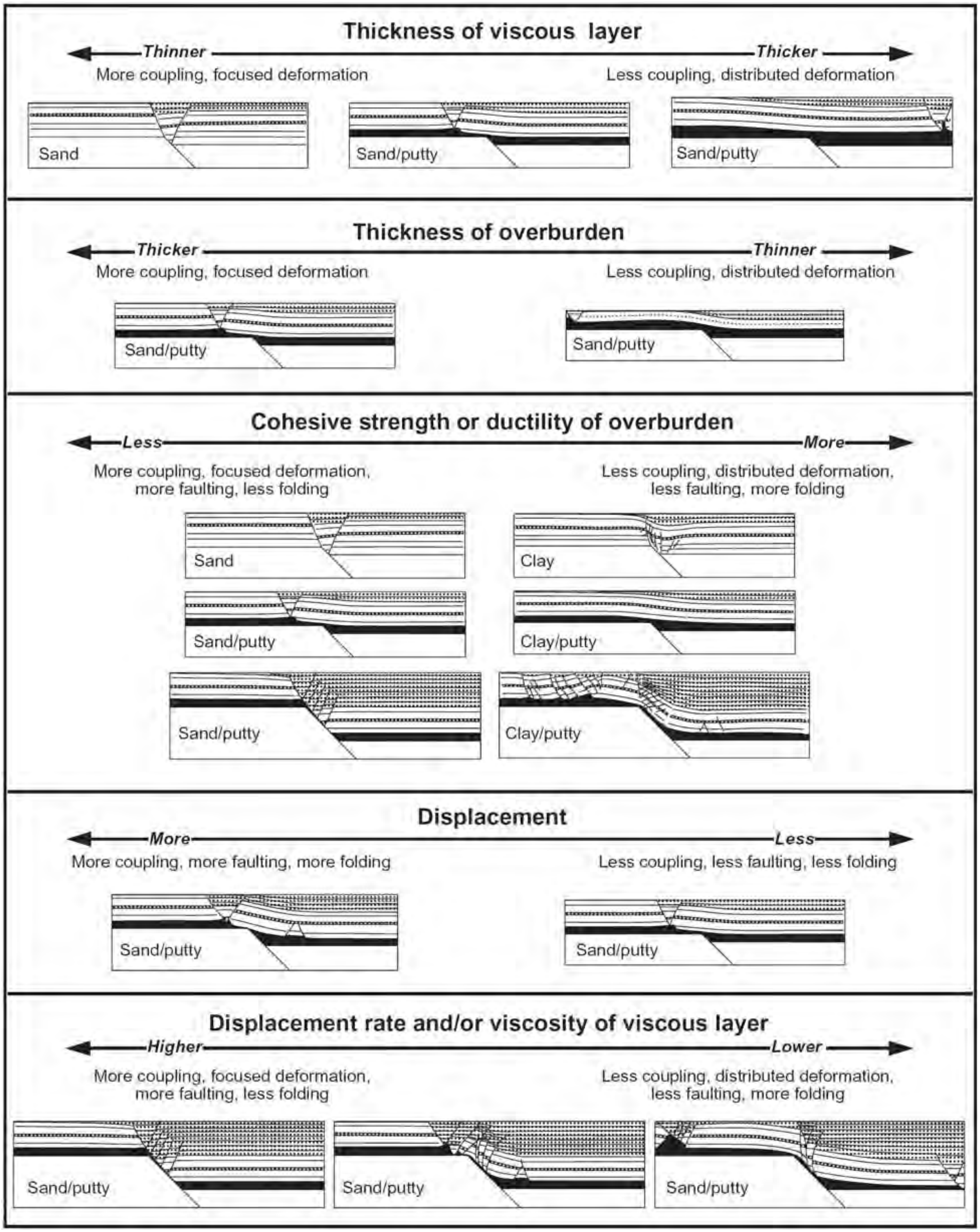


Fig. 22c. Effects of varying five “geologic” parameters on the geometry of an extensional salt detachment system. From Withjack and Calloway, 2000.

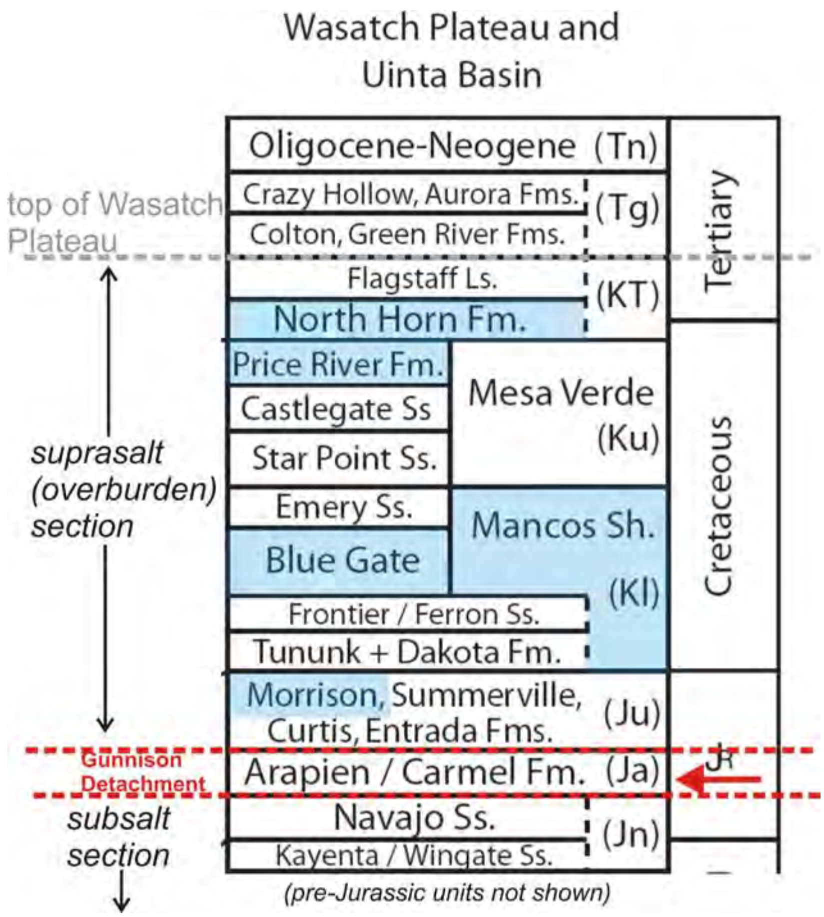


Fig. 22d. The stratigraphic section above the Gunnison Detachment in the Wasatch Plateau contains considerable ductile shales, highlighted here in blue. Adapted from Schelling et al., 2007, their Fig. 4.

<u>4- Effect of Displacement on the Subsalt Fault</u>: The total displacement on the Ancient Ephraim Fault is high in relation to the thickness of salt beneath the Wasatch Plateau, but we do not know how much of this displacement is Neogene, as opposed to Cretaceous and Paleogene. Regardless, simply varying the displacement did not seem to create detached footwall grabens in the models.

<u>5- Effect of Displacement Rate and/or Viscosity of the Viscous Layer</u>: The Wasatch Plateau is not currently subject to a high extension rate, and the gypsum should act as more viscous than salt, so for the Wasatch Plateau this value should be low. Low rate/high viscosity in the models correlates with less coupling and more distributed deformation, including the development of a detached footwall graben like Joes Valley (Fig. 22c, bottom panel, right diagram).

In Summary: Models that created detached footwall grabens such as Joes Valley were associated with intermediate thickness of salt, thinner overburden, ductile overburden, and low displacement rate. The first two of these parameters do not really match the Wasatch Plateau (where salt is thin and overburden is thick), but the latter two parameters do match.

4.2.7.2 Evaporite Dissolution-Collapse Faults

Several authors have described the fault-zone architecture of evaporite dissolution-collapse faults, such as Moab Valley (Fig. 23). Baars and Doelling (1987) describe the Neogene "salt valleys" as follows: "*since about the mid-Tertiary, the Colorado Plateaus were elevated and are currently being eroded by the Colorado River and its tributaries. The erosional regime includes groundwater activity, and wherever natural conduits to the salt are available, dissolution of salt can and does occur. The removal of the salt has resulted in the massive collapse of overlying strata, some of which have been removed at the surface by normal erosion and some of which are now buried under a veneer of alluvium. The overall result has been the formation of elongate, northwest-trending valleys above the salt intruded anticlines. Superimposed stream courses, such as that of the Colorado River, cross the salt anticlines and their collapsed valleys nearly at right angles, rather than running along the valleys*."

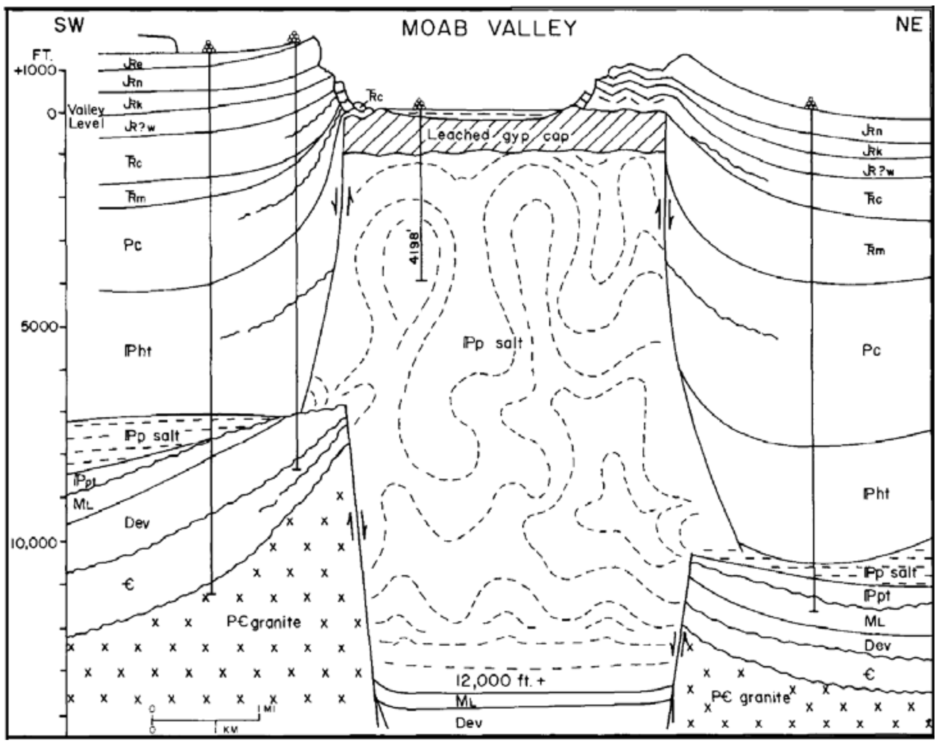


Fig. 23. Highly generalized cross section of the Moab salt-intruded anticline. Deep-seated faults originated in Late Precambrian time and were episodically rejuvenated throughout the Phanerozoic. Cambrian through Mississippian strata thin locally and display fault-related facies changes near the faults. Middle Pennsylvanian evaporites, including salt, were deposited within the paleograben and buried the structure as salt flowage was initiated. Upward growth of the salt bulge continued through late Paleozoic and Mesozoic time, causing excess thicknesses of elastic sediments to accumulate in synclines and thinning by deposition and local unconformities to occur along the rising salt core. Tertiary to Recent near-surface groundwater dissolution of salt created a residual "leached gypsum cap" and subsequent collapse of overlying strata. The valley surface is now largely covered by fluvial and eolian Recent deposits. Flowed salt thickness may exceed 15,000 ft (5,500 m). From Baars and Doelling, 1987.

Berg and Skar (2005) studied the fault architecture of the northern splay of the Moab fault (Bartlett fault) that has a total vertical displacement of 170-300 m, and displaces subhorizontal Mesozoic sandstones. They found the fault possessed many similarities with that of tectonic-seismogenic faults: "*The Bartlett fault consists of a fault core surrounded by damage zones in the footwall and hanging wall* [Fig. 24]. *The fault core is structurally complex and lithologically* *heterogeneous. It consists of a variety of fault rocks and entrained bodies of clastic host rocks (horses) that indicate considerable variation in strain intensity and deformation style. The internal characteristics lead to a locally irregular geometry at the margins of the fault core. These irregularities may have implications for the characteristics in the damage zones*."

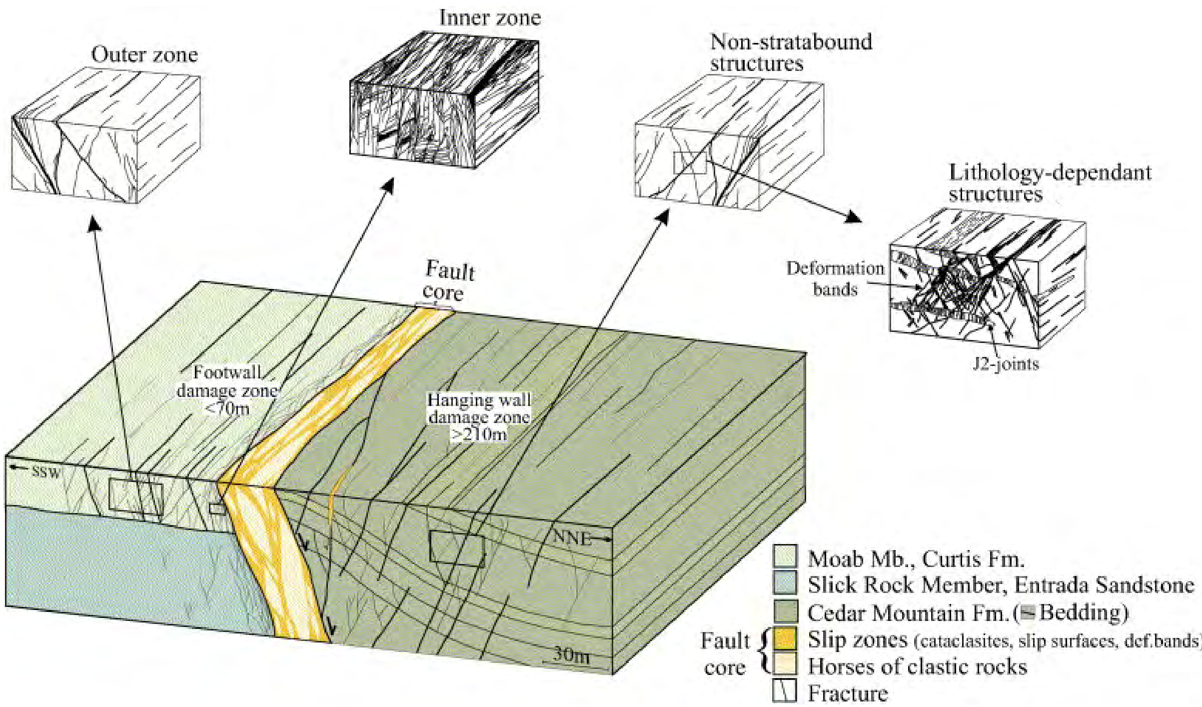


Fig. 24. Schematic block diagram of the asymmetric damage zone along the Bartlett fault. This asymmetry is also typical of tectonic-seismogenic normal faults. From Berg and Skar, 2005.

Of particular interest are the structures in the hanging wall part of the damage zone, which on the EJVF comprises almost all of the fault zone. Berg and Skar (2005) describe them as follows: "*Slip surfaces are the most extensive and prominent fractures, and represent mainly synthetic and antithetic normal faults relative to the master fault zone. Antithetic faults predominate and account for nearly 80% of the observed slip surfaces.…The strike of the slip surfaces ranges from WSW–ENE to NW–SE; however, most strike subparallel to the overall strike of the master fault (WNW–ESE), similar to the footwall. The synthetic slip surfaces dip 60–85° to the NNE, whereas the antithetic slip surfaces dip 23–85° to the SSW. The latter shows considerable variation in dip angle compared with the synthetic slip surfaces, as well as the slip surfaces in the footwall. There is no systematic variation in orientation of the slip surfaces vs. distance from the fault core (Fig. 10). <u>Although the slip surfaces have a dominant dip-slip displacement, slickenlines indicate a small component of lateral slip</u>. The observations indicate a consistent dextral component on the antithetic slip surfaces and a sinistral component on the synthetic slip surfaces*."

The underlined sentence indicates that even evaporite-collapse normal faults can display a small component of strike-slip motion, which is surprising for a process that supposedly involves vertical collapse into void spaces. However, there may be some structure complications because the Bartlett fault is a horsetail splay of the Moab fault which has much larger vertical displacement, so the oblique component of movement may result from a high displacement gradient near the tip of the fault.

The Moab fault zone apparently changes architecture along strike, from a fault core-damage zone zonation, to a wide zone of normal step-faults and antithetic faults with little or no gouge or fault rock (Fig. 25).

Fig. 25. Part of the Moab fault zone north of Moab, UT in the roadcut of US Highway 191. From www.gly.uga.edu/railsback/VFT/MoabFaultTeenplexMerge1Sh-700.jpg

In Summary: From these characteristics alone, the faults in Joes Valley cannot be distinguished from faults formed by evaporite dissolution and collapse.

4.2.7.3 Evaporite Gravity-Slide Faults

The best-studied example of an evaporite gravity-slide fault is the The Grabens at Canyonlands National Park (Moore and Schultz, 1999). They studied both the fault pattern and architecture of one of the largest of a swarm of graben faults and summarize their conclusions as follows: "*We identify the following coherent assemblage of five characteristics for the grabens that demonstrate a clear asymmetric geometry in cross section…. These attributes, either individually or in concert, are persuasive indicators of asymmetric cross-sectional geometry, and they appear to apply to all grabens in the Canyonlands where the observations can be made.*

1. There are significant differences in the amount of stratigraphic offset across asymmetric grabens. These differential offsets, indicating master and antithetic faults, are documented in grabens that vary widely in size (e.g., Devils Pocket, Devils Lane, Cyclone Canyon, Red Lake Canyon).

In the example shown by Moore and Schultz (Fig. 26), the difference between displacement on the master fault and the antithetic fault is large (50%) relative to the displacement on the master fault, whereas in Joes Valley it is small (400 ft difference compared to the average displacement on the EJVF of 750 m, or 16%).

2. The graben-bounding faults form a distinctive map pattern. The fault having greater stratigraphic offset (master fault) is continuous along the graben's length, *whereas that of the facing graben wall (antithetic fault) is discontinuous, segmented, and echelon.*

This type of asymmetry is not observed in Joes Valley, where the EJVF and WJVF have similar surface expression.

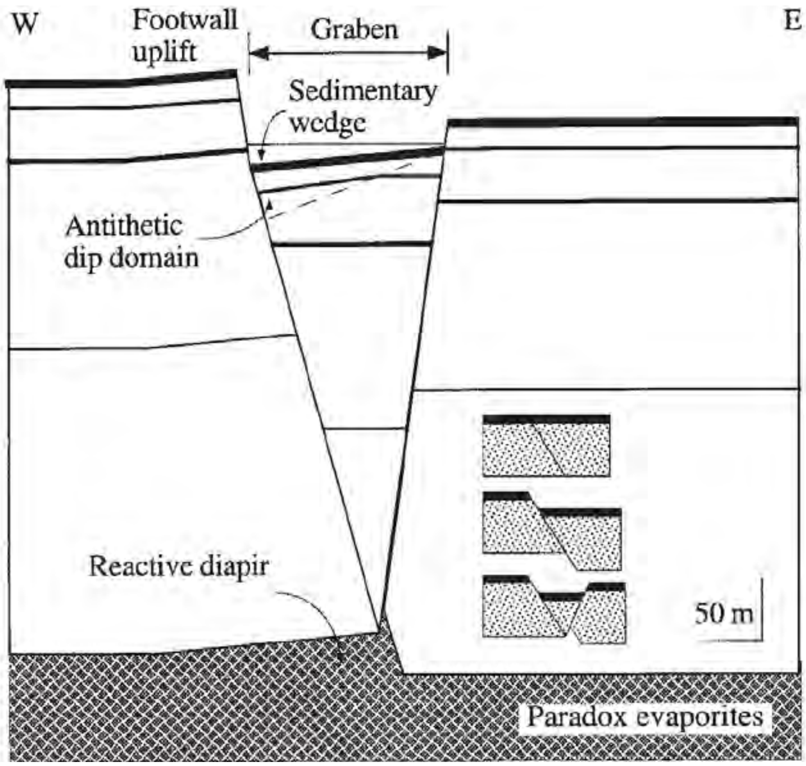


Fig. 26. Balanced cross section for southern part of northern Devils Lane graben at Canyonlands. Horizontal reference line midway down in faulted section is the approximate contact of the Rico (above) and upper Hermosa Formations (below). Patterned region at bottom is the Paradox Member. The inset at lower right shows a simplified deformation sequence (after Vendeville and Jackson, 1992) to incorporate slip along antithetic fault; slip along master (west) fault has been area-balanced following Groshong (1989). Dip of the master normal fault is 85° in upper 100 m, then decreases to 75° down to the Paradox Member; fault throw is 80 m. Dipping beds in the graben define a "fault-bend fold" due to the master fault geometry.

3. Rollover anticlines formed adjacent to the antithetic fault appear related to the translation of strata down the master fault, resulting in local flexure (e.g., Higgs et al., 1991). An interesting related fact is that the widths of preexisting regional joints that parallel the graben also differ considerably across a graben: their greater widths (individual joint openings of perhaps several meters) on the antithetic side are associated with increased surface area and bending of the jointed rocks along the upper, outer surface of the rollover anticline.
There is no sign of a rollover anticline associated with the WJVF. Forward-toppled blocks exposed in roadcuts appear to be restricted to the fault zone, and not part of a larger fold.

4. Footwall uplift and gentle flexure, at least tens of meters in amplitude, occur adjacent to the master fault; these deformations decrease both along strike toward the fault terminations and across strike away from the fault trace. Preexisting joints are closed in the footwall area.
There is no sign of footwall uplift and flexure associated with the EJVF. Exposures created by waterfalls show that some joints are open.

5. Preliminary seismic refraction results (Bush et al., 1996) demonstrate substantial floor tilt in northern Devils Lane graben, down toward the master fault and deeper (>65 m) in the center of the graben than near the ends (~15 m). The graben floor may be described as "spoon shaped," or deepest in the center and tilted down toward the master fault, beneath the overlying sedimentary wedge.

According to the cross-section of Kitzmiller (1982; Fig. 12 of this report) the bedrock surface beneath the floor of Joes Valley is not substantially tilted as a whole. Instead it is composed of multiple narrow fault blocks each of which is rotated to a different degree, but in each case tilted down toward the closest marginal fault. This graben geometry is very different from the "spoon-shaped" geometry of Canyonlands grabens, where one might expect the deepest sediment in the middle of the valley. i.e. beneath Joes Valley Reservoir and in the Reeder Creek area.

In Summary: The cross-sectional characteristics of The Grabens at Canyonlands are quite different than those of Joes Valley. If the asymmetry of The Grabens is related to the unidirectional sliding toward the Colorado River, then it argues that the Joes Valley faults were not formed in response to a similar unidirectional sliding, e.g. as required in Model 2.

4.2.7.4 Ratio of Fault Displacement to Fault Length

There is a large literature on the displacement:length scaling of tectonic faults, but much of it deals with smaller faults. One data set that deals with larger faults is that of Dawers et al., 1993. They measured faults that displace the Volcanic Tableland in northern Owens Valley, CA, that ranged from 30 m long to 10 km long, with corresponding average vertical displacements of 0.3 m to 100 m. The data fit an equation of Davg=0.011L, where Davg is the average vertical displacement in meters and L is the fault length in meters.

For the EJVF, average (Davg) & total (Dmax) vertical displacement is cited as 750 m & 900 m by Foley et al. (1986), and the total fault length is cited as 50 km (50,000 m), yielding a Davg:L ratio of 0.015. This ratio is very similar to the Owens Valley faults.

In contrast, the D:L ratios for salt-related faults tend to be higher. According to Moore and Schultz (1999), Dmax:L ratios for the Devils Lane graben at Canyonlands range from 0.021 to 0.052 (Table 2a). For other grabens in the salt-sliding complex, Dmax:L ratios ranged from 0.013 to 0.059 (Table 2b). To make a direct comparison to the EJVF, with a Dmax of 900m and length of 50 km, I derive a Dmax:L ratio of 0.018.

TABLE 2a FAULT DISPLACEMENT DATA FOR DEVILS LANE GRABEN PAIR

Fault*	D_{avg} (m)	D_{max} (m)	Length L (m)	D_{max}/L	D_{avg}/D_{max}
NW	38.8	82.9	3200	2.9×10^{-2}	0.47
NE	22.7	69.2	3500	2.0×10^{-2}	0.33
SW	47.5	93.3	1800	5.2×10^{-2}	0.51
SE	37.4	80.5	1700	4.7×10^{-2}	0.46
W†	47.4	108.5	4500	2.4×10^{-2}	0.44
E	31.0	97.5	4700	2.1×10^{-2}	0.32

*Faults labeled NW and NE define north part of graben; faults labeled SW and SE define south part of graben. W indicates the composite fault composed of linked master faults (i.e., NW and SW); E indicates the composite fault composed of linked antithetic faults (i.e., NE and SE).

†W composite fault defined by linkage of master faults; E fault, linked antithetic faults.

TABLE 2b FAULT DISPLACEMENT DATA FOR OTHER GRABENS

Fault*	D_{avg} (m)	D_{max} (m)	Length L (m)	D_{max}/L	D_{avg}/D_{max}
DP SE	18.7	30.5	2400	1.3×10^{-2}	0.61
DP NW	29.4	43.9	2500	1.8×10^{-2}	0.67
CC NW	65.5	103.0	4400	2.3×10^{-2}	0.64
CC SE	83.5	135.3	4400	3.1×10^{-2}	0.62
SE TC SE	73.2	121.6	3600	3.4×10^{-2}	0.60
SE TC NW	65.2	121.0	3600	3.4×10^{-2}	0.54
NW TC SE	84.4	129.8	2200	5.9×10^{-2}	0.65

*DP—Devils Pocket graben, SE and NW faults; CC—Cyclone Canyon graben; TC—Twin Canyon graben (SE and NW-bounding faults).

In Summary: The D:L ratio of the EJVF is similar to that of tectonic faults (e.g., Owens Valley, CA,) but is lower than ratios of grabens produced by salt-related deformation at Canyonlands.

4.2.7.5 Ratio of Fault Damage Zone Width to Fault Displacement

The datasets on fault damage zones are not as large as for fault displacement, because the former is more difficult to measure, especially for offshore faults imaged only by seismic lines. Nevertheless, several workers have published regressions of fault zone width:fault displacement.

Childs et al. (2009) pointed out that not all authors measure fault zone width in the same way. They explain: "*For the purposes of data collation I have used the term fault rock to refer to fault gouge, breccia and cataclasite. Field measurement of breccia thickness can be subjective as breccias have a broad continuum of clast sizes and there is no rigidly defined size cutoff distinguishing breccia clasts from fault-bounded rock volumes (Marrett and Allmendinger, 1990). Problems comparing breccia/ gouge thickness data from different sources are therefore inevitable (Evans, 1990). We have, where possible, minimized these problems by referring to descriptions in the source articles. Data from Knott et al. (1996), for example, have been classified here as fault rock thickness, although in the original article, they are referred to as fault zone thickness. The definition provided by Knott et al. (1996) in their article is ''the zone where most fault slip has occurred and usually includes the slip surfaces and the band of fault gouge and cataclasis'' and, since it does ''not include undeformed blocks entrained in the fault zone'', corresponds to the definition of fault rock used here*."

I show the dataset of Childs et al. (2009) for tectonic faults and superimpose (in red) the measurements from the EJVF (Figs. 27, 28). Fig. 27 shows that the 40 m-wide damage zone exposed in the EJVF roadcut plots near the wider limit of fault zones that have a maximum displacement of 900 m. However, only about 8 faults in the dataset have displacements larger than 900 m, while the vast majority of the data points are for smaller faults. Fig. 28 shows the Width:Displacement data labeled as to fault type. Here it can be seen that almost all of the widest fault zones for a given fault displacement are normal faults. For normal faults with 900 m displacement or more, two are wider than the EJVF and four are narrower.

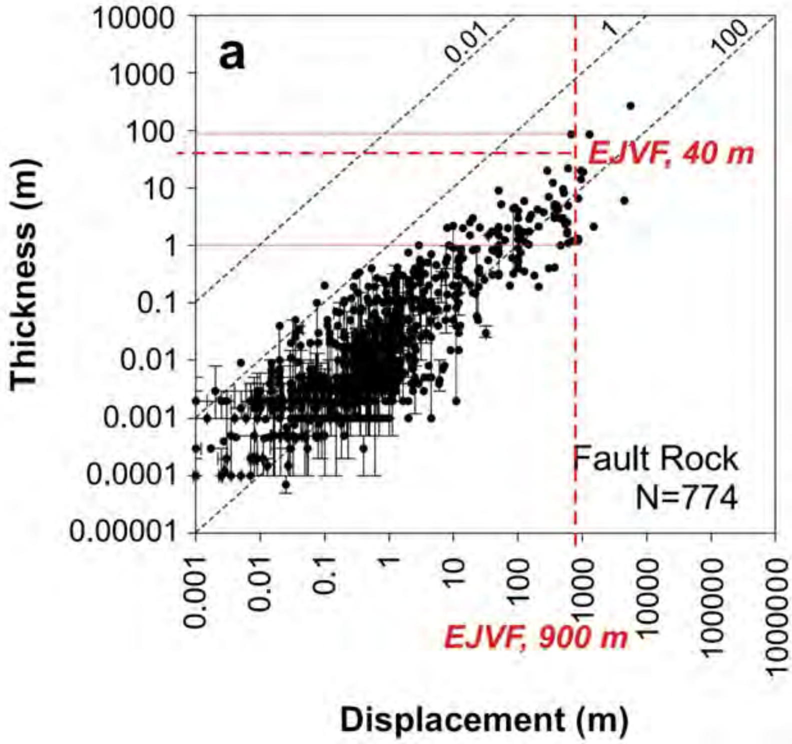


Fig. 27. Worldwide data on the ratio of fault zone thickness to fault displacement (in black and gray), compared to the same values for the East Joes Valley fault (EJVF, in red), based on the roadcut exposure north of Joes Valley Dam. From Childs et al., 2009.

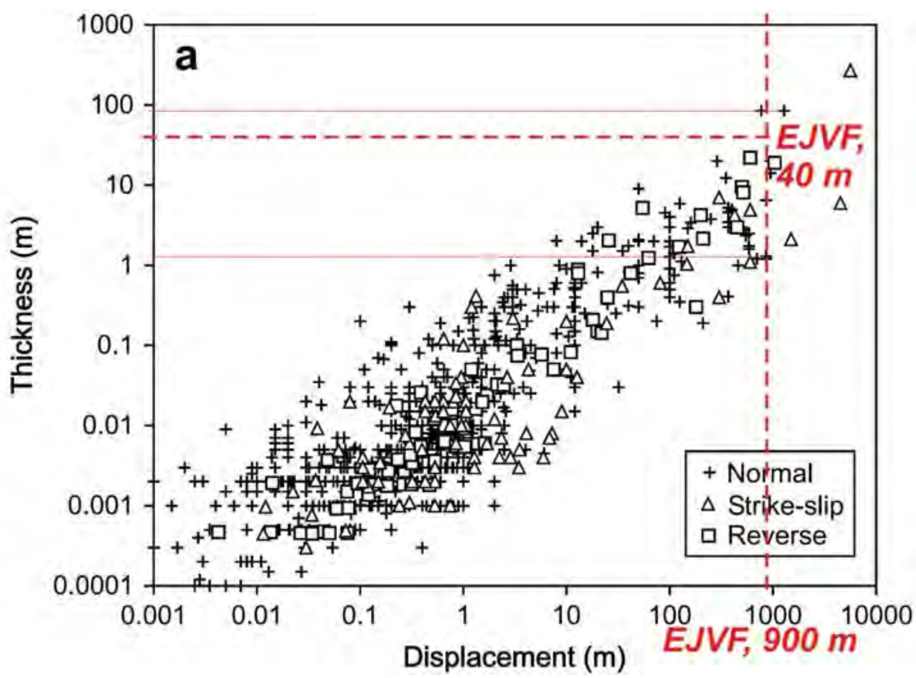


Fig. 28. Worldwide data on the ratio of fault zone thickness to fault displacement (in black and gray) for different fault types, compared to the same values for the East Joes Valley fault (EJVF, in red), based on the roadcut exposure north of Joes Valley Dam. From Childs et al., 2009.

As a check on the Childs et al. dataset I also examined the dataset of Shipton et al., 2006 (Fig. 29). They report a power-law best fit of Width= 0.019 Displacement$^{0.802}$. Thus for a maximum displacement of 900 m they would predict a fault zone width of 4.5 m. The EJVF data point lies one order of magnitude higher at roughly 44 m wide. However, a glance at their graph shows that the body of data points spans a 3-order-of-magnitude range, and that their regression curve for faults with displacements greater than 100 m is controlled by very few points.

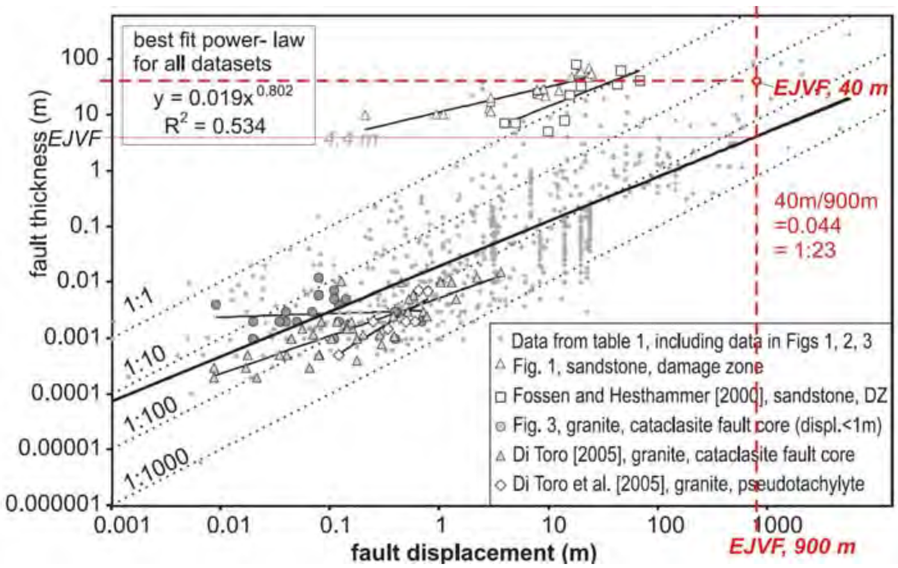


Fig. 29. Worldwide data on the ratio of fault zone thickness to fault displacement (in black and gray), compared to the same values for the East Joes Valley fault (EJVF, in red), based on the roadcut exposure north of Joes Valley Dam. In the exposure the EJVF has a width of ca. 40 m and a maximum vertical displacement of about 900 m, yielding a ratio of about 1:23. From Shipton et al., 2006.

In Summary: the ratio of displacement:length for the EJVF falls close to that for sets of tectonic normal faults elsewhere, and below the ratios found for faults related to salt deformation. The ratio of fault zone width:displacement based on a single measurement (the 100 m-long roadcut on the EJVF) plots near the upper width limit compared to other tectonic faults with similar displacement. Unfortunately, there are no published data from salt-related faults for this same ratio.

4.3 Behavior Parameters

I continue with addressing the criteria suggested by Anderson (2008) as demonstrating that the Joes Valley faults are unusual compared to other tectonic faults in the Basin and Range Province.

4.3.1- High Slip Rate Compared to Other Quaternary Faults in Basin and Range Province

Anderson (2008) noted the apparent high slip rates on the Joes Valley faults as follows: "*With the estimated late Quaternary vertical slip rates for the northern Joes Valley fault of 0.4 to 1.2 mm/yr, the northern Joes Valley fault system has rates similar to that of the main Wasatch fault… With the possible exception of the Bear River fault zone in northernmost Utah (Lund, 2005), no other fault in Utah is known to have a rate comparable to that of the Wasatch. In fact,*

even for the other "highly active" faults in the state, vertical slip rates tend to be about 0.1 to 0.4 mm/yr (Lund, 2005)."
The vertical slip rates mentioned here were measured on single faults in a complex graben, rather than being the net vertical slip rate across the graben in that same time period. Obviously if the WJVF has a late Quaternary slip rate of 1.2 mm/yr and so does the opposing EJVF, then the net slip rate is zero for the fault set, which surely has to merge into a single fault plane far above the base of the brittle seismogenic crust.

I would prefer the fault slip rates to either be cited as net late Quaternary net vertical slip rates (that is, the vertical slip rates summed across all active faults in the graben), or cite the long-term vertical slip rate across the graben based on the apparent offset of strata across the graben (measured by projecting strike lines on formations across the graben). The preliminary results of the latter procedure at the cross-section site of Kitzmiller (1982) indicated a total vertical separation across the graben in latest Cretaceous formations of ca. 120 m. To convert that apparent displacement to a slip rate I have to assume a time span over which the displacement accumulated. Geomorphic evidence presented on page 25 (The Mega-Geomorphology of Seeley Creek) suggests that the Joes Valley graben is a relatively young geologic feature, younger than the Basin and Range Province that began developing in the early Miocene (ca. 25 Ma). If I assume that the 120 m of displacement accumulated since the late Miocene (ca. 5 Ma), then the long-term vertical slip rate across the graben is 120 m/5000 kyr, or 0.024 mm/yr. If I assume that the entire graben developed in the Quaternary (2.6 Ma), then the long-term vertical slip rate is 0.046 mm/yr. These slip rates are comparable to vertical slip rates cited for other Quaternary faults in Utah "back valleys" that are not part of a narrow graben. For example, the Strawberry fault has slip rates estimated from paleoseismic data of 0.04 to 0.17 mm/yr measured over the past 15-30 ka, and 0.03-0.06 mm/yr in the past 150-300 ka (Nelson and VanArsdale, 1986).

4.3.2 Episodic Displacement Events Versus fault Creep

Some authors have noted that fault movement caused by salt tectonics (evaporite dissolution, collapse, or salt flow) is expressed as slow creep at the surface, presumably because the causative mechanisms are slow and continuous in the subsurface, rather than discontinuous as in coseismic faulting (e.g. Furuya et al., 2007). However, recent trenching of surface faults in evaporite areas has shown that these faults also move episodically (Gutierrez et al., 2012a). They concluded that" *Our findings suggest that considering evaporite collapse faults as creeping structures is not a reliable criterion to differentiate between tectonic faults (seismogenic) and dissolution-induced gravitational faults (nonseismogenic).*"

Similar results were obtained by Jesus Guerrero (University of Zaragoza, Spain) on the Kayenta Flats fault, the eastern boundary fault of the Moab graben, Utah (Gutierrez et al., 2012b). This author reviewed his trench exposure across the fault (Fig. 30) and confirmed that it contained many indicators of episodic fault displacement

Therefore, the episodic displacement evidence on Joes Valley faults interpreted from fault trenches by Foley et al. (1986) is not considered in this report to be useful in distinguishing a tectonic origin from a non-tectonic origin for the faults.

Fig. 30. Photograph of the trench exposure across the Kayenta Flats fault, an evaporite-collapse fault on the eastern margin of the Moab valley, Utah. Taken March 24, 2012. Jesus Guerrero at center for scale.

4.3.3 Extension Direction of Fault versus GPS Vectors

The University of Utah GPS network surveyed campaign stations just east of the Joes Valley graben (H100 on Fig. 31) and just west of the Snow Lake graben (SNO0). Unfortunately, SNO0 was only surveyed a single time, so its velocity relative to other local stations and stable North America cannot be computed. There are no other GPS stations sited between Joes Valley and the Wasatch fault. As a result, GPS velocity vectors in publications such as Chang et al., 2006 include strain across the Wasatch fault. For example, the differential strain between continuously recording stations CAST (east of Joes Valley) and SMEL (west of the Wasatch fault) amalgamate strain over the 180 km distance between the stations, which includes the Joes Valley graben, the Snow Lake graben, and the Wasatch fault. Without more detailed station data, it is impossible to say how much of the 2.3±0.2 mm/yr of strain between the stations is attributable to the Wasatch fault, and how much to the other parts of the line.

Both GPS stations east of Joes Valley (CAST and H100) have a more northwesterly vector than stations on the west side of the Wasatch fault, such as SMEL, which have more westerly vectors. This observation suggests that there is an overall component of left-lateral shear across any north-south faults between those stations. However, such shear could be entirely attributable to the Wasatch fault, rather than being proportionally divided among the Wasatch, Snow Lake, and Joes Valley grabens.

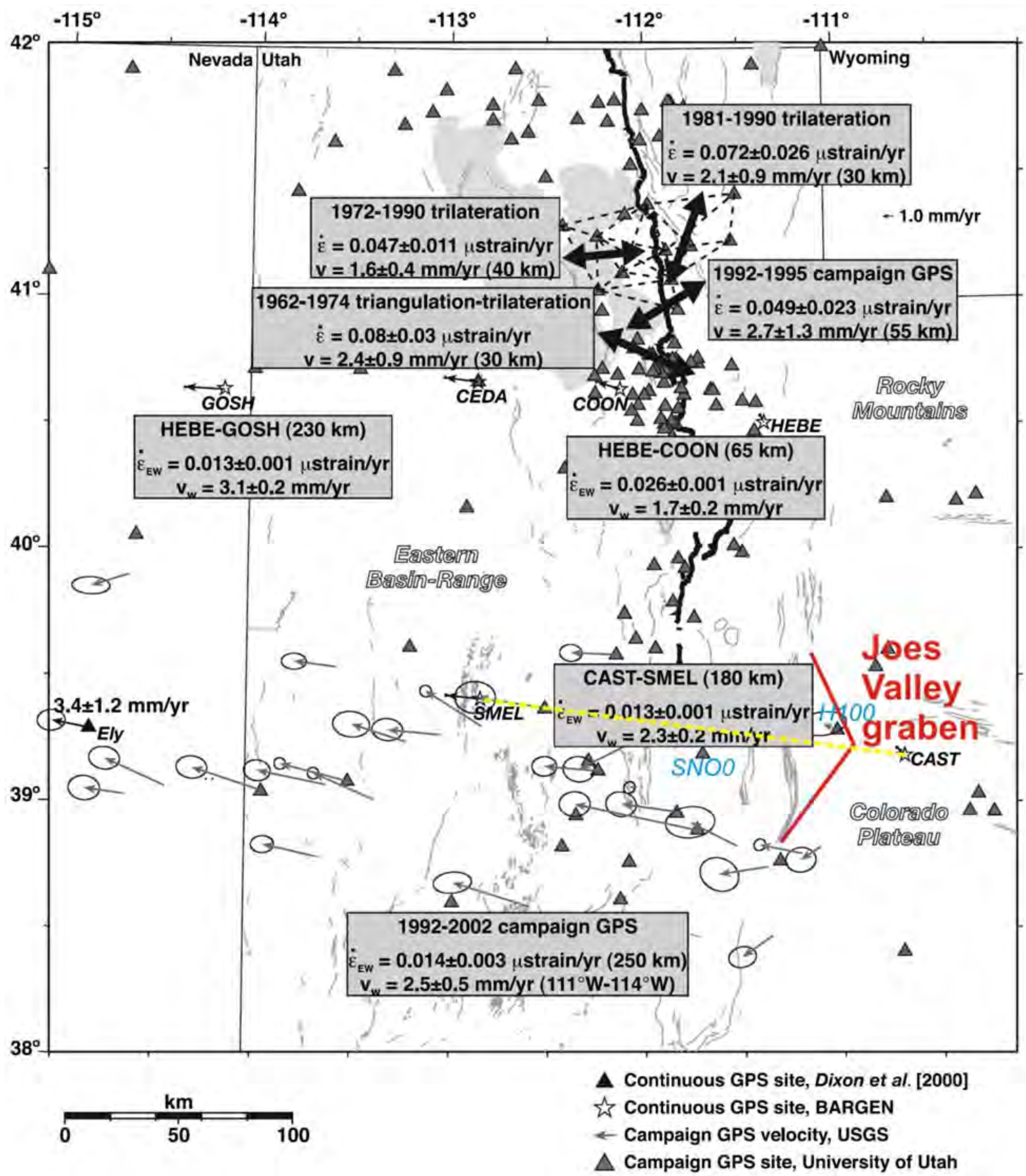


Fig. 31. Map of GPS stations in Utah operated by various agencies, and computed strain rates between eight station pairs (in gray boxes) that bracket the Wasatch fault. The 180 km-line between stations CAST and SMEL crosses the Joes Valley graben, but also includes the Snow Lake graben and the Wasatch fault.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This re-evaluation of the Joes Valley fault zone was made to support the revised probabilistic seismic hazard analysis (PSHA) of Huntington North Dam. The goal is to determine the likely origin of faults and geomorphic features (e.g., scarps, terraces) in the Joes Valley graben that may be the result of large-magnitude earthquakes (tectonic) , but might also have formed by non-tectonic processes, such as mass movement (e.g., landslides) or deformation due to salt flowage. The author reviewed all previous published and unpublished reports and then performed a 7-day field reconnaissance of the faults from Oct. 2-8, 2012. A field review with Reclamation personnel was held Oct. 17-18, 2012.

Previous publications had proposed four structural models for the origin of the Joes Valley faults, but only one of the models assumed the faults penetrated deeply into the crust and could generate large earthquakes. The other three models (and a fourth added here) assume that the faults do not penetrate deeper than about 3 km below the surface, or are evaporite dissolution-collapse faults; in either case, the faults could not generate large earthquakes. I collected field data and performed a literature review to determine which model was most likely, given the field evidence how they compared with the typical characteristics of tectonic vs. non-tectonic faults. The small-scale geomorphic features such as fault scarps and fluvial terraces are essentially similar whether produced by tectonic or non-tectonic faulting, so were not diagnostic. The map pattern of faults and fault-zone slickensides indicate that the East Joes Valley fault and intragraben faults are accommodating a component of right-lateral motion, making them normal-oblique faults. This sense of slip is more typical of tectonic than of nontectonic faults.

A key piece of evidence about fault origin lies in the deep seismic reflection profiles that cross Joes Valley, acquired by oil companies and interpreted by this report, and by previous studies. Four investigators have examined various seismic lines (Foley et al., 1986; Schelling et al., 2007; Coogan, 2008; and this report). All investigators except Coogan interpret the Joes Valley faults to extend beneath the regional detachment fault (Gunnison Detachment) and to penetrate the Paleozoic section beneath, if not the Precambrian basement. This interpretation is powerful evidence that the Joes Valley faults are tectonic and seismogenic. Based on the evidence assessed, I would weight the tectonic-seismogenic model of the Joes Valley faults as the most likely one (i.e., at least 60%).

Recommendations:

1- The PSHA should continue to include the Joes Valley faults as seismogenic faults, either as separate sources, or with the EJVF as an active master fault and the WJVF and intragraben faults as passive antithetic faults.

2- The possible salt detachment origin for the Joes Valley graben should be tested by constructing an analog or numerical deformation model based on the subsurface geometry interpreted from seismic reflection surveys, plus rheological parameters from core samples. The model should be run with various imposed stress fields, to see under what geometric, rheological, and stress parameters the model creates a narrow, detached footwall graben such as Joes Valley. If no model produces such a graben, or if the parameters required to produce a graben contradict known conditions, then this would be powerful evidence that the graben was not produced by an extensional salt detachment. The simple analysis presented in this paper, based on analogy, is too weak to completely discount the salt detachment hypothesis presented in Model 2. Therefore, in order for the non-seismogenic branch of the PSHA logic tree to be properly weighted, we need to see if a salt-detachment model can simulate the Ancient Ephraim-Wasatch Monocline-Joes Valley geometry.

3- The seismic source characterization of Joes Valley faults by Foley et al. (1986), although acceptable for the mid-1980s, is insufficiently precise for the demands of a modern PSHA. I would recommend that the seismic source characteristics input into the next PSHA be refined based on the collection of some new data on the location of Quaternary faults, and the number of and age of Quaternary faulting events on the Joes Valley faults.

4- An updated seismic source characterization would include several components. First, collection of LiDAR data to create a 1 meter or 2 meter DEM of the entire Joes Valley graben. Evidently LiDAR data have been collected south of Interstate 70 along the Joes Valley trend in support of the Level 3 PSHA for the Blue Gate nuclear power plant (Dean Ostenaa, Fugro Corporation, pers. communication, April 2013). This LiDAR DEM presumably shows that Quaternary normal faults extend south of the Interstate, greatly lengthening the extent of Quaternary faulting in this part of the Transition Zone.

Second, the update would require re-excavating old trenches and excavating new ones to obtain more precise age control on faulting events, using AMS radiocarbon dating, luminescence dating, and perhaps cosmogenic surface-exposure dating. New dating would permit refining the mean values of recurrence interval and slip rate, and estimating the uncertainties in those two parameters. It might also permit testing whether the graben-bounding faults (EJVF and WJVF) and the intragraben faults rupture simultaneously, which bear on the behavioral model of the fault (segmentation and rupture scenarios) and allowing for a deterministic or probabilistic estimate of conditional probability of future rupture.

6.0 REFERENCES

Allmendinger, R.W., Farmer, H., Hauser, E., Sharp, J., Von Tish, D., Oliver, J. and Kaufman, S., 1986, Phanerozoic tectonics of the Basin and Range-Colorado Plateau transition from COCORP data and geologic data; A review, in Barazangi, M. and Brown, L.D. (eds.), Reflection seismology; The continental crust: American Geophysical Union, 257 p.

Anderson, L.A., 2008, Evaluation of the seismogenic potential of the Joes Valley fault zone- Joes valley Dam, Emery County Project- Utah: Technical Memorandum No. 86-68321-2008-10, U.S. Bureau of Reclamation, technical Service Center, Denver, CO, May 2008, 23 p. plus appendices.

Anderson, L.W., and K. Mahrer (2002), Screening level seismotectonic and ground motion evaluation for Joes Valley and Huntington North Dam, Technical Memorandum D8330-2002-6, U.S. Bureau of Reclamation, Denver, CO, 18 pp (FINAL DRAFT in D-8330 files).

Arabasz, W. J., 1986, Interpretation of instrumental seismicity and contemporary tectonics of the eastern Wasatch Plateau relevant to seismic exposure of the Joes Valley and Scofield Dams: Technical Report to U.S. Bureau of Reclamation, Engineering and Research Center, Denver, Colorado.

Arabasz, W. J., and Julander, D. R., 1986, Geometry of seismically active faults and crustal deformation within the Basin and Range – Colorado Plateau Transition in Utah, in Mayer, L., ed., Extensional tectonics of the Basin and Range Province, A Perspective: Geological Society of America Special Paper no. 208, p. 43-74.

Baars, D.L. and Doelling, H.H., 1987, Moab salt-intruded anticline, east-central Utah: Geol. Soc. Amer., Centennial Field Guide, Rocky Mountain Section, p. 275-280.

Berg, S.S. and Skar, T., 2005, Controls on damage zone asymmetry of a normal fault zone: outcrop analyses of a segment of the Moab fault, SE Utah: Jour. Struct. Geol., v. 27, no. 10, p. 1803-1822.

Bush, N. I., Harris, C., and Grosfils, E. B., 1996, Refraction seismology in Devils Lane graben, Canyonlands National Park, Utah [abs.]: Eos (Transactions, American Geophysical Union), v. 77, p. F643.

Chang, W-L., Smith, R.B., Meertens, C.M. and Harris, R.A., 2006, Contemporary deformation of the Wasatch fault, Utah, from GPS measurements with implications for interseismic fault behavior and earthquake hazard; observations and kinematic analysis: Jour. Geophys. Res., v. 111, B11405, doi:10.1029/2006JB004326, 19 p.

Childs, C., Manzocchi, T., Walsh, J.J., Bonson, C.G., Nicol, A. and Schopfer, M.P.J., 2009, A geometric model of fault zone and fault rock thickness variations: Jour. Struct. Geol., v. 31, p. 117-127.

Coogan, J.C., 2008, Stratigraphic, structural, and velocity interpretations of seismic reflection profiles CGG-WAS-202 and CGG-WAS-207 in the vicinity of Joes Valley and Snow Lake grabens of the Wasatch Plateau, Utah: unpublished report submitted to the U.S. Bureau of Reclamation, Denver, CO by J.C. Coogan, consultant, Gunnison, CO, 24-March-2008, 14 p. (also published as an Appendix in Anderson, 2008).

Dawers, N.H., Anders, M.H. and Scholz, C.H., 1993, Growth of normal faults; displacement:length scaling: Geology, v. 21, p. 1107-1110.

Delvaux, D., 1991, The Karoo to Recent rifting in the western branch of the East African rift system; A bibliographical synthesis: Royal Museum of Central Africa, Dept. of Geol. And Mineraol., Annual Rept. 1989-1990, p. 63-83.

Evans, J.P., 1990, Thickness-displacement relationships for fault zones: Jour. Struct. Geol., v12, p. 1061-1066.

Foley, L.L., Martin, R. A. Jr. and Sullivan, J.T., 1986, Seismotectonic study for Joes Valley, Scofield, and Huntington North Dams, Emery County and Scofield Projects, Utah: Seismotectonic Report 86-7, U.S. Bureau of Reclamation, Denver, CO, 132 p.

Fouch, T.D., Manley, J.M., Forester, R.M., Keighen, C.W., Pitman, J.K. and Nichols, D.J., 1987, Chart showing lithology, mineralogy, and paleontology of the nonmarine North Horn Formation and Flagstaff Member of the Green River Formation, Price Canyon, Central Utah; A principal reference section: USGS Map I-1979-A.

Furuya, M., Mueller, K. and Wahr, J., 2007, Active salt tectonics in the Needles District, Canyonlands (Utah) as detected by interferometric synthetic aperture radar and point target analysis, 1992-2002: J. Geophys. Res., v. 112, no. B06418, doi:10.1029/2006JB004032.

Grant, J.V. and Kattenhorn, S.A., 2004, Evolution of vertical faults at an extensional plate boundary, southwest Iceland: Jour. Struct. Geol., v. 26, p. 537-557.

Groshong, R. H. Jr., 1989, Half-graben structures—Balanced models of extensional fault-bend folds: Geological Society of America Bulletin, v. 101, p. 96–105.

Gutierrez, F., Carbonel, D. Guerrero, J., McCalpin, J.P., Linares, R., Roque, C. and Zarroca, M., 2012a, Late Holocene episodic displacement on fault scarps related to interstratal dissolution of evaporites (Teruel Neogene Graben, NE Spain): Journal of Structural Geology, v. 34, no. 1, p. 2-19.

Gutierrez, F., Guerrero, J., Bruhn, R., McCalpin, J.P., and Willis, G., 2012b, Interstratal karstification and late Quaternary active faulting in Moab collapse-salt valley, SE Utah (USA): Sociedad Espanola de Geomorfologia, Proc. XII Reunion Nacional de Geomorfologia, Santander, Spain, 2012, p. 417-420.

Hanson, K.L., Kelson, K.I., Angell, M.A. and Lettis, W.R, 1999, Techniques for Identifying Faults and Determining Their Origins., U.S. Nuclear Reg. Comm., Wash., DC, contract rept. NUREG/CR-5503, 504 p.

Hecker, S., 1993, Quaternary tectonics of Utah with emphasis on earthquake-hazard characterization: Utah Geol. Surv., Bull. 127, 92 p.

Higgs,W. G.,Williams, G. D., and Powell, C. M., 1991, Evidence for flexural shear folding associated with extensional faults: Geological Society of America Bulletin, v. 103, p. 710–717.

Hudec, M.R. and Jackson, M.P A., 2012, The Salt Mine; A Digital Atlas of Salt Tectonics: Texas Bureau of Economic Geology, Udden Book Series No. 5,and AAPG Memoir 99, 305 p.

Kitzmiller, J.M., II, 1982, Preliminary geologic map of the Joes Valley Reservoir quadrangle, Emery and Sanpete counties, Utah: Utah Geological Survey Map M-67, scale 1:24,000.

Knott, S.D., Beach, A., Brockbank, P.J., Lawson-Brown, J., McCallum, J.E. and Welbon, A.I., 1996, Spatial and mechanical controls on normal fault populations: Jour. Struct. Geol., v. 18, p. 359-372.

Lund, W.R., 2005, Consensus preferred recurrence-interval and vertical slip-rate estimates; review of Utah paleoseismic-trenching data by the Utah Quaternary Fault Parameters Working Group: Utah Geological Survey Bulletin 134, 109 p.

Marrett, R.A. and Allmendinger, R.W., 1990, Kinematic analysis of fault-slip data; Jour. Struct. Geol., v. 12, p. 973-986.

McCalpin, J.P., 2003, Neotectonics of the Roubideau Creek fault, Uncompahgre Plateau, Colorado; A preliminary assessment: unpublished consulting report submitted to Colorado Geological Survey, Denver, CO by GEO-HAZ Consulting, Inc., Sept. 30, 2003, 43 p.

McCalpin, J.P., 2005, Late Quaternary activity of the Pajarito fault, Rio Grande rift of northern New Mexico, USA; Tectonophysics, v. 408, no.1-4, p. 213-236. (http://www.geohaz.com/2005 Pajarito fault.pdf)

McCalpin, J.P., 2006, Neotectonics of Quaternary fault Q20, Q22, and Q23 in the central Uncompahgre Plateau, Colorado: unpublished consulting report submitted to the U.S. Bureau of Reclamation, Denver, CO by GEO-HAZ Consulting, Inc., Crestone, CO, Job No. 2103, 23-December-2006, 65 p.

McCalpin, J.P. (ed.), 2009, Paleoseismology, 2nd Ed.: Academic Press, Elsevier, Netherlands, 682 p.

McCalpin, James, Piety, L.A. and Anders, M.H., 1990, Late Tertiary and Quaternary faulting north and south of the eastern Snake River Plain. Part 1. Latest Quaternary faulting and structural evolution of Star Valley, Wyoming, in Roberts, Sheila (ed.) Geologic Field Tours of western Wyoming and parts of adjacent Idaho, Montana and Utah: Geological Survey of Wyoming, Public Information circular no. 29, p. 5-14.

Moore, J.M. and Schultz, R.A., 1999, Processes of faulting in jointed rocks of Canyonlands National Park: Geol. Soc. Amer. Bull, v. 111, no. 6, p. 808-822.

Nelson, A.R. and VanArsdale, R.B., 1986, Recurrent late Quaternary movement on the Strawberry normal fault, Basin and Range- Colorado Plateau transition zone, Utah: Neotectonics, v. 1, p. 7-37.

O'Connell, D.R.H, Ostenaa, D.A. and LaForge, R.C., 2005, Probabilistic seismic hazard, ground motion and seiche wave analyses for Joes Valley Dam, Emery County Project, Utah: U.S. Bureau of Reclamation, Denver, CO, Seismotectonics and Geophysics Group, Report 2005-1, March 2005, 130 p.

Powell, J.W., 1873, Geological structure of a district of country lying to the north of the Grand Canyon of the Colorado: American Journal of Science, v. 5, p. 456-465.

Royse, Frank, 1983, Extensional faults and folds in the Foreland Thrust Belt, Utah, Wyoming, and Idaho: Geological Society of America Abstracts, v.15, no. 5, p.295.

Schelling, D.D., Strickland, D.K., Johnson, K.R. and Vrona, J.P., 2007, Structural geology of the central Utah thrust belt, in Willis, G.C., Hylland, M.D. Clark, D.L. and Chidsey, T.C. Jr. (eds.), Central Utah—Diverse Geology of a Dynamic Landscape: Utah Geological Association, Publication #37, Salt Lake City, UT, p. 1-30.

Shipton, Z.K., Soden, A.M., Kirkpatrick, J.D., Bright, A.M. and Lunn, R.J., 2006, How thick is a fault? Fault displacement-thickness scaling revisited, in Earthquakes: Radiated Energy and the Physics of Faulting: Amer. Geophys. Union, Geophysical Monograph Series 170, p. 193-198.

Spieker, E. M. and Billings , M. P., 1940, Glaciation in the Wasatch Plateau: Geological Society of America Bulletin , v. 51, p. 1173-1198.

Sprinkel, D.A., 1996, Stratigraphic and time-stratigraphic cross sections: A north-south transect from near the Uinta Mountain axis across the Basin and Range Transition Zone to the western margin of the San Rafael Swell, Utah: U.S. Geological Survey Map I-2184-D, scale 1:500,000.

Standlee, L.A., 1982, Structure and stratigraphy of Jurassic rocks in central Utah: Their influence on tectonic development of the Cordilleran foreland and thrust belt: in Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Denver, Colorado, Rocky Mountain Association of Geologists, v. 1, p. 357-382.

Tindall, S.E. and Davis, G.H., 1999, Monocline development by oblique-slip fault-propagation folding; the East Kaibab monocline, Colorado Plateau, Utah: Jour, Struct. Geol., v. 21, p. 1303-1320.

West, M.W., 1992, An integrated model for seismogenesis in the Intermountain Seismic Belt: Bull. Seismol. Soc. Amer., v, 82, no. 3, p. 1350-1372.

Willis, G.C., Hylland, M.D. Clark, D.L. and Chidsey, T.C. Jr. (eds.), Central Utah—Diverse Geology of a Dynamic Landscape: Utah Geological Association, Publication #37, Salt Lake City, UT.

Withjack, M.O. and Calloway, S., 2000, Active normal faulting beneath a salt layer: An experimental study of deformation patterns in the cover sequence: AAPG Bulletin, v. 84, no. 5 (May 2000), p. 627–651.

Witkind, I.J., Weiss, M.P., and Brown, T.L., 1987, Geologic map of the Manti 30' x 60' quadrangle, Carbon, Emery, Juab, Sanpete, and Sevier Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1631, scale 1:100,000.

Vendeville, B. C., and Jackson, M. P. A., 1992, The rise of diapirs during thin-skinned extension: Marine and Petroleum Geology, v. 9, p. 331–353.