Welcome to the 2019 Utah Quaternary Fault Parameters Working Group (UQFPWG) Meeting

Utah Geological Survey

Logistics…

- Bathrooms are out the door, and to the left

- In case of emergency, exit out the north doors

Utah Geological Association

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UQFPWG Introduction and overview

- Standing committee of the Utah Earthquake Working Groups created to help coordinate earthquake-hazard research in Utah.
- Review ongoing paleoseismic, earthquake timing, and fault characterization studies ongoing in Utah with the goal of maintaining and updating consensus slip-rate recurrence intervals.
- Identify and prioritize Utah Quaternary faults for future study. This list is incorporated into the annual U.S. Geological Survey, Earthquake Hazards Program, External Research Support (NHEHRP) funding announcements.
- This group is dependent on the active involvement of researchers, consultants, federal/state workers, and the public.

UQFPWG 2018 Review

- Technical presentations
  - Seismic imaging of SLC area from 2015 and 2017- Lee Liberty, Boise State
  - WFZ mapping in Utah and Idaho- UGS
  - Traverse Ridge Paleoseismic Site- Joe Phillips and Nathan Toke, UVU
  - Preliminary results from Levan/Fayette trenching- UGS
  - West Valley Fault Zone Mapping- UGS
  - Wasatch Landslides and the paleoseismic record- Brendon Quirk, U. Utah
  - Thousand Lake Fault, Bicknell, Utah- Joe Phillips and Nathan Toke, UVU
  - FORGE Quaternary faulting- UGS
  - Paleoseismic trenches in Joes valley, Lucy Piety, U.S. Bureau of Reclamation
  - Topliff Hills Fault Investigation- Mike Bunds, UVU
  - Progress towards an Updated Nevada Seismic Model- Rich Koehler, NBMG

UQFPWG 2018 priorities

- Acquire new paleoseismic information to address data gaps for…
  - (a) the five central segments of the Wasatch fault zone(including focusing on the youngest earthquakes [3-5 ka]; large, early Holocene–latest Pleistocene scarps; and secondary faulting [West Valley fault zone and Utah Lake faults and folds]
  - (b) the northern segment of the Oquirrh fault zone
  - (c) the Topliff Hills fault (Bunds, UVU, ongoing)
  - (d) the East and West Cache fault zones.

UQFPWG 2018 priorities

- Use recently acquired lidar data to more accurately map the traces of…
  - the East and West Bear Lake
  - East and West Cache (UGS Awarded, FTR Due Fall 2019)
  - Hurricane fault zone
  - Search for and map previously undiscovered mid-valley Quaternary faults.

UQFPWG 2018 priorities

- Acquire earthquake timing information for the Utah Lake fault zone to investigate the relation of earthquakes on that fault system to large earthquakes on the adjacent Provo segment of the Wasatch fault zone.

UQFPWG 2018 priorities

- Acquire and analyze information on salt tectonics and its relation to…
  - the Main Canyon fault
  - Sevier detachment/Drum Mountains fault zone
  - Bear River fault zone
  - Spanish Valley (Moab area)faults (Pederson, in progress?)
  - Joes Valley fault zone
  - Levan and Fayette segments of the Wasatch fault zone
  - Scipio Valley faults
  - the Gunnison fault.

New table format for priorities past and present…

Study Type	Utah Fault or Fault Segment	UQFPWG Priorities		Investigation Status (as of 2/2019)
		2005	Additions	
Earthquake Timing	Nephi segment, Wasatch fault zone	1	2012 2017	UGS FTR Report, 05HQGR0098 (2005) USGS SI Map 2966 (2007) UGS Special Study 124 (2008) UGS FTR Report, G12AP20076 (2014) UGS Special Study 151 (2014) UGS Special Study 159 (2017) UGS FTR, G17AP00001 (2018)
	West Valley fault zone	2		
	Granger Fault		2017	UGS Special Study 149 (2014)
	Taylorsville Fault		2011 2017	UGS FTR, G15AP00117 (2017)
	Weber segment, Wasatch fault zone – most recent event and multiple events	3 4	2012 2017	UGS Miscellaneous Publication 05-8 (2006) UGS FTR, 07HQGR0093 (2007) UGS Special Study 130 (2009)
	Utah Lake faults and folds	5		
	Acquire earthquake timing information to investigate the relation of earthquakes to large earthquakes on the Provo segment.		2015 2017	UUGG FTR Report, G08AP0016 (2014)
	Great Salt Lake fault zone	6		
	Rozelle section, East Great Salt Lake fault Carrington fault, Great Salt Lake fault zone		2007	UUGG FTR Report, G08AP0016 (2014) Janecke and Evans (2017)
	Collinston and Clarkston Mountain segments, Wasatch fault zone	7	--	UGS Special Study 121 (2007) UGS Open-File Report 638 (2015)
	Sevier and Toroweap faults	8	2016	UGS Special Study 122 (2008)
	Washington fault zone (includes Dutchman Draw fault)	9	--	UGS Open-File Report 583 (2011) UGS Miscellaneous Publication 15-6 (2015)
	Cedar City-Parowan monocline (removed 2016) and Paragonah fault	10	--	UGS Map 270 (2015) 2016 presentation file
	Enoch graben	11	--	UGS Open-File Report 628 (2014)
	East Cache fault zone	12	2013	USU FTR Report, 07HQGR0079 (2012)
	Clarkston fault	13	--	UGS Special Study 121 (2007) UGS Open-File Report 638 (2015)
	Wasatch Range back-valley faults (includes Morgan fault and Main Canyon fault)	14	--	UGS Miscellaneous Publication 11-2 (2011) UGS Miscellaneous Publication 10-5 (2010)
	Hurricane fault zone	15	--	UGS Special Study 119 (2007)
	Levan segment, Wasatch fault zone	16	--	UGS Map 229 (2008) UGS Open-File Report 640 (2015) G17AP00060 (2017), UGS FTR due Fall 2019
	Gunnison fault	17	--	No activity
	Scipio Valley faults	18	2017	No activity
	Faults beneath Bear Lake	19		No activity

Agenda

- 8:00 Refreshments
- 8:30 Welcome, Overview of Meeting, and Review of Last Year's Activities, Emily Kleber, Utah Geological Survey
- 8:45 Technical Presentations of Work Completed or In Progress
- 10:00 Break (15 minutes)
- 10:15 Technical Presentations of Work Completed or In Progress (continued)
- 12:00 Lunch (1 hour, hosted by UGA)
- 1:00 Technical Presentations of Work Completed or In Progress – Posters
- 2:30 Break (15 minutes)
- 2:45 Discussion – Working Group Priorities, Continued Discussion from the Morning Sessions
- 3:30 Discussion – Working Group 2020 Fault Investigation Priorities
- 5:00 Adjourn

Timer and slide advancer

- Please get me or Adam Hiscock you talk **during breaks.**
- 30 minute talks
  - Green- within 30 mintes
  - Yellow- 5 minutes
  - Red- Time is up

- 15 minute talks
  - Green- within 15 mintes
  - Yellow- 2 minutes
  - Red- Time is up

Discussion of Working Group Priorities

- Priority faults for 2020?
- Approve or modify list?

- Bigger questions…
  - What big problem does this group feel like it needs to tackle?
  - What does this group look like in 5 years?
  - Alternate years, with short courses every-other year?

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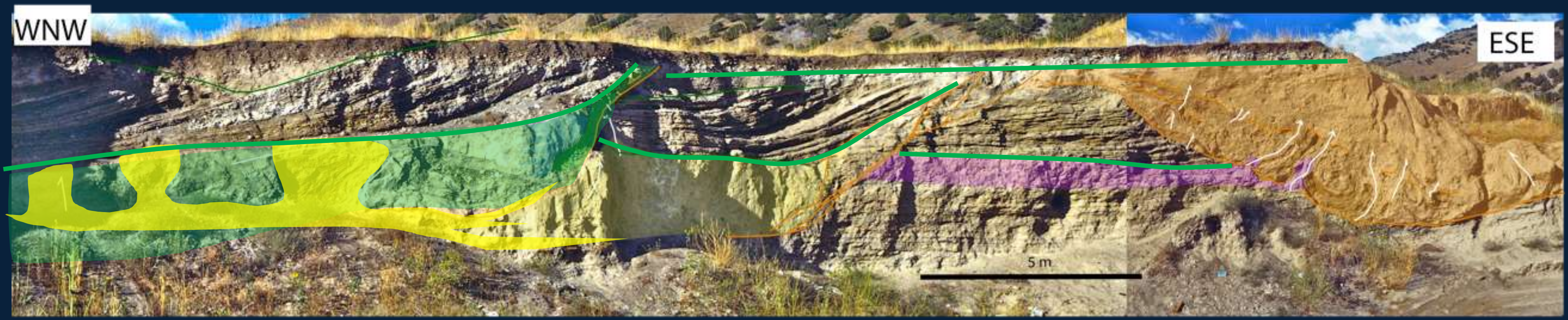
	Gunnison fault	17	--	No activity
	Scipio Valley faults	18	2017	No activity
	Faults beneath Bear Lake	19		No activity

Study Type	Utah Fault or Fault Segment	UQFPWG Priorities		Investigation Status (as of 2/2019)
		2005	Additions	
Earthquake Timing	Eastern Bear Lake fault zone	20	--	No activity
	Provo segment, Wasatch fault zone			
	Penultimate event and long term earthquake record	--	2007 2011 2012 2017	UGS Map 02-7 (2002) URS FTR Report, 02HQGR0109 (2011) UGS FTR Report, G13AC00165 (2015) Bennett and others, 2018 (BSSA)
	Fort Canyon fault, Traverse Mountains salient	--	2012	UVU FTR, G16AP00104 (2017)
	Brigham City segment, Wasatch fault zone			
	Most Recent Event and Rupture Extent	--	2007 2011	UGS Special Study 142, (2012)
	Salt Lake City segment, Wasatch fault zone.	--	2009	
	Penrose Drive	--	2012	UGS FTR Report, G10AP00068 (2010) UGS Special Study 149 (2014)
	Corner Canyon site	--	2012	UGS FTR Report, G14AP00057 (2014)
	Bear River fault zone	--	2007	AGU Abstracts: 2012 and 2013
	Acquire new paleoseismic information to address data gaps for the five central segments of the Wasatch fault zone	--	2012	DuRoss and Hylland, 2015 (BSSA) DuRoss and others, 2018 (GRL)
	Topliff Hills fault	--	2016	No activity
	Northern Oquirrh fault zone	--	2015 2017	Bunds and others, Poster 1 and Poster 2
High Resolution Mapping and Paleoseismic Trench Site ID	Wasatch and West Valley fault zones	--	2014 2017	UGS Open-File Report 638 (2015) UGS Open-File Report 640 (2015) UGS FTR G17AP00001 (2018)
	Faults beneath Bear Lake		2015 2017	No activity
	Hansel Valley fault	--	2011	No activity
	Eastern Bear Lake fault zone	--	2015 2017	Proposed 2017 (UGS), pending
	West and East Cache fault zones	--	2015 2017	G17AP00071 awarded 2017, FTR due Fall 2019
	Hurricane fault zone	--	2014 2017	No activity
	Oquirrh fault zone	--	2015 2017	Bunds and others, Poster 1 and Poster 2

Study Type	Utah Fault or Fault Segment	UQFPWG Priorities		Investigation Status (as of 2/2019)
		2005	Additions	
Salt Tectonics	Levan and Fayette segments of the Wasatch fault zone	--	2016	G17AP00060 awarded 2017, FTR due May 2019
	Main Canyon fault Sevier detachment/Drum Mountains fault zone Bear River fault zone Spanish Valley (Moab area) Joes Valley fault zone Scipio Valley faults Gunnison fault	--	2016	No activity
Other	Warm Springs fault/East Bench fault subsurface geometry and connection	--	2010	BSU FTR G15AP00054 (2015) BSU FTR G17AP00052 (2017)

CACHE VALLEY: LIQUEFACTION, OUT-OF-SYNC EARTHQUAKES, LAKE BONNEVILLE, AND LINKING UP THE WEST CACHE FAULT ZONE



Original photo by Robert Q. Oaks. Jr.

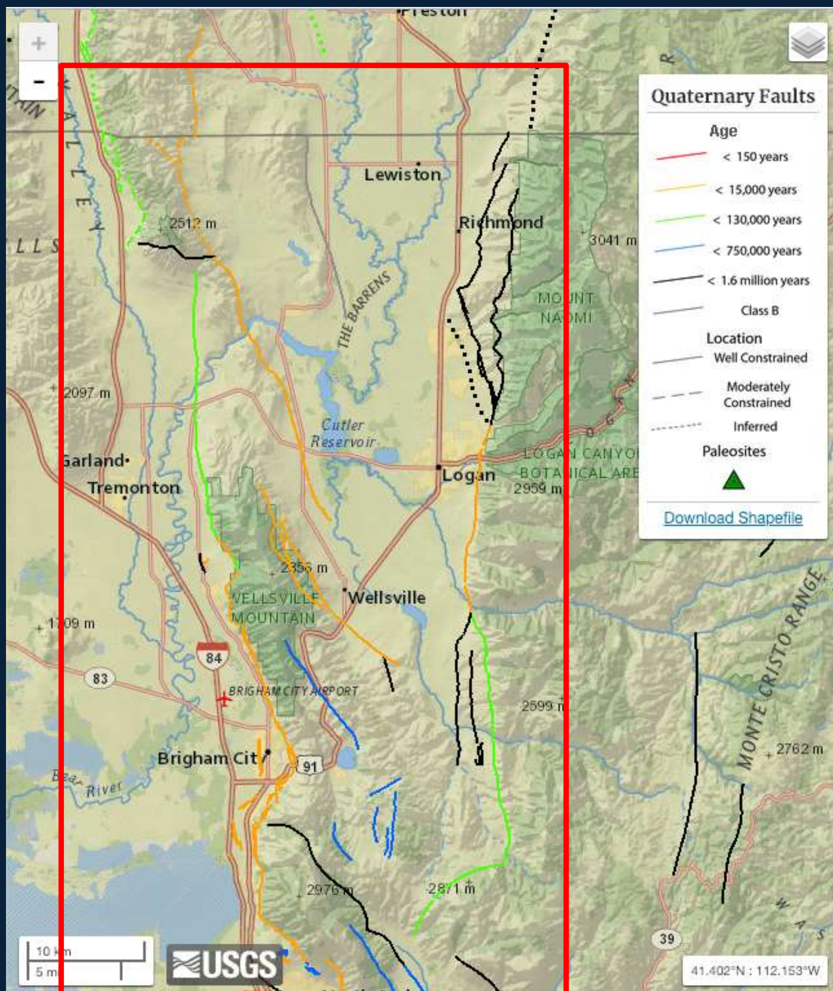
All views of exposure are to the NNE

UtahState University Geology

Susanne Janecke
Robert Q. Oaks, Jr.
Nathan Ellis
James P. Evans
A.J. Knight
and Justin Oakeson

Each colored unit is liquefied

Faults in Cache Valley prior to LIDAR



Jänecke et al., UQFPWG F

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

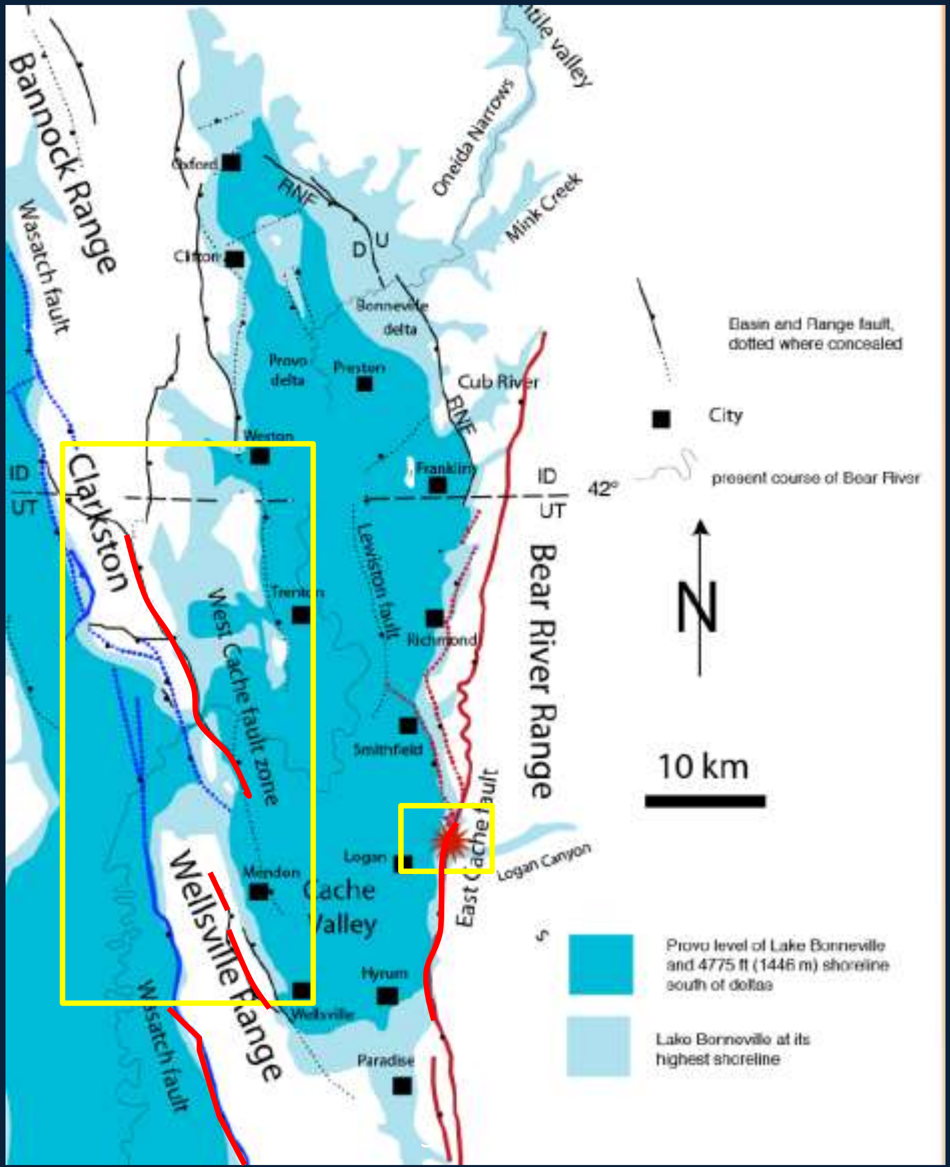
West Cache fault produced at least 3 earthquakes in Holocene (Solomon, 2000; Black et al., 2000, Ellis, 2018 senior thesis)

East Cache fault produced only one Holocene earthquake. (McCalpin, 1987, 1994).

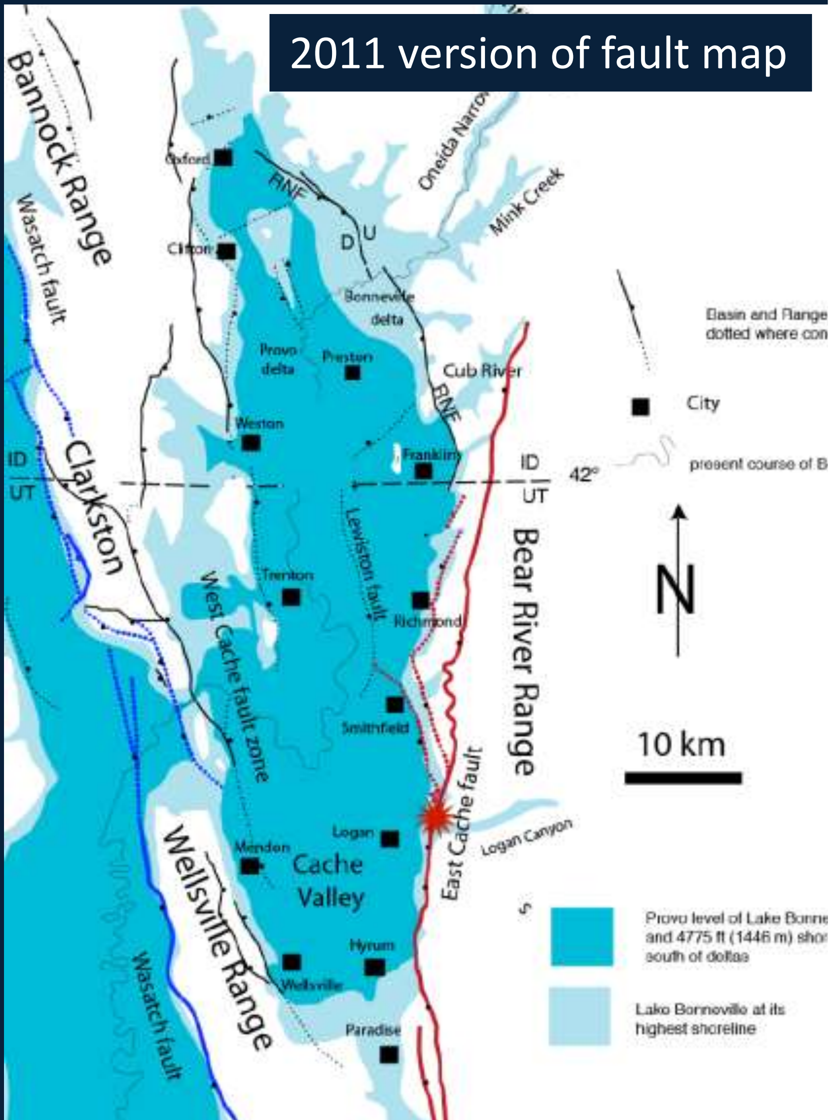
Yet ECFZ is master fault zone

First we will explore an outcrop at a segment boundary, where several faults branch northward

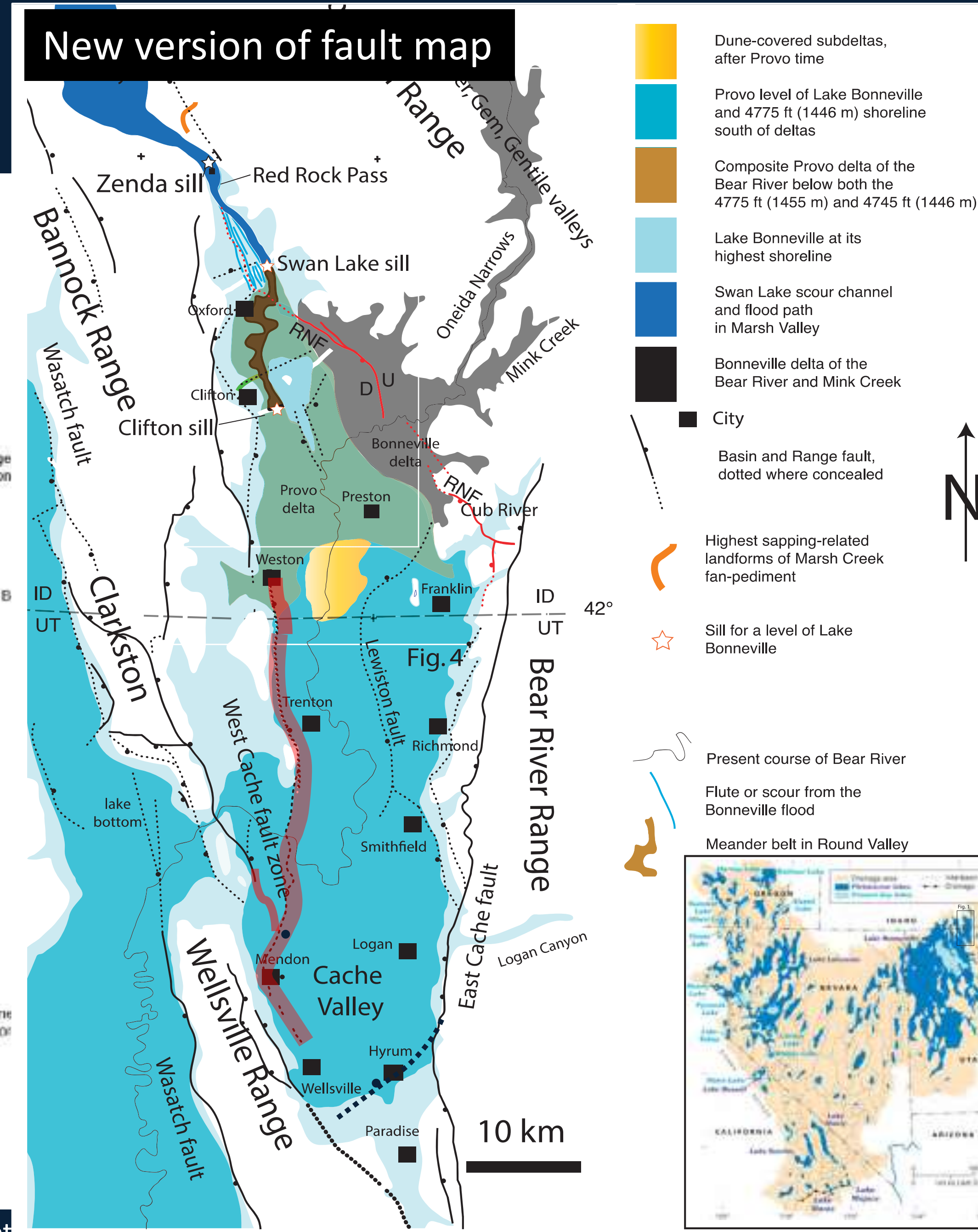
Then use new LIDAR along the West Cache fault zone



WE will conclude that:
Eqs on East and West Cache faults are mostly out of sync



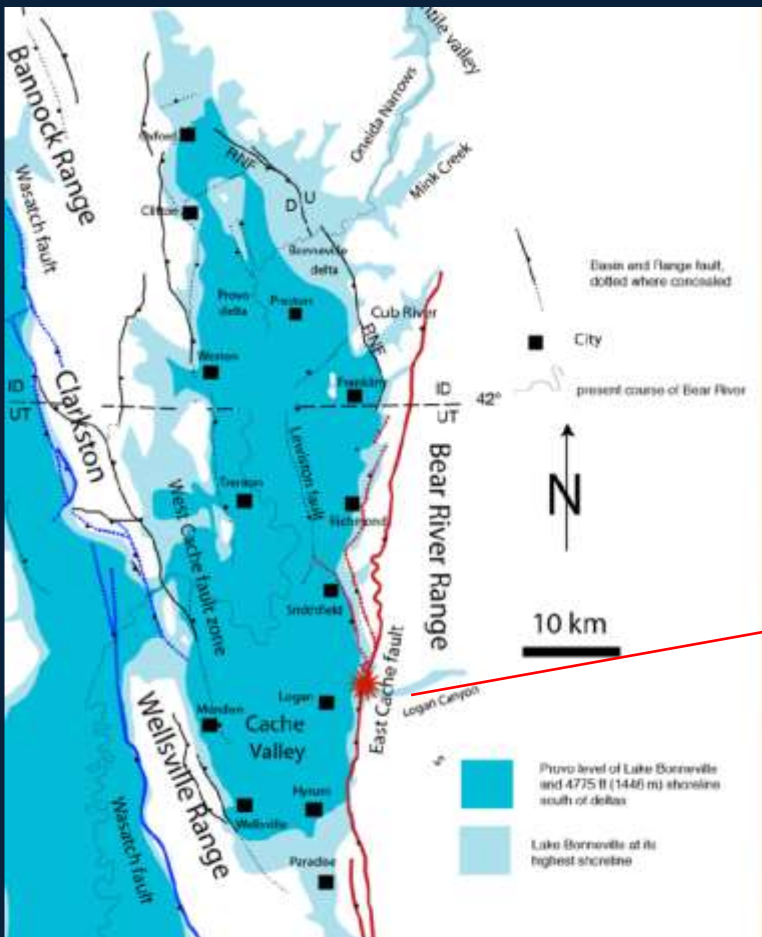
Modified from Janecke and Oaks, 2011



Janecke et

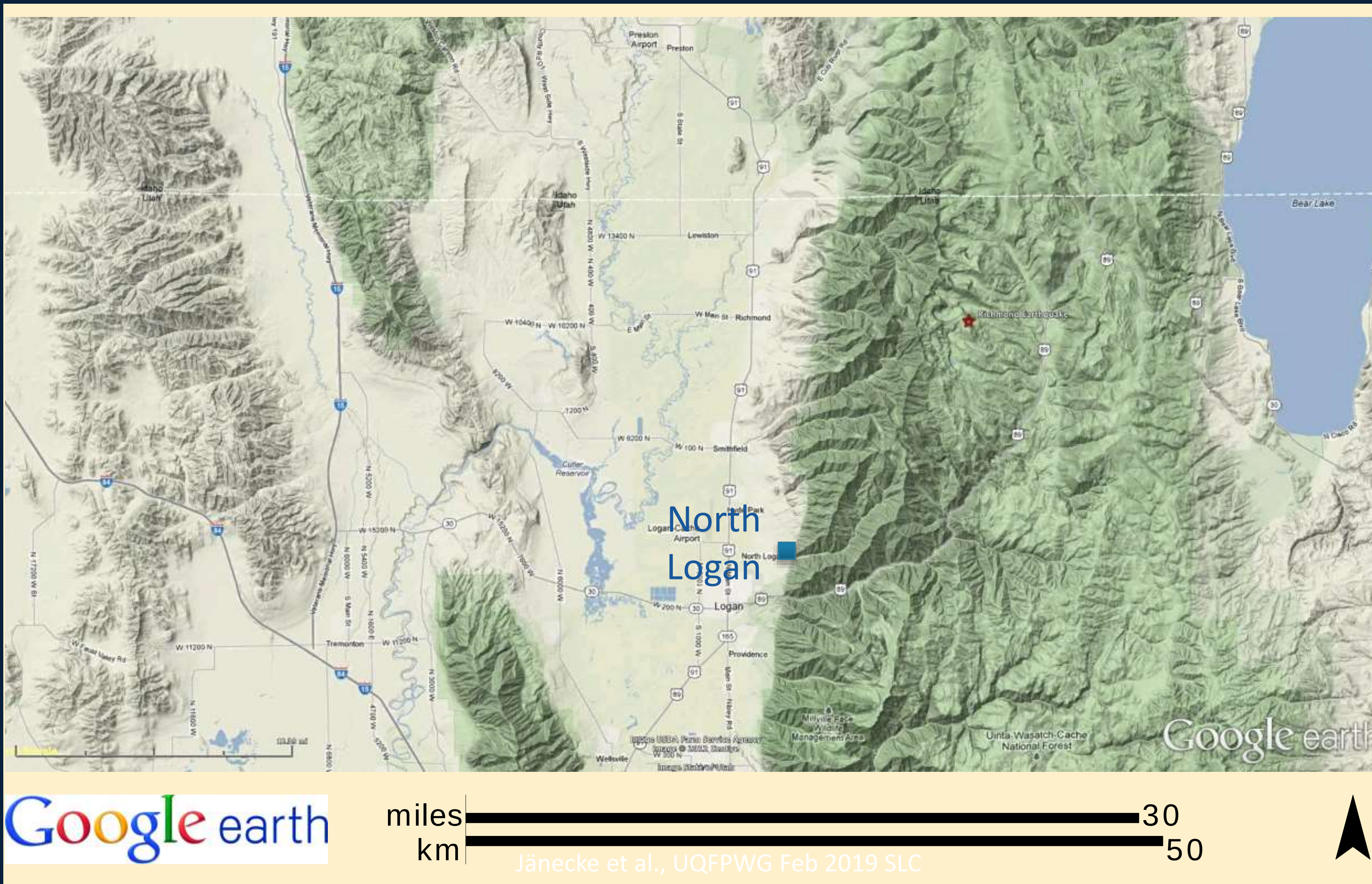
Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River are differentiated from other lacustrine deposits.

- Might this outcrop record THE earthquake that triggered the Bonneville flood?
- If not, what does it record?



from Janecke and Oaks, 2011

Study site is between Bonneville and Provo shoreline, 225 m west of Bonneville shoreline and 40-45 m below it



Jänecke et al., UQFPWG Feb 2019 SLC

Outcrop at mouth of Green Canyon, North Logan, Utah on north wall of a gravel pit

On the 1980's the outcrop was used in field trips by USU faculty. Little of the exposure remained and we worked for many years to re-excavate most of the exposure. Color highlights each liquefied unit. ALL VIEWS NORTHWARD

All views of exposure are to the NNE- little of exposure was left after ~30 years

~2012

Original photo by Robert Q. Oaks. Jr.

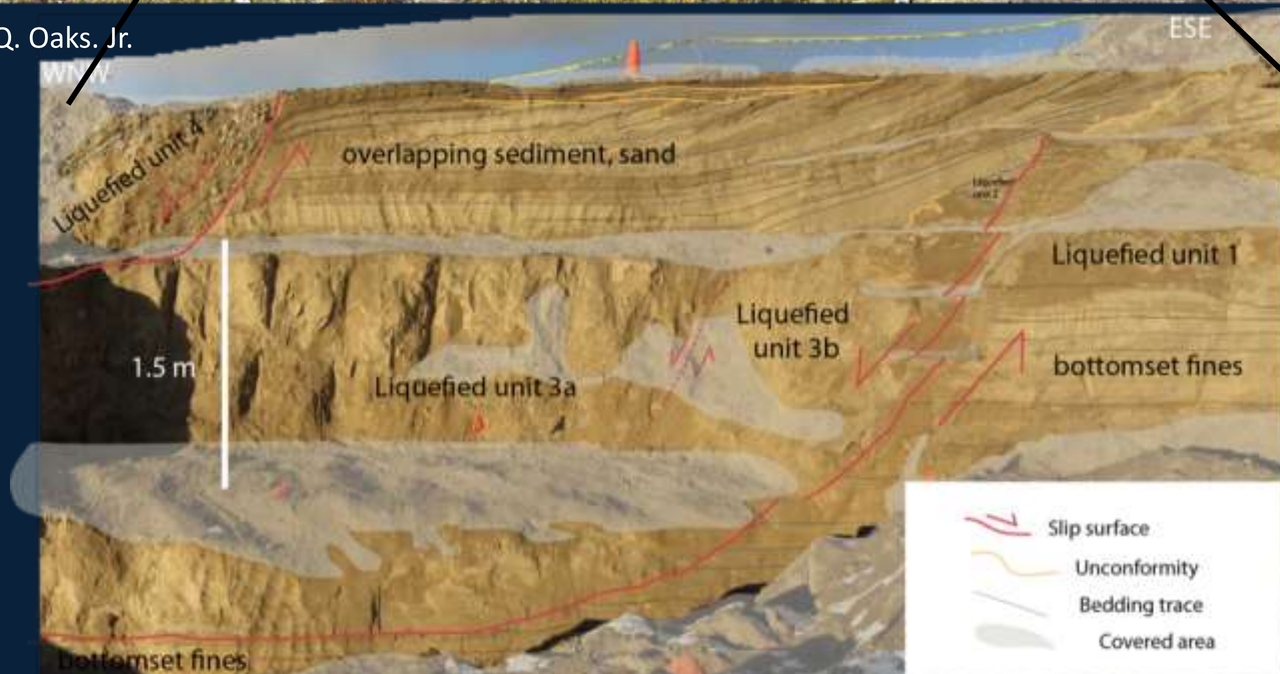
Senior thesis research of Knight and Nutt

Then

Excavation restored most of
of original outcrop- in 3 phases

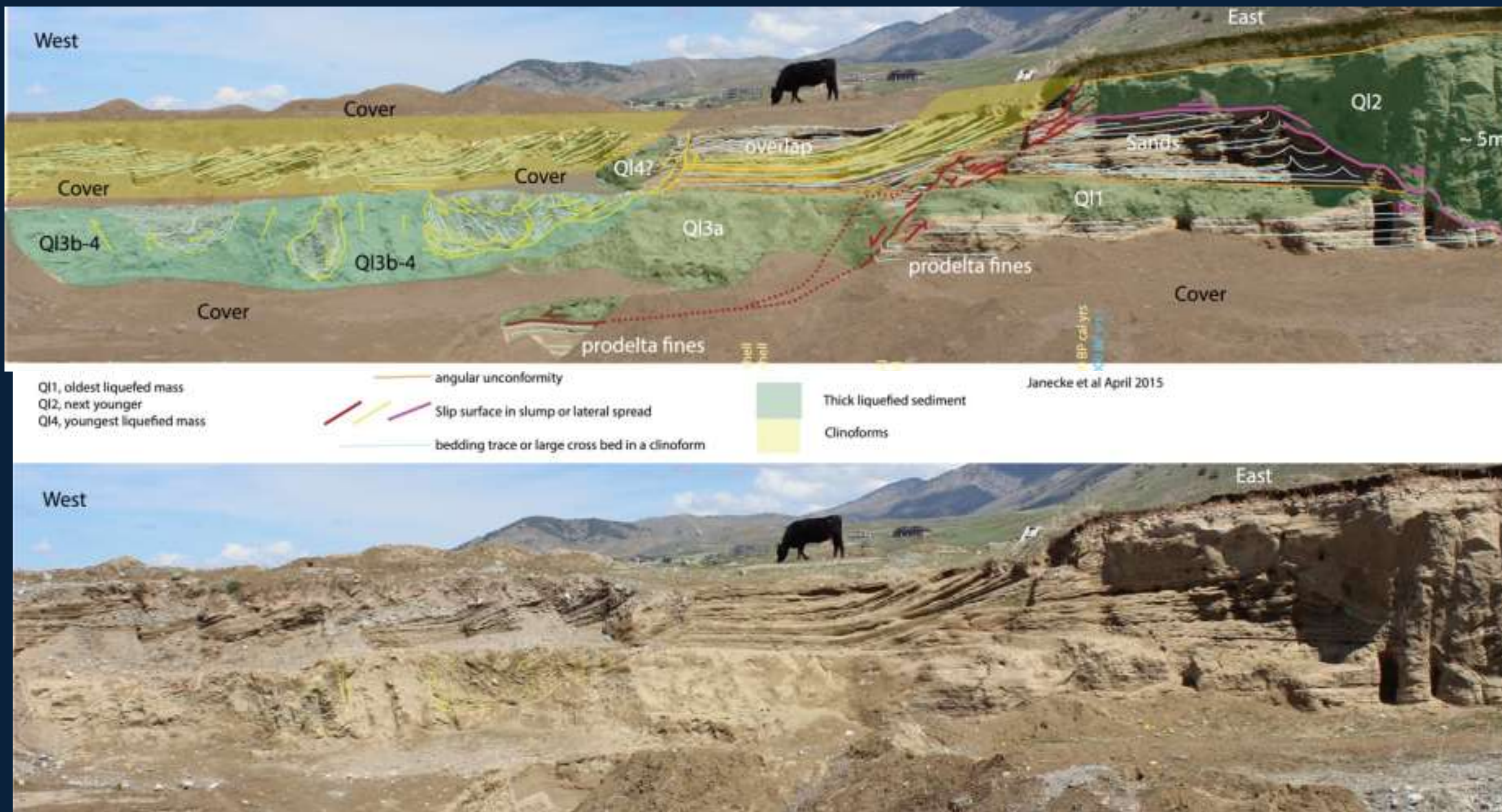
Original photo by Robert Q. Oaks. Jr.

phase 2



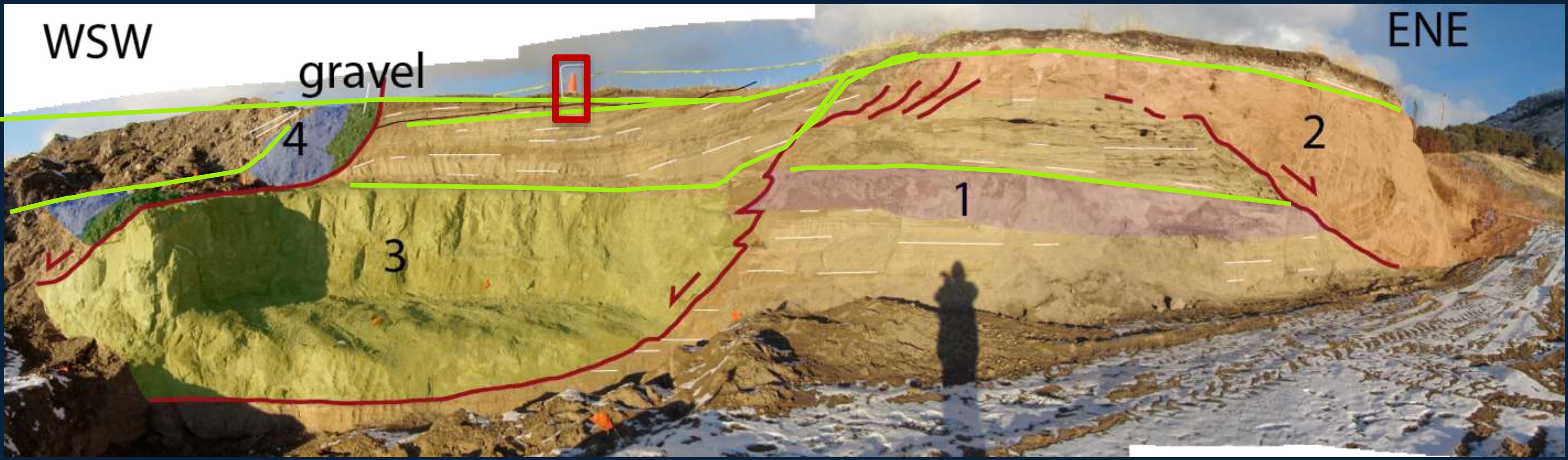
Justin Oakeson worked on the final set of excavations for his senior thesis

By 2015 most of exposure was back. We lost access before we could complete our work



It is complicated!

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



Each bench is 1.5 m high

Cross-cutting relationships show that each is a different age,

from 1-oldest to 4-youngest

Unconformities,

slip surfaces and

overlapping beds

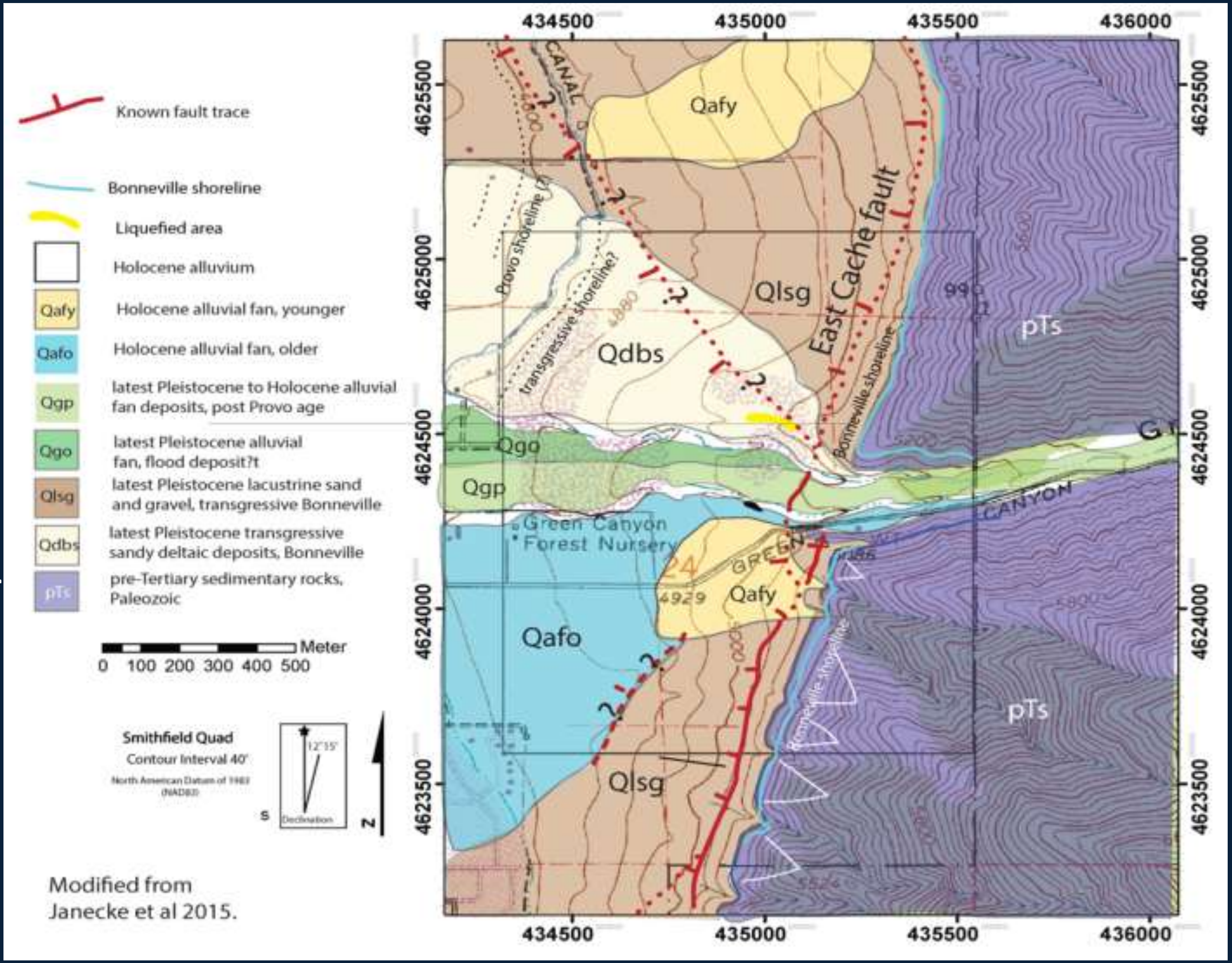
Green Canyon delta of Lake Bonneville

There are strands of East Cache fault around the site

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

and second buried strand may be closer

Erosion during Bonneville flood created an incised channel south of exposure (green units)

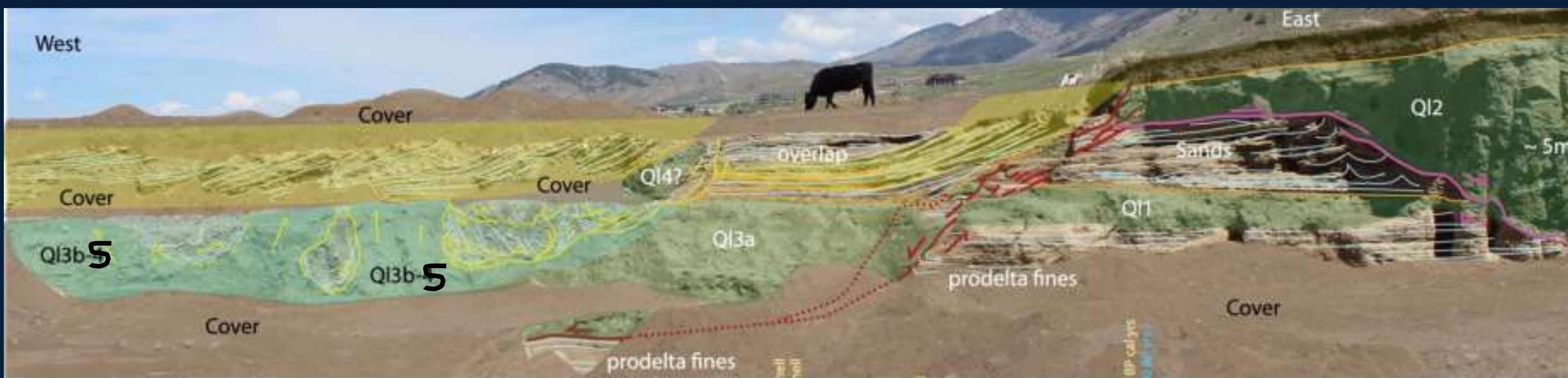


Except for capping gravel and soil, all sediment was deposited in shallow part of Lake Bonneville

Evidence:
1. Gastropod shell,
2. ripples,
3.cross beds,
4.sedimentary facies,
5.radiocarbon and OSL ages

Gastropod shells are common in sandy deltaic beds

Outcrop contains complex relationships and repeated deformations



Ql1, oldest liquefed mass
Ql2, next younger
Ql4, youngest liquefied mass

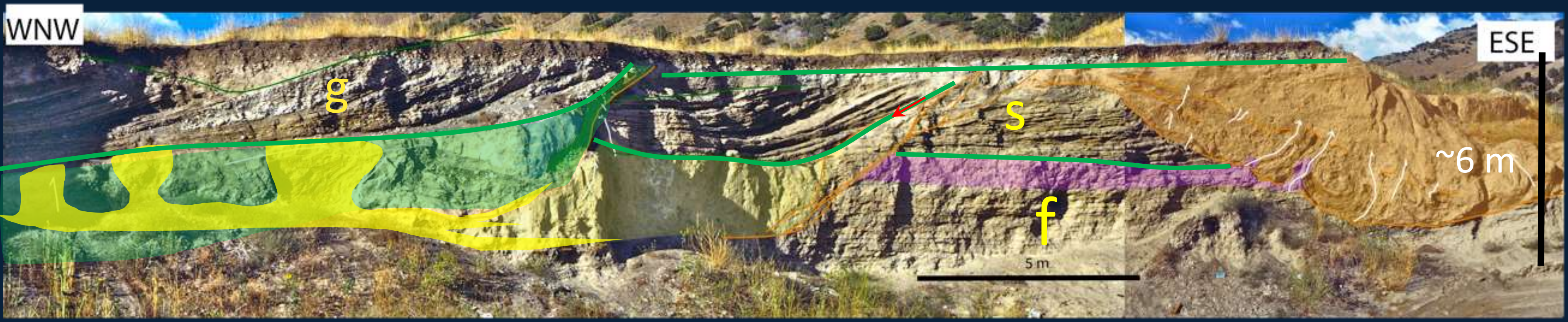
angular unconformity
Slip surface in slump or lateral spread
bedding trace or large cross bed in a clinoform

Thick liquefied sediment
Clinoforms

Janecke et al April 2015

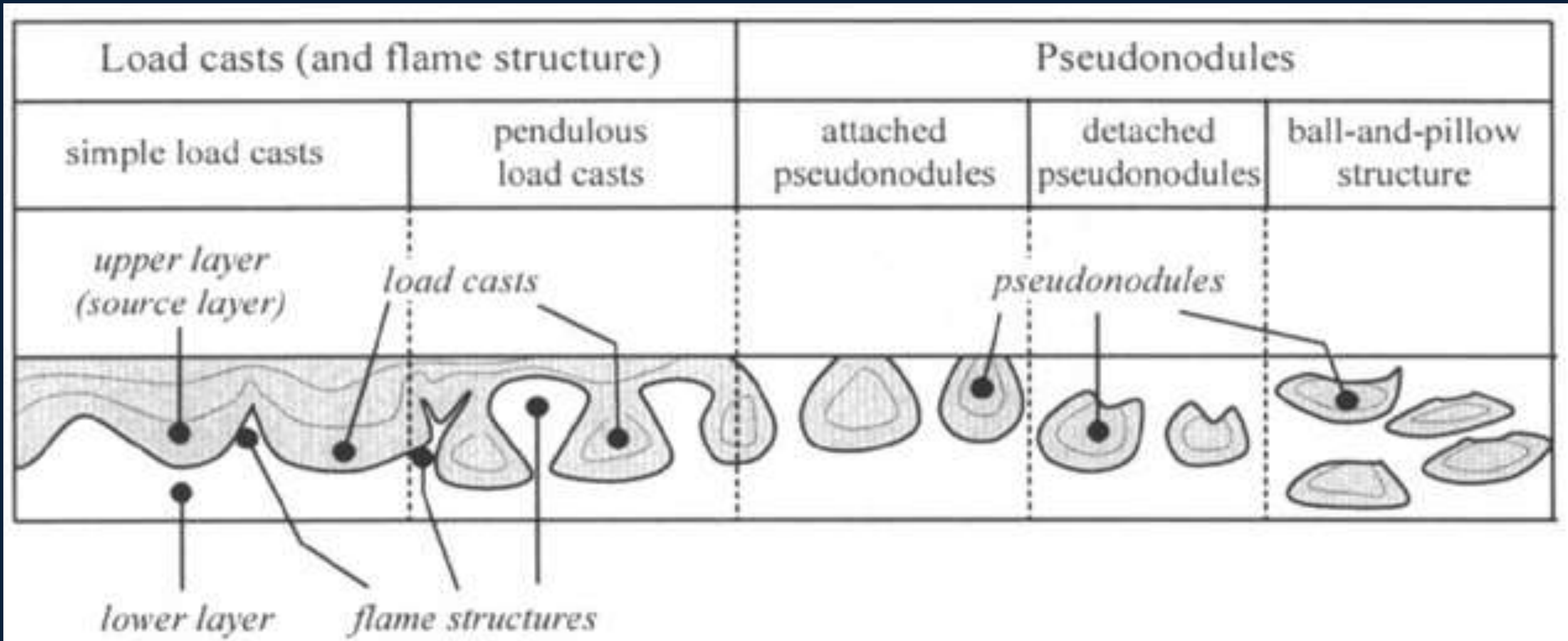
Stratigraphy

Then



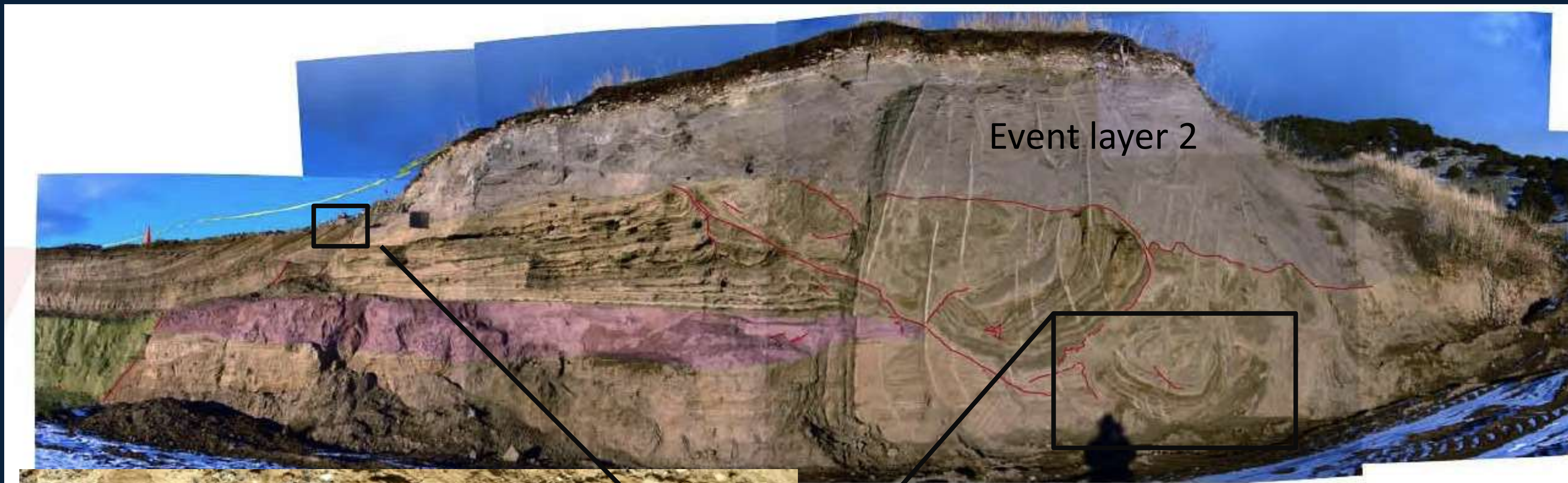
- Undeformed cap of alluvial gravel, flood-related (?)
- over deformed Bonneville deltaic sand (s) and gravel (g)
- over deformed Bonneville prodelta fine sand, silt and clay (f, fines)
- Separated by several unconformities and SLUMPS
- Deltaic gravelly clinoforms gravel (g) are not deformed

The liquefied beds are full of round features called pseudonodules, flames, fluid escape structures and load casts

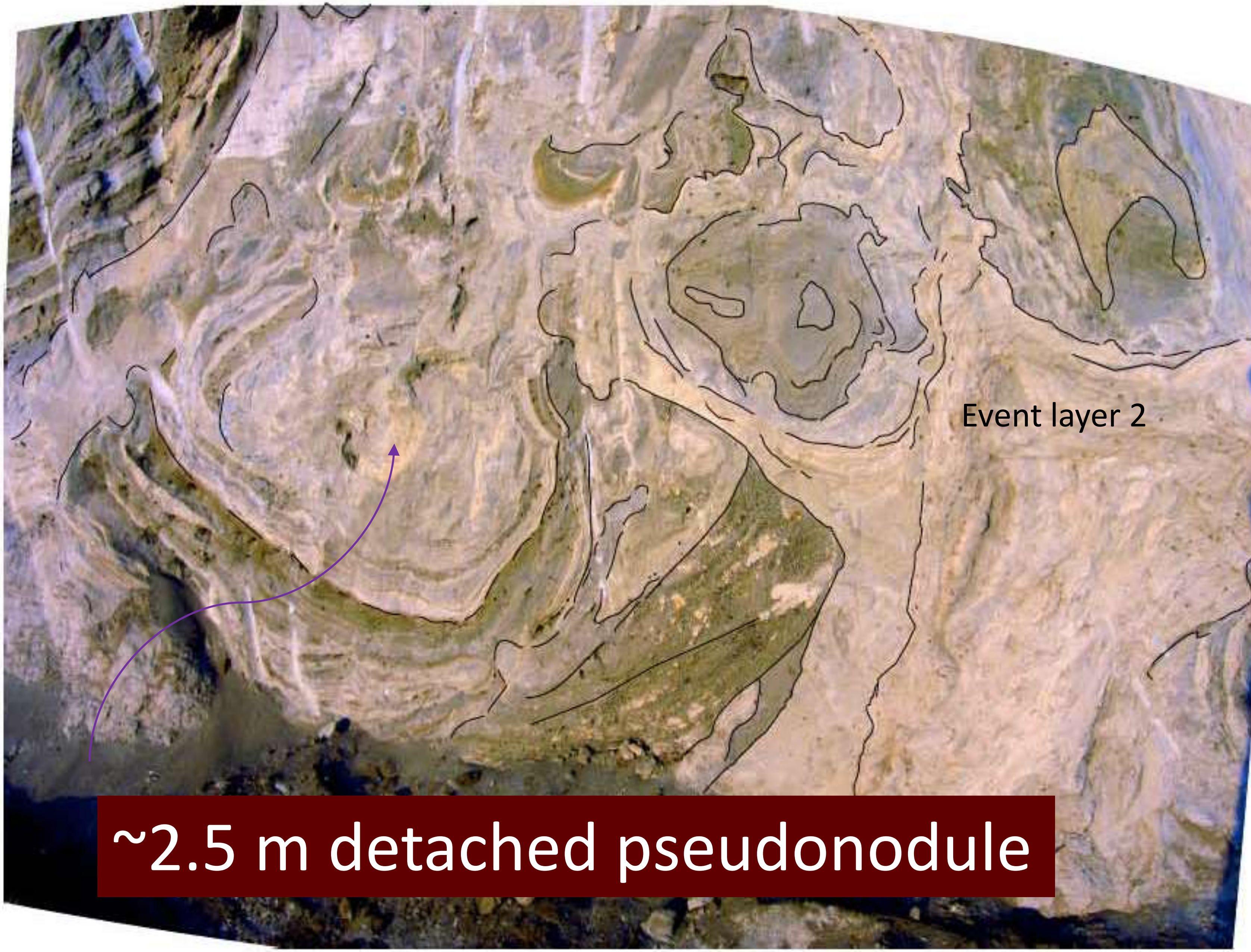


Owen, 2003

Thickest liquefied bed is ~5 m thick

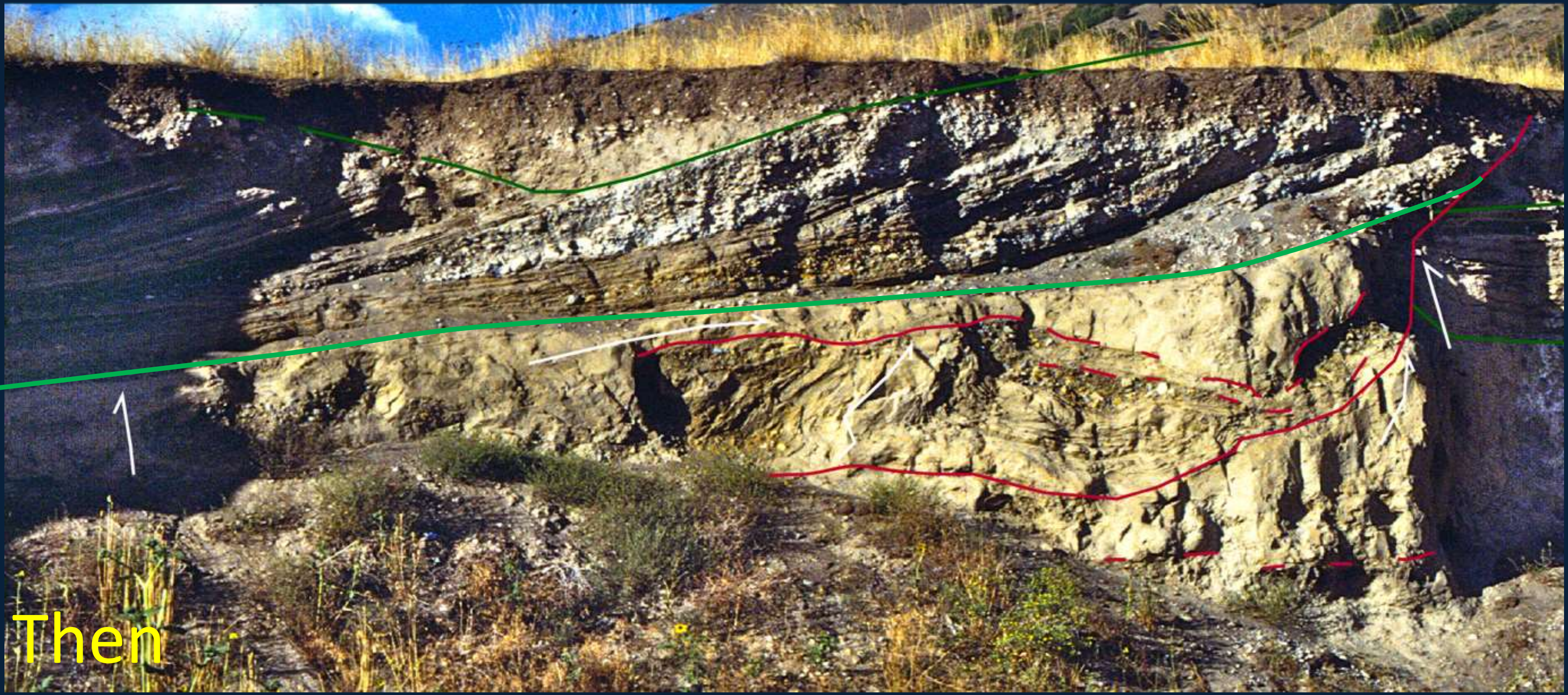


~2.5 m detached pseudonodule


Event layer 2
~2.5 m detached pseudonodule

Many flames and sand dikes

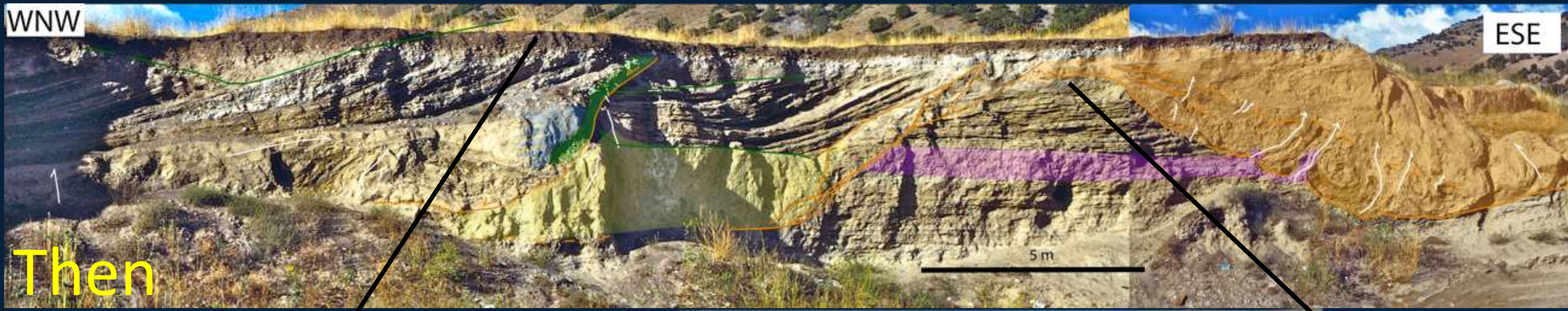
An erosion surface marks the top of each Liquefied event bed (except maybe #2)

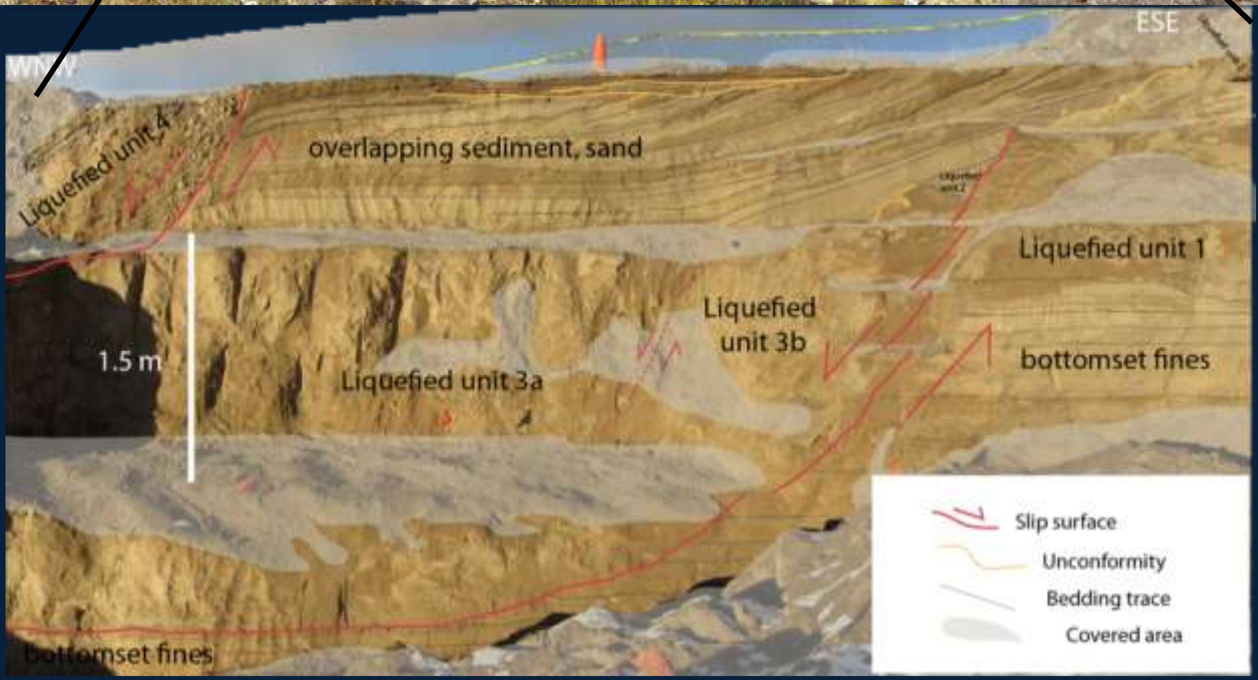


Common elements-cross cutting relationships and erosion surfaces above liquefied beds (green)


Event layer #1

All the deformation occurred during Bonneville transgression,
-before the flood,
-before gravel cap and clinoforms
-and BEFORE incision of channel south of exposure





RESULTS of phase 1:

1. All deformation dates from the Bonneville transgression-within 50 m of Bonneville high-stand

2. No record of an earthquake at the time of the Bonneville flood

3. All “faults” are slip surfaces in nested slumps of lateral spreads

Let’s tour through some of the data

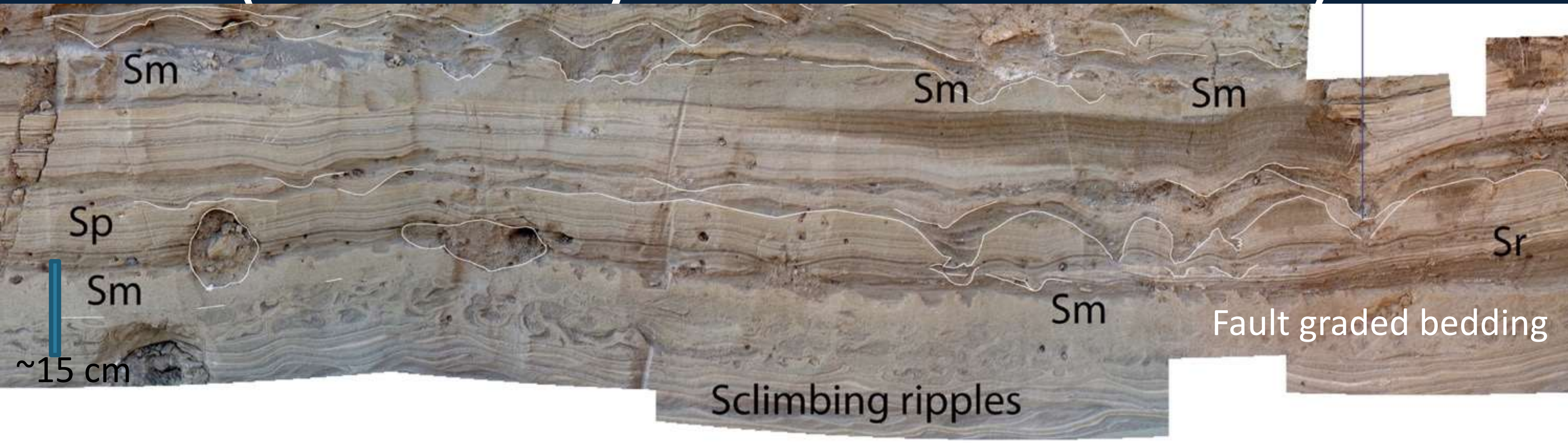
- Deltaic transgressive sand of Lake Bonneville
- Contain 4 thick liquefied units and >=5 events
- That formed sequentially

Overlapping succession between event bed # 3 and event bed #4

- are not as deformed as liquefied beds,
- but are cut by slump
- and exhibit mild soft sediment deformation

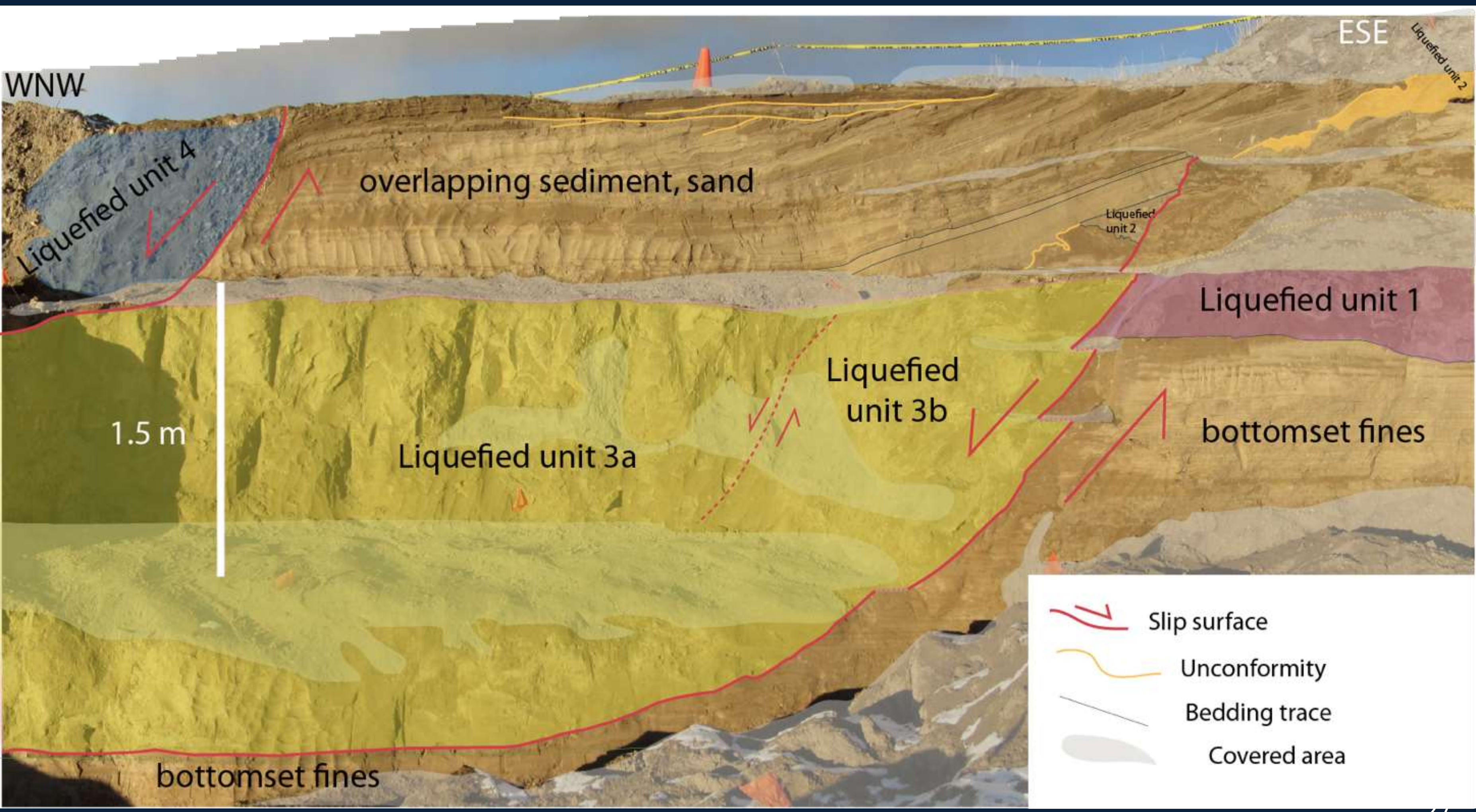
Angular unconformities in overlap succession

"Mild" deformation, including fault-graded beds (which may reflect aftershocks)

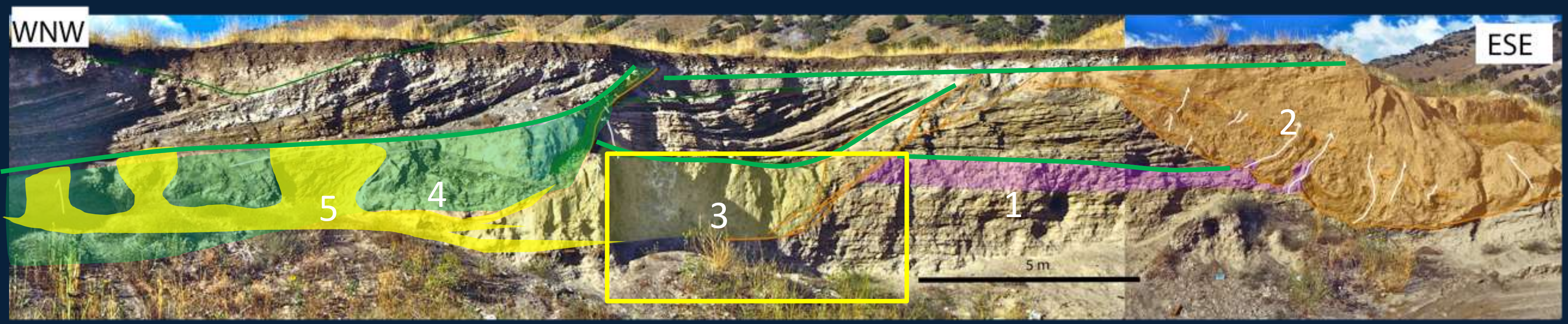


Overlap succession is draped across scarps on bed of Lake Bonneville

Liquefaction and slumping are linked



There is a slip surface below all major liquefied masses except the purple one



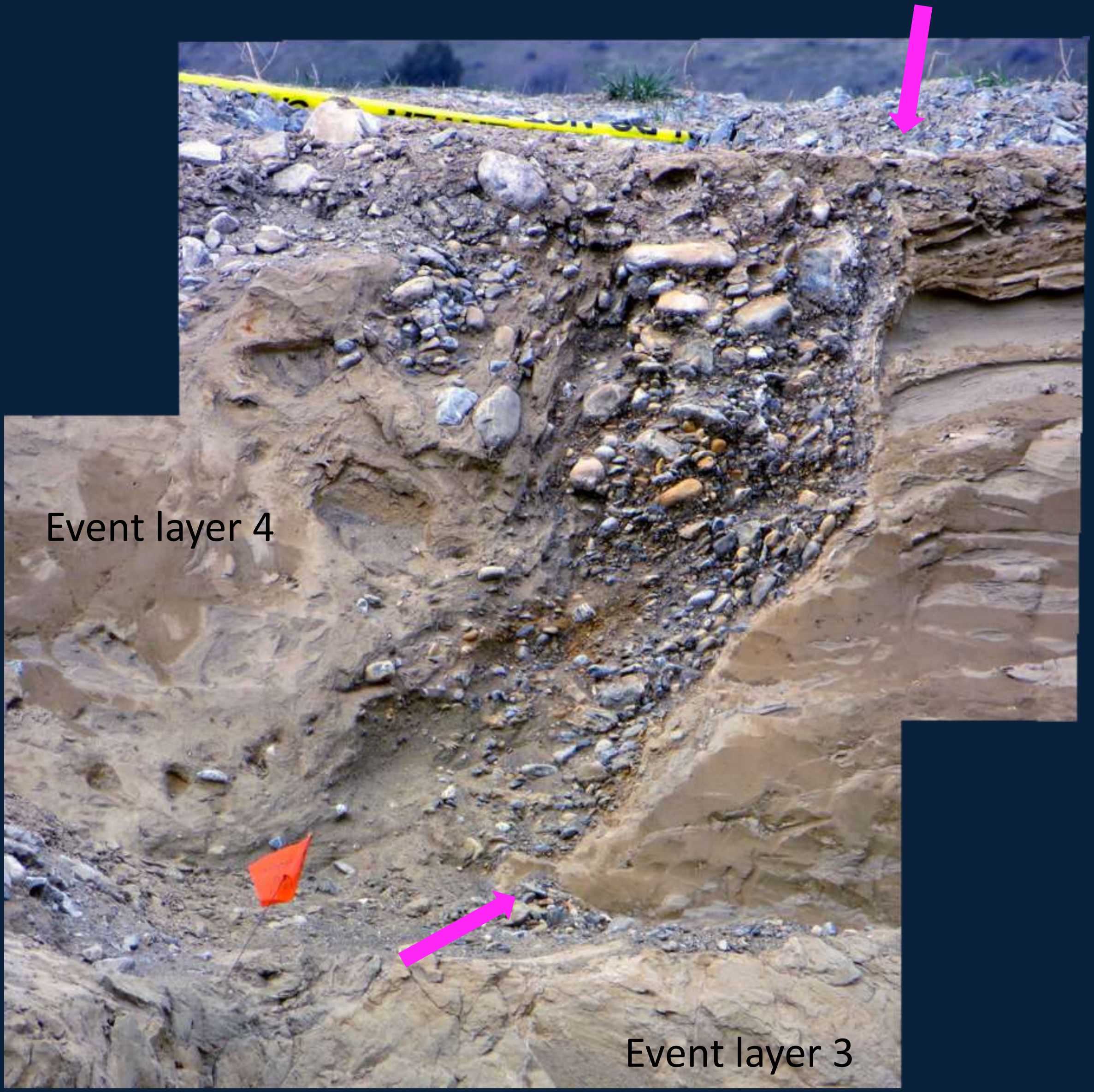
Even green event bed has a slip surface below it.
That surface was deformed by yellow diapirs

Slip surfaces flatten into clay layers of pro-delta fines SLUMP in lateral spread

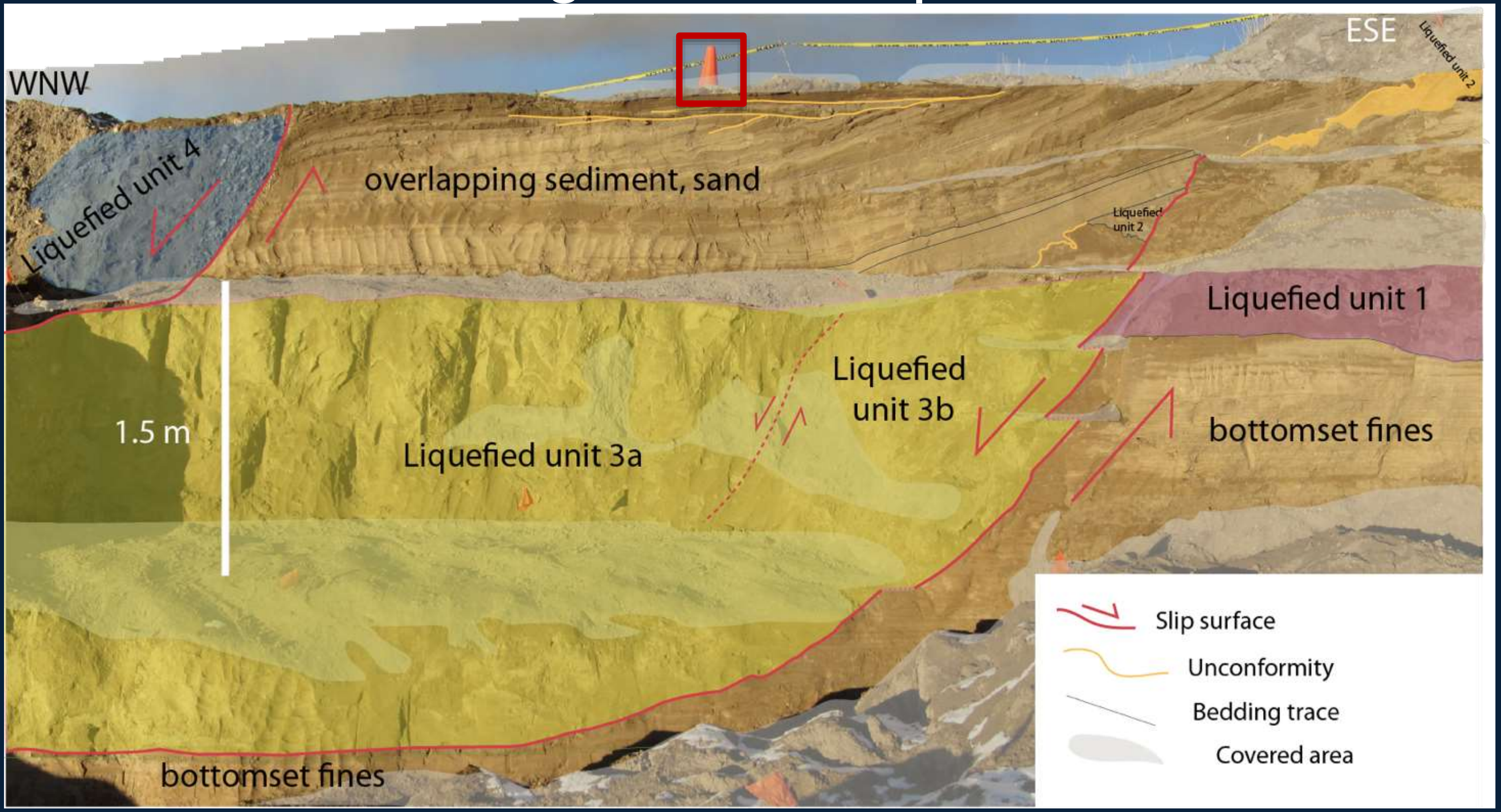
Basal slip surface of one lateral spread

About 1.5 m high

Youngest slump: Listric slip surface with gravel and massive liquefied sand in it hanging wall



Relative ages are very clear due to cross-cutting relationships like these



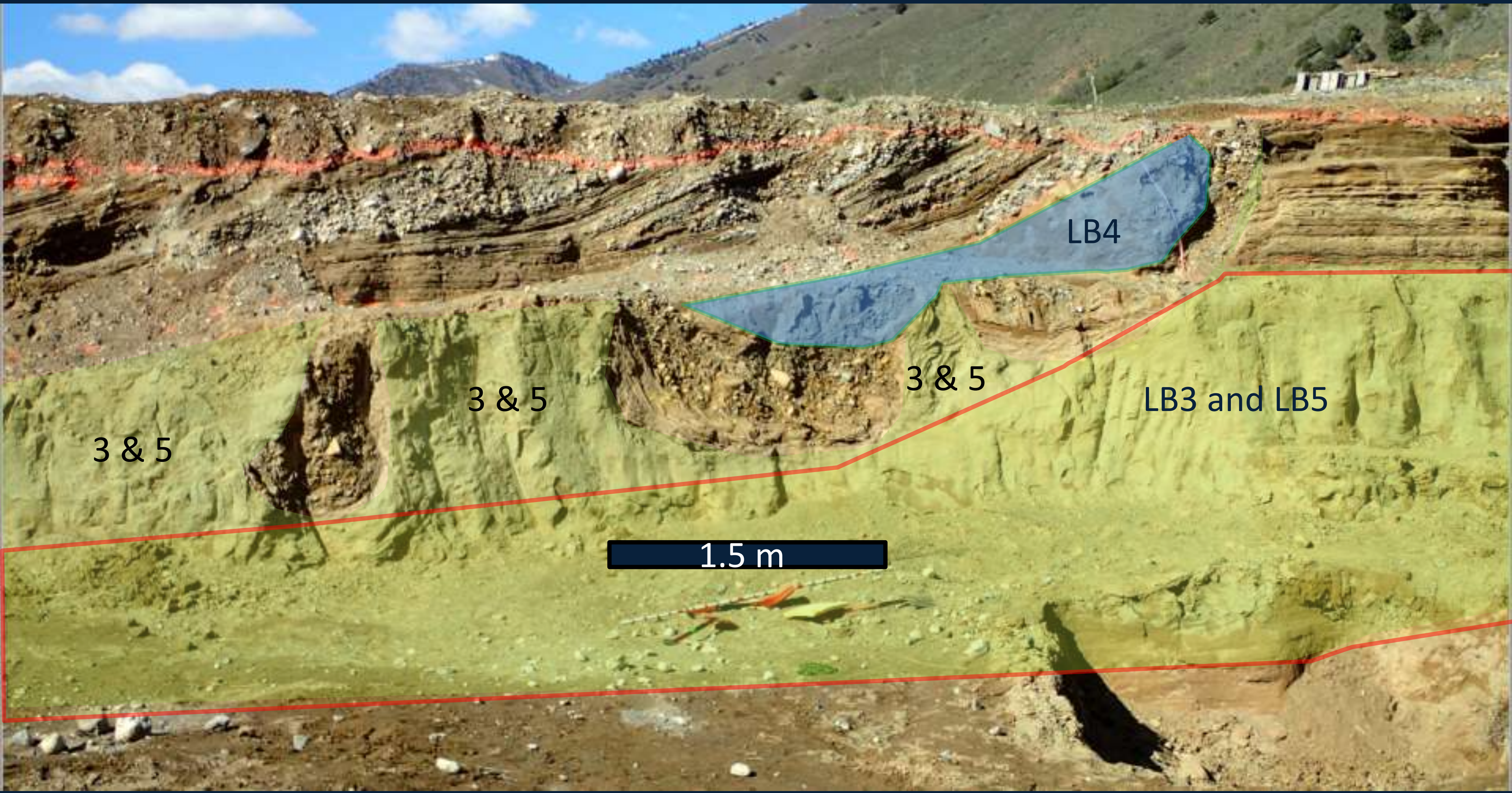
Detailed Chronology:

Each bench is 1.5 m high

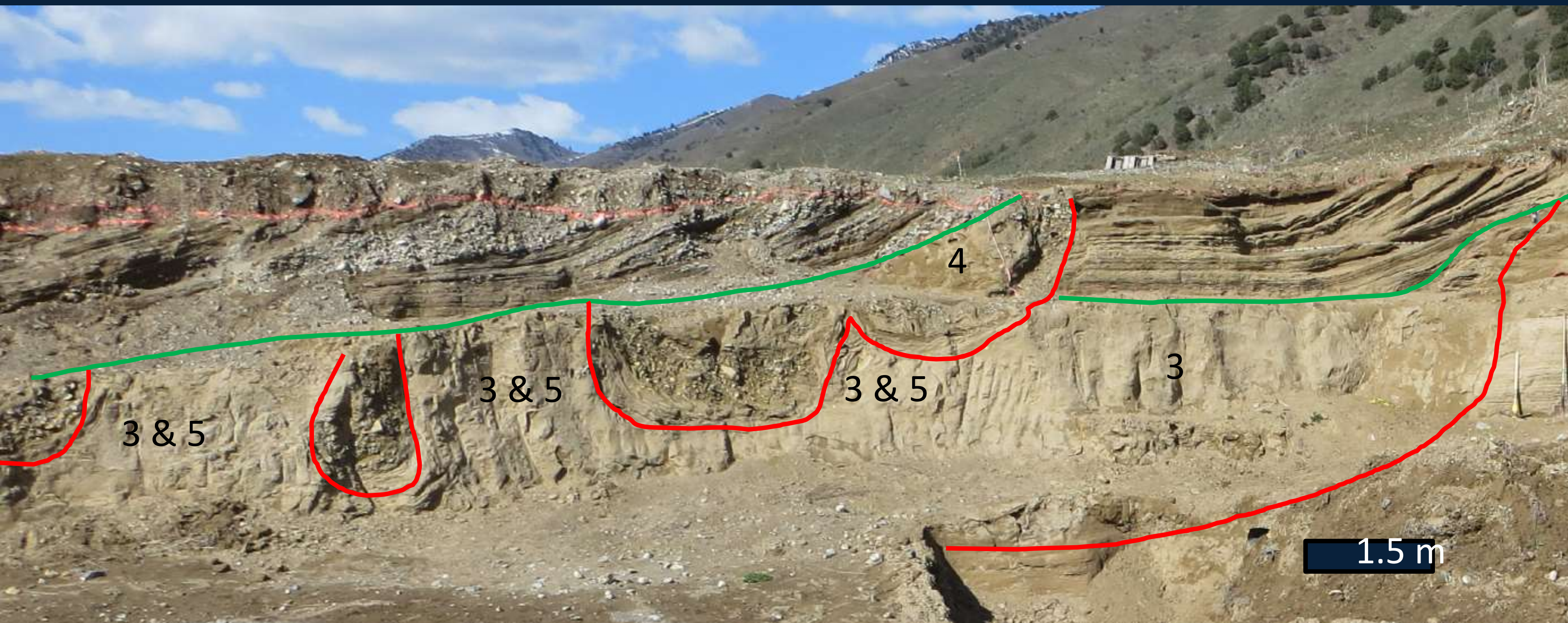
- Lake rises to ~ 40 m below the high stand
- Event bed number 1, possibly after a brief regression
- Erosion of liquefied bed 1
- Deposition of more lake beds
- Event bed 2 ± lateral spreading
- Deposition of more lake beds
- Event 3 and slip surface

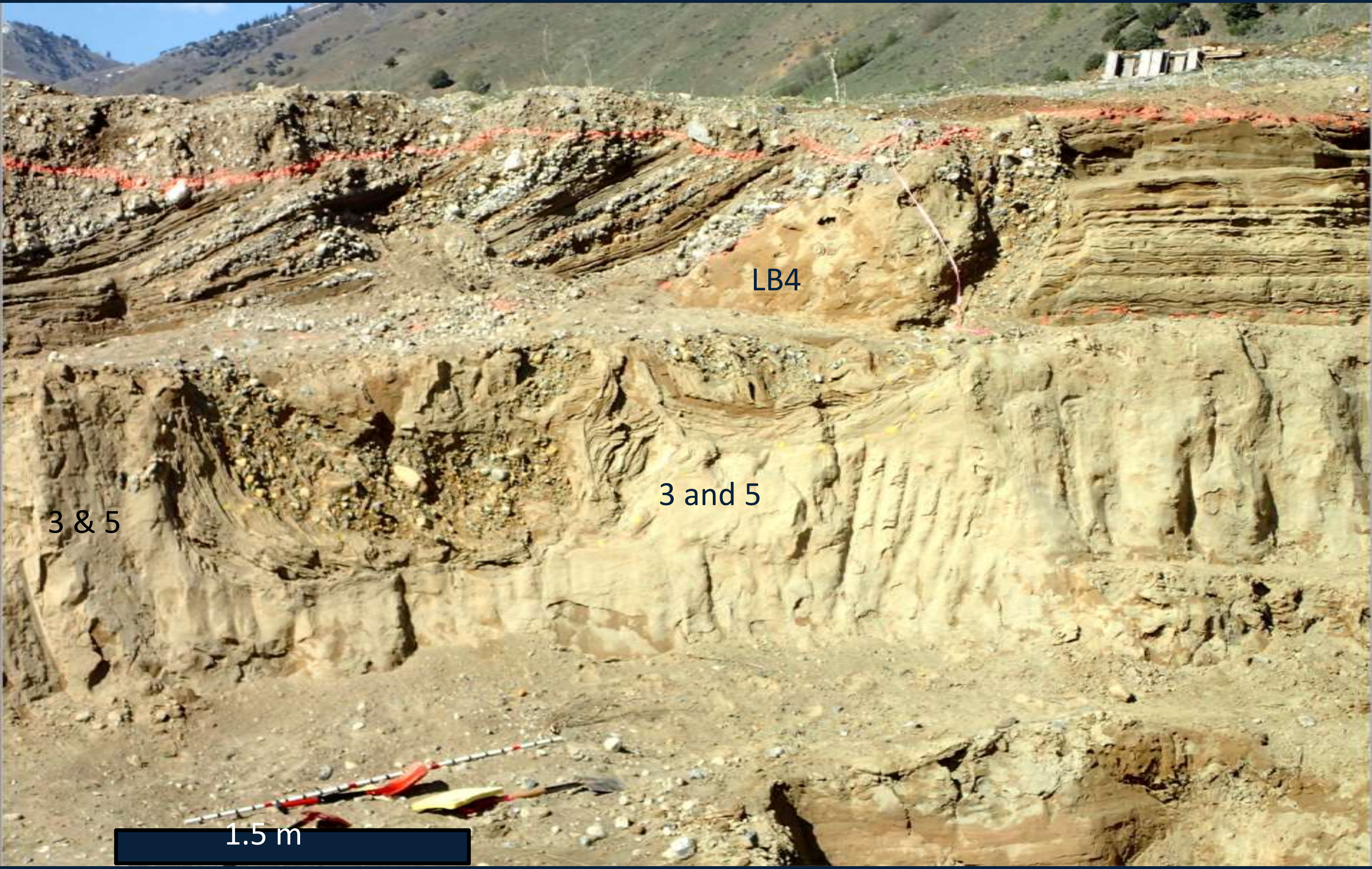
- Overlap beds (OB) are deposited across lateral spread
- A new slump forms, cuts overlap and event 3 bed
- Event bed 4 formed at the same time above the western slip surface
- More deltaic deposition,
- Bed 3 is liquefied 2nd time, it forms diapirs up through Event bed 4!=Event 5

West area exposes a diapiric succession- Event layer 3 deformed twice



Diapirs reflect reliquefaction of event layer 3---- cool



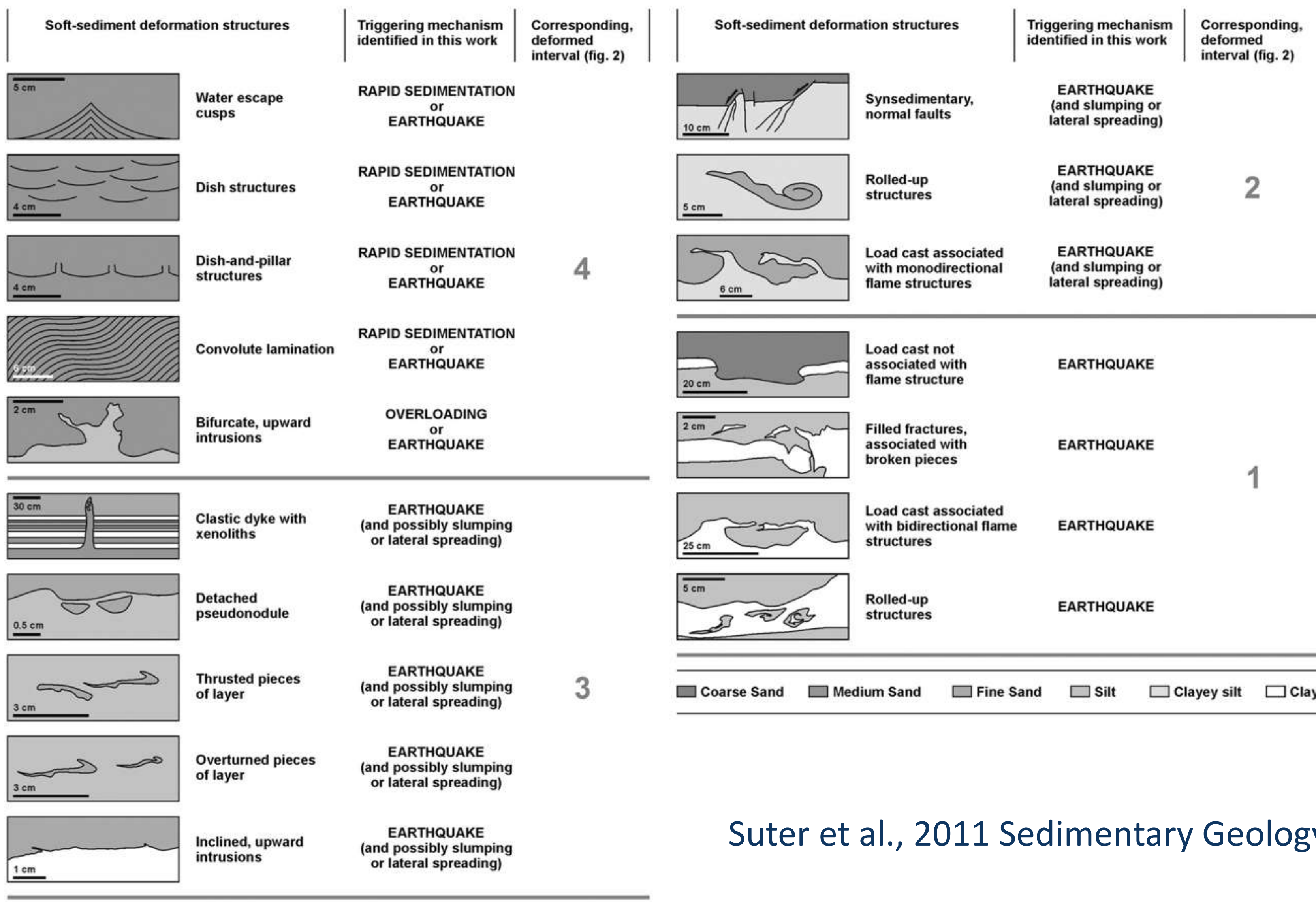

LB4
3 and 5
3 & 5
1.5 m

Why do we conclude that these are seismites?

Lateral spreads and liquefied masses are often activated by earthquakes

Lateral spread triggered by 1964 Alaska earthquake
USGS pics

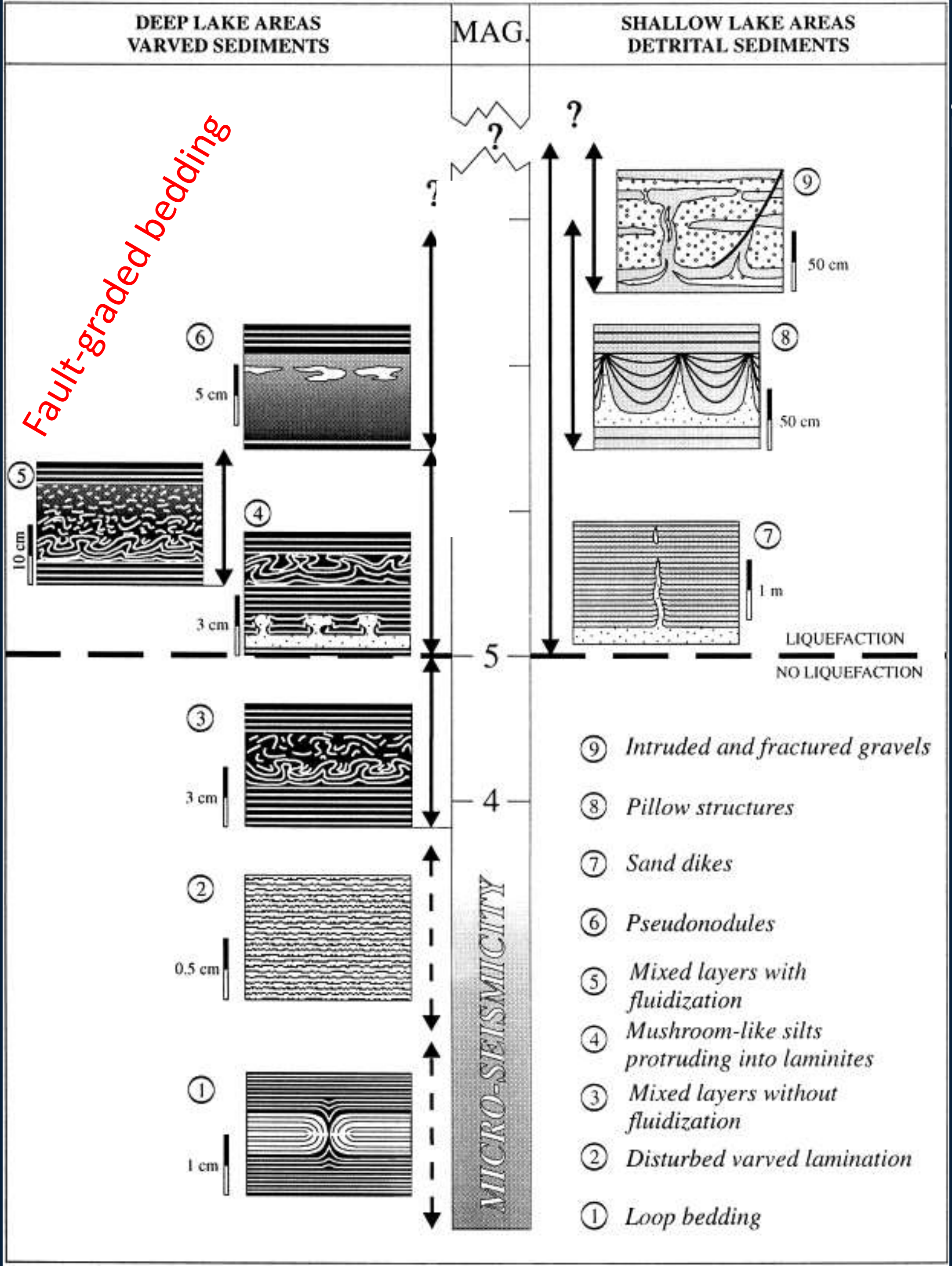
Some features only form during earthquakes



F. Suter et al. / Sedimentary Geology 235 (2011) 188–199

Suter et al., 2011 Sedimentary Geology

Fig. 7. Summary of the 17 types of soft-sediment deformation structures found in each of the 4 deformed intervals of the Aeropuerto section, with their respective triggering mechanism identified in the scope of this study. Numbers correspond to the deformed interval they belong to, labelled in Fig. 2. Soft-sediment deformation structures appear in stratigraphic order, except for deformed interval no. 3, where the clastic dyke crosscuts the entire deformed interval.

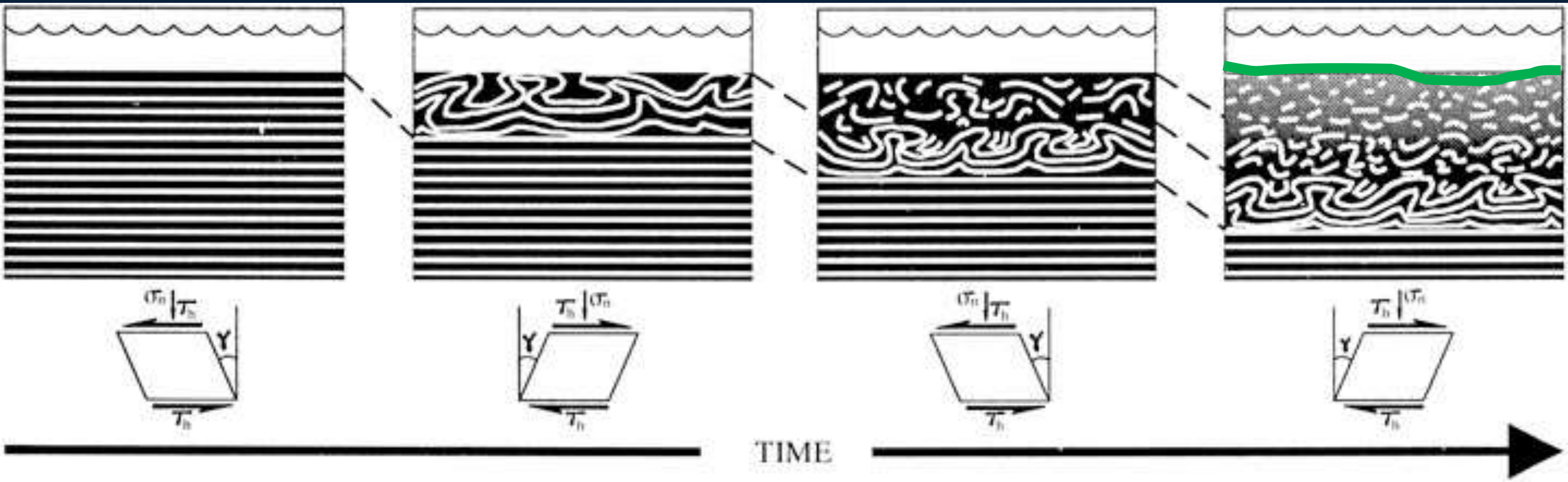


Fault-graded bedding is diagnostic of shaking of a body of water

Intensity of deformation has been related to earthquake magnitude

Modified from
Rodriguez et al., 2000

Fault-graded bedding is diagnostic of seismic shaking of a lake bed



Step 5: We would add erosion of lake bed
- result from a seiche?

Rodriguez et al., 2000

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

- Features consistent with seismite interpretation
  - – Location near E Cache Flt.
  - – Great thickness of structureless, liquefied beds
  - – Injections, sand dikes and sills
  - – The G.C. delta seems too small and gentle for such massive and repeated collapses
  - – "Fault-graded bedding" is common
  - – Fluid escape across brittle faults from oscillatory conditions
  - – Hansel Valley earthquake produced similar liquefaction, slumping and lateral spreads (Robison, McCalpin)
  - – Repeat events
  - – Sand volcano and sand dikes

41

Fault-graded-bedding of event layer 2

1980's outcrop

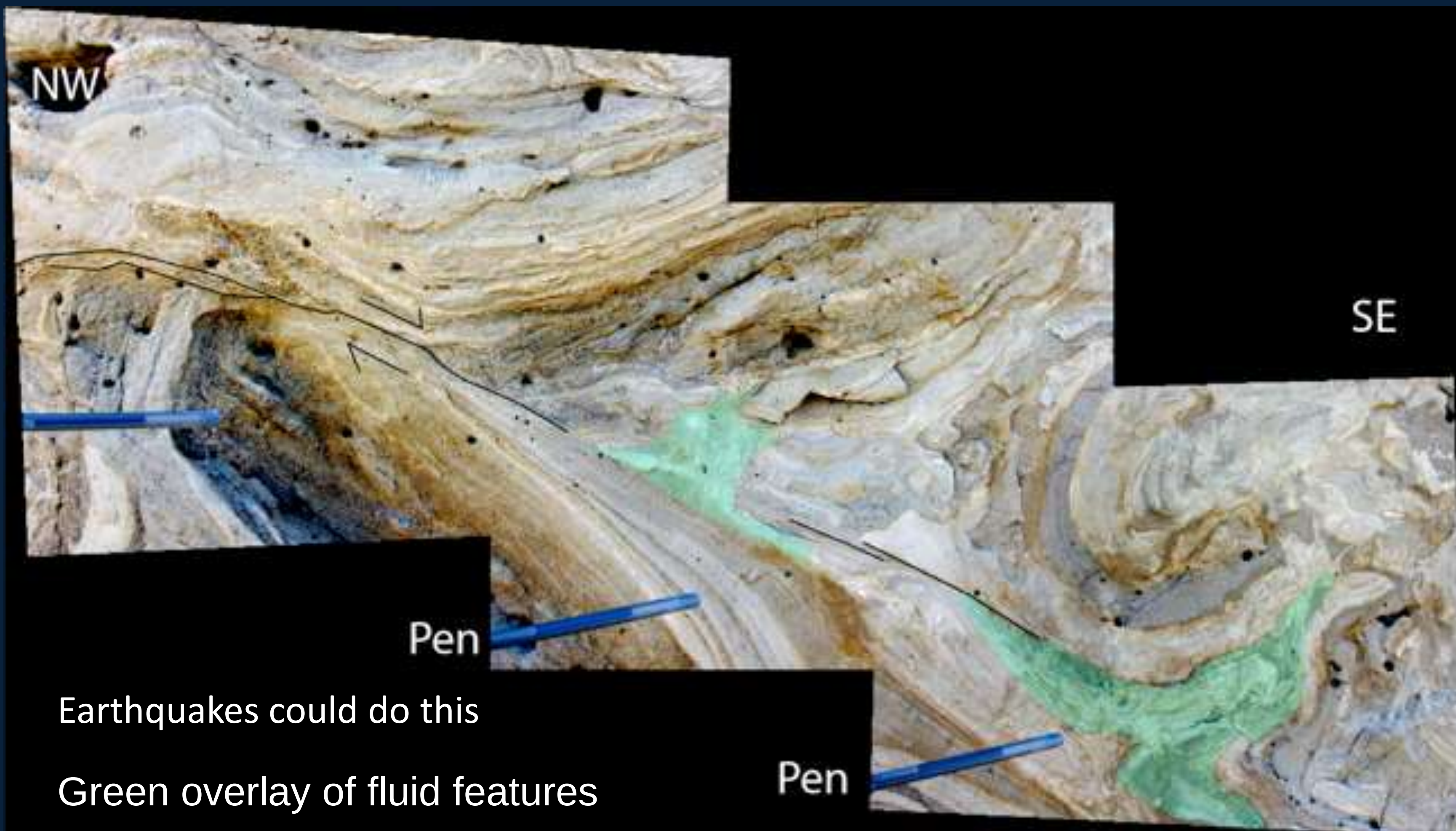
Fluid-escape paths are white

~5-6 m high exposure, 1980s

20 cm high sand volcano

Brittle faults and escaping fluids require high strain rates

Fluid escape across brittle slip surfaces consistent with oscillatory conditions



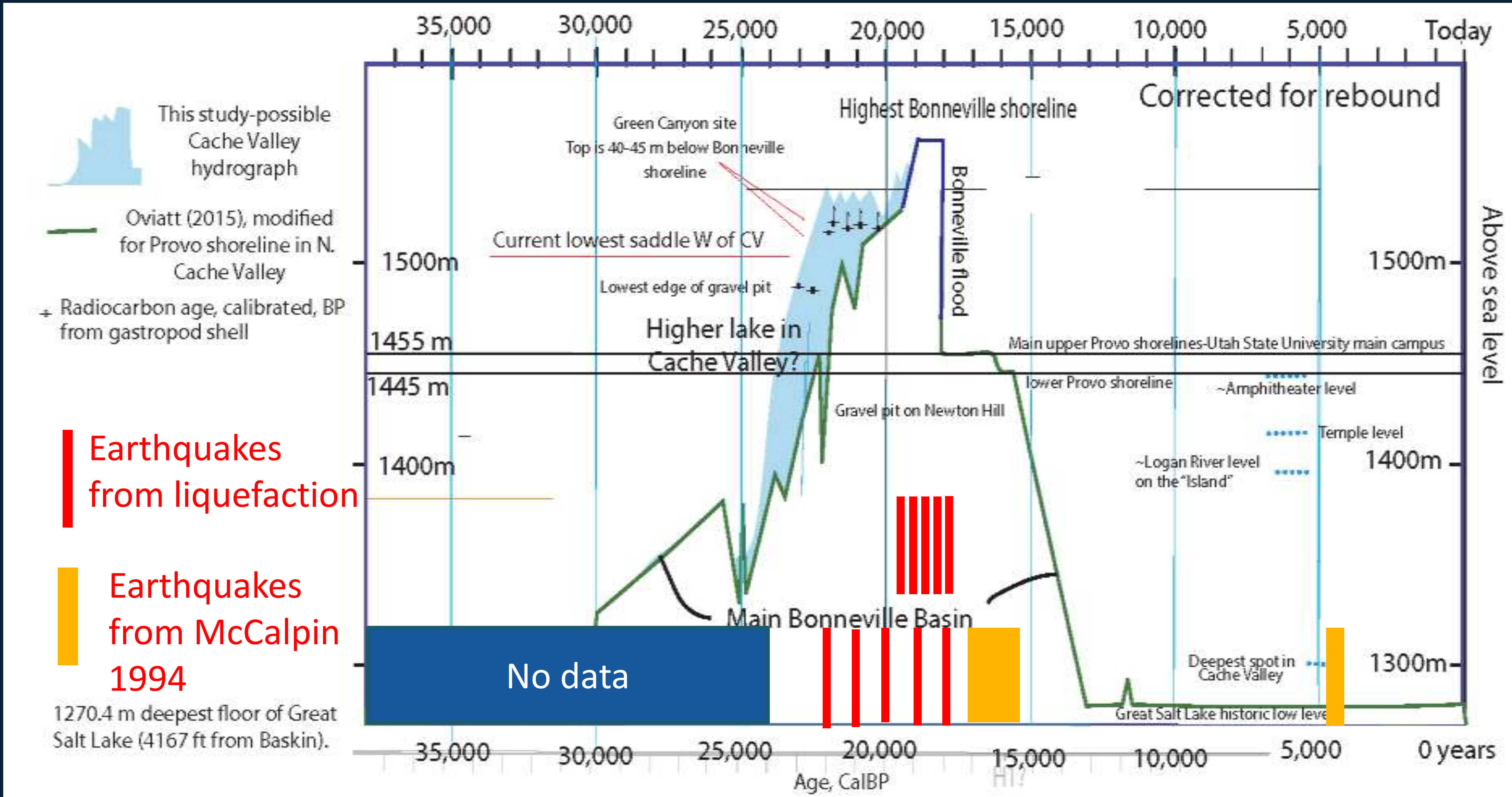
Earthquakes could do this

Green overlay of fluid features

At least 5 strong earthquakes are recorded during highstand of Bonneville

How clustered were the earthquakes along ECFZ?

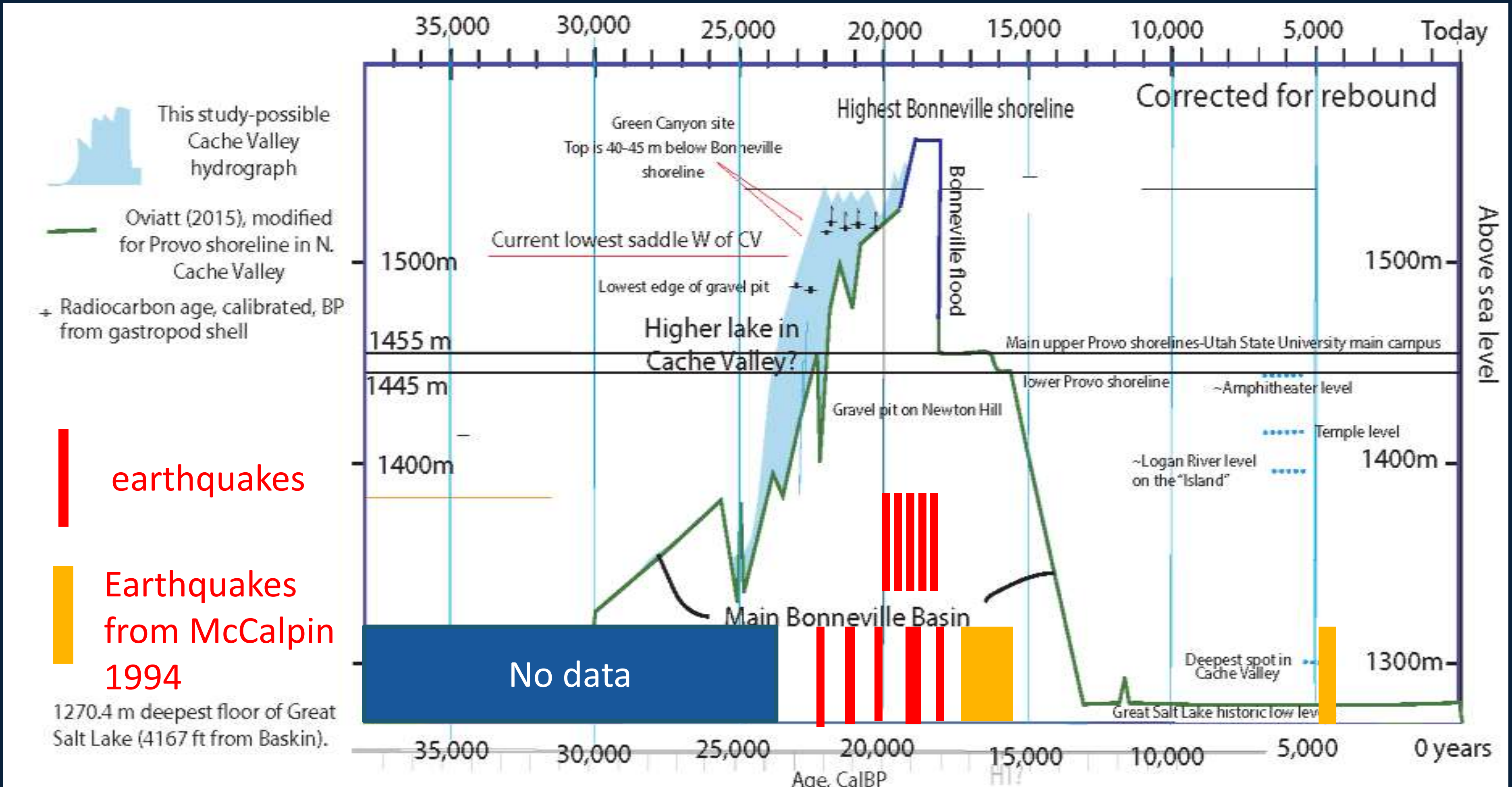
46



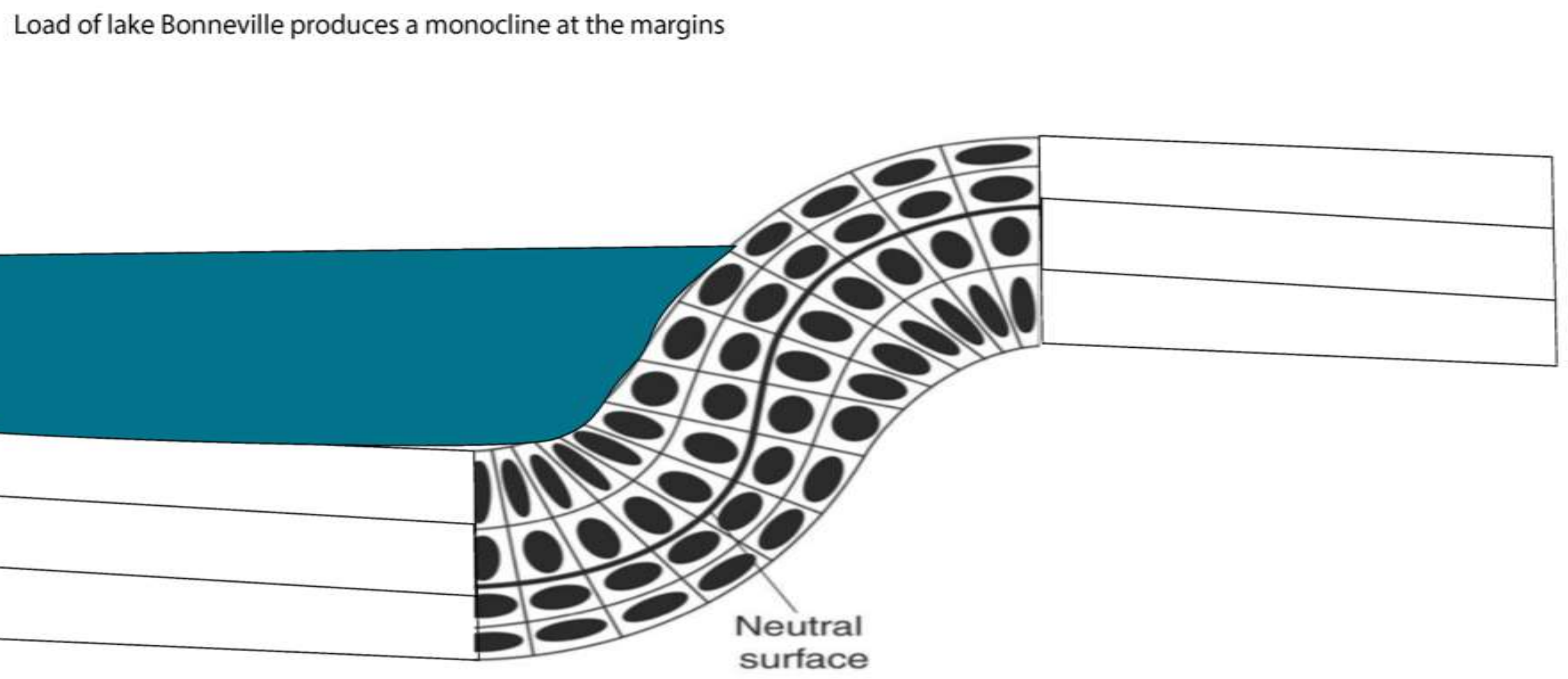
2-6 ky for 6 large eqs depending on hydrograph of Cache Valley (7 Radiocarbon ages from gastropods are all higher and older than Bonneville in published hydrographs). Two options

Jänecke et al., UQFPWG Feb 2019 SLC

• Only one earthquake in Holocene along entire ECF!
• Exact opposite of Wasatch fault zone (Hampel and Hetzel, 2005).
• Exact opposite of West Cache fault zone-(Black et al, 2000; +later part of this talk)

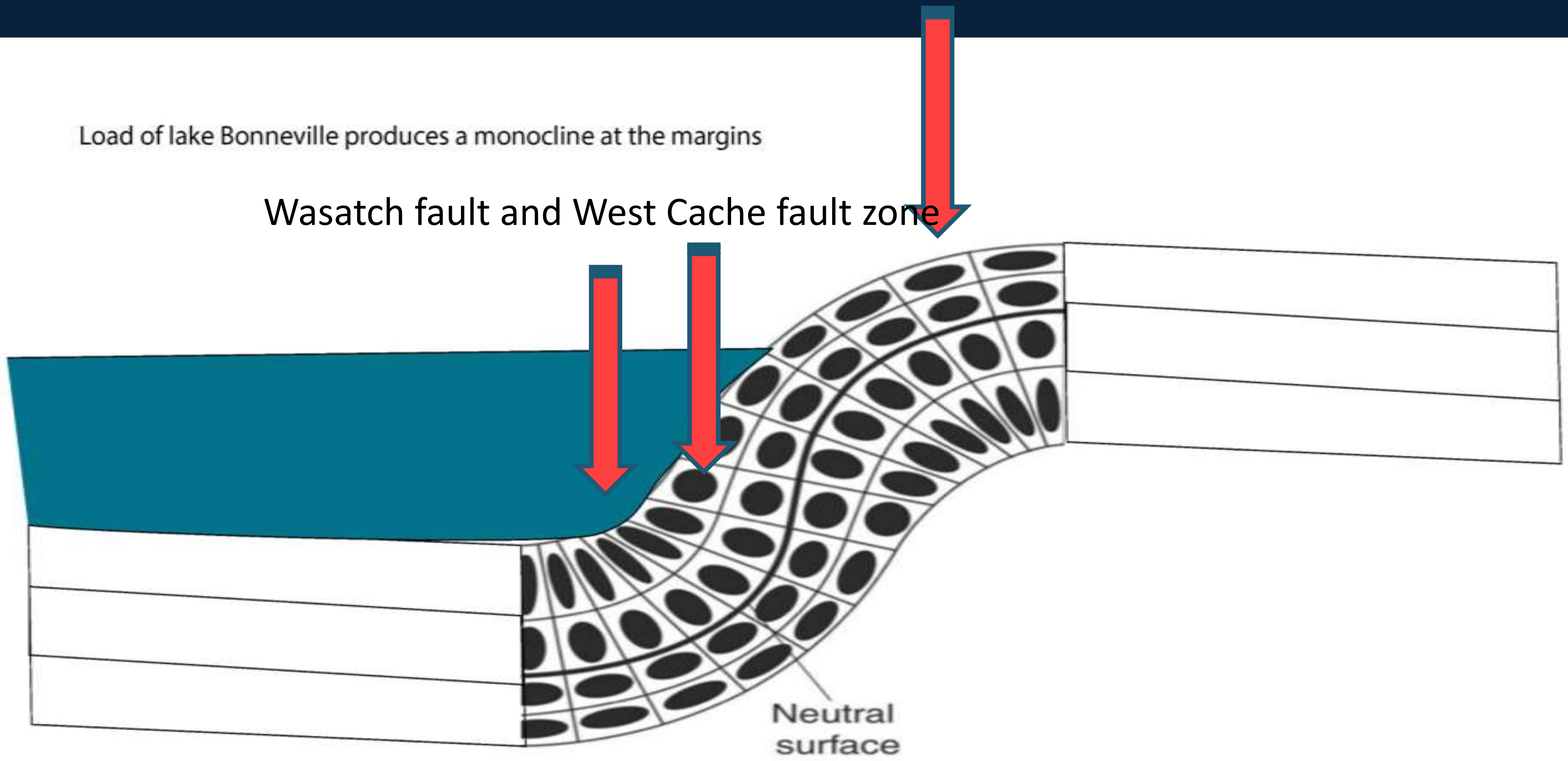


Why did earthquakes clustered when lake was high? Hampel and Hetzel 2005 suggest an answer: Loading by Lake Bonneville, flexure stresses



Much vertical exaggeration, view north

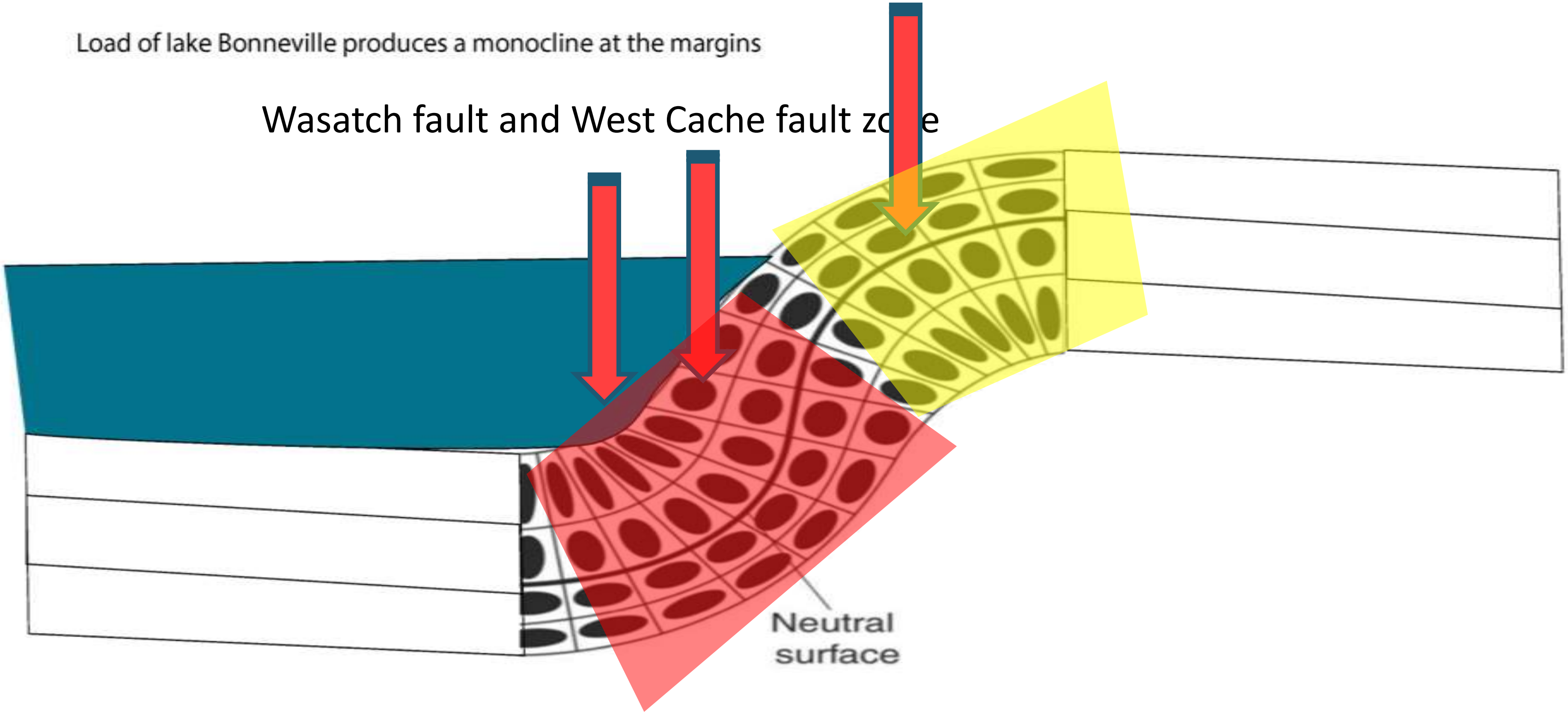
Upper hinge is zone of enhanced upper crustal extension during pluvial



Much vertical exaggeration

Load of Lake Bonneville produces two belts of deformation that are out of sync

East Cache fault zone

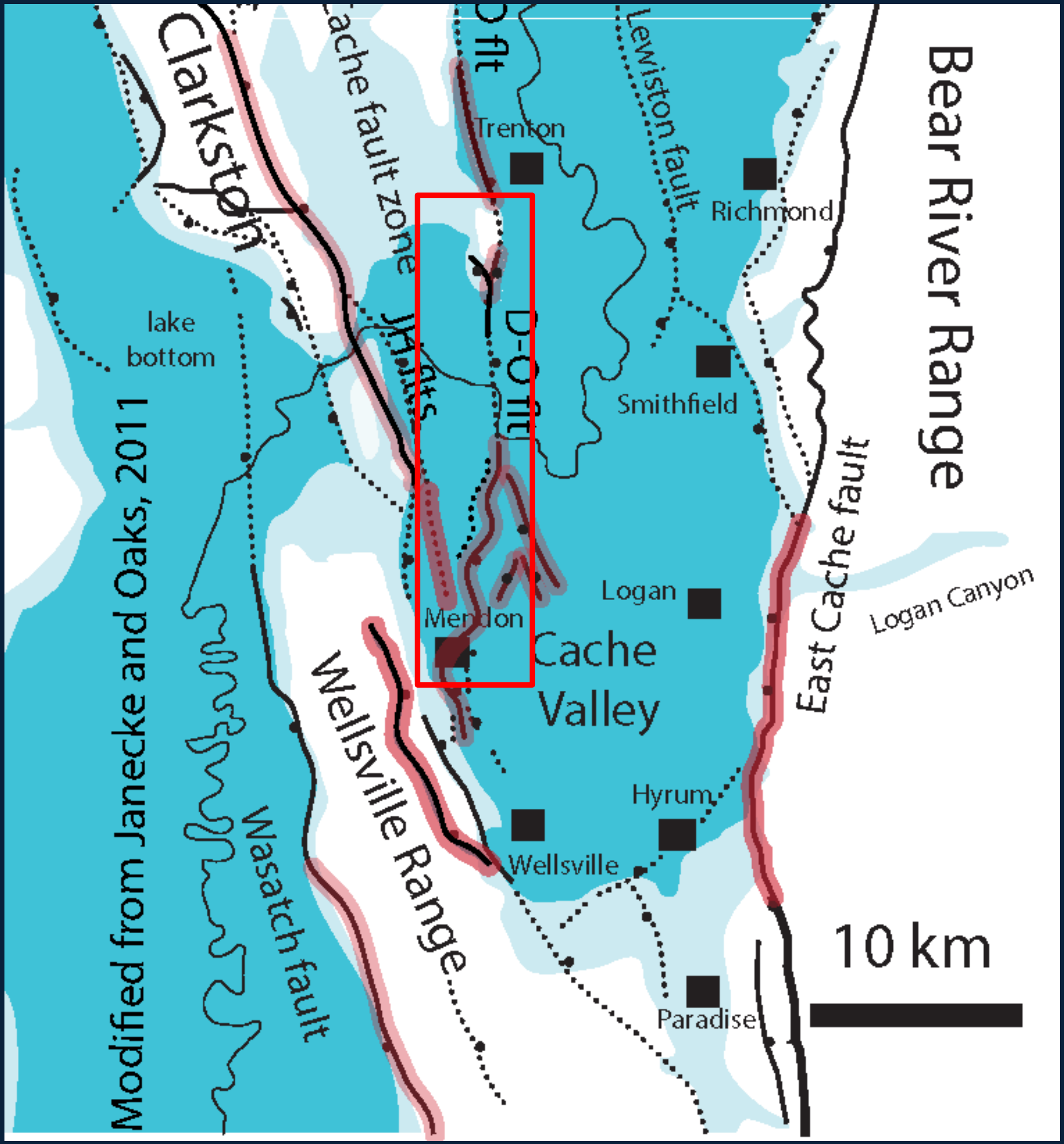


Much vertical exaggeration

2: New active faults of the West Cache fault zone revealed by LiDAR

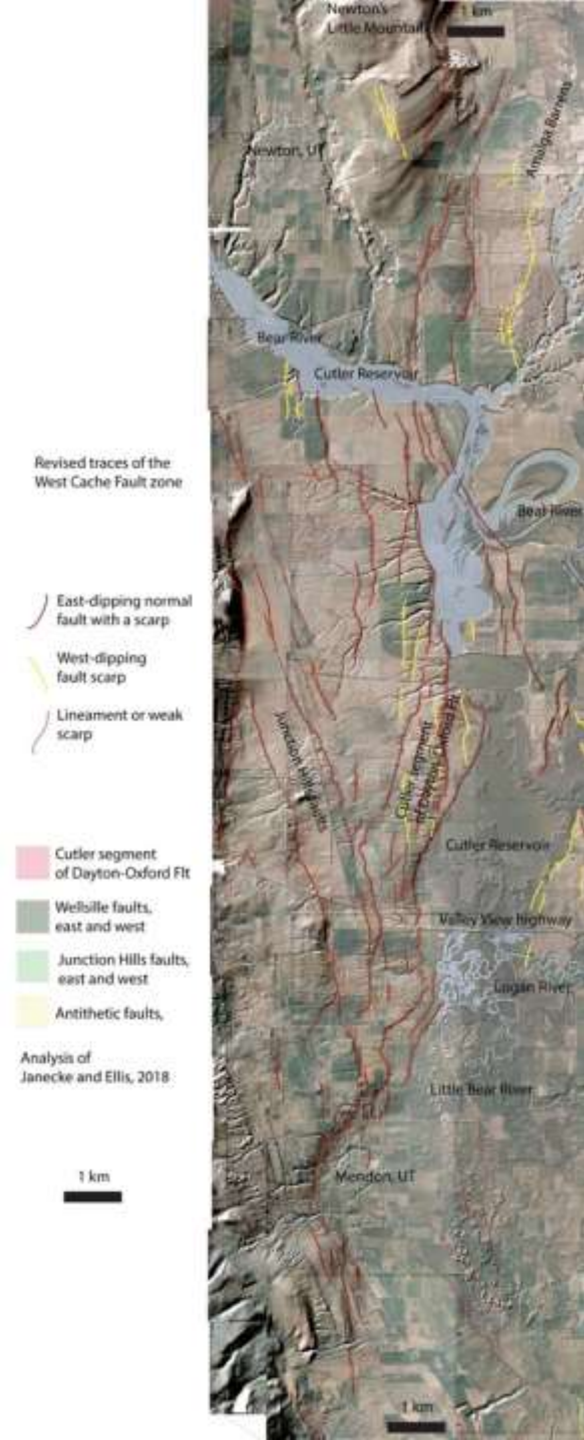
Susanne Janecke
Nathan Ellis
Robert Q. Oaks, Jr.

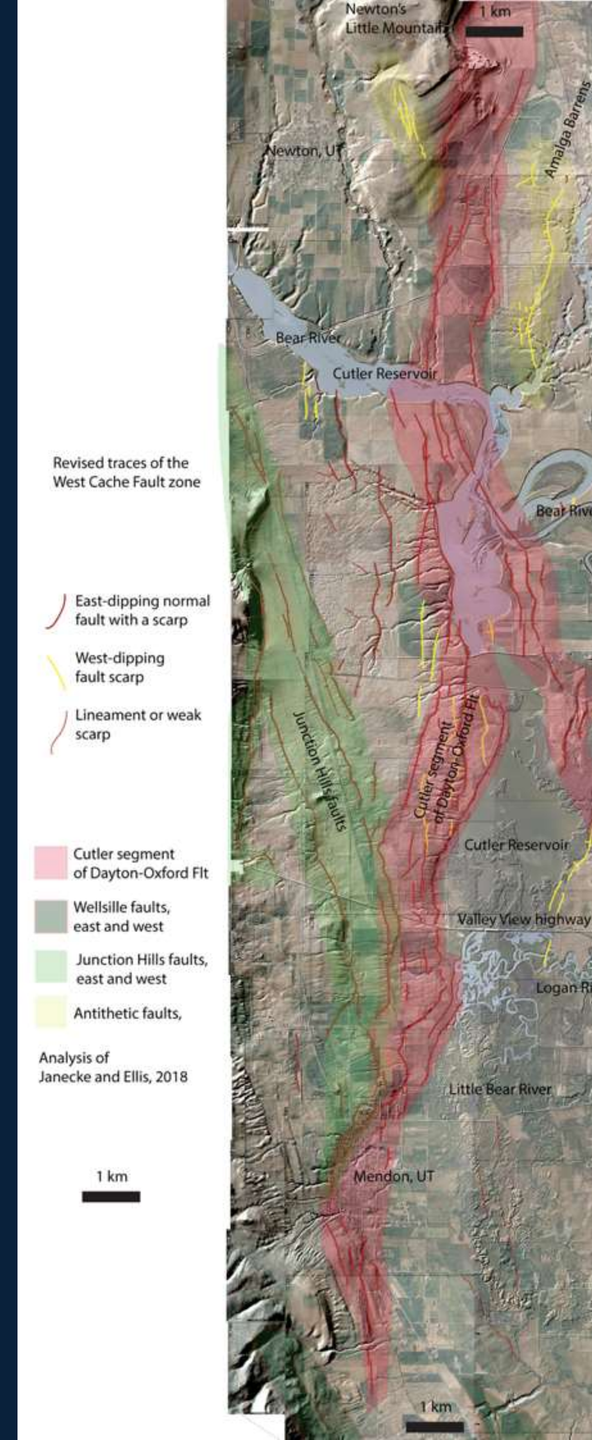
Red segments had Holocene eqs Black et al., 2000; Ellis and Janecke, 2018; this study)



Talk will focus on area in red rectangle

Modified from Janecke and Oaks, 2011


Newton's Little Mountain
1 km
Newton, UT
Amalga Barrens
Bear River
Cutler Reservoir
Revised traces of the West Cache Fault zone
Bear River
East-dipping normal fault with a scarp
West-dipping fault scarp
Lineament or weak scarp
Junction Hills faults
Cutler segment of Dayton-Oxford Flt
Cutler Reservoir
Cutler segment of Dayton-Oxford Flt
Wellsille faults, east and west
Junction Hills faults, east and west
Antithetic faults,
Valley View highway
Logan River
Analysis of Janecke and Ellis, 2018
Little Bear River
1 km
Mendon, UT
1 km


Newton's Little Mountain
1 km
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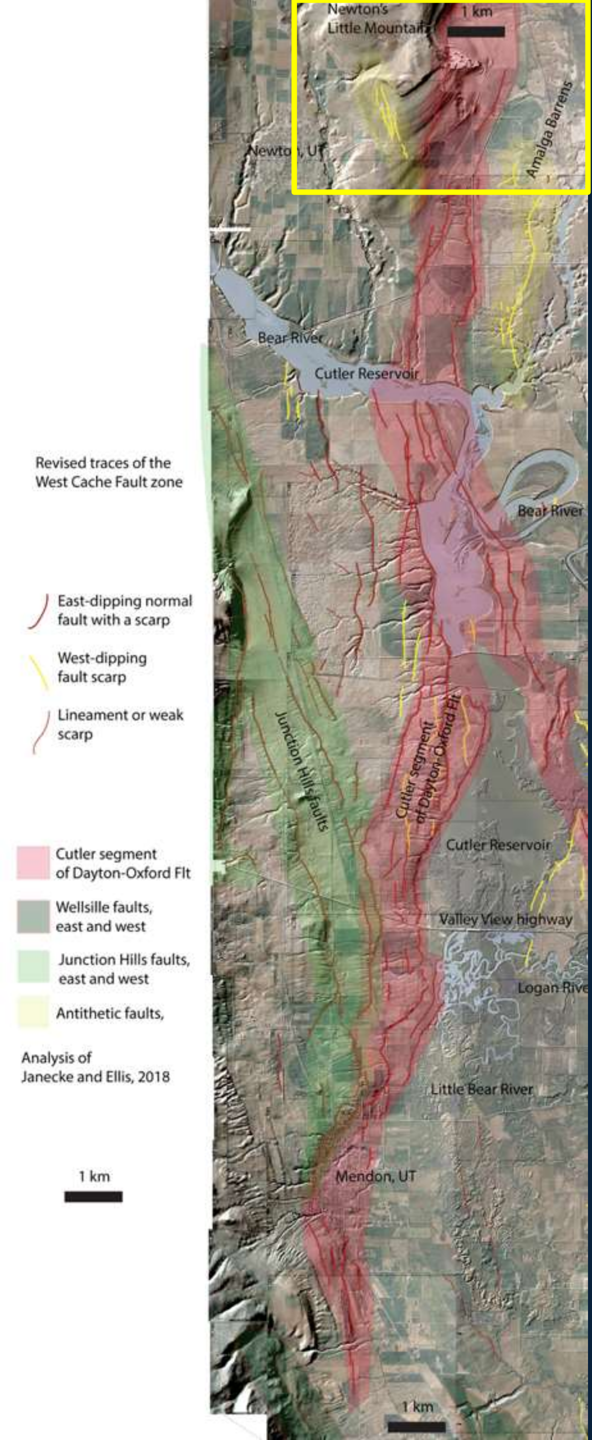
Antithetic faults,
Valley View highway
Logan River
Analysis of Janecke and Ellis, 2018
Little Bear River
1 km
Mendon, UT
1 km

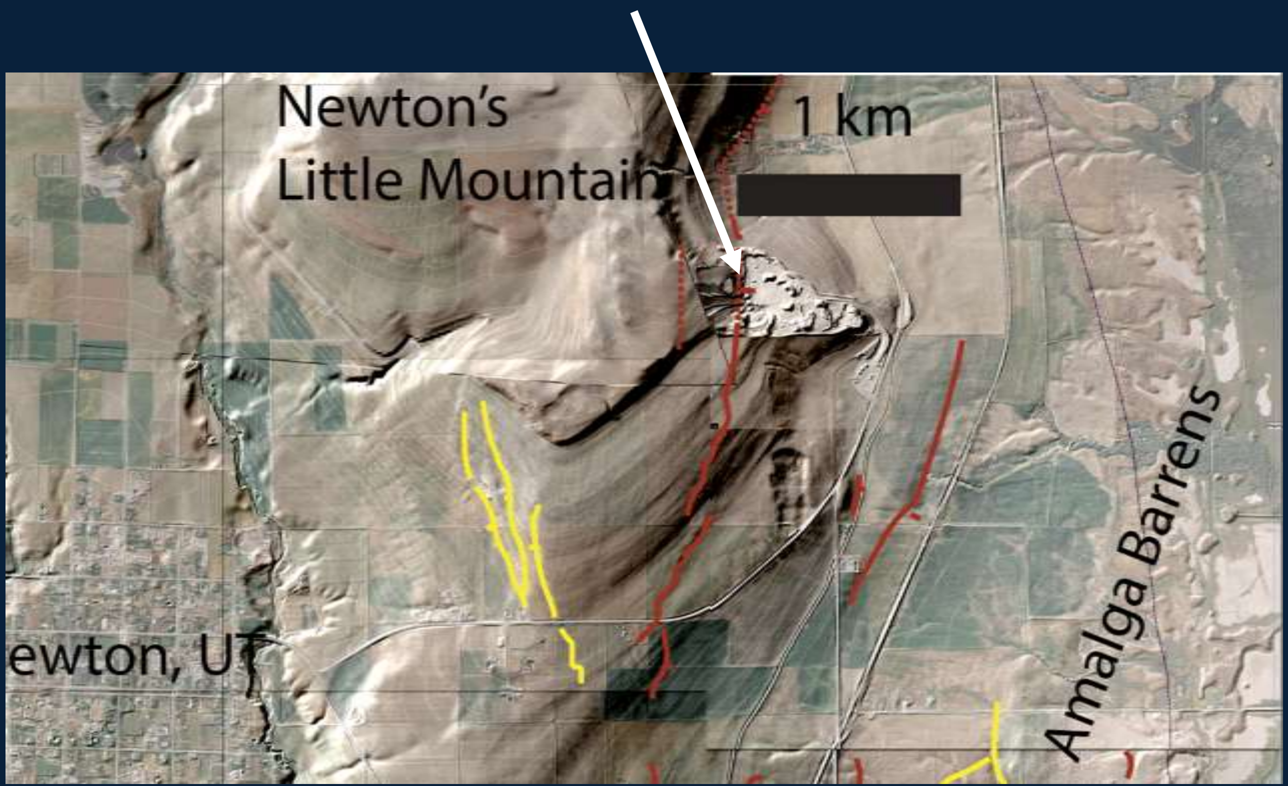
Jäneck LC

There was evidence for complex faulting in Cache Valley prior to LIDAR survey

- Jänecke and Evans (2017)
-
- LIDAR confirms this interpretation
- Dayton-Oxford fault of the West Cache fault zone.
- Ellis 2018 senior thesis on WCFZ

Appendix figure 4B

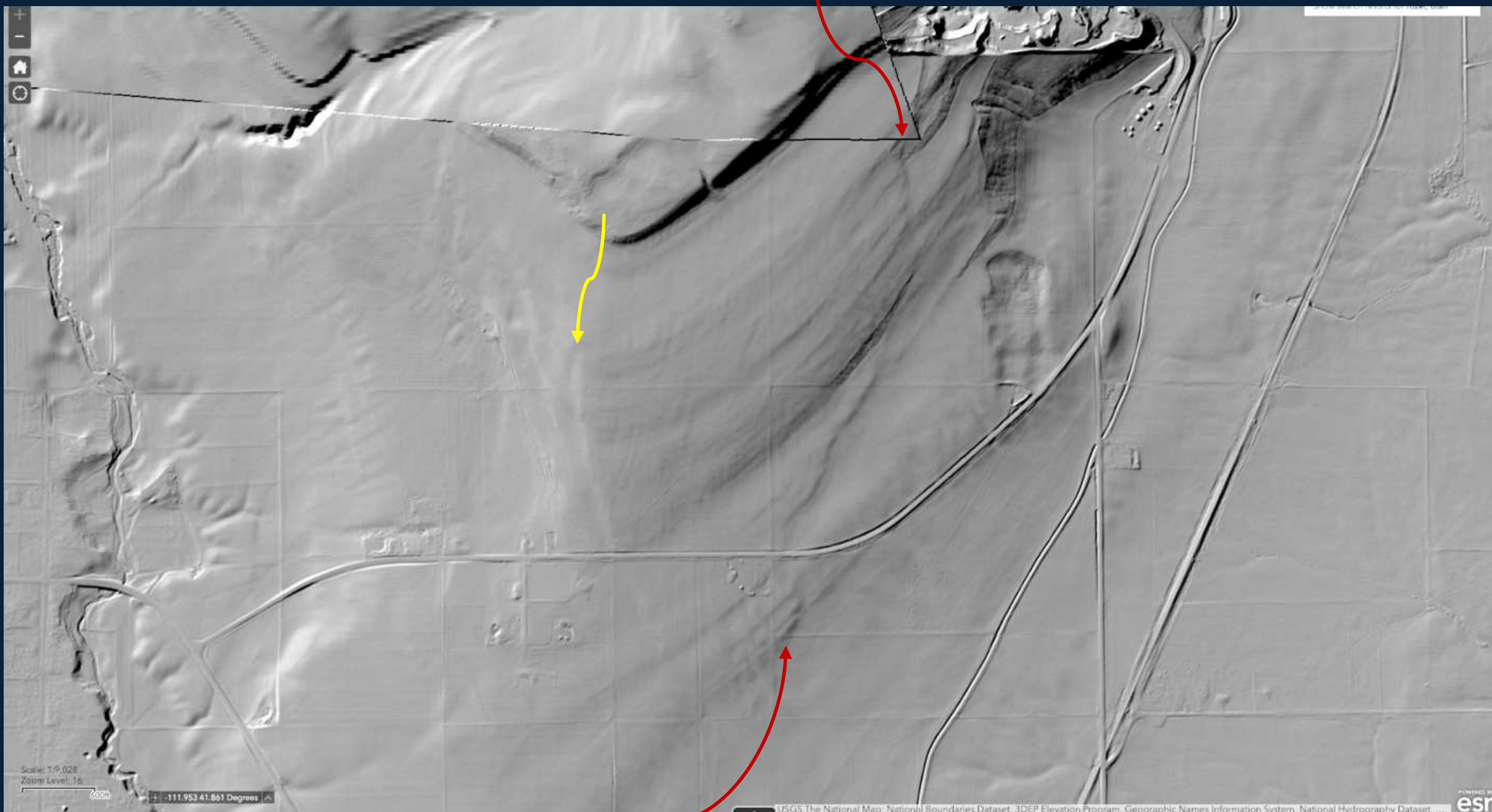




There are E and W facing scarps

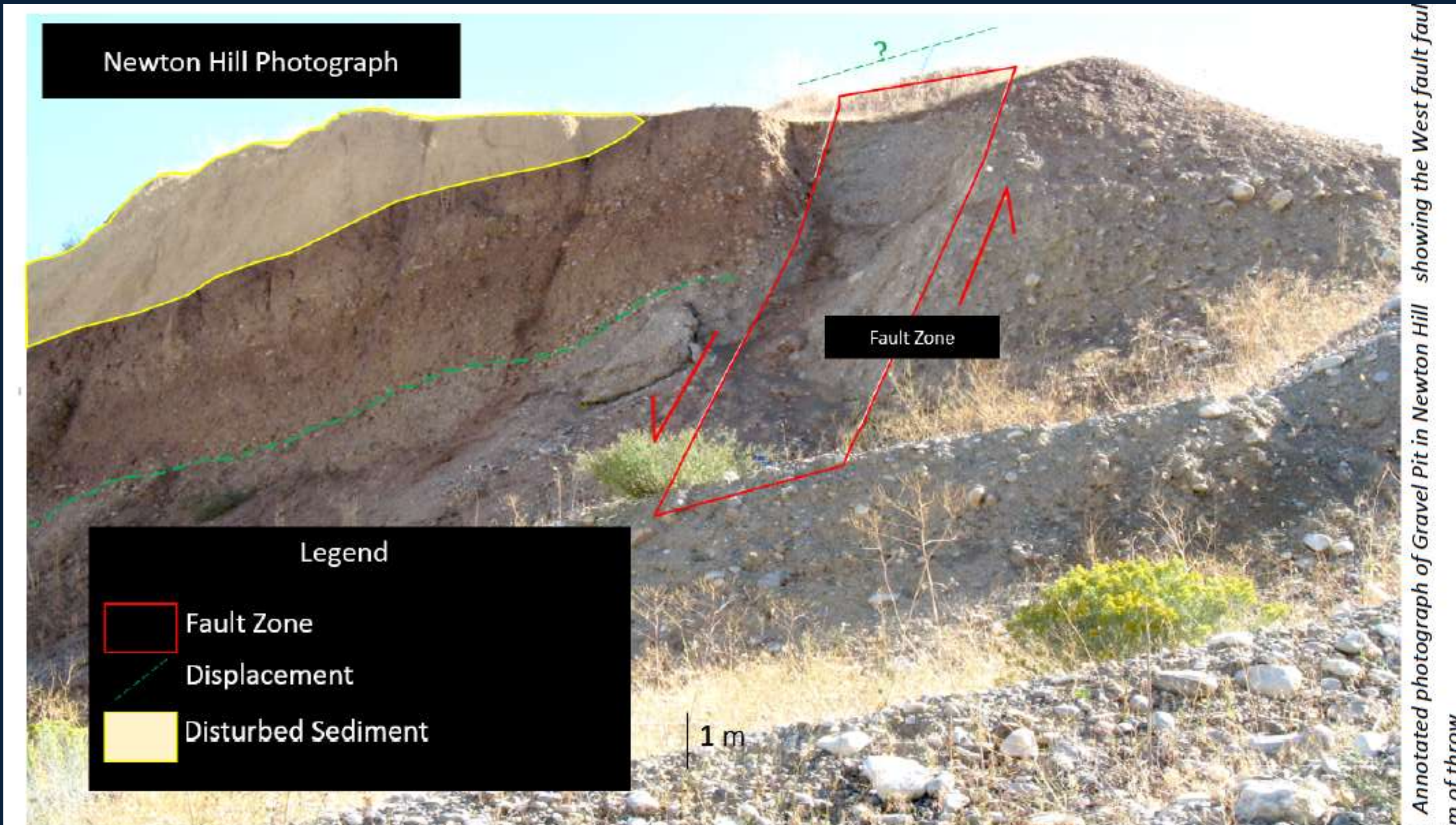
Jänecke and Evans, 2016, Jänecke and Ellis, 2018

East-dipping scarp projects into gravel pit of Oaks et al ongoing research effort Road for scale



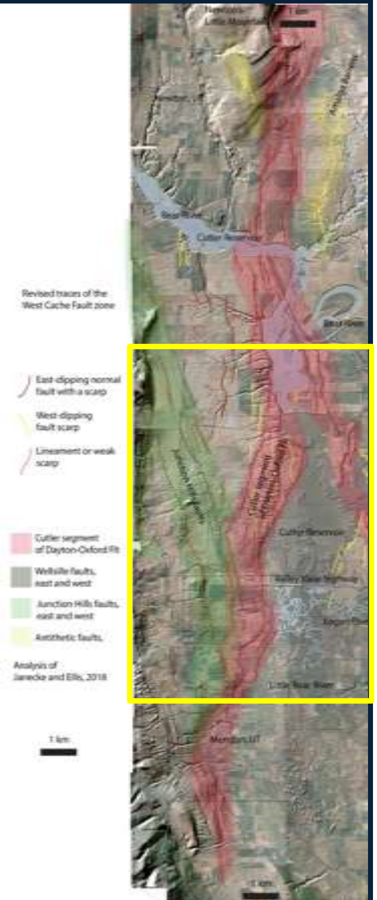
Jänecke et al., UQFPWG Feb 2019 SLC

View south at Dayton-Oxford fault with >1.5 m throw of ~40-50 ka soils



Ages of Oaks et al., 2018 UGS Bonneville volume

Ellis, 2018



East-dipping normal fault with a scarp

West-dipping fault scarp

Lineament or weak scarp

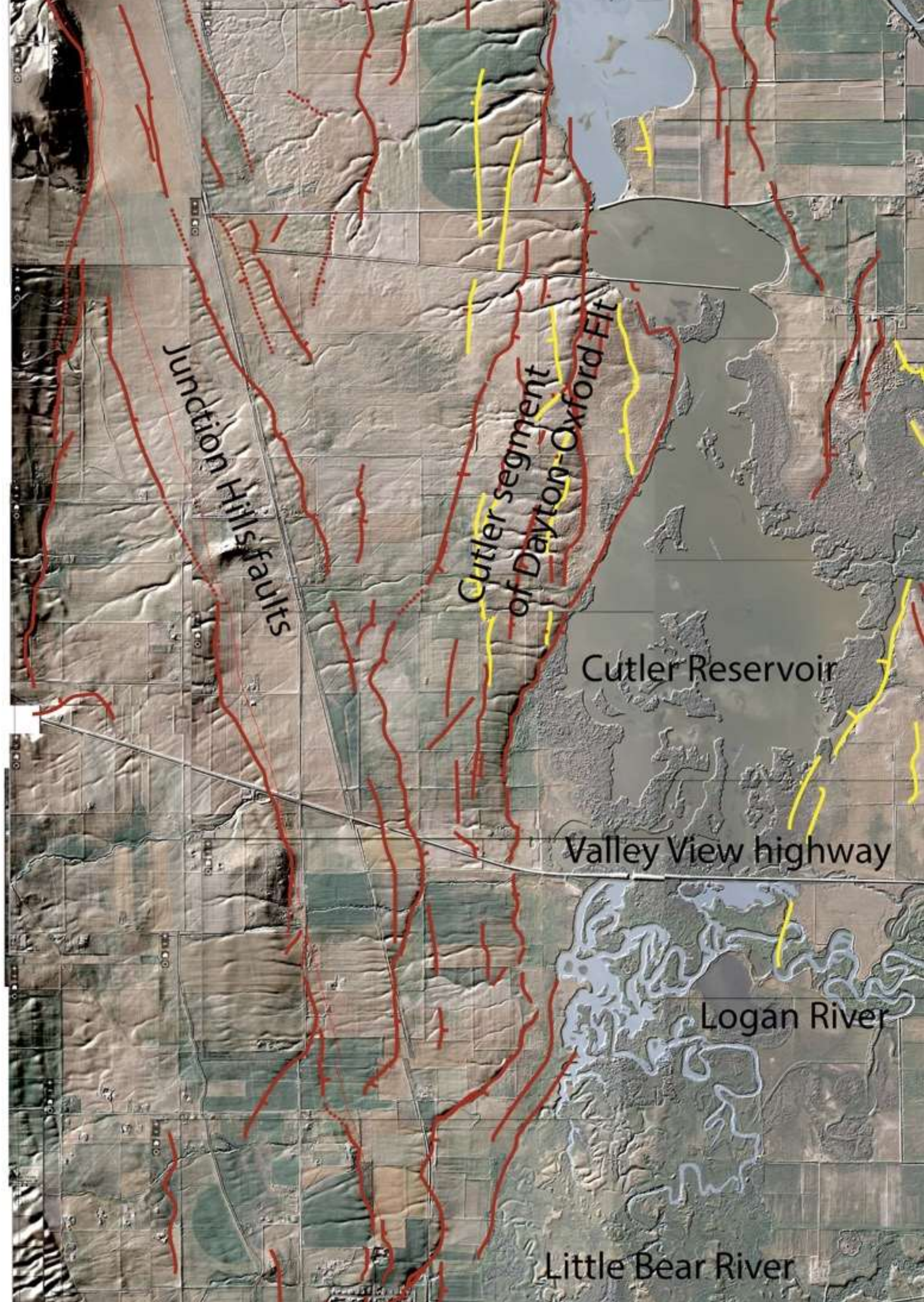
Cutler segment of Dayton-Oxford Flt

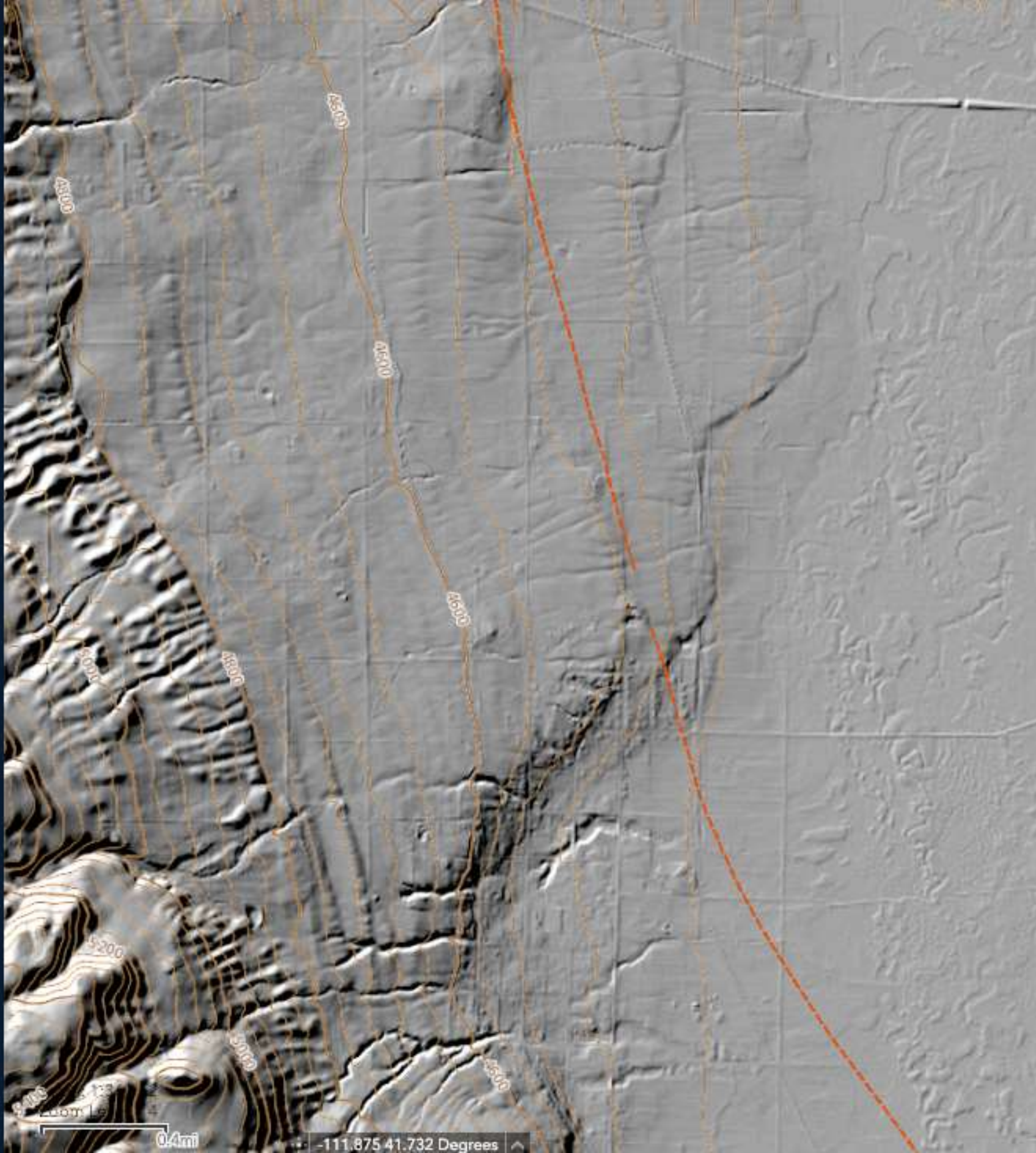
Wellsille faults, east and west

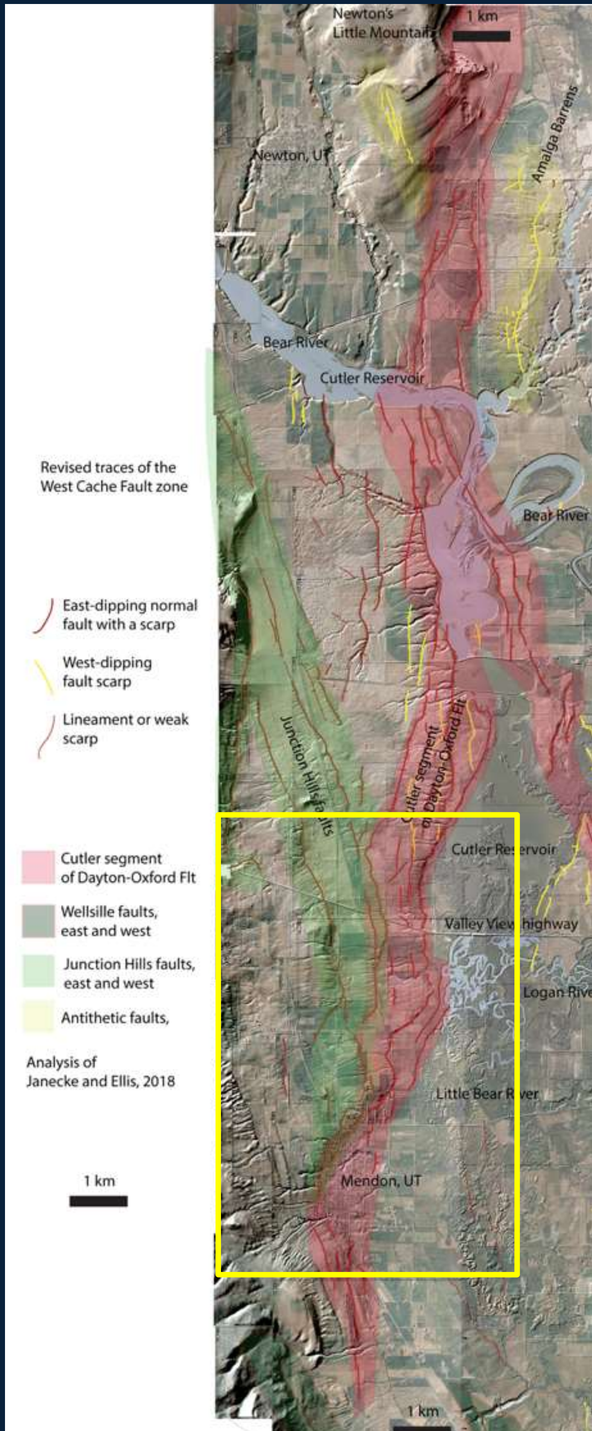
Junction Hills faults, east and west

Antithetic faults,

Analysis of Janecke and Ellis, 2018




4500
4800
4500
4500
4500
4800
5200
0.4mi
-111.875 41.732 Degrees


Newton's
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Wellsille faults,
east and west
Valley View highway
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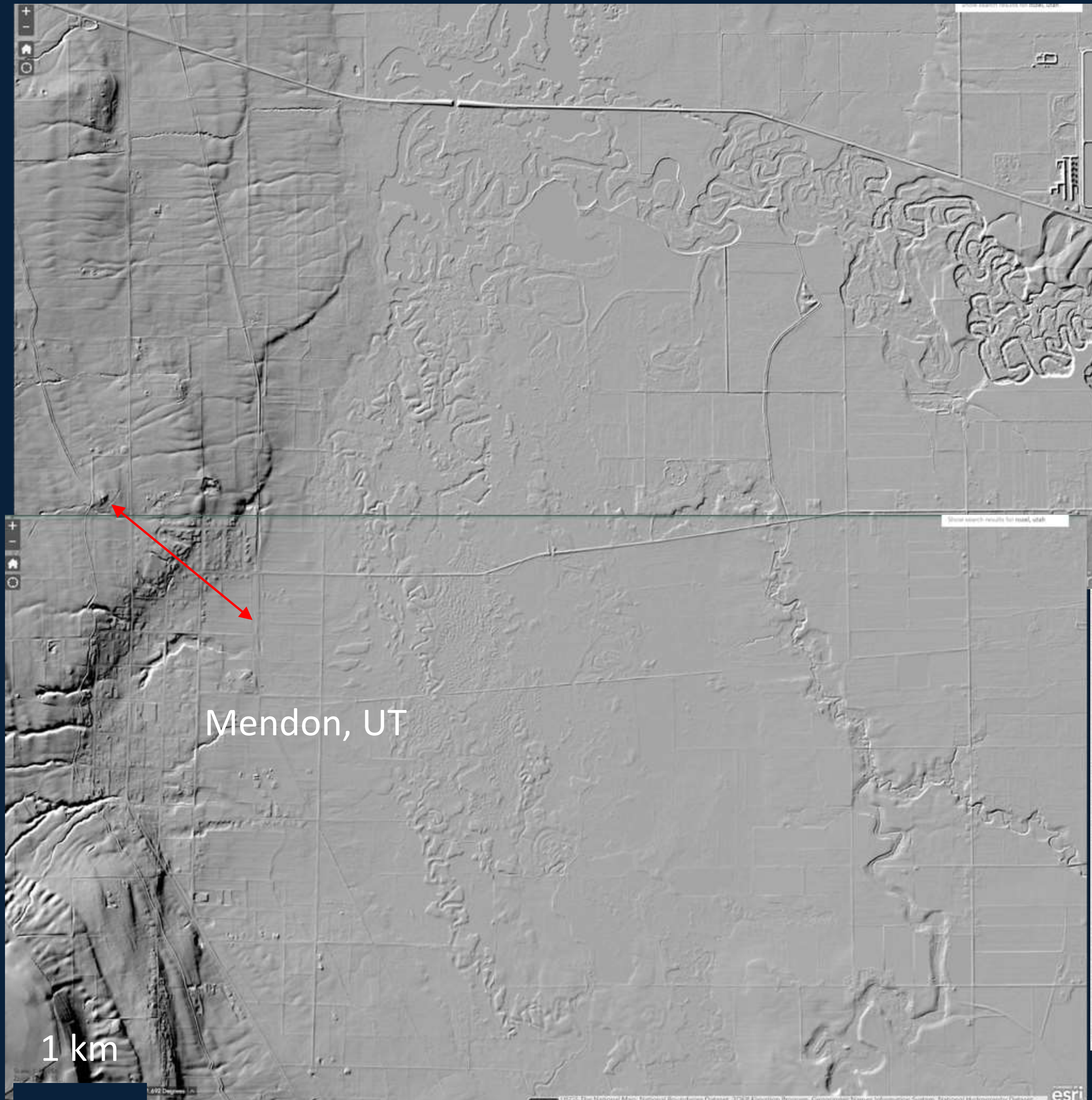
Logan River
Antithetic faults,
Analysis of
Janecke and Ellis, 2018
Little Bear River
1 km
Mendon, UT
1 km

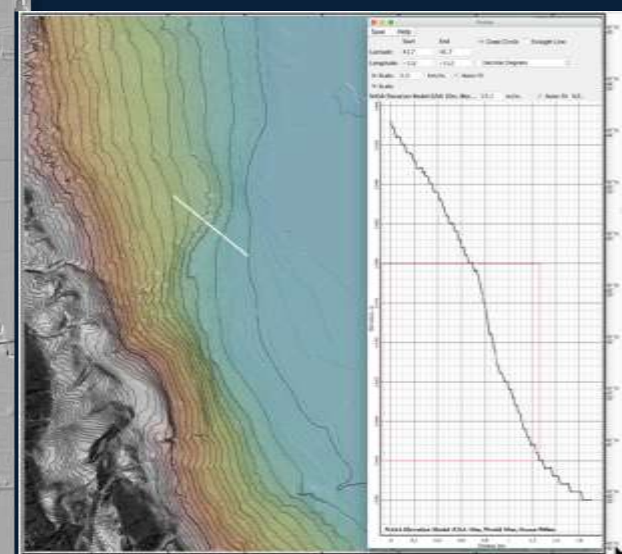
Ja

Jänecke



High scarp in Mendon, Utah results from convergence of faults.

Compound scarp is at least 20 m high and locally >35 m!



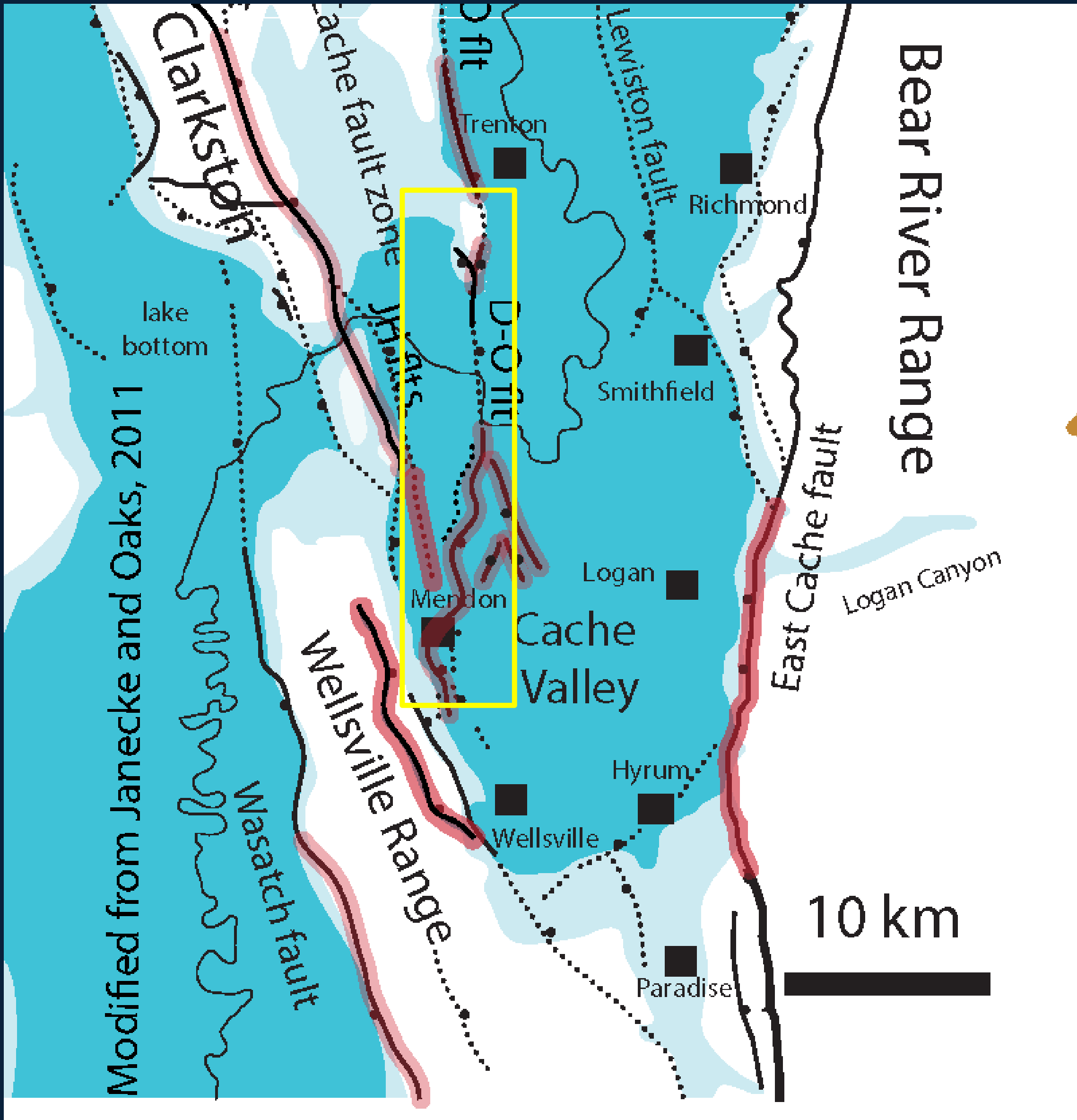


Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River are shoreline is simplified west of Cache Valley. RNF—Riverdale normal fault Great Basin (modified from Morrison, 1991). Geosphere, December 2011

Our work almost doubles length of faults with Holocene ruptures.

West Cache fault zone ruptured across the floor of Cache Valley, & possibly N into Idaho

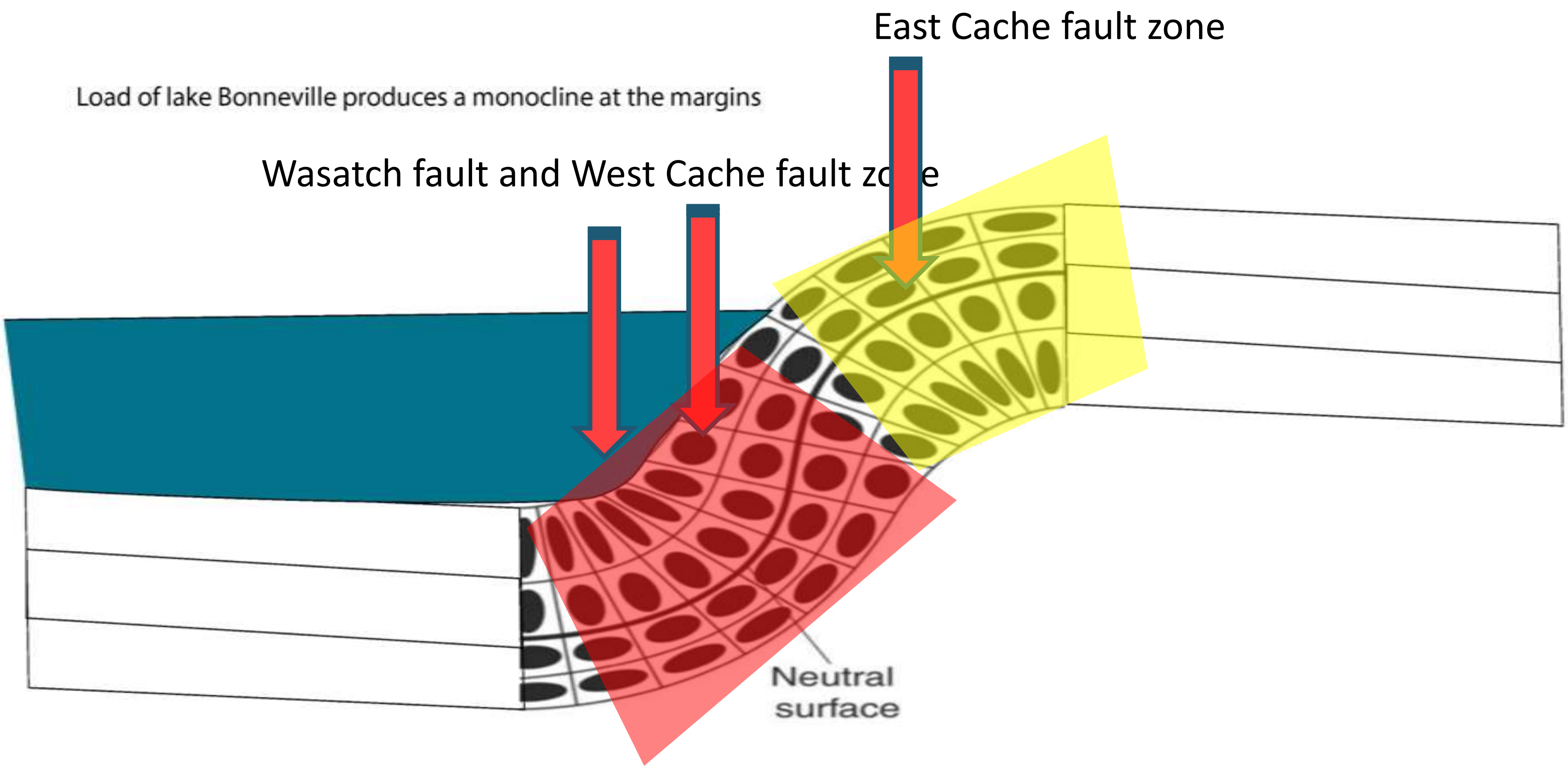
Jänecke and Evans, 2016,
Ellis and Jänecke, 2018

62

These data fit the OUT-OF-SYNC model

- Much more evidence of Holocene ruptures in WCFZ-
  - Esp. Utah part of of Dayton-Oxford fault
- Hard links with D-O flt-NEW FAULT SEGMENT
- >20-m-high fault scarp IN MENDON
- It coincides with the convergence of the Wellsville, Junction Hills, and Dayton Oxford fault zone
- Fault zones are almost 1 km wide
- Several faults have E and W branches

Load of Lake Bonneville produces two belts of deformation since ~20 ka



- East Cache-Riverdale fault belt was more active under Lake Bonneville due to outer arc stretching across an upper monoclinal hinge
- Wasatch-West Cache fault belt generated more earthquakes later on

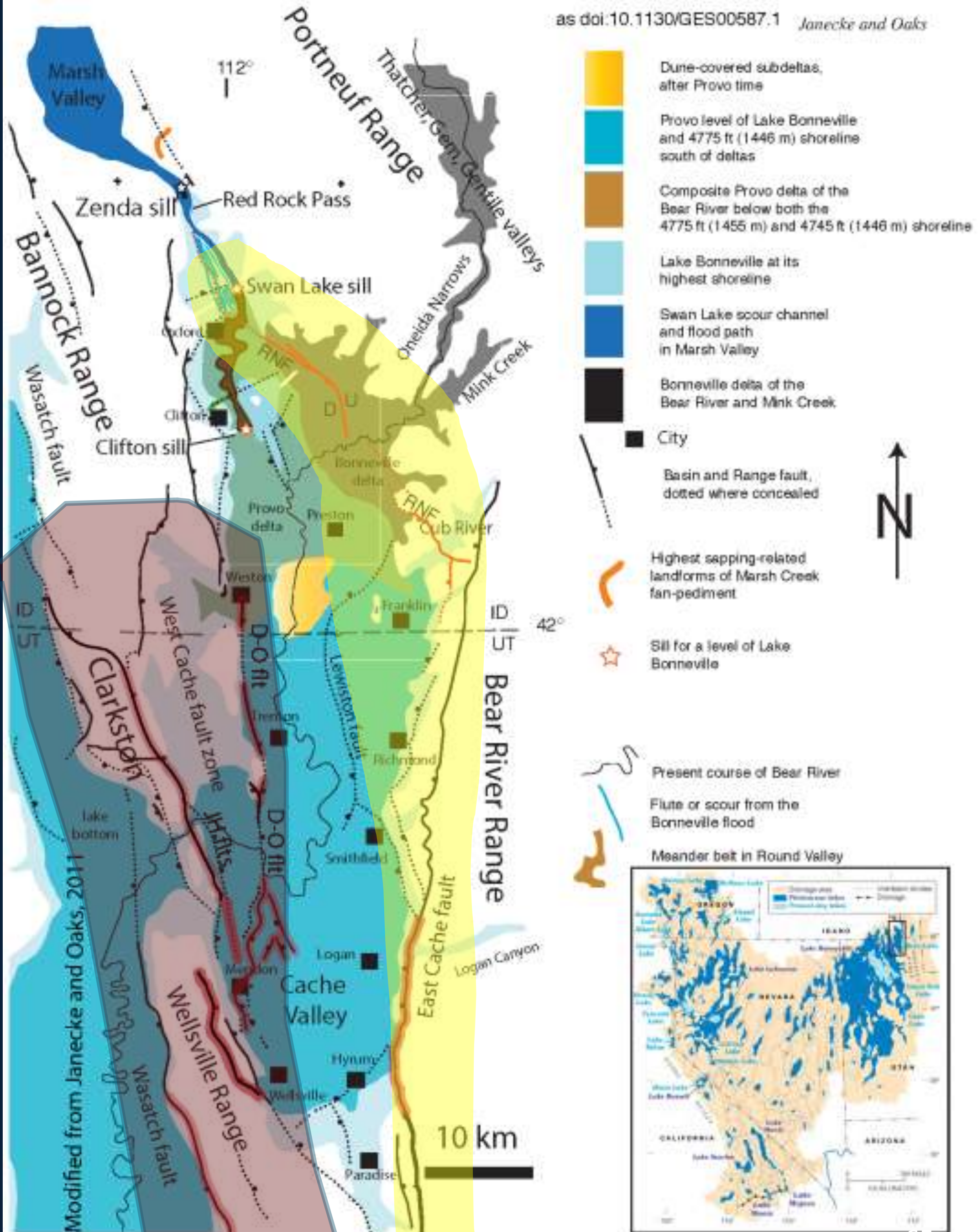
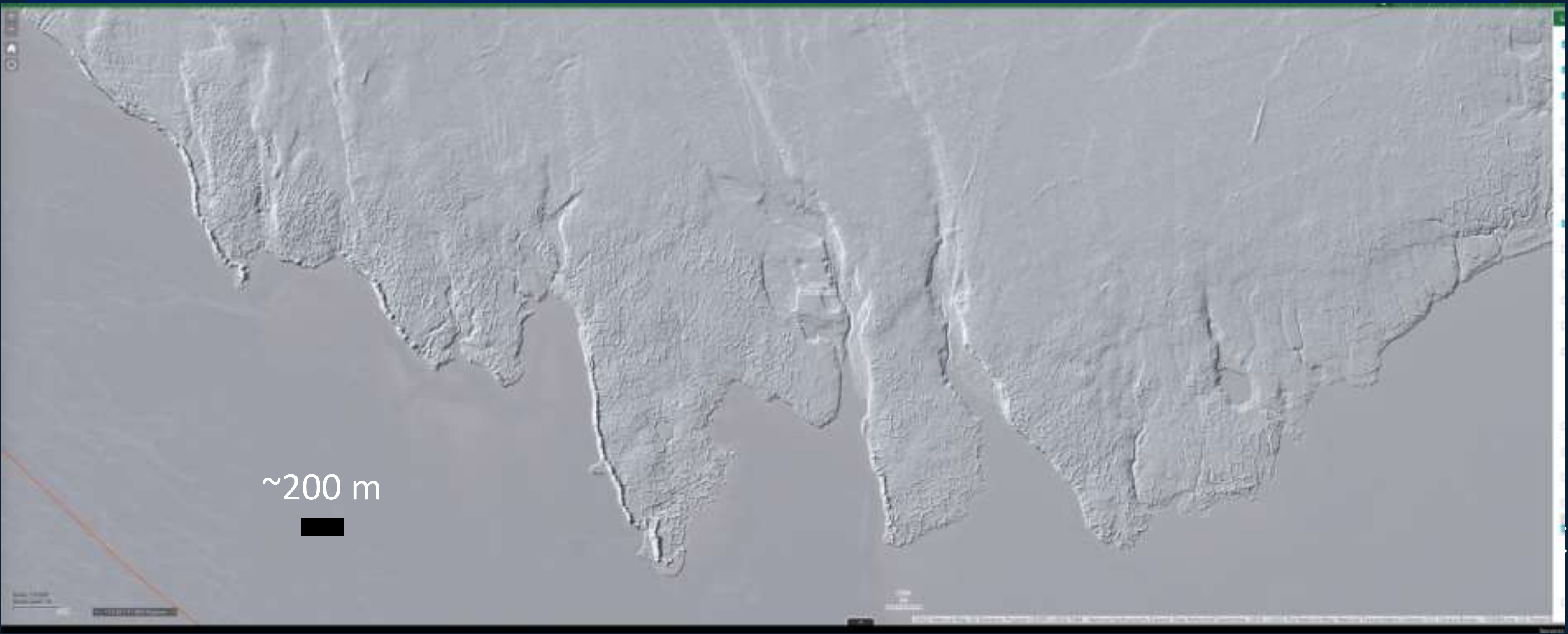


Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River are differentiated from other lacustrine deposits. Provo shoreline is simplified west of Cache Valley. RNF—Riverdale normal fault (+landslide?). Inset map shows location within the Great Basin (modified from Morrison, 1991). Geosphere, December 2011

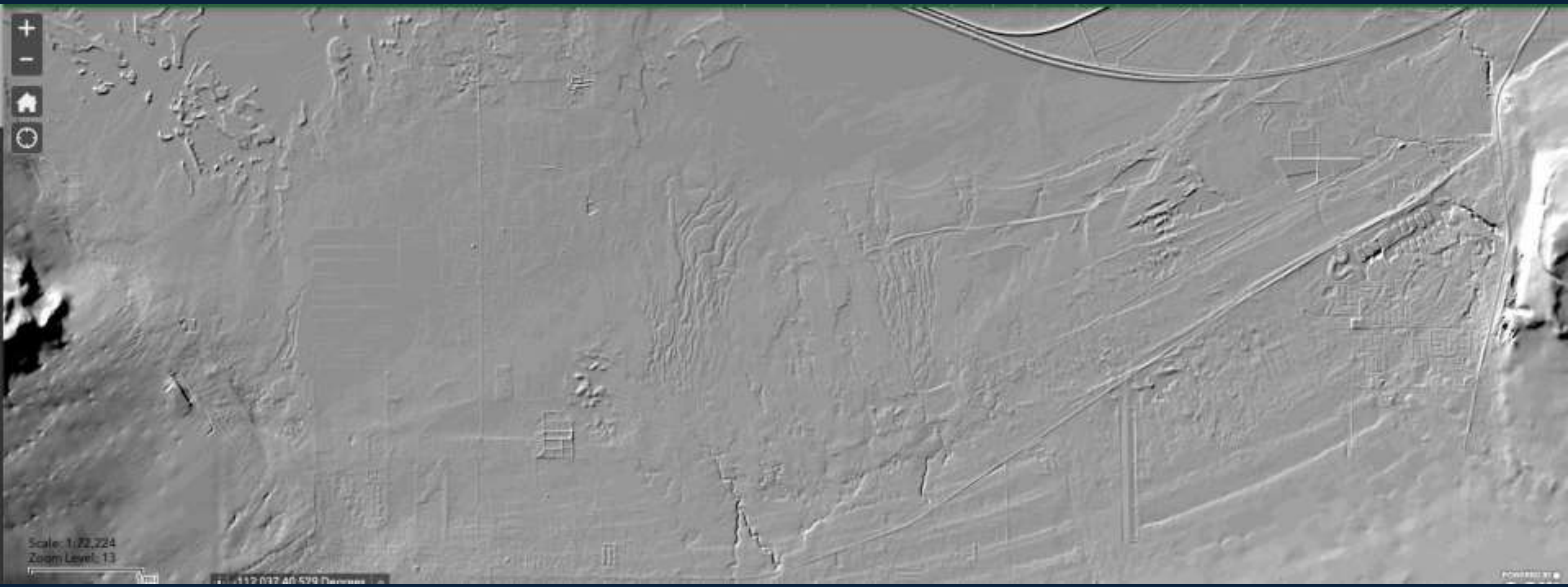
Jänecke et al., UQFPWG Feb 2019 SLC

LIDAR OF Rozel fault zone validated our interpretation of volcanic-style of extension

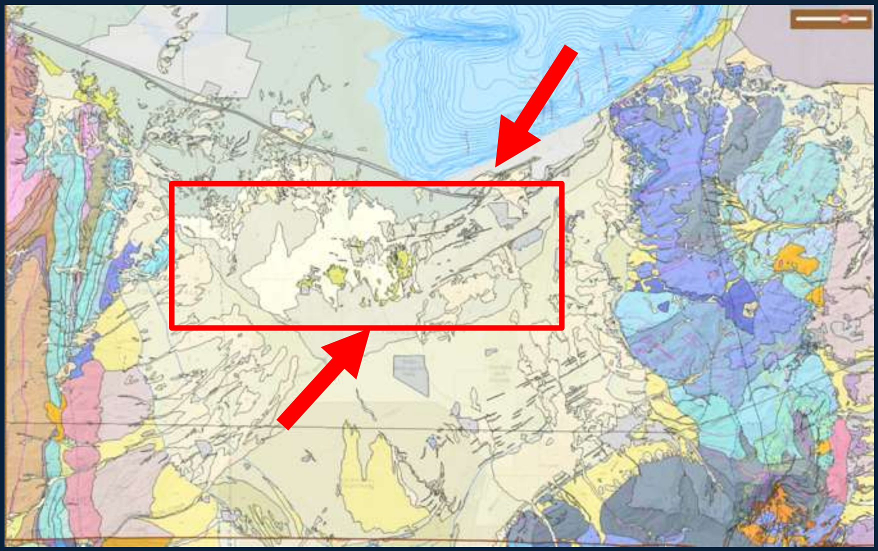


See Susanne Janecke
James P. Evans, 2017 UGA volume

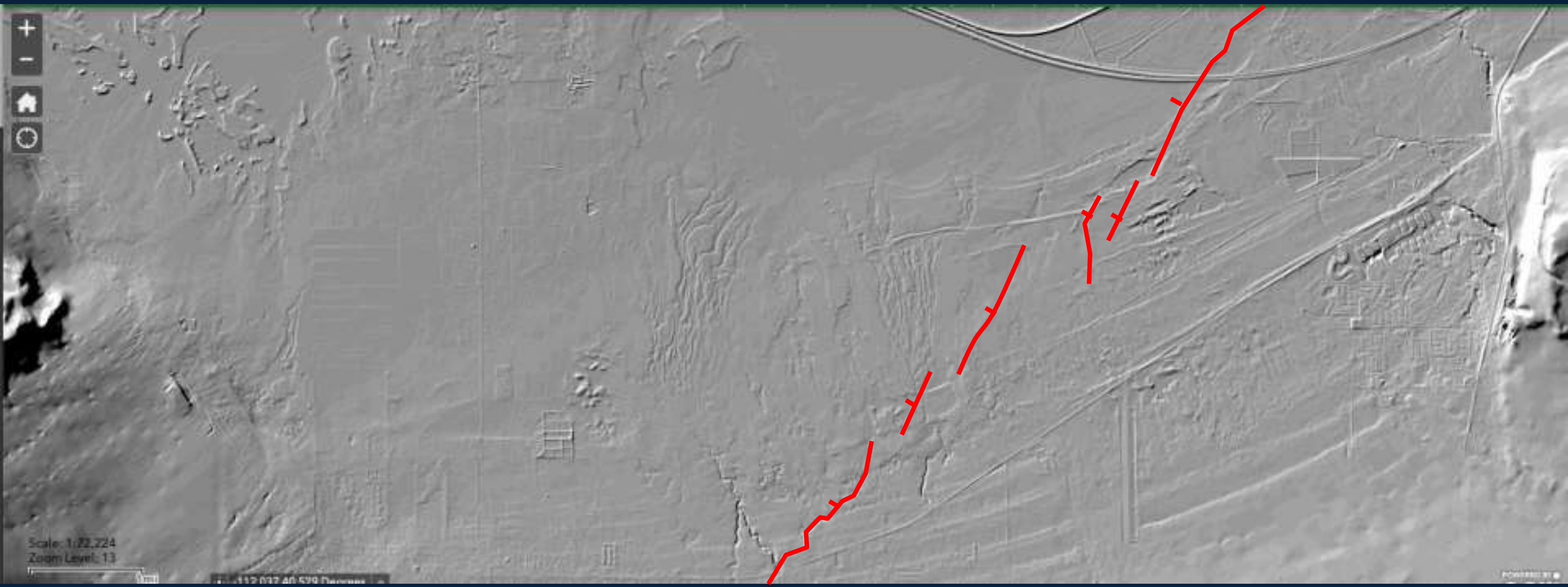
USGS National Map 3DEP Hill shade stretched shows the newest LIDAR



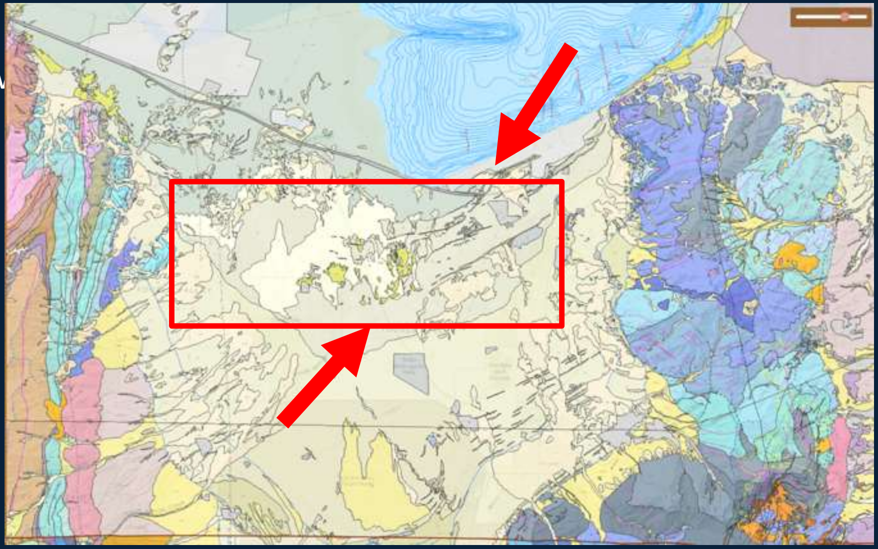
LIDAR reveals active normal faults with NE strikes-as we discussed



Jänecke et al., UQFPWG Feb 2019 SLC



Jänecke et al., UQFPW



Revised traces of the West Cache Fault zone

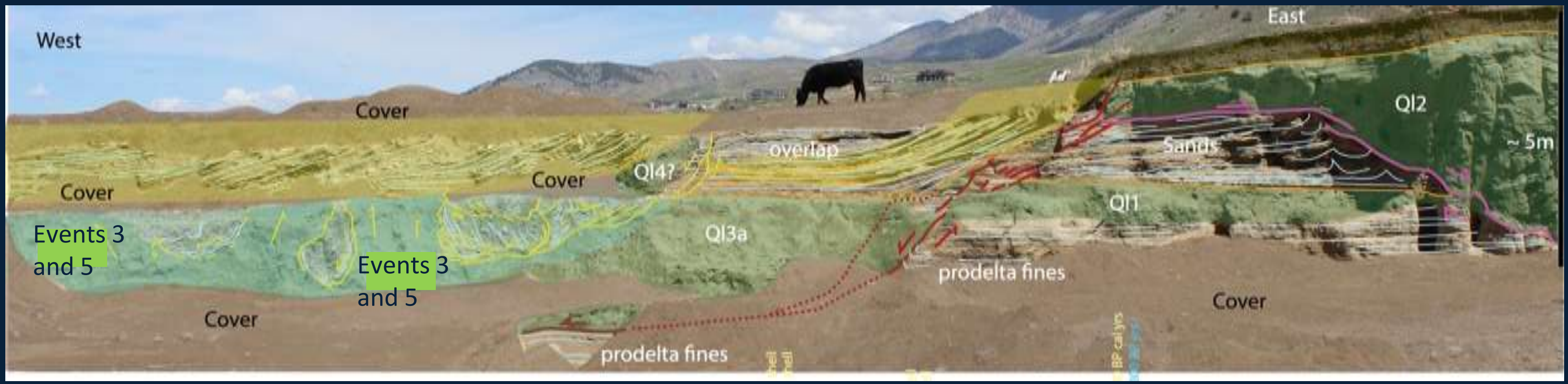
East-dipping normal fault with a scarp

West-dipping fault scarp

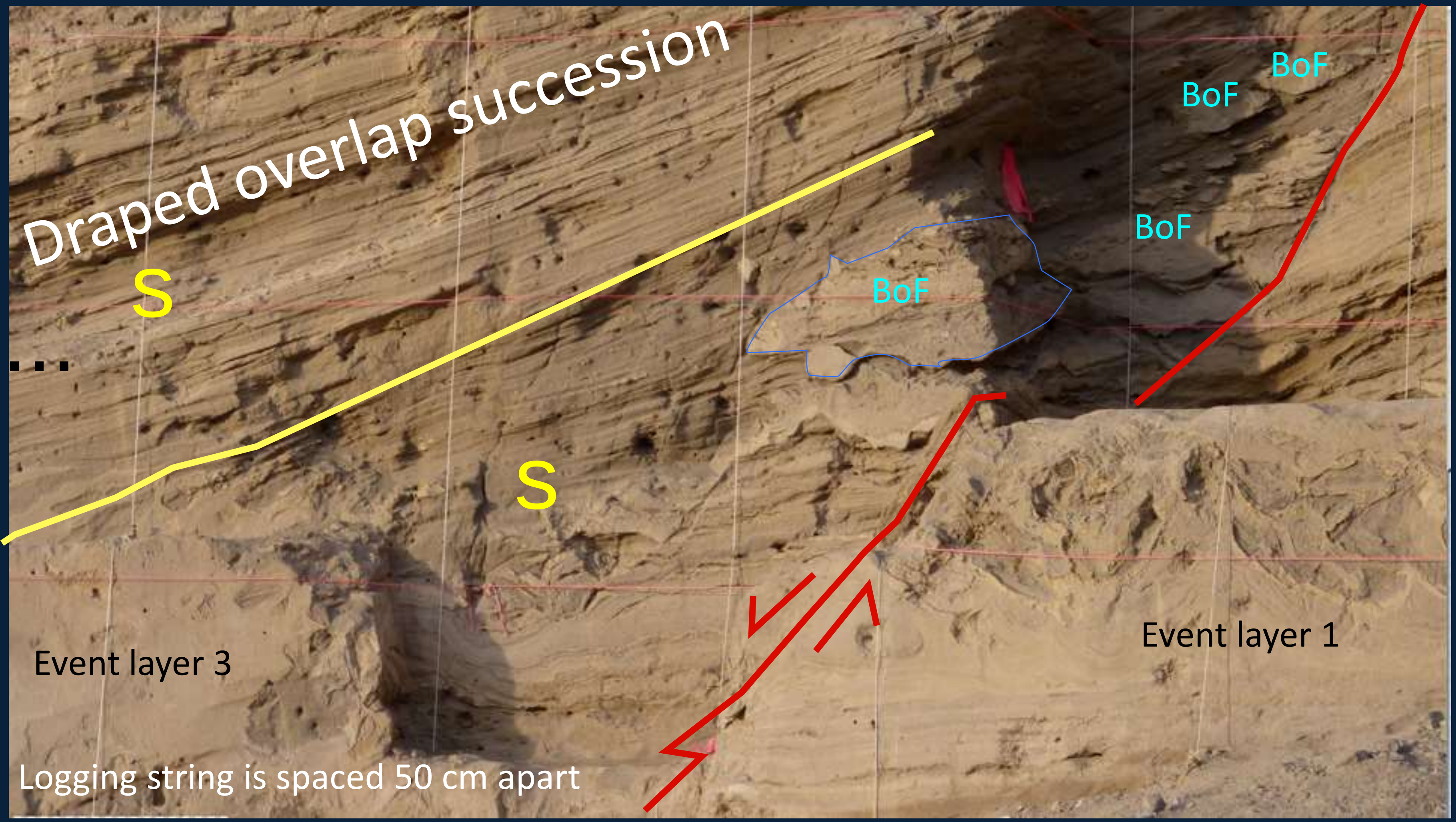
Lineament or weak scarp

Original photo by Robert Q. Oaks. Jr.

now

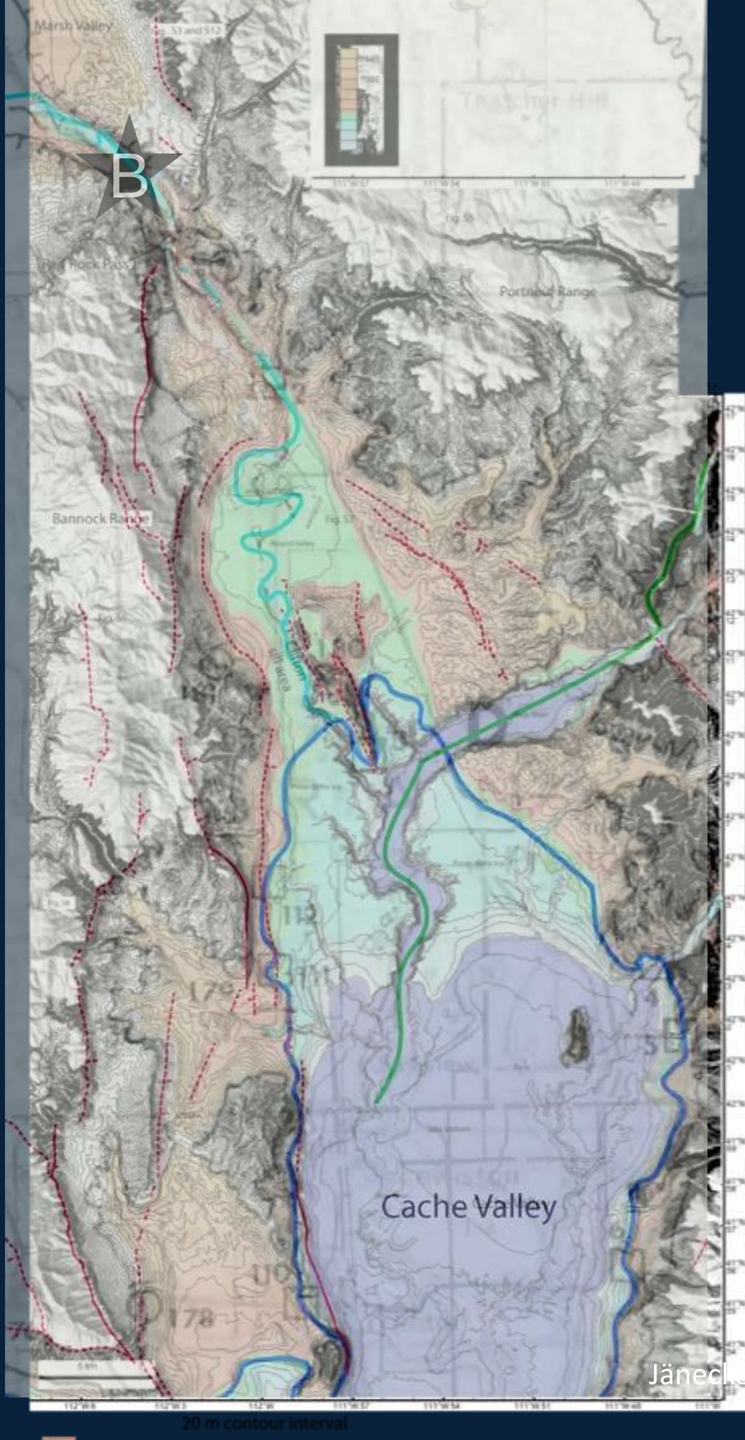


Lacustrine fault wedge contains blocks of footwall



This is analogous to a colluvial wedge along a normal fault

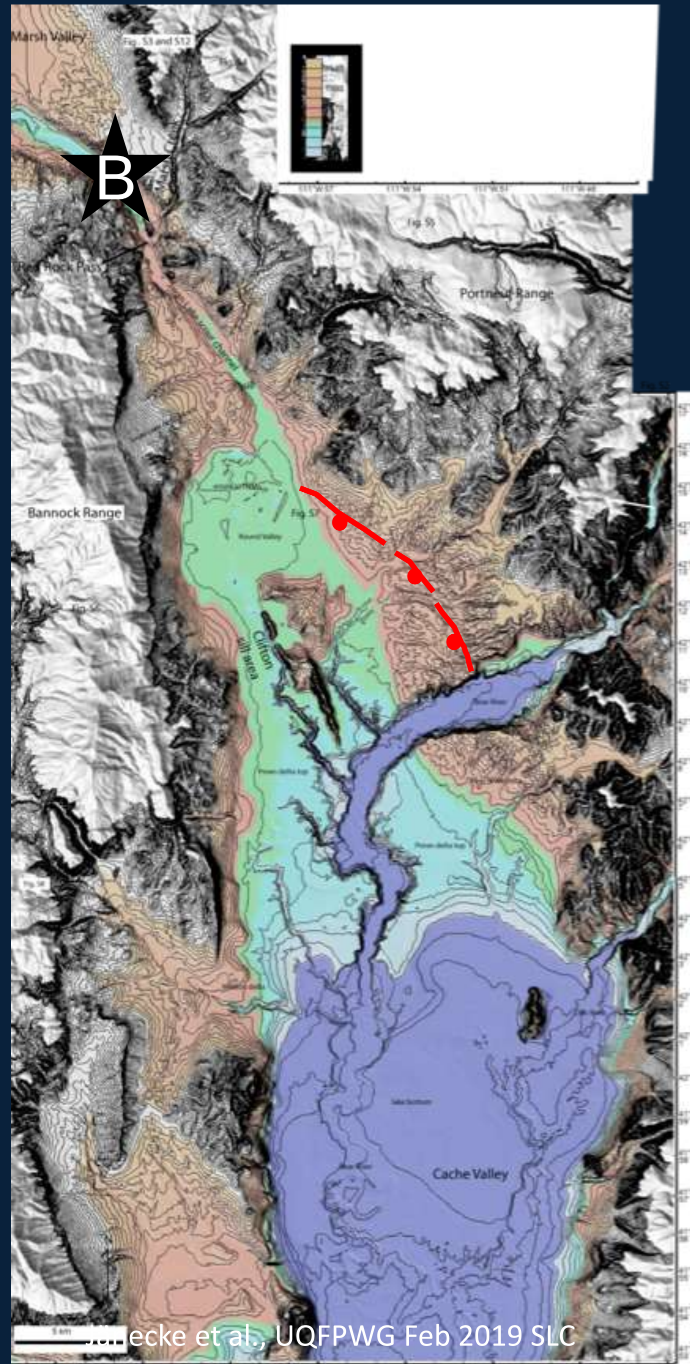
- This talk weaves together two related datasets from east and west Cache Valley:
  1. East Cache fault
     1. Liquefaction that repeatedly deformed lacustrine sediment before and during high stand of Lake Bonneville
     2. Little deformation since then
  2. LIDAR confirms additional faults in West Cache Fault zone –
     1. At least 18 km longer Dayton Oxford fault zone
     2. Hard linkages through the floor of Cache Valley
     3. An enormous fault scarp cuts right through Mendon, UT
     4. First documented Holocene ruptures along the D-O fault zone
     5. Several faults of WCFZ have both east and west strands
     6. Some strands span almost one km E to W.



Dayton-Oxford normal fault may have segment boundary near Newton gravel pit or at left-step in Weston, ID

Jänecke et al., UQFBWG Feb 2019 SLC

An earthquake along Riverdale fault or other structure in east belt could have triggered the Bonneville flood after many centuries of stable outflow



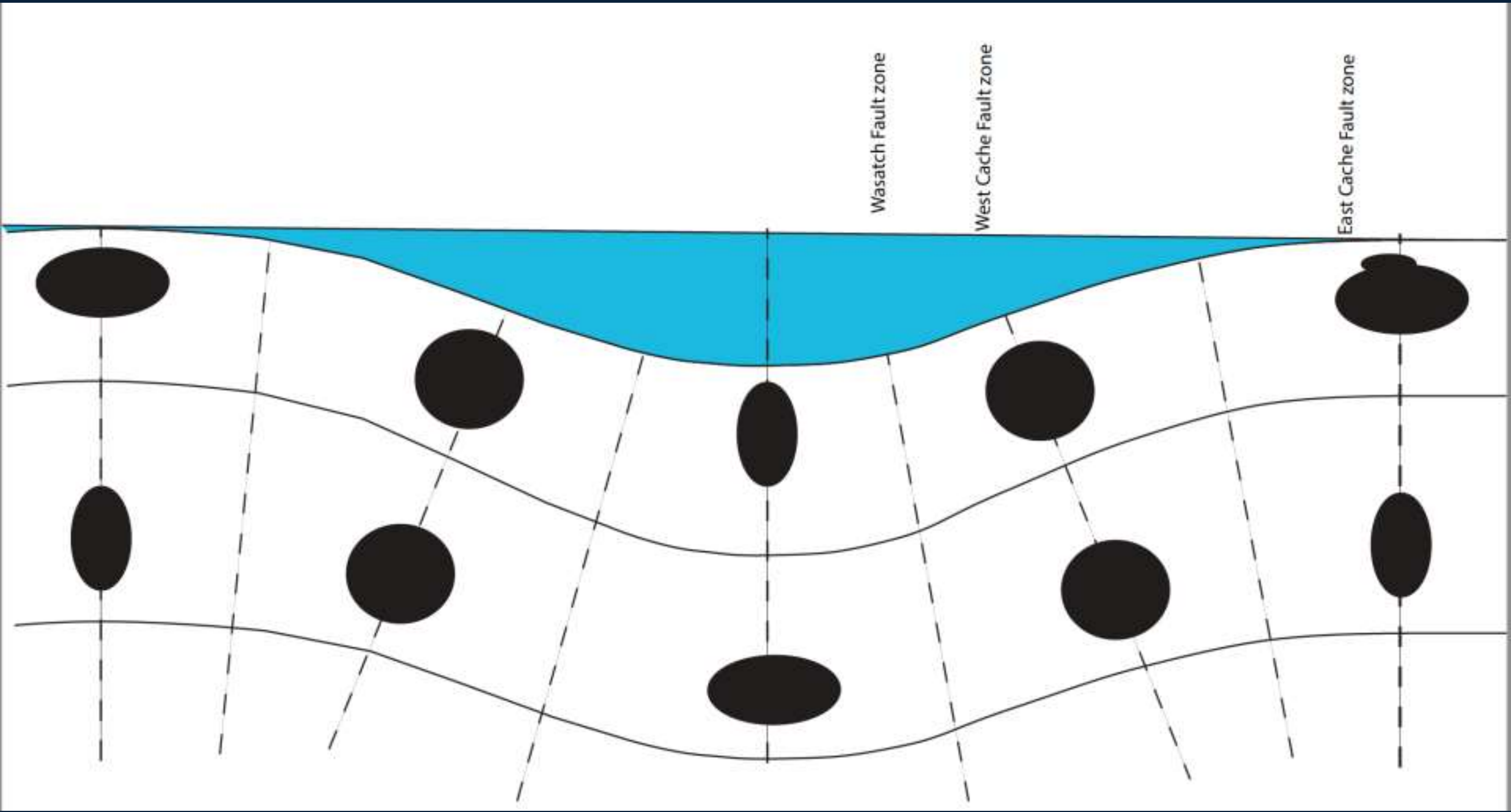
Bonneville s.l.

U. Provo s.l.

L. Provo s.l.

Below Provo

Another visual



Cache Valley: A critical part of Lake Bonneville tells a unique tale of shorelines, thresholds, clustered earthquakes, liquefaction, possible triggers of the Bonneville flood, and late integration with the main basin.

Jänecke, Susanne U., Oaks, Robert Q. Jr, Rittenour, Tammy M., Knight, A.J., and Oakeson, Justin, Department of Geology, Utah State University, 4505 Old Main Hill, Logan, UT 84322-4505, susanne.janecke@usu.edu

Geologic, geomorphic, and geophysical analyses of landforms, sediments, and structures in conjunction with new ^{14}C and OSL age determinations document a revised history of flooding and recession of Lake Bonneville in Cache Valley, Idaho and Utah. The presence of wave-cut cliffs in bedrock throughout the Bonneville basin show that the Bonneville highstand was protracted and probably lasted for centuries. Triangular facets were cut into bedrock in the footwalls of normal faults and were steepened significantly by wave erosion at the highest Bonneville shoreline. Crosscutting relationships further suggest that the Riverdale fault, Idaho, produced a major surface-rupturing earthquake near the Zenda threshold around the time of the Bonneville flood. Thus, fluctuating loads, rebound, and/or pore pressures induced by changing lake levels may have triggered a large earthquake that initiated the Bonneville flood and ended the stable outflow that occurred at the Bonneville highstand.

G.K. Gilbert first observed that the Bonneville flood scoured a major flood channel into Cache and Marsh Valleys, and shifted the outlet of Lake Bonneville a great distance southward into Cache Valley during the occupation of the Provo shorelines. The bedrock ridge at the south end of this Swan Lake scour channel became the new threshold for the outflow that produced the main 4775 ± 10 ft (1455 ± 3 m) Provo shoreline, 10 m above the commonly accepted altitude of 1445 m. The 1445 m contour coincides instead with a lower Provo shoreline (4745 ± 10 ft (1446 ± 3 m) that was controlled by a second bedrock ridge and younger threshold at Clifton, Idaho. The sparse record of shorelines rebounded from the ~1445 m level in Cache Valley indicate that the outlet at Clifton, ID was quickly abandoned when Lake Bonneville reverted to a closed condition. A dry meandering riverbed connects the Clifton and Swan Lake outlets and preserves evidence of the large northward-flowing Bonneville River in Round Valley. The Great Basin's modern divide at Red Rock Pass formed in the Holocene, after Lake Bonneville, when a tributary built a small alluvial fan across the midpoint of the Swan Lake scour channel and created a subtle dam (Gilbert 1880, 1890). Thus, Gilbert showed that the modern drainage divide at Red Rock Pass is unrelated to Lake Bonneville.

The possibility that an earthquake triggered the Bonneville flood led us to explore the late Pleistocene activity of normal faults in Cache Valley. The Wasatch fault has increased its slip rate since the Bonneville flood, but little is known about the response of active normal faults in Cache Valley to loading and unloading by Lake Bonneville. To examine the relationships between ancient seismicity and lake history, we re-excavated deformed Upper Pleistocene sandy lake beds along an ~50 m by 5 m collapsed north wall of an abandoned gravel pit at the mouth of Green Canyon, Cache Valley, northern Utah. USU faculty identified 2 liquefaction events in the outcrop in the 1980's during class trips, and we sought to determine the number, nature, and age of the paleo-earthquakes responsible for the strong deformation there.

The exposure of the paleodelta of Green Canyon coincides with the boundary between the northern and central segments of the East Cache fault. It is ~25 m to ~170 m basinward of two diverging fault strands of the East Cache fault and there are additional buried faults close to the outcrop that roughly follow the main upper Provo shoreline (McCalpin, 1994; this study).

Upward coarsening lacustrine deposition at the site started before 22.4 ± 0.4 ky cal BP (^{14}C) with deposition of prodelta clay, mud and silt, and continued after 18.1 ± 0.3 ky cal BP (^{14}C) as sand and gravel were laid down in a prograding delta. Nearshore lacustrine deposition is indicated by ripples, cross beds, other sedimentary structures, lacustrine shells throughout the exposure, and the position of the beds ~40-45 m below the Bonneville shoreline at Green Canyon.

Ten new age determinations indicate early onset of deep lake conditions in Cache Valley, at or higher than 40-45 m from the highstand. The high altitude of the lake provides additional evidence for Oaks et al (this volume)'s interpretation of Cache Valley Bay. Oaks et al. (2018) dated prior lake cycles in Cache Valley and conclude that Cache Valley Bay was a separate pluvial lake until it became fully integrated into the Bonneville basin in the middle of the Bonneville lake cycle. The integration must postdate the lake beds in Cache Valley that were deposited at higher altitudes than predicted by the Bonneville hydrograph.

We uncovered multiply-deformed shallow lake beds and one capping fluvial gravel in the exposure in the Bonneville delta at Green Canyon. Listric faults in the exposure sole into prodelta clay beds beneath the sandy and gravelly deltaic part of the succession. West-dipping slip surfaces in the exposure are part of nested lateral spreads, not tectonic faults. Cross-cutting relationships are exceptionally clear. The deltaic sediment of Green Canyon was deposited, seismically deformed, and slumped in at least 4 events under subaqueous conditions in a shallow-water, deltaic part of Lake Bonneville. Six ^{14}C ages on *Stagnicola* sp. shells and three OSL ages are stratigraphically consistent within error, and confirm that the lacustrine sediment was deposited and deformed during 4-5 ky of high lake levels prior to the Bonneville flood. The geometry and position in the landscape of a laterally continuous alluvial gravel bed, which caps the highly deformed sandy lake beds in angular unconformity, suggest that the gravel bed was probably laid down immediately after the erosional stripping of the highest units by the Bonneville flood. The gravel cap may be a flood deposit or barely postdate the Bonneville flood because it predates the significant, focused downcutting along the modern channel of Green Canyon Wash that coincided with the occupation of the Provo shorelines ~70 m lower in the landscape. All the deformation in the exposure must therefore predate the earliest occupation of the main Provo shoreline.

The Green Canyon site exposes 3 listric slip surfaces of lateral spreads, 4 sequential thick liquefied units, undeformed flat and cross-stratified lacustrine and deltaic sediment, thin deformed beds. Each thick liquefied mass of sand is a different age, yet all of the deformation occurred when the sediment was saturated by Lake Bonneville and was within ~40 m of its highest altitude. Three of the liquefied units (0.75 to 5 m thick) are localized and displaced in the hanging walls of listric east- and west-dipping slip surfaces of lateral spreads that appear to be coeval with the liquefied sediment above them. Deposition was ongoing, and produced multiple cross-cutting relationships that constrain the relative ages of three similar lateral-spread-liquefaction pairs (LSLP) and one underlying strata-bound liquefied mass (SBLM) that deforms a possible weak paleosol that contains rootlets. Each LSLP and SBLM formed during a discrete event and was followed by deposition of 1-2 m of stratified sediment. Truncations at slip surfaces, fault wedges, disconformities and angular unconformities, overlapping sediment, onlapping sediment, sand dikes and sills, and growth strata separate the 3 LSLP and 1 SBLM from one another. Less extreme deformation modified the intervening lake beds.

The most extreme deformation is expressed in fault-graded beds that are more than 5 m thick. The similarity between the LSLP and SBLM in the Green Canyon pit and secondary deformation generated by the 1934 M 6.6 Hansel Valley earthquake (McCalpin et al., 1992) indicate that seismic shaking is the most likely explanation for the four largest deformational features at the mouth of Green Canyon. The smaller deformational features may have formed during subsequent aftershock sequences. Other evidence for a tectonic trigger includes the presence of small fault wedges, alternating brittle and ductile deformation, buried scarps, small sand dikes, and angular unconformities. We propose that four separate, moderate to large earthquakes shook and liquefied the sediment between ~23 ka and the Bonneville flood (~17 to 18 ky). Those earthquakes triggered each LSLP or SBLM, and also produced listric top-basinward and top-toward-the-range-front slip surfaces.

If each liquefaction event records a moderate to large earthquake between about 23 and 17 ky cal BP, the earthquake frequency along the adjacent part of the East Cache fault zone was high when the basin was full. This evidence plus the paleoseismic data of McCalpin (1994) for one additional earthquake shortly after the Bonneville flood and another major earthquake since then, show that there has been a significant decline in earthquake frequency on adjacent segments of the East Cache fault zone since the deep-water phases of the Bonneville lake cycle. The temporal clustering of the liquefaction triggered by the syn-Bonneville paleo-earthquakes, their position near the East Cache fault zone, and the lack of deformation at the site since the Bonneville flood, are consistent with a high frequency of seismicity during the transgression and high stand of Lake Bonneville. The lake could explain this clustered activity by changing the loading stresses in the crust, by modulating rebound-related stresses, and/or by raising the pore pressure along the slip surfaces with circulating pore water. Similar processes might explain the rough coincidence of the Bonneville flood and last major earthquake on the Riverdale fault zone in northern Cache Valley (Janecke and Oaks, 2011a and b).

The increase in earthquake frequency along part of the East Cache fault zone documented here is in marked contrast to that of the Wasatch fault zone, which had a reduced slip rate during the occupation of Lake Bonneville (Hetzel and Hampel 2005). We explain the opposite responses of the two fault zones as the consequence of opposite flexural stresses induced by the loading and rebound produced by Lake Bonneville along an upper monoclinal hinge (near the East Cache fault) and that along a lower monoclinal hinge (near the Wasatch fault) at the eastern margin of Lake Bonneville. The fact that most of the West Cache fault zone, including 18 long of newly identified faults around Cutler Reservoir, ruptured in the Holocene (Black et al., 2000; Janecke and Evans, 2017; Ellis and Janecke et al., 2018 in prep) suggest that the West Cache fault zone be in synch with the Wasatch fault zone and reflect the stresses near the lower monoclinal hinge of the flexurally bending lithosphere.

- **LARGE LIQUEFACTION FEATURES AND EVIDENCE FOR 4 EARTHQUAKES INDUCED BY LAKE BONNEVILLE IN CACHE VALLEY: A PROGRESS REPORT**
-
- JANECKE, Susanne U.[1], OAKS, Robert Q. Jr[1], RITTENOUR, Tammy M.[1], KNIGHT, A.J.[1], NUTT, Dallas[1], and OAKESON[1], Justin, Dept. of Geology, Utah State University, 4505 Old Main Hill, Logan, UT 84322-4505, susanne.janecke@usu.edu.
-
- It is fairly well documented that the central Wasatch fault increased its slip rate since the Bonneville flood (e.g. Hetzel and Hampel, 2005), but little is known about the response of other active normal faults in the NE Great Basin to loading and unloading by Lake Bonneville. An ~50 m long re-exhumed north face of a gravel pit at the mouth of Green Canyon in Cache Valley, northern Utah, and prior trenching provides evidence for a decrease in earthquake frequency along the East Cache fault zone in the same time period. Progressive excavation, logging, and dating of highly deformed and liquefied deltaic sand, silt, gravel and clay is ongoing in conjunction with undergraduate research projects. The exposure in the hanging wall of the East Cache fault lies within the boundary between its northern and central segments and ~25 to ~170 m basinward of two poorly to moderately expressed fault strands. Excavations reveals deltaic sediment that were deposited, seismically deformed, and slumped at least four times under sub-aqueous conditions in Lake Bonneville. Three ^{14}C ages on Stagnicola sp. shells and three OSL ages confirm that the lacustrine sediment was deposited and deformed late during the transgression of Lake Bonneville, as expected from their position ~40-45 m below the Bonneville high stand. Upward coarsening deposition started before 22.2 $\pm$ 3.7 ka and continued after 18.7 $\pm$ 3.2 ka. The geometry and position in the landscape of a laterally continuous alluvial gravel bed that overlies the highly deformed beds in angular unconformity, suggest that the gravel bed was probably laid down immediately after the Bonneville flood, and prior to significant focused down-cutting in the channel of Green Canyon Wash.
-
- The study site currently exposes three listric and wavy slip surfaces of lateral spreads, four sequential, thick liquefied units, undeformed flat and cross-bedded lacustrine sediment, thin deformed beds, and many cross-cutting relationships. Each thick liquefied mass of sand is different in age, yet all the deformation occurred subaqueously when Lake Bonneville was within ~40 m or less of its highest lake level. Three of the liquefied units (0.75-5 m thick) are localized and displaced in the hanging walls of listric east- and west-dipping slip surfaces of coeval lateral spreads. Multiple cross-cutting relationships define the relative ages of the three lateral-spread-liquefaction pairs (LSLP) and the one strata-bound liquefied mass, and show that each formed in a discrete event. Truncations at slip surfaces, fault wedges, disconformities and angular unconformities, overlapping sediment, onlapping sediment, sand dikes and sills, and growth strata separate the three LSLP and the one strata-bound liquefied mass from one another.
-
- Fault-graded beds that are more than 5 m thick and the similarity between the deformation in Green Canyon pit and secondary deformation generated by the 1934 M 6.6 Hansel Valley earthquake provide evidence that seismic shaking triggered the four large deformational features. Other evidence include fault wedges, alternating brittle and ductile deformation, pseudonodules, buried scarps, sand dikes, and angular unconformities. We propose that four separate moderate to large earthquakes shook and liquefied the sediment between ~23 ka and the Bonneville flood (~17.4 ka). Those earthquakes triggered the LSLP and created both top-basinward and top-toward-the-range-front slip surfaces.
-
- The temporal clustering of the paleo-earthquakes, their impacts near the East Cache fault and the lack of deformation at the site since the flood, suggest episodic slip and loading-induced seismicity during transgression of Lake Bonneville. This evidence plus the paleoseismic data of McCalpin for one additional earthquake shortly after the Bonneville flood and one earthquake since then, show that there has been a significant decline in earthquake frequency on adjacent strands of the East Cache fault in the Holocene. This behavior is in marked contrast to that of the central Wasatch fault, which increased its slip rate after the retreat of Lake Bonneville. Differing responses to flexural loading and unloading along the eastern margin of Lake Bonneville may explain this pattern.
-
- Hetzel, R., & Hampel, A. (2005). Slip rate variations on normal faults during glacial–interglacial changes in surface loads. Nature, 435(7038), 81-84.

Paleoseismic Investigation of the Levan and Fayette Segments of the Wasatch Fault Zone, Utah

Utah Quaternary Fault Parameters Working Group

February 5, 2019

Utah Geological Survey:

Adam Hiscock
Greg McDonald
Mike Hylland
Emily Kleber
Tyler Knudsen
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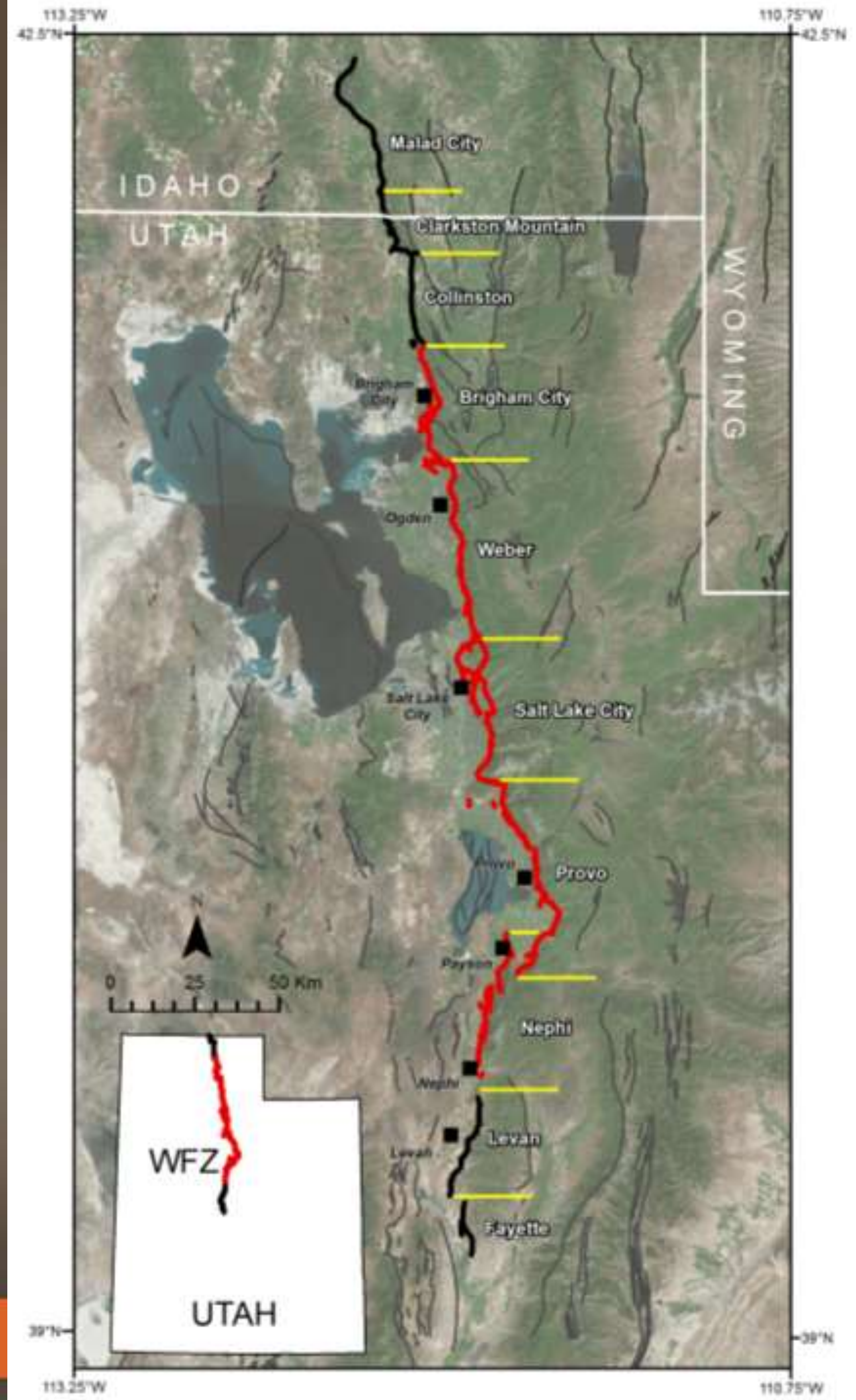
Purpose

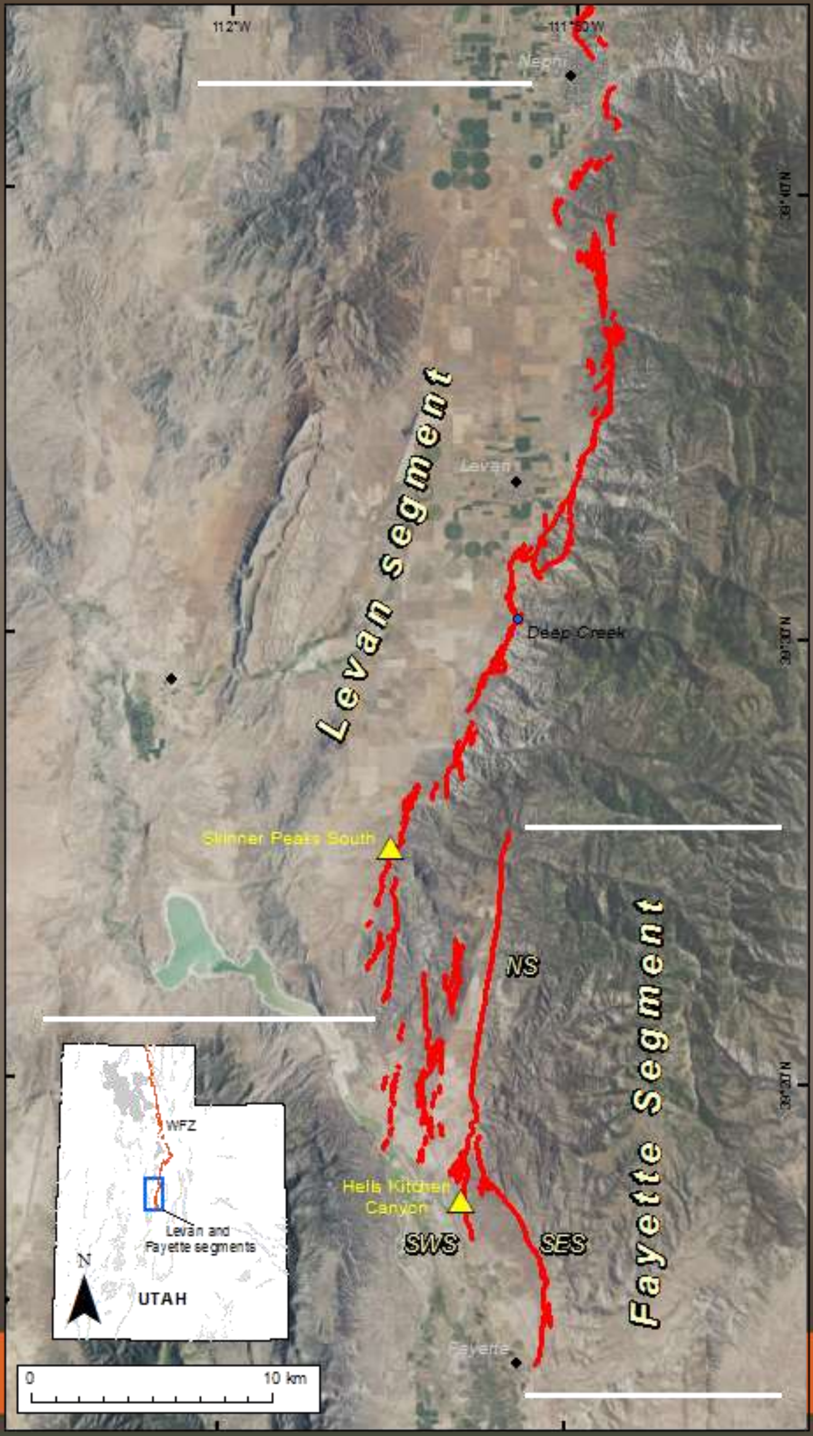
- Southernmost 2 segments of the WFZ – Levan (LS) and Fayette (FS) segments
- Very little paleoseismic data – earthquake timing poorly constrained on LS, non existent on FS
- Both segments show evidence of Holocene rupture
- Data will provide insights into segment boundary evolution
- Large discrepancy between geodetic and geologic strain rates in southern WFZ
- Does salt dissolution play a role in faulting on the LS and FS?



UTAH GEOLOGICAL SURVEY

Location

- Selected 2 sites – Skinner Peaks South and Hells Kitchen South
- Sites on private and public land (BLM)
- Excavated 1 trench at each site on October 10, 2017; backfilled on November 1, 2017



Previous Work on Levan Segment

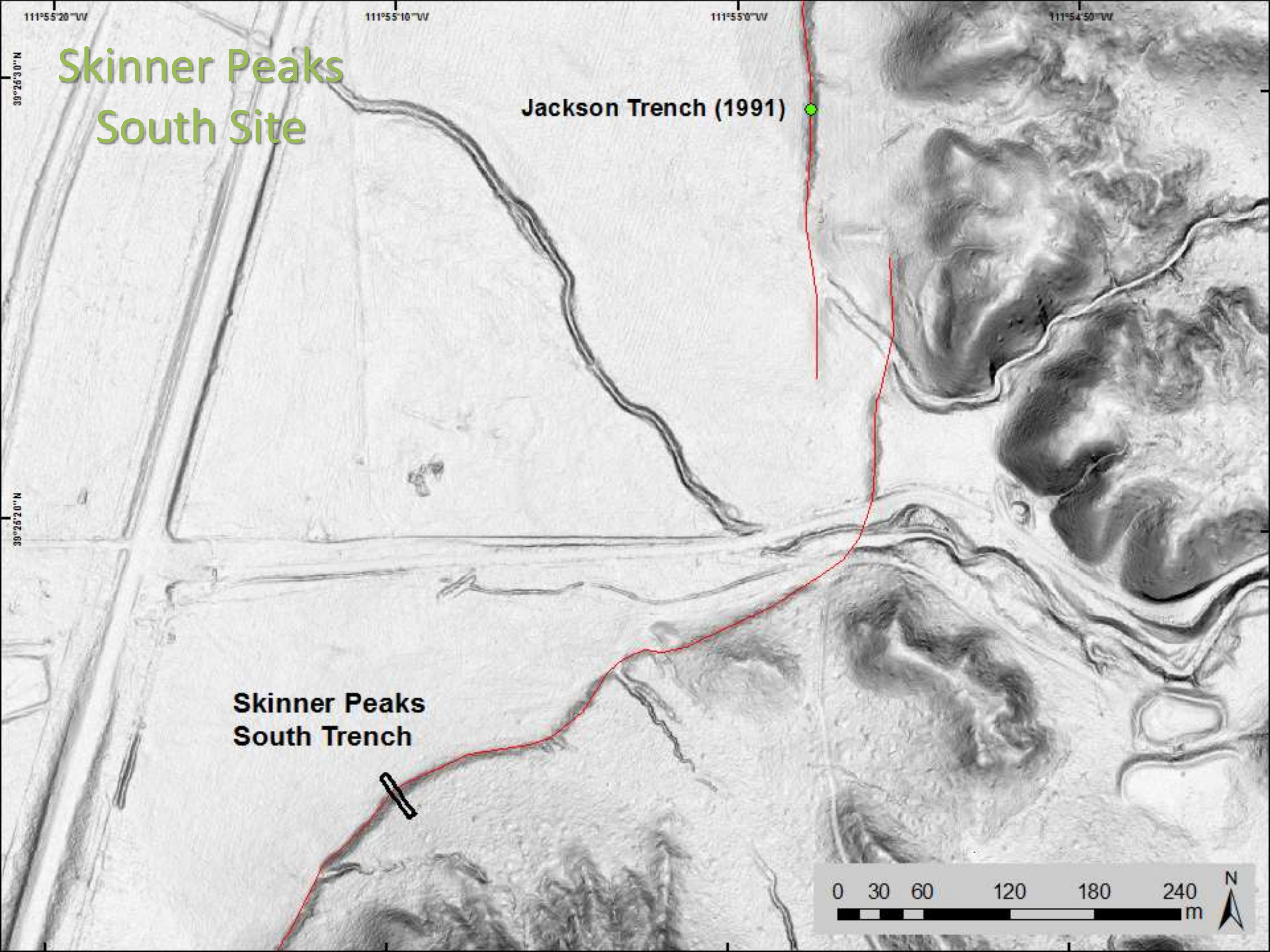
- Jackson (1991) – single trench excavated near Skinner Peaks
  - Evidence for 2 surface-faulting EQ's
  - MRE around 1.0 to 1.5 ka, PE prior to 3.1-3.9 ka
  - Shallow bedrock encountered in footwall – unable to correlate deposits across the fault
- Additionally, Jackson logged Deep Creek natural exposure and constrained MRE age
- Hylland and Machette (2008) – collected C-14 samples from Deep Creek natural exposure as well as faulted fan alluvium near Skinner Peaks
  - Ages consistent with MRE timing of around 1 ka

Previous Work on Levan/Fayette Segments

- Hylland and Machette (2008) – completed 31 fault-scarp profiles on the LS, 21 profiles on the FS
  - Indicated composite scarp morphology on Holocene deposits on the southern LS vs. simple scarp morphology on the northern LS (single-event scarps).
  - Speculated the LS PE may represent spill-over rupture from a FS surface-faulting earthquake
- Hiscock and Hylland (2015) – completed detailed fault-trace mapping for the LS and FS using 0.5-m LIDAR data

Skinner Peaks South Site

- 3-4 meter scarp
- Coarse, volcanic derived fan material
- Local bedrock: Tertiary Formation of Painted Rocks, Member 5 – volcanic conglomerate & welded tuff



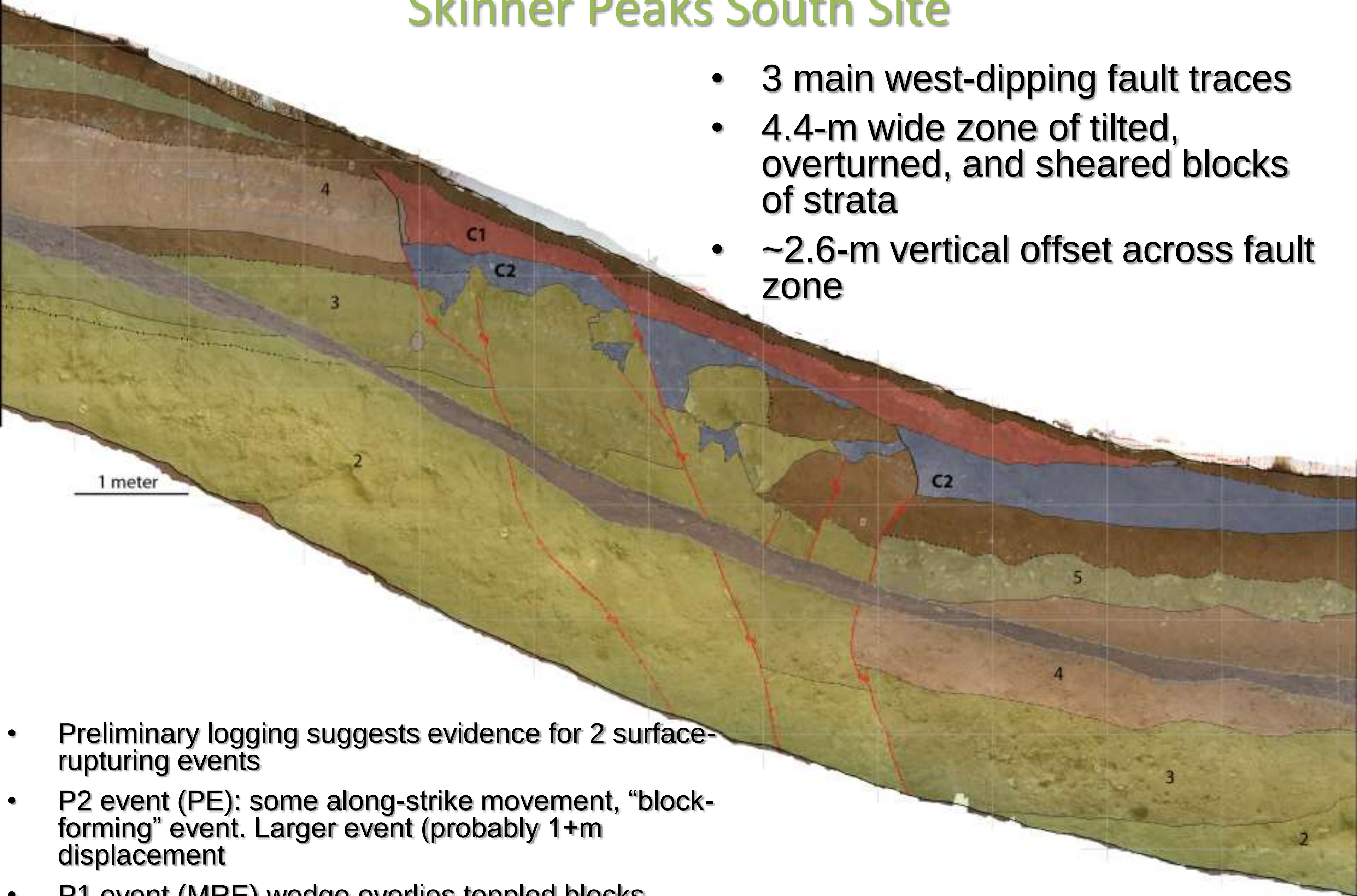
111°55'20"W
111°55'10"W
111°55'0"W
111°54'50"W
39°26'3.0"N
39°26'2.0"N
Skinner Peaks
South Site
Jackson Trench (1991)
Skinner Peaks
South Trench
0 30 60 120 180 240
m
N

Skinner Peaks South Site

Skinner Peaks South Site

- Mapped 5 stratigraphic units
- Unit 1: Highly weathered tuffaceous bedrock exposed HW.
- Units 2-5: Sandy fan gravels several prominent buried soi horizons.

Skinner Peaks South Site



- 3 main west-dipping fault traces
- 4.4-m wide zone of tilted, overturned, and sheared blocks of strata
- ~2.6-m vertical offset across fault zone

- Preliminary logging suggests evidence for 2 surface-rupturing events
- P2 event (PE): some along-strike movement, “block-forming” event. Larger event (probably 1+m displacement
- P1 event (MRE) wedge overlies toppled blocks. Smaller event – thinner colluvium overlying P2 blocks.
- Modeling for 1 and 2 event scenarios

Hells Kitchen South Site

- 1-2 meter scarp
- Carbonate-derived fan material
- Local bedrock: Tertiary units (North Horn, Flagstaff, Colton, Green River formations), Cretaceous Indianola Group

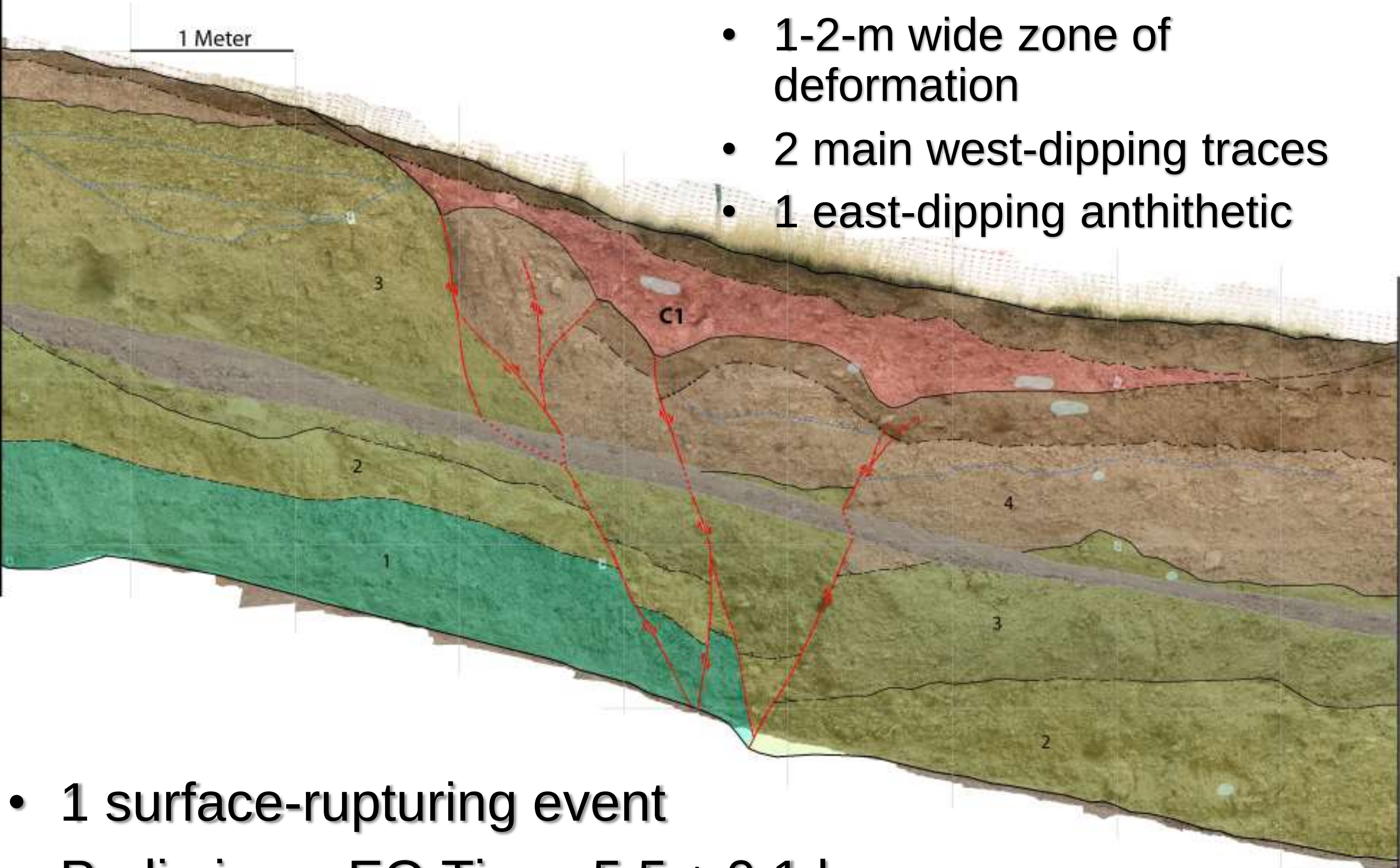
Hells Kitchen South Site

Hells Kitchen South Site

Hells Kitchen South Site

- Mapped 4 stratigraphic units
- Unit 1: post-Bonneville highstand fine-grained loess deposit
- Units 2-4: Coarse fan deposits

Hells Kitchen South Site



- 1-2-m wide zone of deformation
- 2 main west-dipping traces
- 1 east-dipping anthithetic

- 1 surface-rupturing event
- Preliminary EQ Time: 5.5 ± 0.1 ka (2σ)

Sampling Strategy

- Collected 20 C-14 samples
  - NOSAMS Lab, Woods Hole, MA
- Collected 15 OSL samples
  - USGS Lab, Denver, CO

Sample ID	Lab Age (14C yr B.P.)		Calibrated Age (14C yr B.P.)						Calibrated Age (thous. Of cal yr B.P.)	
	mean	±1σ	from	to	%	mean	±1σ	±2σ	mean	±2σ
SPS-S-RC02	1730	25	1704	1568	95.4	1641	40	80	1.6	0.1
SPS-S-RC04	3560	25	3959	3728	95.3	3854	44	88	3.9	0.1
SPS-S-RC05	3320	25	3631	3476	95.4	3543	39	78	3.5	0.1
SPS-S-RC06	170	20	285	...	95.5	164	86	172	0.2	0.2
SPS-S-RC07	895	25	908	738	95.4	827	51	102	0.8	0.1
SPS-S-RC08	3330	25	3634	3480	95.4	3558	42	84	3.6	0.1
SPS-N-RC09	3180	25	3450	3364	95.4	3407	26	52	3.4	0.1
SPS-N-RC10	2050	25	2113	1934	95.4	2014	43	86	2	0.1
HKS-S-RC01	150	20	284	2	95.4	154	84	168	0.2	0.2
HKS-S-RC02	4880	30	5657	5586	95.4	5618	25	50	5.7	0.1
HKS-S-RC03	4720	25	5581	5326	95.4	5452	88	176	5.4	0.2
HKS-S-RC04	4630	25	5455	5305	95.4	5396	47	94	5.4	0.1
HKS-S-RC09	5140	45	5990	5749	95.4	5872	70	140	5.9	0.2

Sample ID	Calibrated Age (yr B.P., ±2σ)	Calibrated Age (thous. Of cal yr B.P.)	
		mean	±2σ
HKS-S-OSL-01	11,290 ± 1,160	11.3	1.2
HKS-S-OSL-02	3,380 ± 560	3.4	0.6
HKS-S-OSL-03	11,550 ± 2,340	11.5	2.3
HKS-S-OSL-04	4,640 ± 860	4.7	0.9
HKS-S-OSL-05	12,710 ± 1,560	12.7	1.6
SPS-S-OSL-01	7,270 ± 2,700	7.3	2.7
max	16,330 ± 2,440	16.3	2.4
SPS-S-OSL-02	8,840 ± 3,200	8.8	3.2
max	23,880 ± 4,080	23.9	4.1
SPS-S-OSL-03	2,540 ± 760	2.5	0.8
SPS-S-OSL-04	2,020 ± 540	2	0.5
SPS-S-OSL-05	1,020 ± 280	1	0.3

Summary & Conclusions

- 1 earthquake rupture at the Hells Kitchen Canyon Site (FS)
  - 5.5 ± 0.1 ka (2σ)
  - First earthquake timing data for FS
- Potentially 1 or 2 earthquakes at the Skinner Peaks Site (LS)
  - Working on various OxCal models
  - Could potentially be seeing MRE from Jackson (1991) trench and Deep Creek natural exposure (Hylland 2007).

Thanks To:

Kelsey Zabrusky - BLM Richfield Field Office

Madsen Family Trust

Skyline Excavators – Todd Nielson

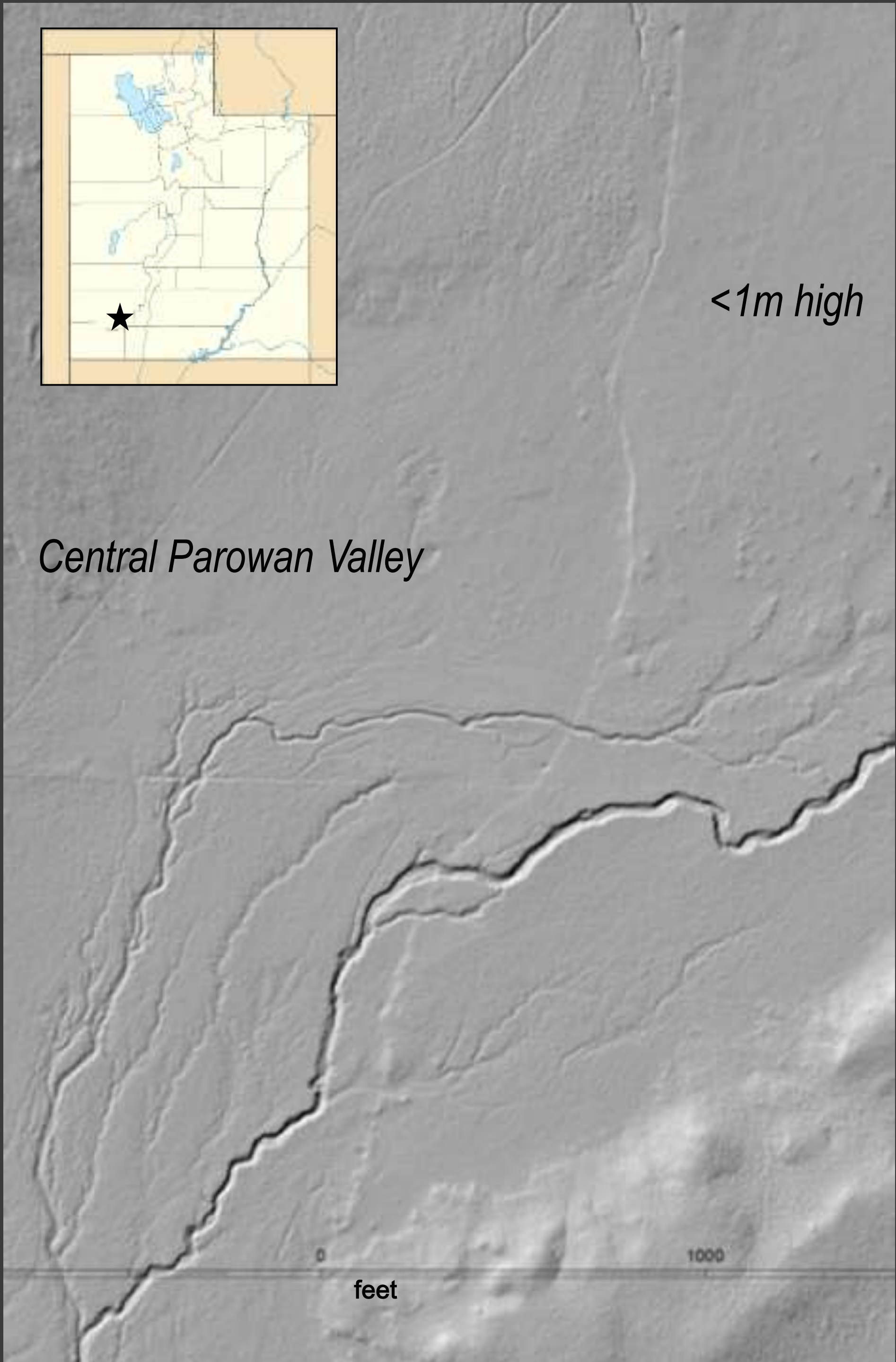
Yuba Reservoir State Park

UTAH DNR GEOLOGICAL SURVEY

Basin-floor faulting in Parowan Valley, Southwestern UT

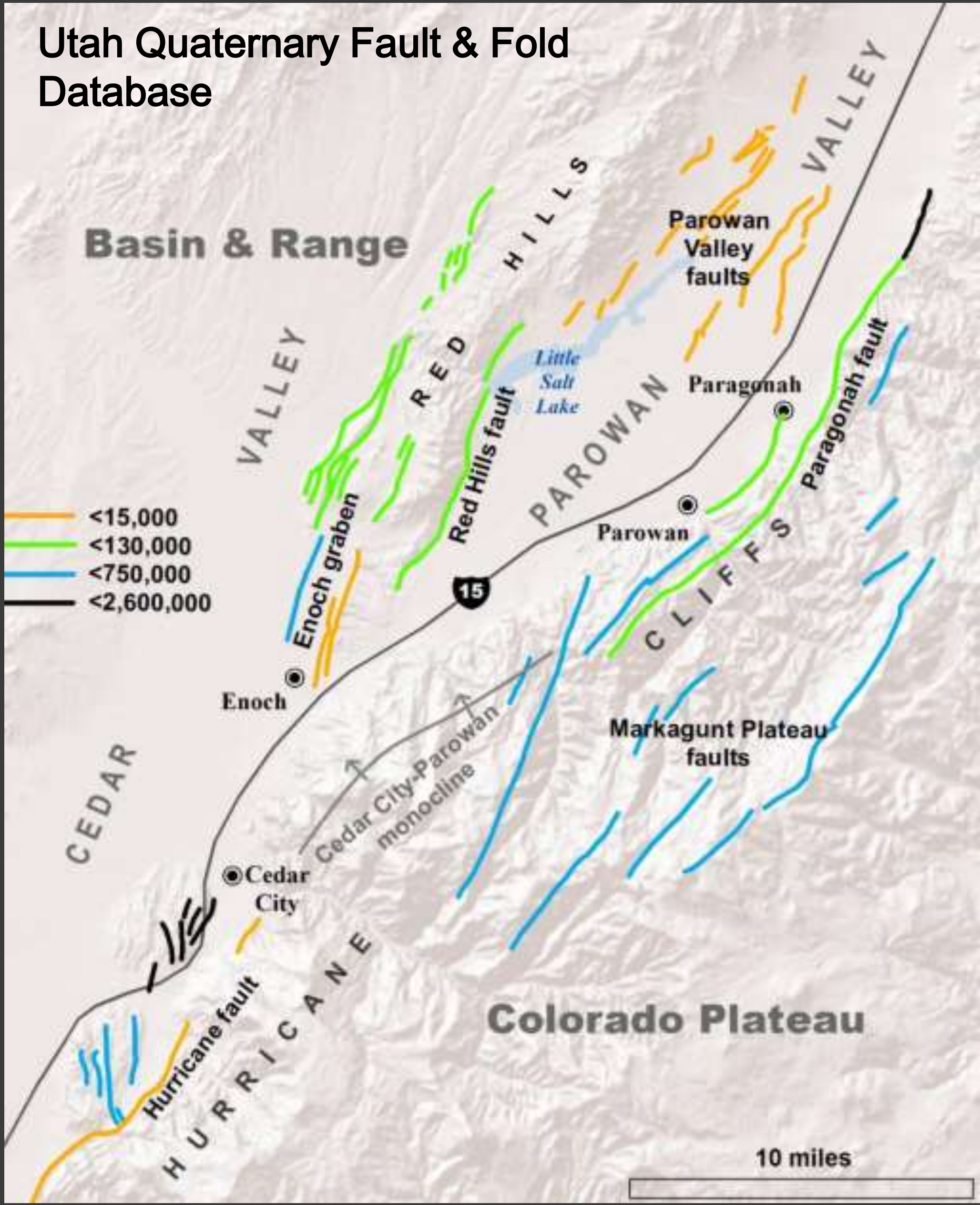
Tyler Knudsen
Utah Geological Survey, Cedar City

- New insights on Parowan Valley and Enoch graben (Cedar Valley) faults
- Observations are a byproduct of investigations into subsidence and earth fissures related to groundwater decline
    - 1-m lidar acquired in 2011



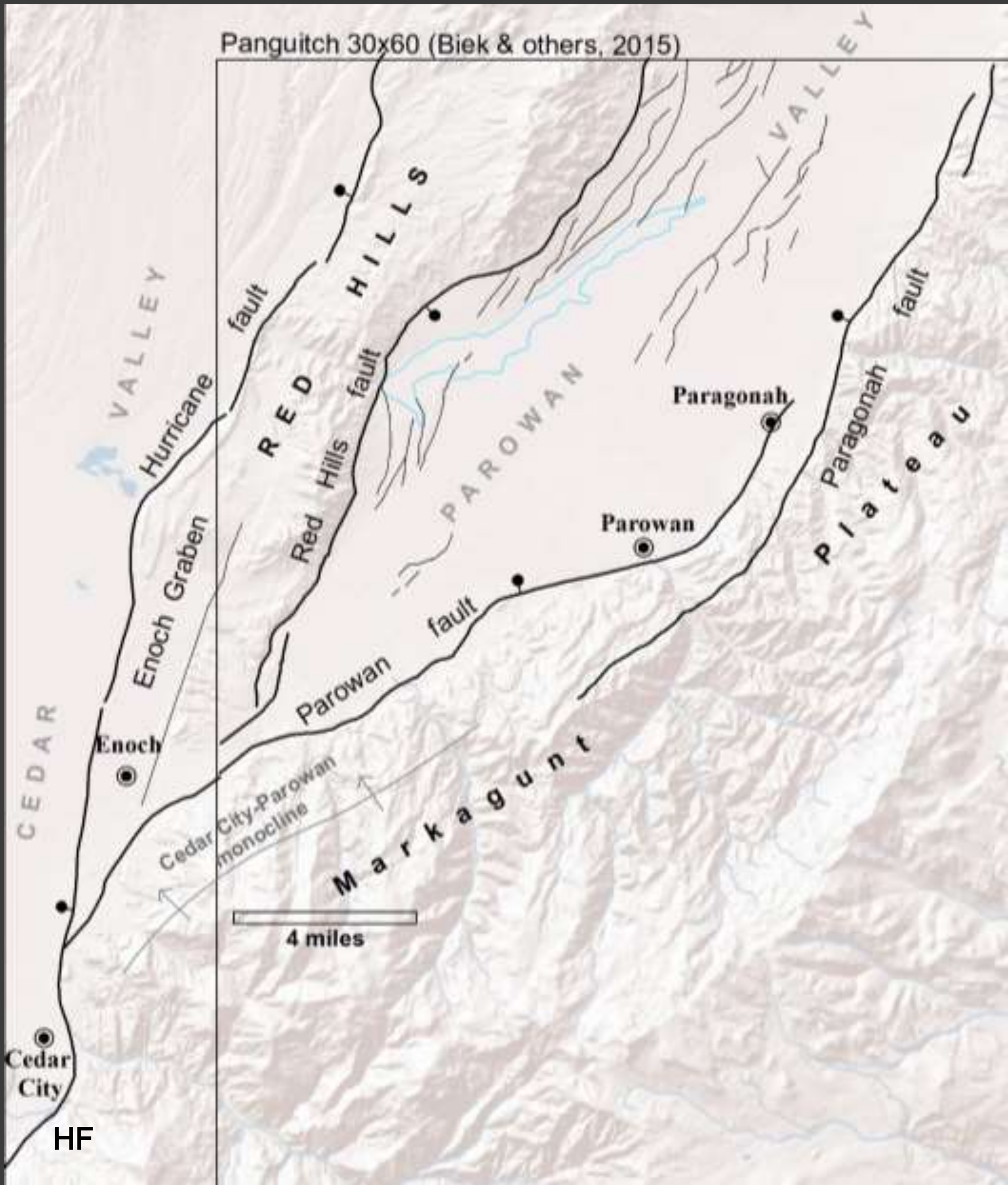
Parowan Valley Faults - Geologic Setting

- B&R /Colorado Plateau transition zone
- Bounded by Paragonah fault zone on east & Red Hills fault to the west
- ~3500 to 6500 feet of unconsolidated sediment near center
- On UQFPWG priority list for more study: Paragonah, Enoch graben, and ~~CC-Parowan monocline~~
- Iron County continues to grow
  - 50,000 (2015)→90,000 (2065)
  - Most live along I-15



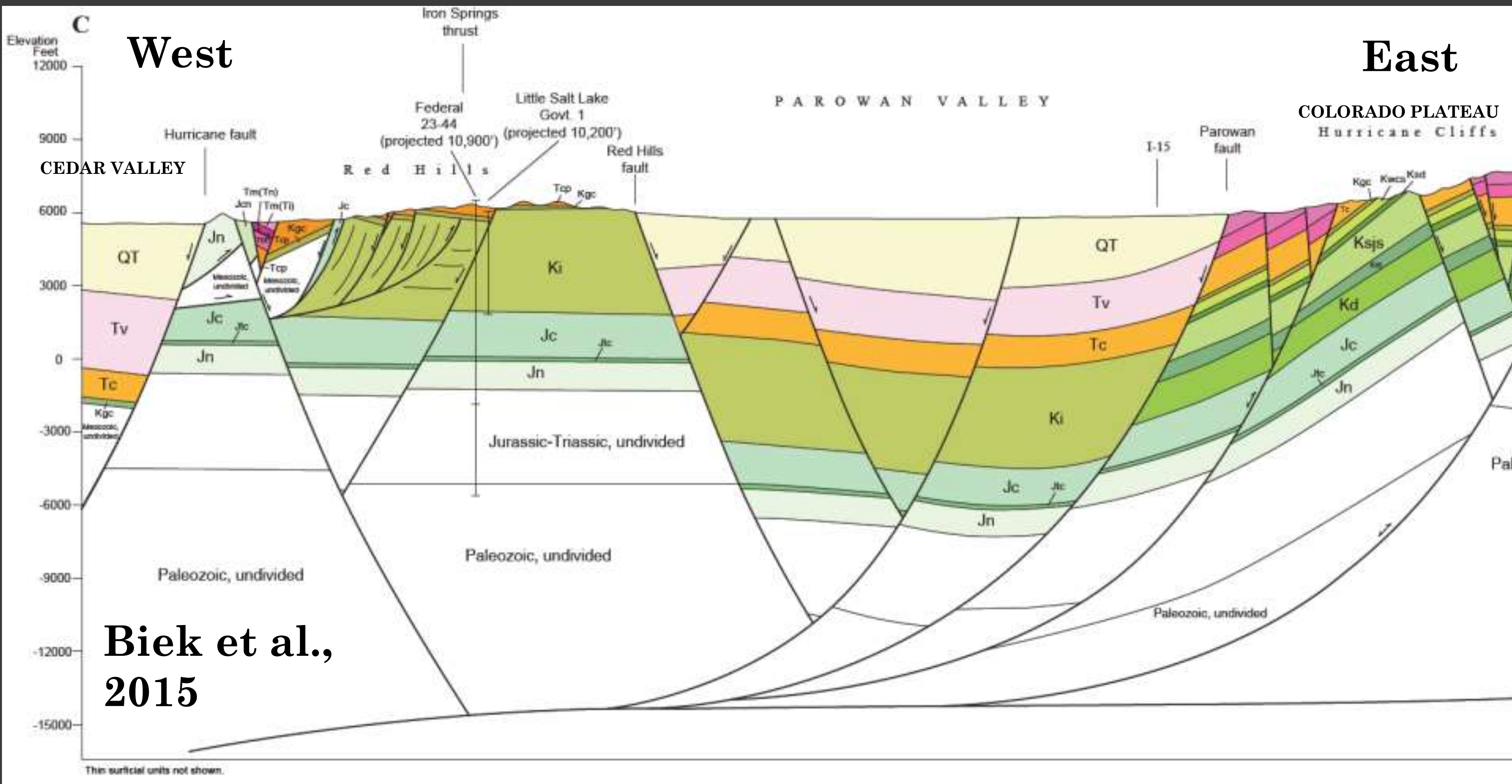
Panguitch 30x60 Map (Biek & others, 2015)

- Debunked Cedar City-Parowan monocline as a Q structure
- Identified Parowan fault zone along southeastern margin of valley
- Supports idea that the Hurricane fault extends north from Cedar City along the western margin of the Red Hills
- Mapped more extensive basin-floor faulting despite 1:62,500 scale



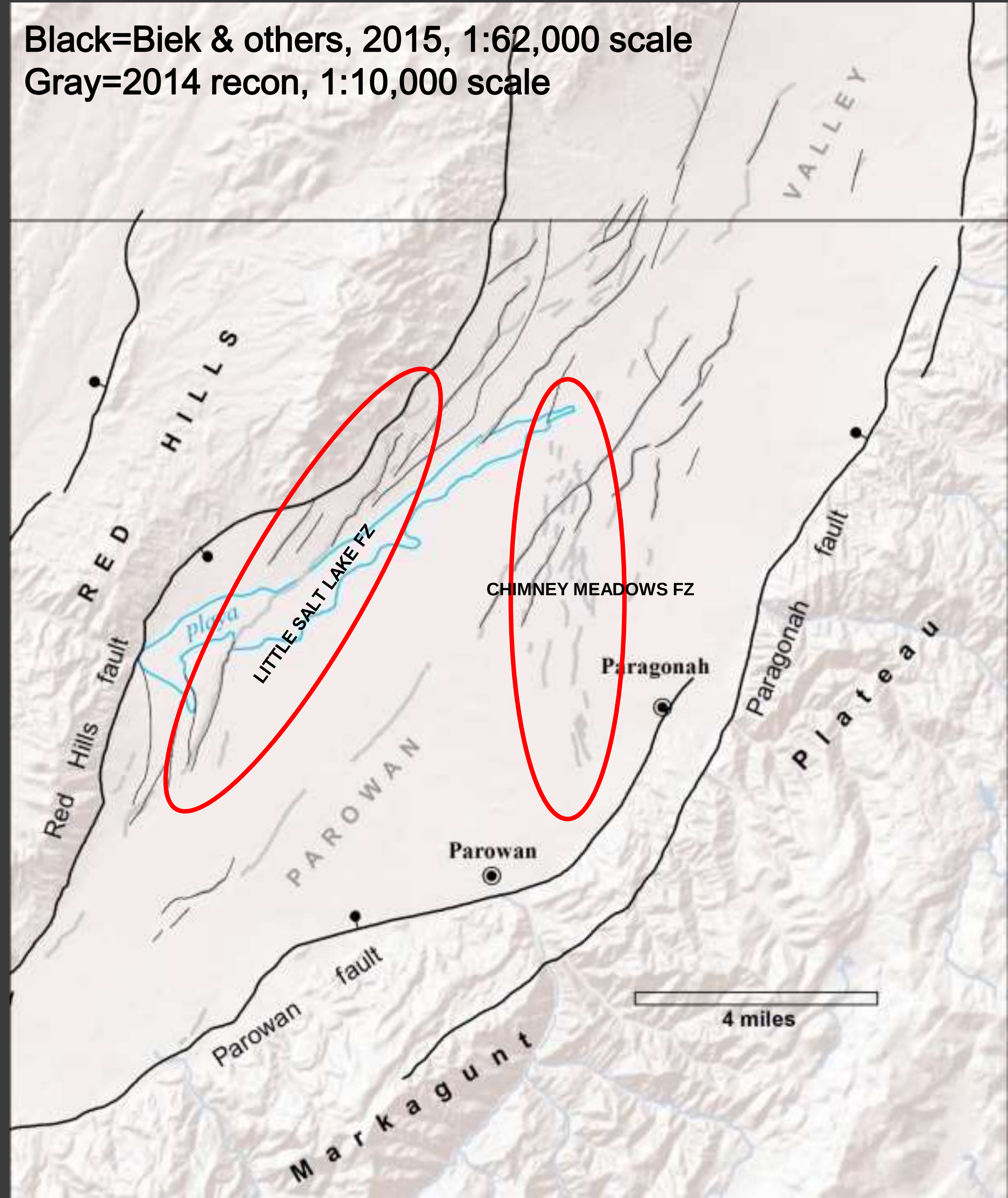
Parowan Valley Structure

- Paragonah-Parowan fault zone is the main breakaway from the Colorado Plateau
- Several 1000s of feet of unconsolidated basin fill
- Basin-floor faults are both east- and west-dipping

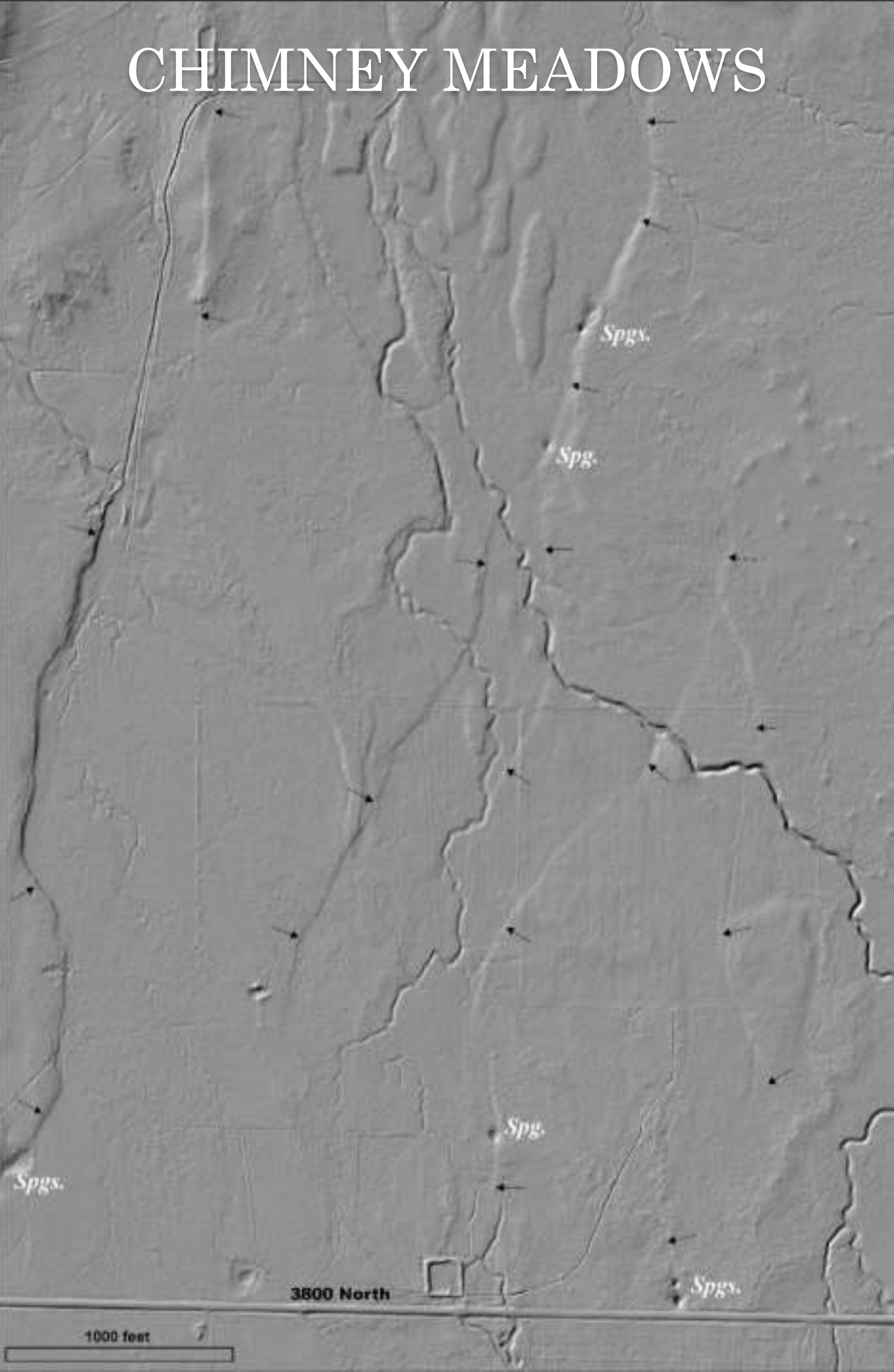


Summer 2014 Field Reconnaissance

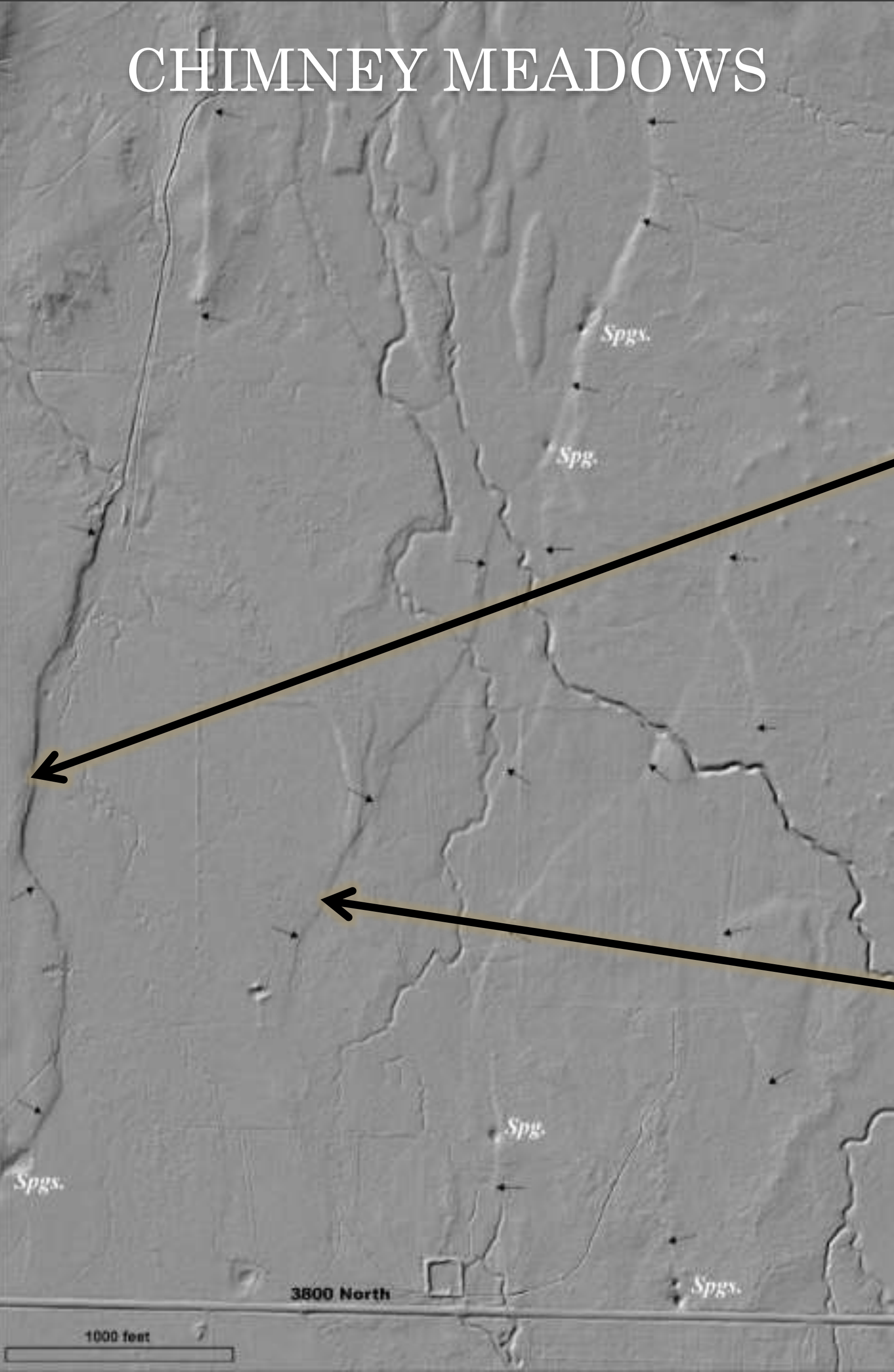
- Spurred by suspected earth fissures related to groundwater declines & subsidence
- Based on 1-m lidar acquired in 2011
- Major discoveries:
  - Evidence for very young ruptures(?)
  - N-S Chimney Meadows fault zone
  - Extended Little Salt Lake fault zone
  - Fissures



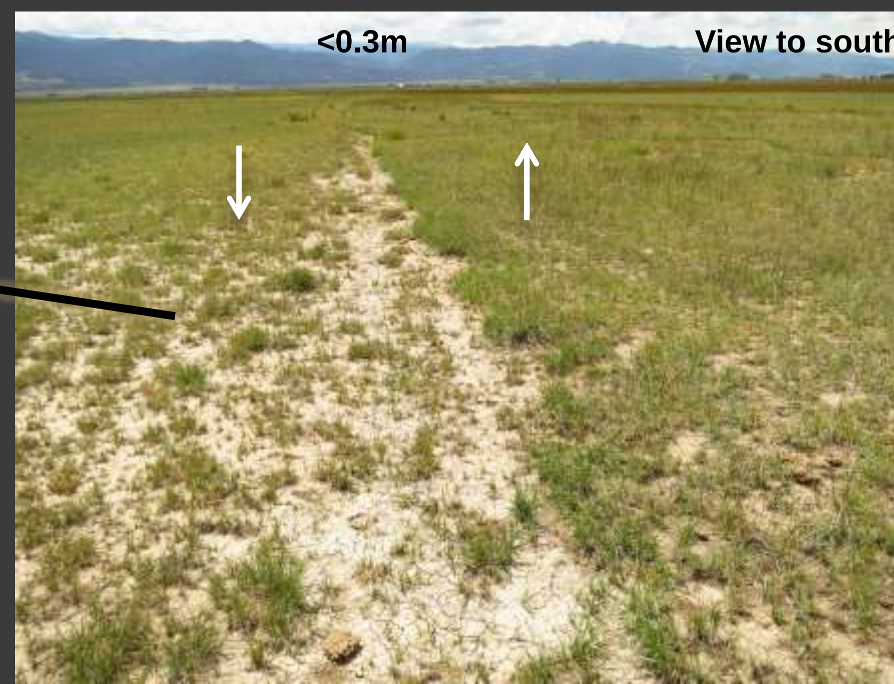
CHIMNEY MEADOWS



- Strike N-S rather than NE-SW
- Both east- and west-dipping
- Closely spaced, discontinuous, anastomosing/branching
- Small displacements ranging from <0.3 m to ~3 m
- Displace Holocene stream & flood-plain deposits along modern drainages (map unit Qaly)
- Many springs localized along the faults

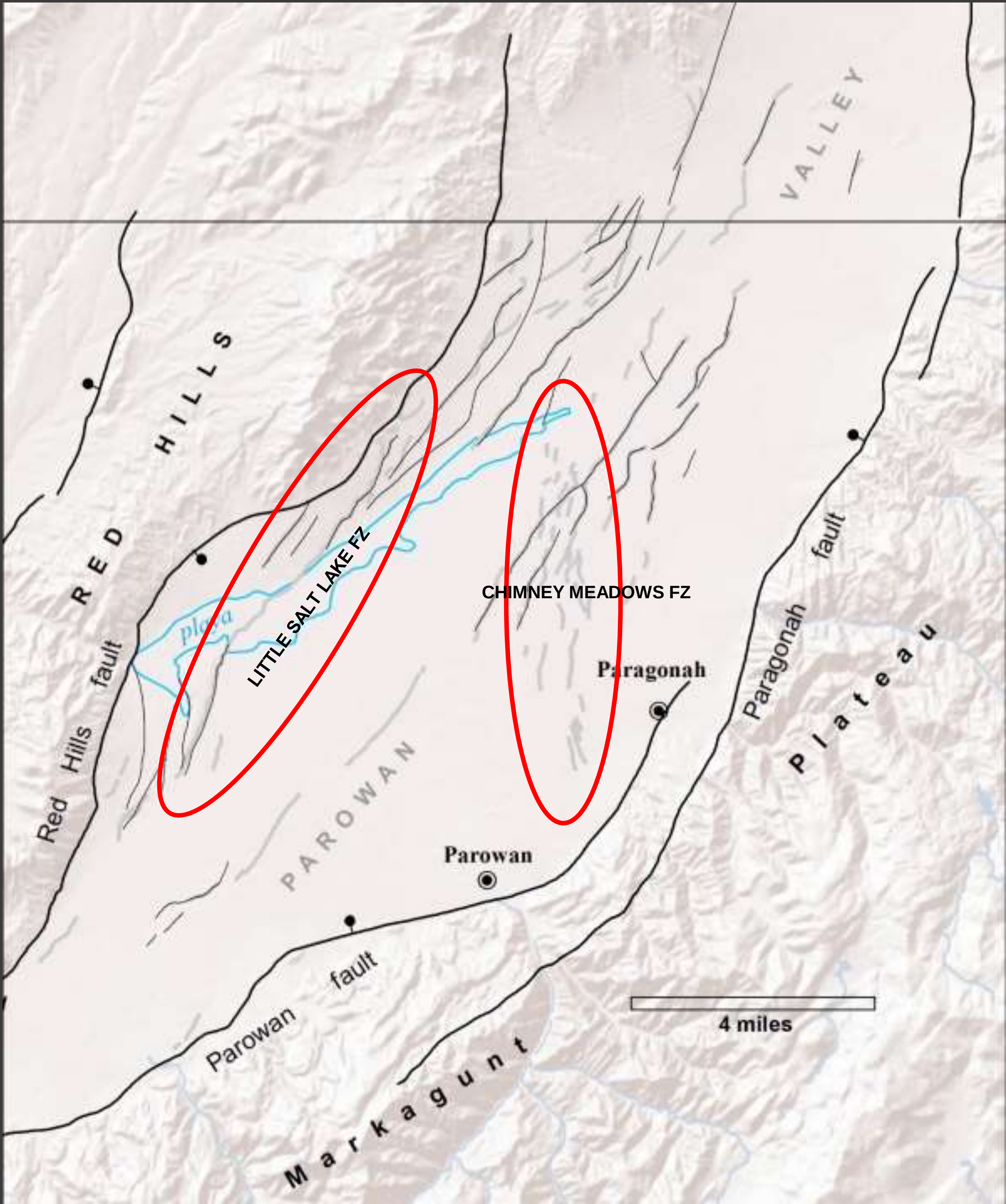

CHIMNEY MEADOWS
Spgs.
Spg.
Spg.
Spgs.
Spgs.
3800 North
1000 feet

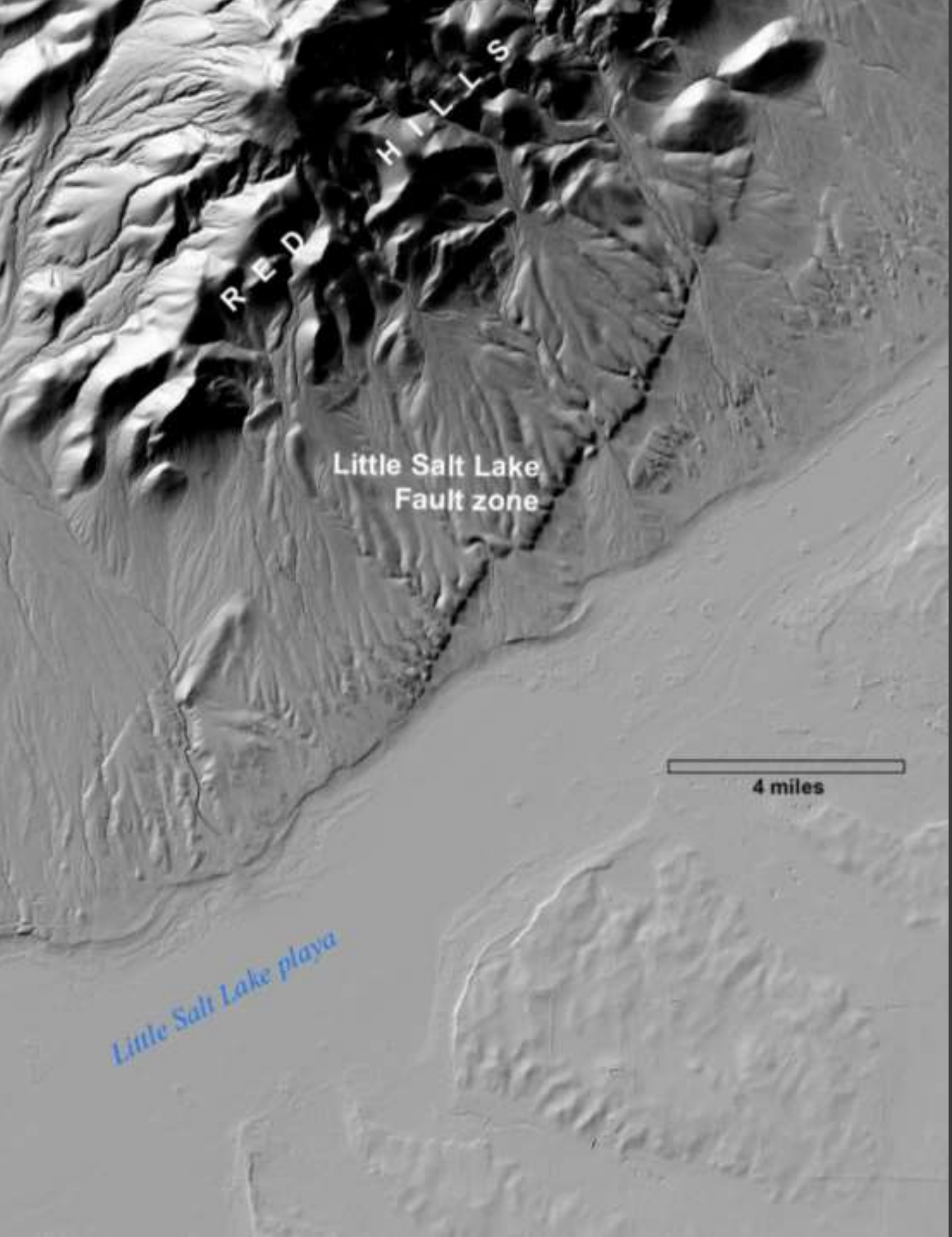

<1m
View to north


<0.3m
View to south

Little Salt Lake Fault Zone

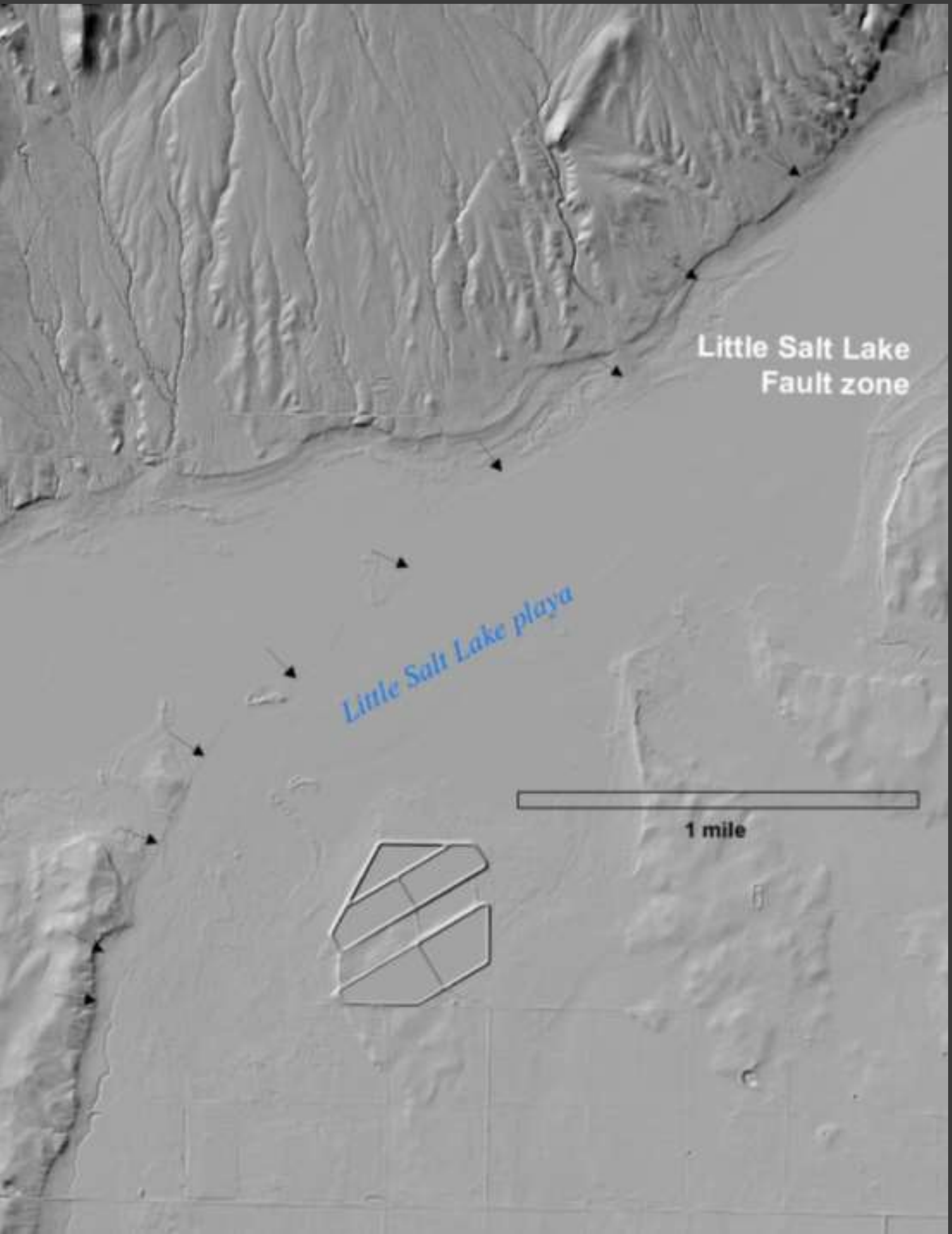
- Described by Williams and Maldonado (early 90s BARCO)
- 3.5 km long





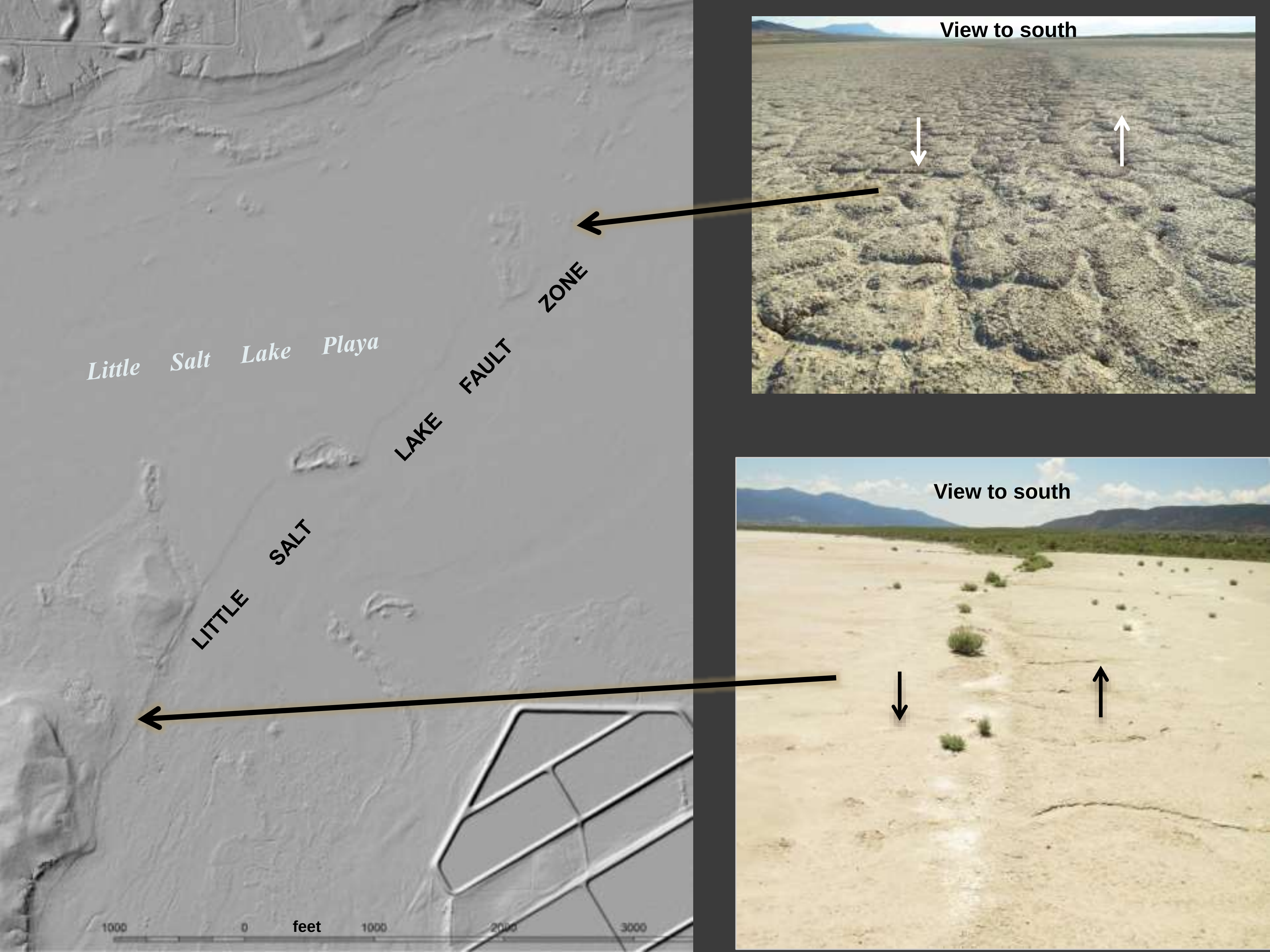
LITTLE SALT LAKE FZ

- Williams & Maldonado, 1992:
- highest (<18 m) intrabasin Q fault in Parowan Valley
- Late Pleistocene/possible Holocene age based on profiles and estimated ages of displaced fan deposits
- No evidence of fault crossing the Little Salt Lake playa



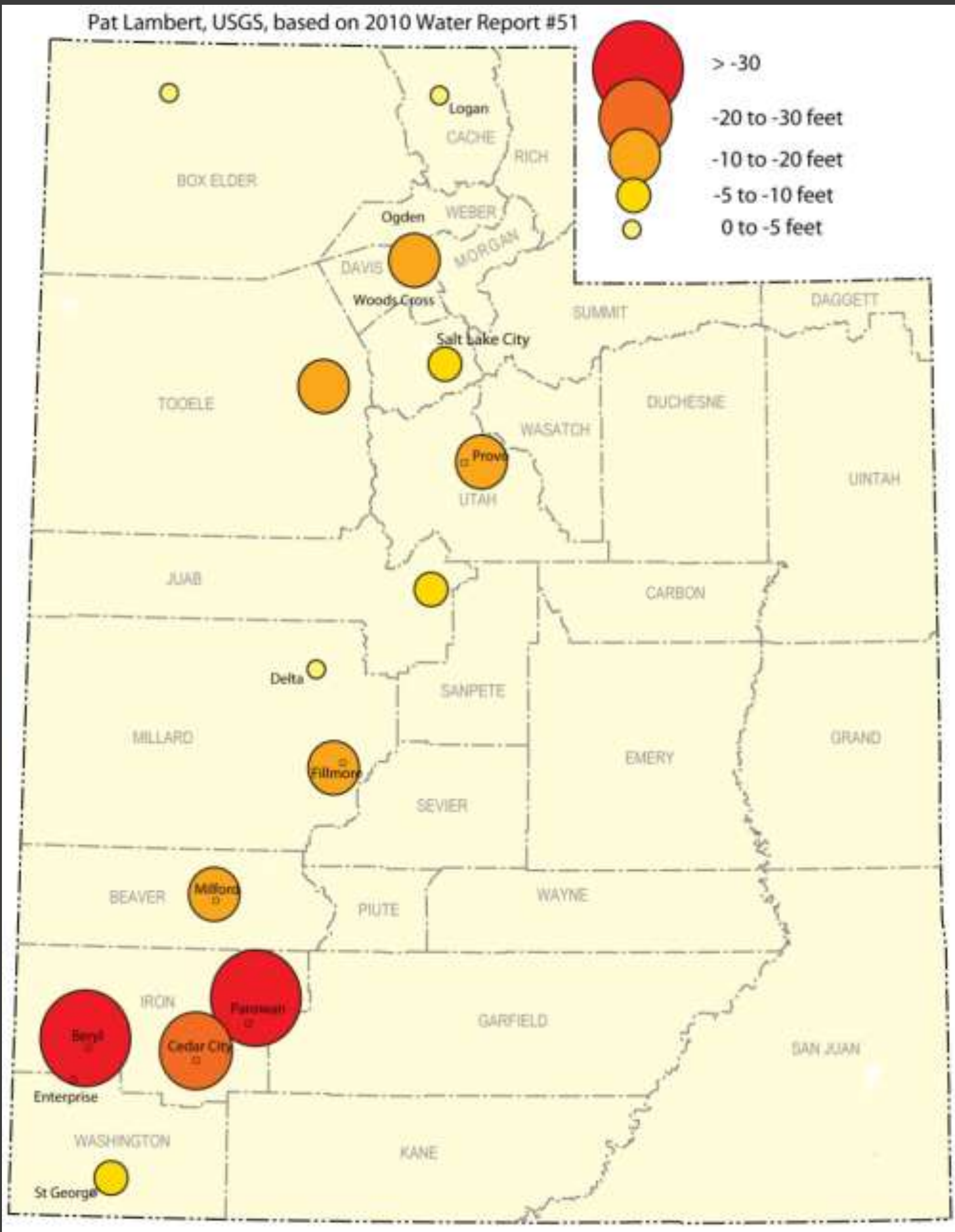
LITTLE SALT LAKE FZ

- Lidar and field reconnaissance confirm that the Little Salt Lake FZ extends across the playa and continues south
- Fault zone appears to be about 10 km long


View to south
View to south
Little Salt Lake Playa
LITTLE SALT LAKE FAULT ZONE
1000 0 feet 1000 2000 3000

Could 1934 M6.6 Hansel Valley be an Analog to Young Small Young Scarps on Floor of Parowan Valley?

It’s Complicated: Let’s Talk Groundwater

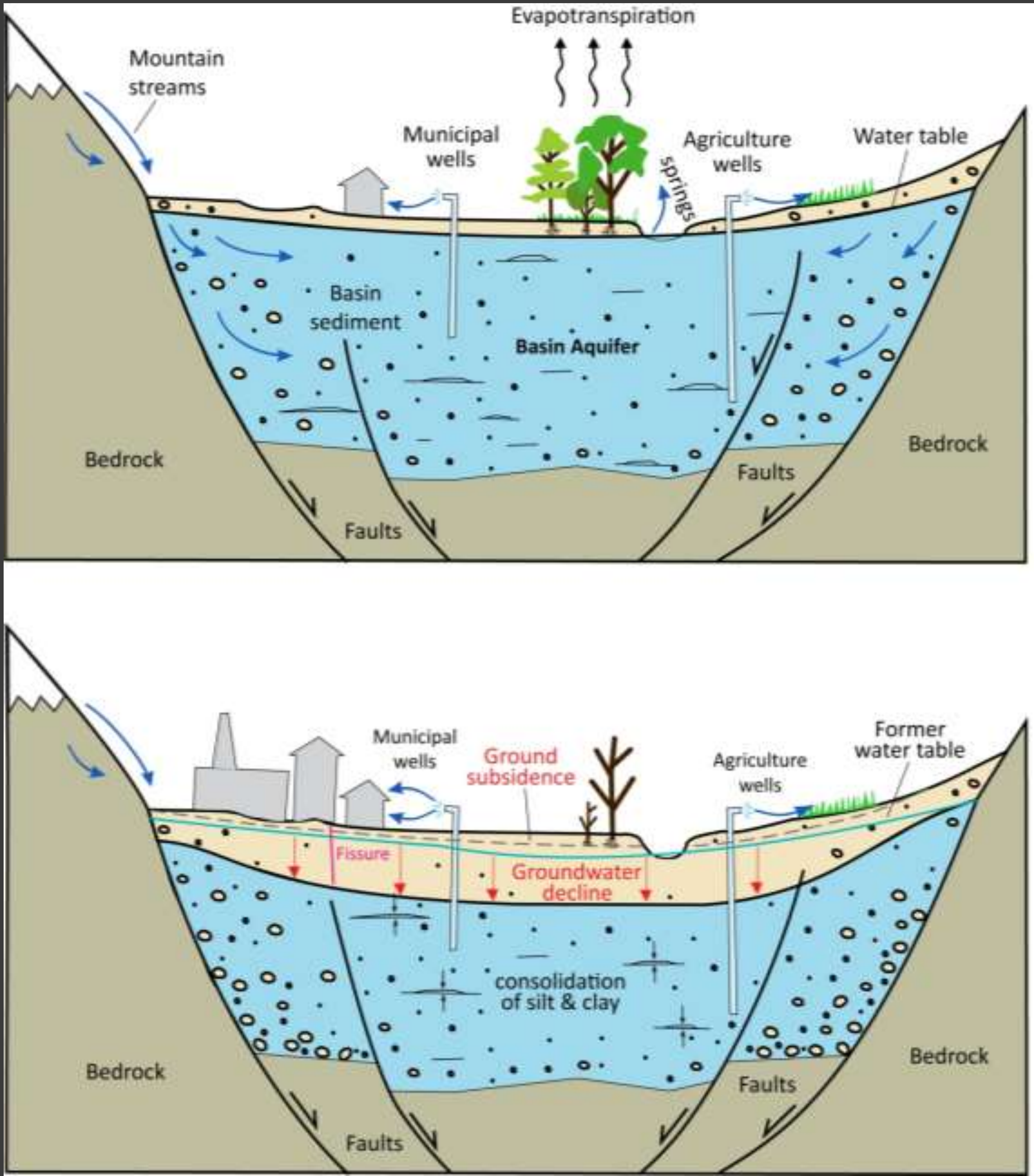


Aquifers with significant declines in water levels

- Iron County basins
  - High desert
  - Limited natural recharge
  - Alfalfa as far as the eye can see
- Beryl-Enterprise -210 ft
- Cedar Valley -100 ft
- Parowan Valley -100 ft
- All three valleys have documented subsidence

Subsidence & Earth Fissures

- Increased population/agriculture/ drought cause discharge to exceed recharge
- Water table drops
- Reduction of pore-water pressure causes compaction of clays/silts
- Development of tension cracks (fissures) due to differential compaction of the aquifer material
- Surface displacement also possible



Subsidence & Earth Fissures

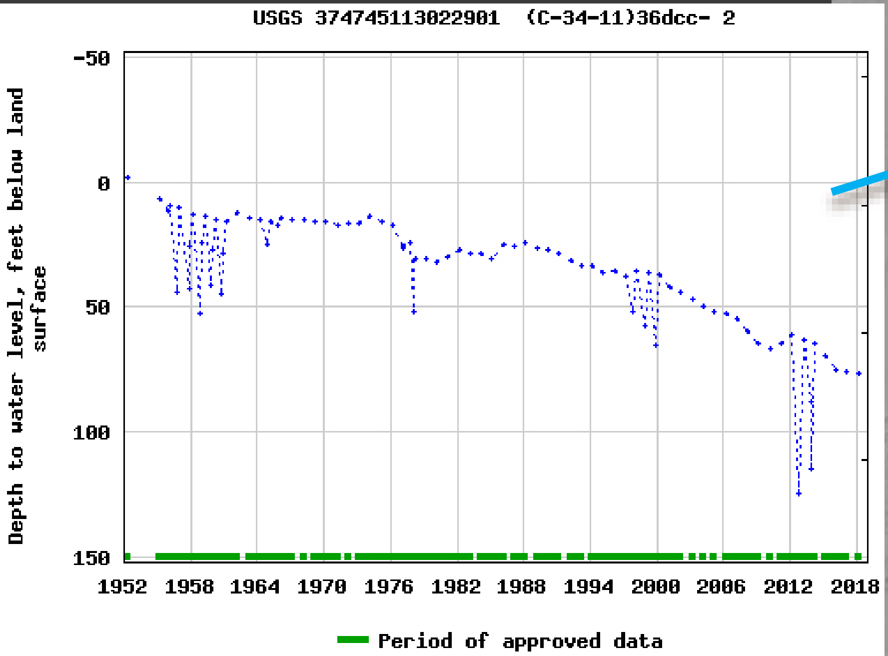
- Some fissures exhibit surface displacement-often localized along pre-existing faults

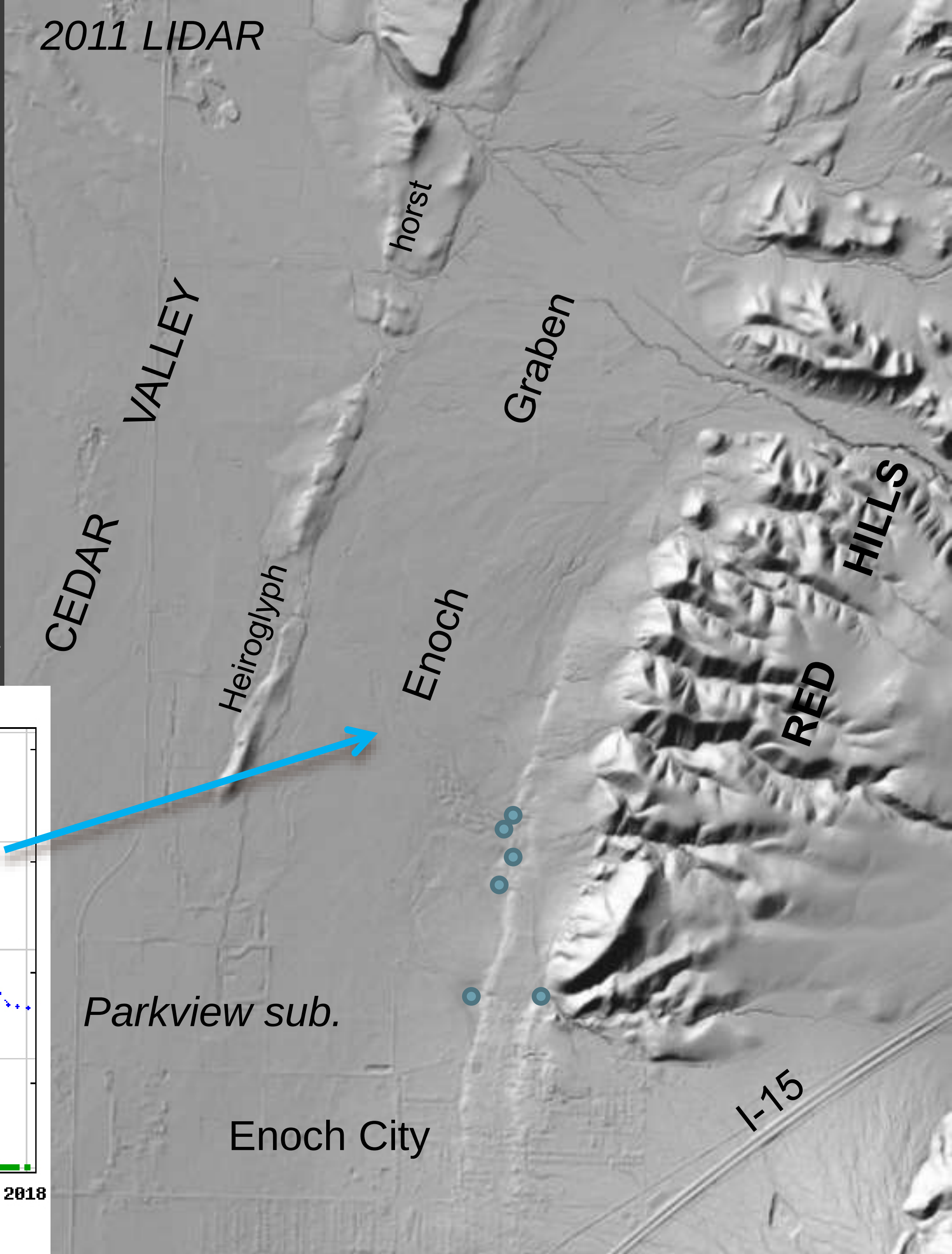
Picacho fault, AZ
Thomas Holzer


(A) Fremont Valley, CA
Thomas Holzer, 1978

Enoch graben

- Groundwater table has dropped about 80 feet
- Dozens of free-flowing springs dried up in the mid-1970s
- Subsidence recognized in 2009 at Parkview subdivision





ENOCH FISSURE CONTINUES TO GROW

- Vertical displacement rate of the Enoch-graben-west fissure has been about 1.7 inches/year

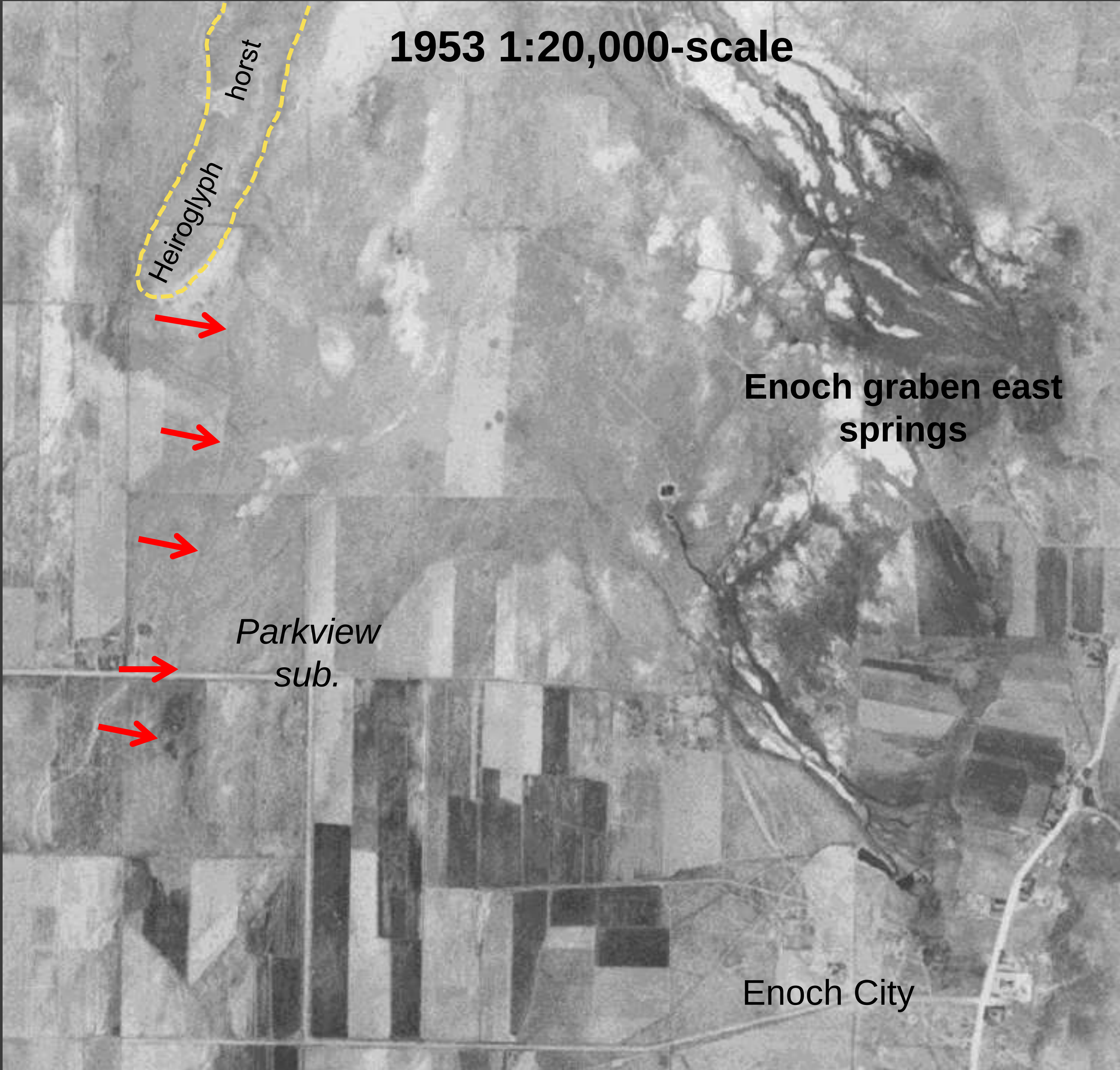
ENOCH FISSURE CON
GROW

- Vertical displa
  Enoch-graben
  been about 1.7

Apr ‘11

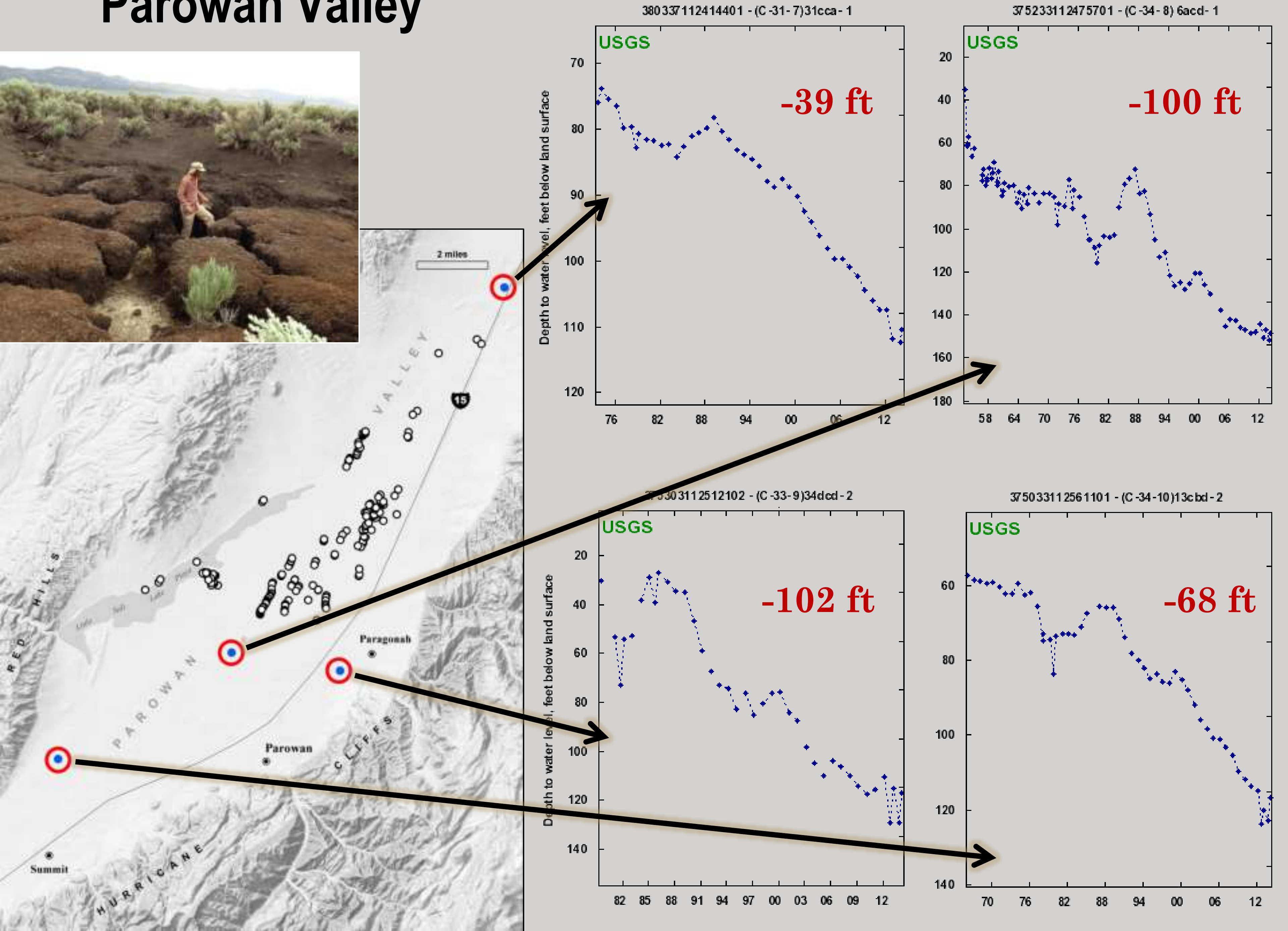
ENOCH FISSURE CONTINUES TO GROW

- But was there a young rupture present before man-induced subsidence began?



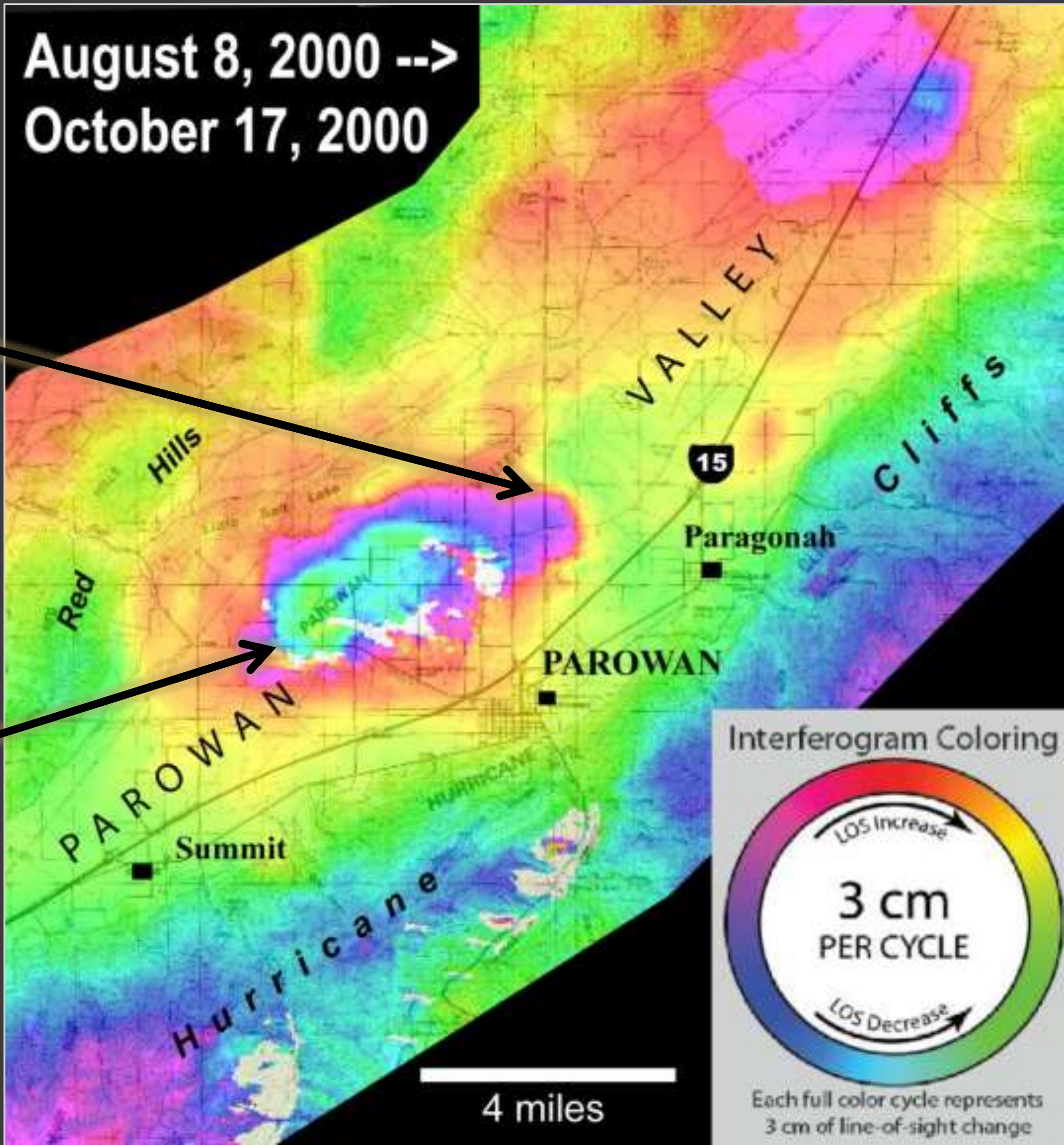
1953 1:20,000-scale
horst
Heiroglyph
Enoch graben east springs
Parkview sub.
Enoch City

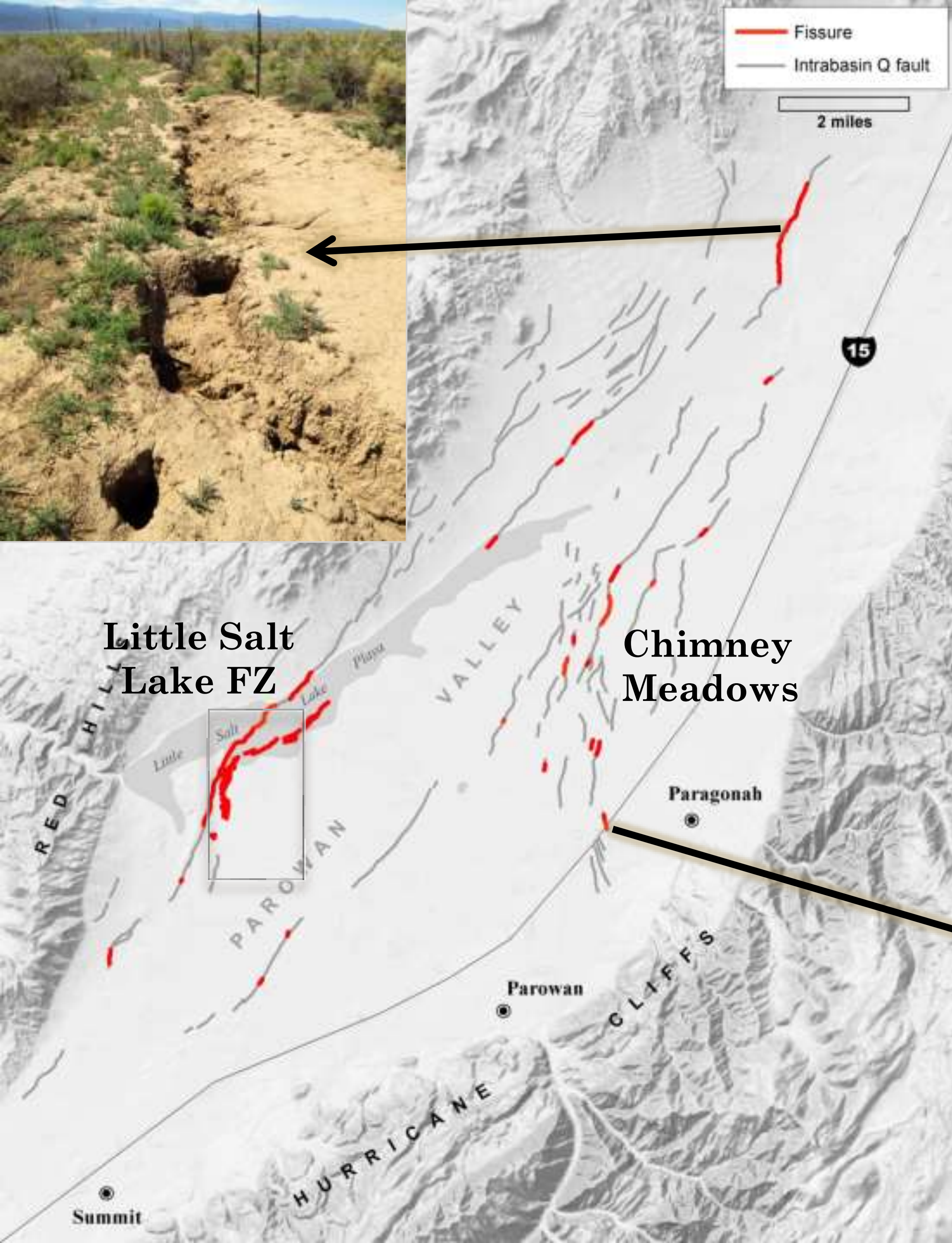
Parowan Valley



Protruding wells

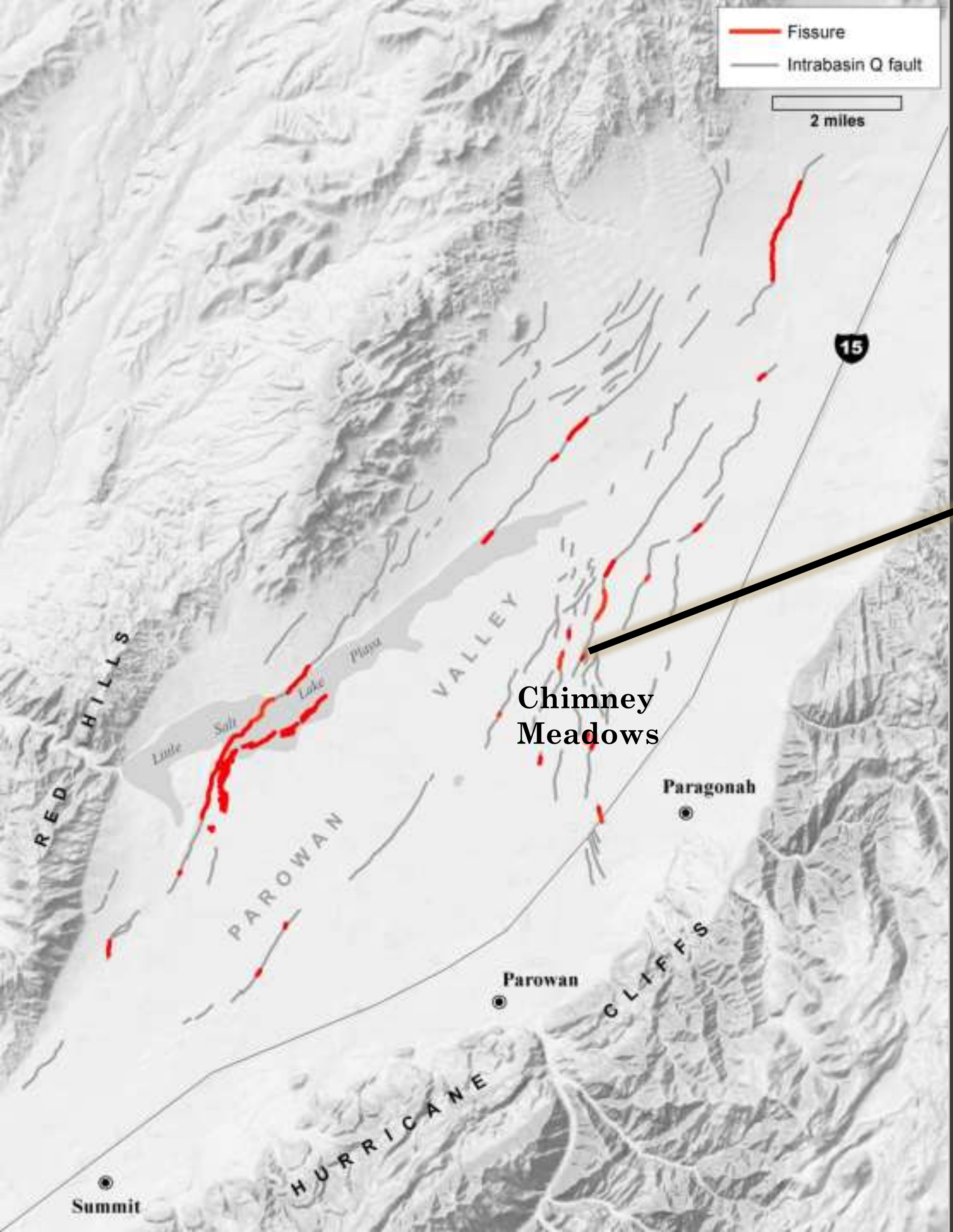
Preliminary InSAR Interferogram (Katzenstein)

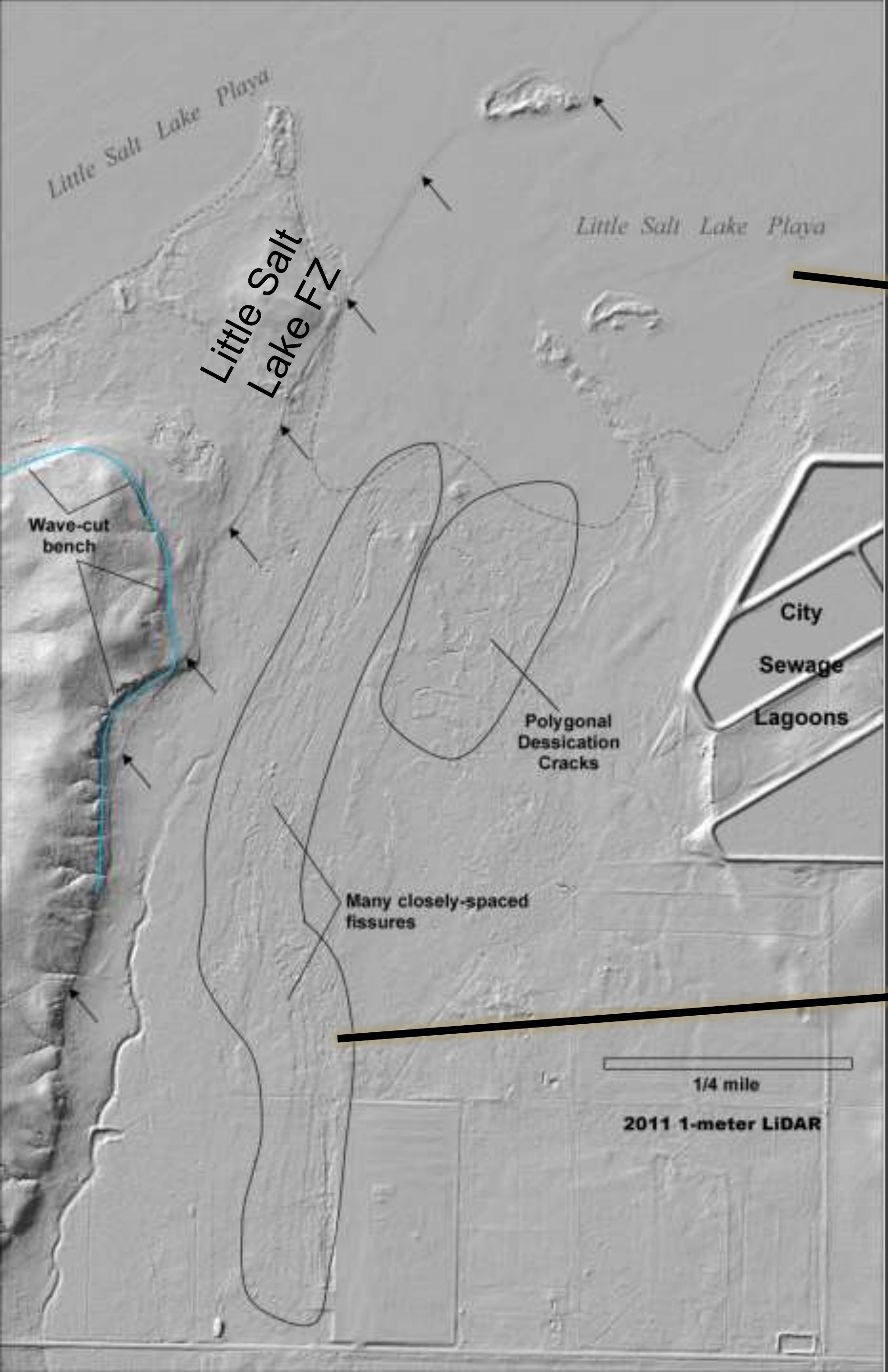


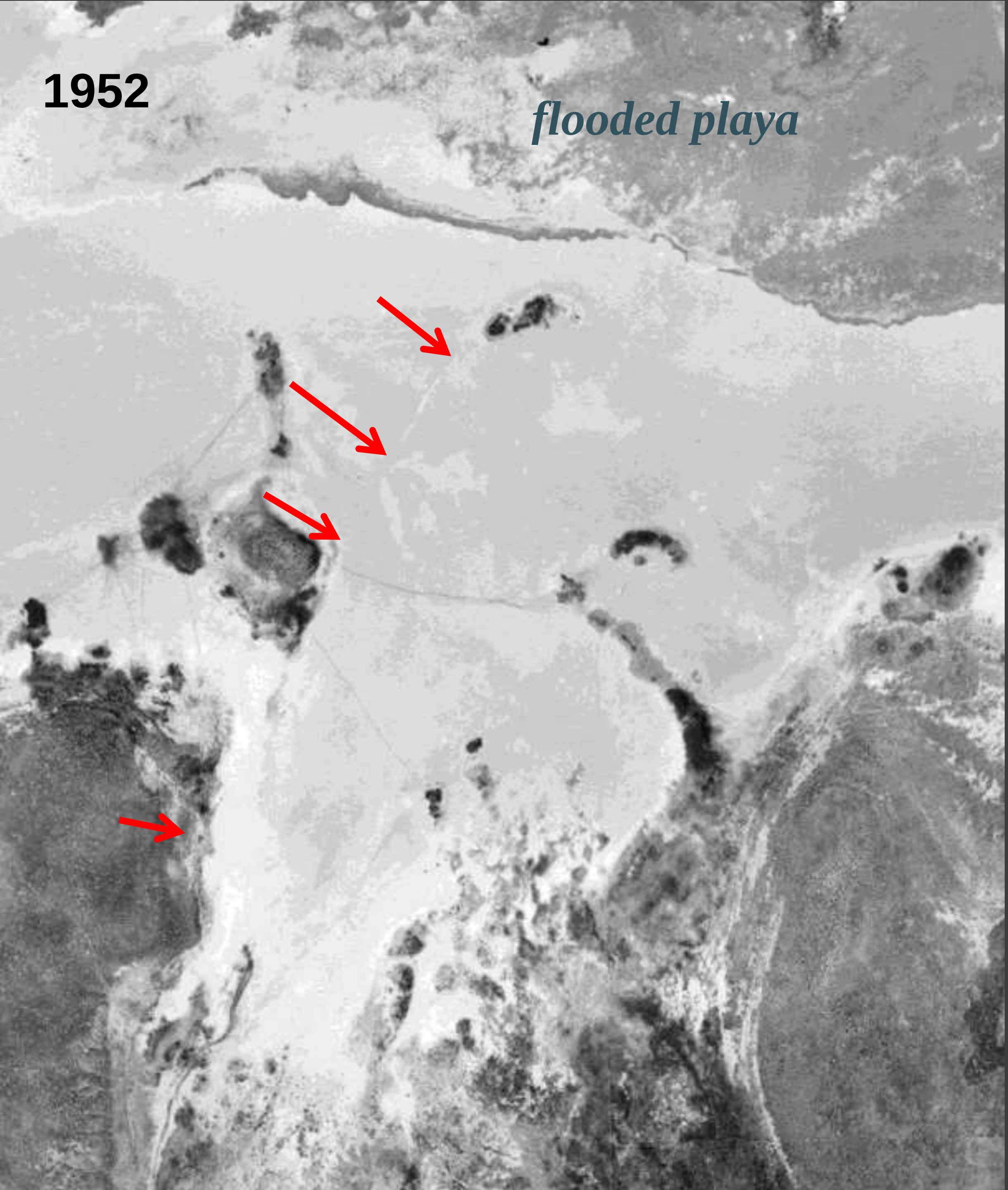


2014 PAROWAN FISSURE INVENTORY

- > 10 miles of suspected earth fissures
- Most are closely aligned with Quaternary-active intrabasin faults

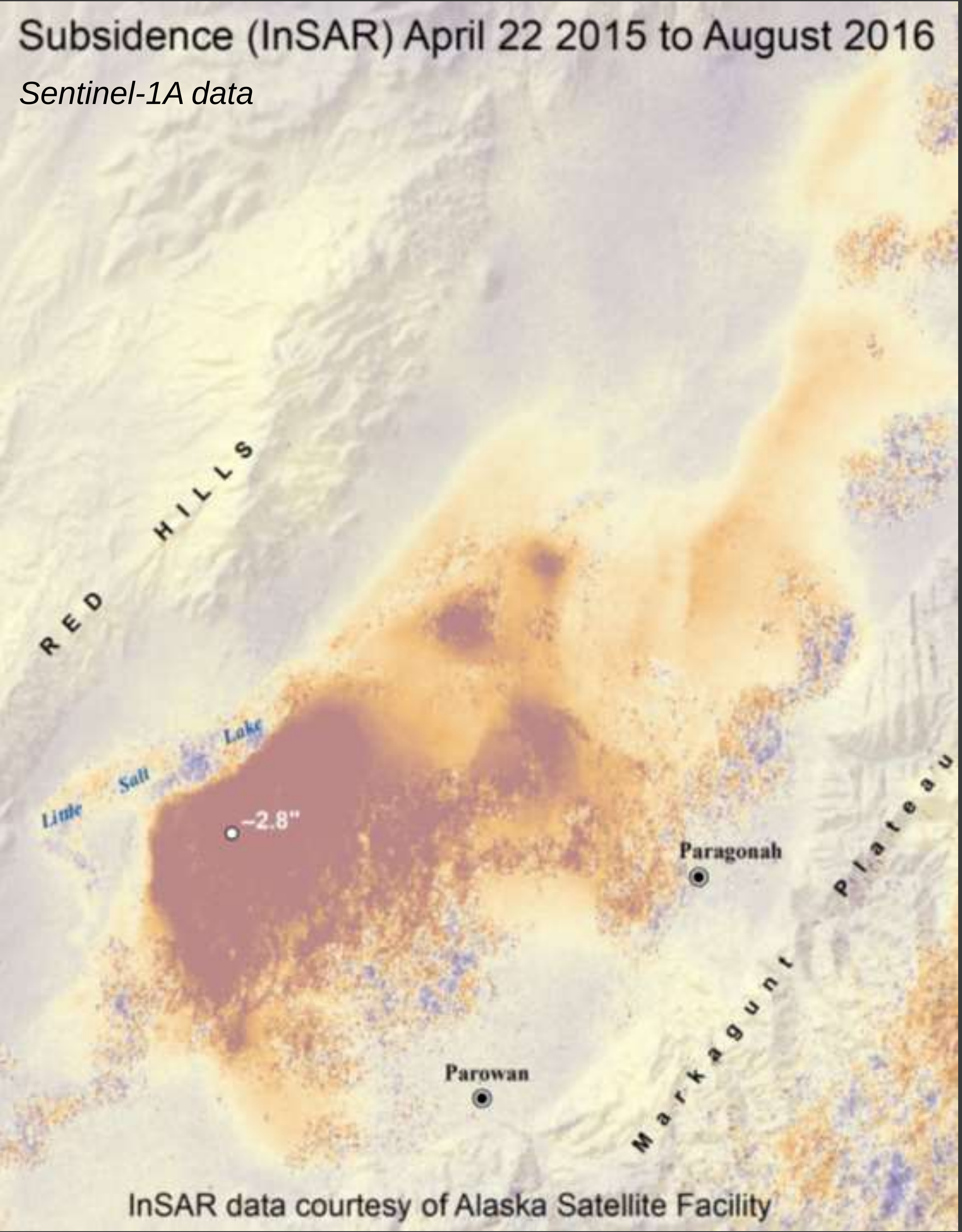

Fissure
Intrabasin Q fault
2 miles
15
Chimney Meadows
Paragonah
Parowan
Summit
RED HILLS
PAROWAN VALLEY
Little Salt Lake Playa
HURRICANE CLIFFS


Little Salt Lake Playa
Little Salt Lake Playa
Little Salt Lake FZ
Wave-cut bench
City Sewage Lagoons
Polygonal Dessication Cracks
Many closely-spaced fissures
1/4 mile
2011 1-meter LiDAR



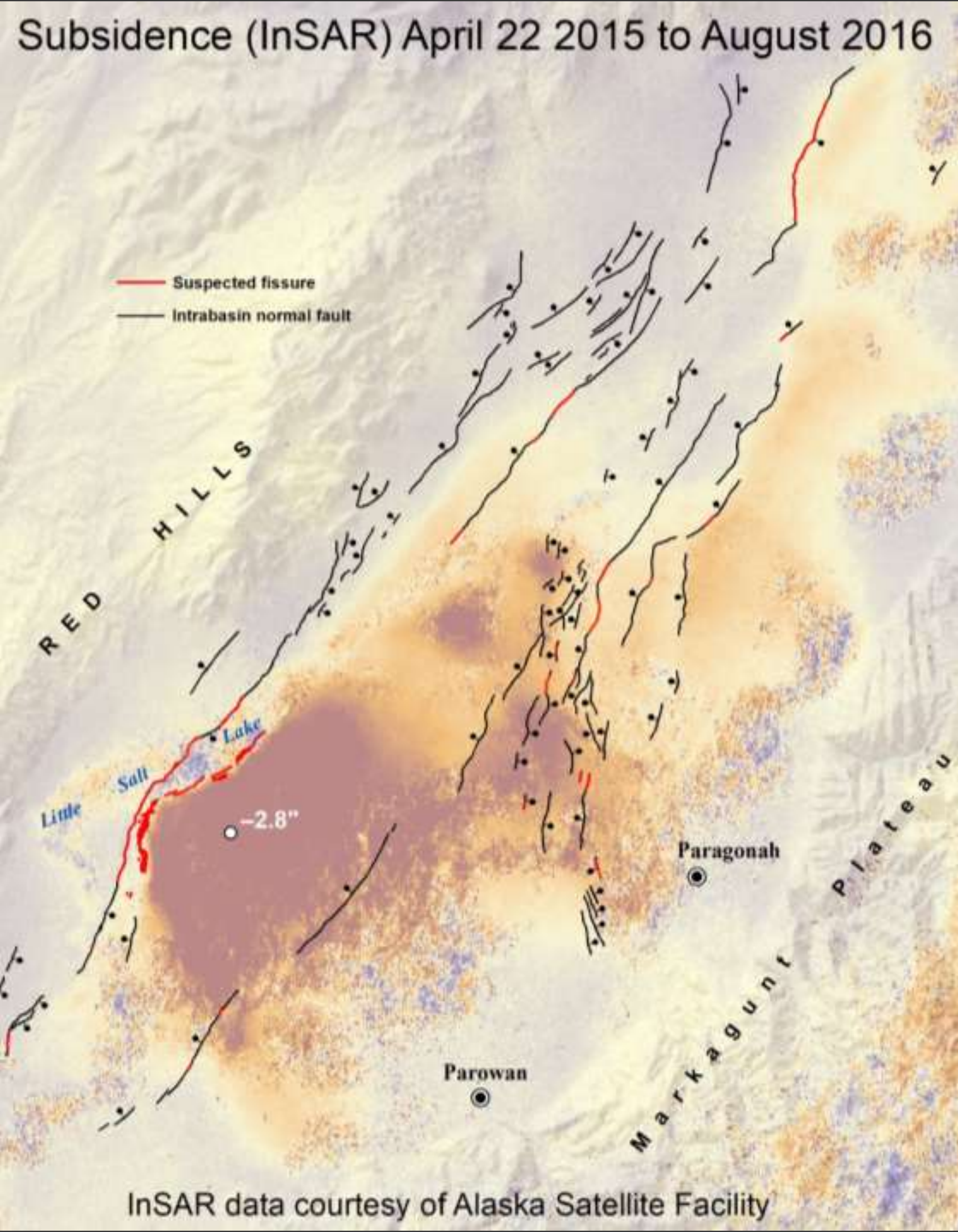
LITTLE SALT LAKE FZ

- Scarp appears to have existed prior to significant groundwater declines and subsidence



INSAR IMAGE

- Alaska Satellite Facility
  - University of Alaska, Fairbanks
  - Developing InSAR products/tools
  - Ground-truthing

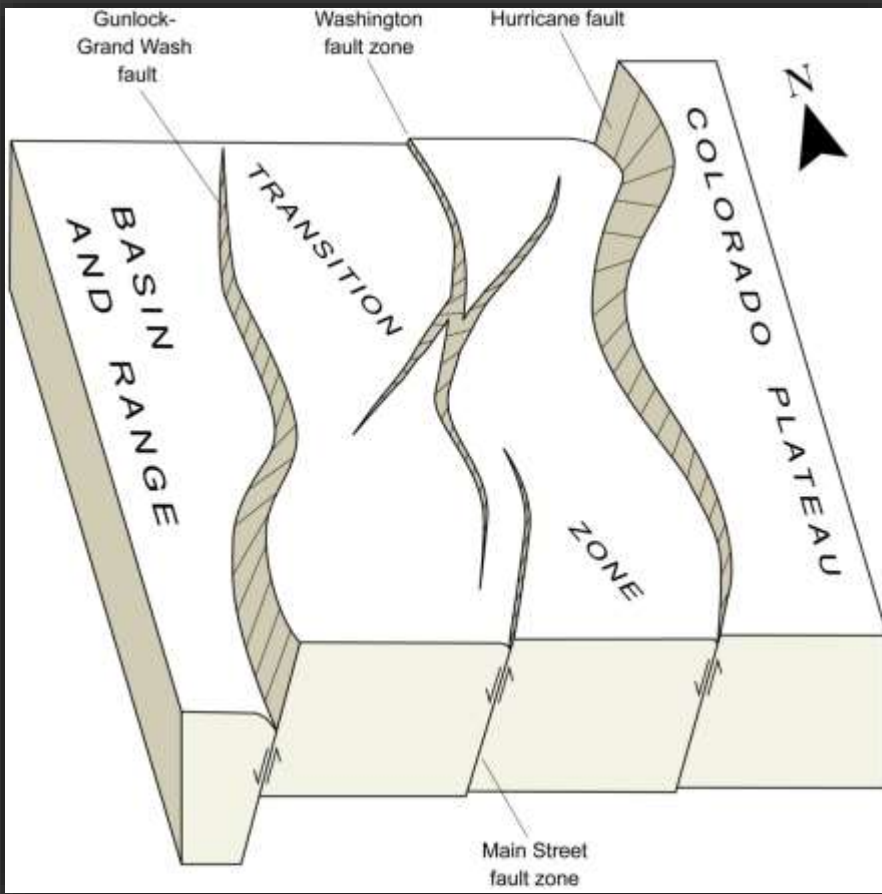


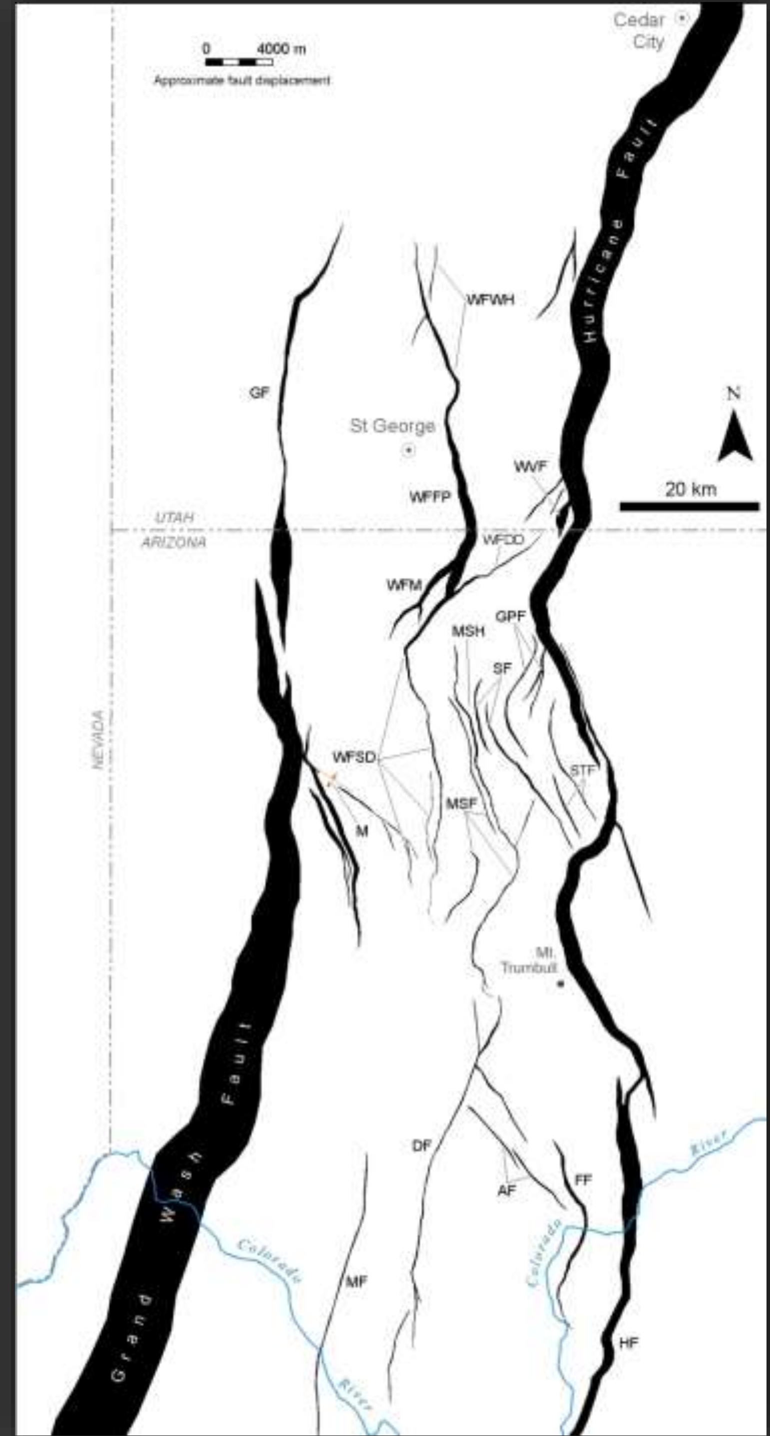
INSAR IMAGE

- Good match to intrabasin faults and suspected fissures
- Faults heavily influence distribution of subsidence
- Faults west and north of Paragonah commonly exhibit subsiding footwalls
- Very little contemporary deformation indicated along the Little Salt Lake fault zone

Final Thoughts

- B & R / CP transition zone is complex
  - Better exposed on Arizona Strip
  - Similar complexity likely exists in Cedar/Parowan Valleys but may be masked by sediment-filled basins

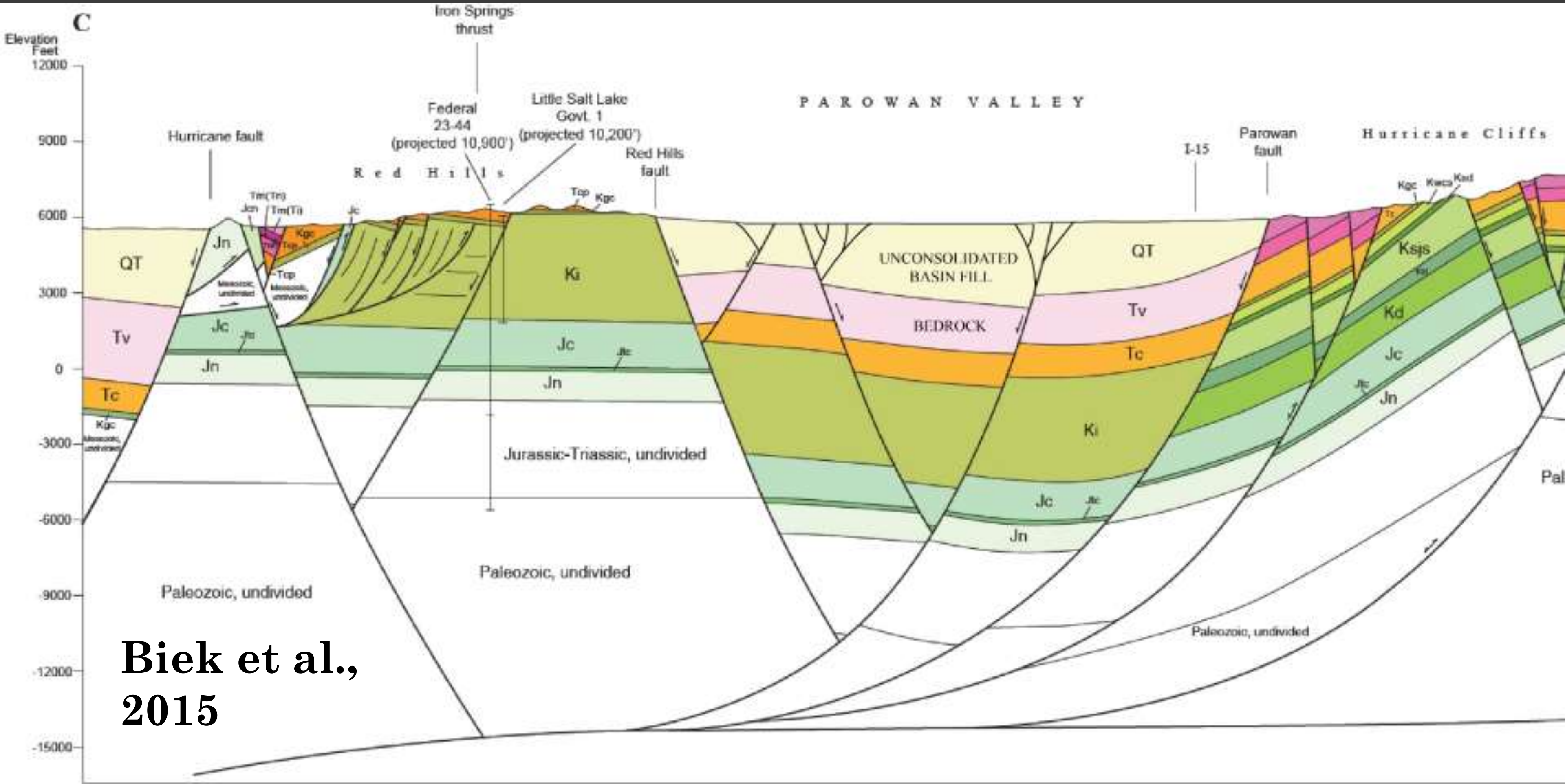




Final Thoughts

- Intrabasin faults are likely discrete in underlying bedrock but become diffuse in unconsolidated deposits as they approach the surface

- Evidence for independent rupture on intrabasin faults(?)



Biek et al., 2015

Final Thoughts

- Contemporary subsidence and fissuring can complicate interpretations of young fault scarps

- Possible Late Holocene scarps identified that predate major groundwater declines & subsidence

  - Chimney Meadows fault zone
  - Little Salt Lake fault zone
  - Enoch-graben-west fault

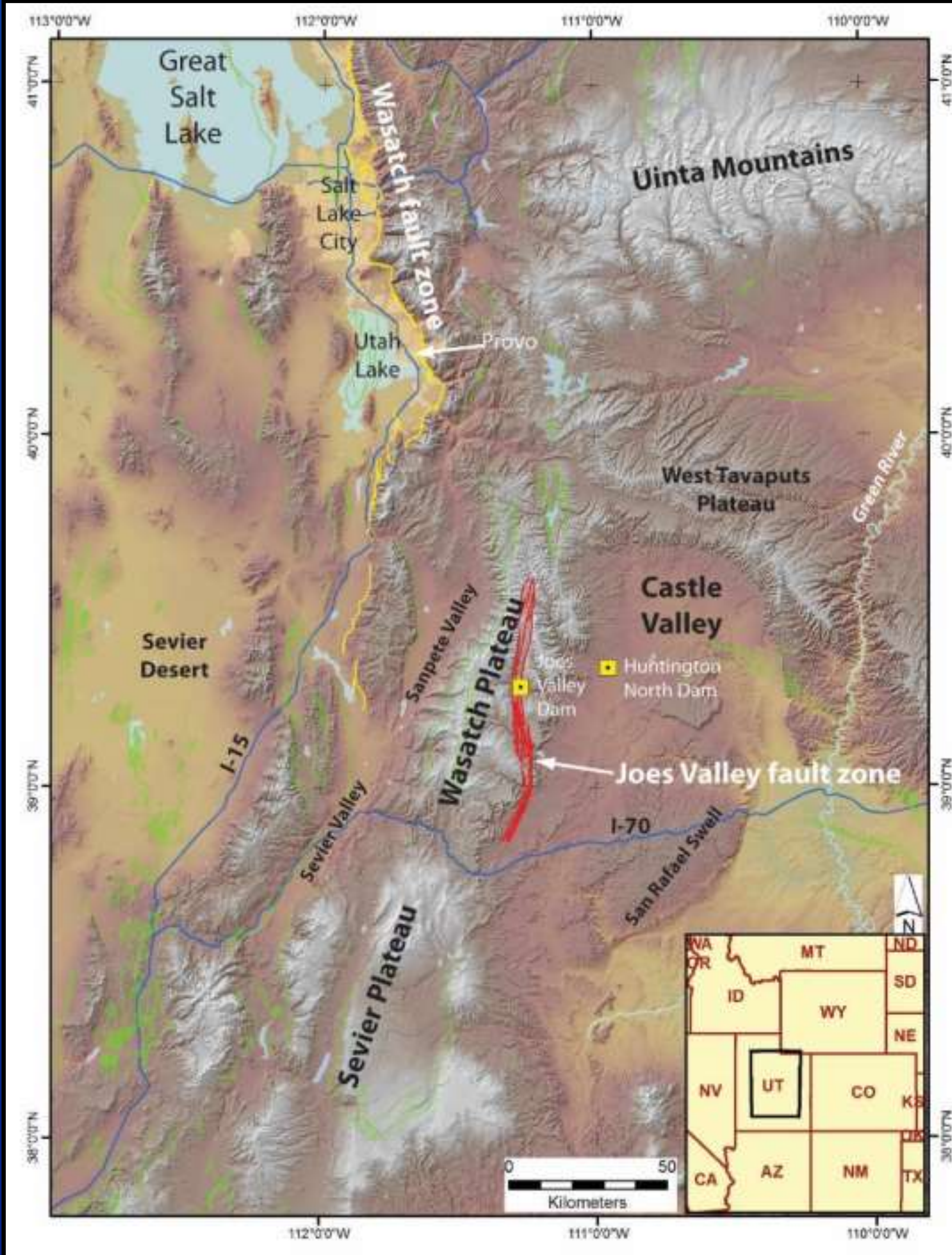
RECLAMATION
Managing Water in the West

Update of Ongoing Studies to Evaluate the Seismic Potential of the Joes Valley Fault Zone, East-central Utah

Lucy Piety, Julia Howe, Kirstyn Cataldo, Sylvia Nicovich, Ralph Klinger, Ryan Levinson, Collen Chupik, and Joanna Redwine
Seismology, Geomorphology, and Geophysics Group
Bureau of Reclamation
Denver, Colorado

U.S. Department of the Interior
Bureau of Reclamation

February 2019



Joes Valley fault zone

- Crosses Wasatch Plateau
- South end extends into Castle Valley
- Roughly parallel with the south end of the Wasatch fault zone (yellow lines)
- In an area with other potentially active faults
- Near the boundary of the Colorado Plateau (east) and the Basin and Range (west)

Red lines=Joes Valley fault zone
Yellow lines=Wasatch fault zone
Green lines=other potentially active faults

Joes Valley fault zone

Topographic scarps are present along the mapped faults within the Joes Valley fault zone

Primary Question: What is the origin of the scarps?

Interpretation 1: Scarps created by ground rupture during several large earthquakes

Interpretation 2: Scarps created by movement of the ground surface caused by deformation or flow of salt or other soft rocks beneath Joes Valley and the Wasatch Plateau

Present evaluation of the Joes Valley fault zone

Using multiple types of evidence to determine the origin of the scarps and the contribution of the fault to seismic hazard:

- **Subsurface geology**
  - Delineate subsurface geology, including faults
  - Determine the existence, extent, distribution, and depth of salt deposits beneath Joes Valley, Wasatch Plateau, and adjacent portions of Sanpete Valley and Castle Valley
- **Contemporary stress directions**
- **Surficial geology**

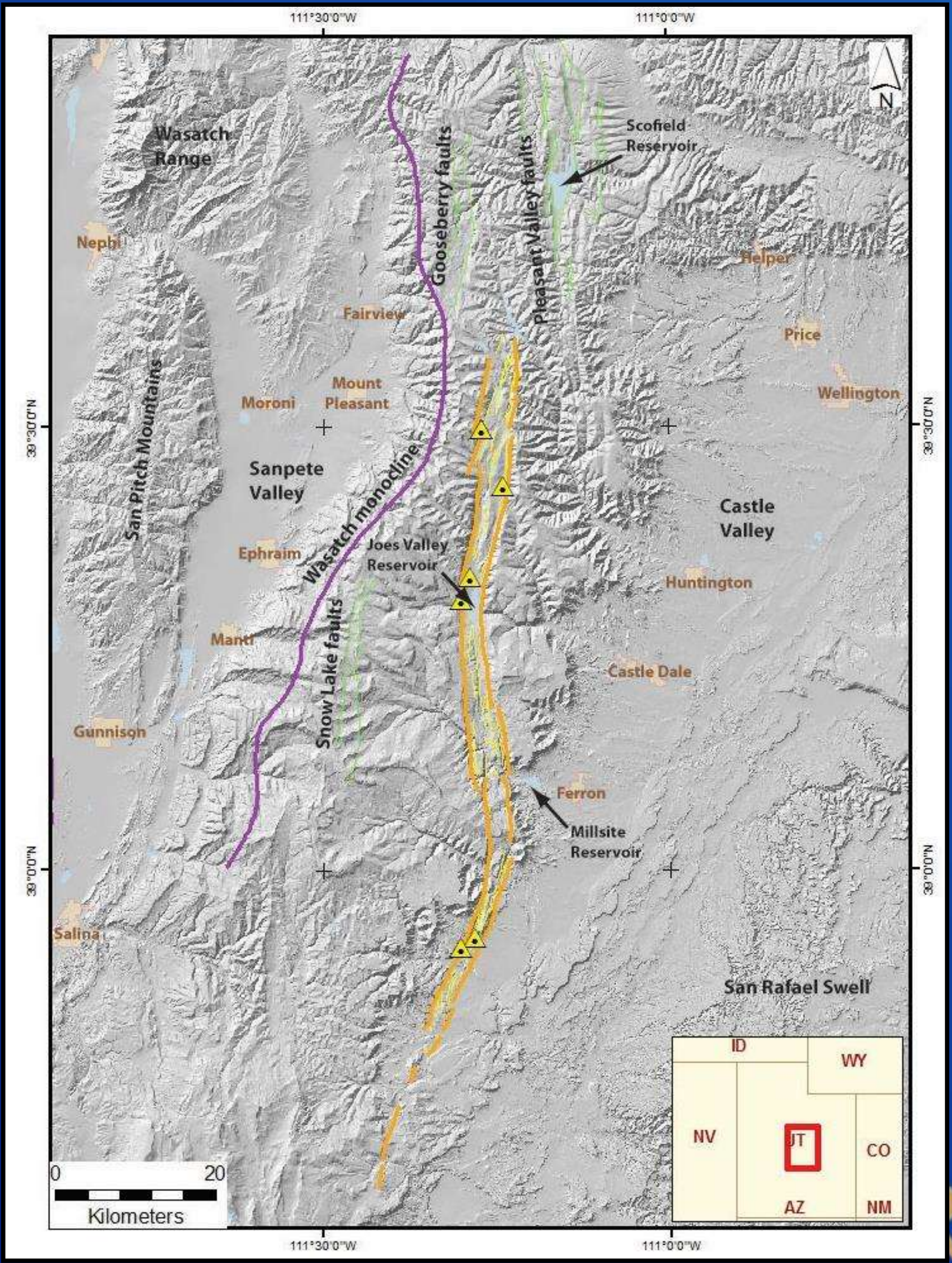
RECLAMATION

- **Surficial geology (2017 and 2018)**
  - **Mapping of fault scarps and other evidence of fault rupture**
  - **Trench excavations and interpretations**
    - 1 completed in September 2017
    - 6 completed between April and November 2018

Purpose:

- Delineate the pattern of faulting
- Estimate the number of ruptures and their timing
- Estimate the recurrence interval of surface ruptures

RECLAMATION



Trenches

6 sites (yellow triangles)

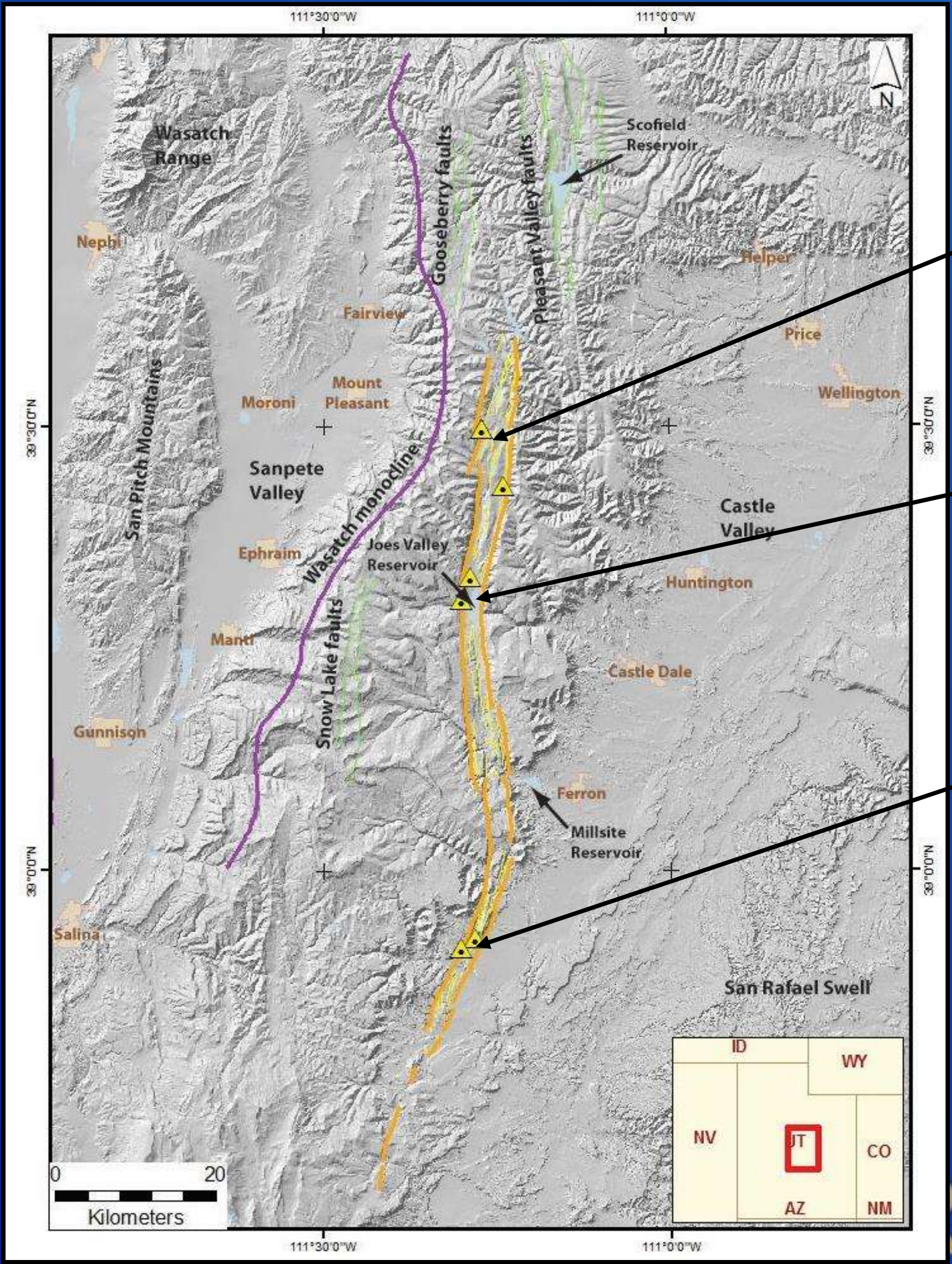
- 2 in north Joes Valley
- 2 in central Joes Valley
- 2 on southern part of the fault zone

Locations

- 3 are on main west faults
- 3 are on faults within the fault zone

RECLAMATION

Trenches on west-bounding faults



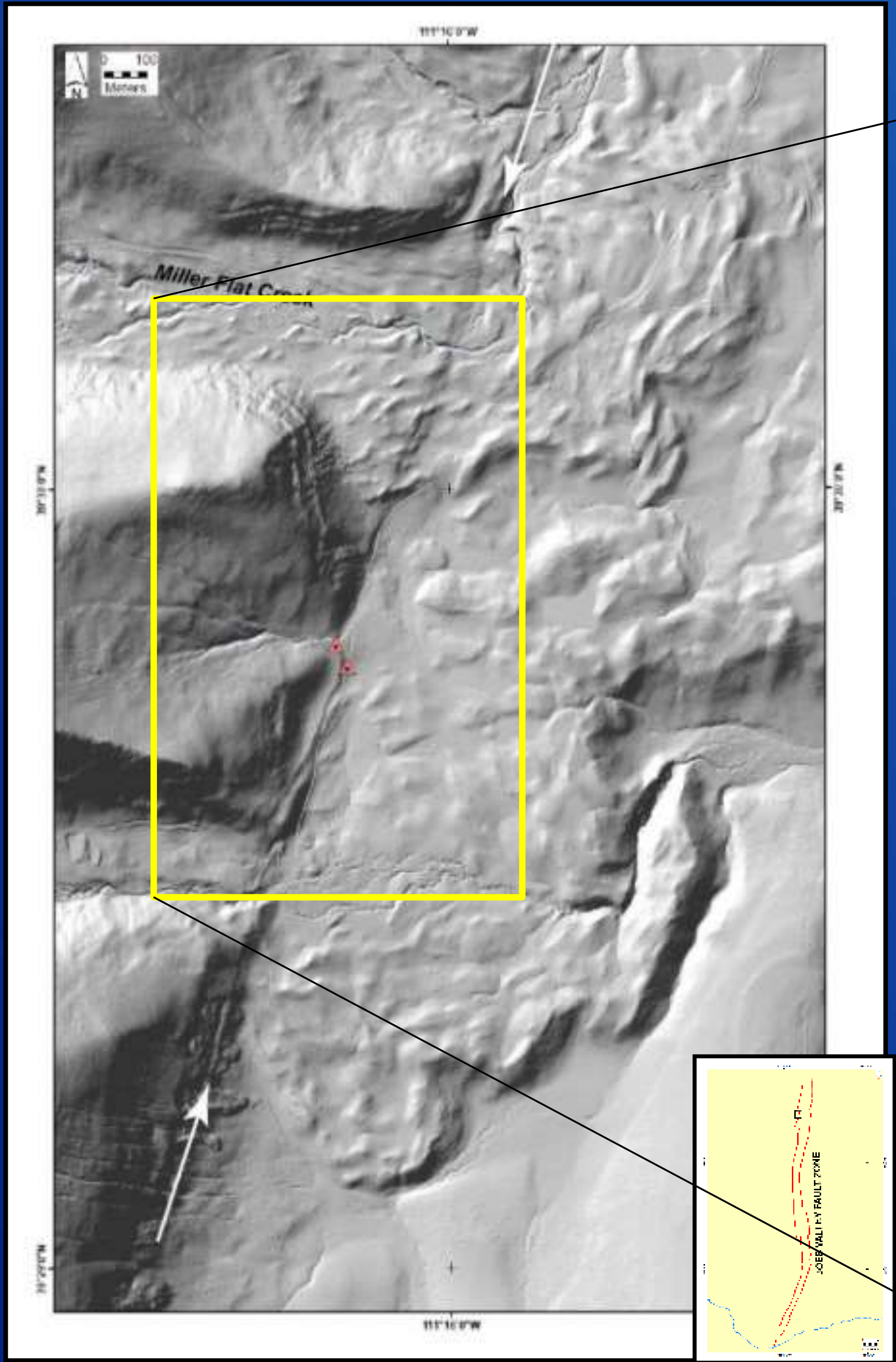
Miller Flat

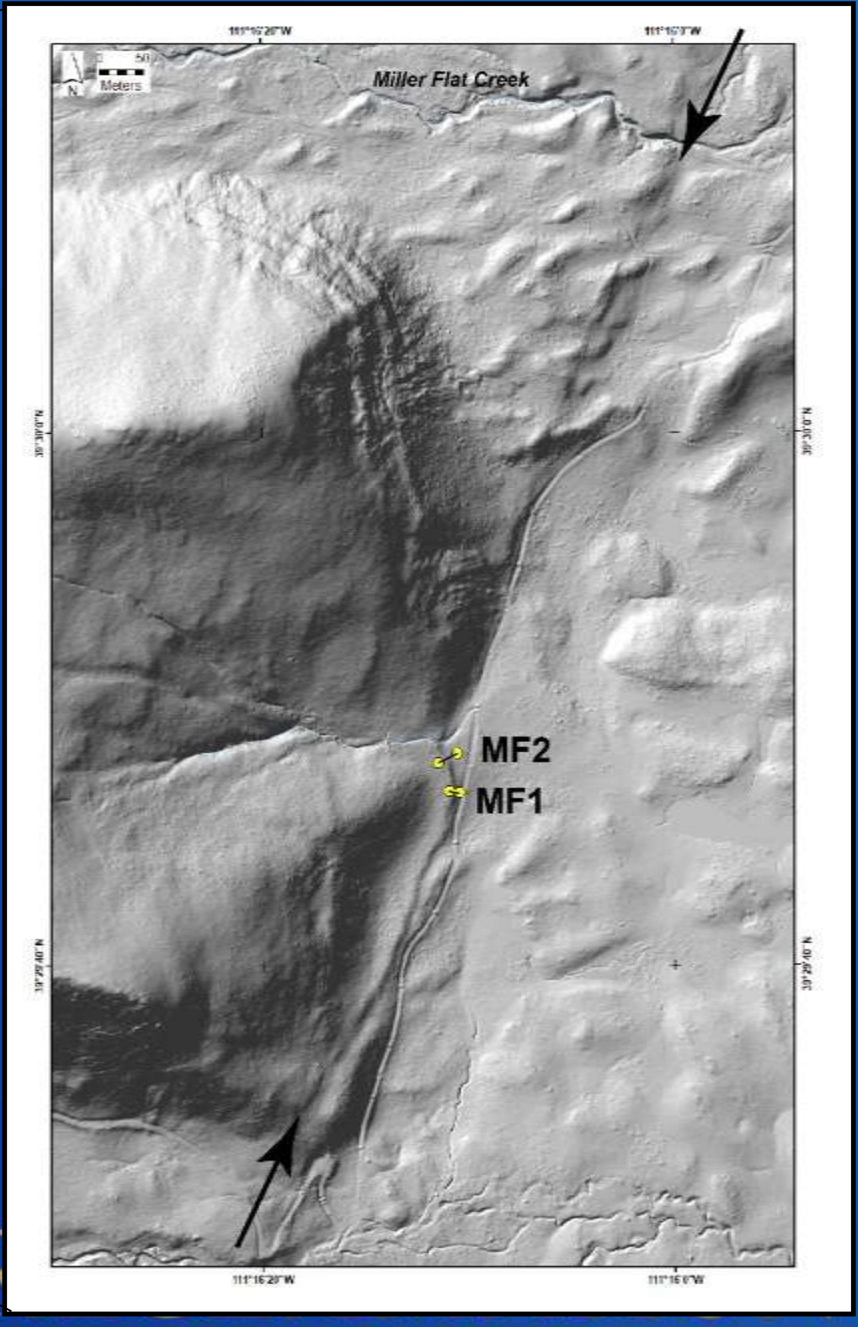
Littles Creek

Link Canyon West

RECLAMATION

Miller Flat trenches





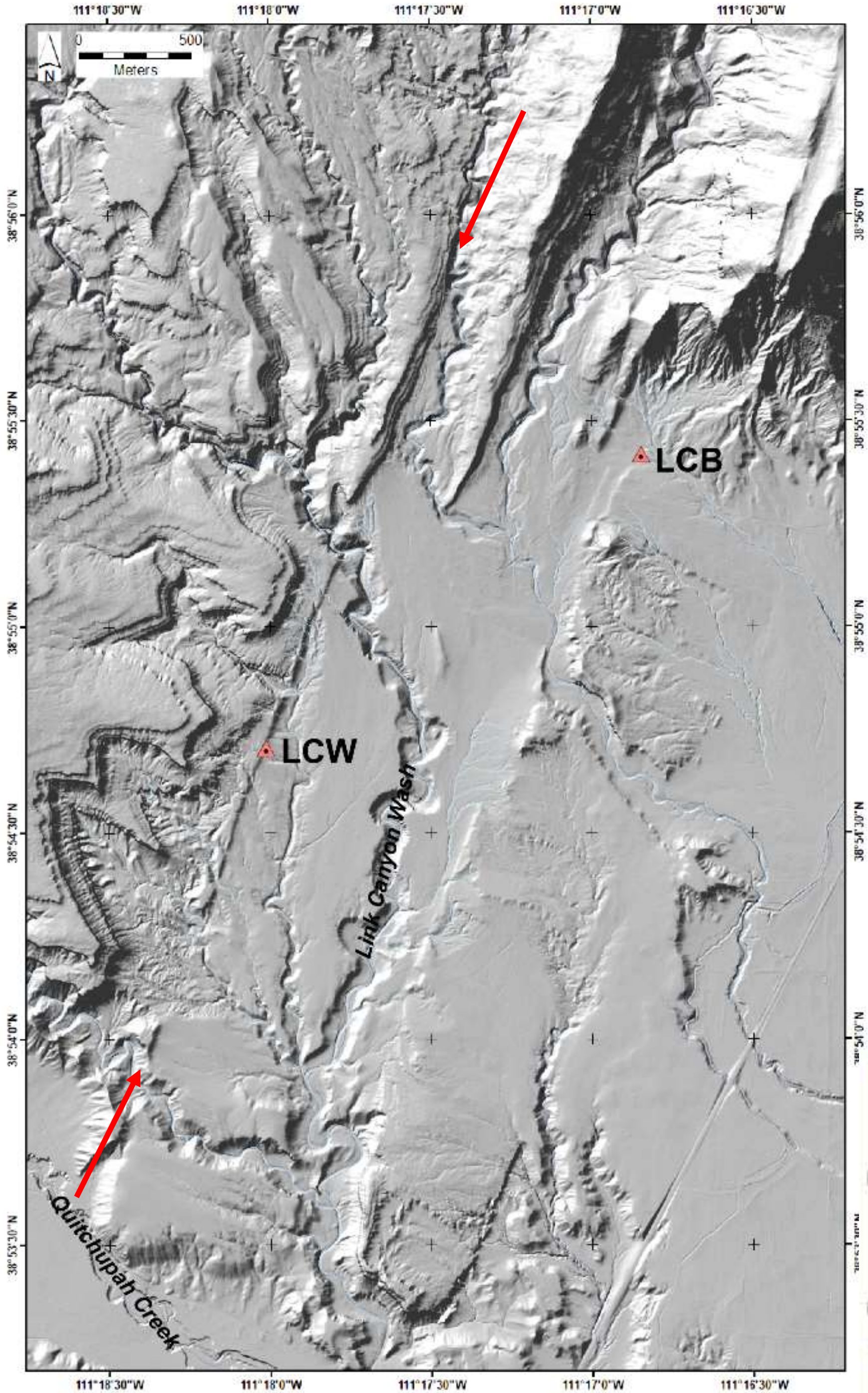
east west

east west

Miller Flat trenches

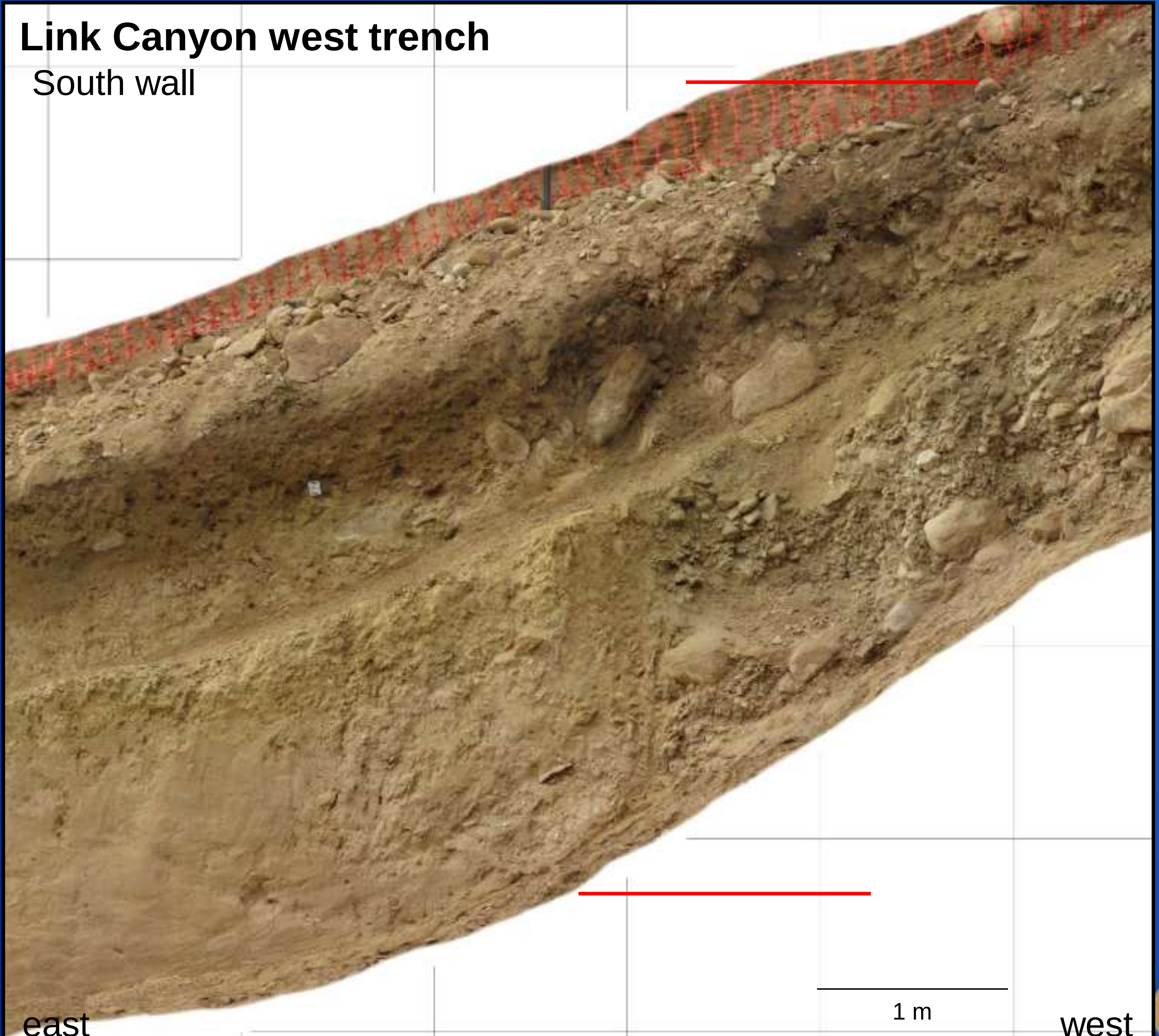
RECLAMATION

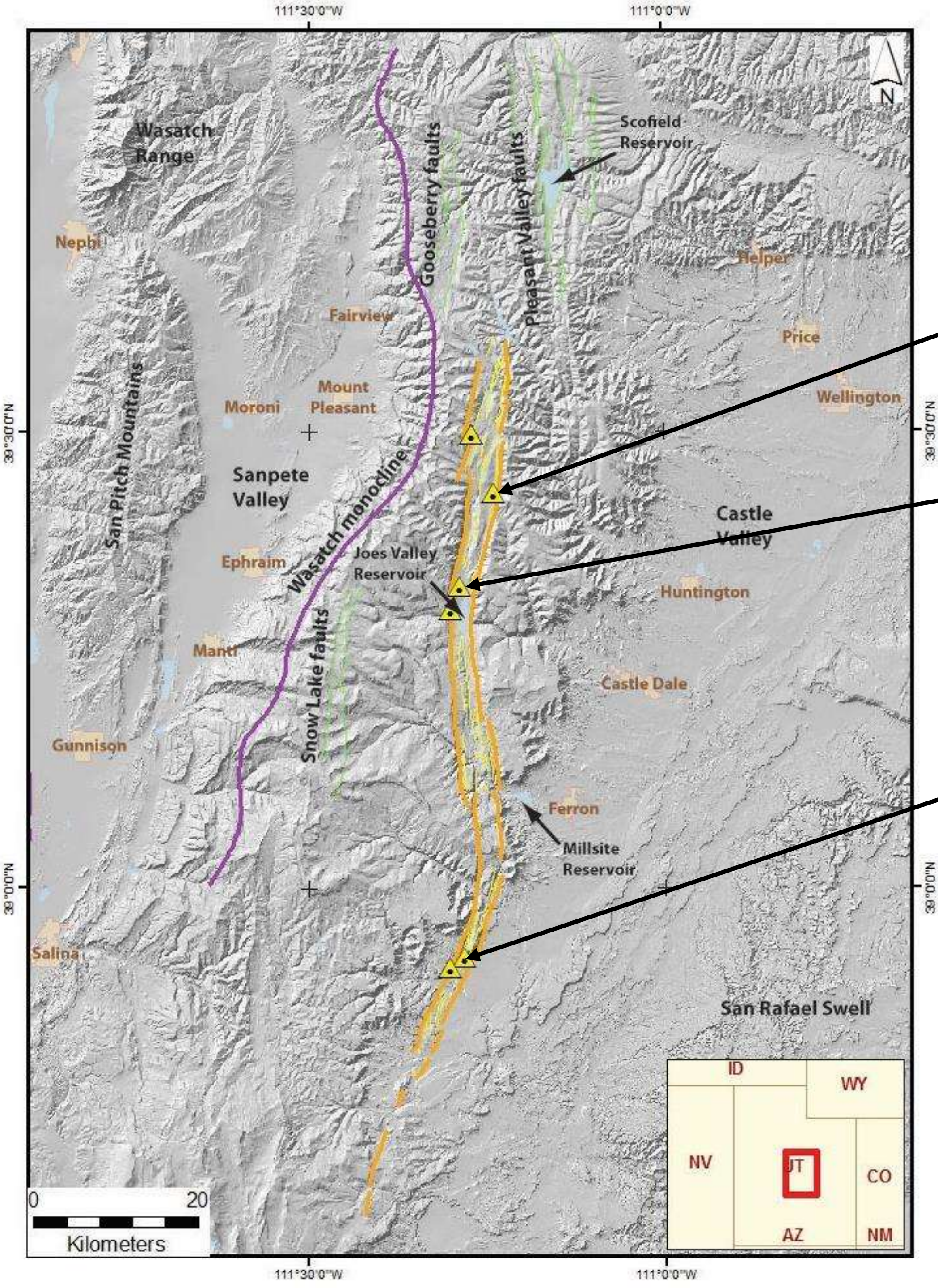
Link Canyon west (LCW) and Link Canyon basin (LCB) trench sites



Link Canyon west trench

South wall





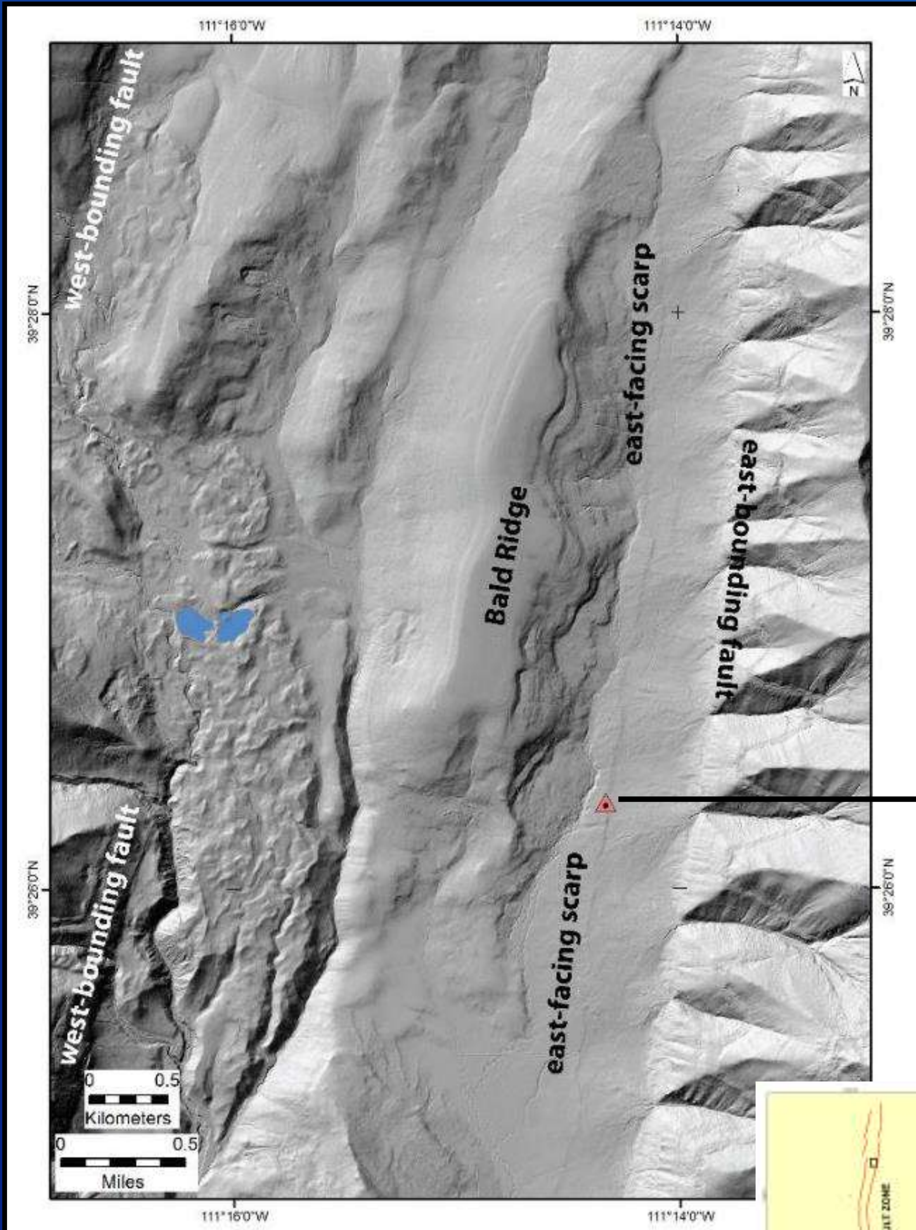
Trenches on faults within the fault zone

Christmas tree (Indian Creek)

Reeder Creek

Link Canyon basin

RECLAMATION

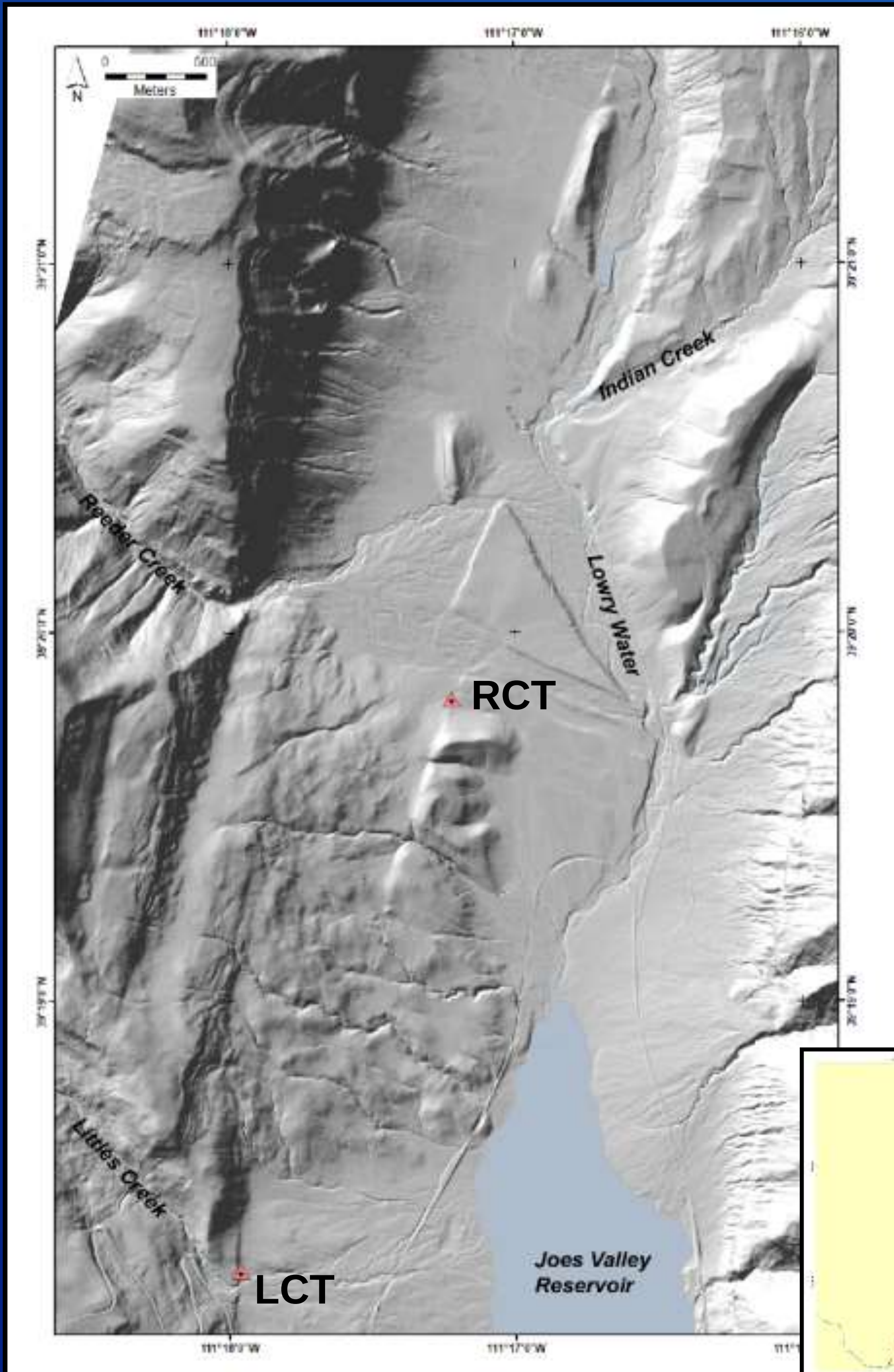


Christmas tree trench

photograph by J. Howe

RECLAMATION

Reeder Creek (RCT) trench site



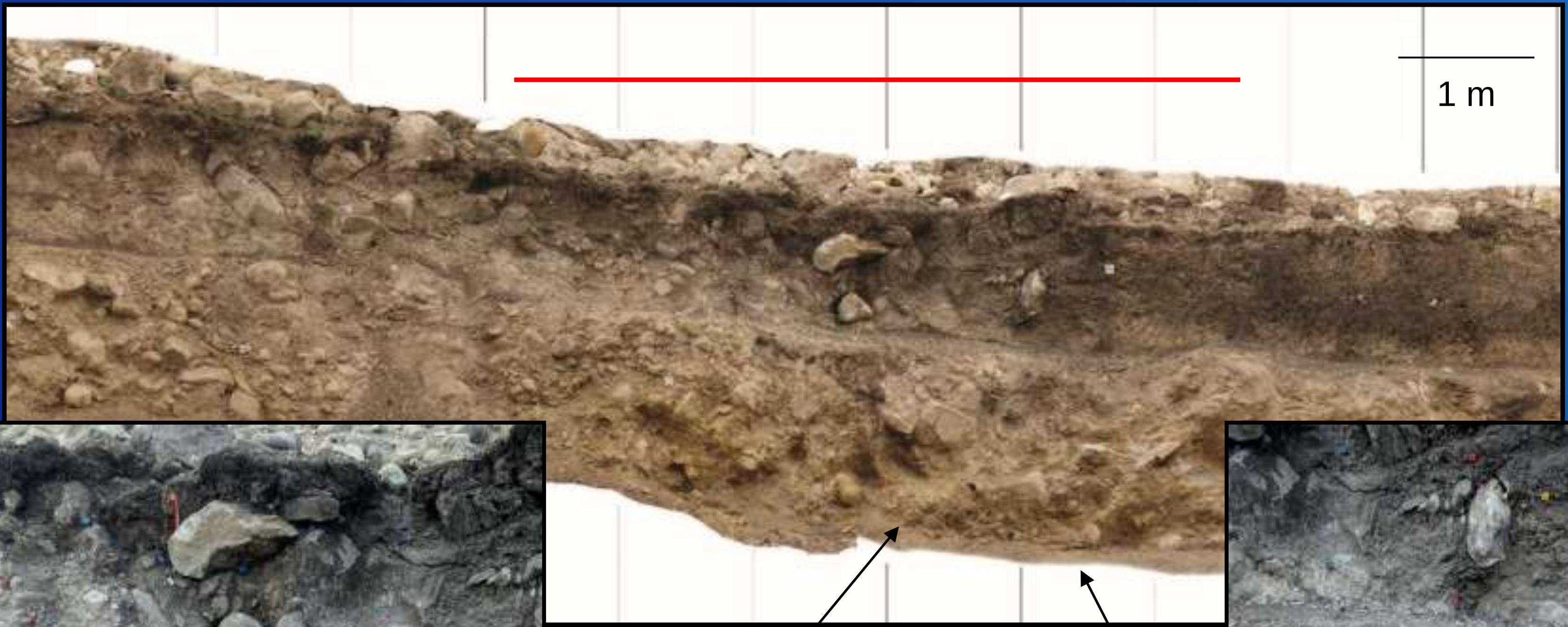
LCT=Littles Creek trench

Reeder Creek trench

South wall

east

west



RECL

Continuing present and proposed studies

- Complete trench interpretations
- Compile data from study
- Compare results to tectonic faults and to faults in areas with salt-bearing units
- Geomechanical model using geologic data
- Determine the implications for seismic hazard

RECLAMATION

SEISMIC LAND STREAMER RESULTS HIGHLIGHT HIGH EARTHQUAKE RISKS FOR THE SALT LAKE CITY URBAN CENTER

- **L.M. Liberty[1], J. St. Clair[1], G. Gribler [1], A.P. McKean[2]**
- [1]Department of Geosciences, Boise State University.
- [2]Utah Geological Survey, Salt Lake City, Utah.
- Corresponding author: Lee Liberty (lliberty@boisestate.edu)

BOISE STATE UNIVERSITY

- **Key Points:**
- A zone of earthquake-induced liquefaction and faulting link strands of the Wasatch fault beneath Salt Lake City
- High liquefaction and site amplification potential raises the hazard by reducing earthquake magnitude where damage may occur
- Seismic land streamers are a new tool to identify and characterize soil, rock and fluid properties for urban hazard and resource assessments

Funding sources:
US Geological Survey
G15AP00054, G17AP00052

Submitted to JGR Solid Earth, Nov, 2018

OUTLINE

- Motivation and Approach – seismic imaging for Vp (water, colluvium), Vs (site response, liquefaction indicators), reflection (stratigraphy, structure)
- Faults – JGR paper in review
- Site response (Vs30) – JGR paper in review, SSA abstract
- Paleoliquefaction - JGR paper in review
- Liquefaction susceptibility - SSA abstract
- Effect asphalt or concrete on surface and body wave signals – manuscript in prep

SEISMIC IMAGING ALONG CITY STREETS USING LAND STREAMERS

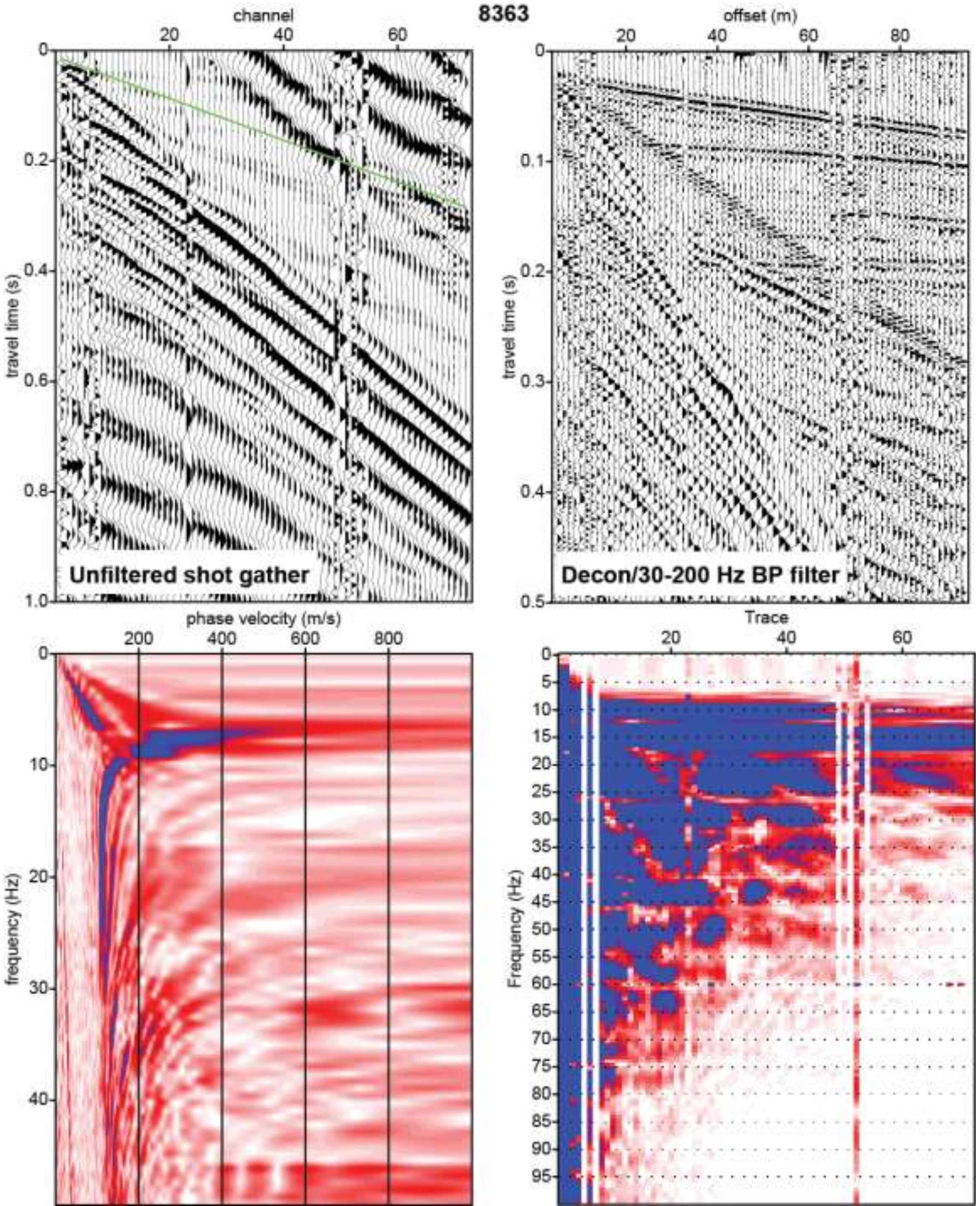
- Late Quaternary structure & stratigraphy (~200 m depth) → reflection imaging
- Identify and characterize active faults → reflection imaging, Vp, Vs
- Vs_{30} site response map → Rayleigh waves
- Depth to water table → Vp
- Liquefaction susceptibility →(Vp) and (Vs_1) to (water depth and soil stiffness for upper ~12 m)
- Relate Vs and Vp to geo-processes to apply to other high hazard regions

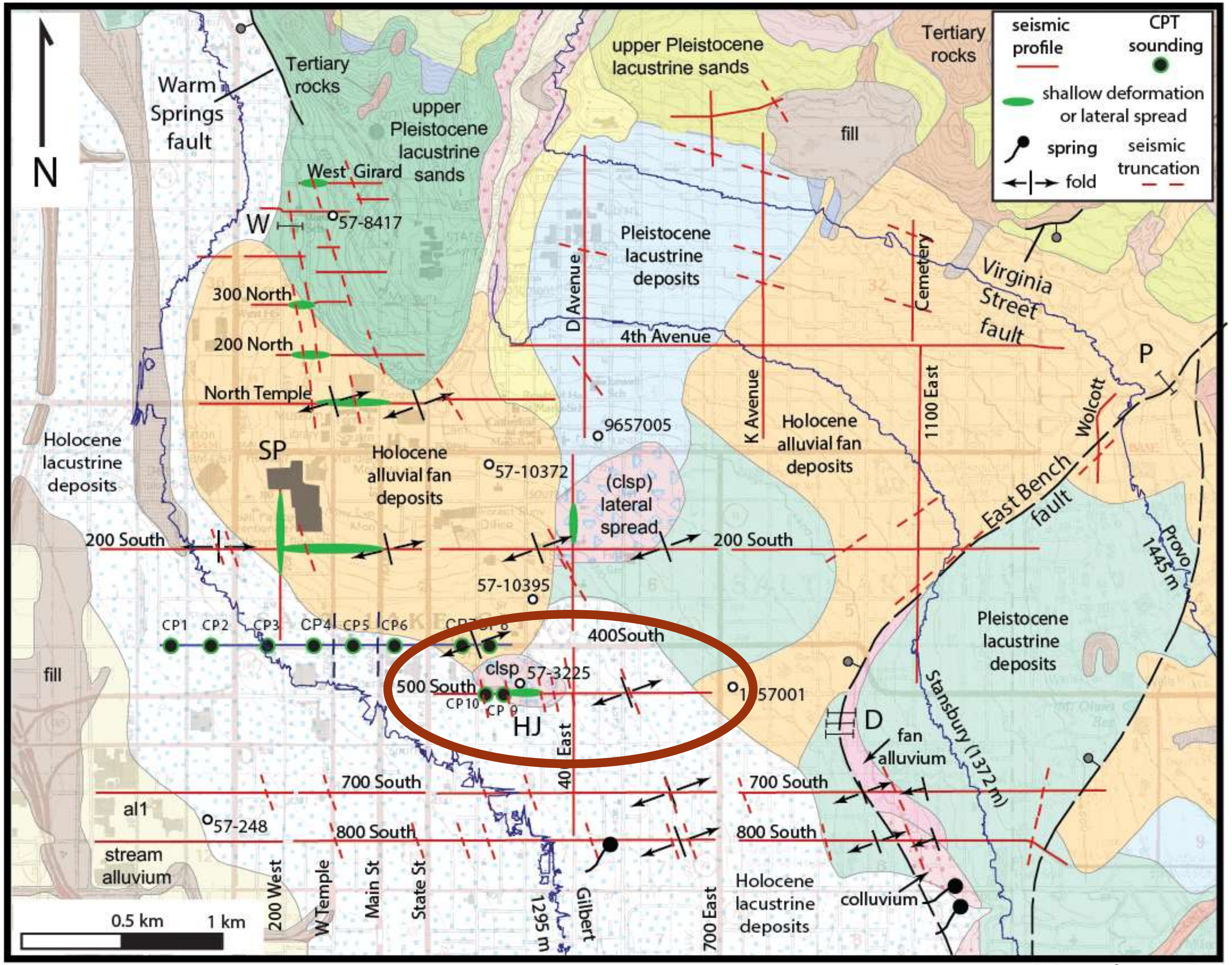
Seismic Land Streamer & Weight Drop System

- Rapid data collection – 4-5 km/day
  (2m spacing every 15 seconds)
- Minimal field crew – one person operation of all data collection operations (seismograph, weight drop source, GPS, source/receiver positioning, vehicle positioning)
- Directly operate on city streets without damage and to minimize traffic flow disruptions
- Predictable source/receiver geometry simplifies data processing (similar to marine seismic processing)
- Real time GPS positioning/integration of Lidar data
- Uniform physical properties of road and sub road reduces static effects from near surface heterogeneities
- Police or flagger assistance to control traffic - near continuous profiling
- Large seismic source relative to imaging depths allows for traffic noise during data collection

LAND STREAMER DATA

- Two-component seismic data





SUMMARY OF SEISMIC CAMPAIGN

- A zone of earthquake-induced liquefaction and faulting link strands of the Wasatch fault beneath Salt Lake City
- High liquefaction and site amplification potential raises the hazard by reducing earthquake magnitude where damage may occur

Map from Personius et al (1992)

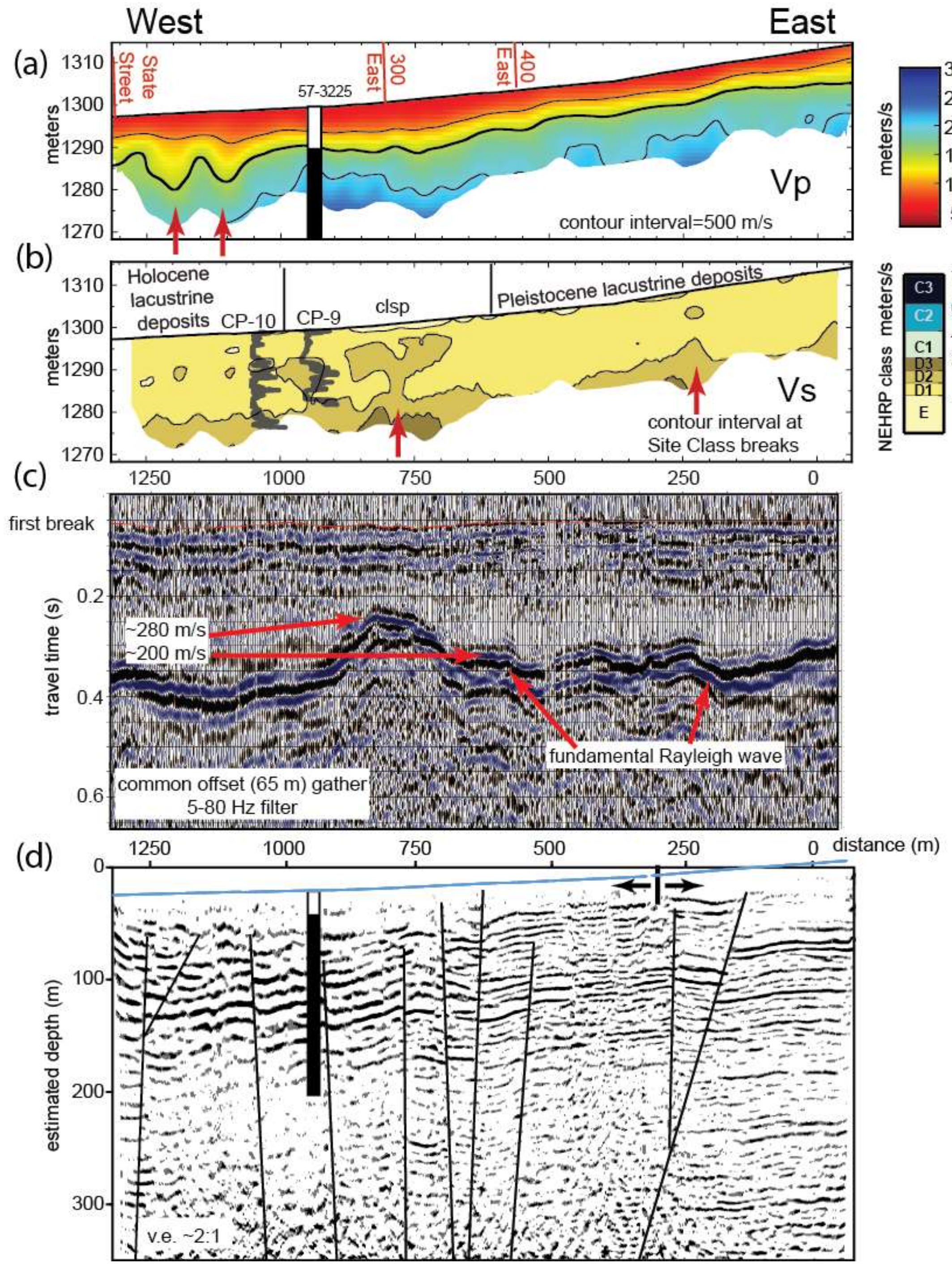
LAND STREAMER DATA – 500 SOUTH

- Vp shows a near constant water table depth (1,500 m/s) along all but the western portions of the profile.

- Vs shows mostly Class D1 soils (180-240 m/s) for upper 20 m. Class D2 soils are measured at greater depths.
- A zone of shallow Vs>240 m/s is coincident with mapped lateral spread.

- Common offset field records clearly show that fast Rayleigh wave speeds relate to mapped lateral spread

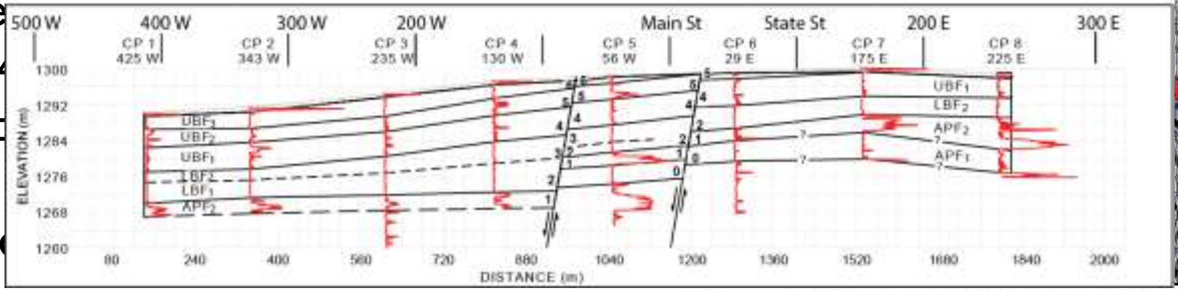
- Mostly west-dipping (Lake Bonneville) reflectors showing lateral reflector truncations that is consistent with faulting.
- Change in reflection frequency coincident with zone of shallow heterogeneities.

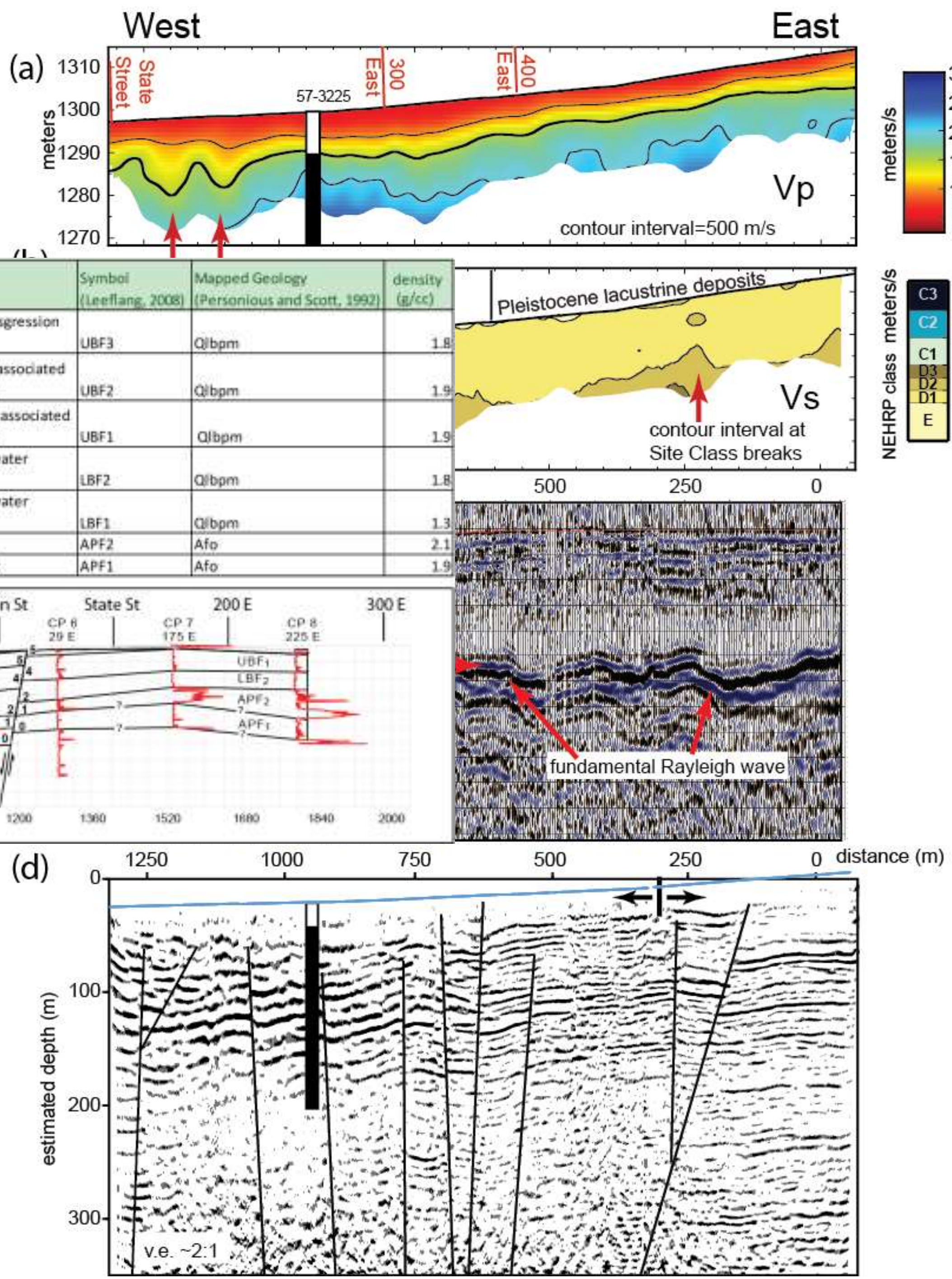


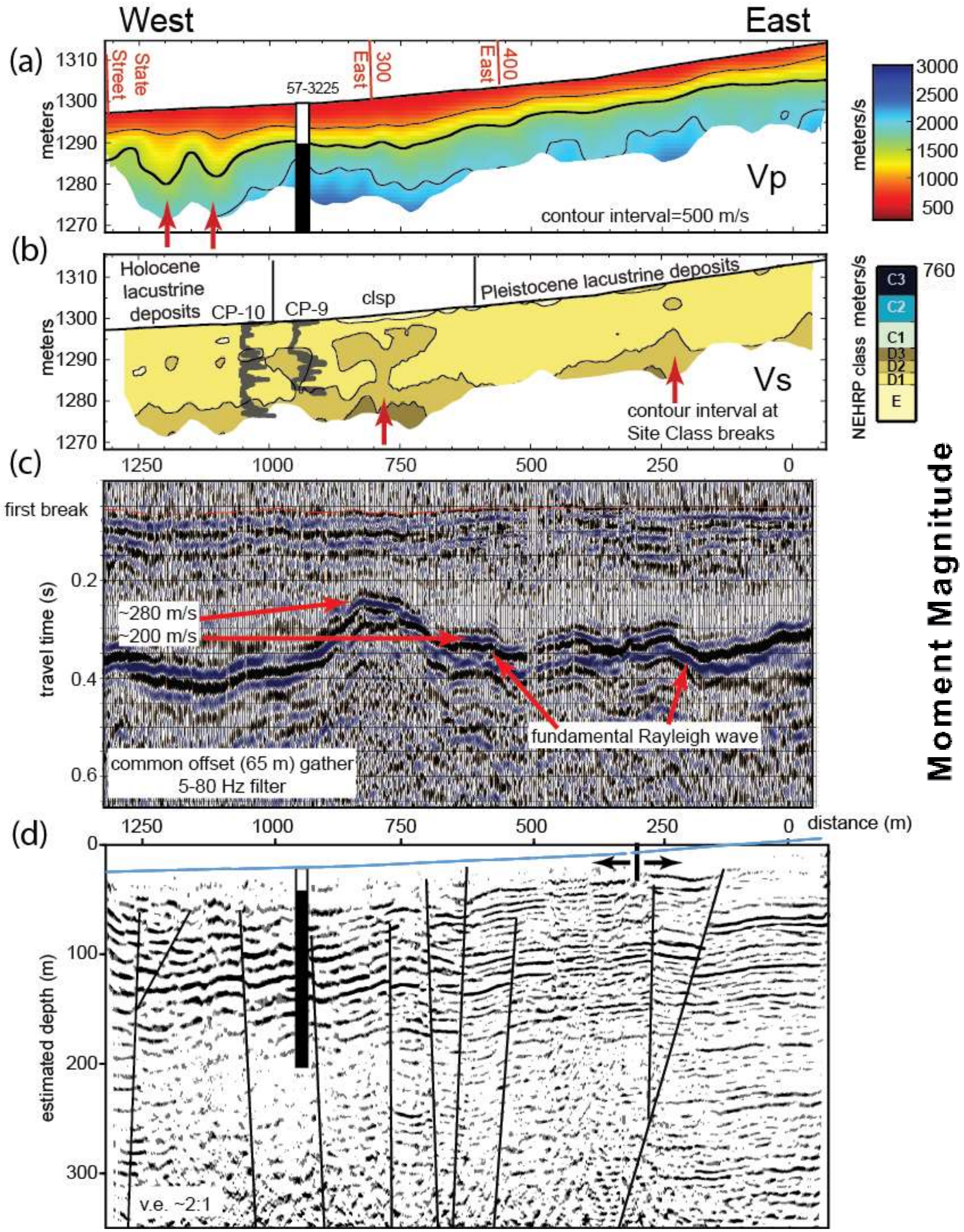
500 SOUTH COMPARISON WITH CPT RESULTS ALONG 400 SOUTH

- Vp shows a near consta (1,500 m/s) along all bu portions of the profile.
- Vs shows mostly Class I m/s) for upper 20 m. Cl measured at greater de
- A zone of shallow Vs>24 with mapped lateral sp
- Common offset field re lateral spread
- Mostly west-dipping (Lake Bonneville) reflectors showing lateral reflector truncations that is consistent with faulting.
- Change in reflection frequency coincident with zone of shallow heterogeneities.

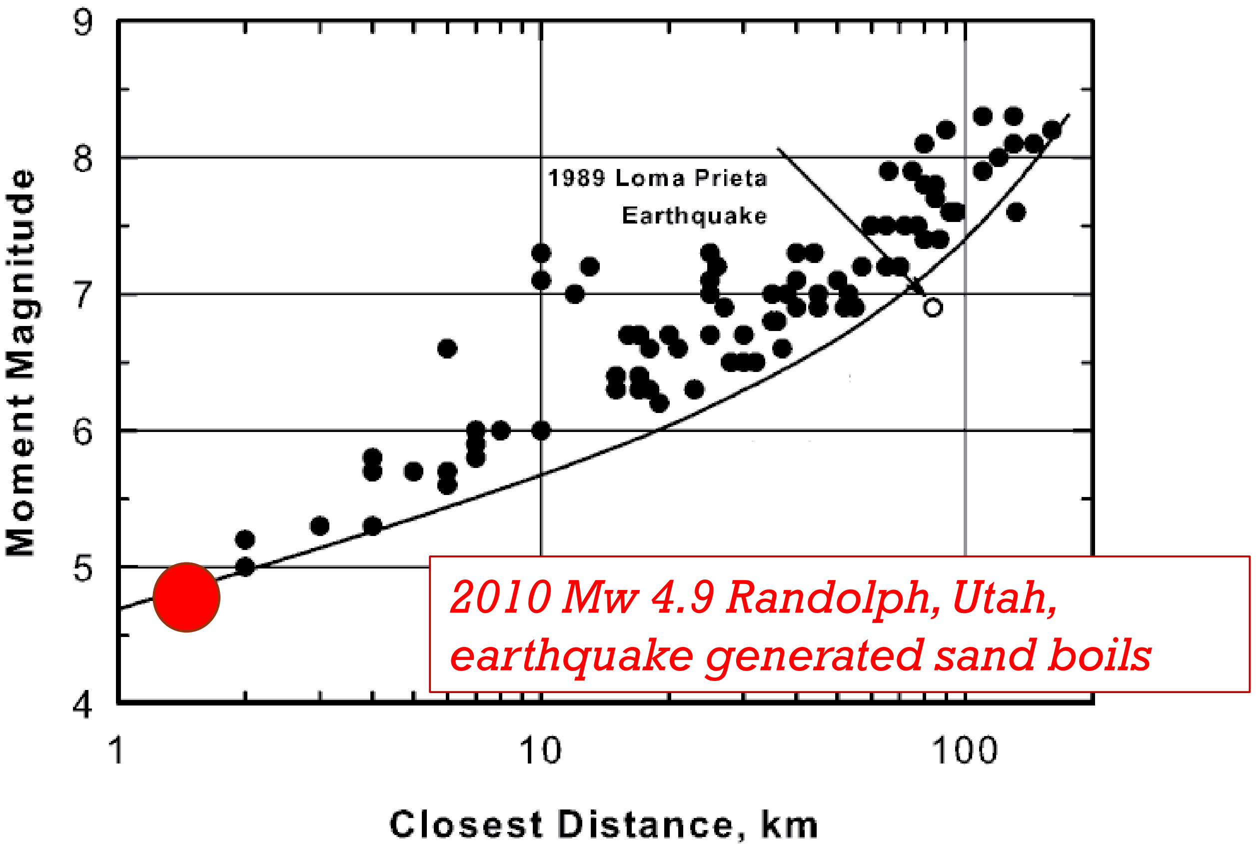
Unit	Age/Description	Symbol (Leeflang, 2008)	Mapped Geology (Personious and Scott, 1992)	density (g/cc)
Upper Bonneville Formation – Unit 3	Upper Pleistocene/clays and silts associated with final transgression of Lake Bonneville	UBF3	Qlbpm	1.8
Upper Bonneville Formation – Unit 2	Upper Pleistocene/thinly bedded highly variable deposits associated with regression of Lake Bonneville following its high-stand	UBF2	Qlbpm	1.9
Upper Bonneville Formation – Unit 1	Upper Pleistocene/thinly bedded clay/silt/minor fine sand associated with regression of Lake Bonneville following its high-stand	UBF1	Qlbpm	1.9
Lower Bonneville Formation – Unit 2	Upper Pleistocene/clays and silts associated with deeper water deposits of Lake Bonneville	LBF2	Qlbpm	1.8
Lower Bonneville Formation – Unit 1	Upper Pleistocene/clays and silts associated with deeper water deposits of Lake Bonneville	LBF1	Qlbpm	1.3
Pre-Bonneville – Unit 1	Middle Pleistocene/alluvial gravels with interbedded silt	APF2	Afo	2.1
Pre-Bonneville 2 – Unit 2	Middle Pleistocene/interbedded alluvial silt and clayey silt	APF1	Afo	1.9





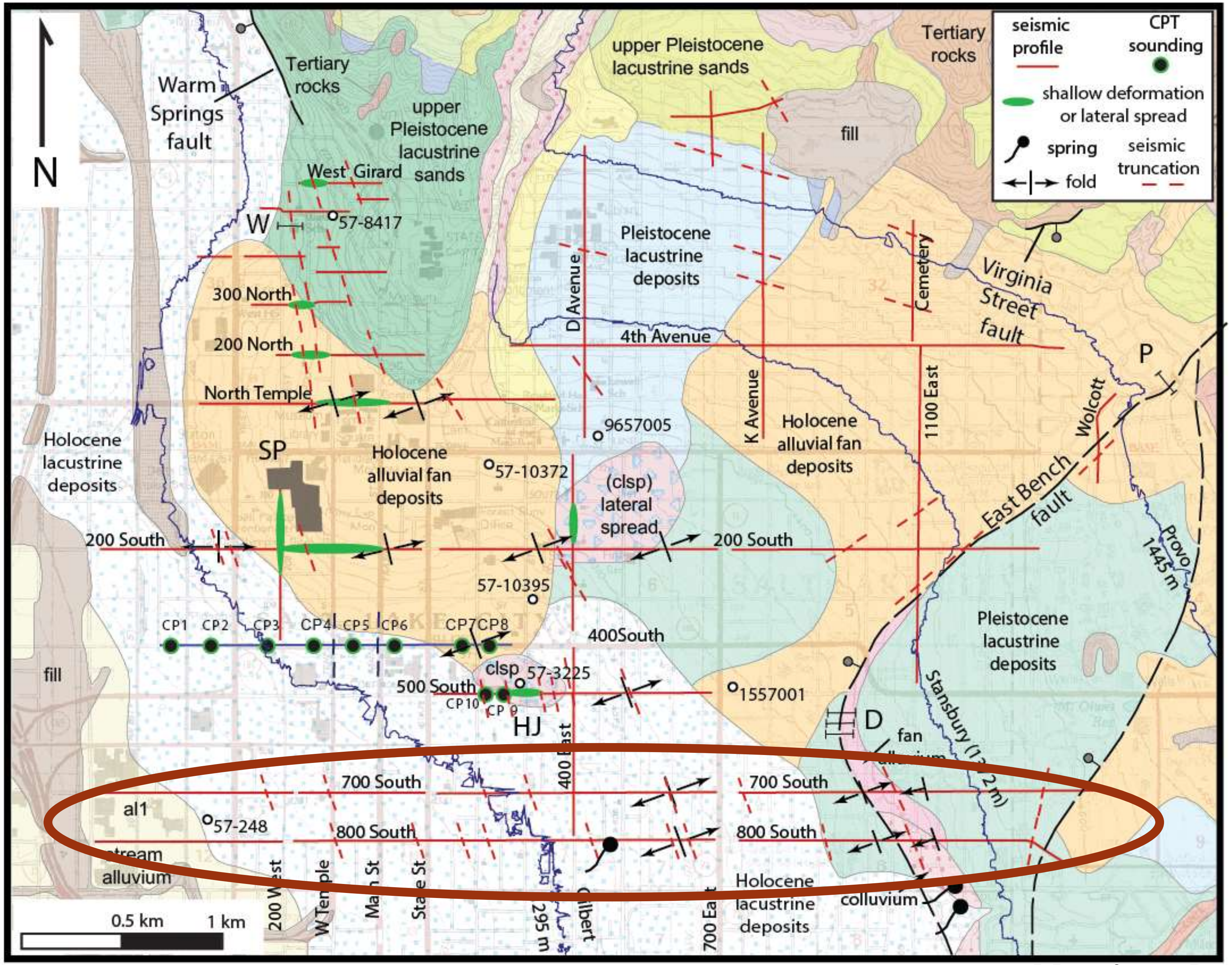


VS RELATED TO LIQUEFACTION



Predicted maximum distance to liquefaction versus moment magnitude (Ambraseys, 1988)

SUMMARY OF SEISMIC CAMPAIGN



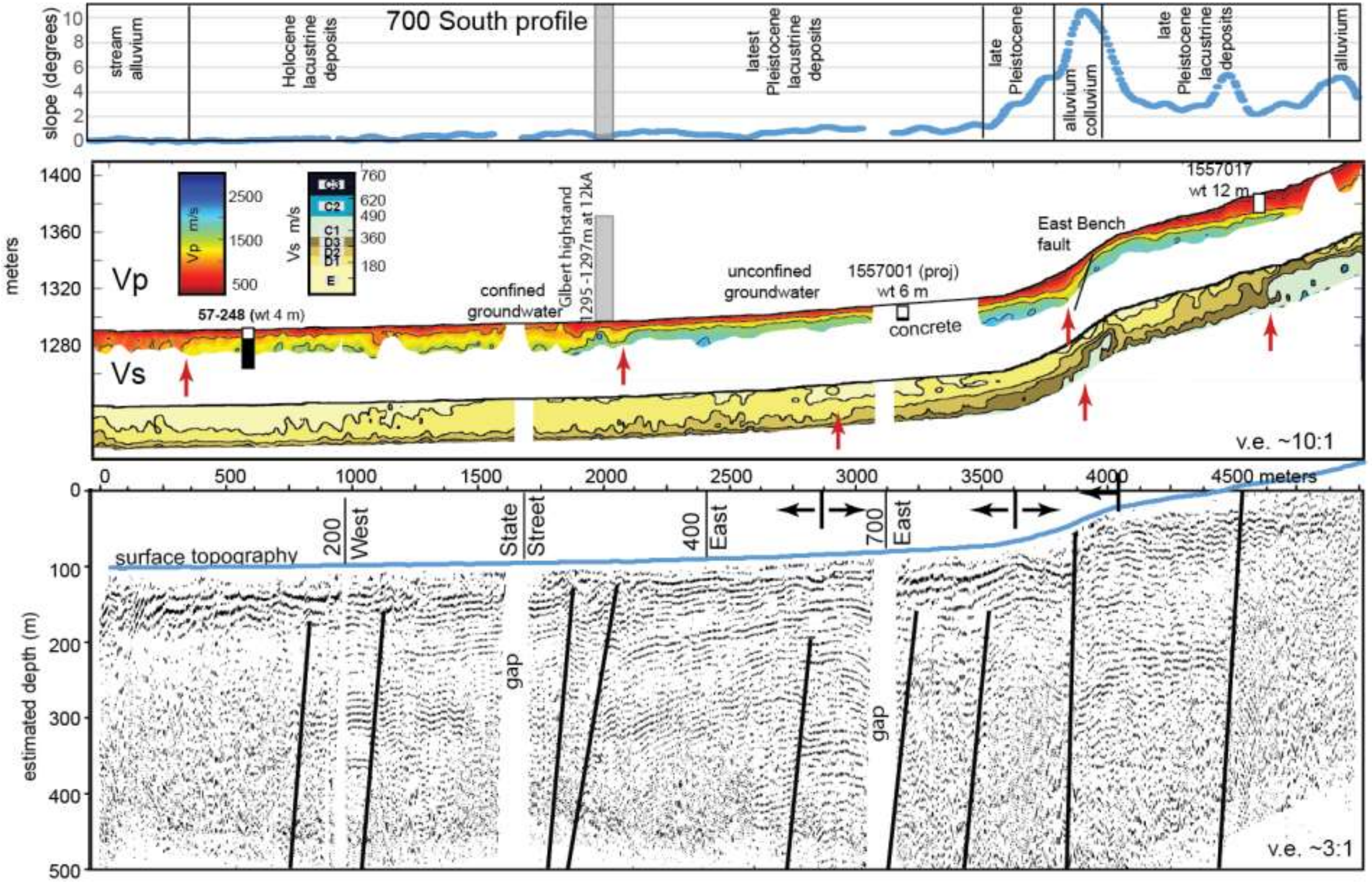
Map from Personius et al (1992)

- A zone of earthquake-induced liquefaction and faulting link strands of the Wasatch fault beneath Salt Lake City
- High liquefaction and site amplification potential raises the hazard by reducing earthquake magnitude where damage may occur

700 SOUTH PROFILE

- Vp shows a transition from an unconfined to confined groundwater system near 200 East
- Well defined colluvial wedge (low Vp) in the hanging wall of EBF
- Class E soils (upper 20 m) mapped to the west of 200 West
- Soft (Class C) rock within the EBF fault zone
- Vp and Vs step near 1300 East may represent a second strand of the EBF

- Folded and faulted strata suggest a distributed fault zone between WSF and EBF
- Poor reflectivity beneath stream alluvium

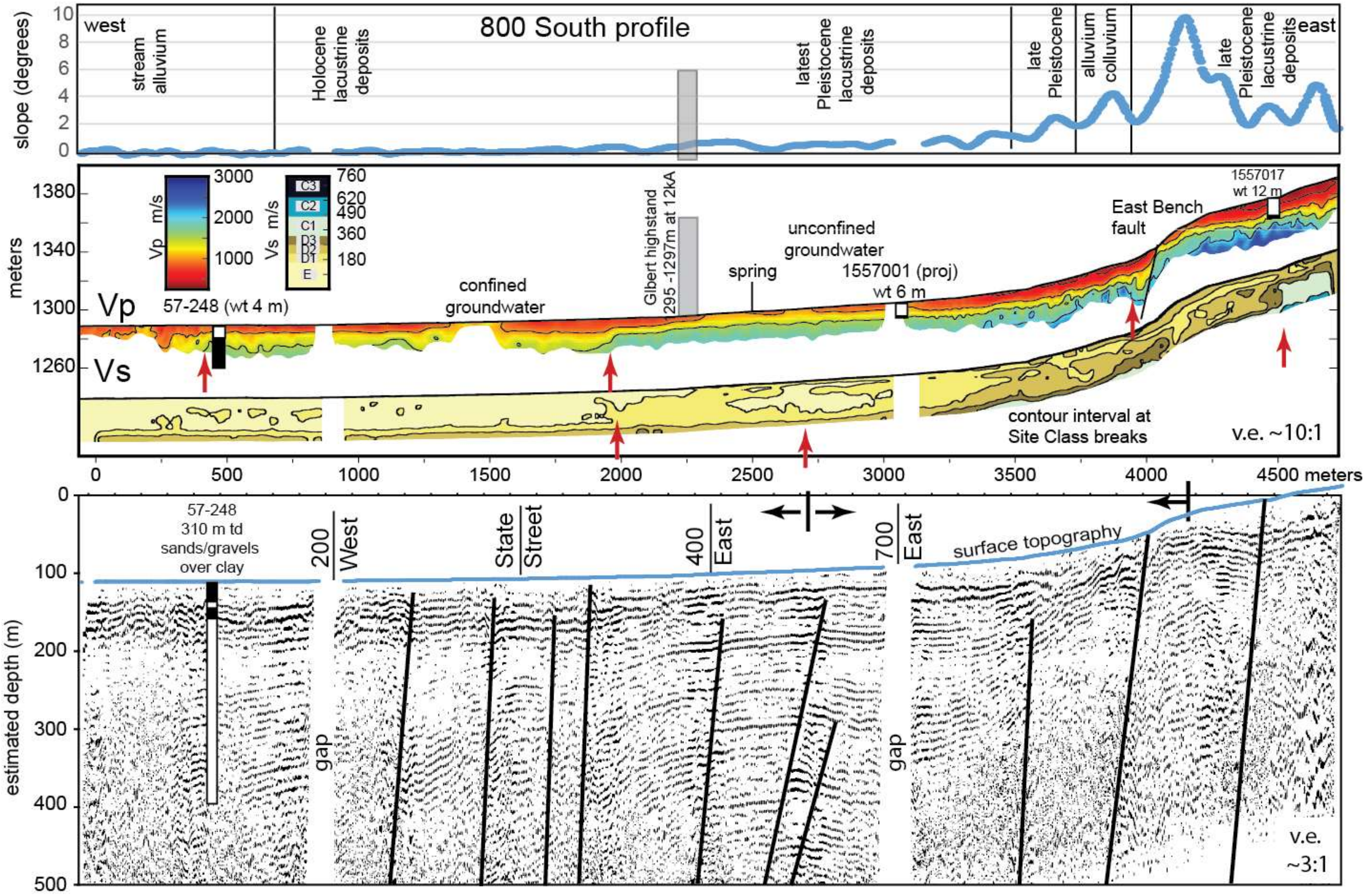


Liberty et al (in review) JGR

800 SOUTH PROFILE

- Vp shows a transition from an unconfined to confined groundwater system near 200 East
- Well defined colluvial wedge (low Vp) in the hanging wall of EBF
- Class E soils (upper 20 m) mapped to the west of 200 West
- Soft (Class C) rock within the EBF zone
- Vp and Vs step near 1300 East may represent a second strand of the EBF

- Folded and faulted strata suggest a distributed fault zone between WSF and EBF
- Poor reflectivity beneath stream alluvium



Liberty et al (in review) JGR

EAST BENCH FAULT ZONE

Hanging wall

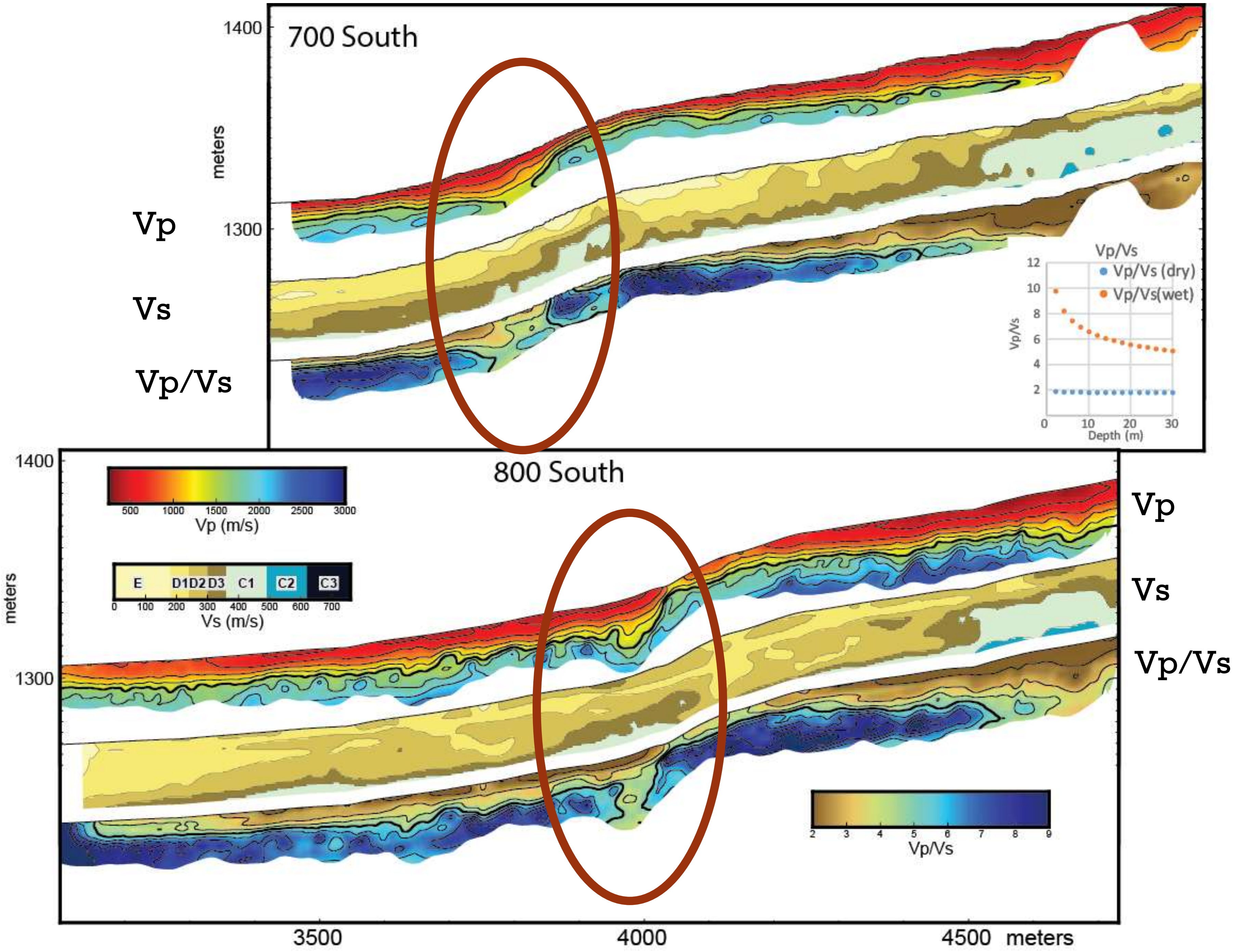
- Slow Vp colluvium
- Slow Vs
- Dry sediments → Vp/Vs ratio < 3

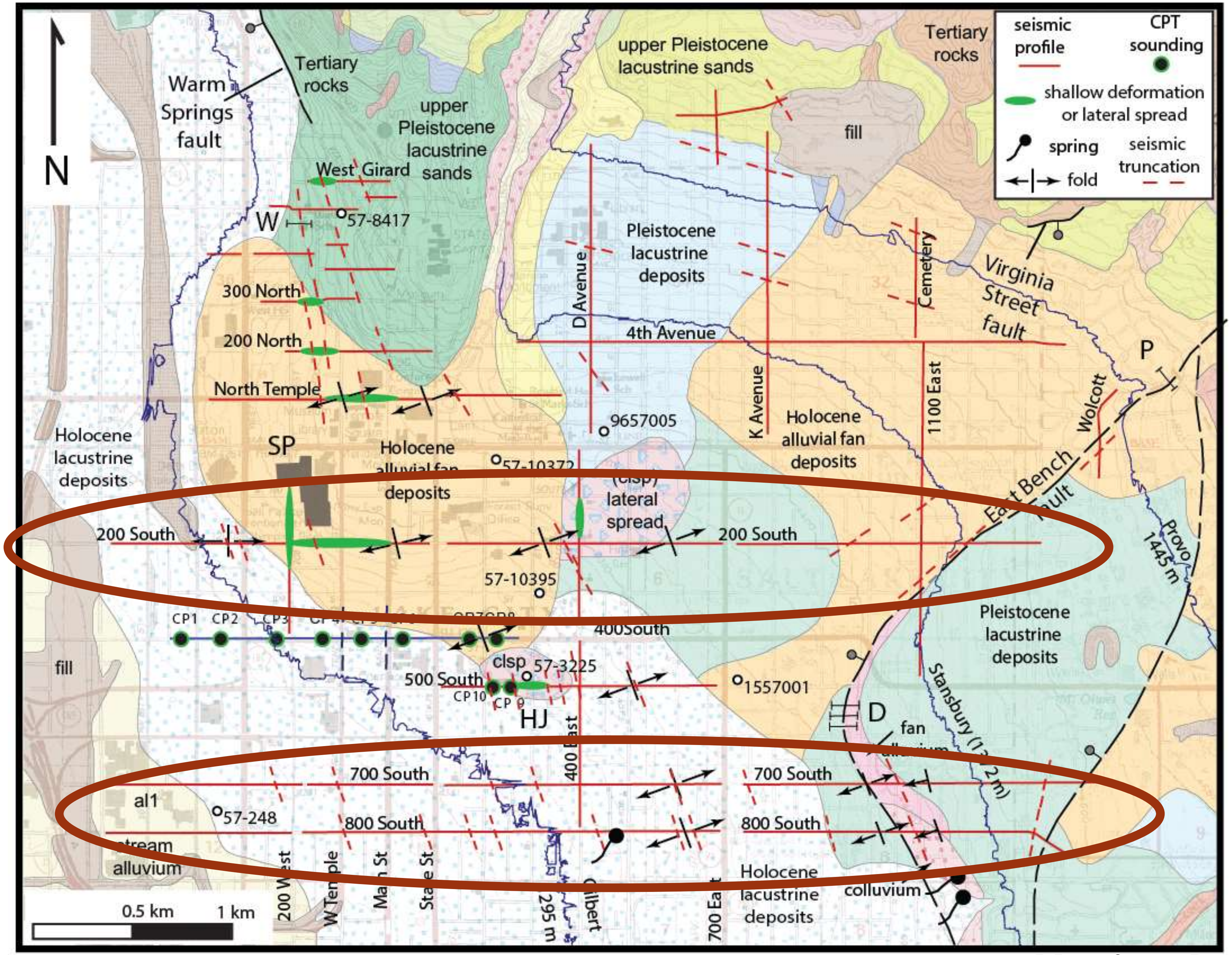
Fault

- Low Vp (dry)
- High Vs (stiff)
- Low Vp/Vs ratio
- Dry, stiff soils

Footwall

- Faster Vp,Vs
- Groundwater springs
- Increased depth to Vp >1500 m/s (dry) farther east





SUMMARY OF 700 SOUTH AND 800 SOUTH

- Folded strata trend NW
- Offset strata with minimal offsets suggest distributed faulting
- Low Vs along the western portions of the profile (below 1290 m elevation)
- No evidence for paleoliquefaction

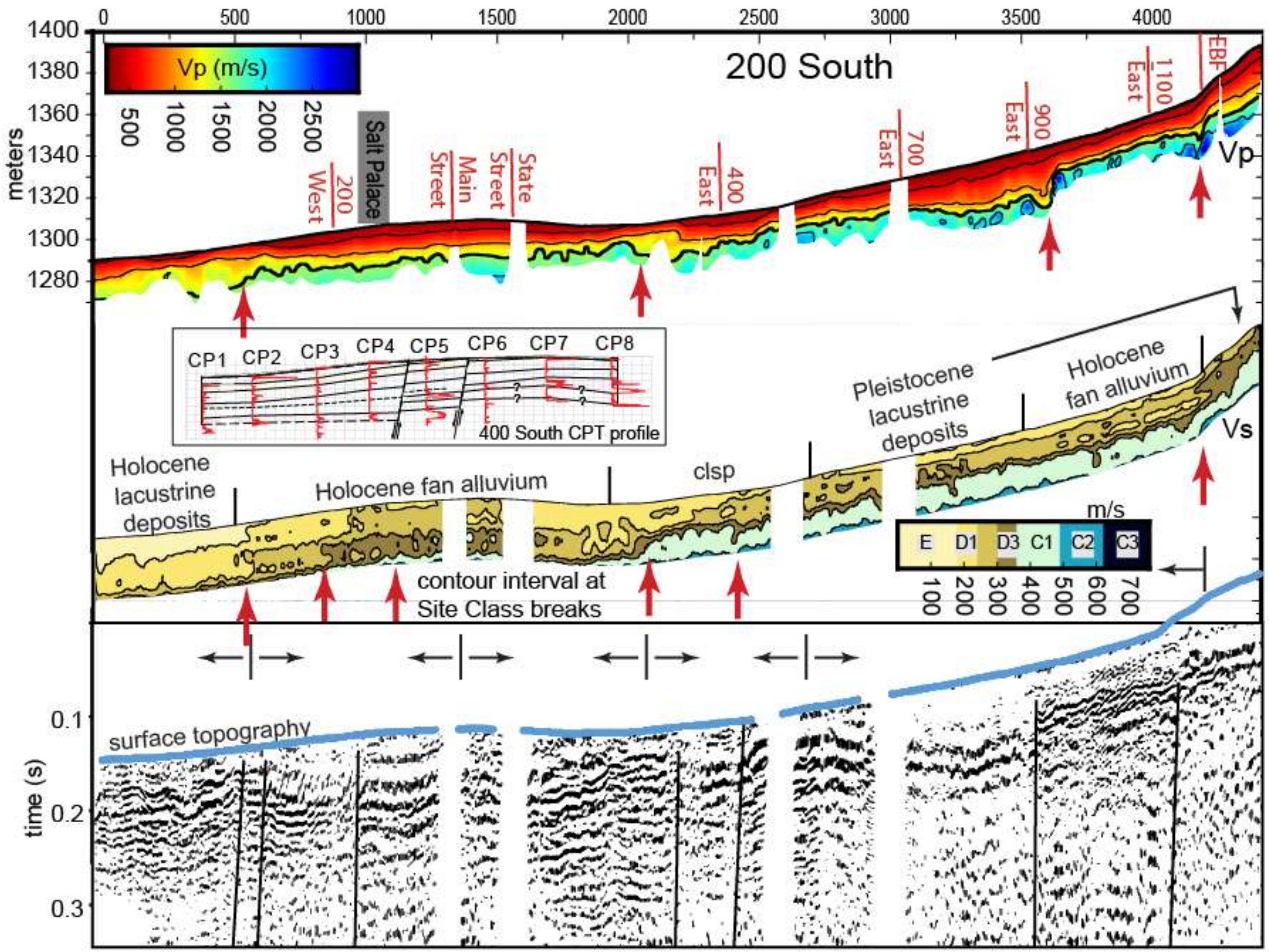
Map from Personius et al (1992)

200 SOUTH PROFILE (ACQUIRED IN 2015)

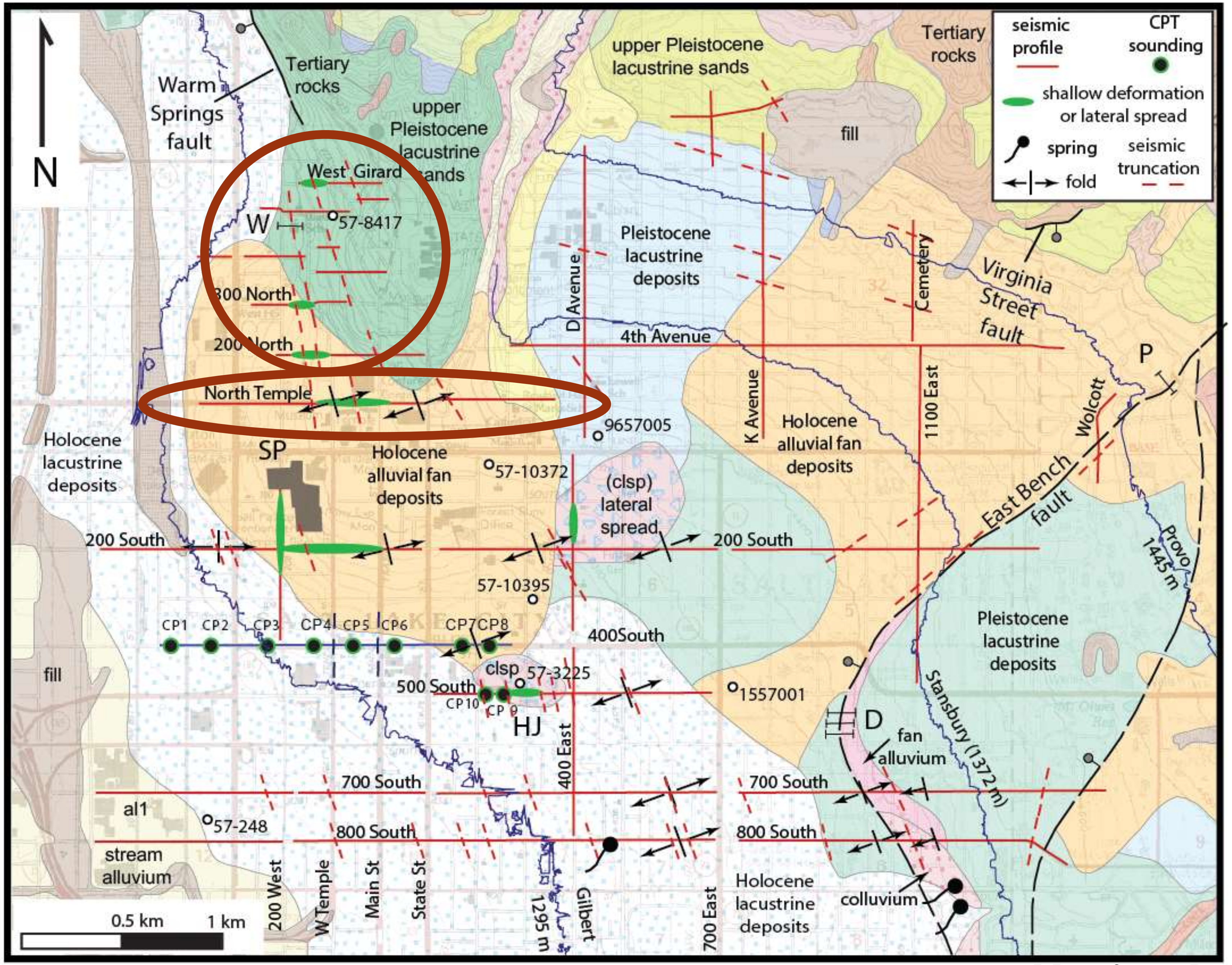
- Vp suggests a complex groundwater surface, likely due to lateral changes in soil properties
- Low Vp relate to fan alluvium

- Class E soils (upper 10 m) mapped to the west of 300 West
- Stiff (Class D) soils near Salt Palace may represent lateral spread.
- Class C rock below 10 m to the east of 500 East
- Vp and Vs step near 1200 East may coincident with the EBF

- Folded and faulted strata suggest a distributed fault zone between WSF and EBF



Liberty et al (in review) JGR

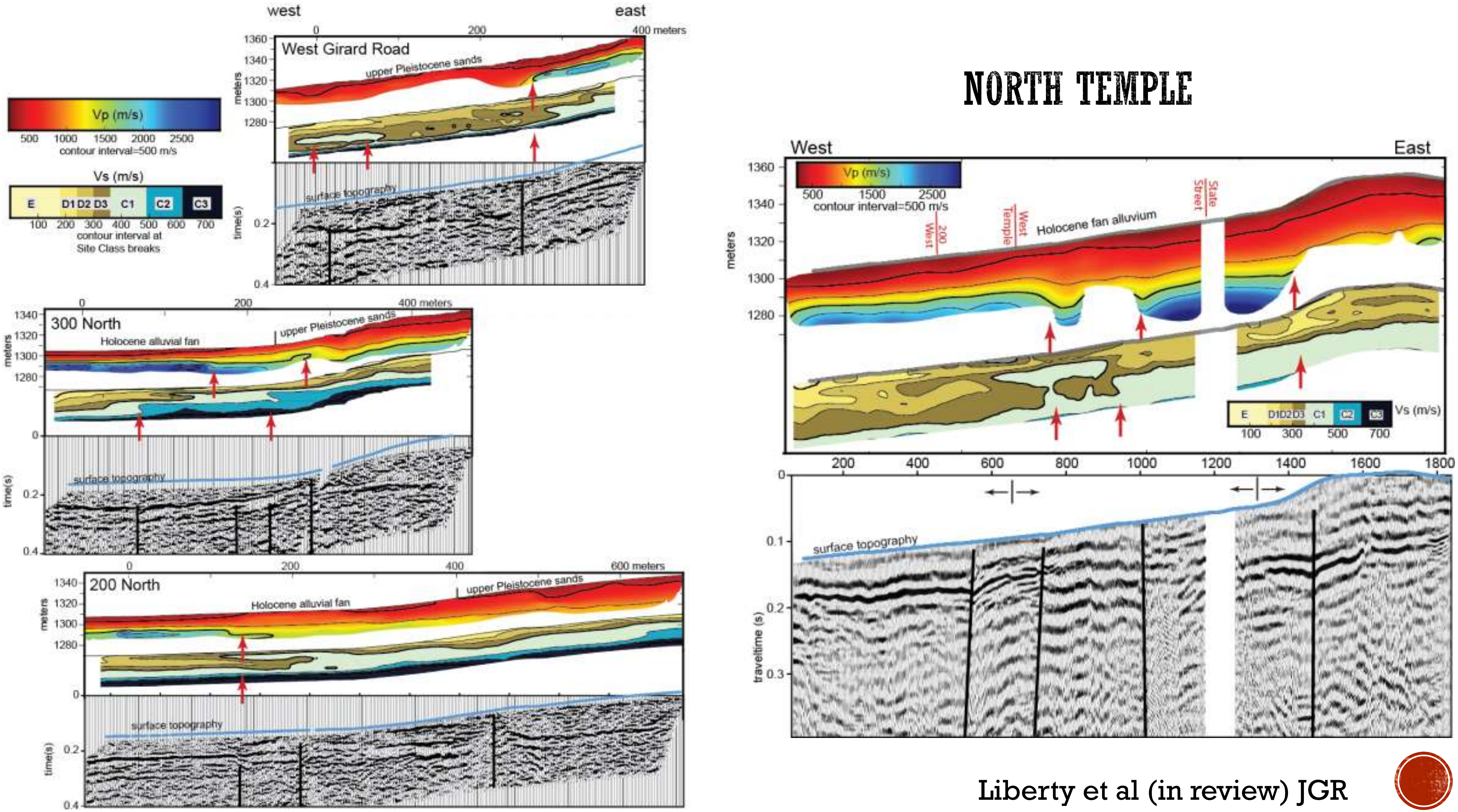


NORTH SALT LAKE CITY

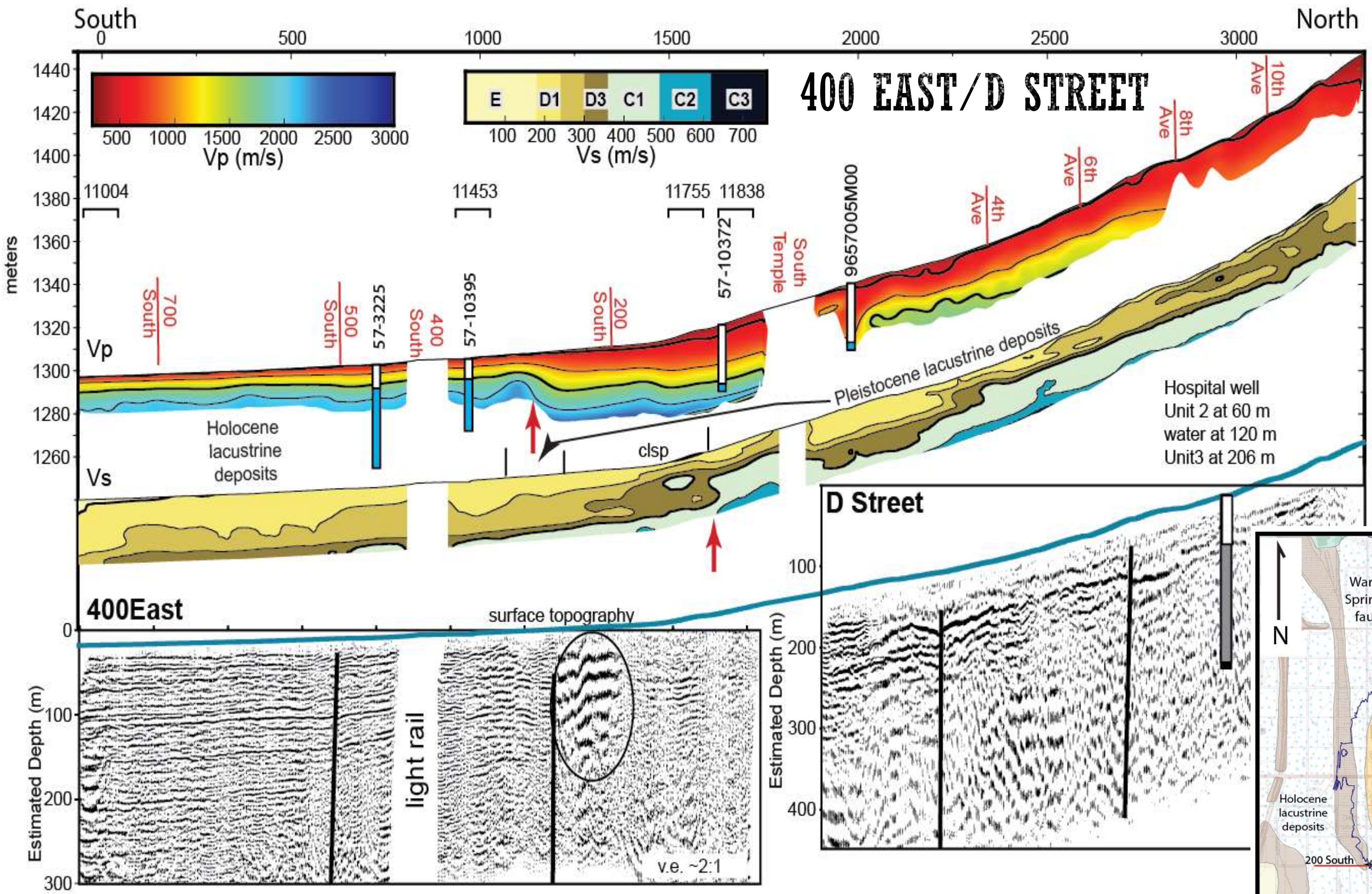
- Folded strata trend NW
- Offset strata with minimal offsets suggest distributed faulting
- Low Vs along the western portions of the profile (below 1290 m elevation)
- No evidence for paleoliquefaction

Map from Personius et al (1992)

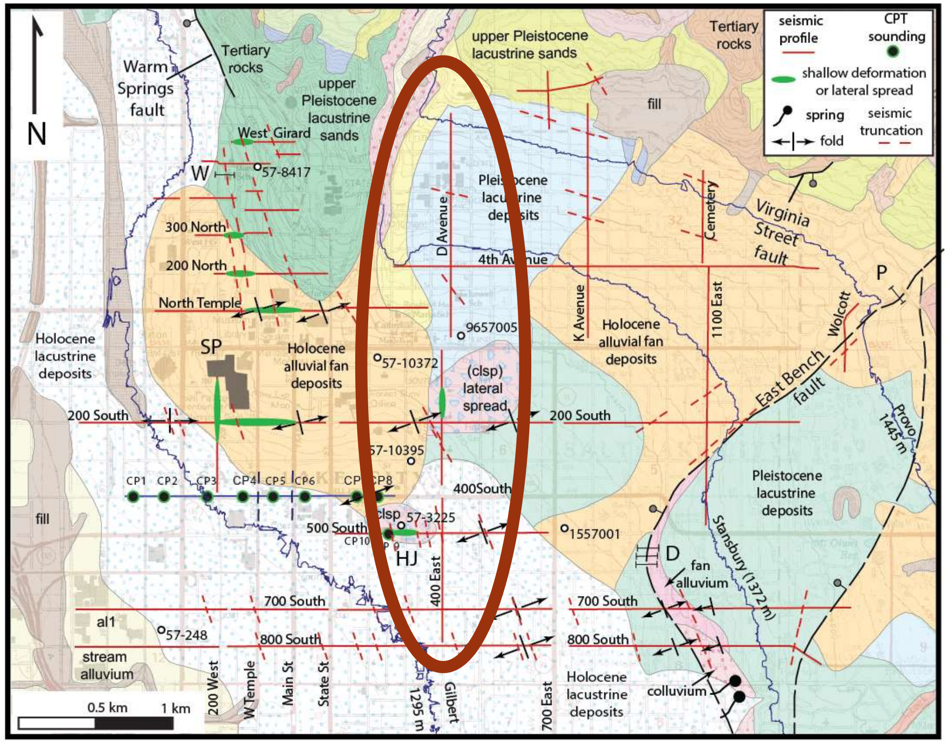
NORTH TEMPLE



Liberty et al (in review) JGR



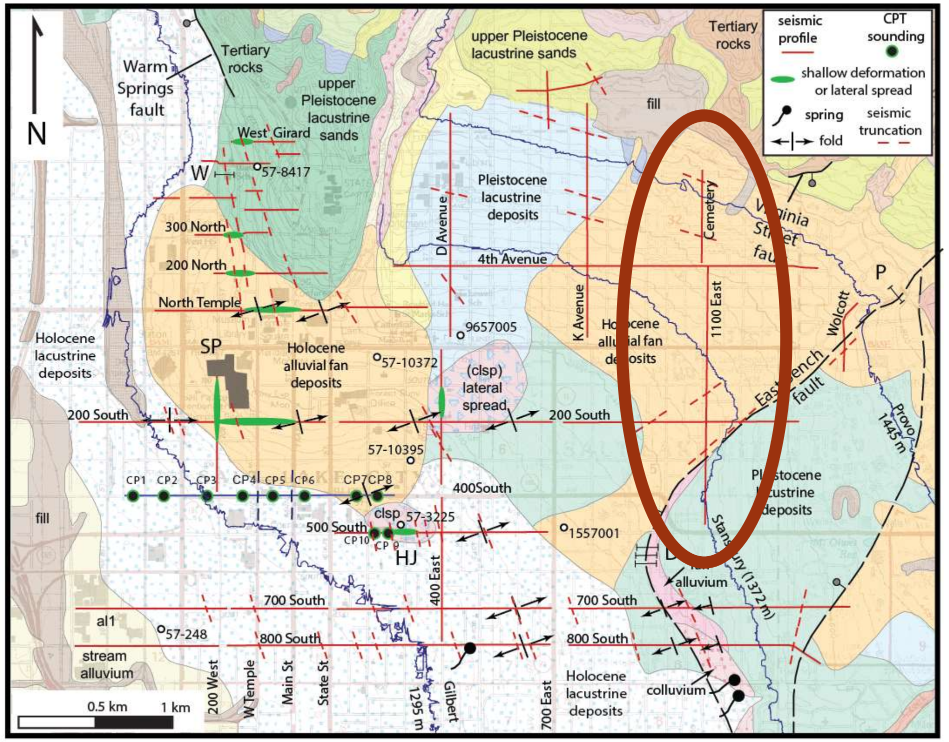
- Vp shows prominent step in water table near 200/300 South
- Low Vp at high elevations relates to fan alluvium or older lake seds
- Class E soils transitions to Class C/D soils
- Stiff (Class D) soils near Salt Palace may represent lateral spread.

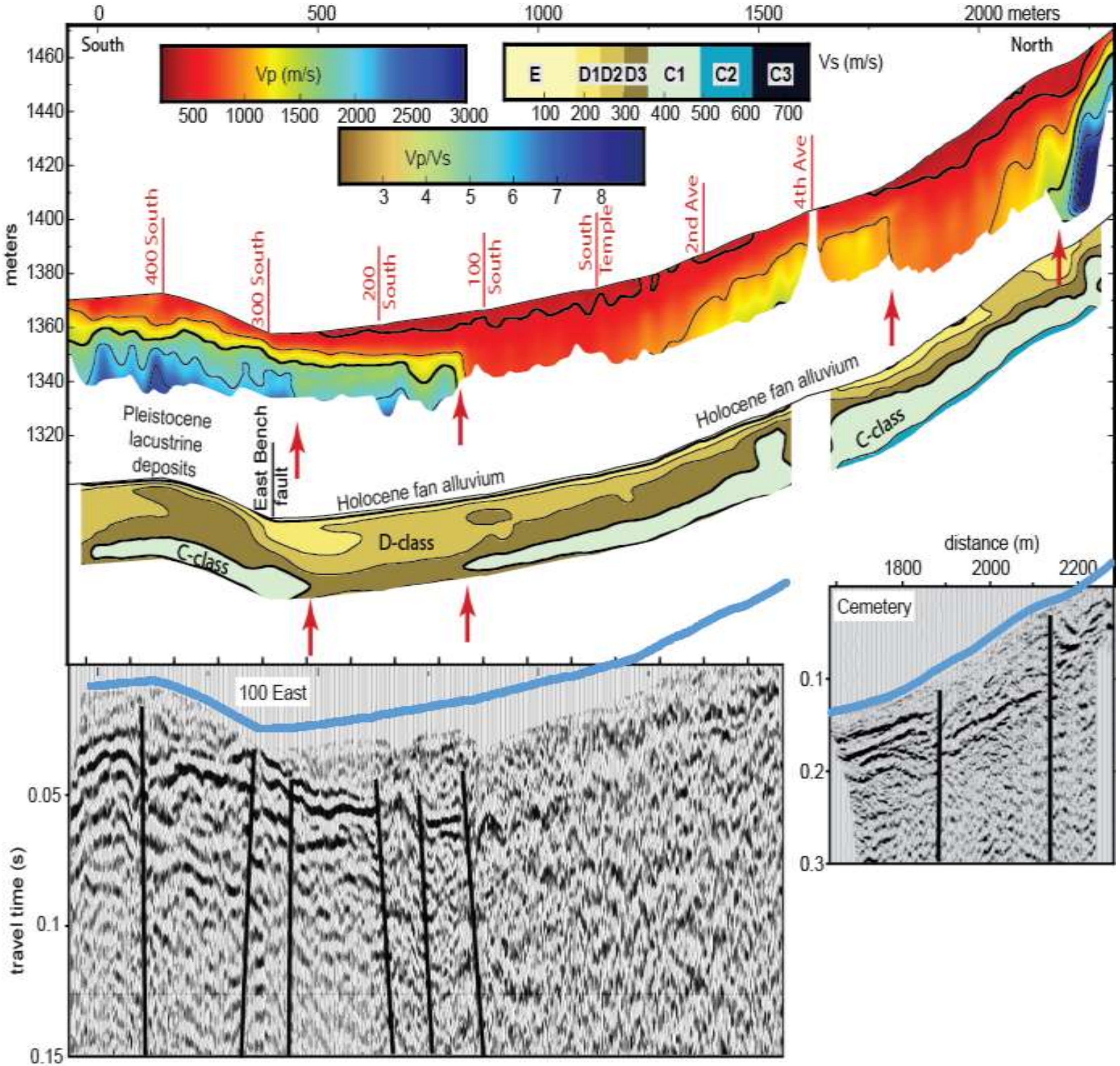


- Axial surface near 500 South
- Truncated reflectors near 200 South
- Water table reverberations near 200 South

110 EAST/CEMETERY

- Vp suggests a complex groundwater surface, likely due to lateral changes in soil properties
- Low Vp relate to fan alluvium
- Class E soils (upper 10 m) mapped to the west of 300 West





VS_{30} MAP FOR DOWNTOWN SLC

36 Vs measurements

McDonald and Ashland (2008)

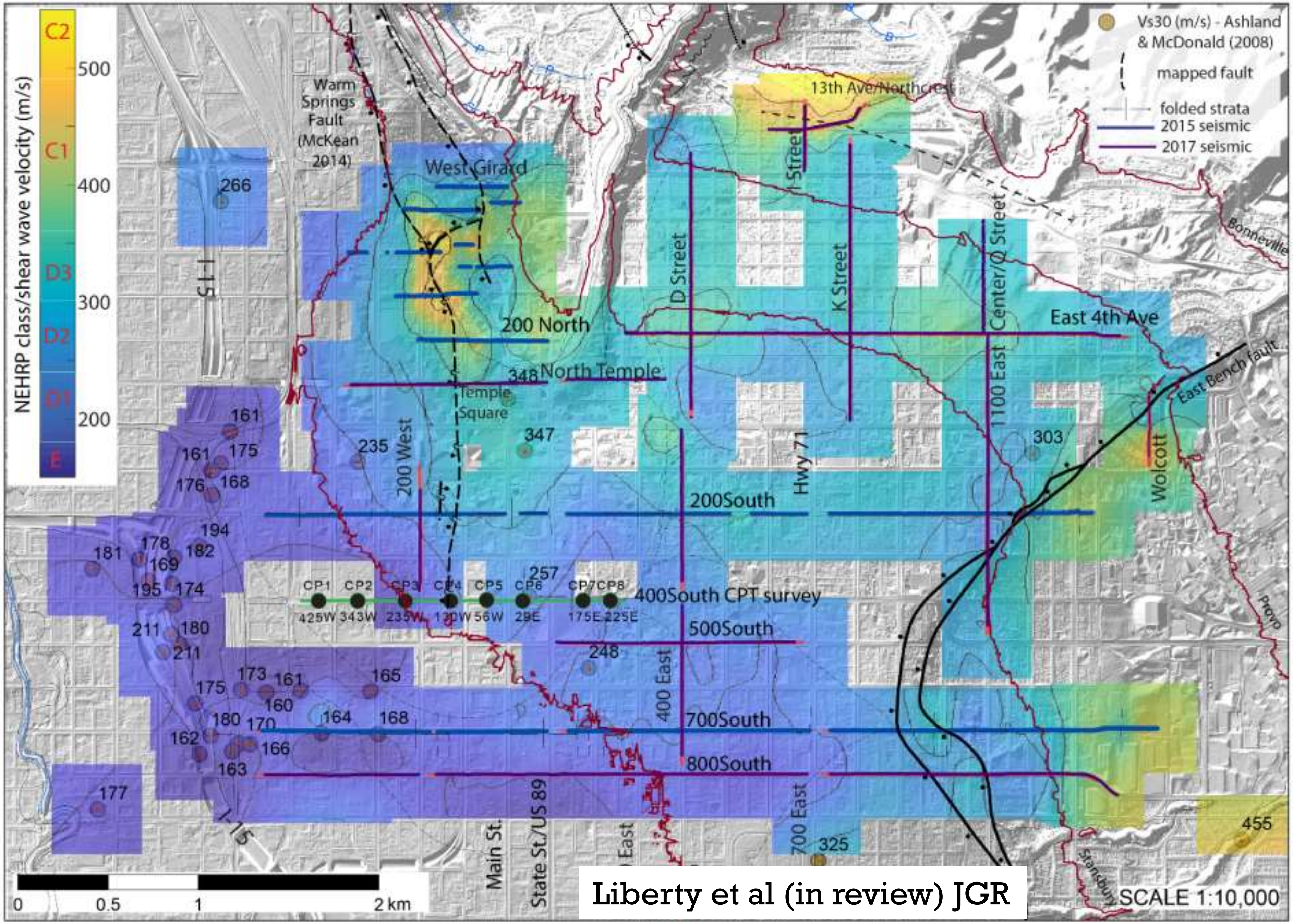
15,000 additional Vs measurements

via seismic land streamer

Low Vs for Bonneville deposits beneath western portions of downtown Salt Lake City

Increase in Vs30 from west to east

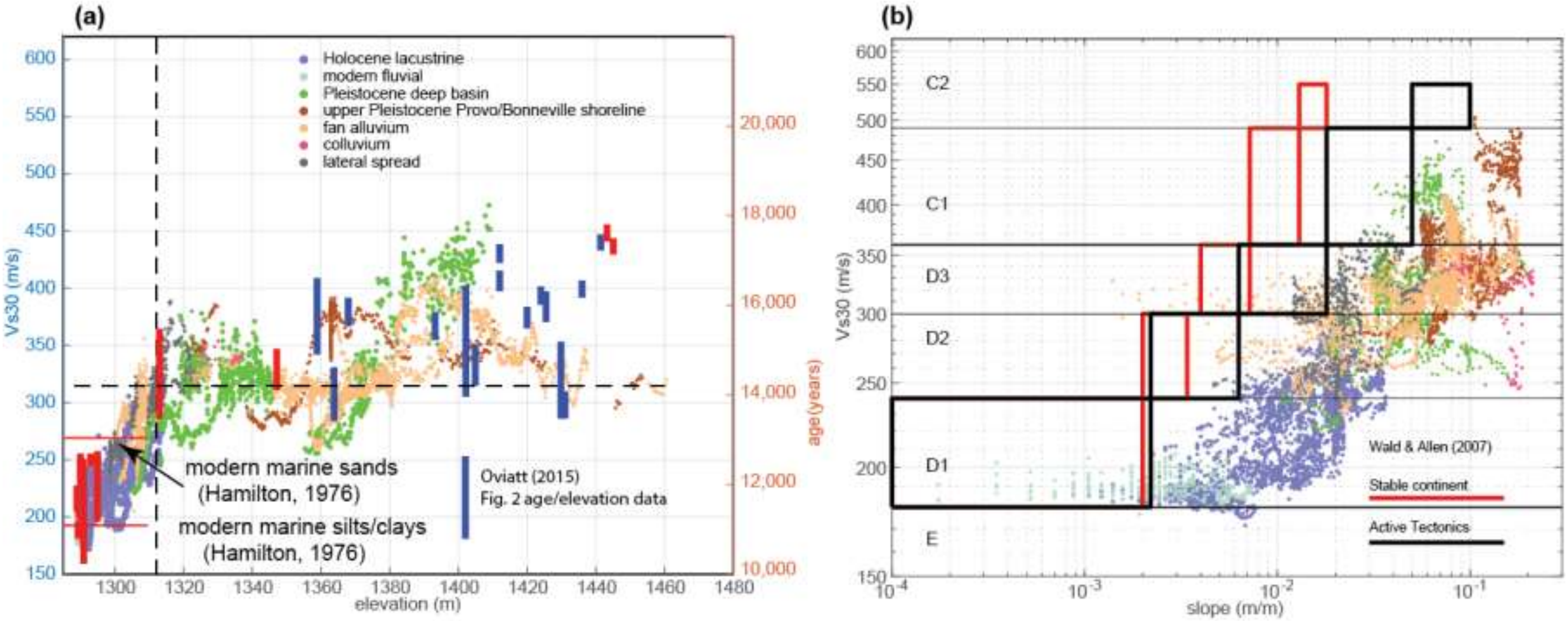
High Vs in the footwall or in fault zones

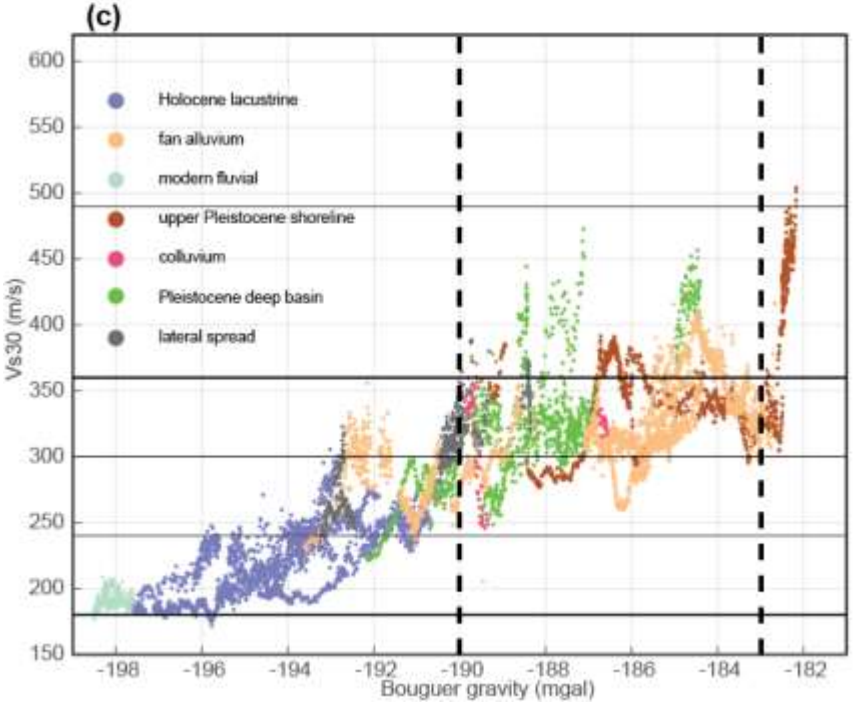


Liberty et al (in review) JGR

VS30 RELATIONSHIPS

TOPOGRAPHY, SLOPE, AND GRAVITY DERIVED BASIN DEPTHS





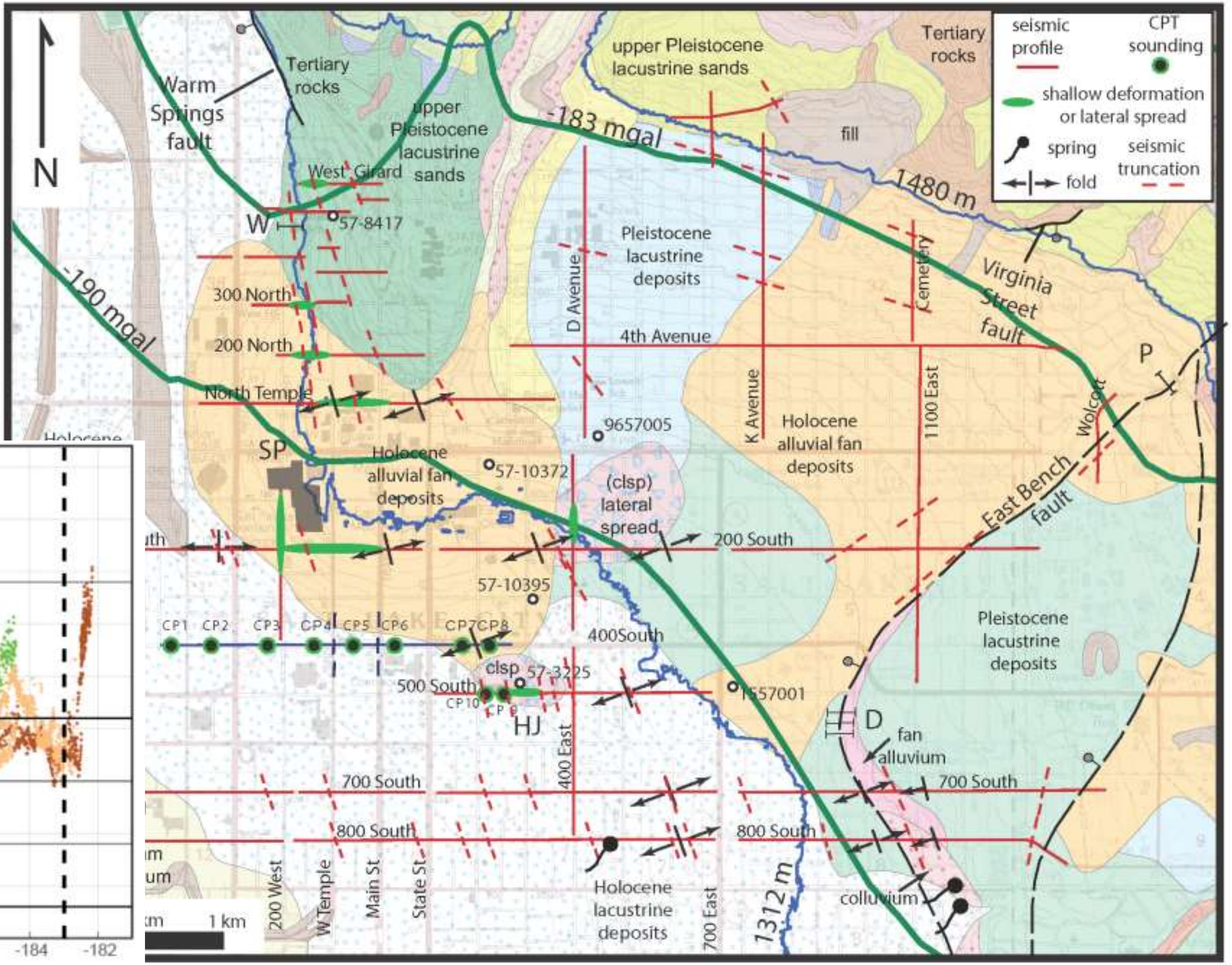
Vs30 relates to surface sediment age (using Oviatt (2015) elevation relation

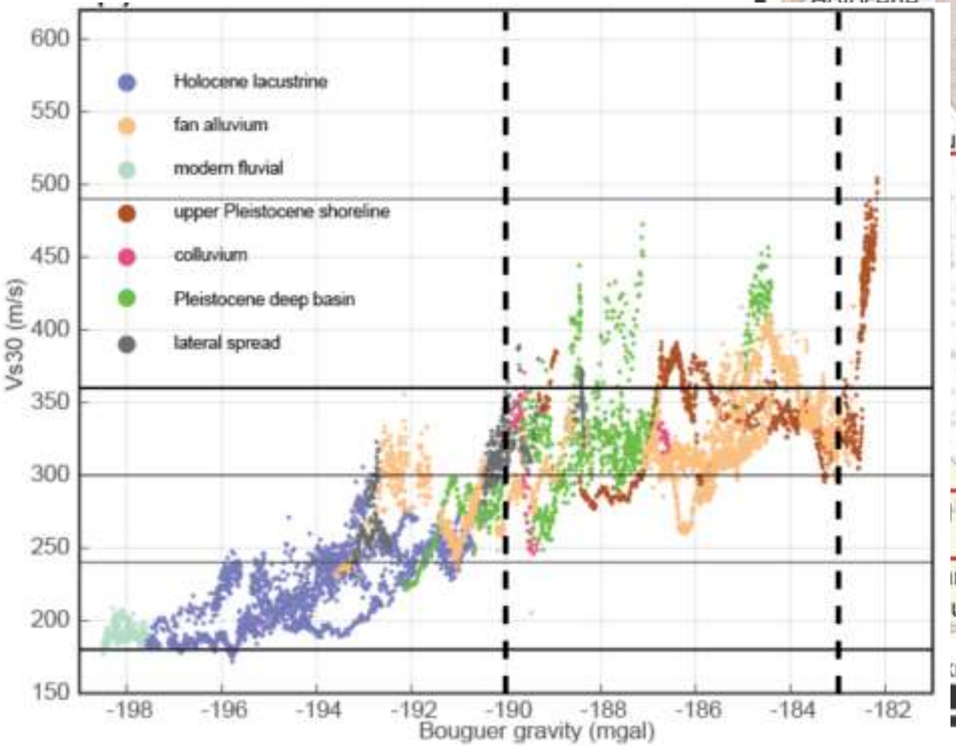
Vs30/slope values consistently below global averages

Vs30/gravity values show two linear relationships that relate to lake and fan deposits

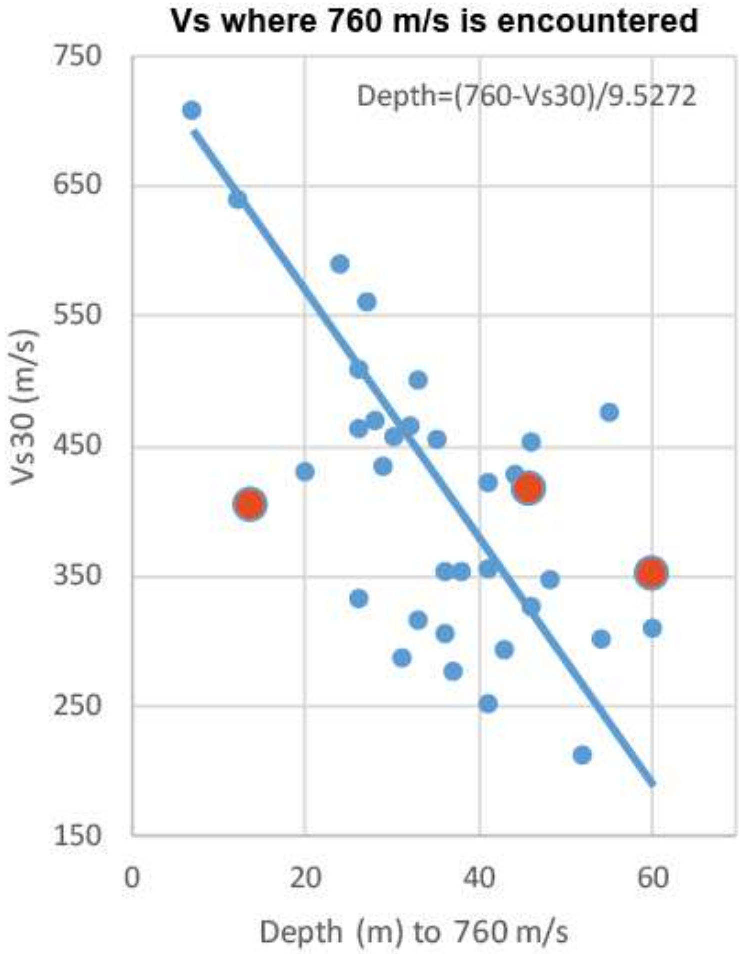
Liberty et al, SSA 2019

GRAVITY & ELEVATION CONTOURS

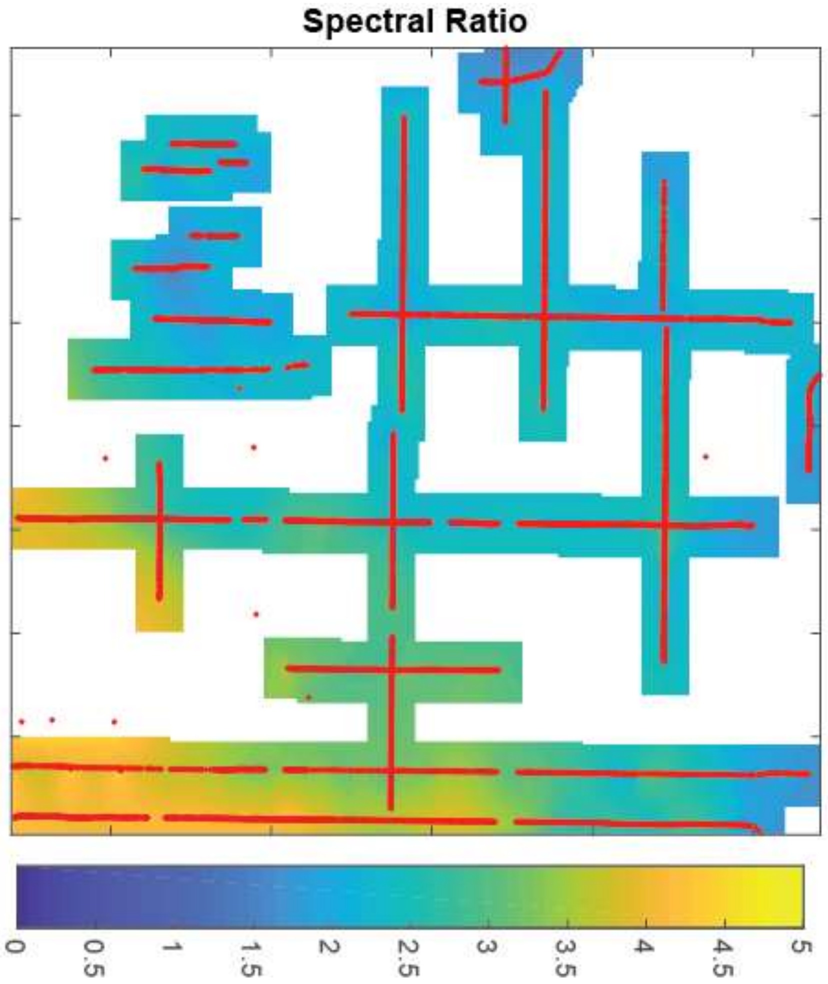




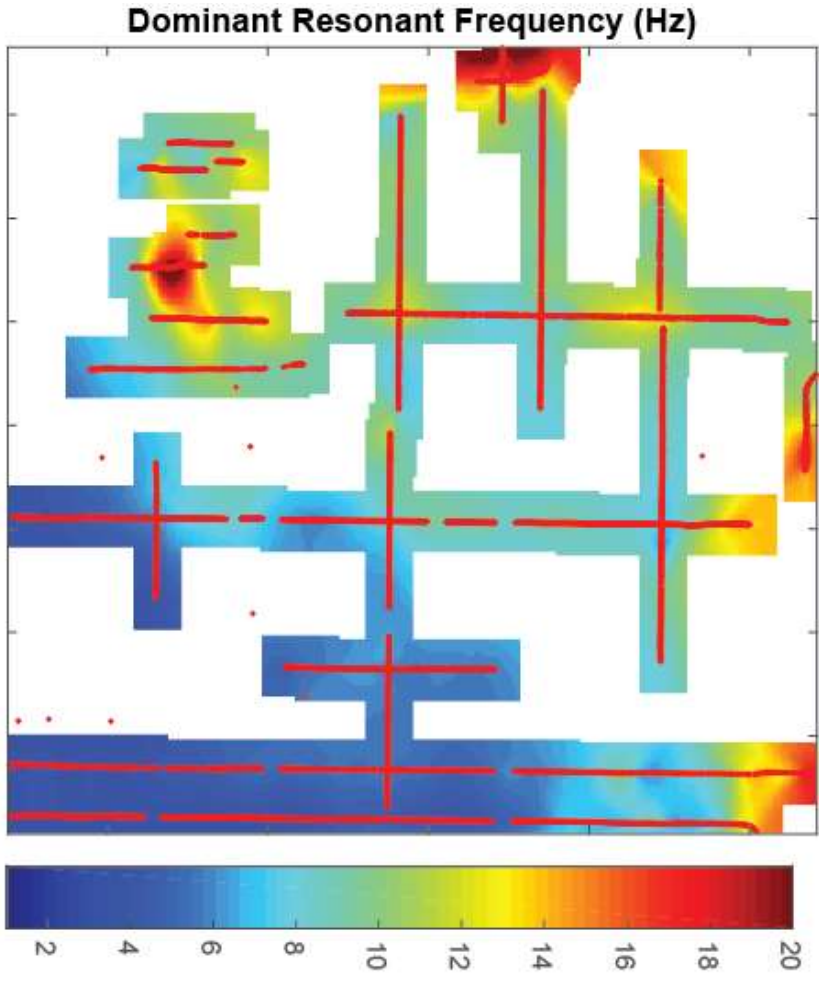
VS30/SITE CLASS B SOIL RELATIONSHIP



From UGS database



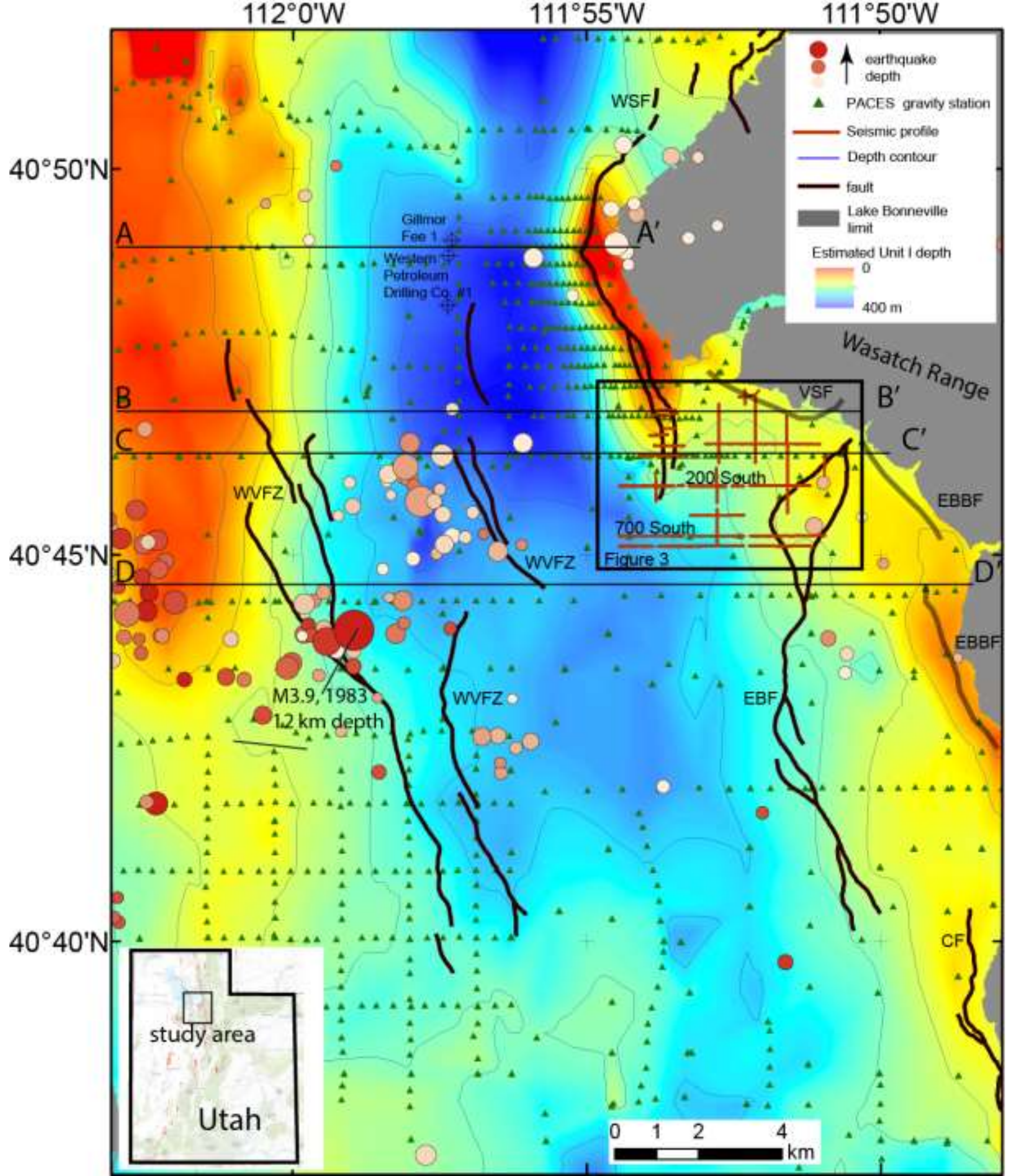
SR=760/Vs30

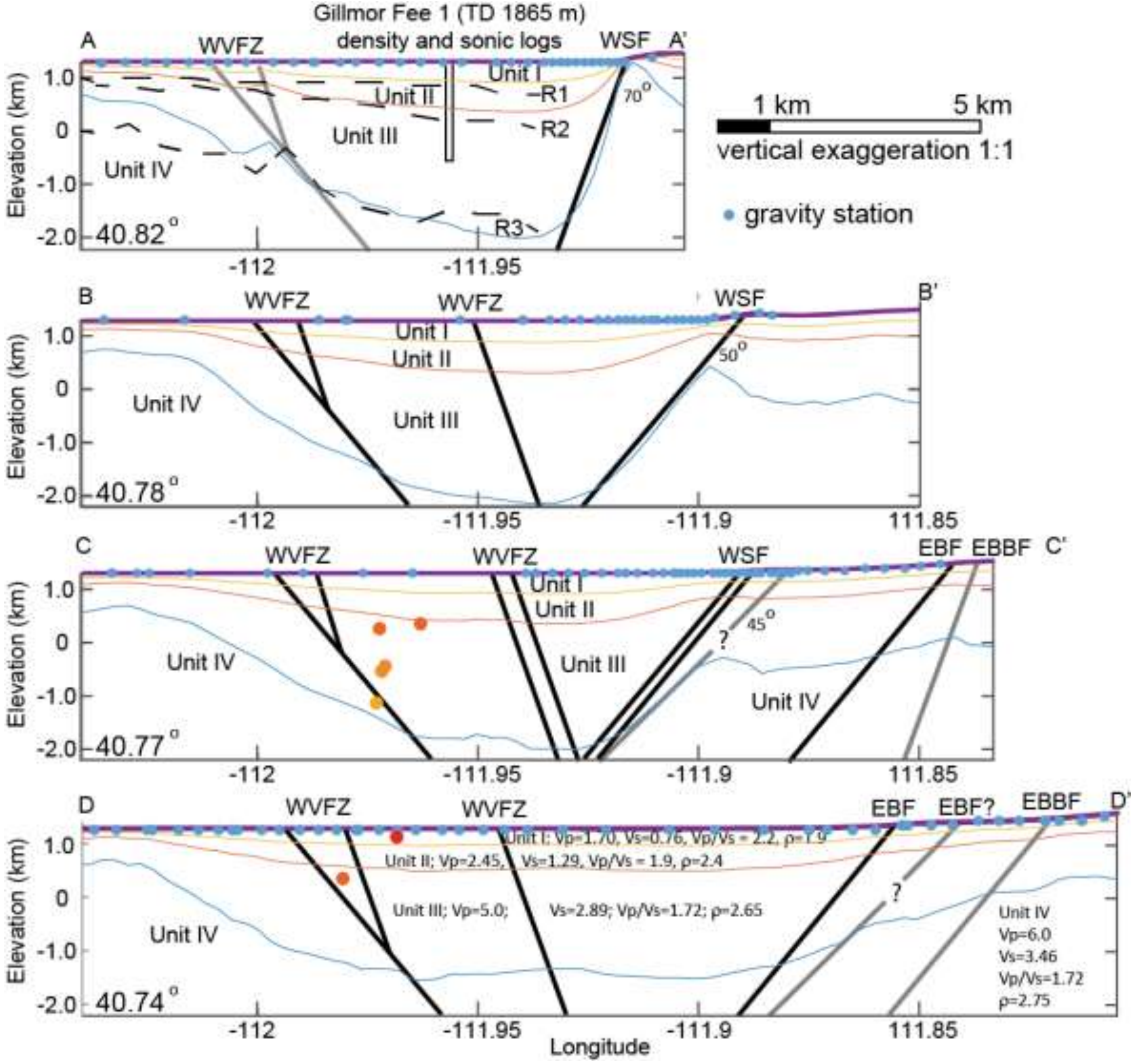


Fn=(2n+1)*Vs/ 4h
Where n=0 (fundamental mode)

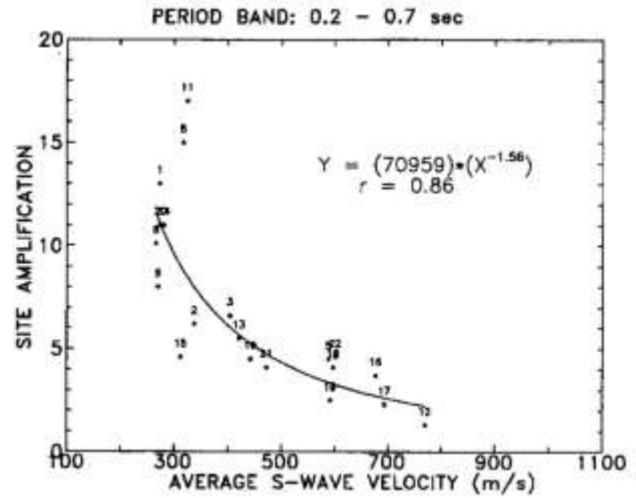
GRAVITY-DERIVED MAP

(SALTUS AND JACHENS, 1995 APPROACH)

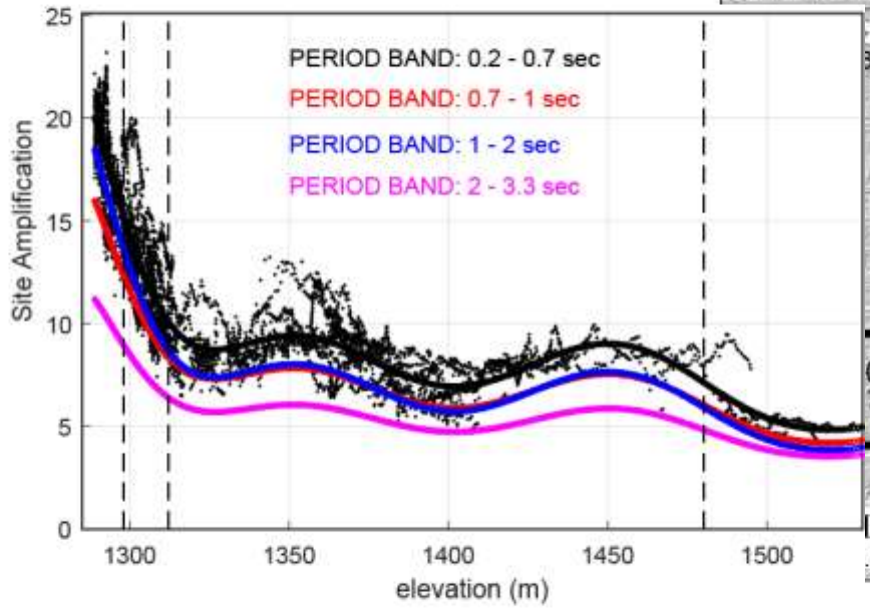


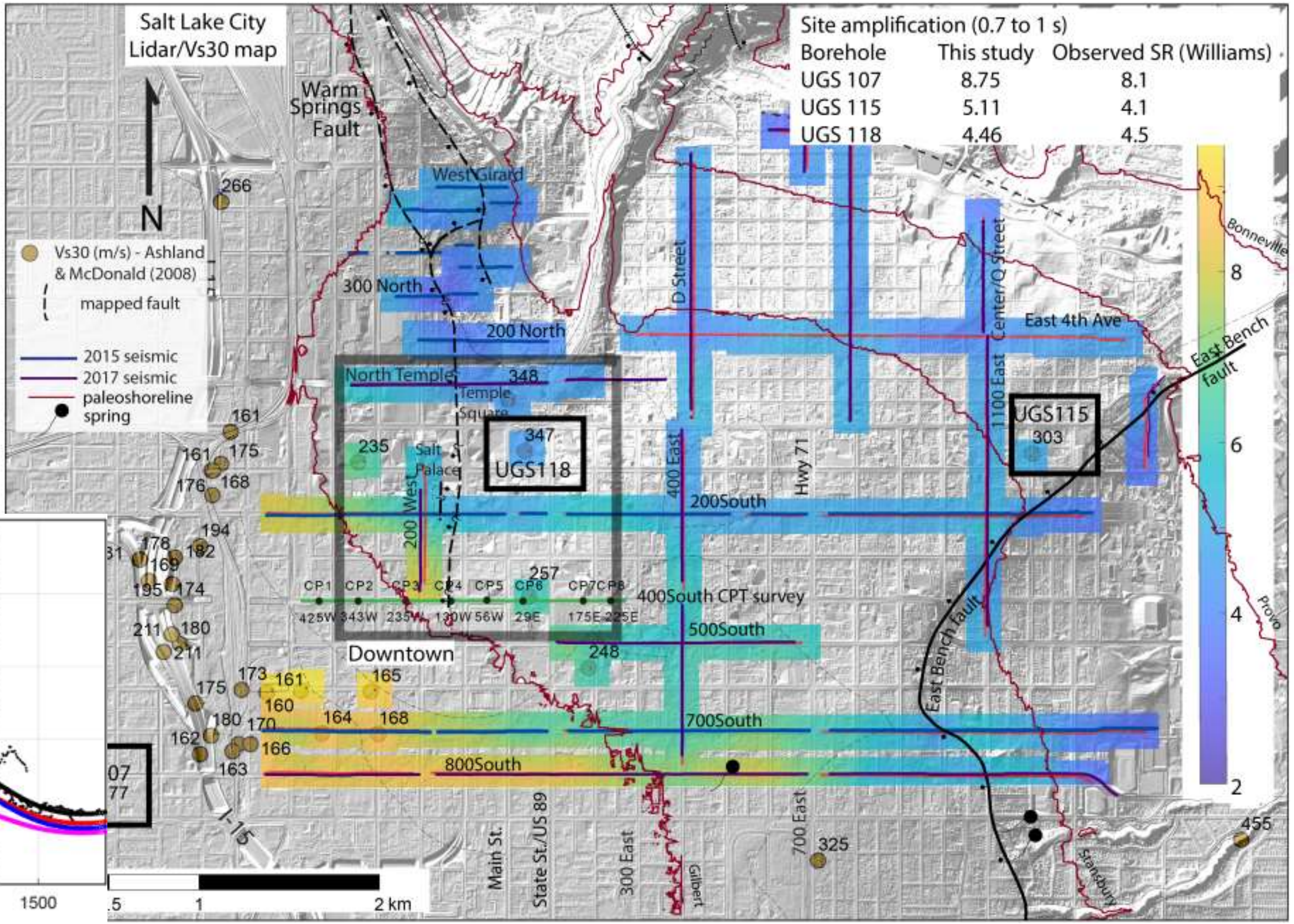


SITE AMPLIFICATION



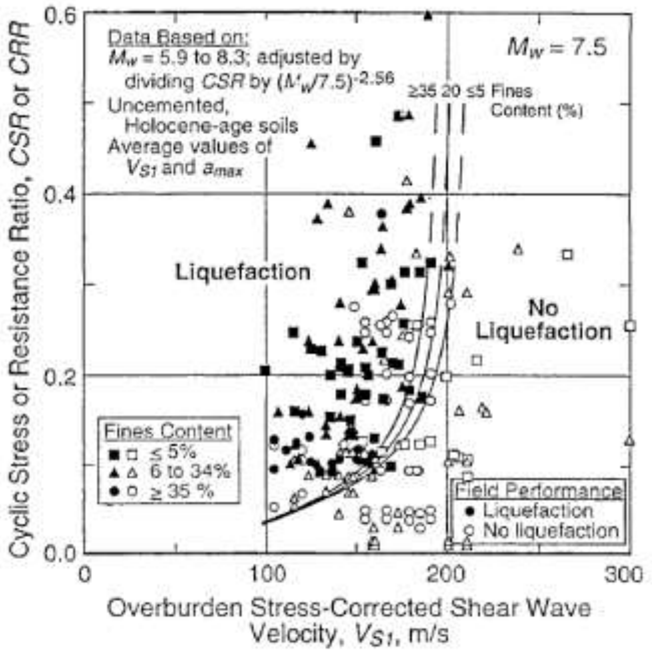
From Williams et al, 1993



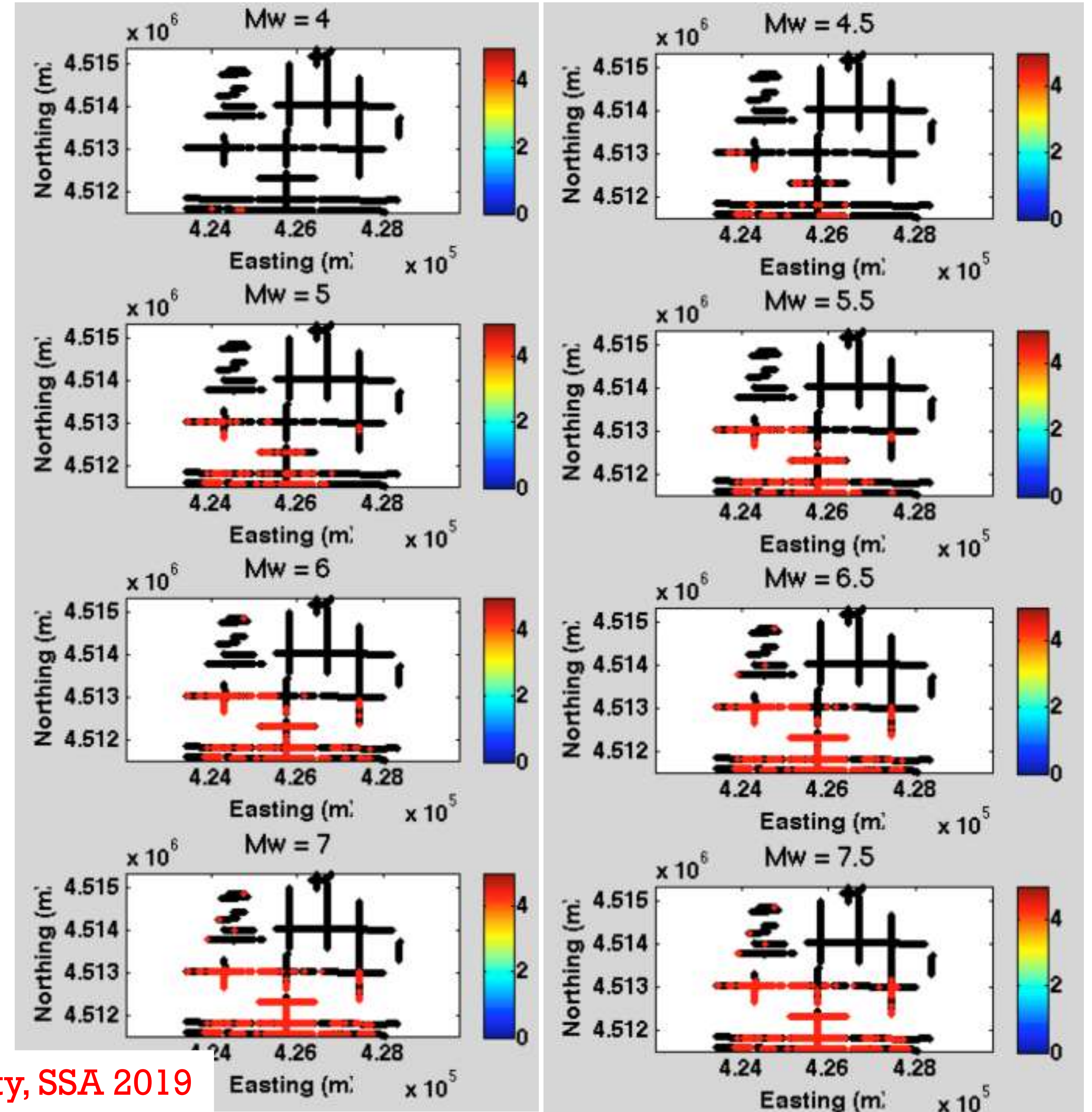


LIQUEFACTION SCENARIO MAPS

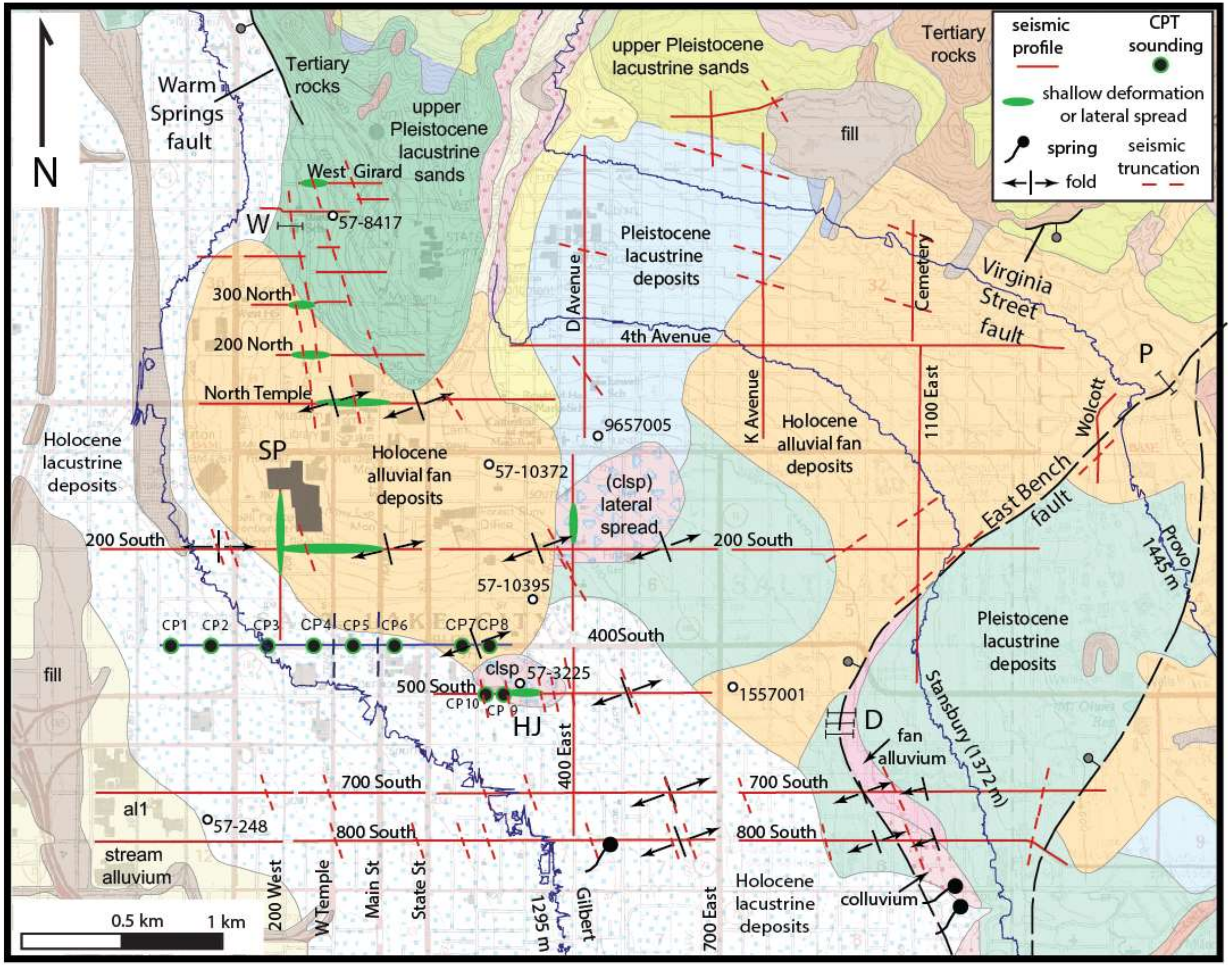
- Vs corrected for overburden and effective stresses via water table depths (Vp) and CPT-derived densities.
- We compare Cyclic Stress Ratios (CSR) for a range of earthquake scenarios to Vs-derived Cyclic Resistance Ratio (CRR) of the soils.



From Youd & Idriss (2001)



St. Clair and Liberty, SSA 2019

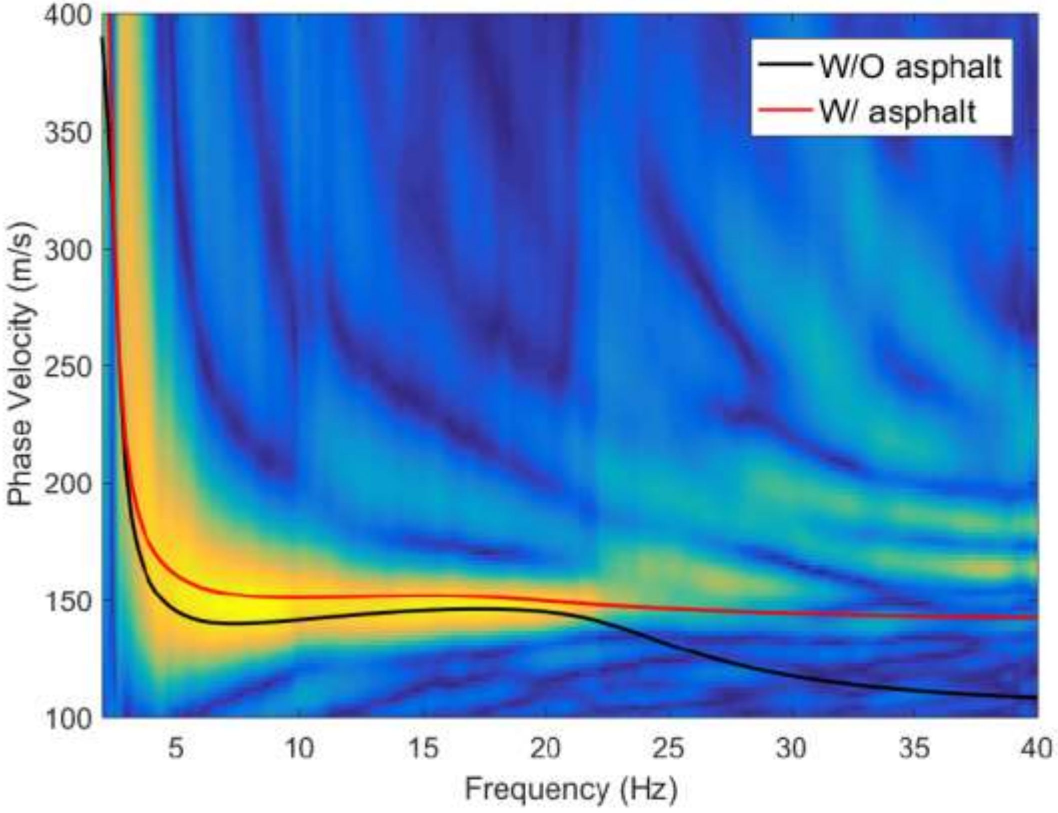


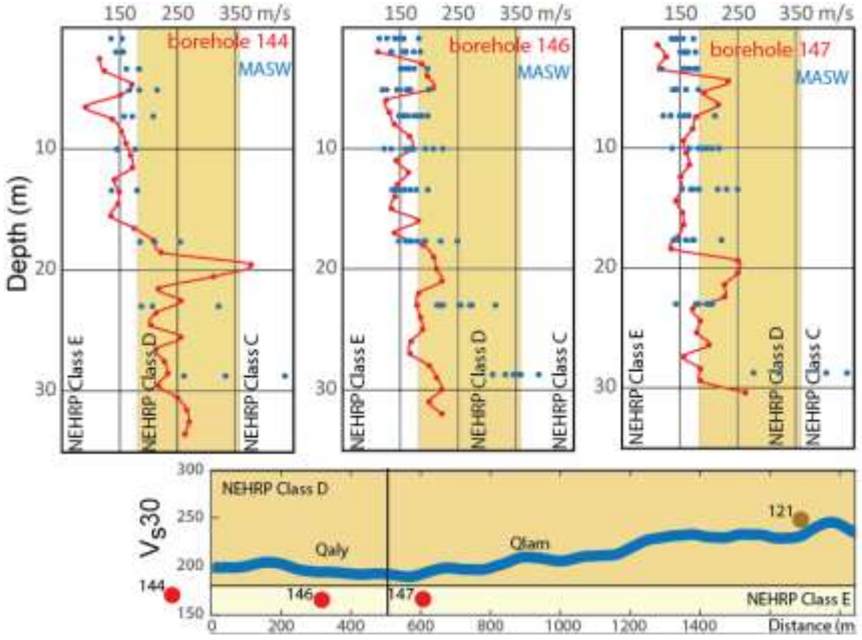
SUMMARY OF SEISMIC CAMPAIGN

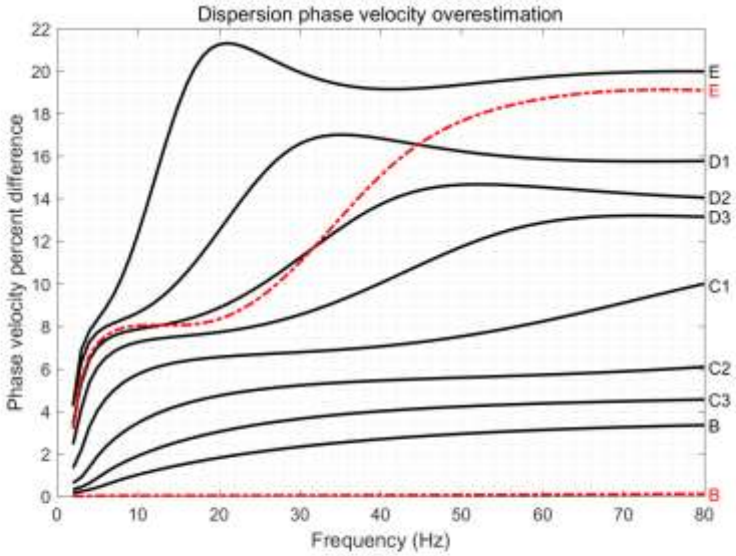
- A zone of earthquake-induced liquefaction and faulting link strands of the Wasatch fault beneath Salt Lake City
- High liquefaction and site amplification potential raises the hazard by reducing earthquake magnitude where damage may occur

WHAT ARE THE EFFECTS OF THE ROAD LAYER ON RAYLEIGH WAVE SPEEDS?

Vs gradient of 4 m/s per meter







Black line = 30 cm road layer: Vs=1,500 m/s

Red line = 10 cm road layer: Vs=800 m/s

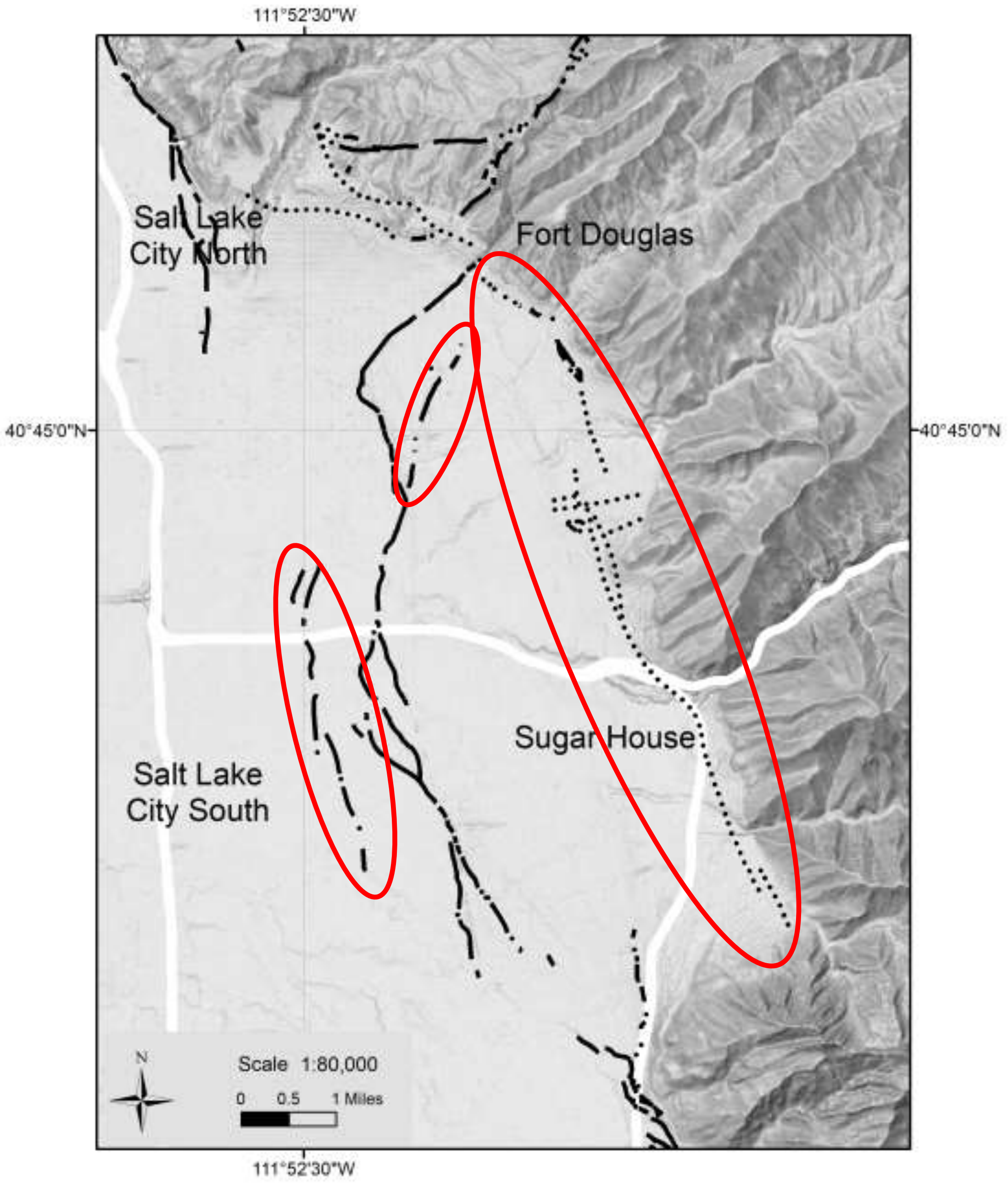
from Gribler, Liberty and Mikesell (in revision)

Normal Faults in Northeastern Salt Lake Valley, New Faults and New Names

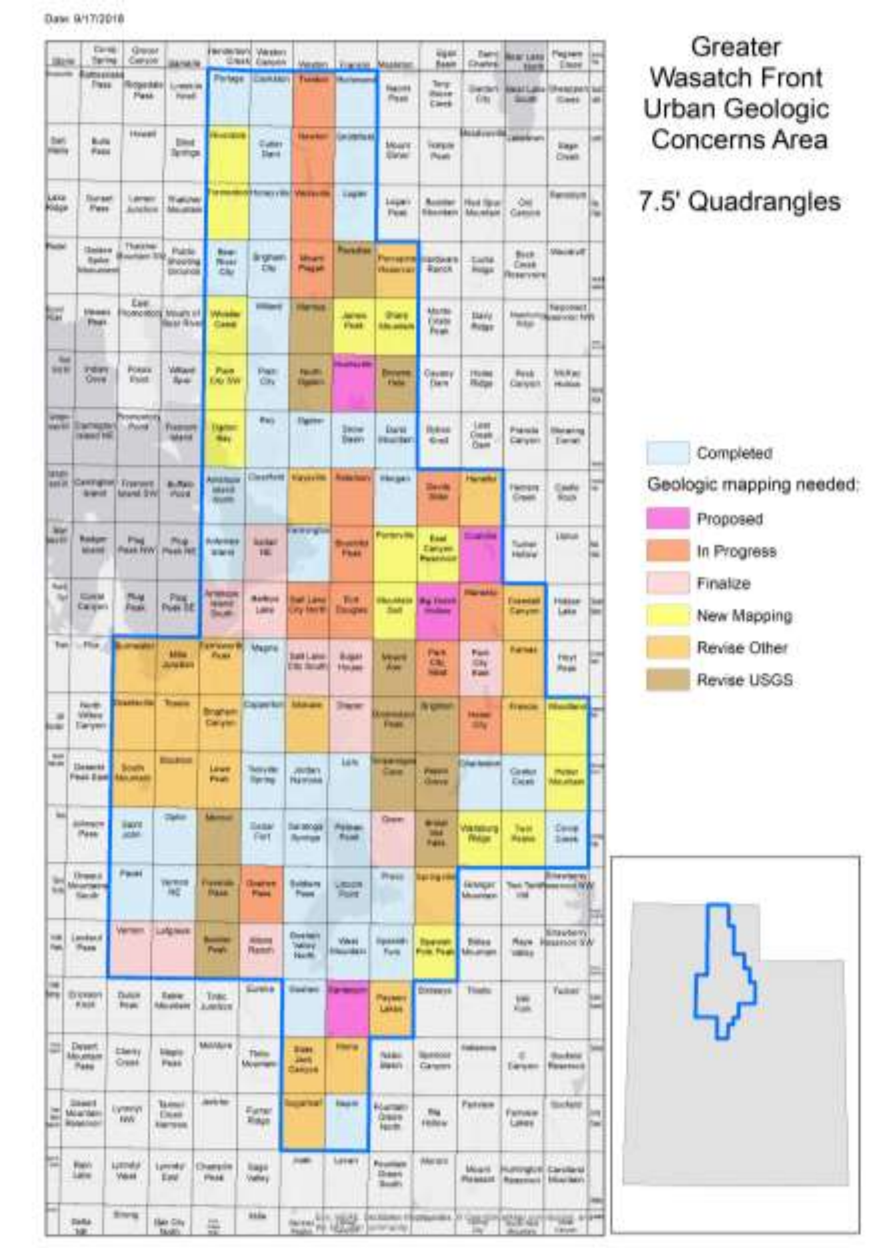
Adam P. McKean and
Zachary W. Anderson
Mapping Geologists with the
Utah Geological Survey

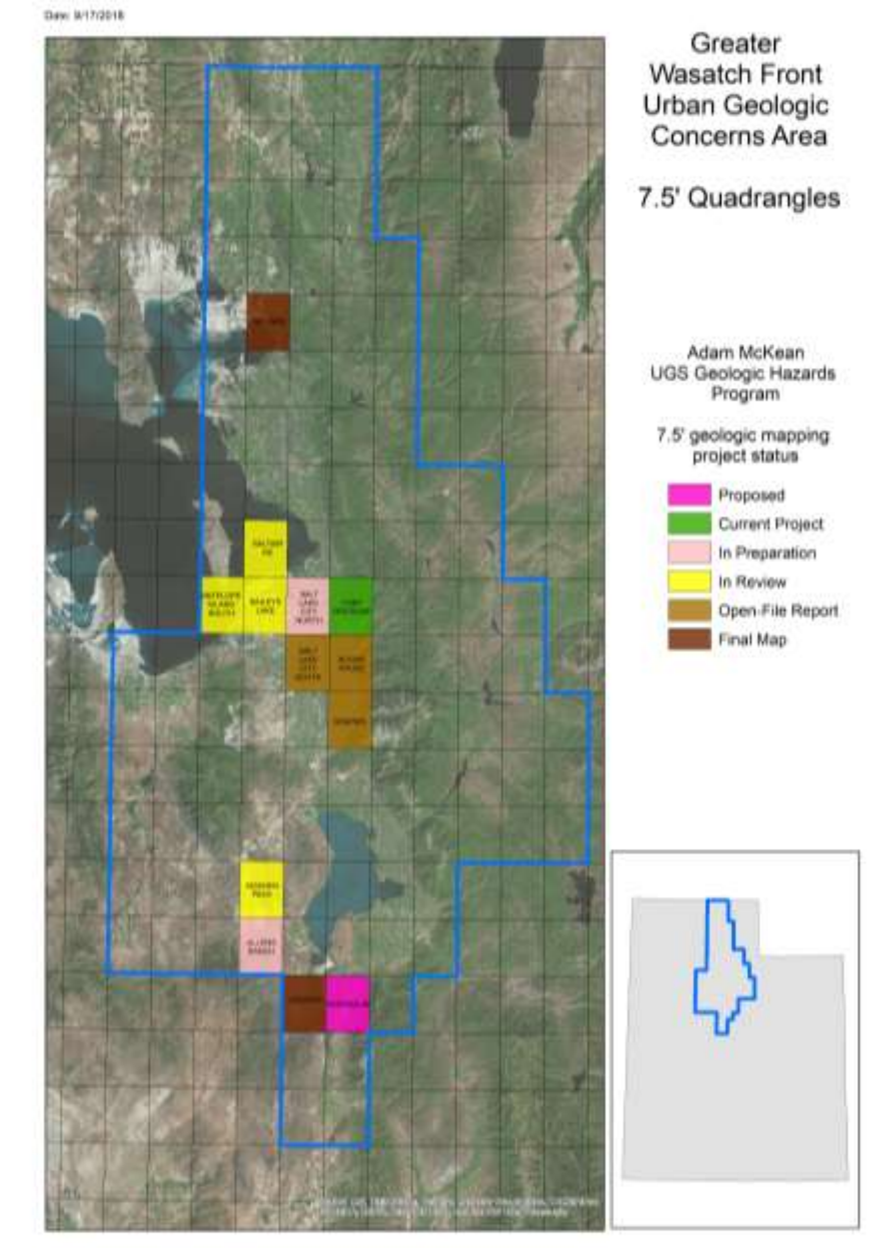
Outline

- New geologic mapping
- New fault names for new and previously mapped faults:
  - Nibley Park Fault
  - Mount Olivet strand of the East Bench fault
  - Foothill fault



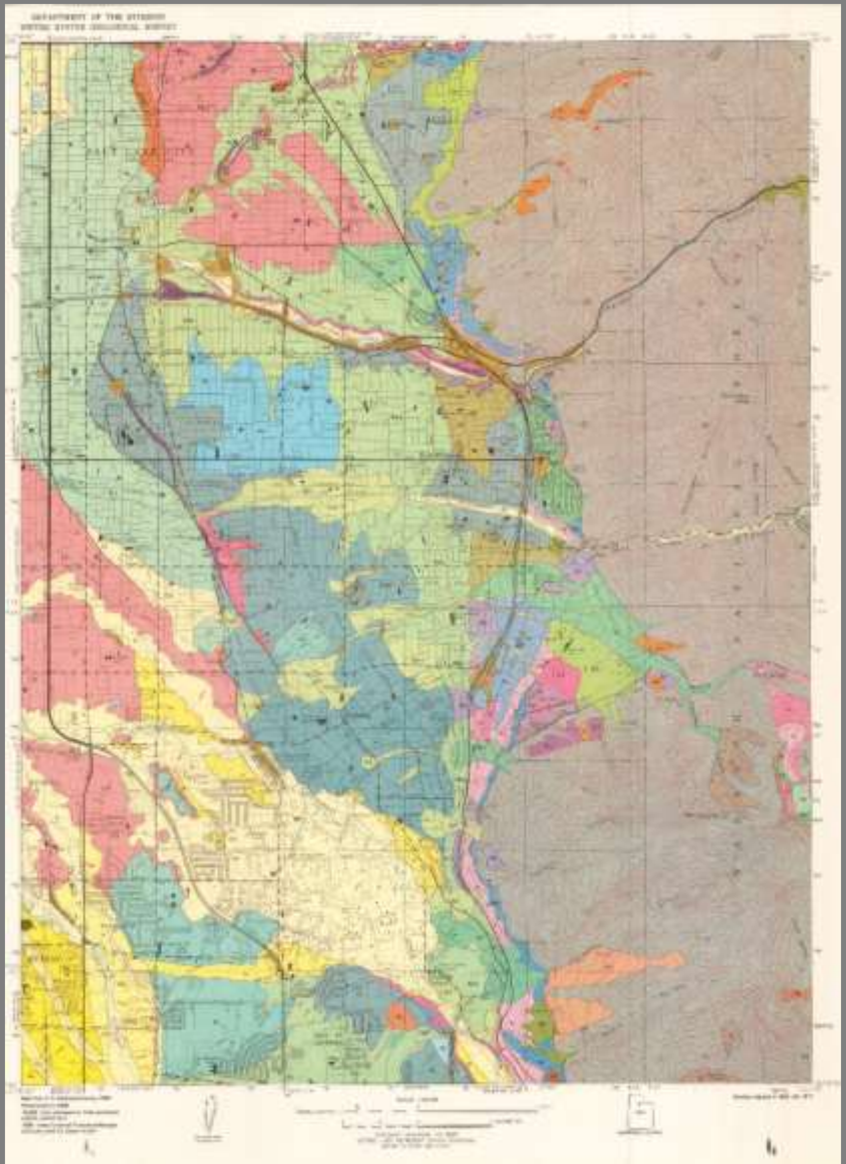
Geologic Mapping in the Wasatch Front





Sugar House 7.5-minute Quadrangle

USGS GQ-380
Crittenden, 1965



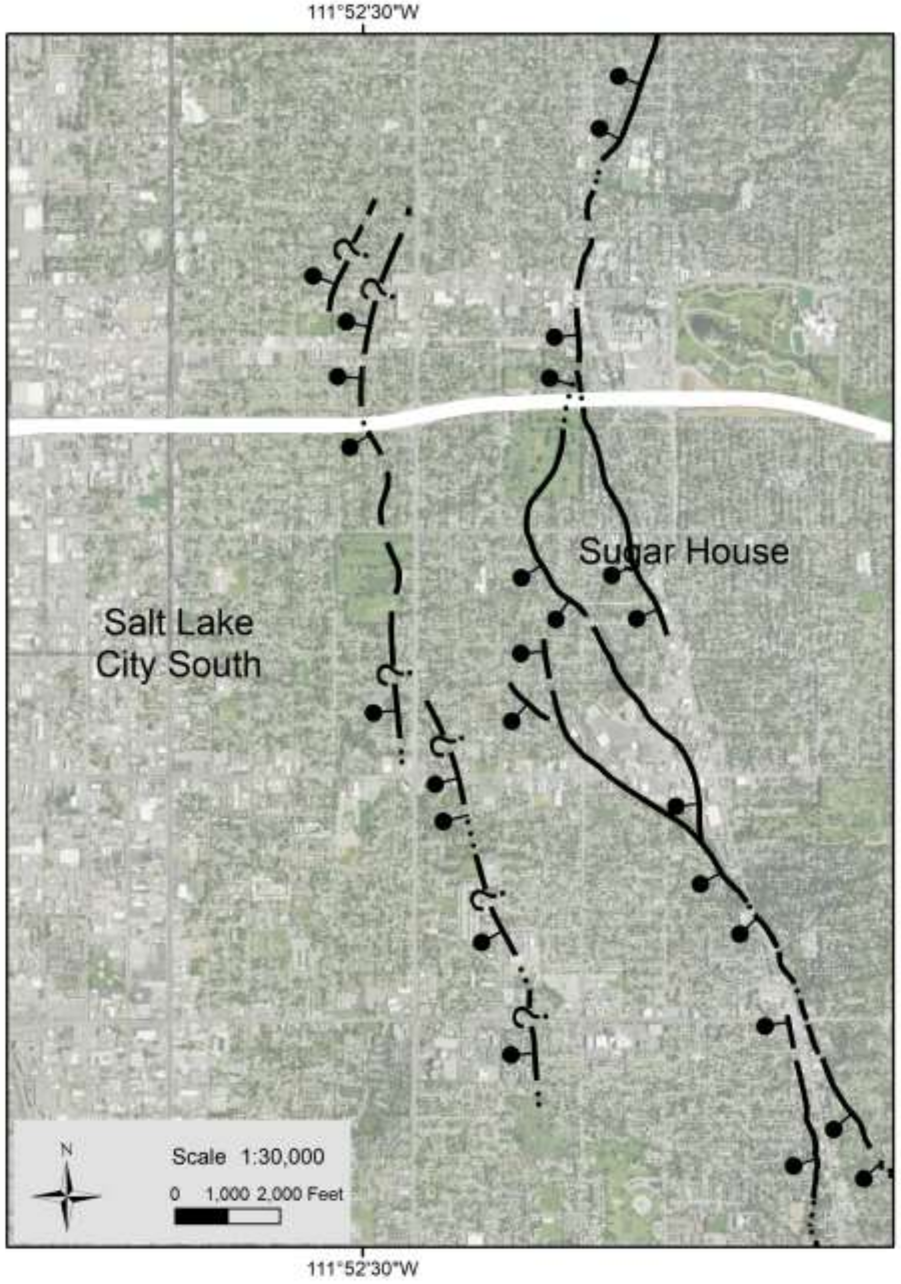
USGS I-766-A
Van Horn, 1972

Nibley Park Fault

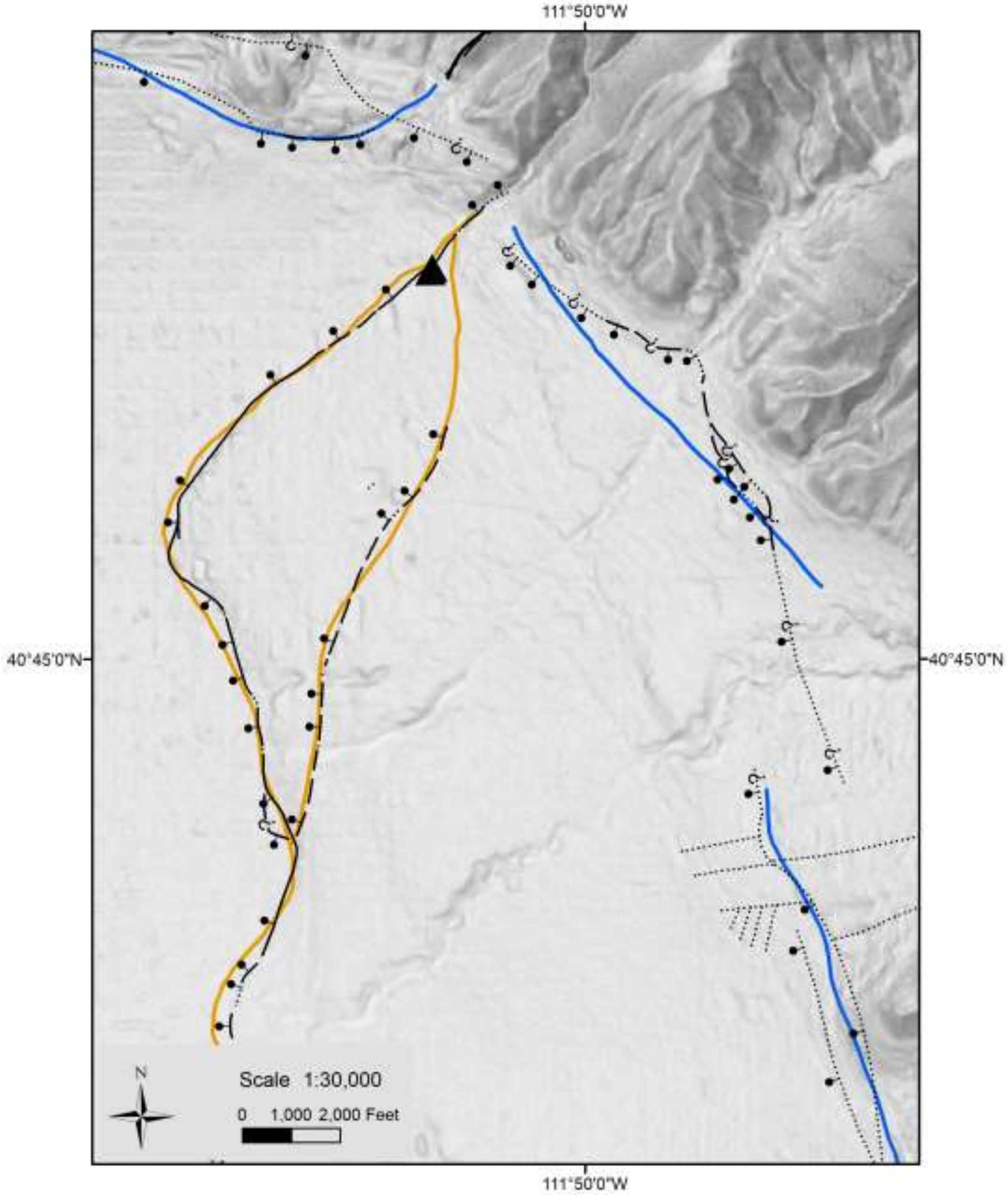
Nibley Park Fault

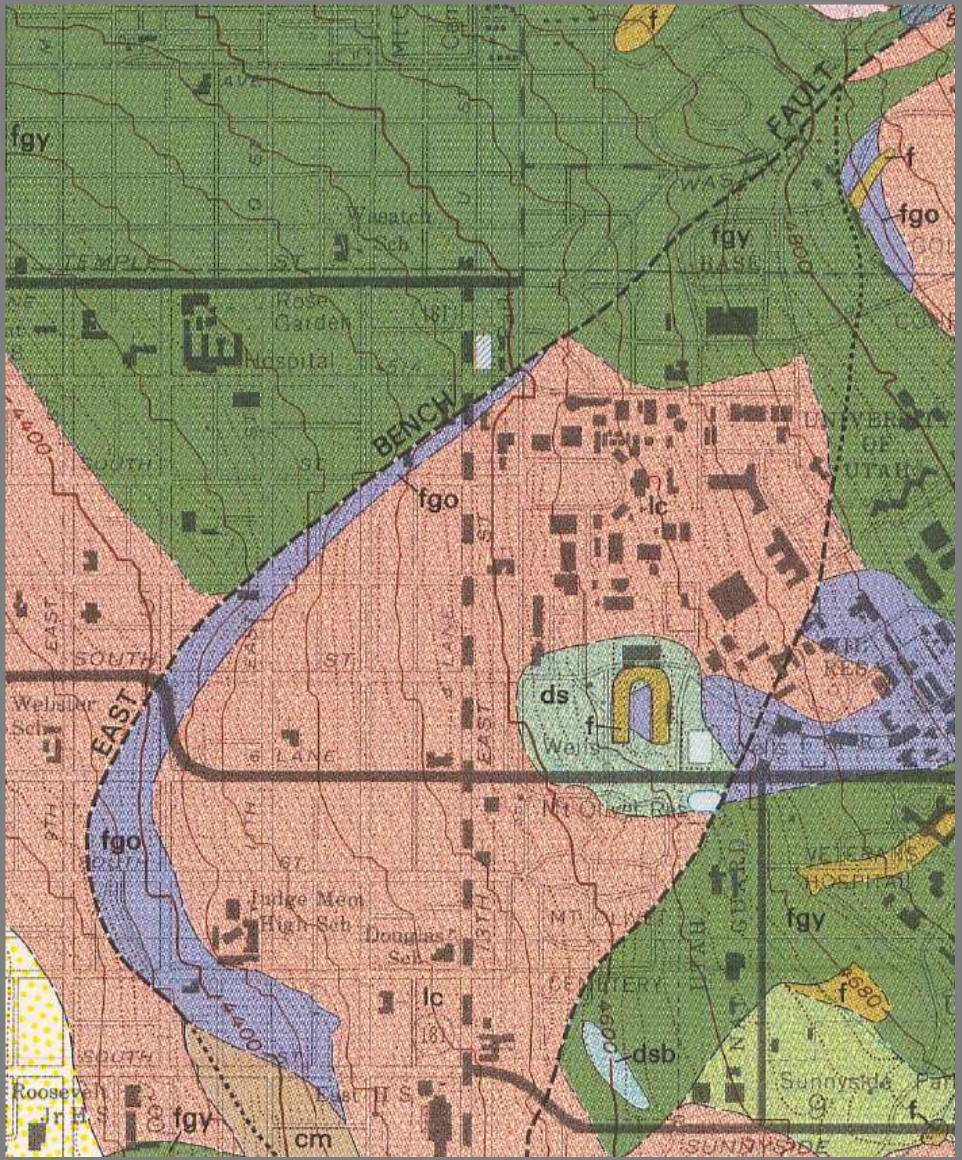
Evidence so far:

- Faint escarpment on aerial photographs
- Down to the west scarp
- Cuts across topography in places
- North south feature, trends parallel to the East Bench fault, between 1500 S and 3900 S
- Spring on the USGS topographic base map where it goes through Nibley Park
- Clearly visible on 0.5 meter lidar imagery
- Profiles from 0.5 meter lidar across the feature show scraps between 5 and 10 feet tall
- Scarp cut by alluvial channels in places, indicating it is older than the Holocene channels
- Displaces post-Bonneville alluvial fans OR it could be an older pre-Bonneville fault draped by Bonneville sediments and post-Bonneville alluvial fan fines



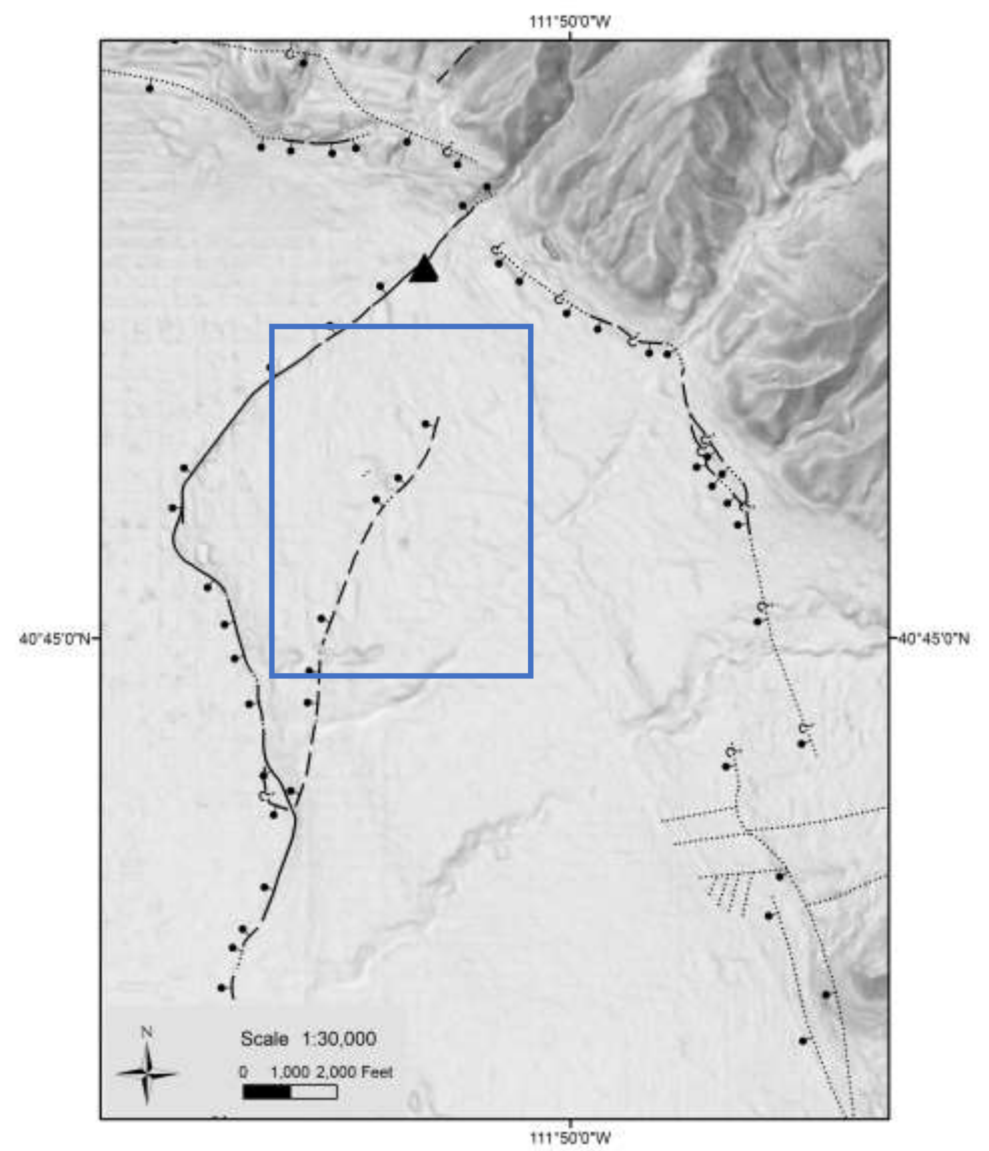
Mount Olivet Strand of the East Bench Fault

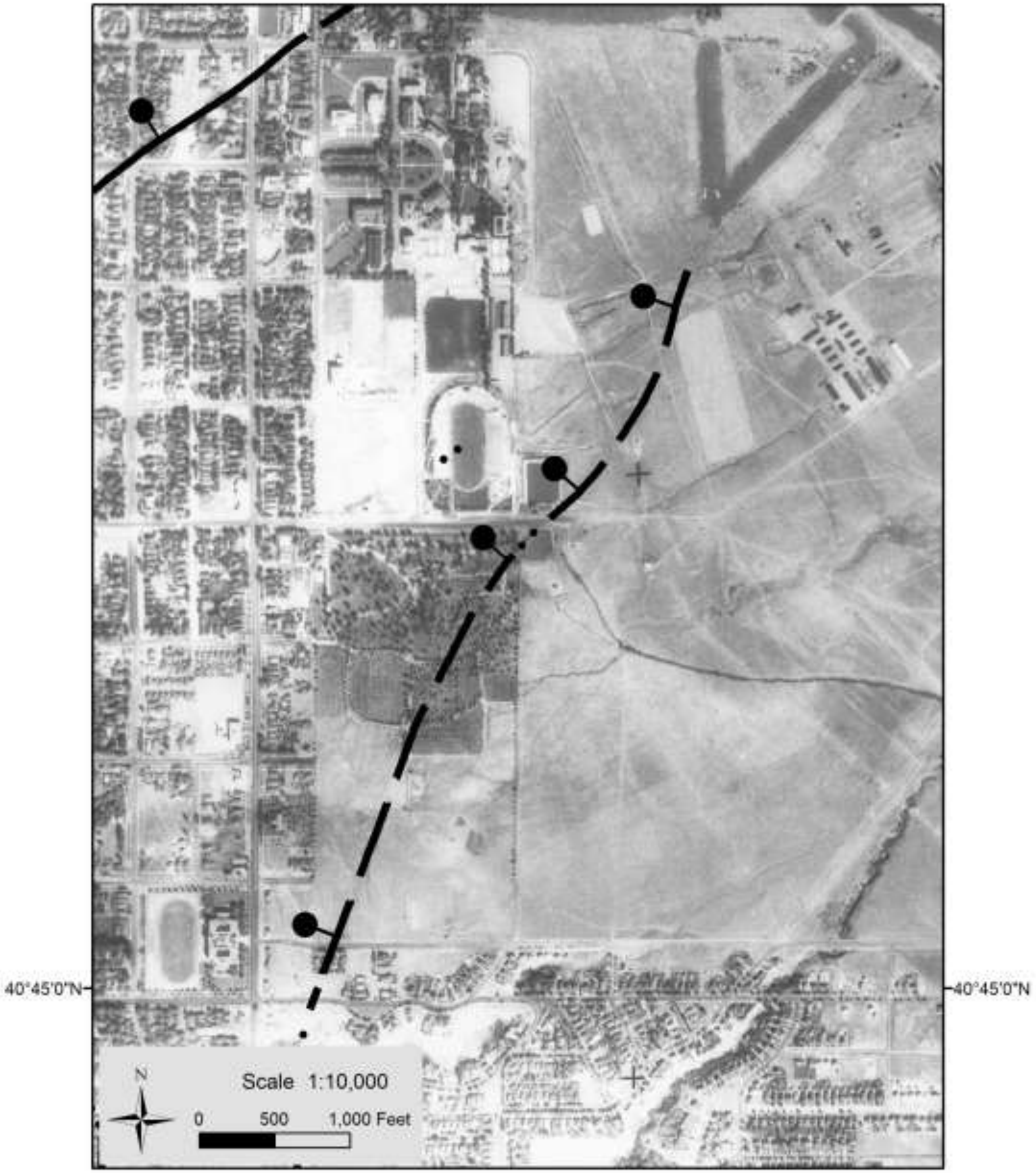




Van Horn and Crittenden, 1987

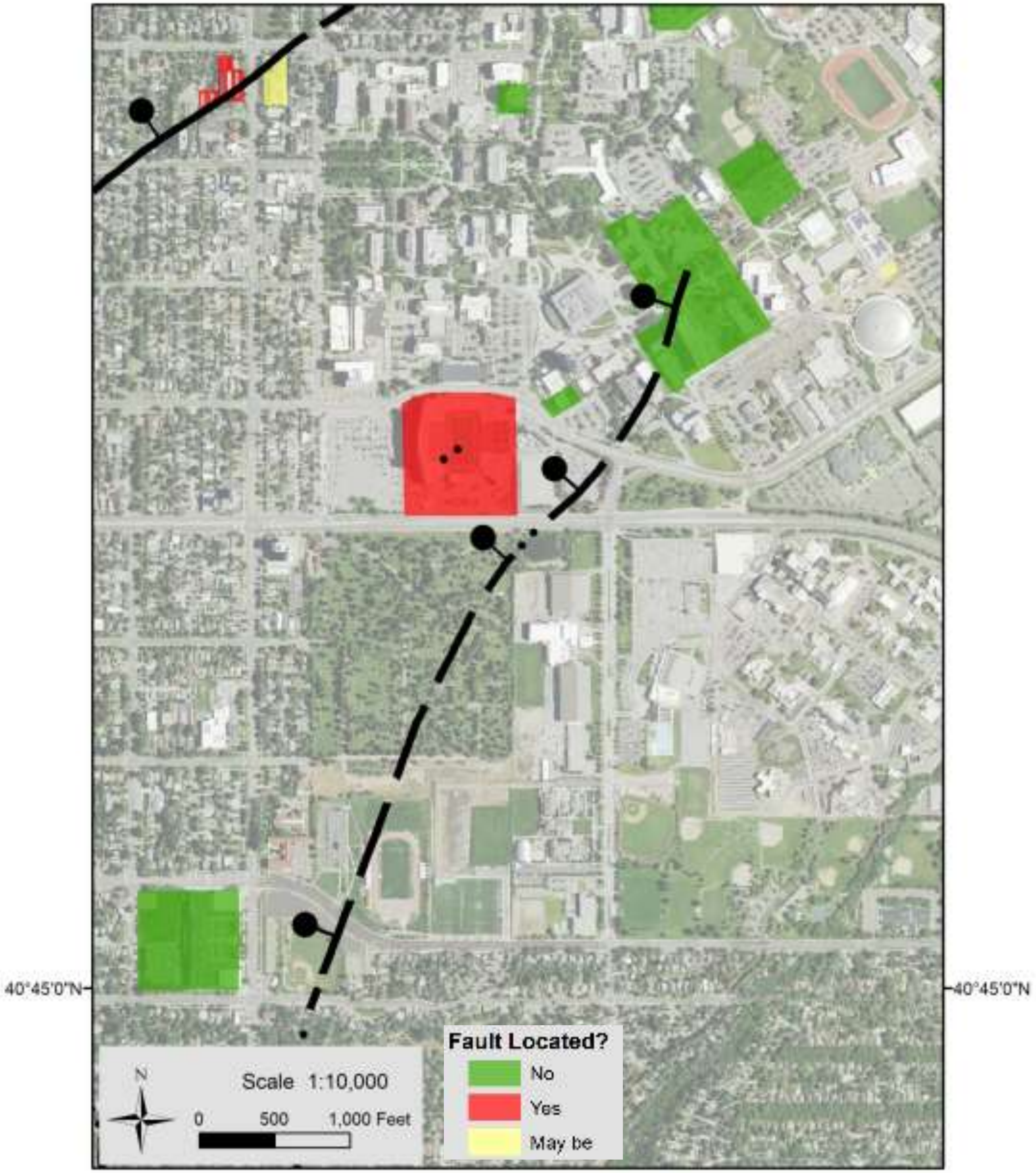
Mount Olivet Strand of the East Bench Fault

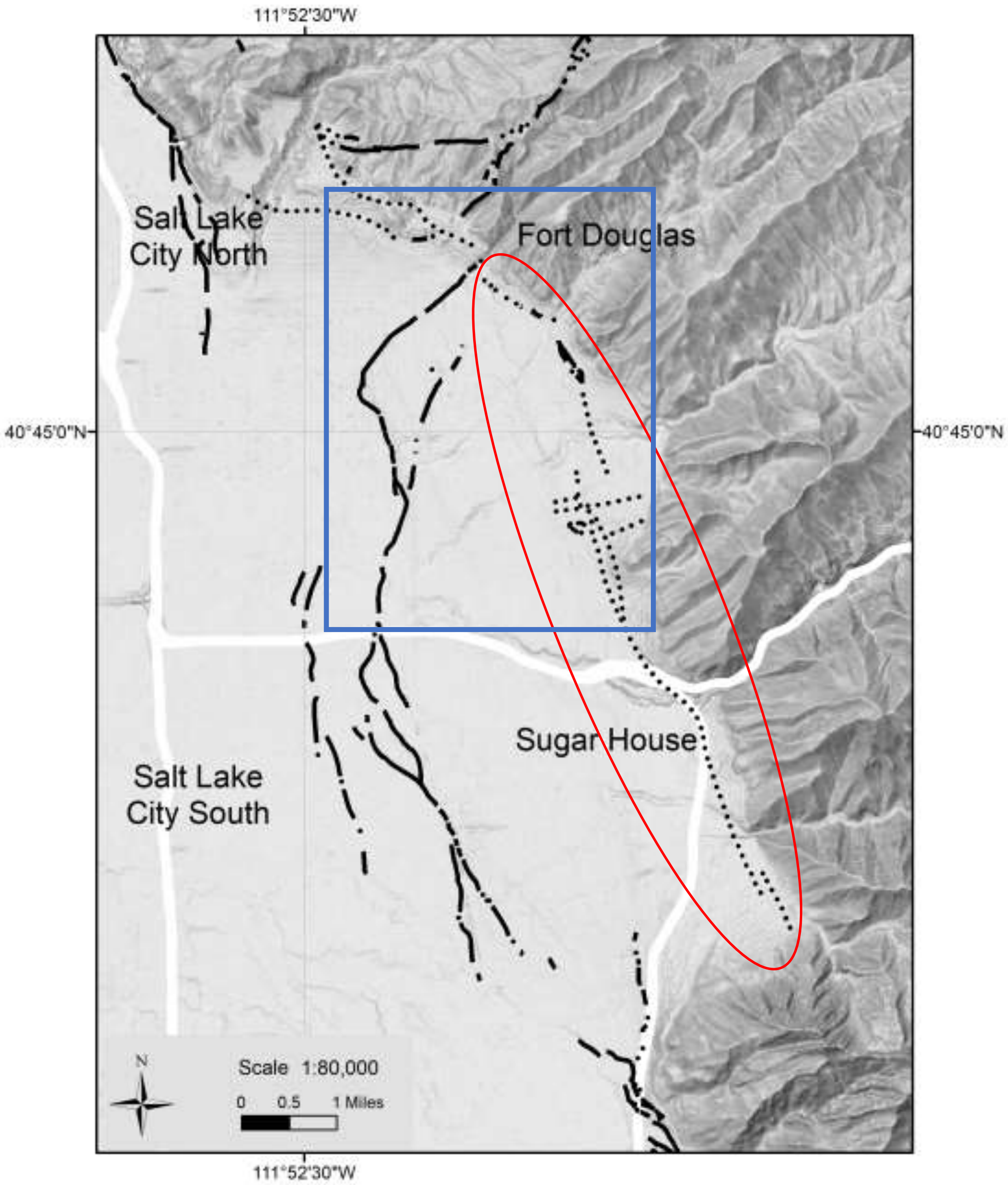




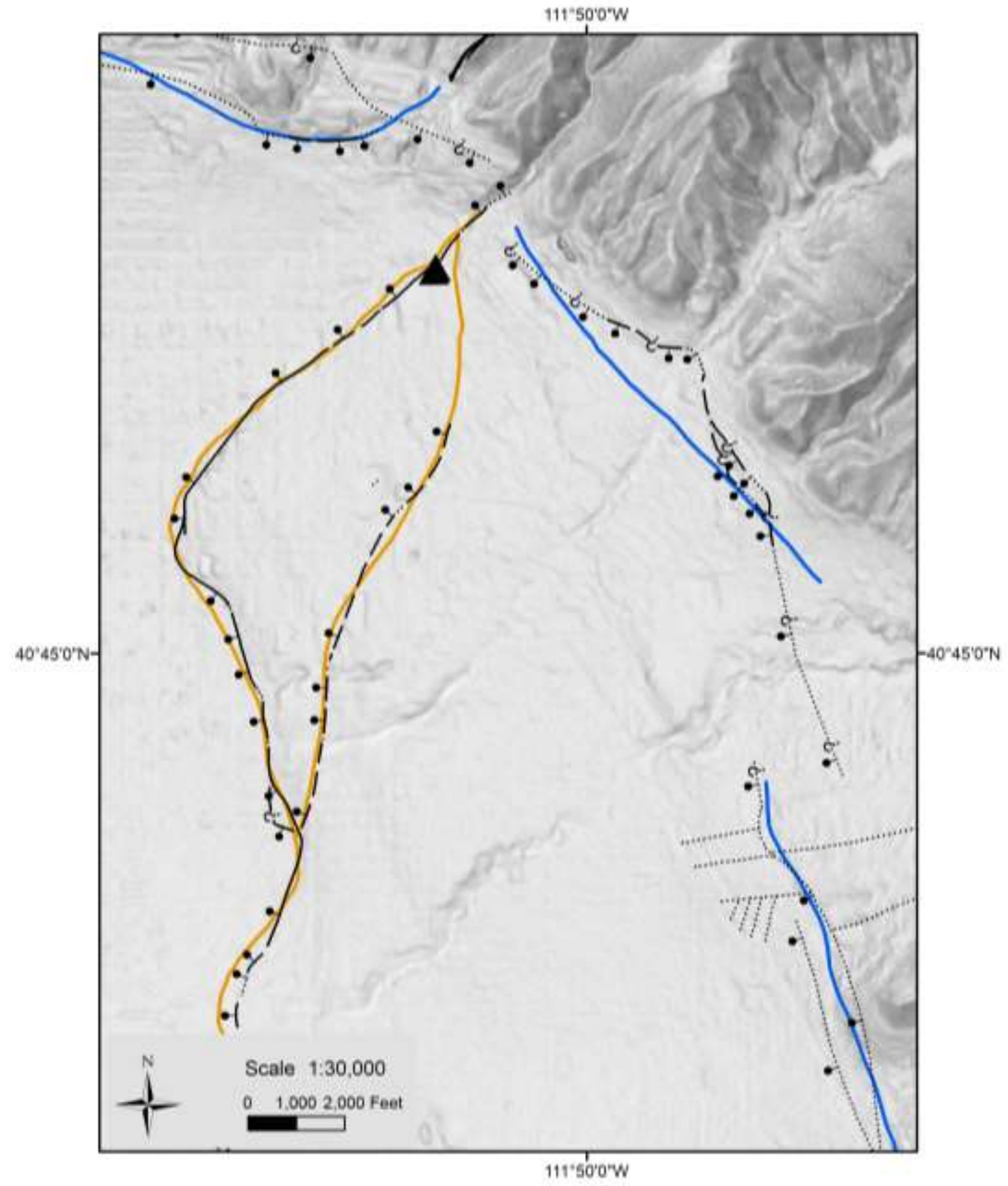
Mount Olivet Strand of the East Bench Fault

- Scarp on 1937 aerial photographs
- Down to the west scarp
- Cuts across topography
- Seismically imaged by Lee Liberty in the Mount Olivet Cemetery (700 S.) and on 800 S.
- Displaces Bonneville deposits but not youngest Holocene alluvium
- Consultant Surface Fault Rupture Investigations show it does not continue through the University of Utah campus





Foothill Fault



Foothill Fault

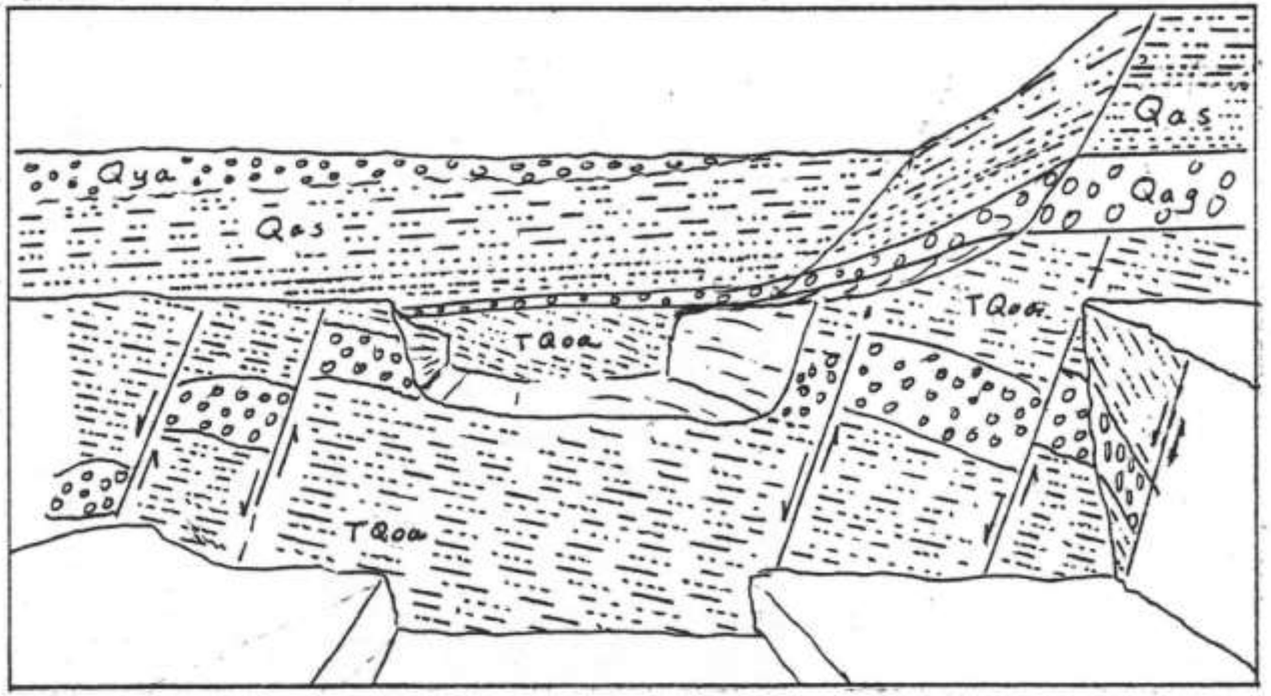
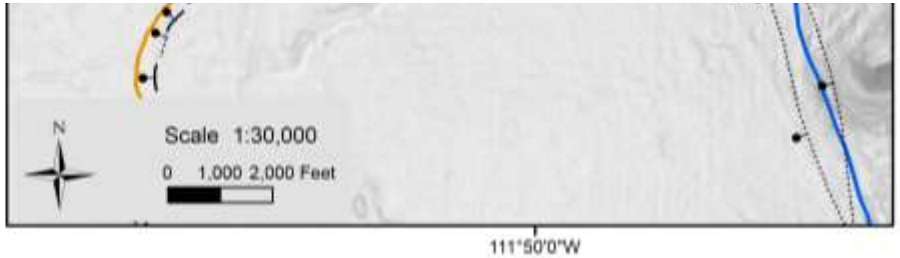
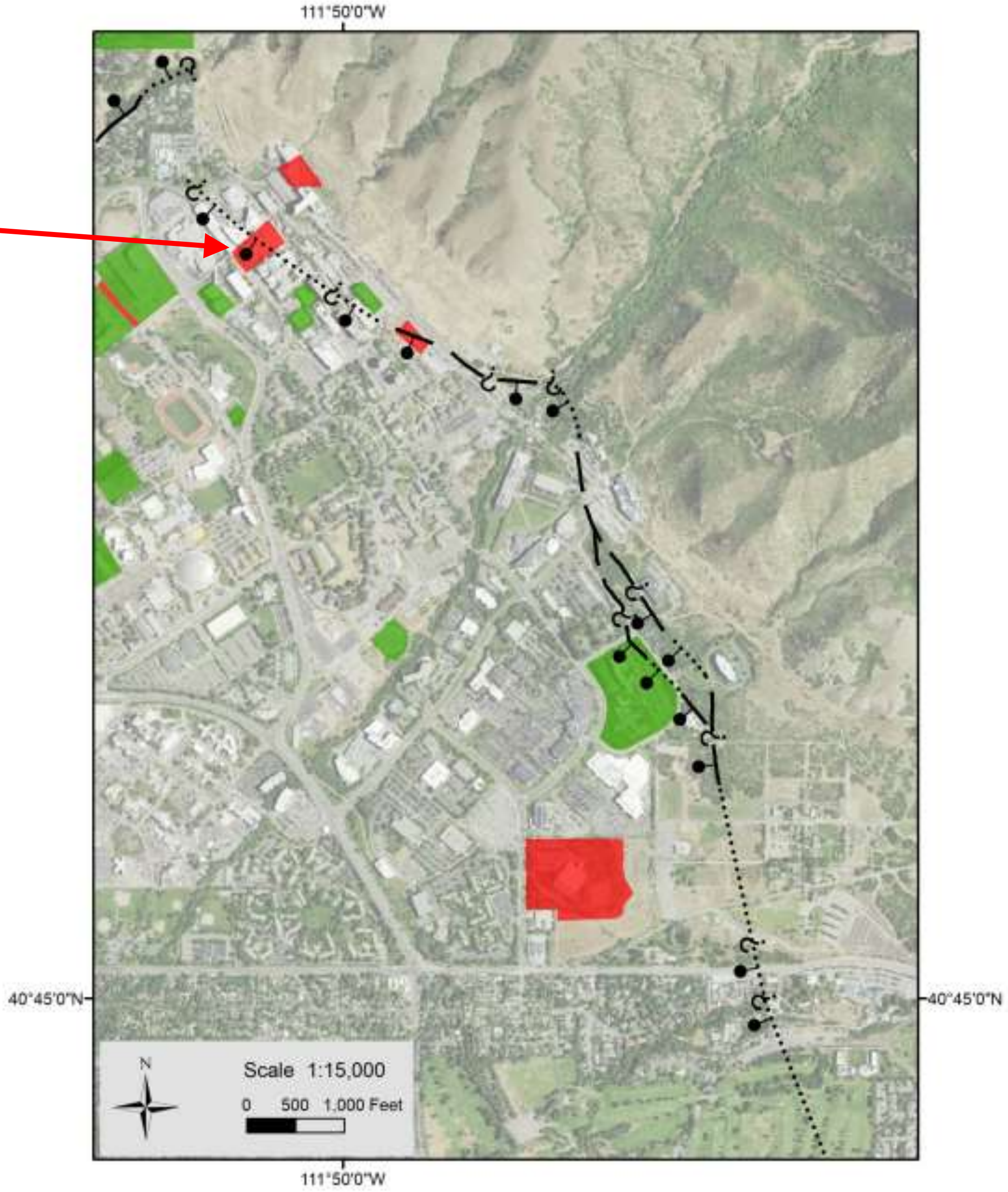


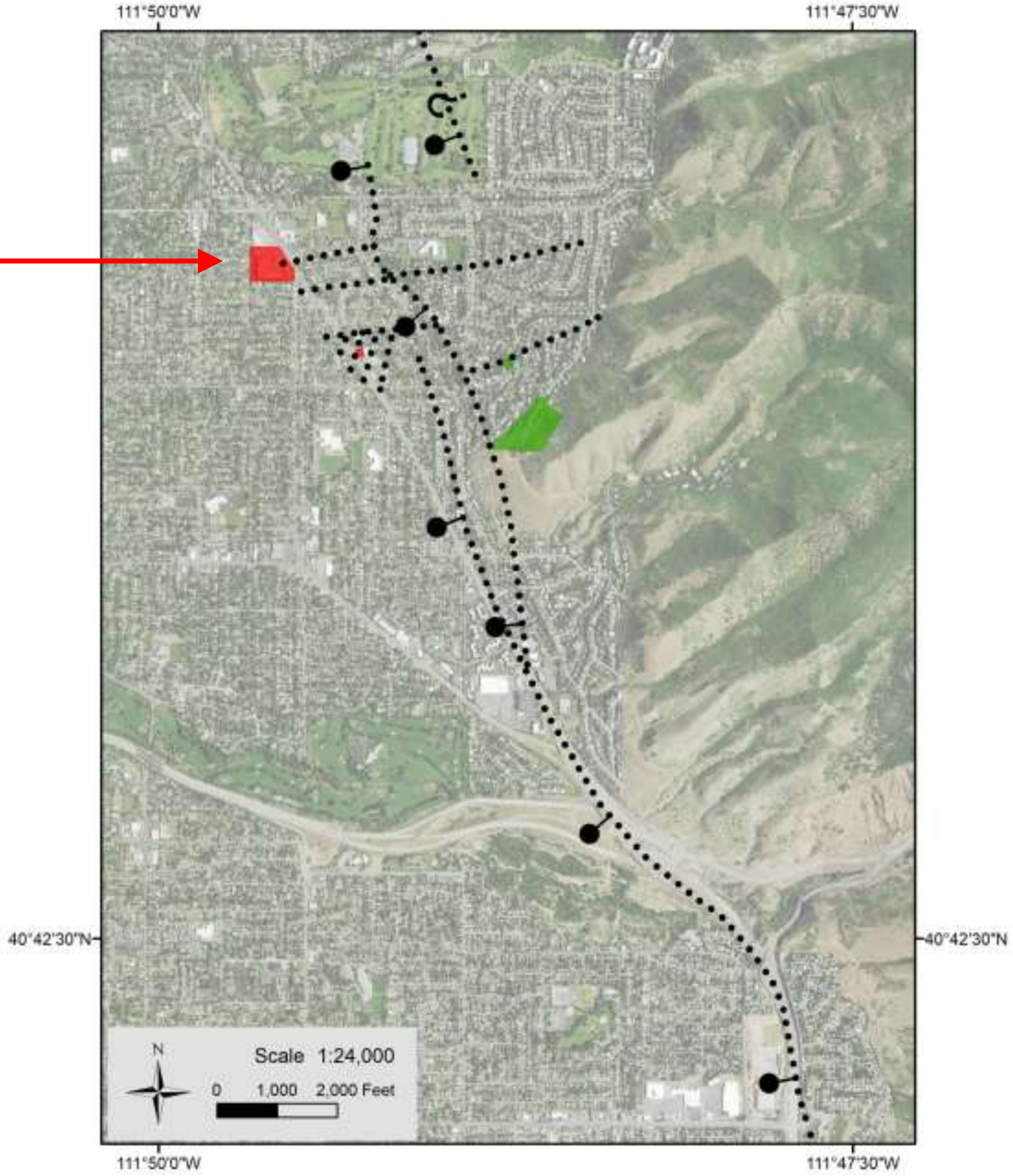
Figure 10. University Hospital, Site 9, Location UH5032; sketch from photograph to show faulted old alluvium (TQoa) beneath undisturbed Lake Bonneville transgressive gravel (Qag), offshore sand and silt (Qas), and younger alluvium (Qya); view northwestward in the corner of the lower level of the excavation; see Figure 7 for location, scale, and symbols.

Everitt, 1980



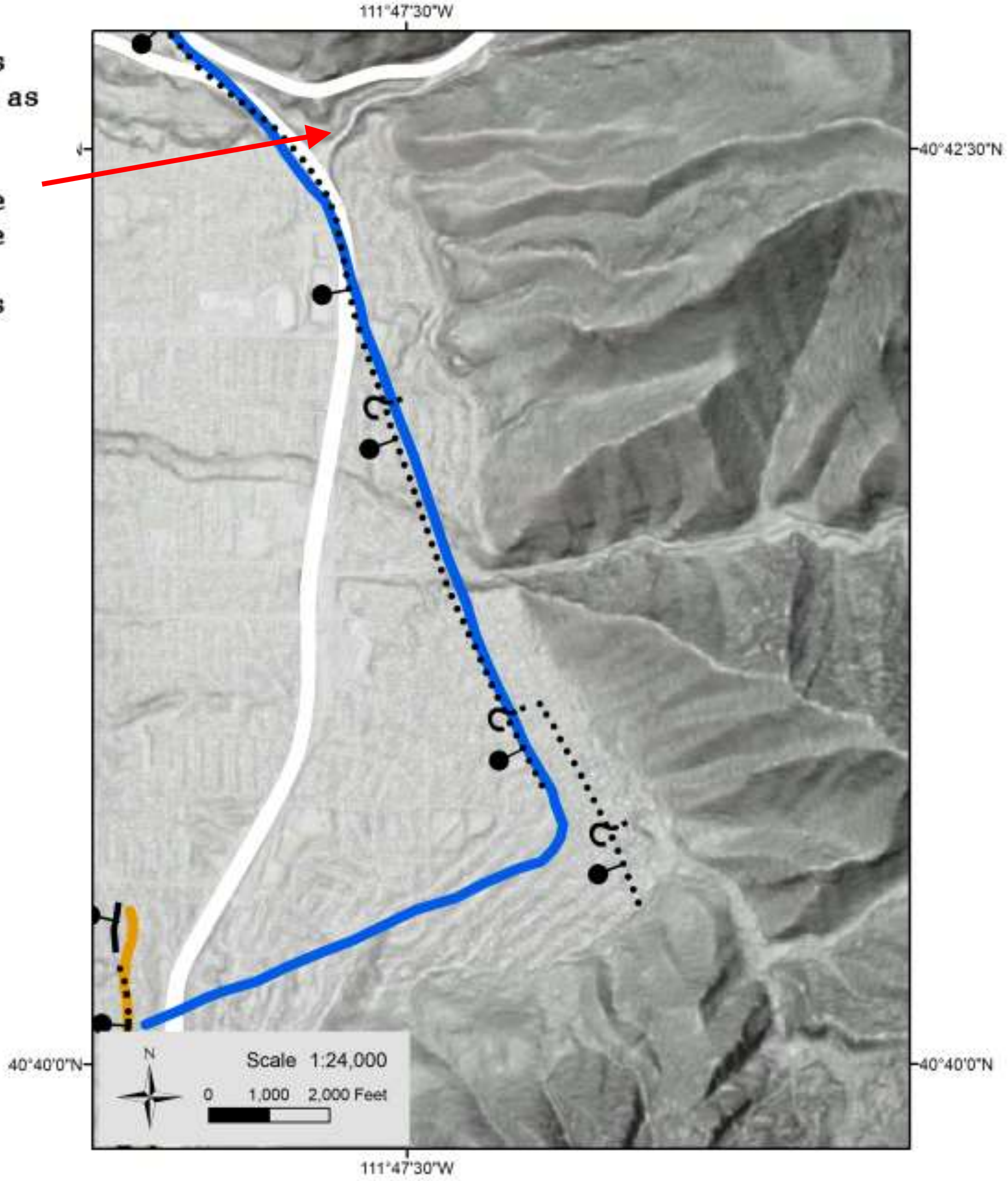


Foothill Fault



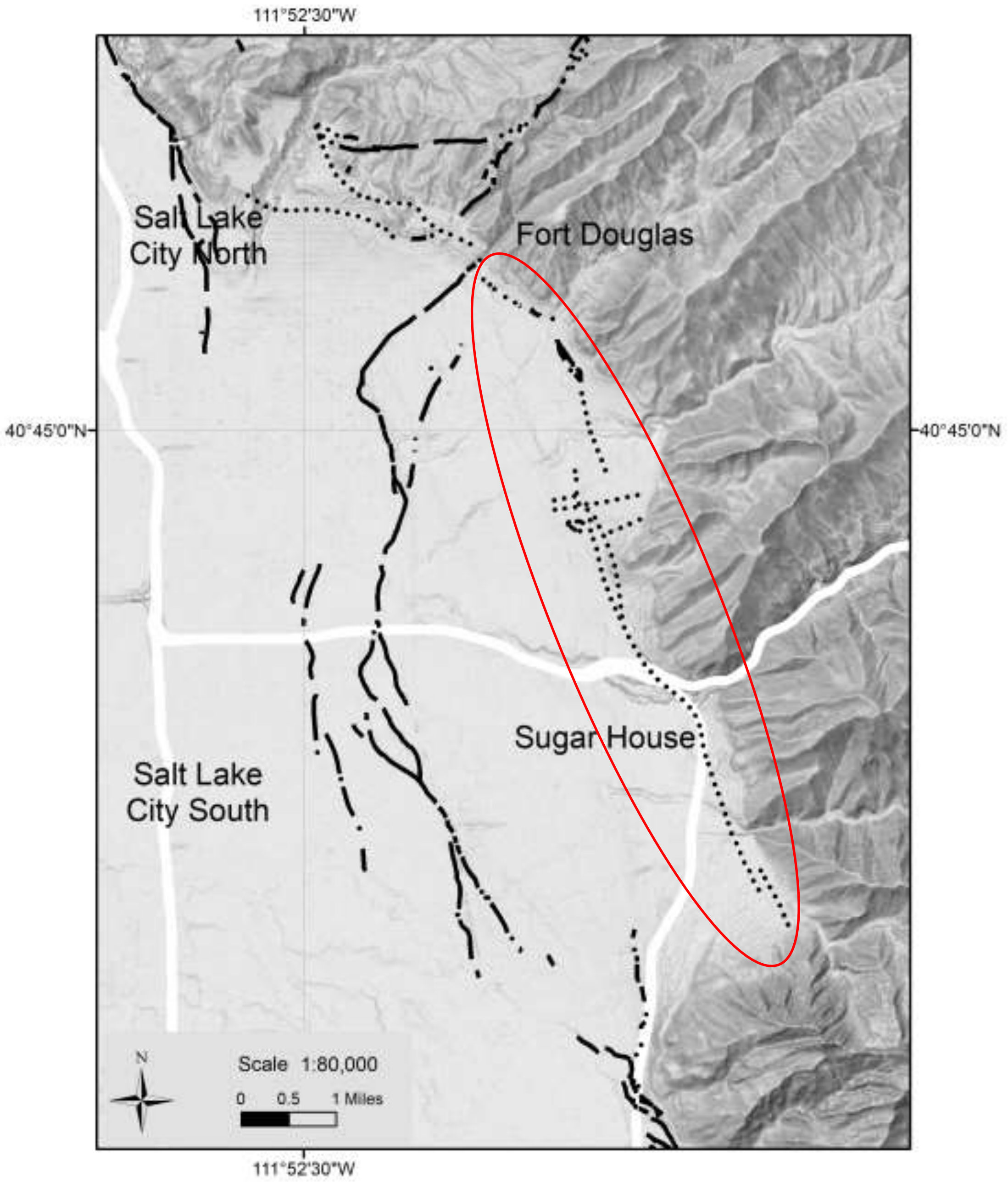
Fault at the mouth of Parleys Canyon

Van Horn (1972a) shows a short fault just south of the mouth of Parleys Canyon that displaces deposits of the last cycle of Lake Bonneville as well as alluvium of post-Lake Bonneville age. We have not found evidence of offset along the fault in deposits of the Bonneville lake cycle; however, evenly bedded fine sand, silt, and clay of the Little Valley lake cycle east of the fault (not shown at this scale) dip about 30° to the southwest. Because the dip is too steep to be an original bedding attitude for sediment this fine grained, the deposits probably were tilted following their deposition. This tiliting may be related to faulting that occurred between the Little Valley and Bonneville lake cycles. (Scott and Shroba, 1985)



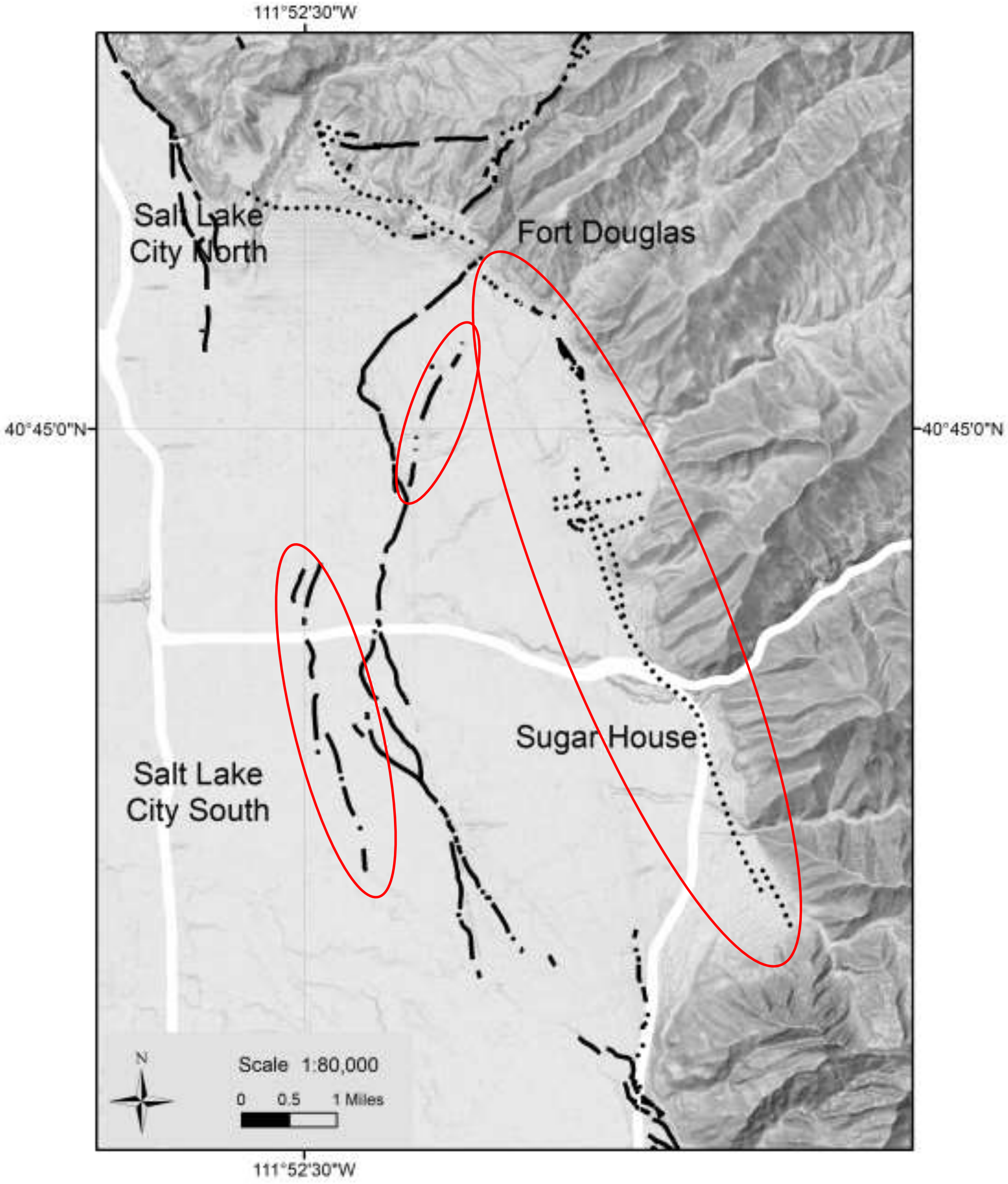
Foothill Fault

- Scarp on 1937 aerial photographs near Red Butte Canyon and Georges Hollow
- Down to the west scarp
- Shallow bedrock on footwall of the fault
- Drill hole data shows a bedrock pediment between Foothill and East Bench fault (100s of feet depth)
- May offset younger deposits near U. Hospital cooling plant
- Consultant Surface Fault Rupture Investigations show it offsets pre-Bonneville deposits
- Foothill fault may continue to the north of the East Bench fault

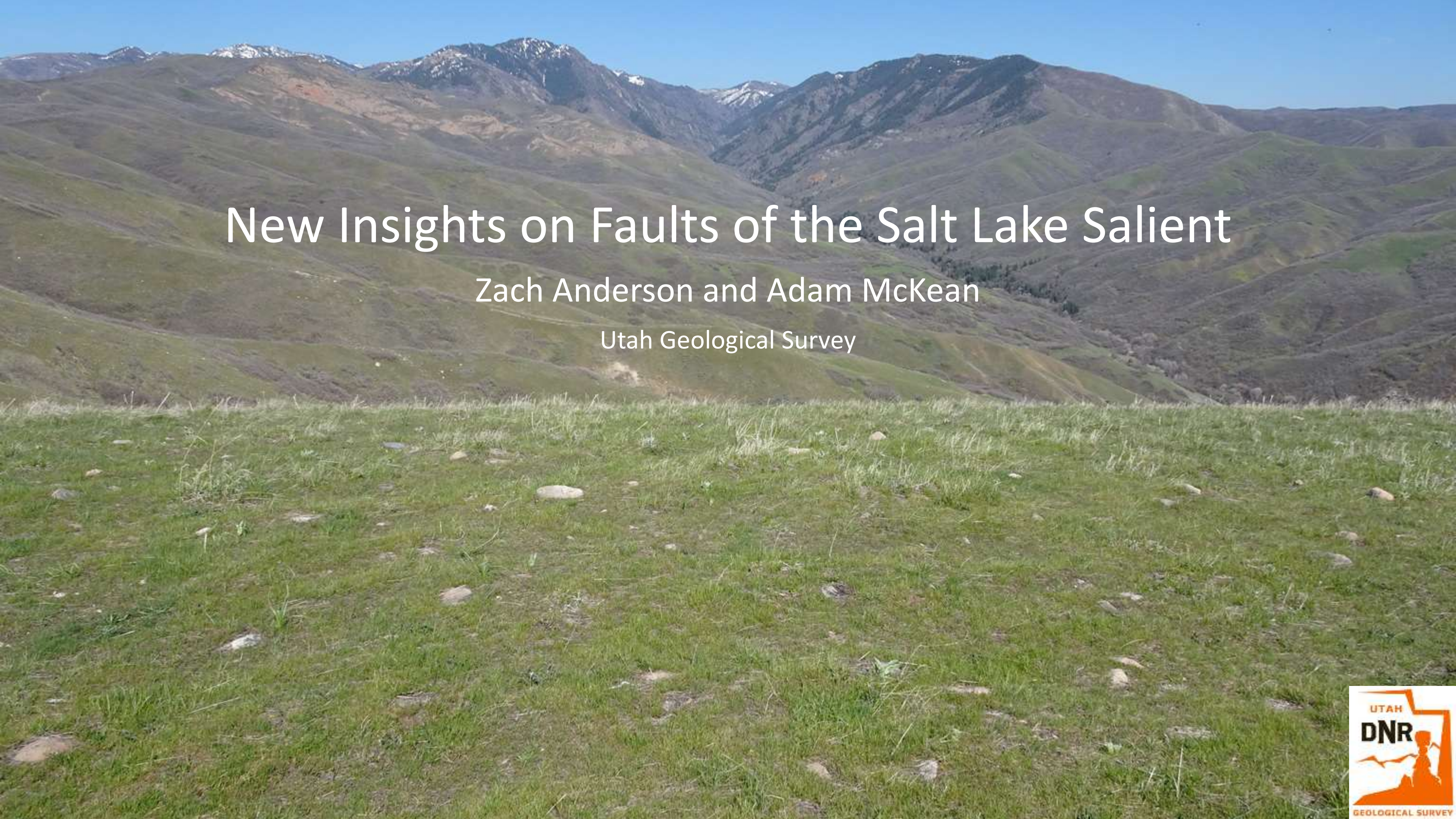


In Summary

- Three new fault names for new and previously mapped faults:
  - Nibley Park Fault
  - Mount Olivet strand of the East Bench fault
  - Foothill fault
- Simplification of the Hospital, Cooling Plant, and basin bounding fault into one, the Foothill fault



Thank you

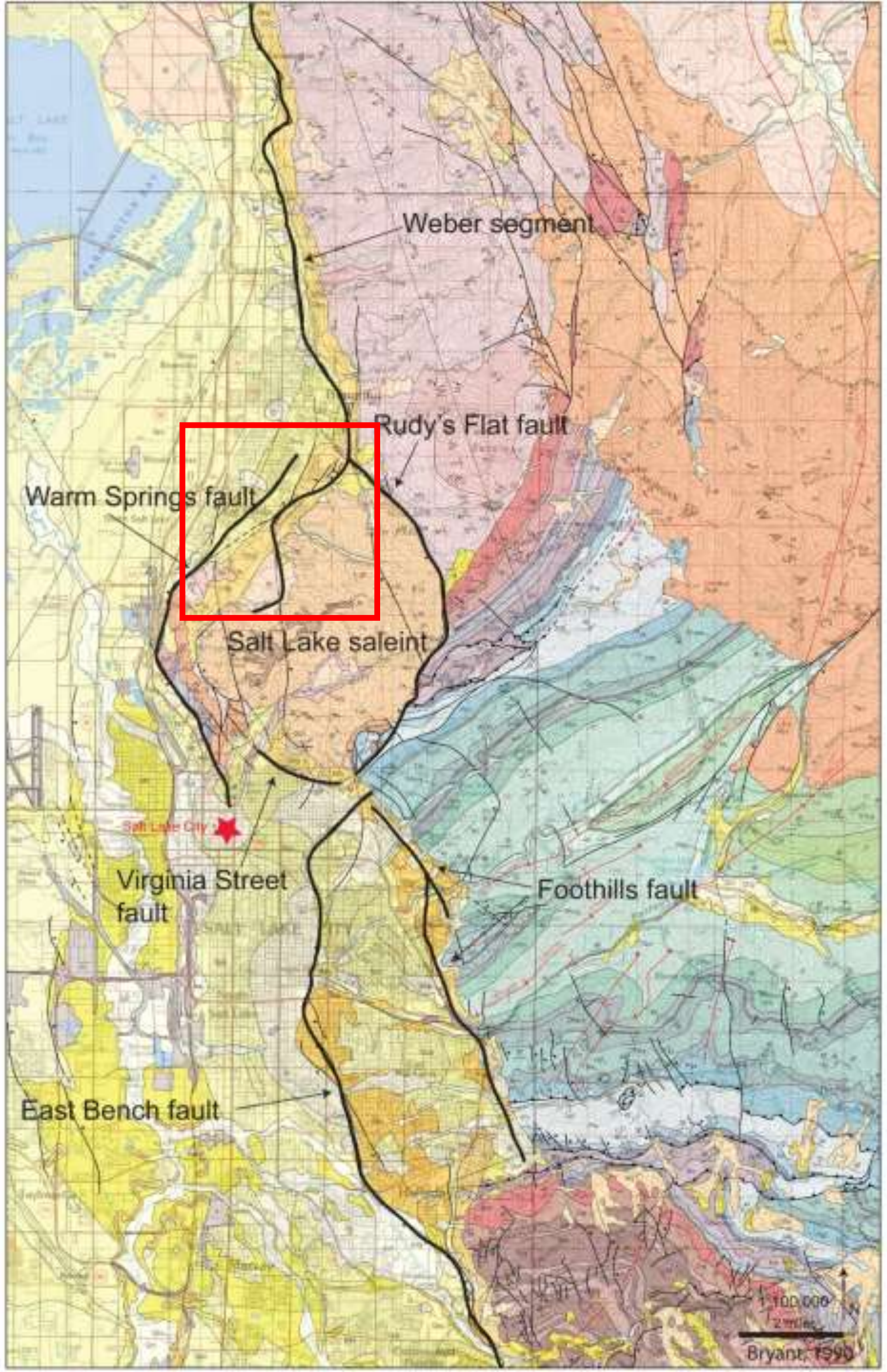


New Insights on Faults of the Salt Lake Salient

Zach Anderson and Adam McKean

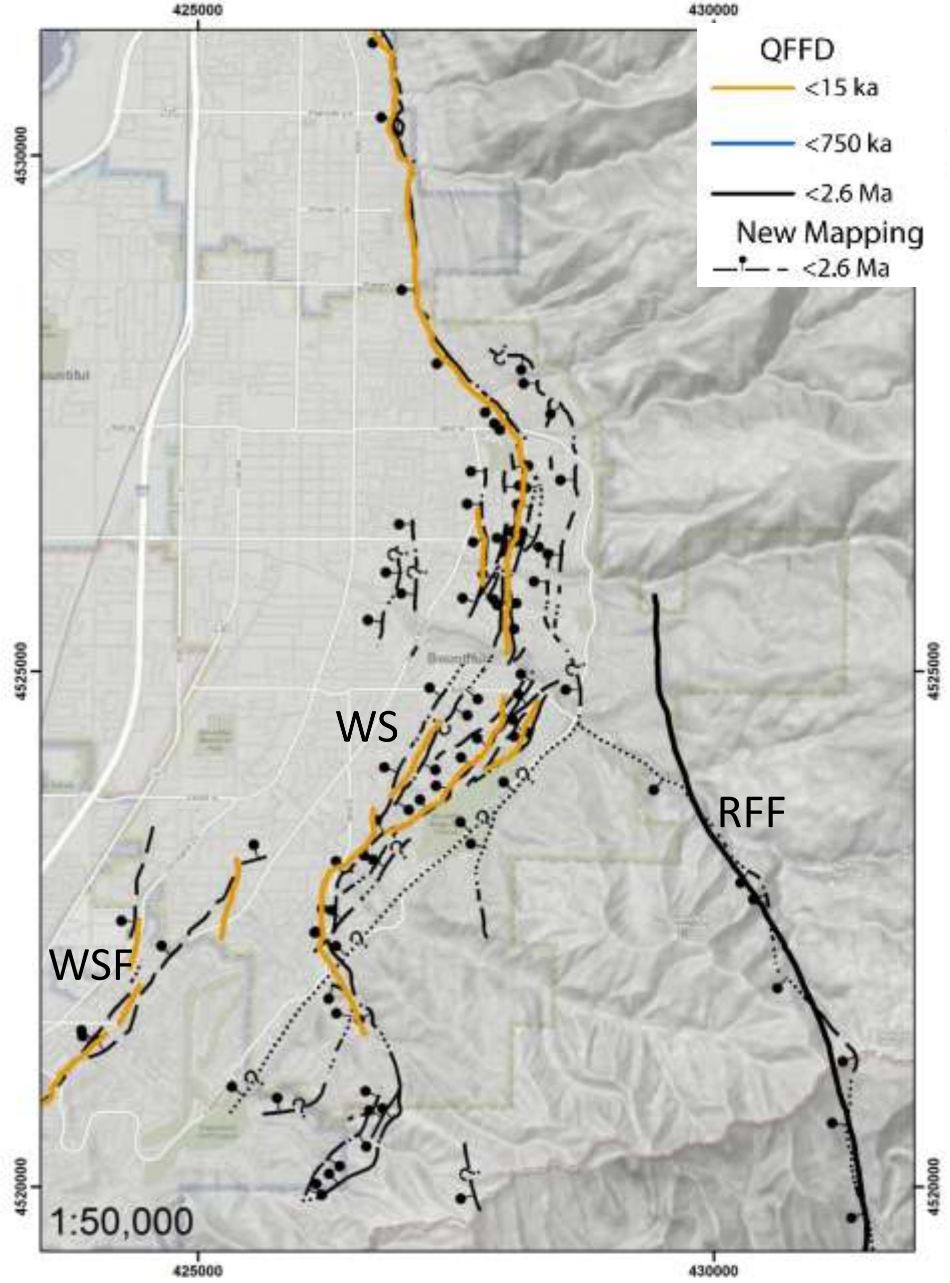
Utah Geological Survey

Salt Lake Salient Faults and Geology

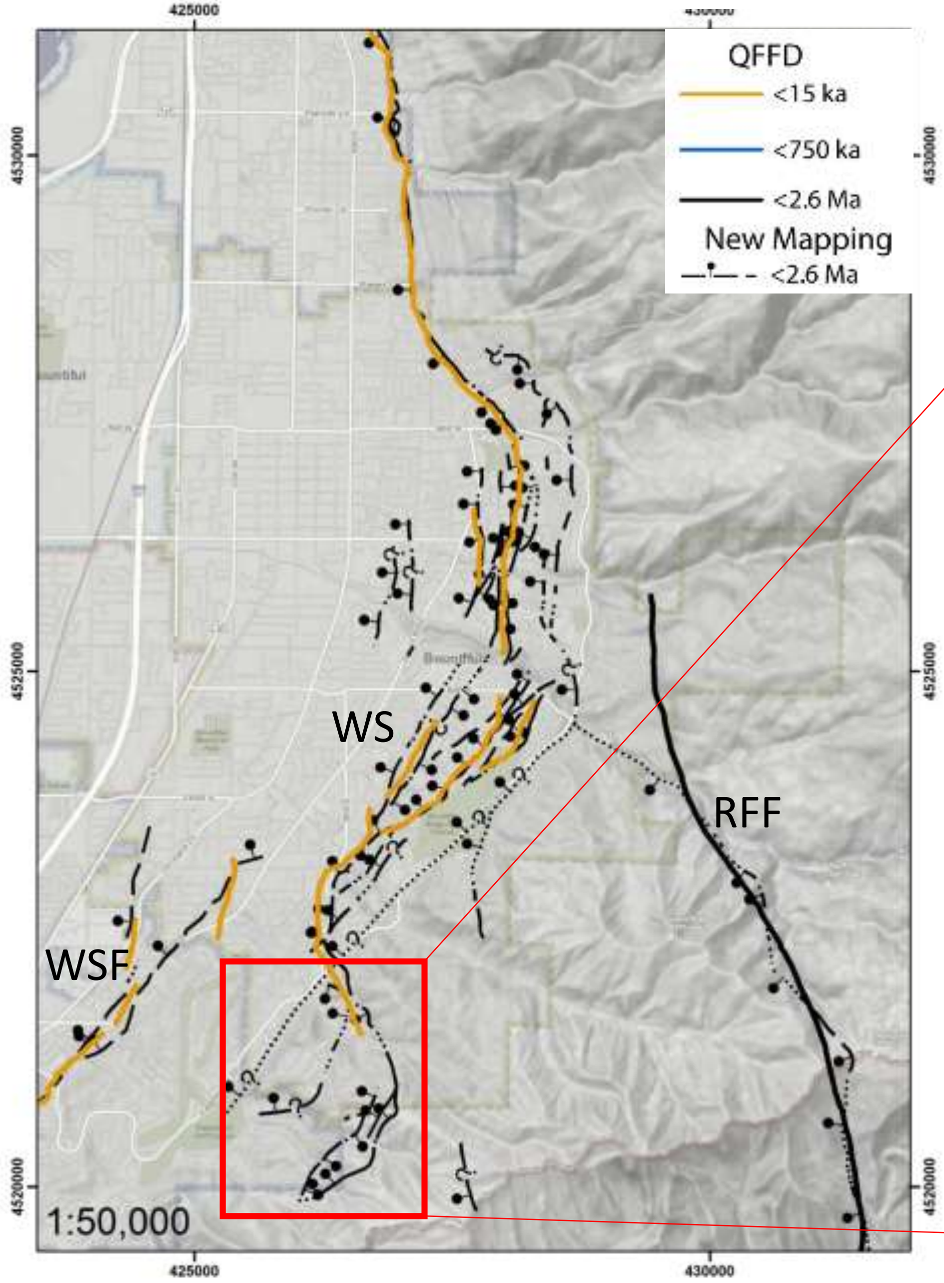


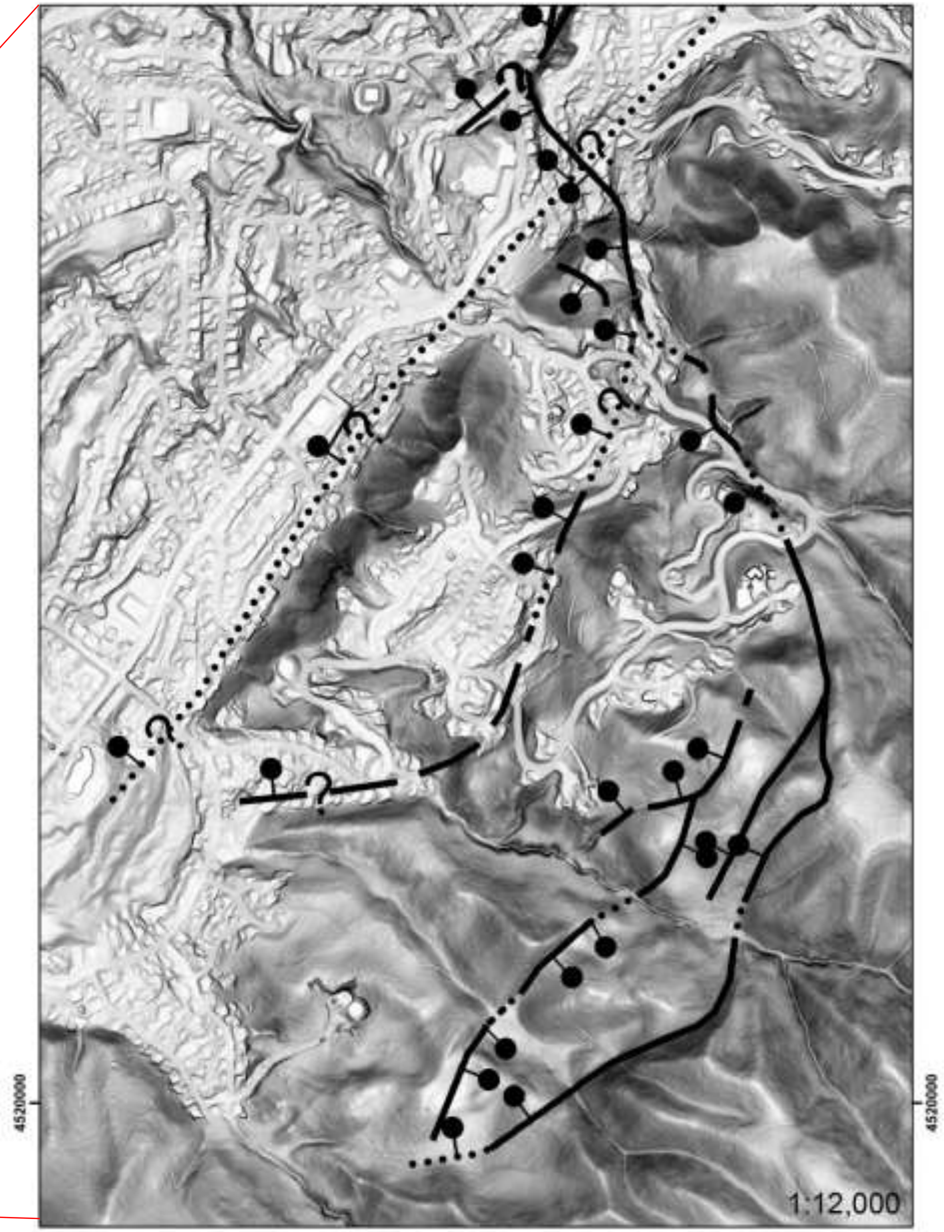
- Highlight new mapping of Quaternary faults around the Salt Lake salient
  - Show evidence for Quaternary movement
- Address structural linkages of fault segments
  - Implication for fault rupture spillover and earthquake hazard assessment
- Mapping-based observations and hypotheses

Southern end of Weber segment



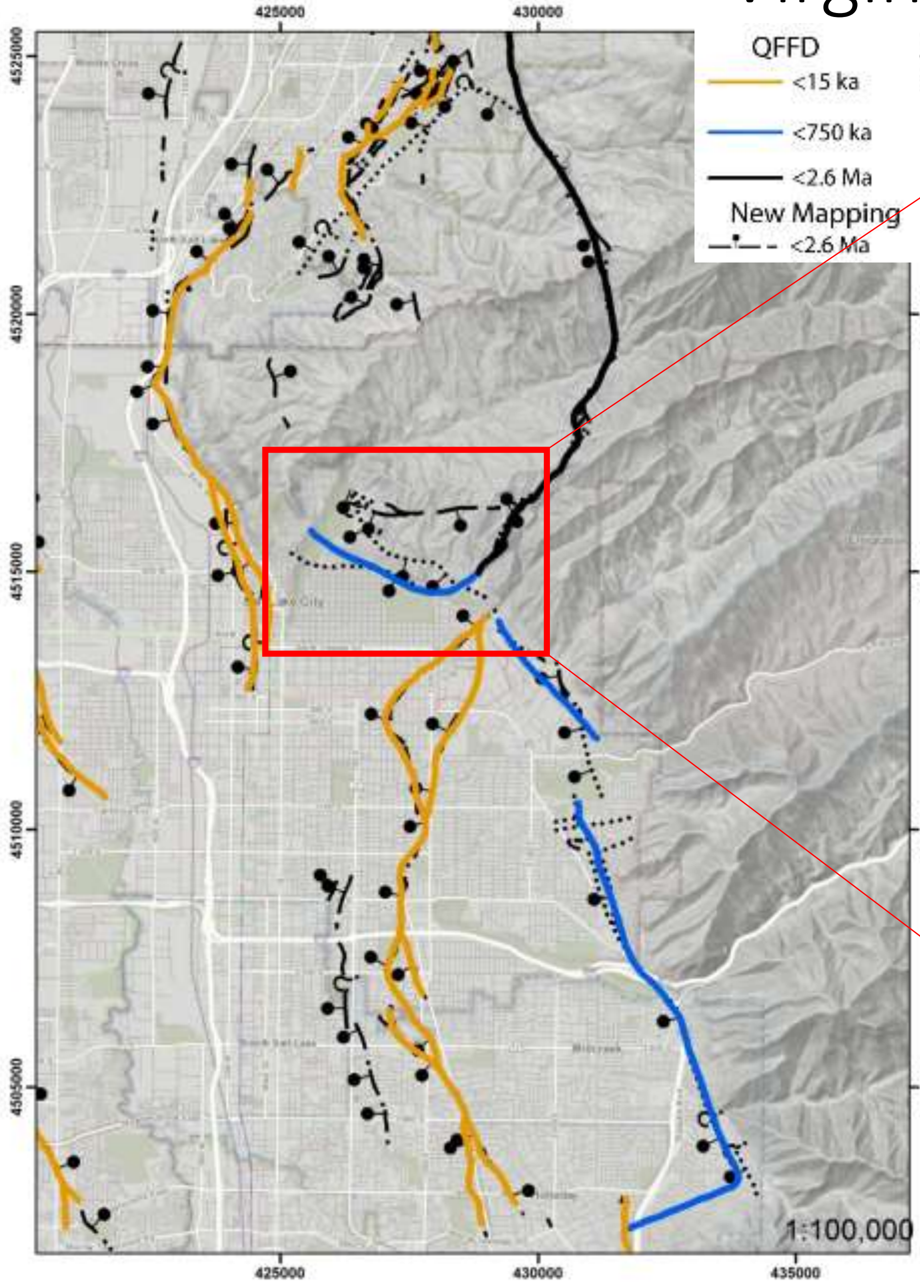
Southern end of Weber

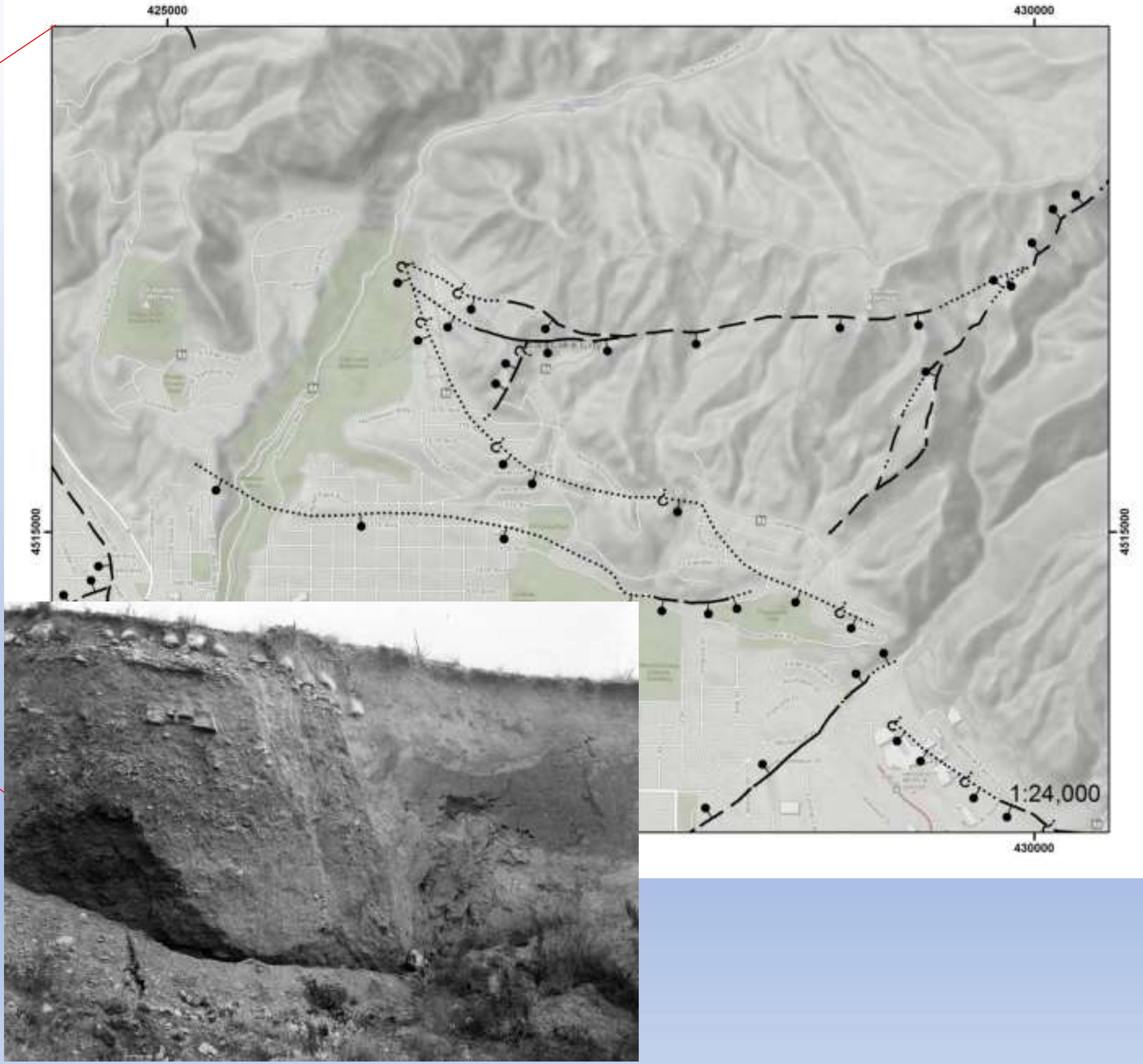




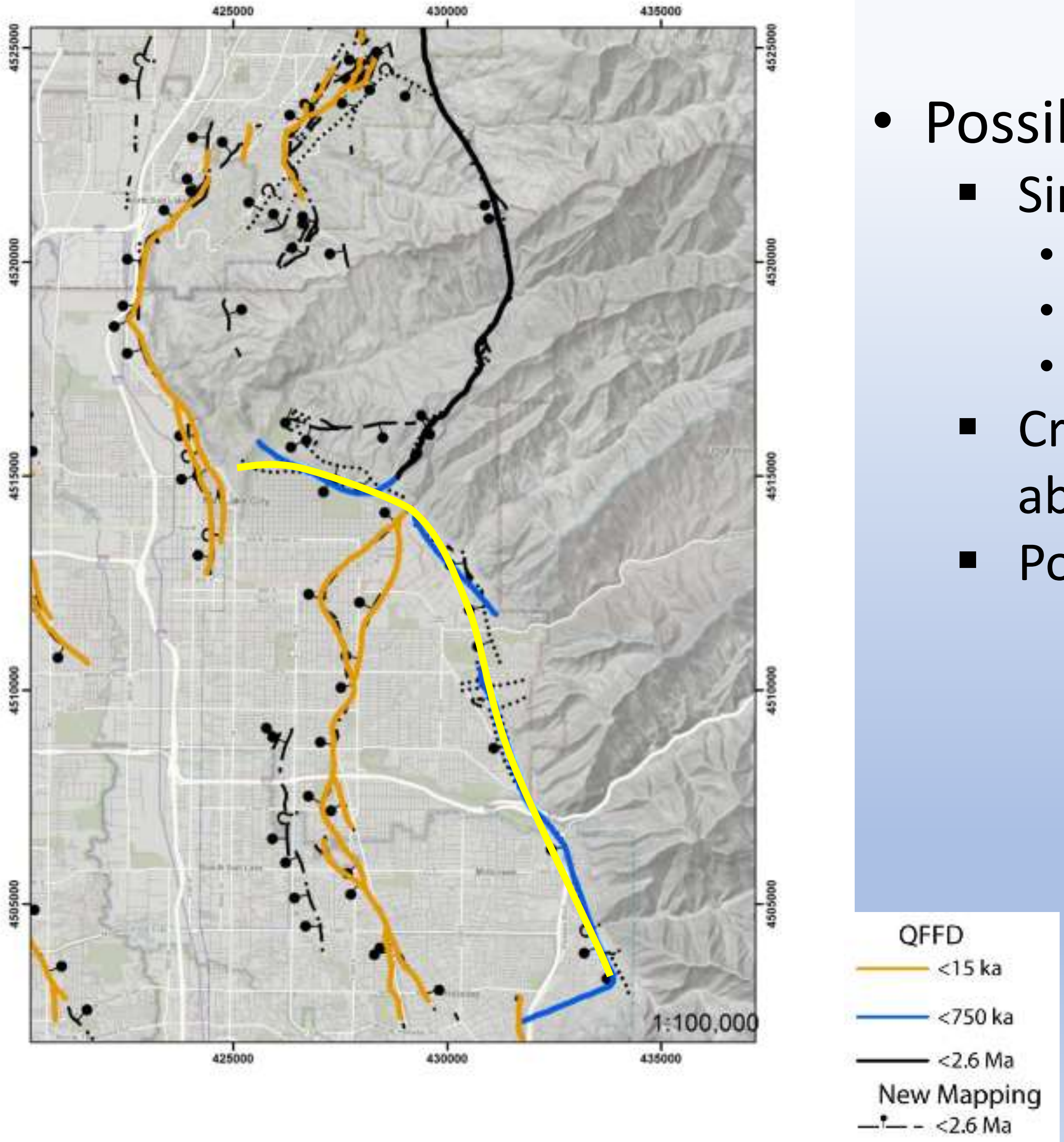
Nelson and Personius, 1993 (1:50,000)

Virginia Street fault





Virginia Street fault



- Possible connection to Foothill fault?
  - Similar map characteristics
    - Few Late Pleistocene to Holocene scarps
    - Older strands likely in range-front bedrock
    - Creates benches of shallow bedrock beneath Quaternary
  - Creates one nice arcuate fault rather than abrupt angles
  - Possibly offsets Rudys Flat fault?

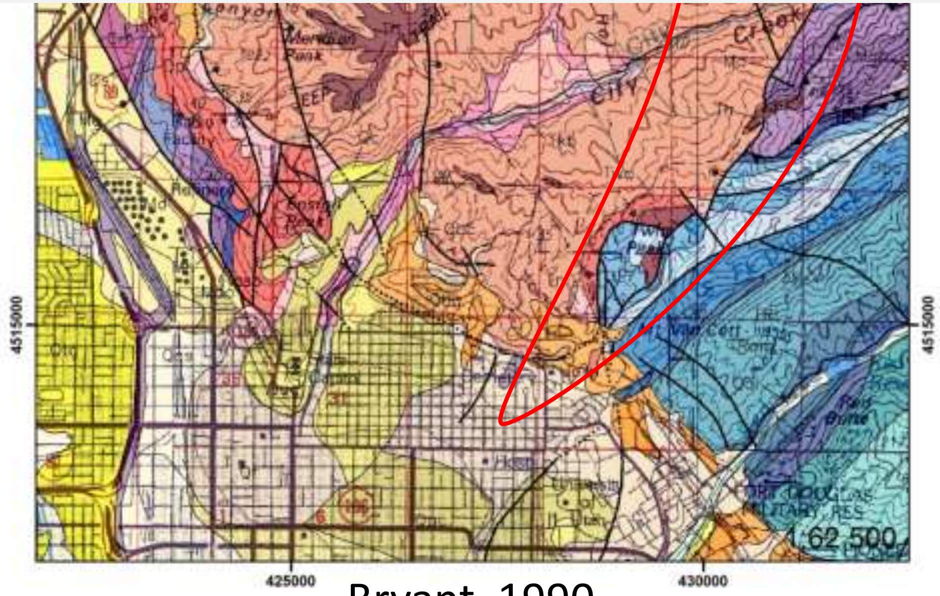
Unnamed (Valleyview?) fault(s)

Unnamed (Edgehill Rd?) fault(s)

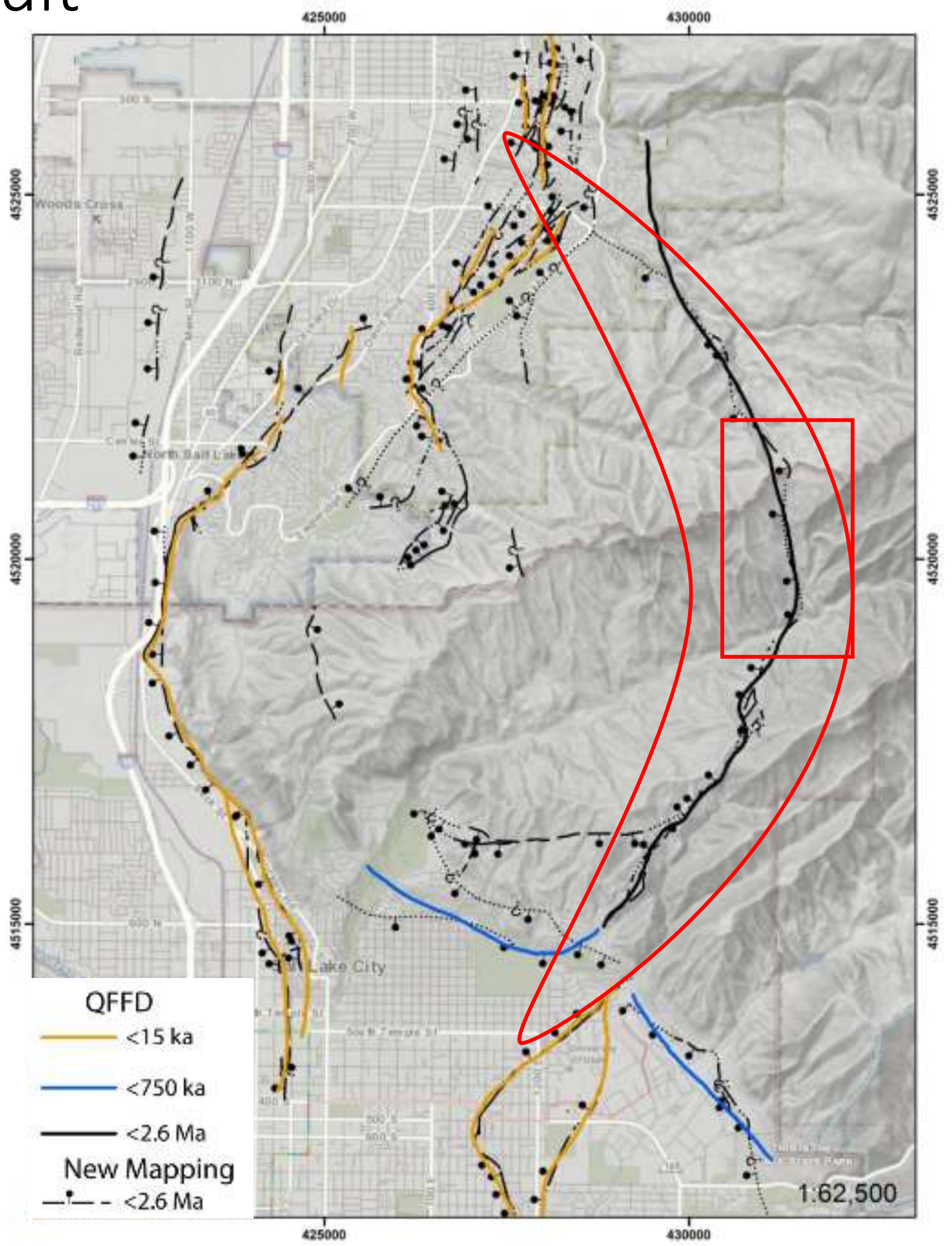
- Deposit is sand to pebbles and cobbles
- Poorly sorted, angular, local Pz rocks
- Not lithified
- Makes up ridge
- Unlike any other conglomerate of SLS
- How old is it?

y's Flat Fault

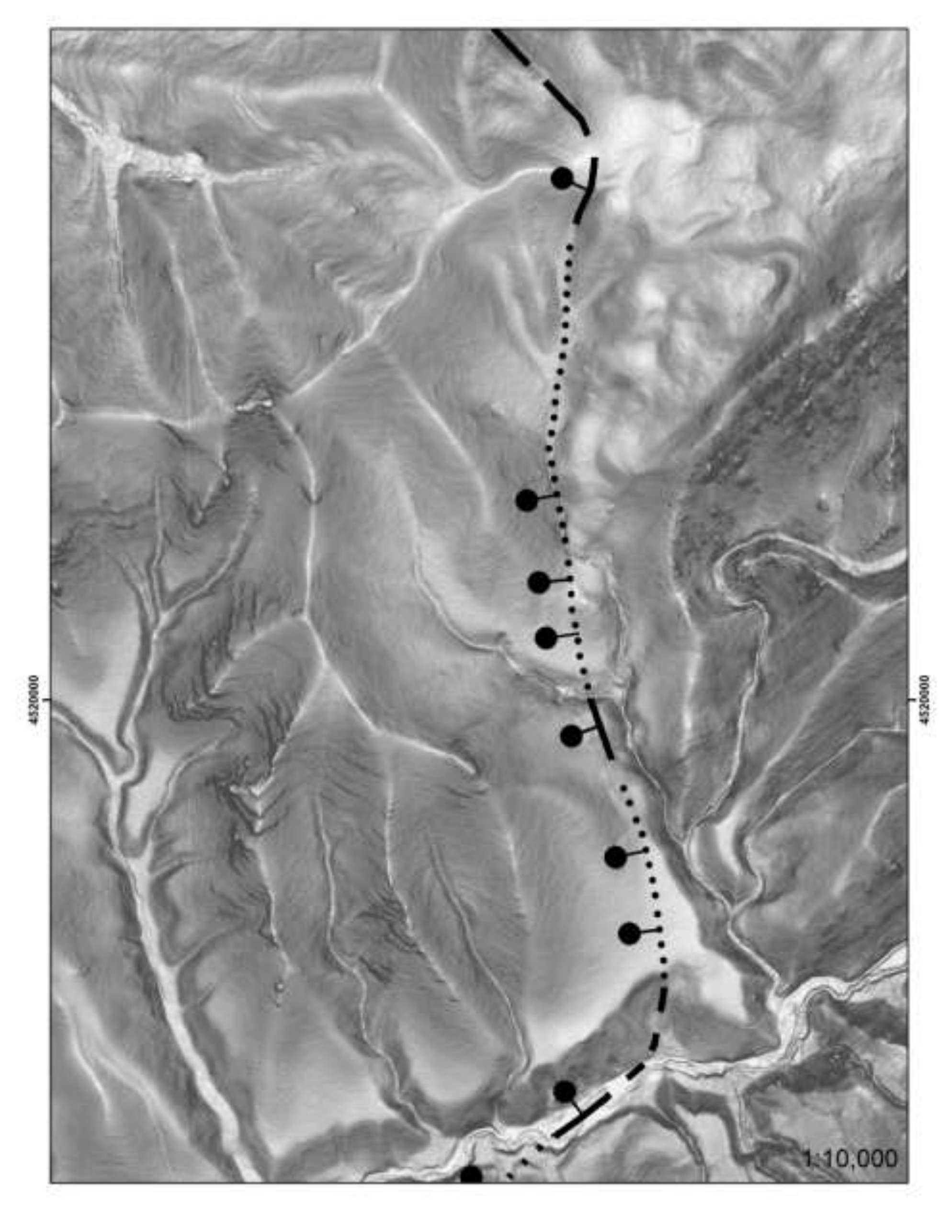
- Lack of evidence for Quaternary scarps/movement
  - Van Horn and Crittenden, 1987; Personius and Scott, 1992; Bruhn and others, 1992; UQFFD, 1993; DuRoss and Hylland, 2014
- Structural connection to East Bench fault or Weber segment
  - Machette and others, 1987; Bryant, 1990; Personius and Scott, 1992; Bruhn and others, 1992; UQFFD, 1993;
- Multi-segment ruptures
  - Jewell and Bruhn 2013; DuRoss and Hylland, 2014; DuRoss and Hylland, 2015; DuRoss and others, 2016

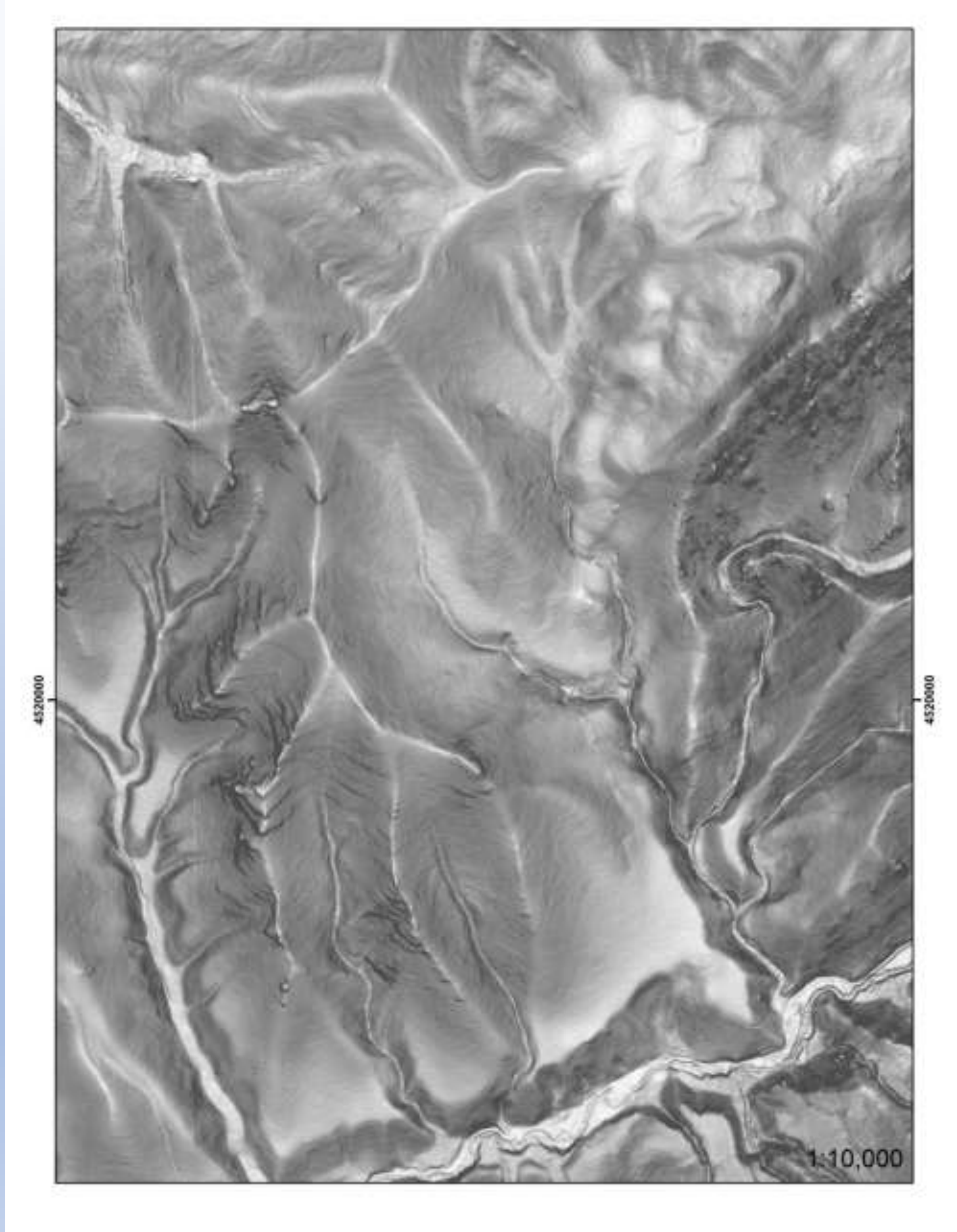


Bryant, 1990

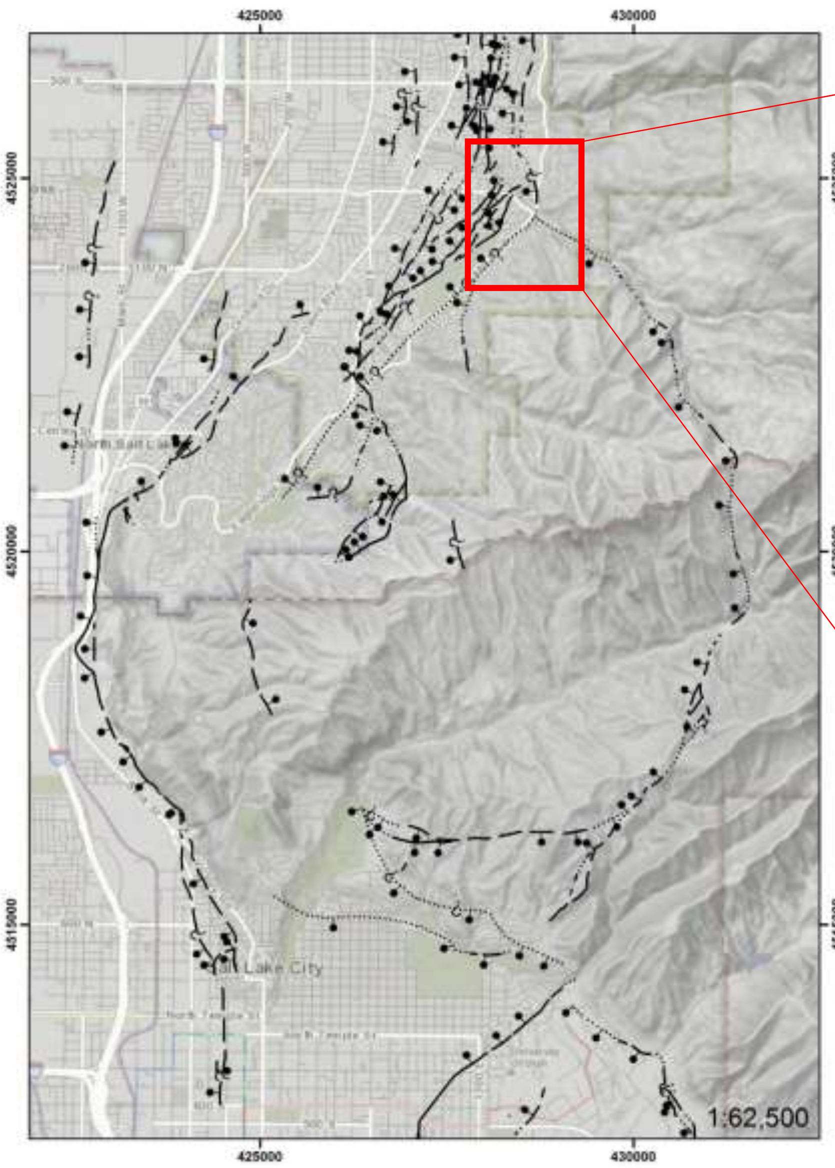


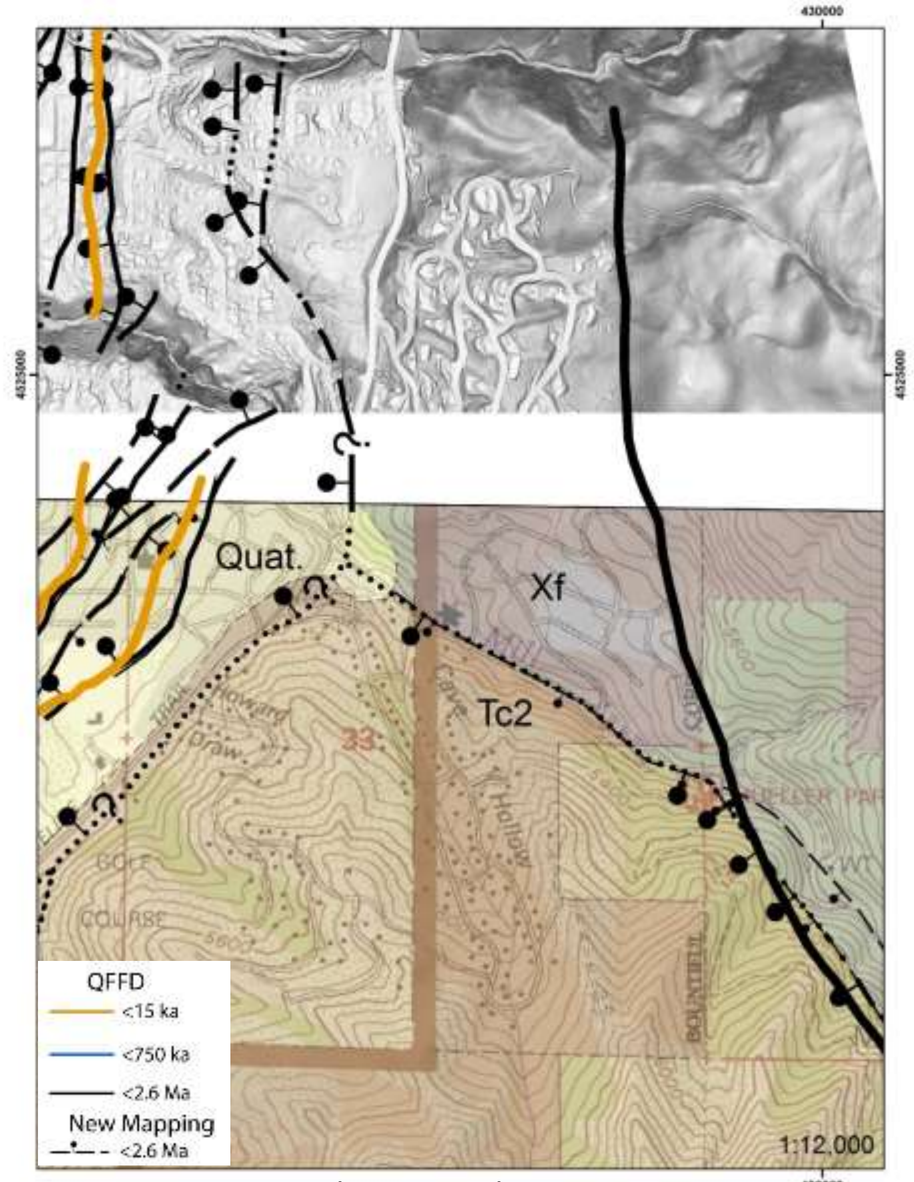
Rudy's Flat Fault





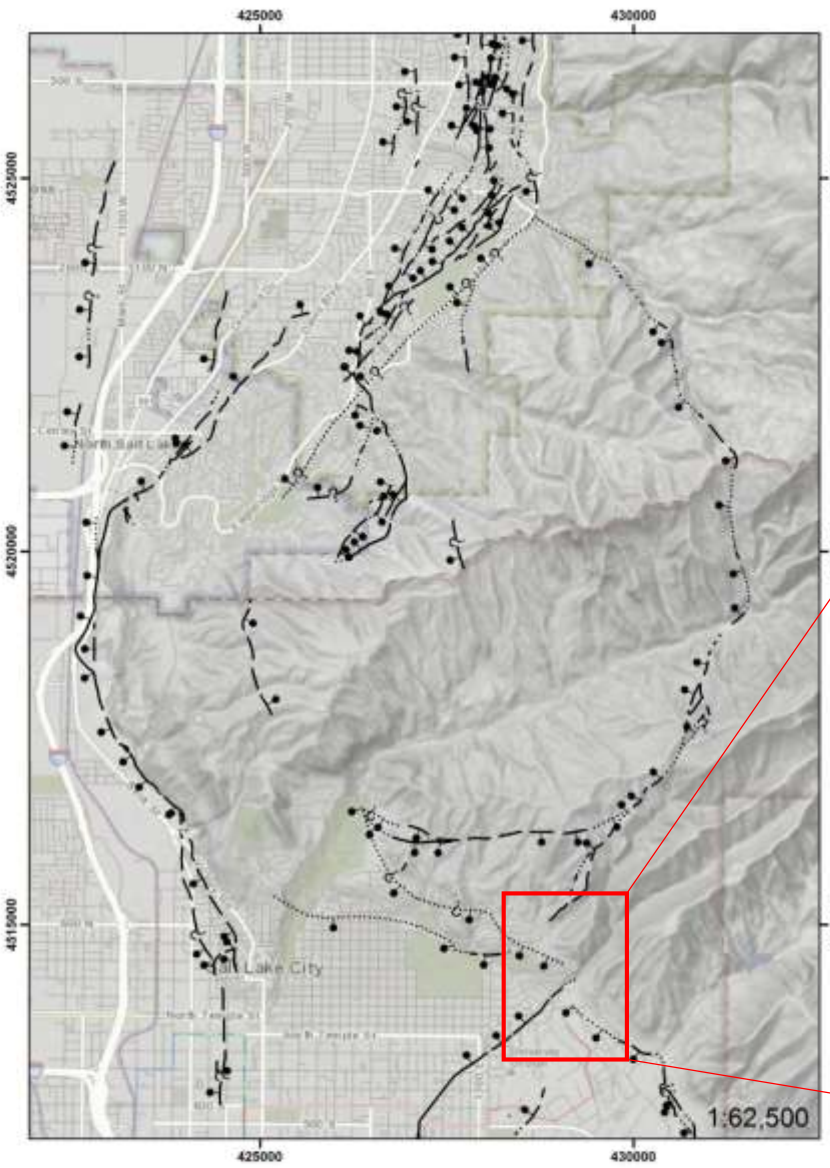
Rudy's Flat Fault – Northern End

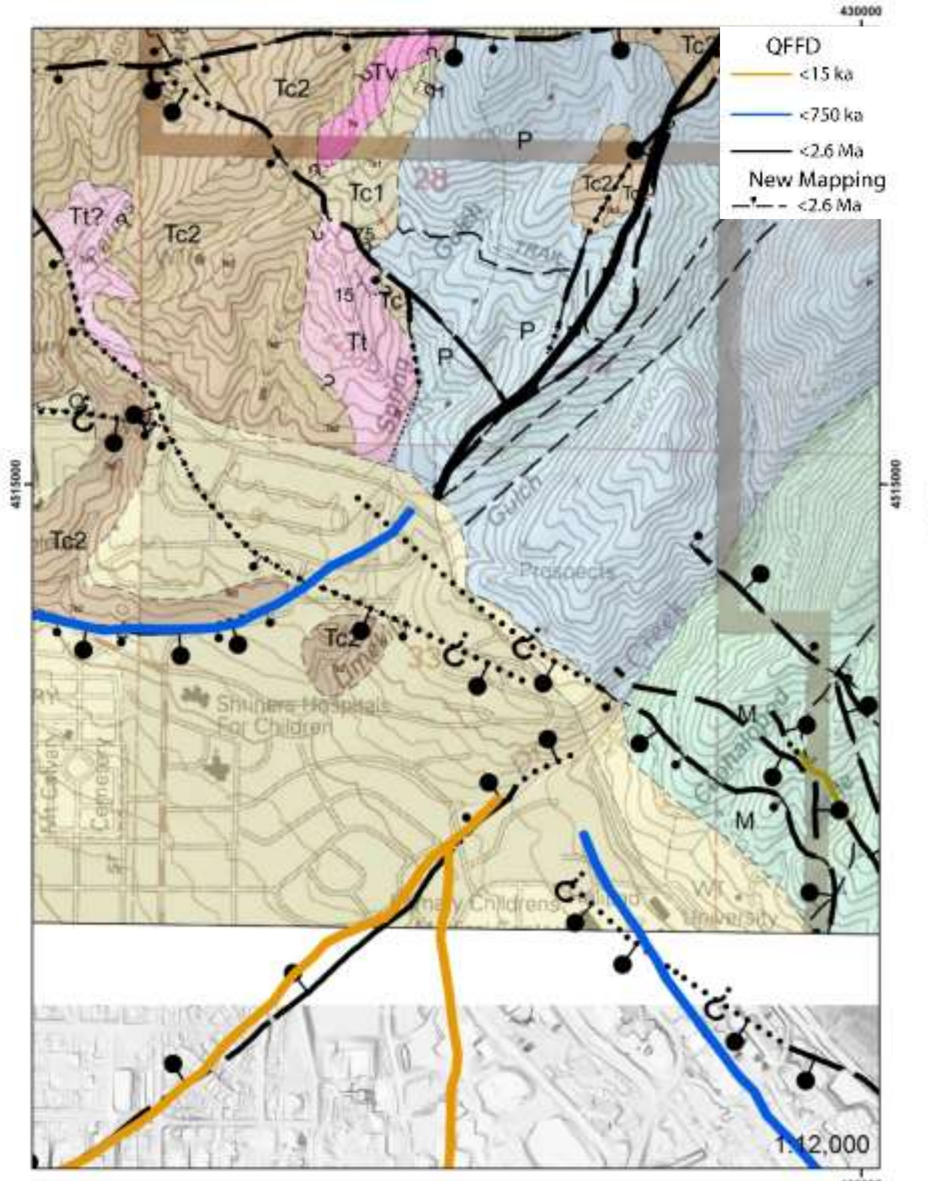




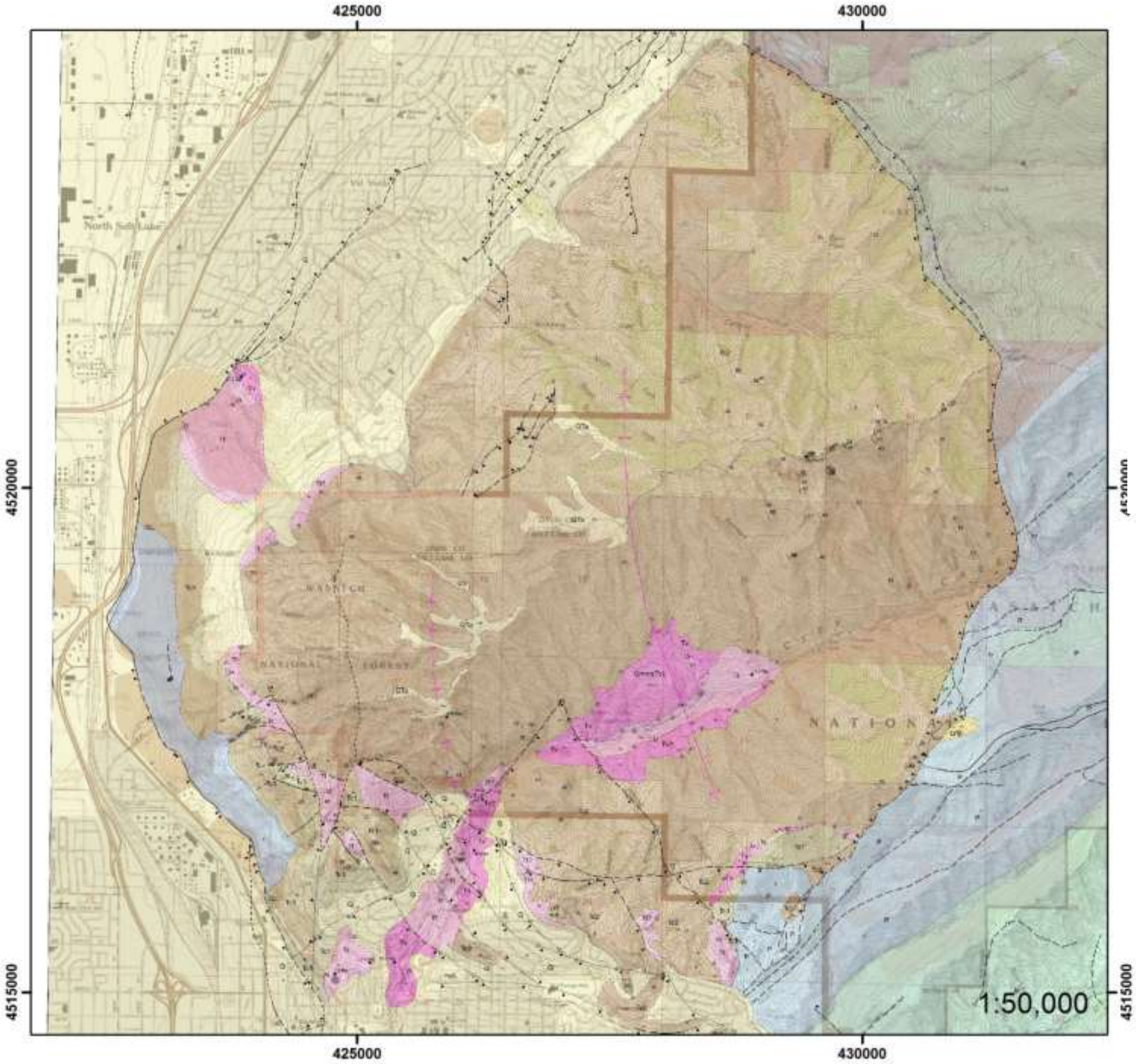
This study (1:24,000); UQFFD, 2019

Rudy’s Flat Fault – Southern End





This study (1:24,000); UGS QFFD, 2019



Poster Teaser

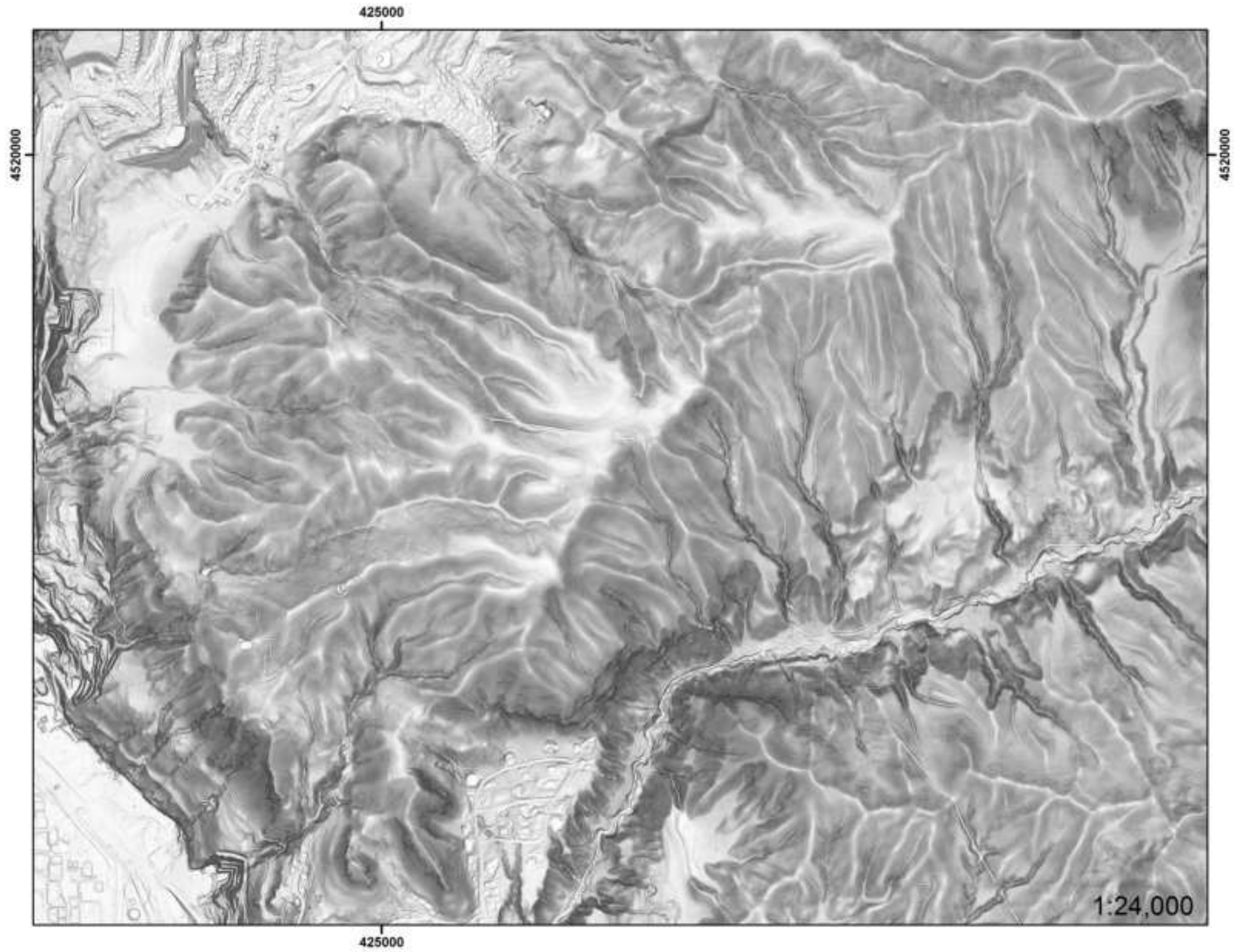
- Rudys Flat fault is abandoned @ ~ 3 Ma when strain is transferred to the Warm Springs fault
- Strain transfer possibly initiated by truncation of RFF by FF/VS faults
- More at my poster

Conclusions

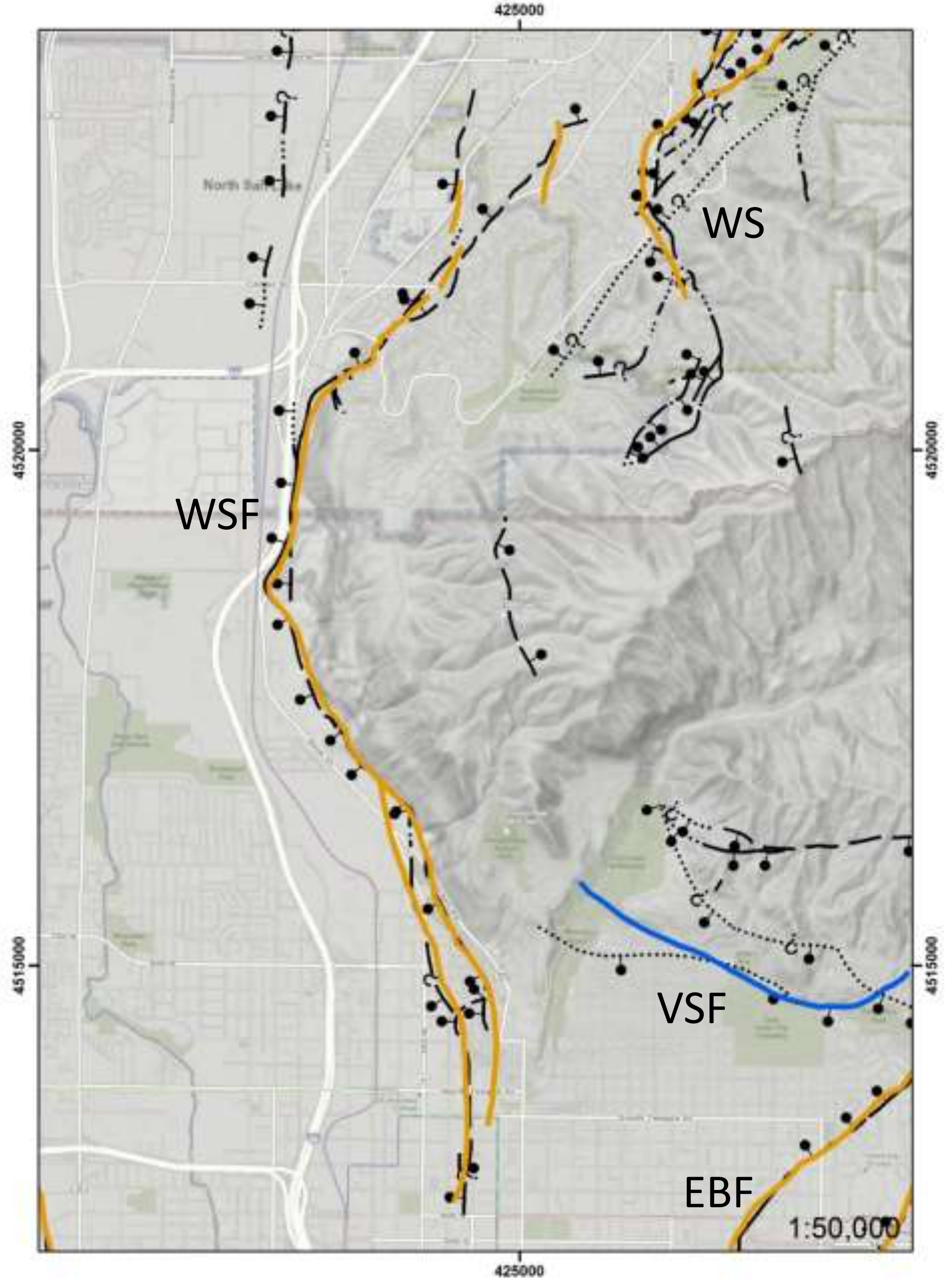
- Geologic mapping has identified multiple new Quaternary faults in and around the Salt Lake salient
  - Extended of Weber segment to the south
  - Extended of Warm Springs fault to the north
  - Better location constraints of Virginia Street fault
  - Unnamed faults with strong lidar signatures (Early Pleistocene?)
  - Faults that cut Early Pleistocene(?) alluvial fans (now inverted topo)
- Rudys Flat fault
  - Little if any evidence of Quaternary movement
  - Mapping suggests 90° junctions with Weber and East Bench. Kinematically viable connections or truncations?

Thanks!

Meridian Peak fault

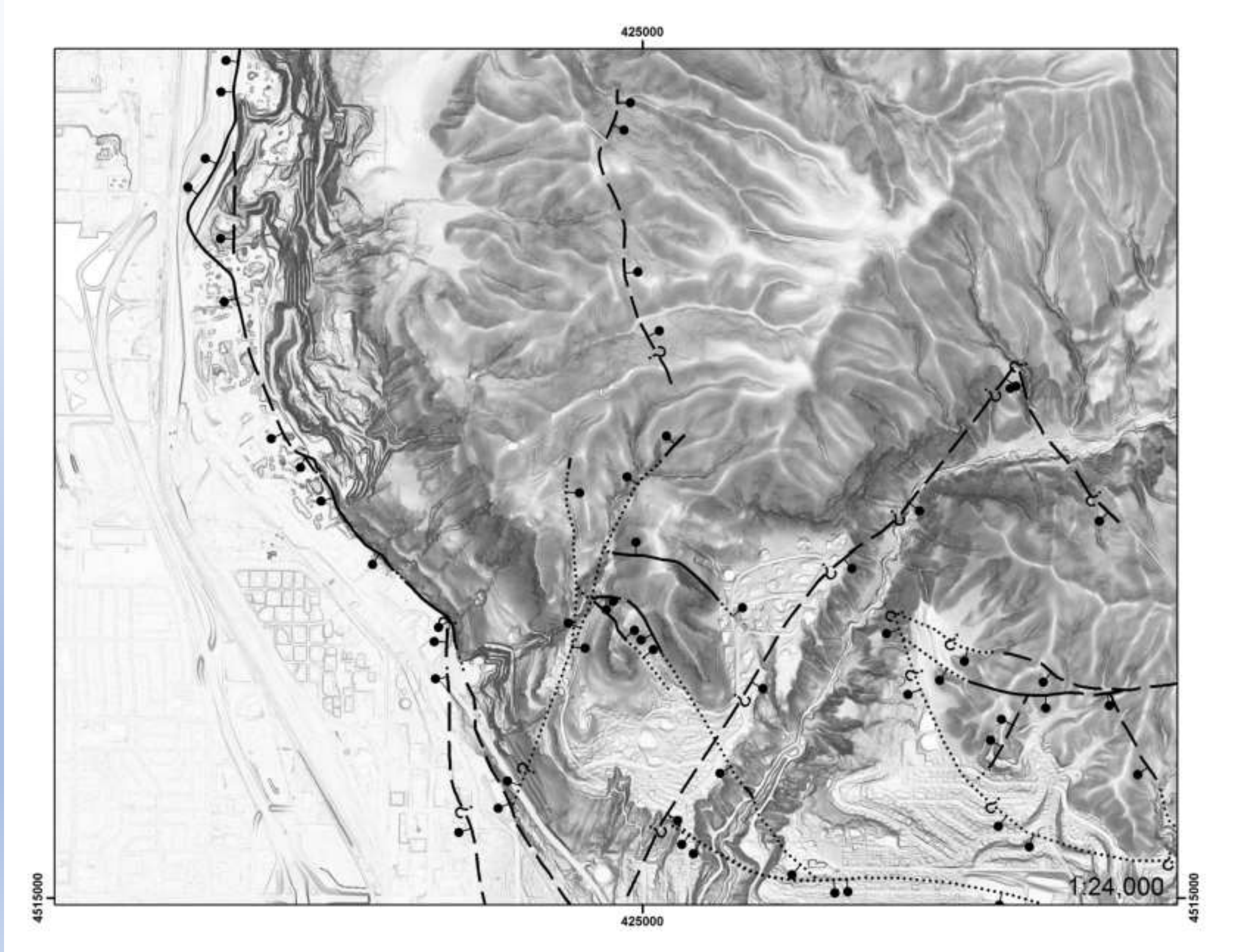


Warm Springs fault



Sketch by W.H. Holmes of the faulted alluvial fan at Jones Canyon (Gilbert, 1890, plate 44).
Note lime kiln on scarp to left of canyon and scarp above house to right of canyon.

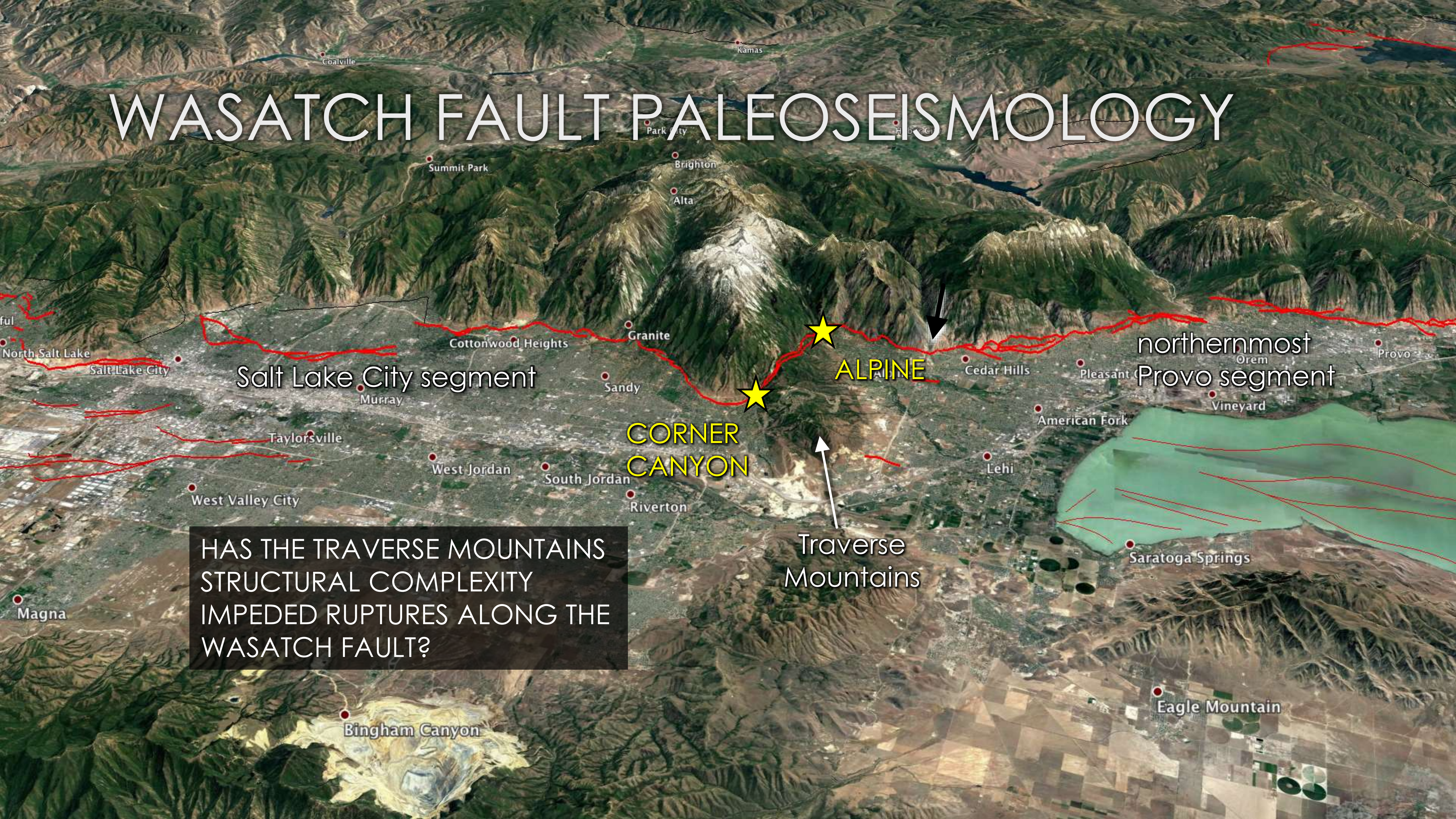
Meridian Peak fault – All faults



UPDATE ON USGS WASATCH FAULT RESEARCH

CHRIS DUROSS (CDUROSS@USGS.GOV)

UTAH QUATERNARY FAULT PARAMETERS WORKING GROUP, FEBRRUARY 2019


WASATCH FAULT PALEOSEISMOLOGY
Coalville
Kamas
Park City
Summit Park
Brighton
Alta
North Salt Lake
Salt Lake City
Salt Lake City segment
Murray
Cottonwood Heights
Granite
Sandy
ALPINE
Cedar Hills
Pleasant
northernmost
Provo segment
Orem
Provo
Vineyard
American Fork
CORNER
CANYON
Taylorsville
West Jordan
South Jordan
Riverton
West Valley City
Lehi
Traverse
Mountains
Saratoga Springs
Magna
HAS THE TRAVERSE MOUNTAINS STRUCTURAL COMPLEXITY IMPEDED RUPTURES ALONG THE WASATCH FAULT?
Eagle Mountain
Bingham Canyon

WASATCH FAULT PALEOSEISMOLOGY

Bulletin of the Seismological Society of America, Vol. 108, No. 6, pp. 3180–3201, December 2018, doi: 10.1785/0120170302

Combining Conflicting Bayesian Models to Develop Paleoseismic Records: An Example from the Wasatch Fault Zone, Utah

by Christopher B. DuRoss, Scott E. K. Bennett, Richard W. Briggs, Stephen F. Personius, Ryan D. Gold, Nadine G. Reitman,* Adam I. Hiscock, and Shannon A. Mahan

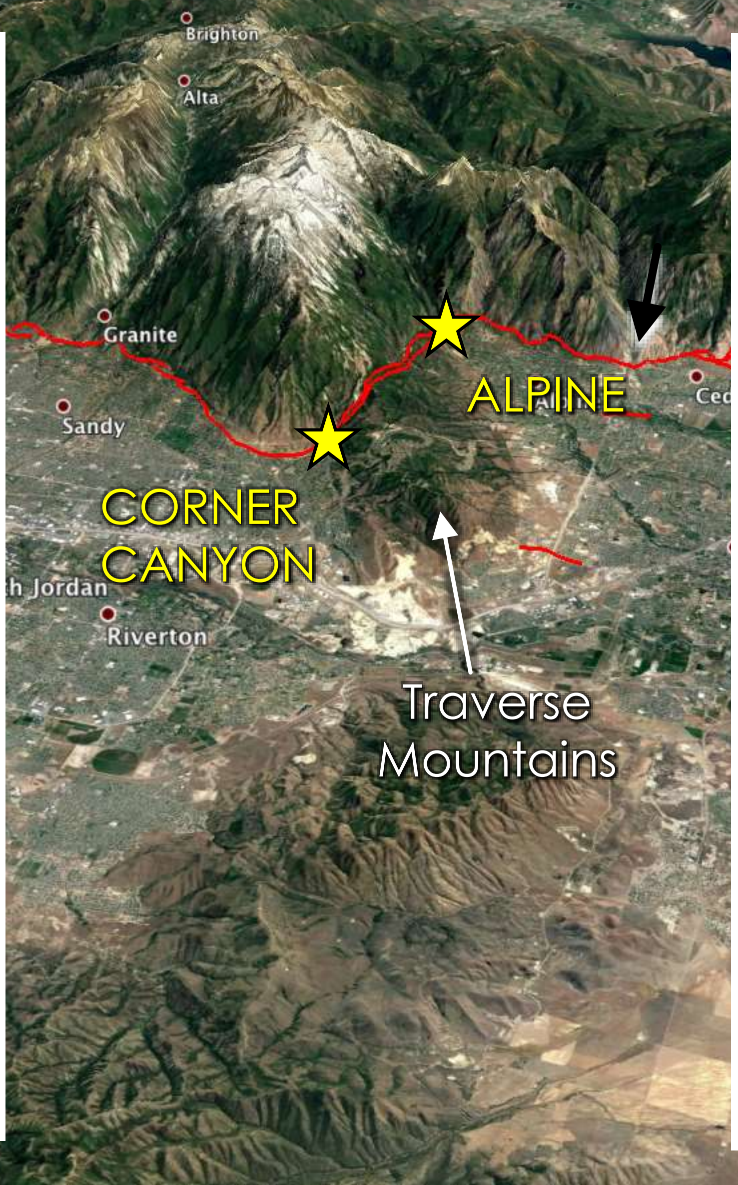
Abstract Bayesian statistical analyses of paleoseismic data result in the probabilistic determination of earthquake times using geochronological data evaluated in the context of a stratigraphic model. However, a fundamental problem in paleoseismology is how to use the Bayesian approach to model sparse and/or conflicting geochronological datasets, such as those derived from sites exhibiting episodic sedimentary and pedogenic processes in moderate- to high-energy environments (e.g., a normal-faulted alluvial fan). Using paleoseismic data for the Corner Canyon site on the Salt Lake City segment of the Wasatch fault zone (Utah), we develop an approach by which multiple Bayesian models are combined to generate an earthquake history at a site. This approach accommodates mutually exclusive interpretations of the geochronological data and thereby limits the influence of sparse data, stratigraphically inconsistent ages, or a single, subjective model interpretation. For the Corner Canyon site, we integrate four OxCal Bayesian models to generate a chronology of six events between ~4.8 and ~0.5 ka. Late Holocene (post-5 ka) mean recurrence and vertical slip-rate estimates are ~0.9 ky (0.7–1.0 ky; 95% confidence) and 1.1 mm/yr (0.8–1.7 mm/yr range), respectively. Although our method increases the uncertainty in the timing of individual earthquakes, it more objectively accounts for potential geochronological errors and different interpretations of stratigraphic age control. By relaxing the need to select a single age model, our approach yields more accurate earthquake-timing results that will better facilitate evaluations of along-fault event correlation and earthquake rupture length.

Electronic Supplement: Photographs of the Corner Canyon site, trench-wall photomosaics and stratigraphic and structural relations, unit descriptions, per-event displacement estimates, OxCal codes, and earthquake elapsed-time probability density functions (PDFs) are included.

Introduction

Bayesian statistical analysis is a method of statistical inference in which information on model parameters before data are observed (a "prior" distribution) is combined with quantitative uncertainty data (a "likelihood" model) to deter- parameters and multiple hypotheses (D'Agostini, 2003). In the context of paleoseismic data, a prior model generally consists of a stratigraphic model with depositional unit depth and ordering information (Bronk Ramsey, 2008), and like-

Corner Canyon site: DuRoss et al., 2018, BSSA v. 108(6), 3180–3201.



Bulletin of the Seismological Society of America, Vol. 108, No. 6, pp. 3202–3224, December 2018, doi: 10.1785/0120160358

Paleoseismic Results from the Alpine Site, Wasatch Fault Zone: Timing and Displacement Data for Six Holocene Earthquakes at the Salt Lake City–Provo Segment Boundary

by S. E. K. Bennett,* C. B. DuRoss,[†] R. D. Gold, R. W. Briggs, S. F. Personius, N. G. Reitman,[‡] J. R. Devore, A. I. Hiscock, S. A. Mahan, H. J. Gray, S. Gunnarson,[§] W. J. Stephenson, E. Pettinger, and J. K. Odum

Abstract To improve the characterization of Holocene earthquakes on the Wasatch fault zone (WFZ), we conducted light detection and ranging (lidar)-based neotectonic mapping and excavated a paleoseismic trench across an 8-m-high fault scarp near Alpine, Utah, located < 1 km south of the boundary between the Salt Lake City and Provo segments (SLCS and PS). We document evidence for six paleoearthquakes (AL6–AL1) from scarp-derived colluvial wedges and crosscutting relations. A ground-penetrating radar survey across the scarp resolved fault-zone width, but not paleoearthquake stratigraphy. Bayesian (OxCal) modeling of 13 radiocarbon and 13 optically stimulated luminescence ages indicates that six earthquakes occurred ~6.2–0.4 ka. Interseismic recurrence ranges from 0.2 to 1.8 ky (mean 1.2 ky). We estimate 6.5 ± 0.7 m of cumulative vertical tectonic displacement across the ≥ 14-m-wide fault zone used near-field observations of scarp-derived colluvial-wedge thicknesses, antithetic faulting, and graben backtilting. This is similar to our independent estimate of 6.5 ± 0.5 m using far-field observations of the offset ground surface and correlation of alluvial-fan stratigraphy across the WFZ. These results suggest that colluvial-wedge thickness at the Alpine site approximates one-half the original west-facing fault scarp height. Per-event vertical displacements range from 0.8 to 1.2 m (mean 1.1 m), which we use to estimate surface rupture lengths that may exceed 50 km from earthquakes as large as moment magnitude (M_w) ~7.0. The late Holocene average vertical slip rate is 0.9 mm/yr (0.7–1.2 mm/yr range). Earthquake frequency has increased in the past ~1 ky, whereas displacement per event has been similar for the past ~6 ky, suggesting that strain accumulation is not the sole factor that controls the frequency and size of earthquakes at the SLCS–PS segment boundary. These findings can be used for a more nuanced characterization of earthquakes at the SLCS–PS boundary and improve earthquake hazard assessments along the Wasatch Front.

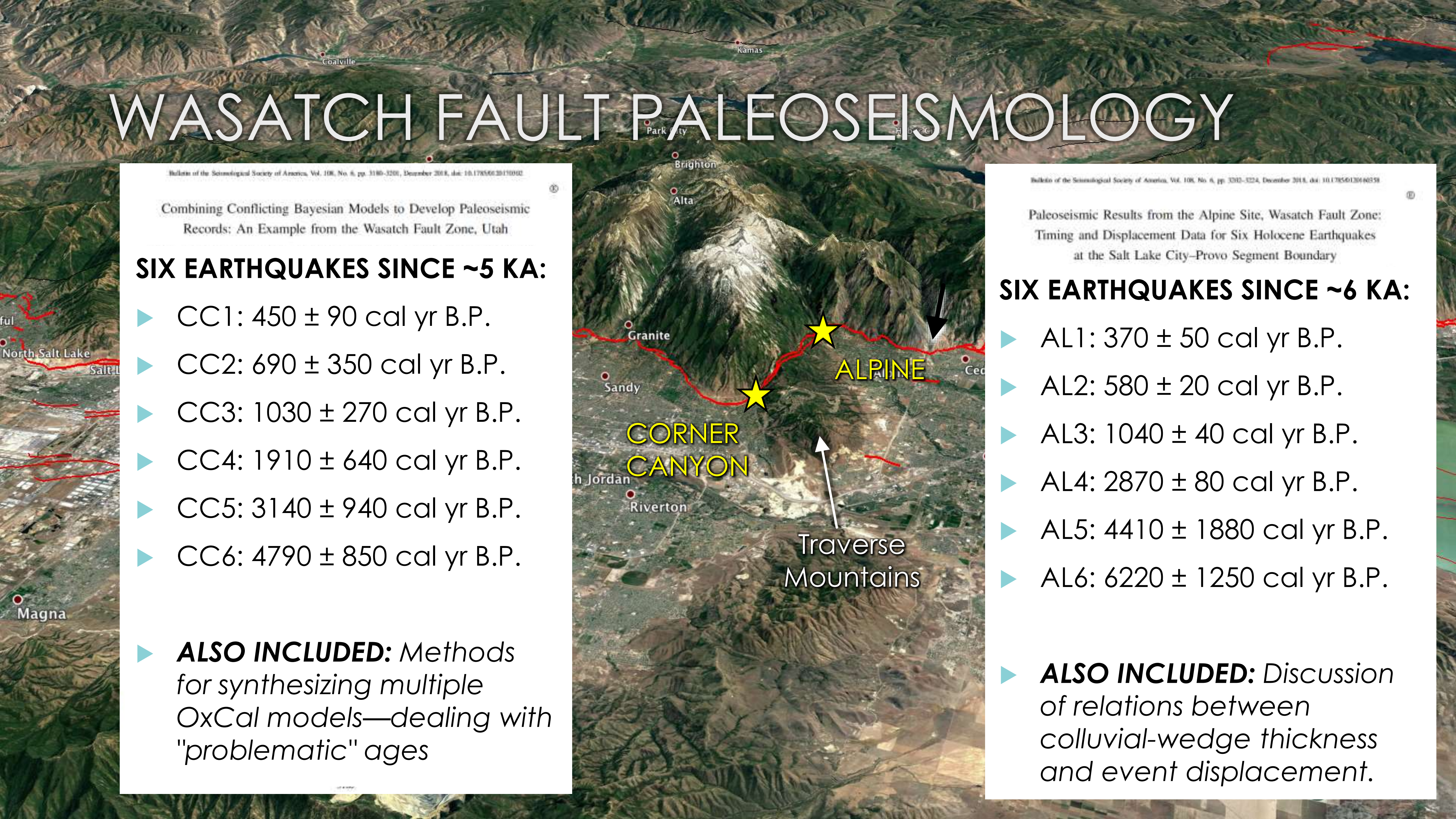
Electronic Supplement: Figures of detailed trench logs and photomosaics, ground penetrating radar results, summary of charcoal identification, colluvial wedge scaling calculations, and code for OxCal model.

Introduction

Normal-fault systems commonly consist of several

Alpine Site: Bennett et al., 2018, BSSA v. 108(6), 3202–3224.

WASATCH FAULT PALEOSEISMOLOGY



Bulletin of the Seismological Society of America, Vol. 108, No. 6, pp. 3180–3201, December 2018, doi: 10.1785/0120170302

Combining Conflicting Bayesian Models to Develop Paleoseismic Records: An Example from the Wasatch Fault Zone, Utah

SIX EARTHQUAKES SINCE ~5 KA:

- CC1: 450 ± 90 cal yr B.P.
- CC2: 690 ± 350 cal yr B.P.
- CC3: 1030 ± 270 cal yr B.P.
- CC4: 1910 ± 640 cal yr B.P.
- CC5: 3140 ± 940 cal yr B.P.
- CC6: 4790 ± 850 cal yr B.P.

- ***ALSO INCLUDED:*** *Methods for synthesizing multiple OxCal models—dealing with "problematic" ages*

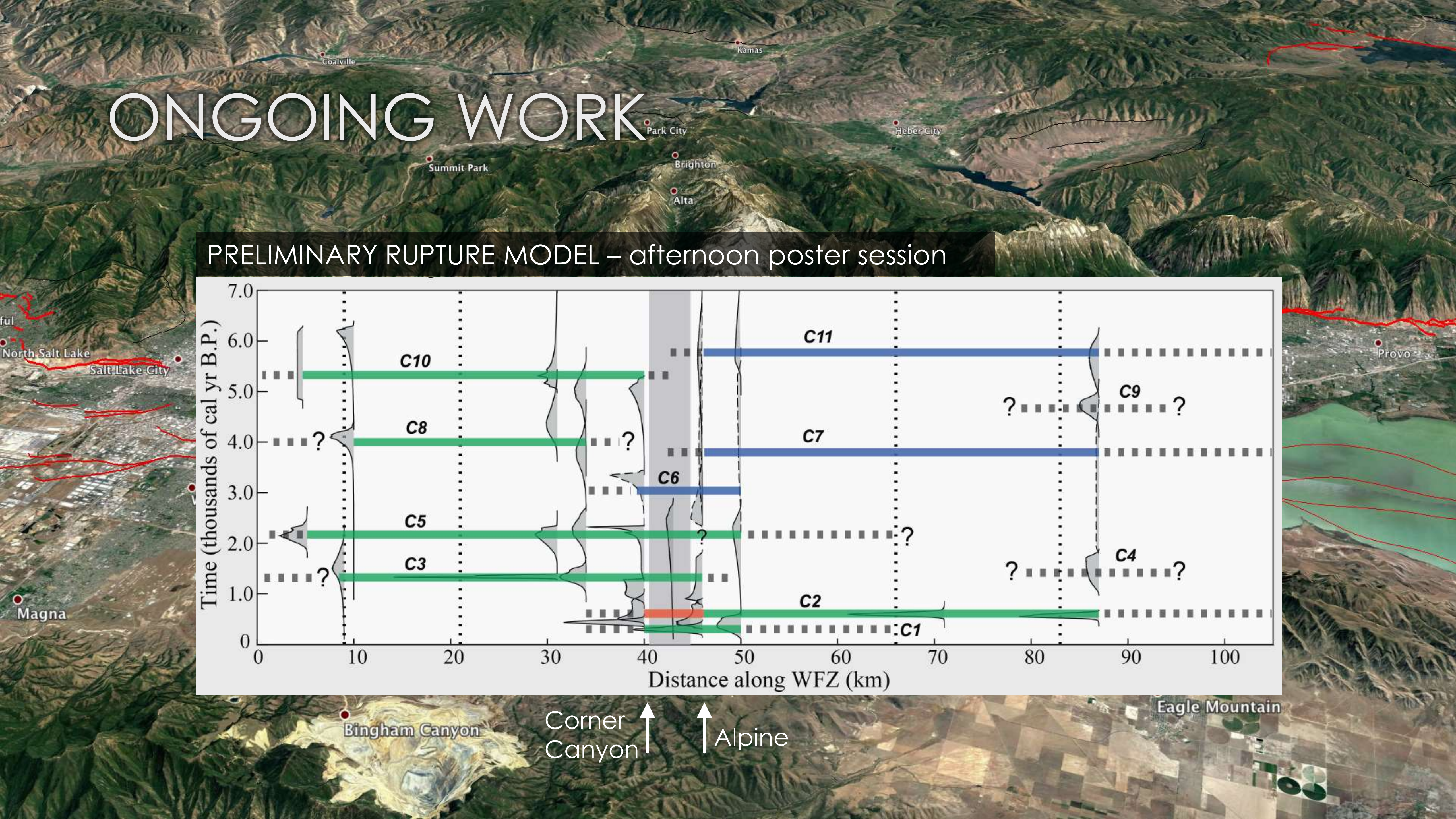
Bulletin of the Seismological Society of America, Vol. 108, No. 6, pp. 3202–3224, December 2018, doi: 10.1785/0120160358

Paleoseismic Results from the Alpine Site, Wasatch Fault Zone: Timing and Displacement Data for Six Holocene Earthquakes at the Salt Lake City–Provo Segment Boundary

SIX EARTHQUAKES SINCE ~6 KA:

- AL1: 370 ± 50 cal yr B.P.
- AL2: 580 ± 20 cal yr B.P.
- AL3: 1040 ± 40 cal yr B.P.
- AL4: 2870 ± 80 cal yr B.P.
- AL5: 4410 ± 1880 cal yr B.P.
- AL6: 6220 ± 1250 cal yr B.P.

- ***ALSO INCLUDED:*** *Discussion of relations between colluvial-wedge thickness and event displacement.*



ONGOING WORK
PRELIMINARY RUPTURE MODEL – afternoon poster session
Coalville
Kamas
Park City
Heber City
Summit Park
Brighton
Alta
North Salt Lake
Salt Lake City
Magna
Provo
Bingham Canyon
Eagle Mountain
Time (thousands of cal yr B.P.)
Distance along WFZ (km)
C11
C10
C9
C8
C7
C6
C5
C4
C3
C2
C1
Corner Canyon
Alpine

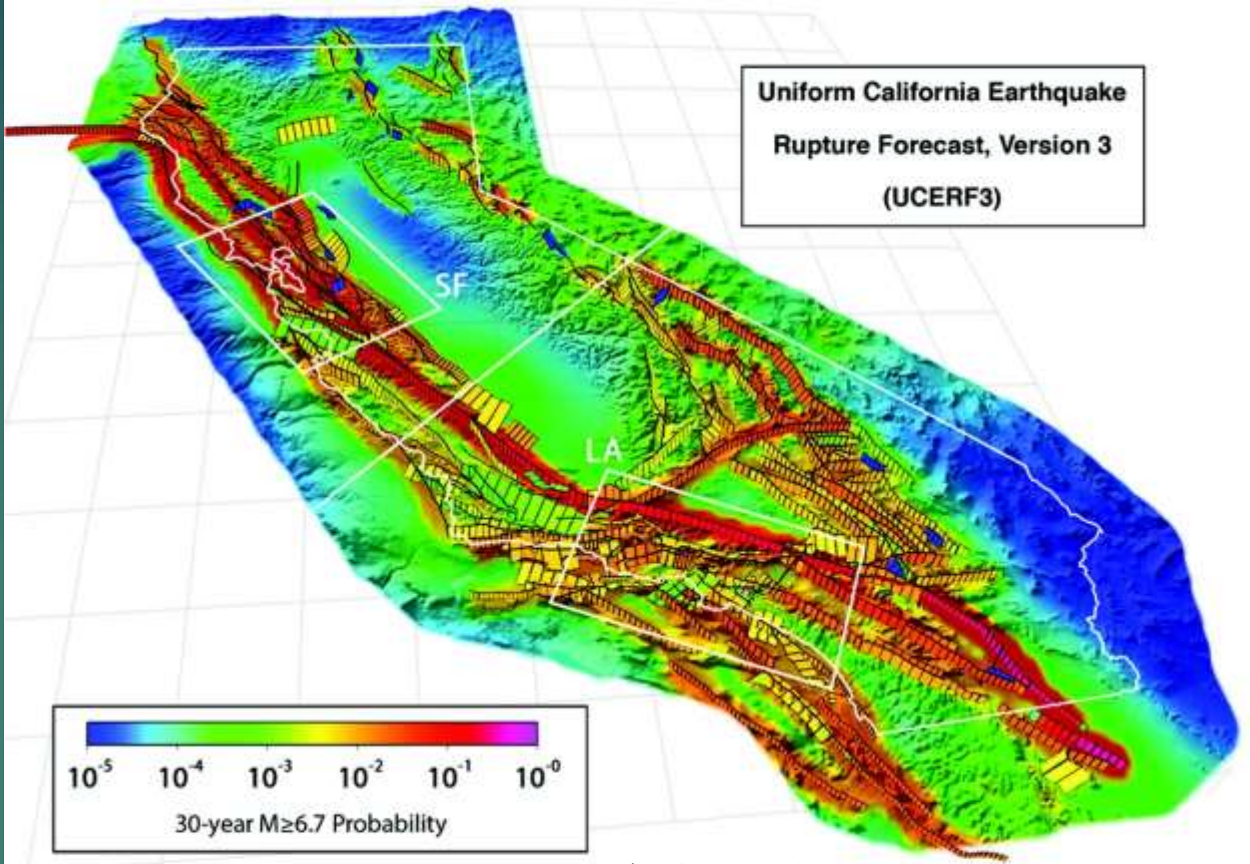
ADAPTING THE UNIFORM CALIFORNIA EARTHQUAKE RUPTURE FORECAST (UCERF) FOR THE WASATCH FAULT ZONE

Research in progress by **Alessandro Valentini** (Univ. of Chieti, Italy), in collaboration with Chris DuRoss, Bruno Pace, Francesco Visini, Ryan Gold, Rich Briggs, and Ned Field

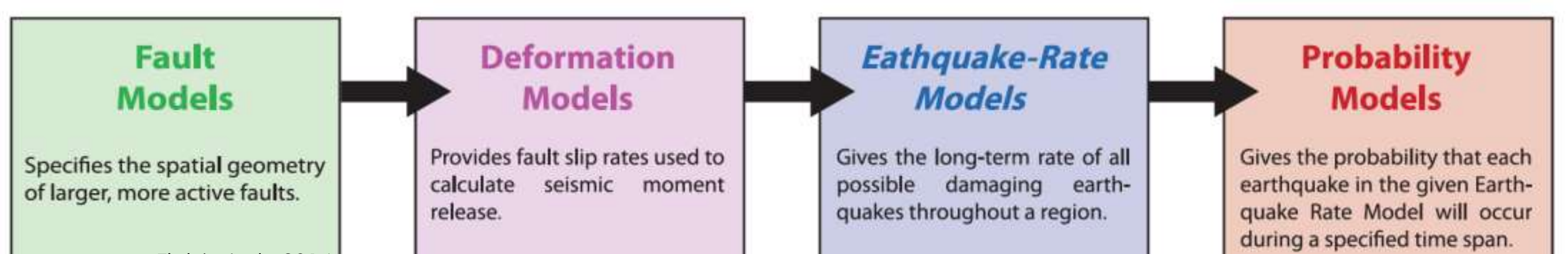
OBJECTIVE

- **PRIMARY RESEARCH QUESTION**: In A UCERF3 framework, how do fault segmentation constraints affect fault rupture rates and seismic hazard?

- **TEST CASE**: Central Wasatch fault zone.



Field et al., 2014

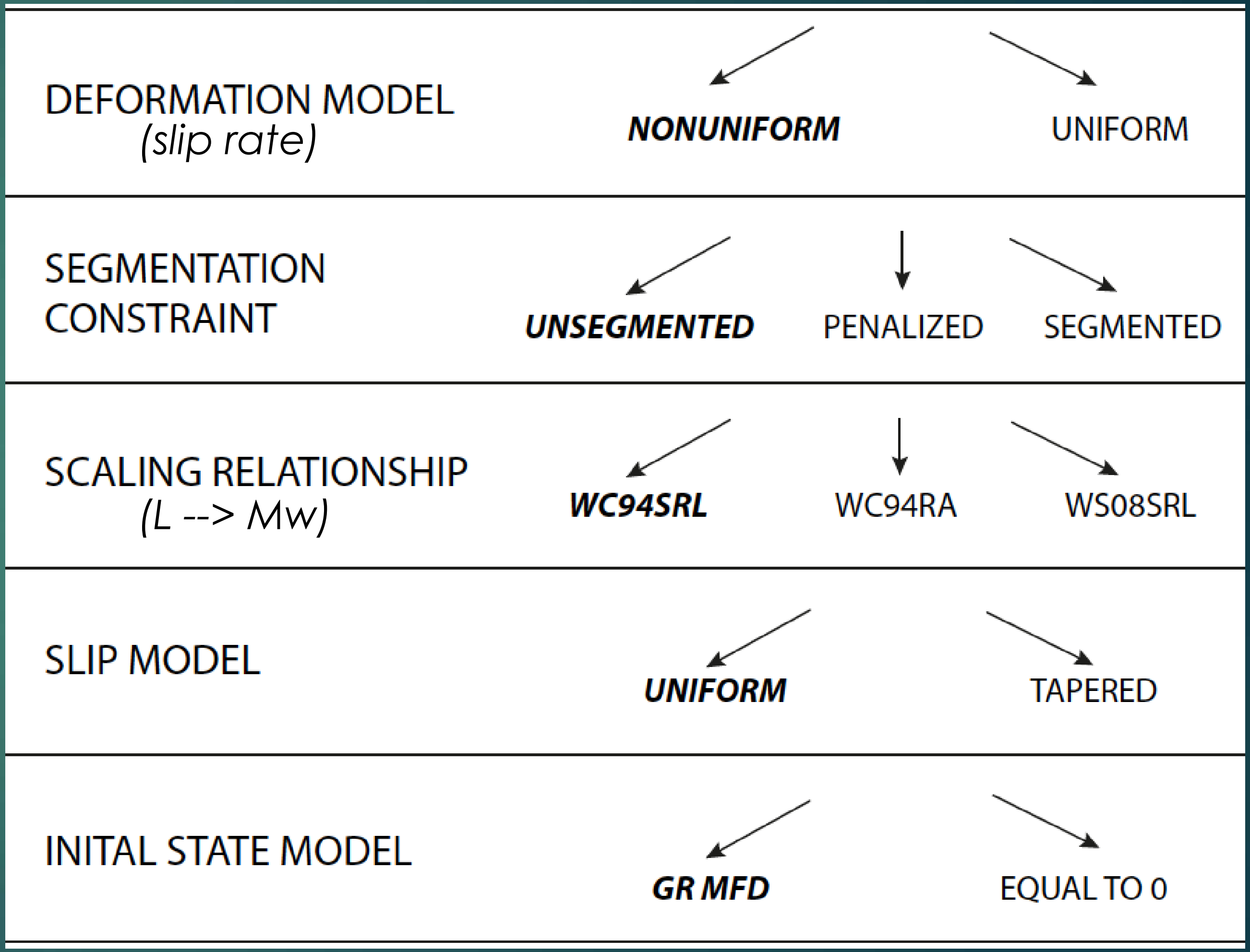


Field et al., 2014

UCERF3 FRAMEWORK

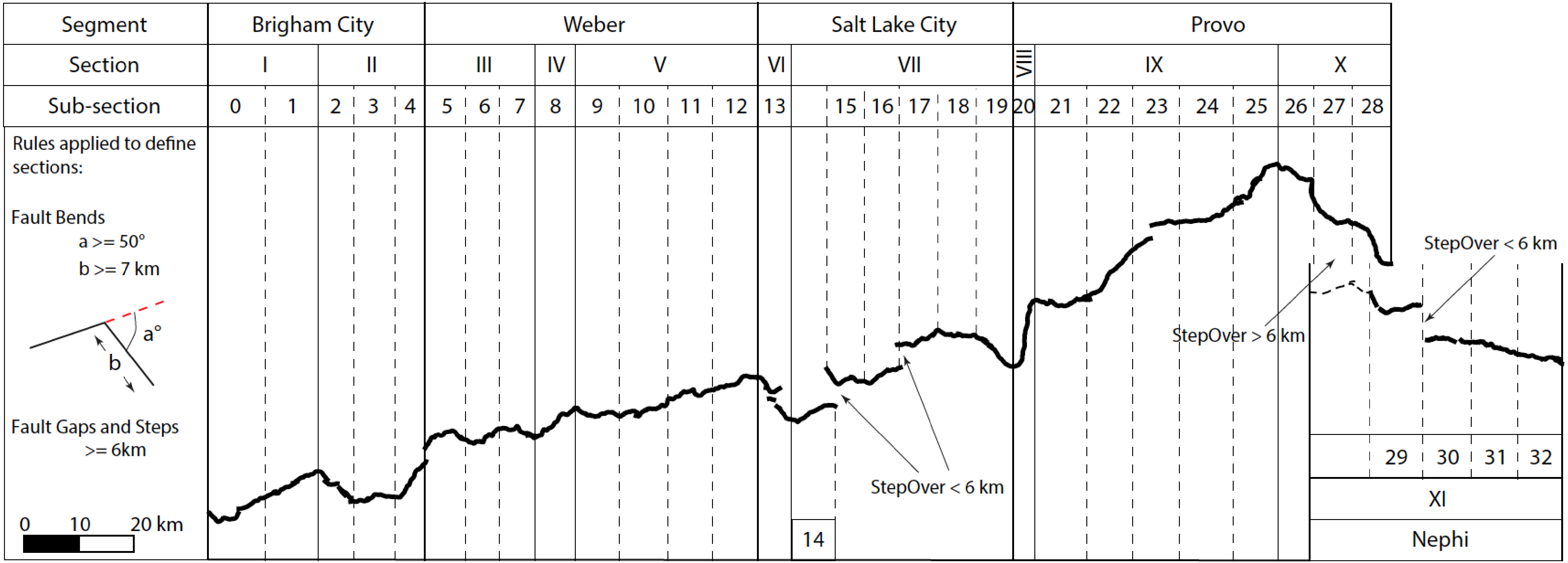
- Solve for the time-independent rates of all possible rupture combinations by satisfying slip rates and paleoseismic event rates through an inversion process.

- **INPUTS:**
  - Fault geometry
  - Seismogenic thickness (15 km)
  - Dip angle (50°)
  - Slip rate profile
  - Paleoseismic event rates



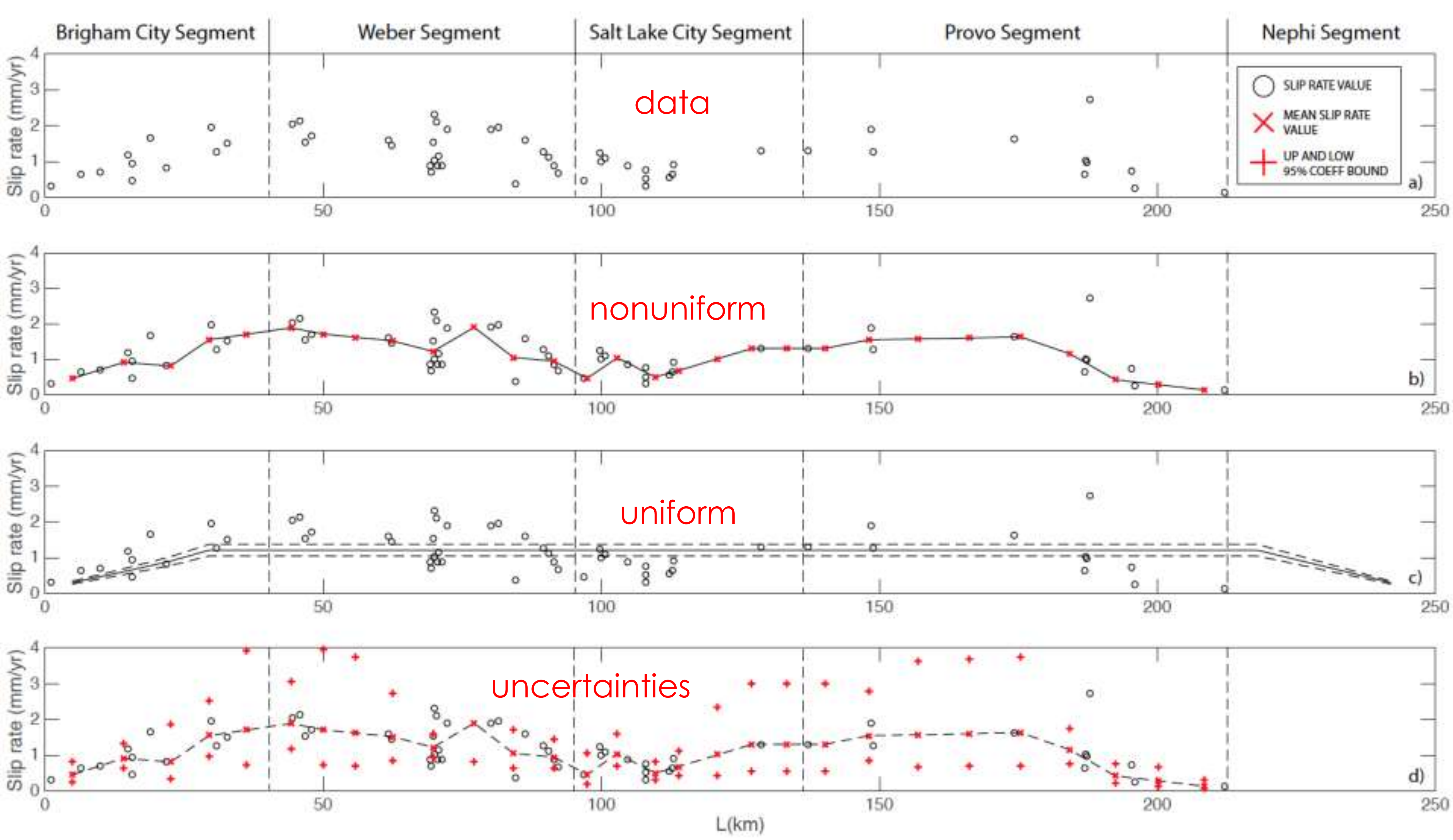
INPUT: FAULT GEOMETRY

- **SUBSECTIONS** = ~½ seismogenic thickness. **SMALLEST RUPTURE** = 2 subsections (13-20 km); **LONGEST RUPTURE** = All subsections (270 km). **UNIQUE RUPTURE COMBINATIONS** = 528.



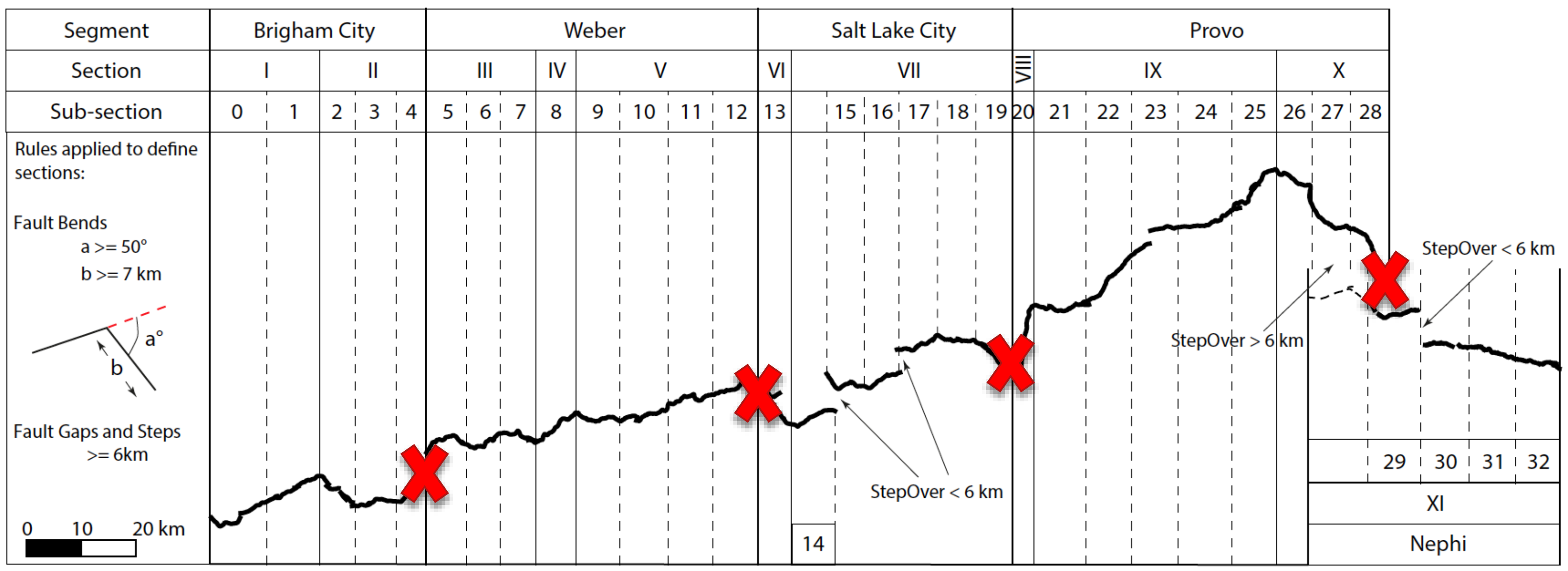
INPUT: SLIP RATE AND EVENT RATES

- **SLIP RATE:** derived from the vertical separation of Bonneville surfaces



SEGMENTATION

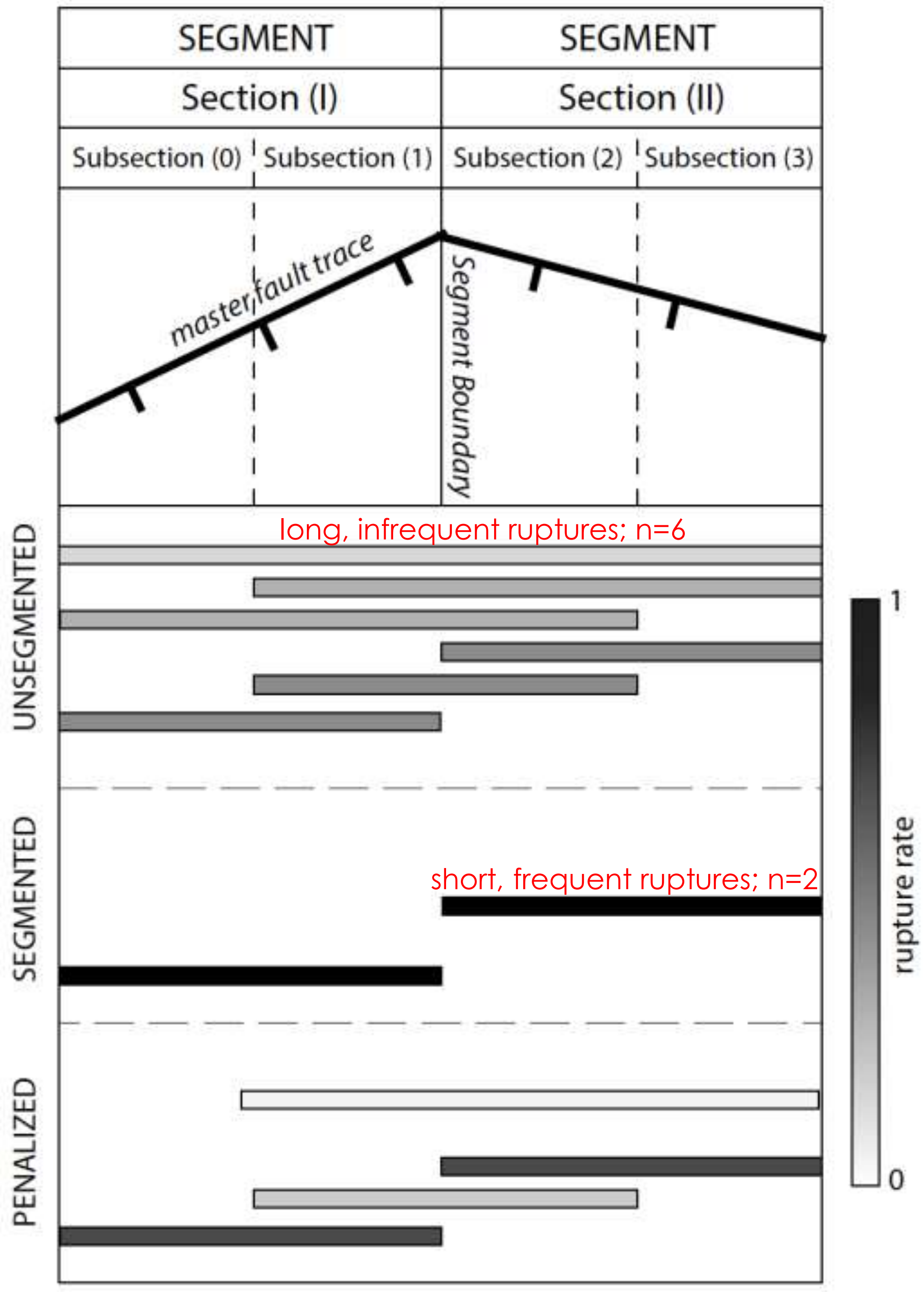
- **IMPOSING SEGMENTATION:** Ruptures crossing a primary structural boundary are penalized (end-member case: rupture rate = 0).



- To test the impact of segmentation models on seismic hazard, we:
  1. **penalize ruptures** that cross structural boundaries
  2. construct models with **varying degrees of rupture penalization**
  3. **compare hazard results** for these models

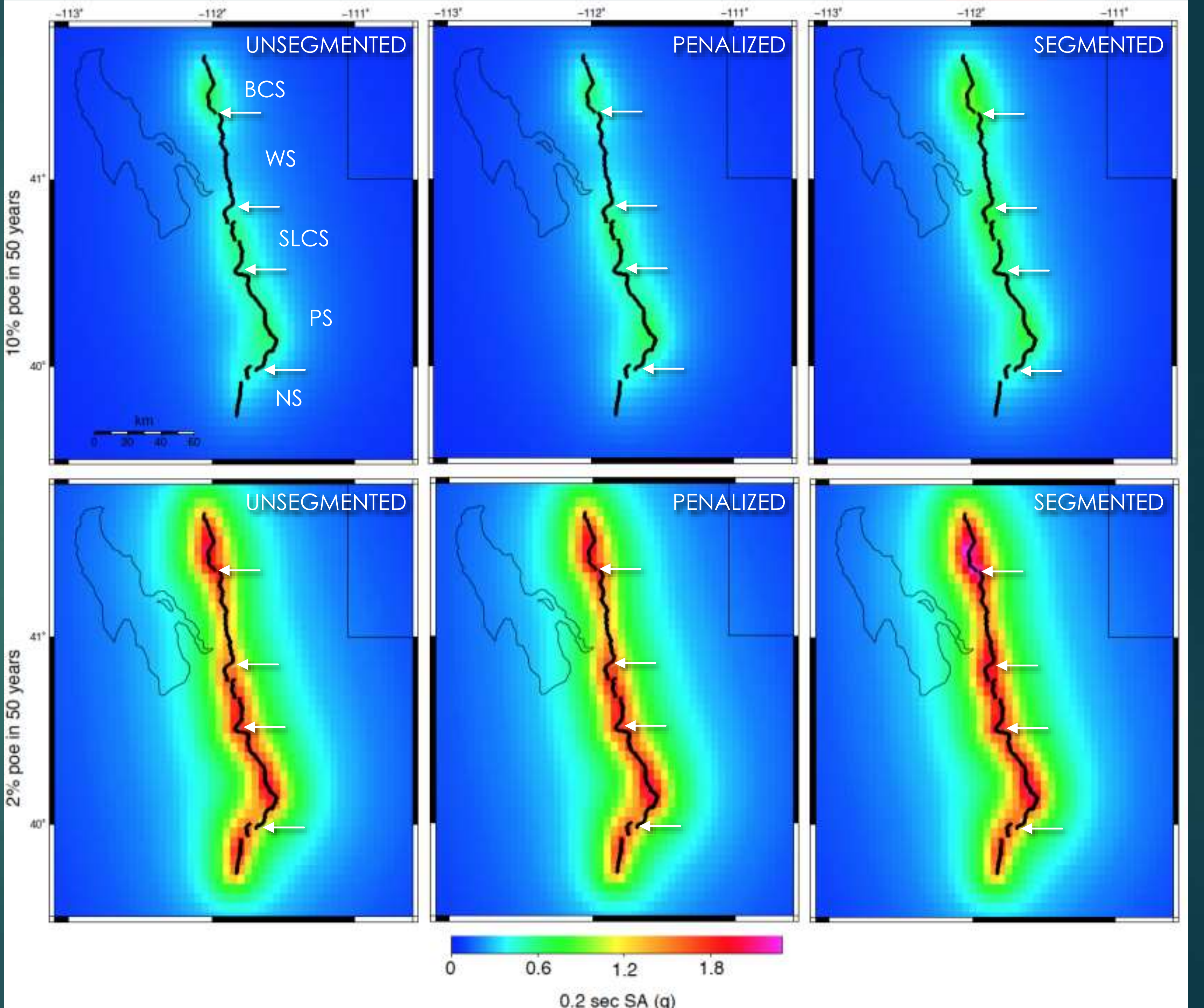
SEGMENTATION

- **3 SEGMENTATION MODELS:**
  - **UNSEGMENTED**: all possible ruptures modeled and allowed to cross boundaries (n = 528).
  - **SEGMENTED**: rate of ruptures crossing segment boundaries reduced to zero (n = 101).
  - **PENALIZED**: some ruptures allowed to cross boundaries (n = 270). Rate of ruptures crossing boundaries reduced (but >zero).



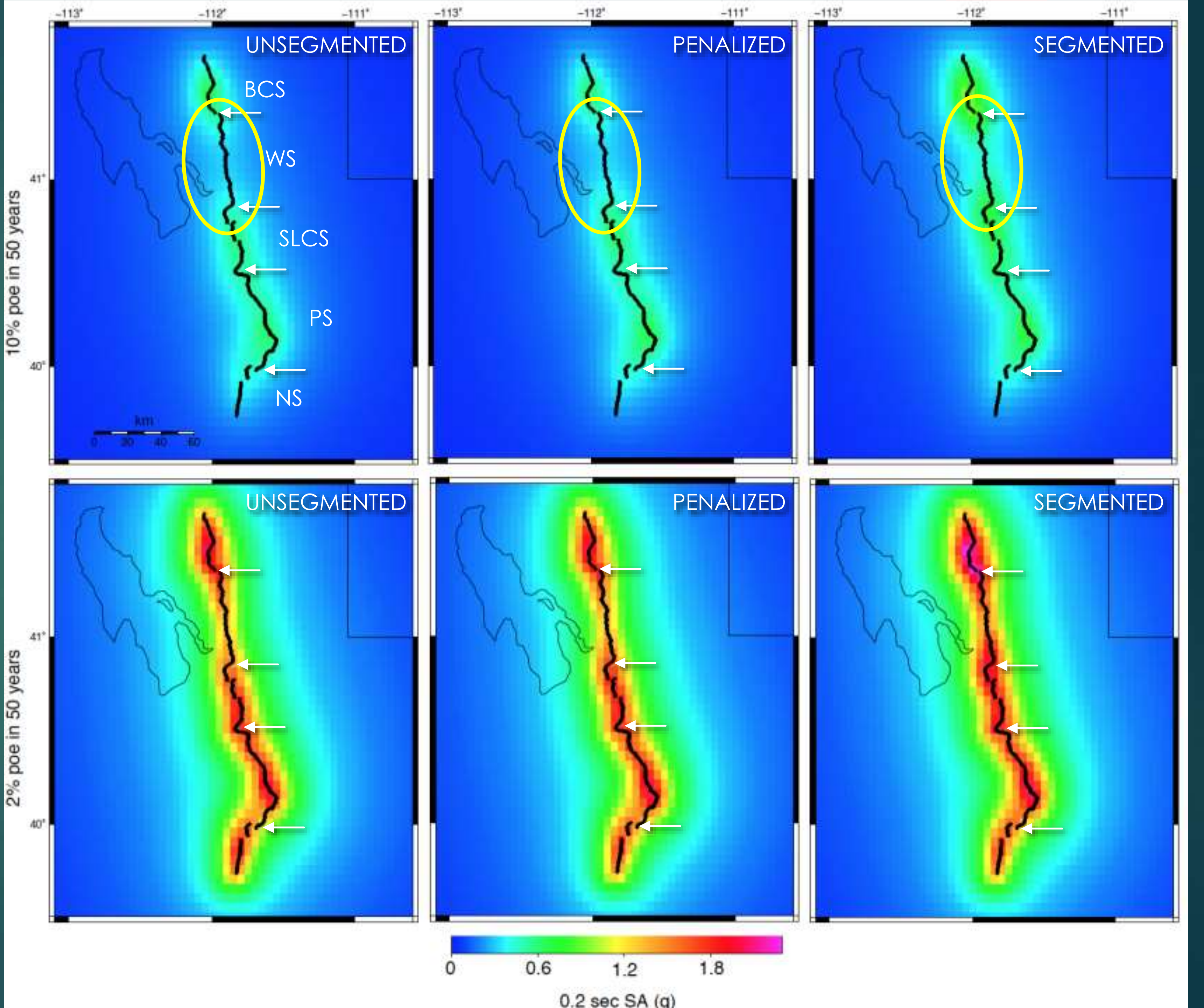
RESULTS

- Hazard in segmented and penalized models generally exceeds that for unsegmented models
  - **UNSEGMENTED**: long, infrequent ruptures
  - **SEGMENTED**: short, frequent ruptures



RESULTS

- Model differences are most pronounced along the northern Wasatch fault zone (northern SLCS to southern BCS)

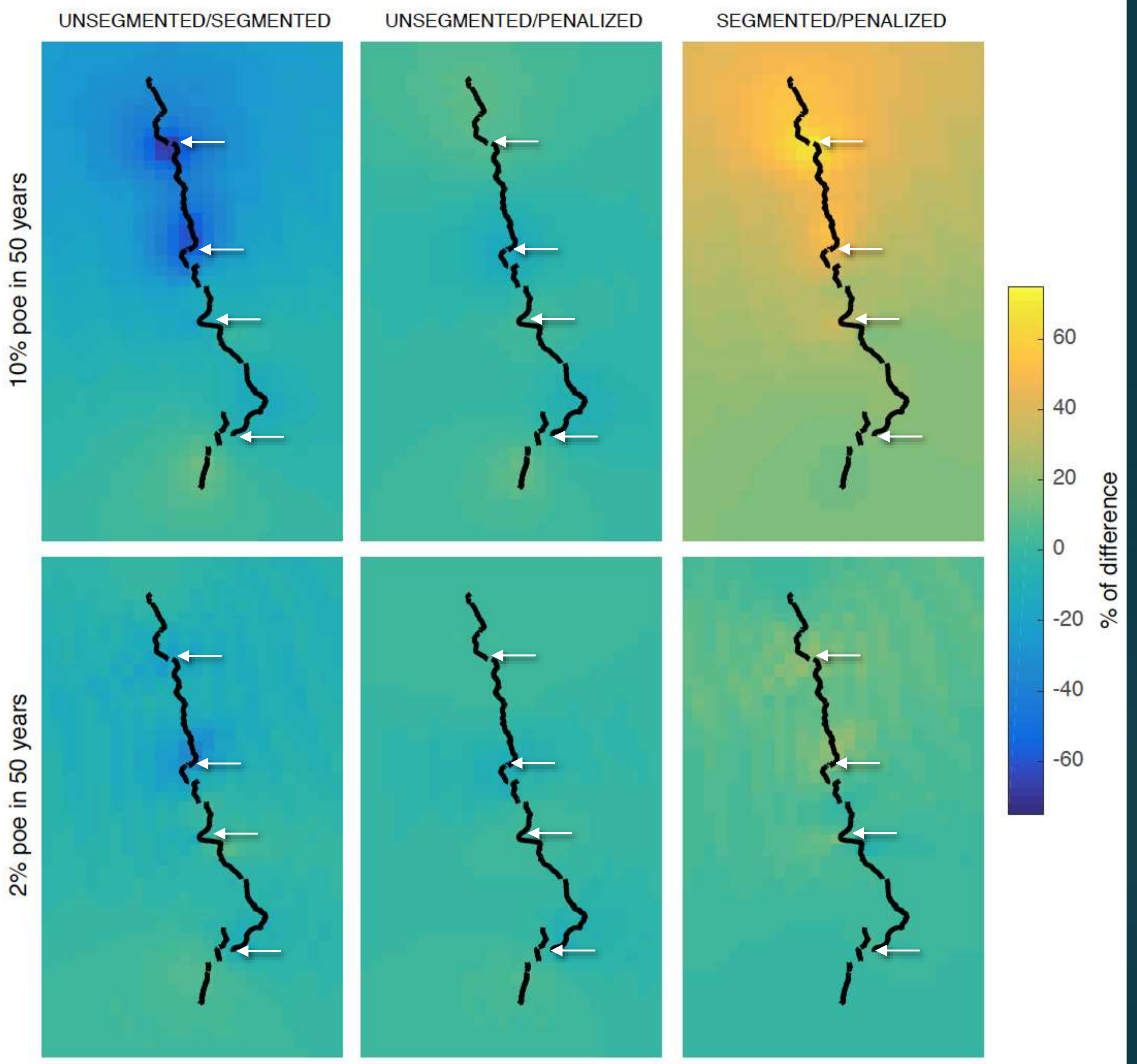


RATIO MAPS

- **SEGMENTATION**: Significant model differences are **~40% to >60%**
- **OTHER PARAMETERS** (e.g., slip rate, Mw regressions, slip model): model differences are mostly **<20%**

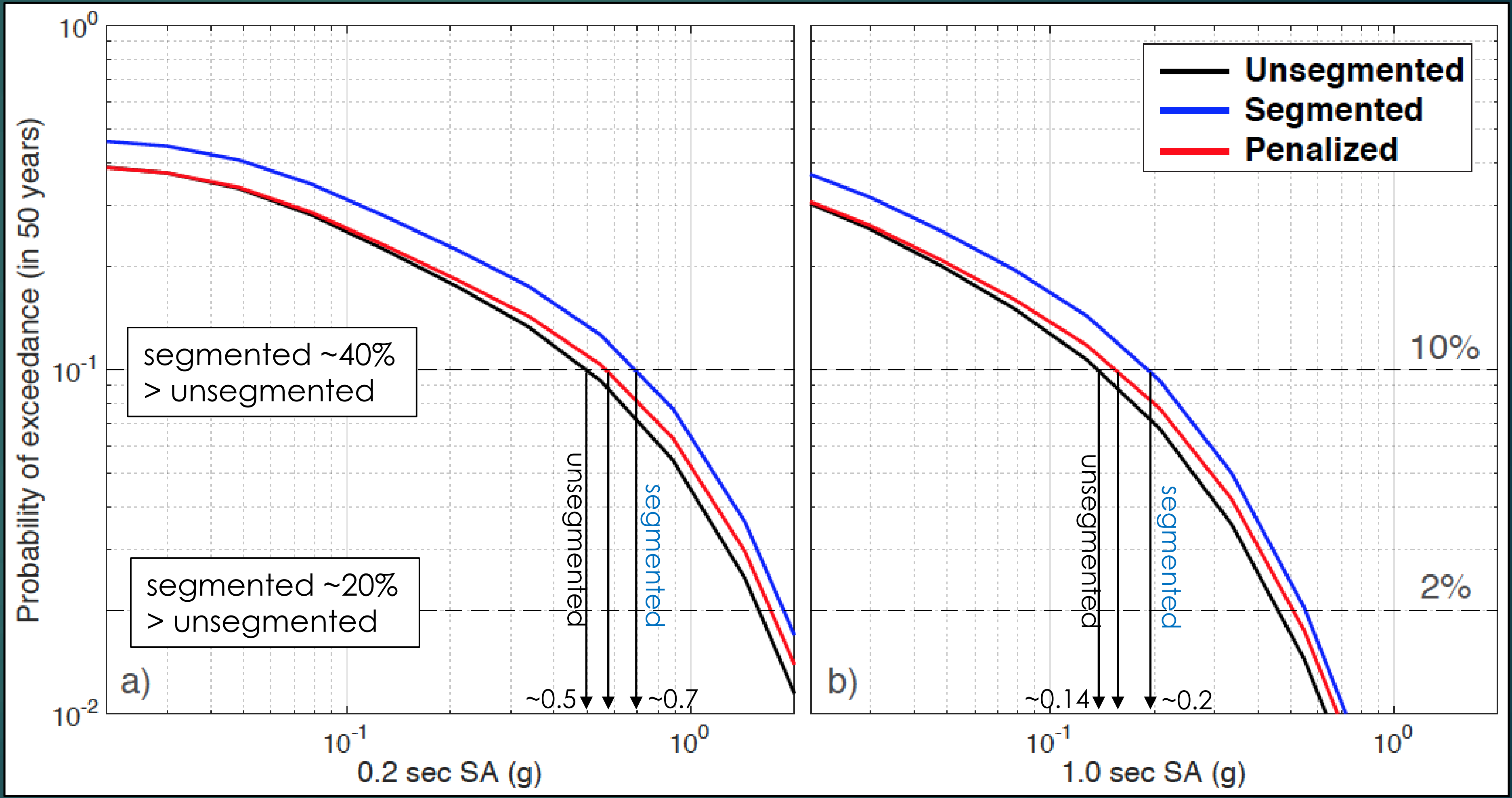
warm (positive):
first model is higher

cold (negative):
second model is higher



HAZARD CURVES

- **HAZARD IN SALT LAKE CITY:** Higher in the segmented & penalized models than in the unsegmented model



CONCLUSIONS

- For the central Wasatch fault zone, **segmentation models have a greater impact on hazard** than other common input parameters.

- Our methods offer a way to **include geologic observations of rupture continuation or termination at structural boundaries** in a fault-based probabilistic seismic-hazard assessment (PSHA).

- **Fault segmentation is a primary source of uncertainty** in fault-based PSHAs—continued research of prehistoric fault rupture lengths will help improve the accuracy of these models.

Lidar Mapping of the Wasatch Fault Zone and Integration into the Utah Quaternary Fault Database

Emily Kleber, Greg McDonald, Adam Hiscock

Utah Geological Survey

Additional mapping from

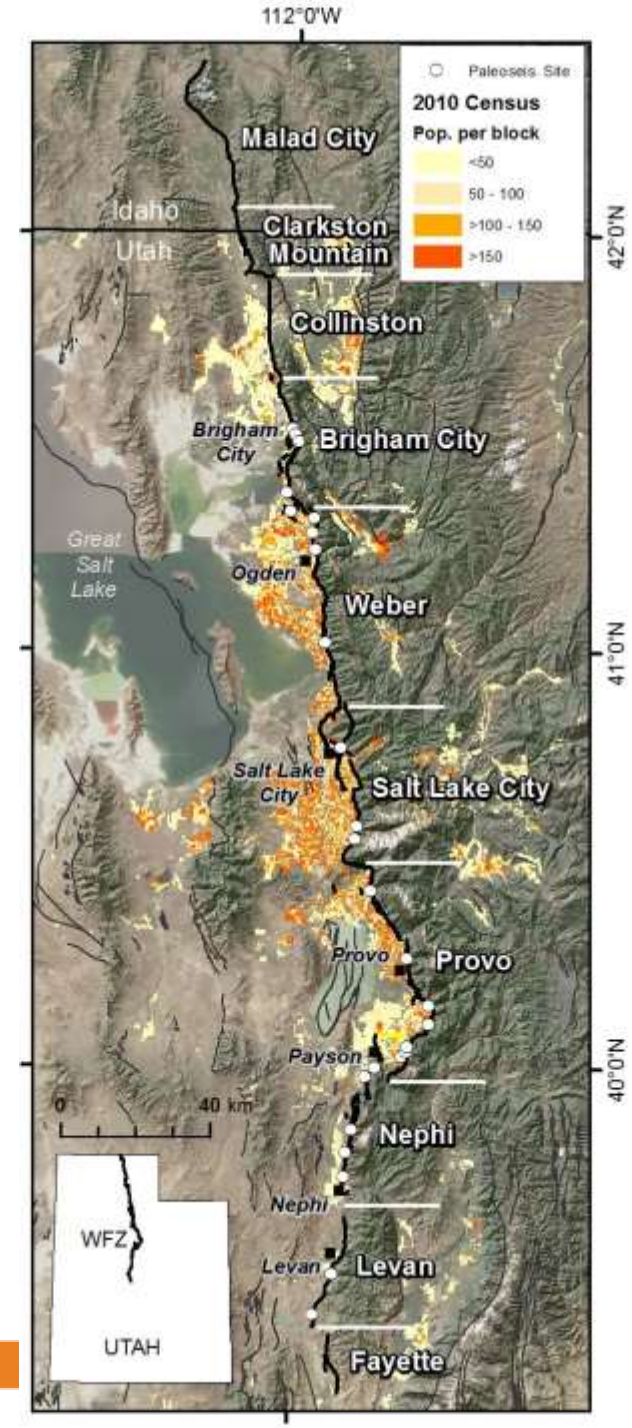
Utah Geological Survey- Adam McKean, Mike Hylland, Kimm Hardy
Mike Lowe, Zach Anderson, Jessica Castleton

U.S Geological Survey- Scott Bennett

Utah Valley University- Nathan Toke

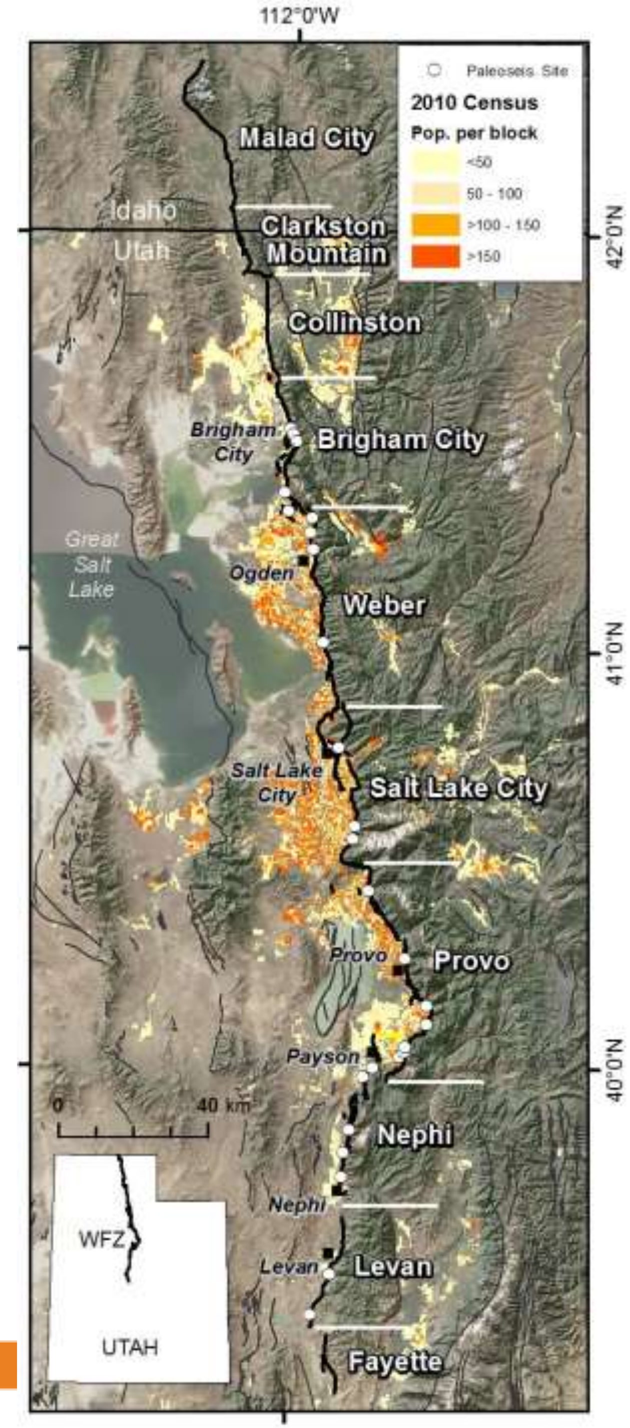
NEHRP funded Wasatch Fault Zone Mapping

- Detailed mapping using high-resolution lidar
  - supplemented with aerial photos and limited field reconnaissance
- Levan and Fayette segments (south end) mapped in 2014-15 by Hiscock and Hylland
- This project
  - Remaining 8 segments
  - 39 7.5-minute quadrangles in Utah; additional 5 quads in Idaho
  - Delineate surface-fault-rupture hazard special study areas
  - Identify potential paleoseismic investigation sites



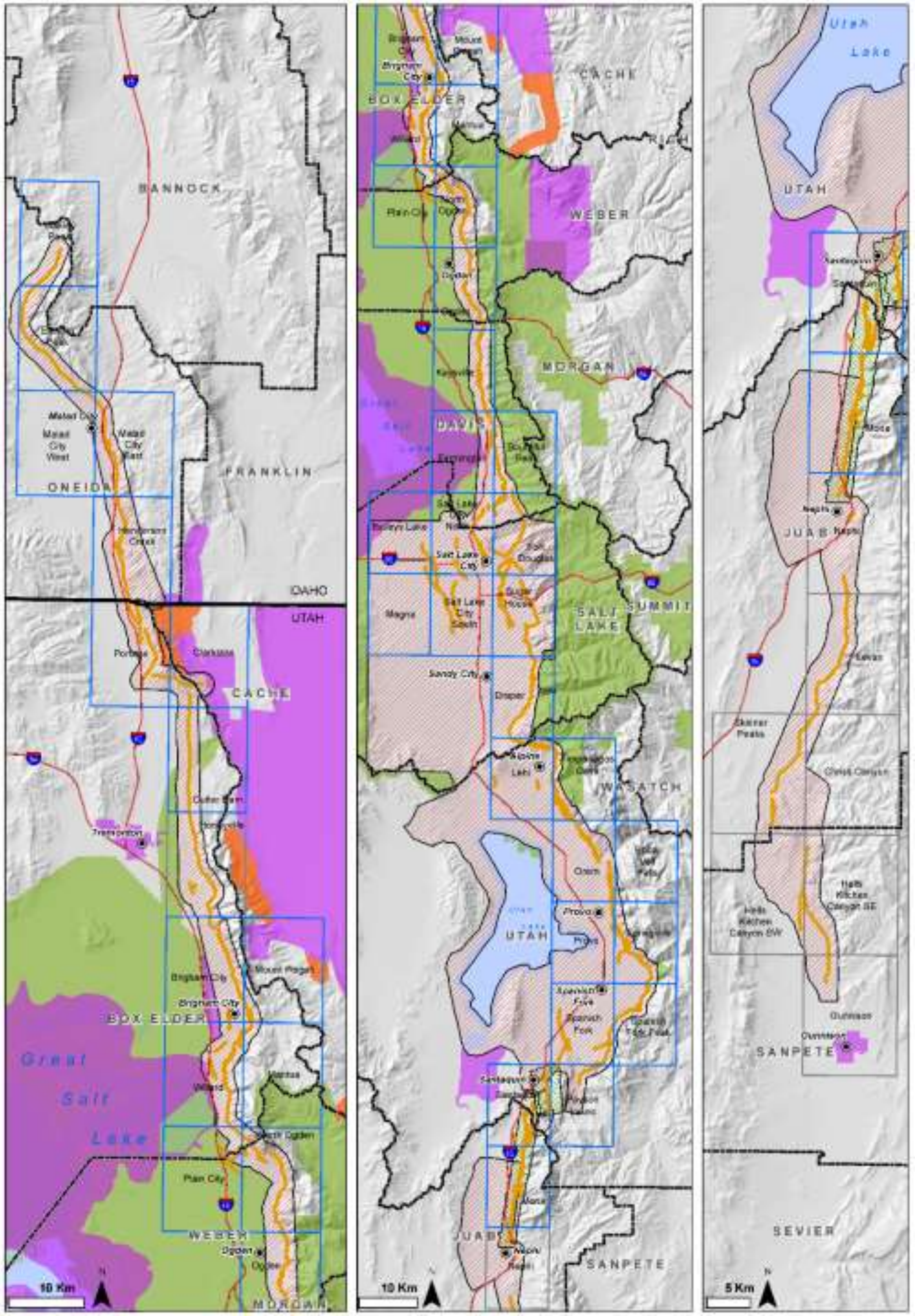
NEHRP funded Wasatch Fault Zone Mapping

- Proposed – May 2016
  - Started – December 2016
  - Ended – November 2017
- FTR report –March 2018
  - Thirty-nine 1:24,000 scale plates
  - 60 potential paleoseismic sites
- Incorporate into Utah Quaternary Fault and Fold Database – Winter 2019

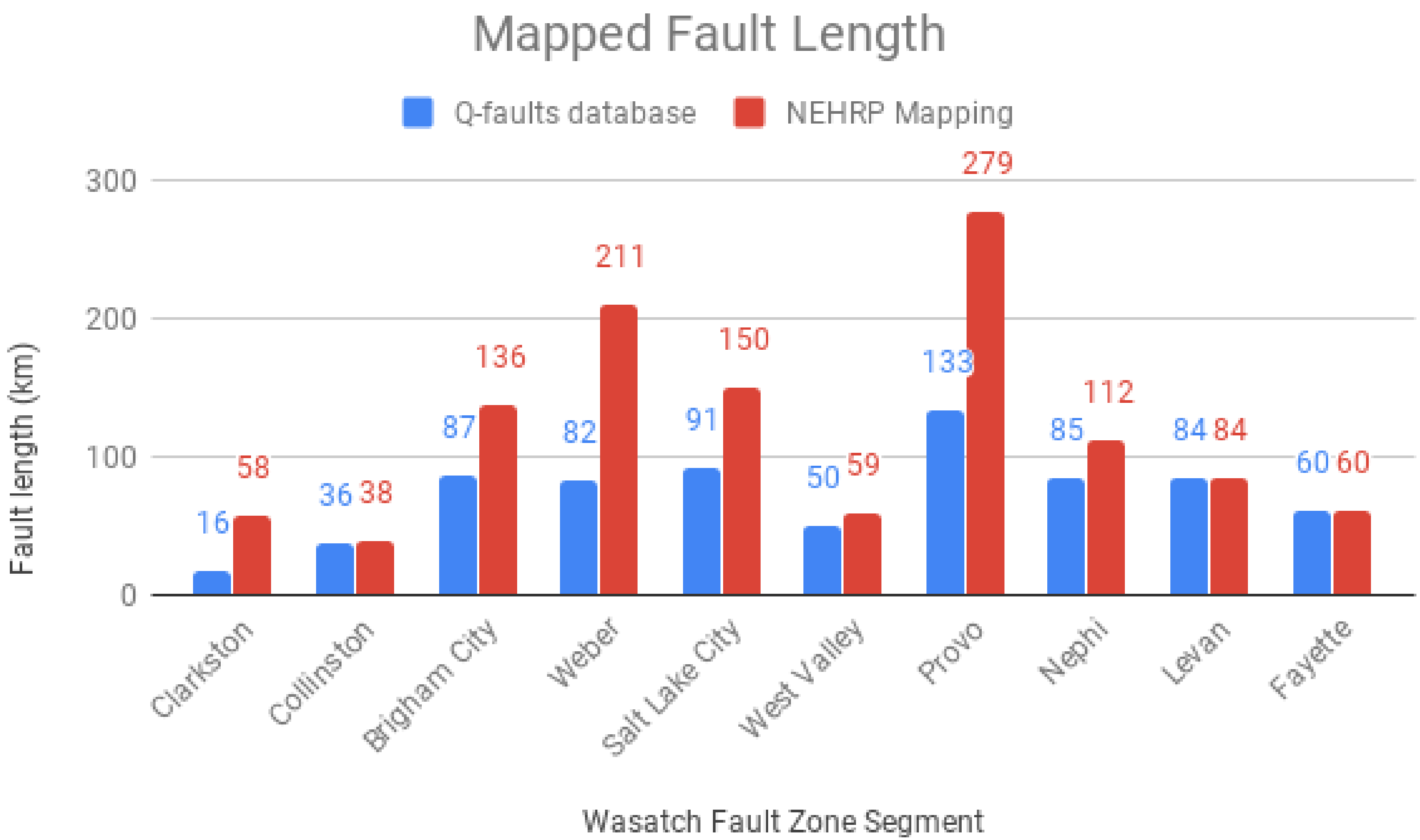


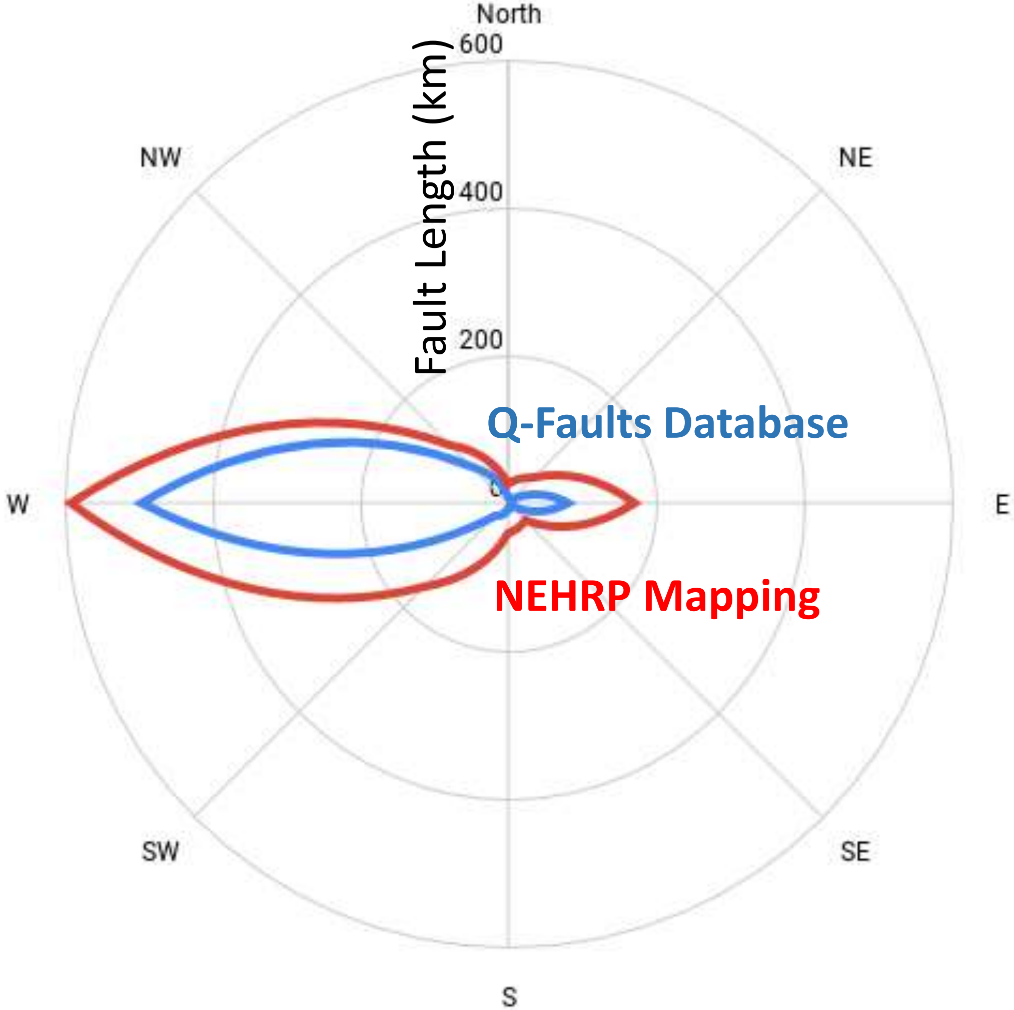
Airborne Lidar Data

- Collected along the Wasatch front
  - 0.5 m lidar-2011-2014
- Lidar derived digital elevation models (DEMs)

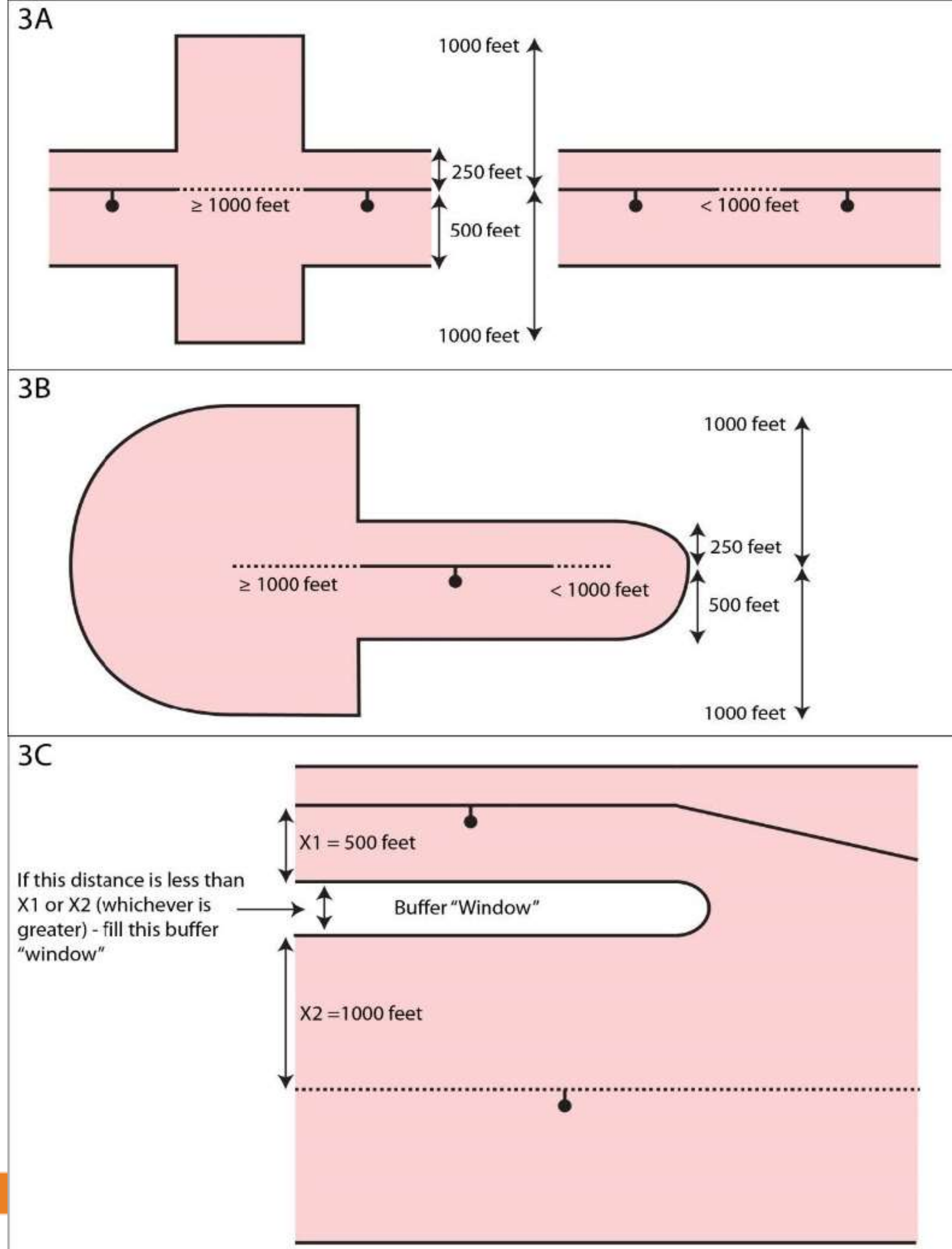


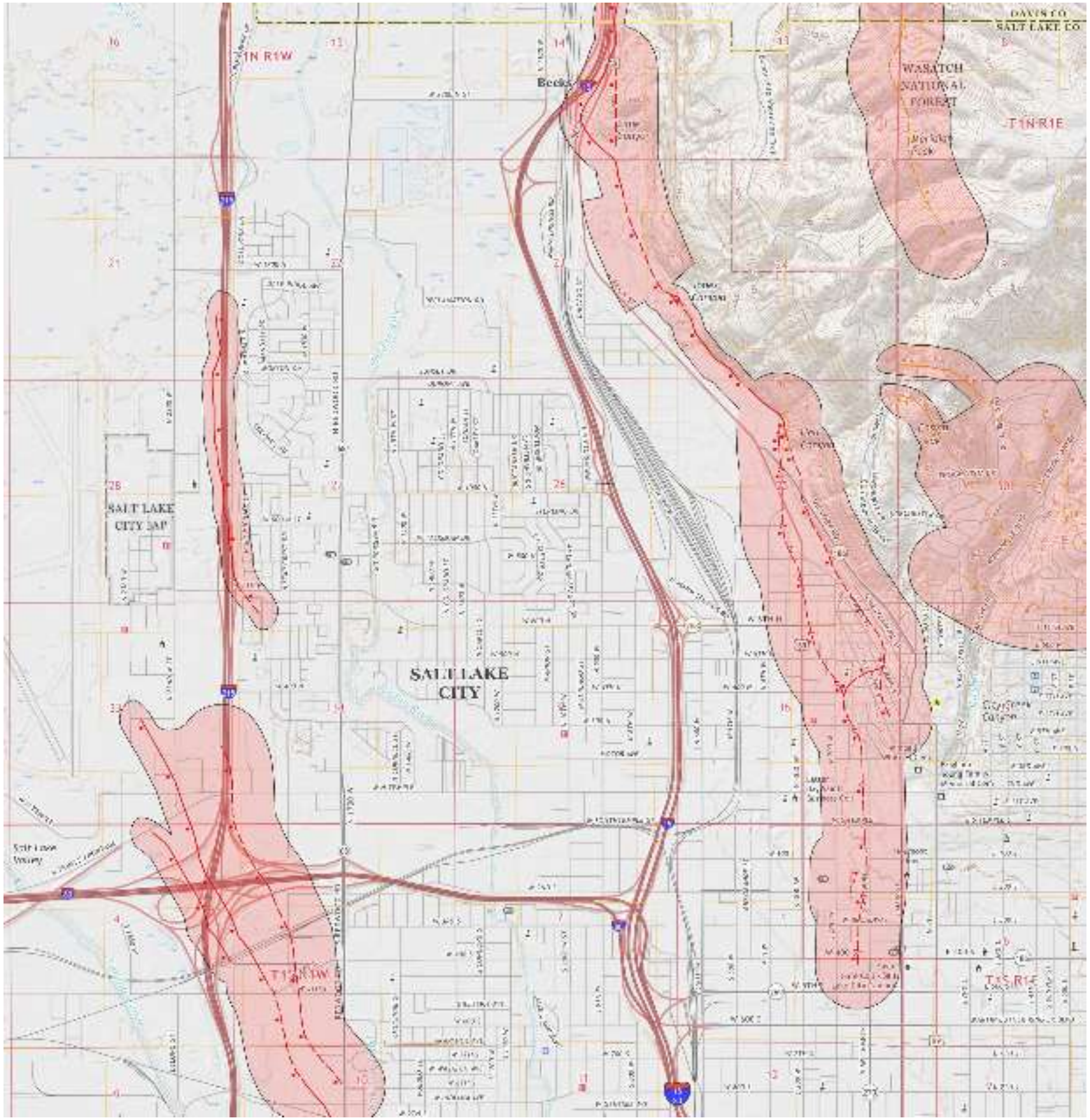
Results of Fault Mapping





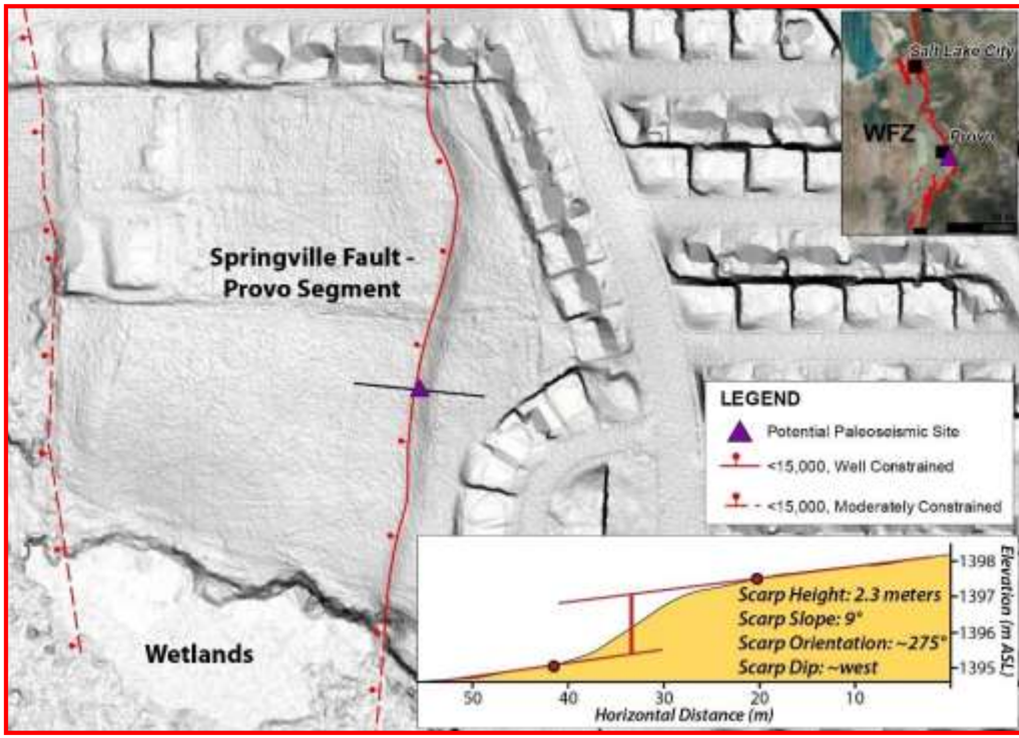
Dip Direction	Q-faults database (km)	NEHRP Mapping (km)
North	9	25
NE	7	48
E	82	171
SE	6	35
S	10	40
SW	24	162
W	496	592
NW	68	112

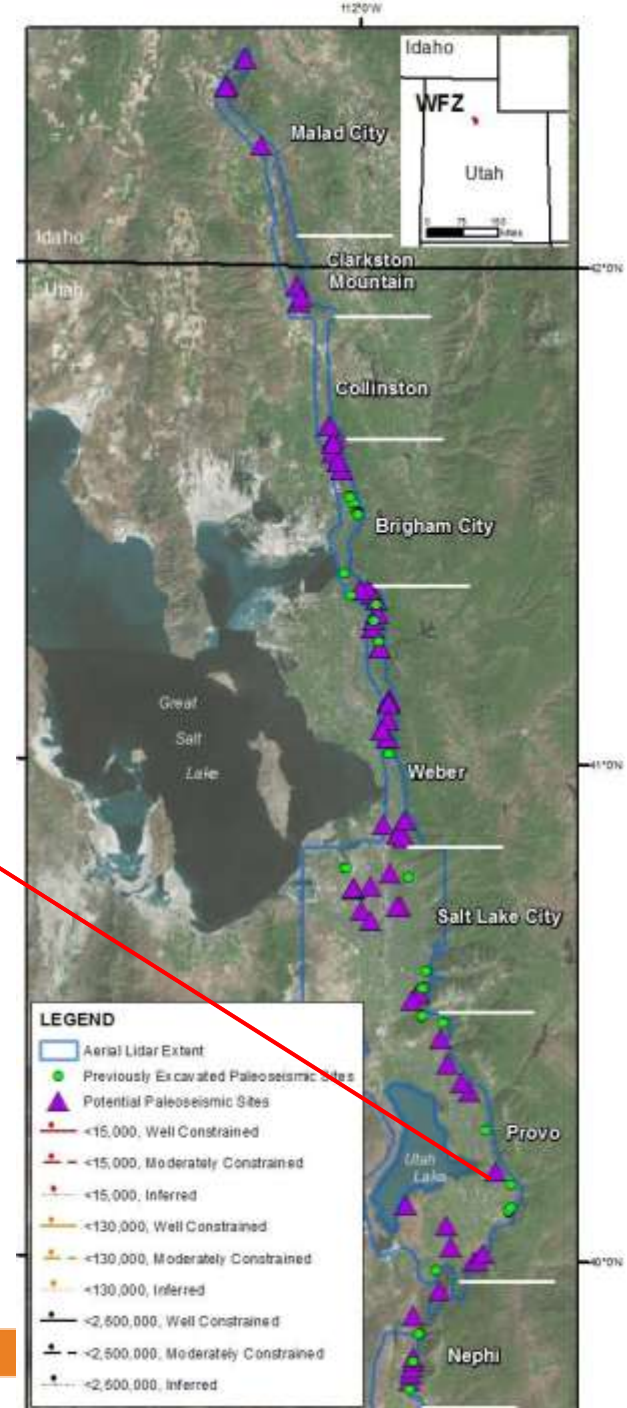

3A
1000 feet
250 feet
≥ 1000 feet
500 feet
1000 feet
< 1000 feet
3B
1000 feet
250 feet
≥ 1000 feet
< 1000 feet
500 feet
1000 feet
3C
X1 = 500 feet
If this distance is less than X1 or X2 (whichever is greater) - fill this buffer "window"
Buffer "Window"
X2 =1000 feet


DAVIS CO
SALT LAKE CO
WASATCH NATIONAL FOREST
T1N R1E
1N R1W
Becks
SALT LAKE CITY
T1S R1E

Paleoseismic Sites

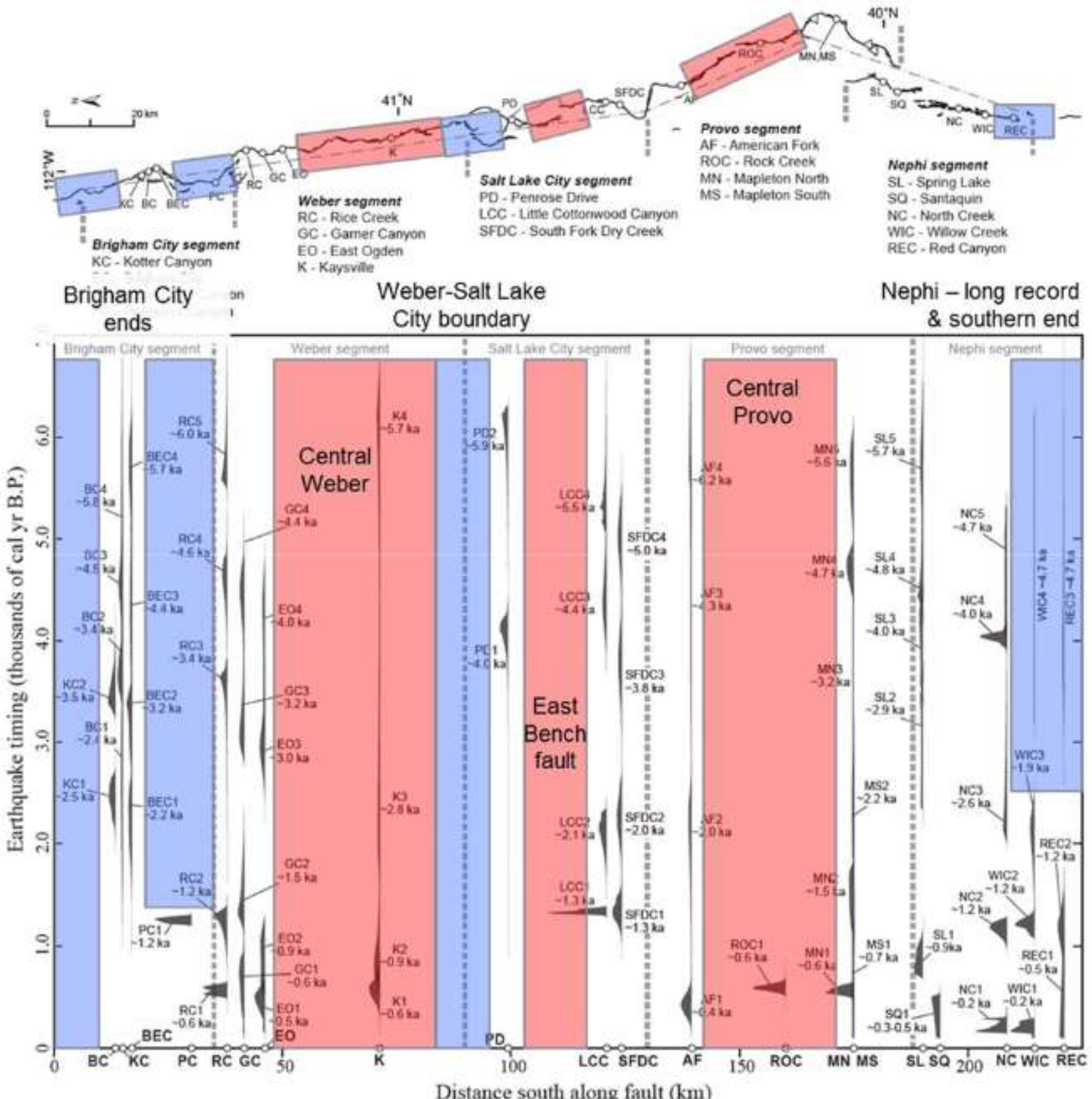
- 60 sites identified





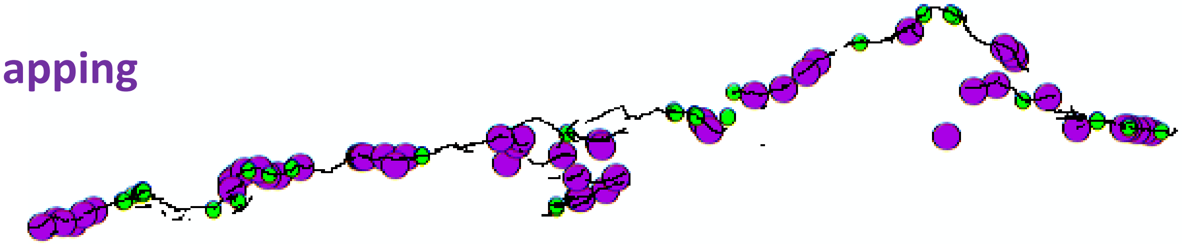
Data gap for central segment

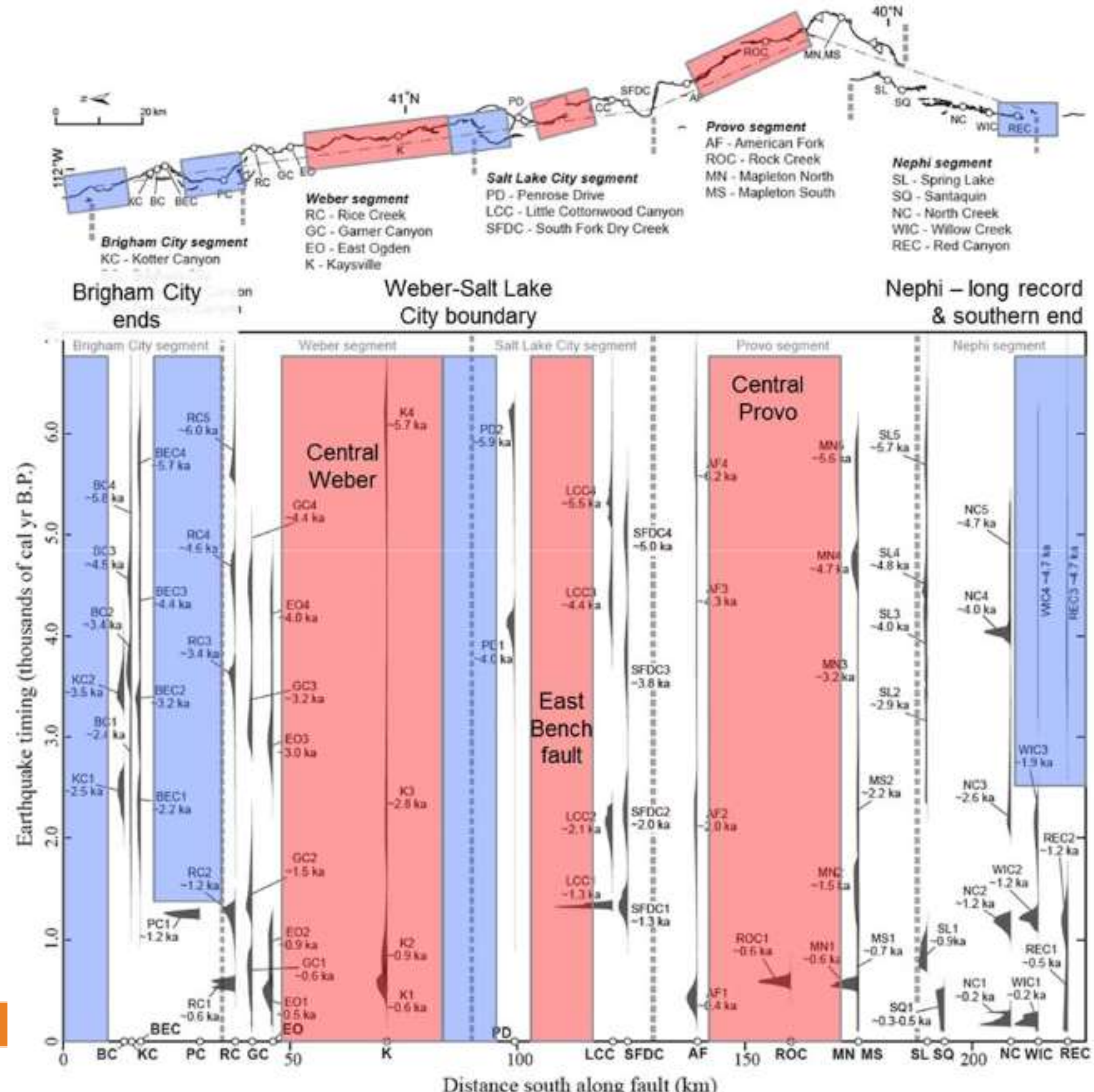
Data gap for segment boundary



Trench site ID by NEHRP funded mapping

Previously excavated trench





Data gap for central segment

Data gap for segment boundary

Ongoing Work

- **FAULT TRACE MAPPING AND SURFACE-FAULT-RUPTURE SPECIAL STUDY ZONE DELINEATION OF THE WASATCH FAULT ZONES, UTAH AND IDAHO (in prep)**
  - UGS Publication- Report of Investigation (ROI)
  - Detail report of mapping methods, and resources, identification of paleoseismic sites, and special study zone delineation.

- Integration of fault mapping to Utah Quaternary Fault Map (ongoing)
  - “Beta” Page to test integration of detailed mapping and special study zones.

- Integration of fault mapping into national USGS Quaternary fault and fold database (pending)

Other Quaternary Faults
Updated January 2019

2352b	East Cache fault zone, Central section
2351i	Wasatch fault, Levan section
2351j	Wasatch fault, Fayette section
2351h	Wasatch fault, Nephi section
2386b	West Valley fault zone, Granger fault
2422	Long Ridge (Northwest Side) fault
2541 (new)	Goshen fault
2542 (new)	East Cedar Valley fault zone
2543 (new)	Dover fault zone
2545 (new)	South Mountain Marginal fault
2540 (new)	Carrington fault
2369a	Great Salt Lake fault zone, Rozel section (new section)
2409	Utah Lake faults

Demo of fault map in poster session...