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Cache Valley: A Critical Part of Lake Bonneville, Record Possible Triggers of the Bonneville Flood, Protracted Bonneville Highstand, Liquefaction, and Cl

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CACHE VALLEY: A CRITICAL PART OF LAKE BONNEVILLE PRESERVES EVIDENCE FOR A PROTRACTED BONNEVILLE HIGHSTAND, POSSIBLE TECTONIC TRIGGERS OF THE BONNEVILLE FLOOD, LIQUEFACTION, AND CLUSTERED EARTHQUAKES ON THE EAST AND WEST CACHE FAULT ZONES

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ABSTRACT

Geologic, geomorphic, and geophysical analyses of landforms, sediments, and structures in conjunction with new radiocarbon (^{14}C) and optically stimulated luminescence (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. 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 relations associated with the Riverdale fault in SE Idaho suggest that a major surface-rupturing earthquake occurred near the Zenda threshold at the north end of Cache Valley around the time of the Bonneville flood (Jänecke and Oaks, 2011a, 2011b). Thus, it is likely that fluctuating loads, rebound, and/or pore pressures induced by changing lake levels may have triggered a large earthquake that in turn initiated the Bonneville flood. The flood ended centuries of stable outflow through the Zenda threshold.

G.K. Gilbert (1880, 1890) first observed that the Bonneville flood scoured a major flood channel from Cache Valley northward that shifted the outlet of Lake Bonneville a great distance southward into Cache Valley. The bedrock sill at the south end of this Swan Lake scour channel became the new threshold for the main 1455 ± 3 m Provo shoreline, 10 m above the commonly accepted altitude of 1445 m (Jänecke and Oaks, 2011a, 2011b). The 1445 m contour in northern Cache Valley coincides instead with a lower Provo shoreline (1446 ± 3 m) that was controlled by a second bedrock sill southeast of Clifton, Idaho. The sparse record of shorelines rebounded from the ~1445 m level in Cache Valley indicate that the outlet at Clifton, Idaho, was quickly abandoned when Lake Bonneville reverted to closed-basin conditions. A dry meandering riverbed connects the Clifton and Swan Lake outlets and preserves evidence of the large northward-flowing Bonneville River across Round Valley. The Great Basin's modern divide at Red Rock Pass formed in the Holocene, after Lake Bonneville, when an eastern tributary near the midpoint of the relict flood channel of the Bonneville River built a small alluvial fan across the Swan Lake scour channel and created a subtle drainage divide (Gilbert 1880, 1890; Jänecke and Oaks, 2011a, 2011b). Gilbert was the first to recognize that that the modern drainage divide at Red Rock Pass is unrelated to Lake Bonneville.

The possibility that an earthquake triggered the Bonneville flood (Jänecke and Oaks, 2011a, 2011b) led us to explore the late Pleistocene activity of normal faults in and near Cache Valley. Just west of Cache Valley, the Wasatch fault zone has increased its slip rate since the Bonneville flood (Hetzel and Hampel, 2005; Karow and Hampel, 2010 and citations therein), but little is known about the response of active normal faults in Cache Valley to loading and unloading by Lake Bonneville. To examine the relations between ancient seismicity and lake history, we re-excavated deformed Upper Pleistocene sandy lake beds along a ~50 m by 5 m collapsed north wall of an abandoned gravel pit at the mouth of Green Canyon in Cache Valley, Utah. Utah State University faculty identified two liquefaction events in the outcrop in the 1980s 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 is within the boundary between the northern and central Utah segments of the East Cache fault zone (McCalpin, 1994). It is ~25 m to ~170 m basinward, respectively, of two diverging fault strands of the East Cache fault zone, and there might be additional buried faults at lower elevation than the exposure near the main upper Provo shoreline (McCalpin, 1989; this study).

Deposition of upward coarsening lacustrine deposition in the delta of Green Canyon started before 22.4 ± 0.4 cal kyr B.P. (^{14}C) with deposition of prodelta clay, mud, and silt, and continued after 20.1 ± 0.3 cal kyr B.P. (^{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 *Stagnicola* gastropod shells throughout the exposure, and the position of the beds ~40–45 m below the Bonneville shoreline at Green Canyon.

Fifteen new age determinations indicate early onset of deep lake conditions in Cache Valley at or higher than 1515 to 1510 m (corrected for rebound)(this study and Rittenour and others, 2019). The high altitude of the lake provides additional evidence for Oaks and others' (2019; this volume) interpretation of Cache Valley Bay. Oaks and others (2019) dated prior lake cycles in Cache Valley, documented their unexpectedly high altitudes, and concluded that Cache Valley was filled by a separate pluvial lake from the main Bonneville basin until the rise to the Bonneville highstand connected them across the Junction Hills. Integration of Cache Valley lake into the main Bonneville basin must postdate the lake beds in Cache Valley that were deposited at higher altitudes than predicted by the Bonneville hydrograph, like the transgressive sediment in the paleodelta at Green Canyon.

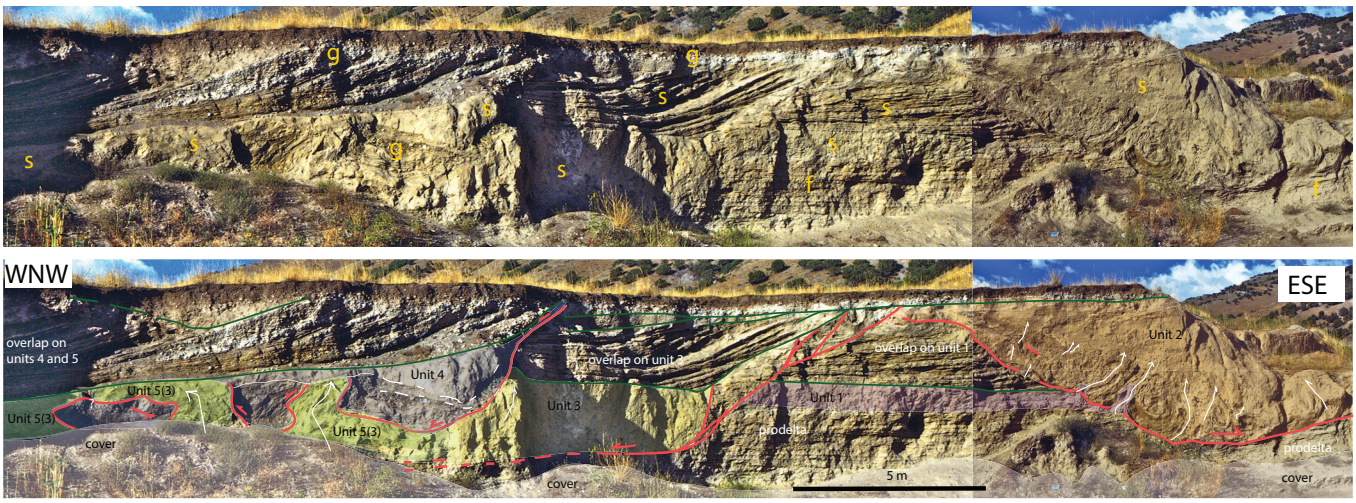

Figure 1. *View to north-northeast of deltaic sediment of Green Canyon in 1980. Colored units are liquefied masses of event horizons 1-5. Unit 3 was activated a second time in a diapiric mode during event 5. Undeformed cap of alluvial gravel is probably flood related (?), and overlies deformed deltaic sand (s) and gravel (g) from the last pluvial along an angular unconformity. Each green line is an angular unconformity. Lower one-third of exposure contains mostly prodelta fine sand, silt and clay (f=fines). Orange lines are slip surfaces of nested slumps in lateral spreads. Each event bed has a major unconformity at the upper surface (green lines).*

We uncovered multiply deformed shallow lake beds and one capping fluvial gravel in the exposure 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 relations are exceptionally clear. The deltaic sediment of Green Canyon was deposited, seismically deformed, and slumped in at least four strong earthquakes under subaqueous conditions in a shallow-water, deltaic part of Cache Valley lake. 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 ~2–5 kyr of high lake levels prior to the Bonneville flood. The geometry and position in the landscape of a laterally continuous alluvial gravel bed, which overlies 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 during the Bonneville flood. The gravel cap may be a flood deposit or barely postdate the Bonneville flood because it predates focused downcutting along the modern channel of Green Canyon Wash that began with the Bonneville flood and occupation of the Provo shorelines ~70 m lower in the landscape. All the deformation in the exposure must therefore predate the Bonneville flood at ~18 ka.

The Green Canyon site exposes three listric slip surfaces of lateral spreads, four sequential thick liquefied units, and less deformed flat and cross-stratified lacustrine and deltaic sediment. Each thick liquefied mass of sand is a different age, yet all of the deformation occurred when the sediment was saturated by the pluvial lake as it approached or stabilized at its highest shoreline. 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 fault-graded beds above them. Deposition was ongoing, and produced multiple cross-cutting relations 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 geosol. Each LSLP and SBLM formed during a discrete event.

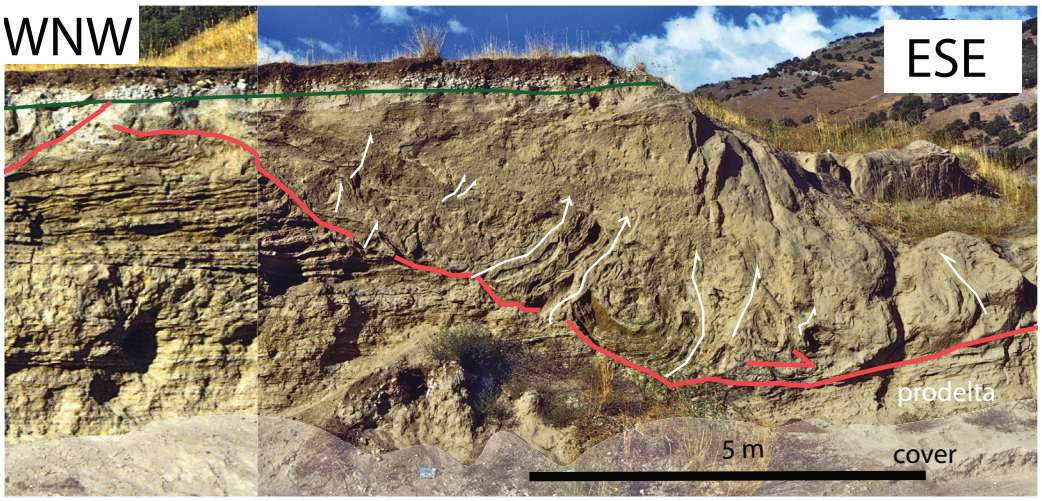

Figure 2. *Fault-graded beds of event bed number 2, as it was exposed in the 1980s above a listric slip surface (longest red line). See figure 1 for its position in the exposure. The largest pseudonodule is about 2.5 m across. Fluid escape (white arrows trace sand dikes and sills) created the pseudonodules low in the event layer. The upper two-thirds of the event layer is massive and disaggregated due to protracted shaking and liquefaction. Fault-graded bedding like this is diagnostic of seismic shaking of sediment under a body of water (Rodriguez and others, 2000). View to north-northeast. Red contacts within the event bed separate more deformed above from less-deformed part of the fault-graded bed, below. Note the fluvial gravel at the top of the outcrop, which might be related to the Bonneville flood.*

Each was subsequently capped by a major erosional surface, upon which 1–2 m of stratified sediment was deposited. The youngest LSLP deformed twice, and its diapirically deformed slip surface records deformation during two strong earthquakes. Seiches likely produced each erosion surface. 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 one SBLM from one another. Less extreme deformation modified the intervening lake beds.

The most extreme deformation is expressed in fault-graded beds that are 1–5 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 and others, 1992) indicate that seismic shaking is the most likely explanation for the five largest deformational events recorded at the mouth of Green Canyon. The smaller deformation 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, brittle fluid-escape structures, buried scarps, sand dikes, erosion of each fault-graded bed, and angular unconformities. We propose that five separate moderate to large earthquakes shook and liquefied the sediment between ~22.4 ka and the Bonneville flood (~ 18 ka; age from Miller, 2016). Those earthquakes probably ruptured the nearby central or northern segments of the East Cache fault because other gravel pits lack liquefied sediment in coeval deposits elsewhere in Cache Valley.

If we are correct that each liquefaction and major diapiric re-liquefaction event records a moderate to large earthquake when a deep pluvial lake filled Cache Valley, then the adjacent part of the East Cache fault zone generated at least five major earthquakes during the last pluvial between about 22.4 ka and the Bonneville flood at about 18 cal kyr B.P.. The paleoseismic data of McCalpin (1994) documents one additional earthquake along the East Cache fault zone as Lake Bonneville paused at the Provo shoreline. The temporal clustering of the ≥ 6 syn-Bonneville paleoearthquakes, their strong spatial association with the East Cache fault zone, the paucity of deformation at the site after the Bonneville flood, and the absence of liquefaction in coeval sediment elsewhere in Cache Valley, are all consistent with a high frequency of liquefaction-inducing earthquakes along the central or northern segment of the East Cache fault during the transgression and highstand of the pluvial lake in Cache Valley. A single mid-Holocene earthquake that occurred ~ 4–5 ka is the only earthquake known to have ruptured the East Cache fault zone during the Holocene (McCalpin, 1994). Altogether, there has been a significant decline in earthquake frequency since the deep-water phase of the Bonneville lake cycle along the East Cache fault zone.

The low earthquake frequency along the Utah part of the East Cache fault zone documented here in the Holocene is in marked contrast to the history of the West Cache fault zone and the Wasatch fault zone; those western fault zones generated numerous Holocene earthquakes (Black and others, 1999, 2000; Solomon, 1999; Hetzel and Hampel, 2005; Ellis and Jänecke, 2018). We explain the opposite earthquake histories of the East and West Cache fault zones as the consequence of opposite flexural stresses induced by the loading and later rebound produced by pluvial lakes along an upper monoclinal hinge (near the East Cache fault zone) and along a lower monoclinal hinge (near the West Cache fault zone and the Wasatch fault zone) at the eastern

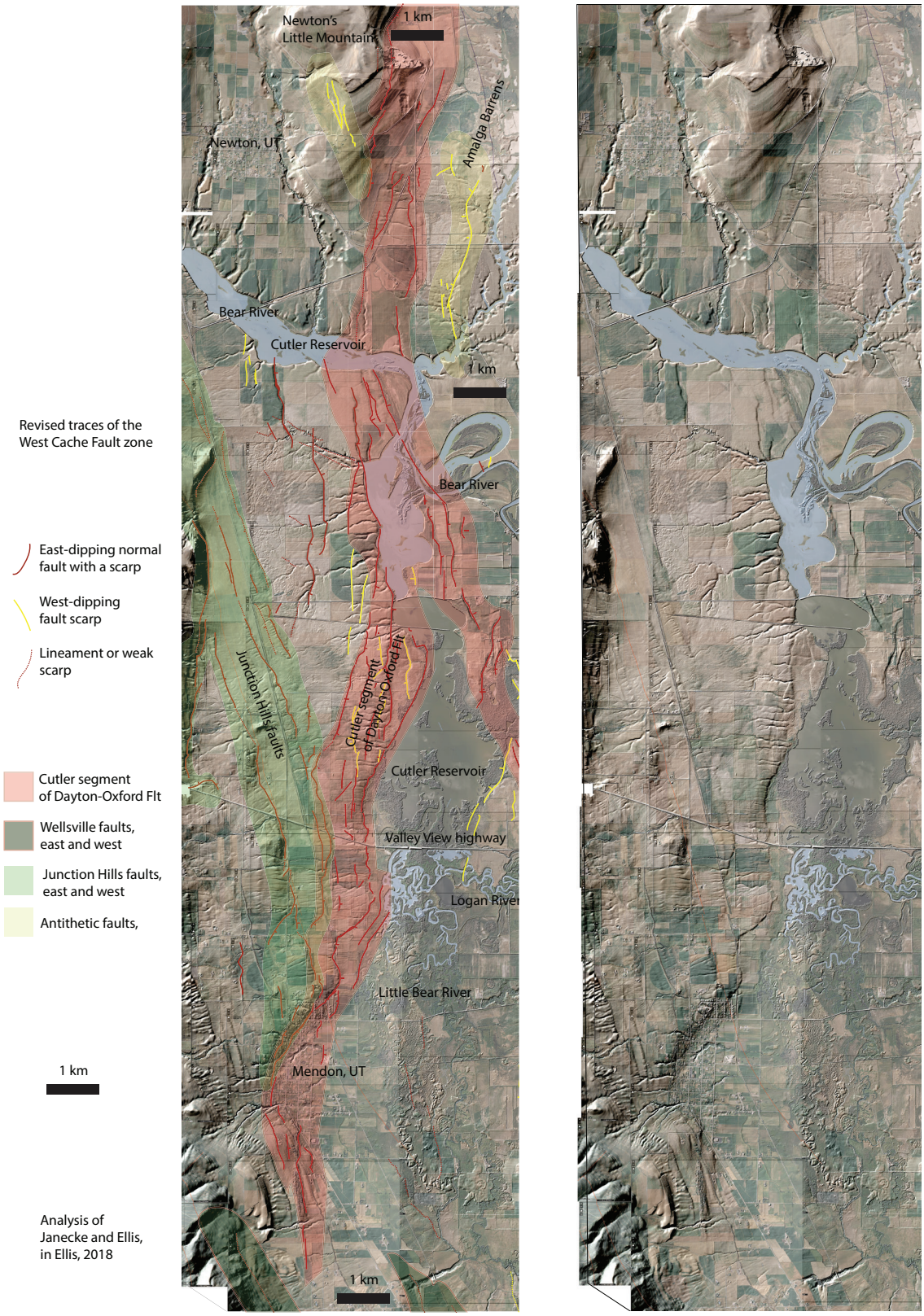

Figure 3. *New traces of the West Cache fault zone identified using lidar by Ellis and Jänecke (2018) on the floor of Cache Valley. Fault zones are up to 1 km wide and contain both east- and west-dipping traces. Geophysical datasets support this interpretation (Evans and Oaks, 1996). The Dayton-Oxford fault is much longer than previously known, connects with both the Junction Hills and Wellsville faults, and joins these other faults to form a very high fault scarp in Mendon, Utah. Jänecke and Evans (2017) identified a small subset of these faults.*

margin of Lake Bonneville and Cache Valley lake. Lateral changes in loading within Lake Bonneville and Cache Valley lake could explain clustered earthquake 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 groundwater. Similar processes might explain the rough coincidence of the Bonneville flood and the last major earthquake on the Riverdale fault zone in northern Cache Valley (Jänecke and Oaks, 2011a, 2011b).

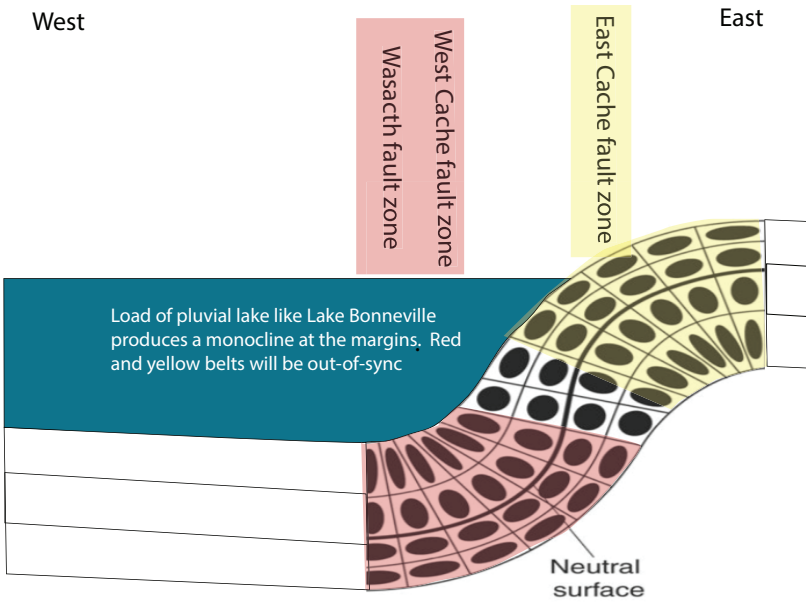

Figure 4. *Conceptual model of enhanced extension along the East Cache fault zone during the last pluvial. Rebound during the Holocene caused the western faults to be more active than the eastern fault zone.*

The West Cache fault zone ruptured at least three times in the Holocene (Black and others, 1999, 2000; Solomon, 1999), and a fourth Holocene earthquake is likely because it displaces Holocene marsh deposits on the floor of Cache Valley along newly identified traces of the Cutler Reservoir segment of the Dayton-Oxford fault zone (Ellis and Jänecke 2018). This fault segment links the Wellsville, Junction Hills, and Dayton-Oxford faults with one another (Jänecke and Evans, 2017; Ellis and Jänecke, 2018; Jänecke and others, 2019). Holocene scarps along most of the new traces nearly double the length of active fault traces mapped in the West Cache fault zone. At least one additional surface-rupturing earthquake is needed to explain the plethora of Holocene fault scarps on the floor of Cache Valley. Altogether these data suggest that the West Cache fault zone and the Wasatch fault zone, were positioned near the lower monoclinal hinge of the flexurally bending lithosphere, and both have been particularly active since Lake Bonneville disappeared.

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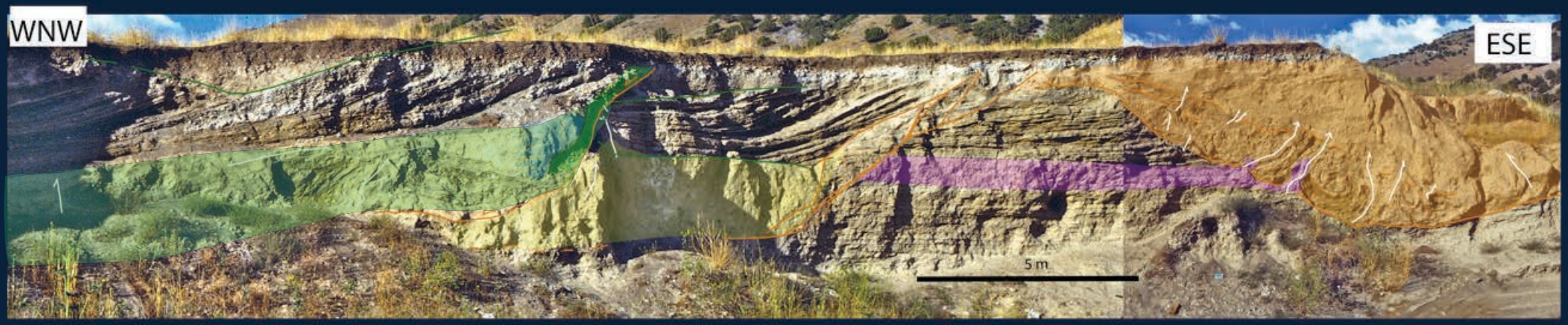
This content is a PDF version of the author's PowerPoint presentation.

Cache Valley: clustered earthquakes, liquefaction, possible triggers of the Bonneville flood

See our abstract for other topics



All views of exposure are to the NNE

Susanne Janecke
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Tammy Rittenour
A.J. Knight
and Justin Oakeson

UtahState UNIVERSITY Geology

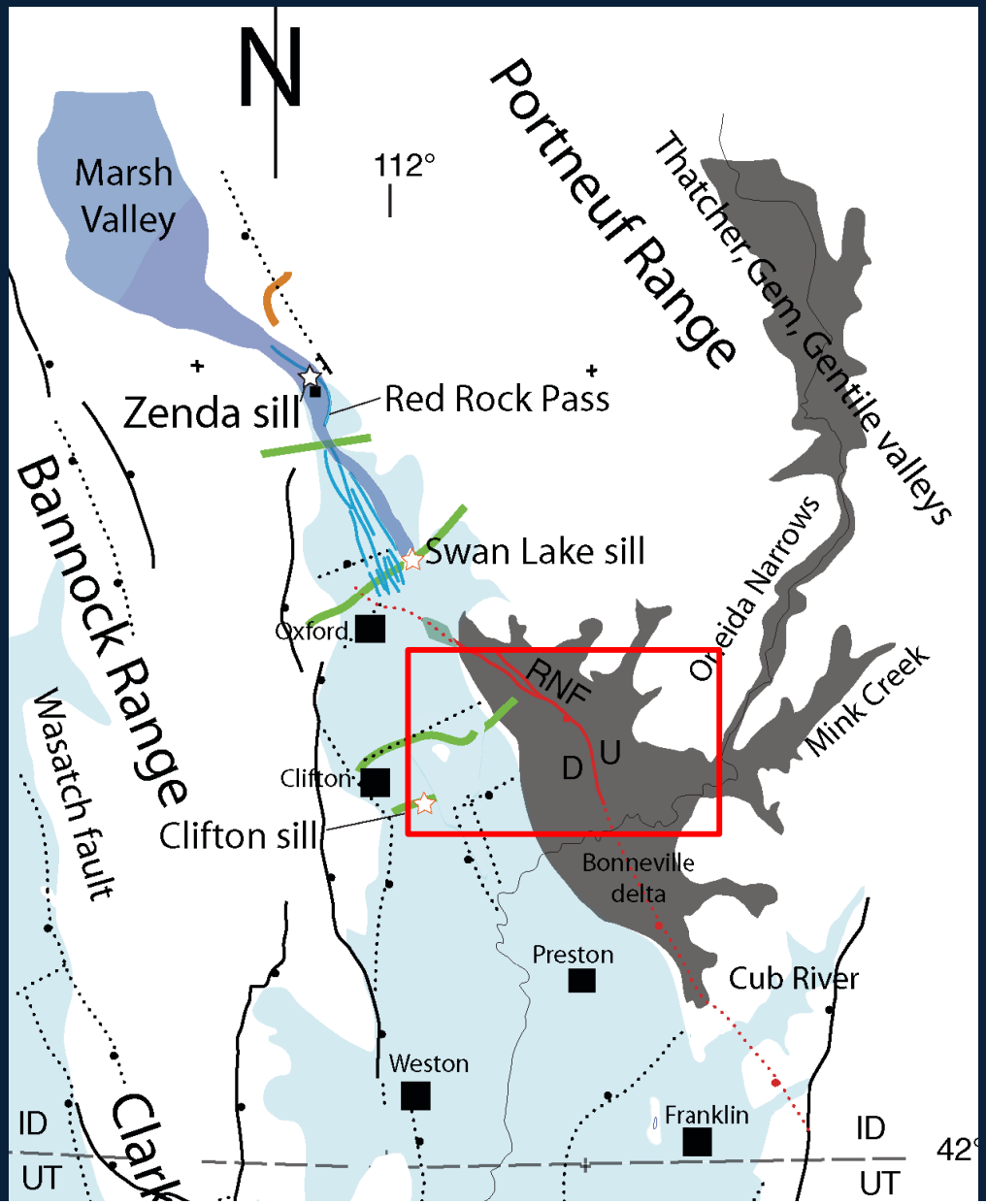
Each colored unit is liquefied

Why are we discussing liquefaction and earthquakes in a Bonneville symposium?- 2 main reasons

Susanne U. Janecke and
Robert Q. Oaks, Jr.
Department of Geology
Geosphere 2011

Dry bed of the Bonneville river in northern Cache Valley

Reason 1: Riverdale fault, Idaho, produced a major surface-rupturing scarp across the Bonneville delta around the time of the Bonneville flood. That earthquake might have triggered the Bonneville flood.
Janecke and Oaks, 2011



Bonneville delta at max extent

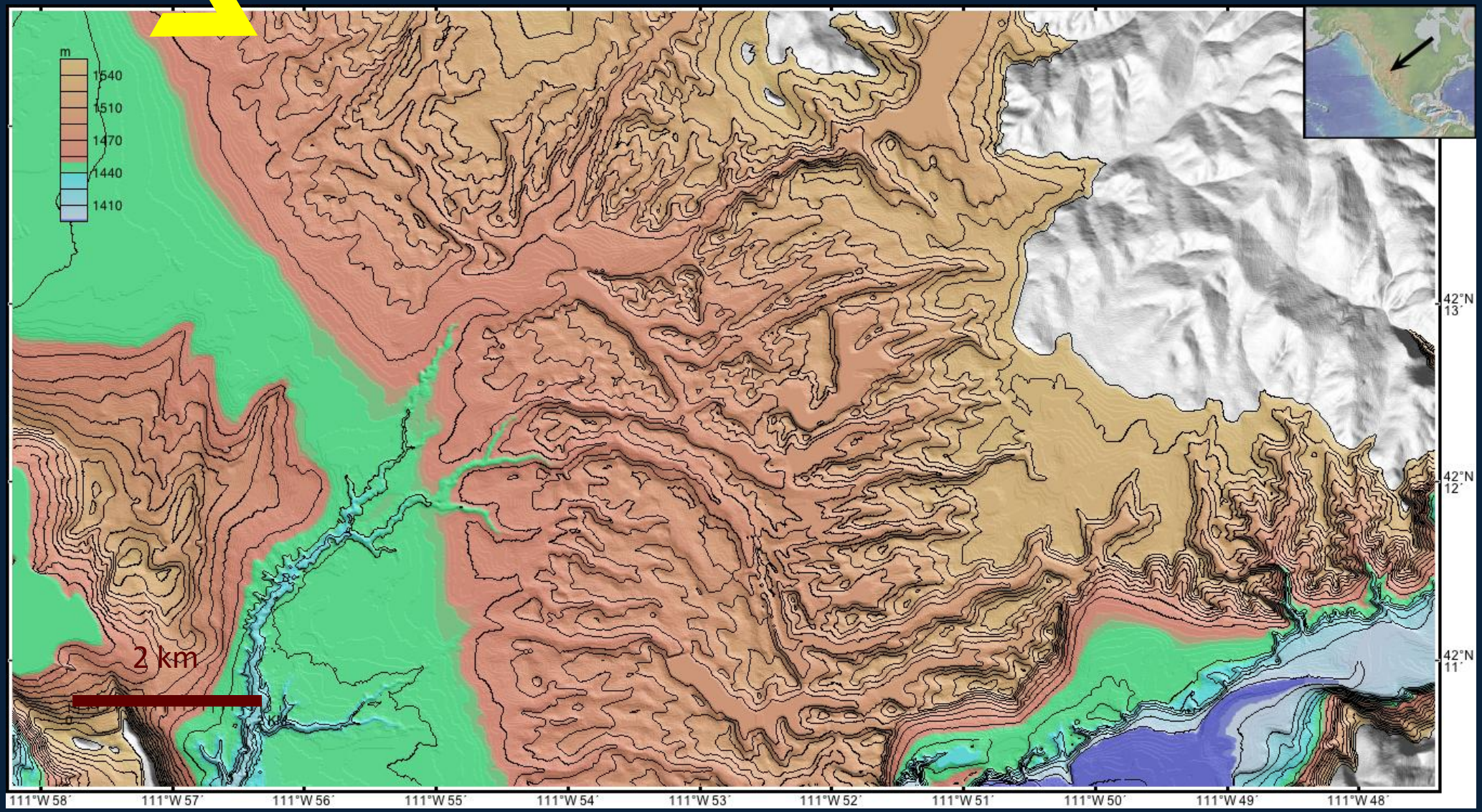
THEN

Riverdale Fault cuts it

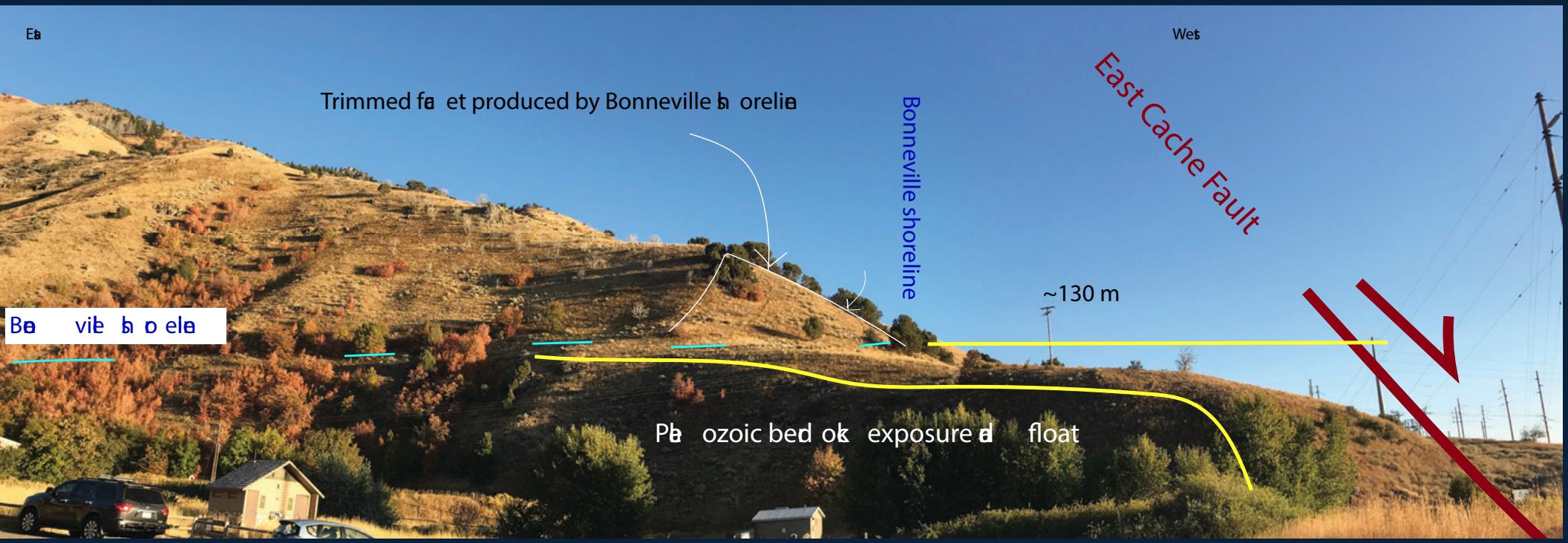
THEN

Provo delta of Bear River

This normal fault is 50 km long and cuts Bonneville deposits for ~10 km across the delta topset



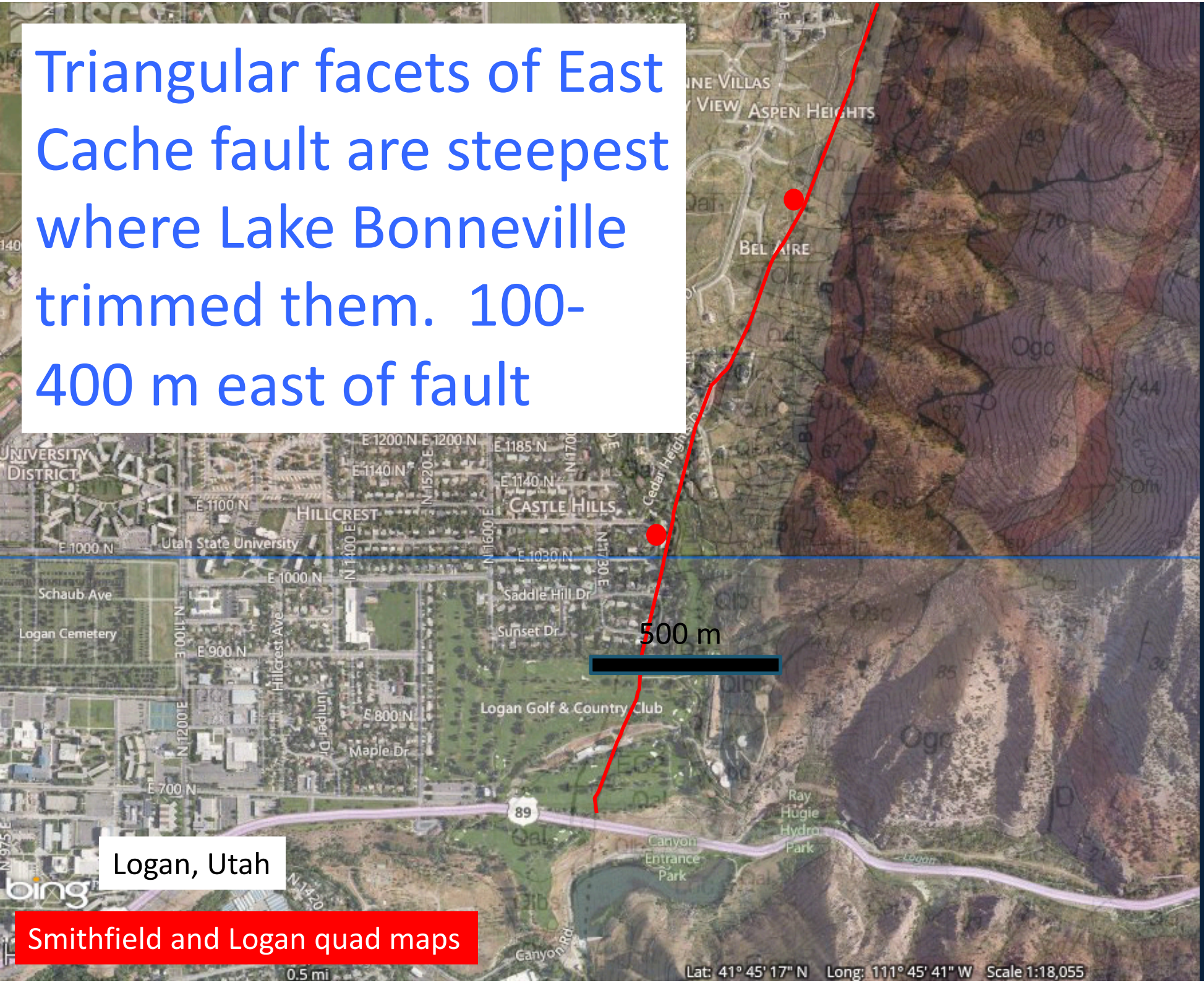
REASON 2: Landscape suggests that Lake Bonneville must have been stable at its highest shoreline for many centuries, maybe >1000 yrs(?)



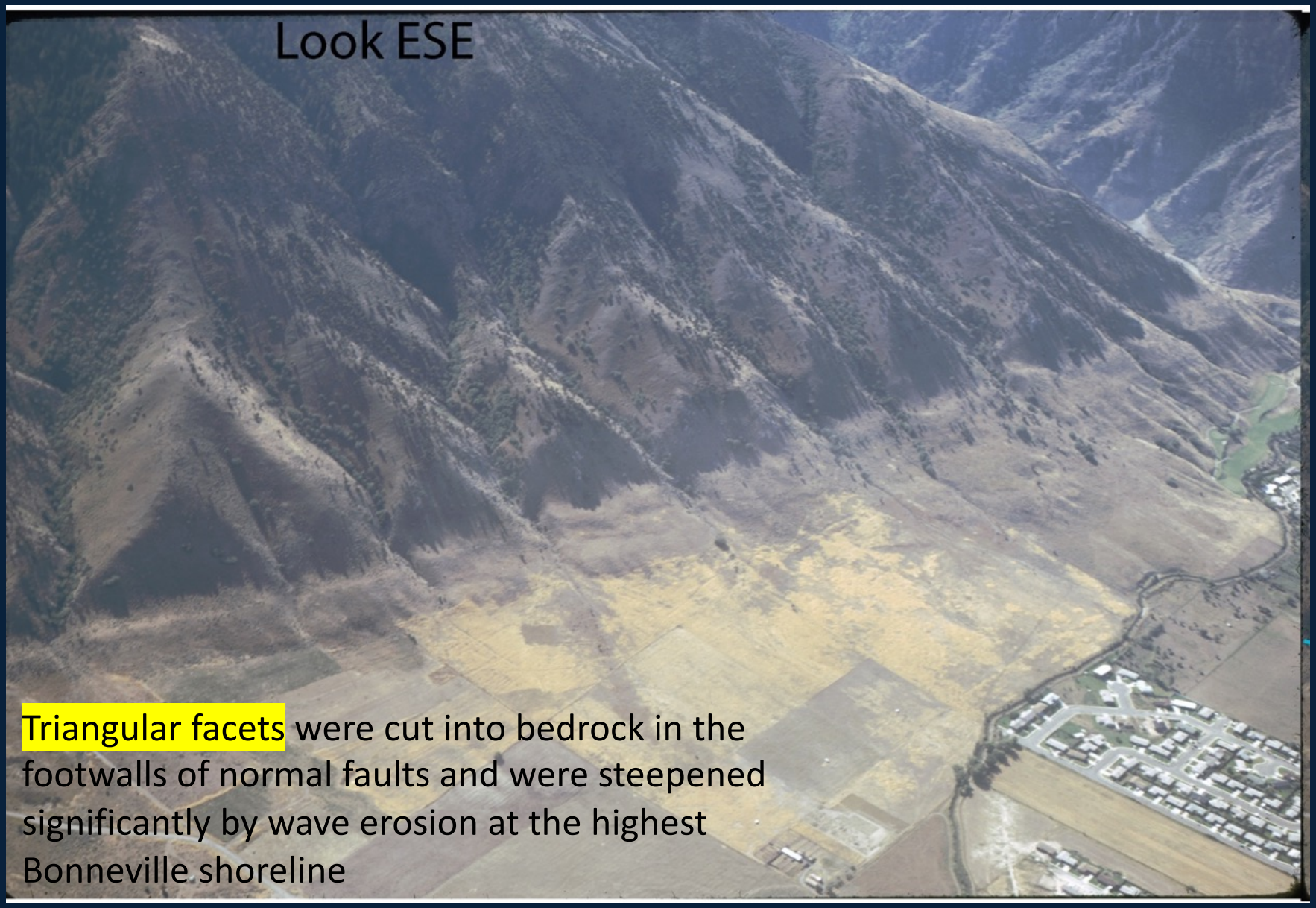
Lake carved cliffs and terraces across hard bedrock
The B. shoreline trimmed and steepened triangular facets in the footwalls of active faults everywhere

Facet composed of Paleozoic bedrock at Green Canyon, near liquefied outcrop

Triangular facets of East Cache fault are steepest where Lake Bonneville trimmed them. 100-400 m east of fault



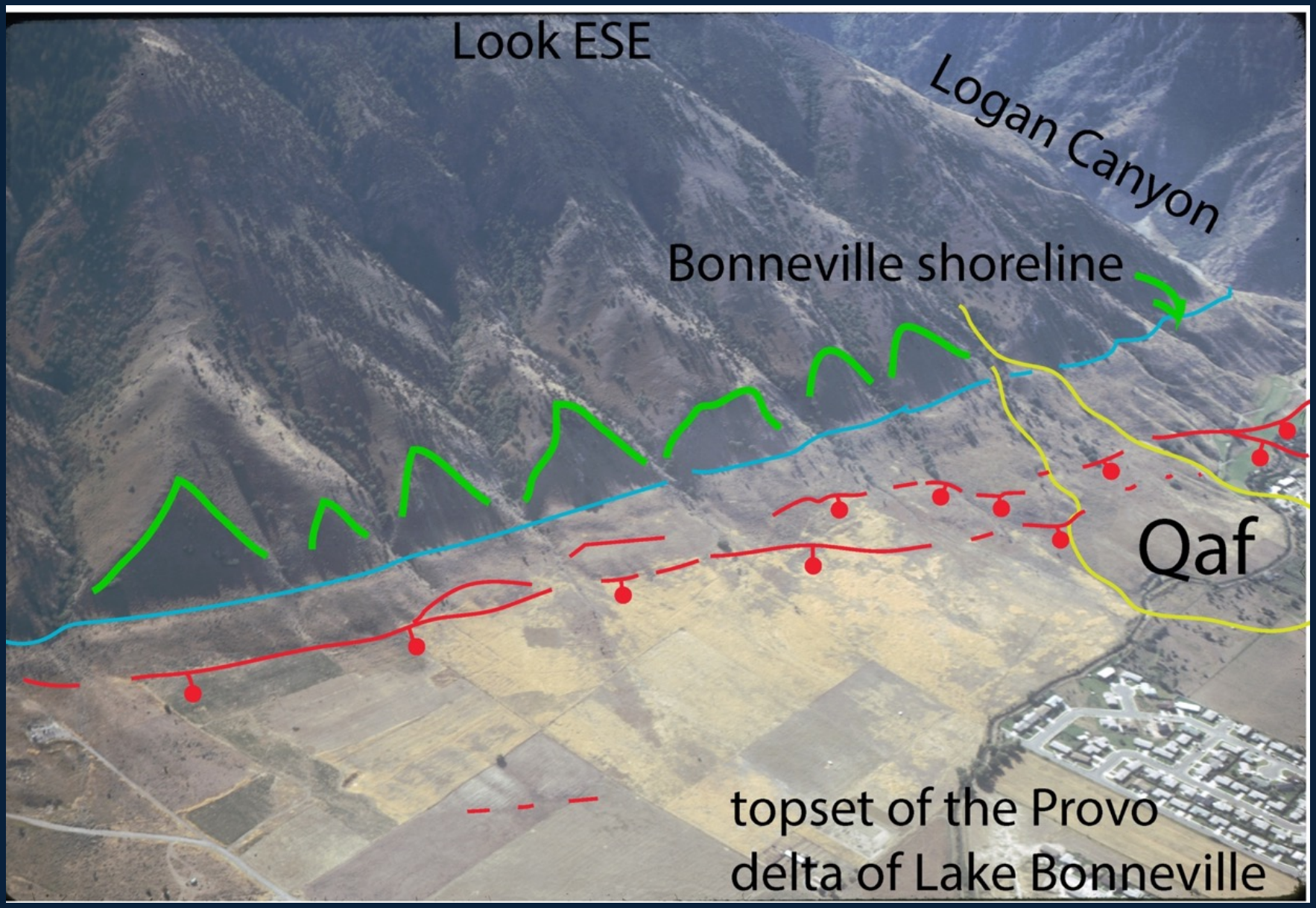
Facets at the B. shoreline are up to 100-80 m high



Triangular facets were cut into bedrock in the footwalls of normal faults and were steepened significantly by wave erosion at the highest Bonneville shoreline

Janecke et al., Geology Dept. USU Oct. 2018

Lake Bonneville must have been pounding on these cliffs for centuries as it was stable and flowing across its threshold at Zenda



Janecke et al., Geology Dept. USU Oct. 2018

- The possibility that an earthquake triggered the Bonneville flood led us to examine a highly deformed outcrop of Bonneville deposits near Logan, Utah
- Might it record THE earthquake that triggered the Bonneville flood?
- If not, what does it record?

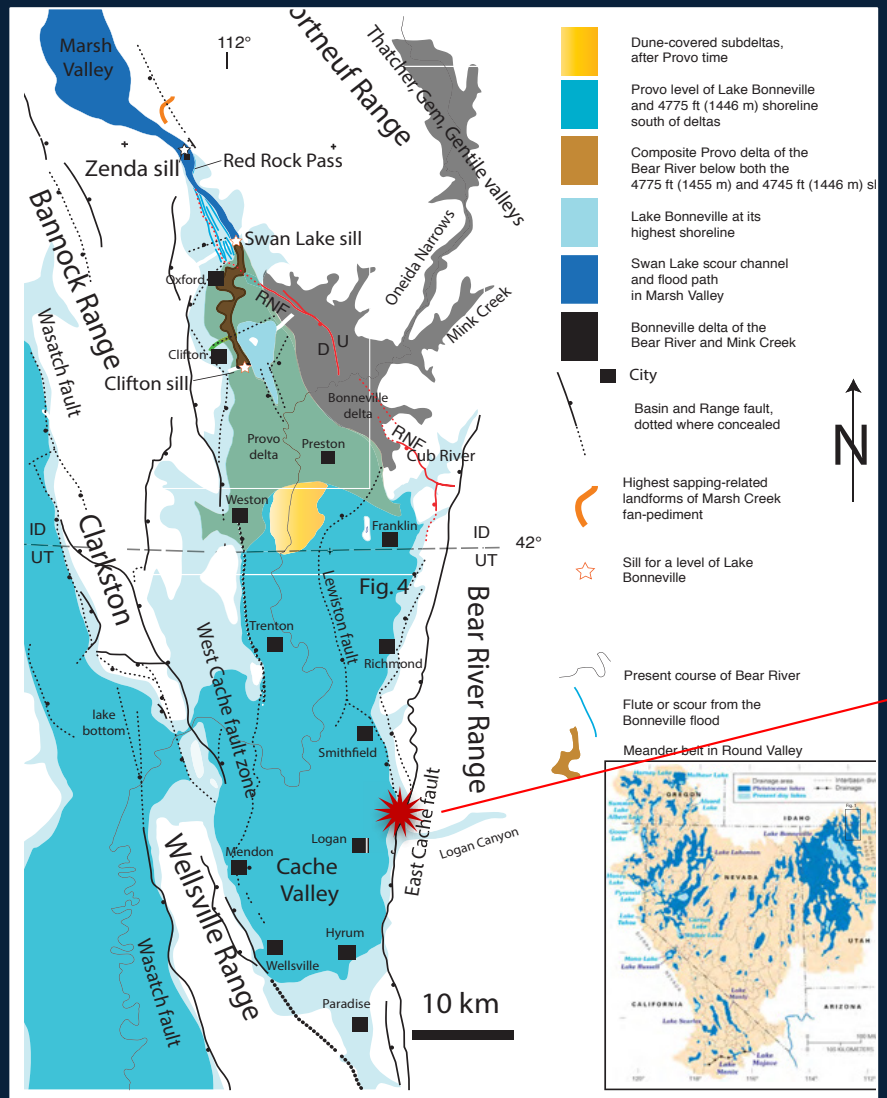
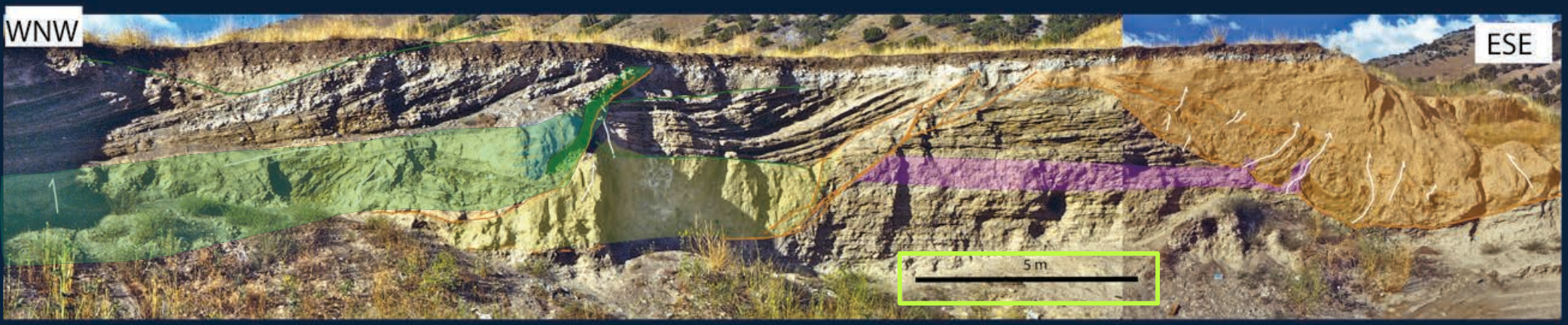


Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River are differentiated from other lacustrine deposits.

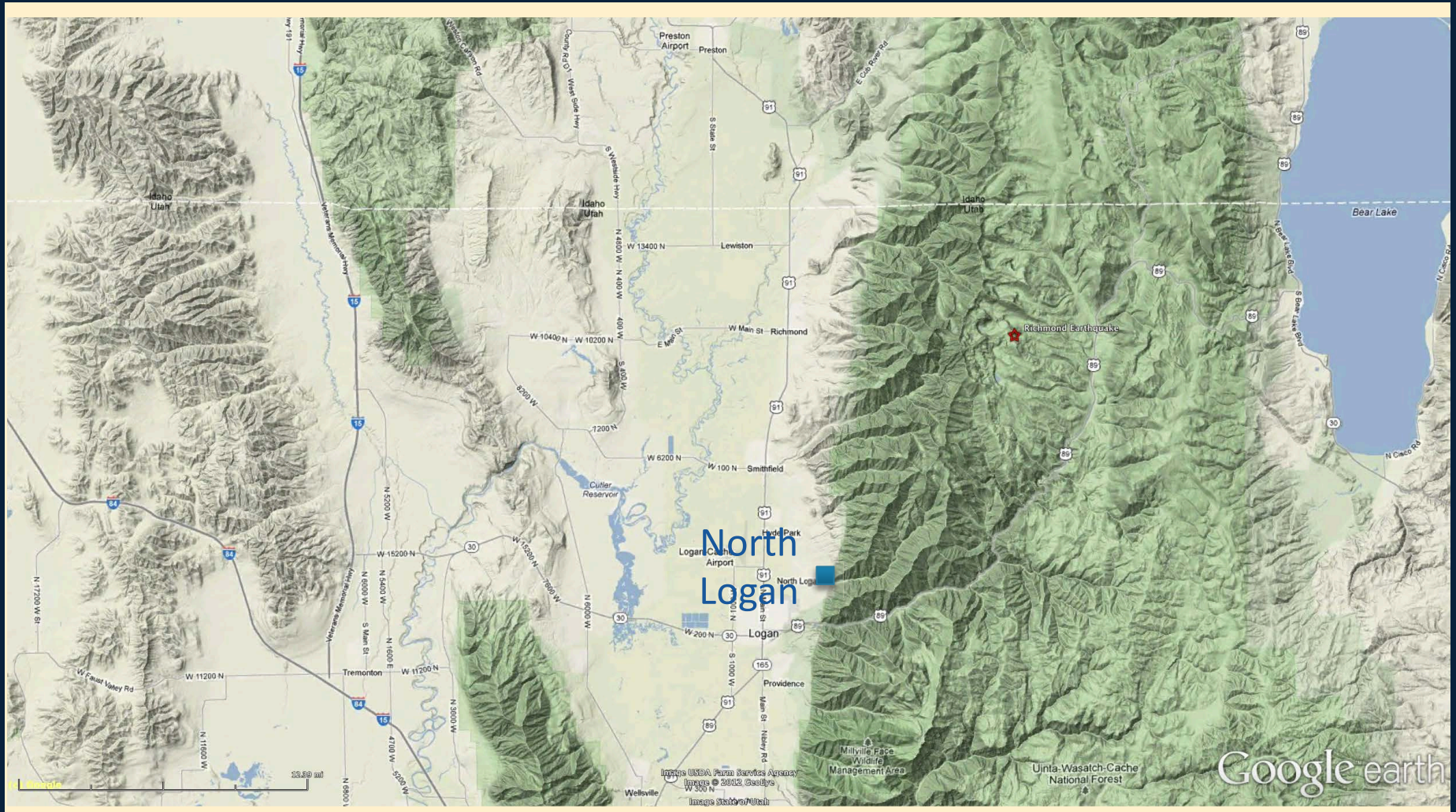
Consider how deformation like this might destabilize the outlet of Lake Bonneville if it occurred near Zenda

The liquefied outcrop of Green Canyon, North Logan, Utah

On the 1980's the outcrop was using in field trips by USU faculty. Our current work shows that 4 major earthquakes produced each of 4 major liquefaction zones -in color. Additional events are possible.



Study site is between Bonneville and Provo shoreline, 225 m west of Bonneville shoreline



miles 30
km 50

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

West Cache fault was fairly active in Holocene (Black et al., 2000), Janecke and Ellis, 2018

Site is at a segment boundary, where several faults branch

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

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

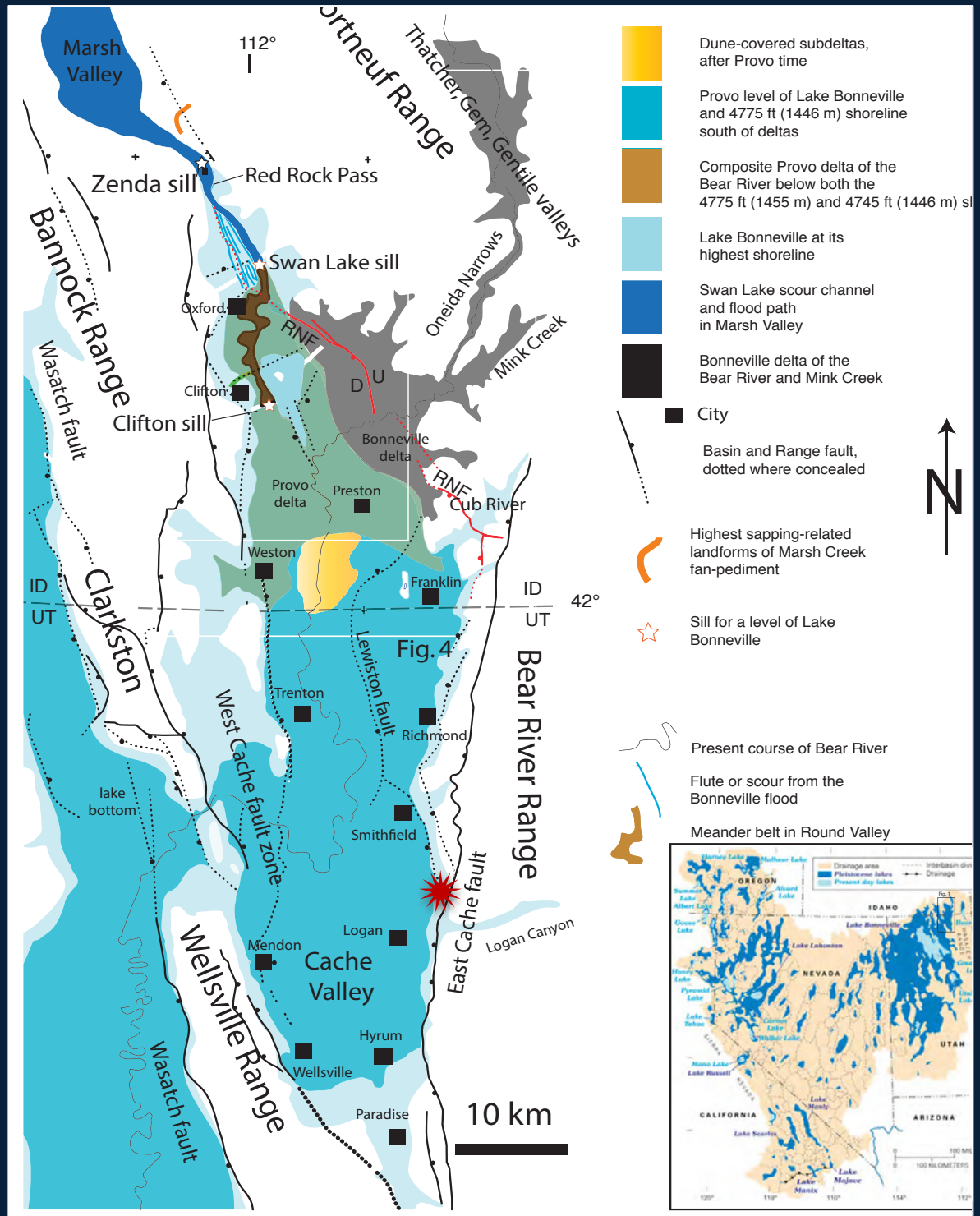
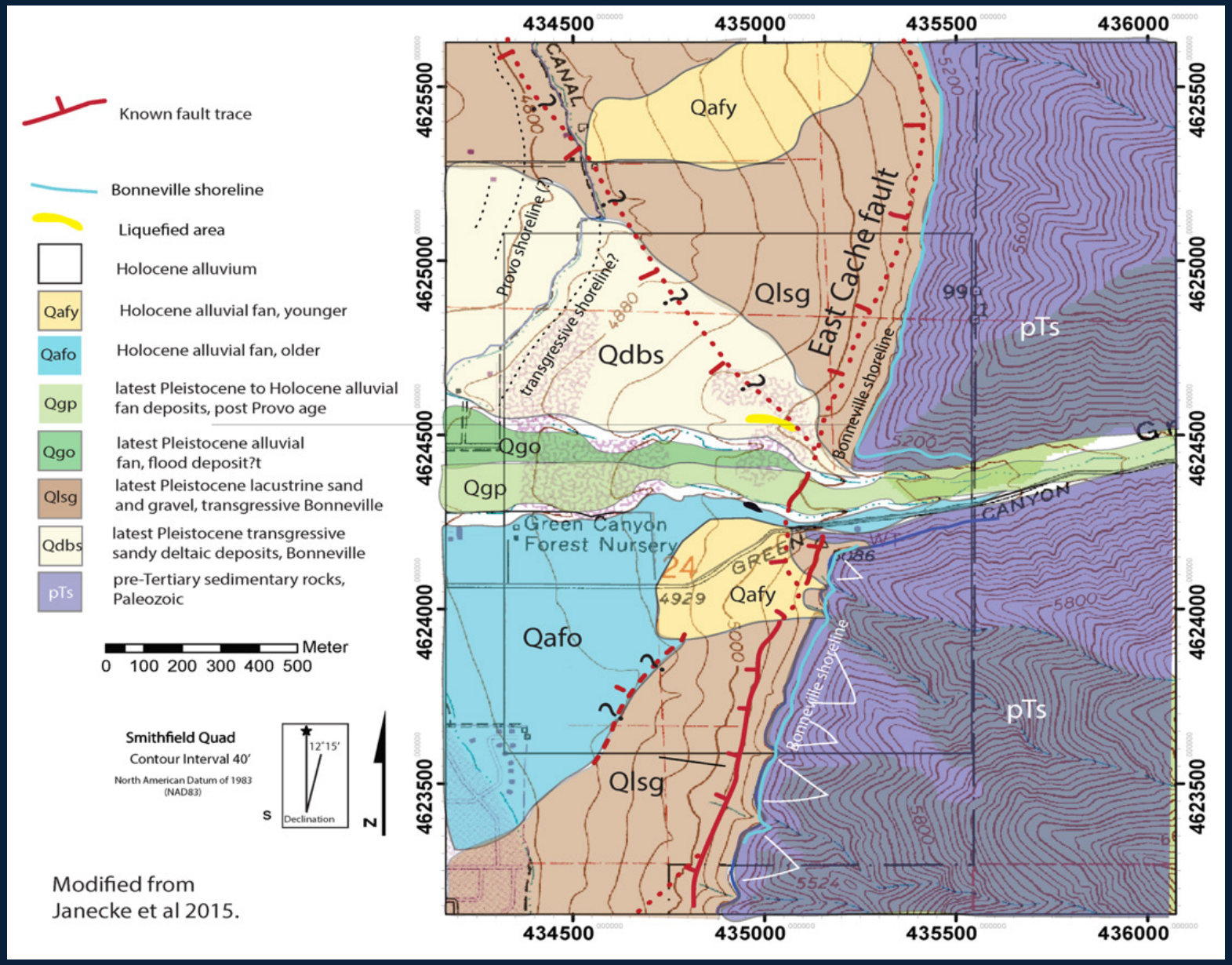


Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River are differentiated from other lacustrine deposits.

East Cache fault surrounds the Green Canyon site

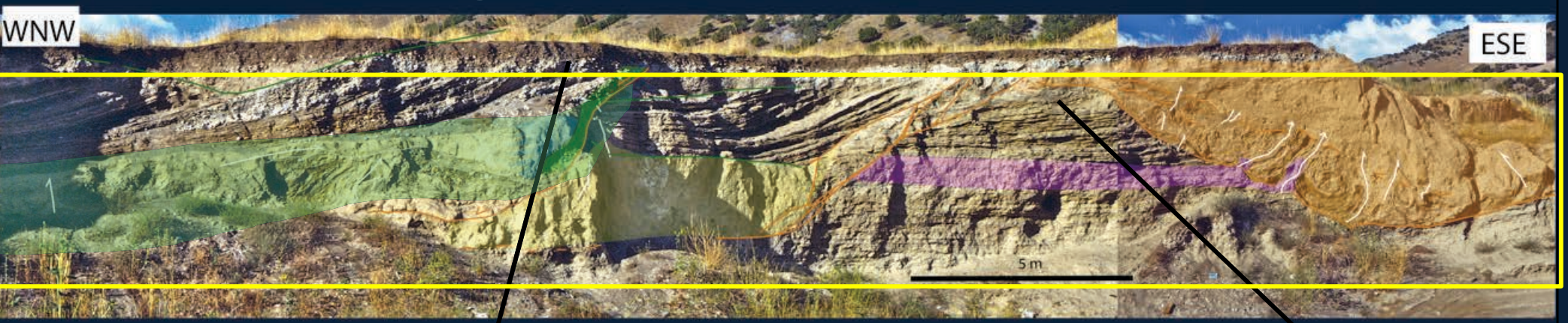
There are strands of East Cache fault around the site

One inactive strand is ~200 m to E along mountain front (McCalpin, 1989) and second buried strand is even closer



Deposition of seds was within 40-45 m of highstand of Lake Bonneville

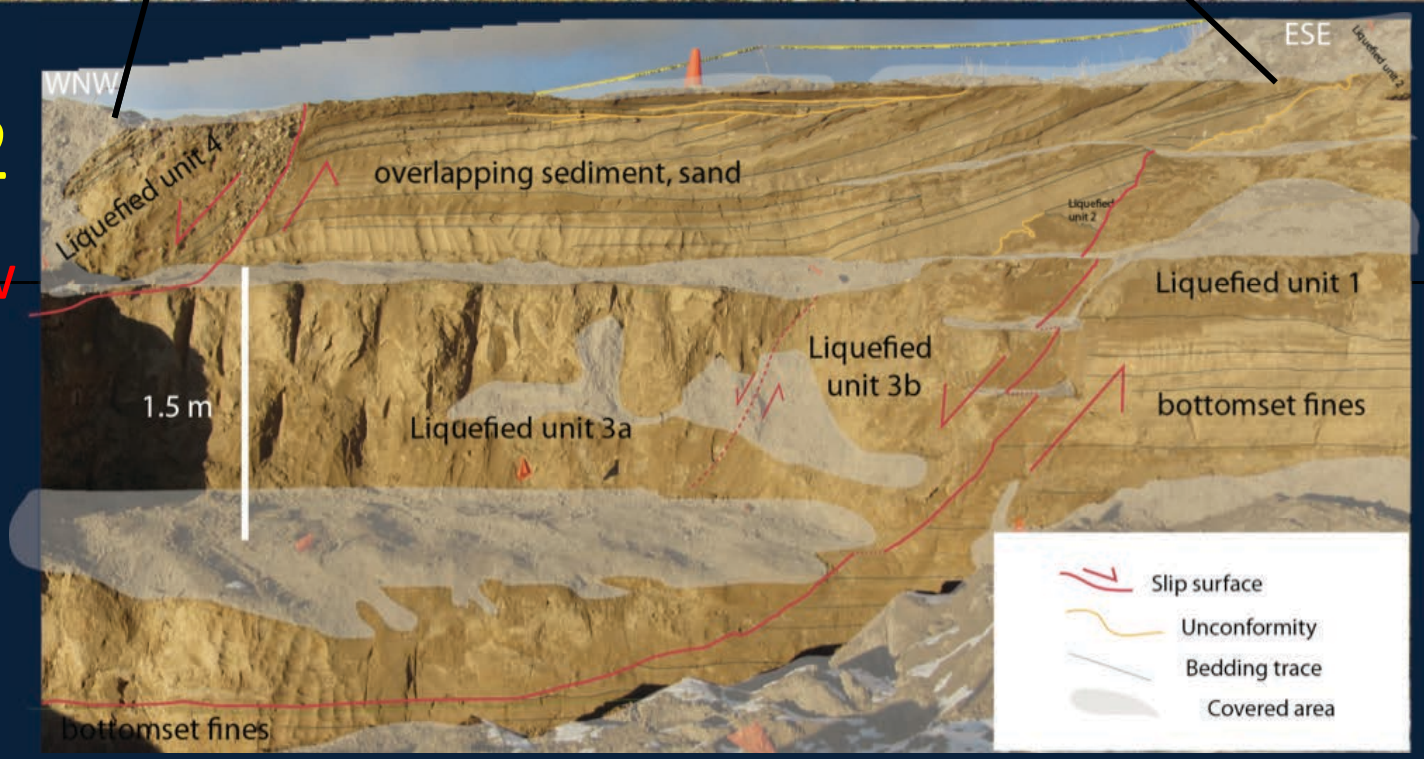
Then



Stage 2

*40-45 m below Bonneville Shoreline

*Colors denote liquefied 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

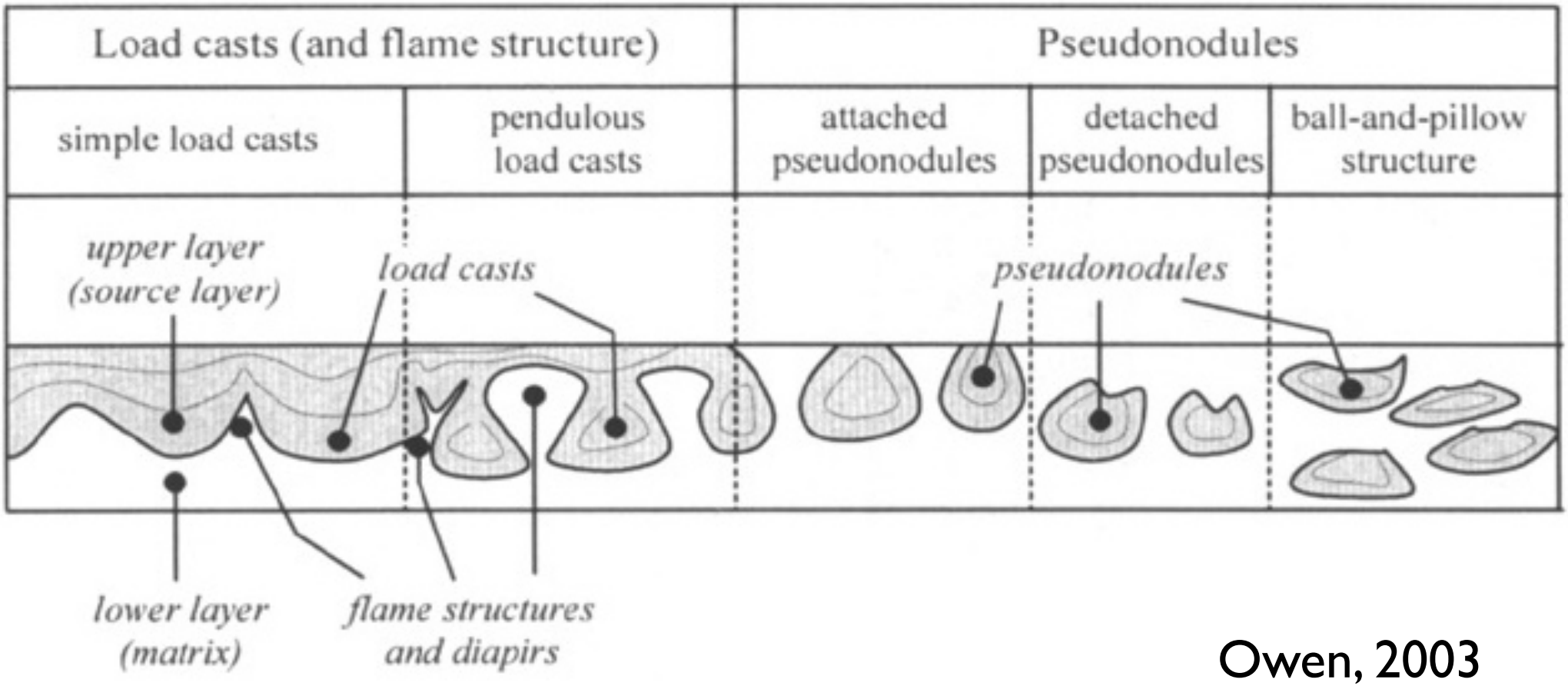
Gastropod shells are common in sandy deltaic beds

There is pervasive liquefaction as well Pseudonodules of all sizes

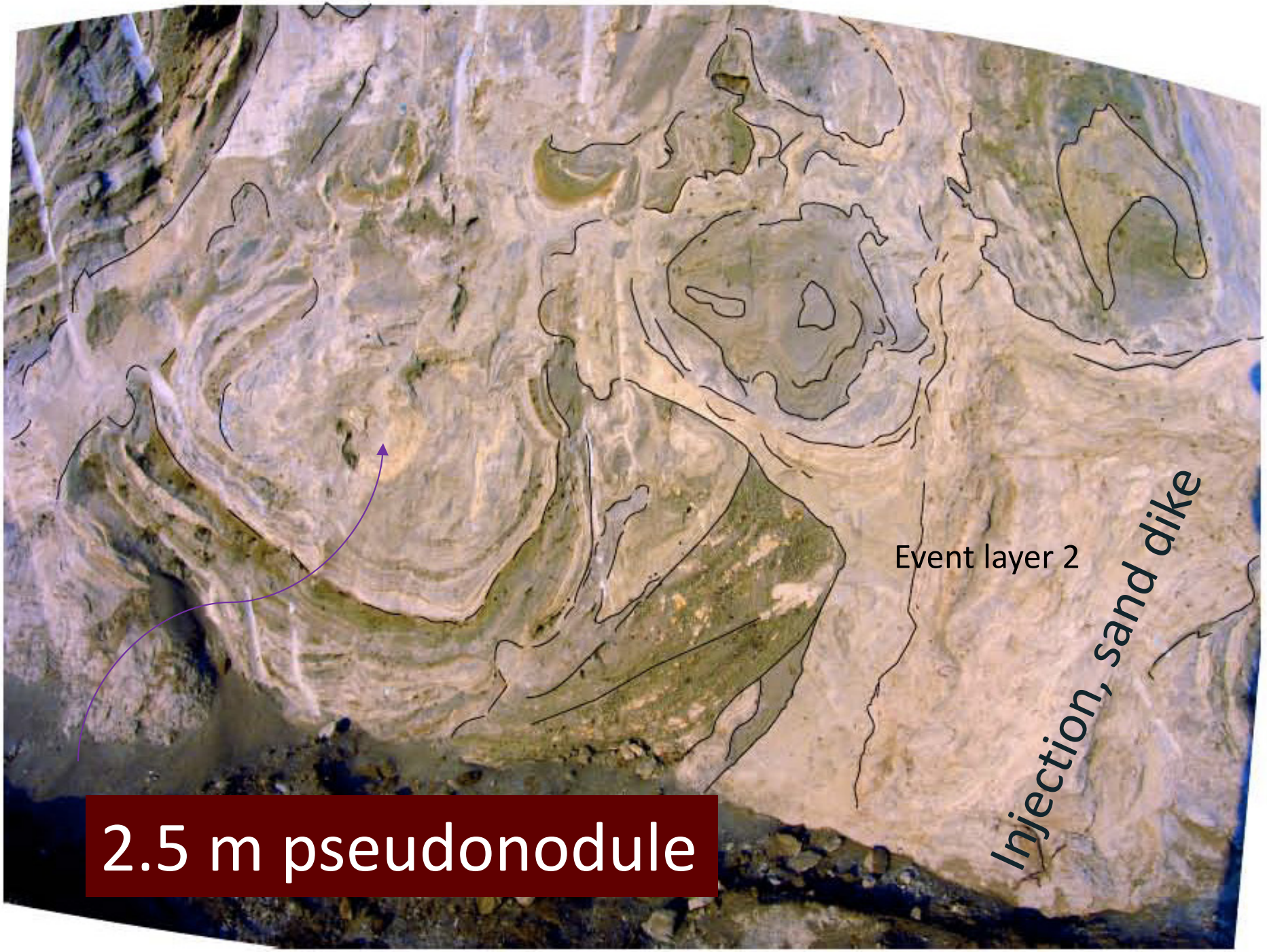
Consider how deformation like this might destabilize the outlet of Lake Bonneville if it occurred near Zenda

All views of exposure are to the NNE

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



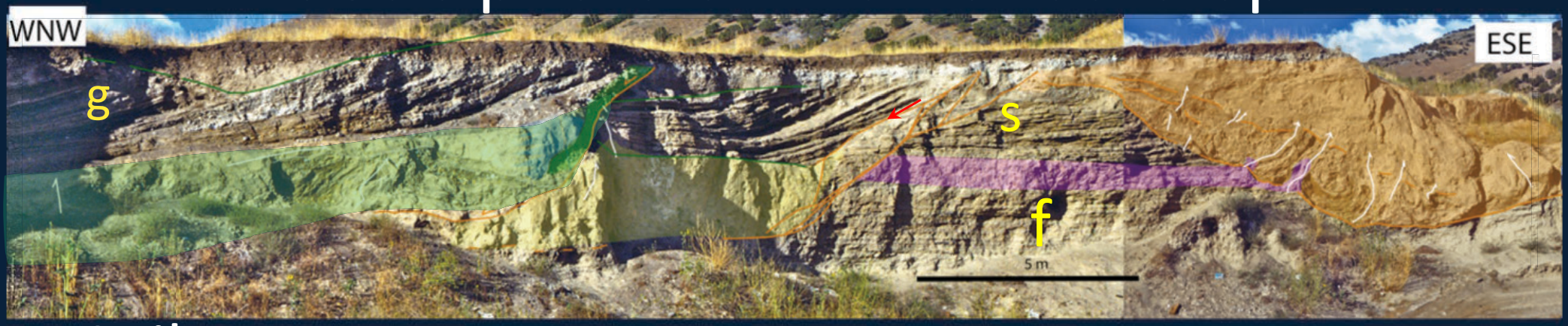
Owen, 2003


Event layer 2
Injection, sand dike
2.5 m pseudonodule

Stratigraphy

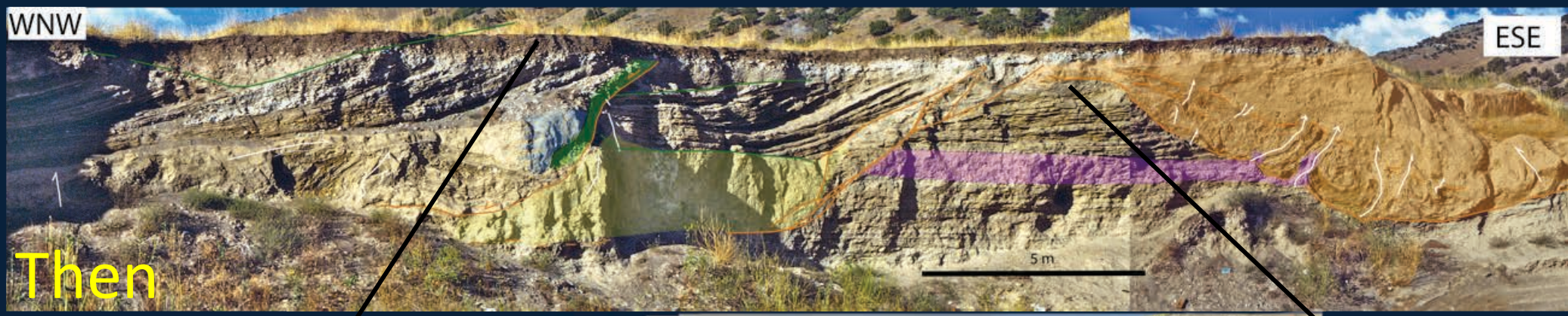
1980's photo of ~half of outcrop:

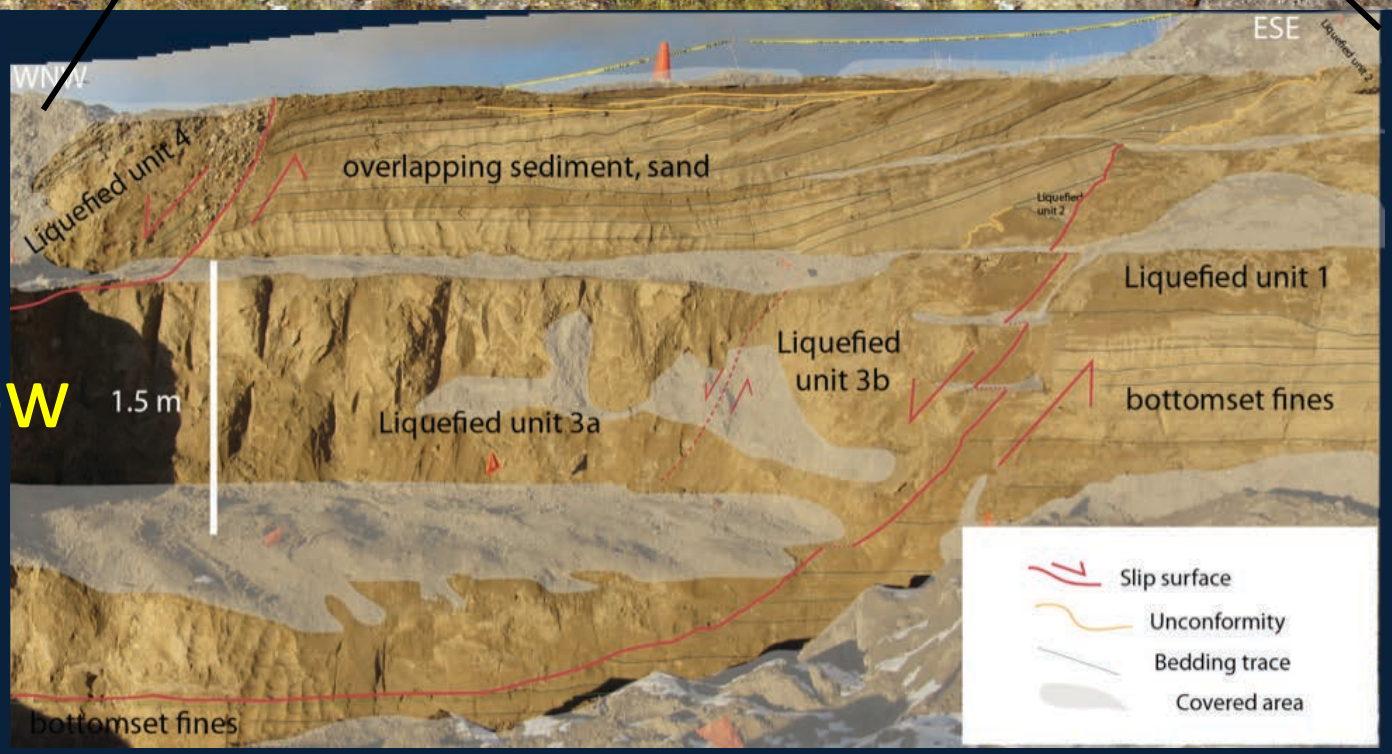
WNW ESE



- Soil
- Intact 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)
- Less deformed Bonneville foresets of gravel (g)

All the deformation was during Bonneville transgression, before the flood,
-before gravel cap and incision of inset channels





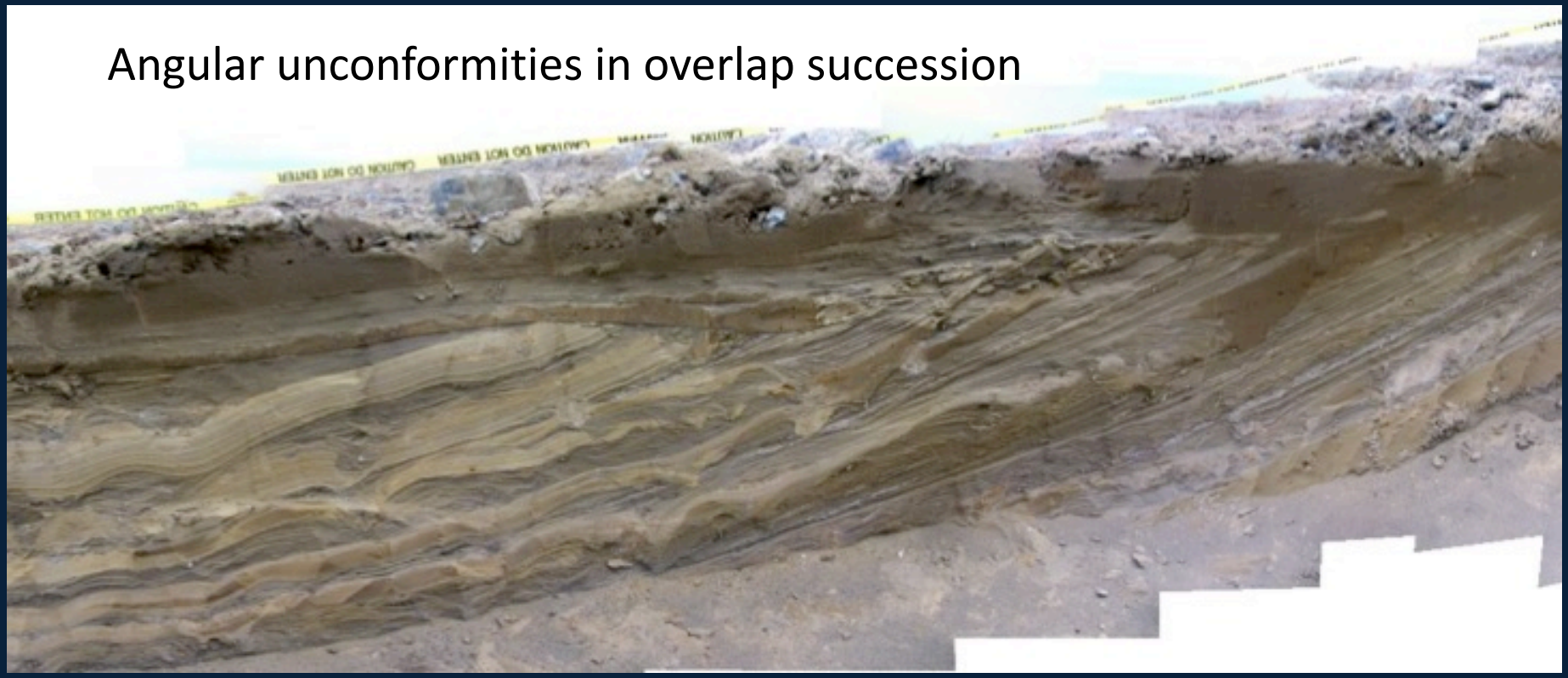
Now

Research questions during initial research:

1. Does the deformed outcrop at Green Canyon record an earthquake at the time of the Bonneville flood?
2. Are there exposed strands of the East Cache fault?

1. No-all deformation dates from the Bonneville transgression close to highstand
2. No-All “Faults” are slip surfaces of nested lateral spreads

Overlapping beds are less deformed, but cut by slip surface in west

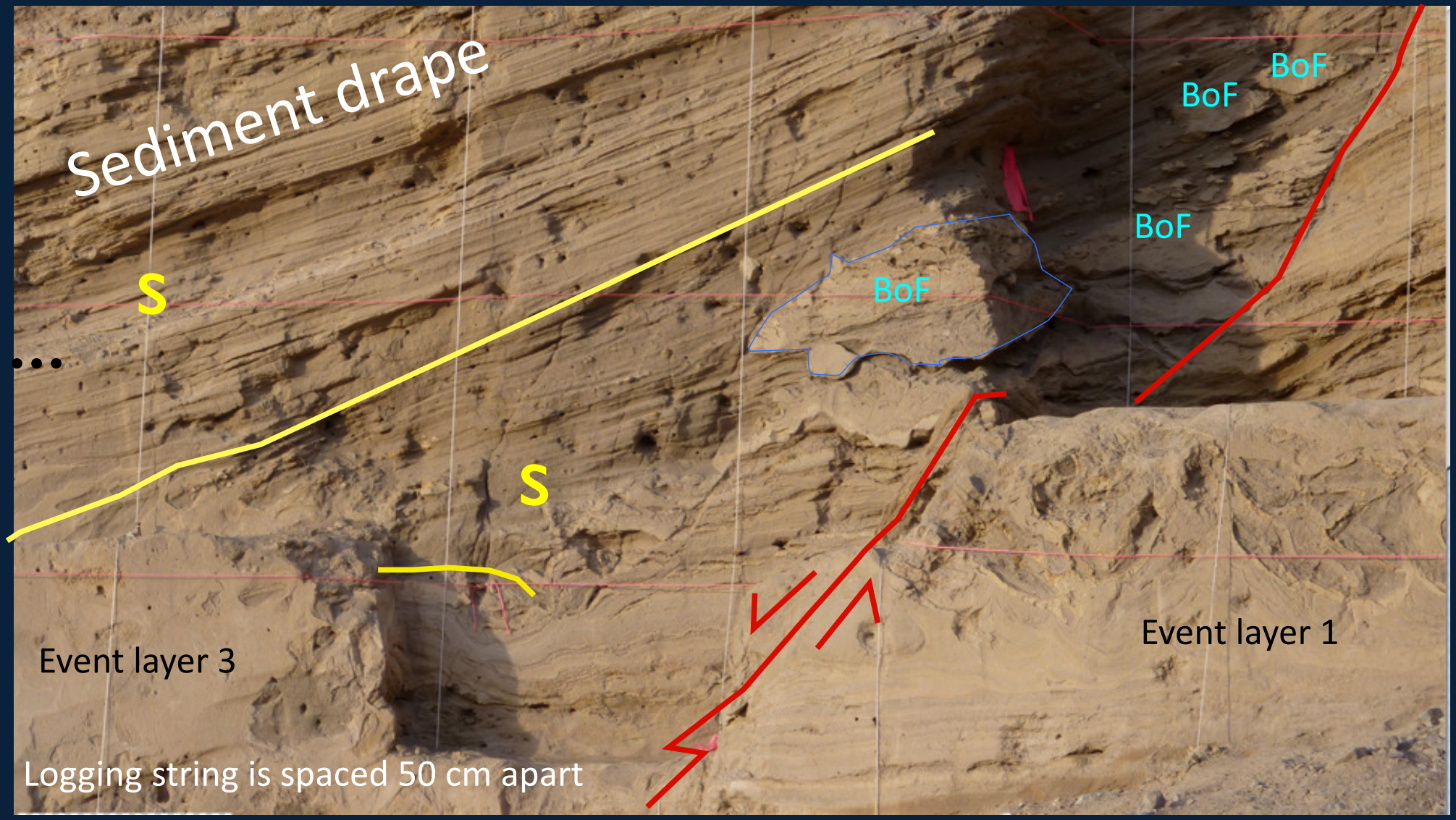


Sediment draped across scarps on bed of Lake Bonneville

2012

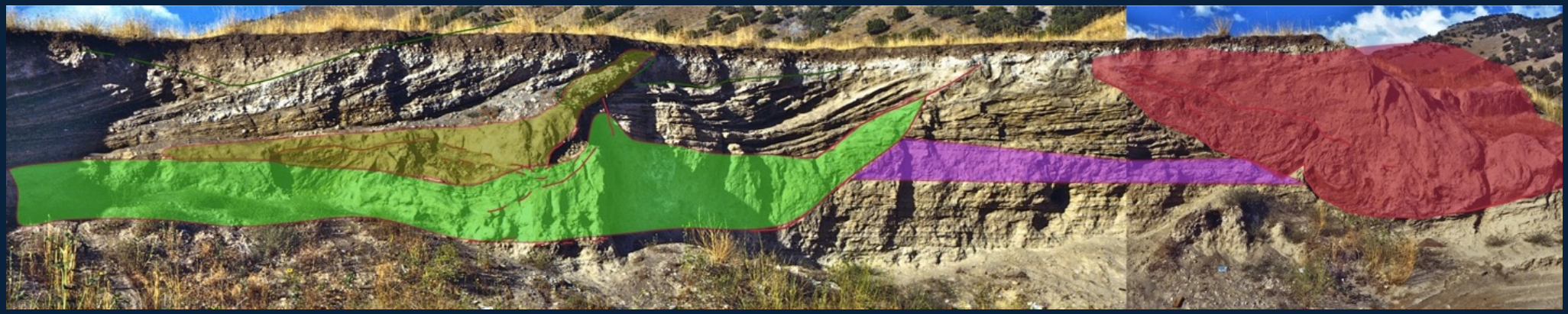

Depositional onlap
10 cm

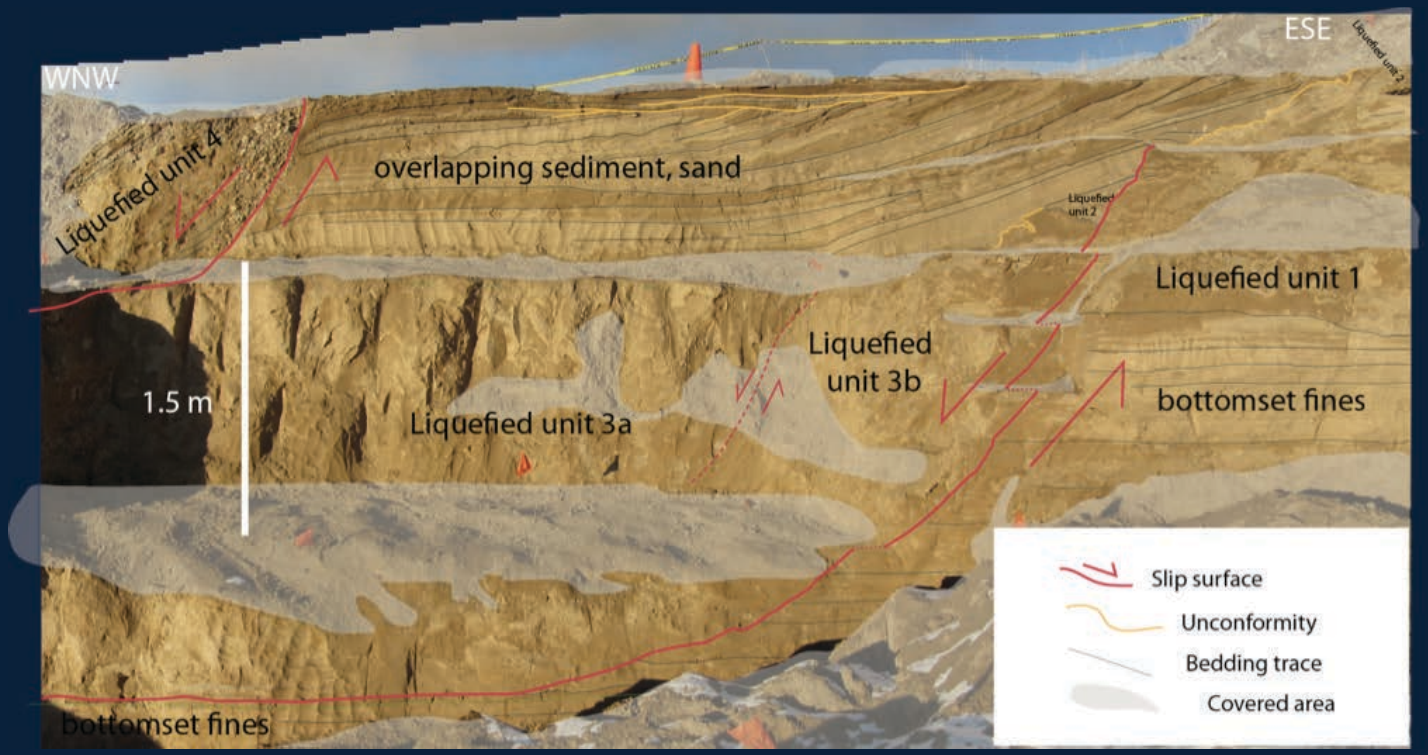
Lacustrine fault wedge contains blocks of footwall



This is analogous to a colluvial wedge along a normal fault

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

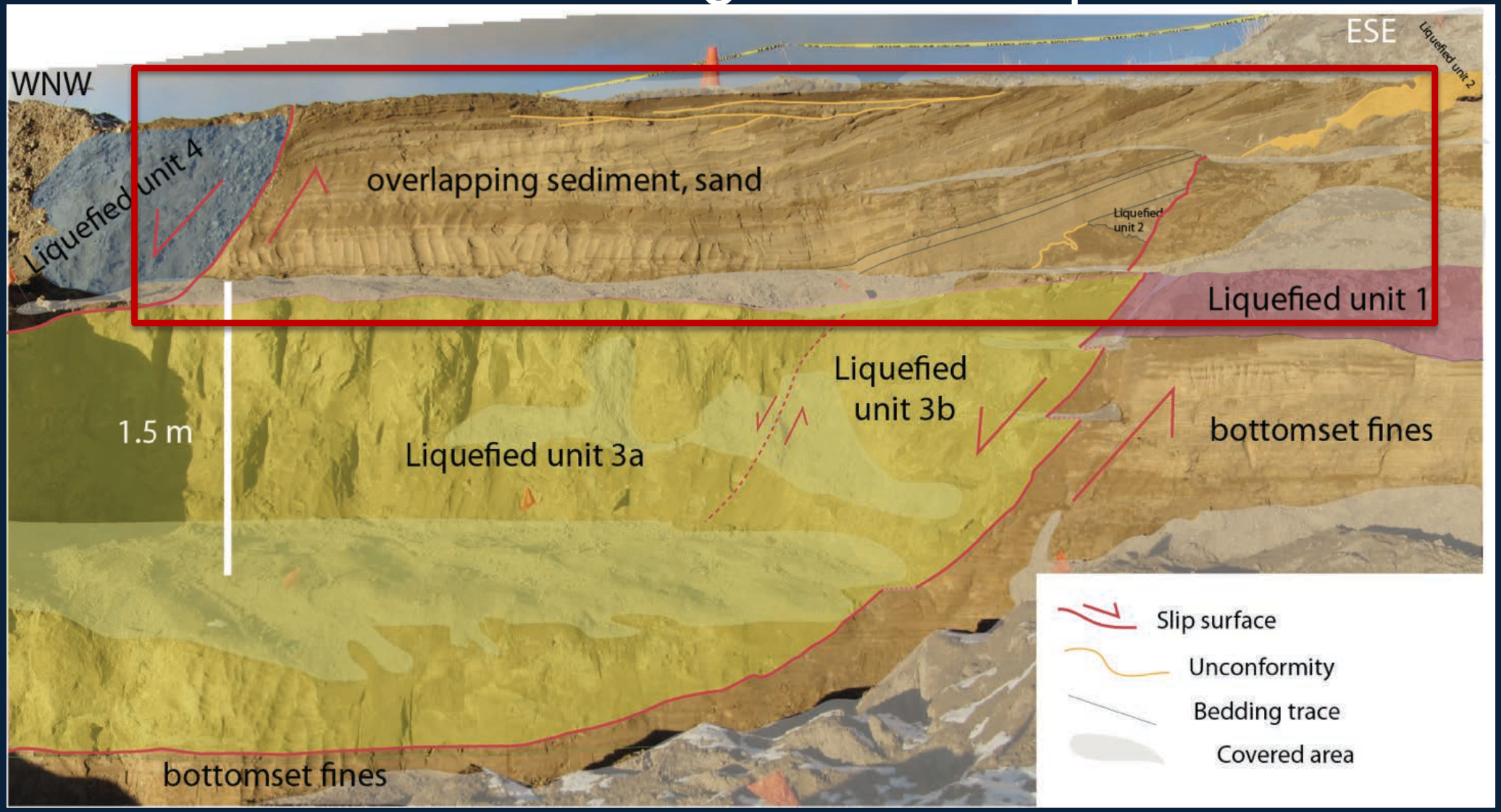




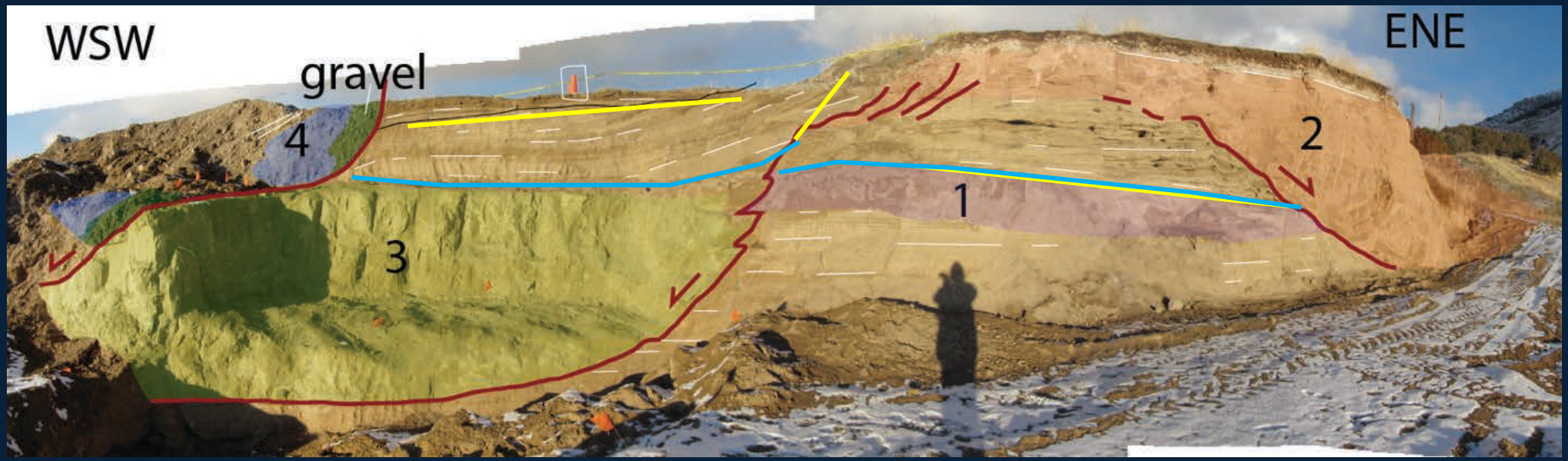
Basal slip surface of the lateral spread

About 1.5 m high

Relative ages are very clear due to cross-cutting relationships



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



Each bench is 1.5 m high

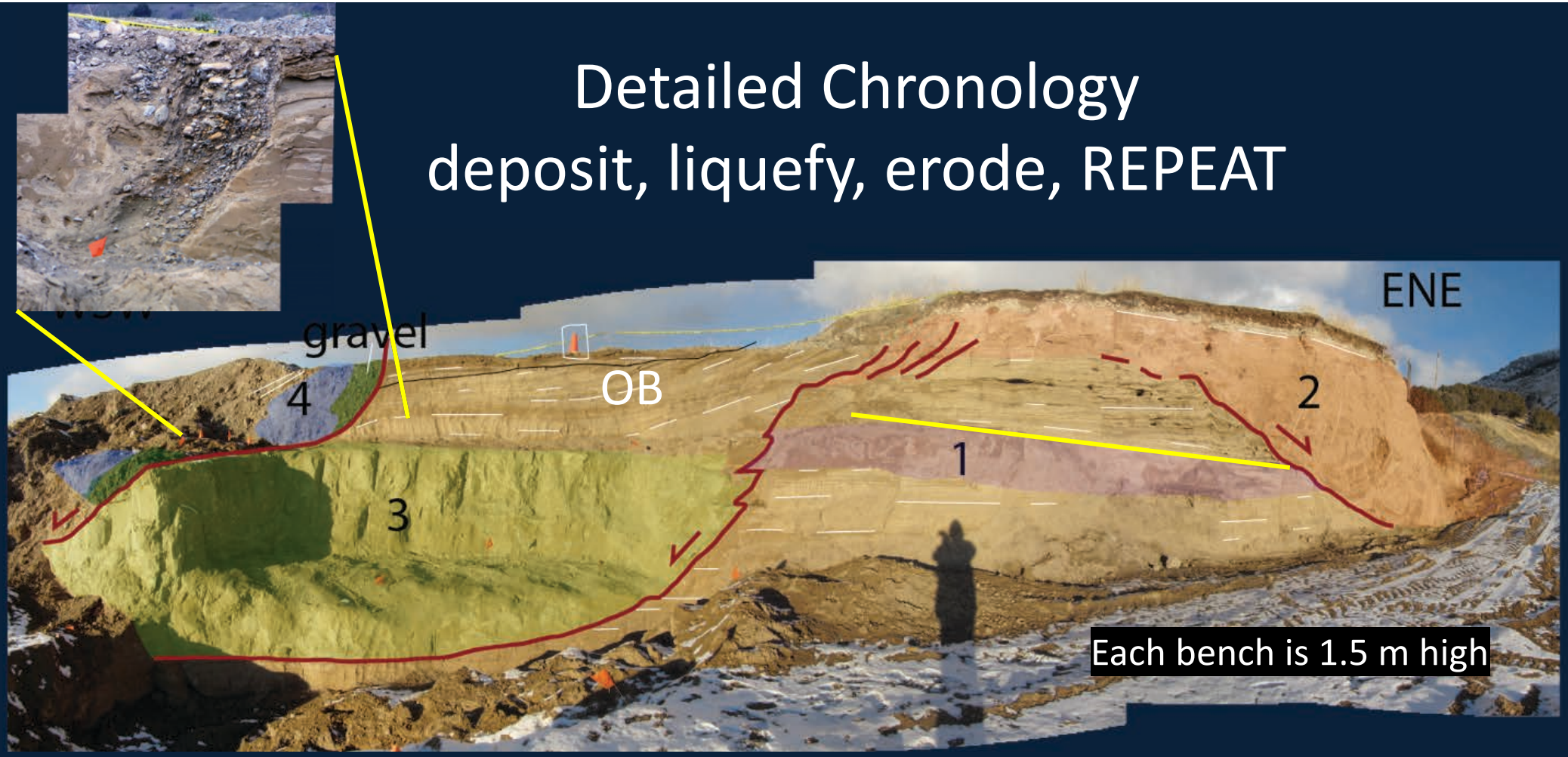
Cross-cutting relationships between these beds and show that each is a different age, from 1 to 4

Unconformities,

slip surfaces and

overlapping beds

Detailed Chronology
deposit, liquefy, erode, REPEAT

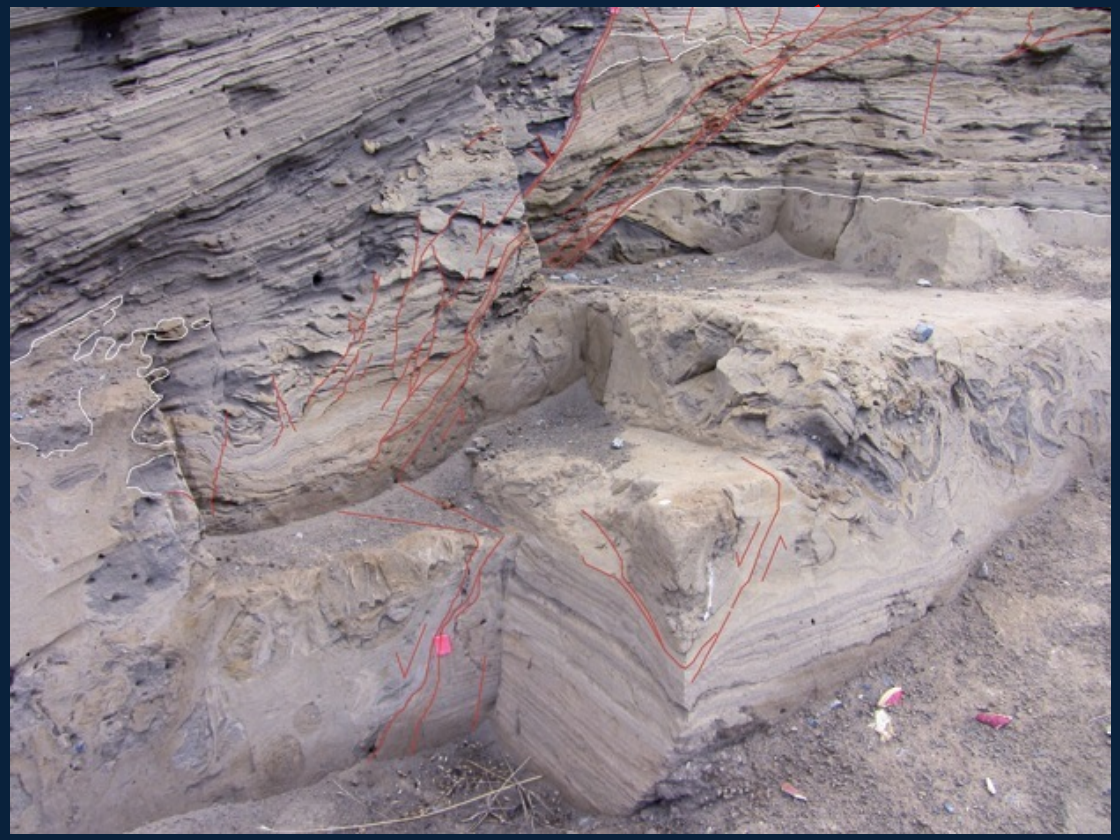


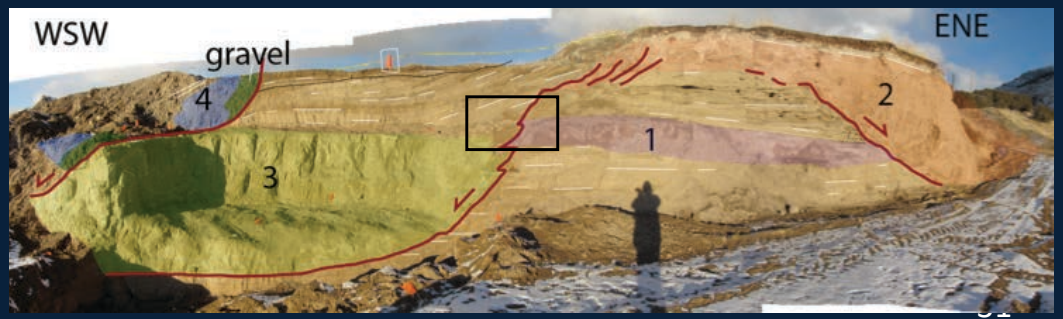
- Lake rises to ~ 40 m below the high stand
- Event bed number 1, possibly after a brief regression
- Erosion of liquefied bed 1
- Deposition of more lake beds
- Event bed 2 ± lateral spreading
- Deposition of more lake beds
- Event 3 and slip surface

- Overlap beds (OB) are deposited across lateral spread
- Shaking causes Event bed 3 to invade overlap succession
- Lateral spread slips again, cuts overlap and event 3 bed
- Event bed 4 activated the western slip surface
- More deltaic deposition

Summary at outcrop

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



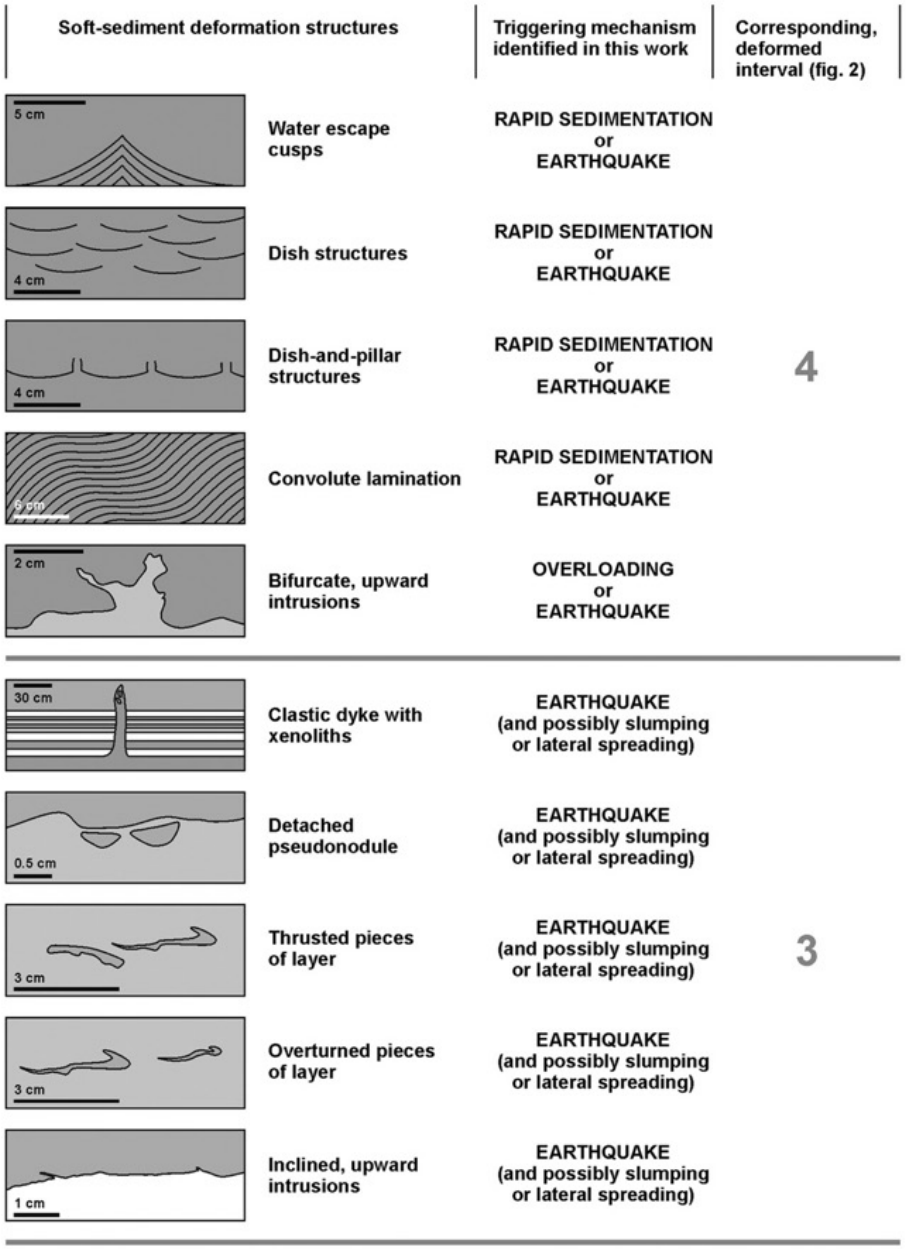


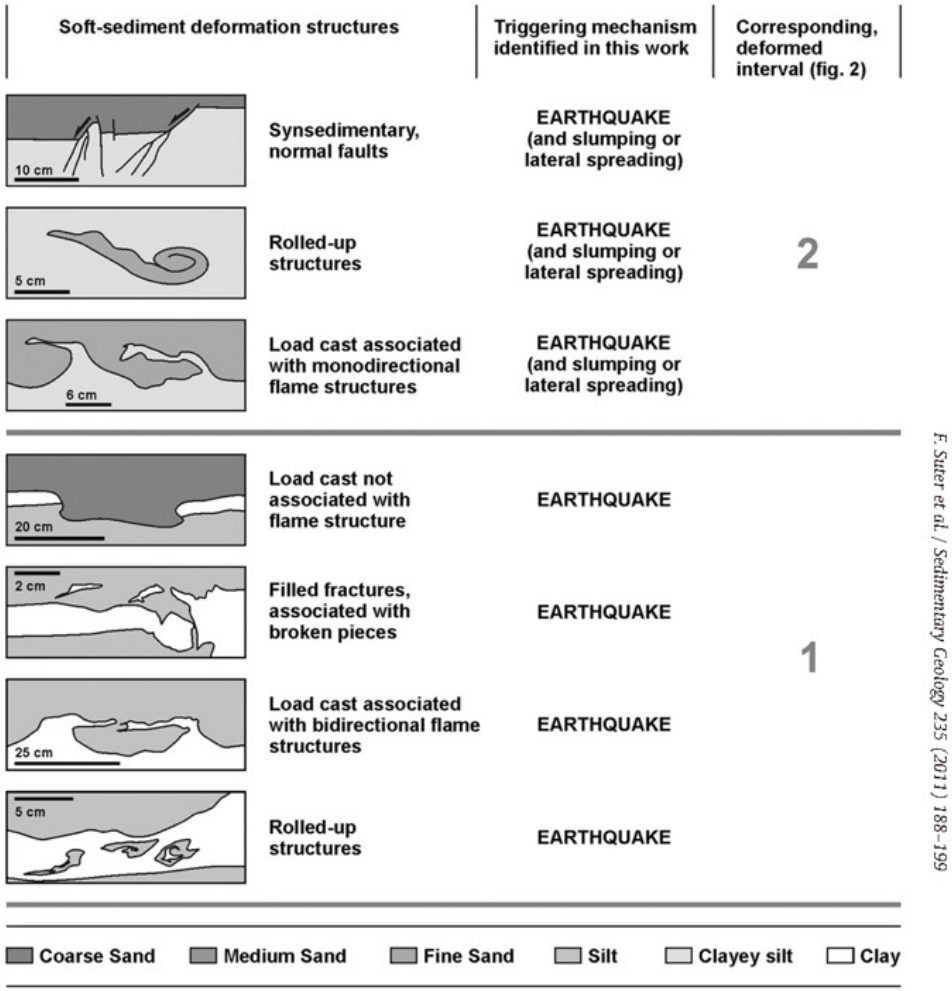
3. Were the lateral spreads and overlying liquefied masses of sand activated by earthquakes?

Consider how deformation like this might destabilize the outlet of Lake Bonneville if it occurred near Zenda

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.

Soft sediment deformation or seismite?

Or some of each?

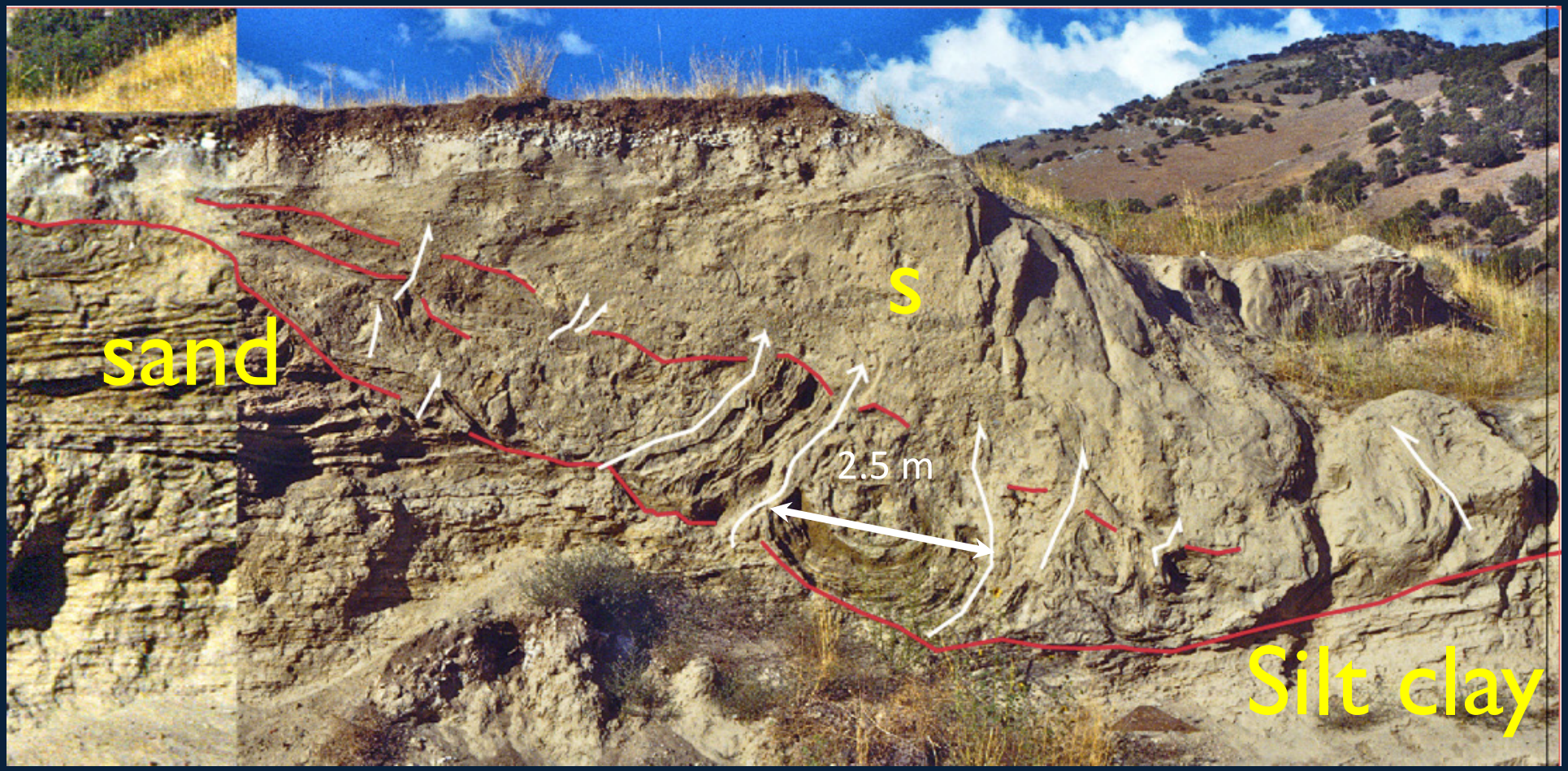
- Features consistent with loading processes

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

  -Possible association of loading structure and regressions in Paola et al's lab experiments

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

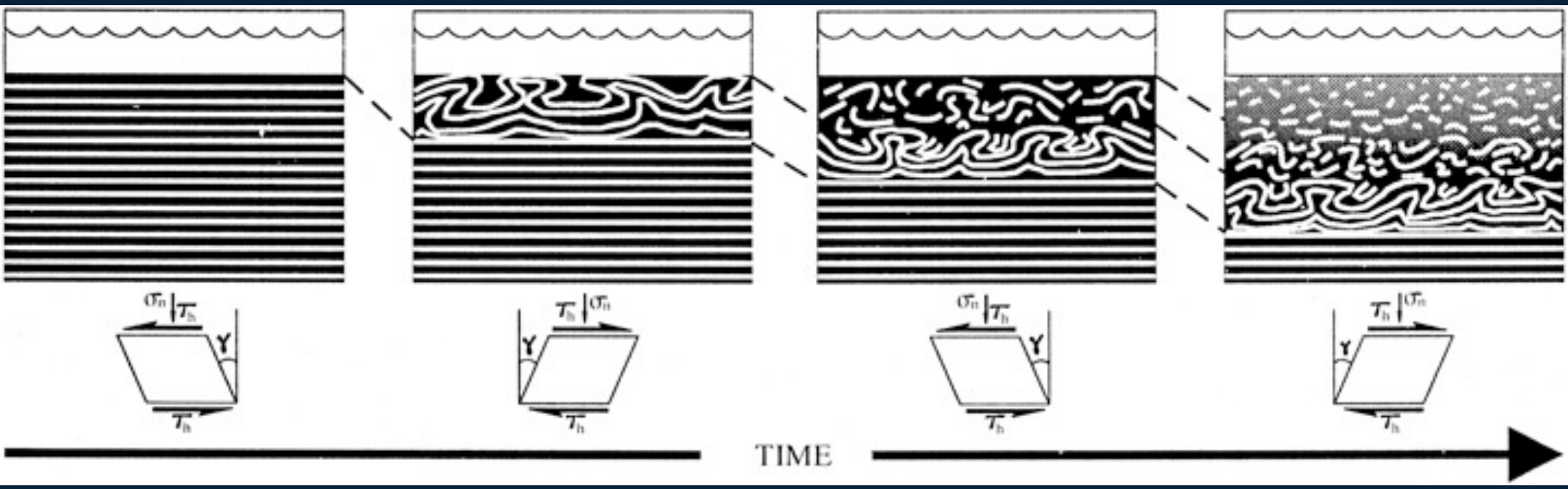
Fluid escape strcts, sand dikes and slip surfaces/faults



1980's outcrop

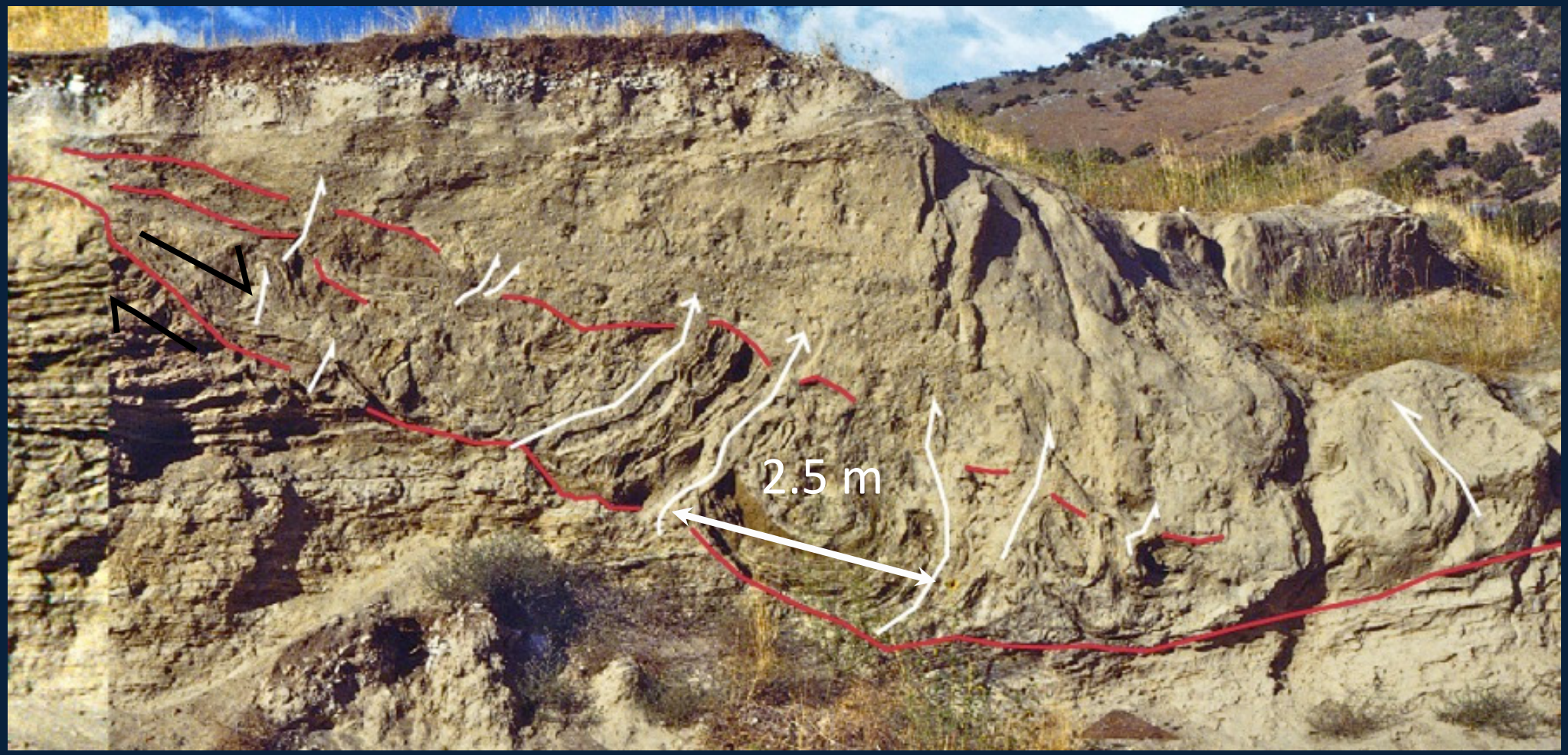
Fluid-escape paths are white

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



Rodriguez et al., 2000

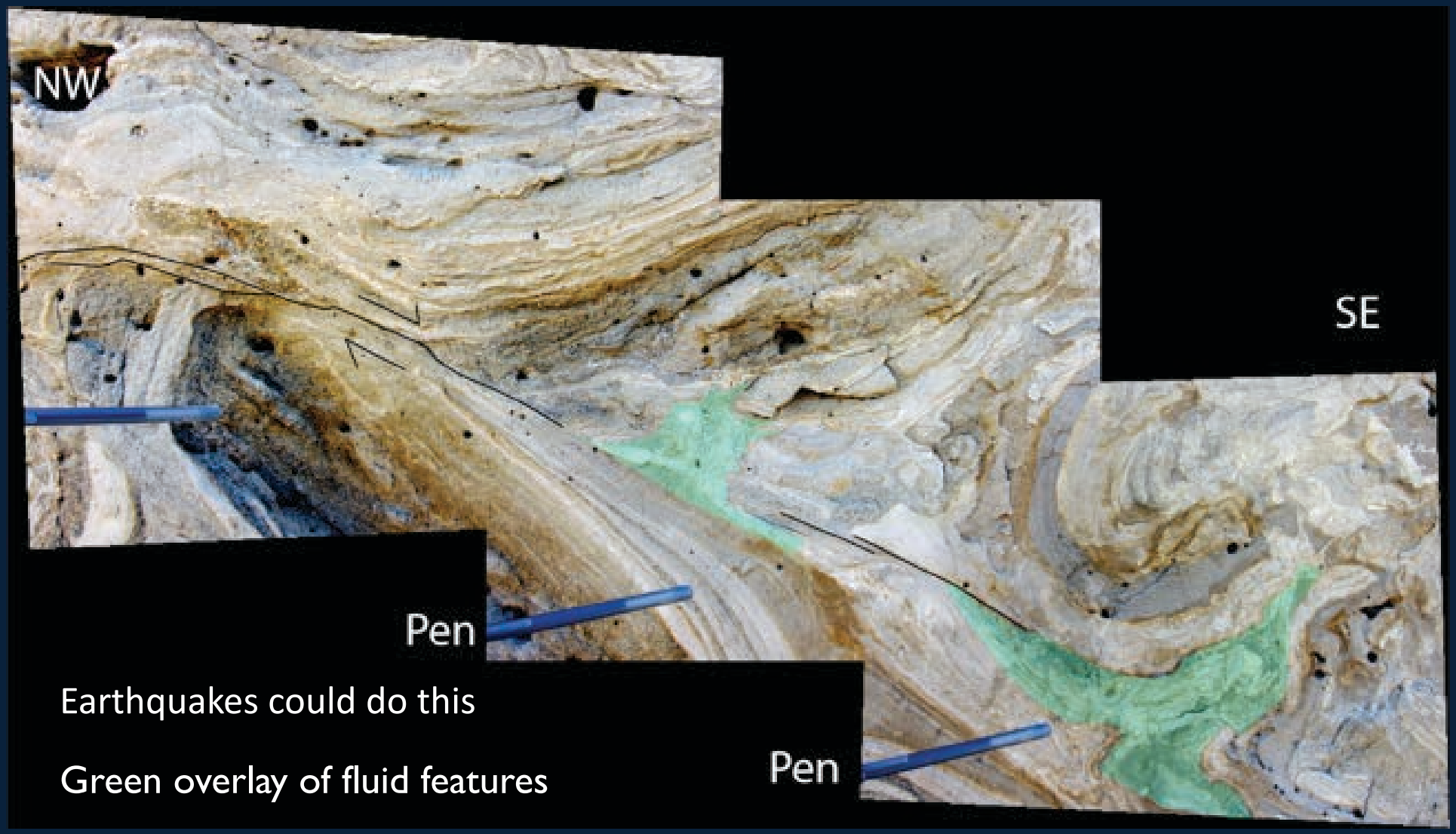
Fault-graded beds



~6 m high exposure, 1980s

15 cm wide sand volcano

Fluid escape across brittle slip surfaces consistent with oscillatory conditions

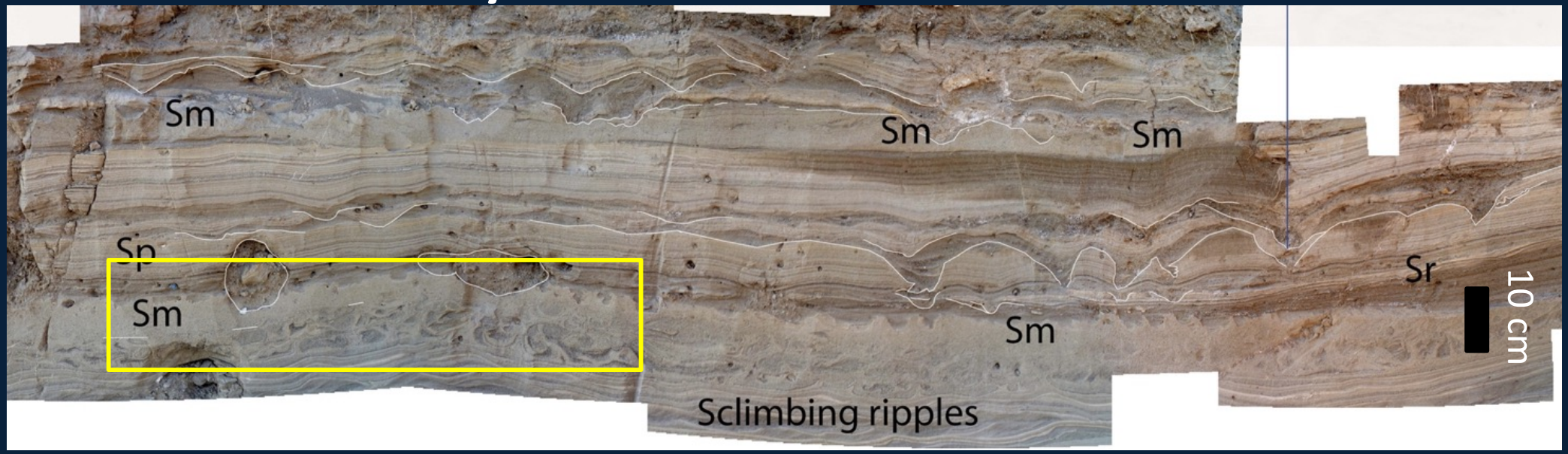


Earthquakes could do this

Green overlay of fluid features

Large clast within liquefied sand body- High energy is needed to churn the sediment

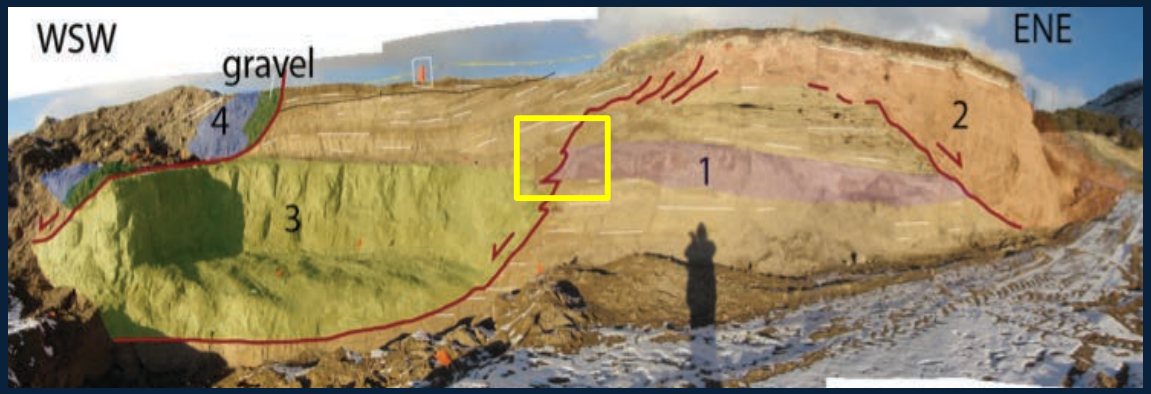
Smaller deformational events may reflect aftershocks



Janecke et al., Geology Dept. USU Oct. 2018

Summary

- Liquefaction occurred at least 4 times under Lake Bonneville (~22 ka to B flood).



Research questions

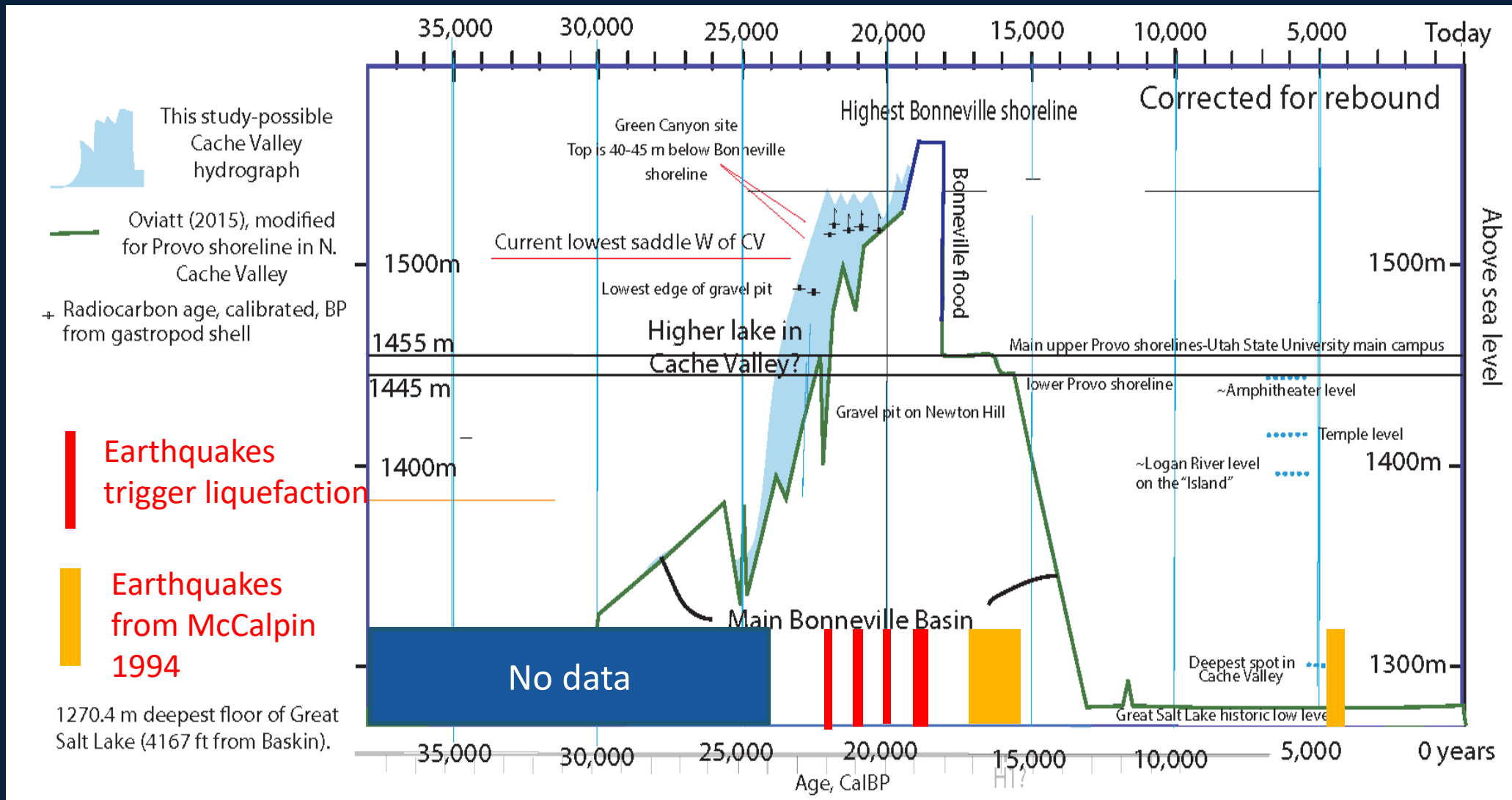
3. Did large earthquakes trigger the liquefaction (and the associated slumps)?-YES

4. How many liquefaction events are there?->4

5. Could liquefaction like this trigger or facilitate the Bonneville flood? YES.

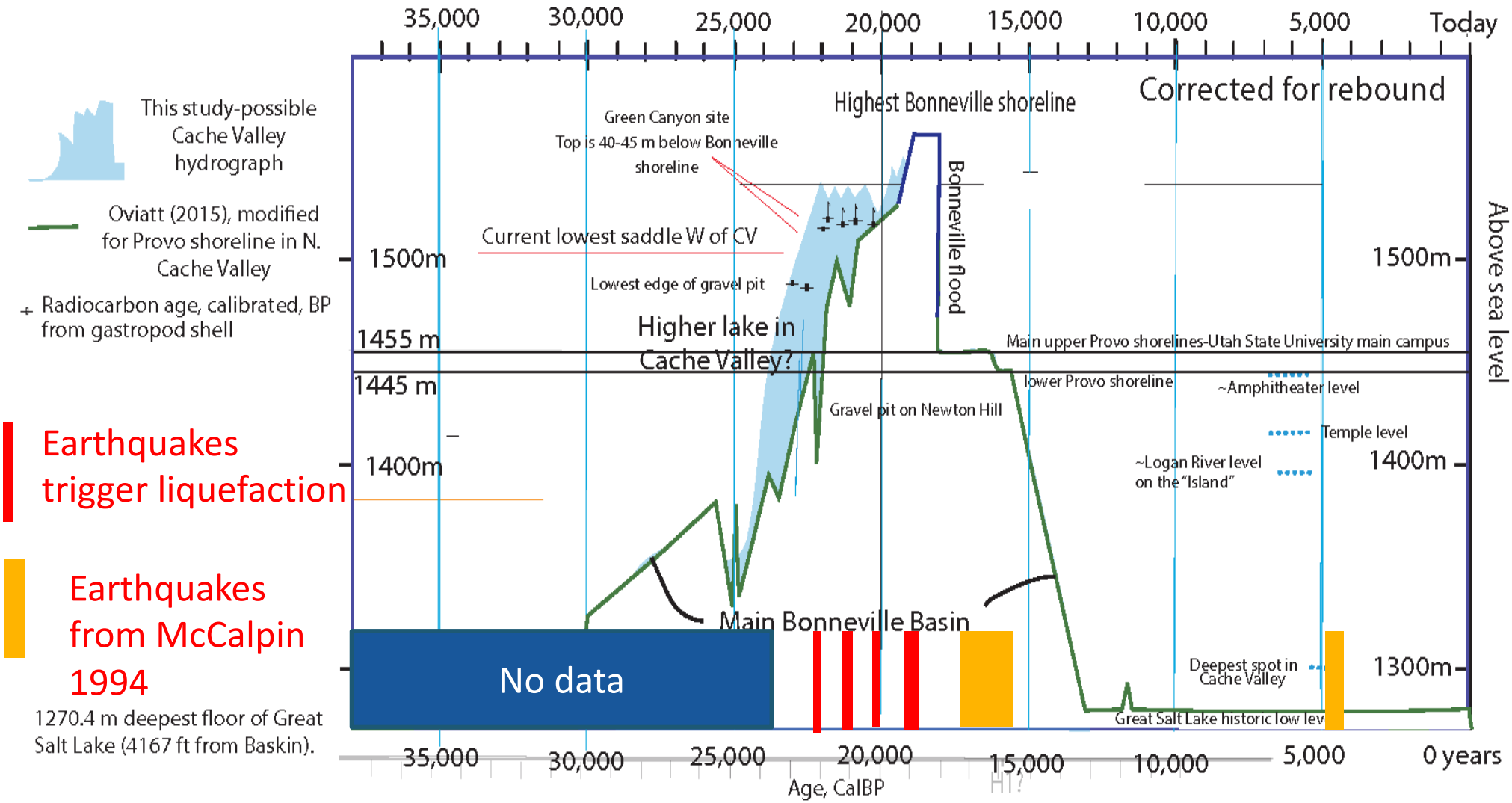
6. Why were earthquakes so clustered under L. Bonneville?

Next figure plots the 4 triggered events in time



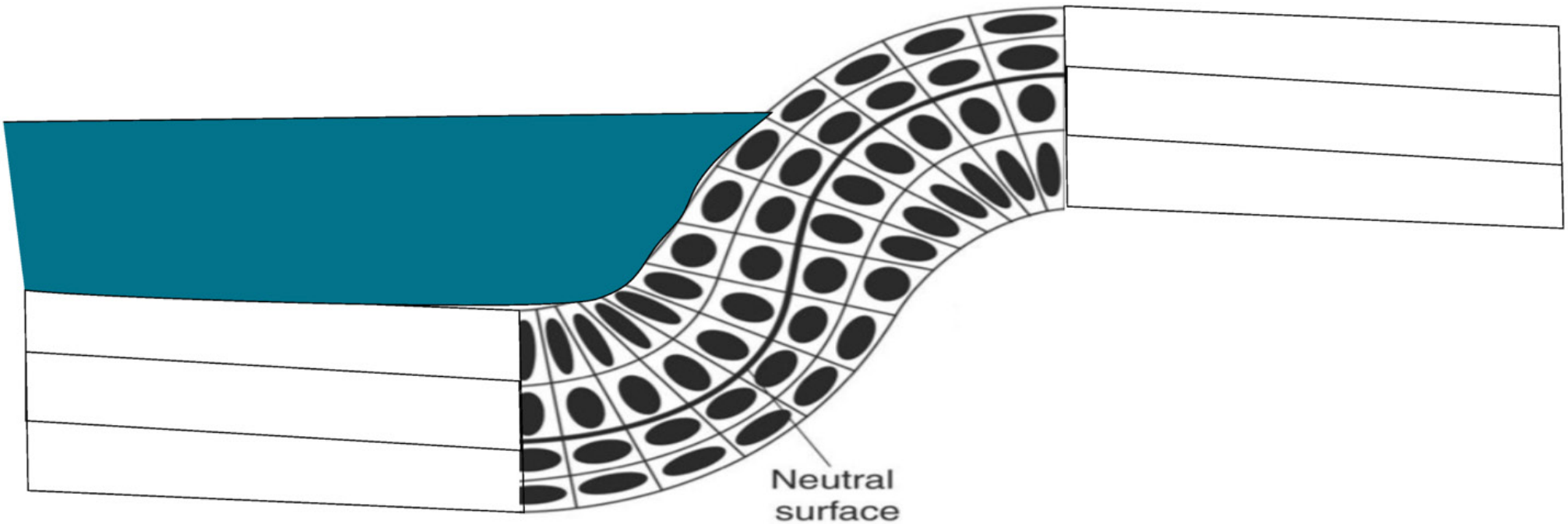
4 events in 5 or 2 ky for depending on hydrograph of Cache Valley (7 Radiocarbon ages are all higher and older than hydrograph predicts. Was Cache Valley separate from Lake Bonneville until the flood? See Oaks et al this meeting)

Earthquakes clustered when lake was high
Why? Hetzel and Hampel, 2005 suggest an answer:
Stresses and flexure



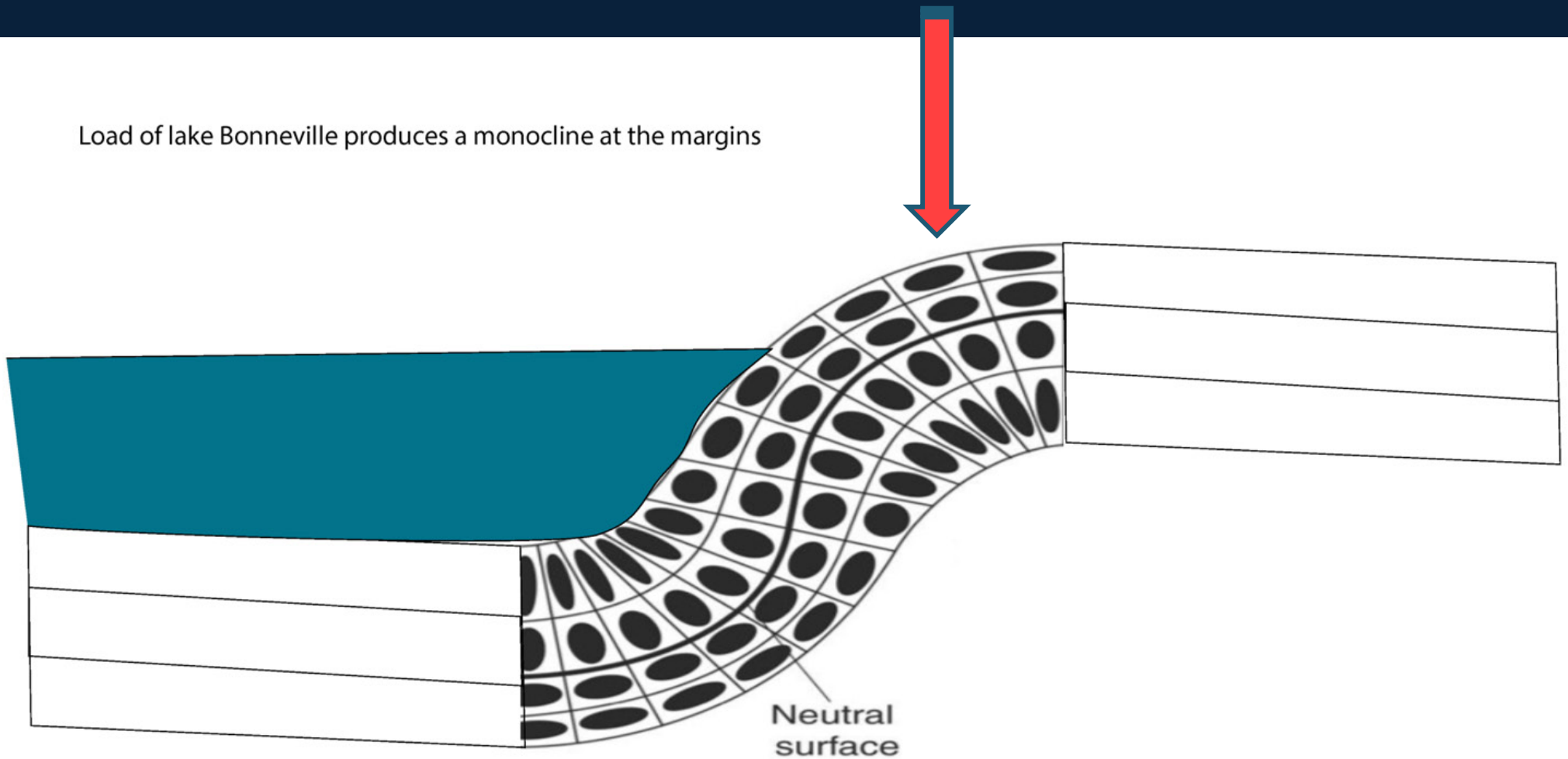
Consider east edge of Lake Bonneville: a monocline from loading

Load of lake Bonneville produces a monocline at the margins



Much vertical exaggeration, view north

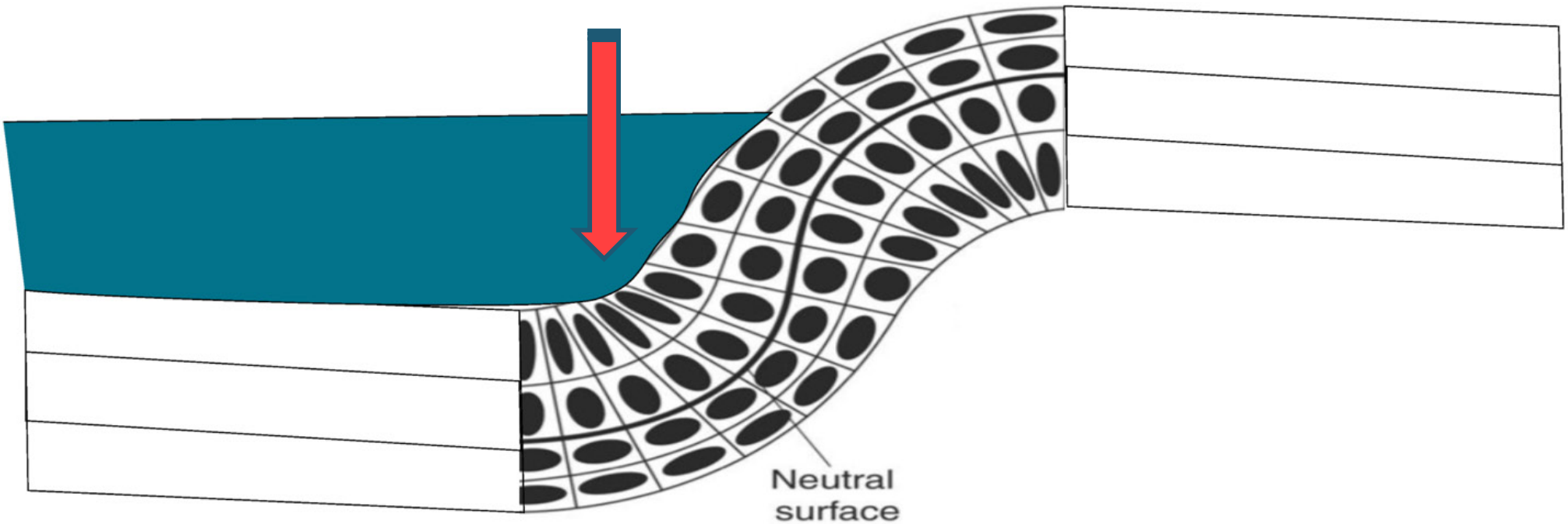
Upper hinge is zone of enhanced extension



Much vertical exaggeration

Whereas lower hinge is zone of reduced extension

Load of lake Bonneville produces a monocline at the margins



Much vertical exaggeration

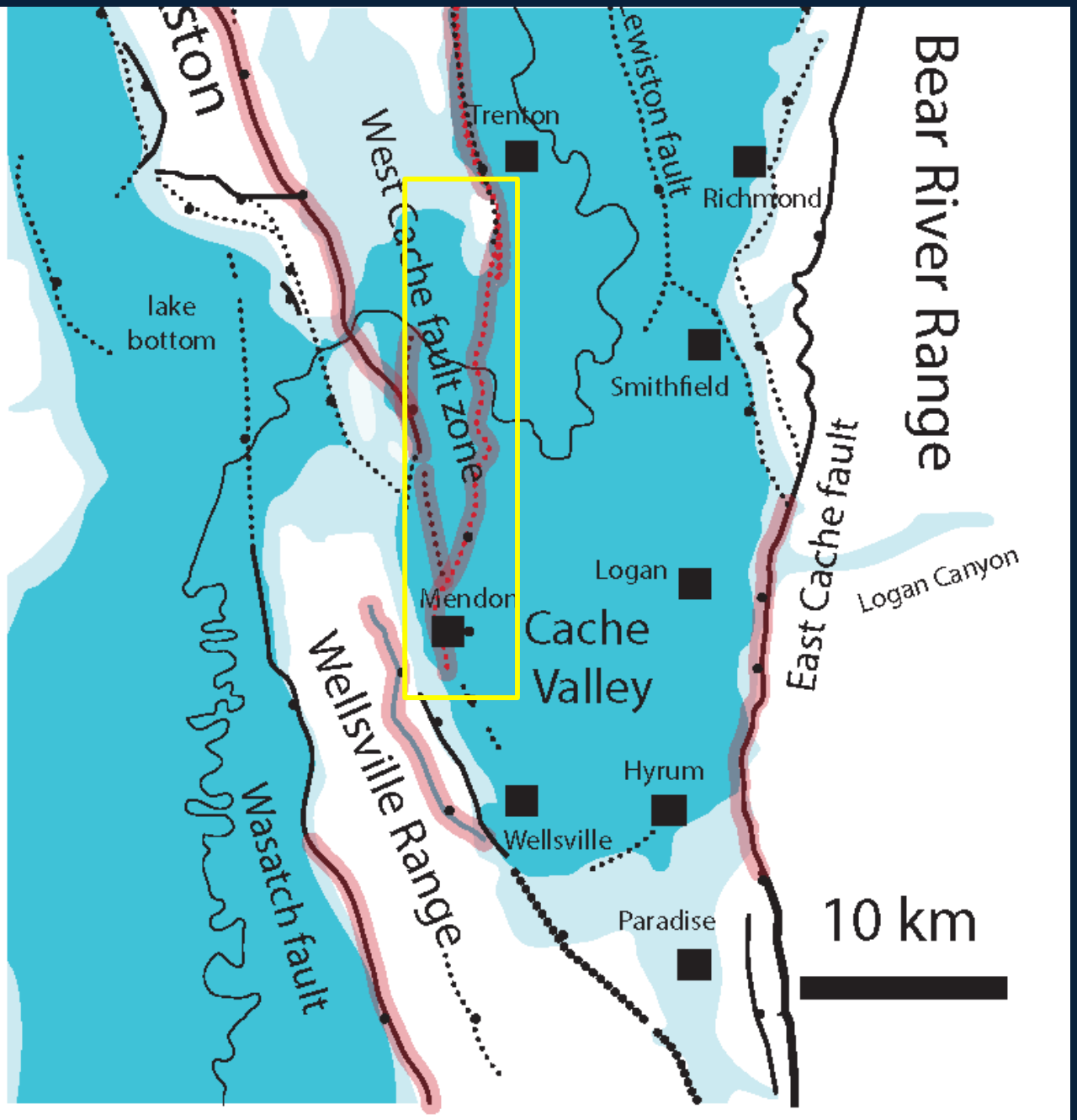
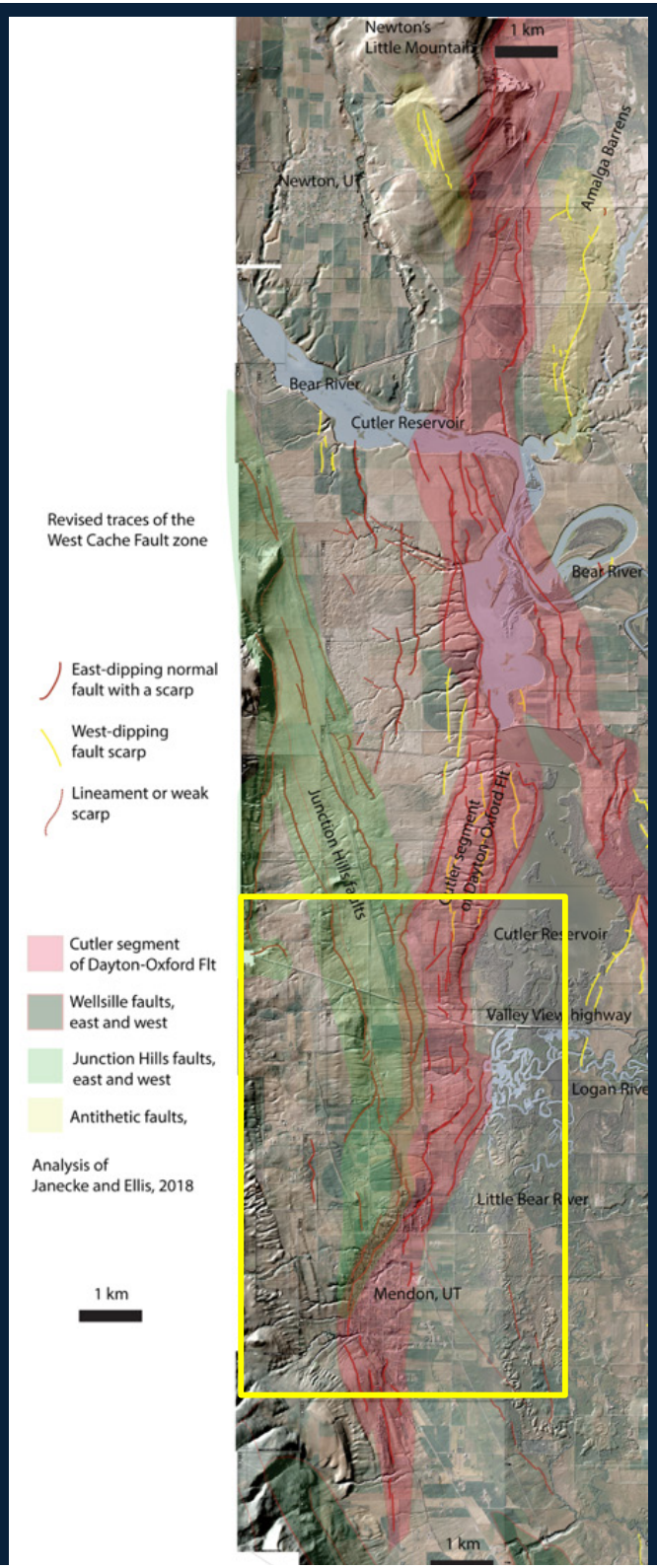


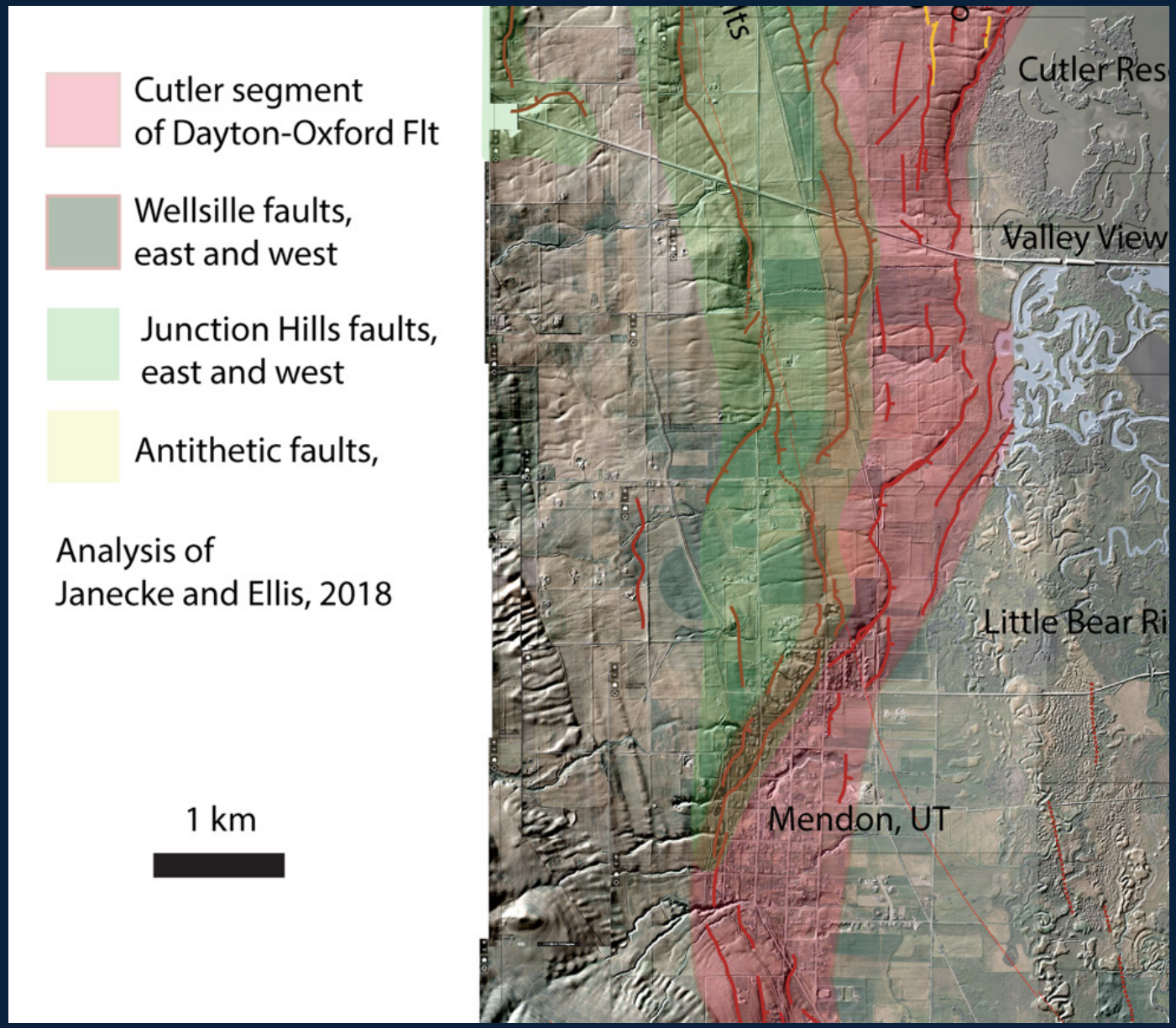
Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River a shoreline is simplified west of Cache Valley. RNF—Riverdale normal fau Great Basin (modified from Morrison, 1991). Geosphere, December 2011

West Cache fault zone was unusually active in Holocene and created a 1-km-wide fault zone on floor of Cache Valley around Cutler reservoir.

Janecke and Evans, 2016, Janecke and Ellis, 2018

Janecke and Oaks, 2011

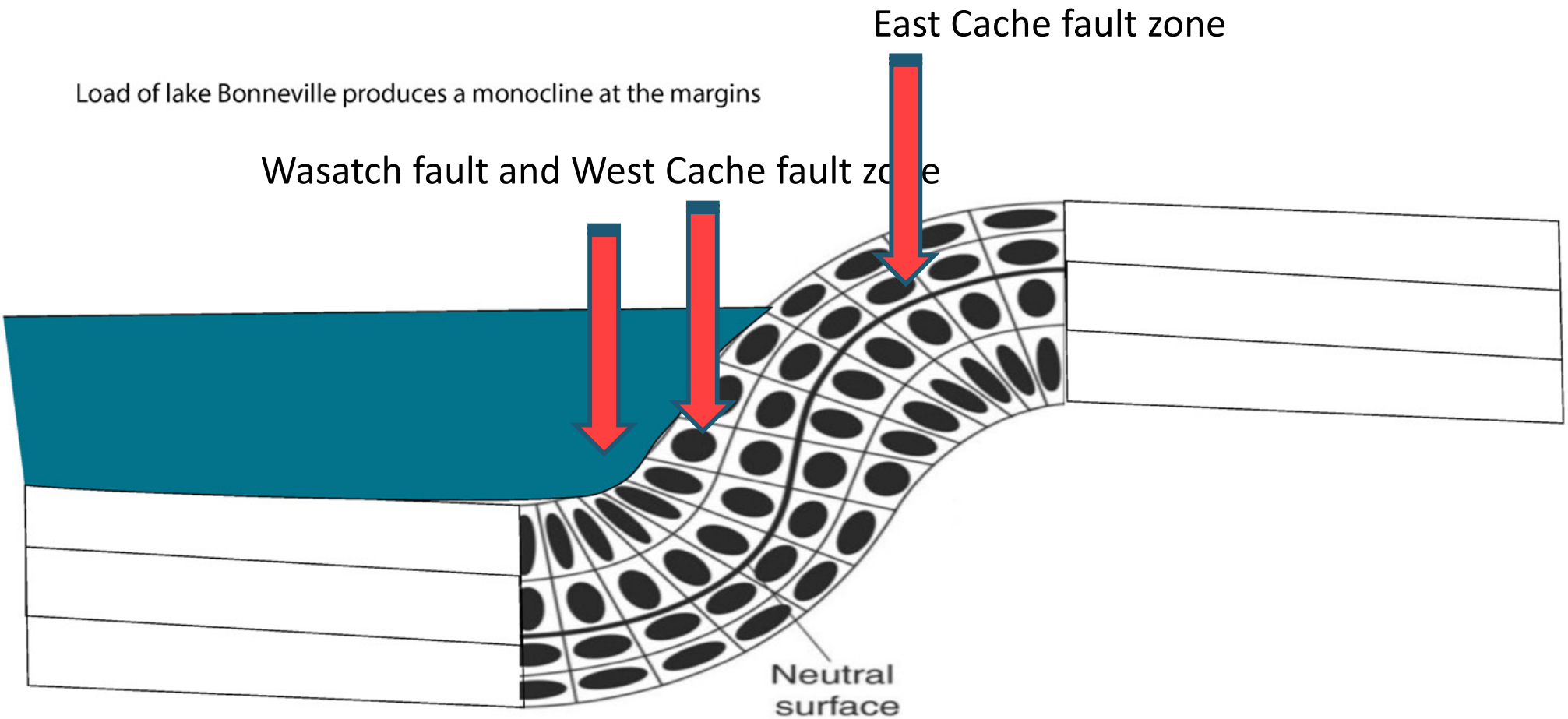




Janecke and Evans, 2016, Janecke and Ellis, 2018

Janecke et al., Geology Dept. USU Oct. 2018

Such bending could produce episodic slip and two parallel belts



Much vertical exaggeration

- The load of Lake Bonneville created parallel belts of activity.
- 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 was less active at the time.

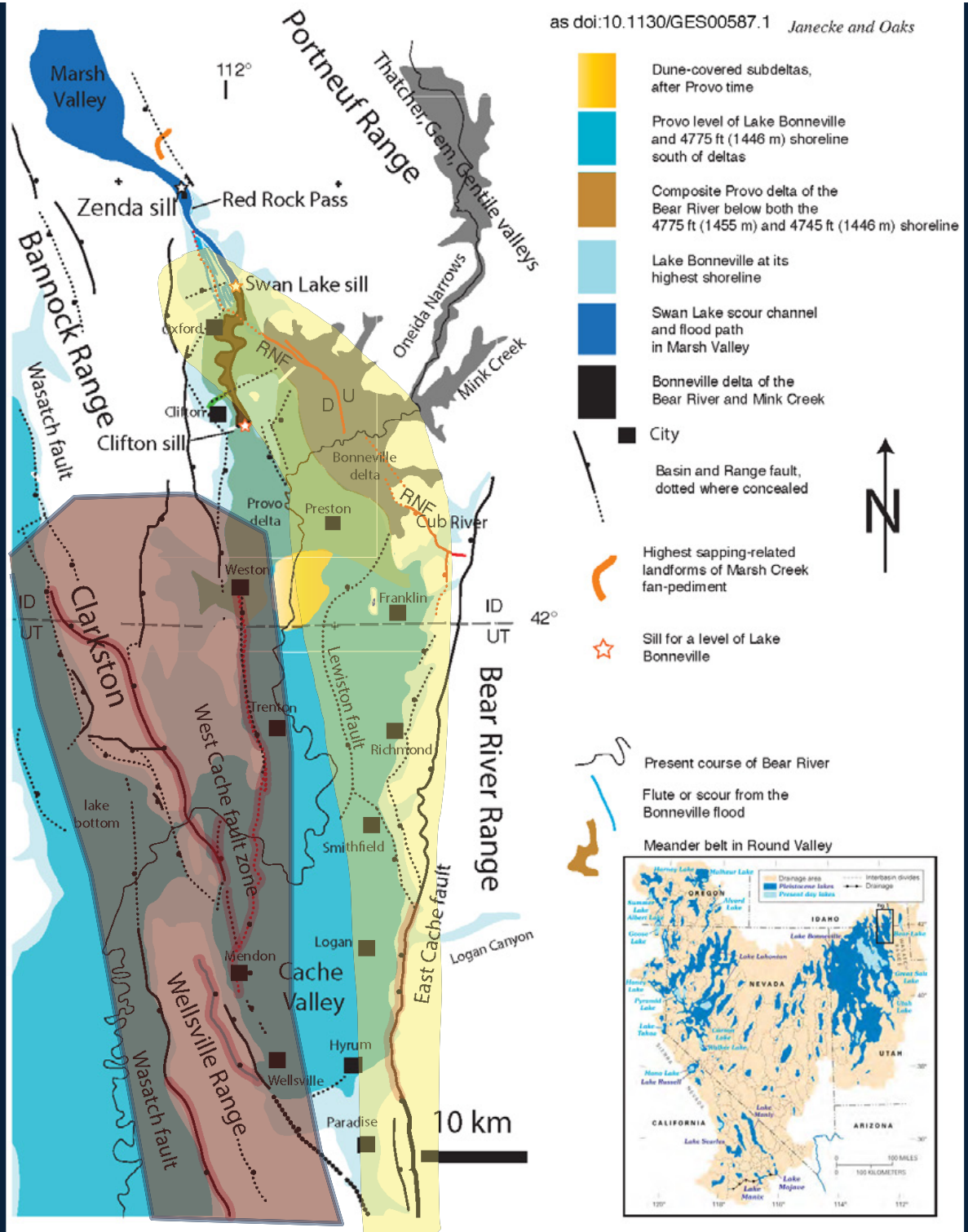
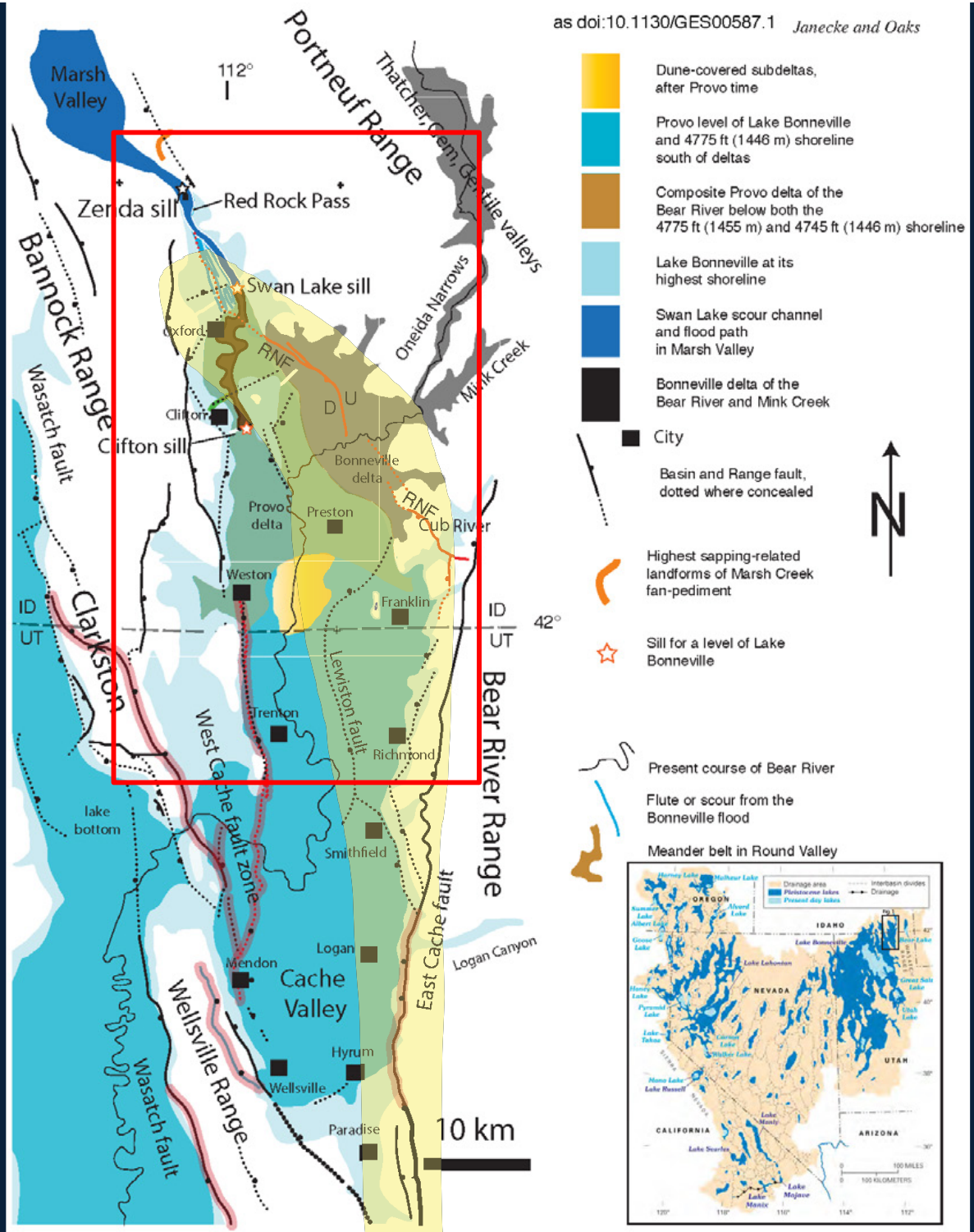


Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River are differentiated from other lacustrine deposits. Provo shoreline is simplified west of Cache Valley. RNF—Riverdale normal fault (+landslide?). Inset map shows location within the Great Basin (modified from Morrison, 1991). Geosphere,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

In Holocene, activity leveled caught up/or slowed

An earthquake similar to the ones recorded in Green Canyon area, in east belt, could have triggered the Bonneville flood—

BUT ONLY after many centuries of stable outflow. It took time to build the lg. Bonneville delta of Bear River and the wave-cut landforms.



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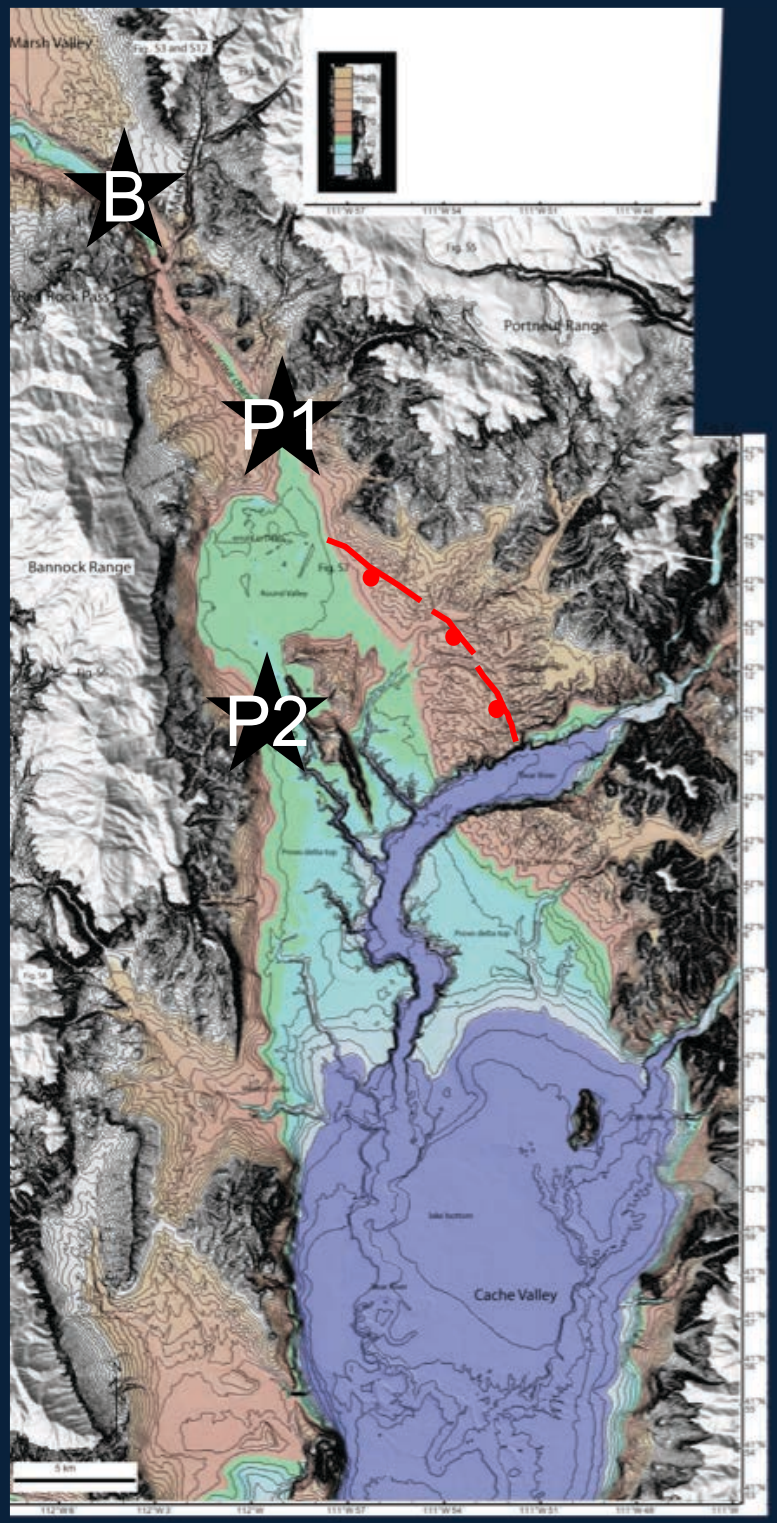
An earthquake along Riverdale fault or other structure in east belt could have triggered the Bonneville flood after many centuries of stable outflow at Zenda.

How?

Janecke and Oaks 2011



Bonneville s.l.

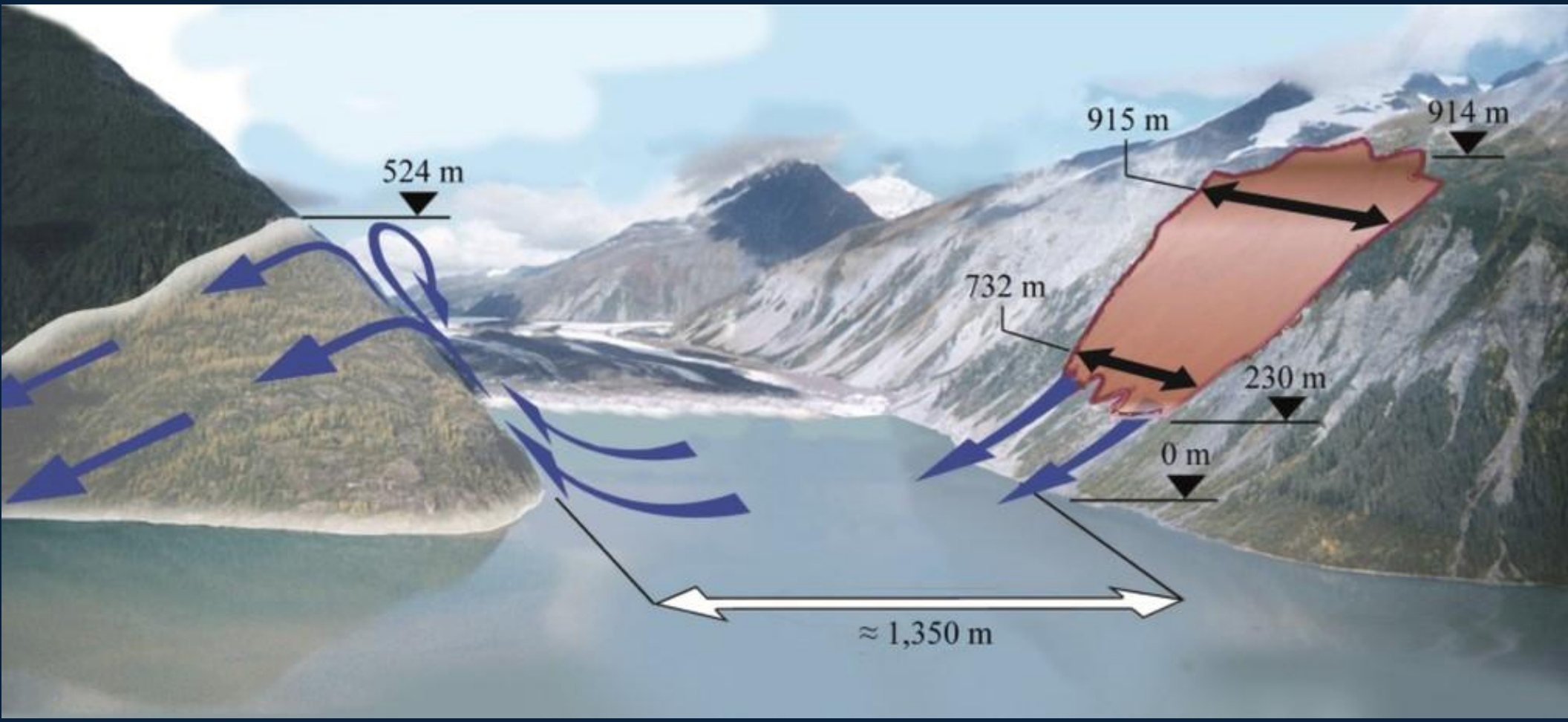
U. Provo s.l.

L. Provo s.l.

Below Provo

Possible impacts of large earthquakes on the Lake Bonneville?

- Seiches from earthquakes and secondary processes
- Shaking and breaking of natural dam composed of Salt Lake Formation
- Scenario like Lituya bay 1958 is possible with an earthen dam




Two additional event layers ?

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.

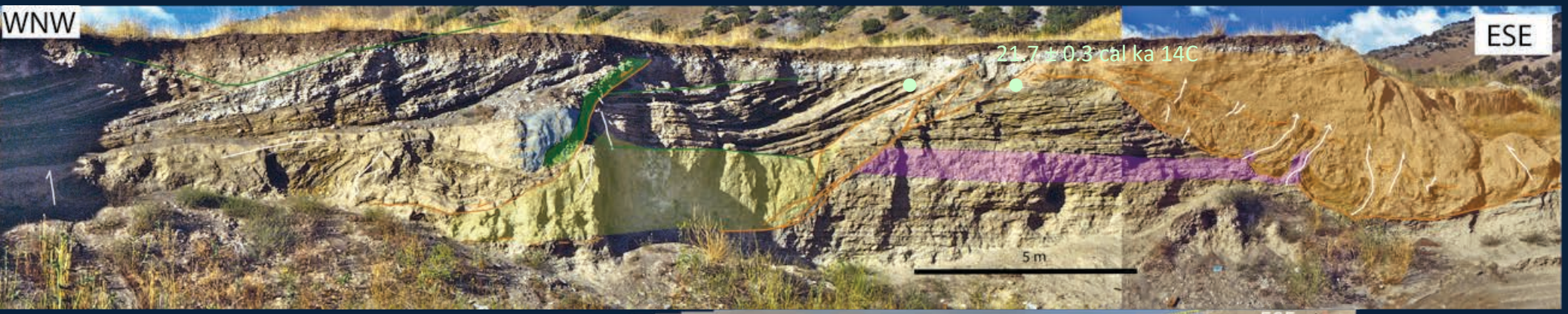
The most extreme deformation is expressed in fault-graded beds that are more than 5 m thick. The similarity between the LSLP and SBLM in the Green Canyon pit and secondary deformation generated by the 1934 M 6.6 Hansel Valley earthquake (McCalpin et al., 1992) indicate that seismic shaking is the most 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.

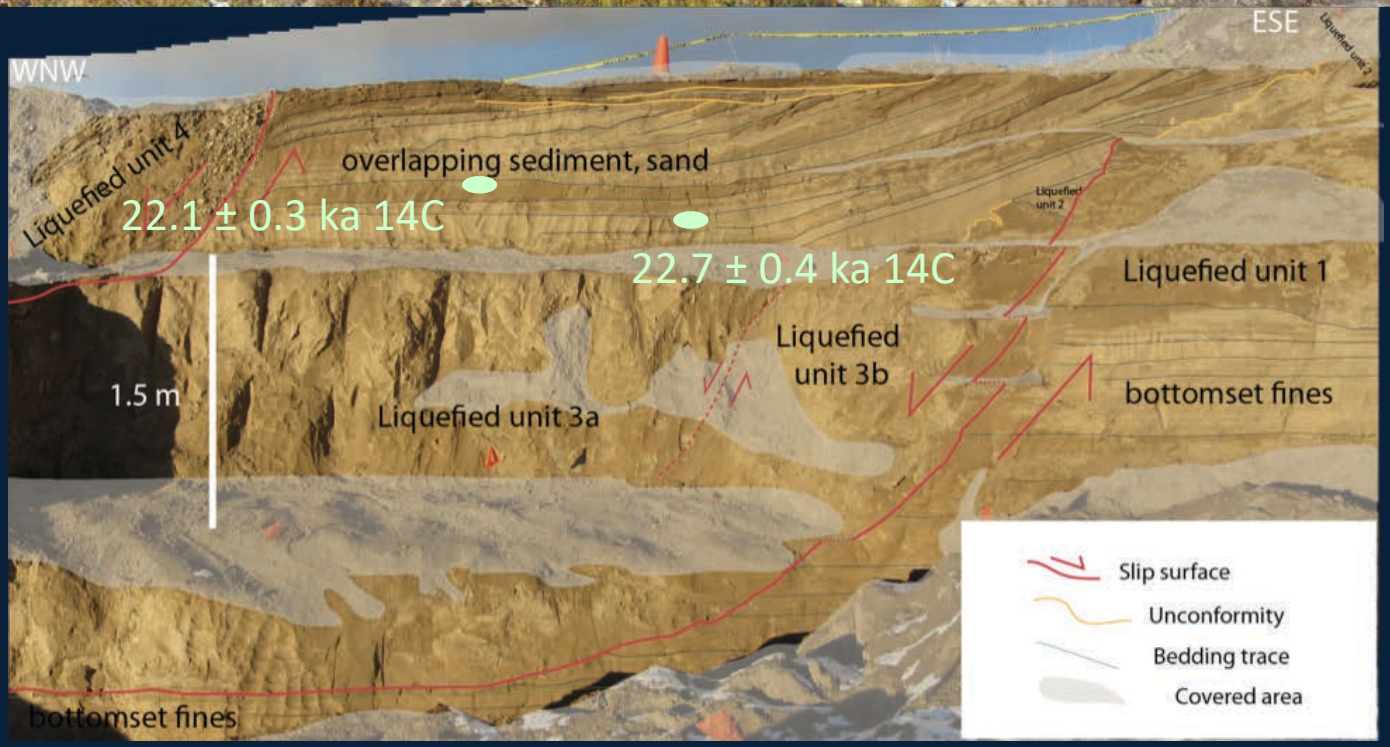
If each liquefaction event records a moderate to large earthquake between about 23 and 17 ky cal BP, the earthquake frequency along the adjacent part of the East Cache fault zone was high when the basin was full. This evidence plus the paleoseismic data of McCalpin (1994) for one additional earthquake 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).

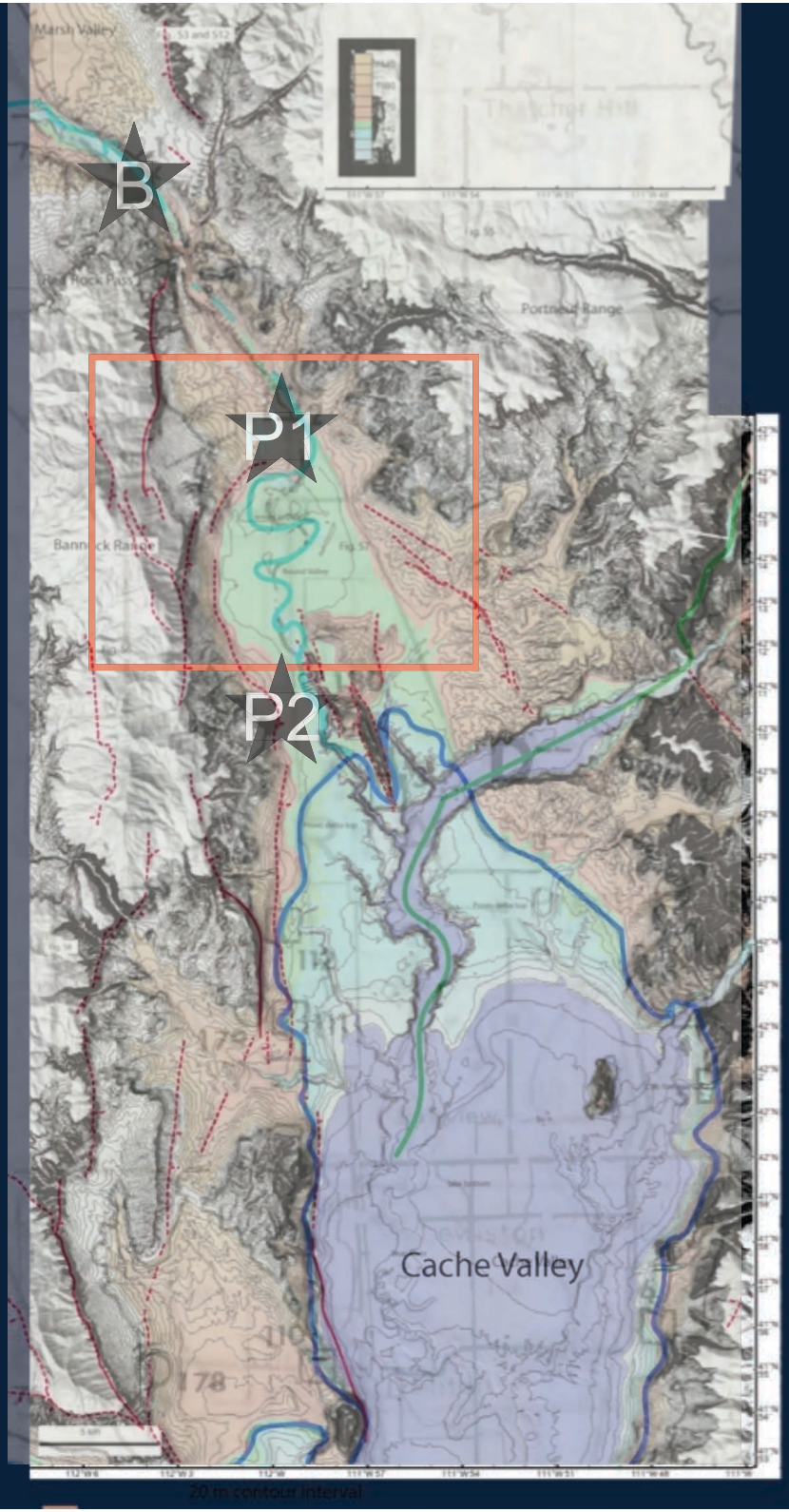
The increase in earthquake frequency along part of the East Cache fault zone documented here is in marked contrast to that of the Wasatch fault zone, which had a reduced slip rate during the occupation of Lake Bonneville (Hetzel and Hampel 2005). We explain the opposite responses of the two fault zones 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.

Jake staff is 160 cm long

Deformation in a very short time interval- ^{14}C







The 1445 m shoreline of Currey 1982 (BLUE) does not connect to the scour channel of Gilbert according to the map.