Lessons from the stratigraphic record of crustal and subduction earthquakes in Holocene lacustrine sediments of northern Cascadia

Lonnie Leithold

North Carolina State University, Dept. of Marine, Earth, and Atmospheric Sciences

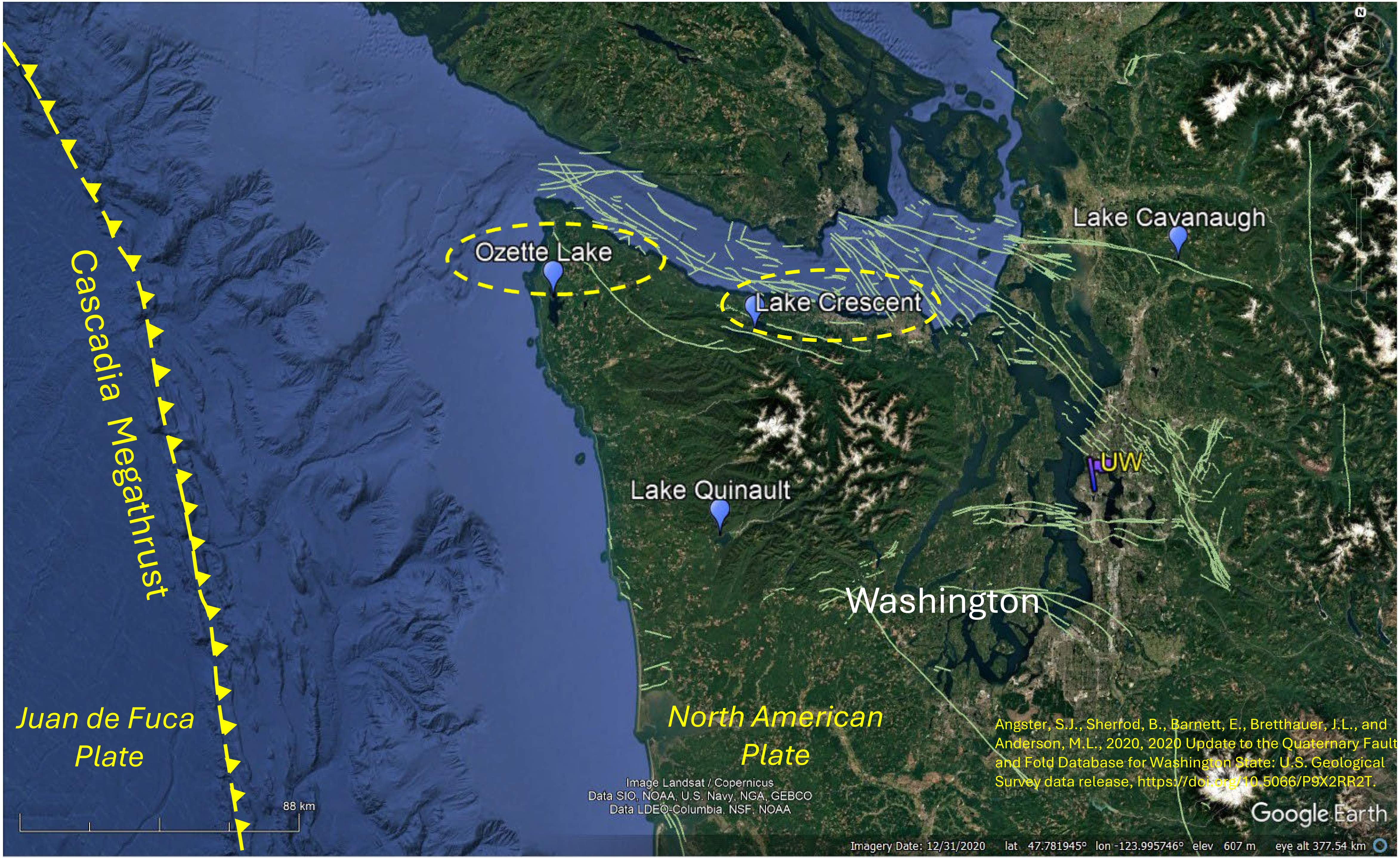
Research in collaboration with Karl Wegmann, Del Bohnenstiehl, Grant Colip, Lillian Slajus, Alli Vo, Audrianna Pollen, Catelyn Joyner, and Danny Brothers (USGS); supported by USGS-NEHRP Grants G15AP00091 & G20AP00056

NC STATE UNIVERSITY

CSD Facility
Continental Scientific Drilling

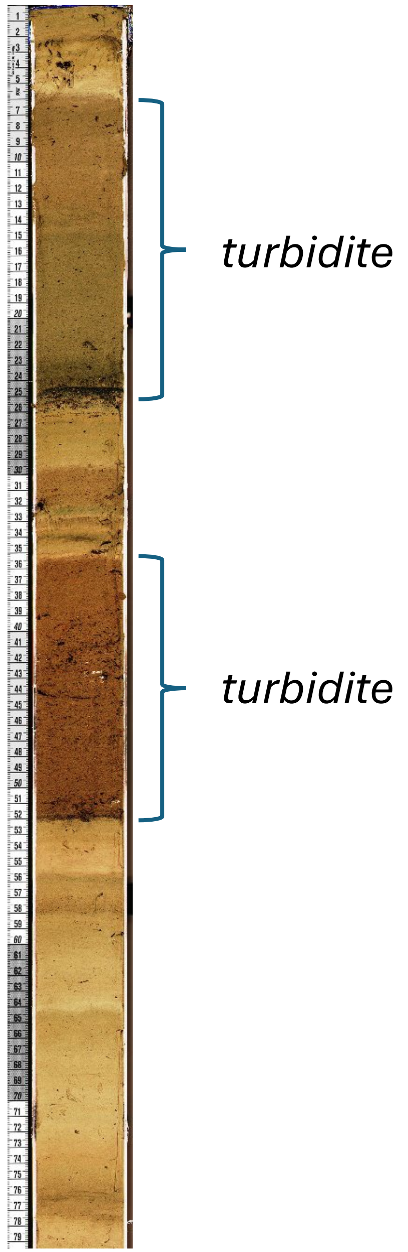
USGS
science for a changing world

nehrp


Cascadia Megathrust
Juan de Fuca
Plate
Ozette Lake
Lake Crescent
Lake Cavanaugh
Lake Quinault
UW
Washington
North American
Plate
Angster, S.J., Sherrod, B., Barnett, E., Bretthauer, J.L., and Anderson, M.L., 2020, 2020 Update to the Quaternary Fault and Fold Database for Washington State: U.S. Geological Survey data release, https://doi.org/10.5066/P9X2RR2T.
88 km
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data LDEO-Columbia, NSF, NOAA
Google Earth
Imagery Date: 12/31/2020 lat 47.781945° lon -123.995746° elev 607 m eye alt 377.54 km

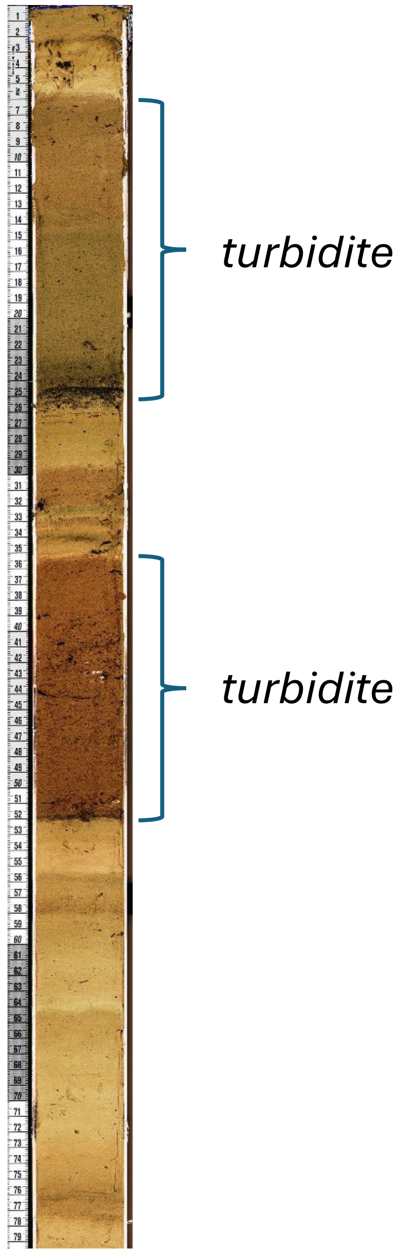
Lacustrine paleoseismology

- Lake sediments provide continuous, high-resolution environmental records at sites distributed parallel and perpendicular to the Cascadia margin
- At shaking intensities > MMI 6, earthquakes trigger subaerial and subaqueous landslides along lake margins and produce *turbidites* that can be distinguished from event deposits formed by other processes



Lacustrine paleoseismology

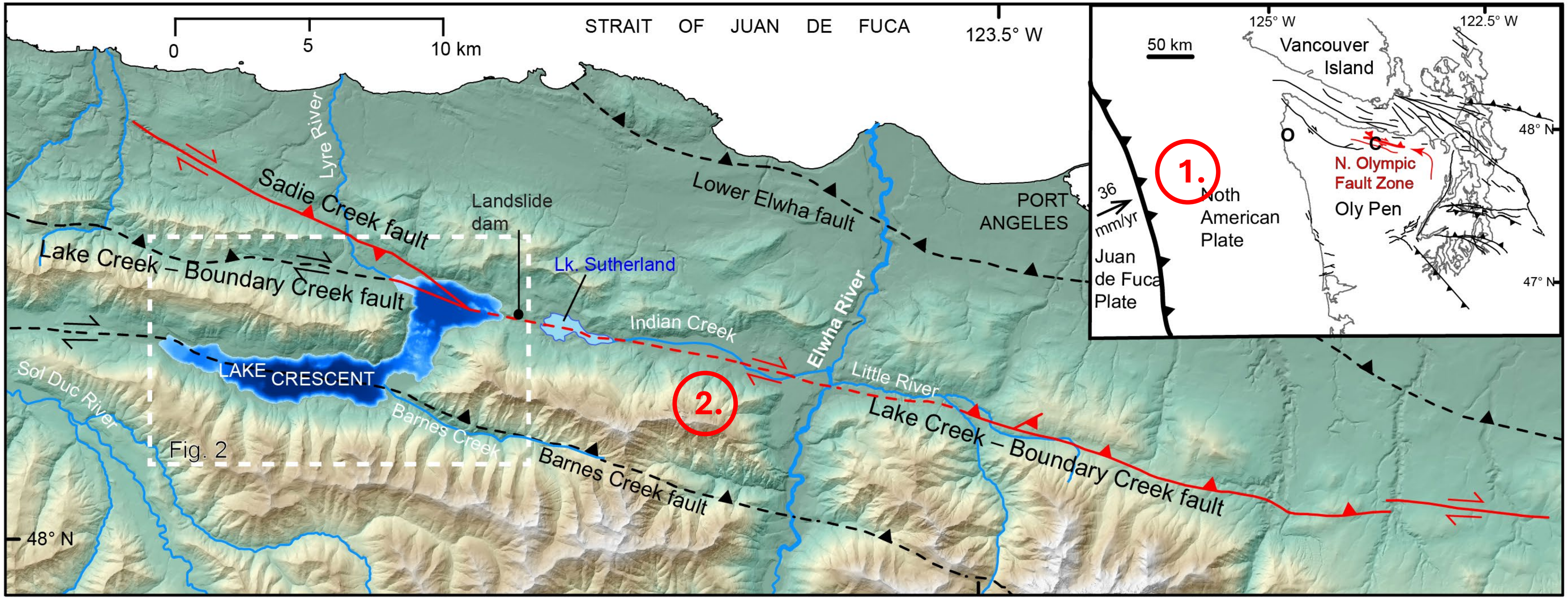
- Earthquakes sourced from the subduction megathrust and from crustal faults result in distinctive types of deposits in some lakes *(Lake Crescent)*
- The concurrence of paleoseismic and paleoclimate records in lake sediments offers the potential for obtaining more precise ages for past earthquakes than is possible using radiocarbon dating alone *(Ozette Lake)*



Lake Crescent (Olympic National Park, WA)

- Occupies parts of two glacially deepened valleys
- Maximum depth is 190 m; surface area is about 20 km^2
- Minimal sediment supply– only one perennial stream
- Steep hillslopes and subaqueous slopes subject to mass wasting during earthquakes

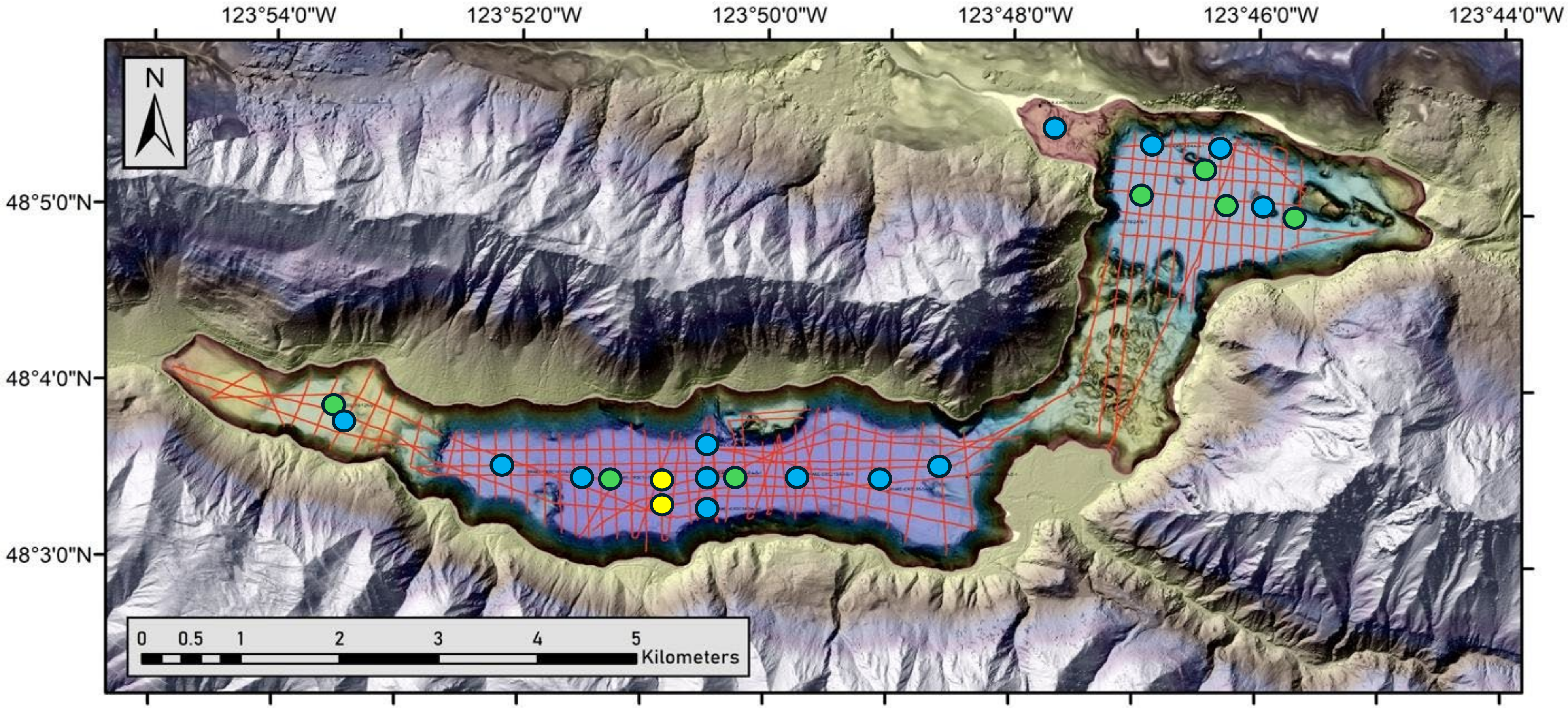
North Olympic Peninsula Earthquake Sources



Two primary earthquake sources affect the North Olympic Peninsula

1. Cascadia Subduction Zone
2. Shallow crustal faults (e.g., **North Olympic Fault Zone**)

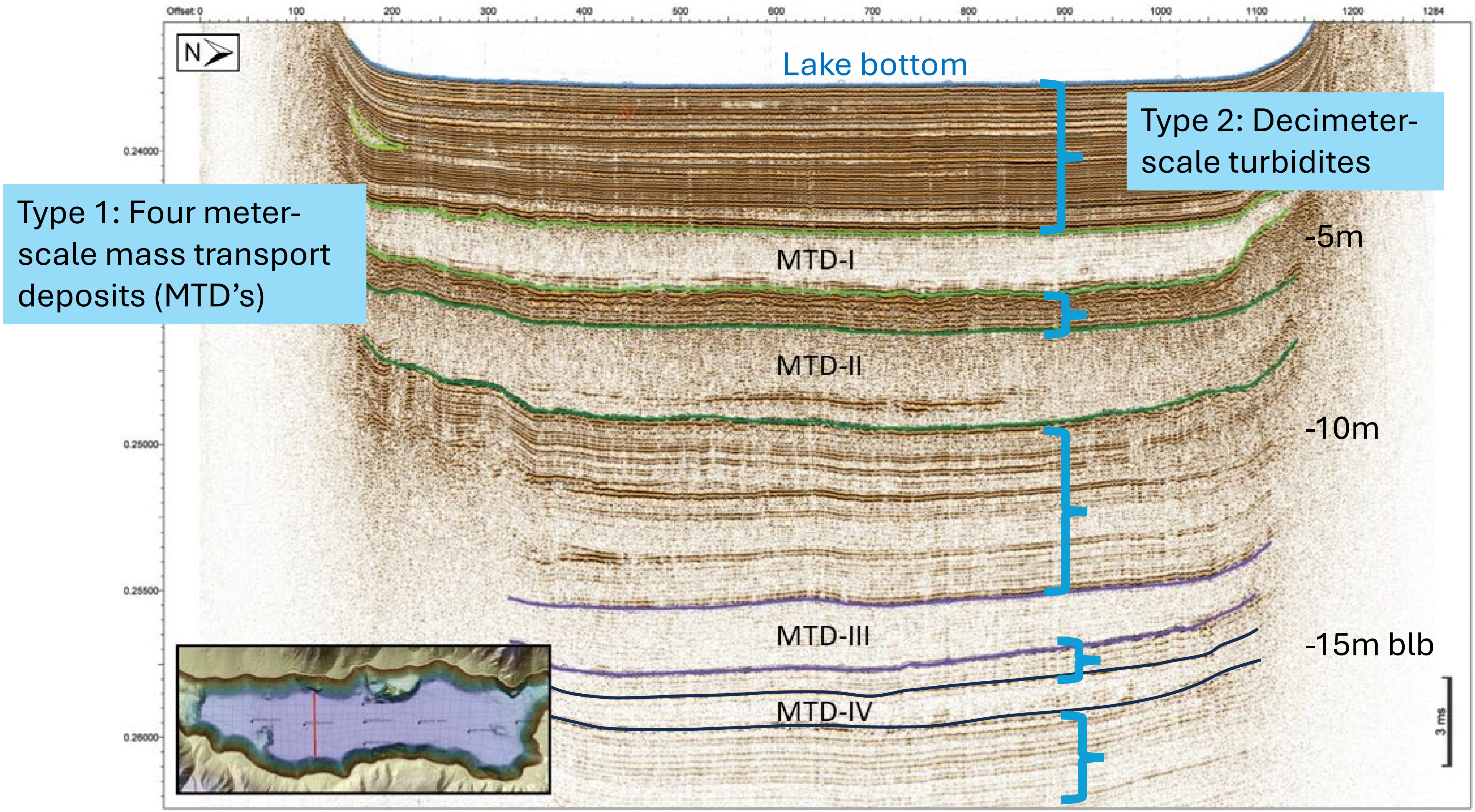
Hypothesis: Sediments at the bottom of Lake Crescent preserve evidence of Holocene earthquakes *from both* the NOFZ and CSZ



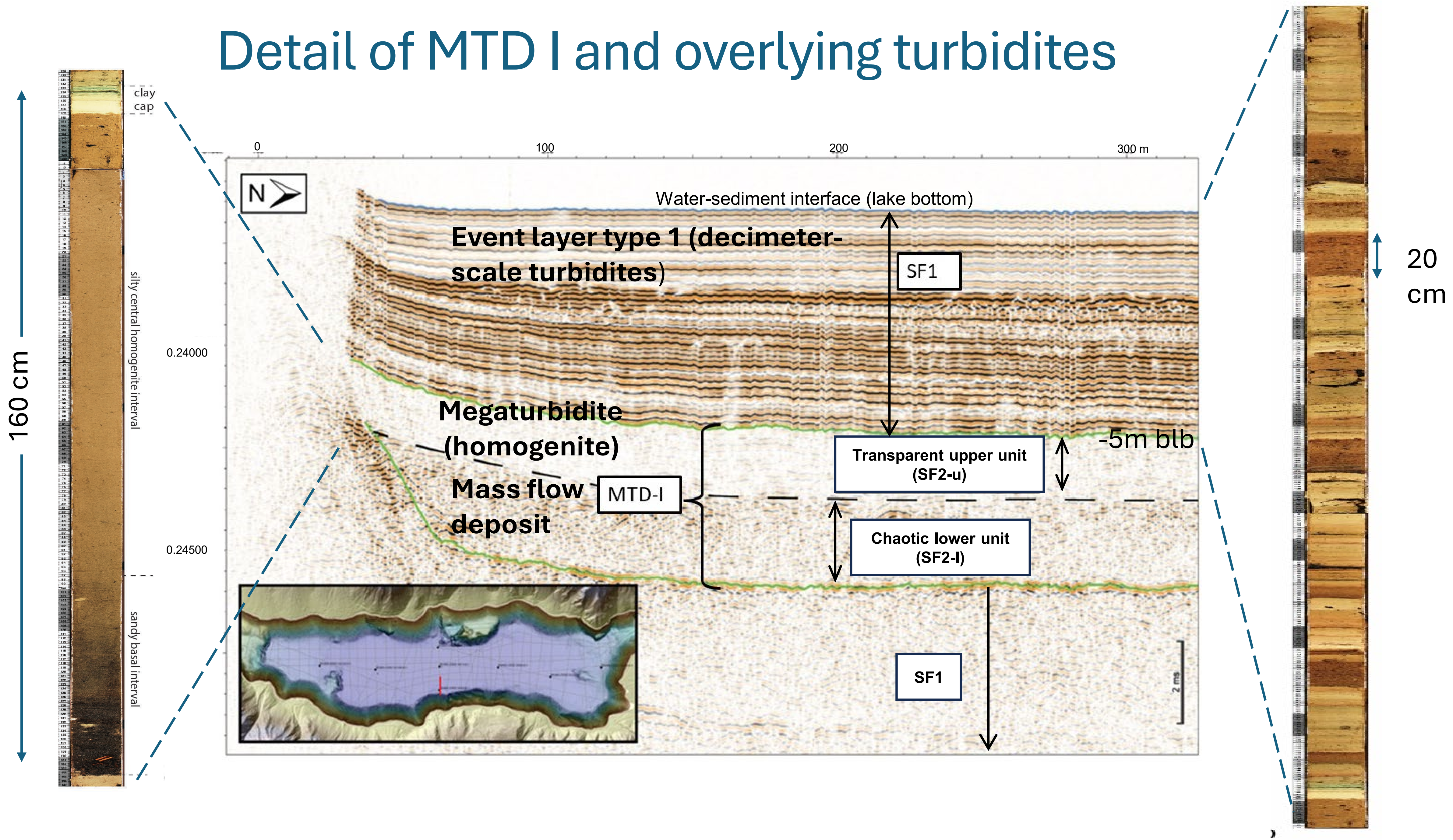
Survey lines (red) from a 2019 USGS CHIRP seismic data collection

Piston cores (2015) Gravity cores (2018) UWITEC cores (2022)

Two types of event deposits in CHIRP seismic reflection profile from lake's southern basin



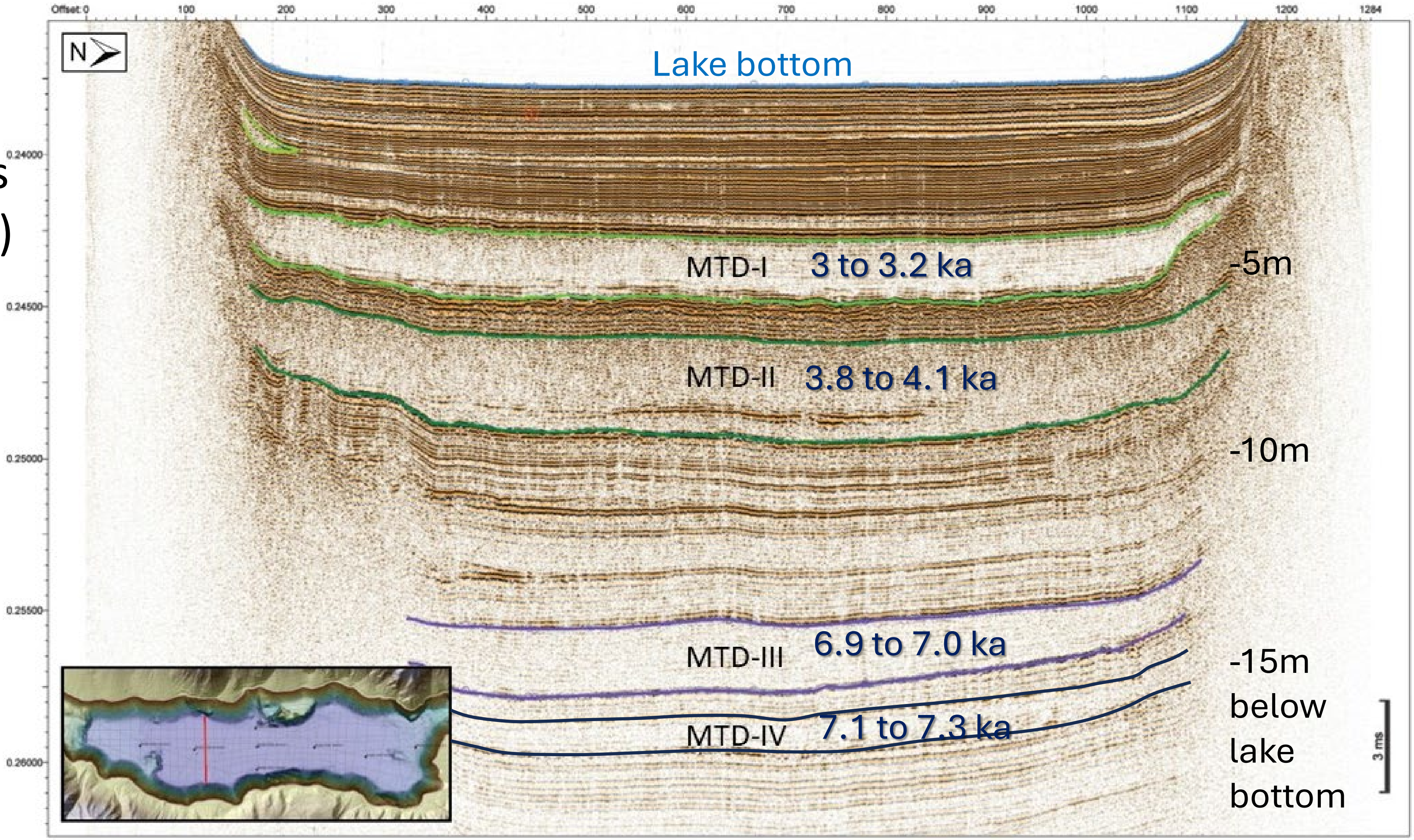
Detail of MTD I and overlying turbidites

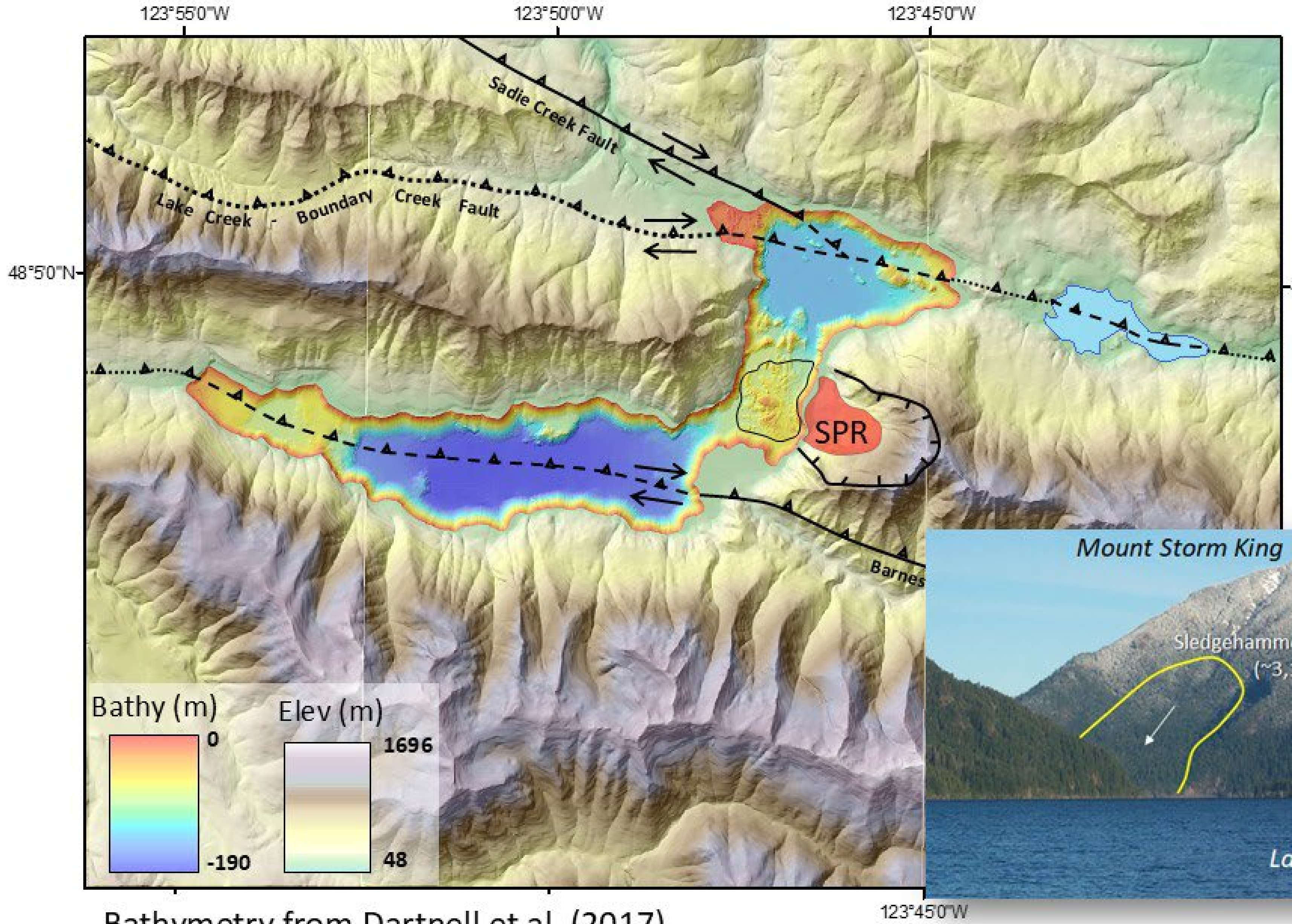


What processes formed the two types of event layers in Lake Crescent?

Type 1 Event Layers

The four meter-scale mass transport deposits (MTD's) formed when **large rockslides entered the lake**, most recently about 3100 years go

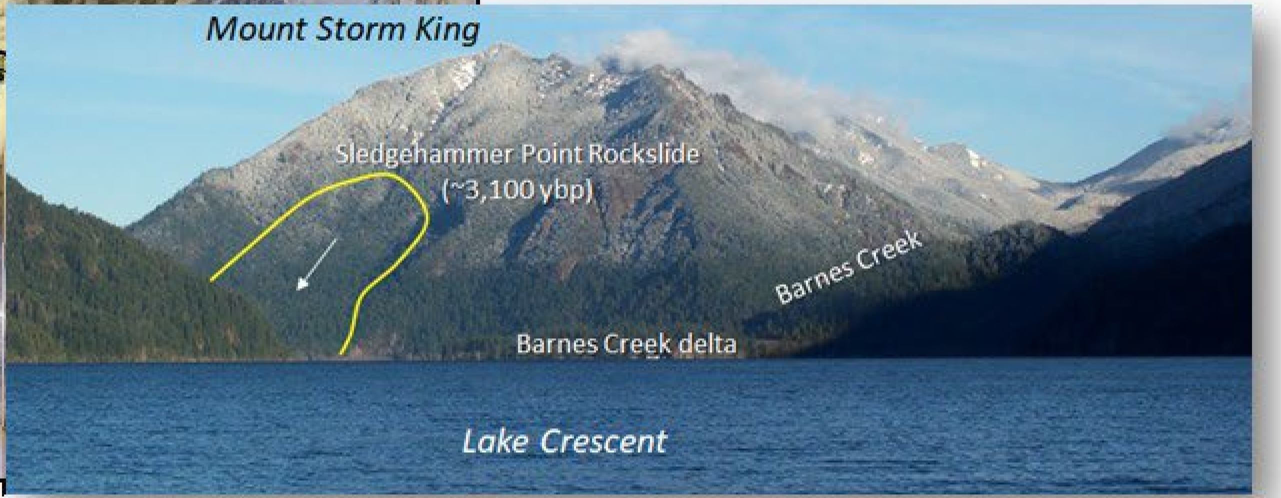




Bathymetry from Dartnell et al. (2017)

MTD I is attributed to the <u>Sledgehammer Point Rockslide</u>, which entered the lake around 3100 cal yr BP

The landslide deposits are visible on the lake bottom between the northern and southern sub-basins



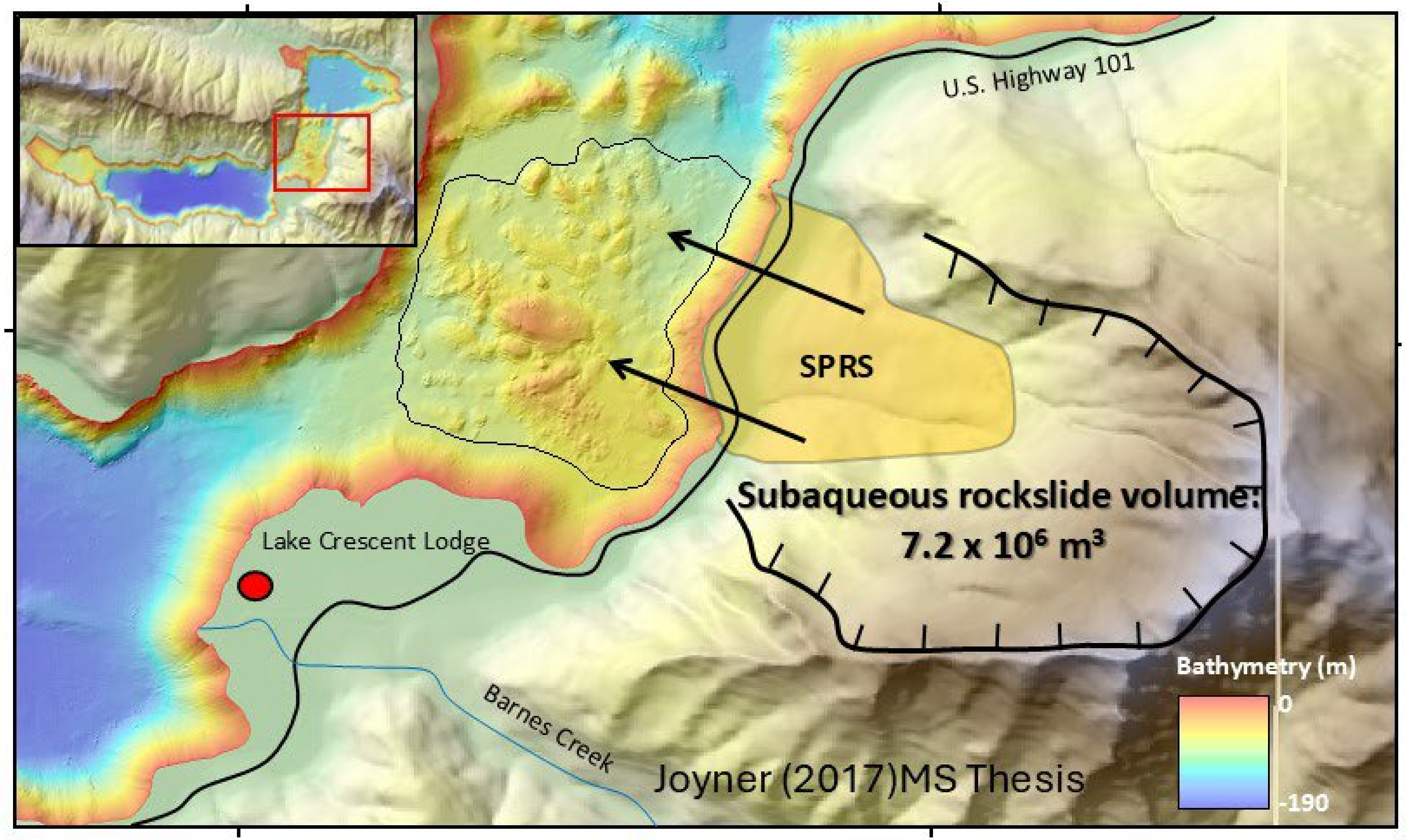
The Sledgehammer Point Landslide and MTD I (ca. 3100 cal y BP)

Lake Crescent MTD I

3. Settling of finest suspended particles in days to months following the event

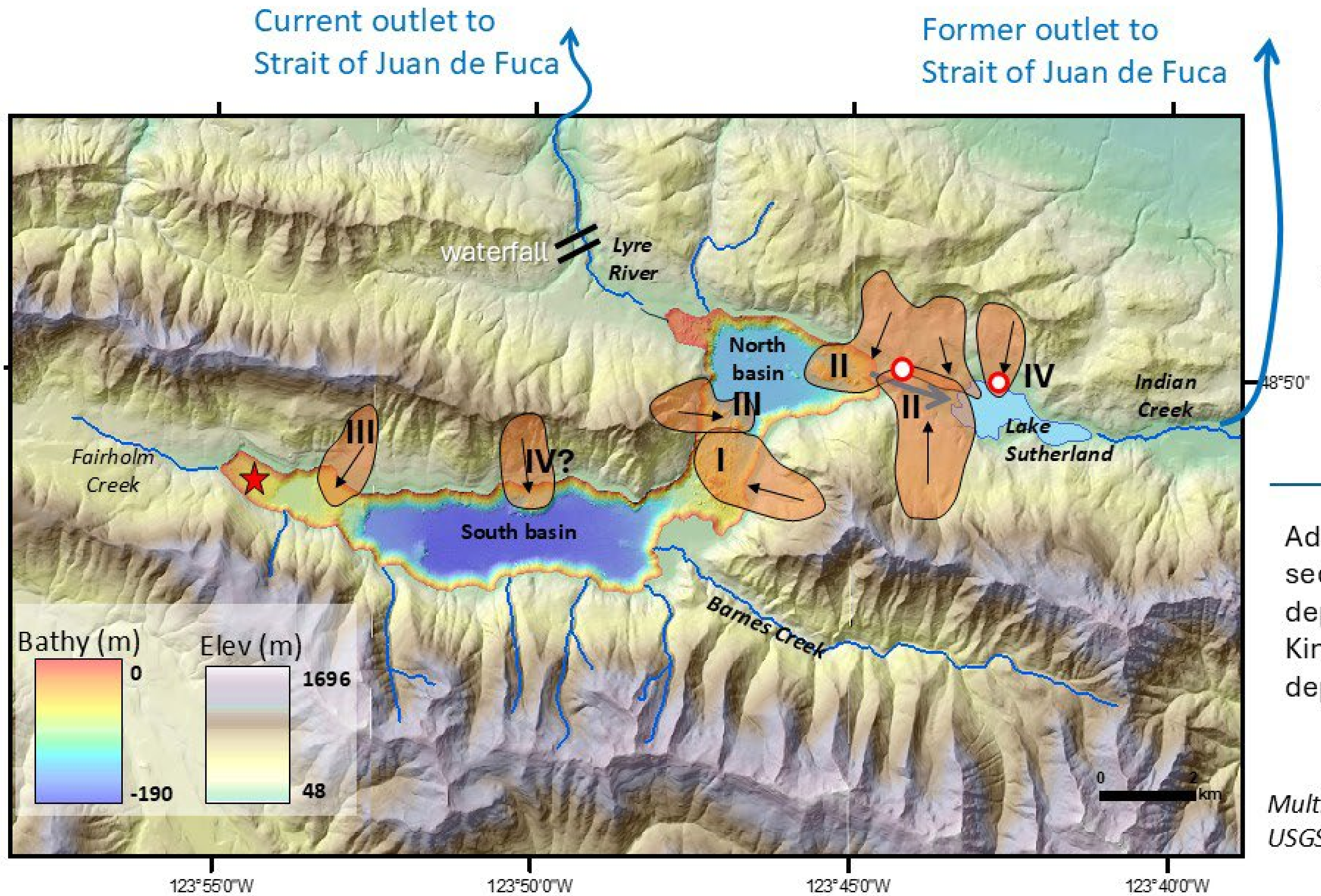
2. Seiche, maintaining sediment in suspension before ponding and settling in the centers of the two lake sub-basins as a plug-flow (homogenite) deposit

1. Landslide-generated Displacement waves and earthquake shaking induce sediment mobilization from lake margins and lakebed erosion.



MTD I is present in all three sub-basins of the lake, has a maximum thickness of 4 m, and a total wet volume of about 8.3 x 10^6 m^3

Rockslides responsible for mass transport deposits



MTD chronology

MTD-I ~ 3.0 ka

MTD-II ~ 4.1 ka (lake separation and drainage change)

MTD-III ~6.9 ka

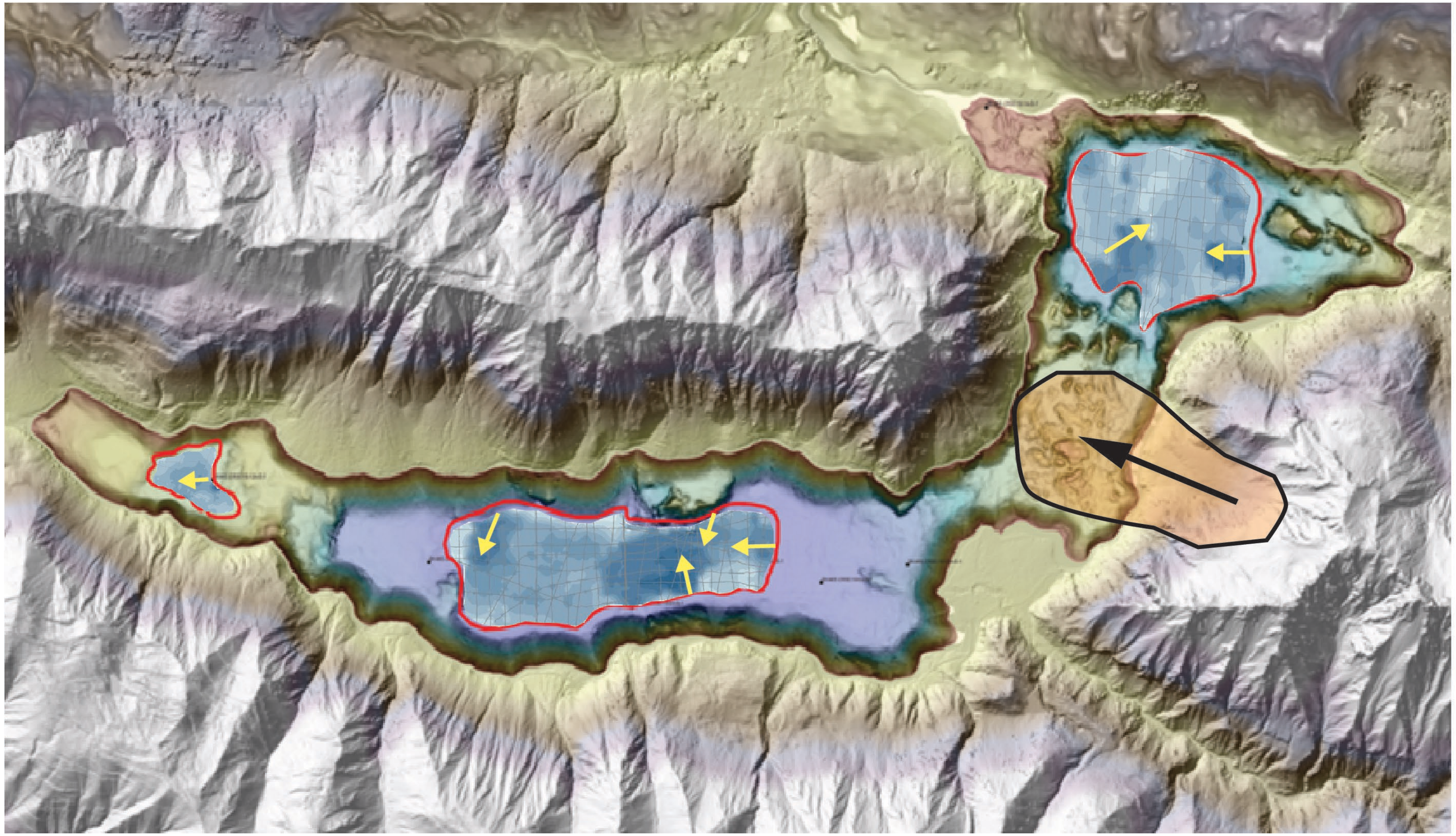
MTD-IV ~7.2 ka

Additional ^{14}C dating of basal sediments from a closed depression (O) on the Mount Storm King & Sutherland rockslide runout deposits and drowned trees (★)

Multibeam bathymetry: Dartnell et al. (2017); USGS data release, doi: 10.5066/F7B56GW5.

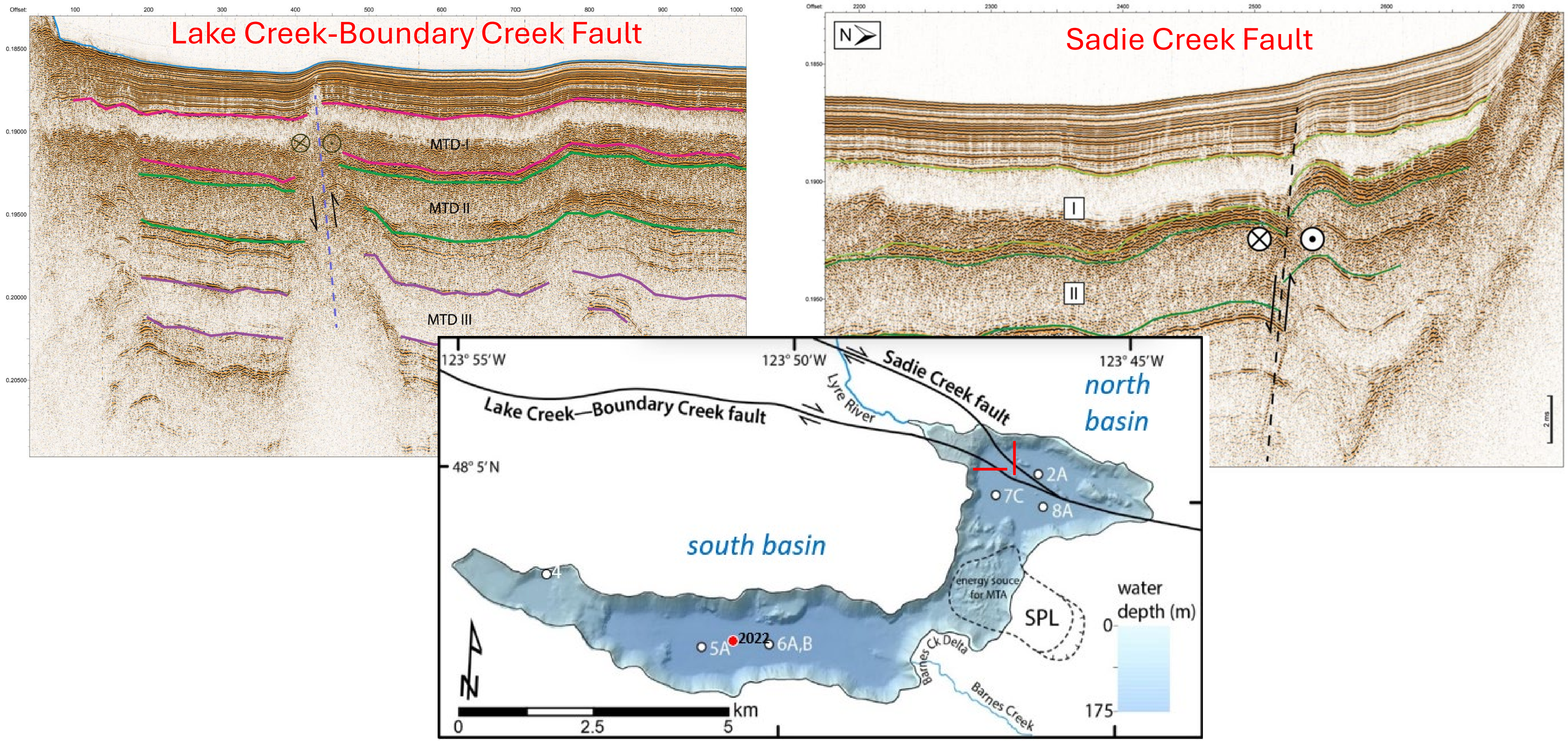
Were the rockslides triggered by earthquakes?

MTD-I, ca. 3100 cal yr BP

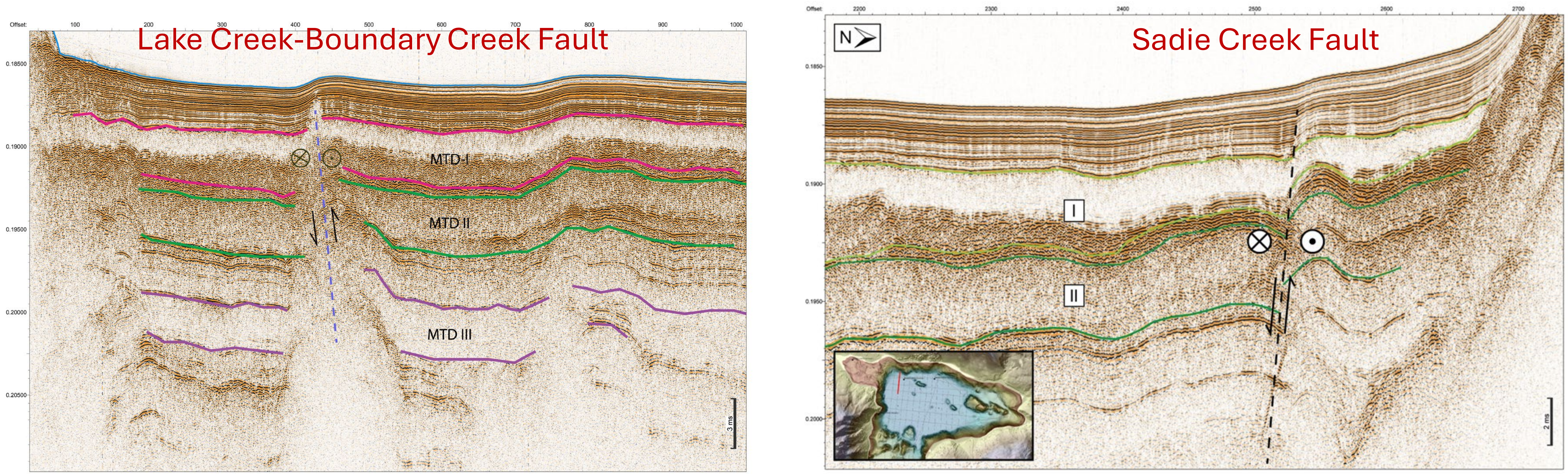


Isopach maps of MTD-I, II, and III indicate synchronous lake-margin failures in all three subbasins and multiple sediment transport pathways – **consistent with earthquake triggers.**

Offset of MTD's by the Lake Creek-Boundary Creek and Sadie Creek Faults



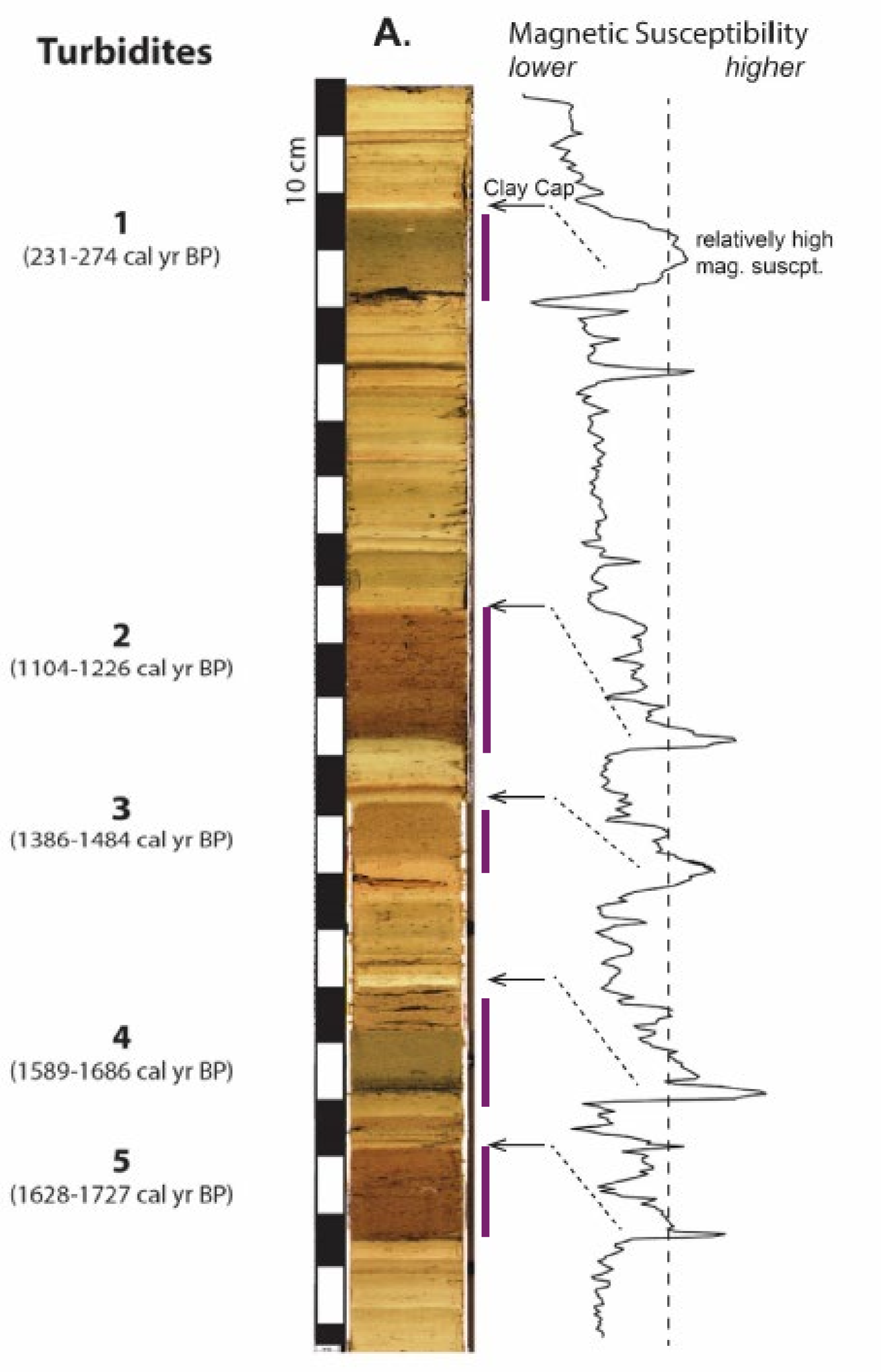
Evidence that the landslides were earthquake-triggered– offset of MTD's by the Lake Creek-Boundary Creek Fault and its splays



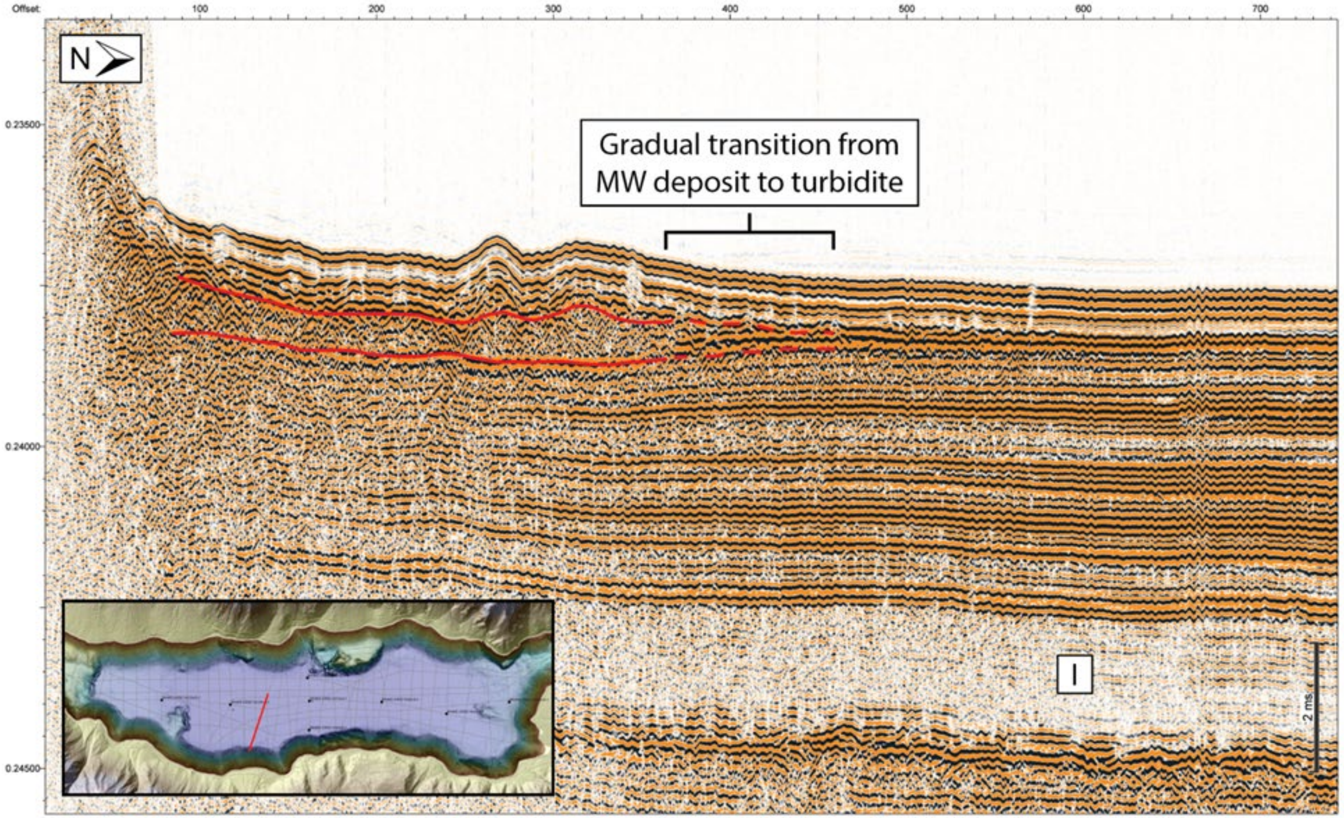
Note: We recognize evidence for **five ruptures of the Northern Olympic Fault Zone in the past 7300 years, including** an event ca. 4000 years ago not recognized in the trench-based study of Shermer et al. (2021).

The last event occurred around 1200 years ago and did not cause a rockslide. It did, however, offset strata above MTD-I, cause a delta failure and deposit a thick turbidite in the southern subbasin.

The Northern Olympic Fault Zone appears to be one of the most active crustal fault systems in northern Cascadia

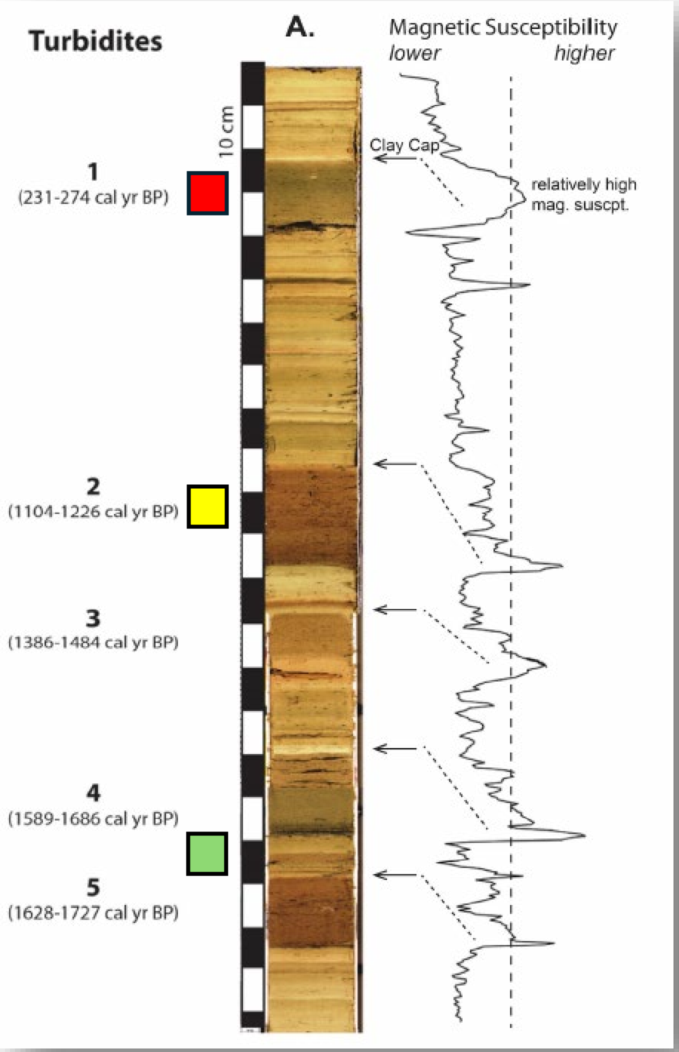


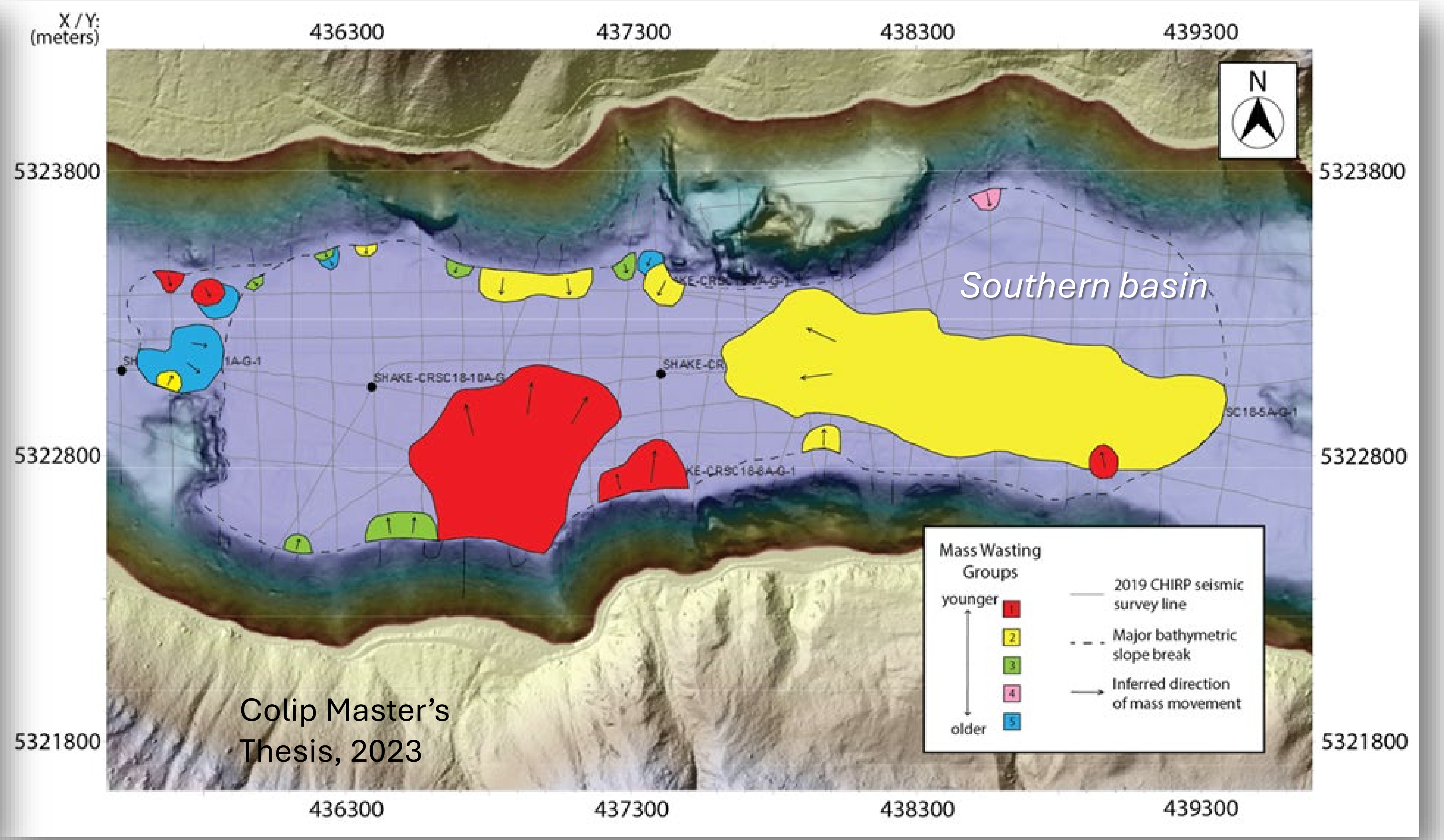
Were the turbidites (type-2 event layers) also earthquake-triggered?



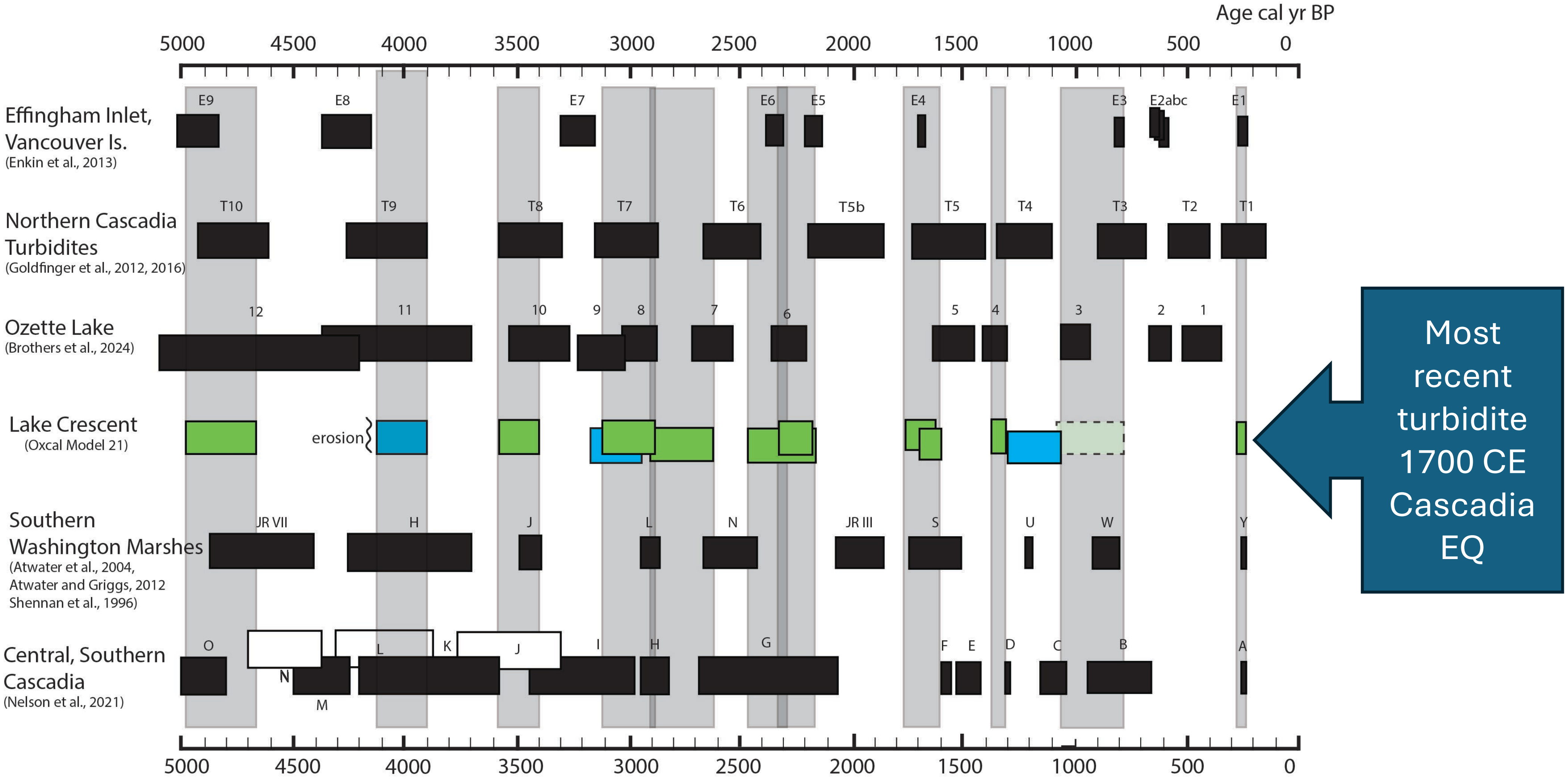
The turbidites are correlated to small subaqueous mass wasting deposits on the lake margins

Five groups of coeval mass-wasting deposits are traceable to turbidites younger than (above) MTD-I, and indicate multiple sources from around the lake– **consistent with an earthquake trigger**





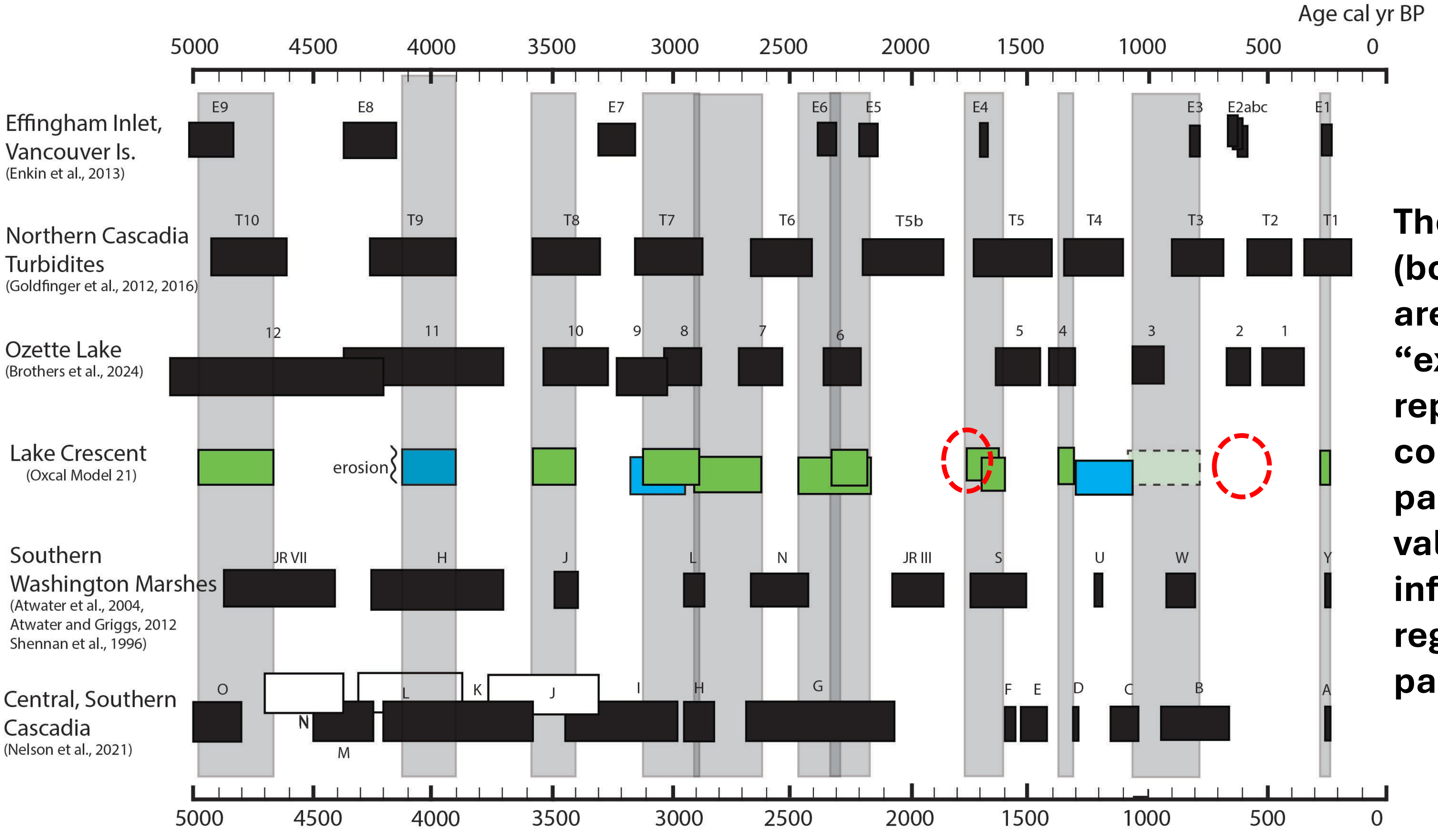
Overlap with records from elsewhere in Cascadia



Lake Crescent event layers

- Well developed CSZ event layer
- Weakly developed CSZ event layer
- MTD triggered by local, upper crustal fault

Overlap with records from elsewhere in Cascadia

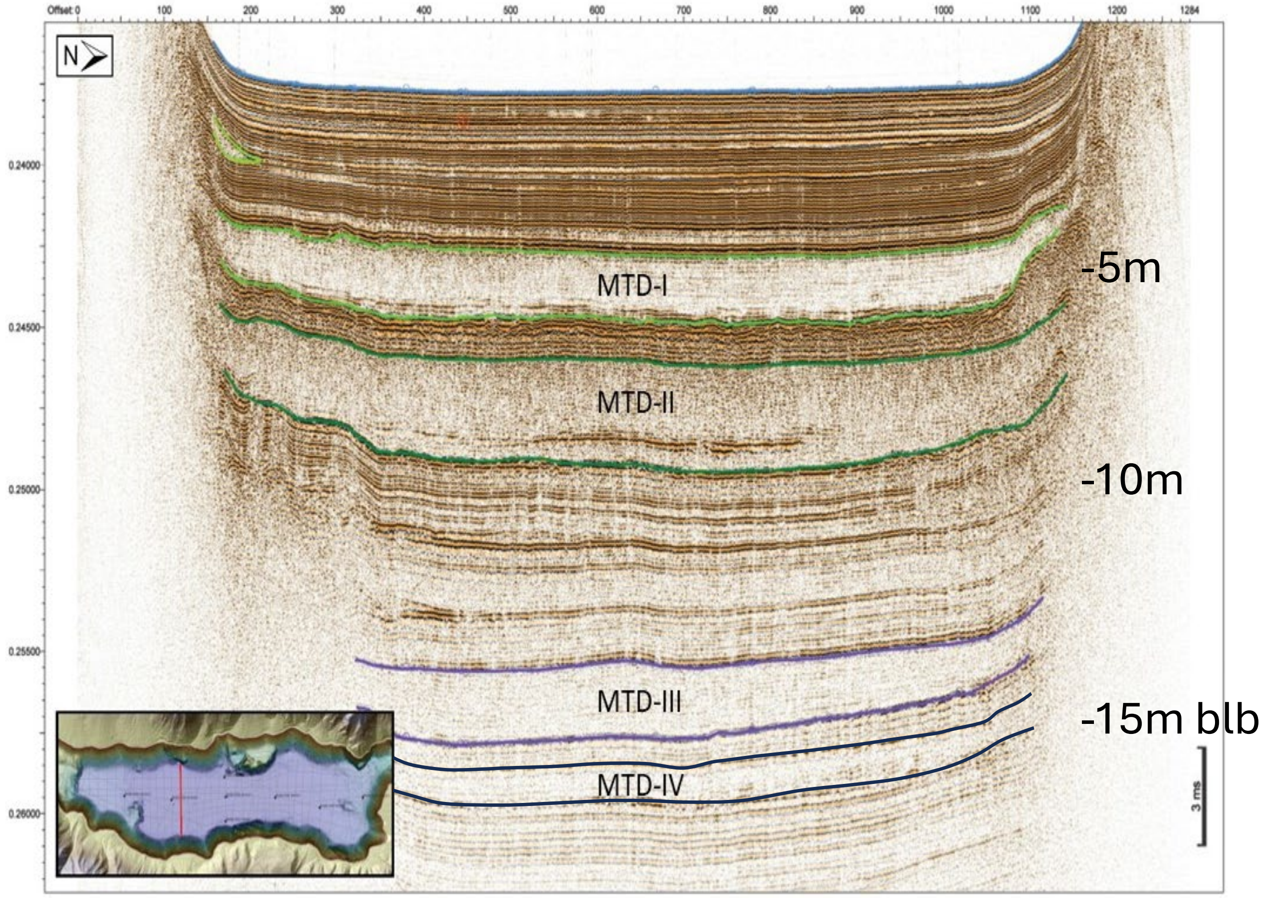


The exceptions (both events that are absent and "extra" ones represented) may contain particularly valuable information about regional paleoseismicity

Lake Crescent event layers

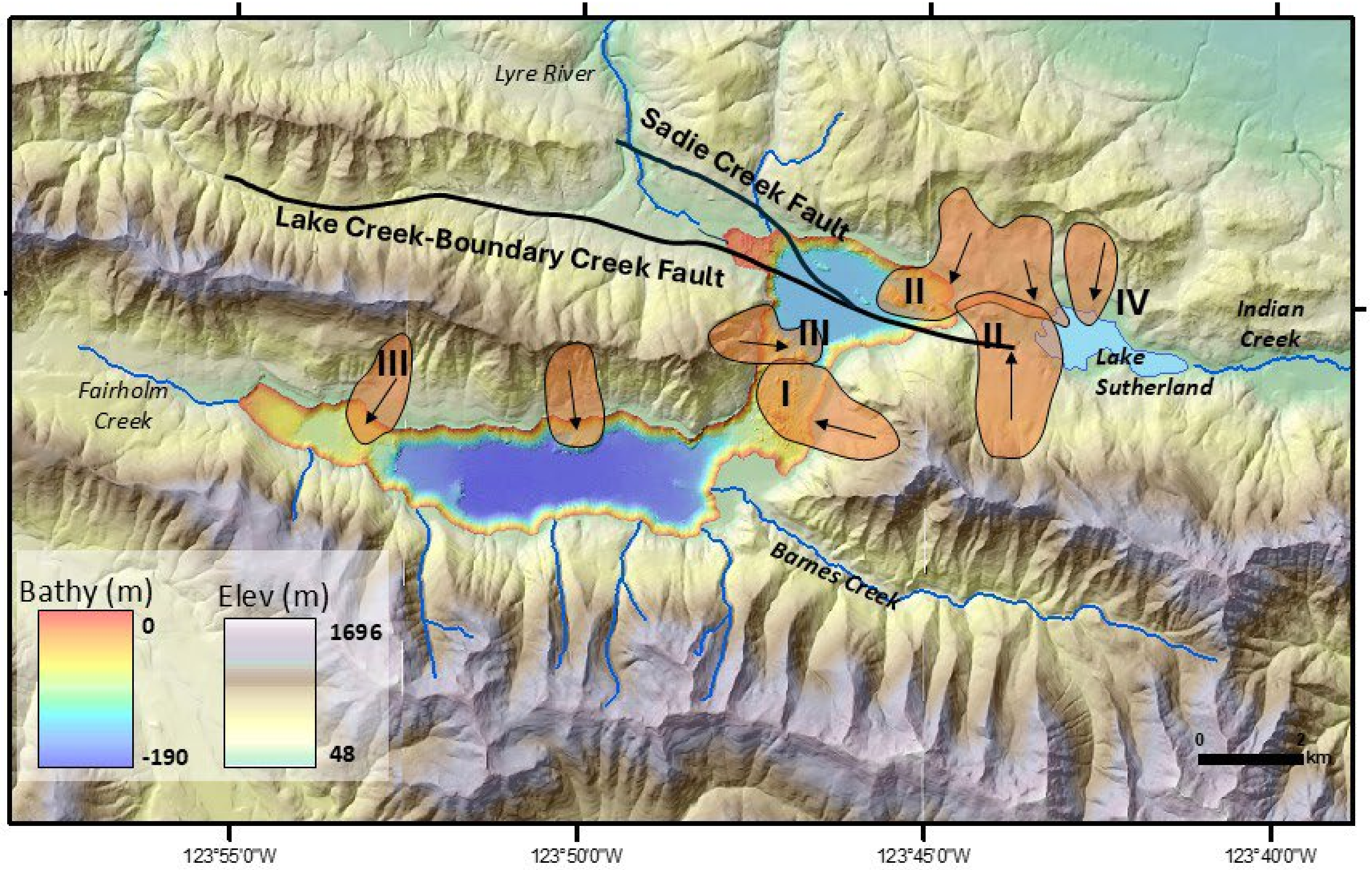
- Well developed CSZ event layer
- Weakly developed CSZ event layer
- MTD triggered by local, upper crustal fault

What accounts for the two types of event layers?



- The four thick mass transport deposits (MTDs) formed as the result of ruptures along the North Olympic Fault Zone
- Thinner turbidites deposited in record earthquakes on faults more distal to the lake, primarily along the Cascadia megathrust, 185 km to the west
- **<u>Why did these earthquakes produce different types of deposits?</u>**

MTDs produced by ruptures along the North Olympic Fault Zone

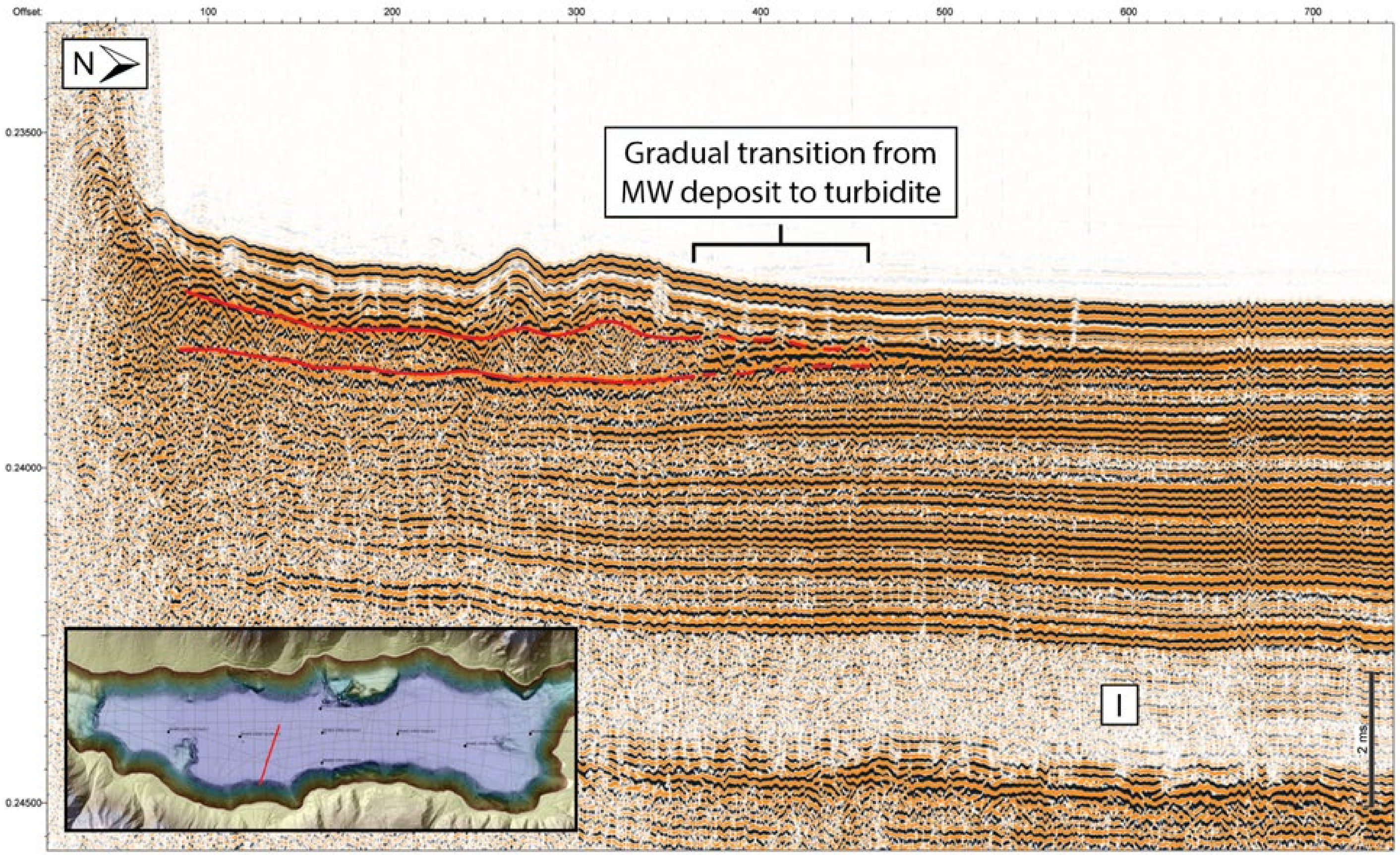


Shallow crustal seismicity resulted in high frequency, high amplitude ground motions, which led to failures of the brittle basalts surrounding the lake

Shaking was particularly intense near ridge tops, where seismic energy was focused

In Chile, Serey et al. (2019, 2020) showed that large volume rock avalanches and rockslides in the last century have been associated almost exclusively with proximal shallow crustal earthquakes

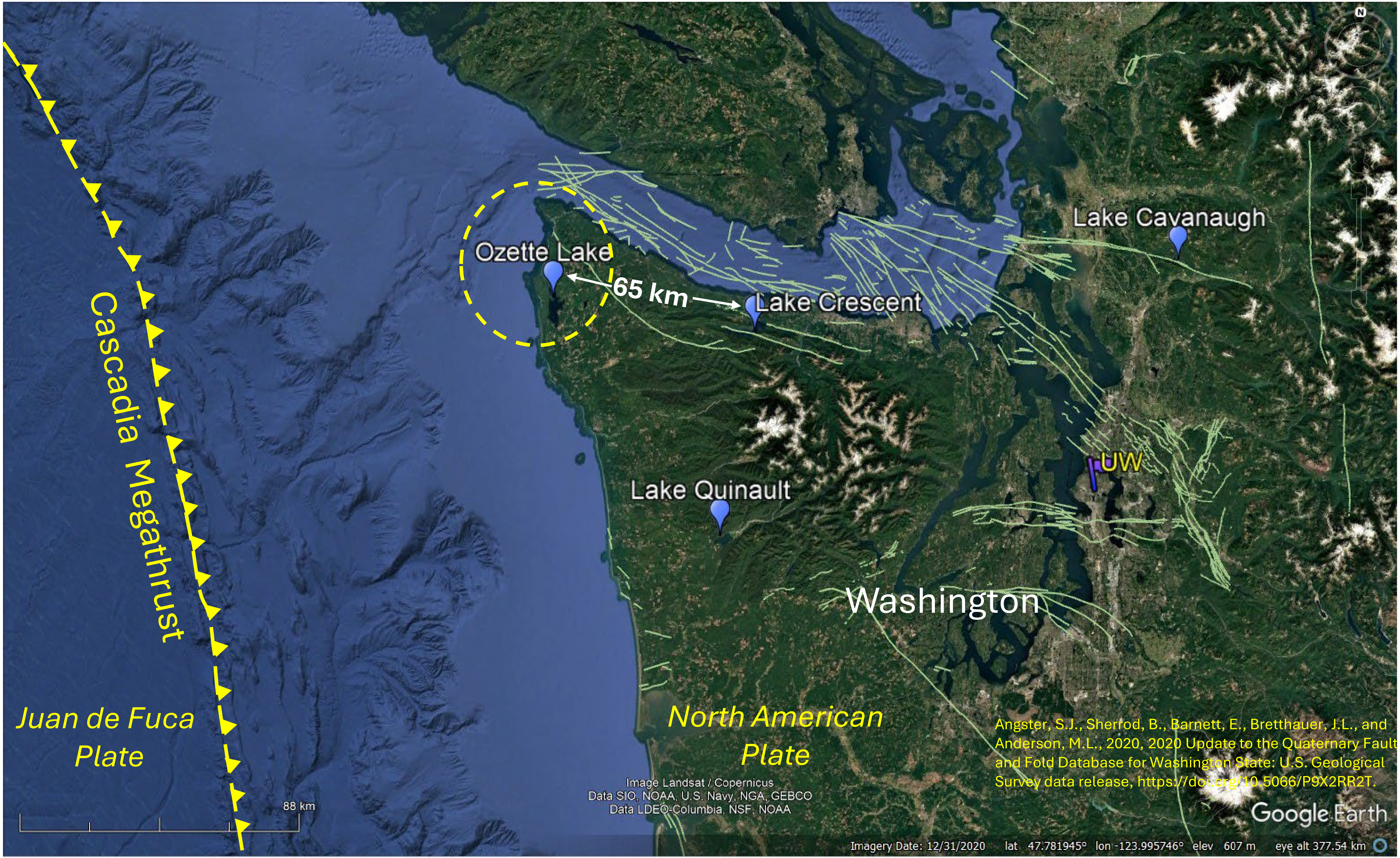
Turbidites were triggered by more distal EQs, especially subduction earthquakes



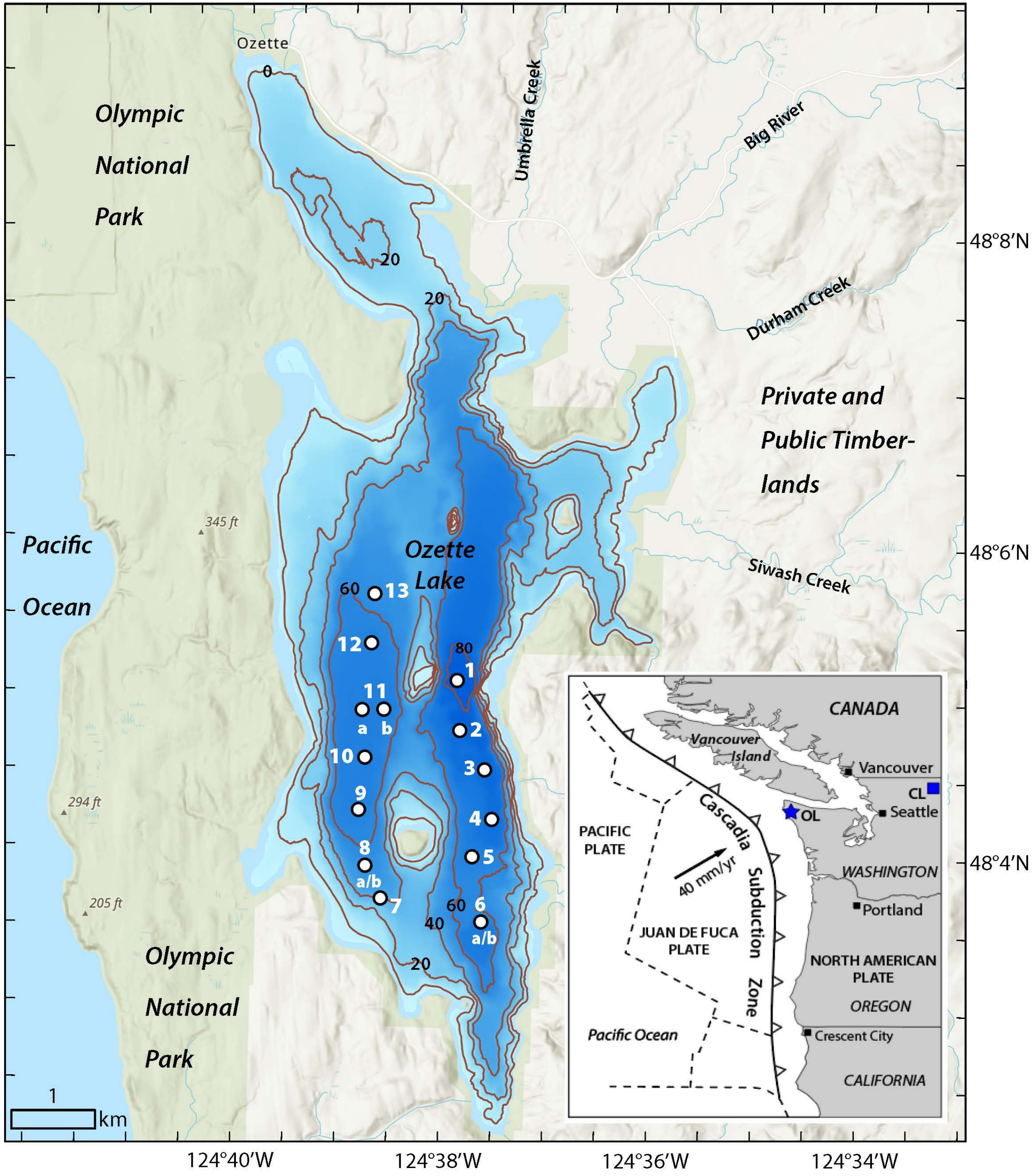
The energy arriving at the lake from deeper, subduction earthquakes was attenuated, particularly the higher frequency waves

Lower frequency seismic waves were absorbed and amplified in soft sediments at the edges of the lake

These events triggered shallow mass wasting, and the deposition of decimeter-scale turbidites on the lake floor

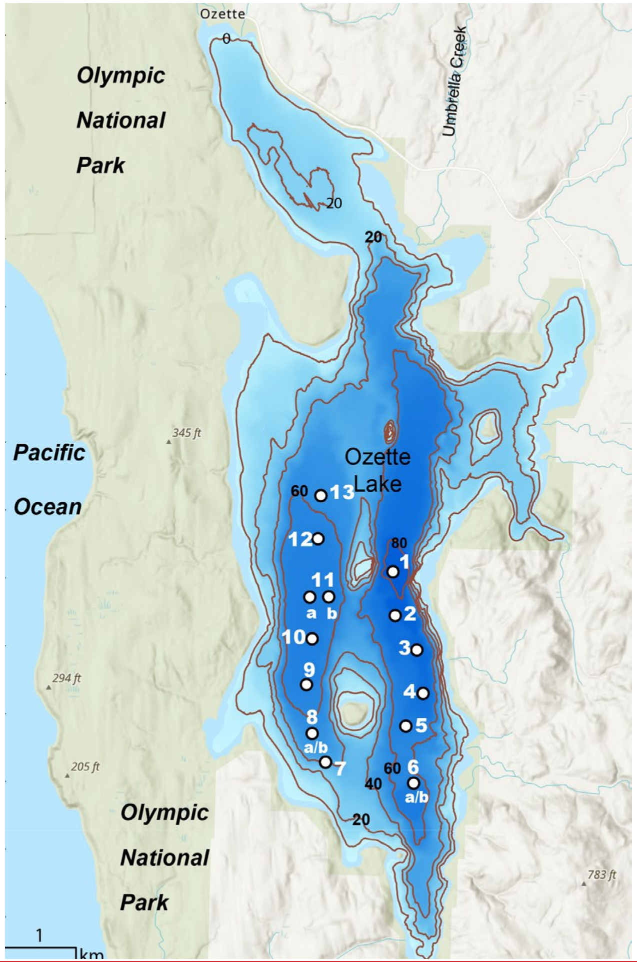


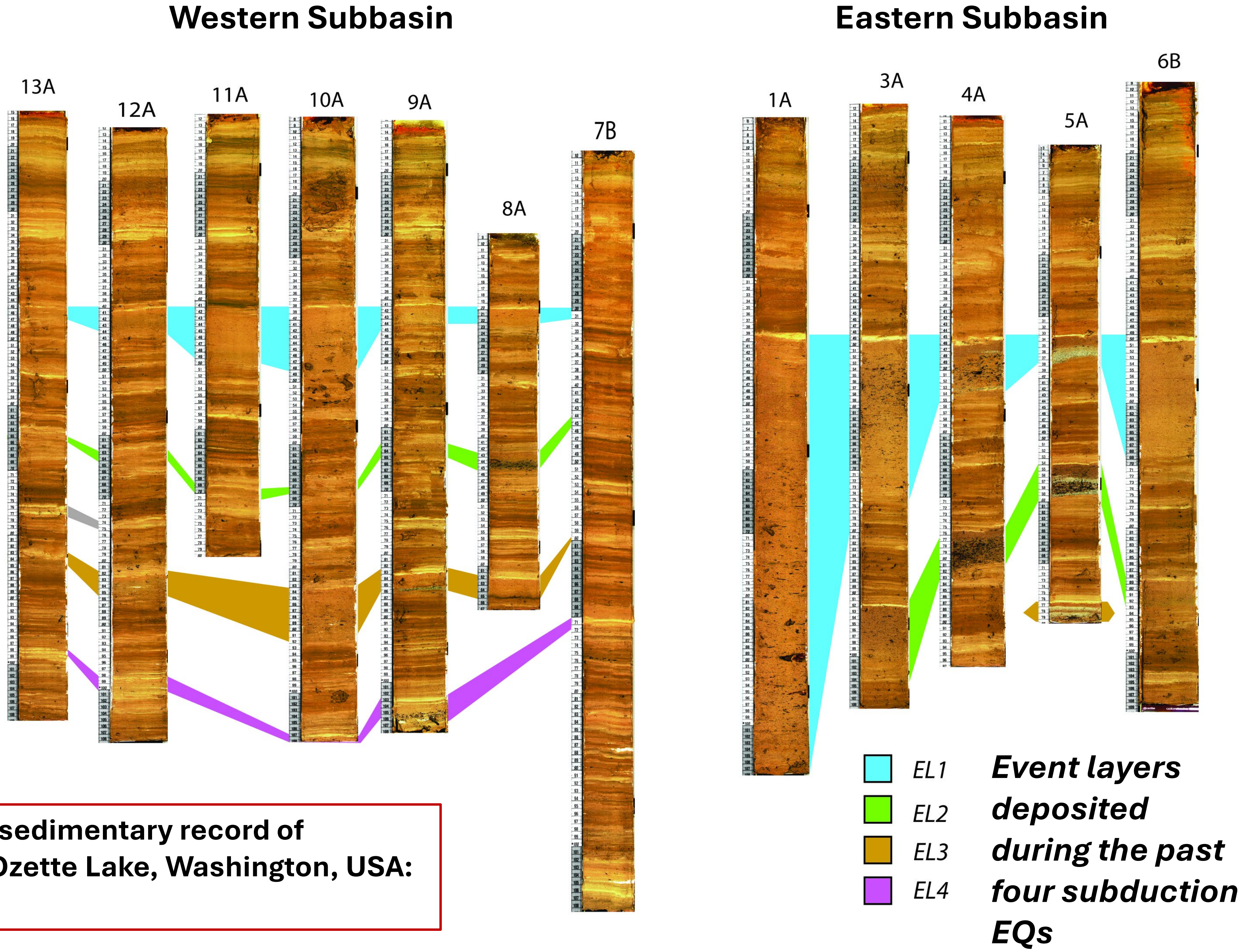
Cascadia Megathrust
Juan de Fuca Plate
North American Plate
Washington
Ozette Lake
65 km
Lake Crescent
Lake Cavanaugh
Lake Quinault
UW
Angster, S.J., Sherrod, B., Barnett, E., Bretthauer, J.L., and Anderson, M.L., 2020, 2020 Update to the Quaternary Fault and Fold Database for Washington State: U.S. Geological Survey data release, https://doi.org/10.5066/P9X2RR2T.
88 km
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data LDEO-Columbia, NSF, NOAA
Google Earth
Imagery Date: 12/31/2020 lat 47.781945° lon -123.995746° elev 607 m eye alt 377.54 km



Ozette Lake

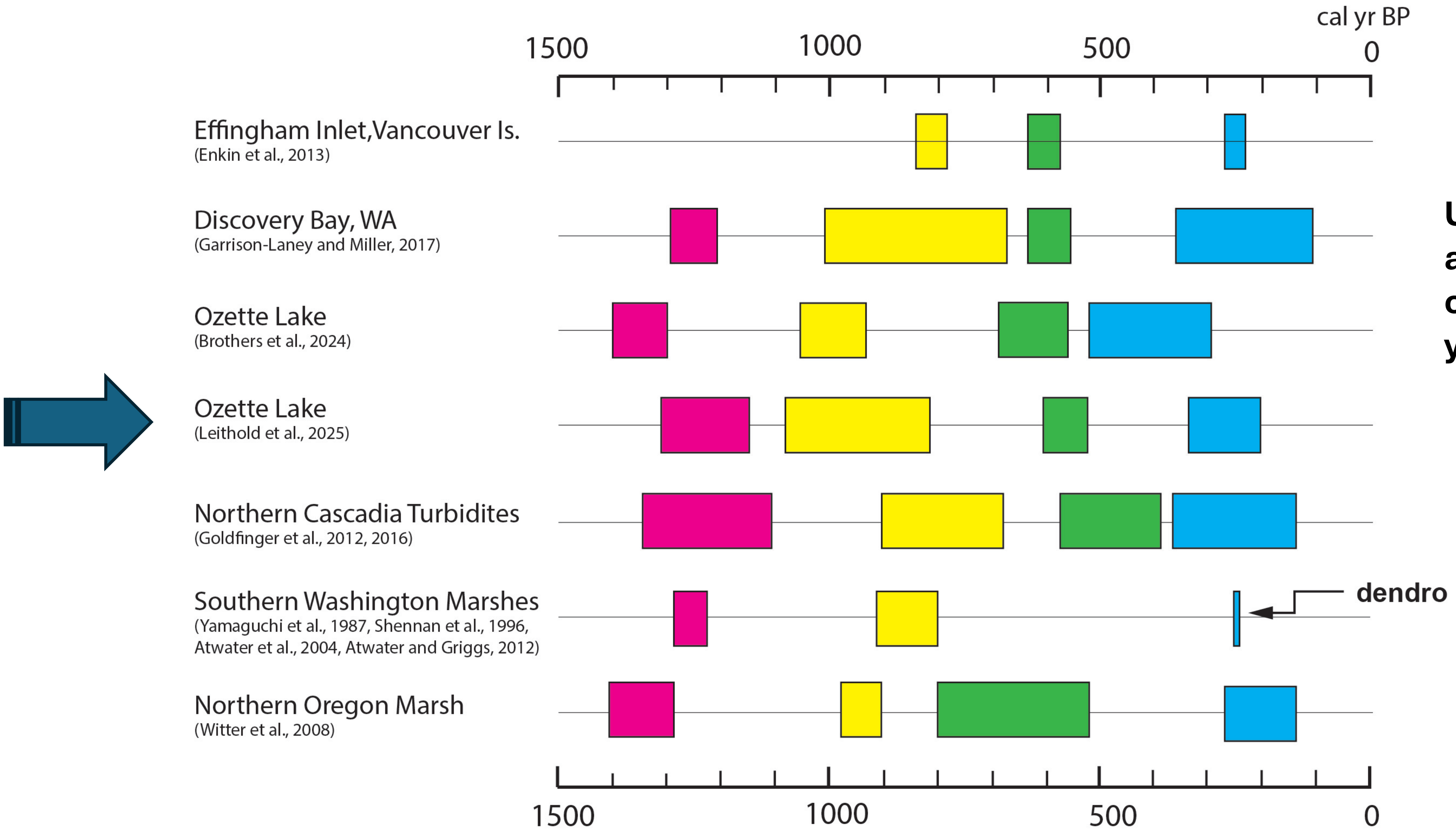
- A glacially formed lake approximately 65 km to the west of Lake Crescent and surrounded by more subdued topography
- Average and maximum depth of 40 and 98 m respectively
- Eastern and western subbasins are separated by a bathymetric high
- Brothers et al. (2025) have identified 30-34 Holocene turbidites attributed to subduction earthquakes



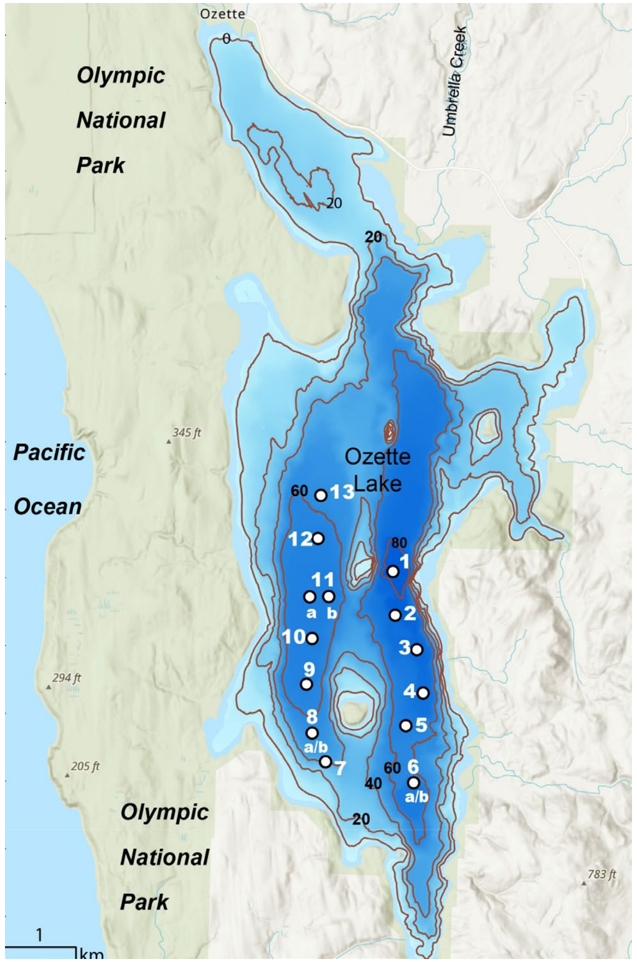


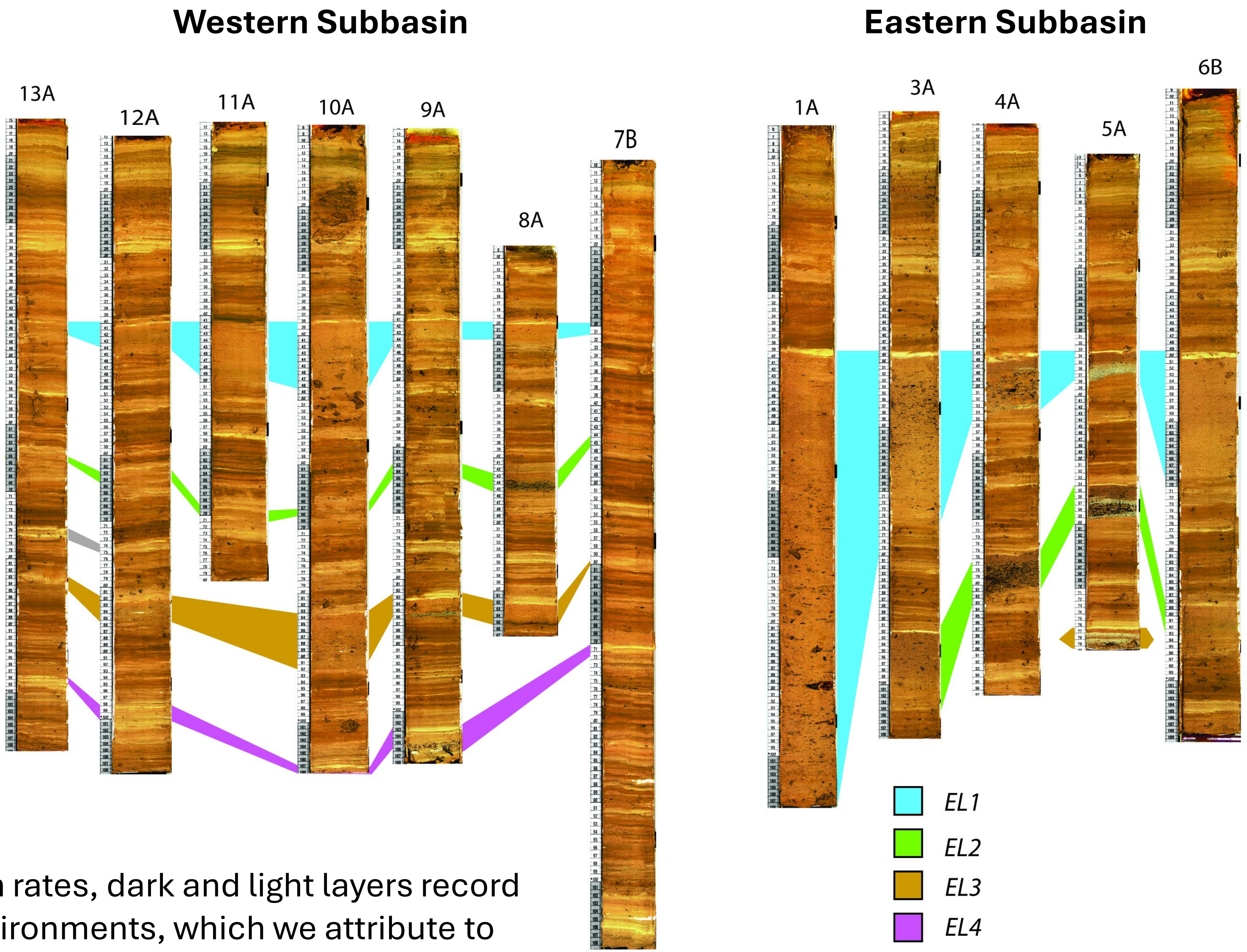
Leithold et al.(2025), A late Holocene sedimentary record of earthquakes and hydroclimate from Ozette Lake, Washington, USA: *Quaternary Research*

Estimated ages for the past four northern Cascadia earthquakes



Uncertainties are on the order of 100 years or more

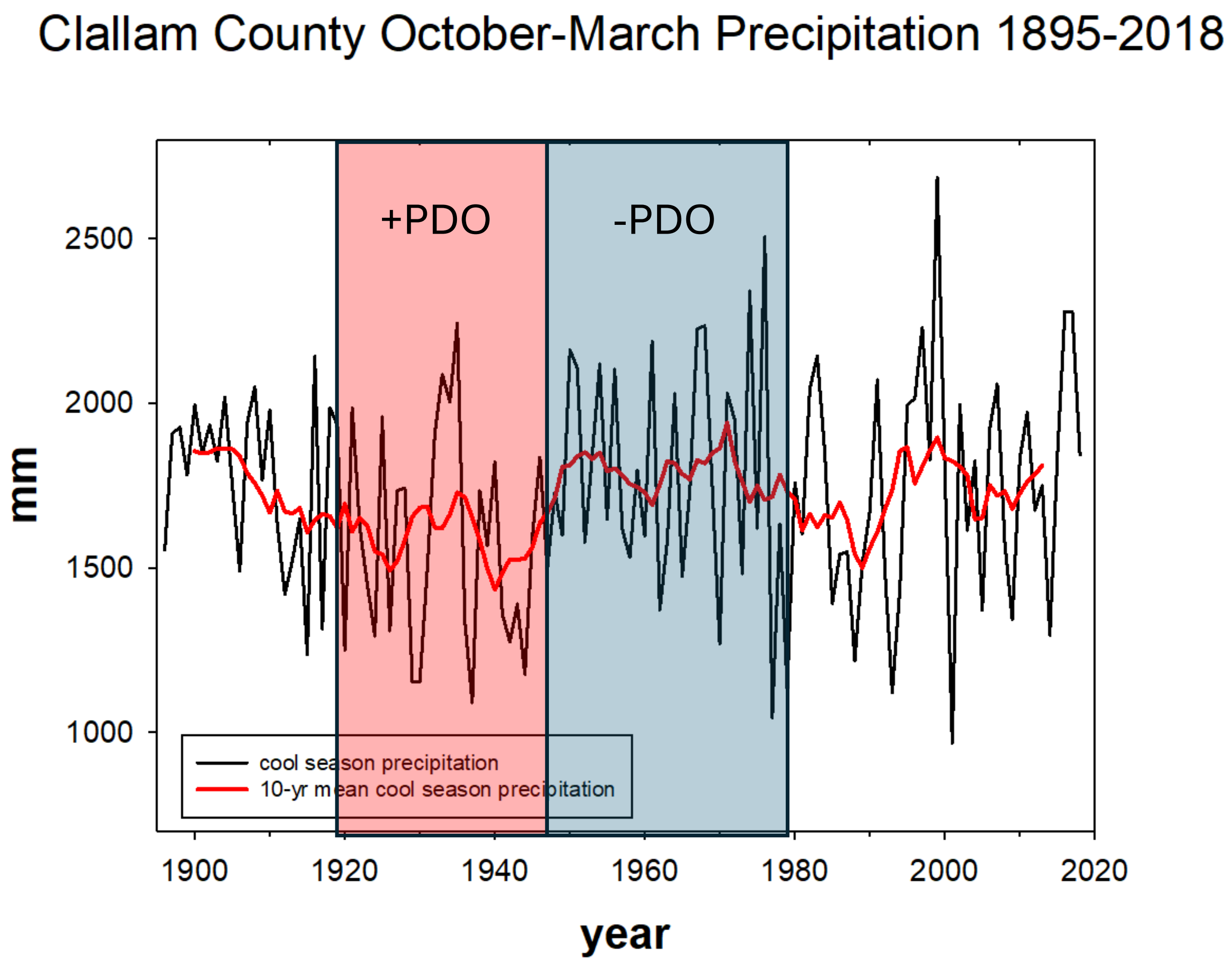


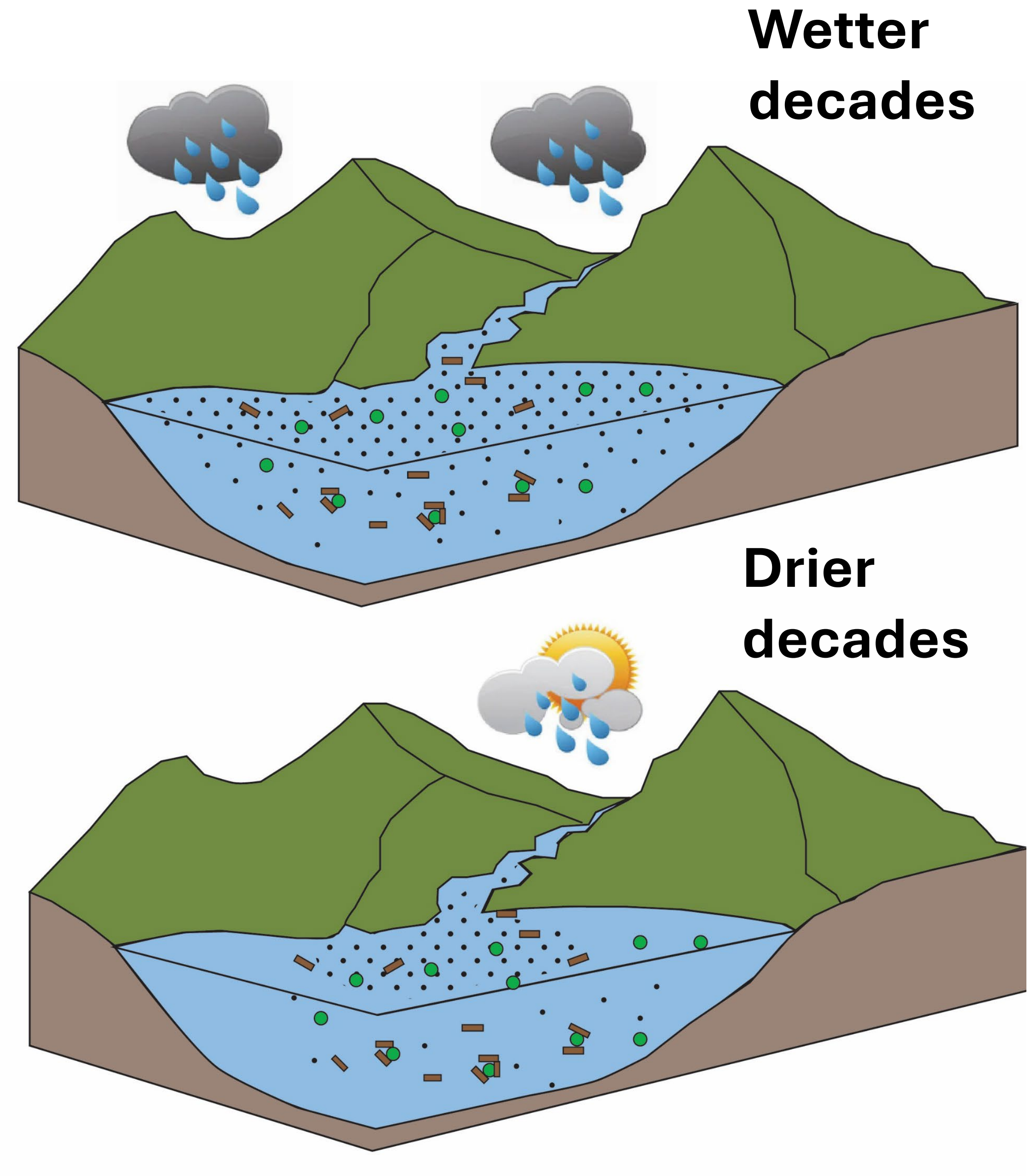


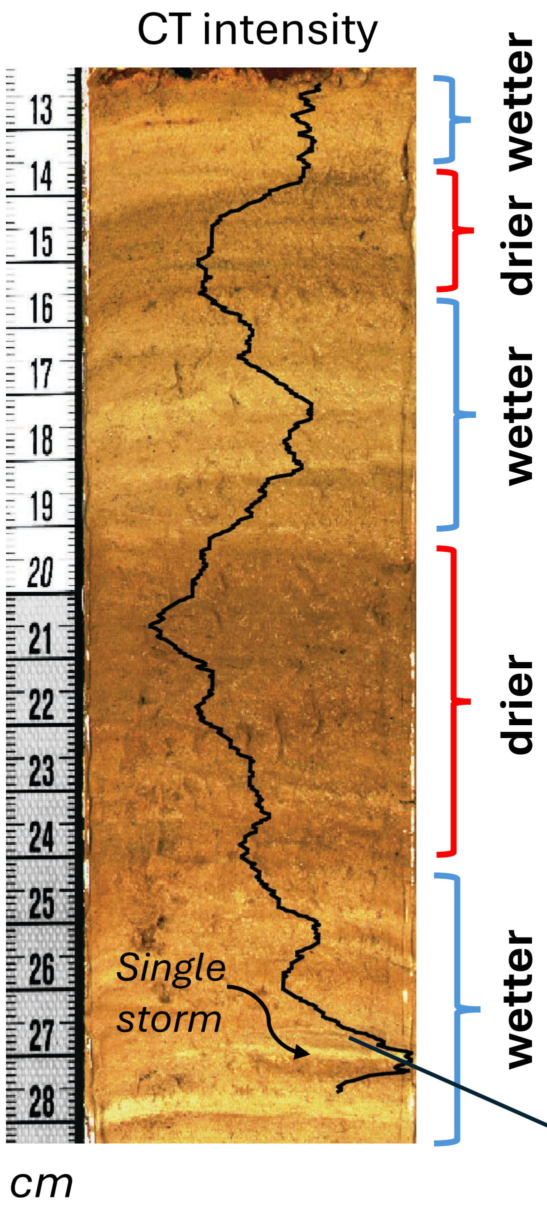
Based on sediment accumulation rates, dark and light layers record <u>decadal-scale</u> changes in the environments, which we attribute to variable **hydroclimate**

Decadal-scale cool-season precipitation variability

- Cool-season precipitation amounts are influenced by the El Nino-Southern Oscillation(ENSO) and related Pacific Decadal Oscillation (PDO)
- For example, during positive ENSO and PDO phases, drier than average conditions occur in the region (wetter conditions occur when ENSO and PDO are negative)







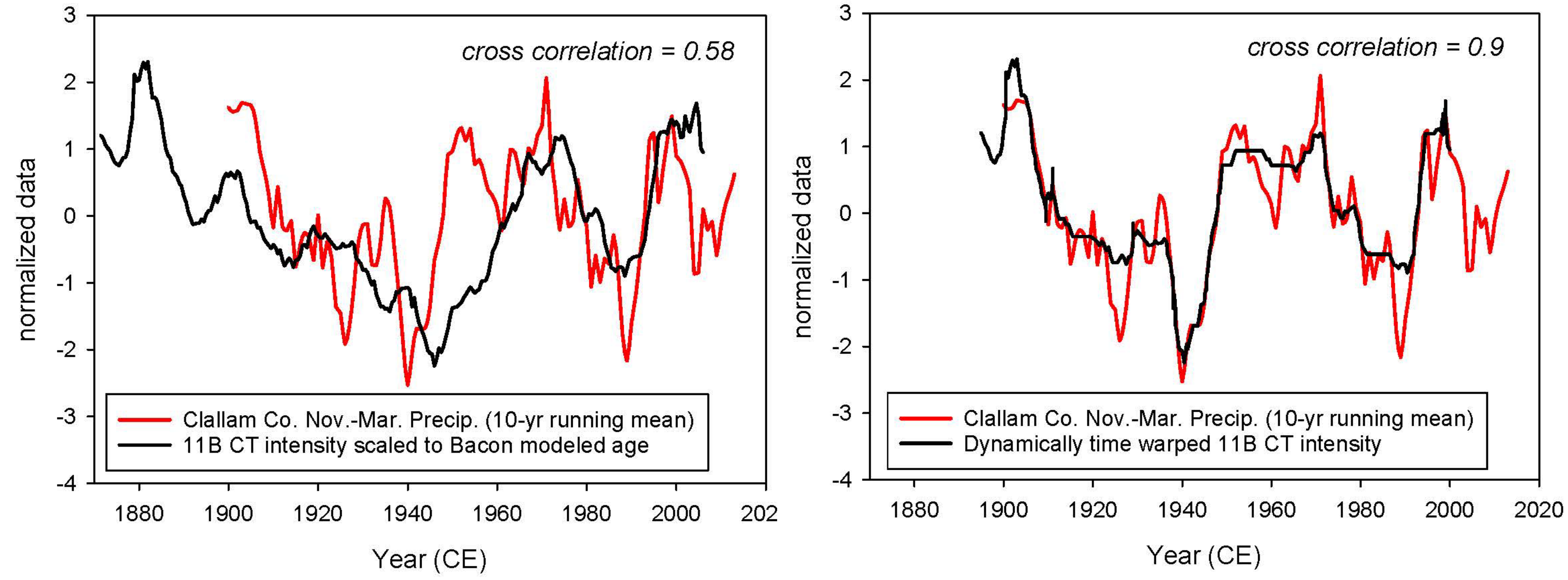
Hypothesized scenario:

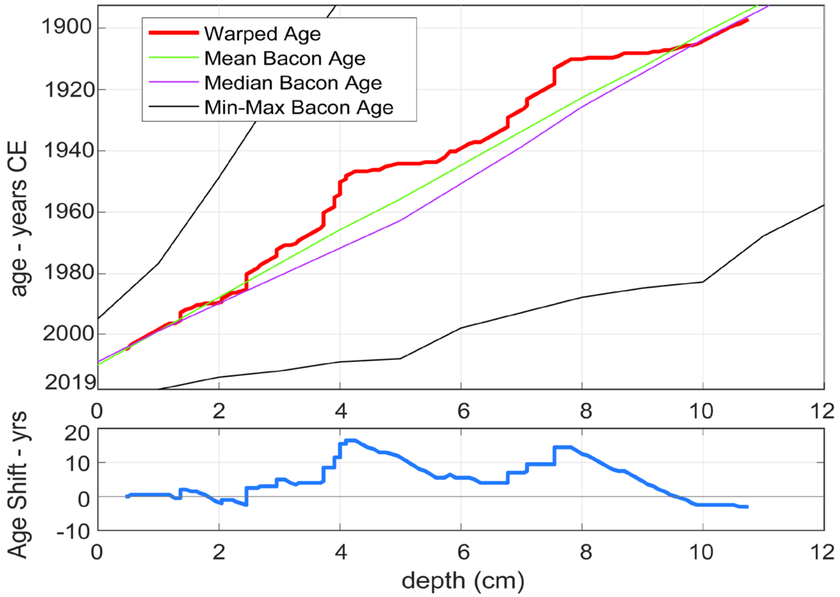
During wetter decades, the relatively constant rain of algal and plant debris is diluted by light-colored, dense, minerogenic sediment

During drier decades, darker-colored, less dense, more organic rich sediment accumulates

CT intensity is a function of sediment density

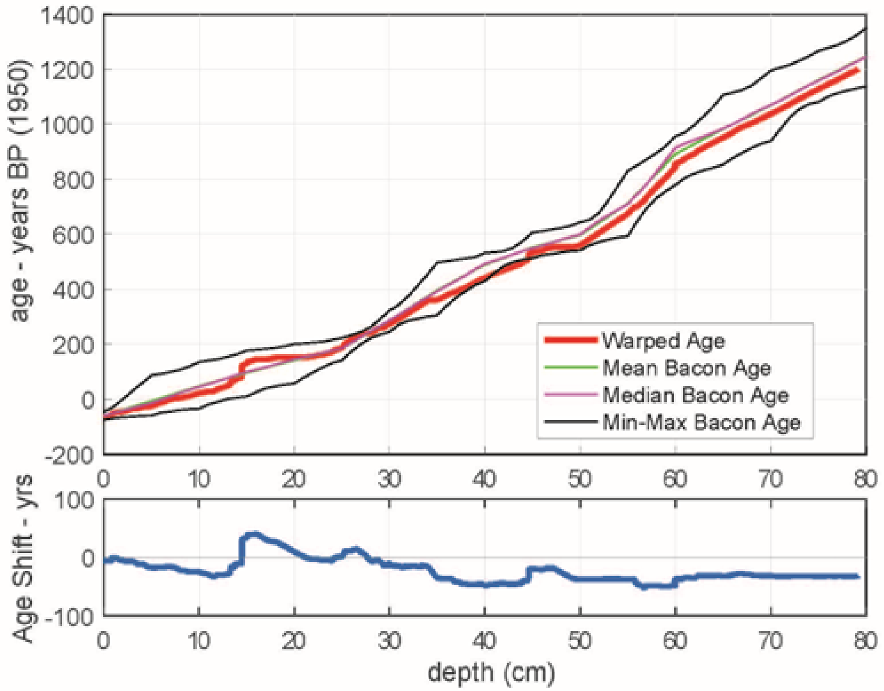
Dynamic Time Warping of CT Record to Historical, Cool-Season Precipitation

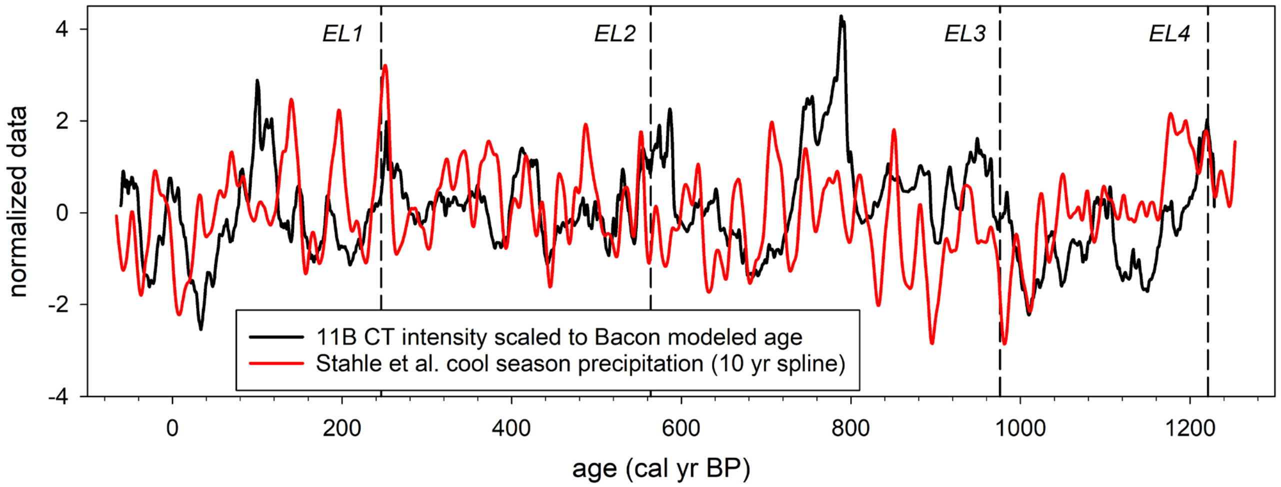


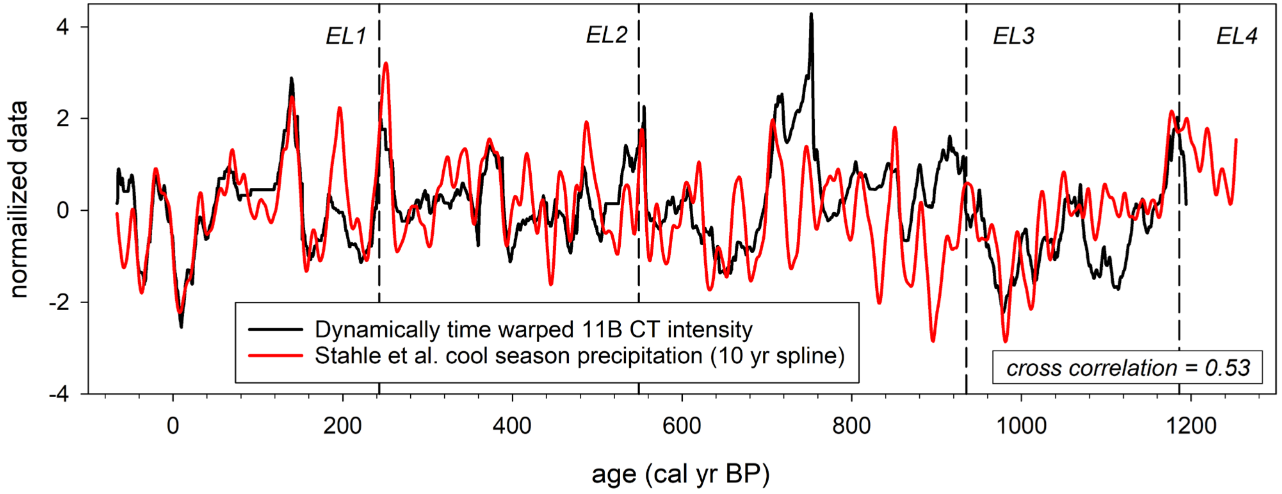


Leithold, E., Wegmann, K., Bohnenstiehl, D., Slajus, L., & Contreras, T. (2025). A Late Holocene sedimentary record of earthquakes and hydroclimate from Ozette Lake, Washington, USA. Quaternary Research, 1-17.

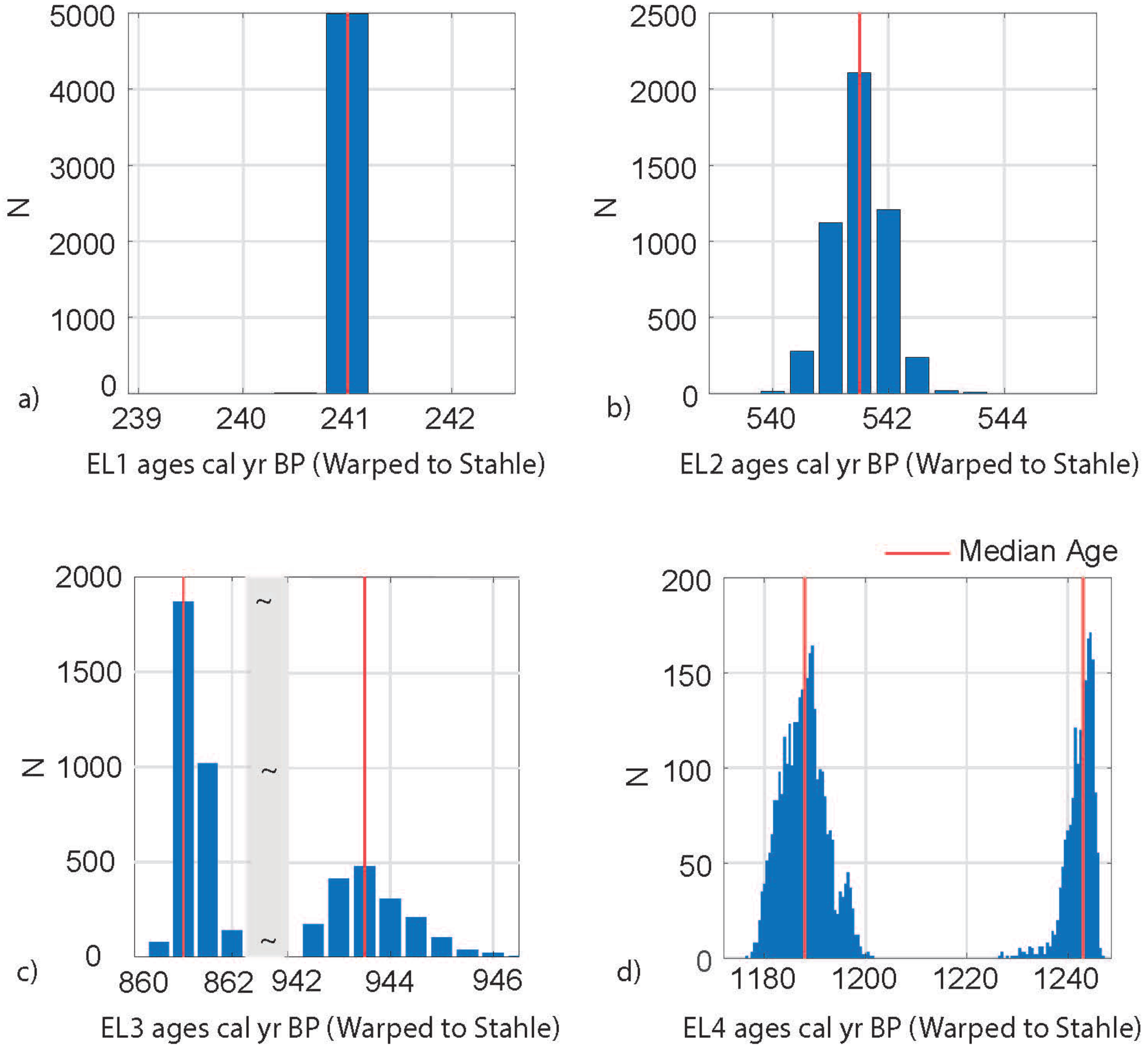
Comparison to the tree-ring- based, seasonal precipitation reconstruction for the Olympic Peninsula by Stahle et al. (2020)







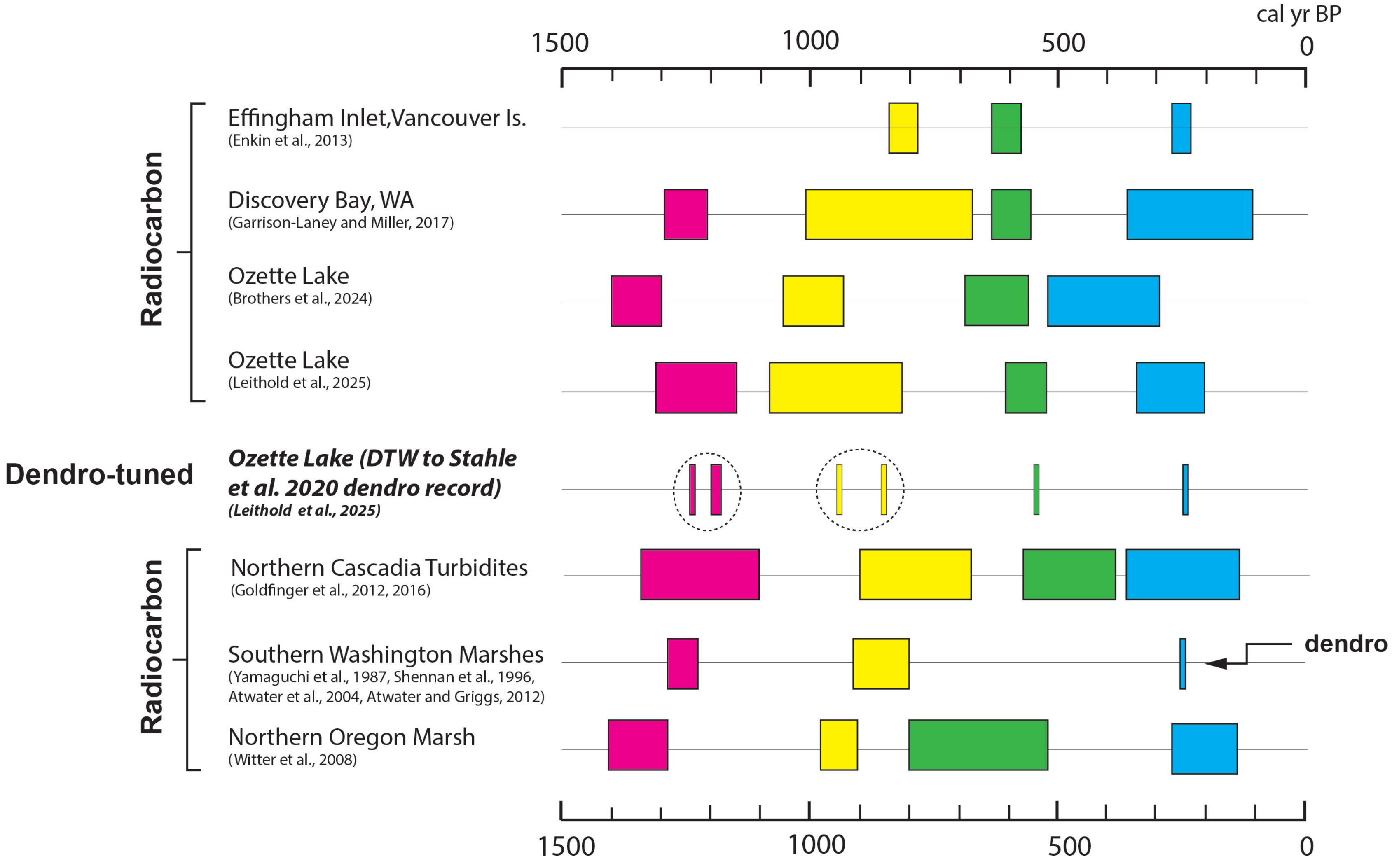
Note precise ages for the four event layers (earthquake-triggered turbidites)



Assessing the uncertainty of DTW-derived ages for the four event layers in Ozette Lake

- Results of 5000 DTW runs where the minimum-maximum range of the age-depth model was taken to be ±3 standard deviations

Age estimates for the past four northern Cascadia subduction earthquakes



Conclusions

- Lake sediments are invaluable sources of information about past seismicity in Cascadia
- They offer insights into the behavior of both crustal faults and the Cascadia megathrust, including the potential to obtain more precise dates for past fault ruptures than is possible using radiocarbon dating alone