Cascadia Great Earthquakes from the Turbidite Record: A progress Report on Marine and Lacustrine Evidence of Earthquake Origin, Segmentation and Clustering

This presentation is dedicated to Eugene (Zhenia) Karabanov, the distinguished Russian sedimentologist who sailed with us, worked with us for many years, made us laugh, and taught us a great deal along the way.

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On the order of 200 people, scientists, co-PI's, students, technicians, post-docs, interns student workers, ships crew, and proposal and paper reviewers and editors have contributed to this work over that time. Thank you all for your contributions! Special thanks to USGS for supporting publication of the most recent work!

We also thank the early workers in Cascadia, Vern Kulm, Hans Nelson, Gary Griggs, Paul Carlson, and John Duncan, and their crews and technicians, without whose diligent work, our work would not have been possible.

Publications to date **See http://activetectonics.coas.oregonstate.edu/publications.htm**

Goldfinger, C., Nelson, C.H., and Johnson, J.E., , 2003, *Holocene Earthquake Records From the Cascadia Subduction Zone and Northern San Andreas Fault Based on Precise Dating of Offshore Turbidites*: Annual Reviews of Earth and Planetary Sciences, v. 31, p. 555-577.

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Goldfinger, C., Morey, A.E., Nelson, C.H., Gutiérrez-Pastor, J., Johnson, J.E., Karabanov, E., Chaytor, J., Ericsson, A., and shipboard scientific party, 2007, *Rupture lengths and temporal history of significant earthquakes on the Offshore and Northcoast segments of the Northern San Andreas Fault based on turbidite stratigraphy*, Earth and Planetary Science Letters, v. 254, p. 9-27.

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Publications to Date

Goldfinger, C., Nelson, C.H., Morey, A., Johnson, J.E., Gutierrez-Pastor, J., Eriksson, A.T., Karabanov, E., Patton, J., Gracia, E., Enkin, R., Dallimore, A., Dunhill, G., and Vallier, T., 2012, ***Turbidite Event History: Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone***, USGS Professional Paper 1661-F, Reston, VA, U.S. Geological Survey, p. 362 p, 64 Figures. In press. Unformatted preprint available at http://pubs.usgs.gov/pp/pp1661f/

Publications in Review

Goldfinger, C., Ikeda, Y., and Yeats, R.S., 2011 submitted, ***Superquakes and Supercycles***. Seismological Research Letters.

Publications in Revision (in press probably in April 2012)

Goldfinger, C., Morey, A., Black, B., and Patton, J., 2012 in revision, ***Spatially Limited Mud Turbidites on the Cascadia Margin: Segmented Earthquake Ruptures?,*** *in* Pantosti, D., Gracia, E., Lamarche, G., Nelson, C.H., and Tinti, S., eds., Research Conference Submarine Paleoseismology: The Offshore Search of Large Holocene Earthquakes: Obergurgl, Austria, Natural Hazards and Earth System Science.

Morey, A.E., Goldfinger, C., Briles, C.E., Gavin, D.G., Colombaroli, D., Kusler, J.E., 2012, in revision, ***Potential Lacustrine Records of Cascadia Great Earthquakes***, *in* Pantosti, D., Gracia, E., Lamarche, G., Nelson, C.H., and Tinti, S., eds., Research Conference Submarine Paleoseismology: The Offshore Search of Large Holocene Earthquakes: Obergurgl, Austria, Natural Hazards and Earth System Science.

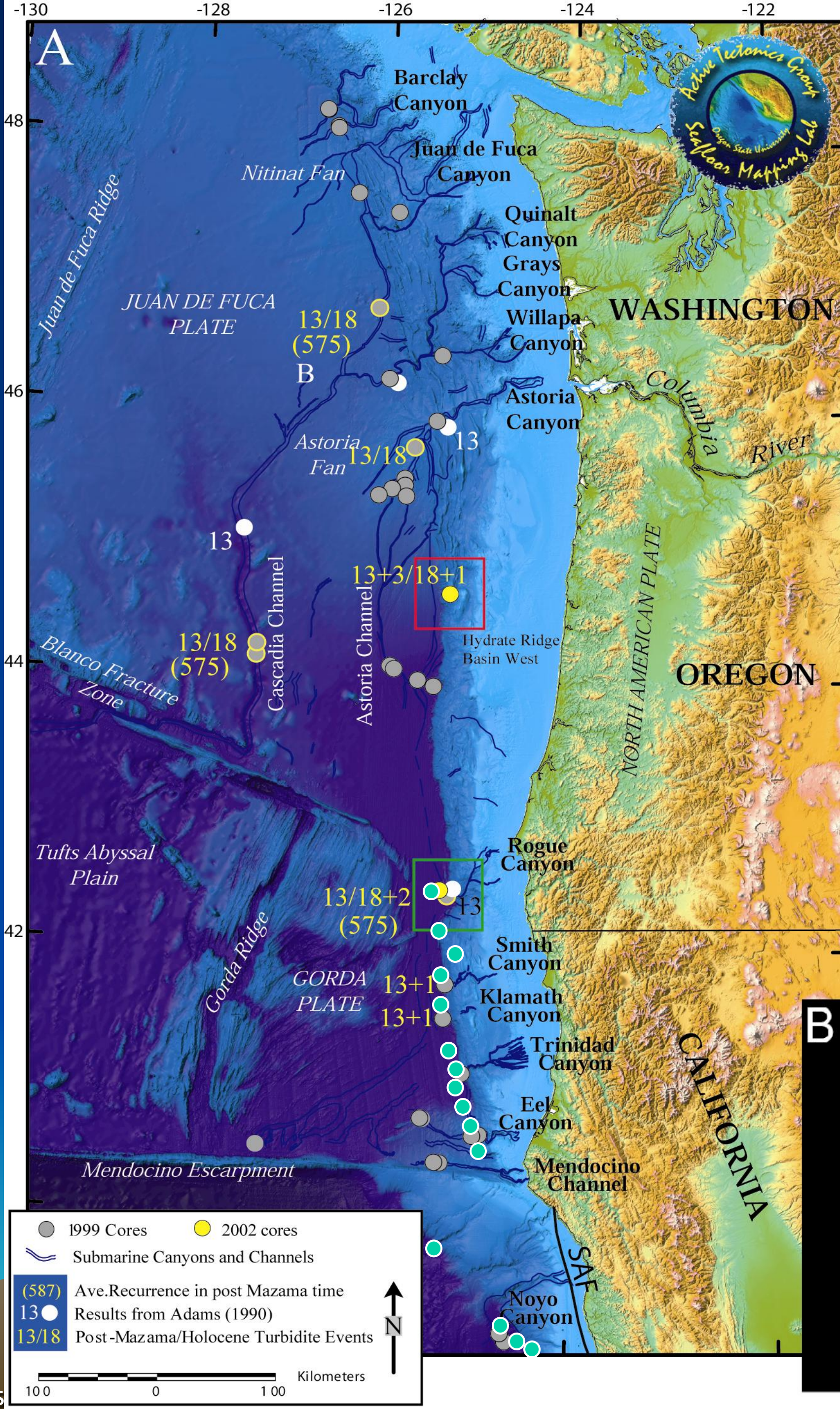
In Cascadia, onshore and offshore paleoseismology has revealed a long history of great earthquakes.

We set out in 1999 to prove the turbidite story wrong, and failed.

Cascadia Turbidite Paleoseismology based on event correlation along strike.

1) **Aerial extent**
2) **Synchroneity, and**
3) **Sedimentology.**

Stratigraphic correlation, tests of synchronous triggering, and 14C ages have led to a credible (we think) record of 43 events of variable size and strike length during the Holocene.



Turbidite Paleoseismology:

Extending the earthquake record

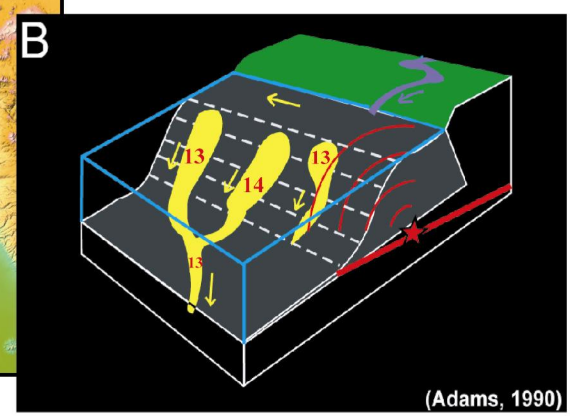
Cascadia Core Sites:

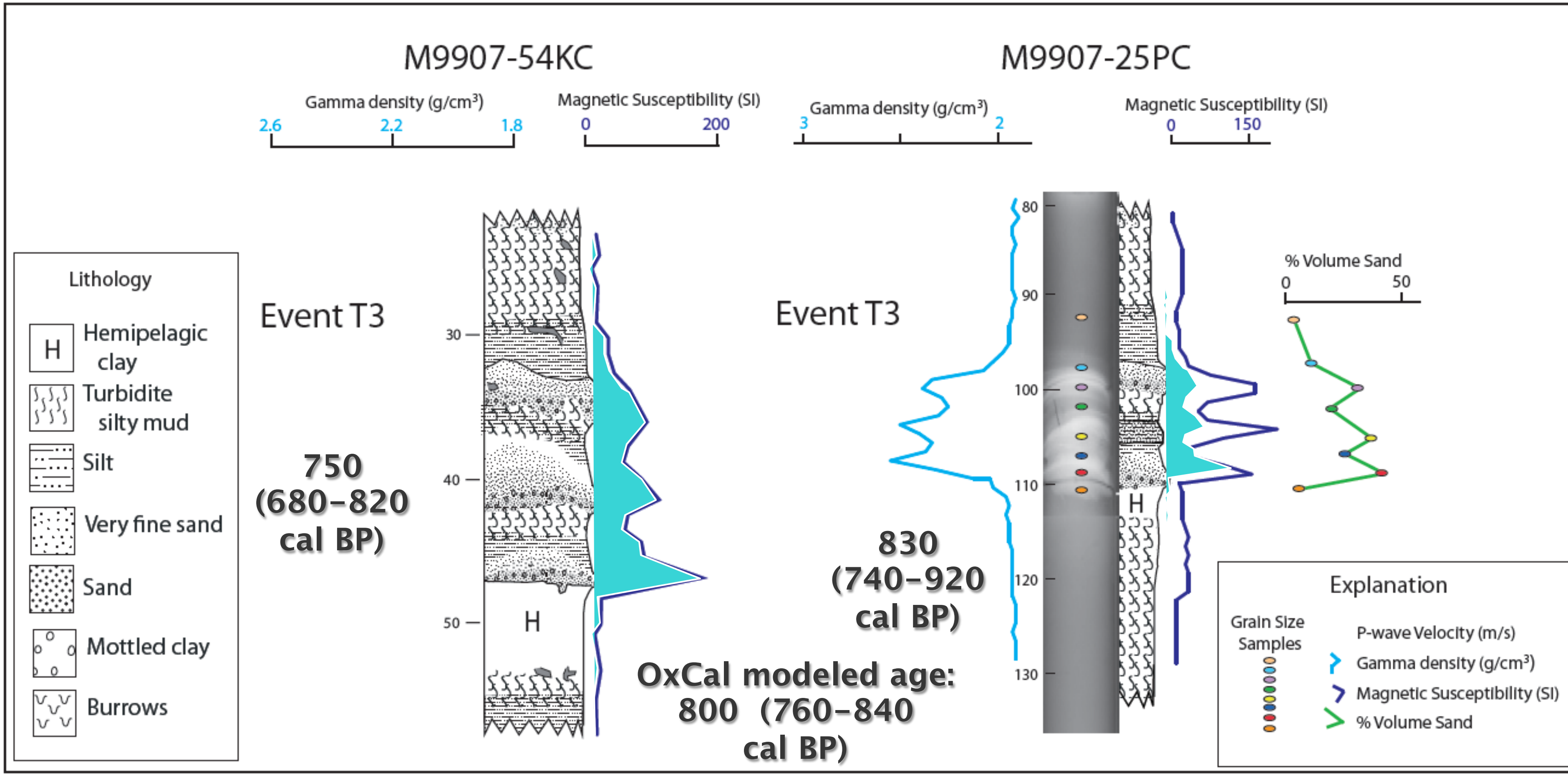
1999 = gray

2002 = yellow

2009 = green

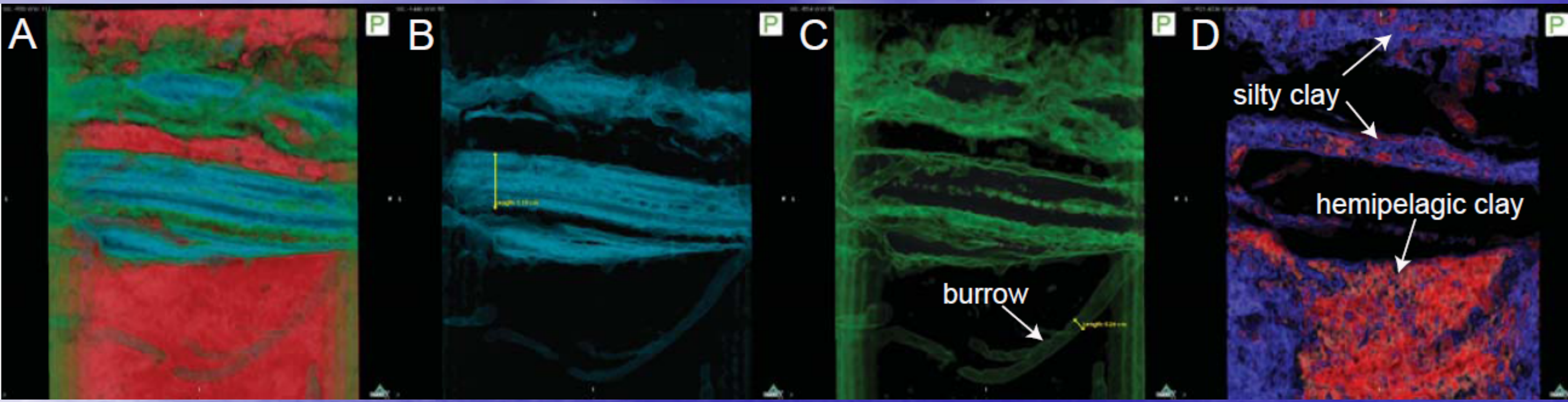
Selected older existing cores = white





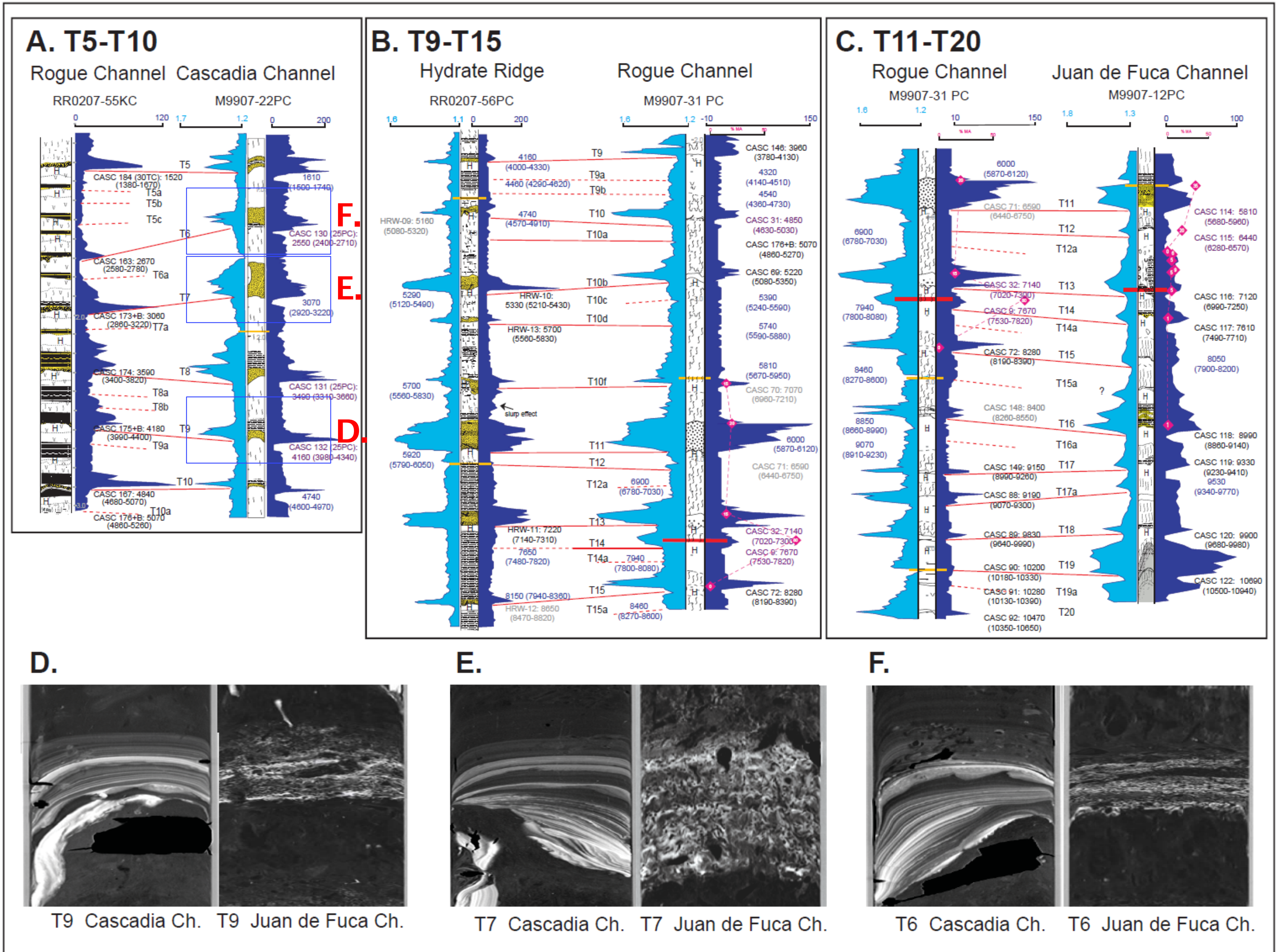
Looking closely, the main structure of these turbidites is a series of fining upward "pulses" (Bouma A-C) capped by a fining upward tail. The multiple structure is commonly maintained through channel confluences, and between isolated sites as shown by this example from two cores 300 km apart, with source areas 420-500 km apart. These channels never meet. Conventional wisdom suggests that hydrodynamics, channel morphology and other factors should control this structure. But that may be a "passive margin" view. We suggest an alternative, the earthquake source may overprint these factors on active margins with very large earthquakes.

Turbidite regional fingerprints based on their structure: Multiple fining upward sequences.

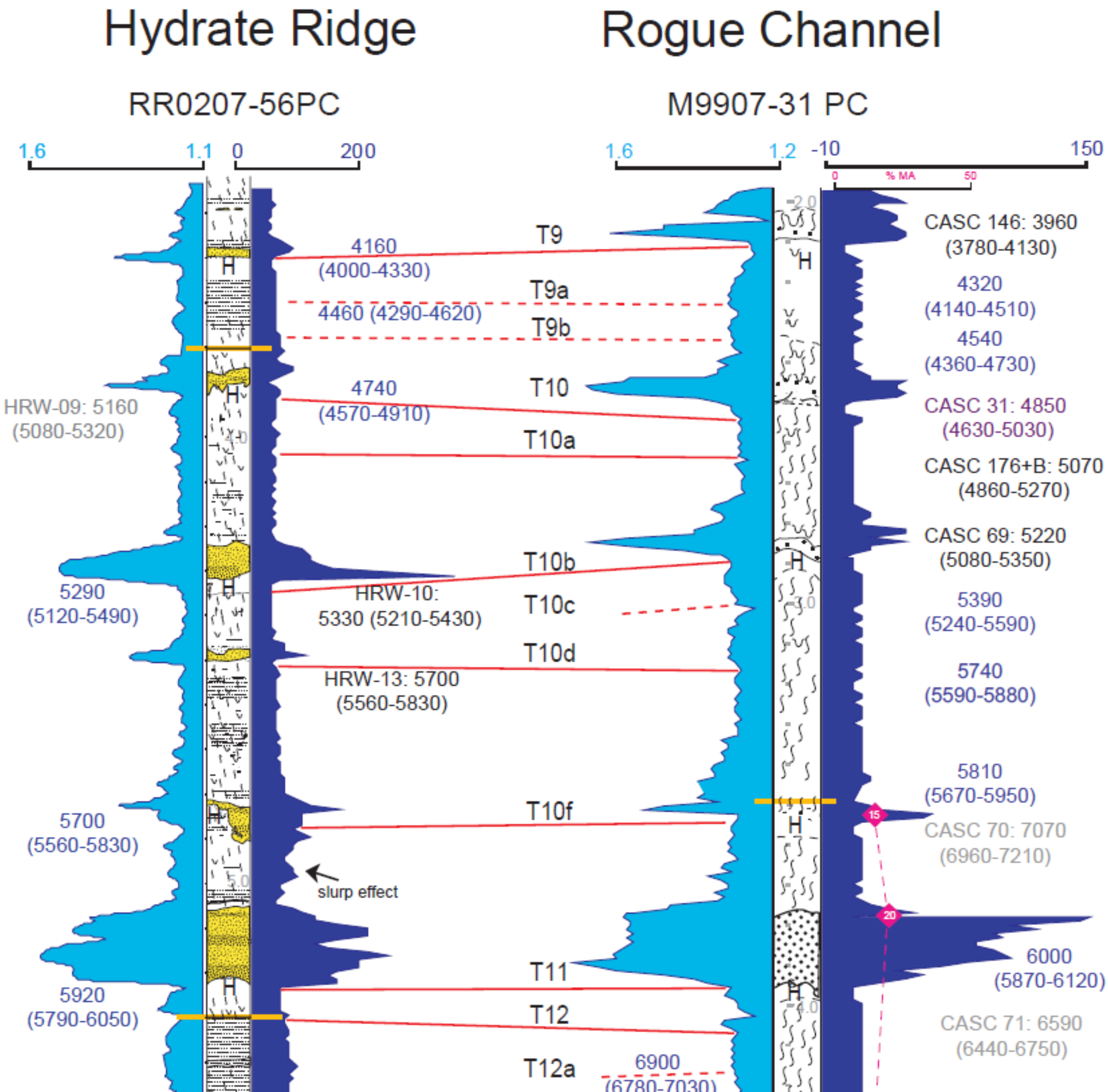


CT imagery is invaluable for understanding turbidite structure and defining stratigraphic boundaries in detail. This image breaks out the sand fraction, the silt fraction, and the hemipelagic clay by their respective CT density values.

The CT can reveal such subtle features as a worm burrow which is apparently lined with material slightly more dense than its surroundings (biogenic clay)



A. T5-T10
Rogue Channel
Cascadia Channel
RR0207-55KC
M9907-22PC
B. T9-T15
Hydrate Ridge
Rogue Channel
RR0207-56PC
M9907-31 PC
C. T11-T20
Rogue Channel
Juan de Fuca Channel
M9907-31 PC
M9907-12PC
D.
E.
F.
T9 Cascadia Ch.
T9 Juan de Fuca Ch.
T7 Cascadia Ch.
T7 Juan de Fuca Ch.
T6 Cascadia Ch.
T6 Juan de Fuca Ch.



Zooming in a bit, here are typical examples of the Holocene sequences.

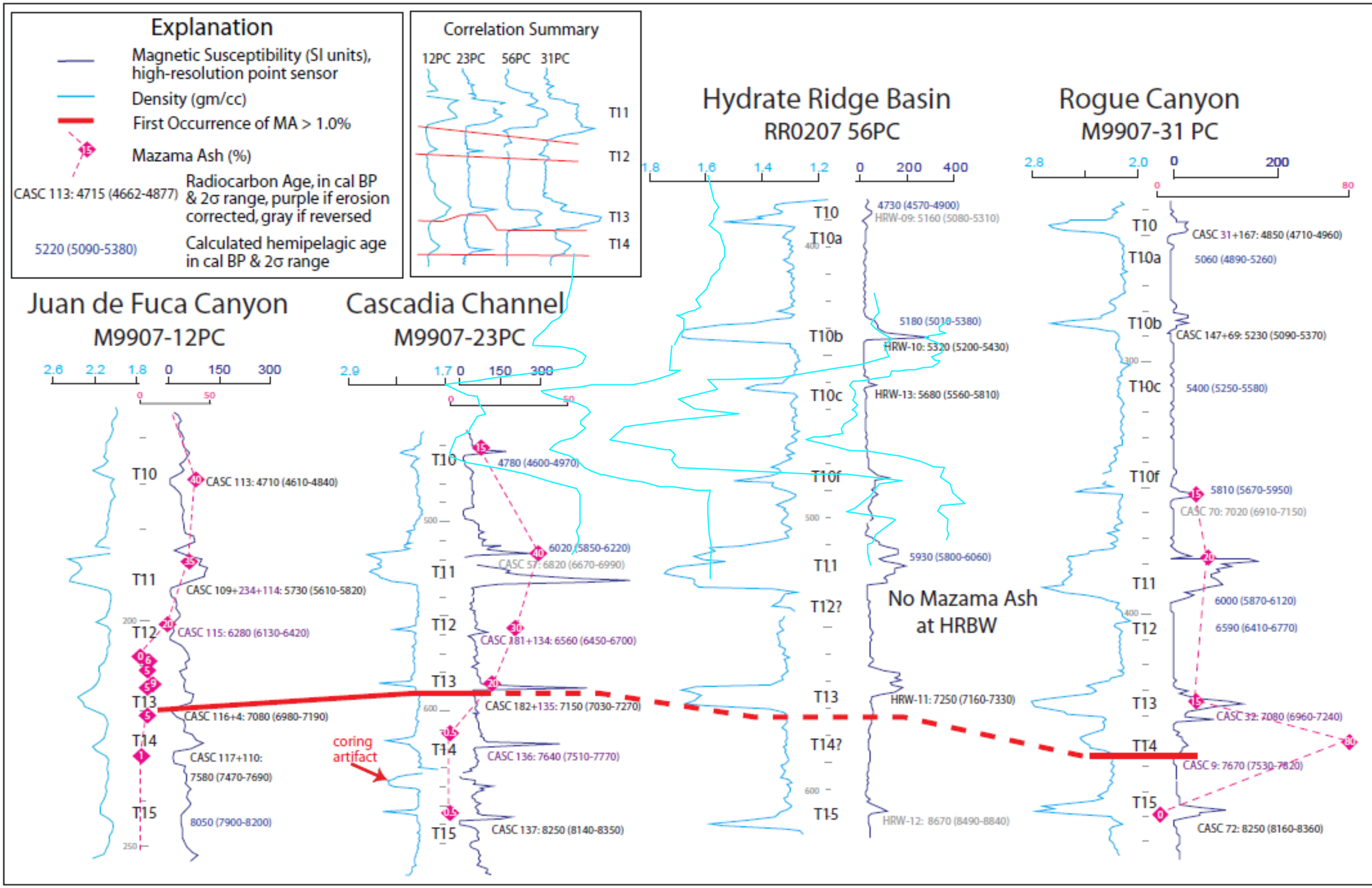
In this case T9-T12 at Hydrate Ridge Basin West and Rogue Apron

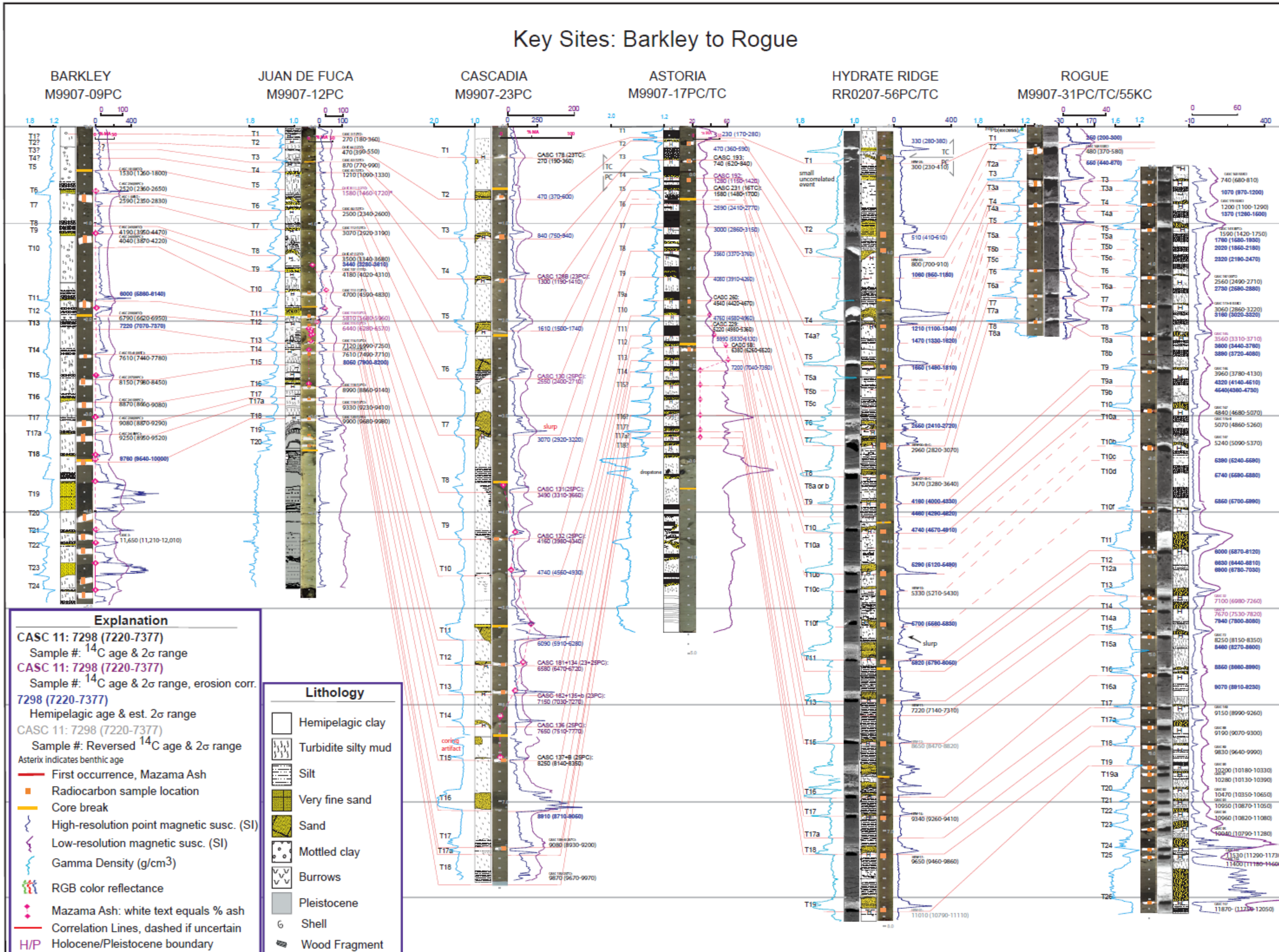
Ages and ranges are of three types:

1. Conventional ages
2. Erosion corrected ages
3. Benthic foram ages (not common)

All ages require corrections for sample thickness, and a time and space variant reservoir correction. Some ages are also corrected for differential basal erosion, which is apparent in some cases though multiple cores

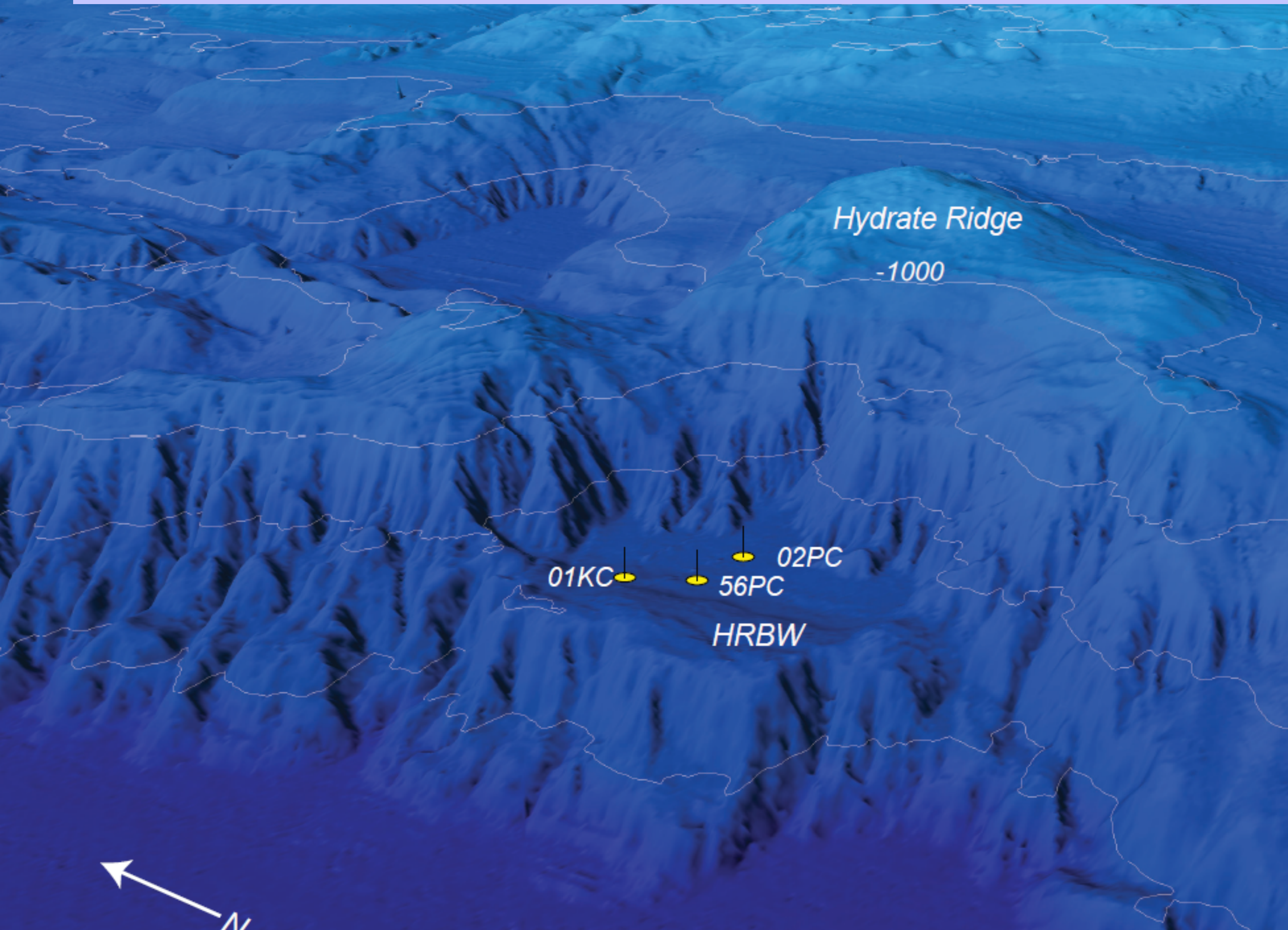
All error ranges, whether calculated or estimated are propagated using sum

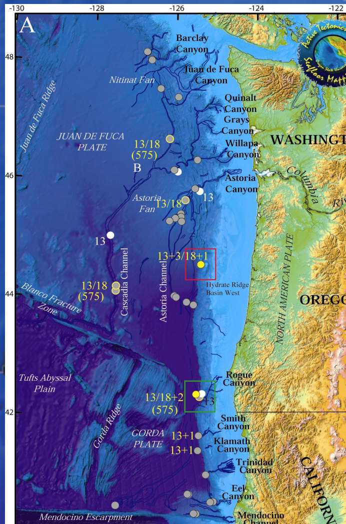

Explanation
Magnetic Susceptibility (SI units), high-resolution point sensor
Density (gm/cc)
First Occurrence of MA > 1.0%
Mazama Ash (%)
CASC 113: 4715 (4662-4877)
Radiocarbon Age, in cal BP & 2σ range, purple if erosion corrected, gray if reversed
5220 (5090-5380)
Calculated hemipelagic age in cal BP & 2σ range
Correlation Summary
12PC 23PC 56PC 31PC
T11
T12
T13
T14
Juan de Fuca Canyon
M9907-12PC
Cascadia Channel
M9907-23PC
Hydrate Ridge Basin
RR0207 56PC
Rogue Canyon
M9907-31 PC
CASC 113: 4710 (4610-4840)
CASC 109+234+114: 5730 (5610-5820)
CASC 115: 6280 (6130-6420)
CASC 116+4: 7080 (6980-7190)
CASC 117+110: 7580 (7470-7690)
8050 (7900-8200)
coring artifact
4780 (4600-4970)
6020 (5850-6220)
CASC 57: 6820 (6670-6990)
CASC 181+134: 6560 (6450-6700)
CASC 182+135: 7150 (7030-7270)
CASC 136: 7640 (7510-7770)
CASC 137: 8250 (8140-8350)
4730 (4570-4900)
HRW-09: 5160 (5080-5310)
5180 (5010-5380)
HRW-10: 5320 (5200-5430)
HRW-13: 5680 (5560-5810)
5930 (5800-6060)
No Mazama Ash at HRBW
HRW-11: 7250 (7160-7330)
HRW-12: 8670 (8490-8840)
T10
T10a
T10b
T10c
T10f
T11
T12?
T13
T14?
T15
CASC 31+167: 4850 (4710-4960)
5060 (4890-5260)
CASC 147+69: 5230 (5090-5370)
5400 (5250-5580)
5810 (5670-5950)
CASC 70: 7020 (6910-7150)
6000 (5870-6120)
6590 (6410-6770)
CASC 32: 7080 (6960-7240)
CASC 9: 7670 (7530-7820)
CASC 72: 8250 (8160-8360)



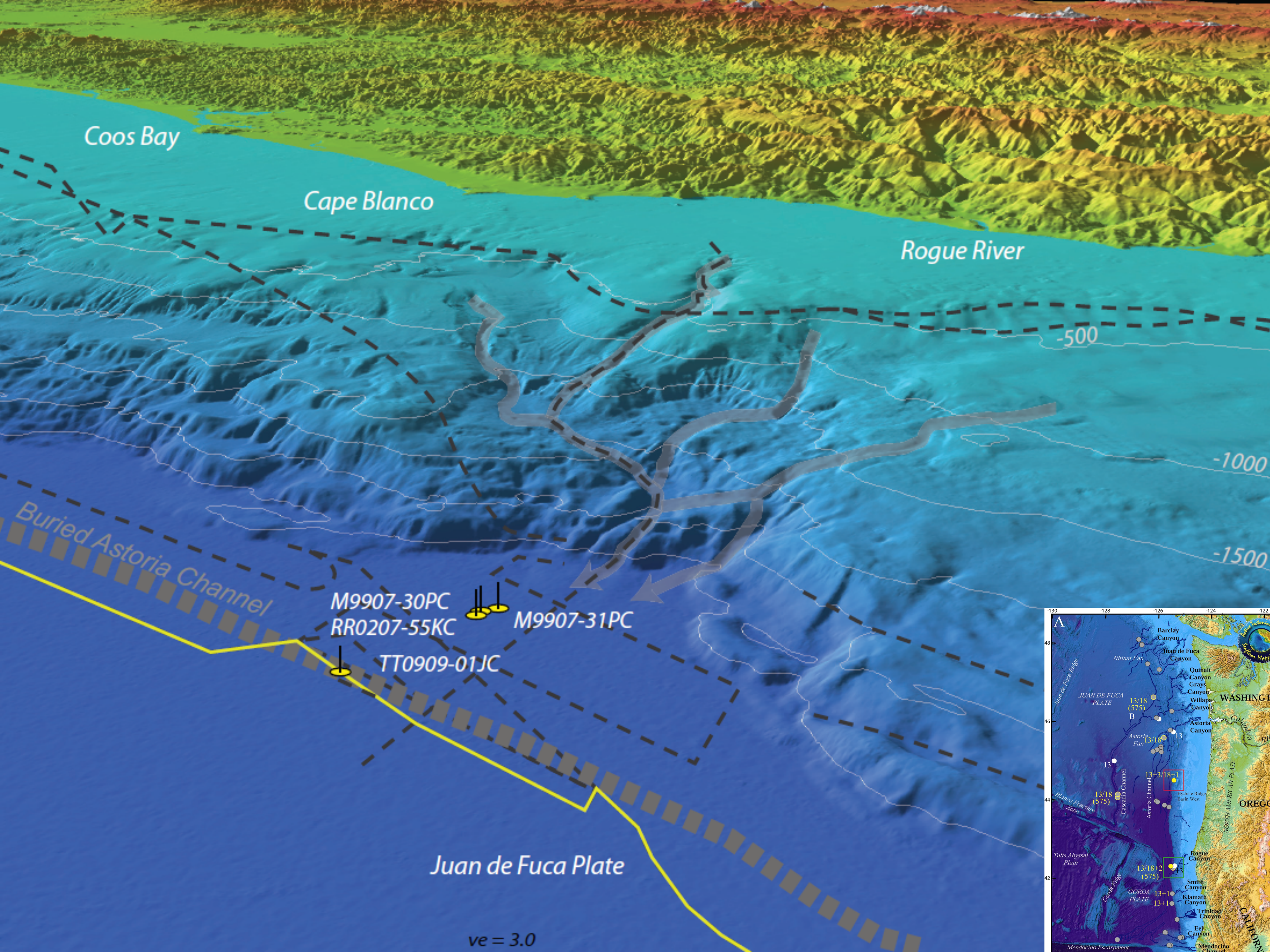
Key Sites: Barkley to Rogue
BARKLEY
M9907-09PC
JUAN DE FUCA
M9907-12PC
CASCADIA
M9907-23PC
ASTORIA
M9907-17PC/TC
HYDRATE RIDGE
RR0207-56PC/TC
ROGUE
M9907-31PC/TC/55KC
0 cm
100 cm
200 cm
300 cm
400 cm
500 cm
600 cm
700 cm
800 cm
Explanation
CASC 11: 7298 (7220-7377)
Sample #: 14C age & 2σ range
CASC 11: 7298 (7220-7377)
Sample #: 14C age & 2σ range, erosion corr.
7298 (7220-7377)
Hemipelagic age & est. 2σ range
CASC 11: 7298 (7220-7377)
Sample #: Reversed 14C age & 2σ range
Asterix indicates benthic age
First occurrence, Mazama Ash
Radiocarbon sample location
Core break
High-resolution point magnetic susc. (SI)
Low-resolution magnetic susc. (SI)
Gamma Density (g/cm3)
RGB color reflectance
Mazama Ash: white text equals % ash
Correlation Lines, dashed if uncertain
H/P Holocene/Pleistocene boundary
Lithology
Hemipelagic clay
Turbidite silty mud
Silt
Very fine sand
Sand
Mottled clay
Burrows
Pleistocene
Shell
Wood Fragment

In addition to ~ 19 turbidites that appear to correlate along much of the margin (though with variable northern and southern limits), there are additional thinner events found almost exclusively along the southern margin south of Hydrate Ridge (44.5N).

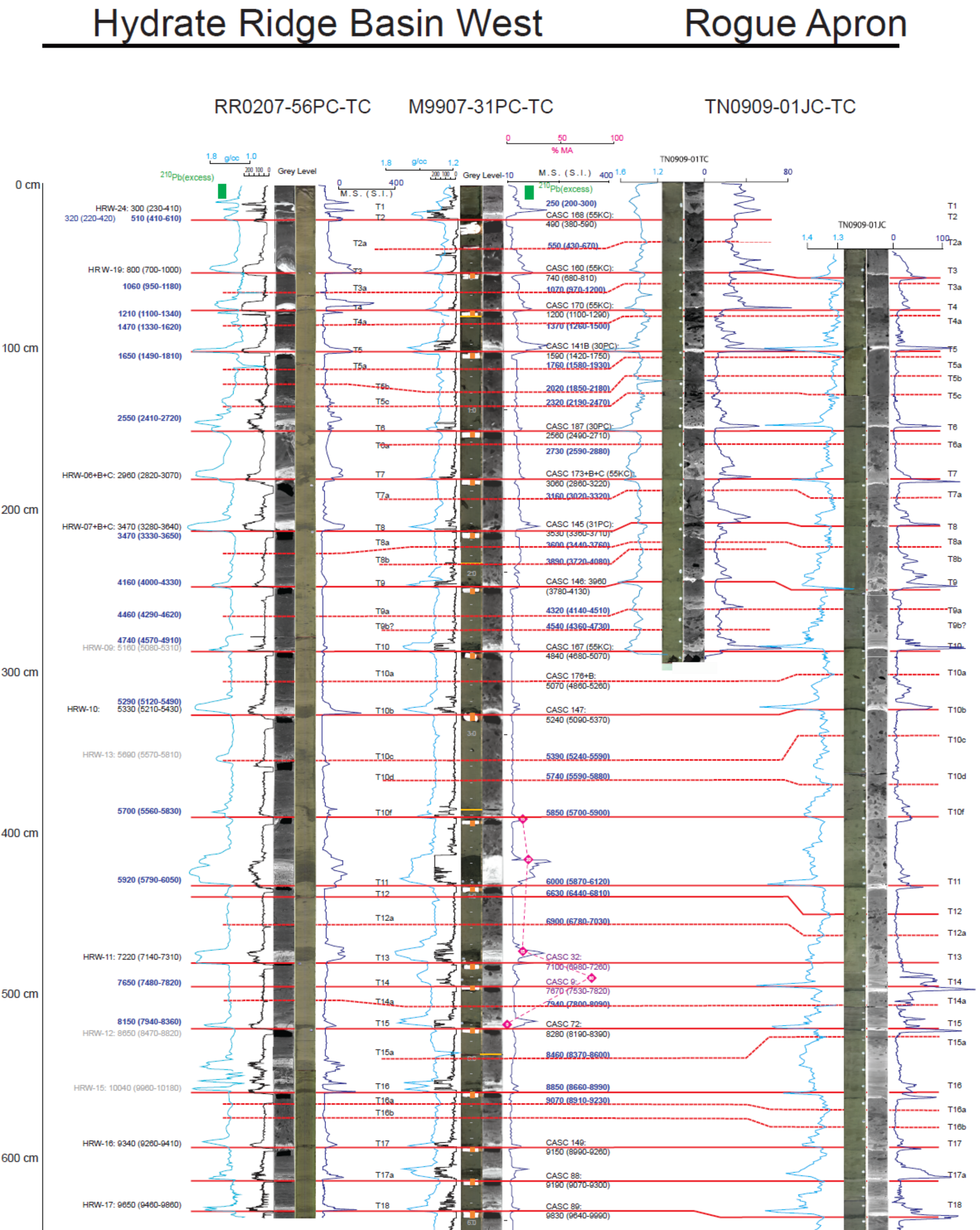




<u>Hydrate Ridge basin is isolated, and cannot receive input from terrestrial sources or storm/tsunami wave</u>



Coos Bay
Cape Blanco
Rogue River
-500
-1000
-1500
Buried Astoria Channel
M9907-30PC
RR0207-55KC
M9907-31PC
TT0909-01JC
Juan de Fuca Plate
ve = 3.0
A
Barclay Canyon
Juan de Fuca Canyon
Nitinat Fan
Quinalt Canyon
Grays Canyon
Willapa Canyon
JUAN DE FUCA PLATE
WASHINGTON
Astoria Canyon
Astoria Fan
Cascadia Channel
Astoria Channel
Hydrate Ridge Basin West
NORTH AMERICAN PLATE
Blanco Fracture Zone
Tufts Abyssal Plain
Rogue Canyon
Gorda Ridge
GORDA PLATE
Smith Canyon
Klamath Canyon
Trinidad Canyon
Eel Canyon
Mendocino Escarpment



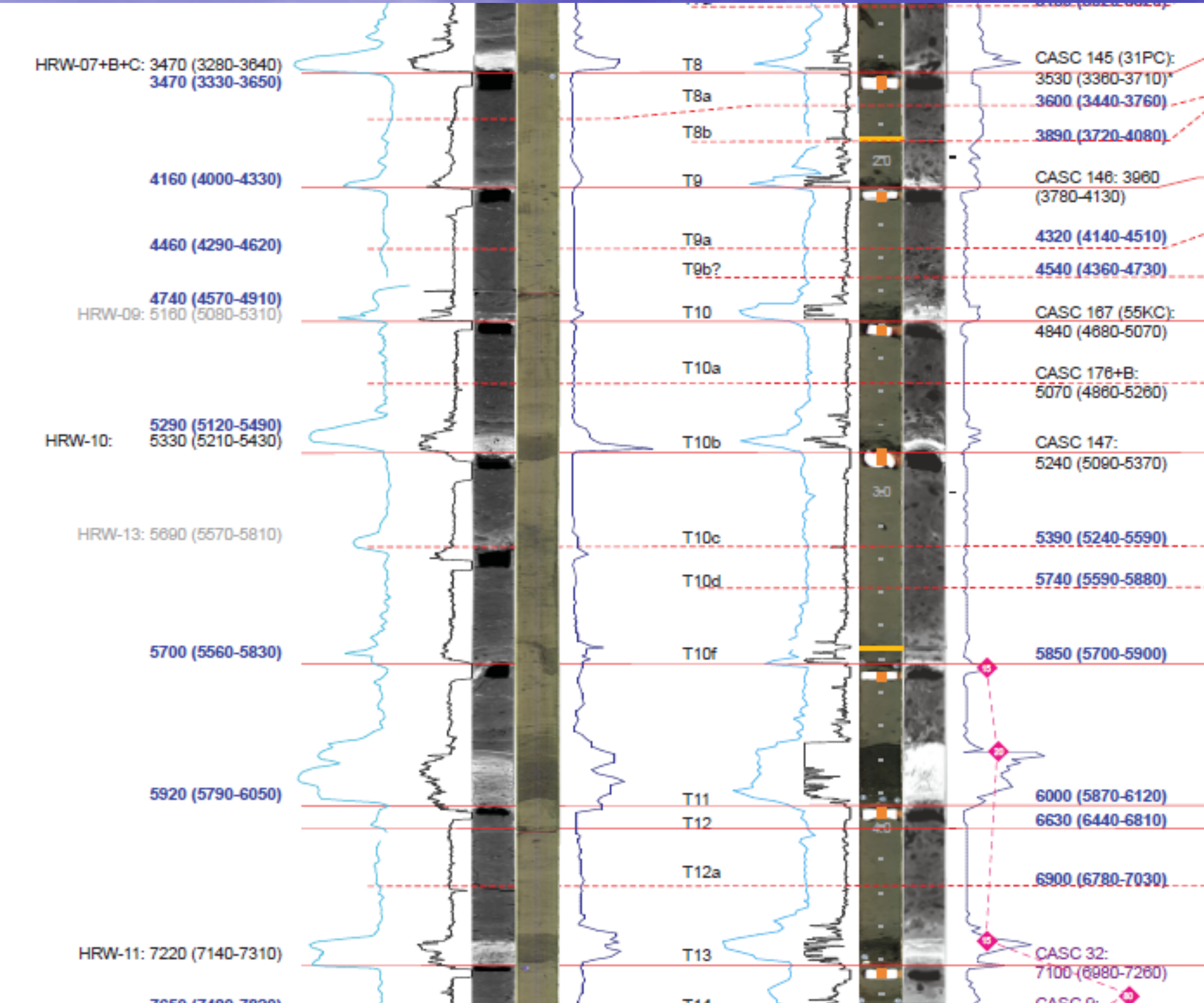
One example of many "flattened" correlation plots between individual pairs and groups of core sites.

Flattened correlation between Rogue and Hydrate ridge, showing along strike dropout of 7 of the thin mud turbidites between two roughly comparable sites.

12 more drop out between Hydrate Ridge and Astoria Canyon, 100 km to the north, also a comparable site.

Hydrate Ridge Basin West

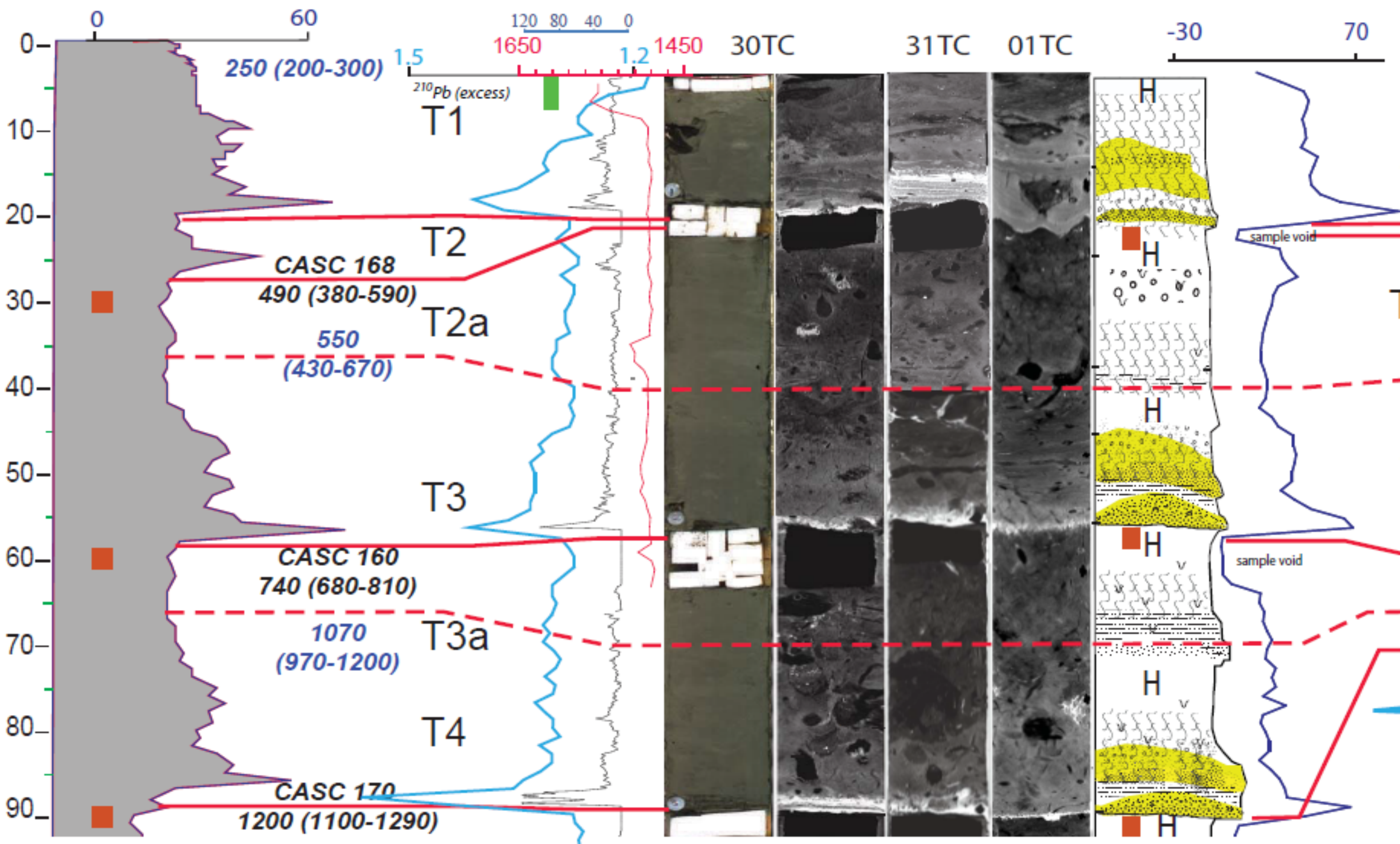
Rogue Apron



Zooming in…

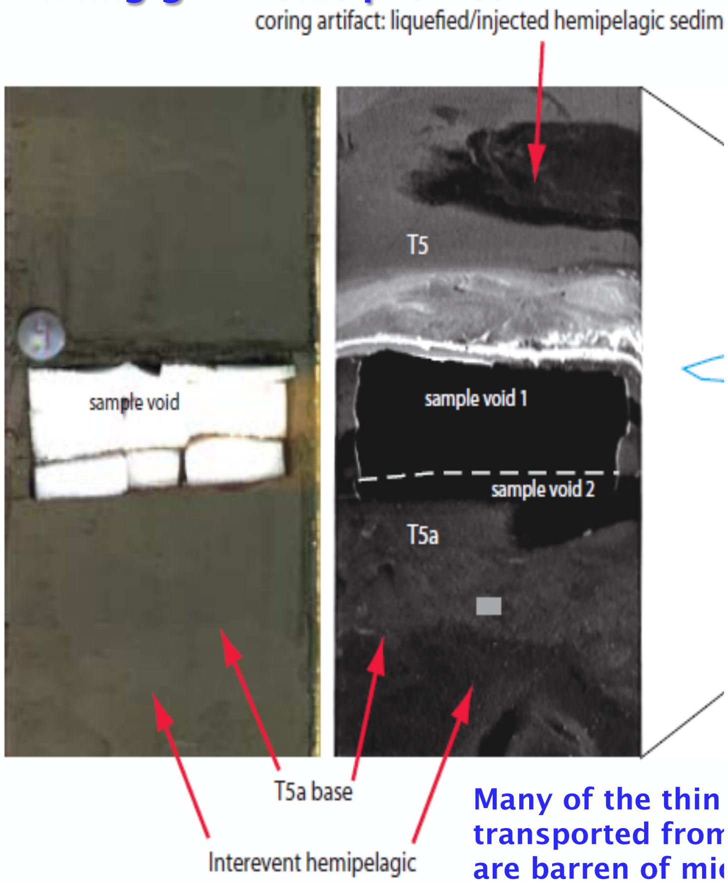
middle Holocene

The southern margin mud-slit turbidites are apparent in geophysical logs, CT imagery, and sedimentological examination

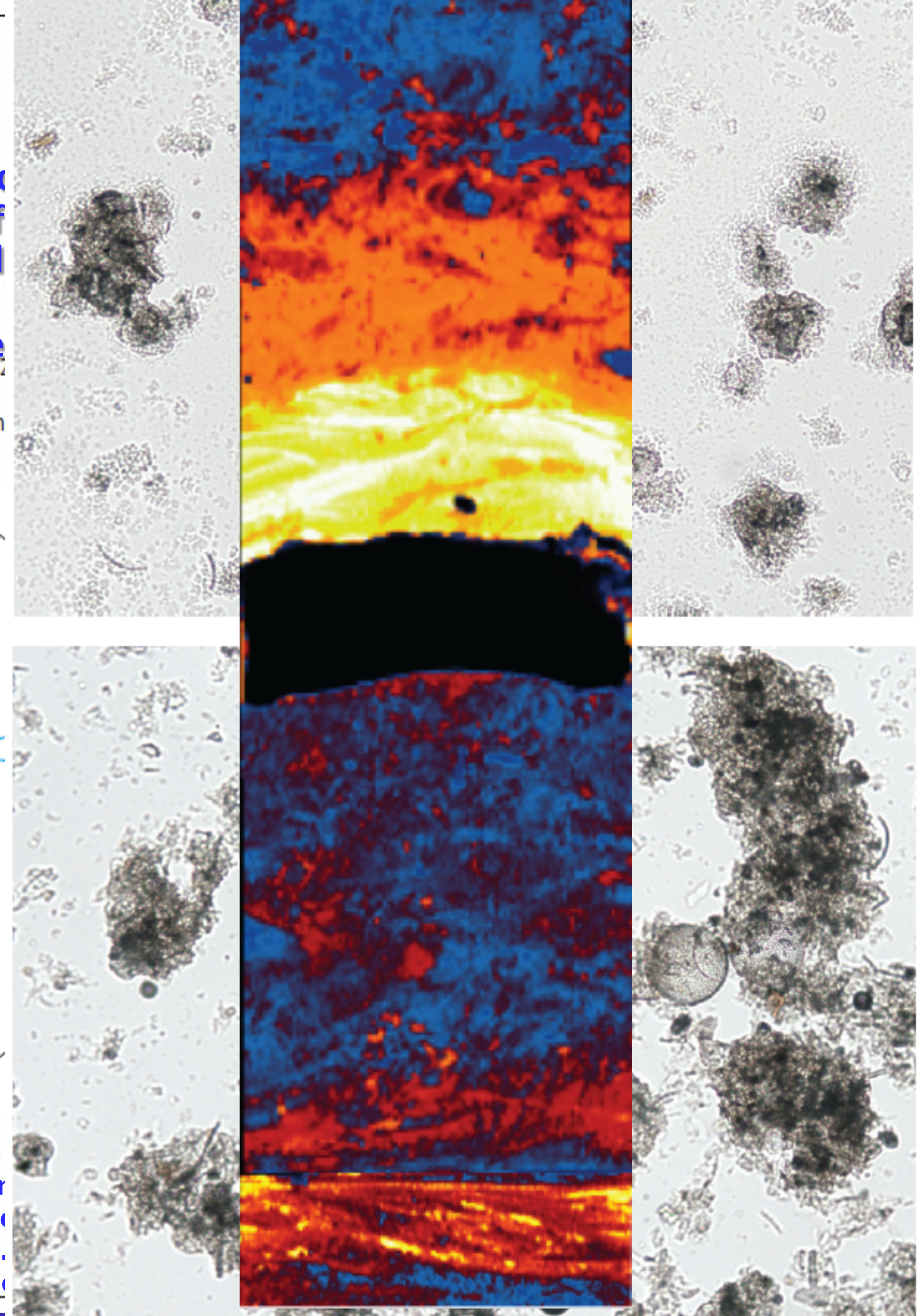


The spatially limited southern turbidites, what are they?

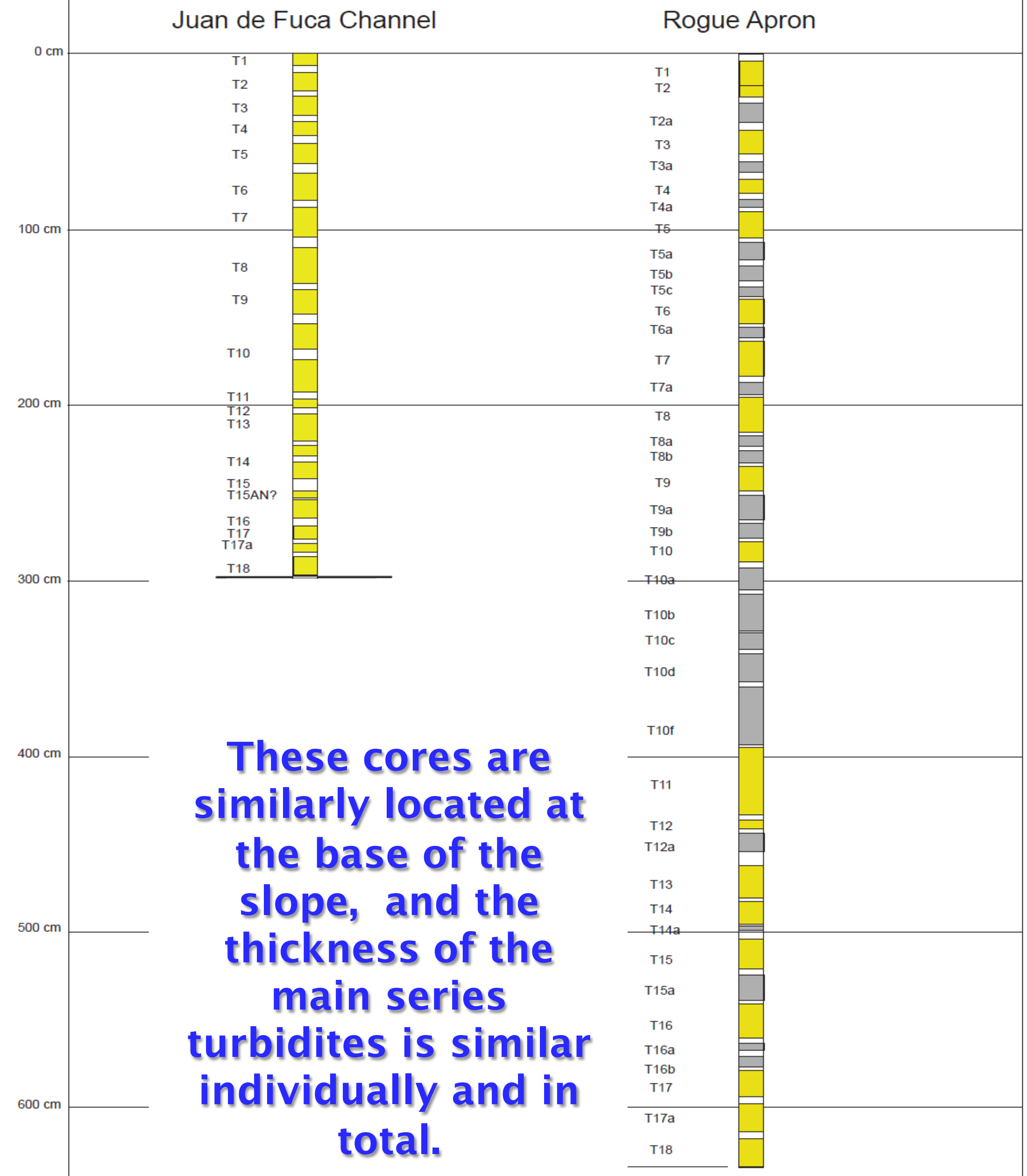
First of all, they are turbidites. They have sharp bases, fining upward sequences, have limited quantities of broken biogenic material etc. They d not have the characteristics of hyperpycnal flows, that is waxing the waning grain size profiles.



Many of the thin transported from are barren of mi organic material. upper slope mat



Why is the JDF Holocene section only half the thickness of that at Rogue?



These cores are similarly located at the base of the slope, and the thickness of the main series turbidites is similar individually and in total.

Schematic comparison of stratigraphic sequences at Juan de Fuca Channel and Rogue Apron at true scale.

What is the difference?

Below the JDF core diagram, we add four units that represent the difference between the two sites.

1) The total thickness of mud turbidites from Rogue Apron;

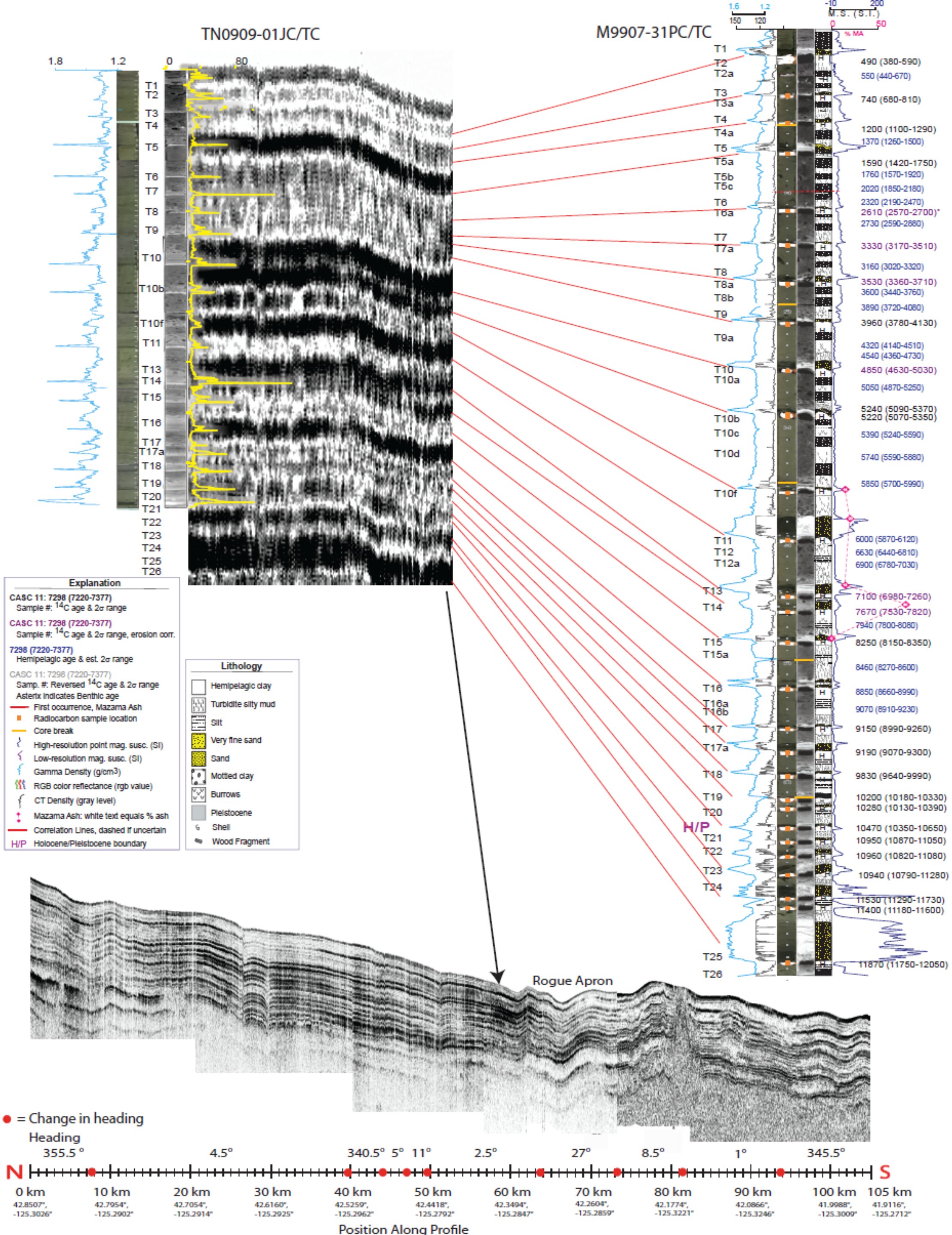
2) The increased overall thickness of Rogue turbidites, 15% greater than JDF, is added to both mud and sand turbidites; and

3) The 150% difference in hemipelagic sedimentation rate (Goldfinger et al., 2012);

4) The difference in basal erosion at the turbidite bases, compiled from Goldfinger et al (2012).

The net difference in Holocene section thickness is ~ 20 cm or 3.1%.

The difference is mostly attributable to the presence of 23 southern Cascadia turbidites present at Rogue Apron.



Multiple lines of evidence, continued…

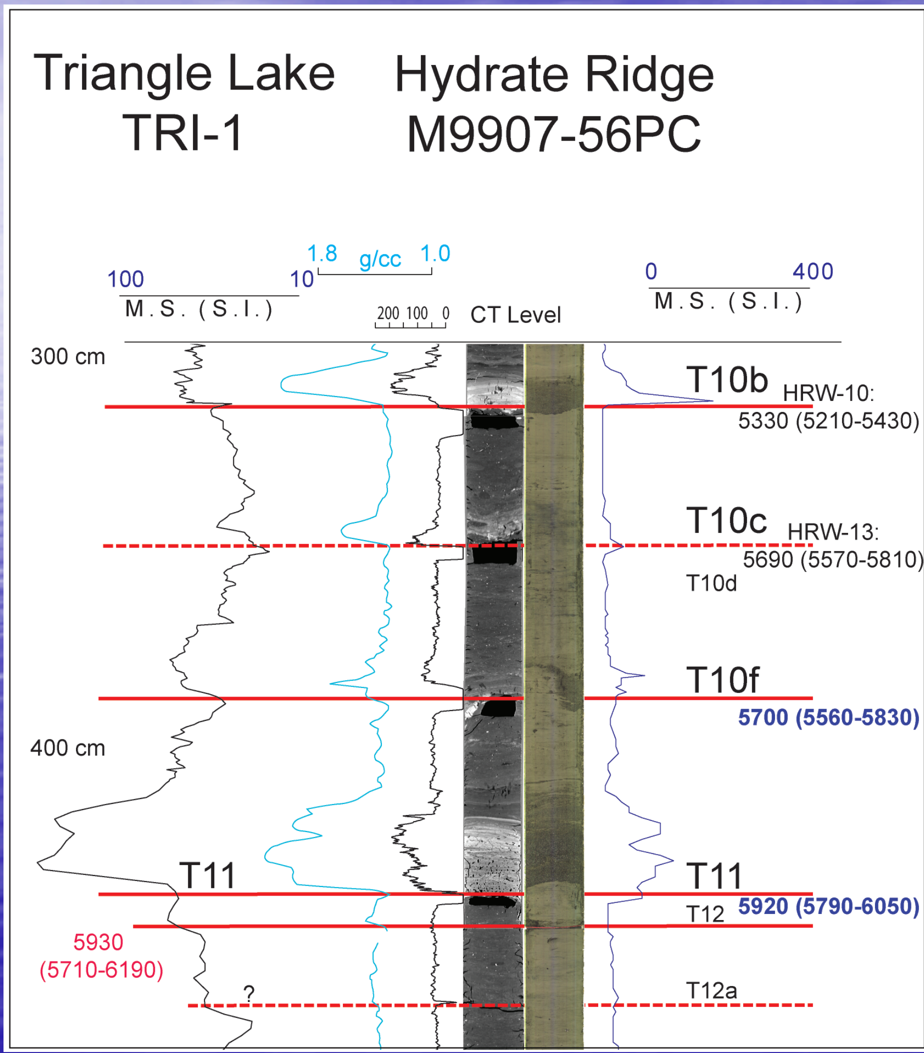
2-6 kHz chirp reflection profiles image the Holocene section with vertical resolution of ~ 18 cm.

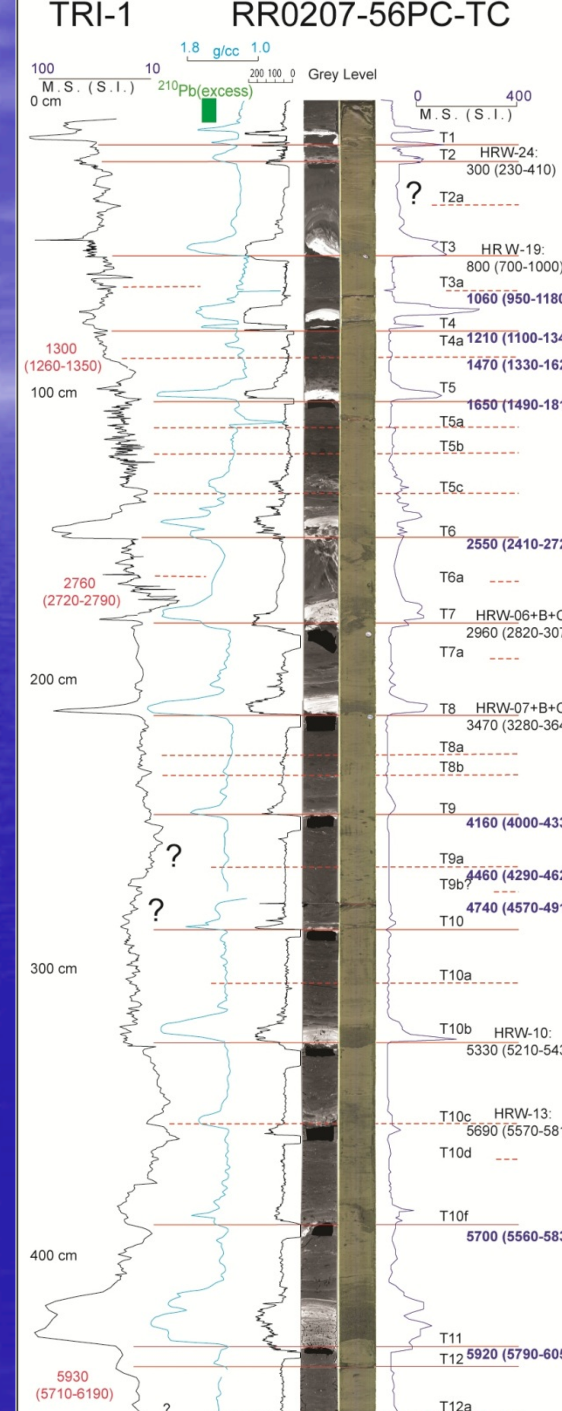
Direct correlation with cores is straightforward with depth conversion, allowing along strike correlation of the larger sandy turbidites for 100's of km along strike.

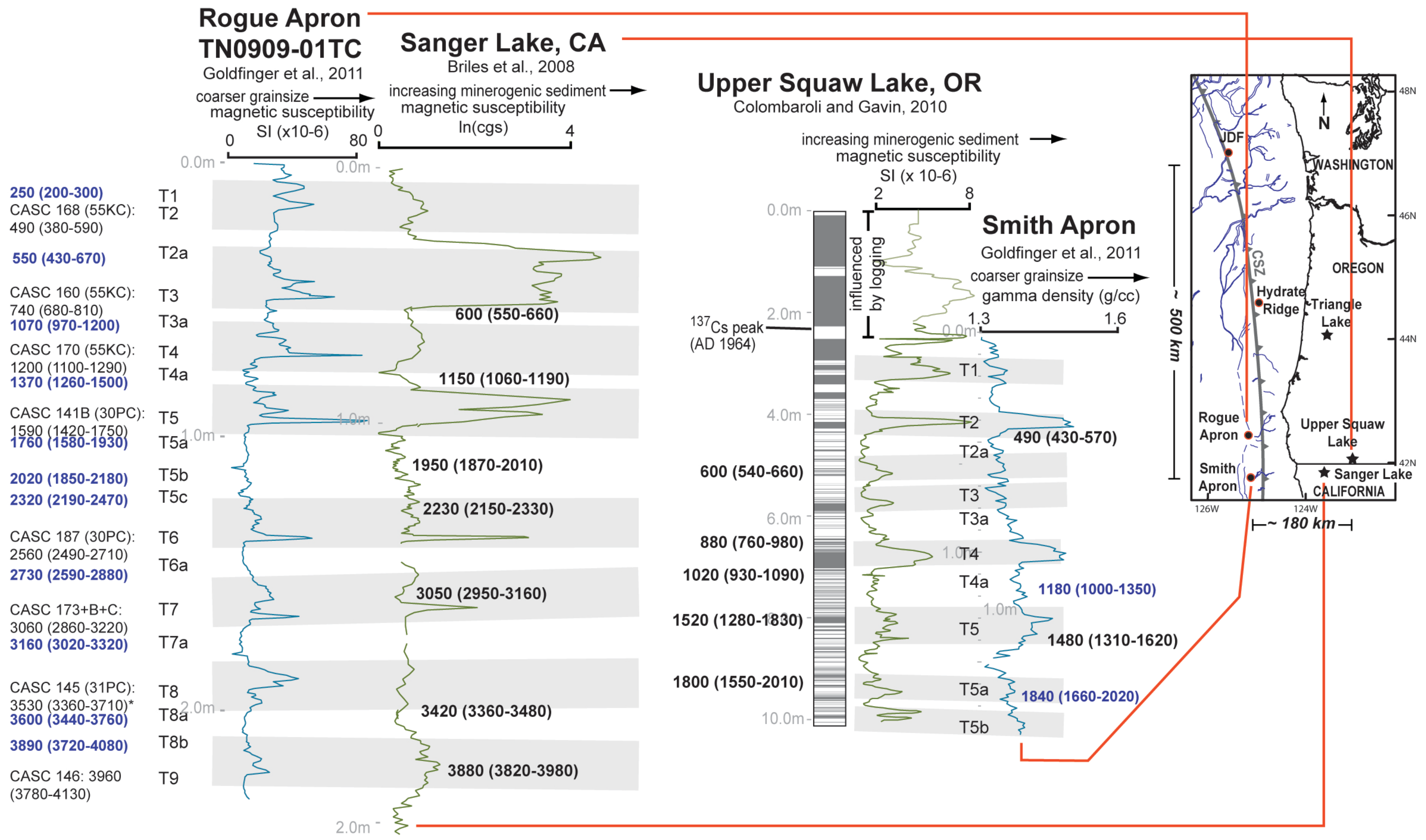
This example, centered on Rogue apron, shows 108 km of margin parallel profile, 5 km seaward of the deformation front.

Multiple lines of evidence, continued….

Lakes!







Rogue Apron TN0909-01TC
Goldfinger et al., 2011
coarser grainsize
magnetic susceptibility SI (x10-6)
0 80
Sanger Lake, CA
Briles et al., 2008
increasing minerogenic sediment
magnetic susceptibility ln(cgs)
0 4
Upper Squaw Lake, OR
Colombaroli and Gavin, 2010
increasing minerogenic sediment
magnetic susceptibility SI (x 10-6)
2 8
influenced by logging
137Cs peak (AD 1964)
Smith Apron
Goldfinger et al., 2011
coarser grainsize
gamma density (g/cc)
1.3 1.6
250 (200-300)
CASC 168 (55KC): 490 (380-590)
550 (430-670)
CASC 160 (55KC): 740 (680-810)
1070 (970-1200)
CASC 170 (55KC): 1200 (1100-1290)
1370 (1260-1500)
CASC 141B (30PC): 1590 (1420-1750)
1760 (1580-1930)
2020 (1850-2180)
2320 (2190-2470)
CASC 187 (30PC): 2560 (2490-2710)
2730 (2590-2880)
CASC 173+B+C: 3060 (2860-3220)
3160 (3020-3320)
CASC 145 (31PC): 3530 (3360-3710)*
3600 (3440-3760)
3890 (3720-4080)
CASC 146: 3960 (3780-4130)
T1 T2 T2a T3 T3a T4 T4a T5 T5a T5b T5c T6 T6a T7 T7a T8 T8a T8b T9
600 (550-660)
1150 (1060-1190)
1950 (1870-2010)
2230 (2150-2330)
3050 (2950-3160)
3420 (3360-3480)
3880 (3820-3980)
600 (540-660)
880 (760-980)
1020 (930-1090)
1520 (1280-1830)
1800 (1550-2010)
490 (430-570)
1180 (1000-1350)
1480 (1310-1620)
1840 (1660-2020)
JDF
N
WASHINGTON
OREGON
CSZ
Hydrate Ridge
Triangle Lake
Rogue Apron
Upper Squaw Lake
Smith Apron
Sanger Lake
CALIFORNIA
~ 500 km
~ 180 km

With many sedimentological characteristics, correlation criteria, chronological data, tephra layers, how can this all be assessed.

As with most geological interpretations, we use the Judge Wapner method, considering "the preponderance of the evidence". There is rarely a single criteria that is the "smoking gun" in geology.

But there is a way to invert the data and estimate the probability of a given hypothesis using Bayes theorem.

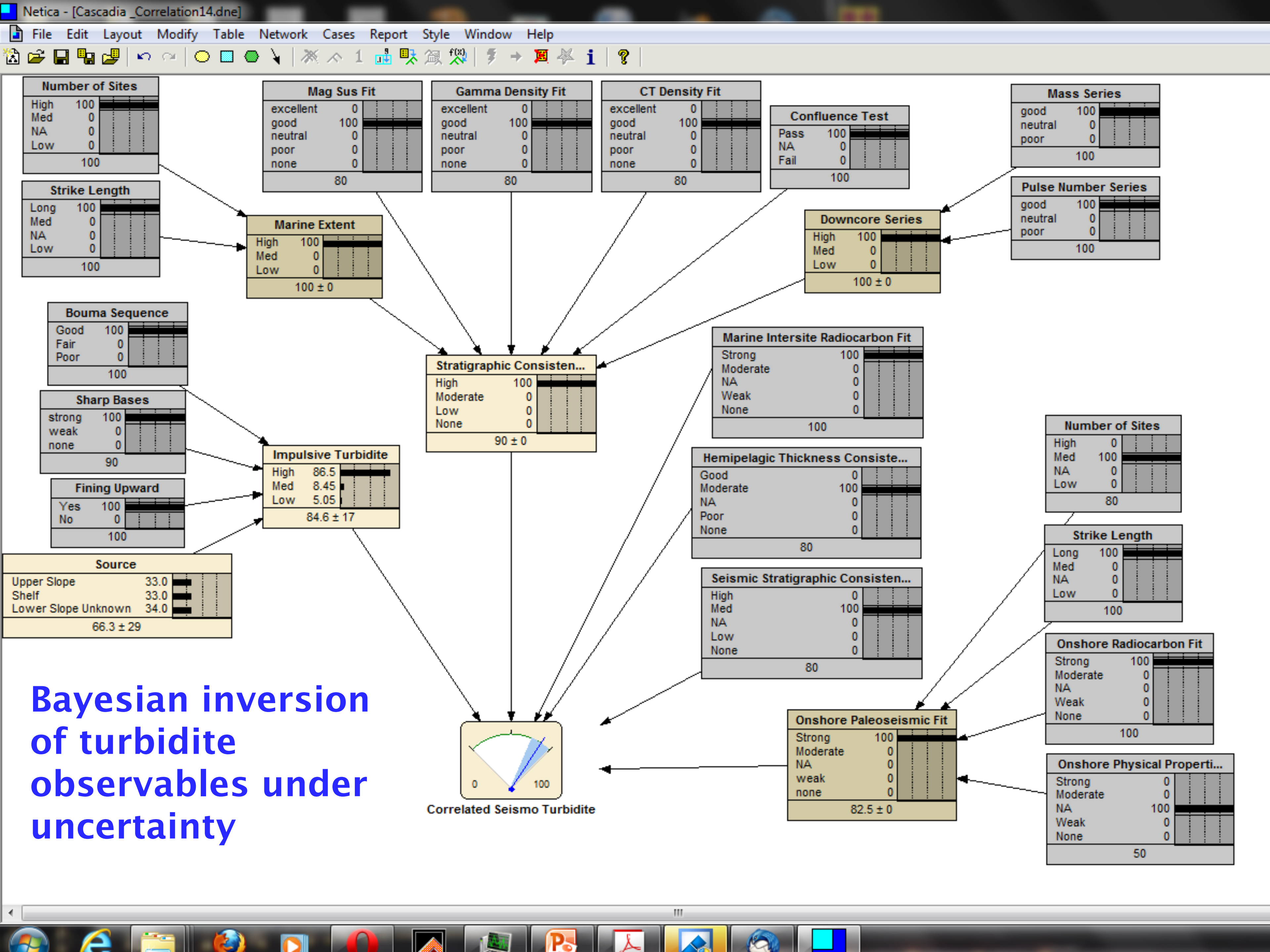
Bayes theorem considers the probability of a hypothesis, given the data. This can be done with or without prior information.

This is the opposite of so called "frequentist" (standard statistics) methods which do not consider multiple hypotheses, or probabilities.

The observables we have to evaluate are:

- Sedimentological character, such as Bouma sequences, fining upward sequences, sharp bases etc.
- Evidence of downslope transport from shallow water
- Geophysical parameter correlation, such as gamma and CT density, magnetic Susceptibility, resistivity, p-wave velocity and others.
- The distance and number of sites that meet threshold criteria for correlation.
- Relative dating tests such as the confluence test
- Downcore parameter series such as mass, number of fining upward units.
- Radiocarbon, Cs137, Pb210 and other dating parameter fits.
- Temporal correlation based on hemipelagic thickness
- Seismic stratigraphic correlation
- Onshore temporal fit
- Onshore stratigraphic correlation
- Onshore strike extent

Bayesian inversion of turbidite observables under uncertainty



Preliminary results: probability of correlation given the input data, T1-18 for (JDF, Cascadia, HR, Rogue) and high precision land sites.

Idnum	freq	finding Correl	probabilities of Correl	P(case)
1	1	*	(0.94 0.06)	4.17444e-008
2	1	*	(0.77 0.23)	4.17444e-008
3	1	*	(0.82 0.18)	4.30094e-008
4	1	*	(0.88 0.12)	4.17444e-008
5	1	*	(0.71 0.29)	4.43127e-008
6	1	*	(0.93 0.07)	4.17444e-008
7	1	*	(0.87 0.13)	4.30094e-008
8	1	*	(0.73 0.27)	4.30094e-008
9	1	*	(0.83 0.17)	4.17444e-008
10	1	*	(0.63 0.37)	4.30094e-008
11	1	*	(0.85 0.15)	4.17444e-008
12	1	*	(0.74 0.26)	4.17444e-008
13	1	*	(0.89 0.11)	4.17444e-008
14	1	*	(0.82 0.18)	4.30094e-008
15	1	*	(0.77 0.23)	4.30094e-008
16	1	*	(0.85 0.15)	4.17444e-008
17	1	*	(0.83 0.17)	4.17444e-008
17a	1	*	(0.81 0.19)	4.30094e-008
18	1	*	(0.79 0.21)	4.17444e-008

Onshore-Offshore space-time diagram for the most recent ~ 2800 years.

(Filled symbols are marine data, open symbols land data; smaller open symbols are bulk peat ages, given lower weighting here.)

Stratigraphic correlation for offshore data shown in blue dashed lines.

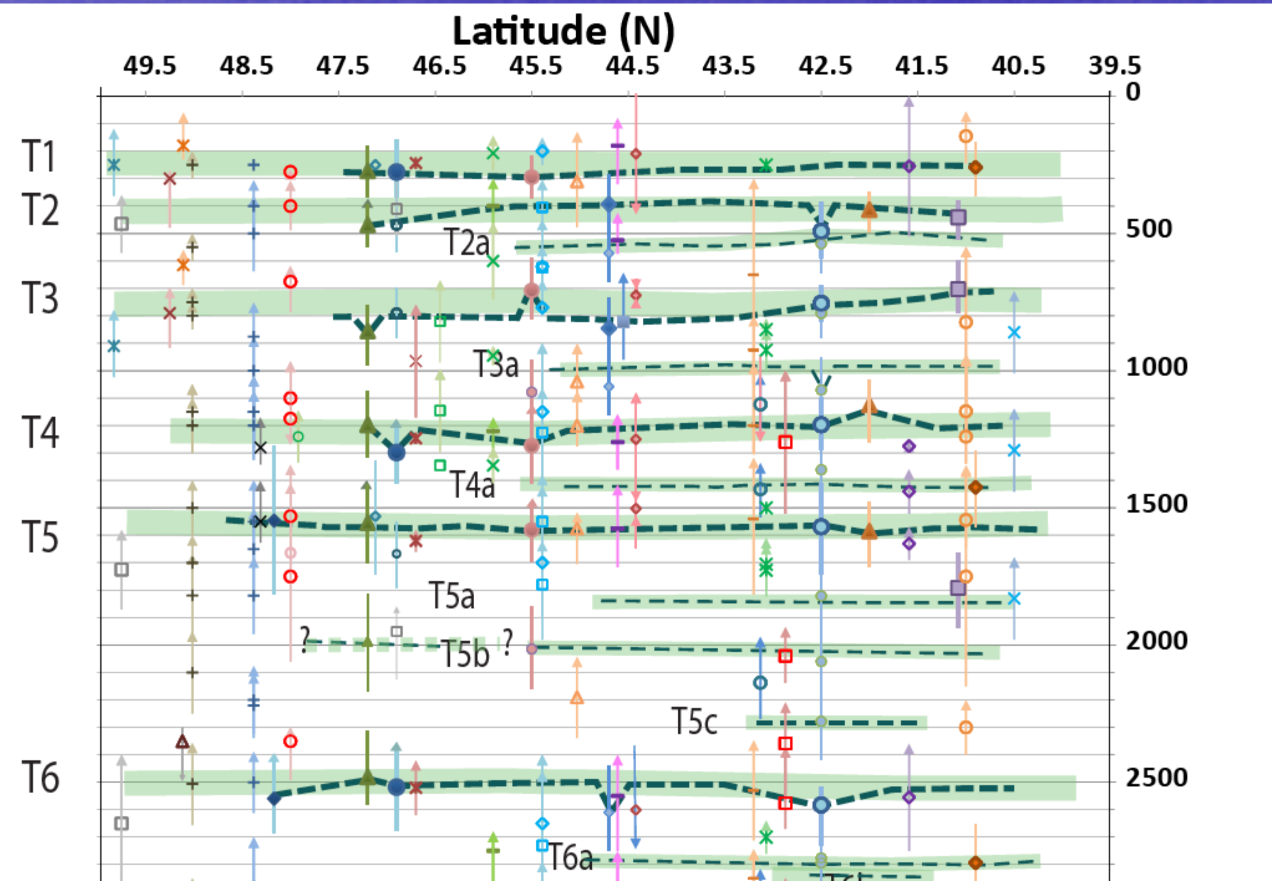
Land Data

- Deserted Lake[20]
- Port Alberni[11]
- Tofino[7,17,18]
- Effingham[11,45]
- Catala Lake[9]
- Kakawis Lake[25]
- Saanich Inlet[6]
- Saanich Varves[6]
- Discovery Bay[41]
- Swantown[40]
- Cultus Bay[46]
- Copalis River[2]
- Johns River[38]
- Willapa Bay[2,3,47]
- Long Beach WA[37]
- Ecola Creek[14,34]
- Ecola 2007[44]
- Netarts Shennan[39,24]
- Netarts Marsh[12,13]
- Salmon River[29]
- Yaquina Bay[14]
- Alsea Bay[14,31]
- Coquille River[43]
- Coos Bay2[30,27,28]
- Bradley Lake[23]
- Sixes River[43]
- Humboldt Bay[33]
- Eel River[33]
- Lagoon Creek[15,16]

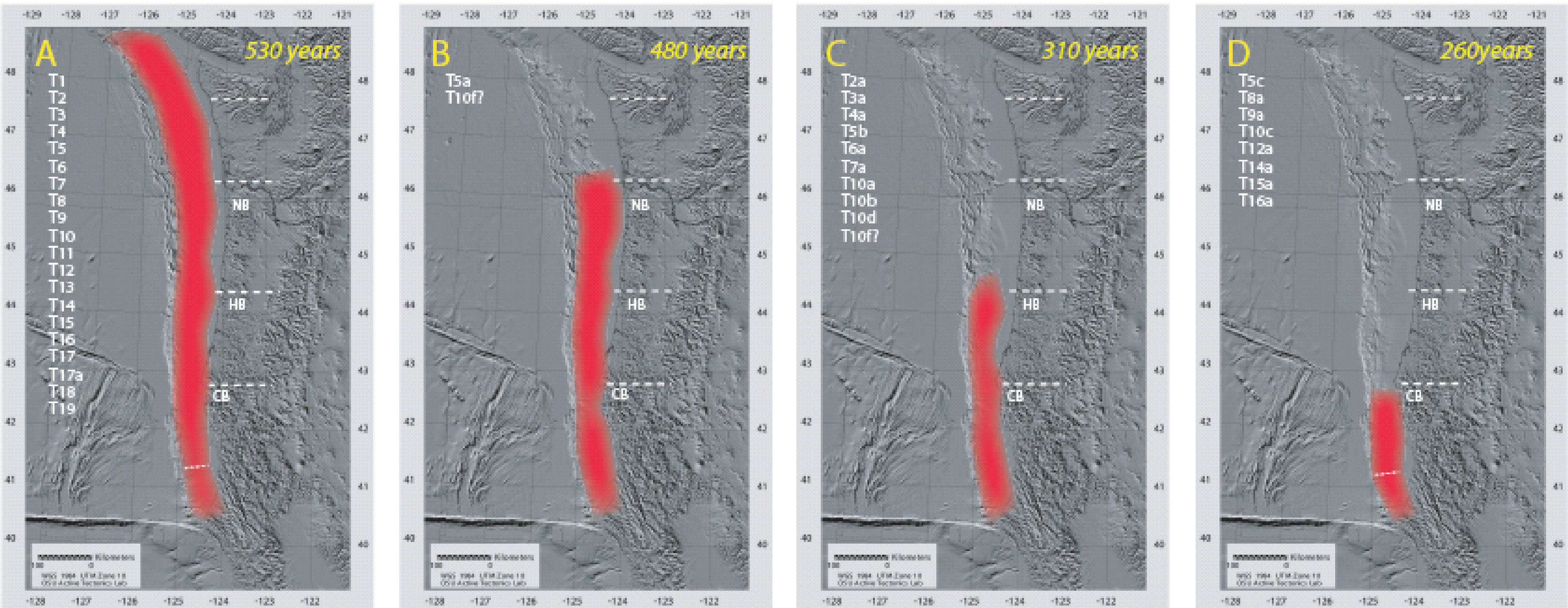
Marine Data

- Barclay Canyon
- Barkley Canyon H
- Juan de Fuca
- Juan de Fuca H
- Cascadia Channel
- Cascadia Channel H
- Cascadia 1996[48]
- Astoria Channel
- Astoria Channel H
- Astoria 1996[48]
- Hydrate Ridge
- Hydrate Ridge H
- Rogue Apron
- Rogue Apron H
- Smith Apron
- Klamath Canyon
- Trinidad Plunge Pool
- Eel Channel

Land Data



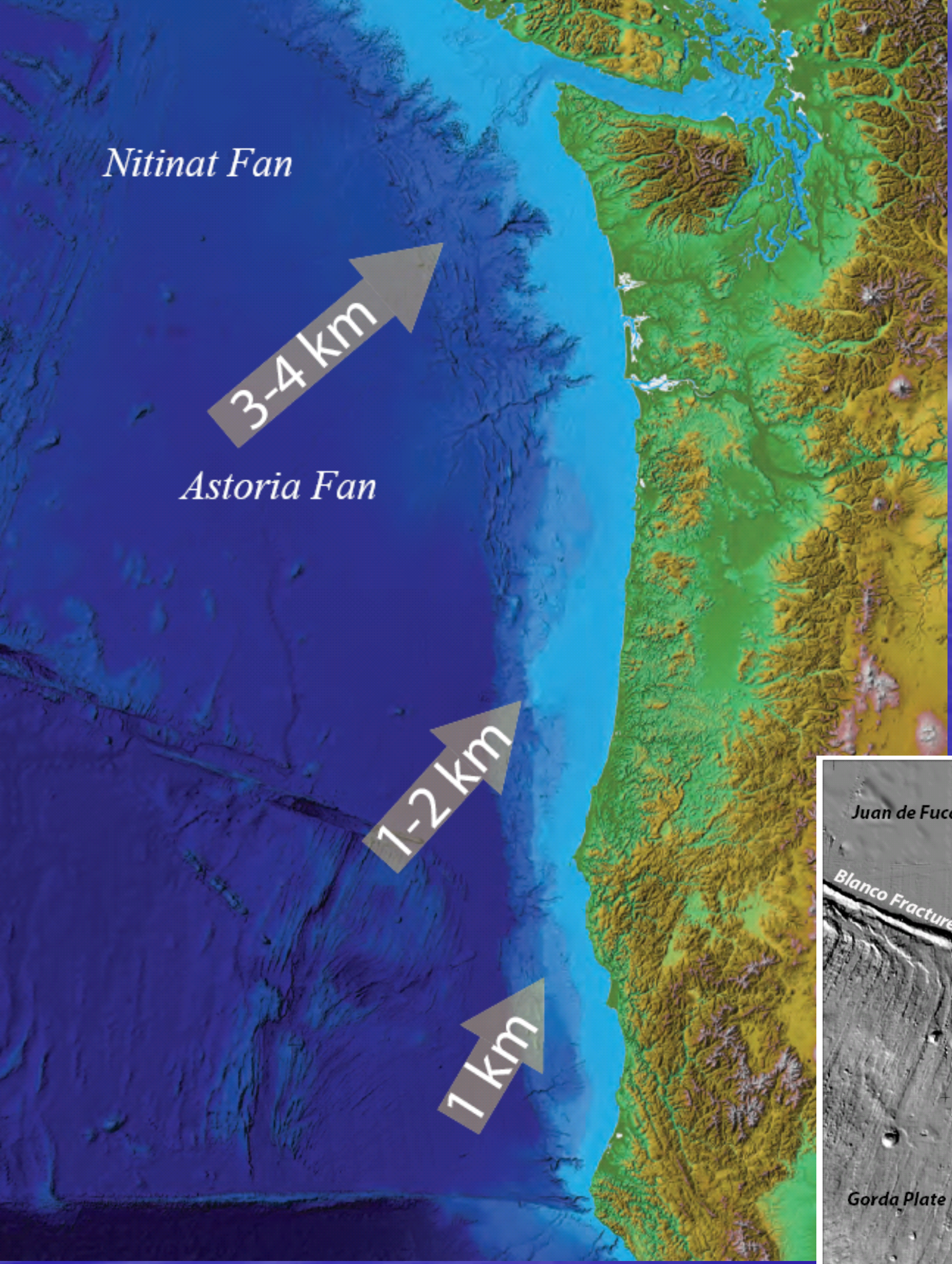
Now the fun begins…..



Rupture lengths from paleoseismic data, past 10,000 years. Segment boundaries are roughly compatible with ETS segment boundaries proposed by Brudzinski et al., 2007, though both sets of boundaries are quite crude.

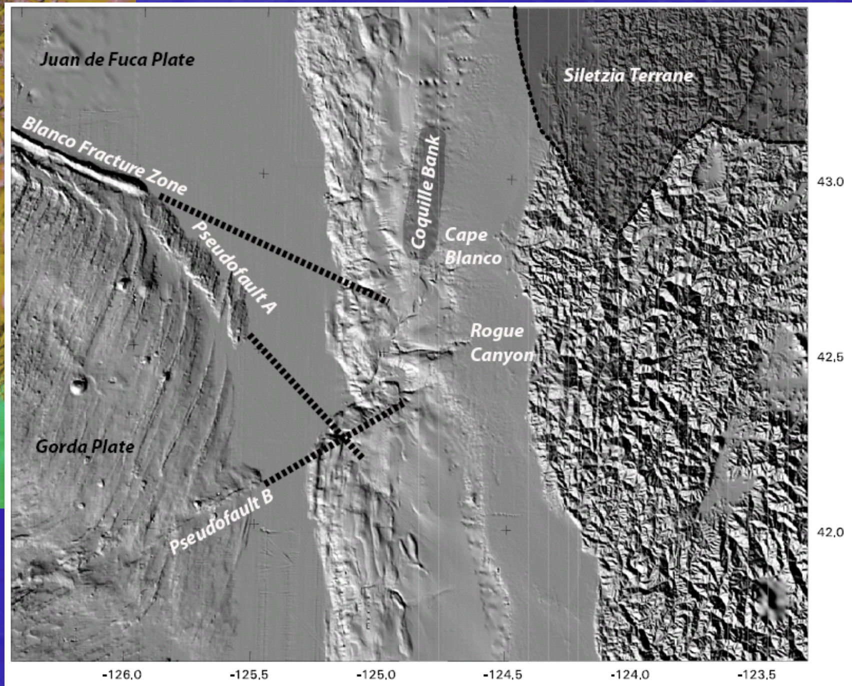
While recurrence interval is ~ 500 years in northern Cascadia, it is only 220-220 years in the south. (220 years in the past ~ 3000 years). The NSAF recurrence during this time is similar, ~200 years.

Why segments in the south but not the north?



Earthquake frequency and segment size may be linked to sediment supply, which decreases southward, exposing plate roughness and perhaps forearc structure that may be obscured by great sediment thickness in the north-central margin.

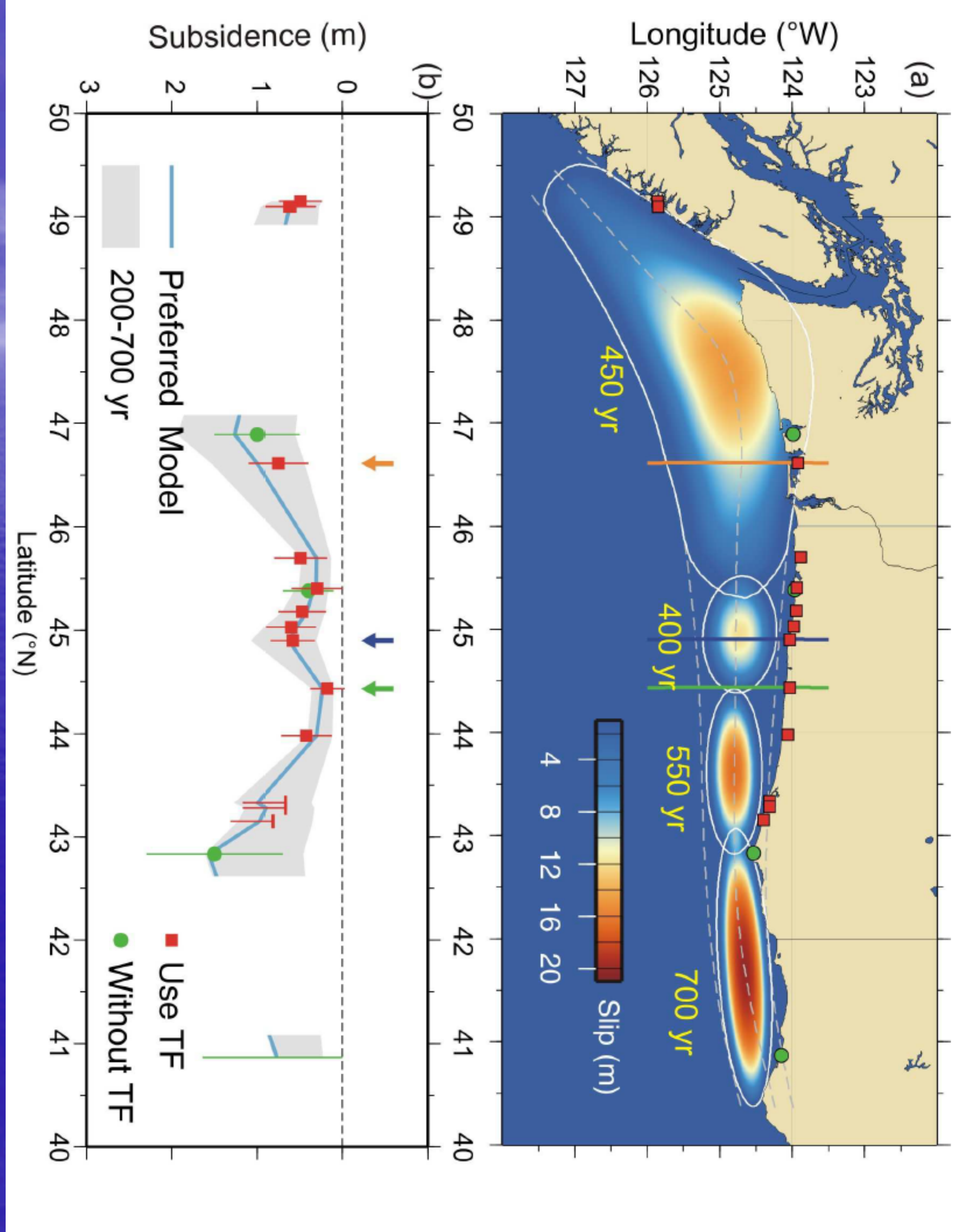
The Blanco Fracture Zone two rift propagators, and perhaps the keel of the Klamath Terrane/Siletzia boundary may serve as segment bounding structures.



USGS National Seismic Hazard Map Workshop, 2012

Evidence of a low slip, low coupling segment boundary in central Oregon is abundant from geodesy and structural geology, and this proposed slip model of the 1700 earthquake. Reasons for this boundary?????

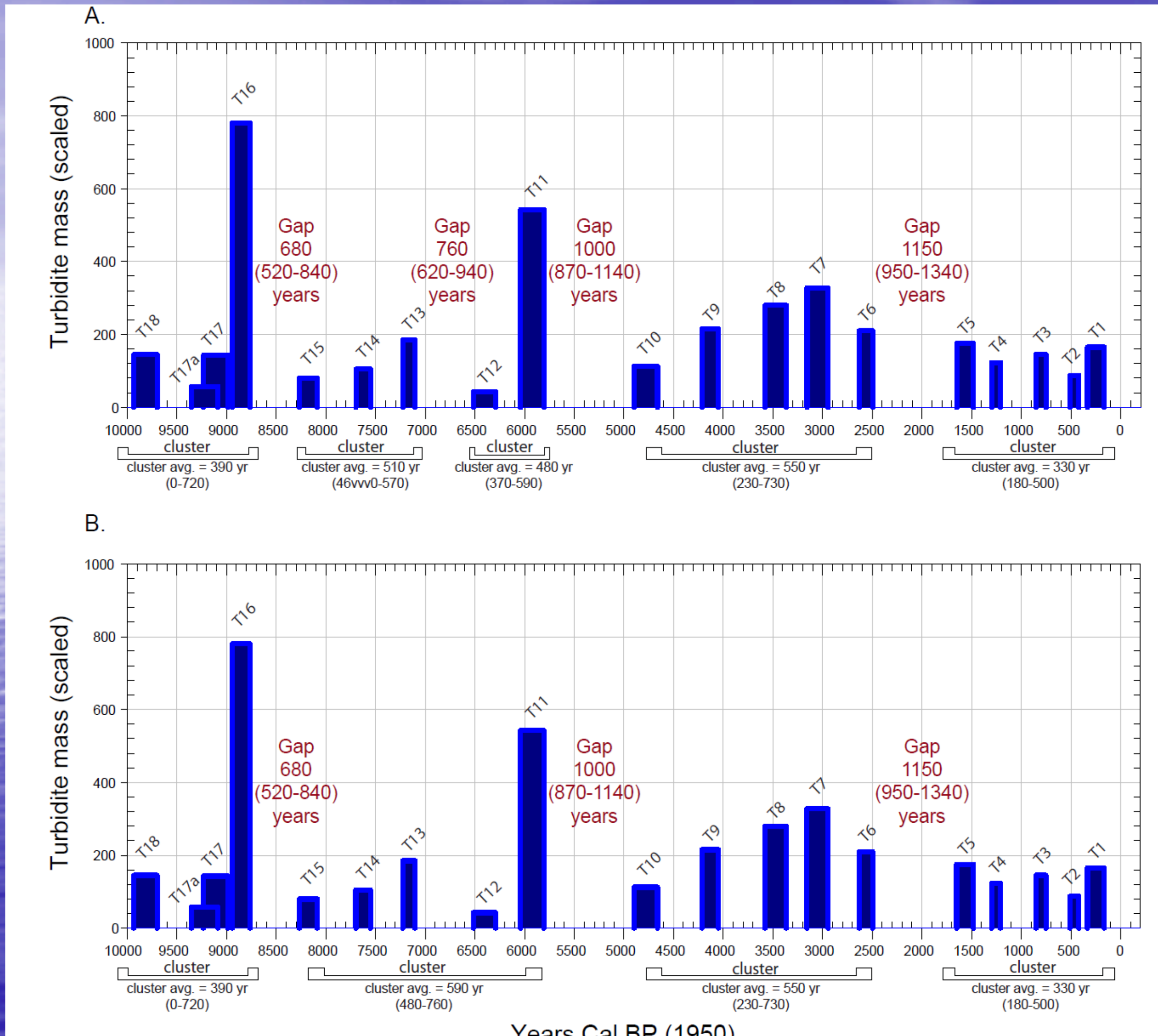
Courtesy of Pei-Ling Wang



Modeling Rupture in the 1700 Great Cascadia Earthquake Based on High Quality Paleoseismic Observations

Pei-Ling Wang1,2, Kelin Wang2, Andrea D. Hawkes3, Benjamin P. Horton4, Simon E. Engelhart4, Alan R Nelson5, Robert Witter6, Yuki Sawai7

AGU Fall meeting 2011.



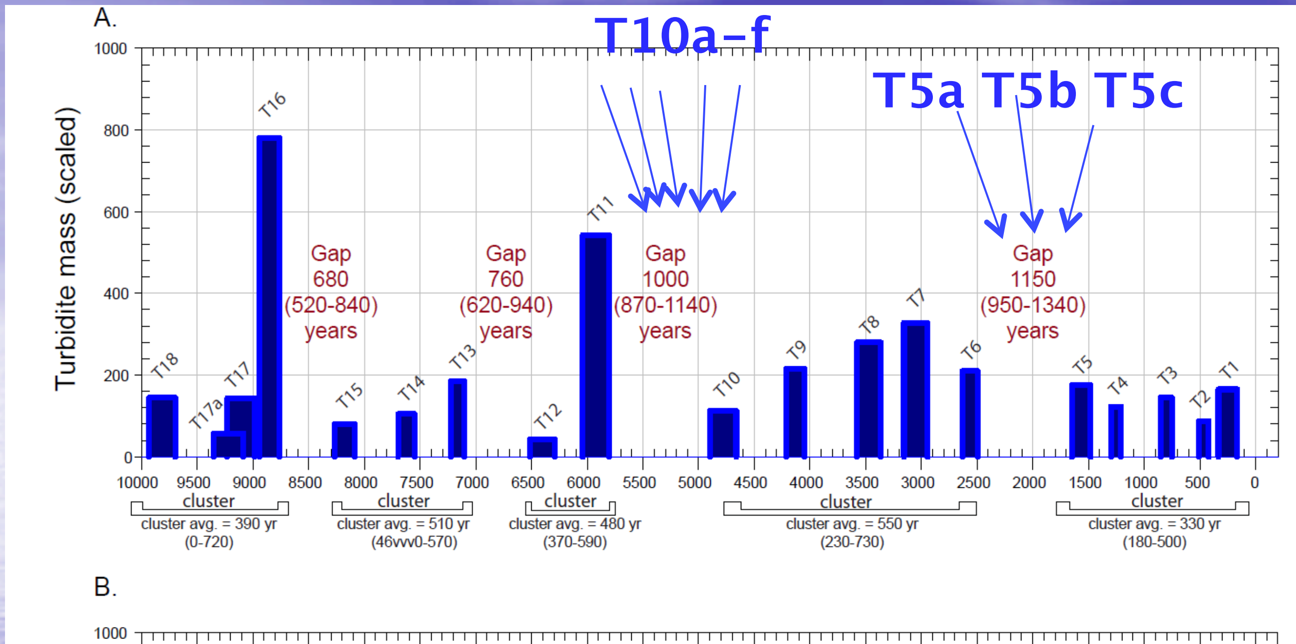
What about clustering?

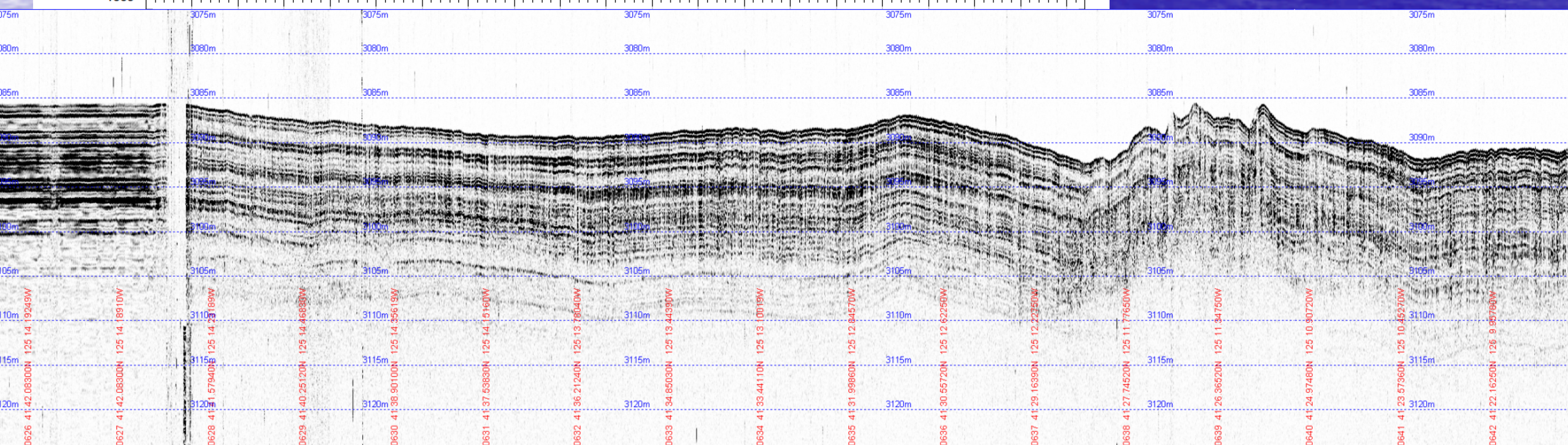
There seems to be a poorly developed clustering, suggested here.

It certainly makes a difference whether the next expected event is part of a cluster or not, if clusters exist, and if the next event reflects a repeat of recent behavior. Clustering seems better developed in the latter half of the Holocene. If a repeat were to occur, a gap may be next.

They exist, but

1) do they mean anything, and
2) what can be done about them probabilistically?



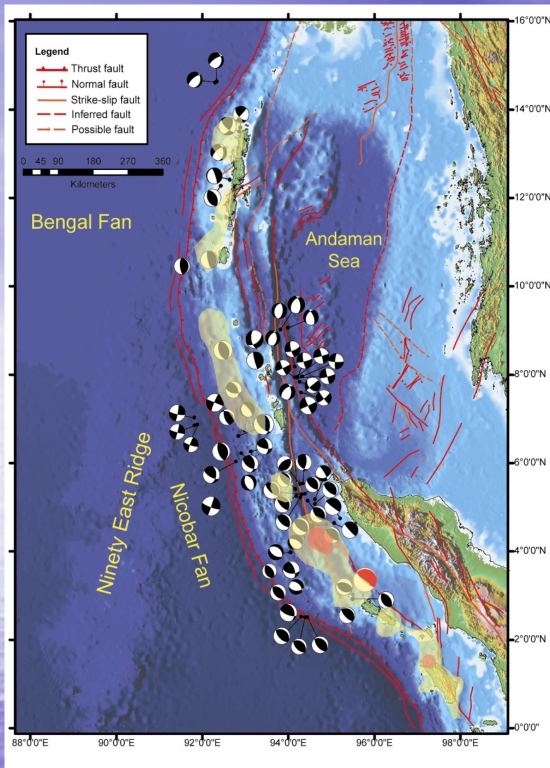


Along the southern margin, clusters do not exist in a temporal sense.

But, the larger events are clustered as in the north, with smaller events interspersed in the long gaps, so if one discounts the smaller events, then there remain "moment clusters"

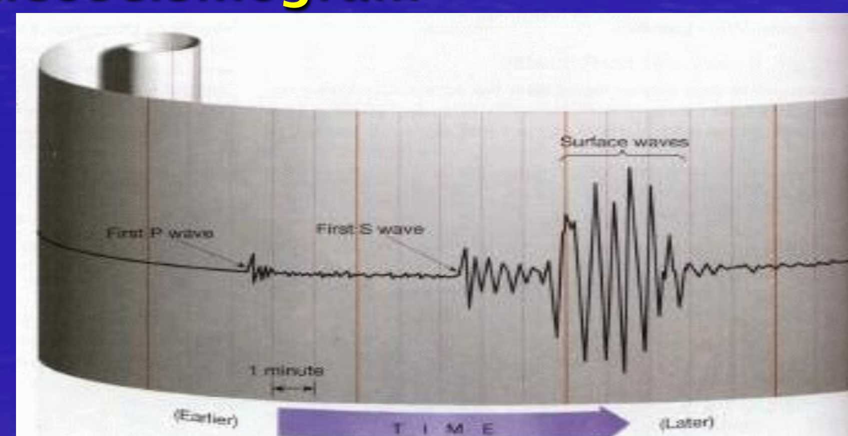
Earthquake clusters you can see!

But wait…Why do they correlate?



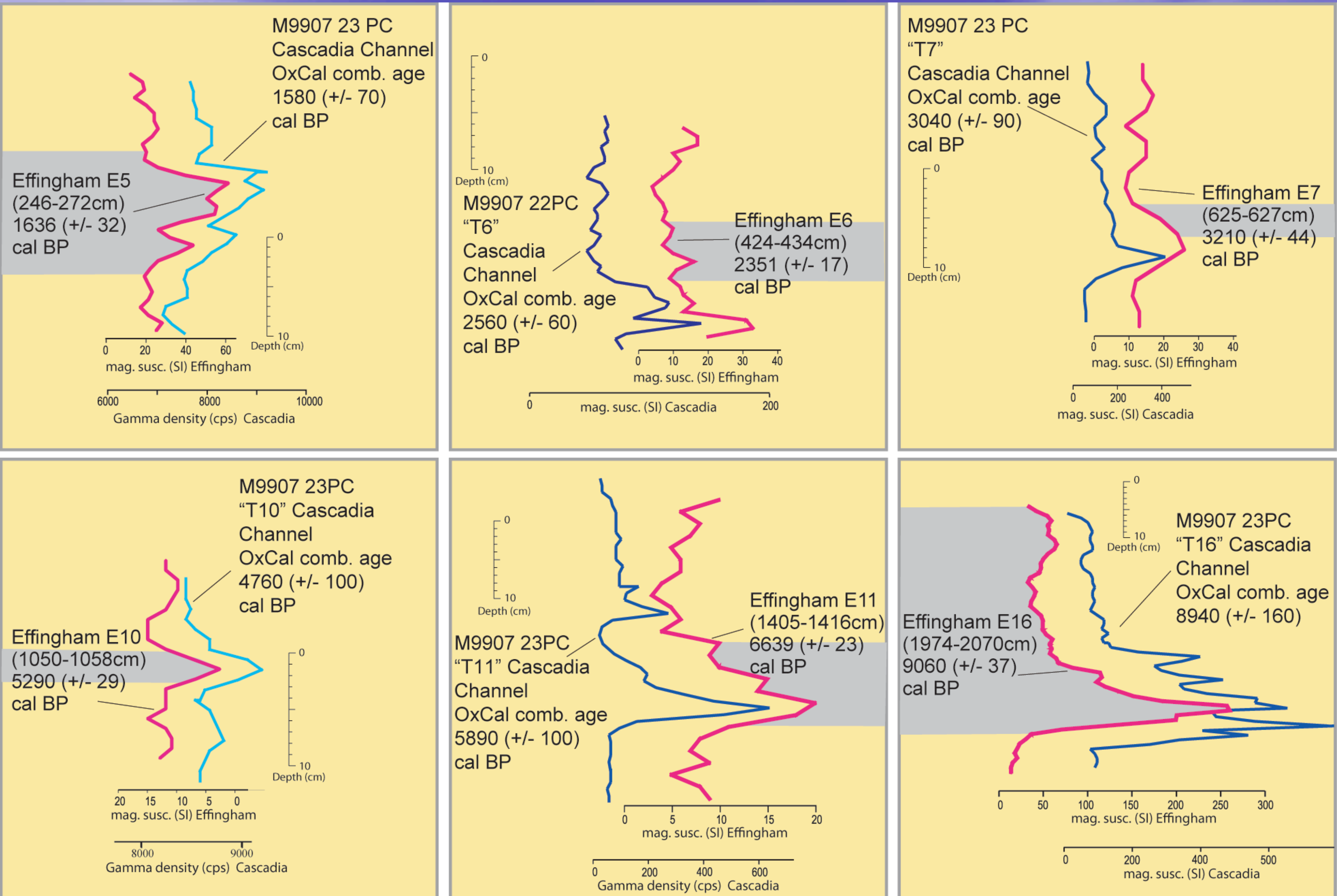
These channels have little in common above the confluences, so it doesn't seem reasonable to call upon geologic similarities to account for the correlation.

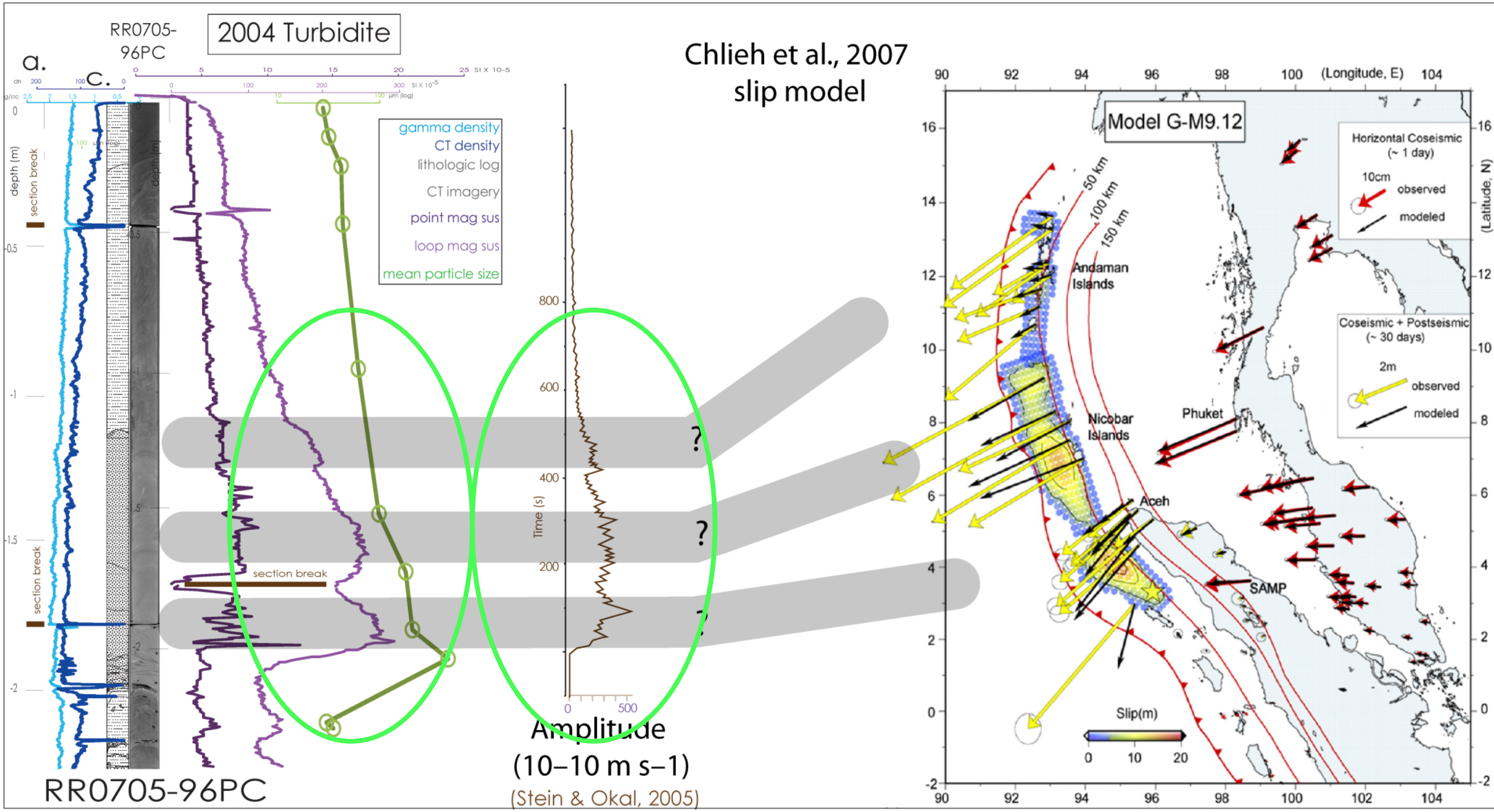
The only thing these signatures have in common is the earthquake. We suspect that the signatures represent unique energy signatures of the source mechanism, a "paleoseismogram"



This hypothesis predicts that a long multi-segment rupture like Sumatra, should produce a multipulse turbidite…. We think that this signal can overprint all the confounding factors like hydrodynamics, complex and retrogressive failures, and topography in the case of very large earthquakes. We also predict it will fail for smaller earthquakes

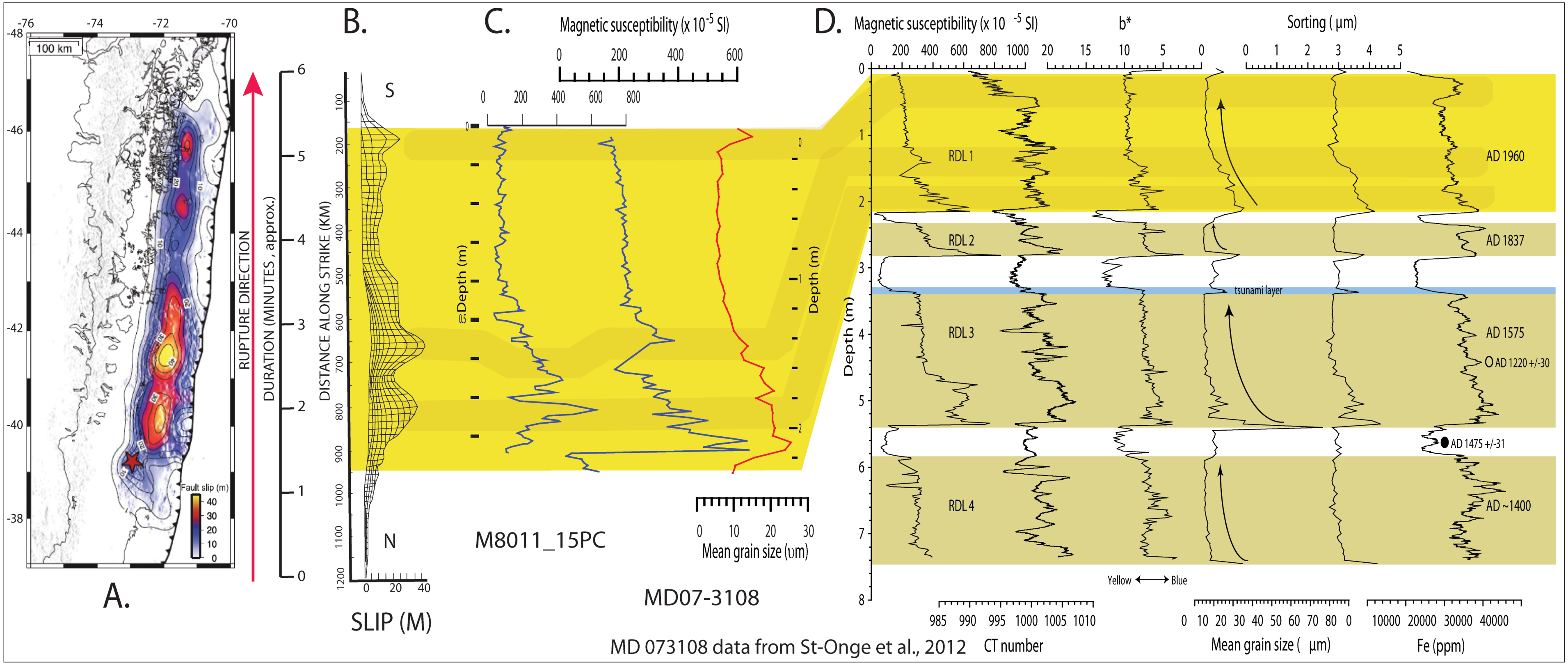
But wait…Why do they correlate? Effingham inlet vs. Cascadia Channel





The 2004 event in 96 PC/TC is well represented in 96PC as a 1.5-2m three pulse sandy event at the seafloor. Pb210 and Cs 137 confirm a very young age.

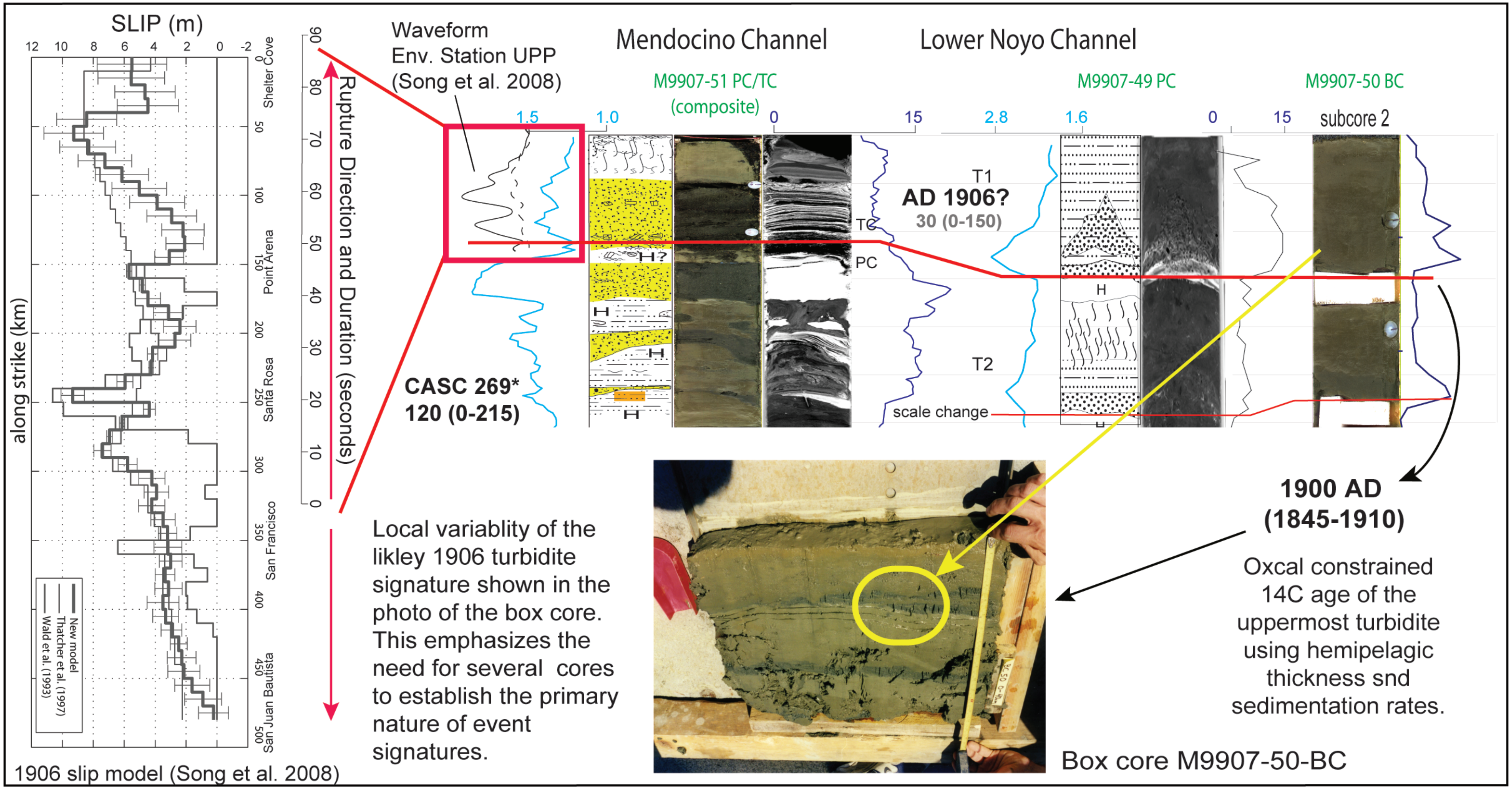
The three-pulse base is compared here to the time history of moment release (brown curve).



It gets better…

The 1960 Chile turbidite appears in numerous cores in the trench and in fjords as a two pulse sandy event at the seafloor. Pb210 and Cs 137 confirm the 1960 age.

The two-pulse base is compared here to the time history of moment release from Moreno et al (2009) and Barrientos and Ward (1990).

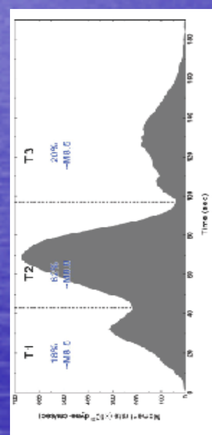


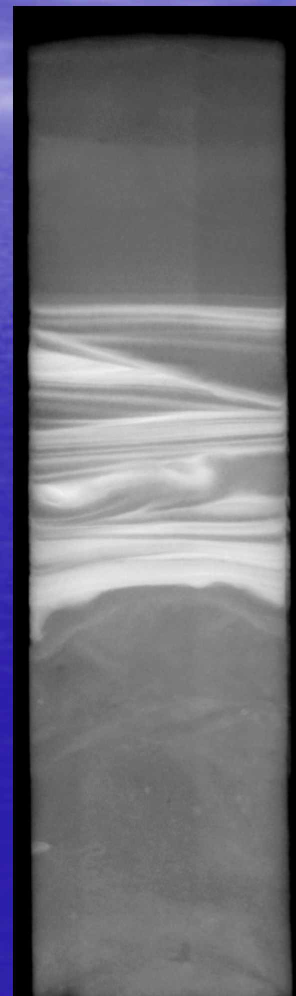
And better…

The 1906 San Francisco turbidite appears in numerous cores offshore as a two pulse sandy event at the seafloor. 14C and sed. rates confirm the 1906 age. The two-pulse base is compared here to the time history of moment release from Song et al (2008) and the UPP waveform envelope.

KT-11-17 ST.6

Moment rate plot from Lee et al, 2011

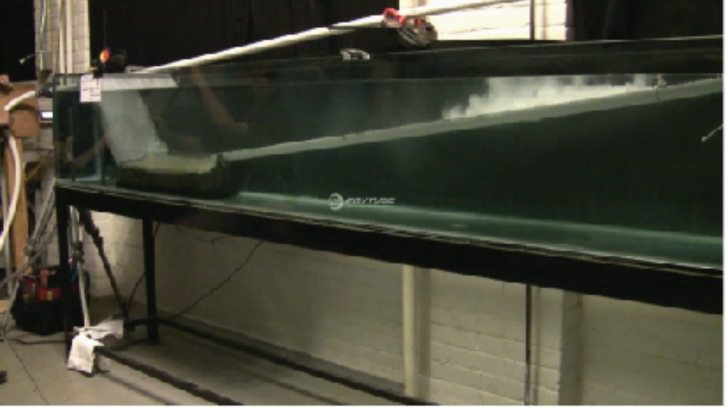


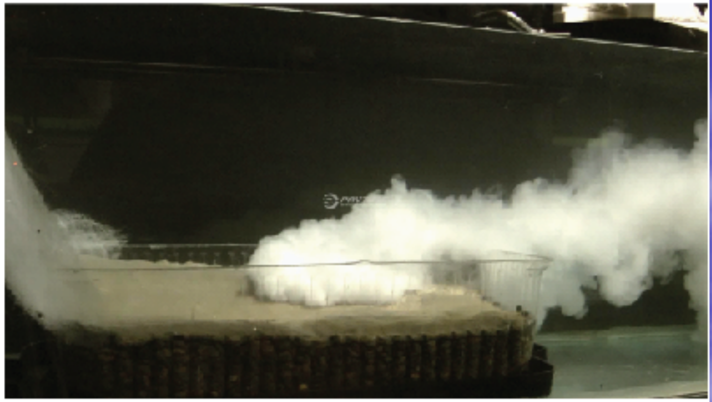


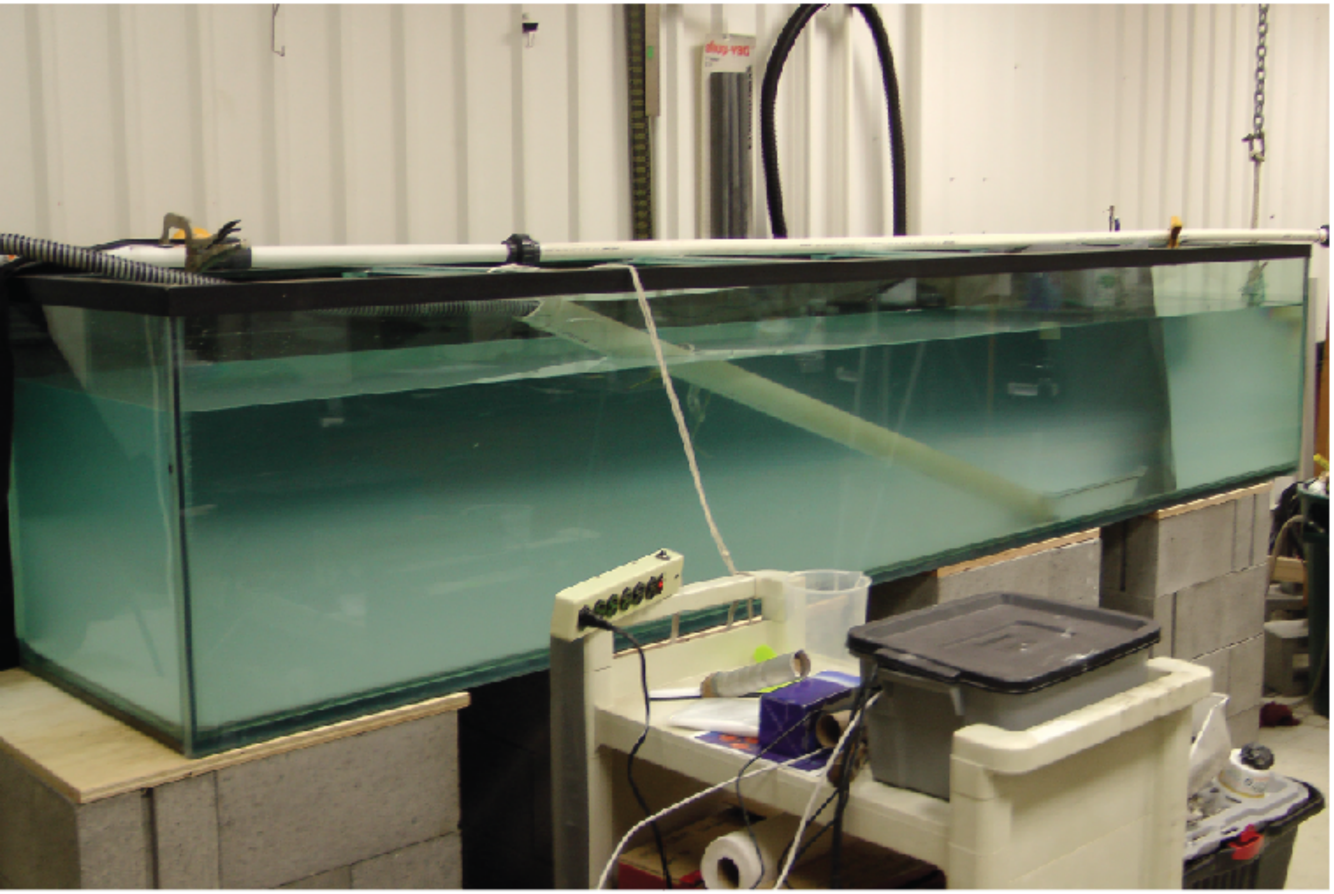
Tohoku 2011 turbidite

More cores in better locations (less proximal) are needed to evaluate the Tohoku moment rate vs. Turbidite structure.

Courtesy Of Ken Ikehara who should remain blameless!



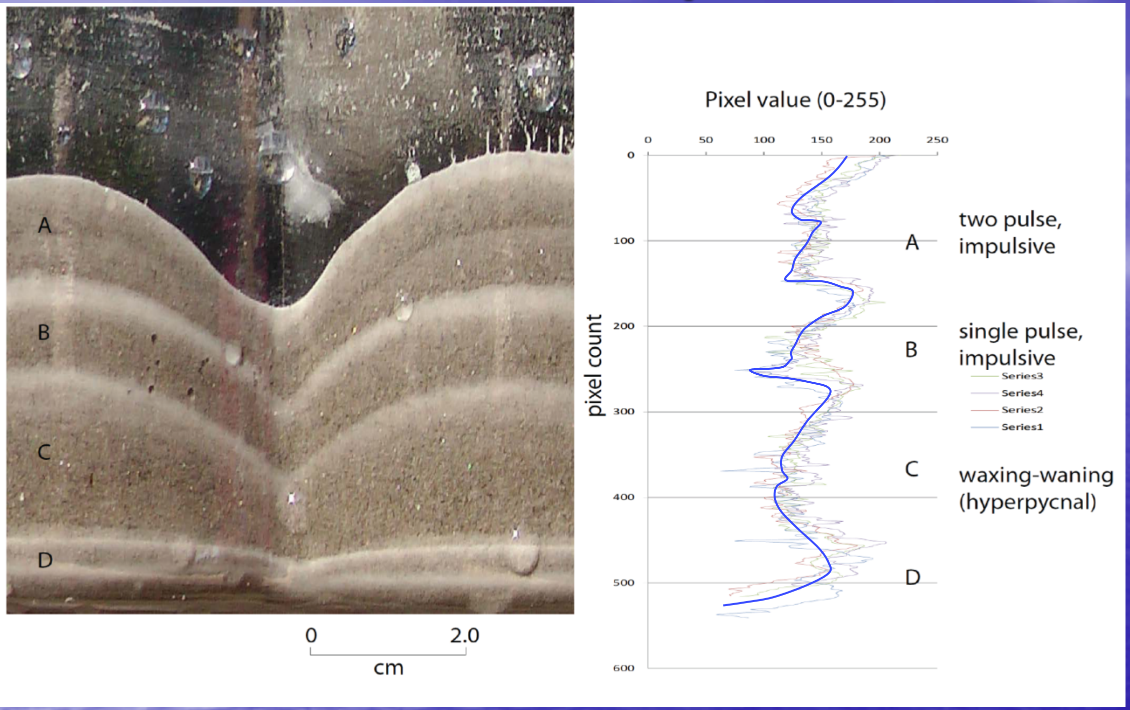


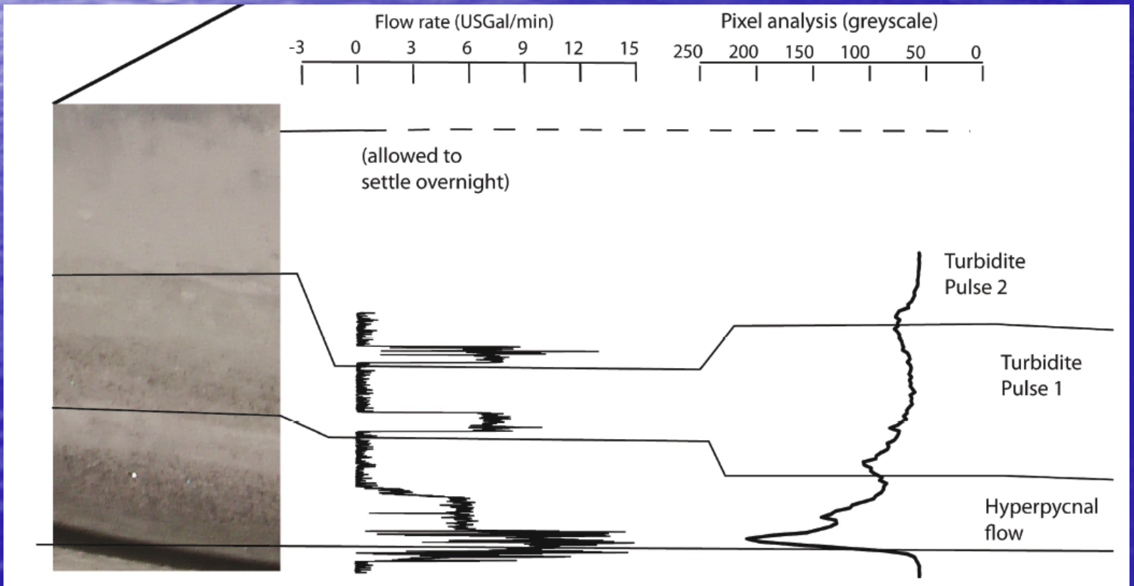


NEHRP supported flume experiments, in progress last 3 years.

Presented at AGU 2011, Garrett et al., 2011 (see our lab website), and NEHRP initial report

Testing recording of input sources in the sedimentary record.



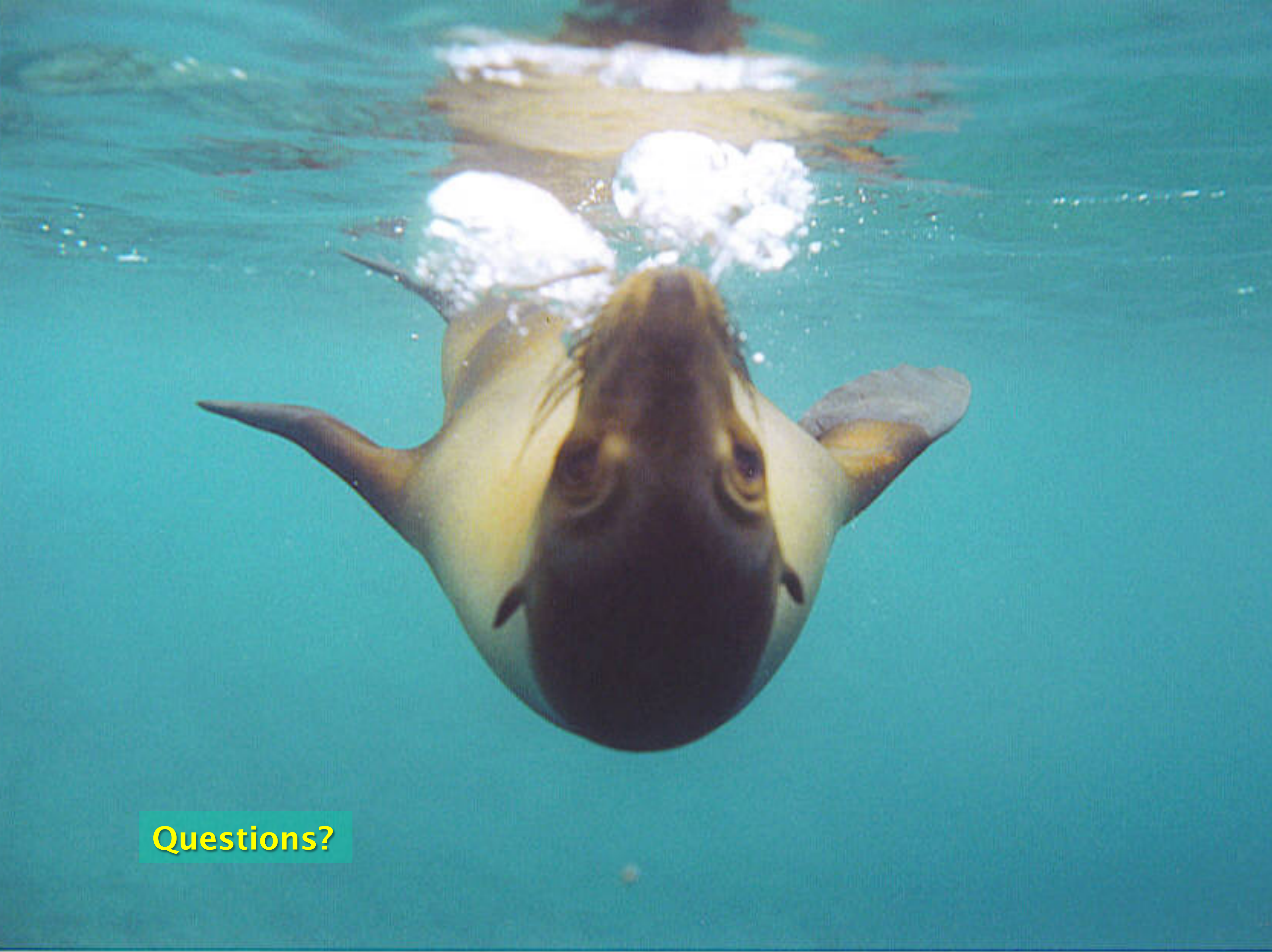


Theoretical and experimental analog results support the recording of input source heterogeneity by turbidite deposits.

Simulations include single and multipulse impulsive sources (earthquakes), and waxing and waning simulated hyperpycnal sources.

We vary all parameters, from slopes, to flow regime, to topography, to material and water density ratios. The results are essentially the same each time, the deposit reflects the flow hydrograph which overprints other secondary factors.

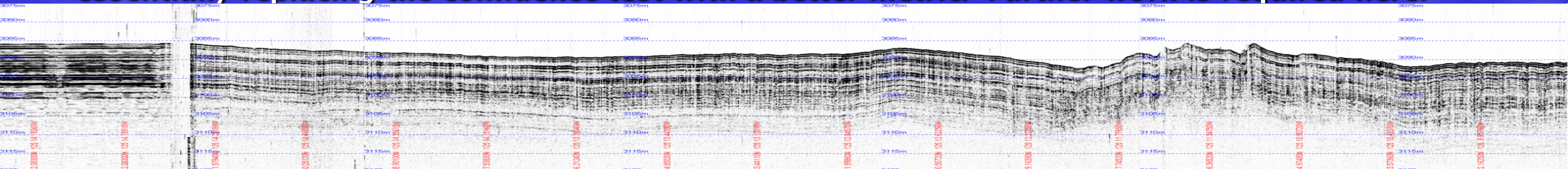

Thanks for your attention!


Questions?

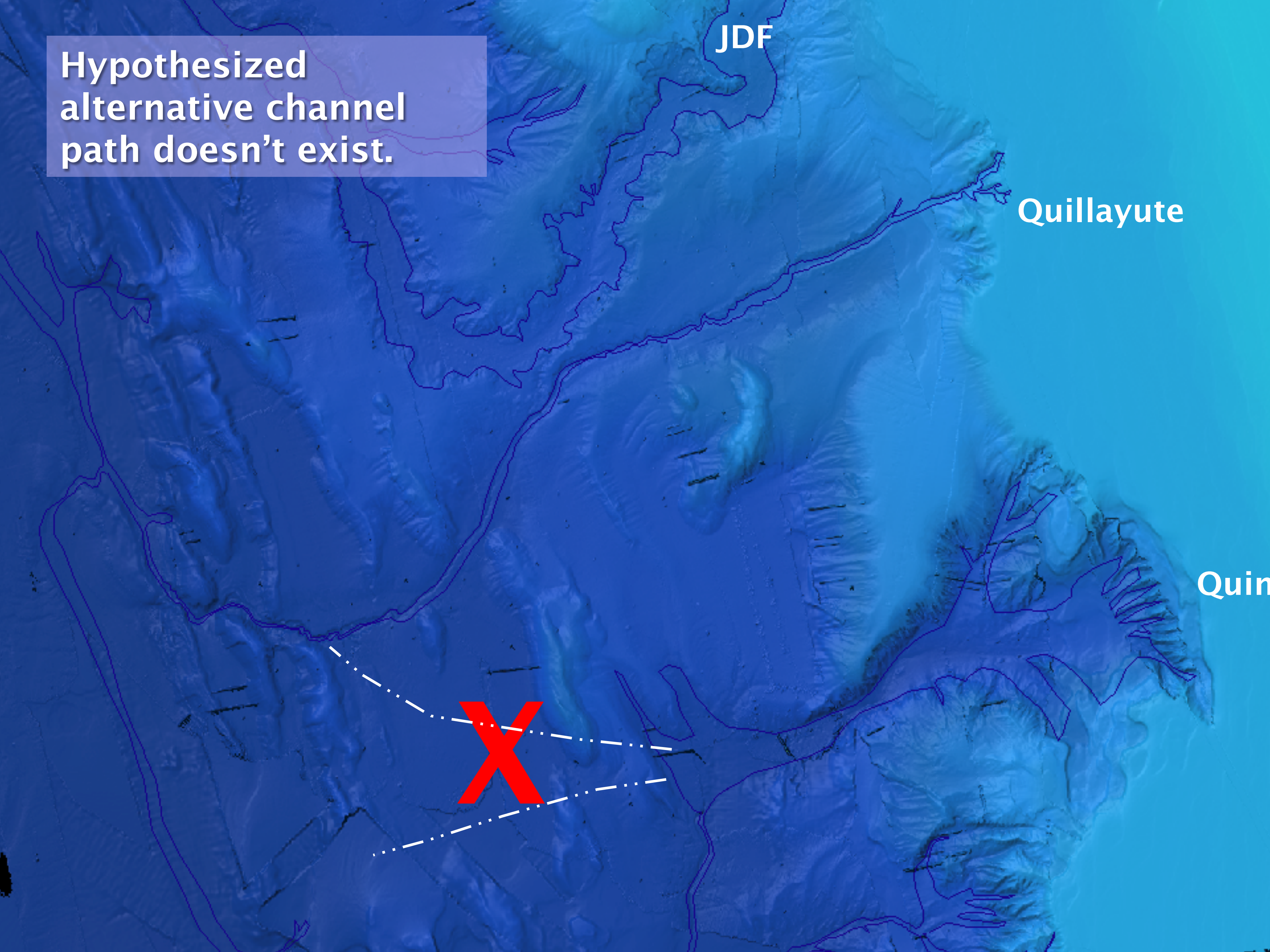
Response to Atwater Open File Report

Brain Atwater has written a handout and report criticizing our work in Professional Paper 1661f. Although Gary Griggs is listed as a co-author, he apparently only worked on one figure, and Atwater states that he is the sole author. The following slides respond to specific ideas suggested in Atwaters report.

- Atwater seems to believe that JDF turbidity currents died before they reached the confluence with Willapa channel, and are rather amazingly replaced by turbidites that flowed around a sharp corner and uphill from Willapa channel. There is actually no evidence that JDF turbidites died on the way to the confluence. Also there is no evidence for backfilling of JDF. Evidence of thinning is downstream is normal, and not evidence of attrition. Thickness changes and even non-deposition in some areas due to bypassing (hydraulic jumping) is not unusual particularly in channelized flows. Atwater suggests that flows from Willapa channel made a ~ 140 degree turn, and flowed uphill 50 km or more to settle out in mid JDF channel. This is unlikely because the levees at the confluence are 10's of meters tall, and are the only barrier that could cause such odd behavior, if it were even physically possible. However, the turbidity currents are known to have been 100's of meters high (Griggs, Nelson, and Duncan's work) so the flows would not be diverted by such a low barrier. New bathymetric data show a sediment wave field extending NW of the channel confluence, attesting to the overwashing of this small barrier and the flow stripping that results when part of a flow is constrained, but the upper part is not. Basic physics of momentum prevents the turbidity current from making such a sharp turn in any case.
- There is not a likely alternative pathway from Quinault Canyon to JDF. This was recently remapped using 2011 multibeam data (next slide) The pathway Atwater supposes from Barnard 1973 contour maps does not exist, and is blocked by an anticline that turns Quinault channel southward. Quillayute channel, on the other hand, does intersect JDF channel, but it's source is similar to that of JDF.
- Recent high resolution 3.5 kHz chirp data show that the abyssal plain turbidites in proximal areas are ubiquitous. Apparently they are delivered both as channelized flows and as sheet flows simultaneously. This complicates the confluence test, but the data also show very little variability, essentially replacing the confluence test with a better metric. Further work is required here!

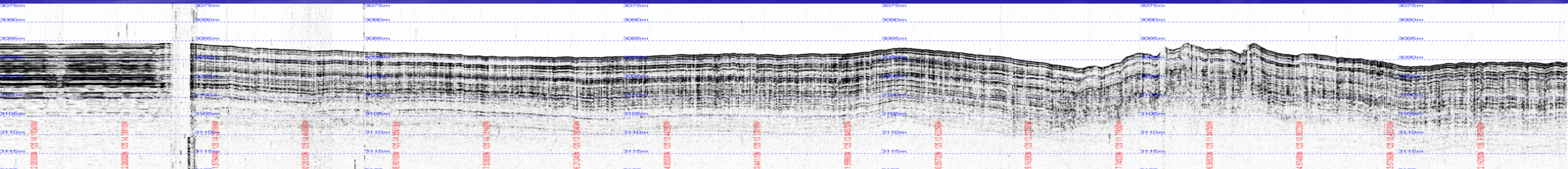


Hypothesized alternative channel path doesn’t exist.

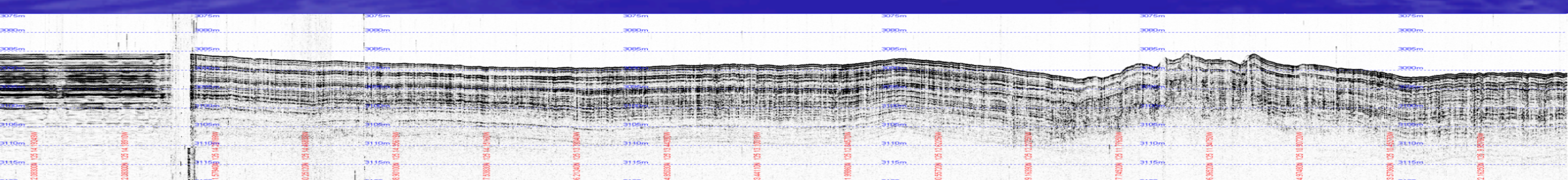


- Complex turbidites are cited as potential evidence of additional events on the northern margin. This possibility always exists, however it's not evidence. Geologic variability is always present, we do not always know the reasons. But the vast majority of the evidence supports multi-pulse single turbidites.
- There is little if any problem with the 13 count of turbidites above the Mazama ash. We do not report that JDF core 05 PC has this count, erroneously stated in Atwaters report. There is no evidence for a "revised count" as hypothesized, though certainty is unobtainable with existing data.
- Brian's several scenarios based on timing rest in part on a misunderstanding of the turbidite sources. Comparing travel times is more complicated than measuring the length of a channel and using a speed estimate. Currents are not solely sourced at the canyon head, rather the entire channel system is a line source, or an amalgamation of line sources. Timing is just not simple at all. We can't do it and we've been thinking about this for ~ 10 years. This is why there are no travel time models in the Professional Paper. What is needed is a much more sophisticated flow model that considers bathymetry, flow paths, ground shaking etc. Stay tuned…
- Geophysical correlation. This report builds on the above mistatements and misinterpretation of counts and flowpaths to say that "one channel feeds the other" to explain the excellent geophysical correlation. This is not the case, for the reasons outlined above, so the alternative proposed by Atwater is unlikely at best.
- There are some people who seem to believe that e-log correlation is questionable. While all geologic interpretation is questionable, this discipline is the basis for virtually all oil exploration. To say it doesn't work is ludicrous. Unfortunately, casual cut and pasting of hard copy images of data is not adequate to evaluate correlations of core logs. Using the actual data is required, as is using modern flattening techniques that are the staple of the oil industry. The data are available for the asking and are on our website for all to use. It's also best practice to incorporate all of the supporting data simultaneously. No one technique, whether it is geophysical logs, radiocarbon data, confluence tests etc. is likely to be the smoking gun. The correlations are variable in quality, ranging from so-so to remarkably good, but they do not stand alone. See Bayesian model.

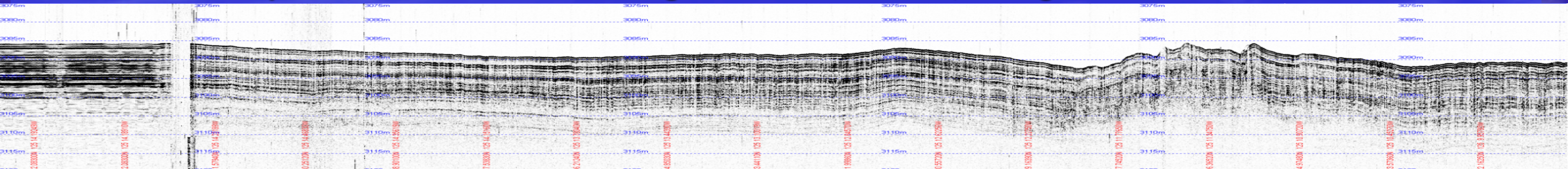
- "Paleoseismograms". There can be no doubt that there are many reasons that a primary seismic shaking signal might be shredded by transport and deposition processes. We proposed this model to explain the data, because the correlations are so simple to do that we use them in classroom exercises. In all we do, we use Bayesian methods to test a hypothesis given the data, not the other way around. Presently there is no working hypothesis that can explain this phenomenon other than seismic shaking. Arguing that it doesn't exist because there are many things that could make it fail is not science. The remarkable consistency, and evidence from Chile, Sumatra and San Francisco suggest that this hypothesis is one that holds promise in the case of the largest earthquakes. It's also a phenomenon that is predicted by theory and experiment. Kneller and McCaffrey predict this behavior in theory 2003 paper, showing that longitudinal structure of a turbid flow should be present in the final deposit, and also that this effect is not competing with hydrodynamics at all, but rather adding a time component not present otherwise. We have a two papers in prep for Tectonophysics on this topic, one on experimental work and the other on field evidence from Chile, San Francisco, and Sumatra. We have been conducting flume experiments for the past three years with NEHRP support to test this hypothesis. The experimental work so far bears out the hypothesis and the Kneller and McCaffrey (2003) prediction. The initial report on this is available on the NEHRP website and at this link:
- http://activetectonics.coas.oregonstate.edu/paper_files/NEHRPexperiment2007final_full.pdf
- Goldfinger, C., 2011, *Possible turbidite record of earthquake source characteristics: a small scale test*, NEHRP Annual Report, Volume 34: Reston, VA, U.S. Geological Survey, p. 18.



- Radiocarbon ages. Brian incorrectly states that the methods do not include error propagation for the age averages, this is not correct, they are fully incorporated. Further, the best ages are provided as OxCal “combines” of the same data. All Oxcal combines pass the X2 and A comb test of synchroneity (at the resolution of 14C of course). Arbitrary doubling of errors is not justified for eroded intervals. Erosion is carefully anlyzed at each site with multiple cores, and analyzed for Cascadia Channel in particular by comparing total hemipelagic thickness inside and outside of the channel. The erosion analysis and corrections bring the totals very close, indicating that large amounts of material are not missing due to erosion.
- The report states that “very little is known about the rates of deposition in lower Cascadia Channel” Actually those rates are the best known, with large numbers of older cores in the area, and shown in PP 1661-F figure 48, and in Table 5. The uncertainly there is quite small. Increasing the error ranges is therefore not justified.
- Coring disturbances can and do cause variability in estimates of thickness of anything in the cores, including hemipelagic. However we have tried to carefully avoid disturbed units in our cores whenever possible, and use CT data so we can have a 3D veiw of core disturbances and their structure.
- Serial ruptures. Brian states that the expectation that there should be serial ruptures “trumps the evidence” against them. Actually there is virtually no evidence for them, or any “expectation” (whatever that is) in Cascadia. We have assessed the hypotheses given the evidence, nothing more. We have not yet found much evidence pointing to serial ruptures, but it may well be there and it wouldn’t be that surprising. The probability of this hypothesis, given the data as we have it today, is very low. However, that could change in the future.



- We agree that the Bradley evidence for one case of serial rupture may be real. We have evidence from offshore and now from lakes that support that interpretation. T16 may also be a serial rupture, more work is needed. So far, that's all we can see, but again, this could change with new evidence. Otherwise, the strong lithostratigraphic support a high probability of 19 (of 43) long ruptures.
- Mud turbidites offshore are not consistent with storms or dam breaching, they are present at Hydrate Ridge, which is completely isolated from onshore sediment sources. Evidence from microfossils at Rogue Canyon shows that the source of the se turbidites is from the mid slope as they are rich in deep water sponge spicules, and very low in organics, indicating a mid slope submarine source. The mud turbidites also do not have the sedimentological content or structure of such flows. They have sharp bases and ubiquitous fining upward sequences. While hyperpycnal flows are not required to have inverse grading, they often do, and this is not observed.
- The separation of T2 into two events is possible, but not our preferred interpretation given the strat correlation, strong radiocarbon series and hemipelagic estimates of time intervals. Bioturbation is not a valid indicator of time, but it's not needed in any case due to good radiocarbon.
- Despite an abundance of literature, and long discourse on this subject in Professional Paper 1661f, the Atwater report ignores decades of literature to state, yet again, that bioturbation is a useful indicator of time. It's just not so. Much of the literature is cited in 1661. We commonly observe individual *Zoophycus* burrows sweeping through meters of the same core. If it worked, we'd be using it. Griggs, who Atwater cites, does not believe it anymore either.
- Energy cycling. The report relates old concepts that relate years of plate convergence to the size of the earthquake, combined with timing from bioturbation, to argue for an alternative scenario



- Atwater suggest to the author group of 1661f that we should work with more sedimentologists. Our advice to Atwater is to please check out the people in the author list, many of them are career sedimentologists, and are highly offended by such cavalier comments. Atwater on the other hand, has no qualifications at all in marine geology, sedimentology, core log correlation or most of the other subdisciplines used in Professional paper 1661f.