Cascadia Great Earthquakes from Paleoseismic data: A Progress Report on Marine, Lacustrine and Onshore Evidence: Moving Toward Paleo-Slip Models

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Turbidite systems located along the continental margin of Cascadia Basin from Vancouver Island, Canada to Cape Mendocino, California, USA have been investigated with swath bathymetry, newly collected and archive piston, gravity, kasten, and box cores, subsurface geophysics, and accelerator mass spectrometry (AMS) radiocarbon dates. The Cascadia Basin is an ideal place to record a long-term earthquake history because: (A) a single subduction zone fault underlies the Cascadia submarine canyon systems; (B) multiple tributary canyons and a variety of turbidite systems and sedimentary sources exist to use in tests of synchronous turbidite triggering; (C) the Cascadia trench is completely sediment filled, allowing channel systems to trend seaward across the abyssal plain rather than merging in the trench; (D) the continental shelf is wide, favoring disconnection of Holocene river systems from their largely Pleistocene canyons; and (E) excellent stratigraphic datums, including the Mazama ash and distinguishable sedimentoligical and faunal changes near the Holocene-Pleistocene boundary are present for correlation of events and anchoring the temporal framework.

Multiple tributary channels with 50-150 km spacing and a wide variety of turbidite systems with different sedimentary sources contain 13 significant post-Mazama turbidites in Cascadia Channel, Juan de Fuca Channel off Washington, Hydrate Ridge slope basin, and Astoria Fan off northern and central Oregon. All of these events are also recorded on Rogue Apron of southern Oregon, with the addition of 23 smaller local events recorded as silt or mud turbidites which appear in the record at all sites from central Oregon southward. 19 significant turbidites are found from Vancouver Island to Northern California, representing10 ka of deposition. In central and southern Cascadia, the thinner mud turbidites observed at Rogue are apparent at all sites with very similar stratigraphy.

We use radiocarbon ages, relative dating tests, and litho-stratigraphic correlation of turbidites to test whether turbidites deposited in separate channel systems are likely correlative, that is, they resulted from a common event. These tests can, in most cases, separate earthquake triggered turbidity currents from other possible sources. The 10 ka turbidite record along the Cascadia margin passes several tests for synchronous triggering, and correlates well with the shorter onshore paleoseismic record at numerous coastal site for the periods of temporal overlap. The synchroneity of a 10,000 year turbidite event record for at least 790 km along the Cascadia subduction zone is best explained by paleoseismic triggering by great earthquakes. Examination of the applicability of other regional triggers such as storm waves and tele-tsunami specifically for the Cascadia margin suggest these potential triggering mechanisms are unlikely in most cases, with the possible exception of the Eel and Trinidad Canyon systems of southernmost Cascadia.

The average age of the oldest turbidite emplacement event in the 0-10 ka series is 9,800 ±~200 cal yr B.P. and the youngest is A.D. 1700, (250 cal. B.P.) thus the northern events define a great earthquake recurrence of ~500-530 years. The recurrence times and averages are also supported by the thickness of hemipelagic sediment deposited between turbidite beds. The southern Oregon and northern California margins represent at least three

segments that include all of the northern ruptures, as well as ~23 thinner turbidites of restricted latitude range that are correlated between multiple sites. Though interpretation of the mud turbidites at Rogue Apron is inhibited by bioturbation and lower response to analytical and imaging techniques, most of the 23 beds nonetheless exhibit sharp bases, fining upward sequences, are typically darker in color, have higher gamma and CT density, and have magnetic susceptibility excursions that mirror the density trends. Sample transects across representative beds reveal that in comparison to adjacent hemipelagic sediment, the 23 mud turbidites show increases in lithic fragment content and grain size, have reduced biogenic content and few fragile planktonic microfossils. Abundant shallow water sponge spicules are present, supporting transport from shallow water.

High-resolution Chirp seismic profiles reveal that turbidite stratigraphy along the base of the southern Cascadia continental slope is continuous, with little variation for several hundred kilometers along strike. The main turbidite beds are imaged in the CHIRP data, which has a resolution of ~ 18-20 cm. The thin mud turbidites cannot be imaged directly, however the accommodation spaces they fill maintains their consistency along strike, providing independent, though circumstantial evidence of stratigraphic continuity. Regional stratigraphy reveals that hemipelagic sedimentation rates and turbidite thickness and mass are similar at widely separated sites, yet the total thickness of the Holocene section is greater by a factor of two in southern Cascadia. This difference is primarily due to the presence of the 23 mud turbidites. Southward from Rogue Apron, the mud turbidites increase in thickness and grain size. In new cores near Trinidad Canyon, the stratigraphy, physical property correlation, and age control suggest that the stratigraphic sequence is nearly identical to that of Rogue Apron, with most of the thin mud turbidites reaching sandy or silty basal grain size. At least two northern California sites, Trinidad and Eel Canyon/pools, also record additional turbidites which may be a mix of earthquake and sedimentologically or storm triggered, events particularly during the early Holocene when a close connection existed between these canyons and associated river systems.

New evidence from inland lakes, including Triangle, Bolan, Sanger and Upper Squaw lakes strongly suggest that these coast range and Siskiyou mountain lakes also contain a turbidite paleoseismic record much like the record in Lake Washington near Seattle. Turbidites in these lakes, long attributed to forest fires, have a temporal sequence indistinguishable from the onshore-offshore paleoseismic record. Preliminary analysis suggests high fidelity recording of both the full margin earthquakes, as well as at least some of the segmented southern ruptures. Geophysical log correlation with the offshore cores shows a sometimes remarkable correspondence, supporting a common origin for the lake turbidites.

The combined stratigraphic correlations, hemipelagic analysis, and radiocarbon framework suggest that the Cascadia margin effectively has three rupture modes: 19-20 full or nearly full-length ruptures; three or four ruptures comprising the southern 50-70 percent of the margin, and 18-20 smaller southern margin ruptures during the last 10 ka, with the possibility of additional southern margin events that are presently uncorrelated. The shorter rupture extents and thinner turbidites of the southern margin correspond well with spatial extents interpreted from the onshore paleoseismic record, supporting margin segmentation of southern Cascadia. The sequence of 41 events defines an average recurrence period for the southern Cascadia margin of ~240 years over the last 10 ka. Time-independent probabilities for segmented ruptures range from 7-12 percent in 50 years for full or nearly full margin ruptures, to ~21 percent in 50 years for a southern segment rupture. Time dependent probabilities are similar for northern margins events at ~7-12 percent, and 37-42 percent in 50 years for the southern margin. Failure analysis suggests that by the year 2060, Cascadia will have exceeded ~27 percent of Holocene recurrence intervals for the northern margin, and85 percent of recurrence intervals for the southern margin.

The long earthquake record established in Cascadia allows tests of recurrence models rarely possible elsewhere. Turbidite mass per event along the Cascadia margin reveals a consistent record for many of the Cascadia turbidites. We infer that larger turbidites likely represent larger earthquakes. Mass per event and magnitude estimates correlate weakly with following time intervals for each event, suggesting that Cascadia full or nearly full margin ruptures may weakly fit a time-predictable model. The long paleoseismic record also suggests a pattern of clustered earthquakes that includes four or five cycles of two to five earthquakes over the last 10 ka, separated by unusually long intervals.

We suggest that the pattern of long time intervals and longer ruptures for those including the northern and central margin may be a function of high sediment supply on the incoming plate smoothing asperities and

potential barriers. The smaller southern Cascadia segments correspond to thinner incoming sediment supply and potentially greater interaction between lower plate and upper plate heterogeneities.

Comment on Atwater handout by the authors of Professional Paper 1661f:

Brian Atwater has written a handout and report criticizing our work in USGS Professional Paper 1661f (The paper is available online at http://pubs.usgs.gov/pp/pp1661f/. The following response isto specific points in Atwaters handout. Please see the powerpoint presentation for more detailed comments.

1) Atwater states that JDF turbidity currents died before they reached the confluence with Willapa channel, and are replaced by and identical sequence of turbidites that flowed around a sharp corner and uphill from Willapa channel. 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, while the turbidity currents are known to have been 100's of meters high (Griggs, Nelson, and Duncan's work). The flows would not be diverted by such a low barrier, but basic physics of momentum prevents the turbidity current from making such a sharp turn in any case.

2) Atwater used a very old paper, Barnard (1973), to suppose that there is an alternative pathway from Quinault Canyon to JDF that somehow negates the confluence test of synchoneity. This was recently remapped using 2011 multibeam data, and the pathway Atwater supposes from 1973 contour maps does not exist.

3) Complex turbidites are cited as potential evidence of additional turbidites on the northern margin, and possible additional earthquakes as well. This is surprising since Atwater first argues that the earthquake origin tests are invalid, then argues for more earthquakes with the same data. This possibility always exists, however it's not evidence. Geologic variability is always present, we do not always know the reasons. The evidence supports multi-pulse single turbidites.

4) 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 handout. There is no evidence for a "revised count" as hypothesized, though absolute certainty is never unobtainable.

5) Atwater'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 anamalgamated line source and speeds are not constant. The handout 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 (a technique which Atwater argues elsewhere doesn't work). Given the evidence, the alternative proposed by Atwater is unlikely at best.

6) Geophysical correlation.Atwater states that e-log correlation is questionable, though he has no expertise or expertise in this field. While all geologic interpretation is questionable, this discipline is the basis for virtually all oil exploration, and practiced daily by thousands of industry geologists and geotechnical analysts. Cut and pasting of hard copy images of data (as in the Atwater handout) 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 online, but were not used by Atwater. Its also best practice to incorporate all of the supporting data simultaneously to develop a lithostratigraphic and geophysical framework. 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 for each bed, ranging from so-so to remarkably good, but they do not stand alone. The conclusions in Professional Paper 1661f do not rest on any single dataset, but in the stratigraphic and temporal framework established by several lines of evidence, including the onshore paleoseismic record.