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# Variability of Recurrence of Cascadia Great Earthquakes Based on Precise Dating of the Turbidite Event Record.

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## Annual Report

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**PI's:**

Chris Goldfinger
*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331; email: gold@coas.oregonstate.edu*

C. Hans Nelson

*Now at Instituto Andaluz de Ciencias de la Tierra,CSIC,Universidad de Granada,Campus de Fuente Nueva s/n,Granada,18071*

Graduate Student: Joel E. Johnson
*College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331; email: jjohnson@coas.oregonstate.edu*

We have been investigating the recurrence pattern of Great Earthquakes along the Cascadia margin using the record of turbidites deposited after margin-wide shaking during great earthquakes.

Concurrent with the discovery of the first buried marsh sequences on land, Adams, (1985; 1990) assessed the possibility that turbidites in channels of Cascadia Basin contained a record of great earthquakes along the Cascadia margin. He examined core logs for the Cascadia Basin channels, and determined that many of them had between 13 and 19 turbidites overlying the Mazama ash datum. In particular, he found that three cores along the length of Cascadia channel contain 13 turbidites and argued that these 13 turbidites correlate along the channel (as did Griggs and Kulm, 1970). Adams observed that cores from Juan de Fuca Canyon, and below the confluence of Willapa, Grays, and Quinault Canyons, contain 14-16 turbidites above the Mazama ash. The correlative turbidites in Cascadia channel lie downstream of the confluence of these channels. If these events had been independently triggered events with more than a few hours separation in time, the channels below the confluence should contain from 26-31 turbidites, not 13 as observed. The importance of this simple observation is that it demonstrates synchronous triggering of turbidite events in channel tributaries, the headwaters of which are separated by 50-150 km. Similar inferences about regionally triggered synchronous turbidites in separate channels are reported in Pilkey (1988). The extra turbidites in the upstream channels may be the result of smaller events. This synchronicity test is a powerful relative dating technique that is completely independent of radiocarbon dating, which rarely has the precision to correlate events.

Funded under this grant, in July, 1999, we collected 44 (4" diam.) piston cores, 44 companion trigger cores (also 4") and eight 30 cm box cores in every major canyon/channel system from the northern limit of the Cascadia subduction zone near the Nootka fault, to Cape Mendocino at its southern terminus (Goldfinger et al., 1999, 2003; Nelson and Goldfinger, 1999). Cores were run through the MST scanner as whole rounds to collect density, velocity, and magnetic susceptibility data, then split, photographed and described on board.

We find that thirteen post-Mazama events are found along 600 km of the margin in the Cascadia, Willapa, Grays, Astoria, Juan de Fuca, and Rogue Canyon/Channel systems (Nelson et al., 2004). Though the Holocene-Pleistocene boundary is a bit less certain as a datum, these same channels also have 18 post-datum events, extending this record to ~ 10,000 years. In previously existing cores, we found only 3 post-Mazama events in middle and lower Astoria Channel, which appeared to contradict Adams (1990) hypothesis for 13 events. In 1999 cores, we find a progressive loss of turbidites from 13 to 10 to 7 to 6 to 5 events at each successive downstream channel splay in the distributary upper Astoria Fan. This down-channel loss of events resulting in only 3 events in the mid-lower Astoria Channel explains the previous contradiction, and shows that the post-Mazama turbidite record is consistent along the margin.

**Mechanisms for Triggering of Turbid Flows**

Adams (1990) made a convincing case for synchroneity of Cascadia margin events. But are these events all triggered by earthquakes? Adams suggested four plausible mechanisms for turbid flow generation: 1) storm wave loading; 2) great earthquakes; 3) tsunamis; and 4) sediment loading. To these we add 5) nearby crustal earthquakes, 6) in-slab earthquakes, 7) aseismic accretionary wedge slip, 8) hyperpycnal flow, and 9) gas hydrate destabilization. All of these mechanisms may trigger individual submarine slides and or turbid flow events, but how can earthquake-triggered events be distinguished from other events? Investigators have attempted to distinguish seismically generated turbidites from storm, tsunami, and other deposits. Nakajima and Kanai (2000) and Shiki et al. (2000) argue that seismo-turbidites can in some cases be distinguished sedimentologically. They observe that known seismically derived turbidites in the Japan Sea and Lake Biwa are distinguished by wide areal extent, multiple coarse fraction pulses and variable provenance (from multiple or line sources), and greater depositional volume than storm-generated events. These investigators observe that known seismo-turbidites caused multiple slump events in many parts of a canyon system, generating multiple pulses in an amalgamated turbidity current, some of which sampled different lithologies that are separable in the turbidite deposit. In the Japan Sea, the stacked deposits are deposited in order of travel time to their lithologic sources, demonstrating synchronous triggering of multiple parts of the canyon system. These turbidites are also complex, with reverse grading, cutouts, and multiple pulses. Gorsline et al. (2000) make similar observations regarding areal extent and volume for the Santa Monica and Alfonso Basins of the California borderland and Gulf of California respectively. In general, these investigators observe that known storm sediment surges are thinner, finer grained and have simple normally graded Bouma sequences. We observe that many, but not all, of the turbidite sequences in Cascadia are similar to the historically known seismic turbidites reported by Nakajima and Kanai (2000; their figure 3).

While there may yet be applicable global, regional or local criteria to distinguish between turbidite triggers, these are at present poorly developed. Thus far in Cascadia, we have not attempted to distinguish between triggering mechanisms with sedimentological criteria, but have used the spatial and temporal pattern of event correlations and Adams' synchronicity test at the confluence of Willapa, Juan de Fuca, and Cascadia Channels to establish a regional correlation that cannot be the result of triggers other than earthquakes. We confirm Adams' results from the channel confluence of 13 post-Mazama events both above and below the confluence. Because turbidity currents deposit their loads in a matter of hours, they are excellent relative dating horizons, the relative age resolution provided by this feature of turbidites is far greater than any radiometric or other absolute technique. The synchronicity of event records established at the confluence effectively eliminates non-earthquake triggers because other possible mechanisms are extremely unlikely to trigger slides in separate canyons only a few hours apart. This would have to have take place 13 consecutive times to produce the core record we observe. The correlation is strengthened by extending the record to 18 Holocene events at all sites between the Smith River and Juan de Fuca Canyon. While this does not have the same power as the confluence test, the similarity is striking, and very unlikely to have occurred without a regional earthquake trigger. An alternative explanation could be a series of earthquakes that took place within hours of each other along the length of the margin. While possible, the precision of the relative dating provided by the time of settling of turbid flows restricts this to only a few hours time for central Washington. Additionally, whatever sequence of events occurred, it would also have to take place in such a way that the stratigraphic record yields 18 events in all locations. Again this is not impossible, but far less likely than the simplest explanation, that of 18 plate wide events. We are presently exploring other correlation techniques that may enable direct linkage of the Rogue and either Cascadia or Rogue records, which do not have a confluence, and thus are not positively correlated.

We can make some additional observations about the applicability of other triggers that might be expected to generate turbid flows. Storm wave loading is a reasonable mechanism for triggering of turbid flows, but is an unlikely trigger in Cascadia. On the Oregon and Washington margins, although deep-water storm waves are large, the canyon heads where sediment accumulation occurs are at water depths of 150-400 m. These depths are at or below the maximum possible for disturbance by storms with historical maximum significant wave heights of ~20 meters, though rare mega storms cannot be ruled out. Tsunamis may also act as a regional trigger, however the 1964 Alaska Mw 9.0 event did not trigger a turbidite observed in any of the cores, although it did serious damage along the Pacific coast (Adams, 1990). Crustal or slab earthquakes could also trigger turbidites. To investigate this possibility, we resampled the location of a 1986 box core in Mendocino channel, where the uppermost event is suspected to be the 1906 San Andreas event. Since 1986, the Mw7.2 Petrolia earthquake occurred in 1992, either on the plate interface or lowermost accretionary wedge landward of this site (Oppenheimer et al, 1993). Despite the epicentral distance of only a few km from the canyon head, we were surprised to find no surface sand in the 1999 box core, nor was it present at other southern Cascadia channel locations. At least for this event, an Mw 7.2 earthquake was not sufficient to trigger a turbid flow, or alternatively, insufficient sediment was present. Conversely, the Mw=6.9 Loma Prieta earthquake apparently did trigger some type of turbid flow in Monterey Canyon at a much greater epicentral distance (Garfield et al., 1994).

The remarkable similarity of turbidite records in channels systems monitoring the northern 2/3 of the Cascadia margin suggests strongly that at least this part of Cascadia has experienced 13 post-Mazama events, and 18 Holocene events. These events were sufficiently large to both generate turbidites, and to correlate along the length of the margin. Further correlation is presently underway using radiocarbon dating, but will face difficulties with the accumulated errors and uncertainties. Nevertheless, the circumstantial case presented by Adams (1990) is now considerably stronger.

South of the Rogue Canyon, the turbidite event frequency for the northern Gorda plate region may also contain 18 events in Smith and Klamath canyons. The northern California channels contain no Mazama ash, and have a more diffuse Holocene/Pleistocene faunal boundary, thus correlation will depend heavily on radiocarbon dates. For the southern Gorda area the events are much more frequent. AMS ages for events in the southern Gorda region indicate average turbidite recurrence intervals of 133, 75, and 34 years respectively for the Trinidad, Eel, and Mendocino channels, increasing progressively toward the Mendocino triple junction. The number of possible earthquake sources for triggers also increases progressively toward the triple junction, and includes the Mendocino and Blanco Faults, internal Gorda plate faults, and perhaps the Northern San Andreas. The potential for sedimentological triggering is also higher, with the Eel, Trinidad, and Mendocino Canyon heads very close to the coast, increasing the likelihood of hyperpycnal flow input. Three earthquakes of magnitude 6.9 to 7.4 have occurred in the past 21 years in the triple junction area. However, we estimate that the 10-14 cm of hemipelagic sediment at the surface in Mendocino Channel represents 50 to 70 of deposition, thus these three earthquakes have not triggered turbid flow events in Mendocino Channel. Nevertheless, with a possible mix of storm and non-subduction earthquake events, we can presently draw no conclusions about correlation with the rest of the margin.

Unlike the other Cascadia systems, both Eel and Mendocino canyon heads erode close to the shoreline where the canyon heads may intersect littoral drift sediment that can be funneled down-canyon by storms. Given the probable mix of interplate, intraplate, and sedimentological (non-earthquake) events in the southern

Gorda region, we are as yet unable to make detailed inferences about the earthquake record in this area.

**Turbidite Recurrence Interval Data**

The average post-Mazama recurrence time based on the Juan de Fuca core is ~ 581 years, with the shortest interval being 222 years (T8-T9), the longest 1488 years (T10-T11). The average post Mazama recurrence interval using an age for T13 averaged from all channels is ~600 years. The mean recurrence time based on all available intervals is ~564 years, which is the Holocene average for 18 events terminated by the AD 1700 event that occurred 250 years before the 1950 reporting standard for calibrated radiocarbon ages (9841-250/17). This average is based on the average of three AMS ages for event T18 from our key cores in Juan de Fuca, Rogue, and Cascadia channels. These ages are 9849 (10287-9784), 9851 (10290-9583), and 9824 (10274-9540) for Cascadia, Juan de Fuca, and Rogue Channels respectively.

In early publications, we suggested that virtually all the turbidite record is the result of great earthquakes, based on identical numbers of events in widely separated cores, and relative dating techniques that demonstrate synchroneity of the triggering mechanism. We are now testing this correlation with radiocarbon ages and physical properties of the core sediments. We observe a systematic variation of turbidite ages as a spread of ages that is greatest in the mid-Holocene, tapering off toward both the early and late Holocene. The pattern could represent either systematic earthquake behavior, or a systematic variation of the "reservoir age" of the ocean water in which the microfossils we are dating live. We suspect the latter, as the dated events pass other correlative tests that strongly suggest synchronous triggering. We also are testing the correlation of events using physical property measurements of the cores containing the turbidite record. We find that a reasonably good stratigraphic correlation can be made between three key core sites at Juan de Fuca, Cascadia, and Rogue Channels using Gamma density and high-resolution magnetic susceptibility records of these cores. This correlation is independent of other correlation methods including the Mazama ash datum, event number comparisons, the "confluence test" of synchronous triggering, and radiocarbon ages, but is consistent with them. That we are able to correlate physical property "wiggle" plots between turbidite channels that are not connected, implies that something of the earthquake shaking signal may be contained in these records.

With strengthened correlations, and improved estimates of the reservoir correction, we infer that the pattern of Cascadia Great Earthquakes appears to include a repeating pattern of a long interval ending in an earthquake, followed by a moderately long interval, then 1 or 2 shorter intervals. Over the last ~8000 years, the pattern appears to have repeated four times, with the most recent AD 1700 event being a long interval following two short intervals prior to the previous long interval between T4 and T5. This long interval is one that is also recognized in many of the coastal records, and may serve as an anchor point between the offshore and onshore records.

**Publications from this grant:**

Nelson, C. H., Goldfinger, C. Johnson, J.E., Dunhill, G, 2000, Variation of Modern Turbidite Systems Along the Subduction Zone Margin of Cascadia Basin and Implications for Turbidite Reservoir Beds, *in* Weimer, P.W., Nelson, C. H. et al. (eds.), Deep-water Reservoirs of the World, Gulf Coast Section Society of Economic Paleontologists and Mineralogists Foundation 20th Annual Research Conference, Dec.3, 2000, Houston, TX., 31p, 15 Figures.

Goldfinger, C., Nelson, C.H., Johnson, J., and the Shipboard Scientific Party, In Revision Holocene Periodicity of Great Earthquakes along the Cascadia Subduction Zone, Submitted to Nature.

Nelson, C. H., Goldfinger, C. Johnson, J.E., Dunhill, G., In Press. 2004, Turbidite distribution, periodicity, and paleoseismic methodology along the Subduction Zone Margin. USGS Prpfessional Paper 04-XXXX 27p, 11 Figures.

Goldfinger, C. Nelson, C. H., Johnson, J., 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.

Goldfinger, C. Nelson, C. H., Johnson, J., 2003, in press, Deep-Water Turbidites as Holocene Earthquake Proxies: The Cascadia Subduction Zone and Northern San Andreas Fault Systems. *In*, Pantosti, D. Berryman, K., eds., Annali Geofisica Special issue on Paleoseismology

11 additional abstracts from GSA, AGU, AAPG and other meetings.

**Student support**

One PhD student,. Joel Johnson has been partially supported by this grant
12 graduate and undergraduate students participated in this project, including original fieldwork and data analysis. They received training in multibeam mapping, coring techniques, sediment data analysis, correlation and other techniques.

**Non-Technical Summary**

Past Great Earthquakes along the Cascadia margin have left a record of submarine landslides spanning more than 10,000 years. Dating of these events has shown that the average repeat time is ~ 600 years. The age sequence shows that there has been a repeating pattern of earthquakes through time, repeating three, and possibly four times in the last 8,000 years. A variety of tests of event timing shows that 18times in the last 10,000 years, at least 700 km of the Cascadia margin has ruptured simultaneously, supporting the hypothesis that essentially all of these earthquakes are in the magnitude 9 range.