Reply to "Comment on 'Statistical Analyses of Great Earthquake Recurrence along the Cascadia Subduction Zone' by Ram Kulkarni, Ivan Wong, Judith Zachariasen, Chris Goldfinger, and Martin Lawrence" by Allan Goddard Lindh

by Chris Goldfinger, Ivan Wong, Ram Kulkarni, and Jeffrey W. Beeson

Introduction

In our article Kulkarni *et al.* (2013), we favored a clustered model for great Cascadia subduction zone (CSZ) earthquakes and our statistical analysis resulted in a probability of 0.65 that clustering was present in the turbidite record. The CSZ clustering analysis was originally motivated by the need to develop a CSZ logic tree for use in probabilistic seismic-hazard analysis. In recognition of the two principal models that could explain the pattern of great earthquake occurrence observed in the turbidite record, we gave weights of 0.65 and 0.35 to clustered versus quasi-periodic behavior in the logic tree, respectively (Wong *et al.*, 2014).

In Lindh (2016), Al Lindh questioned the validity of the turbidite data and our analysis of temporal clustering and states that the CSZ actually behaves in a quasi-periodic behavior. He summarizes his argument in four points, and we wish to respond to each point in the following. We confine our responses to the technical issues raised by Lindh. With regards to his discussion on seismic risk in the Pacific Northwest, we support his views. Certainly, understanding the behavior of the CSZ, particularly its recurrence, is a critical element in earthquake-risk reduction in the Pacific Northwest.

Little Evidence for Clustering of Great Earthquakes

We appreciate Lindh for pointing out the more recent studies that indicate that for a few of the examples we cited, clustering of full-rupture earthquakes may not be characteristic of the behavior that was previously suggested. However, the point we were trying to make is that earthquake clustering, regardless of scale or magnitude, is a behavior that is observed along plate boundaries and crustal faults worldwide. There are physical models that can explain temporal clustering, and the quasi-periodic behavior favored by Lindh is unusual over long time spans. Many factors can come into play that can alter the long-term behavior of a fault. A classic example is the Parkfield, California, segment of the San Andreas fault, where quasi-periodic behavior has been called into question (Jackson and Kagan, 2006). What is unusual about the CSZ turbidite record is that it spans several seismic cycles: 19 major events distributed over a period of more than 10,000 years. This paleoseismic record is one of the longest records of any fault worldwide. To believe that uniform seismic loading or quasi-periodic behavior could characterize a fault or subduction zone over a large number of seismic cycles, in this case more than 10,000 years, seems a bit of an optimistic view of earthquake recurrence.

The analysis of plate boundaries by Sykes and Menke (2006) cited by Lindh is a significant study. Using four or more interevent times per fault segment, maximum-likelihood values of repeat time and its normalized coefficient of variation (COV) were calculated using a Bayesian technique. Several fault segments along relatively simple plate boundaries have COVs between 0 and 0.25, indicating quasi-periodic behavior. However, there are several notable exceptions based on more recent and robust datasets. Lindh cites the small COV of 0.12 for the 1964 segment of the Alaskan subduction zone computed by Sykes and Menke (2006) as being "the very antithesis of a clustered sequence." However, more recent data indicate that the rupture behavior is more complicated than that considered by Sykes and Menke (2006). The 1964 segment also breaks in smaller events at its southwestern end (Carver and Pflaker, 2008), similar to the CSZ (Goldfinger, Nelson, *et al.*, 2012). COVs of 0.5 ± 0.2 determined by Ellsworth *et al.* (1999) have been used in forecasts for the San Francisco Bay area (Working Group on California Earthquake Probabilities, 2003). In our analysis of CSZ great earthquakes, we calculated a COV of 0.5 from 17 interevent times.

Of the seven or so plate-boundary segments evaluated by Sykes and Menke (2006), one segment has a record of nine events that extend back through most of the Holocene, whereas the other segments have intervals that range from 5 to 15 and cover periods of 150–5500 years. In contrast, for the CSZ we considered 18 interevent times in the Holocene. Hence, quasi-periodic behavior may not have been characteristic of the segments considered by Sykes and Menke (2006) if a larger number of events and longer time periods had been available. The problems with using short records are clear, and the statistical tests recently applied to the short instrumental catalog are questionable at best (Dimer de Oliveira, 2012).

It is interesting to note that of the 12 plate-boundary fault segments in Sykes and Menke (2006), the Coquille estuary in southern Oregon (Bradley Lake) and sites along the coast of southwestern Washington yielded two of the four
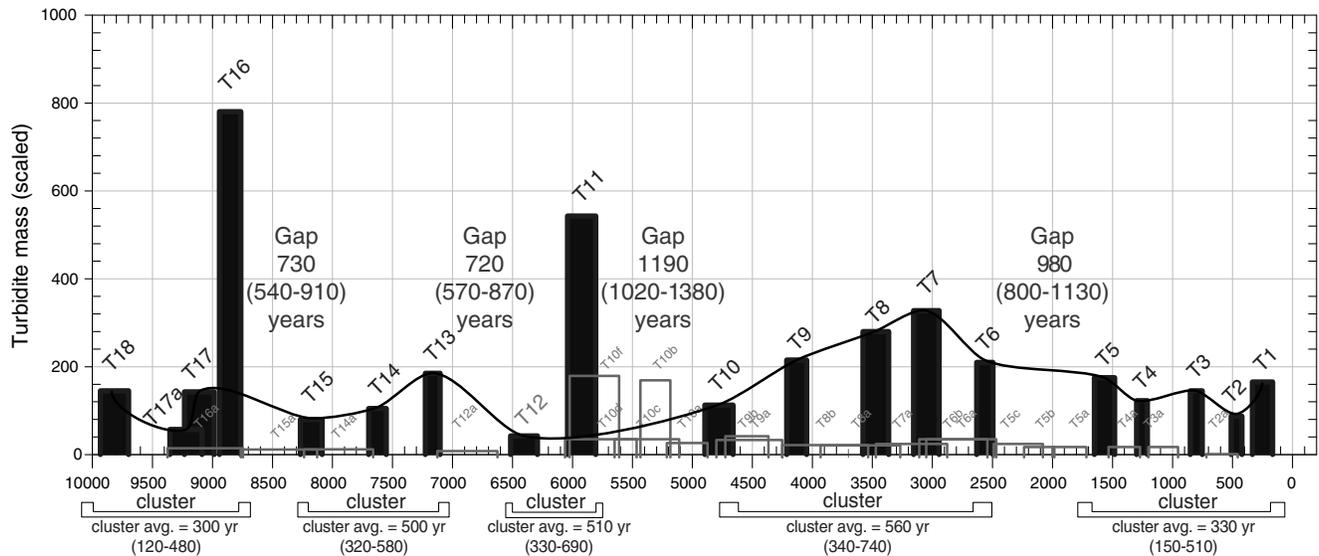
Figure 1. Time series of Cascadia turbidite emplacement for the northern and central Cascadia margin. Bars are scaled with height representing turbidite mass (taller bars are larger turbidites). Bar widths are the 2σ error range from OxCal combined for each event. Turbidite mass is calculated from gamma density data for cores M9907-12PC (Juan de Fuca [JDF] channel) and M9907-23PC (Cascadia channel). Trend line added to upper bound of mass is shown with outlier events T11 and T16 removed.

highest COVs, only exceeded by Parkfield and Wrightwood along the San Andreas fault. Their COVs are about 0.3 but with 68% confidence intervals that extend from 0.2 to 0.5. Sykes and Menke (2006) state that at these sites, as previously suggested by Kelsey et al. (2005) and confirmed by Goldfinger, Nelson, et al. (2012) for the southern Oregon coast, have irregular interevent times that may be due to a mix of full and partial CSZ ruptures. The absence of event T2 prior to A.D. 1700 at Bradley Lake is likely due to the high berm barrier preventing tsunami entry. Thus, the differences in these records (some small events missing from Bradley) are likely due to depositional thresholds. Lindh states that figures 2 and 3 of Sieh et al. (2008) do not show clustering; however, figure 2 does in fact show clustering of smaller events terminated by larger ones, and their figure 3 is not relevant, as it is a map figure with only the large events.

Lindh notes that Scharer et al. (2011), with improved ages, argue against the clustering at Palette Creek on the southern San Andreas invoked earlier by Sieh et al. (1989) and Grant and Sieh (1994). Although Accelerator Mass Spectroscopy ages are an improvement in this study, both sets of ages are severely compromised by the use of charcoal, which sets only maximum limiting ages for the events; they are not event ages. When events have large overlapping tails, short recurrence times, and large errors, definitive definition of clustering is elusive at best; thus, neither interpretation is conclusive.

In any case, we did not try to argue for global dominance of clustering behavior of great subduction earthquakes, we simply suggested that CSZ is apparently clustered and that there are other possible examples (including Cisternas et al., 2005; Santoyo et al., 2005). There are few records on Earth with which this can be tested, as instrumental catalogs are generally too

short (Goldfinger, Ikeda, et al., 2013), and long paleoseismic records are sparse. We expect that there is not a single dominant behavior, as argued by Lindh for quasi-periodic behavior.

We also note that the null hypothesis in our statistical analysis was defined as nonclustering behavior. One would need overwhelming statistical evidence to reject the null hypothesis, but the sample population will never be that large. A single hit against the null hypothesis would not be sufficient to reject it and to conclude that the process was clustered. One would need more than 95% hits before rejecting the null hypothesis.

Cascadia Turbidite Data of Declining Quality Back in Time

Lindh states that it is clear that the data prior to about 5500 years ago are far more irregular (both in their timing and in the turbidite mass estimated for each event) than those for the inferred events after that time. We see no break at 5500 years that defines more or less irregularity in either of these quantities. Beds T16 and T11 dominate the mass deposited per event prior to 5800 yr B.P. and appear to be the basis for this statement (Fig. 1). These beds are present in all core sites used in Goldfinger, Nelson, et al. (2012), and have been shown in more detail in southern CSZ (Goldfinger, Morey, et al., 2013) as well as in lake deposits (Goldfinger, Garrett, et al., 2012; Morey et al., 2013). T11 is a large two pulse massive unit, and T16 is a 3–4 pulse complex bed: distinctive structures and their size make them easily recognizable in our records across numerous sites. The consistent large size in a variety of environments is likely meaningful, as is the downcore pattern of consistent mass per event values (Goldfinger, Nelson, et al., 2012; Goldfinger, Ikeda, et al.,

2013; Goldfinger, Morey, *et al.*, 2013). Because these events were in the first half of the Holocene, Lindh states that decreasing sediment supply must be the cause.

The reduction of sediment supply to the shelf in the Holocene is very well known; however, it is simplistic to assume that sediment supply to the shelf directly controls the mass of earthquake deposits in slope basins, canyons, and the abyssal plain. A test of this, described in Goldfinger, Nelson, *et al.* (2012), their figs. 30 and 31, is that both these large events appear in Hydrate Ridge basin (HRB) cores (RR0207-02PC-TC, RR0207-56PC-TC), a site that is isolated from the shelf, and therefore completely isolated from terrestrial sedimentary sources and wave loading (storm or tsunami) due to its depth. The sediment supply to HRB is solely due to failures of local slopes overlooking the basin, there are no other options. The correlation to other sites is established with well log correlation and radiocarbon ages (which pass the X^2 and Acomb tests, Ramsey, 2001), supported by the mass per event correlation between sites (Goldfinger, Nelson, *et al.*, 2012, their fig. 47). The observation that the pattern of mass per event at sites with potential sediment supply influences is very similar to HRB's pattern indicates that the sediment supply decline to the shelf was a secondary influence (at most) during the Holocene, and exerts no influence at HRB (Goldfinger, Nelson, *et al.*, 2012, their fig. 45). In fact, the similarity of this downcore pattern among sites was used as a correlation tool to link disparate sites (Goldfinger, Nelson, *et al.* 2012). Because there are enough sites spread across numerous depositional systems, some recharged with modern sediments and some not, we see no systematic bias of earthquake sizes or temporal distributions based on sediment supply. Considering the relative lack of influence of sediment supply at many of our sites (described below), the better explanation is that these two very large events, being relatively rare, are simply not uniformly distributed in the ∼10,000-year record. Otherwise, we see no general trend of mass per event in the Holocene at our main sites (Fig. 1).

The influence of sediment supply and sea level is discussed extensively in Goldfinger, Nelson, *et al.* (2012), Goldfinger, Morey, *et al.* (2013), and Goldfinger *et al.* (2016), and does affect the records at sites influenced by sea level. The profound turn-off of Pleistocene shelf-derived materials varies in space and time along the coast, typically at about 10 ka for Juan de Fuca (JDF), Astoria, and Rogue sites, not at all at HRB, and at dramatically younger times in the vicinity of Trinidad and Eel Canyons in southern CSZ. Thus, the CSZ record presented in Goldfinger, Nelson, *et al.* (2012) and Goldfinger, Morey, *et al.* (2013) has already been filtered for sea level effects. The potential influence of sediment supply off Washington is discussed in greater detail below.

Lindh, then, suggests that the sediment supply peak was linked to the Missoula floods. The Missoula flood jökulhlaup events were indeed important events on the Washington margin and in Cascadia basin. Citing figure 3 in Normark and Reid (2003), Lindh claims that the Missoula floods and related turbidity currents might have continued into the

Holocene as late as 9 ka, and could have therefore influenced our paleoseismic record. We can find no data in that paper or in their figure 3, which is far too low in resolution, from which to make such an estimate. The age control comes from Zuffa *et al.* (2000), who placed the younger limit at 12.6 ka. Waitt (1985) considers 12,700[14]C yr B.P. to be the end of the Missoula episodes. Optical ages reported in Hanson *et al.* (2012; paper cited by Lindh) have a weighted mean of 13.5 ± 0.5 ka for the youngest Missoula events. The Pleistocene Missoula floods may well have increased sediment supply over a long period of time for the Washington margin, but they are not directly relevant to the Holocene paleoseismic record off Washington, nor to the correlative Oregon and California sites not influenced by the Missoula flood events.

Building on the unsupported speculations about sediment supply, Lindh further speculates that sea level, stabilizing closer to modern values in the mid-Holocene, may be responsible for the turbidite record becoming more regular in the late Holocene. However, aside from the rare outliers T11 and T16, the record is no more regular in the late Holocene, as previously discussed.

Lindh speculates that a source of noise in the older records is that the turbidite volume was greater (stated without evidence) and therefore the channel geometry may have been different. Channel geometry may have been slightly different, but the consistency of the Washington records does not support significant changes during the Holocene. The channel systems used in Goldfinger, Nelson, *et al.* (2012) were surveyed with modern sidescan and multibeam systems, and are therefore known to be free of major blockages, though there are numerous smaller ones. The older 1968–1986 works cited by Lindh did not have modern geophysical seafloor survey data and could only speculate about broad large-scale differences between Pleistocene and Holocene sediment transport, and so are not relevant to a discussion of Holocene turbidite stratigraphy.

Resolution of Records

Lindh states that the lack of segment B events in the early Holocene is further evidence of the lower resolution of the earlier Holocene records, an assertion that is not supported by evidence or logic. Presence or absence of a particular segmented rupture has nothing to do with resolution. Lindh then adds four segment B ruptures (there are actually only three) to his figure to show that if they were included, rupture timing would be more regular. Our article dealt only with full or nearly full margin ruptures, thus adding a random subset of partial ruptures to the time series is not relevant and misleading. Additionally, the Holocene records are of the same resolution throughout. Cores that reached deep enough to record the entire Holocene at our main sites (JDF, Barkley, Cascadia, Astoria, HRB, and Rogue sites) have all been CT and RGB imaged at 0.5 mm resolution. There is no difference in our ability to see turbidite beds in these cores in the early versus the late Holocene, and the quality of the radiocarbon data is

actually better in the early Holocene when foraminifera abundance was greater. "Flat spots" in the ^{14}C calibration curve occur at various times throughout the Holocene, broadening radiocarbon uncertainties at those times, notably in the latest Holocene. In fact, one of the advantages of submarine paleoseismology is that the resolution only varies with sediment supply, analysis methods, and site selection. We conclude that the turbidite record is neither noisier nor of lower resolution in the early half of the Holocene due to sediment supply changes or any other reason, and therefore does not influence the clustering of earthquakes discussed here. The younger events are not better resolved; they are better corroborated, with more available land data, which Lindh appears to conflate with resolution.

The Role of Sediment Supply on Tectonic Margins

The statements by Lindh regarding sediment supply reflect a common misunderstanding of the relationship of sediment supply to paleoseismic deposits in the submarine environment. Lindh believes that turbidity currents triggered by earthquakes derive all of their sediment from recharge of canyon heads at or near the shelf edge. In general, sediment must be available for failure in earthquakes, otherwise there would be no record. However, in high sediment-supply margins, such as high-latitude CSZ and low-latitude Sumatra, abundant sediment is commonly available through mostly Pleistocene distribution of high sediment loads to submarine fans which are in turn accreted in broad accretionary prisms. For the numerous basins sampled in the Sumatra fore-arc (Patton *et al.*, 2013), the turbidite record is both robust and correlative among isolated basins along strike despite the lack of terrestrial recharge. The Sumatra paleoseismic record is derived almost entirely from sites analogous to Hydrate Ridge, the isolated basin extensively discussed in Goldfinger, Nelson, *et al.* (2012).

The Paleoseismic Record and the Role of Sediment Supply on the Washington Margin

The Washington margin comprises turbidite systems with variable sediment supply and sources. These generally fall into three classes: (1) canyon-channel systems with little or no external Holocene sediment supply. These are relict Pleistocene systems now cut off from terrestrial sources by high sea level; (2) systems that are and have been receiving sediment recharge either directly or indirectly from sediment transported to canyon heads through cross-shelf transport; and (3) systems with no possibility of terrestrial sediment transport due to permanent isolation from land sediment sources. Goldfinger, Nelson, *et al.* (2012) and Goldfinger, Ikeda, *et al.* (2013) include sites from all three types. Although actively recharged systems of type 2 would be expected to contain turbidite records, type 1 and 3 systems would not necessarily be expected to contain such records. JDF, Quillayute, Nitinat, and Barkley Canyons are type 1 systems, with clear evidence of shutdown or at least significant sediment recharge

slowdown at the end of the Pleistocene (Carson and McManus, 1969; Barnard, 1973). Although the turbidite bed thickness and grain-size profiles of relict systems may reflect the cutoff, abundant materials remain available for mobilization, as reflected in the turbidite records in Washington (Goldfinger *et al.*, 2003; Goldfinger, Nelson, *et al.*, 2012; Goldfinger, 2014; Goldfinger *et al.*, 2016).

Not All Turbidite Events Are of **M** 9

Lindh states that Goldfinger, Nelson, *et al.* (2012) and Kulkarni *et al.* (2013) explicitly assume that all but one (event T2) of their segment A events are moment magnitude **M** 9. This is incorrect. Goldfinger, Nelson, *et al.* (2012) used the 1700 event to establish a magnitude tie between the land and marine records. Although the **M** 9 estimate for A.D. 1700 is tenuously based on tsunami modeling from the arrival in Japan, a notoriously noisy method was adopted at that time. They then used strike length of other events, derived from the joint land-marine paleoseismic dataset and estimates of rupture width from Global Positioning System/leveling locking models and other data to estimate the rupture area of the paleoseismic events. This is fraught with acknowledged uncertainties; however, the magnitudes were not an assumption, they were computed. There was variability for full-length events, ranging from **M** 8.5 to 9.15 (Goldfinger, Nelson, *et al.*, 2012, their table 8). Goldfinger, Nelson, *et al.* (2012) also discussed the severe limitations of the data in estimating the length of the events in specific time ranges and areas. The real-world patchiness of earthquakes would increase the variability considerably. In Kulkarni *et al.* (2013), the main series of correlated events was characterized as ~**M** 9, which was a generalization and approximation; however, the point of the paper was not to estimate magnitudes but to examine clustering.

A More Nuanced View

Lindh states that older papers about various land sites present a more nuanced view of the rupture history than the land-marine compilation presented in Goldfinger, Nelson, *et al.* (2012). We disagree. Earlier onshore paleoseismic models were based on correlating detrital radiocarbon ages, and the various methods and large uncertainties that evolved over several decades are subject to the relatively high recording and preservation thresholds of most land paleoseismic records. These earlier studies, many of excellent quality, are nevertheless inherently limited in both completeness and accuracy, and they lack the ability to correlate events along strike independently of the radiocarbon ages. Each of them has estimated event ages of detrital material in different ways, some using peat ages from quite different environments including estuaries, marshes, barrage lakes, and river mouths. Each site has its own sensitivities that limit the completeness and resolution of the preserved record.

The Bradley Lake tsunami overwash record, one of the best of the land records, is guarded by a berm 5.5 m above mean sea level, which blocks all tsunami's smaller than that,

depending on the tide. In addition, correlating earthquakes based on radiocarbon alone is classically problematic. Variability in radiocarbon ages among southern Oregon sites led Kelsey *et al.* (2005) and previous workers to suggest segmentation models. However, there was an issue with the use of averages of detrital dates from Bradley Lake, driving some ages to be erroneously older than the true ages. With the help and assent of the original authors, Goldfinger, Nelson, *et al.* (2012) presented a revision of the Bradley Lake and Coquille River (Witter *et al.*, 2003) dates by using the youngest age for each sample, which yielded close agreement between Bradley Lake, Coquille River, and the offshore record at Rogue Canyon and other marine sites. This revision largely removed the age variability that had prompted earlier segmentation models.

Building on that revision, Goldfinger, Morey, *et al.* (2013) published a new analysis for the central and southern Cascadia margin using new core data, additional radiocarbon ages, CT analyses, and high-resolution Compressed High Intensity Radar Pulse (CHIRP) sub-bottom profiles acquired along the full length of the margin. CHIRP vertical resolution is range independent, and these profiles directly imaged the turbidite sequence (vertical resolution of ~15 cm) along more than 250 km of the central and southern margin-abyssal plain. The profiles imaged continuous beds along this length in the Holocene section, and were correlated directly to the core set. Like the original correlation of Goldfinger, Nelson, *et al.* (2012), no discontinuities or segmentation of the major turbidite beds were found in the new core set of high-resolution profiles (the smaller, spatially limited beds could not be imaged) for the region of southern Cascadia, in which earlier segmentation models had been proposed. We consider the evidence for continuity of the major events in south-central CSZ to be quite strong, and may supersede the earlier models, although further work can always test this and other alternatives. Lindh does not mention these more recent works.

Some Events More Important?

Lindh argues that land events 1 and 5 (our T1 and T6) are more important than other events, citing the qualitative comments in Nelson *et al.* (2006) and Atwater and Hemphill-Haley (1997) regarding which events had greater subsidence, and the boldness of the buried soils. However, event 1 was referred to as "the wimp" at Bradley Lake (A. Nelson, U.S. Geological Survey, personal comm., 2012), after it was pointed out that along-strike variability is inherent and expected in any paleoseismic record. Offshore at virtually all sites, T1 (the A.D. 1700 event) is modest in thickness and mass (Goldfinger, Nelson, *et al.*, 2012) and nowhere does it appear to be a standout. Lindh repeatedly cites evidence from Willapa Bay and the Copalis River (30 km apart) for the degree of subsidence and boldness of soils; however, these sites represent only two closely spaced points along the 1000 km margin where earthquakes were almost certainly not uniform in slip distribution.

Sensitivities always apply to the generation, recording, and preservation of all geologic data (e.g., Nelson *et al.*, 2006). The resolution of the recording system of tsunami and subsidence in the coastal marshes of Willapa Bay is relatively low. Atwater and Hemphill-Haley (1997) estimate the maximum vertical resolution to be >0.5 m. This estimate was improved by Engelhart *et al.* (2013), who demonstrated that with careful analysis the resolvability is 0.2 m or better; however, these modern methods were not used in the older work by Atwater. Given these realities, coastal records are subject to a lower threshold of both resolution and power to determine relative size that is a convolution of three factors: (1) the slip model of the earthquake; (2) the state of the tide; and (3) the vertical motion induced at the site. Although the degree of subsidence and boldness of the soils are important clues, they are just a small part of the larger picture. In Nelson *et al.* (2006), the importance of events 1 and 5 is primarily due to their estimate of rupture length, which they estimate to be long for these events (as well as events we call T6, T7, T8, T9, and T10), and shorter for events 2, 3, and 4. The land-marine compilation indicates that these events are likely all long but of variable magnitude (Goldfinger, Nelson, *et al.*, 2012).

The coastal subsidence data also raise a question of data ambiguity with respect to slip models. Because the coastal subsidence data are by definition close to the coast, they essentially represent a 1D dataset that commonly does not sample inland to any significant extent. When modeling paleoseismic data, the 1D linear dataset is a very poor constraint on the position of the locked plate boundary and the size of the earthquake. Also, a subsidence value may be on the seaward limb, the landward limb, or in the center of the broad area of subsidence. McCaffrey *et al.* (2013) discuss this and suggest that some of the low-subsidence areas may well indicate areas of greater landward extent of the locked or transition zones. Thus, whether greater or lesser subsidence is observed at coast sites cannot define the size of the event.

Lindh cites several older studies from Vancouver Island, including tsunami evidence from Deserted Lake and Tofino, and states that events T2, T3, and T4 did not reach those areas. However, both these sites have an event compatible in age with T2. In addition, as noted above, these sites require an unknown threshold exceedance for the deposition and preservation of tsunami deposits, which also depend on the state of the tide. In contrast, Enkin *et al.* (2013) observe the nearly full CSZ sequence reported by Goldfinger *et al.* (2003, 2008) and Goldfinger, Nelson, *et al.* (2012) at Effingham Inlet in turbidite stratigraphy, corroborating the northward extent of the segment A ruptures. Similarly, Blais-Stevens *et al.* (2011) report a likely correlative 4000-year sequence at Saanich Inlet on southeastern Vancouver Island. Saanich Inlet has likely recorded the full CSZ sequence of nine events in this time range, in addition to nine local events uncorrelated to other sites (Blais-Stevens *et al.*, 2011).

In their study of Lake Washington, Karlin *et al.* (2004) report a series of likely earthquake-triggered turbidites with

time correlatives for Holocene events that overlap with the CSZ series offshore and onshore, with the addition of the Seattle fault earthquake of ~1000 cal. B.P. (the fault runs through the lake). Missing from this record are correlatives for T4 and T6, while others, including a potential T2 correlative, are present. Event T2 is likely too small to be recorded at most onshore sites as discussed in Goldfinger, Nelson, et al. (2012), but may additionally be present at Saanich Inlet, Discovery Bay, Neawanna Creek, Ecola Creek, Netarts Bay, Siletz and Yaquina Bays, and others as summarized in Goldfinger, Nelson, et al. (2012).

Event T2, a smaller bed at most sites offshore, likely falls below the creation/preservation thresholds at some onshore sites. Event T2, however, while thin at northern sites, becomes more prominent in the southern CSZ (Goldfinger, Morey, et al., 2013). The lack of appearance of T2 at Willapa Bay is not surprising, but it appears in all offshore sites including JDF (except the highly compressed Barkley site, which has a compressed section for the past ~1500 years). The regional age grouping of T2 passes the OxCal ^{14}C Acomb and X^2 tests (Lindh incorrectly states that it does not appear in our sites north of the Columbia River). Estimates of magnitude for T2 based on time predictable or mass-based models averaged along strike yields a range of **M** 8.7–8.9 (Goldfinger, Nelson, et al., 2012).

There is also no reason to discount events T3 and T4, as they are present at every land and marine site with only a few exceptions that Lindh cites as falsifying evidence. To the contrary, abundant evidence that these events extend to Vancouver Island is summarized and presented in Goldfinger, Nelson, et al. (2012) as well as in Leonard et al. (2010).

Events 3 and 4 (2 and 3 onshore) are correlated along strike for a distance no less than 700 km (Trinidad, Klamath, Smith, Rogue, HRB, Astoria, JDF, and Cascadia sites), using well log correlation and radiocarbon. Time correlatives are reported in Effingham Inlet (event E3, 785–838 cal. B.P.; Enkin et al., 2013) and Waatch Marsh (Peterson et al., 2013). Goldfinger, Nelson, et al. (2012) and Enkin et al. (2013) use well log correlation methods to link the Effingham Inlet with the offshore JDF/Barkley Canyon core records directly, independent of radiocarbon. The thickness and mass of T3 varies, and is actually quite high off Washington. Offshore, event T4 is correlated over the same distance, appearing at all sites. Onshore potential correlatives are numerous and detailed in Goldfinger, Nelson, et al. (2012) as well as at the above Canadian sites offshore. At some Washington sites (see below), T4 is quite diminutive, and is not prominent at Effingham Inlet; thus T4 may fade northward into the Canadian margin. We find no evidence, however, that T3 or T4 terminates in Oregon or Washington. Magnitude estimates of magnitude for T3 and T4 (as above) yield a range of **M** 8.9–9.1. Similarly, offshore T5 is fully correlated along strike, correlates with onshore records, and yields a range of **M** 8.8–9.1. T6 (onshore event 5) is similar, yielding a range of **M** 9.1–9.2, a bit larger, but all of these events with the likely exception of T2 are in the **M** range.

In comparison to the land record, the requirements for generation and preservation of submarine paleoseismic evidence are simpler, requiring a favorable depocenter, modest ground shaking, and nearby slopes that will fail under seismic loadings. We suggest the recording threshold is lower for turbidites as discussed in Goldfinger, Nelson, et al. (2012). The slope stability is quite low, requiring ground shaking of only tenths of a g in peak ground acceleration (980 cm/s^2) or less for failure. Magnitude thresholds for recording and preservation of submarine landslides were estimated as **M** ~ 7.1 in the CSZ (Goldfinger, Nelson, et al., 2012). We conclude that the turbidite record is likely more sensitive and more complete than the land record in most cases, and that considering the land record as ground truth is not justified.

We further conclude that there is no reason to modify the results of Goldfinger, Nelson, et al. (2012) or Kulkarni et al. (2013), and that the abundant paleoseismic evidence from onshore and offshore support full or nearly full margin rupture for T1, T2, T3, T4, and T5 (and the others as described in Goldfinger, Nelson, et al., 2012). We consider much of the more nuanced view suggested by Lindh to be repetition of previous older models that were largely based on noise in the ^{14}C data of evolving older records, and inclusion of sites that most likely only have partial records due to higher recording thresholds. Overinterpretation of noisy and biased detrital radiocarbon results has been discussed by Streig et al. (2015) in the San Andreas fault paleoseismic records.

Alternative Interpretations of the Turbidite Evidence

Lindh notes that Atwater et al. (2014) used 10 cores (actually 13) and that all of them showed only 6 turbidites on the Washington margin in the past 7500 years. This is incorrect, as Atwater et al. (2014) stated that there were between zero and more than six turbidites in these cores. Beyond that, Atwater et al. (2014) did not examine any cores, they relied on hand-drawn visual logs from student theses from the late 1960s and ignored the modern geophysical analysis of cores in Goldfinger, Nelson, et al. (2012). Modern geophysical data and CT imagery show that these same cores contain many more turbidites than could be observed visually (e.g., Goldfinger, 2014; Fig. 2), a common problem noted by one of the original investigators (Barnard, 1973; Goldfinger, Nelson, et al., 2012; Goldfinger, Morey, et al., 2013). The turbidite count on the Washington margin is as published in Goldfinger, Nelson, et al. (2012), with slight modifications as shown in Figure 2. These data are consistent with the results of Goldfinger, Nelson, et al. (2012), Goldfinger et al. (2003), and Adams (1990) in terms of the turbidite count and the confluence test as described first by Adams (1990). In fact the Washington margin contains seven separate localities that provide six confluence tests in addition to the one described by Adams (Goldfinger, 2014; Fig. 2, inset). They are corroborated by heavy mineral analyses from Duncan (1968), Griggs (1969), Carson (1971), and Barnard (1973), compiled and augmented by Goldfinger, Beeson, et al. (2013),
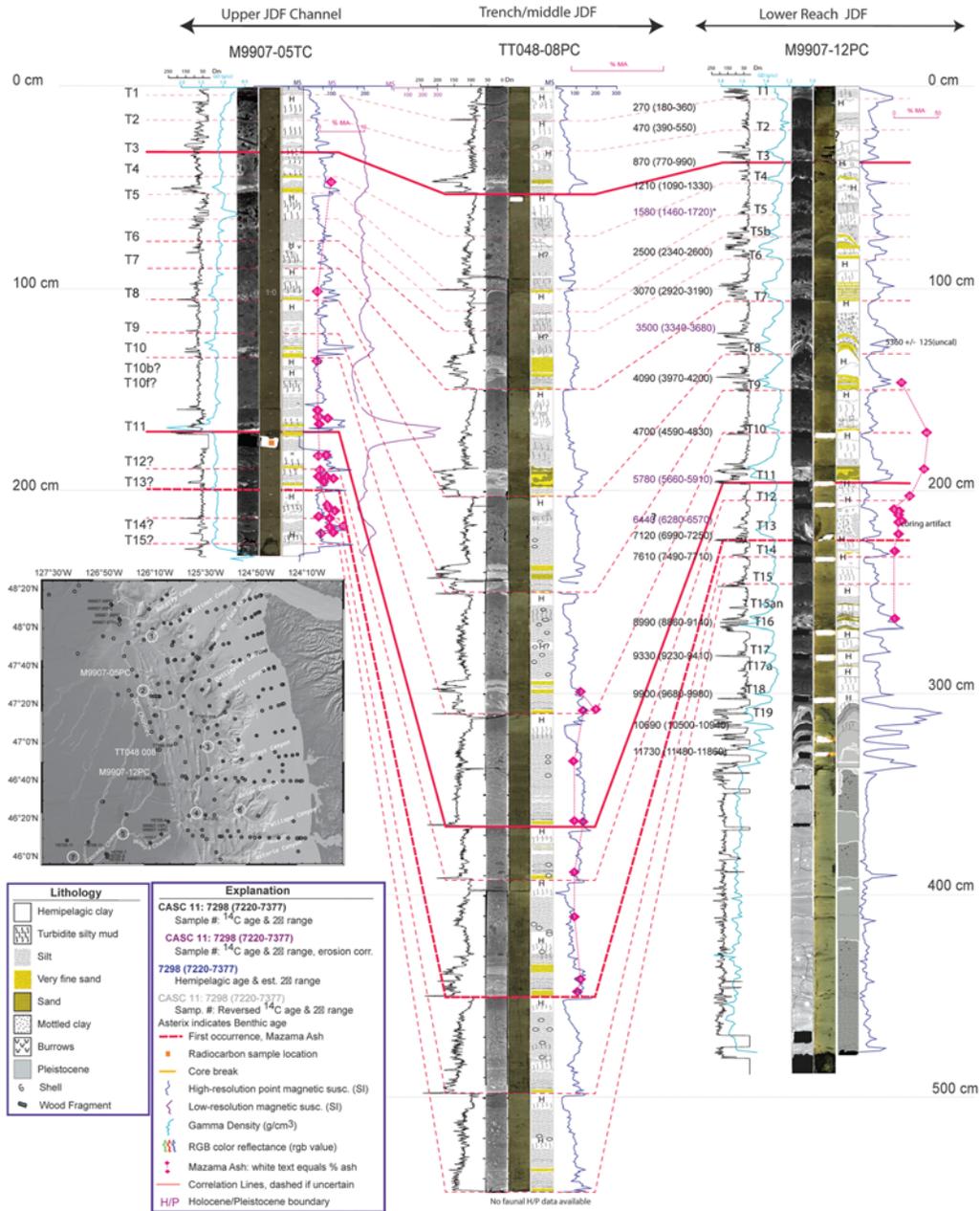
Figure 2. Several cores in JDF channel along the deformation front, Washington margin. Cores M9907-05TC and M990712PC are primary cores used in Goldfinger, Nelson, *et al.* (2012) to establish the turbidite record in this system. Core TT048-08-09PC lies in the middle reach between the two sites, and due to its position upstream of a small landslide, it has the thickest Holocene section (full core). This and other Washington (WA) cores have 13–15 post Mazama turbidites. TT048-08-09PC composite core log redrawn from the original website (see Data and Resources), the cores themselves and geophysical data are available at the Oregon State University (OSU) Core Repository (see Data and Resources). Inset shows core locations and multiple canyon channel confluences. The color version of this figure is available only in the electronic edition.

which show a consistent northern source assemblage defined by low Cpx/hornblende ratio and glaucophane, distinct from the Columbia River source that dominates the northern Washington shelf-fed canyons.

The argument that some of the events represented in Goldfinger, Nelson, *et al.* (2012) do not extend into Washington or Canada is neither supported by modern data on the Washington Canyons and Barkley Canyons as shown in Gold-

finger, Nelson, *et al.* (2012), the original examination of Adams (1990), nor by the turbidite record in Effingham Inlet (Enkin *et al.*, 2013) and Lake Washington (Karlin *et al.*, 2004).

Revised Recurrence Rate and Probabilities?

Lindh proposes that the late Holocene is a better representation of the recurrence rate for the CSZ. Although the

later Holocene is not better resolved, it is better corroborated because the shorter land paleoseismic record is available, and agrees quite well with Lindh. The time of overlap extends fully through the Holocene at Effingham Inlet; however, although it is a marine record, it is in a nearly landlocked inlet and so considered a land record here. Similarly, the land records include not only the well-known coastal subsidence and tsunami evidence summarized in Goldfinger *et al.* (2008) and Goldfinger, Nelson, *et al.* (2012), but also long Holocene records in inland lakes (Goldfinger, Garrett, *et al.*, 2012; Morey *et al.*, 2013). The problem with using a very short record such as the last 1500 years covered by the last five events as suggested by Lindh, regardless of other arguments, is that it uses only 15% of the available time span, and stops short of the well-known ∼1000-year gap between the fifth and sixth major events, replicated at nearly all land and marine sites, including Atwater *et al.* (2004, their events S and N). The tight constraints placed on the time series of the last eight events by virtue of inclusion of numerous land and marine records, and the Bayesian combination of these ages to narrow the two sigma ranges (Goldfinger, Nelson, *et al.*, 2012), make it very unlikely that this 1000-year gap, bounded by a younger cluster and an older cluster, does not exist. Rather it is one of the lynchpins linking the land and marine records.

Using records that are too short is the primary failing of nearly all estimates of seismic hazard and recurrence, as shown by the recent Tohoku earthquake, and indeed by the Parkfield predictions of the 1980s (e.g., Bakun and Lindh, 1985).

Conditional Probability Associated with the Last Five Events

Lindh is interested in the 50-year probability of an $M \geq 8.5$ earthquake occurring south of the Columbia River, and events that will have the greatest impact on hazard in Oregon. We did not calculate such a probability. Thus his comparison is not "apples to apples." His probability of 32% is based only on events T1–T5, which he believes are not all full-rupture earthquakes. These five events give an average recurrence interval of 313 years. If we were to assume no clustering behavior and use only the last five events T1–T5, our calculations also show a similar probability. However, if we were to use T1–T5 minus T2 and no clustering, we would get a probability of 13%. We note that using only five events reduces the sample size (n) to four for the interevent times. The standard error of the estimated mean recurrence time is equal to $s/\mathrm{sqrt}(n)$, in which s is the sample standard deviation of interevent times. An estimate of the mean recurrence time based only on a sample size of 4 would be much less reliable than one based on a sample size of 18 using all events. The 1500-year record used by Lindh is the same as calculating the probability within the most recent cluster, which we agree is ∼32% in 50 years.

We calculated a 50-year probability of 17% using the whole Holocene record for what we believe are full-rupture events including four of the last five events that Lindh

considered, minus T2. It is important to note that because we took a logic-tree approach in calculating our 50-year probability to account for the epistemic uncertainty in interpreting the Holocene record, our estimate is based on a weight of 0.35 that the earthquakes are not clustered. If we assume that the record is not clustered, with a weight of 1.0 rather than a weight of 0.35, the 50-year probability is 6%. The impact of assuming that the turbidite record is not clustered is significant if the entire record is used.

Often time-dependent implicit and explicit earthquake forecasts have suffered severely in recent years, as they have failed to successfully predict anything. The Tohoku earthquake of 2011 clearly was preceded by a range of smaller earthquakes, storing more energy than released for at least 1142 years (A.D. 869–2011; Minoura *et al.*, 2001). Paleoseismic evidence suggests long-term cycling of these very large events on ∼900-year intervals (Minoura *et al.*, 2001). Long-term cycling may explain the poor performance of simple periodic earthquake models (Sieh *et al.*, 2008; Goldfinger, Ikeda, *et al.*, 2013).

Data and Resources

Core data from the University of Washington cores, in addition to thesis publications, were acquired from the cores which are archived at the Oregon State University Core Repository and publicly available from http://osu-mgr.org/ (last accessed August 2015) and https://www.ngdc.noaa.gov/mgg/ (last accessed August 2015).

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