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Were they all giants? Perspectives on late Holocene plate-boundary earthquakes at the northern end of the Cascadia subduction zone

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ABSTRACT

The relative magnitude of plate-boundary earthquakes at the northern end of the Cascadia subduction zone was assessed from the temporal concordance between the ages of coseismically buried late Holocene soils in southwest Washington, their counterparts in central and southern Cascadia, offshore turbidites, and paleoseismic deposits on the west coast of Vancouver Island. Only three of the seven buried soils in southwest Washington that can be reliably traced as buried soils or paleotsunami deposits in the coastal lowlands of south-central and southern Cascadia have well-dated counterparts in northern Cascadia. The three wide-ranging events date from Cascadia earthquakes Y (~250 cal BP), U (~1260 cal BP), and N (~2520 cal BP). All three likely ruptured the entire plate margin, and therefore potentially qualify as “giants” ($M_w \geq 9$). Deposits that may derive from tsunamis generated by earthquakes S (~1570 cal BP), L (~2870 cal BP) and J (~3360 cal BP) can also be found in northern Cascadia, but the ages of these deposits are not yet well-enough constrained to determine whether they are coeval with their southern counterparts. Earthquake W (~850 cal BP), appears to be present in the northern Cascadia paleoseismic record, but yields considerably older ages than in central Cascadia, and may be missing from southernmost Cascadia. The onshore record of an offshore turbidite (T2) displays a similar spatio-temporal pattern to that of earthquake W.

1. Introduction

“In science an important step forward can be finding a question that can be answered with the data at hand” (Frank, 2016). Is our titular query such a question? Do the data at hand support the contention that all the plate-boundary earthquakes at the northern end of the Cascadia subduction zone in the late Holocene were full-margin ruptures, each equaling or exceeding M_W 9?

If the northern Cascadia plate boundary exhibits monotonic rupture behaviour, and all the earthquakes are giants, that would make this plate boundary distinctive, and possibly unique, because the energy release at subducting plate boundaries commonly varies substantially from one earthquake to the next. For example, slip at the Sumatran-Andaman, southern Kuril, and Nazca convergent margins in the historic era has ranged from the breakage of small fault patches, through cascading or stuttering failure of adjoining fault segments, to unlocking of the entire fault boundary. The resultant earthquakes have differed in magnitude from M_w ~7 to ~9 (Satake and Atwater, 2007).

Assessment of the seismic potential of a plate margin is generally based on catalogs of historic events such as those assembled by Satake and Atwater (2007). Cascadia, (Fig. 1A), however, is an exception. That plate boundary has not ruptured since Euro-American colonization began in the late 18th century, and the only accounts of the severity of past earthquakes at the margin are Native tales of prehistoric events (McMillan and Hutchinson, 2002; Ludwin et al., 2005). As a consequence seismic risk assessments are based solely on geological and geophysical inference and models of plate-boundary structure.

Most of the geological evidence comes from the central and southern parts of Cascadia. There, the chronology of recurrent plate-boundary earthquakes and their associated tsunamis has been established from depositional sequences in shoreline marshes and offshore turbidites. The paleoseismic record from northern Cascadia, which we define here as the ~300-km long segment of the subduction zone off the west coast of Vancouver Island (Fig. 1A), is much more limited. There are four major

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reasons for this: 1) tidal marshes have developed in only a few sheltered locations on this fjord coastline; 2) the time spanned by the depositional sequences beneath these marshes is much shorter than in coastal marshes to the south; 3) the geological record of tsunami inundation of the northern coastal lowlands, derived largely from anomalous marine deposits in lakes, is piecemeal; 4) the turbidite sequences off the coast of northernmost Cascadia have not yet been investigated, but, if the truncated stratigraphic records in adjacent areas to the south are any guide, the late Holocene sections of their counterparts in northernmost Cascadia are likely to be incomplete.

Despite these limitations, there now appears to be a gathering consensus amongst the local geological and geophysical community that the northern segment of the plate interface exhibits monotypic seismic behaviour, characterised by giant ($M \geq 9$) earthquakes triggered by rupture of the entire, 1100 km-long plate boundary. This accord primarily arises from the analysis of Holocene turbidite sequences in submarine canyons and channels off the Cascadia margin by Goldfinger et al. (2003, 2012). They tallied 34 seismically triggered Holocene turbidites off southern Cascadia, 19 of which they consider to represent full-margin ruptures. As the canyons and channels in north-central Cascadia display only these 19 events, they conclude that northern Cascadia has been subject only to full-margin ruptures over the past 10,000 years. This interpretation of the turbidite sequences is the subject of active debate (Atwater and Griggs, 2012; Atwater et al., 2014), but forms the basis for assessments of tsunami run-up (Priest et al., 2010), next-event waiting times (Mazzotti and Adams, 2004; Kulkarni et al., 2013; Lindh, 2016), fault-energy budgets (Goldfinger et al., 2013), and analyses of seismite recurrence in fjord basins (Enkin et al., 2013).

If all the late Holocene plate-boundary earthquakes on the northern segment of the Cascadia subduction zone were giants, then by definition they must all be coeval with those farther south. Unfortunately, because the dating of prehistoric earthquakes is based on inherently uncertain radiocarbon ages, their timing can never be precisely determined, and synchroneity can therefore never be conclusively established. As Atwater et al. (2014, p. 829), citing Nelson et al. (1995) note: "Geologic dating usually lacks the time resolution to show whether a long fault broke as a whole during the seconds or minutes of a single earthquake, or whether it ruptured piecemeal in a series of lesser earthquakes distributed across days, years, or even decades".

Although such indeterminacy is an intrinsic problem when events are dated solely by radiocarbon, it is possible to demonstrate variable degrees of overlap between radiocarbon ages as measures of potential coevality. We evaluate the degree of concordance between inferred prehistoric earthquake events in northern and southern Cascadia by means of an overlap coefficient, restricting our analysis, where possible, to coherent groups of radiocarbon ages. We restrict this analysis to the past 4000 years, the temporal span of the paleoseismic record in northern Cascadia.

2. Developing a megathrust earthquake catalogue for northern Cascadia

The most diagnostic earthquake telltales in Cascadia comprise stacked sequences of marsh peat or forest soil abruptly overlain by tidal-flat mud. In some cases the peat is separated from the mud by a thin sand layer. These sequences were first described from outcrops on the banks of channels in the intertidal marshes of Washington State by Atwater (1987, 1988a), who attributed the abrupt

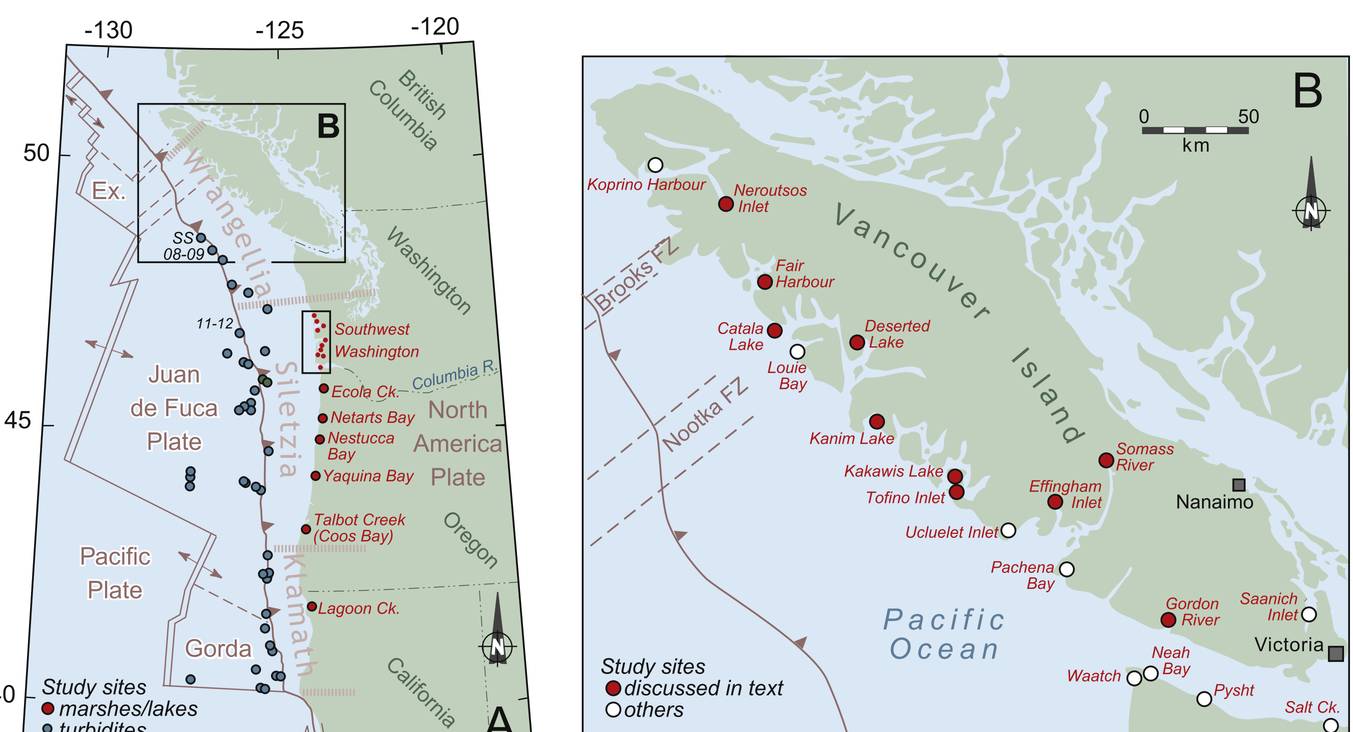

Fig. 1. A. Location and setting of the Cascadia subduction zone showing the extent of the Wrangellia, Siletzia and Klamath episodic tremor and slip zones of Brudzinski and Allen (2007) and paleoseismic sites discussed in the text. Ex.=Explorer Plate; SS=Slipstream Slump.
1B. Paleoseismic sites investigated in northern Cascadia.