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Invited review

Detection limits of tidal-wetland sequences to identify variable rupture modes of megathrust earthquakes

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A B S T R A C T

Recent paleoseismological studies question whether segment boundaries identified for 20th and 21st century great, >M8, earthquakes persist through multiple earthquake cycles or whether smaller segments with different boundaries rupture and cause significant hazards. The smaller segments may include some currently slipping rather than locked. In this review, we outline general principles regarding indicators of relative sea-level change in tidal wetlands and the conditions in which paleoseismic indicators must be distinct from those resulting from non-seismic processes. We present new evidence from sites across southcentral Alaska to illustrate different detection limits of paleoseismic indicators and consider alternative interpretations for marsh submergence and emergence. We compare predictions of coseismic uplift and subsidence derived from geophysical models of earthquakes with different rupture modes. The spatial patterns of agreement and misfits between model predictions and quantitative reconstructions of coseismic submergence and emergence suggest that no earthquake within the last 4000 years had a pattern of rupture the same as the Mw 9.2 Alaska earthquake in 1964. From the Alaska examples and research from other subduction zones we suggest that If we want to understand whether a megathrust ruptures in segments of variable length in different earthquakes, we need to be site-specific as to what sort of geological-based criteria eliminate the possibility of a particular rupture mode in different earthquakes. We conclude that coastal paleoseismological studies benefit from a methodological framework that employs rigorous evaluation of five essential criteria and a sixth which may be very robust but only occur at some sites: 1 – lateral extent of peat-mud or mud-peat couplets with sharp contacts; 2 – suddenness of submergence or emergence, and replicated within each site; 3 – amount of vertical motion, quantified with 95% error terms and replicated within each site; 4 – syncroneity of submergence and emergence based on statistical age modelling; 5 – spatial pattern of submergence and emergence; 6 – possible additional evidence, such as evidence of a tsunami or liquefaction concurrent with submergence or emergence. We suggest that it is possible to consider detection limits as low as 0.1–0.2 m coseismic vertical change.

1. Introduction and structure of the paper

Coastal paleoseismology provides critical information that helps to improve understanding and modelling of seismic hazards, including associated tsunami, at all major subduction zones. Key contributions to practical earthquake hazard assessment include the identification of great (magnitude 8 or 9) earthquakes during the Holocene where there is no historical record (Atwater, 1987); earthquakes of substantially greater magnitude than directly observed (Minoura et al., 2001; Sawai et al., 2008); estimating recurrence intervals of great earthquakes (Atwater and Hemphill-Haley, 1997; Nelson et al., 1995); and defining different patterns of rupture along a subduction zone (Cisternas et al., 2005; Kelsey et al., 2002; Nelson et al., 2006; Sawai et al., 2004). Since publication of the seminal paper (Atwater, 1987), and widespread adoption of well-tested field and analytical methods (e.g. Atwater and Hemphill-Haley, 1997; Hayward et al., 2006; Kelsey, 2015; Nelson, 2015; Nelson et al., 1996; Witter, 2015) debate moved on to questions critical for hazard

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assessment, emergency planning and international building code design (Mueller et al., 2015; Wesson et al., 2007). Key questions include the extent of past great earthquake ruptures (a proxy for magnitude), the identification of the boundaries between rupture segments, the persistence of these boundaries over multiple earthquake cycles, recurrence intervals of great earthquakes in each segment, the role of aseismic slip, and whether segments of plate boundaries that are currently creeping can generate great earthquakes (Briggs et al., 2014; Goldfinger et al., 2012; Hayward et al., 2015; Kelsey et al., 2015; Mueller et al., 2015; Scholz, 2014; Witter et al., 2014).

In order to address these questions, coastal paleoseismology continues to seek evidence to discriminate between alternative hypotheses. This inevitably results in returning to the field evidence and the quantifiable resolution of the age, the extent, and the pattern of vertical surface displacement of each rupture. Tidal wetlands record evidence of relative sea-level change, whether submergence or emergence. Such evidence may reflect coseismic displacement of the Earth's crust, but this requires an evaluation of the evidence leading to one or more interpretations. Submergence is not a synonym for subsidence, or emergence for uplift. Typically, in areas of coseismic subsidence, freshwater peat rapidly submerges into the intertidal zone (Fig. 1). This results in a peat-mud couplet, with a sharp boundary between the units (Atwater, 1987). In areas of coseismic uplift, where clastic tidal flat emerges above the local high tide limit, freshwater peat starts to form. This results in a mud-peat couplet, also with a sharp boundary (Fig. 1). As the amount of coseismic surface displacement decreases, for example towards the periphery of uplift or subsidence, we expect to reach the point at which a line of evidence cannot distinguish between seismic and non-seismic explanations for the field stratigraphy. This is the detection limit for that type of evidence. Similarly, the resolution of radiocarbon dating places an uncertainty on earthquake ages and correlations between sites.

With different interpretations possible from seemingly similar stratigraphic sequences, Nelson et al. (1996) suggested five criteria to distinguish peat-mud couplets that result from great earthquake subsidence from those produced by other processes. They suggested, 1 – lateral extent of peat-mud couplets with sharp contacts; 2 – suddenness of submergence; 3 – amount of vertical motion; 4 – presence of tsunami deposited sediments directly above the peat horizon, and, 5 – synchroneity with other sites. While these criteria were proposed with respect to tidal marsh sequences adjacent to the Cascadia subduction zone, they have proved valuable for numerous studies since (e.g. Briggs et al., 2014; Clark et al., 2015; Dura et al., 2015, 2016, 2011; Engelhart et al., 2013; Garrett et al., 2015b; Grand Pre et al., 2012; Hamilton and Shennan, 2005a; Hayward et al., 2015; Kelsey et al., 2015; Leonard et al., 2004; McCalpin and Carver, 2009; Nelson et al., 2006, ; Shennan et al., 2009; Witter et al., 2003).

In this review, we first introduce general principles regarding indicators of relative sea-level change in tidal wetlands and the conditions in which paleoseismic indicators must be distinct from those resulting from non-seismic processes.

Section 3 summarises the tectonic setting and Holocene chronology of great earthquakes in the region of the 1964 Alaska M_W9.2 earthquake since we use evidence from this region to revisit the criteria recommended by Nelson et al. (1996) for identifying coseismic subsidence and use the evidence to test working hypothesis of variable rupture modes during the late Holocene.

In section 4, we consider developments over the past 20 years in popular methods of reconstructing relative sea-level change and their application to paleoseismic records from tidal wetlands.

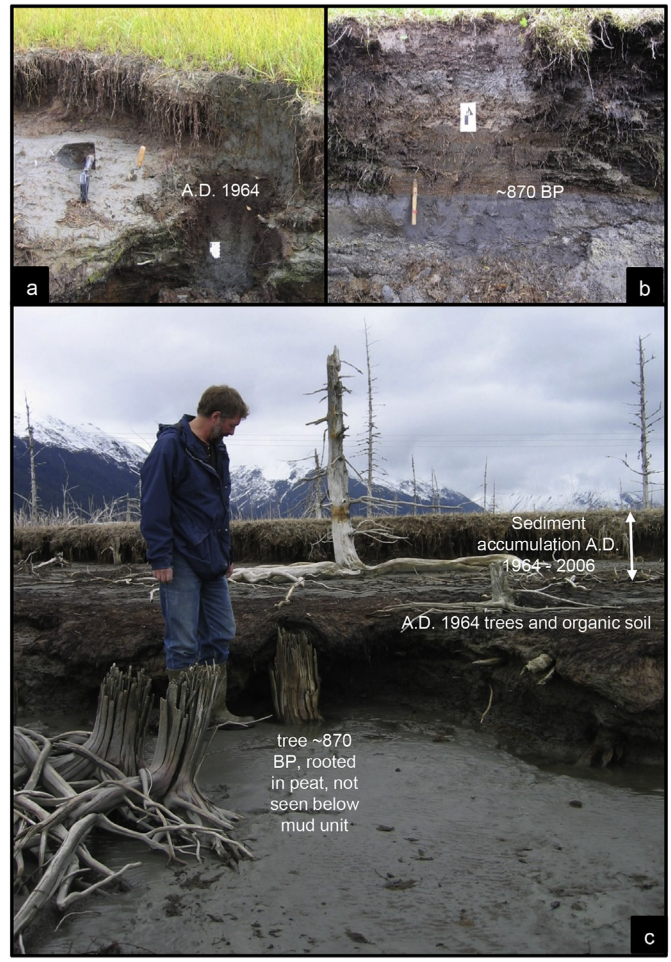

Fig. 1. a) Peat-mud couplet representing the AD 1964 earthquake at Girdwood, Alaska, and ~0.5 m sediment accumulation since (Photograph September 2006). The peat layer represents the freshwater marsh that subsided at least 1.5 m in AD 1964, regional subsidence 1.5 m and locally up to an additional 0.9 m from sediment compaction (Plafker et al., 1969). b) Mud-peat couplet at Katalla, represent coseismic uplift of unvegetated tidal flat ~870 BP and colonisation by freshwater peat-forming communities (Shennan et al., 2014c). c) Ghost forest at Girdwood, with trees killed following subsidence in AD 1964 and subsequent tidal sedimentation. Tree stump from the penultimate great earthquake in the region, ~870 BP, is rooted in a peat-mud couplet a few decimetres below the surface and its top extends to the peat unit of the AD 1964 peat-mud couplet (Photograph May 2006).

Section 5 presents evidence from sites across southcentral Alaska to illustrate different detection limits and how these constrain alternative interpretations for marsh submergence and emergence. In section 6, we evaluate the predicted surface displacement of different rupture modes against the reconstructions of marsh submergence and emergence based on field data.

In the final sections, we consider the broader implications of detection limits of tidal wetland sequences at subduction zones around the world and suggest an expansion of the Nelson et al. (1996) criteria.

2. Indicators of coseismic displacement of tidal wetlands

The detection limits of tidal wetland sediment sequences that produce identifiable paleoseismic evidence depend upon two