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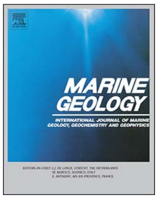

Invited research article

Coastal erosion and recovery from a Cascadia subduction zone earthquake and tsunami

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ABSTRACT

Tsunamis generated by great earthquakes threaten coastal infrastructure, development, and human life. Earlier work has documented the inland extent and frequency of past tsunamis, but little is known about the magnitude of material eroded during prehistoric tsunamis and how erosion and coastal recovery are recorded in coastal stratigraphy. In this study we use high-resolution ground-penetrating radar (GPR) to image and quantify coastal erosion experienced during a late Holocene (~900 cal BP) Cascadia subduction zone earthquake and tsunami along the northern California coast. The GPR profiles illustrate three stratigraphic signatures created during co-seismic subsidence and tsunami erosion and coastal recovery. The first is erosional truncation of the underlying seaward-dipping reflections created by pre-tsunami normal beach progradation. The second is a series of landward-dipping, flat-lying, and channelized reflections marking the filling of erosional topography and coastal reworking of the irregular shoreline following inundation and erosion. The third is an abrupt landward termination of the stratigraphic unit marking coastal straightening and post-tsunami rejuvenation of normal coastal progradation. Erosion from the ~900 cal BP earthquake and tsunami extended > 110 m inland of the contemporary shoreline and removed/reworked 225,000 ± 28,000 m^3 of sand from a 1.7-km stretch of the coast, far exceeding anything experienced during historical El Niños along the Pacific Coast of North America. This study provides the first quantitative estimate of the amount of coastal erosion from a pre-historic earthquake and tsunami and outlines a strategy for estimating erosion during similar events elsewhere.

1. Introduction

Recent tsunamis created by large megathrust earthquakes in Sumatra, Chile and Japan resulted in large losses of life and extensive damage to coastal infrastructure (Bondevik, 2008; Goto et al., 2011; Mimura et al., 2011). These events have renewed efforts to understand the impacts and frequency of past tsunamis on coastlines. New studies have improved our ability to identify their deposits in the sedimentary record (Gelfenbaum and Jaffe, 2003; Switzer et al., 2006; Morton et al., 2007; Gouramanis et al., 2015) and determine the inland extents and frequencies of past tsunamis across the globe (Kelsey et al., 2002; Schlichting and Peterson, 2006; MacInnes et al., 2016). However, despite these advances, identifying past tsunami deposits in areas marked by sandy shorelines without muddy or peaty back-barrier deposits remains difficult.

An important impact of tsunamis is coastal erosion (Paris et al., 2009). Recent tsunamis in Sumatra (Paris et al., 2009; Liew et al., 2010) and Chile (Morton et al., 2011) resulted in extensive erosion of low-lying coastal regions. Coastal erosion can remove important natural resources needed not only for local economic extraction but also as a magnet for the increasingly important tourism industry along many coastal regions (Adger et al., 2005). However, few methods have been developed to quantify coastal erosion experienced during past earthquakes and tsunamis. Understanding the nature of past coastal erosion experienced during earthquakes and tsunamis could be an important tool for establishing proper setbacks and foundation designs for the development of coastal infrastructure.

Tsunamis created by late Holocene ruptures of the Cascadia subduction zone (CSZ) inundated much of the northern California coast (Peterson et al., 2011; Valentine et al., 2012; Fig. 1). The sandy beaches of the coastal plain north of Crescent City, California provide an excellent natural laboratory to explore the impacts of past earthquakes and tsunamis on sandy shorelines. In this study we use ground-penetrating radar (GPR) and optically stimulated luminescence (OSL) dating to build a model of how co-seismic subsidence and tsunami impacts are recorded in beach stratigraphic sections and provide the first

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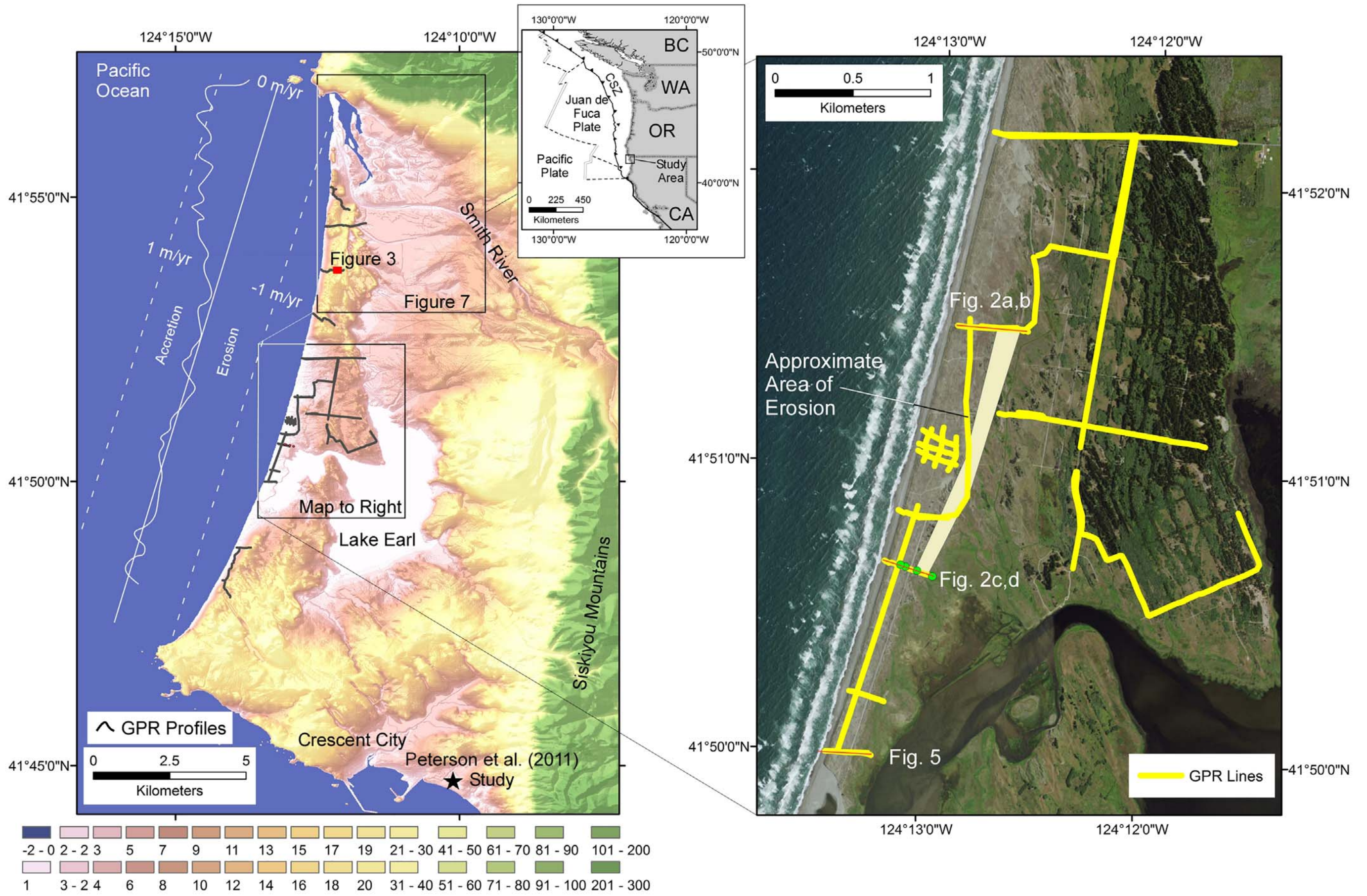

Fig. 1. Digital elevation model (DEM; Gesch, 2007; Left) and aerial photograph (from ESRI; Right) of the study area illustrating the location of the ground-penetrating radar (GPR) profiles and cores (green circles) collected as part of this study. Also shown is the extent (tan polygon) of the tsunami erosional surface discussed in the text. Historical beach erosion and accretion rates are shown as a white line (Hapke et al., 2006). Unless noted by "-", scale bar boxes for the DEM are the lower bounds of the elevation ranges in meters. BC = British Columbia, WA = Washington, OR = Oregon, CA = California, CSZ = Cascadia subduction zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

quantitative estimates of coastal erosion from prehistoric co-seismic subsidence and tsunami erosion.

2. Study area

The CSZ marks subduction of the Juan de Fuca plate beneath the North American plate. It stretches for over ~1000-km across the western Pacific margin of North America (Fluck et al., 1997; Fig. 1). Great (> Mw 8) earthquakes, resulting from ruptures within the fault zone, occur approximately every 300–500 years (Atwater, 1987; Atwater and Hemphill-Haley, 1997; Nelson et al., 2006; Goldfinger et al., 2012; Milker et al., 2016). These earthquakes are known to have generated not only coastal subsidence (Atwater, 1987; Shennan et al., 1996; Nelson et al., 2008; Hawkes et al., 2011) but also great tsunamis (Kelsey et al., 2005) that struck the coast from Vancouver Island, British Columbia (Clague et al., 2000) to northern California (Clarke and Carver, 1992; Valentine et al., 2012). The most recent tsunamigenic event occurred January 26, 1700 (Satake et al., 1996) with two preceding events around 800 cal BP (Nelson et al., 2008; Schlichting and Peterson, 2006) and 1000 cal BP (Kelsey et al., 2005; Schlichting and Peterson, 2006). The turbidite record of events also suggests another great earthquake occurred around 500 cal BP with potentially three other smaller events after 1000 cal BP (Goldfinger et al., 2012), although coastal records for these events have yet to be identified (Nelson et al., 2006; Milker et al., 2016). Their absence in the coastal record may be due to not being large enough to create a signature or creating a signature too small for preservation in coastal settings.

The Crescent City coastal plain is a low-elevation (< 30 m) expanse of Quaternary Smith River alluvial, late Pleistocene marine terrace, and Holocene strandplain and aeolian deposits located between the Saint George and Smith River Faults within the Lake Earl syncline (Polenz and Kelsey, 1999). The southwest-northeast oriented contraction is a result of overall convergence along the CSZ (Polenz and Kelsey, 1999). Subsidence within the syncline led to the development of a relatively flat, low-lying coastal plain. Sediment delivered by the Smith River at the northern portion of the coastal plain is generally transported south forming a prograding strandplain marked by sandy beach and dune deposits backed by a coastal lake, Lake Earl (Fig. 1; Polenz and Kelsey, 1999). These Holocene coastal deposits are backed by late Pleistocene marine terraces stepping up to the abruptly rising Klamath Mountains (Fig. 1). The area is particularly susceptible to tsunamis not only generated by the CSZ but also within the Gulf of Alaska (Peterson et al., 2011). A record of no fewer than six past tsunamis are preserved in marshes from the southern portions of the Crescent City coastal plain (Peterson et al., 2011; Fig. 1). The two most recent of which are dated to 270–560 cal BP and 784–954 cal BP and are thought to represent CSZ earthquakes and tsunamis (Peterson et al., 2011).

3. Methods

3.1. Ground-penetrating radar (GPR)

We collected approximately 20 km of GPR data using a Sensors and Software EkkoPulse Pro. Initially lines were collected with 100, 200,