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Combining onshore–offshore paleoseismic records to test for synchronicity of coastal deformation

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Linking onshore evidence of coseismic vertical deformation with offshore evidence of shaking is a powerful technique for better understanding the size, location and spatial impacts of past large earthquakes at subduction margins.

Coastal paleoearthquake records at subduction margins

Geologic evidence of coastal uplift and subsidence is commonly used to investigate the size, location and recurrence of past earthquakes along subduction margins (e.g. Clark et al. 2019). Large ruptures of the subduction interface are inferred by correlating coseismic deformation over large distances (>100 km). However, such spatial correlations are often based on temporal overlap between earthquake ages with uncertainties of >100 years, meaning that coseismic deformation may not have been synchronous (McNeill et al. 1999). That is, the same patterns of coastal uplift and subsidence could have been generated sequentially over decades by multiple smaller earthquakes.

Accurate correlation of coastal paleoearthquake evidence is further complicated by changes in preservation potential between sites and through time according to sea level and local erosion. Challenges imposed by incompleteness and large age uncertainties are compounded at complex subduction margins, such as the Hikurangi margin in New Zealand, where both upper plate faults and the subduction interface contribute to coseismic coastal deformation (Clark et al. 2019; Delano et al. 2023; Pizer et al. 2023a). Ultimately, incorrect paleoearthquake correlations can have implications for hazard preparedness because the spatial extent and age of past ruptures is used to inform the expected size and timing of future earthquakes (e.g. Nelson et al. 2021). Precise dating and careful interpretation of similarly timed paleoearthquake evidence is therefore essential for inferring synchronicity and potential source faults.

Developing turbidite paleoseismology

Submarine turbidites provide a proxy for past earthquakes recorded in the offshore portion of subduction margins where sediment archives are often longer and more complete than at the coast (Goldfinger 2011). Offshore, large gravity flows called "turbidity currents" transport remobilized sediment to the deep ocean where "turbidites" are deposited and preserved. Turbidity currents can be triggered by a number of processes, including gas-hydrate destabilization, storms and shaking during large earthquakes (Howarth et al. 2021).

The most robust way to rule out non-seismic triggers is to demonstrate that turbidity currents were initiated simultaneously over large areas (>100 km), since regionally synchronous triggering is unlikely to occur by coincidence (Goldfinger 2011). Usually, this is achieved by correlating event beds between cores from widely spaced, disconnected submarine distributary systems based on overlapping age ranges. Therefore, precise dating of turbidites is imperative to minimize age uncertainties and ensure that core-to-core correlations are unique (Hill et al. 2022).

Using turbidites to test for synchronicity of spatially-distributed coastal deformation

An independent test for an earthquake-related trigger for episodes of regional turbidite emplacement can be conducted by comparing turbidite ages against the coastal paleoearthquake record (Ikehara et al. 2016; Usami et al. 2018). Good agreement between the timing of events in both records indicates that turbidity currents were probably initiated by ground shaking during the same earthquakes that produced coseismic coastal deformation. Integrating the spatial information from both proxies can therefore help to reconstruct the extent of past earthquakes. In particular, the combined approach provides an opportunity to test the synchronicity of correlated coastal deformation by examining the number of turbidites deposited in each distributary system within the timeframe of onshore earthquake-age uncertainty (Fig. 1). For example, if a single large earthquake caused widespread synchronous deformation at the coast, we would expect to observe a single turbidite event bed in multiple submarine distributary systems (Fig. 1a). However, if multiple smaller earthquakes caused local deformation at different coastal sites within a few decades, we would expect to observe multiple turbidites offshore (Fig. 1b).

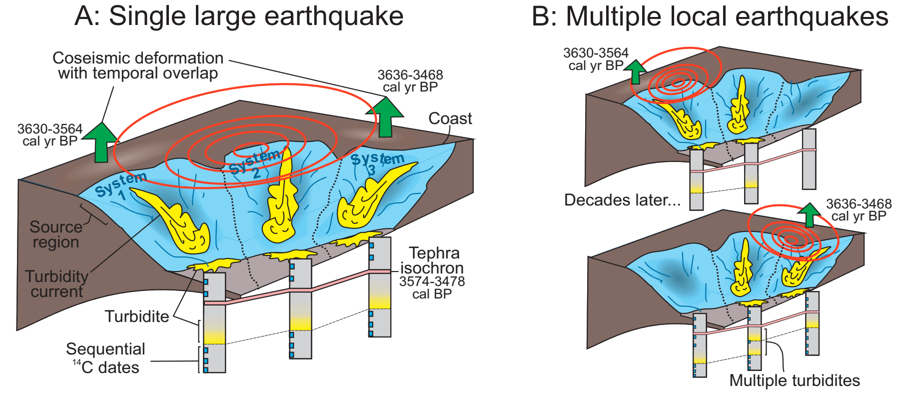

Figure 1: Schematic demonstrating the expected patters of turbidite deposition if coastal coseismic deformation (uplift) was caused **(A)** synchronously at both sites in a single large earthquake, or **(B)** sequentially in multiple smaller earthquakes. Chronology corresponds to the example in figure 2.

We tested the hypothesis in figure 1 with an example from the central Hikurangi subduction margin, New Zealand (Fig. 2), where two coastal sites ca. 100 km apart record similarly timed coseismic deformation. In southern Hawke's Bay, coastal sediments from Pākuratahi display an abrupt change from estuarine silt to forest peat (Fig. 2d), indicating rapid sea-level fall, interpreted as coseismic uplift at 3630–3564 cal yr BP (Pizer et al. 2023a; Fig. 2c). In northern Hawke's Bay, coseismic uplift of a marine terrace at Māhia Peninsula is dated to 3636–3468 cal yr BP (Berryman et al. 2018; Fig. 2c). The earthquake ages are uniquely well-constrained due to stratigraphic evidence of the precisely dated Waimihia tephra isochron, deposited decades after the earthquake (Pizer et al. 2023b). Independent of the overlapping ages, the simplest explanation for coseismic uplift at both sites is earthquakes on nearby upper plate faults. Pākuratahi was recently uplifted by ca. 2 m in the 1931 CE moment magnitude (M_w) 7.4 Napier earthquake (Hull 1990), so similar earthquakes on the Awanui fault could generate comparable vertical deformation. No historical earthquakes have occurred on the Lachlan fault, but coseismic uplift of the

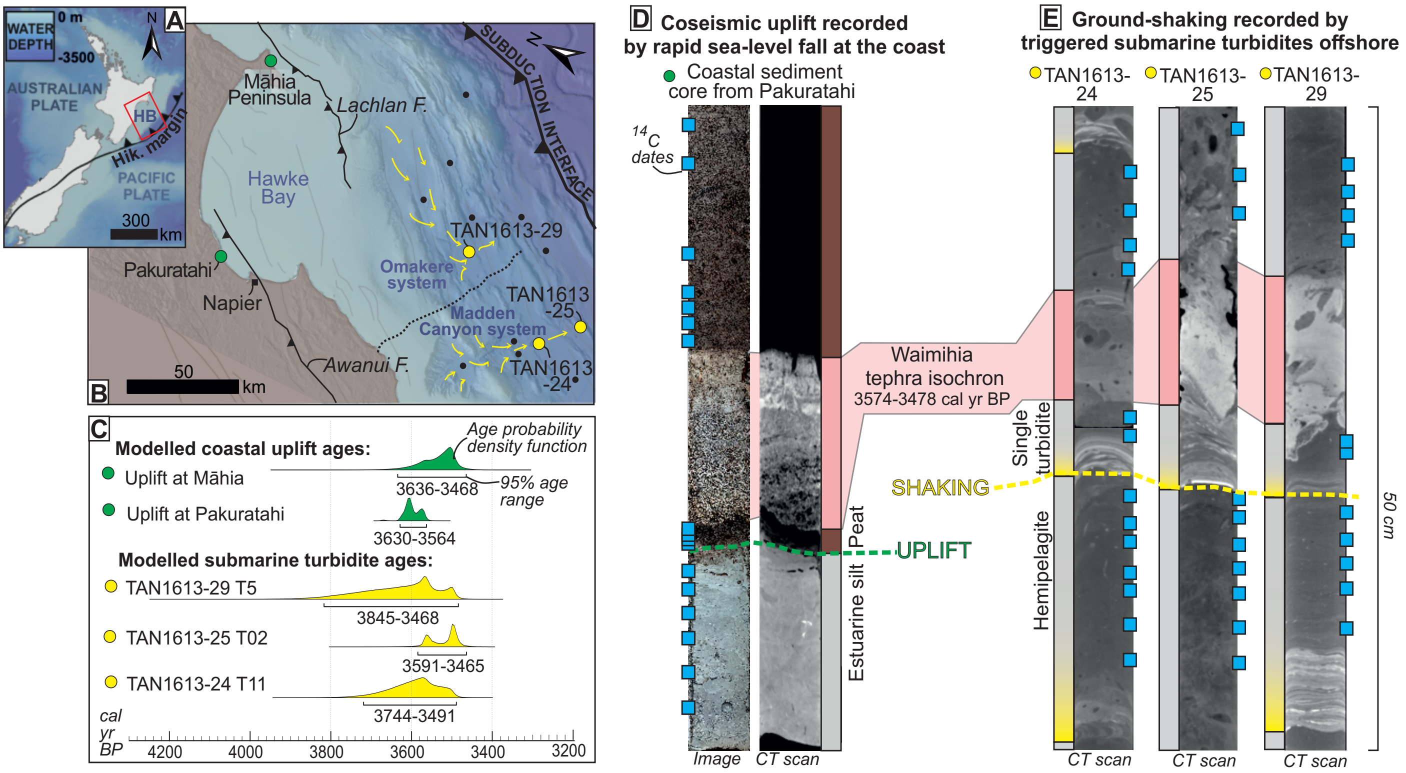

Figure 2: (A) Location of the Hikurangi (Hik.) margin off the east coast of the North Island, New Zealand, and **(B)** central section spanning Hawke's Bay (HB) with faults and paleoseismic sites. Green dots are coastal sites Māhia Peninsula (Berryman et al. 2018) and Pakuratahi (Pizer et al. 2023a). Black dots are submarine turbidite cores. Yellow dots are cores from Madden Canyon and Omakere distributary systems (Barnes et al. 2017), dated in Pizer et al. (2023b). Yellow arrows represent the flow direction of turbidity current pathways. The dotted line represents the boundary between catchments. **(C)** Modeled age probability density functions (PDFs) for correlated turbidites offshore and coseismic uplift onshore. **(D)** Evidence for coseismic uplift at Pakuratahi and **(E)** turbidites in the Omakere and Madden Canyon (as X-ray computed tomography (CT) scans).

Māhia Peninsula has been demonstrated in elastic dislocation models (and repeatedly in the paleorecord; Berryman et al. 2018).

Offshore, sediment cores containing Holocene sequences of submarine turbidites and hemipelagic background sediment were collected from discrete distributary systems along the central Hikurangi margin (Barnes et al. 2017; Fig. 2b). Correlation between the cores is facilitated by the same macroscopic Waimihia tephra isochron identified onshore (Pizer et al. 2023b). In all cores there is a single turbidite directly beneath the tephra layer (e.g. Fig. 2e). Three cores from the Madden Canyon and Omakere distributary systems were selected for high-resolution, sequential radiocarbon dating and age-depth modeling which produced turbidite ages closely matching the coseismic uplift at Pākuratahi and Māhia Peninsula (Fig. 2c).

Together, the upper-slope source areas for turbidity currents in the Madden Canyon and Omakere distributary systems span northern and southern Hawke's Bay (Fig. 2). As a result, we would expect to see multiple turbidites if separate earthquakes were responsible for generating the similarly timed deformation at Pākuratahi and Māhia Peninsula. Since we only observe a single turbidite offshore, we suggest that the coastal deformation at both sites was caused by a single earthquake. The extent of synchronous deformation (and shaking) across >100 km indicates a large magnitude earthquake which probably involved many upper plate faults rupturing together. This style of multi-fault rupture has not previously been considered in Hawke's Bay due to the large stepovers between faults (Fig. 2b). However, as seen for the 2016 M_w 7.8 Kaikōura earthquake on the southern Hikurangi margin (Wang et al. 2018), slip on the subduction interface can help to propagate rupture across seemingly disconnected upper plate faults. The new insights from our integrated onshore–offshore paleoearthquake evidence highlight a need to incorporate complex rupture scenarios within seismic-hazard models and planning for future earthquakes on the central Hikurangi margin.

Summary

Correlating paleoseismic evidence across multiple sites is fundamental for deciphering the spatial extent and source faults for past earthquakes so that future hazard can be accurately assessed. Earthquake age-uncertainties within coastal deformation records are often too large to make unique correlations to confirm synchronous coseismic deformation. Offshore, the same events can be recorded by seismically-triggered submarine turbidites which, if carefully dated and correlated between multiple discrete distributary systems, can aid interpretation of coastal paleoearthquake evidence. For periods where regional turbidite-triggering coincides with coseismic deformation, the number of turbidites can indicate whether correlated coastal evidence represents multiple smaller earthquakes, or one larger one. Using an example from the central Hikurangi margin, we demonstrate the novel perspective provided by integrating onshore and offshore proxies, which has helped to link evidence of coastal uplift at sites separated by >100 km, to a single earthquake. Where possible, the same approach should be developed at other subduction margins to more robustly estimate the size, recurrence and source of past earthquakes.

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