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Relationship between fault source, ground motions and marine turbidites emplaced by the 2016 CE Kaikōura earthquake

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Observations of the 2016 CE M_w 7.8 Kaikōura earthquake, and the seafloor deposits it produced, demonstrate a predictable relationship between fault source, ground motions and the deposition of deep-sea turbidites, confirming key assumptions that underpin turbidite paleoseismology.

Resolving persistent debates about turbidite paleoseismology

Subduction zones have produced some of the largest and most damaging historical earthquakes, but our understanding of the dynamics and hazards they pose is critically limited by the paucity of high-resolution paleoseismic records that span millennia (Sieh et al. 2008). To reconstruct among the most comprehensive records of subduction zone earthquakes, turbidite paleoseismology uses earthquake-triggered event beds generated from deep-sea turbidity currents (Goldfinger et al. 2012; Patton et al. 2015). Whilst turbidite paleoseismology studies are growing, debate persists about the key assumptions that underpin the approach and the validity of their earthquake records (Atwater et al. 2014; Goldfinger et al. 2017; Shanmugam 2009; Sumner et al. 2013). Resolving these debates requires accurate measurement of the earthquake source and accompanying strong ground motions (SGM), together with interrogation of earthquake-generated turbidites in discrete sediment dispersal systems along subduction margins.

The 2016 moment magnitude (M_w) 7.8 Kaikōura earthquake provides a compelling case study because it is amongst the best characterized using instrumental data (Clark et al. 2017; Hamling et al. 2017) and models (Ulrich et al. 2019) (Fig. 1). The earthquake ruptured more than 20 onshore and offshore faults along ~180 km of the northeastern South Island of New Zealand (Litchfield et al. 2018). Models of SGM produced by the earthquake are well corroborated by station data and show motion propagated predominantly in a northeasterly direction along the southern Hikurangi Margin (Wallace et al. 2017).

The spatial relationship between SGM and turbidite deposition

Submarine canyons that supply sediment to the Hikurangi Channel are oriented both parallel and perpendicular to the rupture; an ideal context for evaluating the relationship between SGM and turbidite deposition (Fig. 1b). The distribution and stratigraphy of the Kaikōura earthquake event bed (KEB) was determined using an extensive set of multicores that preserve the sediment-water interface. Cores were collected from over 100 sites during multiple field campaigns along the Hikurangi Subduction Margin that occurred from days to five years post-earthquake. The core sites sampled 20 discrete submarine canyons, or slope-basins, along ~700 km of the southern-central Hikurangi Margin and ~1500 km of the Hikurangi Channel. The KEB was identified in 69 cores from 10 consecutive feeder canyons along a >200 km segment of the southern Hikurangi Margin, using a combination of indicators for recent deposition and short-lived radioisotope dating (^{234}Th, ^{210}Pb) (Howarth et al. 2021; Mountjoy et al. 2018). The KEB was emplaced in canyons up to 120 km northeast of the northern rupture tip, and 15 km southeast of the southern extent of the rupture (Hayward et al. 2022; Howarth et al. 2021) (Fig. 1b).

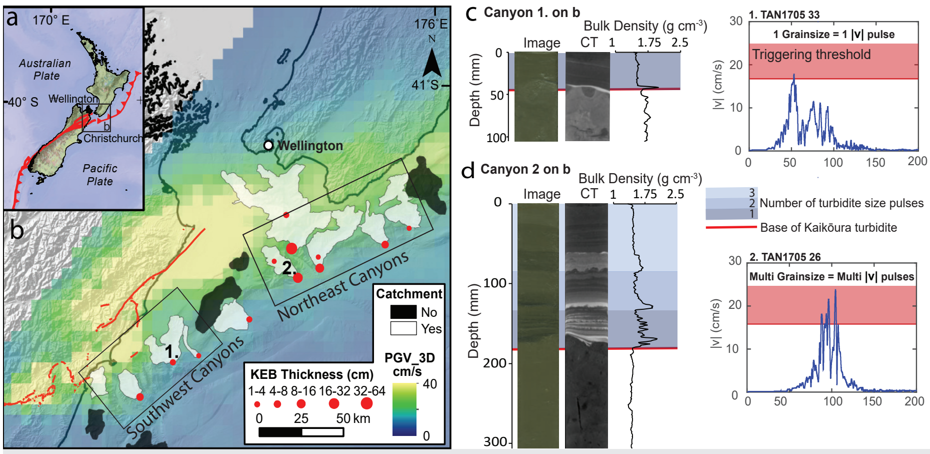

Figure 1: (A) Tectonic setting. **(B)** Kaikōura fault rupture (red lines), ground motions (color ramp) and submarine canyon catchments with the Kaikōura event bed (KEB; irregular white polygons, red circles). **(C-D)** Core image, Computed Tomography (CT) image, density of sediment cores and modeled velocity-time histories for the Kaikōura earthquake at representative canyons. Turbidite structures are sympathetic with contrasts in the SGM between southwestern (C) and northeastern canyons (D). Figure modified from Howarth et al. (2021).

A physics-based ground-motion simulation of the Kaikōura earthquake qualifies the relationship between turbidite deposition and the spatial pattern of shaking. Modeled peak-ground velocities (PGV) were highest along the rupture and northeast of its tip due to the earthquake's nucleation location and rupture direction (Wallace et al. 2017). The pattern of SGM northwards along the rupture, and beyond, directly correlated to the occurrence of the KEB at canyon outlets (Fig. 1b). Comparison of PGV between canyons with the KEB, and those without, indicate that threshold PGVs for emplacing turbidites ranged from 16–25 cm/s, constraining the SGMs required to locally trigger turbidity currents.

These observations reinforce a predictable relationship between fault source, SGM and the deposition of turbidites in discrete canyons along a subduction margin, fundamental to turbidite paleoseismology. However, the Kaikōura earthquake example also demonstrates that asymmetric radiation of ground motions from a specific fault source can complicate the spatial relationships between turbidite emplacement and fault rupture. Careful attribution of fault sources from turbidite paleoseismic reconstructions is needed, informed by physics-based ground-motion simulations to account for nucleation location and directivity effects (Howarth et al. 2021). The nuanced relationship between fault rupture, SGMs and turbidite emplacement realizes the possibility of resolving the dynamics (nucleation location and rupture direction) of paleoearthquakes when turbidite paleoseismology is combined with SGM modeling (Howarth et al. 2021).

Establishing turbidite synchronicity

Paleoseismologists often rely on relative dating techniques such as turbidite "fingerprinting" and the "confluence test", to infer along-margin synchronous emplacement of earthquake-generated turbidites, because absolute dating techniques offer only decadal uncertainties. The validity of both approaches remains contentious and might only be resolved through test cases like the Kaikōura earthquake, where the spatial distribution and structure of the KEB can now be defined with unprecedented detail.

Turbidite "fingerprinting" underpins arguments for synchronicity based on the similarities in turbidite structure between different canyon systems (Goldfinger et al. 2012). The KEB is near ubiquitous in the middle and lower reaches of canyons feeding the Hikurangi Channel (Fig. 2a). In these canyon reaches KEB structure is characterized by one or more grain-size pulses (Fig. 1c, d). Core transects across Opouawe Canyon show a consistent number of grain-size pulses in cores located between 10–50 m above the canyon axis. These field insights informed a coring strategy optimized for turbidite paleoseismology.

Regional core analysis shows that in the southwestern canyons the KEB has just a single grain-size pulse, whereas northeastern canyons have multiple pulses (Fig. 1c, d). Grain-size pulses in the KEB broadly correlate to the number of high amplitude peaks above the triggering threshold (16–25 cm/s) in SGM histories felt in these canyons (Fig. 1c, d). This potential link between ground motion and turbidite structure provides a mechanism to explain why turbidites in discrete canyons, separated by hundreds of kilometers, often have the same number of grain-size pulses (Goldfinger et al. 2012; Howarth et al. 2021), supporting application of turbidite "fingerprinting" as a paleoseismological tool. Regional variability in KEB structure, however, also highlights the challenge of a fingerprinting approach based on turbidite structure alone. If the suite of KEB deposits occurred in the geologic record, a dual fingerprint of single- and multi-pulse turbidites would likely be misinterpreted as two separate earthquakes.

In silt-rich turbidity current systems, such as the Hikurangi Subduction Margin, turbidite fingerprints may be further compounded by the low-preservation potential of silt-rich turbidites. Repeat coring at specific sites, over a five-year period post-earthquake, demonstrates substantial bioturbation is overprinting primary sedimentary structures of the KEB where it is thin (<10 cm) and dominated by silt-rich facies (Fig. 2c). Ongoing work quantifying variability in the volume and rate of bioturbation, together with its sedimentary and biological controls, will evaluate the KEB preservation potential and possible

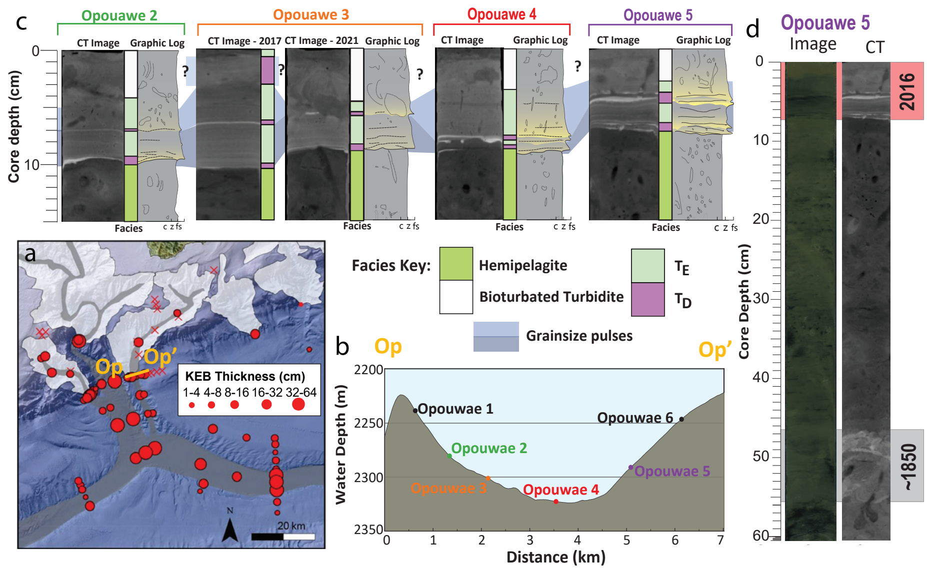

Figure 2: (A) Dense sampling of the Kaikōura event bed (KEB) through a major confluence traversed by the Kaikōura earthquake-triggered turbidity current. **(B)** Core transect across the mid-reaches of the Opouawe Canyon (Op-Op' in yellow) showing correlated KEB structures (grain-size pulses) between turbidites and the influence of bioturbation on preservation **(C)**. **(D)** Representative multicore showing KEB and the underlying penultimate event bed.

implications for the geological record. Hence, we recommend future attempts at turbidite fingerprinting utilize a multi-proxy approach that incorporates both the physical and geochemical characteristics of event beds.

The confluence test assumes that synchronously triggered flows in separate canyons produce a single turbidite above and below the confluences of submarine canyons/channels. Asynchronous flows are additive, producing one deposit in each channel above the confluence, and more than one below (Goldfinger et al. 2012). In practice, the confluence test is achieved by quantifying the number of turbidites between two temporal datums, above and below the confluence. The 2016 Kaikōura earthquake emplaced a single turbidite above and below major canyon/channel confluences (Howarth et al. 2021). Preliminary radiometric ages of the penultimate turbidite across multiple canyons suggests preservation of historical earthquakes (e.g. 1855 CE M_w 8.2 Wairarapa, 1848 CE M_w 7.5 Marlborough) (Fig. 2d), ideal for a critical assessment of the confluence test in the southern Hikurangi Margin.

Conclusions

The predictable relationship between well-constrained observations of the 2016 Kaikōura earthquake fault source, SGMs and turbidite emplacement in discrete distributary systems along the southern Hikurangi Margin validates key assumptions in turbidite paleoseismology. More observational studies of turbidite deposition following well-instrumented earthquakes are required to refine our understanding of how turbidites record earthquake SGMs. However, turbidite paleoseismology's future is bright. Our improved ability to elucidate the dynamics of paleoearthquakes by qualifying spatial variations in ground motions may inform attributes, such as nucleation location and rupture direction, that were previously beyond the reach of paleoseismic investigation.

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