11TH IAG INTERNATIONAL CONFERENCE ON GEOMORPHOLOGY

FIELDTRIP GUIDE

KAIKŌURA PENINSULA TECTONICS, MARINE TERRACES AND SHORE PLATFORMS

2026

IAG GEOMORPHOLOGY | ANZGG Australian & New Zealand Geomorphology Group | manatiaki kōawa rivers GROUP A joint technical interest group of Engineering New Zealand & Water NZ

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Cover Photos: Wairongomai-Mangarara (Credit: Ian Fuller), Aoraki Mt. Cook National Park (Credit: Sam McColl), and Waikato at Taupo (Credit: Sarah McSweeney).

Field Trip Guide: Kaikōura Peninsula Tectonics, Marine Terraces and Shore Platforms

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Proposed walking tour

Well make a short stop in Kaikōura township – for a quick look and last chance to pick up food and water if needed.

Itinerary

7:30 AM – Depart Te Pae (10-minute comfort stop at Cheviot).

10:30 AM – Stop 1: Kaikōura township then bus Avoca Point (Fyffe House).

Location: Shore platform directly in front of the historic house associated with whaling that was central to European colonisation of the area.

View the contact between the Waima mudstone alongside the limestone (Spyglass Formation).

The Micro-erosion Meter (MEM) Network

- This site hosts MEM Profile KM1, part of a network established in 1973 by Kirk (1977). The MEM network provided 43-years of platform downwearing data prior to the November 2016 earthquake.
- Prior to 2016, the mean annual erosion rate across the peninsula was 0.94 mm/yr. Following the 1.0 m uplift, this rate more than doubled to 2.34 mm/yr.
- Process (Slaking): Observe the desiccation cracks on the uplifted Waima mudstone. Post-uplift, the annual "drying hours" increased by 159% at this site (KM1). The extended drying duration drives slaking (clay swelling/shrinking), which fractures the mudstone surface.

11:15 AM – Stop 2: Walk to Point Kean along Armers Beach

Location: Walk east along the road, drop onto the beach and walk along the front of the new marine terrace. Note the riprap structure built prior to 2016 to protect the road from coastal erosion.

The "Incomplete" Paleoseismic Record (also seen at stop 7)

- The "New" Terrace: The platform here is a nascent Holocene Coseismic Marine Terrace (HCMT).
- Survivability: Based on the post-2016 erosion rates (>2.5 mm/yr) and vertical land movement (-3.1 mm/yr), this new terrace is predicted to be eroded entirely within 200 to 552 years, more on this wild prediction later.
- Implication: If the earthquake recurrence interval is 500–850 years, this terrace may be erased *before* the next event preserves it. This suggests that flights of Holocene marine terraces are likely incomplete records of past seismicity.
- Holocene Terraces: Looking across the road into the paddock are two older terraces mapped from bore holes by Howell & Clark (2022).
    - T1 (Lowest, ~4m amsl): Attributed to Earthquake 1 (E1), dated to cal. 437–236 yr BP.
    - T2 (Middle, ~6m amsl): Attributed to Earthquake 2 (E2), dated to cal. 1111–801 yr BP.

12:00 PM – Stop 3: Point Kean Platform (Lunch and comfort stop)

Location: The Mudstone platform tip (MEM profile KM3).

Lithological Control & enhanced Seasonality

- During lunch stop take the short walk to the viewing platform at the top of the path by the toilet block, this provides great views over the platforms and across the Pleistocene terraces behind.
- Mudstone vs. Limestone: We transition here from the mudstone to the indurated Amuri Limestone as we move towards Whalers Bay (stops 4 and 5). Post-uplift erosion rates now show a statistically significant difference based on lithology:
    - Limestone: Averaged 1.19 mm/yr.
    - Mudstone: Averaged 3.21 mm/yr.
- Seasonality: Pre-2016, erosion rates showed distinct seasonal trends (higher in summer due to wetting/drying). Post-uplift, this seasonality has been retained but driven by different processes (Kirk et al., in review). The intense subaerial weathering now occurring in the supratidal zone drives higher summer erosion rates.

12:30 PM – Stop 4: Traverse to Whalers Bay

Route: Walk the shoreline around the base of the cliffs.

Scale Issues in Measurement (SfM vs. MEM)

- The Scale Problem: As we walk from mudstone to limestone, observe the larger scale flaking and block removal in the limestone.
- Key Finding: Structure-from-Motion (SfM) photogrammetry reveals that MEM bolts underestimate total erosion. At mesoscale sites (1 m^2), SfM recorded mean erosion rates of 10.30 mm/yr, nearly five times higher than the MEM average of 2.24 mm/yr at the same locations.
- Process: The SfM data captures "uncaptured" erosion—large flakes or blocks that sit *between* MEM bolts.

2:30 PM – Stop 5: Whalers Bay

Location: The sheltered southern bay.

Stratigraphy & Structure

- Spot the contact between the Amuri Limestone (early Eocene) and the overlying Spy Glass Formation (early Miocene). This contact is phosphatised and bored, representing a hiatus in deposition (Figure 2).

- We walk across the unconformity at about 42° 25.665'S 173° 42.705'E. It can also be seen again in South Bay before stop 8.
- Structure: The bay exists because erosion has exploited a structural depression between domed culminations of the Atia Anticline.
- We will also pass the MEM profile KM7.

3:00 PM – Stop 6: The Memorial Lookout (Peninsula Top)

Route: Climb the track to the first Pleistocene terrace.

The Quaternary "Staircase"

- Pleistocene Terrace Sequence: We are standing on a flight of five marine terraces identified by Ota et al. (1996), which record late Quaternary uplift. The sequence (I–V) exhibits a distinct north westward down-tilt.
  - Terrace I (Highest): Elevation 105 m. Age 100ka (Oxygen Isotope Substage 5c). Correlated via amino acid dating of *Tawera spissa*.
  - Terrace II: Elevation 80 m. Age 96 ka.
  - Terrace III: Elevation 60 m. Age 81 ka.
  - Terrace IV: Elevation 50 m. Age 72 ka.
  - Terrace V (Lowest Pleistocene): Elevation 40 m. Age 59 ka.
  - Uplift Rate: These terraces indicate a long-term uplift rate of 1.1 m/ka.

3:45 PM – Stop 7: South Bay

Route: Before descending the track into South Bay there is a good look out with views. As we descend there is a good view of the new marine terrace (largely vegetated now – see Figure 18). On the path down also keep an eye on the bank to your right – greywacke beach gravels can be seen in the cutting, evidence of the late Quaternary uplift (we are a few km from the closest gravel beach). A wonder over the profile of KM6, visit toilet if needed and walk onto the harbour at South Bay.

Modern Infrastructure & Mudstone Dynamics

- Structural Context: We are now located in the core of the Fyffe Syncline, where the Waima Siltstone is preserved[41].
- Kirk's (1977) MEM Profile KM6: Located on this soft siltstone, this site showed some of the highest post-earthquake erosion rates (up to 4.385 mm/yr).

- Passed the toilet, view the waharoa depicting Māui fishing up Te Ika-a-Māui (north Island), linking the peninsula and its coastal landscapes to wider Māori creation and voyage traditions. Wayne will explain how Kaikōura fits into the story.
- Harbour Response: The 1m uplift rendered the marina unusable. Excavation of the bedrock seafloor was required to restore functionality.

4:30 PM-ish: Time permitting we'll end of Field Trip at South Bay harbour (Stop 8).

1. Geological & Tectonic Context

Kaikōura (pronounced "Kye-koh-ra") Peninsula sits on the northeast coast of Te Waipounamu (South Island), at the onshore edge of the Hikurangi margin where subduction of the Pacific Plate beneath the Australian Plate gives way southward to oblique collision and strike-slip on the Marlborough Fault System (Figure 1). The peninsula itself is an asymmetric anticline bounded by synclines, developed in a cover sequence of Paleocene Amuri Limestone and Oligocene mudstones, with locally overlying Late Cretaceous–Paleogene limestone and siltstone and younger upper Tertiary siltstones (Figure 2). There is an unconformity at the top of the Amuri Limestone marked by a slight angular discordance, that separates the Amuri from the overlying, overtly similar, but sandier Spy Glass Formation of Early Miocene age (Browne et al., 2005). These strata are tightly folded and locally faulted and have been uplifted to form a flight of marine terraces and extensive intertidal shore platforms that ring the peninsula and step up to elevations of more than 100 m above sea level.

Regionally, the peninsula is tied into a broader neotectonic framework that includes high-slip strike-slip and thrust faults such as the Hope, Clarence and Kekerengu faults, together accommodating rapid Quaternary deformation of the Seaward Kaikōura Range and adjacent coast. Offshore, the seafloor drops abruptly into the Kaikōura Canyon and the Hikurangi Trough, placing deep water within a kilometre of the coast and focusing oceanic swell on the peninsula. Uplift of the peninsula is now known to be driven largely by a listric Offshore Splay Thrust Fault (OSTF Figure 1) and subsidiary structures such as the Armers Beach and Te Taumanu faults, which produced up to about 1 m of coastal uplift in the 2016 Mw 7.8 Kaikōura earthquake and have cumulatively raised and tilted the Late Quaternary terrace staircase at mean rates on the order of 1 mm/yr. This combination of rapid tectonic uplift, highly energetic Pacific wave climate and relatively weak sedimentary rocks explains both the prominence of the marine terraces and shore platforms, and the response of the Kaikōura rock coast to individual large earthquakes and longer-term plate-boundary deformation.

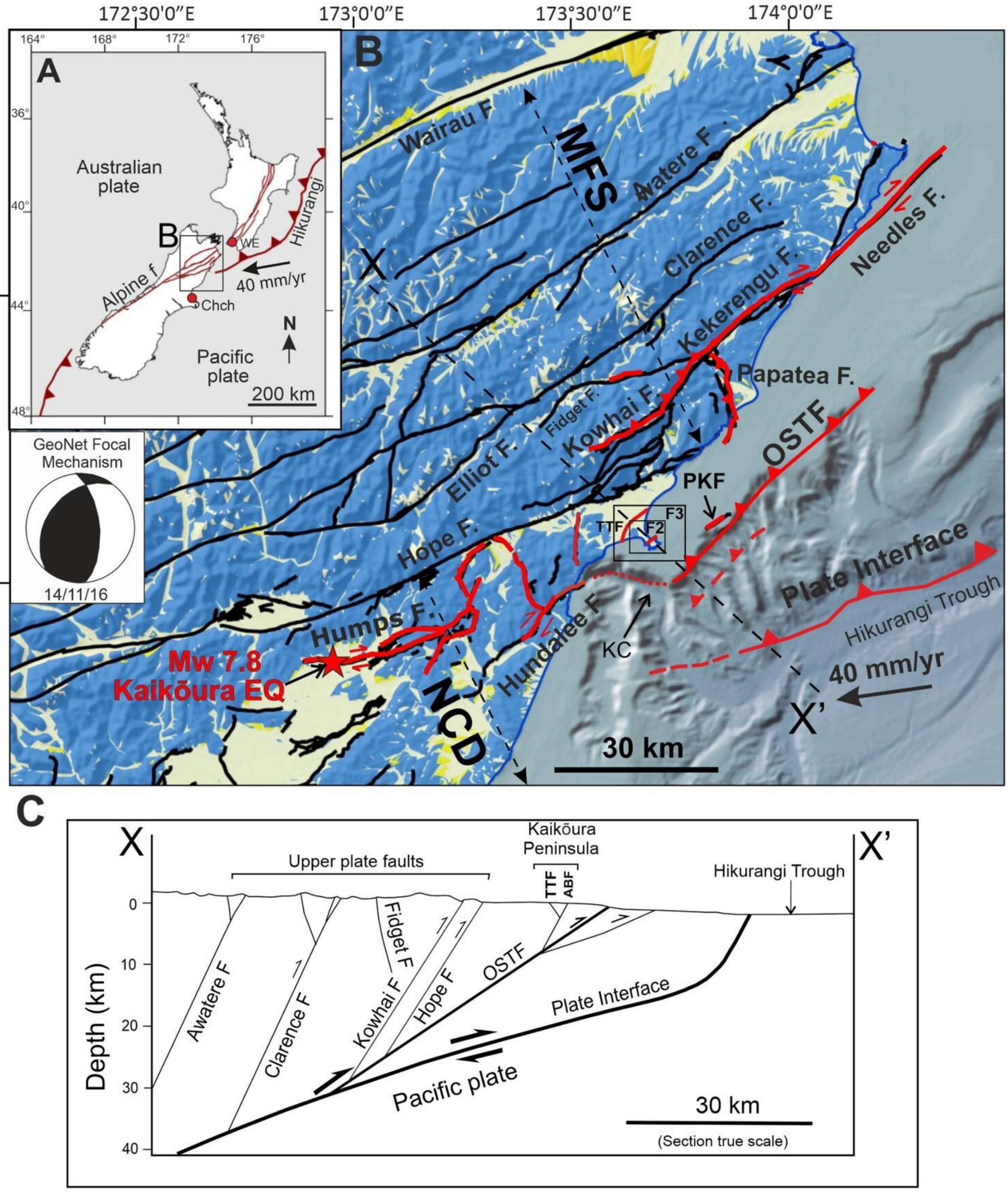

Figure 1. Maps and cross-section showing the plate boundary setting of the Kaikōura Earthquake. A, New Zealand plate boundary. ChCh: Christchurch; WE: Wellington. Pacific Plate motion vector relative to the Australian Plate from Beavan et al. (2002). B, Geology from Rattenbury et al. (2006): Basement (mostly Torlesse Terrane) – blue; Late Cretaceous-Cenozoic strata – dark yellow; Quaternary deposits – light yellow. Active faults (black lines from Langridge et al. 2016) and November 14, 2016 Mw 7.8 Kaikōura Earthquake fault ruptures (red lines with key fault names shown, modified from Mouslopoulou et al. 2019). The epicentral location (red star) and the moment tensor of the 2016 Kaikōura Earthquake are from Chamberlain et al. (2021) and GeoNet, respectively. Onshore topographic basemap is from LINZ and bathymetry

is from NIWA. Abbreviations are as follows: MFS, Marlborough Fault System; NCD, North Canterbury Domain; PKF, Point Kean Fault; OSTF, Offshore Splay Thrust Fault; TTF, Te Taumanu Fault; ABF, Armers Beach Fault; KC, Kaikōura Canyon. The localities of Figures 2 (F2) and 3 (F3), that focus on the Kaikōura Peninsula, are indicated by the rectangles labelled F2 and F3, respectively. C, Regional NW-SE cross section showing upper plate faults in the region surrounding the study area and their geometric relations to the plate interface (modified from Duffy, 2020). The location of the plate interface is from Williams et al. (2013). The section shows no vertical exaggeration. From Nicol et al. (2023).

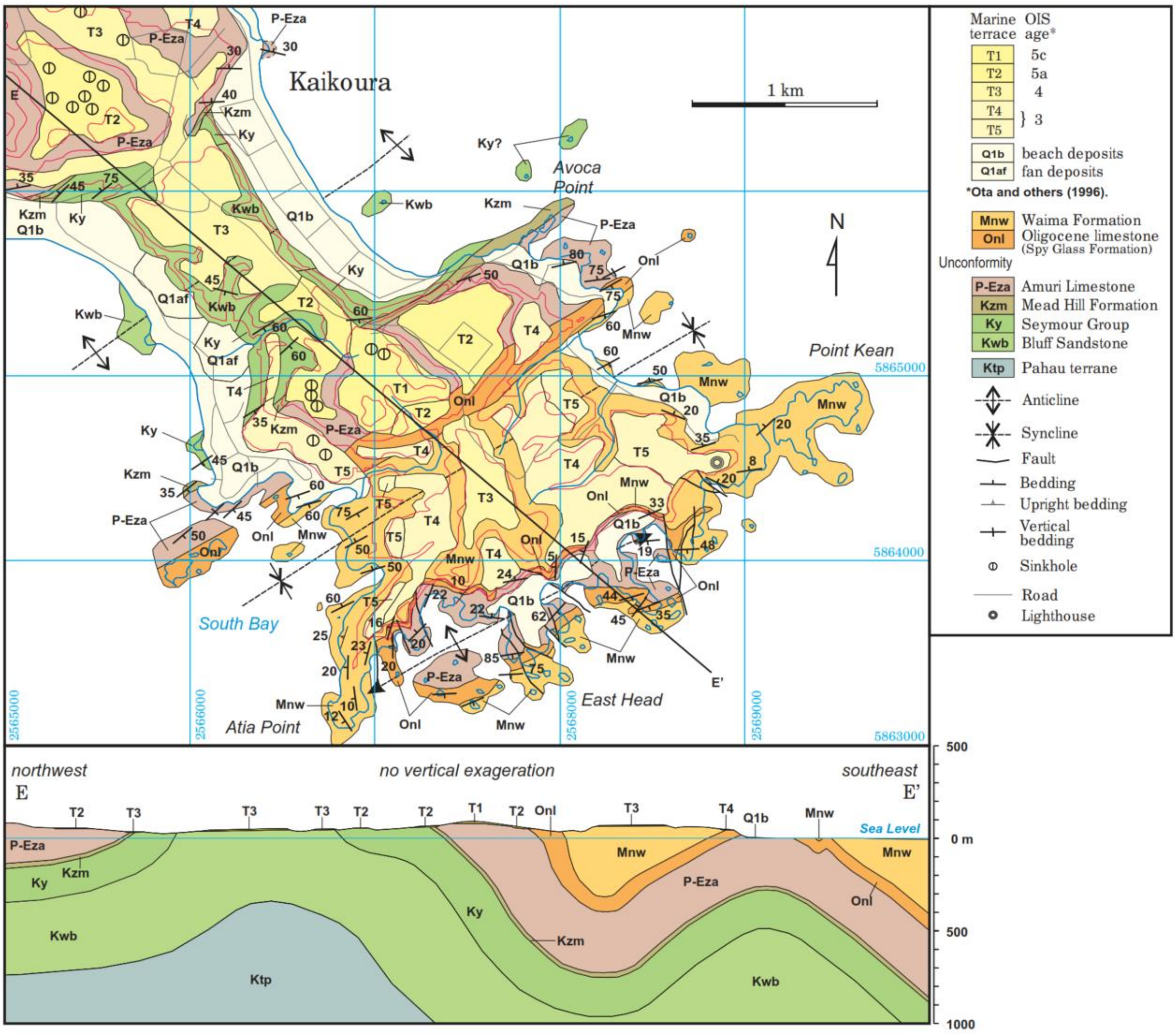

Figure 2. Geological map of the Kaikoura Peninsula. The area has been uplifted and gently folded. NZMS 260 series 1 km grid is shown for reference. Rattenbury et al., (2006).

2. Late Pleistocene marine terraces (Stop 6)

In their paper, Nicol et al. (2023) described the Kaikōura Peninsula as preserving a flight of Late Pleistocene marine terraces, cut into the folded Miocene siltstones and now standing up to ~105 m above sea level, which record long-term uplift over >100 kyr (Figure 3). The highest main terrace (MtC) is correlated with MIS 5e (123 ± 5 ka) and the next (MtB) with MIS 5c (96 ± 5 ka), based on amino-acid and new OSL dating plus correlation to global sea-level curves (Figure 4). Both terraces were originally near-horizontal but are now consistently tilted ~1.2 ± 0.2° towards the northwest and yield maximum uplift rates of roughly 1 mm/yr (Figure 5). Terrace mapping across the newly recognised Armers Beach Fault (ABF) shows that MtB is vertically offset by 23 ± 5 m, implying a Late Pleistocene vertical separation rate of ~0.18–0.31 mm/yr on this structure. Forward elastic-dislocation modelling indicates that the observed elevations and northwest tilts of the Late Pleistocene terraces are produced mainly by repeated slip on a northwest-dipping Offshore Splay Thrust Fault (OSTF – location see Figure 1), with mean cumulative slip of ~80–230 m since MtB formed (slip rates ~0.8–2.7 mm/yr), and a smaller contribution from the ABF (slip rates ~0.3–0.6 mm/yr). Overall, the Pleistocene terrace record shows that thrust faulting beneath Kaikōura Peninsula has generated relatively steady uplift and tilting through multiple earthquake cycles, and that the spatial pattern of this long-term deformation differs from the more complex uplift pattern produced in the 2016 earthquake.

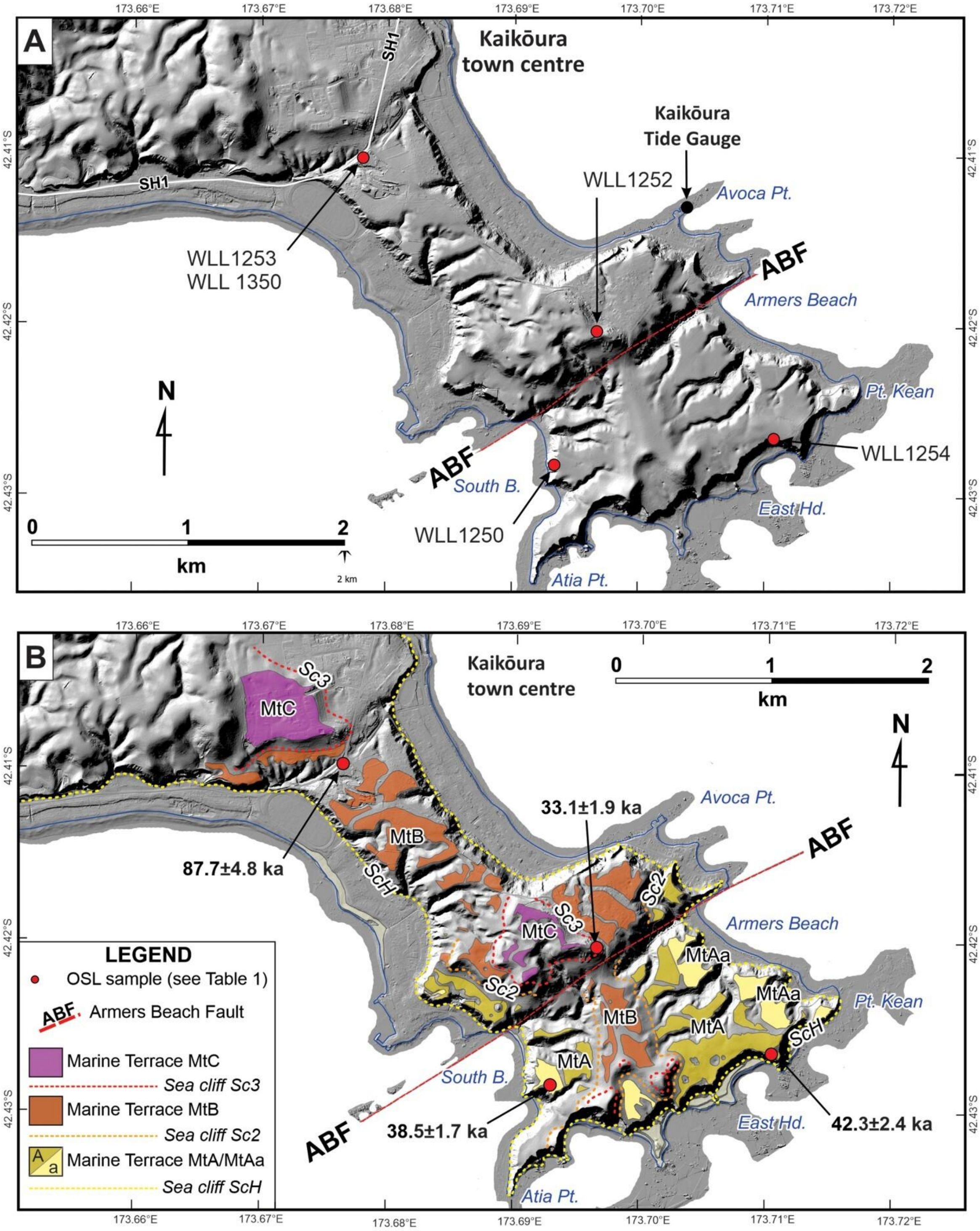

Figure 3. Hillshade of the Kaikōura Peninsula area illustrating its geomorphology and geographic names referred to in the paper. The location of the Armers Bay Fault (annotated ABF) is indicated by the red dashed line. Locations, with annotated lab numbers for OSL ages are shown as red filled circles. State Highway 1 (SH1) mapped as a white line. B, Hillshade model from A draped with coloured, labelled benches and sea cliffs. OSL sample locations are labelled with ages. Note that marine terrace MtB (coloured orange) lies above two sea cliffs on northwest and southeast sides of the ABF, and is vertically displaced (down to the SE) by the fault (Nicol et al. 2023).

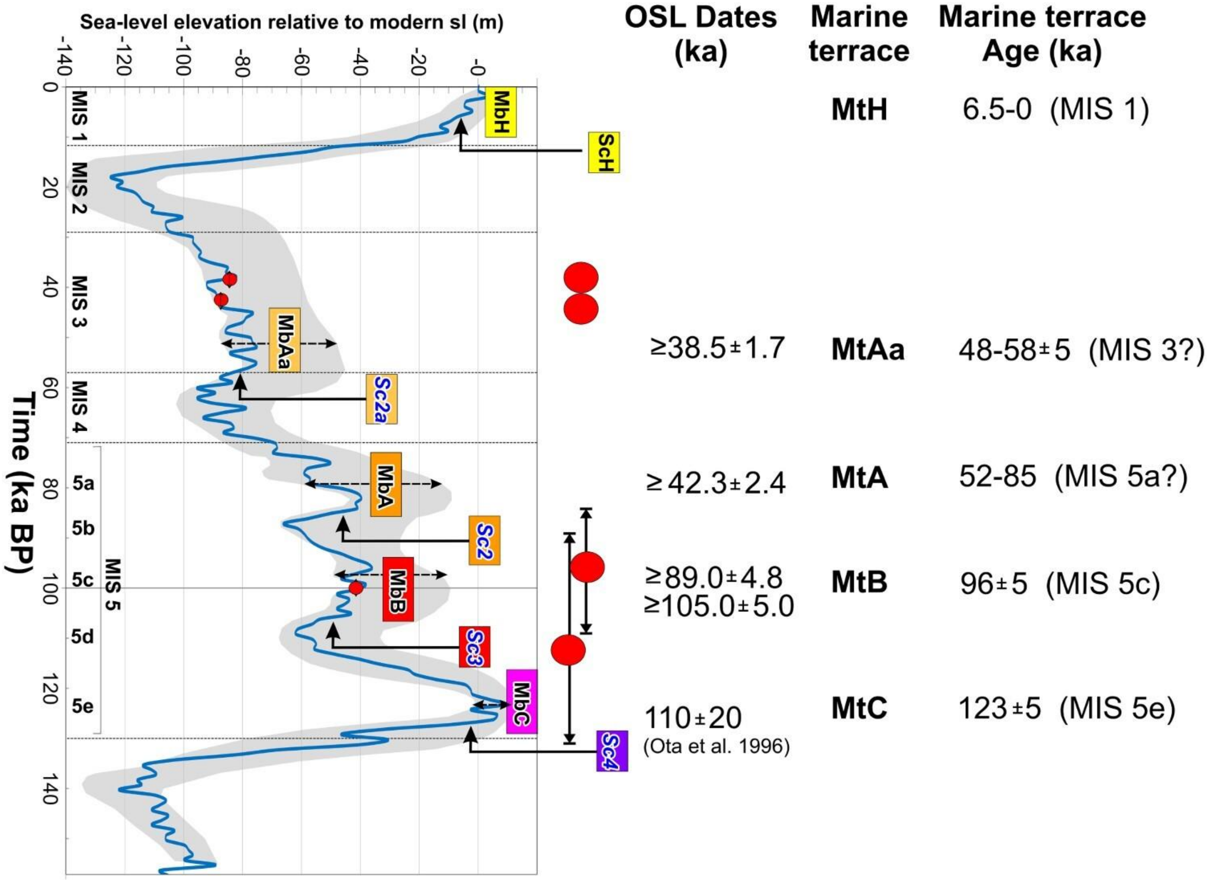

Figure 4. Marine terrace ages and correlations to Marine Isotope Stages and the sea-level curve with absolute sea level relative levels averaged from various sources. Grey polygon on the sea-level curve shows the 2σ uncertainties on the altitude of sea level relative to the present. See Nicol et al. (2023) for details.

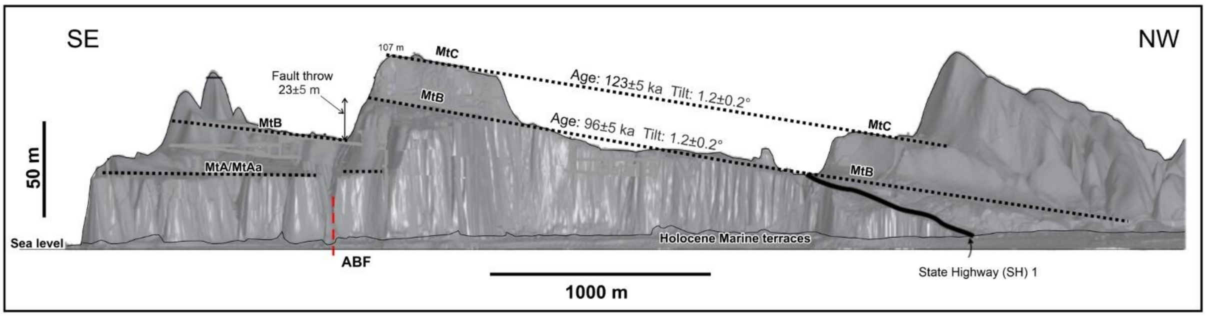

Figure 5. Vertically exaggerated DEM of the Kaikōura Peninsula viewed in profile from the northeast. Profile shows MtC, MtB and MtA terraces and their tilting. Diagram is modified from Duffy (2020).

3. Micro-erosion Meter Studies (Stops 1, 2, 3, 4)

Across more than four decades (1973-2016) a network (Figure 6, with 55 stations in 1993) of Micro-erosion meter and Traversing Micro-erosion Meter (Figure 7) stations were used to measure platform-lowering rates. Kirk's original two-year MEM study (1973–75) gave a mean vertical lowering rate of 1.53 mm/yr (range ~0.38–7.03 mm/yr), with faster erosion on mudstone than limestone and platform lowering contributing ~40 % of the littoral sediment budget (Kirk 1977). Stephenson and Kirk (1998) reported an overall mean of 1.13 mm yr^{-1}, but showed apparent lithological and morphological controls, with ~1.98 mm/yr on Type A (sloping) mudstone platforms, 0.73 mm/yr on Type B (sub-horizontal) mudstone, and 0.88 mm/yr on limestone, although these rates look different they were not statistically significant (Stephenson and Kirk, 1998). There was also a clear cross-shore pattern of higher rates on the landward platform and lower rates seaward, and higher summer than winter rates, all interpreted as evidence that subaerial weathering (wetting–drying and salt) is at least as important as direct wave attack (Stephenson and Kirk 1998).

Decadal and multi-decadal re-measurement showed that the short-term values are representative of longer timescales: Stephenson et al. (2010) found TMEM means of ~0.90 mm/yr over 10 years and MEM means of ~1.09 mm/yr over 30 years, only slightly lower than the original two-year values, the reduction largely due to loss of the fastest eroding bolt sites rather than any systematic decline in rates. The 43-year synthesis up to the 2016 Mw 7.8 earthquake confirms this picture, with average lowering rates across all periods clustering between about 0.5 and 1.2 mm yr^{-1}, statistical tests showing that short-term (2-year) and multi-decadal populations are indistinguishable, and spatial patterns (higher rates on landward, mudstone, and more weather-exposed surfaces) persisting throughout (Stephenson et al. 2019). Together, these studies show that Kaikōura shore platforms have been eroding at roughly 1 mm/yr from the early 1970s until the coseismic uplift in 2016, and the short-term MEM campaigns provide robust estimates of longer-term, decadal, platform lowering.

Although never intended as part of the original programme, we are now able to quantify the geomorphic response to the one metre of coseismic uplift associated with the 14 November 2016 M_w 7.8 Kaikōura earthquake. February 2024 also marked the 50th anniversary of ongoing measurements at Kaikōura. Professor Bob Kirk passed away on 4 March 2024, regrettably Bob was too unwell to note the passing of the 50th year of monitoring.

The following results are contained in Kirk et al. (in review) where all data collected at Kaikōura are reviewed across 12 measurement epochs (Figure 8). Post-earthquake rates more than doubled from the average pre-earthquake erosion rate of 1.00 mm/yr to 2.54 mm/yr. Since 2016, limestone eroded at 1.30 mm/yr and mudstone at 3.27 mm/yr, these are now significantly different (Figure 10), demonstrating how the co-seismic uplift has *elevated* the role of lithology as a control on erosion rates. Seasonal differences in erosion with higher rates in summer than winter observed prior to the earthquake remained pronounced after 2016 (Figure 11) but the subaerial processes responsible have changed from intertidal wetting and drying moderated by biology to supra-tidal subaerial processes. These findings highlight the critical role of changing processes, the geomorphic significance of tectonic events on rock coasts, and the pathway from shore platform to marine terrace generation.

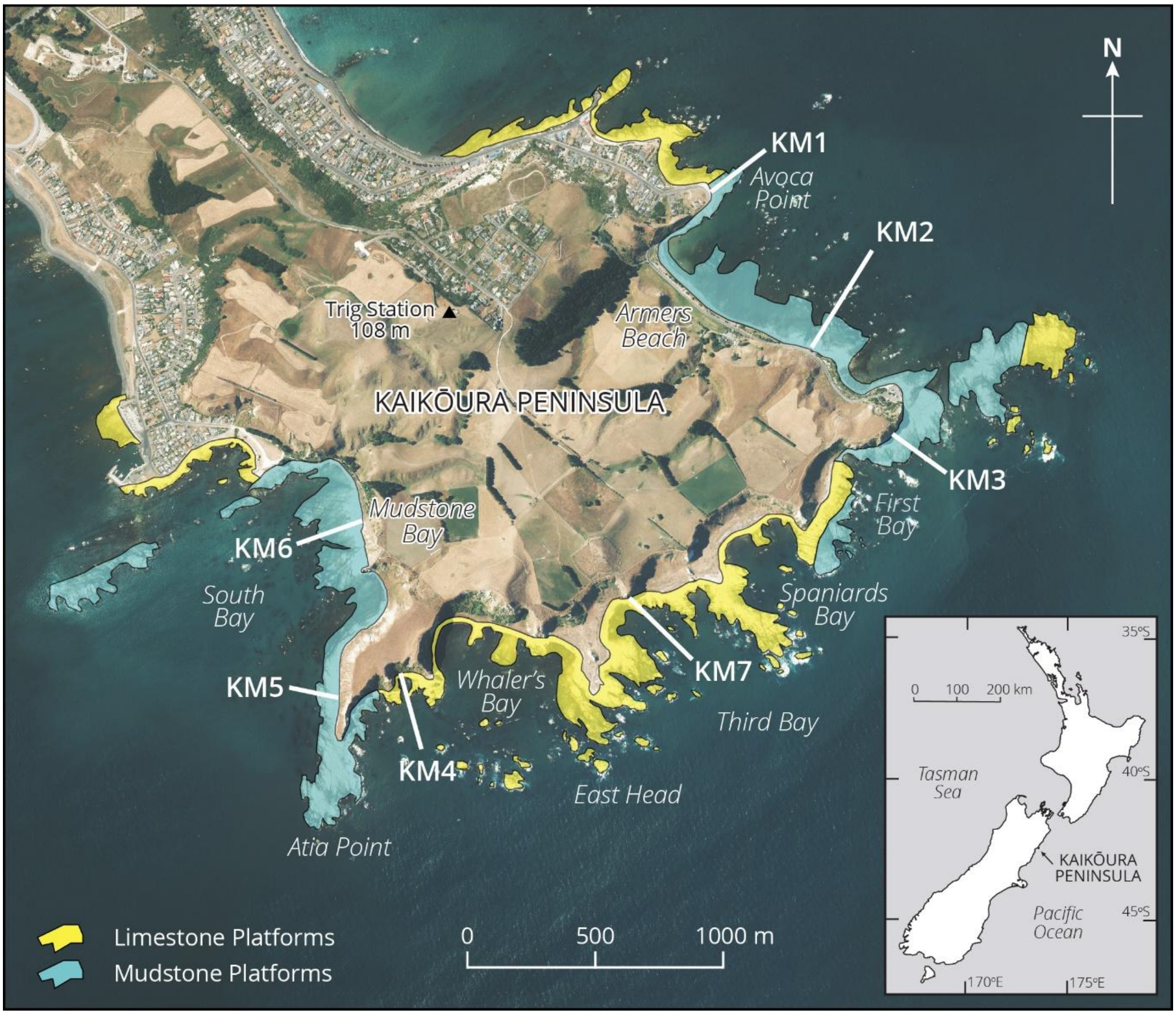

Figure 6. Kaikōura Peninsula, shore platform lithology and position of MEM profiles.

Figure 7. Micro-erosion meter (a) meter used at Kaikōura since 1973 that records 3 measurements and b) the traversing Micro-erosion meter used since 1993 that records 120 measurements.

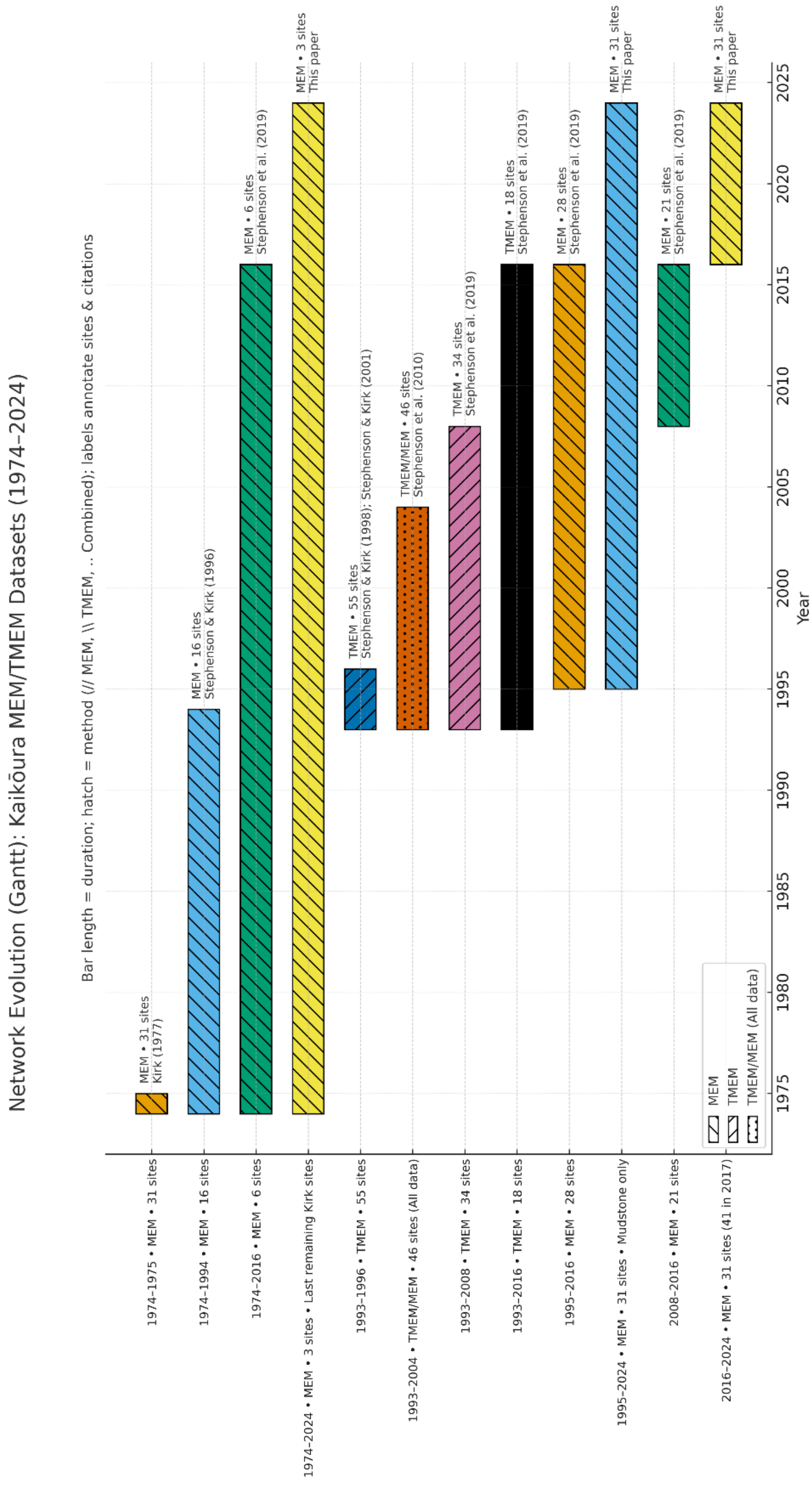

Figure 8. Summary of measurement epochs used to calculate erosion rates from MEM and TMEM data on Kaikōura Peninsula (Figure 9). Epoch durations vary, reflecting the availability and survivorship of measurement sites over time. The number of contributing sites for each epoch is depended on the either the use of the MEM or TMEM or combination of both in the compiled dataset.

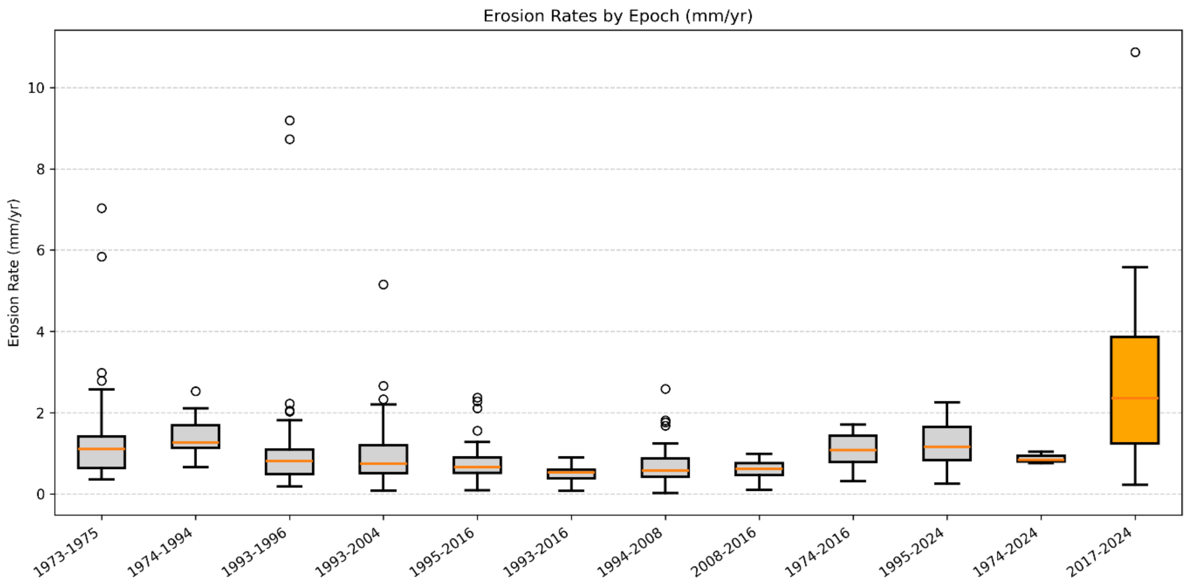

Figure 9. Boxplot of erosion rates (mm/yr) for 12 measurement epochs (Table 1) at Kaikōura Peninsula, derived from mean rates calculated at individual bolt sites. The final epoch (2017–2024), 8 years of post-earthquake measurements (in orange), shows higher and more variable erosion rates.

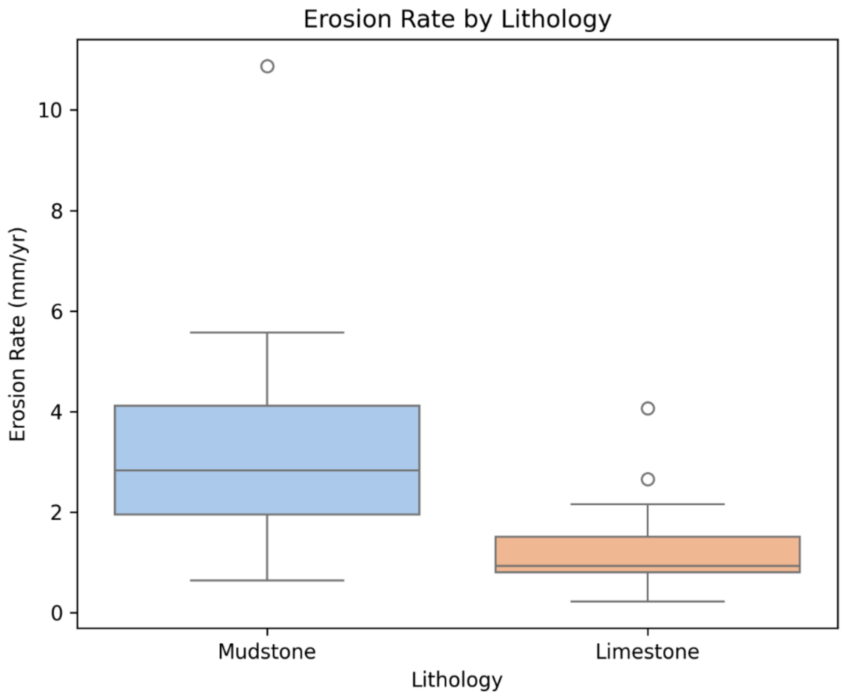

Figure 10. Boxplot comparing erosion rates on mudstone and limestone shore platform surfaces at Kaikōura Peninsula (2017–2024). Erosion rates were calculated from MEM bolt measurements following the 2016 Mw 7.8 earthquake. Mudstone sites exhibit significantly higher erosion rates than limestone sites (Mann–Whitney U = 352.0, p = 0.00033), with mean values of 3.27 mm/yr and 1.30 mm/yr, respectively.

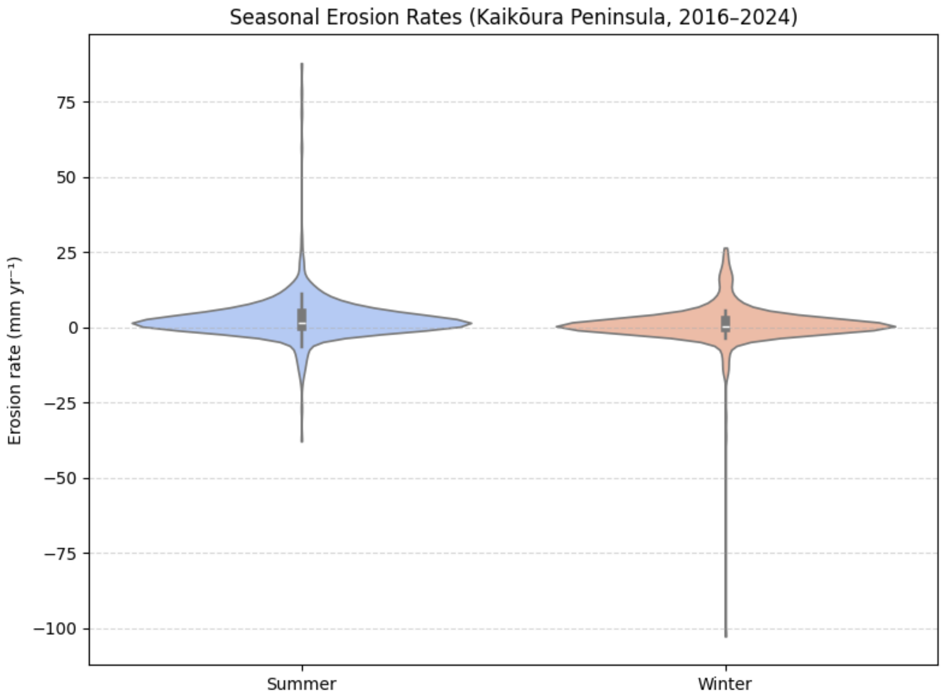

Figure 11. Seasonal erosion rates measured at Kaikōura Peninsula between December 2016 and December 2024. Each violin illustrates the probability distribution of annualised MEM rates for summer and winter, with an overlaid boxplot showing the interquartile range and median. The width of each violin reflects the relative density of values at a given erosion rate. Mean ± SD rates are 3.09 ± 8.34 mm/yr for summer and 1.24 ± 7.41 mm/yr for winter.

Omidiji et al (2022) was the first to report post-uplift erosion rates. High-resolution topographic data obtained from quarterly surveys over four years using the micro-erosion meter (MEM) and Structure-from-Motion Multi-View Stereo (SfM-MVS) surveys to provide rates of erosion and visual representation of surface morphologies. MEM data revealed variations in erosion, weathering and deposition rates across lithologies, tidal positions, and platform elevation after the uplift. After four years, surface downwearing rates for all platforms were on average 2.25 mm/yr, a 104% increase from the pre-uplift rate of 1.10 mm/yr. Average lowering rates on limestone, hard, and soft mudstone platforms were 1.19 mm/yr, 2.31 mm/yr, and 3.21 mm/yr, respectively (Figure 12).

Omidiji et al (2023) then investigated cross-scale erosion comparing the MEM with Structure for Motion (SfM) derived erosion rates, on the newly uplifted platforms and terraces over one year found that point-based MEM readings (mean ~2.24 mm/yr) systematically underestimate erosion compared with co-located SfM models (mean ~2.61 mm/yr at the micro-scale and ~10.3 mm/yr over 1 m^2 patches), because much of the post-uplift adjustment occurs through granular disintegration, flaking and small block removal between the bolts; these results caution against simply extrapolating MEM rates over larger areas, especially on recently uplifted, rapidly reworking surfaces (Figure 13).

The key message is that MEM and SfM give broadly *consistent* erosion rates at the bolt scale, but SfM almost always reveals *more* erosion once you look beyond the three points of the MEM. Over the same 0.01 m^2 "MEM footprint", one-year erosion rates from the two methods overlap closely, MEM 0.13–4.75 mm/yr and SfM 0.19–10.11 mm/yr, with similar mean values and the lowest and highest rates occurring on the same rock types and sites, so at that microscale the methods are effectively interchangeable for short-term monitoring. But SfM picked higher microscale rates than MEM at ~62.5 % of sites, because the MEM mainly "sees" granular disintegration immediately under the probe, whereas SfM also captures adjacent grain loss, mm-scale flaking and small clast detachment that fall between the three bolt positions. When you move up to ~1 m^2 patches using SfM, this divergence becomes systematic: SfM consistently produces higher mesoscale rates than MEM because a significant share of post-uplift adjustment is happening over the space between bolts, through widespread granular breakdown and small block removal. So the similarity is that both techniques agree on the order of magnitude and spatial pattern of erosion at the bolt scale; the difference is that MEM under-samples the surface and tends to underestimate total mass loss over larger areas, whereas SfM trades a little precision at a point for much better coverage of the actual erosion processes operating across the platform and emerging terraces.

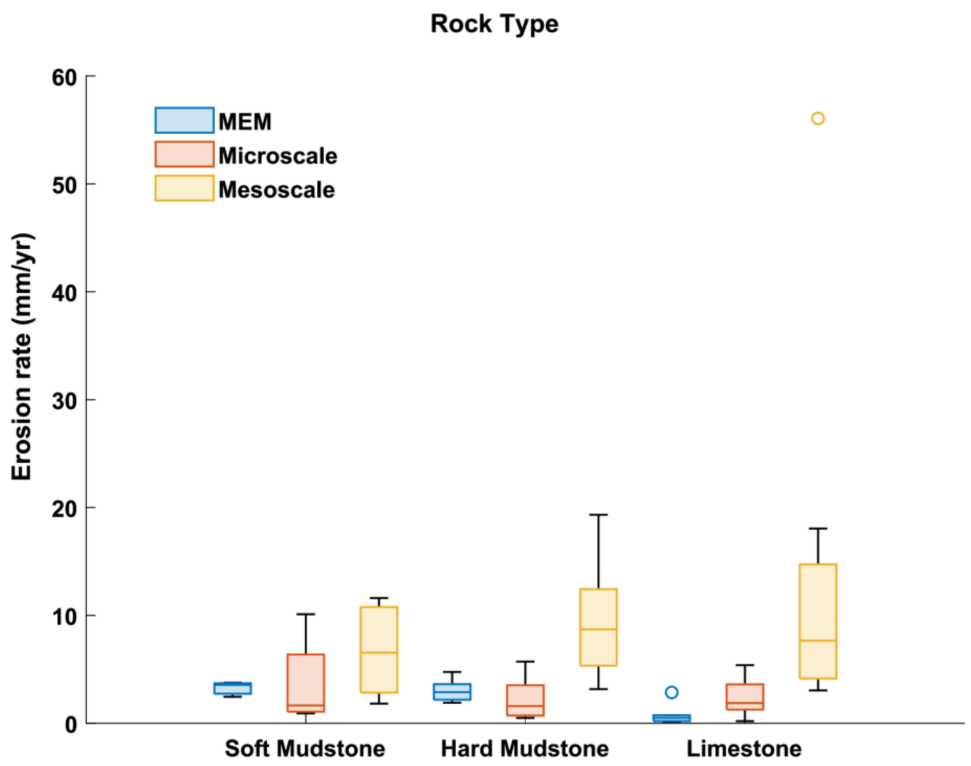

Figure 12. Rock type versus erosion rates estimated from the MEM and SfM-PCs (covering the micro and mesoscale areas) (Omidiji et al. 2022a).

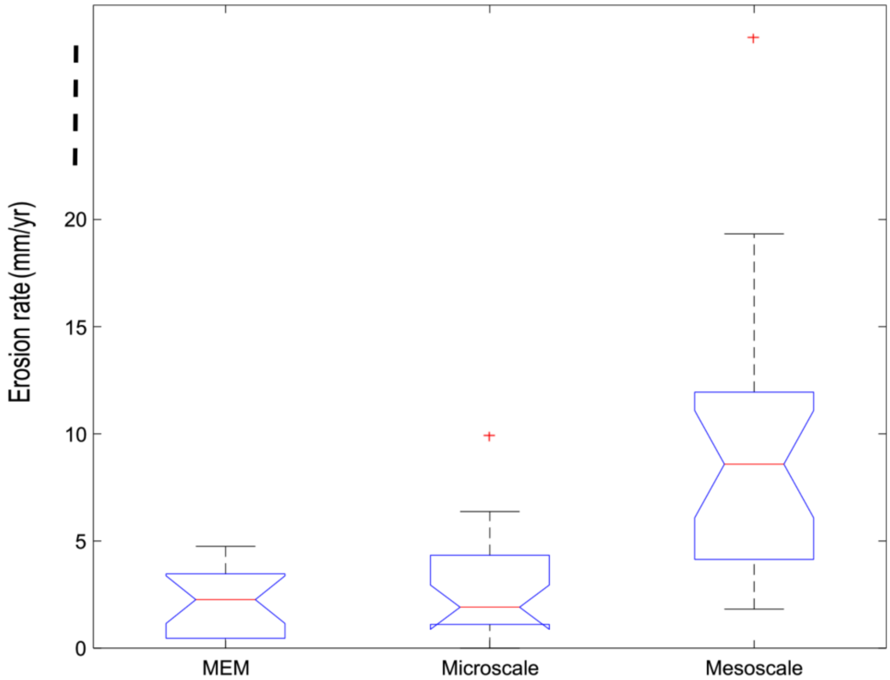

Figure 13. Erosion rates (mm/yr) derived from the MEM and SfM-PCs. The median = horizontal red line within the boxes; whiskers = minimum (q1–1.5 * IQR) and maximum (q3 +1.5 * IQR); outliers = red plus sign (Omidiji et al. 2023).

3. Process Studies at Kaikōura (Stops 3 and 7)

Kaikōura Peninsula has been used for shore platform research to investigate wave and weathering processes and how these interact to drive shore platform development. Early work showed that although the offshore wave climate is highly energetic, much of that energy was dissipated or transformed across the platform, while subaerial weathering driven by wetting and drying, salt crystallisation and slaking operate most intensely on the inner platform (Stephenson and Kirk 2000a,b). Taken together, work at Kaikōura has been central in reframing shore platform development as the product of strongly interacting wave and weathering processes, with waves primarily conditioning exposure and water levels and weathering doing much of the actual downwearing. We have also been able to assess how tectonic uplift moderates and changes these processes since 2016.

Wave-measurement studies at Kaikōura show a progression from demonstrating how little storm energy actually reaches the cliffs and platforms, to quantifying how the 2016 uplift further reduced that energy and reorganised where geomorphic work can occur. Stephenson and Kirk's (2000a) study on the peninsula found that although the offshore wave climate is very energetic, wave energy flux is reduced by up to five orders of magnitude between deep water and the high-tide cliff, and calculated dynamic pressures and shear stresses on the platforms never approached the compressive strength of the rocks, leading them to argue that waves alone are not directly capable of driving platform downwearing at Kaikōura.

Taylor (2003) deployed wave recorders and current meters at KM2 and 3. This work also showed that most incident swell energy is dissipated seaward of the platform edge, with reductions of up to ~90 % in wave energy and energy flux between the offshore and instruments on the platform, and that the on-platform spectrum during larger swell events is strongly weighted towards low-frequency (T > 20 s) energy, consistent with infragravity (IG) motions, which drive turbulent bores and laterally channelled flows across the mid-platform. Infragravity energy was a persistent feature of the local wave field even under moderate swell, with clear IG peaks in the 0.005–0.05 Hz band and strong runup and overtopping events coinciding with these low-frequency bursts

Marshall and Stephenson (2011) measured waves across platforms at Atia Point and Mudstone Bay, showing that attenuation and spectral transformation (gravity-wave energy concentrated at the seaward edge, infragravity energy dominating landward) are controlled mainly by water depth and platform gradient rather than width, reinforcing the idea that much of the offshore swell energy is dissipated or transformed before it reaches the inner platform. The 2016 M_w 7.8 earthquake then provided a natural experiment: Horton et al. (2022a) re-occupied the Mudstone Bay transect used by Marshall and Stephenson and showed that ~0.95 m of co-seismic uplift raised the seafloor enough to cut incident onshore energy by nearly 40% under comparable offshore conditions and shortened the intertidal width by about 50%, so that roughly half of the former intertidal platform is now disconnected from everyday wave attack and behaves as an emerging marine terrace (Figure 14).

A companion study by Horton et al. (2022b) focused on this incipient supratidal terrace, finding that under storm conditions infragravity energy dominates (≈70 % of the spectrum) but even with offshore Hs ≈ 3.5 m the terrace is only shallowly inundated (≤9 cm) for a few hours, with full inundation of the terrace and cliff toe predicted for <0.05 % of tides. Together, these measurements show that pre-uplift platforms already received heavily attenuated, strongly transformed wave energy, and that the 2016 uplift further shifted effective wave–rock interaction seaward, reducing direct wave forcing on the inner platform and enhancing the likelihood that the uplifted surface will be preserved as a new marine terrace (Figure15).

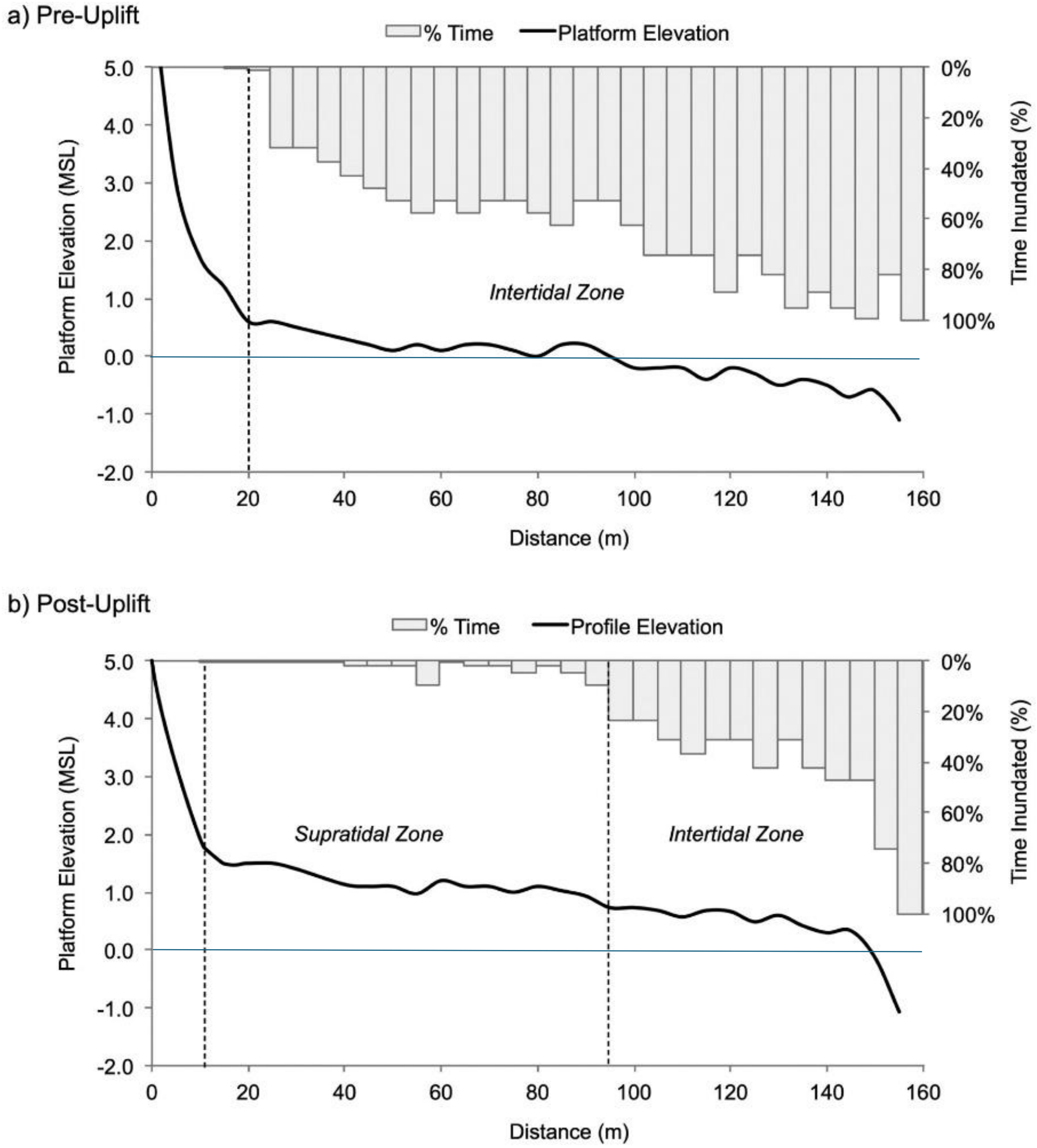

Figure 14. The change of duration of tidal inundation of the Mudstone Bay platform pre- and post-uplift. Time inundation is the percentage of hourly observations over four years where the calculated water level exceeds the platform elevation. Tide and offshore wave data were used for the years a) 2013–2016 and b) 2017–2020. Dashed lines represent the approximate range of the intertidal and supratidal zones (Horton et al. 2022b).

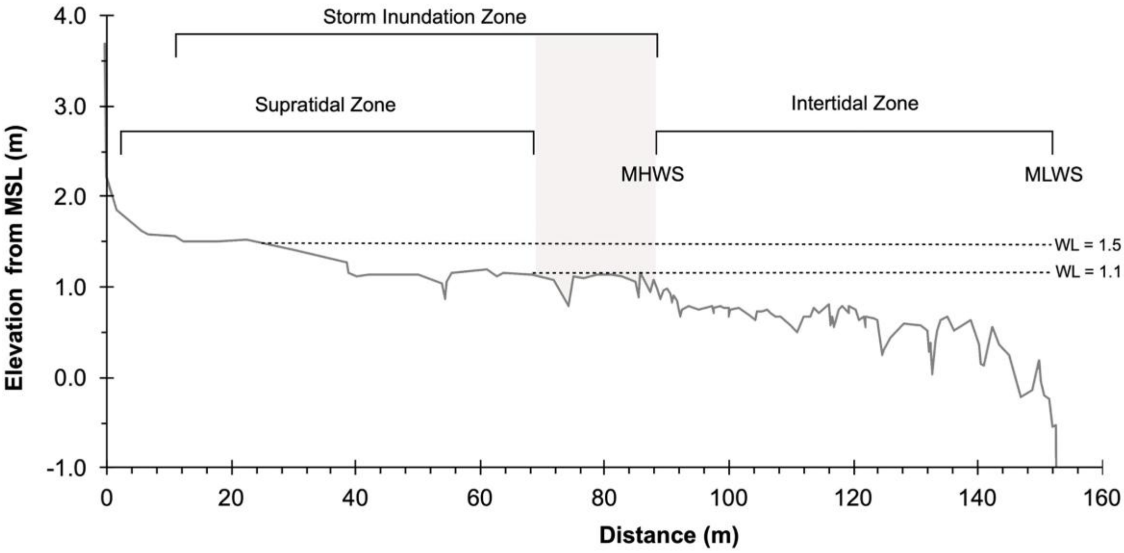

Figure 15. Extent of the intertidal and supratidal zones at Mudstone Bay, Kaikōura. The intertidal zone is defined by the MHWS and MLWS levels, and the supratidal zone as the newly formed marine terrace that has been uplifted following the 2016 earthquake. The grey area marks the transition between the calm and storm inundation, which is dependent on wave conditions under storm events (Horton et al. 2022b).

Investigations of weathering studies at Kaikōura show that shore platform development is fundamentally controlled by subaerial processes driven by wetting and drying, and that the 2016 uplift has reorganised but did not remove this control. Stephenson and Kirk (2000b) documented three key weathering modes on the platforms, salt crystallisation, water-layer weathering and slaking and used Schmidt hammer tests to show that rock strength on both mudstone and limestone platforms is reduced by roughly 10–50% relative to fresh rock. They estimated 104–379 wetting–drying cycles per year at MEM bolt elevations, with the highest frequencies between about 0.6 and 0.9 m above MSL on the inner platform, matching the zone of maximum measured downwearing and leading them to argue that repeated wetting and drying, rather than direct wave impact, is the primary driver of platform lowering at Kaikōura. Horton et al. (2022c) building on this pre-uplift picture using an empirical model that couples tides, offshore waves, solar irradiation and rainfall to re-calculate wetting and drying regimes before (2011–2016) and after (2017–2020) the Mw 7.8 earthquake (Figures 16 and 17). They show that 1.0 m of coseismic uplift has generally shortened the intertidal zone and expanded supratidal mudstone terraces, reducing wetting–drying cycles on most transects by 8–148% but increasing annual drying hours on the new terraces by around 29% or more. This prolonged drying is expected to accelerate slaking and material disintegration on the emergent mudstone surfaces, so that parts of the incipient marine terrace may be rapidly denuded back toward their former intertidal state, while terrace preservation will vary with inherited morphology, lithological resistance and the timing of future tectonic events.

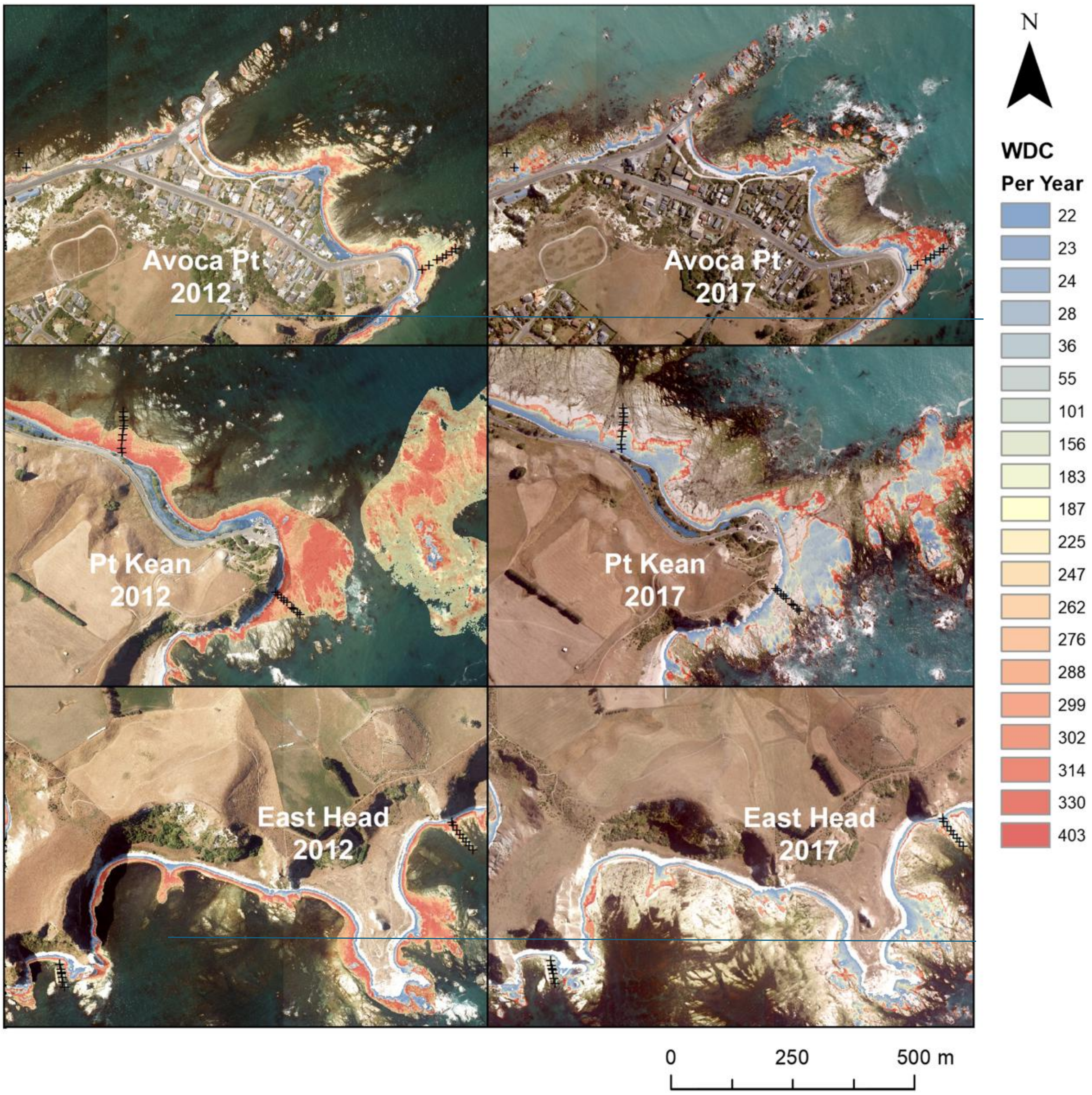

Figure 16. Modelled wetting and drying cycles (WDC) pre-uplift (left) and post-uplift (right) for Avoca Pt (KMZ, KM1), Pt Kean (KM2, KM3), and East Head (KM4, KM7). Base map source: LINZ (2015, 2018). Cross indicates the locations of the shore-normal transects (Horton et al. 2022c).

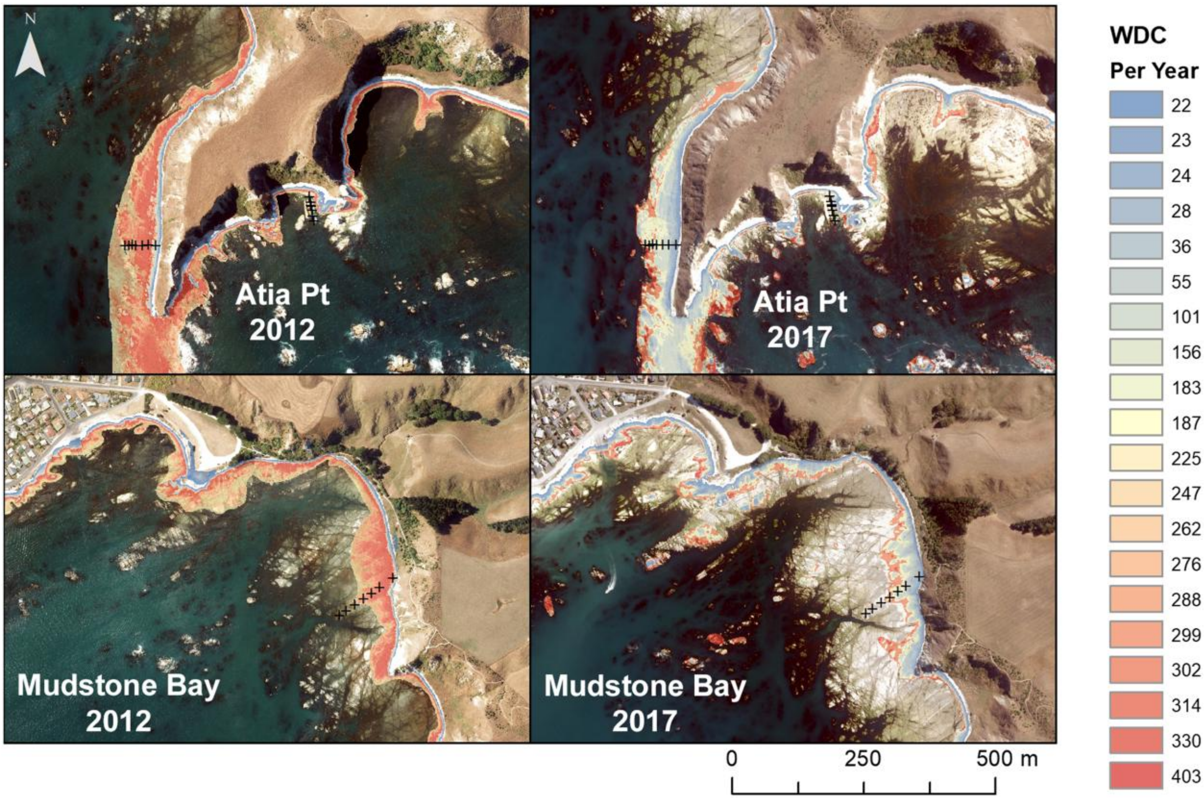

Figure 17. Modelled wetting and drying cycles preuplift (left) and post-uplift (right) for Atia Pt (KM5) and Mudstone Bay (KM6). Base map source: LINZ (2015, 2018). Cross indicates the locations of shorenormal transects (Horton et al. 2022c).

4. Holocene Terraces (Stops 2, 4 , 5, 7)

Around the Kaikōura Peninsula, the Holocene marine terrace sequence consists of at least two late Holocene terraces (T1 and T2) (Figure 18), with local evidence for a fragmentary higher T3 surface, all sitting below an older mid-Holocene terrace whose tread is ~6 m above present mean sea level and is dated to ~6.5 ka. Mapping and radiocarbon dating show T1 and T2 as raised gravel-beach surfaces that are typically a few metres above sea level: shells on the lower terrace (T1) indicate uplift in the last event at ~437–236 yr BP, while the next terrace up (T2) records an earlier event at ~801–1111 yr BP, each formed by ~0.5–1.2 m of coseismic uplift. These ages imply earthquake recurrence intervals of roughly 550–2200 years for upper-plate ruptures and ~500–850 years for subduction-related events, consistent with slip-rate modelling of the offshore faults beneath the peninsula that suggests characteristic repeat times of a few hundred to a couple of thousand years (Howell and Clark, 2022).

The 2016 Mw 7.8 Kaikōura earthquake added a new terrace by uplifting the intertidal platform by ~0.8–1.0 m (Figure 18), and MEM-derived erosion rates more than doubled after uplift (from 0.944 to 2.556 mm yr^{-1}). Using the lower range recurrence estimate (500-850 yrs) and the MEM erosion data, Stephenson et al. (2025) modelled the time required to remove 1 m of uplift. They assumed erosion rates after T1 was uplifted also doubled immediately, thus the pre-November 2016 erosion rate of 0.944 mm/yr was arrived at since the earthquake that generated T1. They then used this interval since the last uplift to estimate the decrease in erosion rates using 0.944 mm/yr and the post-uplift erosion rate of 2.556 mm/yr (the supra-tidal erosion rate). A linear decline from 2.556 to 0.944 mm/yr removes the terrace in ~552 yrs. These timescales overlap (Figure 19) with earthquake recurrence intervals from Howell and Clarke (2022). Including vertical land movement (VLM) (−3.1 mm/yr from Naish et al., 2024), which accounts for sea-level rise and inter-seismic subsidence, removal decreases to 200–183 yrs. Using intertidal and terrace erosion rates with this adjustment yields 208–196 yrs (Figure 19). Erosion and VLM appear rapid enough to remove 1 m of uplift before the next scheduled earthquake. Without further uplift within ~200 years, the 2016 marine terrace will not be preserved (Stephenson et al., 2025).

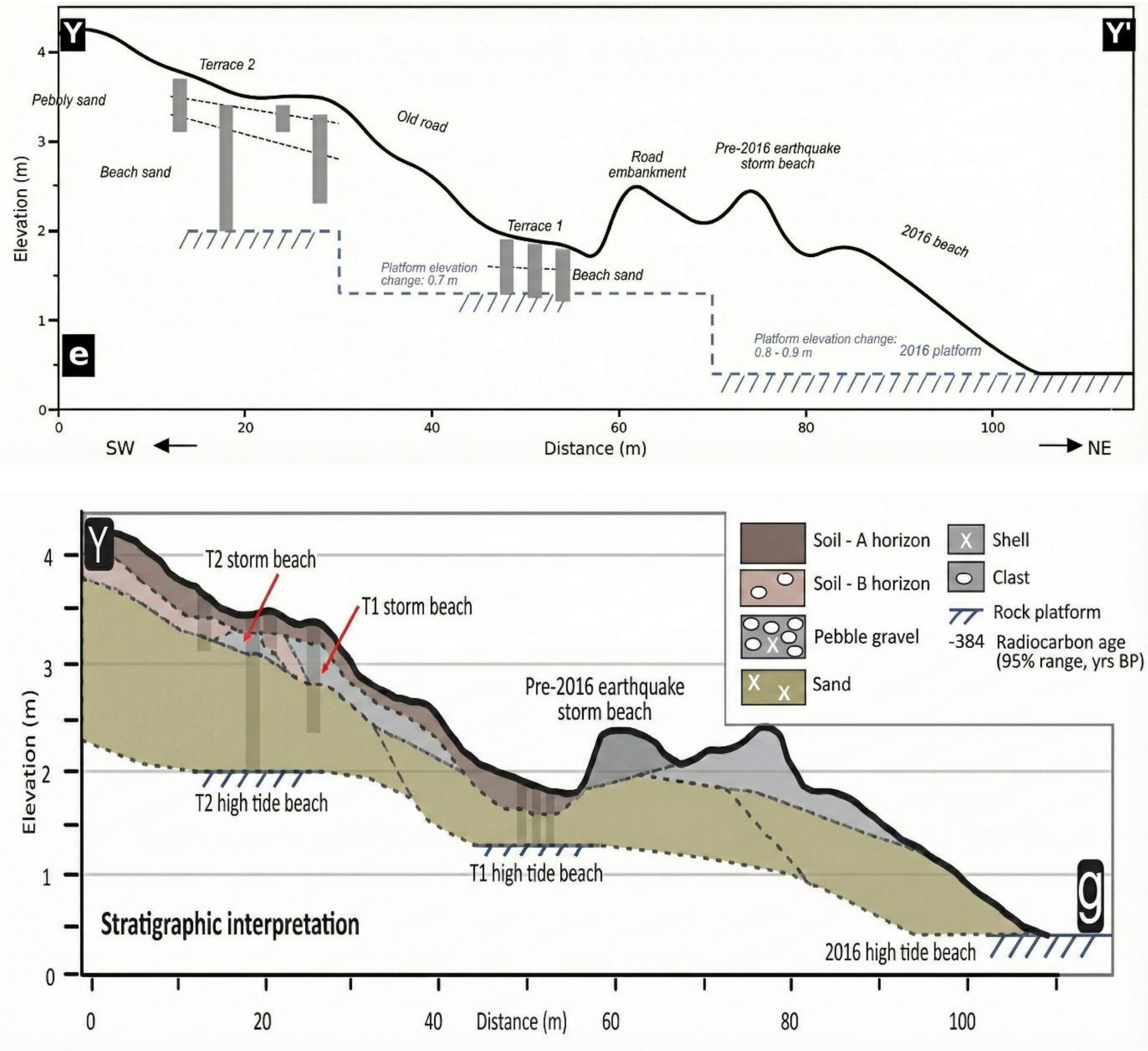

Figure 18. Cross section along profile across the paddock and interpreted stratigraphy along profile (from Howell and Clark 2022).

December 2017 up lifted beach still evident

December 2023

Figure 19. Development of the new marine terrace from December 2017 to December 2023. Arrow indicates same position across images. How does it look today?

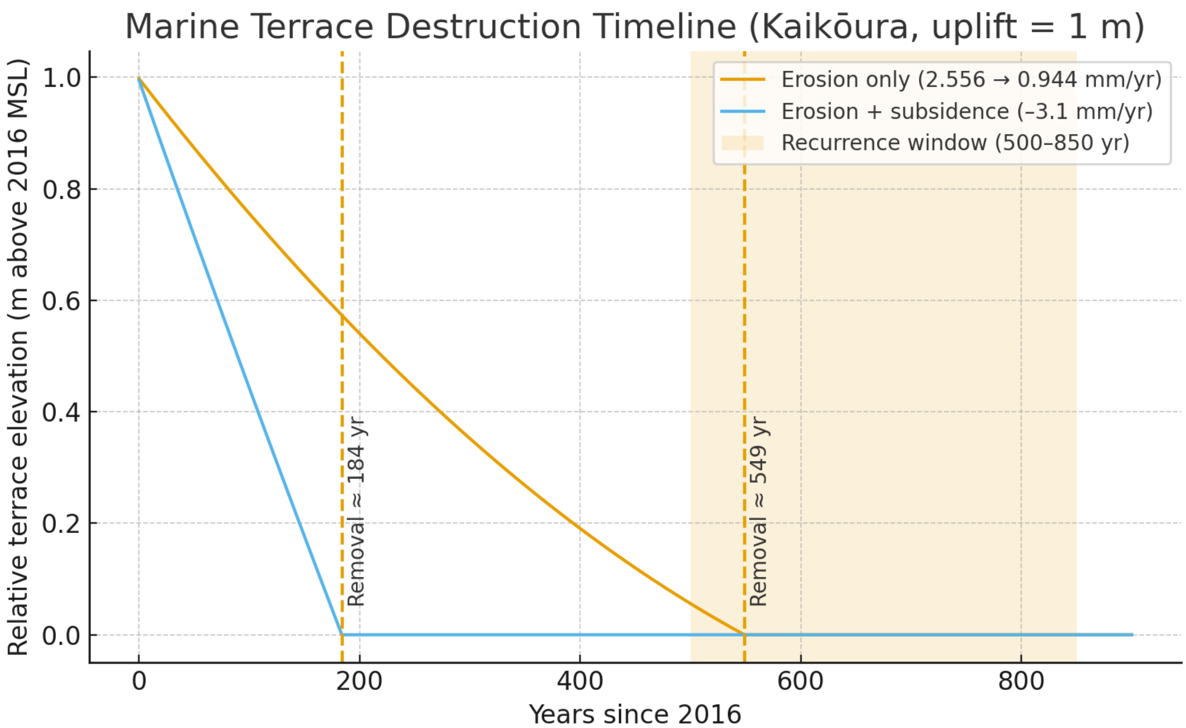

Figure 19. Predicted marine terrace destruction timeline, using MEM erosion rates from before and after the 2016 earthquake to establish time to remove the 1 m of uplift (Stephenson et al. 2025).

5. Social & Economic Impact (Stop 8 – time permitting)

The South Bay Marina is a critical infrastructure asset for the region, supporting commercial fishing and the iconic Whale Watch operations. The 2016 earthquake uplifted the seabed here by approximately 1 m, rendering the marina largely unusable outside of high tides and creating significant navigation hazards. To restore functionality, extensive excavation was required to break up and remove the uplifted limestone bedrock from the inner and outer harbour. The closure of this facility is just one example of the economic impact of the earthquake. With State Highway 1 and the rail line severed by numerous landslides, Kaikōura was effectively isolated. Guest arrivals in the district plummeted from 28,662 in January 2016 to just 8,845 in January 2017, impacting a local economy where accommodation and food services employ over a quarter of the population.

Broader Economic Context:

- National Impact: The earthquake's impact extended far beyond the peninsula. It is estimated to have reduced New Zealand's GDP by $450–$500 million over the following 18 months. For scale, nominal GDP in the year ended March 2016 was about NZ$252 billion, so the quake shaved off on the order of 0.2% of one year's GDP as a cumulative loss spread over two years.

- Infrastructure Costs: Landslides severed the main transport corridor (State Highway 1 and rail line) costing the country approximately $3 million per week in increased freight costs. The recovery effort to restore the road and rail link was one of New Zealand's largest infrastructure projects, costing between $1.1 and $1.3 billion. The recovery removed over 1.5 million cubic meters of rock and debris from the transport corridor to reopen the road and rail line. North of Kaikōura at Ōhau Point approximately 110,000 cubic meters of slip material was removed. Initial estimates for the slips north of Kaikōura were around 353,000 m^3, but sluicing and weather events nearly doubled this volume to over 600,000 m^3 during the work. In addition to repairs, a separate $231 million improvement package was approved for the 60km stretch from Clarence to Ōaro. This funded widening shoulders, safety barriers, and new stopping areas to improve resilience and tourist amenities along the southern coast.
- Insurance & Government: Total insurance claims reached approximately $2.27 billion, with significant commercial losses also felt in Wellington (65% of total business claims). The total fiscal cost to the government was estimated at $2–3 billion.

It was not until the one-year anniversary of the earthquake, on 14 November 2017, that the harbour was officially reopened. The road and rail links followed shortly after, allowing tourism spending to rebound, December 2017 saw $9 million more in spending than the previous year, marking the beginning of true recovery. The South Bay marina was redesigned to facilitate future growth, such as accommodating larger vessels and safer transfers for cruise ship tenders

Overall recovery operation generated a massive economic stimulus for the region, characterized by an estimated government cost of $2–3 billion and total insurance claims of $1.84 billion. This funding mobilized a workforce of 1,700 people who contributed over 2 million hours to the rebuild. This activity proved vital for the local economy; with the tourism industry crippled by isolation, the accommodation and food sectors pivoted to service this influx of recovery workers, effectively replacing tourists as the primary economic driver and providing a lifeline for local suppliers. Additionally, a $5.41 million relief fund was established to directly support community needs.

Much of this section has been extracted from "Shaky Shores: Coastal Impacts & Responses to the 2016 Kaikōura Earthquakes" A publication of the New Zealand Coastal Society: https://www.coastalsociety.org.nz/content/view/publications/shaky-shores-coastal-impacts-and-responses-to-the-2016-kaikoura-earthquakes/

References

Browne, G.H., Laird, M.G., Field, B, D. (2005). Stratigraphic And Sedimentological Teasers, Kaikōura Peninsula, Marlborough In: Pettinga, J.R. and Wandres, A.M. (eds.) Field Trip Guides, Geological Society of New Zealand 50 Annual Conference, Kaikoura, New Zealand. Geological Society of New Zealand Misc. Publ. 119B, xx-yy p.

Duffy, B., Quigley, M., Barrell, D.J., Van Dissen, R., Stahl, T., Leprince, S., McInnes, C. and Bilderback, E., (2013). Fault kinematics and surface deformation across a releasing bend during the 2010 MW 7.1 Darfield, New Zealand, earthquake revealed by differential LiDAR and cadastral surveying. *GSA Bulletin*, *125*(3-4), pp.420-431.

Horton, S.L., Dickson, M.E. & Stephenson, W.J. (2022a). The consequences of uplift on wave transformation across a shore platform, Kaikōura, New Zealand. *Marine Geology*, 451, 106888. doi:10.1016/j.margeo.2022.106888.

Horton, S.L., Dickson, M.E. & Stephenson, W.J. (2022b). Supratidal inundation on an incipient marine terrace. *Geomorphology*, 417, 108443. doi:10.1016/j.geomorph.2022.108443.

Horton, S.L., Stephenson, W.J. & Dickson, M.E. (2022c). Changes in shore platform wetting and drying cycles following the 2016 Kaikōura earthquake: Implications for incipient marine terrace evolution. *Earth Surface Processes and Landforms*, 47(12), 2972–2988. doi:10.1002/esp.5438.

Howell, A. & Clark, K.J. (2022). Late Holocene coseismic uplift of the Kaikōura coast, New Zealand. *Geosphere*, 18(3), 1104–1137. doi:10.1130/GES02479.1.

Kirk, R.M. (1977). Rates and forms of erosion on intertidal platforms at Kaikōura Peninsula, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 20(3), 571–613. https://doi.org/10.1080/00288306.1977.10427603.

Kirk, R.M., Stephenson, W.J., Dickson, M.E.., Horton, S.L., Omidiji, J. Hossain, MD. S., Hemmingsen, M.A., Hemmingsen, S.A. and Hurst, M. (in review). Fifty Years of Shore Platform Erosion Monitoring at Kaikōura Peninsula, South Island, Aotearoa-New Zealand. *Earth Surface Processes and Landforms*.

Naish, T., Levy, R., Hamling, I., Hreinsdóttir, S., Kumar, P., Garner, G.G., Kopp, R.E., Golledge, N., Bell, R., Paulik, R. and Lawrence, J. (2024). The significance of interseismic vertical land movement at convergent plate boundaries in probabilistic sea-level projections for AR6 scenarios: The New Zealand case. *Earth's Future*, v. 12, p. e2023EF004165. https://doi.org/10.1029/2023EF004165.

Nicol, A., Begg, J., Saltogianni, V., Mouslopoulou, V., Oncken, O., & Howell, A. (2023). Uplift and fault slip during the 2016 Kaikōura earthquake and late quaternary, Kaikōura Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics*, 66(2), 263-278.

Omidiji, J., Stephenson, W.J., Dickson, M.E. & Norton, K.P. (2022). Tectonics and shore platform development: Rates and patterns of erosion on recently uplifted mudstone and limestone rocks at Kaikoura Peninsula, New Zealand. *Marine Geology*, 451, 106887. doi:10.1016/j.margeo.2022.106887.

Omidiji, J., Stephenson, W.J., Norton, K.P. (2023). Cross-scale erosion on shore platforms using the micro-erosion meter and Structure-from-Motion (SfM) photogrammetry. *Geomorphology*, 434, 108736. doi:10.1016/j.geomorph.2023.108736

Ota, Y., Pillans, B., Berryman, K., Beu, A., Fujimori, T., Miyauchi, T., Berger, G., Beu, A.G. and Climo, F.M. (1996). Pleistocene coastal terraces of Kaikoura peninsula and the Marlborough coast, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, *39*(1), pp.51-73.

Rattenbury, M.S., Townsend, D.B., and Johnston, M.R., (2006). Geology of the Kaikoura area: Institute of Geological and Nuclear Sciences (New Zealand) 1:250,000 Geological Map 13.

Stephenson, W.J., Dickson, M.E., Hurst, M.D., Omidiji, J., Horton, S.L., Litchfield, N.J., Norton, K.P., Matsumoto, H., Krier-Mariani, R.L., Acharya-Chowdhury, L. & McLean, A.D. (2025). Are Holocene coseismic marine terrace sequences complete paleoseismic records? Rapid erosion of a new marine terrace created during the 2016 Mw 7.8 Kaikōura earthquake suggests not! *Geology*, 53(10), 809–814. doi:10.1130/G53244.1.

Stephenson, W.J. & Kirk, R.M. (1998). Rates and patterns of erosion on intertidal shore platforms, Kaikoura Peninsula, South Island, New Zealand. *Earth Surface Processes and Landforms*, 23(12), 1071–1085. doi:10.1002/(SICI)1096-9837(199812)23:12<1071::AID-ESP922>3.0.CO;2-U.

Stephenson, W. & Kirk, R.M. (2000a). Development of shore platforms on Kaikoura Peninsula, South Island, New Zealand: Part one: the role of waves. *Geomorphology*, *32*(1-2), 21-41. doi: 10.1016/S0169-555X(99)00061-6

Stephenson, W. & Kirk, R.M. (2000b). Development of shore platforms on Kaikoura Peninsula, South Island, New Zealand: II: The role of subaerial weathering. *Geomorphology*, *32*(1-2), 43-56. doi: 10.1016/S0169-555X(99)00062-8

Stephenson, W.J., Kirk, R.M. & Hemmingsen, M.A. (2019). Forty-three years of micro-erosion meter monitoring of erosion rates on shore platforms at Kaikoura Peninsula, South Island, New Zealand. *Geomorphology*, 344, 1–9. doi:10.1016/j.geomorph.2019.07.012

Taylor, A.J. (2003). Change and Processes of Change on Shore Platforms. PhD Thesis. University of Canterbury, Christchurch, NZ. 387p.

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