Observations of the incipient and penultimate stages of Holocene marine terrace development

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Abstract
Flights of Holocene marine terraces are useful for reconstructing past earthquakes, but coastal erosion can remove terraces from the landscape, potentially leading to incorrect estimates of earthquake magnitude and frequency. Relatively little effort has been afforded to studying terrace erosion processes, and this paper presents the first field evidence that we are aware of documenting terrace erosion rates. Two case studies from New Zealand provide a unique opportunity to observe the beginning and end phases of terrace development. We present downwear and backwear erosion measurements, showing that both sets of processes are important. Micro-erosion meter measurements from Kaikoura Peninsula, South Island, confirm that downwear processes are modifying new marine terraces that were created when the peninsula was uplifted about 1 m during the 2016 earthquake. Erosion rates were high immediately following uplift as the relatively barren intertidal rock shore platform rapidly transformed into an incipient marine terrace with cover deposits. However, the Kaikoura earthquake uplifted shore platforms only a small distance above the upper tidal limit and ongoing downwear and backwear erosion may begin to remove parts of this terrace in future decades. We explored this prospect with a case study at Māhia Peninsula, North Island, where 100–300 years have elapsed since the last terrace-forming earthquake. Historical photographs were used to document about 80 years of backwear erosion. Terrace erosion rates have been nearly constant through this period, and extrapolation implies that the terrace will be removed in places by 2030. The erosion data in this paper provide new insights into how terraces can be removed from the landscape, but there are many complicating factors. To help understand these factors we present a new conceptual model of marine terrace creation and destruction for soft-rock coasts.

KEYWORDS
backwear, coastal erosion, downwear, earthquake, marine terrace, micro-erosion meter, shore platform

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Marine terraces are widespread globally and commonly used to infer past tectonic uplift rates, earthquakes, and sea-level history (e.g. Berryman, 1993; Lajoie, 1986; Pedoja et al., 2014). Pleistocene terraces record the integrated long-term effects of uplift and climate-induced sea-level changes (e.g. Chappell et al., Berryman, 1996; Kern, 1977; Zazo et al., 2003), whereas many Holocene terraces occur proximal to active plate margins and record co-seismic uplift that raises sequences by tens of centimetres to metres during each earthquake (Litchfield et al., 2020; Ota & Yamaguchi, 2004; Pedoja et al., 2014). Holocene terraces therefore preserve critical information about the timing and magnitude of discrete earthquakes in areas of ongoing uplift.

The historical record provides unequivocal evidence of marine terrace formation and the local short-term net uplift rate. For instance, at Boso Peninsula, Japan, an earthquake in 1703 AD uplifted the extant shore platform by 6 m, transforming it into a marine terrace and forcing the shoreline 800 m seaward (Matsuda et al., 1978). Interpretations of longer-term uplift rates from terrace sequences are confounded by a range of local factors that complicate efforts to link individual terraces to specific earthquakes. Philibosian and Meltzner (2020) point out that: major subduction earthquakes could occur without forming terraces; terraces could form due to climatic effects rather than tectonic uplift; and uplifted terraces could be erased by continued erosion (e.g. see Matsumoto et al., 2021). This erosion might be further enhanced by interseismic subsidence (e.g. Pfafker & Rubin, 1978) lowering terraces back into the intertidal zone. Furthermore, marine terrace formation might be composite/polygenic, where relative sea-level change results in reoccupation of a previously developed terrace (Malatesta et al., 2022).

Holocene marine terraces have been mapped and dated at multiple locations around the Pacific Rim. Eastern Taiwan is of particular interest, because it has some of the highest global uplift rates, implying that the terrace record may be relatively ‘complete’. Chen et al. (2020) documented six Holocene terraces in this region using LiDAR and field surveys, noting that the sequence is incomplete in some areas, and where all six terraces do occur there is considerable variability in terrace width (40–620 m), which they attributed, in part, to differential coastal erosion. Eastern New Zealand features similarly fragmented Holocene marine terrace sequences, particularly within the Hikurangi Subduction Zone (Figure 1a). High uplift rates (~3 mm/yr) occur at the Pakarai River mouth (Figure 1a), where a suite of seven terraces occur, but even at this site of high preservation, Wilson et al. (2006) considered that the (problematic) height of some terraces may reflect erosion of missing terraces. Litchfield et al. (2020) noted that the youngest terrace (T7) at this site appears to have eroded away since the original mapping by Ota et al. (1991) and Wilson et al. (2006), commenting that the height of the next youngest terrace is now the result of two earthquakes. Along the Wairarapa coast (Figure 1a), Berryman et al. (2011) noted that ~20% of the radiocarbon ages obtained from terraces are anomalously young, possibly because of tsunami contamination, but also because erosion has probably removed some terraces, complicating efforts to correlate them. Litchfield et al. (this issue) recently dated three terraces along the Hawke’s Bay coast (Aramoana, Figure 1a), suggesting that at least one terrace has been completely eroded. Between Gisborne and East Cape (Figure 1a), erosion has eliminated all Holocene marine terraces.
in some locations, whereas in other places up to six terraces are preserved (Ota et al., 1992).

Numerous additional accounts of Holocene terrace formation exist (e.g. Ota & Yamaguchi, 2004; Perg et al., 2001; Ramos & Tsutsumi, 2010). Most studies seek to determine uplift amounts and understand fault dynamics. From a process geomorphology perspective, it is somewhat surprising that relatively little scientific effort has been afforded to understanding (i) the erosion processes that can lead to terrace removal and (ii) the potential ramifications for paleoseismic interpretation of ‘missing’ terraces. As far as we are aware, there is no specific study of Holocene terrace erosion rates and consequences for paleoseismic interpretations. Progress can be made by drawing on the rock-shore platform literature, because a shore platform represents an incipient marine terrace that, on tectonic coasts, is waiting to be uplifted and (potentially) preserved in the landscape.

In order to understand terrace removal, we can use the rock coast literature where a distinction is often made between downwear and backwear processes (e.g. see Dornbusch & Robinson, 2011; Sunamura, 1992; Trenhaile, 1987, 2002a, 2020). Both downwear and backwear are potentially important for marine terrace removal. It is oversimplifying, but conceptually useful, to associate backwear with cliff/terrace retreat and downwear with shore platform lowering (Payo et al., 2015). Backwear refers to erosion processes that operate mainly horizontally, such as wave impacts and quarrying of steep slopes, whereas downwear processes act mainly vertically. In reality, these processes (e.g. supratidal and intertidal weathering, biological erosion and abraison by sediments entrained in fluid flows) operate in tandem, contribute both to downwear and backwear, and all have variable efficacy depending on lithology, climate, and surface elevation relative to the local tidal range.

Research on Pleistocene terraces has shown that numerical modelling can be used to explore how erosion processes influence terrace generation and destruction (Anderson et al., 1999; Matsumoto et al., 2022; Trenhaile, 2002b). Matsumoto et al. (2021) used a numerical model to draw attention to the highly complex erosional situation that exists for Holocene marine terraces. Their simulations indicate that when uplift magnitude relative to the local tidal range is ‘just right’ (i.e. less than the maximum spring tidal range), intertidal conditions can be created that increase erosion rates, creating very wide shore platforms that are more likely to be preserved in subsequent earthquakes. Model results suggest that large earthquakes do not necessarily have higher preservation potential, because they might uplift a narrow shore platform that could be rapidly removed by post-uplift backwear. Shore platform width is also expected to be a function of the duration that relative sea level occupies a fixed elevation to the land (Malatesta et al., 2022). These modelling studies highlight the importance of direct field observations of terrace creation and erosion, which are currently limited.

Here we present new observations from tectonically uplifted marine terraces, where we have a unique opportunity to describe the beginning and end phases of the terrace creation and destruction cycle. We measured (a) downwear erosion on new terraces created during the 2016 Kaikoura earthquake that uplifted shore platforms ~1 m (Stephenson et al., 2017) and (b) backwear erosion of the youngest terrace in the sequence at Māhia Peninsula, which has nearly been removed from the landscape (Berryman, 1993; Berryman et al., 2018). Below we describe the two field settings, document erosion rates at each site, and provide a new conceptual model for terrace creation and destruction that is consistent with these observations.

2 | FIELD SETTING AND PREVIOUS WORK

Our approach combines field measurements and remote sensing data to document rates of terrace erosion at the beginning and end phases of marine terrace development. We focus on two study sites on the uplifted eastern coast of New Zealand, within the complex boundary between the Australian and Pacific tectonic plates: Kaikoura Peninsula in the South Island and Māhia Peninsula in the North Island (Figure 1).

Māhia Peninsula lies west of the Hikurangi Trough, where the Pacific Plate is obliquely subducted beneath the Australian Plate. Up to five Holocene marine terraces occur on the peninsula, but the most spectacular sequence is at Kahutura Point (Table Cape) (Figure 1b), where four uplifted terraces have been studied by Berryman (1993) and Berryman et al. (2018). Extensive dating and detailed facies assessments of the terrace cover-bed sequence suggest that the oldest preserved terrace (T1) formed during an ~2.1 m uplift event at 3530–3350 cal. yr BP, T2 formed during an ~1.4 m uplift at 1810–1730 cal. yr BP, T3 is associated with an ~1.8 m uplift at 1560–1300 cal. yr BP, and the youngest terrace (T4) is thought to have formed very recently, between 300 and 100 cal. yr BP, associated with a large ~3.1 m uplift (Berryman et al., 2018).

Māhia Peninsula lies at the inner edge of the offshore accretionary wedge, comprising northwest-dipping imbricate thrust faults and east-verging folds (Barnes et al., 2002, 2010; Davey et al., 1986). This northern subduction zone contrasts with the Alpine Fault and Marlborough Fault System in the South Island, which is characterized by dextral strike-slip and oblique strike-slip plate motion. Kaikoura Peninsula occurs near the transition between the Marlborough Fault System and the Hikurangi Subduction Zone, and is subject to both subduction and upper crustal faulting (Bai et al., 2017; Duffy, 2020; Furlong & Herman, 2017; Howell & Clark, 2022; Litchfield et al., 2014). Late Pleistocene and Holocene marine terraces are preserved on the peninsula and are associated with long-term uplift rates of up to ~1.5 mm/yr; it is thought that earthquake-related faulting in the vicinity has been occurring for >100 kyr (Nicol et al., 2022). Both Māhia and Kaikoura are currently subsiding in response to interseismic locking on the Hikurangi subduction interface (Hamling et al., 2022).

The suitability of geomorphic comparison of the Kaikoura and Māhia field sites was first noted by Berryman (1993), who reasoned that the general model of shore platform development in the soft mudstones at Kaikoura (Kirk, 1977) is also broadly applicable for the mudstone rocks at Māhia. The value of comparison has now been enriched by the instantaneous ~1 m uplift of Kaikoura Peninsula during the 14 November 2016 Mw 7.8 Kaikoura earthquake (Clark et al., 2017; Stephenson et al., 2017), which created new marine terraces from existing shore platforms.
At Kaikoura we are in a unique position that since 1973, microerosion meters (MEM) have been used to determine lowering rates on intertidal shore platforms around the peninsula (Figure 2) (see Kirk, 1977; Stephenson & Kirk, 1996; Stephenson et al., 2019). Hence, we can document the very first stages of marine terrace development and compare pre-uplift rates of shore platform erosion with post-uplift rates of terrace modification. In contrast, Māhia Peninsula has not been uplifted within the recent historical record (at least the last 100 years), and the youngest dated marine terrace now represents a small remnant of what must once have been a much larger terrace (Berryman, 1993; Berryman et al., 2018). Hence, at this site we can study the penultimate stage of marine terrace truncation.

3 | METHODS

3.1 | Kaikoura

Rates of surface lowering on the uplifted shore platform and new terrace at Kaikoura have been measured using the MEM (High & Hannah, 1970). The MEM enables millimetre-scale surface lowering of rock surfaces to be measured in a relatively small area (<15 cm²) and is widely used in shore platform studies (Stephenson & Finlayson, 2009). MEM sites at Kaikoura were first installed in 1973 on six profiles (KM1–6, Figure 1c) around the peninsula (Kirk, 1977), and a seventh was added in 1993. Five profiles are located on Oligocene mudstone and two on Paleocene limestone.

FIGURE 2 Shore platform profiles before (April 1994) and after the 16 November 2016 Mw 7.8 earthquake showing location of microerosion meter (MEM) bolts. Note that 10 MEM sites were lost between 1994 and 2016 due to erosion. Zone of maximum number of wetting and drying cycles from Stephenson and Kirk (2000b) [Color figure can be viewed at wileyonlinelibrary.com]
The 2016 Kaikoura earthquake uplifted the peninsula ~1 m (Clark et al., 2017; Nicol et al., 2022), fundamentally reshaping the exposure of these shore platforms to the erosion process regime. Stephenson et al. (2017) resurveyed the seven uplifted shore platforms in December 2016 (~1 month after the earthquake) and recorded the location of 55 MEM bolt sites on these platforms in relation to local tidal elevation (Figure 2). Since the earthquake, 45 MEM sites have been measured 12 times at 3-monthly intervals, the first 4 weeks after the earthquake and most recently in December 2019. Prior to uplift, erosion rates measured over two 2-year periods and at decadal scales (20–43 years) demonstrate that platform surface lowering is on average 1.1 mm/yr (Stephenson et al., 2019). Here we report 3 years of erosion monitoring since the Kaikoura earthquake, comparing pre- and post-uplift rates of erosion to explore the longevity of the newly uplifted terraces. In addition, we identify those MEM sites located on the supratidal terrace (incipient marine terrace) and those that remain within the intertidal zone (albeit higher) and describe vertical change in the profiles. As yet we have no data on backwear processes at this site.

3.2 | Mahía

Research at Mahía focused on documenting the erosional removal of the youngest terrace (T4). We undertook fieldwork in 2019 and 2020 using an unmanned aerial vehicle (UAV) to obtain high-resolution overlapping photographs. Centimetre-scale ground control for the survey was achieved using 20 ground targets surveyed with a Trimble R10 Real-Time-Kinematic GNSS system. Imagery was obtained using an Inspire 1 UAV with 360°-rotating camera (12.76 MP Zenmuse X3 FC350) that allowed for consistent and stable collection of nadir-orientated aerial imagery with a resolution range between 1.0 and 2.3 cm/px. Surveys were conducted with approximately 70% front overlap and 65–75% side-overlap. Structure-from-Motion (SfM) photogrammetry was undertaken using Pix4DMapper Pro 4.1.5 in which the point cloud classification tool was used to derive two high-resolution (centimetre-scale) digital terrain models on 01-Sept-2019 and 11-Feb-2020.

Historical vertical aerial photographs for Mahía were obtained from Land Information New Zealand from 1938, 1945, 1967, 1973, 1981, 2003, and 2015. Images were georeferenced using fixed ground control points, with extensive jointing within the rock fabric of the shore platform providing for a large number (>20) of points per image. Horizontal RMS errors ranged between 1.5 and 4.7 m, with larger errors typically associated with coarser-resolution images (e.g. 1945).

The base of the T3 riser and the seaward edge of T4 were manually digitized as polyline shapefiles in ArcMap using the rectified historical imagery and the 2019 digital terrain model. The study area is approximately 2.5 km in length along the edge of T4. In total, nine historical terrace edge positions were mapped, providing a record of erosion over the past 82 years. The Digital Shoreline Analysis System (DSAS) extension for ArcMap (Thieler et al., 2009) was used to cast shore-normal transects at 10 m spacing along 2.3 km of T4. A small number of transects were omitted where shorelines intersected creeks. In total, 227 transects were cast, with ID = 2 the most southern transect and ID = 228 the most northwestern transect (see Figure 6 later). The point-transect intersect method was used for assessing planform shoreline change in which the intersection between the transects and shorelines is recorded as distances or rates of change at each transect.

4 | RESULTS

4.1 | Kaikoura

Surface rates of change from MEM bolt sites are presented in Figure 3. Mean annual rates of change following uplift for each profile range from 0.534 (KM4) to 3.848 (KM6) mm/yr. The overall mean annual rate of downwear (lowering) for all profiles was 2.316 mm/yr post-uplift, compared to pre-uplift rates of 1.1 mm/yr (1993–1996; Stephenson & Kirk, 1998) and 0.944 (1993–2004; Stephenson et al., 2010). Erosion rates pre- and post-uplift are significantly different (Mann–Whitney U test: z-score = −3.73664, p-value = 0.00018).

Mean profile downwear erosion rates from aggregating individual bolt sites obscure the large variations in surface change data that occur at individual bolt sites. After 3 years, rates of change at individual bolt sites ranged from −2.536 to 6.545 mm/yr, where negative values indicate positive elevation change usually resulting from the disaggregation of the surface where the freed material remains in situ. Previously such debris was removed by wave action. Separating MEM bolt sites between those that are still in the intertidal zone and those that are now on the new marine terrace allows us to see if or how erosion rates on the two surfaces are responding. While it is reasonable to hypothesize that erosion rates on the two surfaces would be different, a Mann–Whitney U test of difference of means established no statistical difference (z-score = 0.4714. p-value = 0.638) between erosion rates in the intertidal and those on the supratidal surface. However, we do observe sediment accumulating over individual bolt sites on the upper parts of the new terrace and plant colonization. Figures 4a and b show the early stages of post-uplift sediment accumulation at KM2 (see Figure 1c for location) in 2018. Three years later, at the right of Figures 3b and c at KM2 and KM6, erosion scarps that were developing at the landward edge of the shore-platform/hillslope junction before uplift, can now be seen as supratidal, grassed slopes. To the left of the grassed area, driftwood and seaweed have accumulated. This sediment accumulation represents the very
beginning stages of marine terrace cover-bed formation. At several sites (e.g. KM2A, KM2B, KM6A), the shore platform occurs under the grass and is covered by mud, with burial preventing the relocation of MEM bolt sites.

At KM6A and KM3J, rapid breakdown of the mudstone surface occurred in the early months following the 2016 earthquake, but following the initial high rates of downwear erosion, KM6A had accumulated material and by December 2020 the site had been covered to the extent that the bolts were no longer visible on the surface. KM2B showed negative values (surface accumulation) from December 2017 to December 2019. By December 2020 the site was no longer locatable as the bolts were completely buried. In addition to the sediment accumulation over these surfaces, shells, seaweed and driftwood are being washed in and grasses have partly covered the surfaces. It would also appear that soil production is underway. We have no data yet on whether the surface is periodically swept by waves during storm events and have not considered the possible implications of reworking of supratidally deposited sediments.

We plotted MEM bolt elevation against bolt mean downwear erosion rate (Figure 5) to further explore possible differences between erosion rates on intertidal and supratidal surfaces. One challenge is that the vertical position of bolt sites relative to the tide is more complex than a simple separation of supra- and intertidal zones, because multiple bolts are located between the range of the spring and neap high tides (Figure 5). At Kaikoura, the range between the neap and spring high tide is 0.4 m. Using bolt elevation data and water-level measurements during neap and spring tides made with self-contained tide and wave gauges deployed on the platforms, we determined that neap tides (not accounting for barometric variability) are ~1.1 m above MSL and spring tides are ~1.5 m above MSL. On this basis, nine bolt sites exist above spring high tide (i.e. are supratidal) and...
39 are intertidal (note that only eight supratidal points can be seen in Figure 5 because one is now buried and so cannot provide an erosion rate). During neap high tides, 28 sites are supratidal and 19 intertidal; 14 sites are intertidal throughout the lunar tidal cycle and 19 occur within the neap–spring tide range, so are intertidal at spring tides but supratidal at neap tides. A comparison of erosion rates (Figure 5) and bolt elevation shows a high degree of variability with no clear relationship. The short post-uplift measurement period is not yet sufficiently long to draw confident conclusions on this effect. Monitoring continues, but we are limited by a relatively small number of bolt sites on purely supratidal locations (i.e. supratidal at spring tides).

4.2 | Mahia

The erosion data presented from Kaikoura describes vertical down-wear rates immediately following earthquake uplift. In contrast, erosion data from Mahia allows us to document horizontal backwear of the youngest (100–300 years) marine terrace T4 (Berryman et al., 2018) after the earthquake that produced the terrace. The slope map in Figure 6a clearly distinguishes the Holocene terraces that are evident in the field at Kahutara Point (the excavated trenches of Berryman et al., 2018 are also visible). T4 is the narrowest terrace, but it can be continuously traced across the 2.5 km-long study area. The

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**Figure 6** (a) Slope map from SfM-derived digital surface model (2019) with 2015 aerial photograph. (b) Digitized lines show seaward edge of T4 (2020 not shown as indistinguishable from 2019 at this scale). Location of photograph (c) (view to the east) indicated with * on (a). (d) Topographic ground surface profile from (a) to (a) extracted from digital surface model [Color figure can be viewed at wileyonlinelibrary.com]
digitized terrace edges and DSAS transects show that coastal erosion processes (backwear) have driven the seaward edge of T4 landward between 1938 and 2019. This has resulted in a reduction in the width of T4, which can be measured between the sharp eroding seaward edge of T4 and the lower portion of the T3 riser (see the slope map and the field photograph in Figure 6), because the riser between T3 and T4 has not had any perceptible change across the observation period. In addition, backwear erosion of T4 has continued to enlarge the anomalously wide contemporary shore platform (Figure 6).

In 1938 the minimum width of T4 in the study area was about 8 m (median 33 m), but this minimum had reduced to 2.1 m (median 19 m) by 2020 (Figure 7a). Median recession rates across the study area are 0.15 m/yr, with the fastest erosion rates (~0.4 m/yr) occurring at the promontory of Kahutara Point near DSAS transect P117 (Figures 5, 6, and 7). The slowest erosion rates occur in the lee of a protruding rock outcrop near P10. Erosion rates are very consistent (near linear) through time (Figure 7b), particularly around the promontory between transects 60 and 140, where \( R^2 \) values for linear regression are >0.9 (Figure 8). Assuming this erosion rate continues, T4 will be removed from some sections of the coast by 2030, and at least 30% of T4 is likely to be removed by 2100.

5 | DISCUSSION

Holocene marine terraces provide important, but incomplete, evidence of the magnitude and frequency of past earthquakes. To improve interpretation of these fragmented records we need to enhance our understanding of factors such as interseismic subsidence (e.g. Plafker & Rubin, 1978), Holocene sea-level variability, and terrace erosion processes. Our measurements of backwear erosion at Mahia and downwear erosion at Kaikoura provide the first field evidence targeted specifically at understanding terrace erosion processes.

We begin this discussion by highlighting the modern shore platform at Mahia (Figure 6a): its extensive width (250–300 m) is confounding. If an earthquake were to occur today and transform this feature into a new marine terrace, it would greatly exceed the width of the entire adjacent flight of terraces (cf. Figure 6d). The most recent

![Figure 7](wileyonlinelibrary.com)

**Figure 7** Boxplots in (a) show the width of T4 across all transects in Figure 6a (2019 is omitted for plot clarity). (b) Selected transects showing near-linear retreat rate of the seaward edge of T4 through time [Color figure can be viewed at wileyonlinelibrary.com]

![Figure 8](wileyonlinelibrary.com)

**Figure 8** Change in T4 width between 1938 and 2020. (a) Boxplot summarizes all transects, (b) line plot shows individual transects (see Figure 6a for transect locations). (c, d) Average T4 erosion rate. (e, f) Predicted number of years until T4 is removed, assuming a linear recession rate (LRR) [Color figure can be viewed at wileyonlinelibrary.com]
terrace-forming earthquake at Māhia has a maximum age of about 300 cal. yr BP (Berryman et al., 2018). Since then, backwear has reduced the width of the terrace and increased the width of the modern shore platform. Historical terrace erosion rates have been consistent through time at a maximum rate of about 0.4 m/yr, but extrapolating this maximum rate explains less than half the width of the contemporary shore platform. Multiple hypotheses might explain this anomaly. Perhaps backwear rates were much faster in the years immediately following the earthquake and declined towards current rates owing to increasing wave-energy dissipation across a widening shore platform? If this explanation were true, we would also require an explanation for the sustained historical erosion rate, such as a role for infragravity wave energy (Dickson et al., 2013) and/or recent sea-level rise or other anthropogenic factors (e.g. Hurst et al., 2016). An

**FIGURE 9** Conceptual model showing phases of Holocene marine terrace creation and destruction associated with two earthquakes and backwear and downwear erosion processes. Time increments are ~100 years [Color figure can be viewed at wileyonlinelibrary.com]
alternative or complementary explanation might lie in the complex role of beach inheritance. For instance, the magnitude of the last earthquake may have fortuitously combined with the pre-existing shape of the seafloor bathymetry to uplift a very wide expanse of rock into the intertidal zone, and post-earthquake downwear processes could then have rapidly smoothed this prior seafloor into a planar shore platform (e.g. see Matsumoto et al., 2021).

The previous example demonstrates that many unknown factors complicate our ability to understand the geometry of Holocene marine terraces and associated shore platforms. In this discussion we attempt to simplify the problem with a new conceptual model of marine terrace development (Figure 9). The model integrates (i) our current understanding of shore platform development processes from the rock coast literature, (ii) insights from numerical modelling studies of Holocene terrace development (e.g. Matsumoto et al., 2021), and (iii) our observations of downwear and backwear erosion rates recorded at the initial and penultimate stages of terrace formation at Kaikoura and Mahia. The MEM downwear data from Kaikoura provides new insights into the narrow window of time between uplift and vegetation and cover-bed development, whereas the backwear data from Mahia characterizes the final stages of marine terrace truncation.

The conceptual model describes a rock coast landscape in which erosion processes produce shore platforms, and where two earthquakes spaced 500 years apart uplift the coastal profile. The first panel (Figure 9a) illustrates pre-earthquake cliff retreat processes that produce a gently sloping intertidal shore platform (SP1). The landward cliff erodes by backwear because wave action and weathering processes over-steepen the cliff, leading to failure, and the slope above the cliff is subject to mass-wasting processes that gradually round the profile. Theory implies that in micro-tidal environments the seaward edge is an artefact of pre-uplift coastal erosion processes and remains stable as the shore platform widens over time (Sunamura, 1992). However, cliff backwear rates may decline through time as wave energy is increasingly dissipated across a Widening surface. We illustrate this effect (Figure 9a) over the initial 500-year erosion period (cliff positions t0–t5) but note that the possibility of declining backwear rates is mitigated on relatively soft rock (e.g. mudstone) coasts. For instance, infragravity wave energy is transmitted to terrace risers across very wide platforms even in shallow water (Dickson et al., 2013), while downwear of the shore platform surface increases water depths, increasing the potential for surface gravity waves to transmit across the shore platform to the terrace riser. Pre-earthquake measurements at Kaikoura indicate that maximum rates of downwear on shore platforms occur close to MHW elevation and minimum downwear rates occur near MLW (Stephenson & Kirk, 1998); this is depicted in Figure 9a with vertical arrows, the length of which indicates the rate of erosion. For soft mudstone rocks, such as those that occur at Kaikoura and Mahia, MEM data indicates that the upper region of the intertidal zone is dominated by subaerial weathering processes driven by wetting and drying cycles, and the lower mainly submerged zone may erode predominantly through bioerosion, assisted by mechanical forces associated with waves (Kirk, 1977; Stephenson & Kirk, 2000a,b).

The second panel in the model (Figure 9b) records a sudden halt in the increase in shore platform width because an earthquake at t5 elevates the shore platform, turning it into a marine terrace (MT1). Backwear of the landward cliff toe ceases as the former cliff toe now lies above the intertidal zone and is protected by now-supratidal beach deposits. The earthquake at t5 is similar to the 2016 Kaikoura earthquake in that uplift (~1 m) is smaller than the local tidal range (~2 m). This means that the landward portion of SP1 is instantaneously converted into MT1, whereas the seaward part of SP1 is incorporated into the contemporary shore platform (SP2). Hence, the morphology of SP2 is partly inherited both from the pre-existing shape of SP1 and the geometry of the uplifted seafloor (note: most shore platforms develop at intertidal elevations, see Sunamura, 1992; Trenhaile, 1987).

After the earthquake at t5, erosion processes begin to remove MT1 laterally through backwear (horizontal arrow) and vertically through downwear (vertical arrow). Note that backwear is focused on the seaward edge of the former SP1, where maximum wave energy expenditure is likely to occur. Pre-uplift, wave breaking occurs on or landward of the seaward edge, with energy dissipation then occurring through turbulent bores passing over the near-horizontal shore platform (Krier-Mariani et al., 2022; Ogawa et al., 2011; Poate et al., 2020). Post-uplift, wave breaking occurs against or immediately seaward of the seaward edge, implying that backwear of this feature is likely to ensue. We do not yet have field data to test this hypothesis, but erosion rates are expected to be fast initially, owing to the absence of a wide planar intertidal shore platform that would dissipate wave energy. Clearly this situation is complex and entirely dependent on the morphology of the offshore seafloor that is uplifted, but our assumption that the offshore seafloor is more steeply sloping than the intertidal shore platform is generally supported by bathymetric observations off existing shore platforms at Kaikoura (Stephenson & Kirk, 2000a) and elsewhere (Kennedy, 2016; Savige et al., 2021).

The depiction of downwear erosion of MT1 and SP2 in Figure 9b is based on our Kaikoura MEM erosion rates recorded before and after the 2016 earthquake. Rates are highly variable across the intertidal shore platform and supratidal incipient marine terrace, but on average they are about two times faster than pre-uplift rates. The increase in downwear rates is probably due to the amount of uplift (~1 m) being similar to the tidal range at this site, which means that a portion of the once intertidal platforms is now only just above the high-tide mark; 19 sites are now in the zone of spring and neap high tide, the area where previous MEM rates were highest (Stephenson & Kirk, 1998, 2000b). In the conceptual model we include rapid breakdown and erosion of the shore platform immediately after uplift (t5). In the decades following uplift (t5 and t6, Figure 9c) this contributes to sediment accumulation on the new terrace surface. MT1 weathers in situ and cover deposits begin to accumulate. Observations of the new marine terrace at Kaikoura show that mud, debris, and vegetation have occupied the surface within a few years of the uplift event (Figure 4). Hence, the cover deposits on MT1 in the third panel (Figure 9c) are a combination of pre-existing beach deposits and additional sediments eroded from MT1 and SP2. It is likely that waves crossing the shore platform are contributing to MT1 cover deposits by delivering some of the weathered debris (Figure 9c; storm overwash). Colluvial outwash from the former sea cliff and hillslope is likely to increase the thickness of cover deposits on MT1 through time, and other sources could also be important (e.g. tephra, tsunami deposits; Berryman et al., 2018; Litchfield et al., 2020, this issue).
MEM measurements at Kaikoura show that maximum downwear rates occur near MHW elevation, close to the boundary between SP2 and MT1. Extrapolating these observations several decades into the future leads to a hypothesis that a terrace riser may begin to emerge separating SP2 and MT1 (Figure 9c). Over time, platform downwear, combined with erosion of the seaward edge of former SP1, will deliver increased wave energy to a new terrace riser, initiating backwear of this emerging feature, which begins to reduce the width of MT1. It is also possible that downwear of the seaward edge of MT1 could reincorporate part of the terrace into SP2.

The time period t6–t10 encapsulates a further four centuries of shore platform development processes following earthquake 1 at t5 (Figure 9d). Wave energy and intertidal weathering processes rapidly erode SP2 through a combination of downwear and backwear. This cuts back into MT1, increasing its height relative to the extant shore platform (SP2), confounding efforts to infer the uplift in earthquake 1 on the basis of the height difference between SP2 and MT1.

The final phase of terrace development in the conceptual model is presented in Figures 8f and 9e. A second earthquake occurs at t10, once again lifting the coastal profile and creating a second marine terrace (MT2) from SP2. The combined effect of the two earthquakes is to considerably decrease the nearshore water depth, and in the second earthquake a wide expanse of seafloor is lifted into the intertidal zone creating a wide shore platform (SP3). Note that the width of this feature is largely inherited as a result of uplift. This mechanism is one plausible explanation for the anomalously wide modern shore platform at Mahia (Figures 6a and d). Backwear and downwear processes act together, eroding into the former shore platform (SP2), further increasing the width of the modern shore platform (SP3), especially when intertidal weathering is enhanced (Matsumoto et al., 2021). Widening of SP3 comes at the expense of MT2, consistent with our observations of terrace removal at Mahia. MT2 will be completely removed given a sufficiently prolonged period of relative sea-level stability, and if this situation continues, eventually the width of MT1 would begin to reduce also. If the conceptual model was extended long enough to capture another three or four earthquakes of similar magnitude (which is not unrealistic given what we know already about recurrence intervals of such events), we would see a repeat of the steps explained above, and while the number of terraces observed might reach four or five, it is likely that at least two terraces would have been removed from the landscape.

The conceptual model described in Figure 9 is applicable to a broad range of Holocene coastal terraces formed in relatively soft rocks (e.g. soft mudstones and limestones) with similar uplift histories. We are aware of several sites along the Hikurangi Subduction Zone where the model could be used to help understand marine terrace sequences, such as at Cape Campbell (Howell & Clark, 2022), Aramoana (Litchfield et al., this issue), Waimarama (Miyachi et al., 1989), Cape Kidnappers (Hull, 1987), Pakarara River mouth and Puatai Beach (Litchfield et al., 2020) (see Figure 1). Given the observed number of marine terraces at sites in New Zealand and around the Pacific (commonly three or four, and only rarely six or seven) we are of the view that terrace removal is the norm rather than the exception. Taking this view in addition to the comments of Berryman et al. (2018) and Litchfield et al. (2020, this issue), there is likely to be considerable value in re-examining marine terrace sites that have previously been studied to determine earthquake magnitude and frequency, placing sharper emphasis on the possibility that one or more terraces are missing.

The conceptual model addresses a specific earthquake magnitude frequency scenario and neglects the possible influence of interseismic subsidence. It is beyond the scope of the present paper to consider a broader range of possibilities, but the following comments might be useful to guide future research. First, we draw attention to the numerical model results of Matsumoto et al. (2021), in which it is shown that larger uplift events do not necessarily preserve terraces in the landscape, because a large earthquake might uplift a narrow shore platform that could be very rapidly removed by post-uplift erosion. Second, at subduction zones, geodetic observations support the subduction earthquake cycle concept, whereby coseismic deformation is recovered during the interseismic period (e.g. Savage, 1983). However, the presence of marine terraces at many subduction zones suggests that coseismic uplift is not always fully recovered, or is the result of another process, such as earthquakes on upper-plate faults. This is the case for the Kaikoura and Māhia study sites: although they are currently undergoing interseismic subsidence from Hikurangi Subduction Zone locking, coseismic uplift is most likely to result from earthquakes on nearshore faults (Barnes et al., 2002; Berryman, 1993; Clark et al., 2017; Nicol et al., 2022). It was not possible in our conceptual model to consider all of the potential complications associated with variable earthquake magnitude and frequency and interseismic subsidence, but several promising research trajectories should lead to future improvements in understandings of events and Holocene marine terraces. New field sites will incrementally add to the existing body of knowledge, and improvements in radiometric dating and numerical model process representations should enhance interpretations. The application of terrestrial cosmogenic nuclides (TCNs) may prove particularly useful. TCNs have already been used to determine ages and erosion rates on active shore platforms (e.g. Choi et al., 2012; Duguet et al., 2021; Hurst et al., 2016; Regard et al., 2012; Shadrick et al., 2021; Swirad et al., 2020) and Pleistocene marine terraces (e.g. Perg et al., 2001). This approach could be useful for analysing Holocene terrace bedrock exposure histories, and alongside radiocarbon dating, TCNs might also be useful for elucidating terrace cover-bed accumulation processes. This would provide valuable new data for numerical models of shore platform and Holocene terrace formation, which currently incorporate representations of downwear and backwear processes, but neglect the role of cover deposits (e.g. Matsumoto et al., 2021).

6 | CONCLUSIONS

Geologists have long understood that individual terraces can be missing from flights of Holocene marine terraces. This is problematic because missing terraces could lead to incorrect estimates of paleo-earthquake magnitude and frequency. To date, relatively little research effort has been afforded to understanding the erosion processes that erase terraces from the record. This paper contributes to this research gap by presenting the first direct field evidence of terrace erosion rates that we are aware of. Moreover, the field sites studied have enabled critical observations of (i) terrace removal at the penultimate stage of marine terrace truncation and (ii) surface erosion rates from new terraces uplifted in an earthquake in 2016.
We measured downwear erosion processes on newly created terraces at Kaikōura Peninsula, South Island, New Zealand, using a MEM. Results confirm that post-uplift rates are, on average, about twice as fast as pre-uplift, showing that downwear is an important process in the post-uplift development of terrace surfaces. At this site, the uplift magnitude is smaller than the local tidal range, and it is possible that continued erosion in decades and centuries to come could lead to the surface being partly or wholly absorbed into the contemporary intertidal shore platform. To explore the role of backwear processes we investigated the youngest marine terrace at Māhā Peninsula, North Island, New Zealand, which was uplifted by an earthquake at 100–300 cal. yr BP. Historical photographs were used to document 80 years of terrace erosion by backwear. Erosion rates have been nearly constant through time (median ~0.15 m/yr) and the terrace will likely be removed in places by 2030. The erosion data from Kaikoura and Māhā collectively demonstrate that downwear and backwear erosion processes are each important controls on terrace evolution.

This paper presents a new generalized conceptual model (Figure 9) of erosion processes that can lead to incomplete terrace sequences on soft-rock coasts. The model is anchored in observations of the beginning and end phases of Holocene terrace development at Kaikōura and Māhā, but integrates knowledge of shore platform development processes from the literature as well as insights from published numerical modelling studies. Future improvements in our understanding of Holocene marine terraces are likely to result both from further field evidence, improved radiometric dating, and improved numerical model process representations.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publically available due to privacy or ethical restrictions.

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