Erosion Rates on Newly Uplifted Marine Terraces Following the 2016 Kaikōura M_w 7.8 Earthquake

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Introduction

Since 1973, micro-erosion meters (MEM) have been used at Kaikōura Peninsula, New Zealand (Fig 1) to determine lowering rates on inter-tidal shore platforms. Rates measured over two, two year periods (1973-1975 and 1994-1996) and at decadal scales (20-30 years) demonstrate that platform surface lowering is on average 1.1 mm/yr. The 14 November 2016 M_w 7.8 Kaikōura earthquake caused an instantaneous uplift of 0.8-1.0 m of the peninsula (Fig. 2). The uplift offers the rare opportunity to examine how such an event alters processes and rates of erosion on these shore platforms (Fig. 3), since these platforms are now partially marine terraces as the inner margins of platforms are now above high tidal levels (but perhaps not storm surge, Fig. 3). Here we report 21 months of erosion monitoring since the earthquake, with a view to establishing the longevity of the newly uplift surface and the altered erosion rates on the shore platforms.

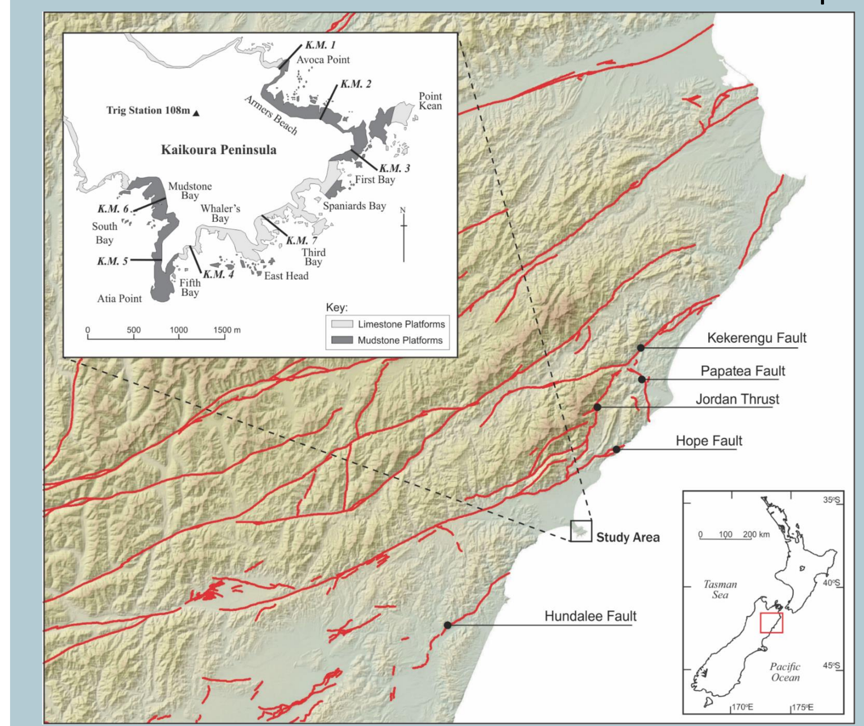

Figure 1. Location of major faults in the upper South Island, New Zealand and Kaikoura Peninsula showing location of MEM profiles and Trig station. Named faults are some of those that raptured during the November 14 2016 earthquake (Langridge et al. 2016; Stephenson et al. 2017; Litchfield et al. 2018).

Figure 2. Seaward edge of a raised shore platform. Holdfasts of bull kelp (*Durvillaea antarctica*), previously located in the subtidal zone (18/12/2016).

Figure 3. View of a raised and inter-tidal shore platform. North side of Kaikōura Peninsula. Profile KM2 (see Fig. 5), crosses centre of platform (18/12/2016).

Methods

Surface lowering on shore platform have been measured using the MEM (High and Hanna 1970). The MEM It comprises an engineering dial gauge attached to an equilateral triangle base, with three legs. The instrument sits atop three bolt permanently installed in the rock surface and precisely relocates using an Kelvin Clamp. The base is rotated 120˚ three times and the three readings are averaged, this average is the converted to a mean annual erosion rate (or swelling) for the site. The bolt sites were installed in 1973 on 6 profiles around the Peninsula and a seventh profile was added in 1993 (Fig 1.). Five profiles are located on Oligocene mudstone and two on Paleocene limestone. These profiles were resurveyed in December 2016 to determine the amount of uplift based on static GNSS observations (Stephenson et al. 2017). Since the earthquake, 45 MEM sites have been measured seven times at 3 monthly intervals. Most recently in September 2018.

Figure 4. The Micro-erosion Meter, used at Kaikōura since 1973 (Kirk, 1977). The MEM sits atop three bolts installed in the rock. Note these sit above the surface, when installed these were recessed. Evidence of the long term lowering of the surface.

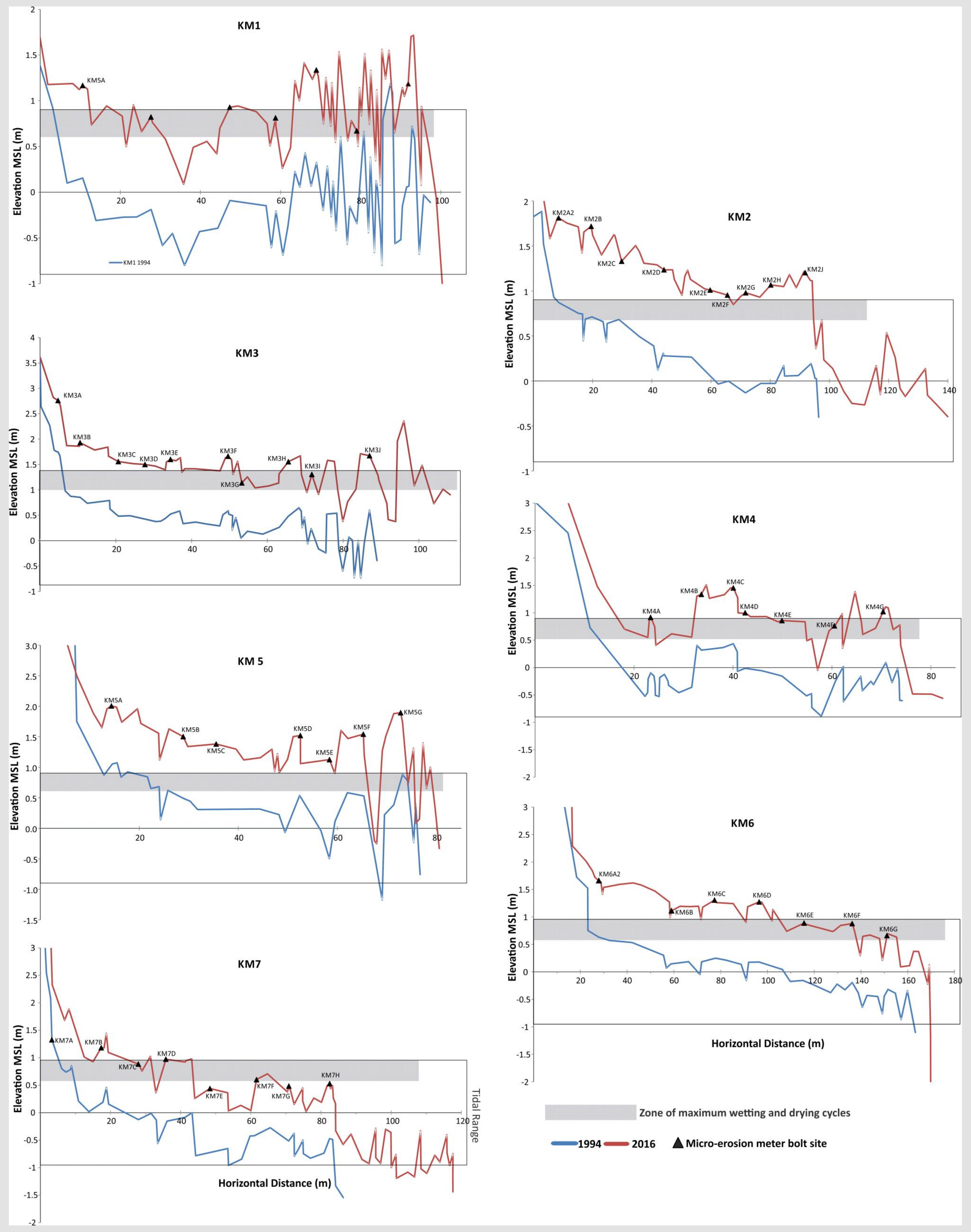

Figure 5. Surveyed platform profiles at Kaikōura and locations of MEM bolt sites. The blue profile was surveyed in 1994 and the red profile in December 2016, 4 weeks after the earthquake, following ≈1 m of uplift. Grey zone – elevation of maximum wetting and drying (Stephenson et al. 2017).

Results

Mean erosion rates (mm/yr) at each measurement period by profile are shown in Table 1. These are compared to pre-earthquake rates from 2 (1993-1996) and 10 years (1993-2014). Mean rates mask highly variable inter-survey rates at individual bolt sites. Figure 6 illustrates this variability for three of the seven profiles, where both surface lowering and swelling are shown. Illustration of that variability are shown in the photo panels of Fig. 6. Rapid break down is evident (Fig 6A.), as is swelling and burial as weathered debris accumulates on the surface (Fig 6B), then larger scale (cm rather than mm) break down is evident in Fig. 6C. Erosion rates from before the earthquake were compared to those after using nonparametric tests of median distribution. Table 2 shows that these significantly different, with different means and distributions.

Figure 6. Erosion and swelling rates from three mudstone profiles at Kaikōura; KM1, 2 and 3. Cross shore variability in rates at each measurement period is evident. Side panels illustrate variety of surface change; rapid breakdown KM1A; erosion, swelling then burial of site KM2B; and larger scale block removal KM3J.

Table 1 Mean erosion rates (mm/yr) for each profile.

Profile	1993 to 1996	1993 to 2004	30/03/2017	24/06/2017	9/10/2017	18/12/2017	13/03/2018	28/06/2018	9/09/2018
KM1	0.614	0.671	2.199	0.100	0.925	1.663	1.684	1.520	2.031
KM2	1.740	1.825	2.912	4.228	3.426	2.912	3.271	1.482	3.036
KM3	0.754	0.931	9.509	3.797	4.781	4.215	3.577	3.907	2.158
KM4	0.910	0.824	0.483	2.121	1.813	1.539	0.717	0.689	0.583
KM5	0.614	0.869	1.955	1.007	1.648	2.332	2.539	2.370	2.341
KM6	2.226	0.691	11.589	4.001	4.389	3.521	3.041	3.774	5.375
KM7	0.839	0.794	0.681	-0.023	-0.478	-0.057	3.470	2.027	2.057
Mean	1.100	0.944	4.190	2.176	2.358	2.304	2.614	2.253	2.512

Table 2 Statistical tests of differences between pre and post earthquake erosion rates.

Null	Test	Sig	Decision
The medians of Erosion Rate are the same across groups	Independent Samples Median Test	0.004	Reject the Null
The distributions of Erosion Rate is the same across categories	Independent Samples Mann-Whitney Test	0.002	Reject the Null
The distribution of Erosion Rate is the same across categories	Independent Samples Kolmogorov-Smirnov Test	0.000	Reject the Null

Implications

The coseismic uplift has altered the process regime operating on these platforms. Zones of maximum wetting and drying have migrated seaward causing previously slow eroding (< 1 mm/yr) MEM sites to accelerate to 2.5 times the pre-earthquake rates. Erosion rates demonstrate rapid adjustment of the platform surface to this disturbance and illustrate how uplifted marine terraces can be rapidly eroded despite being above sea level. Based on the uplift of 0.8 to 1.0 m and assuming a constant lowering rate of 2.5 mm/yr, the new marine terrace could be removed within the next 320-400 years (not accounting for backwear). Preservation of the new terrace is dependent on further uplift beyond the reach of the sea, within that timeframe. Furthermore the amount of terrace preserved will depend on the timing of that uplift within that time frame. This scenario has significant implications for marine terrace preservation and the recording of coseismic events in the landscape. Since the erosion rates we have measured show that newly uplift surface can be rapidly removed from the landscape and there is potential for the record of coseismic uplift to be lost.

References

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