

## Research Article

## Shore platform morphological inheritance from past higher sea levels in a microtidal setting

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## ABSTRACT

Shore platforms along rock coasts have long puzzled geomorphologists regarding their age and formative processes. This study combines cosmogenic nuclide (CN) dating and micro-erosion meter (MEM) measurements to investigate the evolution of microtidal shore platforms on the Otway Coast of Victoria, Australia. CN concentrations across four platforms reveal significantly high values (up to 123,831 atoms g<sup>-1</sup>) compared to previous studies, indicating formation predating the Holocene. Cross-shore CN distribution shows peak concentrations at the seaward edge, decreasing landward. MEM data collected over 44 years demonstrate active contemporary erosion, with downwearing rates closely related to elevation and tidal inundation frequency. Numerical modelling of both CN concentrations and MEM-calculated downwearing rates suggest platform initiation during at least the Last Interglacial period, with subsequent modification during the Holocene. The results indicate that platform width is morphologically-inherited from past higher sea levels, while the contemporary cross-shore morphology results from Holocene downwearing processes. This study provides evidence for long-term morphological inheritance in shore platform evolution, challenging the notion of purely Holocene formation in resistant lithologies. The findings highlight the complex interplay between inherited landforms and ongoing erosive processes in shaping rock coast geomorphology, contributing to our understanding of coastal landscape evolution over glacial-interglacial timescales.

## 1. Introduction

The wide variety of landforms on rock coasts results from erosion by waves, subaerial processes and organisms (Stephenson et al., 2022). Shore platforms form on microtidal coasts where rocks are sufficiently resistant to erosive forces to the extent that they can maintain semi-horizontal ledges in the intertidal zone (Trenhaile, 2002, 2008). Determining the age of these surfaces has confounded geomorphologists for over a century (Bartrum, 1916; Johnson, 1931). It is now well known that erosion occurs sporadically at the instantaneous (hourly) scale through block plucking (e.g. Shetland Islands (Hall et al., 2008), Wales (Buchanan et al., 2020) or Ireland (Cullen and Bourke, 2018)) and

granular disintegration (e.g. New Zealand (Stephenson and Kirk, 1998, 2000) and Australia (Yuan et al., 2018)), yet upscaling these processes to millennia to calculate landscape age is still difficult (Kennedy et al., 2017). Numerical modelling has generally been preferred to bridge the gap between the short and long timescales rather than field-based approaches. (Trenhaile, 2014; Trenhaile, 2001, 2010).

The erosive nature of rock coasts is generally not conducive to the preservation of material that can be used for numerical dating. Inferences on platform age have been made where inactive surfaces are found at the rear of platforms either buried by sediment (Blanco-Chao et al., 2003; Brooke et al., 1994; Trenhaile et al., 1999) or raised above the contemporary erosive zone through relative sea level change

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(Gardner et al., 2006; Kennedy and Beban, 2005). However, such studies are biased to locations where geomorphic conditions enable such raised surfaces to be preserved. Direct dating of encrusting organisms growing on platforms can provide further information (Kennedy et al., 2012), but these may postdate the original timing of erosion (Coombes et al., 2017; Naylor et al., 2012). In addition, diagenetic processes can alter radiocarbon concentrations further complicating interpretation of surface age (Rixhon et al., 2018).

The advent of cosmogenic nuclide (CN) dating techniques provides a novel way to directly date rock surfaces. It has been used to infer rates of sea cliff retreat (Hurst et al., 2016; Regard et al., 2012) and cross platform erosional variability (Swirad et al., 2020) on soft rock (e.g. chalk) coasts in the U.K. and France where the platforms are Holocene in age. On hard rock (e.g. granite) surfaces there are suggestions from western Korea (Jeong et al., 2026) and Brittany, France (Raimbault et al., 2018) that platforms may partly derive their morphology from past higher sea levels in the Pleistocene supporting inferences derived from numerical modelling (Trenhaile, 2010). However, this is not always applicable with cosmogenic nuclide dating of basalt islands in the Sea of Japan (Choi and Seong, 2021) and eastern Korea (Jeong et al., 2026; Jeong et al., 2024) showing the platforms to be of Holocene age. It is therefore clear that on resistant lithologies controversy remains as to their geomorphic age.

In this study, we bridge the gap between the short and long term by combining cosmogenic nuclide methods with measurement of granular scale decay measured through micro-erosion meters (MEM). The intertidal shore platforms of the Otway Coast in southern Australia have been the focus for rocky coast research for almost a century (Kennedy, 2014) with field observations used to infer an evolutionary history into the Pleistocene (Baker and Gill, 1957; Hills, 1949; Jutson, 1949, 1950). Importantly for this site, since 1977 micro-erosion measurements have been undertaken across the intertidal and supratidal zone (Gill and Lang, 1983; Stephenson et al., 2012; Yuan et al., 2020). Through combining scale-dependant measurement techniques we aim to understand the degree to which present day morphology of intertidal shore platforms is inherited from past high sea levels or contemporary erosive processes.

## 2. Regional setting

The shore platforms of Lorne and Marengo, on the Otway Coast of Victoria, Australia (Fig. 1) are our laboratory. The coast has a temperate climate and is microtidal and semidiurnal with a mean tidal range of 0.9 m at Marengo and 1.2 m at Lorne (PoM, 2013). The shore is exposed to a mean daily significant wave height of 2.54 m (McSweeney, 2020). The region is tectonically stable with all the studied platforms formed within lithic sandstones of Late Jurassic to lower Cretaceous non-marine

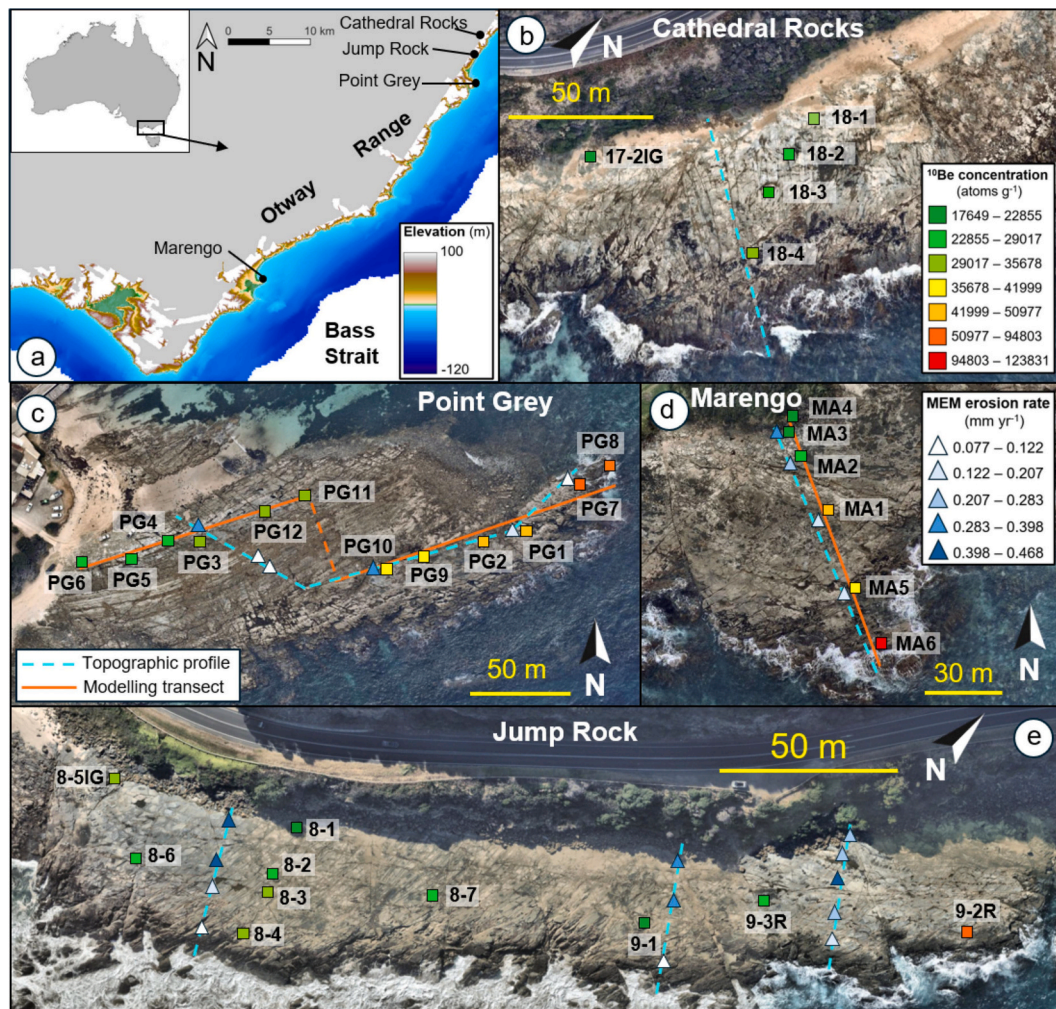


**Fig. 1.** (a) The Otway Coast, Victoria showing a digital elevation model of the coast, MEM transects, and the CN sampling locations. Sampling was undertaken in four main areas: (b) Cathedral Rocks, (c) Point Grey, (d) Marengo, and (e) Jump Rock. Nuclide sampling locations were aligned close to the MEM sites, with the consideration that preservation of the monitoring stations was the priority. The total  $^{10}\text{Be}$  nuclide concentrations show a general pattern increasing towards the seaward edge of the platform. Both values of  $^{10}\text{Be}$  nuclide concentration and MEM erosion rate are classified in the mode of Natural Breaks (Jenks) in QGIS. Topographic profiles of shore platforms are shown in Fig. 2.

feldspathic and lithic sandstones of the Eumeralla Formation (Douglas and Ferguson, 1976; Duddy, 2003) with occasional interbedded thin (< 1 m scale) mudstones. All the sampling sites occur in sandstone units. During the current interglacial period sea level reached modern elevations at c. 7500 years ago and is inferred to have been around 1.5 m higher by 6500 years ago (Kennedy et al., 2024). During the Last Interglacial period sea level is inferred to have been at or above present levels between 120 and 130 ka with a maximum of +3.9 m at 129 ka (Goodwin et al., 2023).

The studied platforms are Cathedral Rocks and Jump Rock (both north of Lorne), Point Grey (south of Lorne) and Marengo Head (Fig. 1). The morphology of these landforms (Fig. 2) has been described by Gill and Lang (1983), Yuan et al. (2018, 2020, 2022a), Kennedy and Milkins (2015) and Stephenson et al. (2012). Cathedral Rocks is around 60 m wide and is found at an average elevation of +1.0 m. Jump Rock (Fig. 3a) is between 40 and 50 m wide, elevated mostly around +2.0 m, range of 1.5–2.5 m above the Australian Height Datum (AHD) which is equivalent to average mean sea level (MSL) between the years 1966 and 1968 (GA, 2017). A rampart up to 0.6 m higher than the average platform surface occurs on its seaward edge. The rear of the platform is buried by angular blocks from road construction in the early 20th Century, but isolated landward cliffs up to several metres high are still exposed at its southern end and in its centre. At the southern edge of the platform a small ledge 9 m wide is found at an elevation of +4.2 m above MSL. Point Grey (Fig. 3b) is a platform that extends 270 m seaward from a headland and is slightly curved in planform. The platform ranges between +0.09 – +0.89 m in elevation, the lowest area occurring in its centre where it is also widest (80 m). A 33.4 m wide ramp marks the landward edge of the platform which terminates at the base of a 2.3 m high sea cliff at an elevation of +2.1 m above AHD.

Marengo (Fig. 3c) is 93.8 m wide, is at an elevation of +1.2 m and extends seaward from a 4.7 m high sea cliff. The mean downwearing rate for the study area is 0.25 mm/yr (1979–2019) (range 0.008–0.86 mm/yr) (Yuan et al., 2020).

### 3. Materials and Methods

#### 3.1. Cosmogenic Nuclide (CN) analysis

The goal of the CN analysis is to determine the age and long-term formation of the platforms. CN concentrations vary with distance from the shore (e.g. modern cliff) dependent on three components: 1) geological inheritance, which is a background signal in the landscape that occurs slowly at depth over long periods of time due to CN production from muons (termed CN-Inheritance henceforth); 2) time, where concentrations are proportional to the minimum age of the platform; and 3) formation, where concentrations reflect the rate of development (from cliff retreat and downwearing) in relation to sea level and any surface cover change (Hurst et al., 2017). We investigated the CN concentrations on the Otway Coast platform through field sampling, laboratory analysis and numerical modelling.

##### 3.1.1. Field sampling

Sampling was undertaken in both shore perpendicular transects and in an alongshore direction to assess regional and platform-specific formation histories. Approximately 2 kg of rock was sampled at 34 locations for  $^{10}\text{Be}$  analysis. The samples were taken from the top 20 mm across the shore platform surface (Fig. 3d, e). These shallow surface samples guarantee  $^{10}\text{Be}$  concentrations that are dominated by spallation production (not muons), which occurs at fast rates near the rock surface.

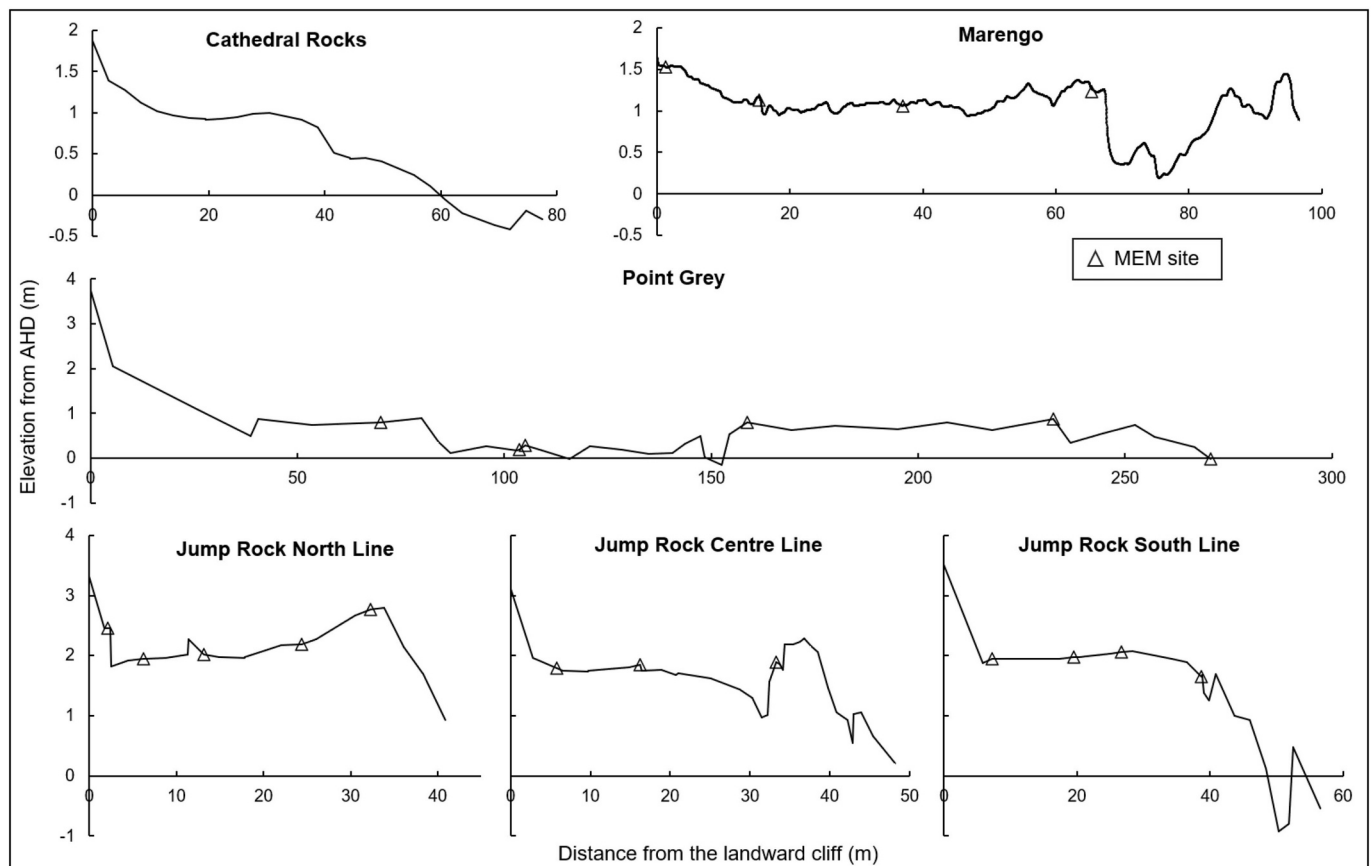


Fig. 2. Topographic profiles of MEM transects across the shore platforms with MEM sites marked. Ramparts are formed at the seaward edge of the Jump Rock shore platform (north line and centre line) with installation of MEM sites.



**Fig. 3.** (a) Jump Rock looking south towards the township of Lorne. The background CN sample was collected from the road cutting at this site (marked by yellow arrow). (b) Point Grey, the widest platform studied, and the location of the CN modelling transect. (c) An oblique view of Marengo looking north, the CN and MEM transect on the southern side of the headland. (d) Sampling rock surface for CN analysis at Jump Rock. The sample is from the upper 20 mm of the rock surface. (e) The rock samples taken for CN dating at Jump Rock, site LOR-8-2. (f) The micro-erosion meter located over a bolt site near CN site MA5 in the seaward half of the intertidal shore platform at Marengo. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Where MEM transects were present CN were sampled parallel to the bolt sites (Fig. 1).

One unexposed sample was additionally collected to account for CN-Inheritance (termed background-sample herein). Such a sample needs to represent the vertical position of the platform below the landscape surface prior to the period of platform formation being investigated. Unlike the high vertical cliffs of softer rock coastlines, where a background sample is typically taken at the base of a cliff near sea level, the Otway Ranges seaward face is a dip-slope of around 30° towards the shore. To mimic the likely landscape surface before the platform existed, we took the sample from the base of a fresh artificial road cut directly behind the platform at Jump Rock, at an elevation of 12.9 m above AHD and 10 m below the hillslope surface.

Observations were recorded for each sample. Topographic shielding was measured using a handheld Suunto compass and clinometer measured towards the highest point on the surrounding landscape. The elevation was extracted from an existing high resolution (1-m grid)

aerial LiDAR dataset, ground-truthed using a Sokkia total station and local geodetic benchmarks.

### 3.1.2. Laboratory analysis

In the laboratory, beryllium isotopes were extracted from quartz in the sandstone samples in the Cosmogenic Laboratory at Centre for Accelerator Science at the Australian Nuclear Science (ANSTO). To do so, the crushed and milled material was wet-sieved, and two nine-hour rounds of HF etching performed in a heated 90 °C ultrasonic tank using 15 g of sample/L 0.5% HF/HNO<sub>3</sub>. Quartz dissolution was conducted in HF, with isolation of Be(OH)<sub>2</sub> using ion-chromatography (Child et al., 2000) and the final AMS target preparation completed by mixing BeO with Nb powder in an optimum mass ratio of 1:4 (Fink et al., 2000). The purity of the final quartz separates was verified using an Agilent 5100 SVDV ICP-OES. The concentrations of aluminium in quartz were between 185 and 280 ppm for the 34 samples. The AMS <sup>10</sup>Be/<sup>9</sup>Be ratios were measured using 6 MV Sirius tandem accelerator at ANSTO and

normalised to the KN-5-2 standard with an assumed ratio of  $8.558 \times 10^{-12}$  (Wilcken et al., 2019). The ratios were converted into  $^{10}\text{Be}$  concentrations. The  $^{10}\text{Be}$  concentration of the background-sample was then subtracted from the platform surface concentrations to remove the CN-inheritance component.

### 3.1.3. Numerical modelling

Diagnostic modelling was conducted to identify the most plausible platform age and formation scenario recorded by the CN data. The Point Grey platform was modelled as it is the widest platform and has the highest number of shore perpendicular CN samples ( $n = 12$ ) and MEM sites. The modelling approach predicts CN concentrations across a rock shore platform (perpendicular to the cliff) as a function of exposure time, sea level, erosion and surface cover (Jones, 2026). The model combines modifications of the approach of Swirad et al. (2020) for calculating time-dependent topographic shielding, water shielding and cliff retreat, with CRONUScalc (Marrero et al., 2016) for calculating cosmogenic nuclide production, and uses a MATLAB optimised solver to find the best-fit variables for a given scenario from the misfit between the predicted and measured nuclide concentrations.

Using this model framework, we first confirm that the measured  $^{10}\text{Be}$  concentration in our modern sub-cliff sample records plausible CN-Inheritance (Fig. 4), consistent with minor surface erosion under steady-state production (similar to Hurst et al., 2016). Next, we test the hypothesis that the platforms formed during the current period of relatively higher sea level (i.e. the Holocene). We predict the best-fit case for a series of scenarios using three models of increasing complexity: 1) zero erosion platform model (no cliff retreat or downwearing), which finds the best-fit total exposure time from a given sea-level history; 2) downwearing platform model (no cliff retreat), which finds the best-fit total exposure time and change in downwearing rate (accelerating, decelerating or constant) from a given modern average

downwearing rate and sea-level history; and 3) cliff retreat platform model, which finds the best-fit total exposure time and cliff retreat rate (accelerating, decelerating or constant), from a given sea-level history, with surface cover (e.g. beach) and a modern average downwearing rate. Finally, we test the hypothesis that the platforms formed over periods of relatively higher sea level (i.e. since at least the Last Interglacial). We use a modified version of the cliff retreat model that applies retreat across the platform during the Last Interglacial, implementing a conservative local mean sea level 2 m higher than today at ~140–120 ka. Based on the observed relationship between measured downwearing rates (section 3.2) and elevation above mean sea level, spatially-variable downwearing rates are additionally applied in this version of the model, with downwearing also changing temporally with sea level as with the other models.

### 3.2. Micro-erosion Meters

A total of 43 micro-erosion meter (MEM) sites, originally installed in the late 1970's (Gill and Lang, 1983) were remeasured as part of this study in 2023 (for full details see Yuan et al. (2020)) (Fig. 1). Each site comprises three stainless steel bolts anchored into the rock and arranged in a triangle (Gill and Lang, 1983) and the surface measured with a dial gauge by rotating the device by  $120^\circ$  resulting in three relative height readings per site (Fig. 2f). These readings are averaged and converted to a rate of erosion (mm/yr).

The measured downwearing rates were projected into the past in a dynamic fashion through adjusting the elevation-dependent erosion rate for the platform position within the intertidal zone throughout the Holocene. We assumed that (i) the downwearing rate of any rock surface follows the spatial pattern derived from the decadal-scale MEM data of Yuan et al. (2020) and (ii) the erosion rate remains constant over each year throughout the modelled time period. This was done as an annual time-step, whereby the downwearing rate was converted to the amount of vertical change in surface height during a 12-month period. This erosion value was added to the MEM site elevation, and its position within the intertidal zone recalculated. The next iteration then used a new downwearing rate, based on the measured elevation dependant erosion rates from the intertidal zone. The position in the intertidal zone was also adjusted at each time step for the position of mean sea level based on the Glacio Isostatic Adjustment modelling reported in Goodwin et al. (2023) and supplied separately (Goodwin pers. comm 2023). The model was run for the past 8000 years.

## 4. Results

### 4.1. Measured $^{10}\text{Be}$ Concentrations

The average  $^{10}\text{Be}$  concentrations across all sites ( $n = 34$ ) was  $37,558 \text{ atoms g}^{-1}$ , with a range of  $17,649\text{--}123,831 \text{ atoms g}^{-1}$  (Fig. 1, Table 1). The lowest concentration was found on a ramp at the rear of a 64 m wide shore platform at Cathedral Rocks, with the next lowest concentration being  $18,463 \text{ atoms g}^{-1}$  at the base of the landward cliff at Marengo (Fig. 1d, 3c), 90 m landward of the location which returned the highest measures of  $^{10}\text{Be}$  in this study. Over 90% of samples exceeded  $20,000 \text{ atoms g}^{-1}$ , with 20%  $> 40,000 \text{ atoms g}^{-1}$ . At each of the four sampled sites  $^{10}\text{Be}$  ranged from  $25,800\text{--}94,803 \text{ atoms g}^{-1}$  (Point Grey (Fig. 1c, 3b)),  $18,463\text{--}123,831 \text{ atoms g}^{-1}$  (Marengo),  $21,054\text{--}64,823 \text{ atoms g}^{-1}$  (Jump Rock, (Fig. 1e, 3a)), and  $17,649\text{--}33,577 \text{ atoms g}^{-1}$  (Cathedral Rocks) (Table 1).

BK = Background/Inheritance Sample.

The background sample from within a road cutting at Jump Rock (MH-JR1) returned a  $^{10}\text{Be}$  concentration of  $17.65712 \pm 0.87217 \times 10^3 \text{ atoms g}^{-1}$ , which are not significantly different to the rear of Cathedral Rocks ( $17.64852 \pm 1.43343 \times 10^3 \text{ atoms g}^{-1}$ ) (Fig. 1). Ideally, sampling to calculate CN-inheritance should be taken from a cave to represent the CN concentration acquired through production by muons

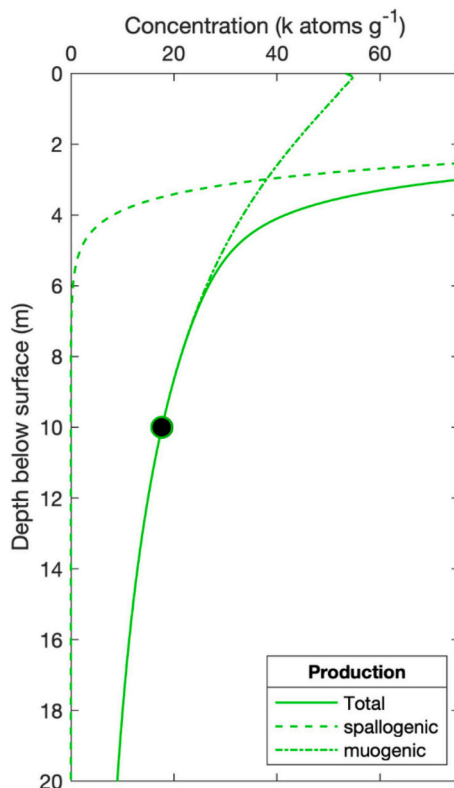


Fig. 4. Theoretical modelling of CN production through time with depth below the surface. Our sample (black dot) aligns with this framework assuming a steady-state surface erosion rate of  $<0.001 \text{ mm/yr}$ .

**Table 1**Cosmogenic nuclide concentrations for samples collected along the Otway Coast of Victoria, Australia.  $^{10}\text{Be}$  half-life is 1.387 million years.

|            | Lab Code | Sample Name | Topographic Shading | Latitude (°) | Longitude (°) | Elevation (m from AHD) | $^{10}\text{Be}/^9\text{Be}$ ( $\times 10^{-14}$ ) | $^{10}\text{Be}$ concn. ( $10^3$ atoms/g) | $^{10}\text{Be}$ concn. Error ( $10^3$ atoms/g) |
|------------|----------|-------------|---------------------|--------------|---------------|------------------------|----------------------------------------------------|-------------------------------------------|-------------------------------------------------|
| Jump Rock  | 5528     | LOR-8-1     | 0.982476            | -38.51836    | 143.99199     | 2.25                   | 3.14                                               | 21.55749                                  | 2.17822                                         |
|            | 5529     | LOR-8-2     | 0.995198            | -38.51849    | 143.99207     | 2.08                   | 3.16                                               | 29.01710                                  | 1.68777                                         |
|            | 5530     | LOR-8-3     | 0.995198            | -38.51854    | 143.99208     | 2.09                   | 4.57                                               | 35.67833                                  | 2.20253                                         |
|            | 5531     | LOR-8-4     | 0.995198            | -38.51863    | 143.99214     | 1.94                   | 3.59                                               | 33.12139                                  | 3.83938                                         |
|            | 5532     | LOR-8-5-IG  | 0.994094            | -38.51865    | 143.99145     | 2.43                   | 3.12                                               | 30.40244                                  | 2.13120                                         |
|            | 5533     | LOR-8-6     | 0.994094            | -38.518715   | 143.99171     | 1.69                   | 3.45                                               | 26.61404                                  | 1.77413                                         |
|            | 5534     | LOR-8-7     | 0.988888            | -38.51822    | 143.99242     | 1.87                   | 3.14                                               | 27.93706                                  | 2.86731                                         |
|            | 5535     | LOR-9-1     | 0.988888            | -38.51785    | 143.99299     | 1.59                   | 2.65                                               | 21.05370                                  | 1.90361                                         |
|            | 5536     | LOR-9-2-R   | 0.988219            | -38.51723    | 143.99374     | 2.55                   | 13.41                                              | 64.82269                                  | 2.23394                                         |
|            | 5537     | LOR-9-3-R   | 0.988219            | -38.51756    | 143.99320     | 1.93                   | 3.25                                               | 26.12885                                  | 1.96653                                         |
| Cathedral  | 5538     | LOR-17-2-IG | 0.923237            | -38.50853    | 144.00362     | 2.27                   | 4.59                                               | 17.64852                                  | 1.43343                                         |
|            | 5539     | LOR-18-1    | 0.975883            | -38.50775    | 144.00412     | 0.87                   | 5.06                                               | 30.57810                                  | 1.47561                                         |
|            | 5540     | LOR-18-2    | 0.975883            | -38.50789    | 144.00418     | 0.95                   | 4.38                                               | 24.91381                                  | 3.15951                                         |
|            | 5541     | LOR-18-3    | 0.975883            | -38.50802    | 144.00427     | 1.03                   | 5.05                                               | 25.00139                                  | 1.67545                                         |
|            | 5542     | LOR-18-4    | 0.993356            | -38.50818    | 144.00437     | 1.05                   | 5.35                                               | 33.57675                                  | 2.37110                                         |
| Point Grey | 8433     | MH-PG1      | 0.999829            | -38.54855    | 143.98944     | 0.94                   | 9.465                                              | 49.13329                                  | 1.63727                                         |
|            | 8434     | MH-PG2      | 0.999829            | -38.54859    | 143.98918     | 0.80                   | 8.989                                              | 50.97734                                  | 1.67277                                         |
|            | 8435     | MH-PG3      | 0.999746            | -38.54856    | 143.98763     | 0.82                   | 7.765                                              | 34.88725                                  | 1.23294                                         |
|            | 8436     | MH-PG4      | 0.999644            | -38.54857    | 143.98743     | 0.87                   | 7.718                                              | 27.06661                                  | 1.02233                                         |
|            | 8437     | MH-PG5      | 0.999614            | -38.54864    | 143.98723     | 0.98                   | 7.254                                              | 25.80030                                  | 0.95021                                         |
|            | 8438     | MH-PG6      | 0.999614            | -38.54867    | 143.98696     | 1.09                   | 6.472                                              | 27.84084                                  | 1.09077                                         |
|            | 8439     | MH-PG7      | 0.999829            | -38.54832    | 143.98974     | -0.34                  | 16.20                                              | 70.26563                                  | 2.12393                                         |
|            | 8440     | MH-PG8      | 0.999829            | -38.54823    | 143.98992     | -0.01                  | 10.36                                              | 94.80349                                  | 3.03001                                         |
|            | 8441     | MH-PG9      | 0.999829            | -38.54823    | 143.98992     | 0.37                   | 4.772                                              | 41.99932                                  | 1.82009                                         |
|            | 8442     | MH-PG10     | 0.999829            | -38.54872    | 143.98863     | 0.58                   | 5.685                                              | 40.64936                                  | 1.58815                                         |
| Marengo    | 8443     | MH-PG11     | 0.999746            | -38.54836    | 143.98822     | 0.83                   | 8.281                                              | 34.72686                                  | 1.15932                                         |
|            | 8444     | MH-PG12     | 0.999746            | -38.54842    | 143.98796     | 0.65                   | 6.184                                              | 30.35173                                  | 1.14377                                         |
|            | 8445     | MH-MA1      | 0.999837            | -38.78010    | 143.66558     | 1.19                   | 6.500                                              | 46.94344                                  | 1.74049                                         |
|            | 8446     | MH-MA2      | 0.997811            | -38.77993    | 143.66549     | 1.18                   | 4.797                                              | 28.90999                                  | 1.69574                                         |
|            | 8447     | MH-MA3      | 0.984779            | -38.77984    | 143.66544     | 1.57                   | 5.899                                              | 22.85482                                  | 0.91453                                         |
|            | 8448     | MH-MA4      | 0.893361            | -38.77979    | 143.66545     | 1.57                   | 3.129                                              | 18.46268                                  | 1.07175                                         |
| BK         | 8449     | MH-MA5      | 0.999909            | -38.78036    | 143.66572     | 1.49                   | 8.785                                              | 41.77187                                  | 1.36922                                         |
|            | 8450     | MH-MA6      | 0.999909            | -38.78059    | 143.66583     | 1.23                   | 21.58                                              | 123.83134                                 | 3.77158                                         |
|            | 8451     | MH-JR1      | 0.396710            | -38.51571    | 143.99415     | 12.95                  | 4.295                                              | 17.65712                                  | 0.87217                                         |

penetrating from above (Hurst et al., 2017; Hurst et al., 2016). For the studied sites caves are absent, though do occur elsewhere in the region. Clearly the CN exposure history for the samples was similar with both locations only having recently been exposed to subaerial processes. The Cathedral Rocks location has the highest active sea cliffs of the studied sites so potentially the sampled site had been protected by a large rock overhang which has only recently (past 150 years) collapsed, the evidence of collapse being removed by modern wave processes which are observed to sweep the platform during storm events. To test the feasibility of the CN-inheritance concentration, following Hurst et al. (2017), our value is considered feasible with steady-state surface (cliff top) erosion of  $<0.001$  mm/yr (Fig. 4).

After analysis of the spatial distribution of CN, the location (Point Grey) with the widest platform was selected for further analysis to understand cross sectional landform evolution as they provided the most detailed dataset. There is a strong relationship between nuclide

concentration and distance from the landward cliff (Fig. 5). After correction for CN-inheritance, at Point Grey, nuclide concentrations are around 20,000 atoms  $\text{g}^{-1}$  at the landward 150 m of the platform and around 40,000 atoms  $\text{g}^{-1}$  220 m from the landward edge, after which they rise to around 100,000 atoms  $\text{g}^{-1}$  at the intertidal platform edge almost 300 m from the landward cliff. At Marengo, the second widest platform, the  $^{10}\text{Be}$  concentration increases from close to zero at the base of the landward cliff to around 40,000 atoms  $\text{g}^{-1}$  in the centre with a more than doubling of the concentrations at the intertidal seaward edge of platform (Fig. 5).

#### 4.2. Modelled $^{10}\text{Be}$ Concentrations

The measured  $^{10}\text{Be}$  concentrations were modelled for a series of scenarios of increasing complexity, using an assumption that the platforms formed entirely during the Holocene. First, we consider zero

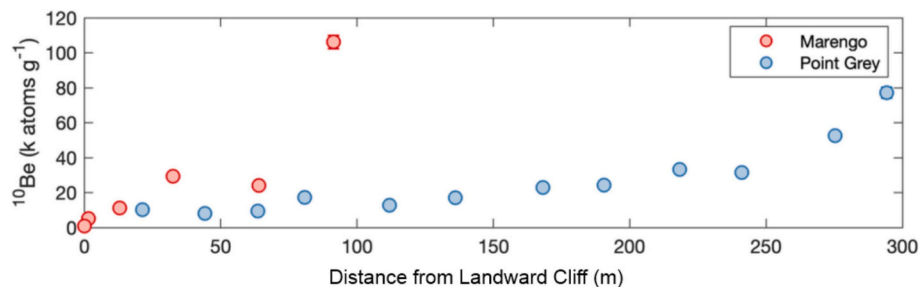


**Fig. 5.** Background corrected CN concentrations from rock platforms.  $^{10}\text{Be}$  concentrations in this study from transects across two platforms, at Point Grey and Marengo. Each point represents the mean and standard deviation of a measured sample, corrected for CN-inheritance. For both transects, there is a clear trend of increasing concentrations with distance from the cliff.

erosion to test if the measured concentrations are simply the result of platform stability and sea-level change. The model is able to accurately predict the  $^{10}\text{Be}$  concentration at the seaward edge of the platform (Fig. 6), with a model time of 24.8 ka, and implies exposure from at least the Last Glacial Maximum is required to explain the highest concentrations. However, this scenario produces a near-uniform concentration across the platform, which overpredicts the measured concentrations inland of the seaward edge by more than a factor of four. This result indicates that erosion should be included as a key process in accounting for decreasing nuclide concentrations, at least on the landward portion of the platform.

Second, we investigate the impact of erosion via just downwearing, and landward cliff retreat with downwearing. The scenarios use a modern spatially-uniform rate of downwearing of 0.251 mm/yr, based on the MEM measurements for this site (Yuan et al., 2020). This rate is slightly higher (by c. 0.021 mm/yr) than the mean down wearing rate for the entire MEM network across the region (section 4.3). For the downwearing scenario, the best fit result better predicts the landward half of the platform, with a model time of 5.8 ka, but fails to replicate the trend of increasing concentrations towards the seaward edge of the platform (Fig. 6). For the scenario that also includes cliff retreat, concentrations are better predicted for the landward and seaward portions, but with a step change in concentrations in between. This step occurs because of the cliff being located at this point at the start of the model run (23.0 ka) and implies a pre-Holocene history for at least the seaward portion of the platform. However, even in this case, the seawardmost concentration cannot be explained, indicating a longer history is required.

In a final test, we assume that formation occurred over multiple periods of higher sea level, since at least the Last Interglacial. We also evaluate the impact of spatially-variable downwearing by using trends

in MEM rates across the intertidal and supratidal zone (Section 4.3). The relatively low  $^{10}\text{Be}$  concentrations measured along the landward two-thirds of the platform are not well explained by this scenario (Fig. 6). However, the trend and absolute concentrations near the seaward edge is much better predicted.

#### 4.3. MEM Downwearing

From 1979 to 2023 the total measured downwearing at the 42 remaining MEM sites ranged from 0.08 to 23.82 mm, equivalent to a rate of downwearing of 0.002 to 0.53 mm/yr (mean 0.23 mm/yr, median 0.21 mm/yr). One site installed by Gill and Lang (1983) exhibited a higher rate of erosion of 0.86 mm/yr (Yuan et al., 2020) and the bolts have subsequently been lost due to erosion in 2021. The spatial pattern of shore platform surface lowering is closely associated with elevation, specifically the frequency of tidal inundation (Fig. 7). The peak rate of downwearing (0.48 mm/yr) occurs at an elevation close to MHWS with the rate decreasing both to the upper limit of the swash zone (refers to the high elevation zone where rock surface experiences daily tidal wetting caused by wave swash during high tides rather than direct tidal inundation) as well as to MLWN. In this semidiurnal tidal environment, the maximum tidal frequency occurred at MHWS (two cycles per day) and then decreases both towards spray zone with longer exposure period and towards MLWN with longer inundation period. A wide range of downwearing rates (0.12–0.86 mm/yr) were observed in the spray zone which tended to remain exposed under mean tidal conditions, although no significant relationship between elevation and downwearing was found. The spray zone also showed significant fastest downwearing (median: 0.36 mm/yr) compared to the swash zone (median: 0.21 mm/yr) and below swash zone (median: 0.08 mm/yr) as examined with the non-parametric Kruskal-Wallis test ( $P$ -value = 0.005).

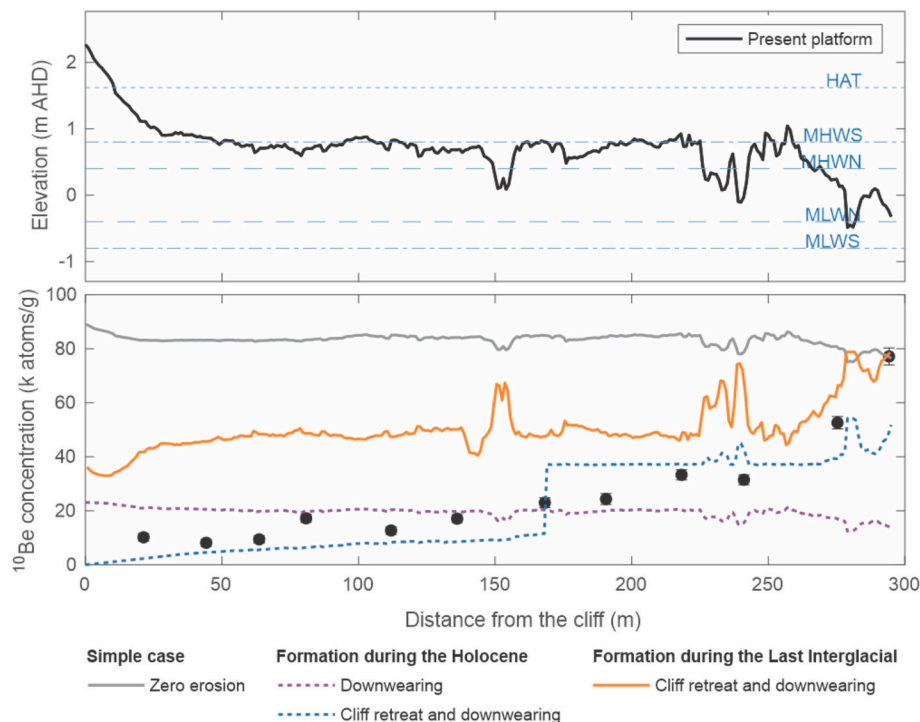


**Fig. 6.** Modelled  $^{10}\text{Be}$  concentrations indicate platform formation since at least the Last Interglacial. (Top panel) Profile of the Point Grey platform where we have the most extensive sequence of concentrations. Present-day tides are shown for context: HAT, highest astronomical tide; MHWS, mean high water spring; MHWN, mean high water neap; MLWN, mean low water neap; MLWS, mean low water spring. (Lower Panel) Best-fit predictions of  $^{10}\text{Be}$  concentrations across Point Grey platform for a series of scenarios (see Methods). The zero-erosion scenario predicts a formation history since at least 24.8 ka for the highest concentrations but is unable to replicate the lower concentrations towards the landward cliff. Scenarios with erosion (downwearing, and cliff retreat with downwearing) over the Holocene are unable to predict the highest concentrations and trend of steadily increasing concentrations across the platform. The only scenario to predict this broad trend and the highest concentrations on the platform edge includes cliff retreat and downwearing during the Last Interglacial.

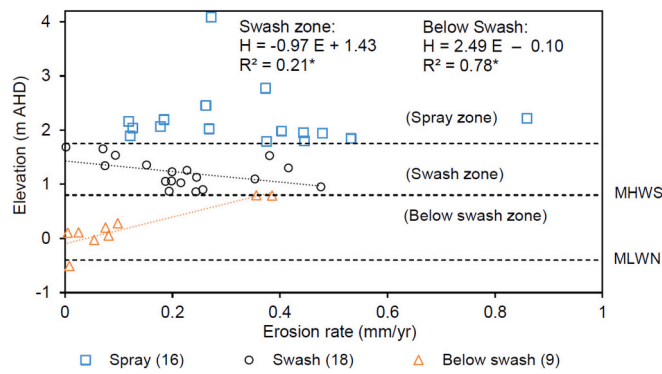


Fig. 7. Spatial pattern of downwearing rates and elevation. A significant positive relationship has been shown below swash zone (orange dashed line) under MHWS level while a significant negative relationship in the swash zone (black dashed line). No such relationship is shown in the spray zone. \* significant correlation ( $P < 0.05$ ).

#### 4.4. Modelled Downwearing through Time

Based on the decadal MEM records, a general model of the spatial pattern of downwearing rate is developed (Fig. 8). In the central intertidal zone, the erosion rate is zero at MLWN (−0.4 m) and then increases with elevation, peaking at MHWS (0.8 m), followed by a decreasing trend until reaching the upper boundary of the swash zone (1.74 m). In the spray zone, the downwearing rate is deemed as constant at 0.36 mm/yr.

Late Pleistocene (c. 12,000 years ago), sea level along the Victorian coastline rapidly increased from 34.6 m below the present sea level but remained 2 m below at 8000 BP (Goodwin et al., 2023; Lewis et al., 2013). Consequently, the shore platforms at Point Grey and Marengo were entirely subaerially exposed until the early to mid-Holocene. It was assumed that the shore platform homogeneously down wore in this supratidal zone and the MEM modelled back-casted CN sample elevation changes were not displayed before 8000 BP because all surfaces experienced the same amount of erosion (Fig. 9). Sea level continued to increase at rates of 1.2–4.2 mm/yr between 8000 and 6500 BP, remaining 1.7 m above present sea level during mid-Holocene (6500–6000 BP) and

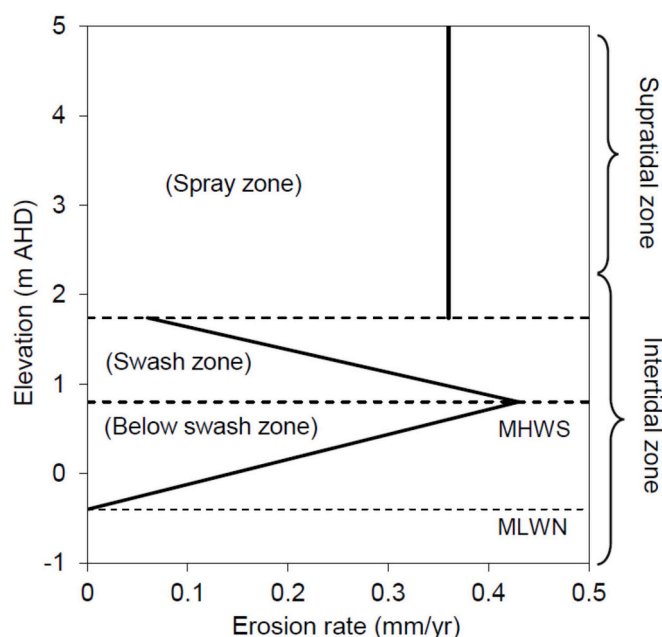


Fig. 8. Downwearing rate change model derived from 44-year MEM data.

then gradually lowered to present elevations with a slow rate of  $<0.4$  mm/yr (Fig. 9). This is the period when heterogeneous elevation changes occurred over the shore platform in an intertidal environment. At Point Grey (Fig. 9a), most of the CN sample surfaces (PG 1–6, 9–12) are located in the swash zone. The elevation of each modelled location on the platform began to differ from each other with the lowering of sea level since 6000 BP. This is because of the measured negative relationship between downwearing and elevation in the intertidal zone. In contrast, the two lower surfaces (PG 7 and 8) currently located near MSL at the seaward end of the platform were mainly situated below MLWN and therefore experienced less erosion, especially between 7000 and 2000 BP in a subtidal environment. As a result, surfaces located in different elevation bands (e.g. swash zone vs below swash zone) tended to converge while surfaces of similar elevation (e.g. swash zone) tended to diverge since mid-Holocene. Over the past 8000 years, the higher sample surfaces (PG 1–6, 9–12) could have total erosion ranging from 2.15 to 2.57 m, compared to an average erosion of 0.47 m on two lower surfaces (PG 7 and 8). Similar surface change pattern was observed at Marengo where all sample surfaces (MA 1–6) are located in the swash zone and began to diverge since mid-Holocene, with a total vertical erosion of 1.79–2.22 m from 8000 BP to present (Fig. 8b).

## 5. Discussion

CN concentrations in rock surfaces are directly proportional to the age of a surface and its rate of erosion, the older the surface the higher the concentration of CN. The CN concentrations, specifically  $^{10}\text{Be}$ , found on the sandstone platforms of the Otway coast in this study are amongst the highest values measured globally, similar to the ancient platforms of the western Korean coast (Jeong et al., 2026) (Fig. 10). The maximum measured  $^{10}\text{Be}$  concentrations were over six times the concentrations along the chalk cliffs of the French (Regard et al., 2012) and English (Hurst et al., 2016) side of the English Channel, limestone-sandstone platforms of Yorkshire, U.K. (Swirad et al., 2020) and Devon, U.K. (Shadrick et al., 2022), and mostly double that of sandstone platforms in eastern Korea (Choi et al., 2012; Jeong et al., 2024). The lower end of the Otway platform concentrations (1 standard deviation below the mean) was significantly higher than the average of these platforms (Fig. 10). It is therefore indisputable that the platforms of the Otway coast are of greater antiquity than most of those previously studied and therefore have an inheritance of form which stretches beyond the Holocene to the Last Interglacial period and perhaps even older.

The geology in which a platform is eroded is the primary boundary condition for landscape evolution (Naylor and Stephenson, 2010). Platform elevation is a direct function of rock hardness (Dickson et al., 2004; Thornton and Stephenson, 2006) and structure (Kennedy and Dickson, 2006), with more erodible platforms tending to be lower in elevation. Tidal range determines the vertical range in which intertidal processes can operate, which means microtidal shoreline are dominated by semi-horizontal platforms, whose gradient increases in macrotidal areas (Matsumoto et al., 2017; Trenhaile and Layzell, 1981). The chalk cliffs of the English Channel are much less resistant than the sandstones on the Korean coast and the Otway Ranges. Mineralogy of the chalk coastlines also limit CN studies to flint nodules (Regard et al., 2012; Shadrick et al., 2022) while the sandstone platforms have CN-bearing minerals evenly distributed across their entire surface. The implication for CN studies is that the softer platforms are much less resistant to erosion, hence the regular removal of rocky material continually reduces the CN-concentrations.

The cross-shore distribution of CN provides an indication of the evolutionary history of a shore platform. In the soft cliffs of Europe, step-changes in the cross-shore concentrations have been used to suggest periods of episodic landward cliff retreat during the Holocene as the principal mode of platform formation (Hurst et al., 2017; Regard et al., 2012; Shadrick et al., 2022; Swirad et al., 2020). In eastern Korea, the CN concentrations peak in the centre of the Pleistocene platforms. Choi

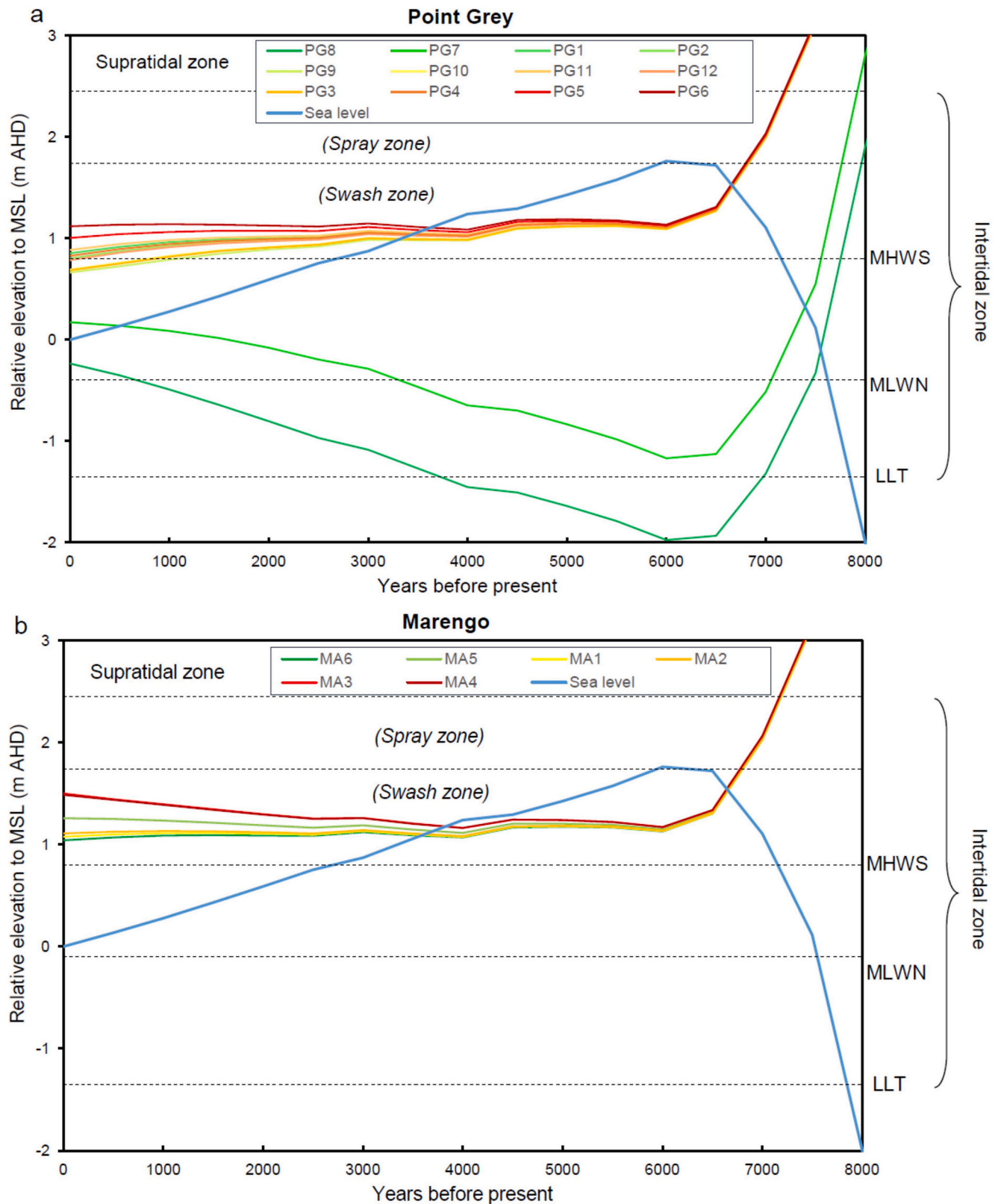


**Fig. 9.** Sea-level change and modelled back-casted platform elevation change over the past 8000 years at (a) Point Grey and (b) Marengo, taking into account both sea level change and the elevation change due to granular-scale downwearing. The coloured lines represent the elevation relative to present mean sea level of each MEM site during the Holocene. The platforms are initially subaerial, but as sea level rises the sites become intertidal and start downwearing. Downwearing results in a decrease in elevation, while at the same time elevation is also affected by sea level change. The blue line represents sea level change. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

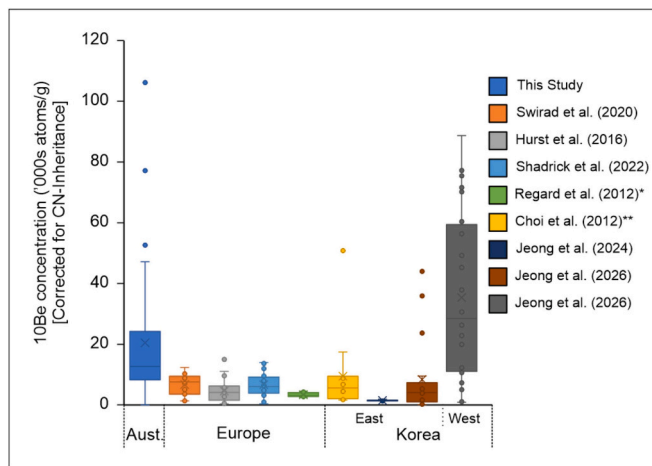


**Fig. 10.** Box-and-whisker plots for the range of  $^{10}\text{Be}$  measured in samples (corrected for CN inheritance) from present and previous studies. The platforms from the Otway Ranges (this study) and the western Korean coast are clearly older than those investigated in Europe. \*Not corrected for CN-Inheritance, \*\* data as reported in Jeong et al. (2026).

et al. (2012) suggested that is due to the landward part of the platform being protected by subaerial debris during the intervening glacial period between when the platform was initially formed and today. In our study, the peak CN concentrations occur at the seaward edge of the platform and rapidly decrease in the landward one third of the platform length before being low for the further two thirds of the platform (Fig. 5). There is neither a distinct mid platform step nor peak in concentrations. This therefore suggests that the mode of evolution is neither a Holocene-age stepped landward cliff retreat, nor an entirely relict Pleistocene age surface. Further work investigating the concentrations of  $^{26}\text{Al}$  in relation to  $^{10}\text{Be}$  could explore whether there is a more complex history of repeat burial and exposure of the shore platforms (Shadrick et al., 2022) to build on the findings of the ancient platform age presented here.

The measured rates of downwearing for the past 44 years clearly indicate that surface is an active landscape from the hourly (Gomez-Pujol et al., 2007; Yuan et al., 2018) to decadal scale (Stephenson et al., 2012; Yuan et al., 2020). The measured downwearing rates do however show that the erosion rates are highest in the platform centre and rear, while those at the intertidal seaward edge are minimal to zero. There is a close relationship between erosion in the vertical plane and elevation. Projecting the downwearing rates back through the Holocene indicates that the platform when in the upper intertidal zone may lower at a similar rate to the regional eustatic regression experience in Australia in the mid to late Holocene (Lewis et al., 2013). This ability along the Otway Ranges coast to ‘keep-up’ with sea level fall implies that the surface morphology, specifically the decimetre-scale relief across the platform may reflect Holocene erosive processes, but cannot explain the overall platform width and extent. It can therefore be inferred that the seaward edge of the platform (at the surface) is much older than its landward parts.

The combined CN and MEM data suggest the contemporary shore platforms along the sandstones of the Otway Ranges coast are an outcome of erosive processes dating back to at least the Last Interglacial. This provides the first quantitative confirmation of hypothesis on platform age developed in the mid 20th Century (Gill, 1972b; Jutson, 1949). The evolution of the platform is initiated as lateral erosion under higher past sea levels through landward cliff retreat, and during this period the primary morphology (width) was created. As sea level fell during the following cold period the platform was stranded and became inactive. It might have been the locus of talus accumulation as hypothesised in Korea (Choi et al., 2012) or near Sydney, Australia (Brooke et al., 1994), but such material, if present, has been entirely removed today. The

Postglacial Marine Transgression during the late Pleistocene and Holocene returned the platform to the intertidal zone, but rather than causing further landward cliff retreat, it primarily initiated surface downwearing. Wave energy at the landward cliff would also be lower today than during the Last Interglacial period because eustatic sea level is lower during the Holocene (+3 – +5 m versus +2 m (Goodwin et al., 2023)) and wave energy today is attenuated over a shore platform that may not have been present in the past.

The contemporary downwearing of the platform centre and rear, while the seaward edge remains stable in the vertical plane would be expressed morphologically as a relative high point at the seaward edge of the intertidal platform. This is well observed at Jump Rock (North and South line) as a rise over 0.5 m at distance of 35 m from the landward edge of the platform, and more subtly at the other locations (Fig. 2). Such a feature is termed a rampart, and they have been the subject of geomorphic enquiry for almost a century (Wentworth, 1939) with particular interest has been paid to their presence along the Otway Coast (Gill, 1972a). Rampart formation may relate to geological as well as differential weathering processes (Bird, 2008; Gill, 1972a; Woodroffe, 2003). In the case of our study site where the rocks are of a similar hardness and lithology (Kennedy and Milkins, 2015; Yuan et al., 2020), it appears that weathering-driven downwearing is the principal process leading to rampart formation. It is worth noting that the presence of a rampart has also been used as an indicator of the stability of the seaward edge of a shore platform and therefore implying a lessened role of wave-action in their erosion (Stephenson, 2001). The seaward edge of the platforms in our study, extend below the low tide limit (Kennedy, 2015; Kennedy, 2016), and are much more rugose than the intertidal platform surface. Block plucking is apparent based on repeat visual observations over the two past decades by the authors as well as evidenced by occasional scattered boulders which are mobile on the intertidal surfaces. The scale of erosion of the intertidal seaward edge is however unknown, partly due to a sampling bias in CN and MEM studies. The installation of MEM sites tends to avoid areas of microrelief (Yuan et al., 2022b) and therefore potential sites of block plucking. High-resolution aerial surveys indicate that these sites represent between half to three-quarters of the physical surface characteristics of each site (Yuan et al., 2022a). As we aimed to sample for CN in comparable locations to the MEM, it means the locational bias is carried through each proxy. This bias does not affect the conclusions, but carries the caveat that rock plucking especially on the seaward edge, shown to be a major factor in evolution of some shore platforms (Buchanan et al., 2020; Cullen and Bourke, 2018; Trenhaile, 2002), cannot be discounted as an active process degrading the seawardmost edge of the intertidal platform. The potential non-linear evolution of the intertidal seaward edge is also possibly reflected in the large range of CN concentrations across the entire field laboratory, greater than any other part of the platform. Partial dissection, or recent activation, of an inherited surface is likely and requires further field investigations.

## 6. Conclusions

Cosmogenic- $^{10}\text{Be}$  concentrations, exceeding  $100 \times 10^3$  atoms/g (average  $> 30 \times 10^3$  atoms/g) show that shore platforms on the Otway Coast are old features whose evolution extends beyond the Holocene. Diagnostic numerical modelling indicates that the platforms most likely initiated during the Last Interglacial period. Combining these cosmogenic nuclide values with the longest continual record of intertidal downwearing monitoring reveals that platform width and primary planform are morphologically inherited from past higher sea levels, whereas contemporary cross-shore features of decimetre-scale relief result from Holocene downwearing. Ramparts likely form because landward portions lower faster than the seaward margin, leaving a relatively stable, rugose seaward edge. While block plucking at the seaward margin remains a potential contributor, our combined proxy approach underscores the importance of long-term inheritance plus

ongoing erosive processes in shaping resistant rock coasts and cautions against assuming purely Holocene formation.

### CRediT authorship contribution statement

**David M. Kennedy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard Jones:** Writing – review & editing, Writing – original draft, Formal analysis. **Runjie Yuan:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **David Fink:** Writing – review & editing, Validation, Methodology. **Toshiyuki Fujioka:** Writing – review & editing, Methodology, Data curation. **Martin Hurst:** Writing – review & editing, Methodology, Data curation. **Wayne J. Stephenson:** Writing – review & editing, Methodology. **Colin D. Woodroffe:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Data availability

Data can be accessed from Mendeley Data. <https://data.mendeley.com/datasets/dctfzyvr6f/1>

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