Erosion of rocky shore platforms by block detachment from layered stratigraphy

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ABSTRACT: The majority of shore platforms form in rocks that are characterised by layered stratigraphy and pervasive jointing. Plucking of weathered, joint and bed bounded blocks is an important erosion process that existing models of platform development do not represent. Globally, measuring platform erosion rates have focused on microscale (< 1 mm) surface lowering rather than mesoscale (0.1-1 m) block detachment, yet the latter appears to dominate the morphological development of discontinuity rich platforms. Given the sporadic nature of block detachment on platforms, observations of erosion from storm events to multi-decadal timescales (and beyond) are required to quantify shore platform erosion rates. To this end, we collected aerial photography using an unmanned aerial vehicle to produce structure-from-motion-derived digital elevation models and orthophotos. These were combined with historical aerial photographs to characterise and quantify the erosion of two actively eroding stratigraphic layers on a shore platform in Glamorgan, south Wales, UK, over 78-years. We find that volumetric erosion rates vary over two orders of magnitude (0.1-10 m³ yr⁻¹) and do not scale with the length of the record. Average rates over the full 78-year record are 2-5 m³ yr⁻¹. These rates are equivalent to 1.2-5.3 mm yr⁻¹ surface lowering rates, an order of magnitude faster than previously published, both at our site and around the world in similar rock types. We show that meso-scale platform erosion via block detachment processes is a dominant erosion process on shore platforms across seasonal to multi-decadal timescales that have been hitherto under-investigated. © 2019 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

KEYWORDS: rock coast; intertidal platform; discontinuities; erosion; multi-decadal

Introduction

Rock coasts are characterised by the erosion of bedrock at the coast (Kennedy et al., 2014a). The landward retreat of cliffs through cliff failure threatens clifftop assets and pose a hazard to human lives, which may be exacerbated by future rising sea levels and changing storm intensity and frequency (Trenhaile, 2014). Cliffed coasts are often fronted by low-gradient shore platforms that modify the delivery of wave energy to cliffs resulting in morphodynamic feedbacks between shore platform erosion and cliff retreat (Trenhaile, 2000; Matsumoto et al., 2016; Stephenson et al., 2018). Existing morphodynamic models are capable of reproducing archetypal rock coast topography across centennial to millennial timescales, but represent rock decay and erosion processes only in an abstract fashion (Trenhaile, 2000, 2019; Matsumoto et al., 2016; Hurst et al., 2017). Therefore, knowledge of the processes and rates of erosion on shore platforms is important to improve predictions of future rock coast erosion (Trenhaile, 2019) and the risks this poses to society.

Lithology and rock mass properties are an important control on shore platform erosion. A significant proportion of the world's rock coasts are formed in layered rocks, particularly sedimentary rocks (Kennedy et al., 2014b; and references therein), and thus the nature of bedding and jointing is an important influence on the nature of erosion (Kennedy and Dickson, 2006; Naylor and Stephenson, 2010). Shore platform erosion can occur by gradual lowering of the platform surface due to rock decay and abrasion (Robinson, 1977; Stephenson et al., 2012; Cullen and Bourke, 2018; Trenhaile and Porter, 2018), or by sporadic plucking of platform blocks to generate boulders (Dornbusch and Robinson, 2011; Knight and Burningham, 2011; Stephenson and Naylor, 2011; Naylor et al., 2016). Processes of rock decay operating at the micro-scale (mm-cm) (e.g. salt weathering, surface swelling, and bioerosion) facilitate gradual surface lowering at the micro-scale (Stephenson and Kirk, 2000; Porter et al., 2010; Coombes and Naylor, 2012). But these micro-scale processes are also important preparatory mechanisms enabling meso-scale (cm-m) erosion to occur, particularly when focused at sites of weakness such as joints or bedding, helping to prepare the rock for subsequent detachment (Naylor et al., 2012). Quantifying platform erosion rates by a variety of processes, therefore, requires measuring changes across a range of temporal scales, from...
several years to decades (Stephenson et al., 2012), or even centennial-millennial timescales inferred from cosmogenic nuclides (Choi et al., 2012; Regard et al., 2012; Hurst et al., 2016; Trenhaile, 2018).

Shore platform erosion rates have primarily been quantified by measuring surface lowering (hereafter lowering rates) using micro-erosion meters (MEM) (Stephenson and Finlayson, 2009; Moses et al., 2014). With two of the longest instrumental MEM records over 43-years on the Kaikoura Peninsula, New Zealand (Stephenson, Kirk, & Hemmingsen, 2019), and 32-years Otway Coast, Australia (Stephenson et al., 2012), demonstrating average lowering rates of 0.3 to 1.2 mm yr⁻¹. Published, measured vertical erosion rates on shore platforms were collated by Sunamura (1992) and ranged between 0.03 and 25.4 mm yr⁻¹ (ignoring values in clay lithology). Similarly, a more recent compilation of MEM data from across the UK revealed lowering rates varied between lithology and ranged between 0.03 to 8.6 mm yr⁻¹ averaged over < 3 years (Moses, 2014). While MEMs have provided valuable information on mm-scale erosion, their spatial coverage is limited to sparse, single point erosion measurements, biased towards slowly eroding sites (Stephenson and Finlayson, 2009; Trenhaile, 2018) and topographically smoother areas of platform surfaces where other rock decay processes such as biota are less prevalent (Moura et al., 2012). MEMs do not capture larger meso-scale erosion processes, such as the sporadic detachment of bedrock blocks, which have the potential to dominate shore platform erosion (Kennedy and Dickson, 2006; Naylor et al., 2016).

The discussion above serves to highlight the need for monitoring of shore platform erosion with a cross-scale approach, integrating micro-meso spatial scales, and annual to millennial timescales (Naylor et al., 2012, 2014; Trenhaile, 2018). There have been six notable advances in quantifying shore platform erosion in the past decade that help to bridge gaps between the different spatial and temporal scales of erosion processes;

- First, a shift attention from rock material (i.e. lithology) to rock mass properties (i.e. discontinuities) (Kennedy and Dickson, 2006; Trenhaile and Kanyaya, 2007; Cruslock et al., 2010; Naylor and Stephenson, 2010).
- Second, bridging the gap between processed-based and evolutionary-scale studies by measuring platform erosion at larger spatial scales, for example, meso-scale (cm-m) block detachment (Dombusch and Robinson, 2011; Stephenson and Naylor, 2011).
- Third, monitoring rock coast sediment production and the role of storms in driving block detachment and transport (Paris et al., 2011; Naylor et al., 2016; Cox et al., 2018; Erdmann et al., 2018; Johnson et al., 2018).
- Fourth, improving multi-scale quantification of erosion rates and patterns through the analysis of multi-temporal digital elevation models (DEMs), using structure-from-motion (SfM) photogrammetry applied to oblique, overlapping aerial photographs collected from unmanned aerial vehicles (UAVs) (Fonstad et al., 2013; Cullen et al., 2018; Swirad et al., 2019).
- Fifth, advancing our conceptual and numerical models of rock coast erosion to show how preparatory rock weathering and decay processes help facilitate erosion (Naylor et al., 2012; Coombes, 2014).
- Finally, improving long-term (millennial) quantification of erosion using cosmogenic nuclides (Choi et al., 2012; Regard et al., 2012; Hurst et al., 2016; Raimbault et al., 2018).

The quantification of spatial patterns and scales of erosion has improved in the past decade, with recent analysis of SfM-derived DEMs in shore platform settings focused at the micro-scale; for example examining abrasion trails (Cullen and Bourke, 2018), surface roughness (Cullen et al., 2018) and vertical lowering (Swirad et al., 2019). SfM techniques allow spatially continuous DEMs to be derived, circumventing the issues of limited spatial coverage and bias that plague MEM techniques (Stephenson and Finlayson, 2009; Trenhaile, 2018). These novel SfM methods have started to be applied to study coastal boulder dynamics (Autret et al., 2018; Gómez-Pazo et al., 2019) but have not previously been applied to quantify meso-scale shore platform erosion by block detachment processes.

Despite our advancements in the past decade on meso-scale platform erosion, we have very little understanding of the rate, scale, and multi-decadal patterns of block detachment from platforms.

The relative efficacy of block detachment processes depends on the geological properties of the substrate; the lithology and structure influence the location, rate and spatial scale of rock decay and erosion processes (Dickson et al., 2004; Naylor and Stephenson, 2010). In particular, the combination of joint spacing, bedding thickness, and orientation of discontinuities relative to wave energy dictate the size and shape of boulders that are liberated from the platform surface (Knight and Burningham, 2011; Stephenson and Naylor, 2011).

Dombusch and Robinson (2011) quantified erosion rates of block-detachment and bed layer edge retreat on stratigraphic layers of chalk shore platforms using ortho-rectified aerial photographs and soft copy photogrammetry over a 34-year timeframe (1973-2007). They found that the volumetric erosion losses were similar to those measuring gradual surface lowering on soft sedimentary chalk shore platforms. Whilst other approaches using repeat Real-Time Kinematic Global Positioning System (hereafter dGPS) and handheld GPS measurements, combined with field observations of block-removal, have documented meso-scale block detachment processes operating on shore platforms on the NW coast of Ireland (Knight and Burningham, 2011) and in Glamorgan, south Wales (Naylor et al., 2016). Earlier studies on the Glamorgan Coast of South Wales, UK have provided photographic evidence of block removal and the geological and geomorphological controls on this process (e.g. Trenhaile, 1972; Stephenson and Naylor, 2011) with recent work measuring joint-block removal during storm events (Naylor et al., 2016).

Here, we combined UAV-SfM, historical aerial images, and ground-based photographs to investigate intertidal shore platform erosion over a 78-year period (to our knowledge the longest known observational record of platform erosion globally) on the densely bedded and jointed limestone shore platforms on the Glamorgan Coast, South Wales, UK. Firstly, we assessed erosion patterns and timing across two discontinuity-rich stratigraphic layers on the platform. Secondly, we combined historical aerial photography with recent UAV-derived imagery to quantify the long-term (78-years) volumetric rates of platform erosion by block detachment from the stratigraphic layers. Finally, we interpreted our results in the context of existing rock coast erosion rates to highlight the importance of meso-scale block detachment for rock coast evolution.

**Study Site**

The 23 km long Glamorgan Heritage Coast is comprised of Jurassic Blue Lias Limestone, where platforms are gently sloping (c.3°), within the macrotidal (6-11 m) Bristol Channel, South Wales, UK (Figure 1). The region is exposed to westerly prevailing winds and waves, with a fetch greater than 500 km across the Atlantic Ocean, and thus waves predominantly approach from the southwest (Figure 1C). The specific study region is a
section of shore platform approximately 500 m alongshore and 200 m cross-shore (e.g. cliff to sea), which is backed by c. 35 m vertical cliffs (Figure 1C). The bedrock geology consists of alternating bands of shale and limestone that are densely jointed (Trueman, 1930). This study concentrated on two relatively thick limestone beds c.300 m apart (Figure 1D-E), Layer 24 and Layer 19 (numbering from Trueman, 1930), hereafter site A and site B. MEMs deployed at the site (on Layer 21, between sites A and B) measured vertical lowering rates of 0.005-0.196 mm yr$^{-1}$, averaging 0.042 mm yr$^{-1}$ (Swantesson et al., 2006). Quarrying of limestone blocks was first observed at this site by Trenhaile (1972), and recent data has shown that quarrying of exposed stratigraphic layers occurs during high frequency, low magnitude storm events (Stephenson and Naylor, 2011; Naylor et al., 2016). Stephenson et al. (2018) monitored wave characteristics across the shore platform over four days using three pressure transducers deployed across the intertidal platform situated between site A and site B studied in this paper. Low-moderate wave energy conditions were operating during this time, revealing that wave heights did not reduce across the shore platform, with highest wave energies recorded nearest to the cliff during high tide conditions. By incorporating previous measurements and observations of block detachment and transport trajectories of platform-derived boulders (Naylor et al., 2016), Stephenson et al. (2018) suggested that quarrying of blocks from the platform surface would be focused at the elevation where waves break, depending on the phase of the tidal cycle.

**Methods**

**UAV-derived DEMs and Orthophotos**

Two high-resolution UAV surveys were conducted on the Glamorgan Coast, first in November 2017 and then in March 2018 using a DJI Phantom 4 Pro™. One survey covering both sites with multiple overlapping flights were flown at 20 m elevation to collect an area of c. 350 × 150 m in a matrix grid pattern oriented parallel to the cliff, with oblique photographs at 70° look angle, collected with 80% overlap. We deployed 25 high-visibility targets arranged in a quincunx pattern (i.e. targets in each corner and the centre, with additional targets scattered systematically around the area being flown) for each of the five flights across the survey extent. The precise location of the targets was recorded using dGPS to provide ground control points (GCPs) to geolocate the resulting orthophotos and DEMs (Turner et al., 2016). SfM photogrammetry and georeferencing of the aerial photographs captured from the UAV were carried out using the Pix4D Mapper Pro (v4.0.25) software package. Images captured using the rolling-shutter mode were input into a Pix4D project file. Absolute geolocation occurred by selecting the centroid of each GCP target, with known eastings and northings, on a minimum of 5 images per target, and manual tie points ($n=6$) were selected across the model domain, one in each corner and two across model domain, to increase the point cloud accuracy (Turner et al., 2016). A point cloud mesh with a density of 6,932 points/m$^2$ was created, from which Pix4D generated a DEM and a TIF orthomosaic with a 0.008 m/pixel resolution.

The generated DEM and orthomosaic allowed us to quantify multi-decadal to seasonal scale platform erosion of actively eroding layers within ArcGIS (v10.5). Firstly, we georectified historical aerial imagery and cliff-top photographs to the UAV-derived DEM, which allowed for a direct comparison of change through time.

**Historical aerial imagery**

Orthorectified historical aerial imagery was obtained in a digital format from the Welsh Government. Images dating from 1940 onward, were variable in quality, resolution, and spatial...
coverage (e.g. time-periods not consistently available for both sites and often not at low tide). A comprehensive list of available data is provided in Table I. Data availability lead to a multi-method analysis, whereby lower-resolution historical aerial and ground-based imagery in 1979 (site A only) and between 1992 and 2009 for both sites have been included to provide qualitative evidence for the timing and patterns of erosion within the 78-year erosion record. Approximate digitisation occurred for some of these data for visualisation purposes, but associated uncertainty was not calculated, nor have these data been included in the volumetric erosion rate analysis. In contrast, the high-resolution data have been utilised to calculate volumetric rates of change, alongside propagated errors.

Historical aerial images were georeferenced to the 2017-UAV derived orthomosaic, within ArcGIS (v10.5) using a first-order polynomial transformation; which rectified the photographs to the correct orientation and spatial referencing system (British National Grid) to quantify geomorphic change over 78 years. We identified 20 GCPs across the platform surface where no notable change could be observed over the length of analysis (78-years). The lithology allowed us to use the intersection of joints, faults, and fractures across the platform surface as control points for all time periods (Figure 2). The spatial accuracy georectified historical images were reflected by root-mean-square positional errors (Rocchini et al., 2012) unique to each set of aerial photographs (reported in the results section).

Measuring geometry of rock layers

Two independent users (both are authors) digitised the edges of the stratigraphic layers at sites A and B within ArcGIS from each available set of georectified aerial photographs. Previous efforts to explicitly map platform edges or shoreline positions have not rigorously quantified user digitising uncertainty (Dornbusch and Robinson, 2011; Ruggiero et al., 2013). User digitising uncertainty was determined as the distance calculated between the line mapped by one user and the line mapped by the second user and regular intervals along each line. A root-mean-square digitising error was computed from these distances for each time period (Rader et al., 2018).

A positional uncertainty \( \delta_{xy} \) was derived for each time step by incorporating error in dGPS (\( \delta_{GPS} \)), geo-rectification (\( \delta_{gr} \)), and user digitising (\( \delta_{dig} \)). The total positional uncertainty of the mapped layer edges can be expressed as:

\[
\delta_{xy} = \sqrt{\delta_{GPS}^2 + \delta_{gr}^2 + \delta_{dig}^2}
\]  

(1)

The total uncertainty (\( \Delta_{tot} \)) in mapped layer extent was then quantified by performing a buffer analysis on the mapped layer edges by \( \delta_{xy} \). Figure 3 shows an example of the layer edges at site A digitised from the 2017 aerial photography with associated uncertainty buffer.

Bed thicknesses were obtained from the 2017 DEM by systematically measuring the step size at c.1 m intervals (\( n=100 \)) around each stratigraphic layer. The bed thickness accounts for both the limestone bed layer and the shale interbedding. Our thickness calculations did not account for any gaps formed through rock decay processes (as shale often erodes faster, undercutting the limestone layer; Naylor and Stephenson, 2010) or for the presence of surface erosion features such as dissolution pools on the platform surface (Naylor et al., 2012). Therefore, our volumetric change calculations are measured from the top of the underlying platform layer to the assumed flat surface of the upper platform.
Quantifying platform erosion

Volumetric erosion rates and uncertainties were calculated between 1940 and 2018. Area polygons were constructed within ArcGIS software from digitised layer edges at each time-step, using the same seaward extent (based on the tidal level of the 1967 photograph which limits the extent of analysis; Figure 2). Planform erosion was calculated as the difference in area between two-time steps; uncertainty in the area change was propagated in quadrature (square root of the sum of squares, similar to Equation 1). Volumetric erosion (and uncertainty) was calculated as the area of erosion multiplied by the mean bed layer thicknesses of 0.41 ± 0.001 m (standard error) and 0.30 ± 0.002 m at site A and site B, respectively.

The majority of previous studies that have quantified shore platform erosion rates report gradual vertical lowering rates, such as those derived from micro-erosion-metres (MEMs) (Moses et al., 2014). In order to compare our erosion rate measurements to those existing published rates, similarly to Dornbusch and Robinson (2011), we convert our volumetric erosion rates to equivalent platform lowering rates at sites A and B. We derived minimum constraints on the equivalent vertical lowering rates at each time period by dividing the total volumetric erosion rates by the total area of each eroding stratigraphic layer exposed at the platform surface, including parts of the shore platform where the layer has not been eroded. We also calculated maximum constraints on the equivalent vertical lowering rates during each time period by dividing the total volumetric erosion rates by the total eroded area of the stratigraphic layers, i.e. only in the area that has eroded during that respective time period. We also calculated minimum and maximum equivalent vertical lowering rates by comparing digitised edge layers from the first to the last timestep (i.e. over the whole 78-year record of 1940 – 2018).

Results

Erosion patterns over a 78-year period (1940-2018)

Site A

The change in extent of the stratigraphic layer at site A is shown in Figure 4, which demonstrates persistent erosion across the 78-year analysis. In 1940, site A presented the maximum recorded platform extent, with the narrowest section measuring c.13 m wide (Figure 4A). The platform layer reached the cliff base and was partially covered by a fringing boulder beach. Erosion between 1940 and 1967 concentrated at the layer edges, resulting in the platform layer narrowing through time and by 1967, with the narrowest landward-most region (c.7 m from cliff) eroding from c.13 m to 4 m wide. Platform erosion continued between 1967 and 1981, and significant

![Figure 3](image_url)

**Figure 3.** Example of digitising uncertainty between two users on the site A, using the 2017 UAV-orthomosaic. User line 1 (pink) and user 2 (blue) used to calculate the distance between vertices. The positional uncertainty allowed us to propagate error buffers (light blue). [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 4](image_url)

**Figure 4.** Seasonal to annual platform change for site A, 1940-2018. (A) Platform erosion between 1940 and 2017, derived from high-resolution UAV, dGPS and cliff-top photographs. Connection of stratigraphic layer to the cliff lost between 1971 and 1981 (blue line). (B) Four-month winter season change (November 2017 – March 2018), three main erosion areas leading to the detachment of five blocks, overlaid onto 2017 orthophotos. Inset (upper right) illustrates one of the detached blocks, and the joint spacing of site A. [Colour figure can be viewed at wileyonlinelibrary.com]
morphological change occurred between 1979 and 1981. During the 2-year window (1979-1981), the continuous connection of the platform layer to the cliff base was lost; the stratigraphic layer was cut through exposing the layer beneath (Figure 4A) and the ‘bridge’ was eroded. Over the 11-years between 1981 and 1992, erosion primarily occurred along the western edge of the platform layer, which is orientated towards the direction of dominant wave attack. The approximate digitisation of the lower-resolution photographs allowed us to estimated volume loss of c.51 m$^3$ (no $\Delta_{vol}$) between 1992 and 1994; a volume more than 6 times larger than the volume lost during the erosion event that led to a key morphological change between 1979 and 81 identified above (Figure 4A). Subsequently, between 2009 and 2017, material was quarried from the western edge along the platform joints, resulting in a linear pattern. The erosion pattern provides further evidence of the geological control that discontinuities have on shore platform erosion. Finally, between November 2017 and March 2018, 4-blocks were removed from the platform, equating to $2.70 \pm 4.41$ m$^3$ yr$^{-1}$ (Figure 4B).

Site B

At site B, between 1940 and 1992, the platform layer was connected to the cliff base and primarily eroded on both sides at the landward-most region, narrowing through time to c.5 m wide in 1999 (Figure 5A & Figure 6A). Loose, quarried blocks that are the product of erosion were observed on the underlying platform surface between 1991 and 1999 (Figure 6A). Between 1999 and 2001 further erosion dissected the platform layer, so that the platform was cut into two sections, a landward-most section, nearest to the cliff, and the main section, c.25 m seaward from the cliff (Figure 5A). Cliff-top photographs demonstrated subsequent erosion on the north-eastern edge of the main section between 2002 and 2005 (Figure 6B-E), isolating ‘islands’ from the main section of the platform layer (Figure 6D).

Site B continued to erode between 2003 and 2009, with the main seaward section situated c.45 m from the cliff. Monitoring of the platform layer edges using dGPS, straddling winter storms between 10 November 2007 and 15 January 2008, revealed that c.6 m$^3$ (no $\Delta_{vol}$) of erosion took place due to block detachment, with a secondary event (c.0.4 m$^3$, no $\Delta_{vol}$)

Figure 5. Seasonal to annual platform change for site B, 1940-2018. (A) Platform erosion between 1940 and 2017, derived from high-resolution UAV and dGPS. Connection of stratigraphic layer to the cliff lost between 1999 (blue line) and 2001 (red line). (B) Four-month winter season change (November 2017 – March 2018), three main erosion areas leading to the detachment of two blocks, overlaid onto 2017 orthophotos. Inset (upper right) illustrates one of the detached blocks, and the joint spacing of site B. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 6. Cliff-top and ground photographs of platform change for site B, 1999 – 2005. (A) Platform area in 1999, photograph taken from the upper region, facing seawards. Platform edge highlighted in white, and areas with quarried material highlighted by dashed lines. (B & C) Ground photos of platform extent between 2001 and 2002, red & white stars indicate tie points between the two photographs. (D) Cliff-top photo of platform, with the island, little island, and main highlighted. (E) Ground photo of platform extent in 2005, with a white star as a tie point to B & C. Refer to Figure 5b for scale. [Colour figure can be viewed at wileyonlinelibrary.com]
occurring on the same north eastern edge between January and March 2008 (Figure 5A). Similar erosion patterns occurred between November 2017 and March 2018, whereby 11.18 m$^3$ yr$^{-1}$ (± 2.34 m$^3$) of material was quarried at some time during the 4-month period, from two isolated locations (Figure 5B).

Erosion rates over a 78-year period (1940 – 2018)

Volumetric erosion rates were calculated over a 78-year period (±$\Delta$$_{tot}$) for multiple time-periods (Table II, Figure 7). Erosion rates were therefore, measured and compared over multi-decadal, decadal, and seasonal timescales as the data allow. Volumetric erosion rates vary over two orders of magnitude (0.1-10 m$^3$ yr$^{-1}$) and do not vary systematically with the length of the time period. As expressed in Figure 6, the resolution of data resulted in high-uncertainty bandings for particular time periods (i.e. 1981 – 1992), yet the overall propagated uncertainty over the 78-year period is relatively low (see uncertainty values in Figure 2). Average volumetric erosion rates for site A and B over the 78-year period were 2.34 (± 0.61) and 4.80 (± 0.91) m$^3$ yr$^{-1}$, with the averaged equivalent lowering rates on the order of 2.4-5.3 mm yr$^{-1}$, and 1.2-2.6 mm yr$^{-1}$ at sites A and B, respectively (Table II). While both layers had similar magnitudes of average erosion between 1940 to 2018, erosion rates varied through time and were not consistent between sites, either in magnitude or morphological behaviour (Figure 7). For example, site A experienced its greatest rates of erosion between 1967 and 1981 (8.40 ± 5.14 m$^3$ yr$^{-1}$), whilst site B exhibited very little change (0.11 ± 4.37 m$^3$ yr$^{-1}$) during the same period (Table II, Figure 7). Morphologically, the platforms responded asynchronously through time, with the erosion of the uppermost platform (i.e. the erosion of the bridge) occurring between 1979 and 1981 on site A, yet between 1999 and 2001 on site B.

Discussion

Erosion of stratigraphic layers by block detachment

At both of our sites, platform edge erosion was focused on the upper intertidal zone of the shore platform. First, discontinuities such as faults create separations between the layers that sporadically cut across the shore platforms, these develop localised regions where platform edges are exposed and become available for other agents of erosion (e.g. Naylor et al., 2012). Second, we speculate that the initiation of erosion of an exposed stratigraphic layer can result from a combination of abrasion by boulders on the upper shore platform, and damage by falling blocks due to cliff failure, but have not been able to make direct observations of these processes. This damage to the platform eventually results in weakened bedrock suitable for plucking to create a hole in the stratigraphic layer, resulting in layer edges forming. Once edges are established, block detachment is focused at the landward shore platform, where wave energy delivery is measured to be highest at this site under low-moderate wave energy (Stephenson et al., 2018).

The processes operating eroded the upper section at both sites laterally to form a ‘bridge’, which narrowed through time (Figure 4 and Figure 5). These bridges subsequently breach to create two sections: a landward and a seaward unit. The disconnection of the layers resulted in the landward segment

Table II. Volumetric erosion rates and the range of equivalent surface lowering rates for the layers at sites A and B. Propagated uncertainty for site A and B are relative to the platform areas

| Time-step    | Volumetric erosion rate (m$^3$ yr$^{-1}$) | Propagated uncertainty (± m$^3$ yr$^{-1}$) | Equivalent lowering rates (mm yr$^{-1}$) | Equivalent lowering rates (mm yr$^{-1}$) |
|--------------|------------------------------------------|------------------------------------------|-----------------------------------------|-----------------------------------------|
|              | Site A B                                  | Site A B                                  | Minimum Maximum                         | Minimum Maximum                         |
| 1940-1967    | 3.40 0.72                                | 2.97 2.01                                | 1.70 0.36 3.72 0.78                      | 1.70 0.36 3.72 0.78                      |
| 1967-1981    | 8.40 0.11                                | 5.14 4.37                                | 4.20 0.05 9.19 0.12                      | 4.20 0.05 9.19 0.12                      |
| 1981-1992    | 4.68 2.43                                | 6.39 5.85                                | 2.34 1.21 5.12 2.66                      | 2.34 1.21 5.12 2.66                      |
| 1992-2009    | 5.30 6.90                                | 2.02 1.98                                | 2.65 3.46 5.81 7.56                      | 2.65 3.46 5.81 7.56                      |
| 2009-2017    | 2.82 1.88                                | 0.85 0.52                                | 1.41 0.94 3.08 2.06                      | 1.41 0.94 3.08 2.06                      |
| 2017-2018    | 2.81 11.18                               | 4.41 2.37                                | 1.35 5.60 2.96 12.25                     | 1.35 5.60 2.96 12.25                     |
| 1940-2018    | 4.80 2.34                                | 0.91 0.61                                | 2.40 1.17 5.26 2.57                      | 2.40 1.17 5.26 2.57                      |

Figure 7. Volumetric rate of erosion across each time-period on site A (left) and site B (right), from 1940 to 2018. The rates of change per time period, per site, are expressed in a solid line, with the propagated error uncertainties in transparent bands. Error bands have been cropped to zero (i.e. do not fall into negative numbers). The average rate of block detachment (i.e. 1940-2018: 2.34 and 4.80 m$^3$ yr$^{-1}$) is expressed in dashed lines, with a banding of uncertainty (± 0.61 and ± 0.91 m$^3$ yr$^{-1}$).
eroding in a landward direction, whilst the seaward segment is periodically eroded along all edges in a seaward direction, where erosion was observed to be more rapid on edges with an aspect facing towards the dominant wave direction (e.g. site A between 1992 and 2009). Finally, the 4-month change (November 2017 – March 2018) demonstrated that there are isolated cases of meso-scale block detachment from multiple points around the layer edge; showing meso-scale erosion can occur at high frequency (i.e. seasonally) and can be spatially variable. While both sites exhibited similar morphological behaviour over the 78-year period, perhaps unsurprisingly they did so asynchronously, due the dependencies of erosion by block detachment on rock mass properties (Stephenson and Naylor, 2011), degree of rock decay (Naylor et al., 2012), previous erosion history (Naylor et al., 2016) and hydrodynamic conditions (Stephenson et al., 2018).

Infrequent aerial photography over the period studied prevented us being able to directly link block detachment erosion events to specific periods of stormy conditions, with the exception of winter 2007/08. During this period, Naylor et al. (2016) demonstrated that storm waves drive the detachment and transport of joint-bounded blocks from the stratigraphic layers at both site A and B. Yet our results demonstrated that platforms are not always responsive to high-magnitude wave events. The winter of 2013/2014 was noted as an especially stormy winter, and has been suggested to be the most energetic since 1948 (Masselink et al., 2016). Between 2009 and 2017 both study sites on the Glamorgan coast experienced close to their slowest erosion rates in any time period over the 78-year record (Table II, Figure 7). There are several reasons why high energy wave events may not always result in the more erosion. Firstly, rock decay processes focused at discontinuities in the rock mass help to prepare the platform for block detachment by waves (Naylor et al., 2012). Erosion may only take place when sufficient time has passed that the joints and bedding planes have weakened sufficiently for wave-driven detachment to occur. The corollary is that where erosion has recently occurred locally, discontinuities and interbedded shale layers might not be sufficiently weakened to allow further block detachment, even when wave energy is high; so antecedent erosion matters. Secondly, the timing of storm events relative to the tides will influence where in the intertidal zone wave energy is focused and how waves are transformed into shallow water. At low tide, large waves may break offshore or on the lower shore platform. At high tide, waves may not transform to breaking condition and thus wave energy may be reflected out to sea by the sea cliff (Stephenson et al., 2018). Block detachment requires the combination of a block ready to be eroded, and the delivery of wave energy great enough to detach, then entrain the block and initiate transport (Naylor et al., 2016).

Comparison to shore platform lowering rates at Glamorgan and globally

The calculation of equivalent vertical lowering rates is intended only to allow direct comparison to other studies of shore platform erosion that have focused on measuring gradual surface lowering. On the Glamorgan coast, the detachment of bedrock blocks resulting in the retreat of bedrock steps defined by stratigraphic layers is instead a process operating along the dip and strike of bedding, aided by discontinuities (Naylor and Stephenson, 2010). The equivalent rates of vertical lowering, which at their most conservative span 1.2-2.4 mm yr⁻¹ between the two sites (Table II), are on the order of nearly two orders of magnitude larger than direct measurements of vertical lowering rates at the same site, averaging 0.042 mm yr⁻¹ (Swantesson et al., 2006). The comparison between vertical lowering and block-detachment suggests that meso-scale, block detachment processes dominate shore platform erosion at our field site. Our equivalent lowering rates are more rapid than the majority of lowering rates in sedimentary rocks measured elsewhere in the world. These include a variety of calcareous shore platforms in Portugal (Moura et al., 2011) and along the margins of the Mediterranean Sea (Furlani et al., 2014). They also include long-term records from sandstones on the Victoria coast, Australia (Stephenson et al., 2012); sandstone shore platforms on the Coast of Canada (Trenhaile and Porter, 2018); and shale and sandstone shore platforms on the coast of Yorkshire, UK (Robinson, 1977; Swirad et al., 2019). However, we note that similar vertical lowering rates have been observed on softer chalk shore platforms (Foote et al., 2006). Indeed, similar to our work, Dornbusch and Robinson (2011) previously investigated block detachment and stratigraphic layer step retreat on chalk shore platforms in south-east UK. They derived equivalent surface lowering rates of the same magnitude as we have calculated for the Glamorgan coast. Importantly, their rates of meso-scale block detachment on softer chalk platforms were of the same order of magnitude as measured vertical lowering rates.

Focusing of rock decay and erosion at discontinuities play an important role in landscape development across terrestrial and coastal landscapes (Scott and Wohl, 2019). The meso-scale blocky processes documented throughout, now need to be included in numerical models of shore platform evolution (Matsumoto et al., 2018), similar to recent developments in the modelling of hillslope sediment transport (e.g. Glade et al., 2017). We therefore advocate for a change in monitoring approach in order to capture both microscale and meso-scale geomorphic changes on shore platforms. Time series of high-resolution DEMs (1-100 mm pixels) using SfM and high precision GPS facilitates topographic change detection and has begun to address this research need (Cullen et al., 2018; Swirad et al., 2019). These need to span from single event timescales to capture individual block detachment events, up to multiannual to multi-decadal records to capture the integrated, time-averaged rates of rock decay and erosion processes and their long-term spatial and temporal variability.

Conclusions

Overall, the results of our quantitative, volumetric meso-scale erosion rate study demonstrate that block detachment processes dominate over gradual surface lowering over a 78-year period, on the Glamorgan coast. This unprecedented length of time series for shore platform erosion studies was possible because we used high-resolution orthophotographs and SfM-derived DEMs to accurately georectify historical aerial photographs, giving historical data a ‘new lease of life’. We found that volumetric erosion rates varied by over two orders of magnitude (c.0.1-10 m³ yr⁻¹) and did not correspond to time period over which they were averaged. Average rates over the full 78-year record were 2-5 m³ yr⁻¹. These rates correspond to approximately 1.2-5.3 mm yr⁻¹ equivalent surface lowering rates (i.e. when averaged across the extent of the eroding platform layer). These rates are nearly two orders of magnitude larger than locally measured surface lowering rates, and predominantly much larger than surface lowering rates measured in sedimentary rocks on shore platforms globally. Our results highlight that meso-scale platform erosion via block detachment processes can potentially dominate shore platform evolution across...
seasonal to multi-decadal timescales and have been hitherto under-investigated globally. Improved understanding of shore platform erosion will ultimately allow us to better assess erosion risks and hazards for society.

These data also allowed us to describe the spatial and temporal patterns of erosion, showing that morphological evolution of the platforms was similar over the 78-year record, but that erosion rates and patterns were asynchronous, strongly suggesting that local geological, rock decay and antecedent factors as well as storm events influence meso-scale block detachment and thus platform erosion rates. Future platform erosion and modelling studies would greatly benefit from taking this localised spatial and temporal variability into account.

Our results highlight that meso-scale platform erosion via block detachment processes can dominate shore platform evolution across seasonal to multi-decadal timescales in discontinuity rich rocks and have been hitherto under-investigated globally. Improved understanding of multi-scale platform erosion will ultimately allow us to better assess and model erosion risks and hazards for society.

Data availability statement

Research data are not shared.

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