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Cherith A. Moses

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# Rock coast geo model: process-response dynamics, resilience and vulnerability

Cherith A. Moses

Geography and Geology, Edge Hill University, Ormskirk, Lancashire, L39 4QP

mosesc@edgehill.ac.uk

## Abstract

Geology and geomorphology link starkly in coastal environments, exemplifying the importance of Fookes' geo model approach to understanding site dynamics. Cliffs, and the shore platforms that front them, are subject to both marine and subaerial processes. Throughout his work, Fookes emphasises the role of climate as a weathering agent, influencing material properties and requiring consideration in engineering projects. Comparatively, more is known about the operation of rock weathering processes on shore platforms than on cliffs. Yet, with changing climate, it is becoming apparent that winter salt and frost weathering, and summer salt and wetting-drying weathering contribute to more frequent occurrences of coastal rockfalls. Increasing storm activity and rising sea levels are enhancing marine and subaerial processes. Rock coasts are amongst the most rapidly eroding coastlines in Europe. New applications of technologies, including seismometers, Lidar and InSAR, provide a fuller understanding of rock coast process-response geo model behaviour and the resilience of rock coasts on engineering timescales. Communicating scientific understanding of rock coast dynamics to policy-makers, planners and the public remains a challenge. Assessments of hazard, risk, resilience and vulnerability of rock coasts associated with climate change provide useful communication tools. Databases such as the British Geological Survey GeoCoast geohazard data product, and EMODnet Geology (European Marine Observation and Data Network) coastal behaviour data products integrate and visualise available data and information to communicate situational awareness to a broad audience.

## 1. Introduction

Much of Peter Fookes' work is of direct relevance to rock coasts in relation, for example, to geomaterial properties (Fookes, 1991), rock slope stability (Fookes and Sweeney, 1976), the durability of rock and both reinforced and unreinforced concrete materials for breakwaters and coastal protection works (Fookes and Poole, 1981). In his Glossop Lecture he notes that characterising near-surface hazard events and short-term occurrences, including coastal change, is an important part of the work of engineering geology in helping to reduce engineering risk (Fookes, 1997). Throughout his work, the importance of geomorphology in engineering geology is emphasised together with the value of the geo model for integrating and communicating geological and geomorphological understanding for engineering projects (Fookes and Vaughan, 1986; Fookes, 1997; Griffiths, 2014; Hearn, 2021).

*Engineering Geomorphology – Theory and Practice* (Fookes et al., 2007) Part 4, consisting of nine chapters, is dedicated to coasts, including the hazards associated with cliff retreat on rock coasts and their management. Coasts feature again throughout *Geomodels in Engineering Geology – an Introduction* (Fookes et al., 2015). A key value of the geo model is that it facilitates the study of process-response systems (Fig. 1). Using this approach, geomorphological and geological data, relevant to understanding ground conditions, are categorised and may be quantified to model climate change impacts on the coastal system or to establish design life for coastal defence measures (Griffiths and Stokes, 2008). The geo model approach has been applied to identify the Coastal Behaviour Systems and sediment cells that underpin the development and review of UK Shoreline Management Plans (Hosking and McInnes, 2002; McInnes et al., 2011). It is also applied to risk appraisal and analysis (McInnes and Moore, 2014) and cliff instability and management (Halcrow Group Ltd, 2009; Lee and Clark, 2002; Moore et al., 2002, 2010, 2016; Moore and McInnes, 2011; Moore and Davis, 2015; Saroglou and Alexandrou, 2016; Sellwood et al., 2000). Further applications of the geo model approach are to be found in guidance for both decision-makers and practitioners (e.g. Blanco et al., 2019; Environment Agency, 2020; McInnes and Moore, 2014; Moore and McInnes, 2011, 2021).

This paper focuses on rock coasts, where the geo model approach has been successfully applied to understand ground behaviour to inform the design of engineering solutions addressing coastal management needs e.g. at Clayton Bay and Filey Bay, Yorkshire, NE England (Halcrow Group Ltd., 2009; Moore et al., 2002), and Lyme Regis, Dorset, SW England (Moore et al., 2016; Sellwood et al., 2000). The importance of climate, and climate change, to engineering projects by influencing morphology and magnitude-frequency of weathering and erosion processes may be captured in the geo model (Fookes, 1997). To inform development and application of rock coast geo models (Fig. 1) at specific sites and, more broadly, for decision-making at the coast (Blanco et al., 2019; Moore and McInnes, 2021), this paper reviews recent developments in understanding the response of key components of the rock coast geo model to climate change and sea level rise.

Rock coasts are cliffed and composed of consolidated material irrespective of its hardness (Sunamura, 1992). They are typically classified as either ‘soft’ or ‘hard’ depending upon the materials in which they are developed. Soft rock coasts range from those developed in weak surficial deposits through to bedded and jointed weak rock (Lee, 2002; Lee and Clark, 2002). Hard rock coasts are considered to range from those developed in weak, sedimentary rocks through to resistant, igneous rocks (Trenhaile, 1987; Sunamura, 1992). Rock coasts make up more than half the world’s coastline, with an earlier, widely used, estimate of 80% (Emery and Kuhn, 1982) refined to 52% using remote sensing methods (Young and Carilli, 2019). Approximately half the coastline of Europe is rock coast (Prémaillon et al., 2018; Regard et al., 2022), of which 80% is hard rock, 13% soft rock and 7% intermediate (calculated from EMODnet coastal typology data product, Regard et al., 2022). In the UK, 60% of the coastline is rock coast (18% soft, 42% hard rock) and in Ireland 57% (1% soft, 56% hard rock; Salman et al., 2004). Cliff retreat rates are generally highly variable: hard 0.029 ± 0.029 m yr$^{-1}$; intermediate 0.10 ± 0.04 m yr$^{-1}$; soft 0.23 ± 0.13 m yr$^{-1}$ (median and variance between 17% to 83% quantiles; Prémaillon et al., 2018; Regard et al., 2022). These values, calculated from a global database, mask the stochastic nature of coastal cliff retreat and site-specific variations. For example, on the soft rock, London Clay coastline, Isle of Sheppey, Kent, UK, an historical average of 1.02 ± 0.08 m yr$^{-1}$ has been measured, with a maximum rate of 1.93 ± 0.08 m yr$^{-1}$

at Warden Point (Nicholls et al., 2000). On the Cretaceous Chalk coasts of NW Europe, historical cliff retreat rates average 0.49 ± 0.38 m $yr^{-1}$ with site-specific rates, measured over short periods of a few years, of > 1.2 m $yr^{-1}$ (Moses and Robinson, 2011).

Rock coasts are dynamic on engineering timescales of concern to engineering geologists, their behaviour driven by the interaction of lithology with marine and subaerial processes. Improving understanding of the response of rock coasts to climate change is of importance for climate-resilient project design. With UK predictions of warmer, wetter winters, and hotter, drier summers with increased intensity of heavy summer rainfall events, and increased rates of sea level rise (Kendon et al., 2022), the need to understand the dynamics of the rock coast geo model is ever more pressing. This is particularly the case for predictive modelling of cliff behaviour in future climate scenarios, the topic of Fookes' (1997) Glossop Lecture. This paper, therefore, uses the geo model approach to review current understanding of the influence of climate, via marine and subaerial processes, on the process-response dynamics of rock coasts. A range of rock types is included, but the focus is largely on the Cretaceous Chalk coasts of SE England and N France and the London Clay coast of SE England which are two of the most intensively studied globally (Fig. 2). Following a brief introduction to the key characteristics of rock coasts, emphasis is placed on more recent new applications of a variety of technologies to improve understanding of rock coast dynamics. Although still some way from full understanding and quantification of all parameters of the rock coast geo model to allow future changes to be modelled in a deterministic way, as noted by Griffiths and Stokes (2008), this paper highlights the significant research progress being made. It also addresses the increasing emphasis placed on understanding coastal risk, resilience and vulnerability for decision-making (Blanco et al., 2019; Moore and McInnes, 2021) by highlighting some of the ways these are represented to draw attention to rock coasts.

This paper considers only the components of rock coast geo models that are present on the shoreline, namely the cliff and foreshore (Fig. 1). It is important to note that the geo model should also consider regional geological and geomorphological history as well as current ground conditions (Fookes, 1997). Rock coast geo models, therefore, need to be considered in the context of broader inland, nearshore and offshore ground conditions. This is particularly the case in engineering projects in the energy industry, including the siting of offshore energy developments and infrastructure required to bring energy onshore (Guinan et al., 2020; Nyberg et al., 2021; Yeomans et al., 2023). Advances continue to be made in mapping the geology of seabed environments to inform geo models for ground engineering from offshore to onshore (Asche et al., 2022; Mellett et al., 2015; Moses and Vallius, 2020).

## 2. Rock coast geo model characteristics

The two key morphological components of the rock coast geo model are cliffs and the foreshore, or shore platform (Fig. 1). Two types of rock coast are recognised, (i) plunging cliffs, with vertical or sub-vertical cliffs that descend far below sea level and (ii) cliffs with shore platforms where vertical or sub-vertical cliffs are fronted by gently sloping or horizontal to sub-horizontal platforms. Their geomorphology is described by Trenhaile (1987) and Sunamura (1992), and by Bird (2016) who also addresses their management. Two types of shore platform are differentiated based on morphology: Type A dip gently seawards with no discernible break of slope, Type B are horizontal or sub-horizontal, terminating at the seaward end with a marked scarp (Sunamura 1992, 2015). It is often difficult to differentiate the two types of shore platform in the field because the edge of the platform is seldom exposed at low tide, making it difficult to measure its full horizontal extent, or width, which is an important parameter in the long-term modelling of cliff retreat (Kennedy, 2015). Plunging cliffs are generally considered stable, with no appreciable retreat (Trenhaile, 1987; Sunamura 1992, 2015). Research interest has, therefore, focussed on rock coasts with cliffs fronted by platforms that are formed as the cliffs retreat. In comparison to soft coastlines, such as beaches, dunes and salt marshes which have uniform substrates and morphologies dominated by a few processes, rock coasts present more complex environments. They may be inherited from former sea levels and climates and have complex geological settings with varying degrees of resistance to a range of processes including weathering, marine, biological, and mass movements (Stephenson and Naylor, 2010). In the UK, because of their relatively rapid cliff retreat rates, there has been a particular interest in the erosion and management of soft rock coasts, principally London Clay and glacial till (Lee, 2002; Lee and Clarke, 2002; Brew 2004, 2007) but also Cretaceous Chalk which may be included in both categories of ‘soft’ and ‘hard’ rock coast (Moses and Robinson, 2011). Many UK coastal cliffs have national and international conservation designations because of their geological, geomorphological and biological significance (May and Hanson, 2003) and these also require consideration in engineering projects.

Detailed reviews of cliff and shore platform development in Great Britain are provided in Kennedy et al. (2014) *Rock coast geomorphology: a global synthesis* which is the most comprehensive review of rock coast geomorphology to date (cliffs: Lim, 2014; shore platforms: Moses, 2014). Typically, cliffs developed in well-jointed rocks are vertical to sub-vertical, with rockfall debris accumulated periodically on the platform below the cliff (Fig. 3a, b, c). Cohesive clay cliffs generally exhibit a crenulated and irregular cliff line and cliff face due to rotational slumps being a dominant mode of retreat. In both cases, fall and slump debris protect the toe of the cliff from marine attack for a period until the debris is removed by wave processes (Fig. 3d). At the junction of the cliff and platform there is often either a ramp or a step (Fig. 3a, b). Ramps are associated with protection of the junction from erosion, either by rockfall debris or deep beach sediment (Trenhaile, 1987; Kirkby, 2023), whilst steps are considered to form where there is a harder, more resistant, bed present at the foot of the cliff (Trenhaile, 1987). The rate of removal of rockfall debris is related to the exposure of the shoreline to wave action and also the size of debris. On well-jointed lithologies, larger rockfall debris travels furthest from the cliff and may form a protective apron (Fig. 3c) with the finer debris being removed first, as recorded on the Chalk coasts of SE England and N France (Hénaff et al., 2006). The size of larger clasts that remain intact during the fall is related to the pattern of discontinuities - bedding, jointing and fractures - in the cliff (Mortimore et al., 2004a; Lim, 2014).

Discontinuity patterns also exert a control on foreshore development (Moses, 2014;). Across shore platforms individual beds may be stripped back by wave impact removing joint or fracture bounded boulders (Fig. 3a, Fig. 4a, b). These boulders usually reside on the middle to lower section of the platform, whilst boulders derived from rockfall debris tend to remain on the upper platform close to the toe of the cliff. Movement of boulders across the platform may cause impact abrasion (Fig. 4c).

Where boulders or cobbles remain static they may protect the platform surface from abrasion (Fig. 5a). Downwearing of shore platforms occurs both at a micro-scale (mm to cm) on the exposed rock surface and at a meso-scale (10s of cm to m) when individual steps are eroded. Step removal is stochastic and may be related to the occurrence of resistant layers (Fig. 5b). At low tide, shore platforms are exposed to a range of subaerial weathering processes including solution, wetting-drying, salt weathering and frost weathering. When the platform is inundated as the tide rises, then marine abrasion processes also operate. Where platforms are backed by hard engineering structures there may be enhanced downwearing due to wave reflection, and this may be compounded by the use of heavy plant in construction (Fig. 5 c, d). In addition to removing rock when moving, heavy machinery may compress and weaken the surface so that it is more susceptible to marine erosion. The surface depressions created then act as a trap for beach sediment, exacerbating erosion beyond the life of the construction project as seen on the Chalk shore platforms of East Sussex (Dornbusch et al., 2007). Organisms that inhabit shore platforms may also cause erosion, e.g., by abrasion on and into the rock surface. Seaweed cover is thought to mainly provide protection from marine abrasion and mitigate the impact of subaerial weathering. The presence of beach material precludes biological colonisation of the platform surface and there is often an abraded area close to the toe of the beach where sediment regularly moves back and forth (Fig. 5e). Generally, subaerial weathering processes are considered to be most effective on the middle to upper parts of the platform that are exposed for the longest time during the tidal cycle. The middle and lower parts of the platform may be dissected by shore-normal runnels (Fig. 5 f, g). Relatively little is known about their initiation, formation and contribution to platform development, but they are thought to be linked to abrasion by sediment movement in the incoming and outgoing tide (Moses, 2014).

## 3. Rock coast geo model dynamics in response to climate change

### 3.1 Cliff retreat rates: decadal

The most common approach to assess changes in cliff retreat rate and behaviour in response to climate change is to measure cliff line movement, from 1st Edition Ordnance Survey maps, published in the 1800s, to the present day, using a combination of data sources including maps, aerial photographs, LiDAR surveys and often also direct measurements from field surveys. The most intensively studied lithologies are those that erode most rapidly and thus are potentially the most sensitive to variations in climate and relative sea level rise (RSLR). Studies considered here include Cretaceous Chalk, glacial till, London Clay and composite materials (Table 1a).

Results are variable with some studies finding an increase in cliff retreat rates in recent decades, from approximately 1950 in most cases, whereas others indicate a decrease in recent cliff retreat rates when compared to longer term historical rates, usually measured over approximately 130 – 150 years. This is the case even within the same lithology. For example, studies on the Cretaceous Chalk of SE England show a recent decrease in cliff retreat rates whilst in contrast, studies conducted in Northern France show a recent increase. These are considered in detail in Moses and Robinson (2011) and, in summary, linking measured rates to factors known to influence cliff retreat (geological structure, rainfall, the occurrence of frost, wave climate, beach width and volumes and platform height and width) has proved difficult, mainly due to the very different scales at which the data are recorded. These and other studies (Table 1a) identify a range of, now well-established, factors that influence cliff retreat rates at specific sites and across a range of soft rock cliffs (reviewed by Sunamura, 2015). Increasing shore platform width may reduce wave attack at the toe of the cliff, although measuring shore platform width from maps and air photos is problematic (Dornbusch et al., 2008c). Other factors include changes in beach volume and beach level related to variations in longshore drift due to the presence of coastal defences, groynes and harbour breakwaters and occurrence of mass movement material with long residence times. For example, large-scale rockfalls on Cretaceous Chalk cliffs may have a residence time of 10 to 40 years (Mortimore et al., 2004a) and the erosion cycle for large-scale rotational slumps on London Clay coasts may be 30 to 40 years up to 100 years where exposure to wave energy is low (Hutchinson, 1973; Dixon and Bromhead, 2002). Bray and Hooke (1997) suggest that cliff height, through its control on the volume of debris deposited, influences the cycle of erosion from the initial mass movement to removal of debris from the toe of the slope: low, simple cliffs of < 20 m height, cut in soft glacial sediment, 5 – 10 years; medium cliffs of ~ 20 - 40 m height and composed of consolidated clay, or soft sedimentary rocks, 30-40 years; and for high cliffs of > 40 m and up to as much as 200 m height in harder sedimentary rocks, 100 – 150 years. Removal of coastal defences may trigger a period of rapid cliff retreat as has been the case at Happisburgh, Norfolk, UK, where a 1 km stretch of cliff retreated by ~ 140 m over a 20-year period following the removal of sea defences (Payo et al., 2018).

Despite these complications, increased rainfall, water levels and wave energy associated with storm activity and variations in tidal cycles are key influences on cliff retreat rates on soft rock cliffs (Brooks et al., 2012; Pye and Blott, 2015; Burningham and French, 2017). Yet, it remains difficult to establish the role of RSLR, particularly the rate of RSLR, in driving coastal cliff retreat. To address this, there is increasing interest in investigating centennial and millennial timescale cliff retreat using a combination of cosmogenic isotope dating and numerical modelling (Section 3.2). At annual to seasonal timescales, new applications of a range of technologies are yielding insights into cliff and shore platform response to climate-related driving factors (Section 3.3).

### 3.2 Cliff retreat rates: Holocene

Over approximately the last ten years, the dating of accumulated cosmogenic isotopes, such as $^{10}$Be, combined with numerical modelling has emerged as a tool to understand cliff and shore platform erosion over millennia (Table 1b; Fig. 6). The aim, providing context for historical and current rates of cliff erosion, is to facilitate calibration of long-term dynamic models of cliff and shore platform erosion. This is considered central to the development of predictive models of cliff retreat that account for climate change (Hurst et al., 2016, 2017; Trenhaile, 2018; Shadrick et al., 2021, 2022, 2023a). The value of modelling millennia-scale, Holocene, cliff retreat rates is posited to be that such long-term retreat rates (i) incorporate long return period mass wasting events characteristic of coastal cliff retreat, (ii) are unaffected by human intervention on the coast and (iii) include pre-historic rates of RSLR that are comparable to projected future rates (Hurst et al., 2016, 2017; Shadrick et al., 2021, 2022, 2023a). Shadrick et al. (2022) consider this to represent an advancement over the well-established and widely used Soft-Cliff and Platform Erosion (SCAPE) model (Walkden and Hall, 2005) which is reliant on historic cliff retreat rates and designed primarily for use on soft rock cliffs. More recent developments to SCAPE, however, incorporate rock hardness, enabling its application to hard rock coasts (e.g. Walkden et al., 2020; SCAPE+, National Network of Regional Coastal Monitoring Programme of England, 2023). The use of cosmogenic isotopes is considered to have transformed the ability to investigate coastal cliff retreat over centennial to millennial timescales (Hurst et al., 2016; Trenhaile, 2018; Shadrick et al., 2022), potentially informing predictions of future rock coast geo model behaviour.

Cosmogenic isotopes are produced by the interaction of cosmic rays with the rock surface. Their concentration indicates the period of exposure of the surface, providing a geochronometer to quantify how long the surface has been exposed or to interpret its rate of weathering and/ erosion (Fig. 6). A range of isotopes may be used, dependent on rock type, and $^{10}$Be, used in rock coast studies published to date, requires the presence of quartz (Moses et al., 2014). On Chalk shore platforms it is therefore the indigenous siliceous flint that is sampled rather than the Chalk. At the simplest level, as the cliff retreats and the foreshore is exposed, concentrations of $^{10}$Be increase across the shore platform with the most recently exposed, upper platform, accumulating lower concentrations compared with the longer-exposed middle and lower platform. This simple distribution, which underpins the studies of Holocene cliff retreat, is complicated by a range of additional factors. For example, sea water shields the rock surface and $^{10}$Be concentrations decrease with water depth. Local water levels, influenced by tides and RSLR may, therefore, reduce the concentration on the lower platform. In addition, downwearing of the shore platform removes the richest $^{10}$Be from the surface, exposing lower concentrations. The result is a ‘humped’ distribution of $^{10}$Be across the platform that is dependent on both the rate of cliff retreat and shore platform downwearing (Fig. 6). Higher rates of cliff retreat result in lower $^{10}$Be concentrations. Increasing tidal ranges may cause the $^{10}$Be peak to migrate seaward; rising sea level may result in higher $^{10}$Be content because of a suggested associated reduction in platform downwearing. More detailed explanations of the principles and the methodological approach are provided by Hurst et al. (2016, 2017).

Cosmogenic isotope geochronology, combined with numerical modelling, has been applied on sandstone and Chalk rock coasts to ascertain Holocene rates of cliff retreat (Table 1b). In studies to date, two different modelling approaches are used: steady state geometric or morphodynamic process-based modelling. For the Cretaceous Chalk cliffs of SE England and NW France, studies using a steady state geometric modelling approach indicate either comparable (Regard et al., 2012) or increasing cliff retreat rates from the Holocene to modern, historic period (Hurst et al., 2016; Duguet et al., 2021). Use of a morphodynamic process-based modelling approach indicates declining cliff retreat rates from the Holocene to the modern, historic period (Shadrick et al., 2023a). For sandstone cliffs both modelling approaches yield a decline in cliff retreat rates from Holocene to modern (Swirad et al., 2020; Shadrick et al., 2021, 2022). This is considered to be due to lower rates of platform downwearing on sandstone when compared with chalk (Shadrick et al., 2023a). Studies of Holocene cliff retreat rates using cosmogenic isotopes remain small in number and methodological approaches are in ongoing development. The dynamic process-based modelling approach allows for transient cliff retreat rather than Holocene-averaged cliff retreat rates (Shadrick et al., 2023a; Table 1b). There are also variations across the studies in the modelling assumptions, in both approaches, that may influence the results. Parameters such as cliff morphology, platform morphology, width and gradient, downwearing rate and presence/absence of beach or mass movement sediment may be represented in a variety of ways. For example, platform morphology may be fixed or dynamic through model simulation time (Shadrick et al., 2023a); after initial exposure the platform may be assumed never to have been reburied or shielded by sediment cover (e.g., Swirad et al., 2020); either geology (e.g., Swirad et al., 2020) or physical processes (e.g., Shadrick et al. 2022) may be factored as the dominant control. Hurst et al. (2017) investigate a range of factors that may influence modelled results, concluding that ‘cliff retreat rates derived from cosmogenic $^{10}$Be might be considered as maximum estimates’ (ibid, p82). Nonetheless, this approach has been used to forecast cliff retreat rates for the next century suggesting an increase of up to one order of magnitude by 2100 on historically stable coastlines (Shadrick et al., 2022). Whilst there is discussion on the validity of such predictions, they highlight some of the key process-response issues that require further research and refinement to improve predictive capability for future rock coast responses to climate change and SLR (Dickson et al., 2023; Shadrick et al., 2023b; Matsumoto et al., 2024).

All of these cosmogenic isotope studies are predicated on the assumption that active cliff retreat has occurred throughout the Holocene, an assumption that is open to challenge, at least for the Chalk and sandstone cliffs of East Sussex, SE England (Dornbusch, 2022). Combining evidence, including historic cliff retreat rates calculated over 400 years, presence of mid-Holocene terrestrial habitats fronting contemporary cliffs, and a geomorphological landscape type interpretation, Dornbusch (2022) suggests that cliff erosion can only have started in the last few centuries. The main line of evidence is that remnants of Eemian (last interglacial 130,000 to 115,000 ya) cliffs are still present in places. In addition, it is suggested that, despite sea level rise, there has been a persistent decrease in erosion rates to less than half the maximum rate observed in the late 19th to early 20th century along this coastline. Whilst millennial-scale studies of cliff retreat based on cosmogenic isotopes may offer potential insights into cliff response to RSLR, the wide range of assumptions of the various modelling approaches and the assertion that ‘we cannot use historical rates to assess the risk associated with rock coasts’ (Shadrick et al., 2022, p.7) require further examination (Acharya-Chowdhury et al., 2024; Dickson et al., 2023; Matsumoto et al., 2024; Shadrick et al., 2023b). A better understanding of (i) shore platform downwearing and equilibrium state, (ii) lithological controls on rock coast evolution, (iii) linkages between shore platform downwearing and cliff retreat and (iv) inheritance is required.

### 3.3 Cliff retreat: annual and seasonal

Studies on the Chalk coast SE England and NW France show that cliff retreat rates are higher in winter, associated with a higher frequency of rockfalls linked to subaerial rather than marine processes: higher number of rain days and frost days, heavier winter rainfall, sequential wet years that elevate ground water levels. The longer the period of antecedent rainfall, the deeper and larger the slide. It has also been noted that rockfalls may occur during the summer when dry periods are interrupted by rainfall (Mortimore and Duperret, 2004; Duperret et al., 2005; Moses and Robinson, 2011; Lim, 2014). On cohesive clay coasts, higher cliff retreat rates are associated with higher rainfall levels and wave energies during the winter period (Hutchinson, 1973; Dixon & Bromhead, 2002; Brooks et al., 2012; Pye and Blott, 2015; Burningham and French, 2017). Annual and seasonal variations in cliff retreat rates are strongly influenced by the moderating effects of rockfall debris, episodically protecting the cliff toe from wave attack, and fluctuating beach levels with higher summer beach levels protecting the cliff toe, as is well demonstrated on the Holderness tills (Pringle, 1985). Cliff retreat rates on decadal timescales are well documented, although this has been predominantly in terms of cliff top retreat (Moses and Robinson, 2011; Section 3.1). More recently annual and seasonal cliff erosion dynamics have received increasing attention associated, in part, with noticeable changes in seasonal weather. Recent summer heat waves in the UK have sparked concern for a potential increase in frequency of summer rockfalls associated with higher rock temperatures (Ground Engineering, 2022, a, b). There is a particular research interest, therefore, in gaining a more detailed understanding of the influence of lithological, marine and subaerial factors on cliff retreat rates at annual and seasonal timescales.

Studies have focussed on collecting higher temporal and spatial resolution data and new applications of technologies and of mathematical analytical techniques. For example, using a team of volunteers to collect a 7-year database of rockfall location and volume over 37.5 km of Chalk cliffs in northern France, Letortu et al. (2014a, b) investigate the influence of triggering factors on location and volume of fall material. High rainfall was found to trigger massive rock falls, with material lost from across the whole cliff face, of 200 to 1400 $m^3$ and up to more than 10,000 $m^3$. Marine processes were found to trigger rockfalls predominantly located only at the cliff foot and of smaller volumes < 200 $m^3$. Similar findings are reported for interbedded claystone-sandstone cliffs in California (Young et al., 2021). Winter frost action triggered small debris falls, also < 200 $m^3$, either on the cliff top or cliff foot rather than from across the whole cliff face. Deciphering the mechanisms associated with these triggering factors, however, remains difficult in the absence of high resolution spatial and temporal data on lithological, meteorological and marine parameters (Letortu et al., 2015a). A further study at the same site, using repeat terrestrial laser scanning (TLS) surveys, every 4 to 5 months over a 3-year period, indicated that the key precursor for larger rockfalls is the formation of a notch at the base of the cliff (Letortu et al., 2015b). Whilst it has frequently been argued that notch development at the toe of the cliff is largely responsible for initiating rockfalls on jointed rock coasts (Hutchinson, 1971; Trenhaile and Byrne, 1986; Sunamura, 1992), evidence for this on the Chalk coasts of southern England and northern France has been sparse (Moses and Robinson, 2011). It is more common for the base of Chalk cliffs to project seawards as a ledge and some slight notching has been identified above the height of wave attack where it is related to subaerial weathering of weaker beds (Costa et al., 2004; Hénaff et al., 2006; Lageat et al., 2006). Based on field evidence, notching has been considered to be of secondary importance for Chalk cliff retreat where rock structure is held as the dominant control on the type and volume of rockfall with different types of failure attributed to different Chalk units (Mortimore et al., 2004a; Duperret et al., 2004). Models, however, suggest that as the depth of the notch increases the removal of support at the toe of the slope results in the development of a tension crack within the cliff (Hutchinson, 1971; Hoek and Bray, 1981; Styles et al., 2011). Hoek and Bray (1981) also model the critical depth that the notch must reach to trigger failure. However, where cliff toe notches develop, they are usually localised and any relationship between their depth and size of resulting rockfall has not been investigated in the field. Few studies quantify the rate of erosion at the toe of the slope, though Ellis (1986) measured a rate of 7.2 mm $yr^{-1}$ at Friar’s Bay, between Brighton and Newhaven in East Sussex, SE England, using the Micro Erosion Meter (MEM). A comparable figure, of up to 3.5 mm over a 6-month period, has been recorded at an adjacent site using Unmanned Aerial Vehicle (UAV) digital photogrammetry (Gillham et al., 2019), with authors noting that erosion at the toe of the slope is localised and highly variable. Mortimore et al. (2004a) have noted that notches are most commonly associated with harder chalks as they may be short-lived in softer rocks that collapse readily (Moses and Robinson, 2011; Trenhaile, 2015).

Other studies suggest that coastal cliffs behave in a similar manner to non-marine cliffs, as self-organising systems where precursory rockfalls are important for the development of large scale rockfalls. For example, on composite cliffs, of Jurassic limestones, shales and mudstones, capped by a sequence of Cretaceous sandstones and Quaternary glacial tills, in North Yorkshire, on the basis of 32 monthly TLS scans, Rosser et al. (2007) found no evidence of basal notching, limited seasonal control, limited control of wave action at the cliff toe, and limited environmental controls. The key finding, that large rockfalls were preceded by a series of smaller debris and rock falls, suggested that the frequency of the largest events could be estimated by analysis of the smaller events. The high spatial and temporal resolution of TLS survey data can facilitate such analyses. On a complex cliff consisting of three types of limestone at Marsden Bay, NE England, Westoby et al. (2020) have investigated this further. Cliff fall data, collected by monthly TLS survey over a 24-month period for a 0.6 km stretch of coast, were analysed to examine magnitude-frequency and power law scaling used to predict rockfalls. Over the survey period, precursory rockfalls accounted for approximately 80% of the total eroded volume but less than 50% of the erosion scars on the cliff face; erosion rates were higher in winter, associated with short-term increases in rainfall and wave activity from winter storms; varying sensitivity of the different limestones to environmental forcing was dependent on jointing patterns. The authors suggest that it may be possible, using power law scaling and high-resolution datasets, for coastal managers to predict rockfall occurrence from marine forecasts or real time offshore wave buoy data and wave transformation modelling. Gillham et al. (2019) have experimented with this, using power law scaling to predict rockfall activity in relation to significant wave height (Hs). Finding statistically significant correlations between Hs and power law scaling coefficients, they applied Monte Carlo simulations to predict erosion scenarios based on Hs probabilities and sea level forecasts derived from the UKCP09 medium emission climate model. They use these to estimate an ~ 11% chance that the A259 road, located 42.1 m behind a cliff, would be breached by coastal erosion by 2090. In this case the cliff erosion dataset was collected by UAV as it is cheaper and quicker than TLS. Even more rapid and cost-effective high resolution data collection is now possible using LiDAR-equipped smartphones (Luetzenburg, 2022; Tavani et al., 2022) and which are being tested for rapid assessment of cliff behaviour (Bessin et al., 2023).

To further investigate the role of marine processes in cliff retreat, a growing number of studies deploy seismometers, often combined with TLS surveys, to detect cliff micro-displacements in response to wave impact (Table 2). Usually, seismometers are emplaced at or close to the cliff top which means that ground movements are detected only as waves impact on the toe of the cliff and not as they travel across the platform where they are out of the instrument detection range. As waves move across the platform their energy is dissipated, as indicated by pressure sensor studies, with platform elevation and width being dominant controls on energy reaching the cliff toe (Ogawa et al., 2016). Tidal range also influences wave energy dissipation and in macro-tidal environments waves of < 2 m may travel unbroken across the platform at high tide (Stephenson et al., 2018). Although seismic studies indicate that vertical cliff-top ground motions increase with increasing significant wave height (Hs) and tidal elevation, this is mediated by cliff-platform junction elevation and beach gradient. For example, during winter storms Earlie et al. (2015, 2018) found that where Hs is < 2 m elevation of the cliff-platform junction is an important control on energy delivered to the cliff but where Hs is > 2 m, the beach gradient exerts more influence on energy delivery. Ground motions become more uniform along the coast at water depths of > 2 m, as may be associated with storms, at the foot of the cliff. Additionally, seismic studies indicate that the type of wave impact is more important than Hs with waves that break directly onto the cliff face delivering more energy than breaking or unbroken waves (Table 2).

Seismometers have also been deployed in a slightly different way to identify the timing of cliff falls and elucidate their trigger processes on the Maastrichtian Chalk cliffs, Jasmund peninsula, Rügen, Germany (Dietze et al., 2020; Table 2). This weakly cemented chalk has an annual cliff retreat rate of 25 cm yr$^{-1}$, comparable to the Cretaceous Chalk cliffs of SE England and N France. Of 81 failure events recorded, 65 occurred during a wet winter, 11 during a dry winter, and across the entire study period 50 occurred overnight between 8 pm and 8 am. Dietze et al. (2020) suggest that overnight accumulation of dew increases cliff water content, ultimately driving cliff retreat at this site. Other studies on the Cretaceous Chalk cliffs also identify water content of the cliffs as an important trigger for rockfalls, though usually associated with higher winter rainfall (Duperret et al., 2004; Moses and Robinson, 2011) rather than overnight fluctuations as identified by Dietze et al. (2020). Also, although the number of frost days have been linked with a greater occurrence of rockfalls of winter rockfalls (e.g. Hutchinson, 1971; Prémaillon et al., 2018) there are no direct field measurements on cliffs. Frost shattering on shore platforms has been measured, however, indicating that a minimum of 10 frost cycles below sea water freezing temperature (-2.5 $^{o}$C) are required and for durations of 2 – 3.5 hrs in order for rock breakdown to occur (Dewez et al., 2015). Field observations suggest that following a night of freezing, as temperatures rise in the morning a rain of debris is released from cliff faces (Mortimore et al., 2004a), indicating that frost action is superficial.

Despite the constant exposure of coastal cliffs to wave wash, splash and spray, salt weathering which, like freeze-thaw weathering, is a superficial weathering process has received little attention. More recent research, however, indicates that sea water may weaken chalk cliffs at depth (Lawrence et al., 2013, 2018). Salt weathering is usually associated with granular disintegration and surface spalling and flaking to create small scale surficial features such as alveoli, though larger scale tafone may also develop (Pye and Mottershead, 1995). To be effective it requires a salt supply and environmental conditions that cause evaporation or facilitate temperature fluctuations both of which are required for salt crystals to develop and grow. Rock breakdown occurs due to salt crystal growth, differential thermal expansion and hydration. Porous rocks are particularly susceptible to salt weathering (Robinson and Moses, 2011). Duperret et al. (2005) investigated the occurrence of salt weathering on the Chalk cliffs of Northern France, suggesting that it is mainly surficial because the thermal conditions within the chalk do not allow the salts to crystallise out of solution. However, solution of carbonate rocks may occur in sea water and chemical solution at depth in chalk, brine-saturated, oil reservoirs has been found to result in a reduction in rock strength (Heggheim et al. 2005). Seawater may further contribute to weakening chalk when magnesium ($Mg^{2+}$) and sulphate ($SO_4^{2-}$) from seawater concentrate in the rock. Sulphate may act as a catalyst for the substitution of calcium ($Ca^{2+}$) from the chalk by $Mg^{2+}$. When this dolomitization process occurs at grain boundaries, the different size of the $Mg^{2+}$ compared with $Ca^{2+}$ may cause stress and, consequently, a decrease in the mechanical strength of chalk (Austad et al., 2008; Nermoen et al., 2015; Minde and Hiorth, 2019).

This ‘salt water weakening’ has been investigated on the Cretaceous Chalk cliffs of East Sussex, SE England, where saturation by meteoric waters is already known to contribute to cliff retreat through a reduction in rock strength and thus also angle of friction in cliffs (Mortimore et al., 2004b). Lawrence et al. (2013) tested samples collected both from the cliff face, exposed to sea water saturation, and also from inland quarry sites unaffected by salt from seawater. On the coast, samples were collected from 2 different zones (i) in direct contact with the sea at high tide, (ii) not in direct contact with the sea but zone affected by waves, splash and spray. In addition, samples collected from the inland quarry were subjected to salt wetting-drying experimental cycles to assess the impact on rock strength. Triaxial strength testing indicated that samples that had experienced salt water saturation were up to 55% weaker than those that had not. The authors then investigated how far into the cliff face this salt water weakening effect extends (Lawrence et al., 2018). Three ~ 9 m long cores were extracted horizontally into the cliff at two contrasting sites, both in Newhaven Chalk: an engineered cliff protected by a sea wall and a natural cliff where the lower section is in contact with the sea at high tide. Cores were drilled using air flush to ensure that the pore water content and chemistry was not affected. Laboratory tests assessed the impact of salt water on chalk strength and extent to which any weakening effects penetrated the cliff. Chloride and sulphate concentrations provided a proxy for presence of sea water. The sea wall site had a sea water penetration depth of only 0.6 m whereas the natural cliff site showed sea water present up to and beyond 6 m depth into the cliff. Cores from both sites showed a decrease in rock strength at the cliff face, increasing with depth into the cliff and with the decline being greater at the natural cliff site. The authors note that there is not a straight correlation between Chalk weakening and salt content and that there are other processes that also weaken chalk close to the cliff face, including heterogeneity within the Chalk e.g. in relation to sedimentation, bioturbation, diagenesis and notch development and oversteepening of the cliff face. Nonetheless, the results demonstrate that chalk is weaker at the cliff face and for several metres into the cliff and the effect that this has on cliff stability merits consideration. That salt can penetrate to depths of more than 7 m into the cliff face has not previously been demonstrated or considered. Assessment of the mechanisms requires further investigation to identify whether any reductions in rock strength are greater in the presence of sea water compared with meteoric water.

Most recently, efforts are being made to shed further light on high-resolution spatial and temporal responses of cliffs to lithological, marine and subaerial parameters leading to cliff fatigue and cliff failure. Letortu et al. (2022) report results from the first 4 months of a 13-month continuous, multi-parameter monitoring programme on Cretaceous Chalk cliffs in northern France (Table 2). The study site, St Marguerete-sur-Mer, Normandy, has previously been monitored and there is general consensus that the main drivers of erosion are: lithological control (Costa et al., 2004); intense rainfall events (Duperret et al., 2004; Lageat et al., 2006; Letortu et al., 2015b) and marine factors (Letortu et al., 2015a, 2015b, 2019). Letortu et al. (2022) report some unexpected findings which analyses of the full 13-month dataset, yet to be published, may help to elucidate.

### 3.4 Foreshore: shore platform downwearing

Shore platforms may play a key role in influencing temporal variations in cliff retreat rates. For example, on cohesive clay shorelines in both coastal and lakeshore settings, it is generally agreed the primary control on the long-term rate of cliff retreat is the rate of lowering of the shore platform, and beach if present, fronting the cliff toe and the water level at the cliff toe (Moses and Robinson, 2021). Understanding shore platform downwearing is important, therefore, for a number of reasons: firstly, shore platforms are dynamic, and the level of the shore platform can determine the height of the platform-cliff junction, the level and behaviour of the beach and thus the extent to which wave action and associated spray impacts on and up the cliff face (e.g. Brew 2004, 2007); secondly, removal of sediment by platform downwearing not only leaves the cliff face more exposed but also removes weight from the toe of the slope and may therefore contribute to mass movement and retreat of the cliff (e.g. Hutchinson, 1973; Dixon and Bromhead, 2002); thirdly, weathering and erosion of the areas around engineering structures such as groynes and sea walls can reduce their engineering lifespan (e.g. Dornbusch et al., 2007; Dornbusch, 2010); fourthly, shore platforms provide sediment to the coastal sediment budget (e.g. Dornbusch et al., 2006; Payo et al., 2018; Moses and Robinson, 2021).

There is an ongoing ‘wave versus weathering’ debate, concerning the relative roles of marine and subaerial processes as the dominant processes in their formation (e.g. Dickson et al., 2013; Kennedy et al., 2011; Matsumoto et al., 2016, 2018; Stephenson and Kirk, 1998; Trenhaile, 2019, 2020; Trenhaile and Kanyaya, 2007). Present-day shore platforms may be inherited features that pre-date the relatively stable sea levels of the late Holocene over the last 2000 years (Regard, 2012; Thébaudeau et al., 2013; Moses, 2014). Because of the links between shore platforms and cliff retreat, understanding the key drivers for shore platform development is important in informing models of cliff retreat and their response to future climate change. Platform width is influenced by erosion rates of the cliffs at the inner edge relative to the outer, seaward edge of the platform. If the cliff retreat rate is greater than that of the outer platform edge, then the platform width may increase until waves no longer reach the cliff. This is known as static equilibrium, whereby the platform width remains constant but downwearing continues and so the platform slope declines. If cliff retreat rate equals the platform edge retreat, then platform width and gradient remain constant over time, known as dynamic equilibrium. Platform elevation, width, gradient and level of the cliff-platform junction are influenced by rock hardness and tidal range, and so can vary locally and regionally.. Rock structure, via discontinuities such as joints, fractures and bedding planes, influences platform morphology and the production of boulders and coarse debris. Boulders may be present on shore platforms and are derived either from cliff falls or platform erosion or a combination of the two (Moses, 2014).

A dominant area of research has involved measurement of shore platform downwearing rates, incorporating both subaerial weathering and marine erosion. These studies, reviewed in detail in Moses and Robinson (2011) and Moses (2014), provide insights into the role of lithology, annual and seasonal climatic variations and wave energy. The most intensively studied shore platforms in the British Isles are on Blue Lias limestone in south Wales and Cretaceous chalk in SE England, with a limited number of studies on other rock types. Platform downwearing rates vary according to lithology, with the most rapid downwearing on softer cohesive clays and the lowest rates on harder limestones: glacial till > London Clay > chalk > schist > limestone > basalt & granite (Table 3). It is also now well-established that there are variations in platform downwearing rates across platforms from the cliff toe to the platform seaward edge: upper > middle > lower (Moses, 2014). Higher rates of downwearing on the upper platform are associated with abrasion caused by beach material being drawn across the platform by wave action (Fig. 5e). Where the beach depth is greater than the layer mobilised by wave action (active layer) then it protects the platform from abrasion and this can often be seen as a ramp at the cliff-toe junction when it is revealed following storm activity. The upper platform is exposed to subaerial processes for the longest time period during the tidal cycle and so this means that subaerial weathering processes such as wetting-drying, salt weathering and frost weathering can operate effectively (Moses, 2014; Moses and Robinson, 2011, 2021). Similarly, these processes can operate effectively on the mid-platform whilst the lower platform has less opportunity to fully dry out between tides and is often covered with a thick layer of seaweed which may protect the platform surface from weathering and erosion (Coombes et al., 2013; Gowell et al., 2015). The presence of seaweeds on hard engineering structures may also protect them from weathering and erosion (Baxter et al., 2022).

The extent to which the presence of organisms may erode or protect shore platforms is debated. Bioerosion is associated with, for example, limpets and sea urchins which abrade the rock surface and bivalve molluscs that bore directly into the rock to depths of 10 to 20 cm (Trudgill 1987; Trudgill et al. 1987; Andrews & Williams 2000; Brew 2004, 2007; Naylor et al. 2012). Bivalve molluscs, known as piddocks, such as *Pholas dactylus* and *Hiatella arctica*, occur most frequently on the lower shore where densities of more than 700 individuals per square metre to depths of 15 cm have been recorded on cohesive clay platforms (Brew et al., 2004, 2007). On the middle to upper shore platform, other organisms, such as Mud Shrimp and limpets may contribute to downwearing. For example, on the cohesive clay shore platform at Warden Point, Kent, SE England, high densities of Mud Shrimp, which were recorded up to depths of 1 cm on the upper platform, are considered to have contributed to higher rates of platform downwearing. Their role, however, was not so visible on the glacial till platform, at Easington, Yorkshire, NE England, where the upper part of the platform is frequently covered by sand bars preventing colonisation (Brew, 2004). The middle part of the platform, on chalk for example, often has a high density of limpets where their grazing and abrasion of the rock surface may contribute as much as 35% of platform downwearing (Andrews and Williams, 2000). Although, as is noted above, the presence of a dense cover of seaweed may protect the lower platform from weathering and erosion this may not be the case where the coverage is of lower density. Low density seaweed cover may contribute to platform downwearing via a whiplash effect whereby fronds sweep over and abrade the platform surface as they are agitated by wave action (Trudgill, 1985, 1988). The relative roles of organisms in protecting or eroding shore platforms and their contribution to seasonal, annual and longer term downwearing remains an area of discussion. Seasonal variations in shore platform downwearing rates are generally higher in the winter than in the summer, usually attributed to frost weathering and wave-driven abrasion rather than any biological processes (Moses and Robinson, 2011; Moses, 2014).

Elevation of the shore platform, and height of sediments accumulated on it, relative to mean sea level (msl) is an important control on cliff toe erosion. If the elevation is above msl then waves will not directly impact the toe of the cliff, even at high tide, though wave splash and spray may do so. If platform elevation is at or below msl then waves may, depending on the depth of beach material, reach the toe of the cliff directly causing erosion and saturating the toe area (e.g. Hutchinson, 1973). Even if waves are prevented from reaching the toe of the cliff by the presence of beach material, saturation may still occur due to fluctuations in the water level within the beach (Duperret et al., 2005). Variations in platform elevation and the level of the cliff-platform junction have been related to geology, tidal range, exposure to wave action and, locally, protection by deep beach or rockfall sediment (Moses, 2014).

Until recently, understanding of shore platform dynamics has been informed largely through direct measurement of downwearing rates combined with field survey. Shore platform downwearing rates have typically been measured directly, at discrete points on the platform, usually no more than 30-50 $cm^2$ area using an MEM, Laser Scanner or Traversing Erosion Beam. Aerial coverage is achieved by arranging the sites in a transect across the platform and duplicating measurement sites. Usually, however, the total measurement area remains relatively small because of time constraints for recording measurements within the tidal range. Details of the measurement methods and a discussion of their relative merits is provided in Moses et al. (2014). Although they have the advantage of providing directly measured rates, these are usually measured over short timescales of 1 to 3 years. Also, these instruments measure surface downwearing at a micro-scale of millimetres and so cannot record meso-scale downwearing caused by the removal of individual beds. This has previously been addressed using photogrammetry combined with Differential Global Positioning Systems (DGPS) survey. For example, Dornbusch and Robinson (2011) measured step backwearing by block removal over a 28-year period on chalk shore platforms in Sussex, SE England. When averaged across the platform, the downwearing rate of 0.6 to 5 mm $yr^{-1}$ is comparable to rates measured directly using the MEM (Moses, 2014). Although quantifying shore platform downearing rates from aerial photographs using photogrammetry facilitates coverage over larger areas and longer, decadal, time scales it can be difficult to identify suitable fixed points for analysis meaning that the accuracy decreases across the platform from upper (more accurate) to lower (less accurate; Dornbusch et al., 2008a). Dornbusch and Robinson (2011) address this discrepancy by also including detailed field survey data in the calculation.

The accuracy of measuring longer term shore platform downwearing over decades has been improved by combining historical aerial photographs with contemporary UAV photo-mosaics, analysed using Structure-from-Motion (SfM) photogrammetry. This method enables downwearing rates to be calculated on decadal timescales and across 100s of m of platform. For example, Buchanan et al. (2020) cover an area of platform 500 m alongshore and 200 m across shore, measuring downwearing over a 78-year period on Blue Lias limestone, Glamorgan, Wales. In addition to calculating an overall average platform downwearing rate, this method also facilitates calculation of annual and seasonal changes and identifies areas of intense erosion associated with the backwearing of individual beds. The rates, 1.25 – 5.3 mm yr$^{-1}$, are a similar order of magnitude but higher than those measured using only the MEM or laser scanner at the same site (0.042 ± 0.005–0.196 mm yr$^{-1}$; Swantesson et al., 2006) and on the Carboniferous limestone platforms of nearby Gower (0.033 ± 0.009 mm yr$^{-1}$, Shakesby and Walsh, 1986). This is most likely because meso and macro scale erosion is included in the calculation, which is also averaged over a much longer time period and area of platform when compared with direct measurement methods. SfM photogrammetry has also been used at a more local scale to measure the amount of erosion caused by boulder movement impact across platforms during individual storm events (Cullen & Bourke, 2018). Swirad et al. (2019) use SfM to investigate shore platform downwearing on Jurassic shale and sandstone platform in N Yorkshire, NE England. Measurements were recorded over 15 sites, each 0.5 x 0.5 m, across the platform measured 13 times over a one-year period from April 2016 to April 2017. The mean erosion rate of 0.528 mm yr$^{-1}$ is lower than the average of 3.21 ± 4.76 mm yr$^{-1}$ measured by Robinson (1977a, b) at the same site using the MEM but shows the same cross-platform variations being higher closer to the cliff and also where the duration of tidal inundation is highest. In contrast, on mudstone and limestone platforms of the Kaikoura Peninsula, New Zealand, downwearing rates calculated using SfM are much higher (10.299 mm yr$^{-1}$) than those measured at the same site using the MEM (2.244 mm $yr^{-1}$; Omidiji et al., 2023). The authors further refine the SfM method to discern micro- and macro-scale down downwearing rates, both of which are higher than MEM-measured rates. These higher values are attributed to the inclusion of intense granular disintegration, flaking, micro- and polygonal cracking and biological activities which are better captured using SfM than MEM.

Even more extensive areas of platform can be measured from satellite imagery. Mider at al. (2020) have measured platform downwearing along a 30 km stretch of coast, for a 3.5-year period, on the Cretaceous Chalk of East Sussex, SE England. They utilise Persistent Scatterer Interferometry to assess Synthetic Aperture Radar (SAR) data acquired by Sentinel-1 SAR satellite. Using radar images has the advantage, over aerial photography, that radar waves can penetrate most clouds. Interferometric Synthetic Aperture Radar (InSAR) techniques can provide reliable ground surface measurements over relatively long time periods with millimetre precision. Although it has been used by geologists to measure ground movement since the 1990s, this is its first application to the measurement of shore platform downwearing. Interestingly on this softer lithology, the published average of 0.36 mm $yr^{-1}$, across the study area (Mider et al., 2020) is ~ an order of magnitude lower than the average from studies at the same field sites where it was measured directly using the MEM (1.5, Foote et al., 2006, to 3.5 mm $yr^{-1}$, Ellis, 1986). This may be due to the relatively coarse spatial resolution of SAR data which, at 30 m, can capture seawall, beach and platform together and so does not always exclusively measure platform lowering. It may also partly be a function of the methodology. Satellite Altimetry provides net ground surface movement over time and so must also consider net vertical ground motion (VGM) when quantifying surface erosion. East Sussex VGM is 1.363 mm $yr^{-1}$ (Yuan et al., 2022). The corrected figure of 1.7 mm $yr^{-1}$ is comparable to MEM-measured rates for the same sites. Whilst it merits further investigation, this new application of InSAR has enabled a comparison of downwearing rates on platforms in front of natural, unprotected, cliffs (2.5 mm $yr^{-1}$) with those protected by hard engineering structures (1.7 mm $yr^{-1}$), and also comparison of downwearing rates on individual units of Chalk with different strength properties (weaker, Seaford Chalk, 2.02 mm $yr^{-1}$; stronger, Lewes Nodular Chalk, 1.98 mm $yr^{-1}$; all figures from Mider et al., 2020, corrected for VGM).

The new application of InSAR to the study of shore platform erosion dynamics may address a particular knowledge gap, namely information on seasonal-annual timeframes over hundreds of metres to kilometre scale, which is considered potentially critical in understanding the future evolution of rock coasts and their response to climate change (Kennedy et al., 2017). Also critical to this is the vexatious issue of understanding how shore platform width and gradient change over time (Stephenson, 2001). This is important for modelling longer term cliff retreat rates, to inform modelling approaches dependant on whether platform width increases or remains constant as cliffs retreat, resulting in static and dynamic equilibrium respectively (Trenhaile, 2020). A variety of methods have been used to assess changes in platform width over time including tidal elevation, the distance between mean high and mean low water lines (for example, derived from historical maps, LiDAR profile and DGPS survey, Dornbusch et al., 2008b), morphology, sedimentology, biology and wave processes (Kennedy, 2015). More accurate delimitation of platform width can be facilitated with increasing availability and use of seamless terrestrial and marine topographic, LiDAR and bathymetric, datasets in which mapping is not limited by physical access (Kennedy, 2015).

## 4. Rock coast geo model resilience, risk and vulnerability

Understanding coastal risk, resilience and vulnerability informs decisions taken by planners and policy makers (Blanco et al., 2019; Moore and McInnes, 2021). From a management perspective, in comparison to unconsolidated sediment beaches that may recover following an erosion event (e.g. Brooks et al., 2017), rock coasts cannot be restored once they are eroded (Sunamura, 1992; Blanco et al., 2019). Unlike salt marshes, that can respond dynamically to sea level rise adjusting their elevation by sedimentation and biogenic growth, rock coasts can only respond by erosion and the redistribution of sediment along and offshore (Naylor et al., 2010). Erosion management efforts on rock coasts therefore focus on mitigating the risk of erosion, for example by maintaining beach volumes (Moses and Williams, 2008) or by installing sea defences, reprofiling, draining and slope stabilisation measures (Moore et al., 2016; Palmer, 2002; Windle et al., 2015). The resilience of the rock coast geo model depends on its ability to withstand major disruption, as defined by Aven (2011), caused for example by high rainfall or high wave energy associated with winter storms, and to recover within an acceptable time. Softer rock coasts, with higher cliff retreat rates, may therefore be considered to have lower resilience. Although harder rock coasts are usually considered to be resilient, they have more limited capacity for a dynamic response to climate change pressures (Naylor et al., 2010).

Where rock coasts are densely populated, as is the case in many parts of the UK coast particularly in SE England, understanding their resilience to climate change is important for effective coastal management. In some cases, this has been approached by assessing the future risk of cliff collapse using probabilistic approaches. Such studies are usually site specific and require there to be a good understanding of the scale or magnitude of the cliff erosion hazard (e.g. Mortimore et al., 2004a), a database of historical frequency statistics (e.g. Lee 2011, 2016), or high resolution cliff erosion datasets (e.g. Rosser et al., 2007; Gilham et al., 2019; Westoby et al., 2020) and where quantitative data are not available, an expert judgement of the likelihood of occurrence (Fookes et al., 2007). In addition, such assessments are concerned chiefly with lithological and process controls without considering social and economic parameters. To address this, there is a growing interest in the use of coastal vulnerability indices that incorporate physical, social and economic parameters and can be mapped at local, regional and national scales using GIS. The earliest coastal vulnerability index (CVI), which was developed primarily for use in the US, used only physical parameters, including geology, geomorphology, elevation, shoreline change rate, wave and tide regime and sea level rise (Gornitz and Kanciruk, 1989; Gornitz, 1990, 1991) before social and economic factors were incorporated (Gornitz et al., 1991; Gornitz and White, 1992; Gornitz et al., 1994). Although Pethick and Crooks (2000) use an entirely geomorphology-based approach in their consideration of UK coastal vulnerability, others include geology, geomorphology and the degree to which the coast is exposed to wave action. For example, regional coastal slope, geomorphology, mean tidal range, relative sea-level rise, wave height and shoreline change, aspect and cliff type are used to calculate and map coastal vulnerability for parts of the coastline of Ireland in Counties Wicklow and Dublin (Caloca-Casado, 2018; GSI 2023). For the coast of mainland Great Britain, the British Geological Survey (BGS) has produced a database of a range of geological and geomorphological properties that influence coastal vulnerability, including geology, geomorphology, behaviour and coastal context e.g. shape, profile, height. Analysis of key variables and combinations of data available within the BGS GeoCoast product include lithology, cliff strength, backshore buffer and geomorphology (BGS GeoCoast, 2023). For the coast of Northern Ireland, coastal vulnerability has been assessed and mapped by combining data on coastal characteristics, coastal forcing and the principal socio-economic elements for which coastal erosion poses a threat (McLaughlin et al., 2002; McLaughlin and Cooper, 2010; Table 4). The measurement and mapping of coastal vulnerability provides important information for policy makers of the underlying causes and potential for ameliorating vulnerability (Pethick and Crooks, 2000), assisting national level assessments on the basis of which resource allocation is often prioritised. The further application of the index at regional and local scales may facilitate the identification of setback lines or hazard zones to control planning, to identify infrastructure at risk and inform development or management plans (McLaughlin and Cooper, 2010). At a European level, EMODnet Geology data products visualise coastal migration data from both field and satellite data and coastal type, including lithology and geomorphology. These products can be used to identify areas of coastal retreat associated with eroding rock coasts, alongside other coastal types. A new product integrates data on coastal resilience and vulnerability from scientific papers and published/unpublished government reports providing the first pan-European assessment of coastal vulnerability (EMODnet Geology, 2023; Moses et al., 2024). All data products are available on the EMODnet Map Viewer in the catalogue for EMODnet Geology, Coastal Behaviour (https://emodnet.ec.europa.eu/geoviewer/).

## 5. Rock coast geo model and climate change

The purpose of this chapter has been to review, from a predominantly UK and N European perspective, current understanding of rock coast erosion dynamics and response to climate change as viewed through the Fookes geo model. Recent research developments informing understanding of process-response and impacts of climate change are highlighted. The geo model is readily applied to categorise and quantify ground conditions in relation to the key components, cliffs and foreshore, providing the foundation of site investigation (Fookes, 1997; Fookes et al., 2000, 2001, 2007, 2015). With improving data availability, it may also be extended to nearshore and offshore environments for offshore and coastal infrastructure projects (Section 1). In addition to lithology the geo model integrates geomorphology, facilitating description and analyses of dynamic process-response mechanisms and rates in a site investigation (Brunsden, 2002; Griffiths and Stokes, 2008; Griffiths, 2014; Hearn, 2021; Moore et al., 2016; Sellwood et al., 2000). It provides a valuable means of communicating that information and its relevance to engineering priorities, identified as a priority for geoengineering and environmental management (Griffiths and Culshaw, 2004; Griffiths and Lee, 2022). The use of the geo model also forms the basis for quantifying risk, resilience and vulnerability and establishing the degree of uncertainty that exists in the interpretation of ground conditions (Griffiths and Stokes, 2008). The value of the geo model is dependent on the level of detail that is built into it in relation to the different parameters associated with geological, geometrical, atmospheric and oceanic controls (Fig. 1; Griffiths and Stokes, 2008). This chapter highlights some of recent research advances that not only enhance the level of detail that can be built into geo models but also raise further questions and identify gaps in our understanding of the rock coast geo model and its response to climate change.

Predictions of the response of rock coasts to climate change and RSLR are informed by understanding of present and past responses to marine and subaerial controls. Although the climate response is complicated by a range of factors, it is recognised that increased rainfall, water levels and wave energy associated with storms drive higher rates of cliff retreat dependent on the frequency of storm occurrence (Section 3.1, 3.3). Although sea level rise, particularly increasing rates of RSLR, is generally expected to increase rates of cliff retreat (Section 3.2), it is also recognised that this may not be the case and that the future behaviour of cliffs may differ from their historical patterns of change (Lee, 2002; Lee and Clark, 2002; Shadrick et al., 2022). It is possible that rapid RSLR level rise may reduce rates of cliff retreat – deeper water levels and less subaerial exposure of foreshores may reduce shore platform downwearing rates through reduced abrasion and weathering, and if waves remain unbroken then the delivery of wave energy to the cliff toe will be reduced (Section 3.3, 3.4). Higher sea levels will, though, assist in raising ground water levels within the cliff mass and increase the vertical extent of wetting of the cliff face both of which reduce rock mass strength rendering the cliff more susceptible to mass movements (Section 3.3). Numerical, geometric and process-based, models that are used to simulate rock coast behaviour under future climate scenarios are underpinned by the understanding that cliffs and shore platforms are linked sub-systems (Section 3.2). Although understanding of the modes, mechanisms and rates of cliff retreat and shore platform downwearing is continually improving, establishing a clear quantitative link between the two remains elusive: firstly, models often focus on retreat at the toe of the cliff, assuming that the cliff top retreat rate is a reflection of this; secondly, studies of historical cliff retreat focus on the cliff top rather than the toe and there are very few measurements of cliff toe retreat, so the relationship between the two remains to be tested; thirdly cliff retreat and shore platform downwearing are measured on different temporal and spatial scales making it difficult to relate the two; fourthly, measurements of shore platform downwearing remain incomplete relying predominantly on short term, micro-scale measurements. The use of InSAR, as discussed in Section 3.4, presents an important opportunity to address this knowledge gap. It has been used to date to separately measure shore platform downwearing (Mider et al., 2020) and coastal landslide ground movement (O'Connor et al., 2021). Combining both cliffs and shore platforms over tens of kilometres and several decades to quantify concurrent rates of retreat and downwearing respectively would provide new insights into quantitative links between the two to inform simulation model development and validation. Meanwhile the increasing volume of high-resolution data from the application of a range of techniques, including S-f-M photogrammetry, LiDAR, UAV, seismic sensors, alongside InSAR and other more traditional data collection methods continues to improve the level of detail that can be captured in the geo model. Combined with robust analytical methods and the expert judgement espoused by Fookes and others, rock coast geo model ground conditions, risk, resilience and vulnerability and potential future responses climate change are increasingly better captured to inform engineering projects, policy and planning.

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**Figure Captions**

Figure 1. Key components of the rock coast geo model.

Figure 2. Location and geology of study sites, UK, Ireland, N. France.

Figure 3. Cliff and shore platform characteristics.

Figure 4. Meso- and micro-morphologies typical of platforms formed in well jointed and bedded sedimentary rocks.

Figure 5. Visual evidence of platform erosion.

Figure 6. Schematic representation of expected ‘humped’ relationship between distance from the cliff and $^{10}$Be concentration, assuming equilibrium retreat of the cliff-platform system (after Hurst et al., 2016).

**Table Captions**

Table 1. Cliff retreat and sea level rise

a) decadal scale recent and historic cliff retreat rates
b) millennial scale Holocene and historic cliff retreat rates

Table 2. Cliff response to marine processes: insights from seismograph studies.

Table 3. Summary of shore platform downwearing rates for the British Isles.

Table 4. Coastal characteristics, coastal forcing and socio-economic parameters commonly used in the assessment of coastal vulnerability.

| **Recent rates relative to historic rates** | **Lithology** | **Location** | **Key drivers** | **Data sources** | **Total yrs** | **Authors and notes** |
|---|---|---|---|---|---|---|
| Decreasing | Cretaceous Chalk | East Sussex | Reduction in beach width<br>Increase in shore platform width | 1st edition map; 1973 air photos; 2005 Lidar survery; 2006 beach survey | 130 | Dornbusch et al. (2008b)<br>1873-1925/28: 0.37 m/yr<br>1925/28-1973: 0.35 m/yr<br>1973-2001: 0.27 m/yr |
| Increasing | Cretaceous Chalk | Northern France | Sediment starvation: large rockfalls with long residence time + harbour breakwaters & groynes | Historical maps; air photos | 300 | Prêcheur (1960)<br>300 yrs: 0.08 – 0.8 m/yr<br>Henaff et al. (2002)<br>1824-1986: 0.05 – 0.07 m/yr<br>1947-1995: 0.14 m/yr<br>Costa et al. (2003, 2006)<br>1966-1995: 0.21 m/yr<br>Costa et al. (2004)<br>1966-1995 0.26 m/yr |
| Increasing | Glacial till | Yorkshire | Sea defences<br>Sea level rise<br>Beach levels<br>18.6 yr nodal tidal cycle | Historical maps; direct measurements; biannual beach surveys | 160<br>50 | Pye & Blott (2015)<br>Epoch 1: 1852-1908<br>Epoch 2: 1908-1951<br>Epoch 3: 1951-1989<br>Epoch 4: 1989-2013<br>Retreat rate in Epoch 4 > other Epochs on undefended sections.<br>Lee (2011)<br>Early 1950s: 1.2 m/yr<br>2000: 1.5 m/yr |
| Decreasing | London Clay | Kent | Historic human interference (beach | Historical maps; field survey; | 131 | Nicholls et al. (2000)<br>1867-1897 : 3.29 ± 0.33 |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  |  | levels)<br>Occurrence of large rotational slumps with long residence time | dGPS survey |  | m/yr<br>1897-1998 : 1.67 ± 0.1 m/yr<br>Hutchinson (1965, 1968), Bromhead (1979), Dixon & Bromhead (2002)<br>Air photos and field survey |
| Increasing | Composite (Pliocene + early-mid Pleistocene marine deposits overlying Palaeogene and Cretaceous basement) | Suffolk | Higher rainfall and surges associated with positive phases of the NAO<br>Complex interaction of<br>• met-ocean forcing,<br>• inherited geological and geomorphological controls,<br>• Evolving anthropogenic intervention | Historical maps; air photos; EA annual beach survey; dGPS survey; geomorphological mapping | 127 | Brooks et al. (2012)<br>1883 -2010: 3.49 ± 0.4 m/yr<br>1993-2010: 4.66 ± 0.55 m/yr<br>Burningham and French (2017)<br>Cluster-based segmentation of shoreline, graphically indicating shoreline change, 1881-2015; 1990-2015. |

**Table 1a**

| Cliff retreat rate (cm/yr) | | Lithology | Location | Modelling approach | Authors |
|---|---|---|---|---|---|
| Holocene | Historic (measurement period, yrs) | | | | |
| 2 – 6 | 22-32 (150) | Cretaceous Chalk | East Sussex, SE England | Steady state geometric model | Hurst et al., 2016 |
| 5 – 9 | 10-18 (29) | Cretaceous Chalk | Normandy, NW France | Steady state geometric model | Duguet et al., 2021 |
| 11-13 | 15 (45) | Cretaceous Chalk | Normandy, NW France | Steady state geometric model | Regard et al., 2012 |
| 6 – 18 (2000 y BP)<br>15 – 110 (7000 y BP) | 22 – 40 (130) | Cretaceous Chalk | East Sussex and Kent, SE England | Morphodynamic process-based model | Shadrick et al., 2023a |
| 4.5 ± 0.63 | 2.7 ± 2.9 (7) | Jurassic shale & sandstone | Yorkshire, NE England | Steady state geometric model | Swirad et al., 2020 |
| 7.5 – 17.5 (2400 y BP)<br>25 – 100 (7000 y BP) | 2 – 25 (130) | Carboniferous and Jurassic sandstone | Devon, SW England; Yorkshire, NE England | Morphodynamic process-based model | Shadrick et al., 2021, 2022 |

**Table 1b**

| Key findings | Site location and geology | Monitoring techniques | Monitoring period | Authors |
|---|---|---|---|---|
| - Vertical cliff-top ground motions increase with increasing Hs and tidal elevation<br>- Peak seismic activity:<br>high tide; wind direction aligned with max fetch<br>- Secondary peak: when waves reach ramp | Staithes, north Yorkshire, UK<br><br>interbedded mudstones, shale, siltstone, ironstone, and sandstone, are capped with glacial till | 4.5-Hz integrated seismic system triaxial geophone installed at top of cliff; LIDAR (airborne, at each low tide) + TLS (monthly) surveys | 8 months (September – April, year not specified) | Lim et al., 2011 |
| - Episodic displacements associated with extreme wave conditions cause failure (time lag)<br>- Displacements under normal conditions unlikely to weaken rock mass | | Güralp 6TD broadband seismometer installed at top of cliff; weather data (rainfall, atmospheric pressure, wind direction and wind velocity), tidal data (predicted tidal height and observed tidal residual), oceanographic data (significant wave height and peak wave period). | 2 x 16-day periods, summer (July 2009) and winter (November-December 2009) | Brain et al., 2014 |
| - Under storm conditions ground motions become more uniform along the coast (where > 2 m water depth)<br>- Ground motions higher on headlands than bays<br>- Platform width, elevation and topography dominant control on delivery of wave energy to cliff | | 7 x Güralp 6TD broadband seismometer installed at ~ 100 m intervals, 10 m inland from cliff edge; weather and oceanographic data as above | 8 months (December 2013 -July 2014) | Jones et al., 2018 |
| - Type of wave impact more important than Hs: energy of waves breaking directly on cliff face > breaking/unbroken | Del Mar, California, USA<br>Sandy claystone, | Nanometrics Compact Trillium broadband seismometer, installed at top of cliff; high | 45 minutes (March 2016) | Thompson et al., 2019, |

| | | | | |
|---|---|---|---|---|
| | sandstone, overlain by Pleistocene terrace deposits.<br>Onaero Bay, Taranaki, New Zealand<br>Sandstone, mudstone overlain by Quaternary deposits | resolution video to record impact time of each wave.<br>As above + Geospace Technologies HS-1-LT geophone, water pressure transducer installed at cliff toe, offshore wave data, tidal level data | <br>30 days (December 2017 -January 2018) | 2022 |
| - Failure events occurred most frequently overnight and during a wetter winter.<br>- Water content most important: (i) subsurface flow towards the cliff, (ii) rain directly onto the cliff, (iii) condensation of water vapour onto the cliffs at night.<br>- Marine, wind and frost processes negligible. | Jasmund peninsula, Rügen, Germany.<br>Weakly cemented Maastrichtian chalk. | Nanometrics Trillium Compact 120-s seismometers and PE6/B 4.5-Hz geophones, installed at 4 cliff-top sites along 7 km + 10 UAV surveys, weather, sea level and groundwater data. 81 failure events recorded. | 25 months (March 2017 – April 2019) | Dietze et al., 2020 |
| - Thermal amplitude greatest at cliff top (rockfalls caused by frost weathering most likely to develop preferentially at top of cliff)<br>- Cliff top ground motion: displacement up to 50 μm (in line with previous studies but considered high for the relatively calm wave conditions and due to elasticity of the chalk.<br>- Significant cliff face displacements usually during spring tides (time lag > 1 day from highest tide to maximum | St Marguerete-sur-Mer, Normandy<br>Upper Cretaceous Chalk, partly overlain with 10-15 m thick clay and sand Palaeogene deposits | 44 sensors of 9 different types installed to measure:<br>- Cliff mechanical response (seismometers, geophones, extensometers, fibre optic);<br>- Marine forcing (pressure sensors, video camera);<br>- Subaerial forcing (weather station, temperature sensors, fibre optic devices, piezometer).<br>+ TLS topographic surveys (3-monthly); 1 x Ground | 13 months (November 2018 – January 2020) | Letortu et al., 2022 |

| | | | | |
|---|---|---|---|---|
| displacement)<br>- Cliff top displacement strongly linked with Hs<br>- Most favourable conditions for displacement = medium Hs, low wind speed, high water level, high tide coefficient, low rainfall, medium temperature (recorded extension displacement on existing fractures).<br>- Least favourable conditions for displacement = high Hs, high wind speed, high water level, medium tide coefficient, high rainfall, high temperature (recorded contraction displacement on existing fractures) contrary to what is expected. | | penetrating radar (GPR) and 1 x Electrical Resistivity Tomography (ERT) survey to assess chalk homogeneity and internal structure and properties). | | |

**Table 2**

| Lithology | Rate (mm/yr) | Measurement period (yrs) | Measurement method |
|---|---|---|---|
| Glacial till | 42 | 1 | TEB |
| London Clay | 18 | 10 | TEB |
| Chalk | 4 | 2 - 28 | MEM, laser scanner, photogrammetry |
| Schist | 1 | 1 | MEM |
| Limestone | 0.05 | 1 | MEM, laser scanner |
| Basalt & granite | < 0.05 | NA* | MEM |

**Table 3**

| Sub-index | Variable | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Coastal characteristics | Shoreline type | High cliff > 40 m | Medium cliff; 20 to < 40 m | Low cliff; 10 to < 20 m | Shingle ridge or bar | Shingle beach or dune |
| | Rivers | absent | | | | present |
| | Solid geology | Plutonic<br>Volcanic (lava)<br>High–medium grade metamorphics | Low-grade metamorphics; sandstone and conglomerate well cemented | Most sedimentary rocks | Coarse and/or poorly sorted unconsolidated sediments | Fine unconsolidated sediment, volcanic ash |
| | Drift geology | Bedrock<br>Urban | Till or boulder clay | | Raised beach deposits | Alluvium<br>Blown sand<br>Peat<br>Glacial sands and gravels<br>Glacial outwash sands<br>Recent marine |
| | Elevation | > 30 m | 20 to < 30 m | 10 to < 20 m | 5 to < 10 m | < 5 m |
| | Orientation | Not relevant | | Easterly | | Northerly |
| | Inland buffer (m from MHW) | 500 to 1000 m inland | | | | 0 to < 500 m inland |
| Coastal forcing | Significant wave height | 0 to <0.74 N<br>0 to <0.24 E | 0.74 to <1.49 N<br>0.24 to <0.48 E | 1.49 to <2.23 N<br>0.48 to <0.72 E | 2.23 to <2.98 N<br>0.72 to <0.96 E | >2.98 N<br>>0.96 E |
| | Tidal range (m) | > 5 | 3.5 to <5 | 2 to <3.5 | 1 to <2 | <1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Difference in modal and storm waves (m) | <0.10 N<br><0.10 S | 0.10 to <1.70 N<br>0.10 to <0.25 S | 1.70 to <3.30 N<br>0.25 to <0.40 S | 3.30 to <4.90 N<br>0.40 to <0.55 S | >4.9 N<br>>0.55 S |
| | Frequency of onshore storms (%) | 0 to <2.8 | 2.8 to <5.6 | 5.6 to <8.4 | 8.4 to <11.2 | >11.2 |
| Socioeconomic | Settlement | No settlement | Village | Small town | Large town | City |
| | Cultural heritage | Absent | | | | Present |
| | Roads | Absent | | A class | | Motorway<br>Dual carriageway |
| | Railways | Absent | | | | present |
| | Land use | Water bodies<br>Marsh/bog and moor<br>Sparsely vegetated areas<br>Bare rocks | Natural grasslands<br>Coastal areas | Forest | Agriculture | Urban and industrial<br>Infrastructure |
| | Conservation designation | Absent | | International | | National |

**Table 4**

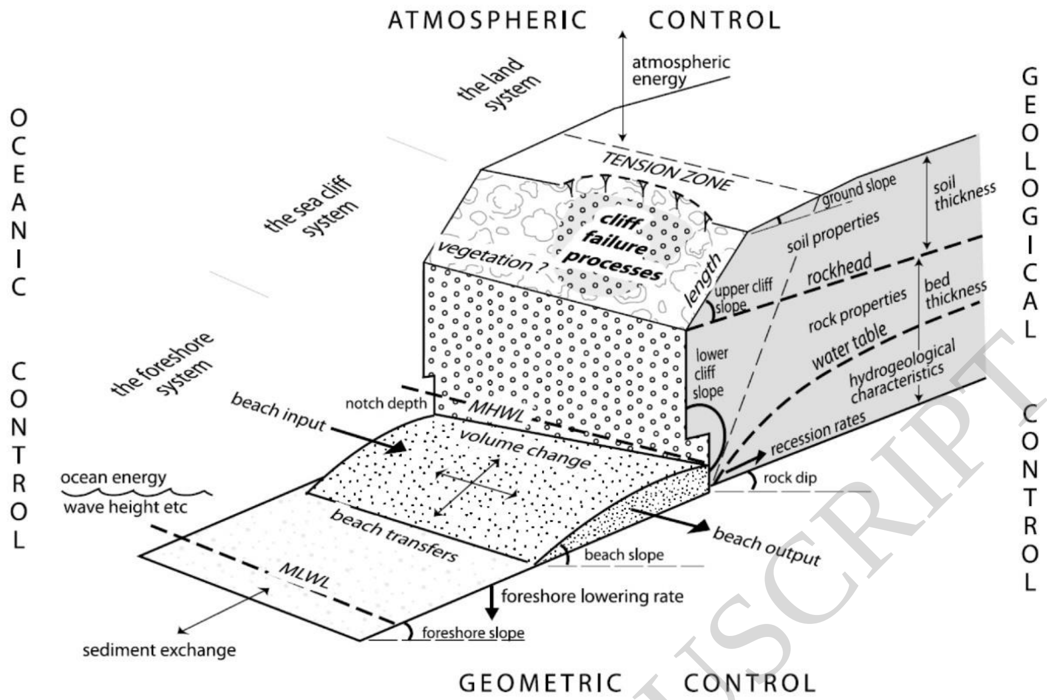
ATMOSPHERIC CONTROL
atmospheric energy
the land system
OCEANIC CONTROL
GEOLOGICAL CONTROL
TENSION ZONE
the sea cliff system
cliff failure processes
vegetation ?
length
ground slope
soil thickness
soil properties
rockhead
upper cliff slope
rock properties
bed thickness
water table
lower cliff slope
hydrogeological characteristics
the foreshore system
notch depth
beach input
MHWL
volume change
recession rates
rock dip
ocean energy
wave height etc
beach transfers
beach output
beach slope
MLWL
foreshore lowering rate
foreshore slope
sediment exchange
GEOMETRIC CONTROL

**Figure 1**

1. South Tyneside, NE England, Magnesian Limestone
2. Yorkshire, NE England, Jurassic sandstone and shale, glacial till
3. Norfolk, E England, glacial till
4. Suffolk, E England, composite Pleistocene, Plioecene, Palaeogene and Cretaceous deposits
5. Isle of Sheppey, Kent, SE England, London Clay
6. Kent and East Sussex, SE England, Cretaceous Chalk
7. Normandy, N France, Cretaceous Chalk
8. Glamorgan, S Wales, Carboniferous limestone
9. North Devon, SW England, Carboniferous sandstone
10. Burren, Co. Clare, W Ireland, Carboniferous limestone

**Figure 2**

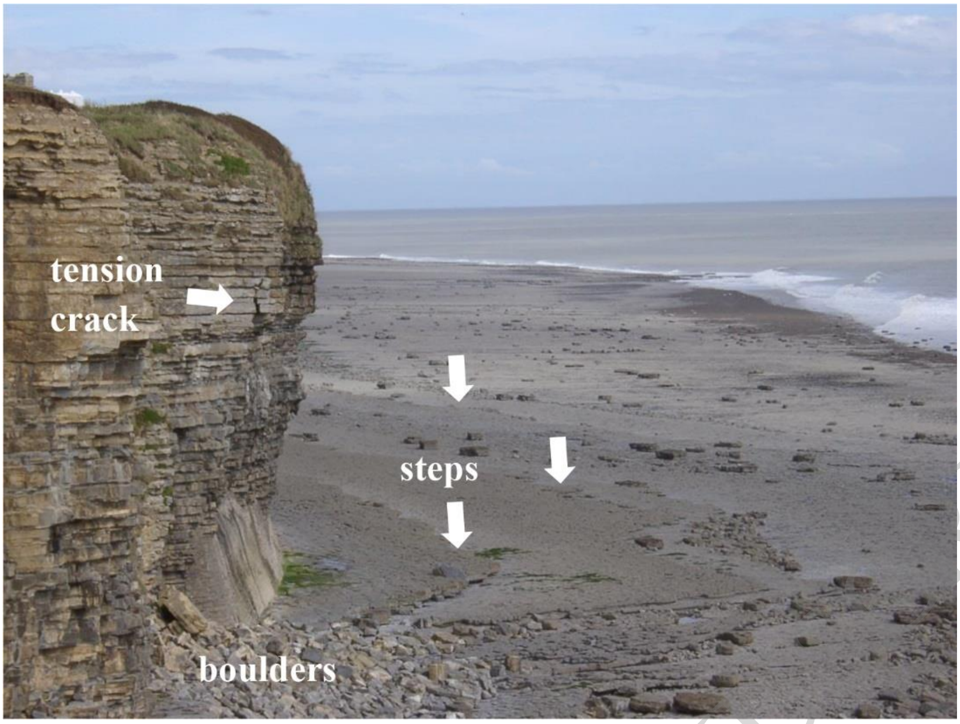

Figure 3a

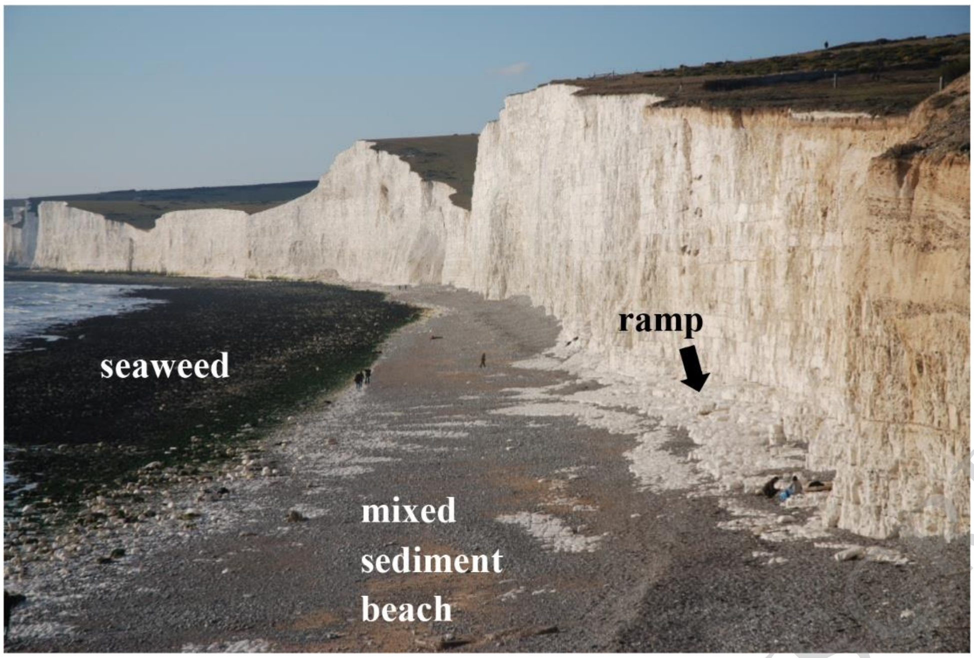

Figure 3b

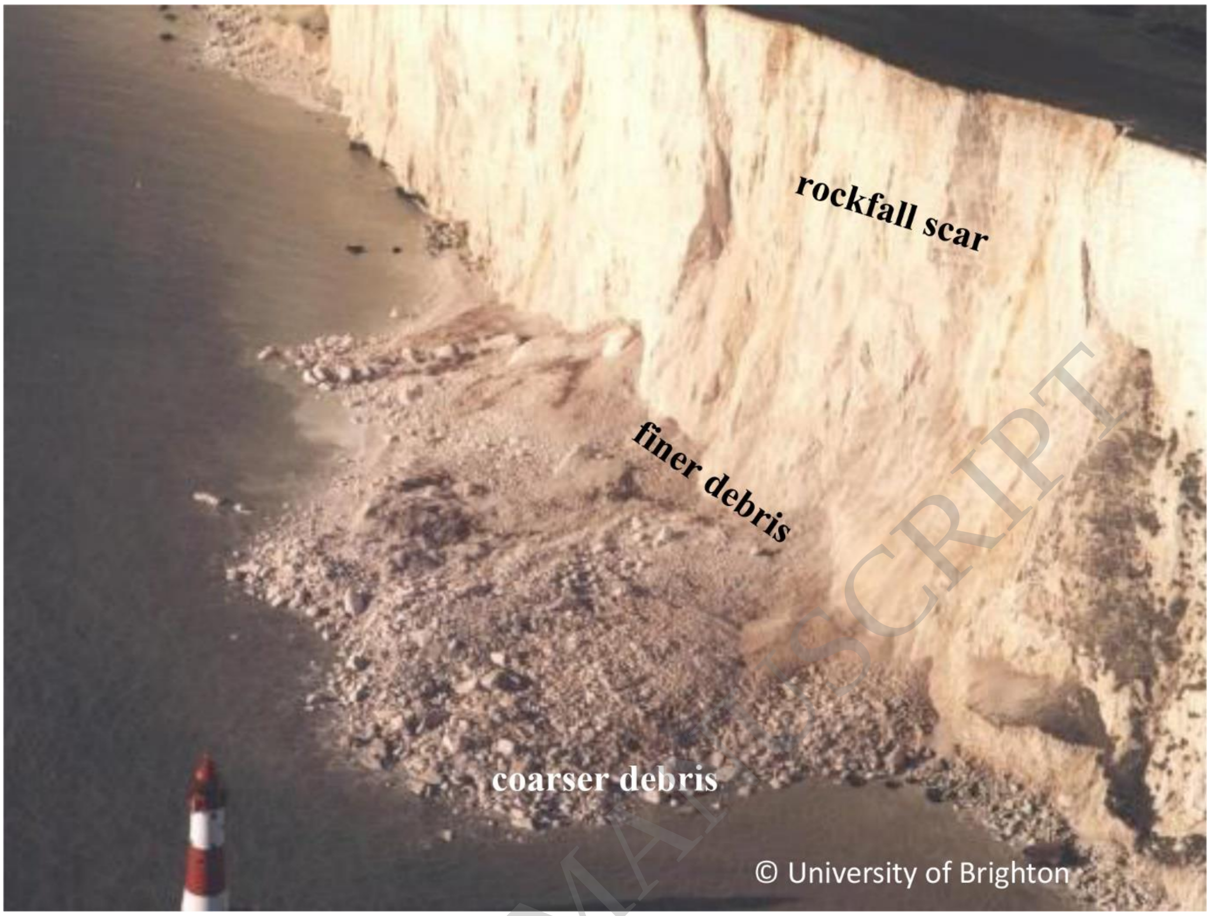
rockfall scar
finer debris
coarser debris
© University of Brighton

Figure 3c

©Port of London Authority (Maynard & Bromhead, 2015)

Figure 3d

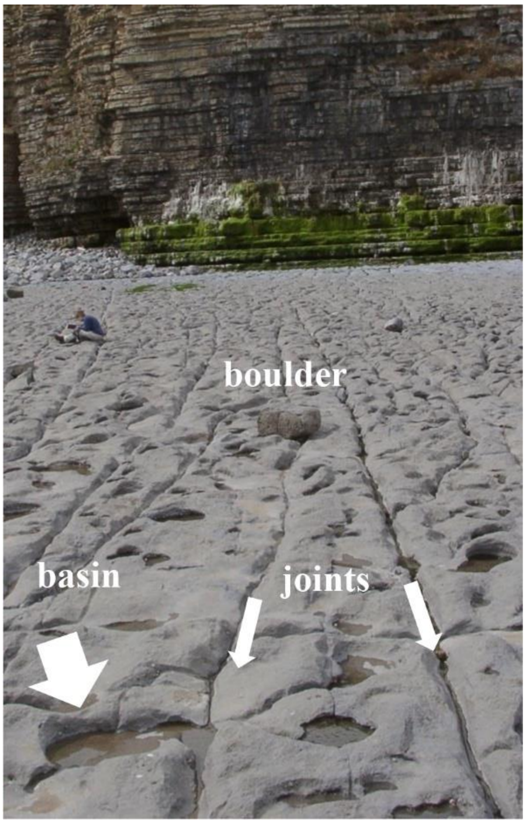

Figure 4a

Figure 4b

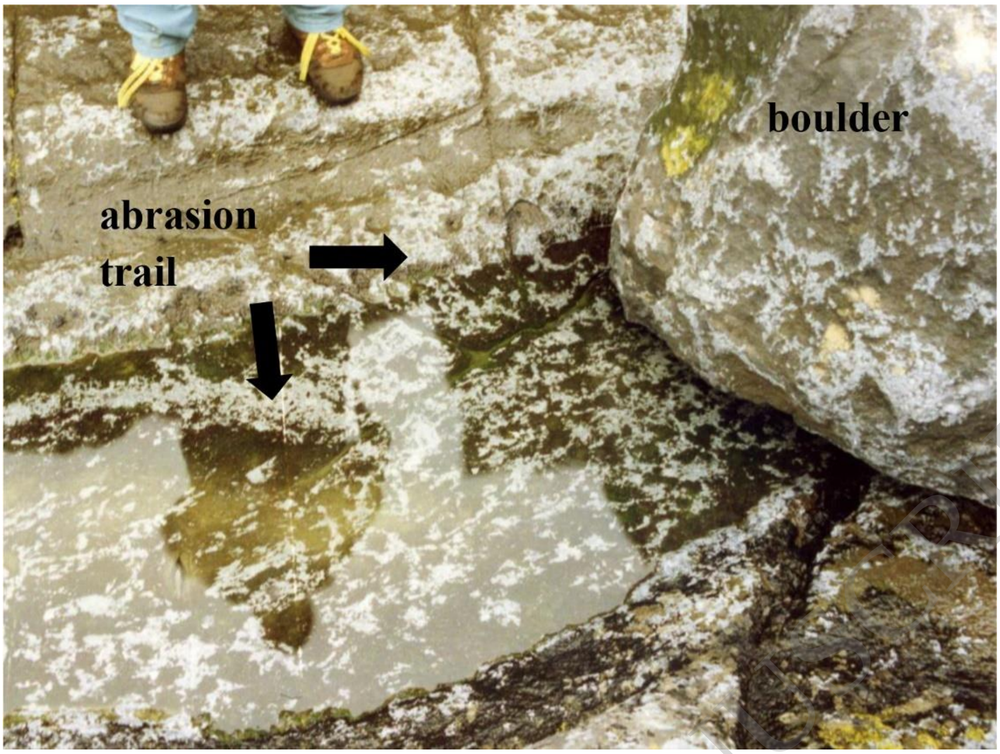

**Figure 4c**

**Figure 5a**

**Figure 5b**

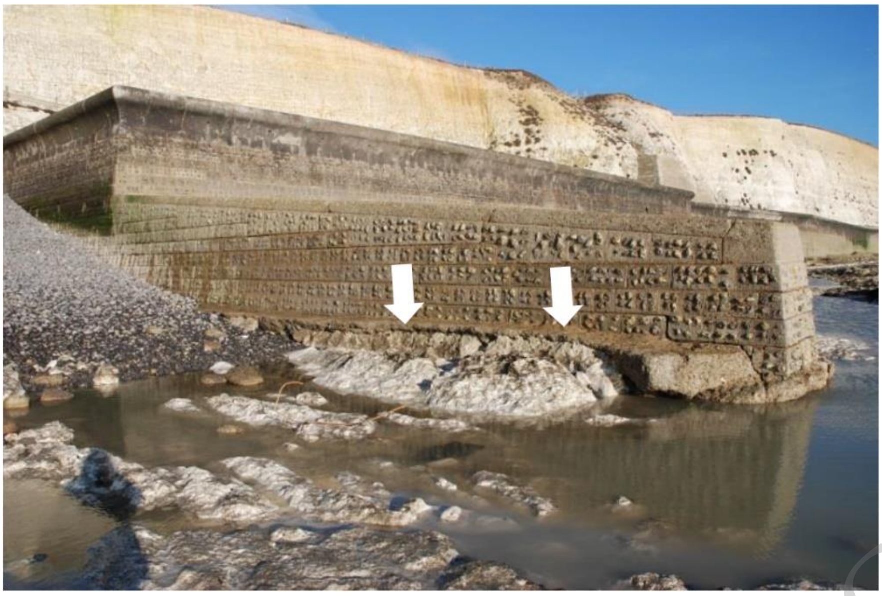

**Figure 5c**

**Figure 5d**

Figure 5e

**Figure 5f**

**Figure 5g**

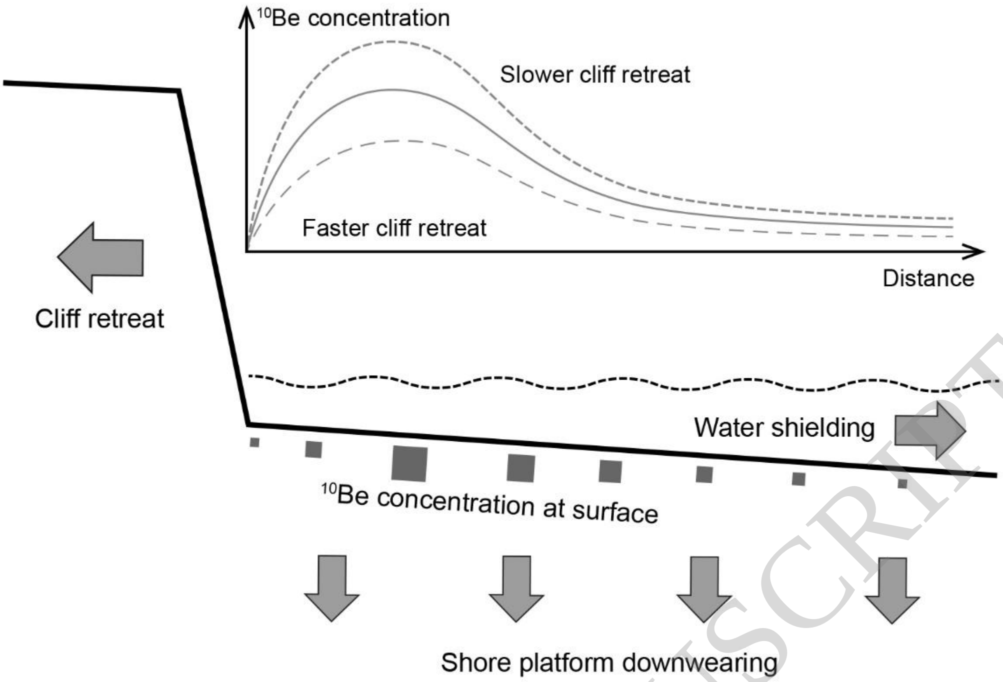
$^{10}$Be concentration
Slower cliff retreat
Faster cliff retreat
Distance
Cliff retreat
Water shielding
$^{10}$Be concentration at surface
Shore platform downwearing

**Figure 6**