Weathering and Biogenic Processes on Rock Coasts in the British Isles

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Abstract: An abundance of moisture, salts and organic life make rock coasts a unique weathering environment. Here, mechanical and chemical processes act to break down rocks alongside the influence of waves, tides and geological factors. Organisms concurrently break down (bioweathering and bioerosion) and protect (bioprotection) coastal rocks in direct and indirect ways, enhancing or impeding other inorganic modes of decay. Some species also build physical structures (bioconstruction) that have geomorphological and ecological consequences.

Studies of particular weathering processes are well represented in the British Isles, and demonstrate the overriding controls of lithology and tidal position. The complexities arising from the interactive and combined influences of different processes are also evident. Biogenic processes are of greatest importance for the geomorphology of carbonate rock coasts and cohesive shores in Britain and Ireland, but weathering is largely secondary to waves in the evolution of harder rock coasts. The importance of typically fine-scale rock decay in facilitating larger-scale erosion is recognised, however, but warrants more attention, and the value of interdisciplinary and applied weathering research on rock coasts is stressed.

Keywords: weathering, rock breakdown, British Isles, bioerosion, bioweathering, bioprotection, bioconstruction

Mechanical, chemical and biological processes act to break down rock *in situ*, altering material properties and behaviours, producing sediment, and preparing materials for erosion and transport. Weathering science is concerned with the dynamics of these processes, their spatial and temporal controls, the geomorphological features that result, and their significance for landform and landscape evolution (Yatsu 1988; Robinson and Williams 1994; Robinson and Moses 2011). The efficiency and relative importance of rock breakdown for geomorphology varies in time and space depending on the physical and chemical properties of the rocks involved, and the environmental conditions to which they are exposed. Rock weathering creates micro-scale surface morphologies (sub-millimetre) and contributes to the development of meso-scale landforms (millimetres to meters) and – over longer periods of time – landscapes (meters to kilometres) (Viles 2001; Turkington *et al.* 2005). The critical importance of environmental factors in rock breakdown (particularly temperature and moisture regimes) means that different environments have characteristic weathering geomorphologies, including the coastal zone (Mottershead in press). Here, workers have considered the influence of key variables such as lithology and tidal position on weathering processes, and their relative importance in rock coast systems more generally under varying conditions of wave exposure and climate (Trenhaile 1987; Trenhaile 2011).

This chapter gives an illustrative overview of weathering processes and their controls on rocky coasts, both in the intertidal and supratidal zones, focusing specifically on examples from the British Isles (England, Scotland, Wales and Ireland). The intention is to review the range of rock breakdown mechanisms in this environment, and in doing so identify the particular nature of their operation in the British Isles. As well as mechanical and chemical modes of breakdown, specific attention is given to the roles of organisms in the direct (active) and indirect (passive) destruction and protection of coastal rocks. As weathering is the primary focus, processes of marine erosion are not given specific attention, but see Trenhaile 2011 and Stephenson *et al.* in press for recent discussions of marine processes, and Chapters 2.1.1 and 2.1.2 in this volume for examples from the British Isles. Similarities and differences in the nature and style of weathering between locations in the British Isles are identified where possible, and scale linkages between weathering and landform components of the rock coast system (i.e. platforms and cliffs) are also considered. Some synthesis and future directions for research are presented in the final sections. Where appropriate, weathering of hard materials used in coastal engineering (i.e. quarried rock and concrete) is discussed alongside ‘natural’ *in situ* rock, as this has much to contribute to our understanding of rock breakdown in the coastal environment.

Coastal Weathering in the British Isles

The remarkable geological variability of the British Isles gives rise to a rich diversity of coastal processes and landscapes (see May and Hansom 2003, and Chapter 7 of Bird 2010 for a review of coastal landscapes in the British Isles). Pioneering geomorphological research on rock coasts in Britain was concerned with establishing relationships between morphometric parameters such as the width, gradient, and elevation of shore platforms, and boundary conditions of wave climate and tidal range (see Trenhaile 1974a; Trenhaile 1974b; Trenhaile 1980). Over the last 30 years or so, more has been done to identify and measure particular breakdown processes that may, at least partly, influence landform-scale interactions on rock coasts in Britain and Ireland (see 'Cross-scalar Linkages'). The distribution of studies specifically on weathering, however, remains largely defined by the activities of a few individuals (Table 1). Often being undertaken as part of broader studies on the morphodynamics and vulnerability of rock cliffs and shore platforms (reviewed in Chapter 2.1.1 and Chapter 2.1.2, respectively), nationally and internationally important work on weathering exists for the Liassic limestones and shales of South Wales, the Jurassic rocks of North East England, the Cretaceous chalk of southern England, the Carboniferous sandstones and schists of south-west and southern England, and the Carboniferous limestones of North West Ireland (Table 1).

Measuring Weathering on Rock Coasts

Although weathering remains generally understudied at the coast (Naylor *et al.* 2010; Trenhaile 2011), a range of methods and approaches have been used to characterise and quantify rock breakdown. By far the most common approach to deriving rates of change is to measure relative change in rock surface elevation through time. The micro-erosion meter (MEM) and traversing micro-erosion meter (TMEM) have been widely employed for this purpose on shore platforms and supratidal rocks (see review by Stephenson and Finlayson 2009), including in Britain (e.g. Robinson 1976; Robinson 1977c; Robinson 1977b; Shakesby and Walsh 1986; Mottershead 1989). Rates derived using these methods on rock coasts in the British Isles are reviewed in Chapters 2.1.1 and 2.1.2. Laser scanners can also be used to measure rates of surface change with higher measurement resolution and accuracy (e.g. Swantesson *et al.* 2006). Measurement of change in surface elevation relative to a known datum has similarly been used to derive weathering rates in England (e.g. Mottershead 1997; Mottershead 2000; Mottershead *et al.* 2003).

Rates of rock surface lowering as measured using these methods (often termed 'downwearing' on rocky shores) represent the removal of material and as such are typically reported in terms of erosion rather than weathering (Williams *et al.* 2000; Stephenson and Finlayson 2009). Some inferences can be made, however, about the decay processes operating based on the spatial and temporal nature of the erosion data collected (Trenhaile 2011). Differences and changes in the porosity, hardness and strength of rocks also provide direct evidence of *in situ* deterioration (e.g. Stephenson and Kirk 2000b; Blanco-Chao *et al.* 2007; Chelli *et al.* 2010) and the influences of these sorts of changes on the behaviour of rocks under coastal conditions can also be observed (e.g. Coombes and Naylor 2012). Measuring textural change at the rock surface is another useful way to infer the nature, rate and relative efficiency of different breakdown processes on coastal rocks (e.g. Williams *et al.*

2000; Gómez-Pujol *et al.* 2006) as is the presence of distinctive weathering morphologies such as tafoni and honeycombs (see ‘salt crystallisation’ and ‘Chemical Breakdown’).

Another valuable approach for assessing the efficiency of – and susceptibility of different lithologies to – particular modes of breakdown involves placing materials in the field for the specific purpose of monitoring decay (e.g. Robinson and Jerwood 1987a; Moses *et al.* 2006; Coombes *et al.* 2011) and using rock blocks in laboratory simulations (see Goudie 2000 and Moses 2000 for reviews). The advantage of rock exposure blocks is that they can be removed from the field for examination after a known period of time, enabling rates to be more easily derived and subsequent laboratory tests to be carried out. Microscopy techniques such as scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD) have proved particularly useful for observing coastal weathering artefacts at the micro-scale (e.g. McGreevy 1985; Naylor and Viles 2002; Coombes *et al.* 2011) (see Fig. 3 for examples). However, a challenge for weathering geomorphologists is how to upscale microscopic observations to the landform and landscape scale (Taylor and Viles 2000; Viles 2001; Viles 2012). A multi-method and multi-scale approach combining field and laboratory measurements of rock surface lowering, surface morphology, and rock properties and behaviours, coupled with microscope observations perhaps offers the greatest potential for advancing understanding of the complex roles of weathering in rock coast systems.

Weathering Processes

Rock breakdown processes at the coast are typically categorised according to the overriding mechanism of operation, whether mechanical, chemical or biological (Mottershead in press; Fig. 1). While such a categorisation can be misleading given the undoubted interaction of these processes in the field (see Hall *et al.* 2012 for a recent critical discussion of weathering nomenclature), this nevertheless serves as a useful framework within which particular processes can be discussed and compared, and is as such adopted here. Inorganic decay (mechanical and chemical) is discussed first, and the involvement of organisms in the direct and indirect breakdown of coastal rocks is then explored alongside their protective and constructive roles.

Two important points are stressed from the outset. First, different lithologies are more or less susceptible to particular modes of breakdown than others; porous chalk, and argillaceous shales and mudstones are prone to breakdown in association with the absorption of water for example, while the mineral composition of other rock types is more conducive to chemical and biologically-mediated modification. Equally, the structural geology of some coastlines makes them more predisposed to erosion by waves, although weathering can have a facilitative role in this context (see ‘Cross-scalar Linkages’). Rock properties and geological setting are therefore paramount in the following discussions.

Secondly, it is important to recognise that particular processes (whether mechanical or chemical, and involving organisms or not) operate synergistically to varying degrees, and it is their interacting and cumulative influence (the 'total weathering' outcome *cf.* Hall *et al*. 2012) that is of greatest relevance for geomorphology (e.g. Fig. 2). 'Water-layer weathering' is mentioned separately here as a term often applied to the combined action of several of the processes discussed below including solution, hydration and dilation, oxidation, and salt crystallisation, which act to lower and smooth rocks in areas of standing water on rocky shore platforms (Trenhaile 1980; Trenhaile 2011; Stephenson *et al.* in press).

Mechanical Breakdown

Wetting and drying (slaking)

Repeated wetting of rocks by tides and rain, and drying upon exposure to the air, wind and insolation, causes expansion and contraction of minerals (e.g. Fig. 3a). This acts to progressively weaken rock cement and widen discontinuities in shales, mudstones and other argillaceous rocks (Trenhaile 1987; Yatsu 1988). Identifying the operation of wetting and drying in isolation of salts and thermal influences is not easy in the tidal zone, but this has been attempted in the field and in the laboratory (e.g. Stephenson *et al.* 2004; Kanyaya and Trenhaile 2005; Trenhaile 2006; Porter and Trenhaile 2007). Primary controls on the efficiency of wetting and drying as a breakdown mechanism are rock composition and porosity, and the wetting and drying regime involved as determined by moisture availability, temperature and tidal position (Trenhaile 2006; Sumner and Loubser 2008).

In the British Isles, slaking is most efficient in summer, when drying between successive tides can occur more quickly and to a greater degree. Rates of lowering on intertidal shales in Yorkshire, North East England, are significantly higher during the summer months (May to October) and on areas of rock platforms that dry out fully compared to areas that remain damp (Robinson 1977a). Here, tidal wetting and drying causes bedding laminae to crack into polygons, liberating fragments of shale from the surface that can then be removed by waves. Lower rates of downwearing on these shores during stormier winter periods suggest that slaking in summer is an important mechanism of decay in the middle and lower intertidal zones. On cohesive London Clay platforms on the Isle of Sheppey, Kent, average rates of lowering on the upper to lower mid-shore are in the order of 15 mm per year (Moses *et al.* 2010). Here, slower rates of downwearing have also been recorded during autumn and winter months (Charman *et al.* 2007), but the overall trend is for faster lowering during the stormier winter period compared to summer (Moses *et al.* 2010).

In contrast to argillaceous rocks, wetting and drying alone is less important for the breakdown of other lithologies (e.g. Kanyaya and Trenhaile 2005), particularly under a temperate climate. In laboratory experiments examining the decay of rocks forming intertidal platforms in Europe, limestone showed little evidence of deterioration after 40 wetting–drying cycles and chalk lost around 1% mass (Moses 2002; Moses *et al.* 2006). In other laboratory tests, swelling and shrinking of argillite and basalt by up to 0.14 mm and 0.04 mm, respectively, is attributed to wetting and drying in the absence of salts (Trenhaile 2006). In the field, swelling of limestone and mudstone by several millimetres on rocky shores in Australasia is attributed at least in-part to tidal wetting and drying alongside salt crystallisation and possible biological influences (Stephenson and Kirk 2001; Stephenson *et al.* 2004; Gómez-Pujol *et al.* 2007) (also see Chapters 4.1 and 4.2). In comparison, swelling of shale in the order of 0.3 mm per year has been reported for platforms in North East England (Robinson 1977a). Comparable swelling (up to 0.4 mm) has been measured on chalk platforms in southern England, but the overall trend here was surface lowering over a three year period (Foote *et al.* 2006). In Britain, Mottershead (1989) measured episodic swelling of supratidal greenschists in the order of 0–0.1 mm in south Devon over monthly, seasonal and annual timescales. This was attributed to the desiccation of the rock during dry weather, and possibly during frosts, rather than swelling during wet periods. These observations may be more indicative of the importance of salt crystallisation over hydration for the expansion of rocks in this zone.

Warming and cooling (thermoclasty)

As well as having a critical influence on chemical weathering, biogenic processes, and other mechanical decay mechanisms such as salt crystallisation, thermal regimes can instigate the breakdown rock via the expansion and contraction of minerals in response to temperature. The development of thermal gradients within rock masses and thermally-induced inter-grain stresses in granular rocks are important for decay alongside temperature fluctuations at the rock–air interface (e.g. Warke *et al.* 1996; Gómez-Heras *et al.* 2006). Both high-magnitude, rapid changes in rock temperature (‘thermal shock’) and the cumulative effect of repeated lower-magnitude fluctuations (‘thermal fatigue’) can act to weaken rocks making them more susceptible to other decay processes (Yatsu 1988; Mottershead in press).

In the coastal zone, temperature appears to be positively correlated to the swelling and shrinking of rocks, at least in the absence of rain (e.g. Hemmingsen *et al.* 2007). In South Wales, expansion and contraction of coastal limestone and mudstone during periods of dry, warm weather is recognised as an important mechanism of decay (Williams and Davies 1987) and breakdown rates of supratidal greenschist show a positive correlation with summertime air temperatures in southern England (Mottershead 1989). Such relationships may represent enhanced salt weathering during warmer weather alongside any thermoclastic effects. In southwest England, frequent temperature variations in the order of several degrees occur on rock platforms over a timescale of 15–30 minutes, attributed to wind patterns and interruptions to insolation by passing cloud (Coombes 2011b). Such thermal cycling probably contributes to the progressive weakening of coastal rocks to some degree, particularly in association with tidal wetting and drying, and is most pronounced during summer. In the laboratory, granular breakdown of limestone, granite, and concrete has been observed over a timescale of months under simulated intertidal conditions using a temperate summertime thermal regime (Coombes 2011a). However, rock breakdown in response to temperate thermal cycling in isolation of salts and wetting–drying remains to be evaluated. In North West England, spatial variation in the rate of sandstone weathering is partly attributed to thermal differences between aspects, but this is complicated by the co-occurring influence of temperature on chemical and biological processes (Mottershead *et al.* 2003). In general, very little has been done to directly assess these complex interactions on temperate shores.

In comparison with fatigue effects, thermal shock may be most relevant in very hot and cold climates where rock surfaces can experience high magnitude changes in temperature over diurnal and shorter cycles (Yatsu 1988; Sumner *et al.* 2004). Very rapid, high-magnitude temperature changes do occur on British shores, however, when rock surfaces heated by the sun are cooled by tidal water. In North East England, heating of dark slates during summer at low tide, and rapid cooling by incoming tidal waters, is thought to instigate the detachment of rock fragments (Robinson 1977a, 1977c). In Cornwall, platform slates have been found to cool by as much as 15 °C in a matter of minutes following tidal inundation, when low tide coincides with warm, sunny weather (Coombes 2011b; Fig. 4). Thermal changes of this magnitude far exceed the 2 °C per min commonly quoted as the threshold for thermoclasty, but this has never been directly examined as a breakdown mechanism on rocky shores. The magnitude of tidally-induced thermal cycling can, however, be expected to vary depending on factors such as shore position, rock type, the timing of the tides, and the season. These variables control the period of time rocks are exposed to insolation, the intensity of insolation, the rates at which rocks heat up and cool down, and the temperature of seawater acting to cool the surface. Porosity is also an important factor influencing rock thermal behaviour, as porous rocks absorb more water when submerged and retain more moisture when exposed to the air and insolation. This enables surface cooling via evaporation, which can occur for a greater proportion of time compared to less porous, quick-drying rocks (Coombes and Naylor 2012). Importantly, these relationships are enhanced or depressed by other material properties such as albedo and thermal capacity, as well as by organisms (see ‘Biogenic Processes’).

Frost weathering (cryoclasty)

Internal pressures created by the volumetric expansion of water and the growth of ice crystals in rock pores, fissures, and cracks during ice lens development can cause the fracturing, scaling, granular disintegration, and catastrophic decay of rock (Matsuoka and Murton 2008). The nature and rate of rock breakdown by frost and ice is largely governed by the freezing regime involved (i.e. how quickly ice forms and how many cycles of freezing occur) and the physical properties of the rock such as porosity and strength (e.g. Nicholson and Nicholson 2000) (also see Chapter 5 of this volume).

In the British Isles, intense periods of freezing weather are generally rare at the coast, and as such the relative geomorphological importance of frost and ice in our current climate is much less than at lower latitudes and higher altitudes (e.g. Trenhaile and Rudakas 1981; Trenhaile and Mercan 1984; Porter *et al.* 2010). Infrequent but intense periods of frost have nevertheless been linked to the breakdown of porous rocks in England. Harris and Ralph (1980) report the breakdown of consolidated London Clay to a depth of 300 mm during the harsh winter of 1962/1963, and Williams and Robinson (1981) recorded considerable damage on chalk platforms in southern England during the same winter; porous rocks such as chalk are particularly susceptible to frost weathering as liquid water can enter the rock prior to freezing (Williams 1980).

Robinson and Jerwood (1987a) have described the artefacts of frost weathering on chalk coasts in England, observing cracking and spalling at a scale of tens of centimetres. Small protruding areas of rock are most affected, as they cool more quickly, removing surface irregularities and wearing back steps on platforms. Laboratory experiments have shown that the breakdown of chalk by frost is most effective under upper-shore conditions, as rocks here are exposed to longer and more frequent periods of freezing compared to lower shore levels (Robinson and Jerwood 1987b). In a freeze-thaw experiment involving 40 cycles of 6 hours of freezing (at –10 °C) and 6 hours of thawing (at +5 °C), blocks of chalk and limestone from quarries in East Sussex and South Wales lost around 2.5% and 4.5% mass, respectively, via spalling and fracturing at their edges (Moses 2002; Moses *et al.* 2006). In the field, higher rates of downwearing on chalk platforms in England during winter compared to summer may be partly attributable to frost alongside the influence of higher-energy waves at this time of year (Foote *et al.* 2006). While frost weathering can be enhanced in the presence of salts, particularly halite (Goudie 1974; Williams and Robinson 1981; Williams and Robinson 2001), there is some conflicting evidence for this (e.g. McGreevy 1982). The rate and temperature at which ice forms in rock are suppressed by salts, so that extended periods of exposure to freezing conditions, of around five to six hours, are required for frost weathering to be effective on chalk platforms (Robinson and Jerwood 1987a).

With the exception of periods of unusual cold such as those described above, the contribution of frost and ice to contemporary rock coast evolution in the British Isles is probably limited, especially on for lithologies other than chalk. However, freeze-thaw over annual timescales, frost shattering, and ice-wedging of larger slabs of rock would have been effective geomorphological processes during past periods of colder climate, and are thus relevant for inherited coastal landscapes in Britain. Past periods of more intense frost and ice weathering would have contributed to the development of what are now raised coastal rock platforms in Scotland (e.g. Gray 1974; Gray 1978; Sissons 1981; Dawson *et al.* 1987) and Ireland (e.g. Stephens 1956). Rates of weathering by frost on the chalk cliffs and platforms in southern England are also thought to have been greater during past cold periods such as the Little Ice Age (Williams 1980; Robinson and Moses 2011).

Salt crystallisation (haloclasty)

The potential for haloclastic breakdown of rock is high in the coastal zone given the abundance of mobile salts in solution and in the air. The growth of salt crystals from solution in pores and cracks can exert pressures capable of gradually weakening and breaking off fragments of rock, and the expansion of salt crystals during their hydration and warming can exacerbate this process (Goudie *et al.* 1970; Goudie 1974; Cooke 1979; Goudie and Viles 1997; Goudie 1999). A long history of laboratory-based simulation in weathering science has demonstrated the effectiveness of these – and other – mechanisms of breakdown (see Goudie 2000 for a review) along with the complex co-influence of the nature of the salt solution, temperature and drying regimes, rock type, porosity and microporosity, and the degree of rock saturation (e.g. Davison 1986; Rodriguez-Navarro and Doehne 1999; Yu and Oguchi 2009). In comparison, the influence of these factors on the efficiency of rock decay in the field has been more rarely explored (e.g. Trenhaile and Mercan 1984).

In the British Isles, the frequency at which salt crystallisation occurs within coastal rocks is probably less than in warmer climates, at least in the intertidal zone where surfaces are repeatedly wetted by semidiurnal tides (Trenhaile 1987). Greater biological cover in the intertidal zone also limits the frequency at which rocks become sufficiently dry for crystallisation to occur (see 'Bioprotection'). Salts that are less abundant in seawater but which have low solubility, such as sodium sulphate, may therefore be more involved in coastal rock weathering in temperate environments given that they tend to crystallise out of solution first, so that complete drying of the rock is not always necessary (McGreevy 1985; Goudie and Viles 1997). In south Devon, higher rates of greenschist decay in the supratidal zone occur in the summer (averaging 0.625 mm per year), attributed to the crystallisation and thermal expansion of halite (Mottershead 1989). In contrast, weathering can be most effective on rocks that are continually moist and shaded from direct solar insolation (Mottershead 1997), indicating the importance of chemically-based salt decay. Salt efflorescences (white crystalline deposits on rocks) form on platforms in northern England during summer (Robinson 1977a) and on the slates, shales, granites, and limestones of south west England around pools and within crevices when low tide coincides with warm weather (pers. obs.). However, surface efflorescences are less significant for rock decay than crystallisation with the rock structure, observation of which necessarily requires laboratory investigation.

Experimentally, relatively few rock weathering studies have used salt solutions representative of seawater or – recognising the critical importance of temperature on crystallisation – thermal regimes that adequately replicate conditions in the British Isles. Exceptions include a study by Mottershead (1982), which demonstrated the efficiency of haloclasty in the breakdown of greenschist under supratidal conditions using a cycle of 1-hour immersion in seawater and 23-hours drying. Davison (1986) reports mineral debris production in the order of 0.3 g per cm^2 from mica schist exposed to 50 cycles of wetting and drying with seawater under a southwest England thermal cycle, and Tingstad (2008) observed evidence of breakdown at a micrometre scale in experiments replicating salt weathering of Carboniferous limestone cliffs in South Wales.

Salt weathering simulations replicating intertidal conditions are even rarer. Synthetic seawater has been used in tidal weathering simulations for rocks forming European shorelines, with UK limestone and chalk showing some limited breakdown after 40 cycles (Moses 2002; Moses *et al.* 2006). As part of the same study, limestone placed in the upper intertidal zone on a shore platform in southern England lost weight faster than lower on the shore. This is probably indicative of enhanced salt crystallisation at higher shore levels where rocks are exposed to air and dry out more frequently. For example, higher occurrence of surface and sub-surface salts have been found in limestone and concrete exposed for several months at Mean High Water compared to Mean Tide Level (Fig. 3b–c; Coombes 2011a).

Hard materials used to build flood defences, and port and harbour infrastructure are subject to salt weathering processes just as are natural rocks (e.g. CIRIA 2007). In Devon and Cornwall, the durability of geomaterials used to build historic coastal structures is related to the relative efficiency of salt decay between different lithologies, as well as chemical weathering (Mottershead 2000). Comparisons between coastal and inland sandstone structures in North West England further suggest that marine salts enhance weathering rates significantly, by as much as 59%, although lithological differences and the influence of biogenic processes can make direct comparisons between locations difficult (Mottershead *et al.* 2003). Concrete is particularly susceptible to chemical and mechanical alteration by salts when exposed at the coast (Neville 2004; CIRIA 2010). In South West England, salt crystals occur more frequently on and within porous engineering materials like limestone and concrete under intertidal conditions (Fig. 3b–c) compared to less-porous materials such as granite, for which crystallisation is largely restricted to the surface.

As well as having geomorphological importance with regards to the progressive weakening of coastal rocks, a particular form of breakdown often attributed to the action of salts is cavernous weathering. Cavernous morphologies occur in many parts of the world and vary considerably in geometry (see Mustoe 1982). Being typically small (several millimetres to centimetres in width and depth) and densely spaced, ‘honeycomb weathering’ perhaps best describes this type of surface feature in the British Isles, although much larger examples (‘tafoni’) have been reported on coastal slopes in England (Mottershead and Pye 1994). Honeycomb development is most efficient on granular rocks, and is largely a supratidal phenomenon as this is where salts deposited in sea spray, splash, and fog crystallise more frequently. Gypsum is thought to be important in the development of cavernous weathering morphologies in sandstone cliffs in Northern Ireland (McGreevy 1985), and haloclasty aids the disintegration of the harder basalt shores of the same coastline via the formation of micro-cracks alongside the expansion of clay minerals (McKeever *et al.* 1990). In Scotland, Kelletat (1980) describes well-developed tafoni on sandstone cliffs and raised shore platforms, and in England tafoni have been studied in detail on the greenschists of south Devon (Mottershead 1982; Mottershead and Pye 1994). Vulnerable materials placed in the coastal zone for engineering purposes are also subject to cavernous weathering in the British Isles (Mottershead 1994; Pye and Mottershead 1995). While salts are undoubtedly important, the mechanism of honeycomb development is still not entirely understood, but involves other mechanical, chemical (see below) and biological processes alongside salt crystallisation depending on lithological factors and local environmental conditions (see Mustoe 2010, Brandmeier *et al.* 2011, and Mottershead in press for some recent discussions).

Chemical Breakdown

Chemical weathering involves the reaction of mineral ions in rock with air, water, or biological matter. These processes act to break down components of the rock, which are either transported away in solution or transformed to alternate physico-chemical states *in situ*. At the coast, rocks are broken down by various chemical processes including oxidation (involving oxygen and hydroxides), carbonation (involving carbonate or bicarbonate), and hydration and hydrolysis (involving H^+ and OH^- ions in water) via the gradual dissolution and transformation of mineral ions such as calcium, iron, and aluminium. In all instances the availability of liquid water is paramount. Ollier (1984) and Trenhaile (1987; 1998) provide some useful discussion of chemical weathering of particular lithologies. Certain minerals in rocks, including feldspar, are chemically unstable in the marine environment rendering them susceptible to chemical decay, while rocks composed of minerals such as quartz and muscovite are probably more stable (Mottershead 2000). Chemical weathering in association with salts and microorganisms is also important, including the etching and dissolution of hard quartz grains (Brehm *et al.* 2005). Mottershead (1982), for example, suggests that hydrolysis is important in the weathering of silicate rocks in south Devon, but that mechanical salt weathering (i.e. crystallisation) is the primary breakdown process.

Chemical weathering is generally more efficient in tropical and warm temperate environments, but can operate in cooler temperate regions to varying degrees depending on lithology. Solution is certainly most efficient on carbonate rocks (i.e. the dissolution of limestone and chalk) and may dominate the formation – or at least the extension – of shallow basins on limestone shorelines in the British Isles (Wood 1968; Trenhaile 1972; Lundberg 1977). Pitting of chalk platforms on the Isle of Thanet, Kent, is also thought to have a solutional or other chemical origin (So 1965). The extent to which seawater weathers coastal rocks via dissolution is still not entirely clear however, given that it is typically saturated with carbonates. Solution may be enhanced by wave action (Kaye 1957) and biogenic processes are particularly important for facilitating solutional weathering in the intertidal zone (see 'Biosolution'). Most researchers have, however, concluded that solution is relatively unimportant in the intertidal zone (see Trenhaile 1987, and Spencer and Viles 2002 for some further discussion).

As well as contributing to their breakdown, chemical processes can act to harden rocks, at least in the short term. This involves the transformation of minerals to more physically and chemically stable forms, and/or the transport and deposition of weathering products in surface layers. The opposite process can also be true of course, whereby loss of chemical weathering products renders rock more susceptible to subsequent decay and erosion. In both cases, changes in the wetting–drying and thermal behaviour of materials that can result from such modification are important for the efficiency of other breakdown processes, as previously discussed (e.g. Coombes and Naylor 2012). The development of distinctive coastal morphologies such as honeycombs is also controlled to some extent by chemical transformations. In concrete, chemical transformation and deposition of expansive minerals such as brucite [$Mg(OH)_2$], ettringite [$Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$] and halite ($NaCl$) occurs in seawater (e.g. Fig 3d). This can be a purely chemical process associated with reactions between salt ions and the cement paste (calcium silicate hydrate), but also operates in tandem with biogenic processes (Haynes *et al.* 2010; Liu *et al.* 2010; Coombes *et al.* 2011).

The examples of mechanical and chemical rock breakdown processes reviewed above demonstrate that study of these phenomena has been, and continues to be, particularly strong in the British Isles. Despite some bias in the locations where experiments have been carried out, one overriding conclusion to make is that while evidence exists for the widespread operation of these various weathering mechanisms, lithology is paramount in defining their efficiency and relative geomorphological significance between locations in Britain and Ireland. Equally important is the recognition that particular modes of decay are rarely found to be operating in isolation, such that the complexity of coastal rock weathering and the need for further experimental work is clearly evident (see ‘Conclusions and Future Directions’).

Biogenic Processes

As well as directly contributing to the weathering and erosion of rocks, microorganisms, animals, and higher plants can enhance or impede the efficiency of other inorganic breakdown processes (Fig. 1). Interest in such organic–inorganic interactions, including the influence of geomorphology on ecology, falls under the broad umbrella of biogeomorphology (Viles 1988; Naylor *et al.* 2002; Viles *et al.* 2008). The roles of biogenic processes in rock coast geomorphology, however, remain relatively underexplored, often being noted as potentially important but not often studied quantitatively. Wright (1967) indicated that the influence of local conditions of salinity, temperature, and tides on biology are translated into surface forms on rock platforms around the British Isles, and Trenhaile (1980 and 1987) provides some of the first overviews of the possible geomorphological roles of biota on rocky shores more generally, recognising that organisms have both erosive and protective functions. More recently, researchers have begun to explore rock coast biogeomorphology in greater detail, indicating that there is significant potential for further work in this area (e.g. Moura *et al.* 2012; Naylor *et al.* 2012).

Most rock surfaces at the coast are colonised by microorganisms, living within thin layers of secreted polysaccharides (extracellular polymeric substances, EPS) called ‘biofilms’ (Trudgill 1988; Decho 2000). Marine biofilms contain algae, cyanobacteria, and diatoms along with other detrital material, and can develop within a matter of days (MacLulich 1986; MacLulich 1987). Some microorganisms are restricted to the surface of rocks (epiliths), while others exploit niches below the surface (endolithis) and as such can be particularly effective agents of rock modification and breakdown (Golubic *et al.* 1981; Viles 2000; Viles 2012). Some endoliths actively bore into rock (euendolithis), while others occupy pre-existing pores and cavities (cryptoendoliths), and/or cracks and fissures connected to the surface (chasmoendoliths). Lithology is a critical control on microbial niche occupation, with porous and calcareous rock types being most amenable to endolithic colonisation, but not exclusively (Pohl and Schneider 2002; Hoppert *et al.* 2004; Coombes *et al.* 2011). These microbial communities are ecologically critical, contributing significantly to primary productivity in the marine zone, acting as settlement cues for other sedentary organisms, and providing food for motile grazing species (e.g. Thompson *et al.* 2004; Hutchinson *et al.* 2006).

Coastal rocks are also colonised by a diversity of macro-organisms, which cover surfaces to varying degrees depending on the spatial and temporal distribution of environmental stresses (i.e. heat and desiccation) and ecological interactions with other species (i.e. competition and predation) (e.g. Menge and Lubchenco 1981; Menge and Sutherland 1987; Menge and Olson 1990). Above the tide line, lichens and higher plants are able to colonise coastal slopes and cliffs (Malloch *et al.* 1985; Larson *et al.* 2000), while encrusting species such as barnacles and canopy-forming seaweeds (green, brown, and red macroalgae) occupy the majority of intertidal space on temperate shores (Hawkins and Jones 1992). An often well-defined biological zonation (e.g. Fig. 5a) means that biogenic processes may be the dominant mode of rock alteration in one zones, while other inorganic processes such as abrasion (which can prevent colonisation) may dominate in another.

Bioerosion and Bioweathering

There is a wealth of terms used to describe the ways in which coastal organisms interact with rocky substrate (see Spencer 1988a and 1988b for full discussions) (Fig. 1). The traditional classification is based on the concept of ‘bioerosion’ (e.g. Trudgill 1985), which can be conceptualised as two distinct sets of processes. The first and more widely studied on temperate rock coasts is ‘biomechanical erosion’ or ‘bioabrasion’. This involves the direct removal of substratum by the rasping and grinding activities of grazers and rock-boring organisms. Second, ‘biochemical erosion’ or ‘biocorrosion’ includes biologically-driven or biologically-assisted solutional (‘biosolution’) and corrosional processes. These processes operate directly (actively) via the secretion of chemical compounds able to dissolve rock minerals (e.g. Brehm *et al.* 2005) and indirectly (passively) via the alteration of local conditions that influence chemical reactions such as pH, humidity, and temperature. While biomechanical erosion produces mineral sediment, biochemical decay produces a solutional product (Torunski 1979; Schneider and Torunski 1983). Importantly, the means by which intertidal organisms alter rocky substrates undoubtedly involves both biomechanical and biochemical processes, individually or in combination. 'Bioweathering' is a separate term used in the literature, but its distinction from bioerosion is not often made clear within the above classification framework; whereas bioabrasion sits best under the umbrella of bioerosion, bioweathering describes primarily fine-scale (sub-millimetre) biochemical/biocorrosional processes (and some biomechanical processes) acting to modify hard substrata *in situ* (Fig. 1). Crucially, bioweathering does not involve the transport or removal of material, but instead can produce altered layers, sometimes called 'weathering rinds', that have different geomorphological properties and behaviours compared to unweathered rock (Fig. 3d).

Rock boring

Organisms bore into rock at a range of spatial scales (Fig. 6). Several species of mollusc and marine worms bore using specially adapted structures (i.e. biomechanical bioerosion) and/or by secreting rock-dissolving chemicals (i.e. biochemical bioerosion) (e.g. Fig. 5b). On the chalk coast of East Sussex, several rock-boring organisms act to break up platforms, including polychaete worms (*Polydora ciliata*) and bivalve molluscs such as piddocks (Pholadidae) (Trudgill 1988; Fornós 2002). On cohesive clays and mudstones in eastern England, bristleworms (*Polydora* spp.) and piddocks (*Petricola pholadiformis*) occur in considerable numbers (> 20,000 per m^2), the actions of which must render these shores more susceptible to wave erosion (Brew 2005). In general, piddocks are confined to softer rock types in the British Isles such as cohesive clays, chalk, and softer shales and limestones, while other bivalves including *Hiatella arctica* can readily bore harder limestones (e.g. Trudgill and Crabtree 1987). In South West England, piddocks (*Pholas dactylus*, *Barnea candida* and *B. parva*) bore chalk and cohesive clays, having significance for biodiversity as well as geomorphology (Pinn *et al.* 2005). The boring sponge (*Cliona*) creates small slits (1–2 mm) in carbonate rocks (Fig. 5b), which can be particularly dense on limestone shores including as those in western Ireland and Anglesey, North Wales (Trudgill 1987; Trudgill 1988). In South Wales, spionid polychaete worms (*Boccardia* spp.) erode hard platform limestones to a depth of around 10 mm at densities of tens of thousands of individuals per metre square (Naylor 2001) (Fig. 6). Here, bioerosion is thought to be important for facilitating meso-scale erosion (Naylor *et al.* 2012). Rock-boring by marine organisms on non-carbonate, harder materials in the British Isles is comparatively poorly documented.

At the micro-scale, microorganisms are efficient borers of carbonate rocks chiefly via biochemical means (e.g. Schneider 1976; Golubic *et al.* 1981). This occurs by processes such as acidulation, although the exact mechanism of penetration is not always clear (Garcia-

Pichel 2006; Tribollet 2008). Despite the fine-scale of operation, boring microorganisms can pepper rock surfaces with holes at considerable densities in the intertidal zone (see Naylor *et al.* 2012 for some recent discussions) (e.g. Fig. 3e and Fig. 6). This may be more significant for altering the mechanical properties and behaviours of rocks, and consequently the efficiency of other physical and chemical breakdown processes, rather than actual 'downwearing' of the surface (see 'Cross-scalar Linkages' section).

Micro-boring has been observed on limestone shores in South Wales (Naylor 2001), and in western Ireland microscopic cyanobacteria and algae are thought to be just as important as macro-boring species (if not more so) in the morphological development of limestone coasts (Trudgill 1987). The critical control of lithology on the relative efficiency of biogenic decay at this scale is illustrated by rock block exposure experiments undertaken in Cornwall (Coombes 2011a; Coombes *et al.* 2011), where significant differences between material types were evident after only eight months (Fig. 7). Limestone was heavily bored by filamentous cyanobacteria and algae to an average depth of 34 ± 12.3μm, with boreholes present in 99% of observations. After the same period, concrete had become pitted and etched by diatoms and coccoid cyanobacteria (e.g. Fig. 3f), while granite showed limited evidence of bioweathering and no borehole erosion. Such differences are largely attributable to mineralogical influences on niche occupation, given that biochemical and biomechanical means of penetration are more efficient on relatively softer and calcareous substrates. The implication here is that biologically-mediated processes of rock modification and breakdown are expected to be of greater geomorphological (and ecological) significance on coastlines composed primarily of carbonate rocks, such as those in western Ireland and southern Wales.

Grazing

Grazing molluscs (limpets, snails, and chitons) exploit microbial biofilms as a food source (e.g. Fig. 5c), rasping away mineral rock fragments as they feed (bioabrasion). Andrews and Williams (2000) assessed the erosion of Upper Chalk platforms by grazing limpets (*Patella vulgata*) in East Sussex, southeast England, concluding that these organisms lower the platforms at a minimum rate of 0.15–0.49 mm per year. This represents around 12%–35% of the total lowering on these shores, although such estimations necessarily involve assumptions about population density, distribution, and seasonal activities that should be considered (Naylor *et al.* 2012). Trudgill (1988) also attributes lowering of 0.25–0.5 mm to the grazing activities of limpets and snails on soft rocks in southern England, presumably per year. These bioerosion rates are at the lower end of the range of values estimated for grazing molluscs on carbonate shores in the Balearic Islands (0.369–2.095 mm per year) (Fornós *et al.* 2006). No comparable studies of bioabrasion are available for harder rock types. While grazing trails can often be observed on a variety of lithologies, the efficiency of grazers as erosive agents is assumed to be lower on harder and less porous rocks in the British Isles, but this warrants further investigation.

Organic swelling and shrinking

Organisms occupying cracks and void spaces in rocks can induce mechanical stresses via their swelling and shrinking upon wetting and drying – a biomechanical breakdown process (Fig. 1). This includes macro-biological structures as well as microbial cells, although this mechanism is yet to be examined in detail for marine biofilms. Swelling and shrinking of lichen thalli in response to moisture can pluck small rock fragments (10–50 μm) from the surface of limestones, as observed in north and west Ireland, contributing to the formation of solution basins (Moses and Smith 1993). A similar mechanism was used to explain short-term (hourly) expansion and contraction of supratidal rocks in Victoria, Australia (Gómez-Pujol *et al.* 2007), and can be assumed to operate to varying degrees on lichen-covered supratidal rocks in the British Isles. Organisms may also create mechanical stresses by growing in confined spaces on rocky shores. This includes barnacle encrustations and mussels, which often preferentially colonise surface discontinuities that provide less stressful habitat conditions (cooler and wetter) and refuge from wave impact and predation, especially during juvenile life-stages (e.g. Fig. 5d).

Seaweed plucking

The drag forces acting on the thalli of marine vegetation during storms, most notably kelp (*Laminaria* spp.), can pluck off fragments of rock to which they are attached. This can be common in some parts of the world, including Antarctica and New Zealand (e.g. Smith and Bayliss-Smith 1998; Garden *et al.* 2011), and while studies of the phenomenon are not common in the British Isles this does undoubtedly occur (e.g. Fig. 5e). Seaweed holdfasts attach to rocks via the secretion of chemical adhesive compounds and by growing into surface micro-cavities (Milligan and DeWreede 2000). This is largely a superficial process, but the mechanical disintegration of rocks during holdfast growth has been observed to depths of up to 10 mm on granitic and limestone rocks in western Ireland (Morrison *et al.* 2009).

Biosolution

'Karren' is a term most often applied to surface morphologies on terrestrial rocks of primarily solutional origin (Ginés *et al.* 2009). While solution may occur at the coast via the action of rainwater, solution is not typically considered important in the tidal zone owing to the saturation of seawater with respect to carbonates (see 'Chemical Breakdown' section). However, biological activity can be important for enabling solution and karren development on carbonate rocky coasts. Carbon dioxide produced by faunal respiration in enclosed bodies of water is not absorbed by photosynthesising organisms during the hours of darkness, causing its accumulation and the consequent lowering of pH and increase in water aggressivity (Emery 1946; Trudgill 1976). In western Ireland, $CaCO_3$ saturation in tide pools at night was found to be roughly half of that measured during the day, with a corresponding drop in pH (Lundberg 1977). On chalk platforms in East Sussex, the pH of water in pools is also lowest at night (Moses 2002). As well as the influence of respiration on such diurnal patterns of water chemistry, the solubility of CO_2 is greatest at lower temperatures, which tend to occur at night.

By enhancing the acidity of surface waters in the intertidal zone, organisms indirectly contribute to the solution and pitting of rock surfaces, and the development and extension of surface depressions and enclosed basins (Trudgill 1987; Trudgill 1988). Such biosolutional processes are probably most important at higher tide levels on carbonate shores, when low tide occurs at night, whereas rock borers and grazers are more important geomorphic agents lower on the shore (see 'Ecological Interactions and Biogeomorphological Zonation'). On temperate shores, coastal karren features are thought be to distinct from those in other climates due to the particular biological communities found in isolated pools of water (Lundberg 1977). In western Ireland, observations of relict pinnacle 'photokarst' in flooded marine caves indicate that the majority of solutional forms found on middle and upper eulittoral rocks are attributable to the biosolutional influence of microscopic algae (Simms 1990). Alongside other bioerosive processes, biosolution also probably contributes to the fretting of chalk platform surfaces in Kent (Wood 1968) and the zonation of marine karren on limestone outcrops in the Bristol Channel (Ley 1979). On engineered structures, biochemical weathering of concrete by seaweed secretions can occur (e.g. Jayakumar and Saravanane 2009), but the significance of this process in a durability context and its efficiency in temperate coastal waters is not yet clear.

Organic influences on environmental regimes

Organisms alter the thermal cycling of rocks by moderating the absorption of solar radiation and the exchange of energy with the air and water. Biological structures also retain moisture at the surface of rocks and, where endolithic colonisation is occurring, below the rock surface. This can enhance or impede drying and cooling by evaporation. In the coastal zone, these influences may be of most relevance for protecting rocks from mechanical decay associated with fluctuations in temperature and moisture (see 'Bioprotection' section), but they may also enhance decay (e.g. Papida *et al.* 2000). Greening and discolouration of rocks by microorganisms enhances thermal cycling in stone for example, being most pronounced on lighter coloured rocks like chalk and limestone (Warke *et al.* 1996; Smith *et al.* 2011). Dark coloured lichens also exacerbate internal stone thermal regimes relevant to thermoclastic breakdown (Carter and Viles 2004). Even at a micro-scale, bioerosion by cyanobacteria can enhance water absorption and retention, modifying the frequency and magnitude of wetting–drying and warming–cooling cycles (Coombes and Naylor 2012). Such influences may have implications for the penetration and crystallisation of dissolved salts within rocks, but assessing this remains a challenge. By creating wetter and more humid conditions at the rock–air interface, organic coverings may equally enhance chemical decay of coastal rocks, but this has not yet been adequately assessed.

Bioprotection

Bioprotection involves the prevention or limitation of weathering and erosion by organisms (Naylor *et al.* 2002; Carter and Viles 2005) (Fig. 1). This can occur directly where an organism actively hardens or stabilises a surface, or indirectly, such that the efficiency of other decay processes is reduced. Generally very little work has been done on the protective functions of organisms on rock coasts. Researchers have often inferred a protective role of marine biota, but very few quantitative studies of bioprotection exist.

Encrusting organisms such as calcareous algae (e.g. *Lithothamnion* spp.), barnacles, and mussels harden rock surfaces which may make them less susceptible to wave impact and abrasion. Many species are, however, excluded in highly abrasive environments so that bioprotection by such means is probably limited in the presence of mobile sediment. At a microbial scale, an extensive cover of biofilm can protect rocks from salt crystals (Mottershead *et al.* 2003) and probably regulates rock surface temperatures to some degree by retaining moisture at low tide (e.g. Coombes and Naylor 2012). Microorganisms also contribute to the formation of stable crusts on marine concrete via the transformation, mobilisation, and redeposition of minerals near the surface (Fig. 3d). The dampening influence of seaweeds on wave impact has also been suggested as a bioprotective process on hard rock and cohesive coasts (Kirk 1977; Trenhaile 1980; Brew 2005). In reality this is probably limited for smaller, common seaweeds such as Fucoids (Trenhaile 1987), but macro-algae are suggested to limit downwearing of carbonate platforms in Europe by buffering thermal oscillations and trapping abrasive sand (Moura *et al.* 2012). Above the tide line, the shielding of intertidal rocks from rainwater by lichen may be important in limiting solution on limestone coasts (e.g. Mottershead and Lucas 2000). Lichens also actively stabilise rock surfaces, and some species are thought to reduce thermal stresses (Carter and Viles 2005; McIlroy de la Rosa *et al.* in press).

By retaining moisture and shielding surfaces from insolation, seaweeds in South West England have been found to reduce diurnal thermal extremes at the rock–air interface (by around 25%) and buffer short-term (minutes–hours) fluctuations in temperature and relative humidity (by more than 70%) during low tide (Coombes *et al.* in press-a). These influences on near-surface microclimates are thought to limit the efficiency of mechanical decay associated with repeated heating and drying and salt crystallisation (Trenhaile 1980; Trenhaile 1987; Stephenson and Kirk 2000b; Moura *et al.* 2012). Seaweed canopies are also likely to limit the destructive effects of hard frosts on temperate shores via thermal blanketing.

As well as their influences on surface microclimates, organisms also moderate internal rock thermal regimes. For example, a common species of barnacle on British shores (*Chthamalus montagui*) can reduce average and peak rock temperatures 10 mm below the surface by a matter of several degrees depending on lithology (Coombes *et al.* in press-b). This occurs via direct shielding of the surface from insolation, and the ponding of water within the barnacle shell structures (called ‘tests’) which facilitates evaporative cooling of the rock when heated.

By reducing the amplitude of short-term thermal fluctuations below the rock surface, epibiota may limit the efficiency of thermal breakdown processes as well as the frequency of salt crystallisation within the rock structure (e.g. Gowell 2013). The magnitude and relative significance of these bioprotective effects must vary in relation to many factors including material type, surface coverage and thickness of the organic layer, the environmental conditions (i.e. climate) to which the colonised surface is exposed, and the nature of physical and ecological disturbance regimes (e.g. Coombes *et al*. *in press*-a).

Bioconstruction

Bioconstruction involves the organic production of sedimentary deposits, accretions or accumulations, and as such has direct landform-building connotations (Naylor *et al.* 2002). Construction can be via the active or passive collection and cementation of material, by tube-building worms for example (Naylor and Viles 2000), or the direct production of mineral matter by organisms, such as the secretion of skeletal calcium carbonate by corals (Spencer and Viles 2002). Bioconstructions range from micro- to macro-scale features that may be transient or semi-permanent in times (with respect to 'decay rates') depending on the materials they are built from, the environmental conditions to which they are exposed, and whether the structures are 'maintained' by the engineering organism (Cocito 2004; Jones 2012).

Geomorphologically, bioconstructions often represent landforms in themselves, and may equally have bioprotective functions by limiting the efficiency of other breakdown processes (see 'Bioprotection') (Fig. 1). The honeycomb worm (*Sabellaria alveolata* and *S. spinulosa*), for example, is a temperate reef builder found on some exposed and moderately exposed shores in the west of England, Wales, and a few sites in Ireland and Scotland (Wilson 1974; Jackson 2008; NIEA 2009). On the carbonate platforms of South Wales, *S. alveolata* is able to settle and start building tubes of several centimetres in length over a matter of months (Naylor and Viles 2000). Here, these worms have constructed reefs of several meters in scale by cementing considerable amounts of sand into their tube structures (Fig. 8). These reefs, which fringe the rock platforms at mid and low tide levels, appear to provide some protection against wave impact depending on reef morphology, as well as reducing transport and erosion of sand (White 2011).). *S. spinulosa* may equally have a role in wave dissipation via its bioconstructions, but this has never been examined quantitatively. In Scotland, extensive *S. spinulosa* reefs have been suggested to protect subsea pipelines to some extent by 'self-burial' mechanisms (Braithwaite *et al*. 2006).

Larger-scale bioconstructions like coral reefs are not as important in the British Isles as in warm water environments (e.g. Spencer and Viles 2002) at least in the near-shore zone, but other smaller-scale bioconstruction may be locally significant. *Lithothamnion* spp., barnacle encrustations, and mussel beds (*Mytilus*) represent widespread bioconstruction in Britain and Ireland given that they often cover rock surfaces by several millimetres to centimetres (e.g. Fig. 5f). These biogenic structures must protect the underlying rock from waves, salts, and bioeroding organisms to some extent (see ‘Bioprotection’), whilst recognising the possibility that their water-retaining structures and means of attachment may enhance breakdown compared to bare rock.

There are clear associations between the geomorphologically-defined process of bioconstruction and the creation of physical habitat by organisms, which can be thought of as a type of physical ecosystem engineering (Jones 2012; Jones *et al.* 1994, 1997, 2010). Formation of biogenic constructions like worm reefs creates habitat for other organisms by increasing habitat heterogeneity and the availability of physical refuge (e.g. Archambault and Bourget 1996; Harley 2006; Gutiérrez *et al*. 2010). These facilitative interactions are significant in maintaining biodiversity on temperate coasts (Dubois *et al.* 2002; Cocito 2004). Equally, bioerosion has ecological consequences via the creation of ‘negative’ habitat, such as the holes, pools, and topographic complexity produced by rock-boring molluscs (e.g. Pinn *et al.* 2008), grazers, and microorganisms (e.g. Coombes *et al.* 2011).

Ecological Interactions and Biogeomorphological Zonation

A complicating factor in the study of rock coast biogeomorphology is that organisms rarely colonise rocks in isolation. This undoubtedly gives rise to interactions between different species that have a range of bioerosive, bioprotective, and bioconstructive roles (e.g. Fig. 5f). In Ireland, encrusting barnacles are thought to limit algal bioweathering in the middle eulittoral zone, while lichen (*Verrucaria* spp.) may have a similar effect at higher shore levels (Trudgill 1987; Simms 1990). Foliose and filamentous algae have also been found to limit microbial bioerosion of limestone on European shores (Naylor and Viles 2002). Perforation of rocks by borers facilitates subsequent removal of weakened surface layers by grazers (Schneider and Torunski 1983), while grazing enables deeper penetration by light-limited micro-borers (Golubic *et al.* 1975; Trudgill 1985; Spencer 1988a; Trudgill 1988). Furthermore, grazing intensity is closely related to the abundance and productivity of microorganisms in marine biofilms (e.g. Skov *et al.* 2010), which must have implications for the spatial distribution and relative efficiency of micro-scale biogeomorphological processes on rock coasts. Such ecological interactions that influence the abundance and distribution of species across the shore (alongside other environmental factors) are clearly important in defining and predicting the relative importance of bioerosion, bioprotection, and bioconstruction, but are rarely included in biogeomorphological assessments. Importantly, biogenic processes operate alongside – and interactively with – those inorganic processes described above. The relative importance of organic and inorganic modes of rock breakdown consequently varies in time and space in association with ecological and environmental factors such as lithology and tidal position. This complexity makes assessing the geomorphological roles of organisms on rocky shores a significant and worthy challenge.

The combined and interactive influences of biogenic, mechanical, and chemical breakdown processes on rock coast geomorphology are well illustrated on the limestone shores of County Clare, Western Ireland. Here, biological zonation is translated into surface morphological forms at the landform–landscape scale (Lundberg 1977; Drew 2009). Where lichens (*Verrucaria* spp.) dominate in the supratidal zone, small and shallow circular basins are present at low densities in which solution (including the influence of rainwater) and salt crystallisation are probably most important for their development. In the lower *Littorina* zone, larger shallow depressions are attributed to bioabrasion (i.e. grazing), while on the mid shore where barnacles dominate, undercut pools are found. These pools probably develop via a combination of bioerosion by limpets, which graze the pool walls and extend them laterally, and bioprotection of pool edges by encrusting barnacles. This is also the mechanism thought to contribute to the development of pools on limestone shores in South Wales (Naylor 2001) (also see Fig. 5f). On the limestone shores of Ireland, mussels and Echinoids (urchins) dominate the mid-tide zone, where pools are large, deep, and interconnected. The dominant species here is the urchin *Paracentrotus lividus*, which bores into rock by mechanical means at a rate of 2.5–15 mm per year (Trudgill *et al.* 1987). Compared to a general lowering rate on these shores of around 0.1 mm per year, this urchin species is primarily responsible for the deepening of pools in this zone, where they form dense colonies and ultimately contribute to the development of rock benches. The boring bivalve *Hiatella arctica* also occurs here, excavating limestone at rates of 1.25–10 mm per year by combined biochemical and biomechanical means (Trudgill and Crabtree 1987). Importantly, burrow excavation by these rock borers cannot continue indefinitely, but may have greatest geomorphological significance through the progressive increase in burrow density and the sequential colonisation – mortality – recolonisation of rock surfaces that must act to prepare materials for subsequent erosion by waves. Alongside these macro-scale rock borers, microscopic cyanobacteria and algae are just as important in the morphological development of these shoes over longer timescales (Trudgill 1987).

Cross-scalar Linkages

The relative contribution of subaerial weathering to shore platform morphodynamics has been comprehensively reviewed elsewhere (see Trenhaile 1980; Trenhaile 1987; Stephenson 2000; Trenhaile 2011; Stephenson *et al.* in press). Generally, weathering can be the dominant formation process where waves are insufficient to explain erosion, such as in some parts of Australasia (e.g. Stephenson and Kirk 1998; Stephenson and Kirk 2000a; Stephenson and Kirk 2000b) (see also Chapter 4.2). On the macro-tidal, high energy coastlines of the British Isles, however, weathering is largely a secondary process acting to superficially modify rocks primarily cut by marine processes (Wright 1967; Trenhaile 1980; Trenhaile 1997; Trenhaile 1999). Geological and lithological factors are particularly important controls on the morphodynamics of British rock coasts (Trenhaile 1972; Trenhaile 1974a; Trenhaile 1974b), but the geological diversity of the British Isles means that the importance of weathering processes can vary considerably between locations, and over relatively short distances. Compared to the limestone shores of western Ireland where bioerosion dominates metre-scale platform morphology (see previous section), biogenic processes are largely negligible on the carbonate-poor basalt platforms and cliffs in north-eastern Ireland (McKenna *et al.* 1992). Here, marine erosion dominates coastal change via the removal of entire blocks of rock. Block removal is mainly controlled by jointing patterns, but physical and chemical weathering of mineralised joints does facilitate wave erosion to some extent. Occurrence of Carboniferous sandstones and shales on these shores also means that salt weathering is locally important for surface morphological development. Salt weathering is not, however, considered significant in the general development of intertidal rock platforms in the British Isles, as evaporation rates and crystallisation events are limited by semi-diurnal tides (see 'Salt crystallisation'). Equally, while marine-derived salts certainly weather coastal cliffs in the British Isles and contribute to rock breakdown behind the cliff line (e.g. Inkpen and Jackson 2000; Robinson and Moses 2002), the contribution of salt weathering to overall rates of cliff retreat is limited compared to the influence of waves and rainfall patterns (see below).

Weathering plays a role in the broader rock coast system via linkages between typically fine-scale breakdown processes and meso-scale erosion. Mechanical, chemical, and biological weathering reduces the resisting force of rock masses, making platforms and cliffs more susceptible to the assailing force of waves (Trenhaile 1980; Sunamura 1992; Stephenson 2000; Naylor and Stephenson 2010; Trenhaile 2011; Stephenson *et al.* in press) (see also Chapter 4.3). The concentration of organic activity in water-holding pools and crevices, which often develop along joints and bedding planes, can weaken rock masses and facilitate the removal of larger blocks by wave quarrying (Trudgill 1988; Stephenson *et al.* in press). Bioerosion can also reduce rock hardness and alter material properties such as water absorption (e.g. Coombes and Naylor 2012). These processes have been termed 'facilitative bioerosion' with reference to the Blue Lias platforms of South Wales (Naylor *et al*. 2012). Bioerosion is also thought to considerably reduce the mass strength of cohesive shores in England (Brew 2004). In north-western Ireland, rock-boring sea urchins and bivalves certainly reduce limestone rock mass strength and facilitate erosion in the lower intertidal zone (Trudgill and Crabtree 1987; Trudgill *et al.* 1987). In the Bristol Channel, solutional and biosolutional weathering of limestone is similarly concentrated within joints and along bedding planes (Ley 1979), and weathering of discontinuities in the Tertiary volcanic basalts of northeast Ireland acts to loosen blocks that are subsequently dislodged and eroded by wave quarrying (Carter *et al.* 1987). Frost weathering of structural joints also contributes to the liberation of boulders and their subsequent entrainment by waves on the granite shores of northwest Ireland (Knight and Burningham 2011).

On cliffs, weathering contributes to instability and mass movement to some degree, and is of importance for introducing sediment onto the foreshore that is subsequently mobilised by waves and involved in abrasion (e.g. Robinson 1977b) (also see Chapter 2.1.1 for a full discussion of cliff processes in the British Isles). For example, the expansion and contraction of clays contributes to instability in limestone and mudstone cliffs of the Glamorgan Heritage Coast, south Wales (Williams *et al.* 1996), where frosts also widen joints and reduce the interlock resistance along tension fractures (Williams *et al.* 1993; Williams *et al.*

1998). The frequency of cliff falls in southern England is linked to frost events (e.g. May 1971), and in Northern Ireland the freezing and thawing of soil water occupying rock joints is thought to contribute to the instability of basalt, chalk, and sandstone cliffs when heavy rain coincides with cold weather (McKenna *et al.* 1992). Rainwater can also produce dissolution pipes in cliffs, often in association with pre-existing fissures and joints. In-fill and expansion and contraction of clay debris in these voids contributes to high-magnitude failures on the chalk cliffs of the English Channel, which can involve several thousand cubic meters of rock (Duperret *et al.* 2004). In southern England, the loss of small fragments of rock from chalk cliff faces occurs via wetting and drying, thermal expansion and contraction, and salt crystallisation, but rainfall and groundwater processes are thought to be most important for instability and retreat (Dornbusch *et al.* 2008; Robinson and Moses 2011).

Conclusion and Future Directions

Further assessment of the efficiency of particular weathering processes on coastlines of the British Isles would be of use as laboratory studies have so far been generally biased towards more extreme climates and particular lithologies. Experiments and monitoring of decay of a greater range of rock types found in the British Isles would also be of value, with particular attention being given to the operation of mechanical and chemical breakdown under a temperate climate regime. The efficiency and relative contributions of rock breakdown by thermal cycling under temperate warming regimes is relatively unknown for example, and the influence of tidally-induced thermal changes on rock platforms is yet to be explored in any depth. More also needs to be done to examine the influence of tidal position, wave exposure, and lithology on the relative efficiency of different rock breakdown processes at the coast. More broadly, an enduring challenge for weathering geomorphologists is to identify the roles of typically fine-scale processes in the evolution of large-scale landforms and landscapes (Phillips 1995; Viles 2001; Robinson and Moses 2011; Viles 2012). In the coastal zone this includes the roles of rock decay in cliff and platform morphodynamics, for which linkages between weathering and other components of the rock coast system warrant further attention. The role of weathering in altering the geomechanical properties and behaviours of rock masses, including joint strength and how this links to erosional dynamics at larger spatial scales as driven by waves, should be further explored (Naylor *et al.* 2012).

The importance of rock weathering – and erosion of rocky coasts more generally – in coastal sediment budgets is yet to be adequately determined in the British Isles (Naylor *et al.* 2010). The supply of weathered and eroded rocky material from cliffs and platforms may be locally critical for the formation, maintenance and decay of sand, shingle, and cobble beaches and barriers, but this remains vastly understudied (see Dornbusch *et al*. 2006 for an exception). These linkages are of particular relevance for predicting the possible response of rock coast systems to climate change, which represents a major uncertainty for their management (see

Chapter 1.1). Indeed, the influence of climate change on the weathering of rock coasts in Britain and Ireland is certainly not clear, but will conceivably involve changes in the spatial and temporal distribution, relative efficiency, and rates of particular modes of decay (Viles 2002; Smith *et al.* 2011). A wetter climate may increase the importance of solution in the supratidal zone on carbonate shores for example, while more extreme and variable temperatures may enhance breakdown associated with heat and moisture fluctuations including salt crystallisation, wetting and dying, and thermal cycling. The implications of possible geographical range shifts of bioerosive, bioprotective, and bioconstructive species is also yet to be assessed in a geomorphological context.

Laboratory-based simulations using appropriate thermal regimes and numerical modelling alongside quantitative field experiments at multiple spatial-temporal scales offers potential to answer some of these questions. New environmental monitoring equipment such as iButtons® and waterproof Tinytags provide new opportunities for the collection of high-resolution environmental data in the intertidal zone (e.g. Denny and Harley 2006; Coombes 2011b; Coombes *et al.* in press-a) (e.g. Fig. 4), and the application of high-precision monitoring techniques including laser scanning and photogrammetry should continue to provide information on the scales at which cliffs and platforms weather and erode in the British Isles (see Chapters 2.1.1 and 2.1.2). More precise and more sensitive tools to measure rock surface hardness, such as the Equotip durometer, further offer considerable opportunities for rock coast weathering studies (Coombes 2011a; Viles *et al.* 2011). The development of new microscope and micro-analytical techniques have significantly improved our understanding of microorganism–rock interactions (Cutler and Viles 2010; Viles 2012), and the continued collaboration between geomorphologists and microbiologists promises to be a fertile area for rock coast biogeomorphological research.

Much remains to be done more generally on the roles of biogenic processes in the weathering and protection of hard coasts in temperate regions (as well as other parts of the world). Fundamentally, if adequate assessments of rock coast biogeomorphology are to be made, more needs to be done to incorporate ecological understanding of species interactions and dynamics. This will necessarily involve more interdisciplinary thinking by teams of ecologists and physical scientists working in one location and, ideally, to the same research agenda. Indeed, the importance of ecological interactions between different bioeroders, bioprotectors, and bioconstructors alongside other inorganic breakdown processes warrants much more attention in a geomorphological context at different spatial and temporal scales. Highlighting the relevance of geomorphological processes for ecology, such as the roles of weathering and erosion in creating physical habitats and in biodiversity maintenance on rocky shores (i.e. physical ecosystem engineering), should go some way to engage ecologists more in rock coast geomorphological research.

Increased risks of coastal flooding and erosion in association with climate change means that a necessary management response will be the continued use of geomaterials in coastal engineering for hard defence (Defra 2010). Weathering science is therefore of notable applied relevance in the coastal zone in a context of engineering durability (Fookes *et al.* 1988; Fookes *et al.* 2005). Continued articulation of the practical value of weathering science is critical if application and funding is to be maintained in this area. Engaging with engineers and coastal managers in issues of durability, ecological enhancement, and bioprotection of hard artificial coastal structures offers opportunities here, and research on the cross-scalar linkages between weathering processes and the morphodynamics of rock coast systems would also help place weathering geomorphology more firmly on the agenda of coastal management.

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Captions

Table 1. *Some examples of rock coast weathering studies in the British Isles, broadly organised by tidal position and material type*

Fig. 1. A rock weathering nomenclature.

Fig. 2. Combined mechanical (cracking and shattering, *i*), chemical (water ponding and solution, *ii*) and biological (lichen colonisation, *iii*) weathering and/or protection of basaltic columns of the Giant's Causeway, County Antrim, Northern Ireland (average block width = 45 cm) (photo courtesy of B. Harmon).

Fig. 3. Micro-scale weathering artefacts observed using SEM on different hard materials after exposure on rock platforms in Cornwall, U.K. (a) disaggregation of marine concrete cement and aggregate grains (indicated) indicative of repeated mechanical expansion and contraction (cross-section view, 10 months of exposure at MHW); (b) halite deposits on Portland limestone (cross-section view, 10 months of exposure at MTL); (c) sub-surface salt deposits (lighter areas, indicated) in inter-oolith spaces of Portland limestone, also note upper zone of boring (cross-section view, 10 months of exposure at MHW); (d) crusting and pitting of marine concrete in association with chemical alteration and microbiological colonisation (cross section view, 10 months of exposure at MTL); (e) borehole erosion of Portland limestone by cyanobacteria, note degradation of oolitic structure by multiple generations of boring (plan view, 8 months of exposure at MTL); (f) biopitting and cell etching (indicated) of concrete by cyanobacteria (plan view, 20 months of exposure at MTL). Images reproduced from Coombes 2011a.

Fig. 4. Rock surface temperatures recorded on a mudstone and slate shore platform in Cornwall, U.K. at MTL. Rocks are heated by the sun when low tide coincides with hot weather, and rapidly cooled by the returning tide, indicated (reproduced from Coombes 2011b with permission from Elsevier).

Fig. 5. Biogenic features on hard rock coasts and structures: (a) zonation of terrestrial plants, lichen, barnacles, and seaweed (*Ascophyllum nodosum*) on the historic 'Old Quay' at Newlyn, Cornwall (granite construction, age > 550 years); (b) limestone boulder at Portland Port, Dorset, heavily bored by piddocks (larger holes) and boring sponges (*Cliona*, smaller holes); (c) grazing trail on an experimental limestone block at MTL, Zennor, Cornwall (block surface = 100 mm^2); (d) colonisation of joints and crevices by juvenile mussels (*Mytilus edulis*) on a slate platform, Porthleven, Cornwall; (e) transport of limestone boulders by seaweed (*Laminaria*) following rough sea conditions, Isle of Portland, Dorset; (f) bioabrasion by grazers (*Patella* spp.), solution, bioprotection of topographical high-points by barnacles (mainly *Chthamalus* spp.), and bioconstruction by encrusting algae

(*Lithothamnion* spp., indicated) all contributing to the morphological development of pools on Plymouth Breakwater, Devon (limestone construction, age > 150 years).

Fig. 6. Rock–boring operating at a range of spatial scales, based on observations on limestone rocks in South West England and south Wales (redrawn from Naylor *et al*. 2012 with permission from Elsevier).

Fig. 7. Occurrence (mean + SE) of weathering features associated with mechanical, chemical, and biological weathering of different materials after exposure at MTL on rock platforms in Cornwall for 8 months (percentage occurrence in 150 SEM observations per material type) (reproduced from Coombes *et al*. 2011 with permission from Elsevier).

Fig. 8. *Sabellaria alveolata* reef bioconstructions on a Blue Lias rocky shore platform, Glamorgan Heritage Coast, south Wales (photo courtesy of A. White).