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Patterns and rates of erosion produced by high energy wave processes on hard rock headlands: The Grind of the Navir, Shetland, Scotland

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Abstract

The Grind of the Navir is an ignimbrite headland on the exposed Atlantic coast of the Shetland Islands, Scotland. During storms, offshore wave heights exceed 20 m and deep water close inshore allows high-energy waves to impact on these cliffs. The cliff top at ~15 m above sea level is awash with wave water when wave heights exceed 8 m, a condition met in storms in most years. Detailed mapping, ground photography and patterns of lichen colonisation and growth allow the processes, patterns and rates of erosion to be assessed on different parts of the headland over the past 100 years.

Recent fractures in the rock of the cliff face and top indicate that wave impact forces exceed the 1.5 kPa tensile strength of the rock and fresh sockets low on the cliff face record the removal of fracture-bounded blocks that are lost to seaward. On the upper part of the cliff face, upward moving water flow is capable of removing blocks from both vertical faces and stepped overhangs. Clefts in the cliff face are extended inwards and upwards by crack propagation and block removal, leading to the development of slot caves.

The movement of waves across the cliff top in fast-moving bores quarries blocks from the cliff face close to the edge and from rock steps on the cliff top, promoting further rock fracturing. Socket sizes and block characteristics indicate that blocks of >1 m^3 are rotated from sockets on the cliff top platform and carried landwards for up to 60 m to be deposited in a series of boulder ridges on the cliff top. Multiple boulder movements during a storm in January 2005 generated impact marks and orientated striations that allow the pattern of water movement to be reconstructed across considerable areas of cliff top.

The average rate of erosion at The Grind is estimated at 1.3–6.0 mm/yr on the cliff face and 5 mm/yr on the cliff top, although erosion rates vary in both time and space. Although block movement on the cliff top occurs in most years, erosion of rock by block removal is most active during major storms. Nevertheless, some parts of the cliff top and face remain blackened by lichen and so have experienced little recent erosion over the last 70 years or so. Although erosion occurs at the base of the cliffs, in recent decades it has been concentrated on upper part of the cliff face and top. Cliff-top erosion is most intense where stepped geos act as channels for waves to access the cliff-top. The most active features on the cliff top are the boulder ridges where substantial changes can be traced to storms over the past century. Unlike conventional models of cliff erosion where erosion is concentrated by wave attack at the waterline, wave impacts on this headland may occur on any part of cliff face and top and appear particularly effective on the upper cliff and cliff top platform.

Keywords: cliff-top storm deposits; wave dynamics; marine erosion; coastal evolution; rock coast; block quarrying; Scotland; Shetland

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1. Introduction

Quantifying the processes operating on hard rock sea cliffs is problematic since small changes are barely perceptible over human life spans and large scale rock slope failures occur rarely and often only during high magnitude events. Access to and measurement of the cliff face is difficult, particularly where its base passes below sea level. Due to their slow evolution, many rock cliffs are composite forms which retain elements inherited from earlier periods of different sea level or climate. Erosion of the cliff also tends to destroy the evidence of the mechanisms and rate of its retreat. It is not surprising therefore that progress in understanding the development of rock cliffs has been slow (Trenhaile, 2002). However, in some locations exposed to severe wave conditions the rate of change on hard rock cliff faces may be unusually high offering opportunities to isolate individual changes and rates of change. The Shetland Islands is one such location, lying to the north of mainland Britain and possessing an outer hard rock coast that is exposed to the full force of Atlantic storm waves (Fig. 1).

The Shetland nearshore wave energy environment is extreme, with evidence of wave overwash on cliffs at elevations of up to 40 m above sea level (Hall et al., 2006). The cliff coastline is characterised by spectacular marine caves, inlets and blowholes (May and Hansom, 2003). At sites where cliffs between 10 and 40 m high plunge into deep water, the platform or ramp of the upper cliff may carry boulder accumulations as part of a suite of *cliff-top storm deposits* (CTSDs) (Hall et al., 2006). CTSDs are mobilised only during storms and represent an important record of change on the cliff top and, where dated, provide an archive of information about past storms (Williams and Hall, 2004; Hall et al., 2006).

This paper examines the processes and rates of marine erosion at The Grind of the Navir, an extremely exposed headland at Eshaness, in the west Mainland of Shetland (Fig. 1). Here, waves in storms surmount the cliff top at 15–22 m above sea level, producing bores of water that surge over the full 50–60 m width of the cliff-top platform. Evidence of recent erosion is present on both the cliff face and cliff top where multiple scars and sockets indicate that blocks of various sizes have been extracted. The rear of the platform holds a striking series of boulder ridges up to 3.5 m high where blocks continue to accumulate. Whilst this assemblage of features is replicated at other CTSD sites (Williams and Hall, 2004; Hall et al., 2006), The Grind is a local beauty spot and has been photographed repeatedly for over a century so that a photographic record exists to constrain the pattern and timing of block extraction and movement. This record also allows the surface discoloration of rock surfaces by weathering and lichen growth to be used as a relative indicator of their age and reveal the patterns and rates of erosion not only on the cliff top but also on the cliff face. Detailed observations after storms in 1992, 1993 and 2005 have provided insight to the processes of rock fracture, block extraction and block movement on the upper cliff face and top. These data are used elsewhere to constrain mathematical and physical models of the impact of storm waves on the headland (Hansom et al., submitted for publication). The Grind of the Navir thus represents an exceptional site where wave impacts can be directly related to the processes and rates of marine erosion acting on a hard rock headland over timescales of 10^1–10^2 yr.

2. Site description and morphogenetic environment

The Grind of the Navir was first described nearly 200 years ago:

> "The most sublime scene is where a mural pile of porphyry, escaping the process of disintegration that is devastating the coast, appears to have been left as a sort of rampart against the inroads of the ocean. The Atlantic, when provoked by wintry gales, batters against it with all the force of real artillery—the waves having, in their repeated assaults, forced for themselves an entrance. This breach, named the Grind of the Navir, is widened every winter by the overwhelming surge, that, finding a passage through it, separates large stones from its sides, and forces them to a distance of 180 feet. In two or three spots the fragments which have been detached are brought together in immense heaps, that appear as an accumulation of cubical masses, the product of some quarry." (Hibbert-Ware, 1822)

The headland stands exposed to Atlantic waves from between SW and NW at the end of an impressive strike-aligned cliff line of up to 40 m high that extends north from Eshaness (Fig. 2A). Water depths increase rapidly offshore, reaching −50 m at 750 m from the base of the cliff (Fig. 2B).

2.1. Wave environment and storm history

Fast-moving and rapidly-developing depressions in the northeast Atlantic generate exceptional wind speeds and a high-energy wave regime. Modelling of extreme waves in deep water at Schiehallion, 160 km west of Shetland, and data from a wave buoy nearby suggest that wave heights of 20 m occur about 100 times per year (BP Exploration, 1995). Mathematical and physical

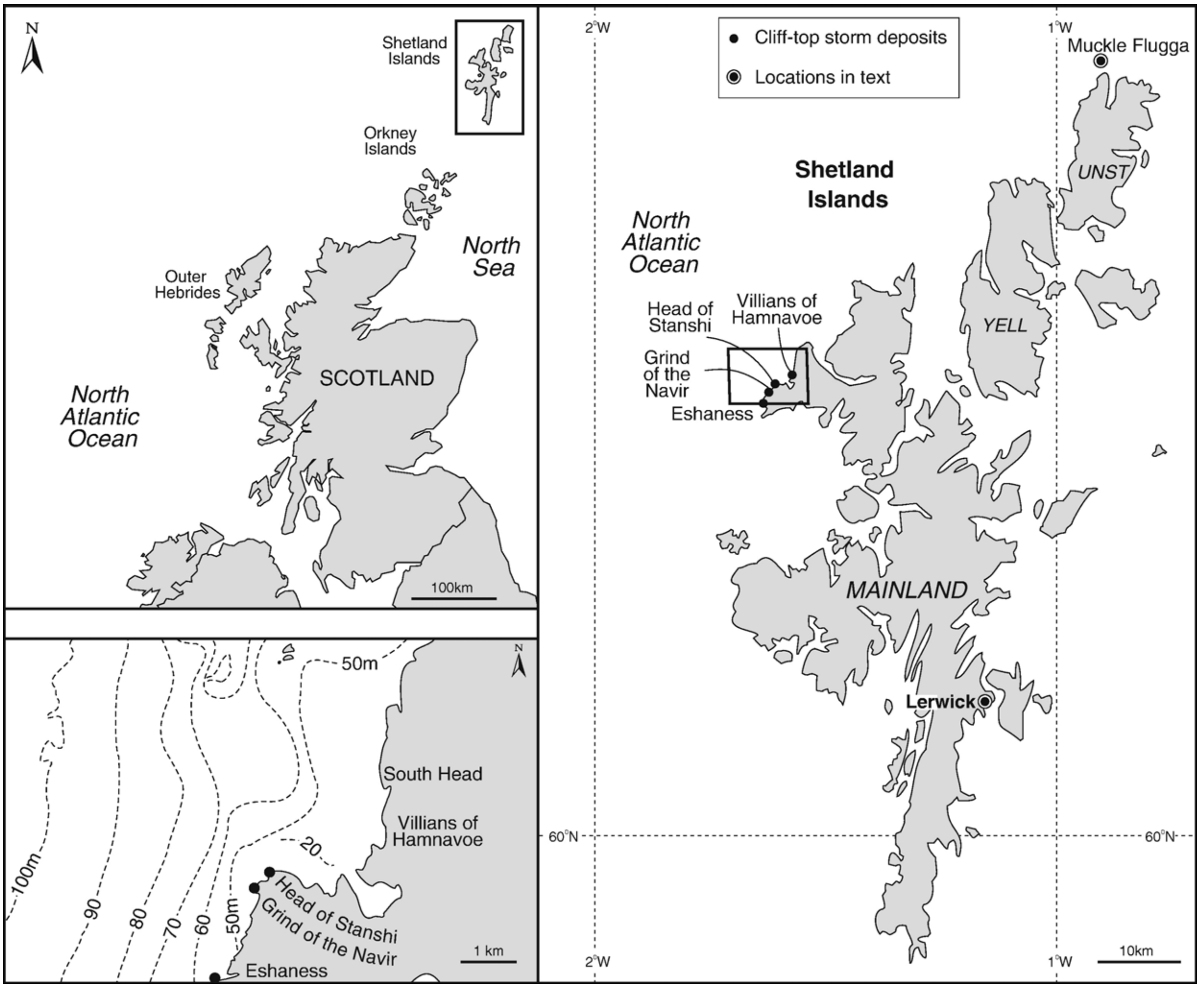

Fig. 1. The location of Shetland cliff-top storm deposit (CTSD) sites mentioned in the text.

modelling in a wave tank indicate that 20 m high deepwater waves will generate breaking waves of a height roughly equivalent to the deepwater wave height on the cliff faces at The Grind (Hansom et al., submitted for publication), implying that the entire cliff top at 15–22 m may be inundated during storms.

Reports in The Shetland Times of shipwreck, cliff fall, changes in coastal morphology and severe storm inundation in Shetland during or after storms in 1953, 1992 and 1993 suggest that regional sea states during these events were amongst the most severe of the 20th century. Observations after the 1/1/1992 and 17/1/1993 storms showed scour of cliff tops by wave action at several sites on Shetland, including The Grind (Fig. 1) (Hall et al., 2006).

2.2. Geology

The cliffs at Grind of the Navir are developed in Devonian rhyolitic ignimbrites, which dip eastwards at 8–17°. The upper platform of The Grind transects the dip slope and marine erosion has opened a strike-aligned cleft (*Strike Geo*) at the rear of the headland (Fig. 2). The principal vertical joint sets define the geometry of the headland, including its cliff faces, slot caves and rock steps. The largely orthogonal joint systems allow wave quarrying to produce cuboidal blocks of which the largest intact boulders are >1 m^3 in size and tabular in shape, with C-axis dimensions often determined by the spacing of horizontal fractures of ~0.3 m.

2.3. Erosional features

The central part of The Grind at 15 m acts as an entry point for waves reaching the cliff top and is called here *The Gateway*. It lies above a stepped rock slope (Fig. 2) and it is backed by a small bedrock depression occupied by a cliff-top pond. The Gateway is flanked by twin rock towers, termed here the *North* and

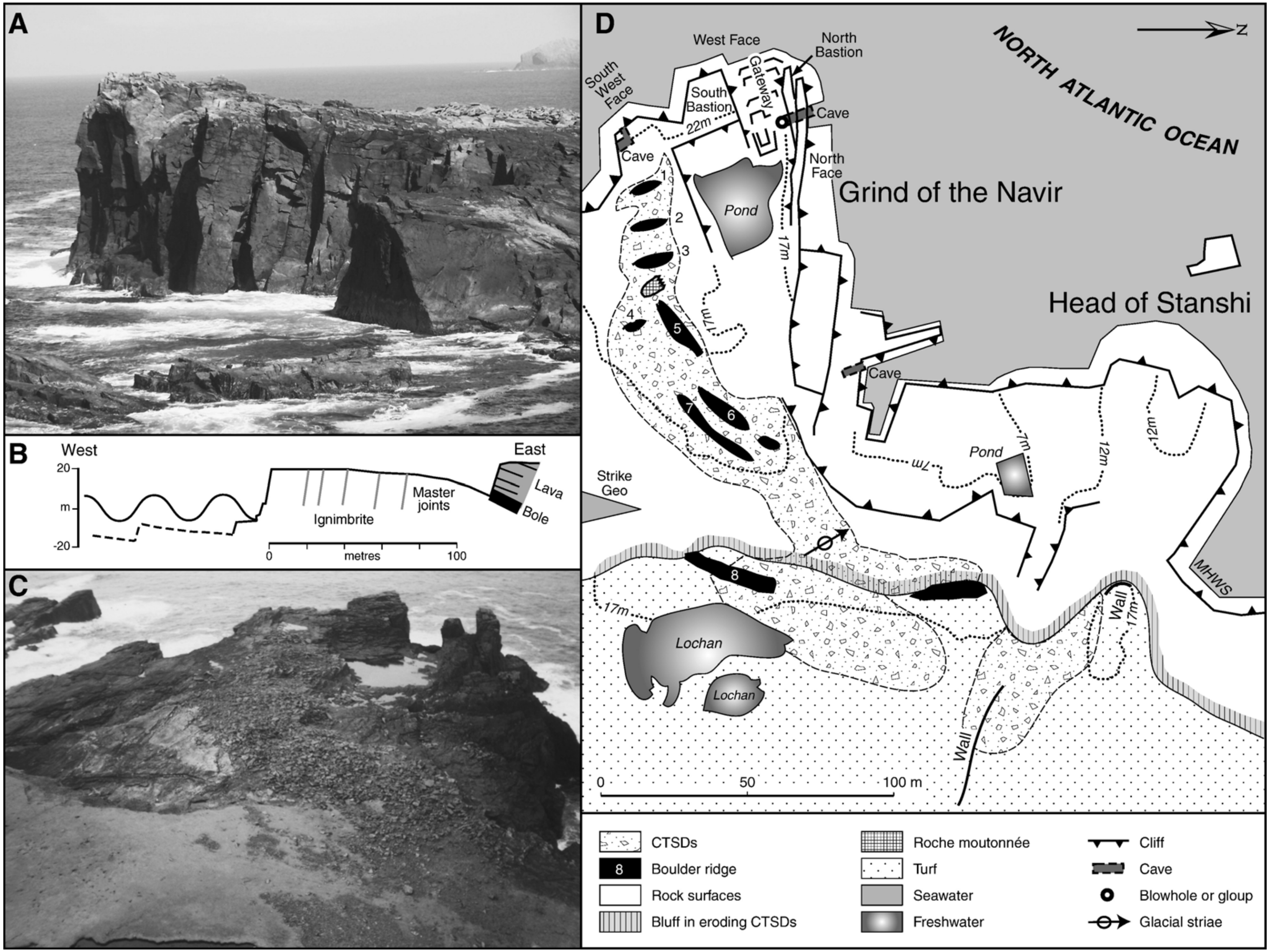

Fig. 2. Geomorphology of The Grind of the Navir. A. View of the The Grind from the south. B. Sketch geological and bathymetric section. C. Oblique aerial view from the east. D. Schematic geomorphological map.

South Bastions. Joint-aligned slot caves penetrate the headland.

The cliff-top rock platform is up to 60 m wide and usually clear of wave-transported boulders. The platform, the pond floor and the sides of the bounding ridges are stepped and display multiple sockets and scars from which joint-bounded blocks have been quarried by wave action. Rock surfaces may carry striations, chips and crescentic marks from the impact of moving blocks. These generally lower rock surfaces are fresh, with sharp edges, no discoloration and negligible lichen growth, and contrast markedly with the generally higher rock surfaces that are older, more weathered and with variable degrees of darkening due to lichen growth and incipient chemical alteration.

2.4. Depositional features

On the southern ridge of the headland lies a series of four subdued boulder ridges (Ridges 1–4) (Fig. 2). To the rear of the pond a further three sub-parallel, arcuate boulder ridges (Ridges 5–7) are separated by block-covered swales (Fig. 3). Discrete clusters of blocks, locally imbricate, occur at the base of Ridge 5 and in gullies on the rear of the cliff-top platform. Ridge 5 is an impressive feature, up to 3.5 m high, and made of angular, fresh and weathered boulders up to 3.0 m in A-axis length (Fig. 4). The landward ridges (Ridges 6 and 7) are up to 50 m long but lower than Ridge 5 and with generally smaller blocks. Ridge 8 is a lower, discontinuous feature, trending N–S and partly lost to erosion.

Between The Grind of the Navir and the Head of Stanshi lies a cliffed embayment with joint-aligned inlets and clefts (Fig. 2D). To the rear of this area is a stripped zone of relatively closely-jointed rock backed by the eroding face of Ridge 8. The ridge grades landward into spreads of angular gravel with clusters and spreads of lichen-covered boulders. To the north, the Head of Stanshi is characterised by a broad, wave-

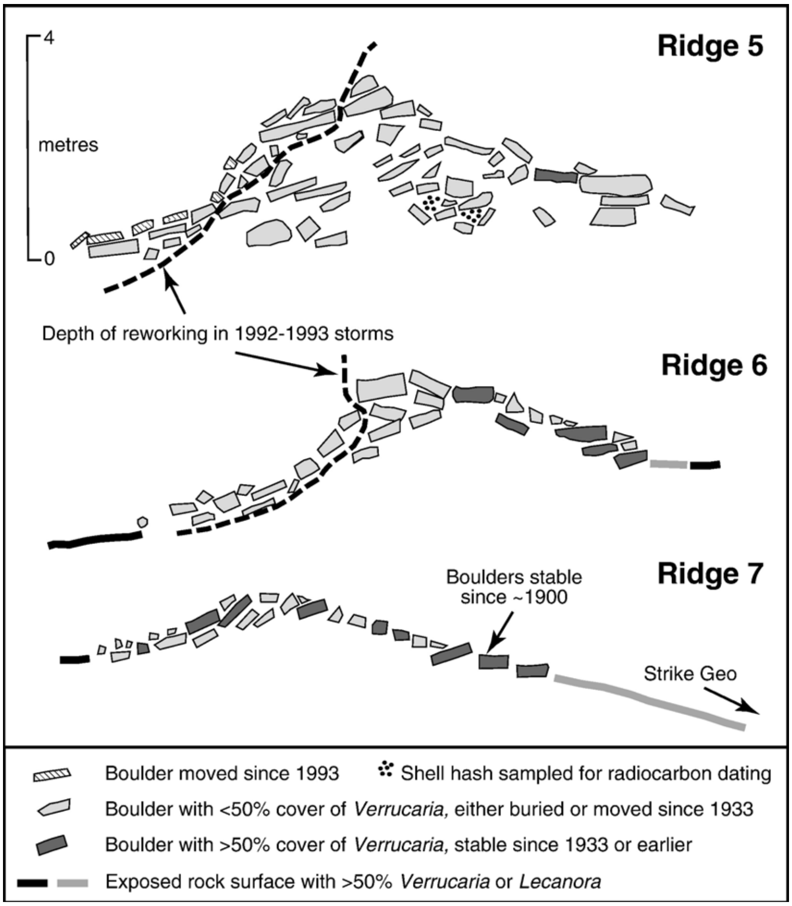

Fig. 3. Cross sections of cliff-top boulder Ridges 5–7 showing depth of storm reworking as well as relatively stable, lichen-covered, boulders.

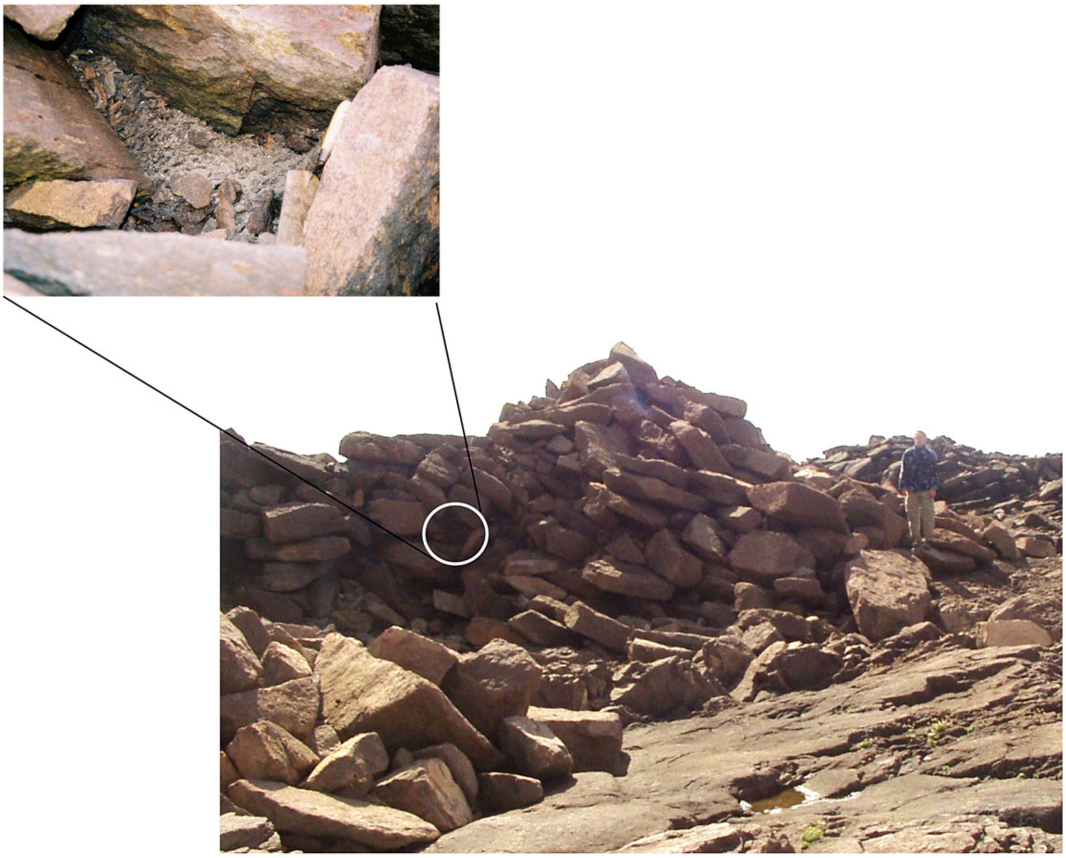

Fig. 4. Ridge 5 is 17 m above sea level, 3.5 m high and ~50 m from the cliff edge. The inset shows the location of radiocarbon-dated wave-emplaced shell hash.

scoured cliff-top rock platform at 12–15 m above sea level with an eroding 2 m-high bluff to landward. The ground behind this bluff is turf-covered and littered with angular cobbles and boulders.

3. Methods

In order to establish the patterns and rates of erosion at The Grind of the Navir, a combination of field methods was employed to establish the location and extent of datable surfaces including detailed ground survey, time series geomorphological mapping and ground photographic interpretation. These were then used in association with lichen cover and distribution, weathering and discolouration of rock surfaces to produce estimates of the timing and pattern of erosion on the cliff face and top and of boulder transport over the past century.

3.1. Mapping

The headland was surveyed using a Leica SR 530 GPS in July 2003 at a scale of 1: 100 to produce a base map and digital terrain model. The main bedrock features, together with the boulder ridges and zones of cliff-top breccia were also surveyed to produce a geomorphological map (Fig. 2D).

The changes resulting from the severe storms of 1/1/1992 and 17/1/1993 were identified by an earlier survey in 1995. No detailed survey of The Grind was made in 1992, however, so it is not possible to allocate changes to a particular storm, although the available photographs indicate that the 1992 storm generated most change. The locations of scars and sockets were plotted on base maps (Fig. 5), together with the resting points of blocks at the rear of the pond area and on the ridges. Following the storm of 01/04/2005, the pattern of block removal and transport was again plotted. The long axis of impact marks, striations and crescentic marks left by blocks moving over the platform surface were mapped to establish the direction of water flow during wave transport (Figs. 6 and 7) The A-axis orientation of imbricate clusters of boulders further confirmed the directions of wave transport (Fig. 7).

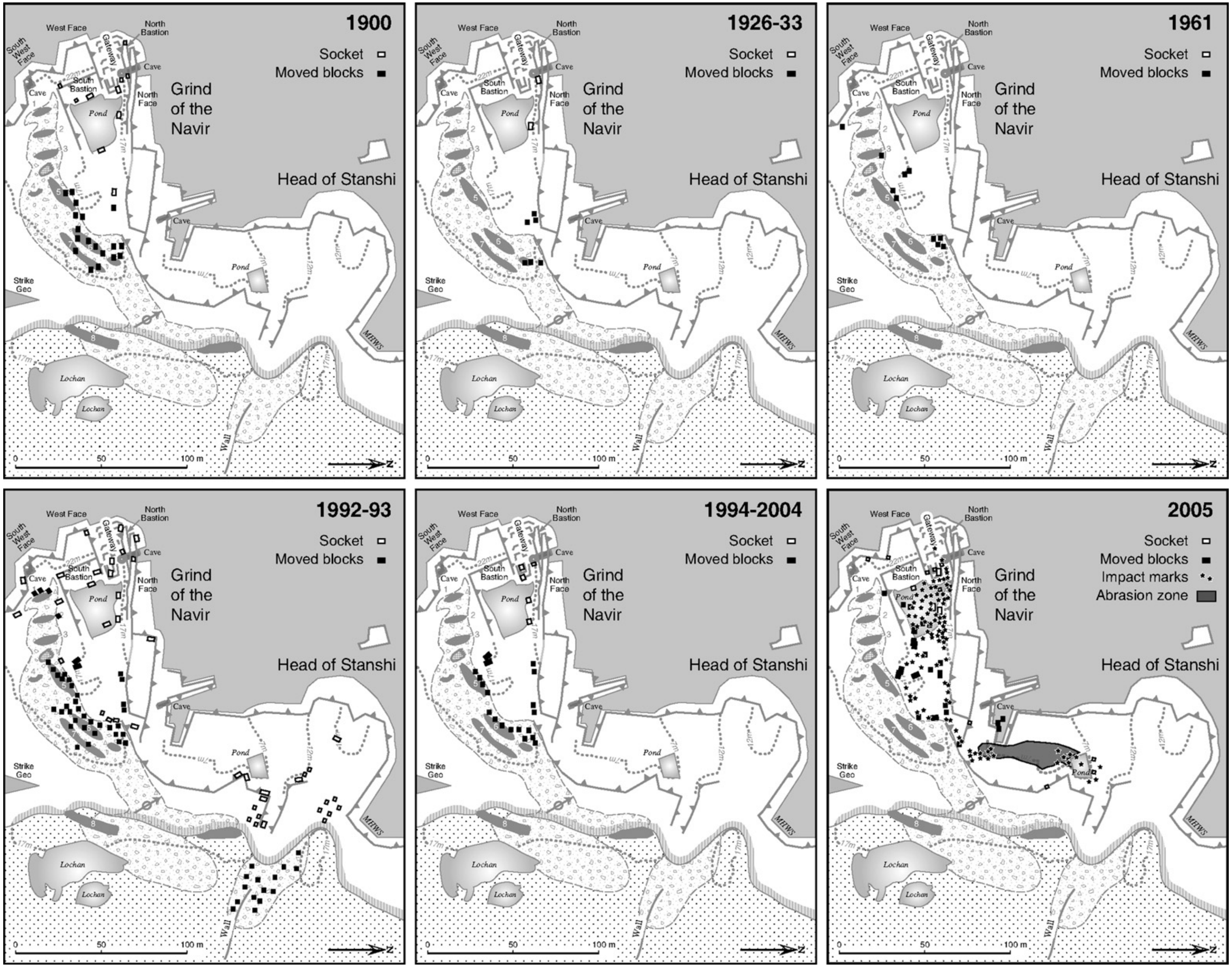

Fig. 5. Erosion and boulder transport at the cliff top and platform at intervals since 1900.

3.2. Ground photo interpretation

Changes at The Grind can also be tracked using the substantial archive of ground photos held by The Shetland Museum spanning the period 1900–1933 (http://photos.shetland-museum.org.uk/shetlands/app), together with a images dating from 1961 and 1974 held by The British Geological Survey (http://www.bgs.ac.uk/photoarchive/home.html). Allen Fraser (Lerwick Meteorological Office) provided images from 1988 and May 1993. Each archive photograph from 1900–1974 was retaken in 2004 to emulate the original field of view and camera location.

Comparison of archive images from 1900 onwards with those of 1993–2005 allowed the sites of 20th

Fig. 6. Evidence of rock fracture, lift and transport. A. Fracture, lift and clast removal at The Gateway after the storm of 12/01/2005. B. Fresh impact marks, chips and scrapes in The Gateway after the storm of 12/01/2005. C. Block lift, chock stone and flipped and moved boulders near Ridge 1 after the storms of 1992 and 1993.

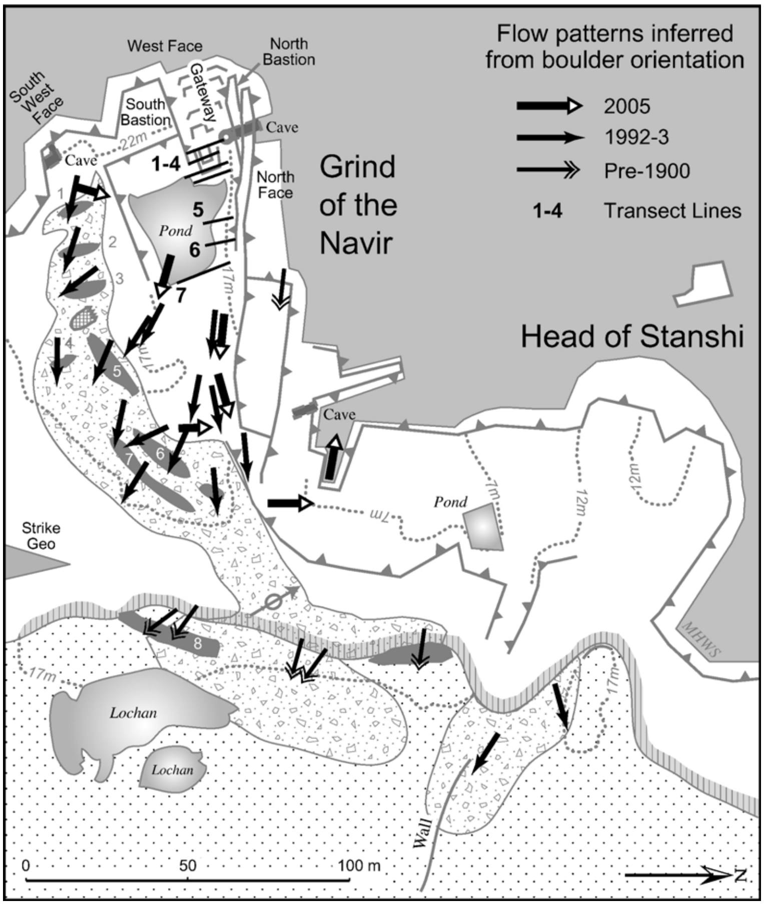

Fig. 7. Cliff-top wave water flow patterns inferred from boulder orientation (augmented by striation and impact trails).

century erosion to be identified. Erosion scars from before 1991 generally show as light tones on monochrome images, allowing bedrock configuration to be compared and contrasted with that of the present day. In addition, changes in the silhouette profiles of the bedrock steps and boulder ridge crests over the last ca. 100 years can be plotted (Fig. 8), together with the locations of boulders of distinctive shape that have remained static over this time period.

3.3. Weathering and discoloration of rock surfaces

Weathering of ignimbrite blocks and sockets occurs quite rapidly at The Grind and provides an indicator of the relative exposure age of the surfaces of blocks and the rock sockets. Surfaces exposed in and after the 1992–1993 storms retain clasts of soft, dark grey pumice but older surfaces show only cavities where this material has been weathered and/or washed out. Fresh ignimbrite surfaces show Munsell hues of 10R 5/6–4/6 which darken to 5YR 5/2 within 10 years and to 2.5YR 5/4 in 70 years. A coating, produced by diagenesis or late stage alteration, locally gives bright spots with hues 2.5YR 7/8–7/6 on fresh joint surfaces which darken to 2.5Y 8/3–7/3 in 10 years.

3.4. Lichen distribution

Lichen cover provides additional information about the duration of exposure of rock surfaces. The rock shore above the waterline at The Grind supports three main types of lichen:

(a) Black *Verrucaria maura*, which produces a tar-like patina in the spray zone (Dalby et al., 1978) from near the cliff base to the cliff top and on blocks, including the seaward faces of stable blocks in the breccias inland of the main ridges,

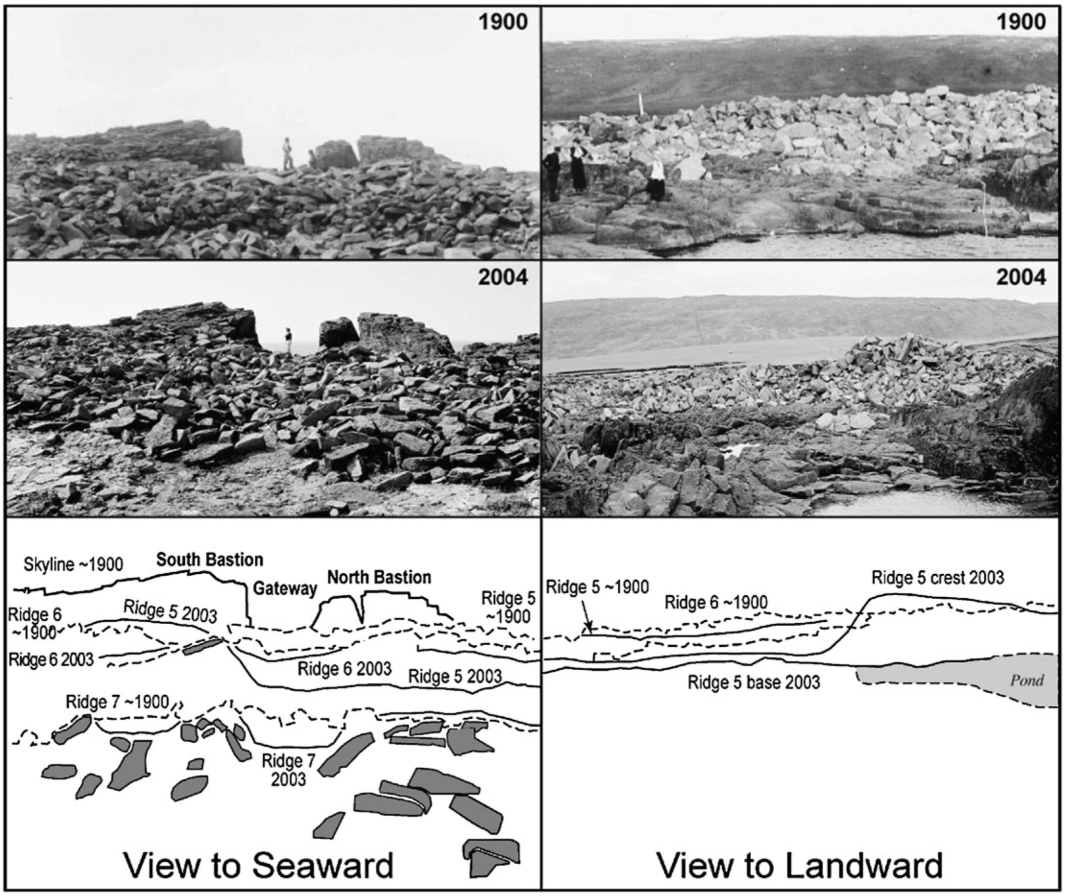

Fig. 8. Changes in profiles of Ridges 5–7 between 1900 and 2003.

(b) Orange *Caloplaca marina*, formes ringed colonies on surfaces not regularly covered by sea water or heavy spray and
(c) Grey *Lecanora* sp., which may entirely cover lee surfaces unaffected by heavy spray (Dalby and Dalby, 2005).

At The Grind, small colonies of *V. maura* develop in the micro-pits of roughened surfaces within the first 10 years of exposure. Measurements in 2004 on block surfaces that were bare and had no *Verrucaria* in 1993 show that the mean diameter of individual colonies was 7 mm and cover was limited to <5% of the surface. Images of older surfaces dated from photographs indicate that a 50–100% cover of *Verrucaria*, with blackening of the rock surface, requires ≥70 yr.

C. marina quickly colonises relatively sheltered surfaces on cliffs (Williams and Hall, 2004). Thalli diameters reached an average of 30 mm in 10 years on block surfaces exposed by the 1992–1993 storms on the highest points and rear of the cliff but this lichen is absent from rock surfaces of this age at The Gateway, presumably due to the greater exposure at this site.

Lecanora colonises relatively sheltered surfaces. Post-1993 growth at The Grind reaches a maximum diameter of 38 mm so blocks with thalli of greater diameter on the boulder ridges are regarded as already being stable before this date.

Weathering and lichen growth take place together and allow three generations of rock surface to be identified at The Grind:

(a) *Fresh*, with Munsell hues of 10R 5/6–4/6 and lacking discoloration or lichen growth;
(b) *Weathered*, discoloured to Munsell hues of 5YR 5/2 and showing 5–50% cover of *V. maura* and
(c) *Blackened*, with Munsell hues of 2.5YR 5/4 and 50–100% cover of *V. maura*.

On the cliff-top platform of The Grind, photographic evidence indicates that fresh surfaces were first exposed from 1989–2005, weathered surfaces from

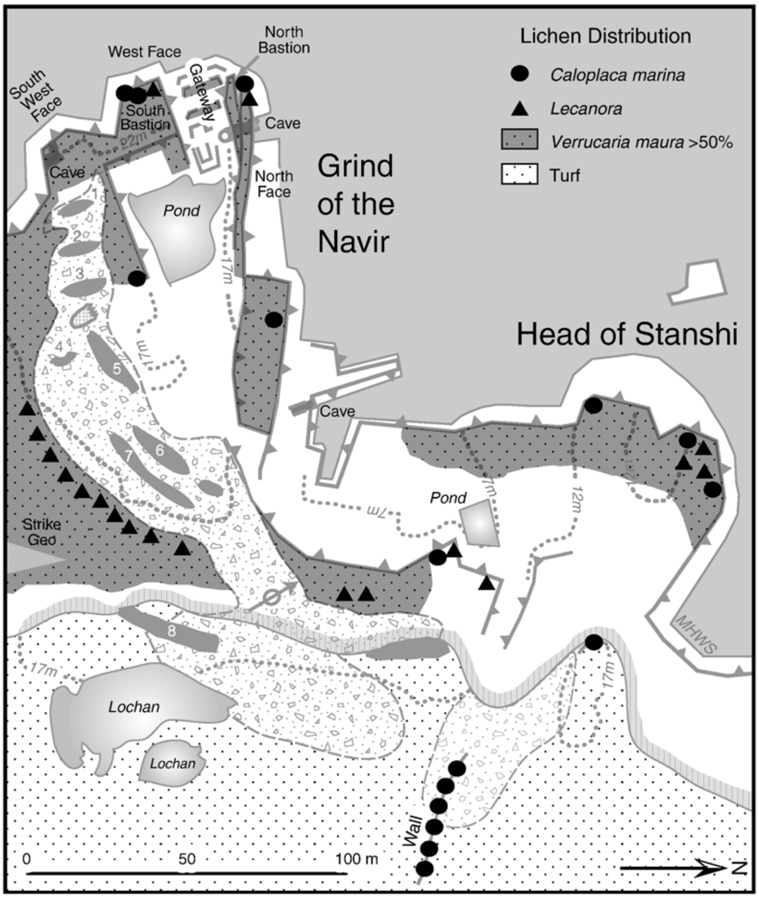

Fig. 9. Zones of lichen growth on the cliff top.

1933–1990 and blackened surfaces from before 1933 (Fig. 9).

3.5. Patterns and rates of erosion

These relative age criteria allow the exposure age of rock surfaces to be estimated for locations where photographic evidence is not available both on the cliff face and top. The distribution of surfaces of different hues and lichen cover on cliff faces, the cliff-top platform and on large boulders on the cliff-top ridges or on the turf to the rear of the platform can then be related to the timing and patterns of both erosion and boulder transport over the past century. Combined rock and boulder surface data from weathering, lichen growth and photo interpretation was plotted on a series of base maps to show changes through time (Fig. 5). Around The Gateway, a combination of photographic evidence and the mapping of old surfaces blackened by growth of *V. maura* allows the sequence of block removal to be reconstructed over the past century in a series of cross profiles (Fig. 10). Lowering is an intermittent process, yet average rates of surface lowering can be calculated for this part of the cliff top (Table 1). With the same caveat, patterns of cliff face weathering and blackening (Fig. 11) allow estimates to be made of rates of retreat. The minimum amount of erosion needed to expose a fresh face is the loss of a single joint-bounded block or slab. Surveys of vertical fracture spacing on the apex of the cliff top allow an estimate of the size of the blocks lost from the cliff face. Combining the average surface area of cliff face displaying blackened or weathered or fresh faces in photographs together with estimates of the depth of the blocks lost allows an approximation of the rate of cliff retreat over the last 100 years or so (Table 1).

4. Results

The main morphological elements of The Grind of the Navir existed before 1900. The name translates in Old Norse as “the gateway of the borer”, suggesting that it was named during the Norse dominion of Shetland between the 9th and 15th centuries. The description provided by Hibbert-Ware (1822) of The Grind, engravings from 1860–1870 and the 1:10,560 scale Ordnance Survey map of 1880 all establish that The Gateway, bastions, ponds and most, if not all of the backing ridges were in existence by the mid-19th century. The series of photos from around 1900 confirm that the cliff-top pond and boulder Ridges 5–8 were in existence at that time. Indeed, samples of shell hash from the core of Ridge 5 (inset Fig. 4) with calibrated radiocarbon ages of 1670–1840 and 1720–1880 AD suggests that Ridge 5 is 125–335 years old (Hall et al., 2006).

The distribution of lichen (Fig. 9) suggests that large areas of the cliff top have experienced little change since 1933 and numerous boulders with blackened surfaces on Ridges 1–4 indicate that these storm ridges predate 1933. Ridge 8 and the partly turf-covered CTSDs seaward of the lochan also carry boulders with blackened and lichen-covered surfaces shown in photographs from around 1900 and appear on the OS map of 1880, so deposition must have occurred earlier. In contrast, the tongue of

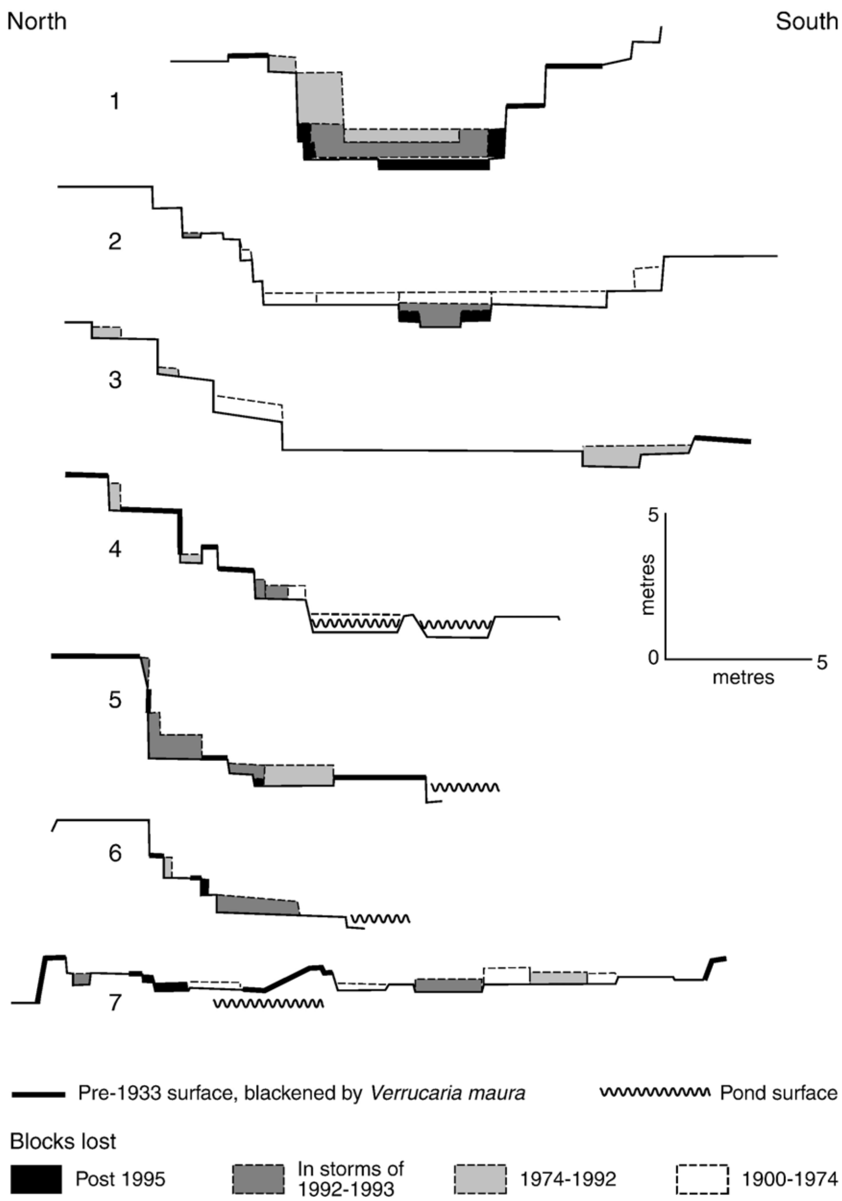

Fig. 10. Cross profiles of the northern wall of The Grind pond, showing sites of 20th century block loss.Transect locations on Fig. 7.

Table 1
Estimated rock losses from the cliff face and the cliff top since 1933 at The Grind of the Navir, Shetland

Cliff face

Location	% Blackened	% Weathered	% Fresh	Total surface area (m^2)	Average joint spacing (m)	Average rate of cliff retreat (mm/yr)
N. Face	87	13	0	1170	0.14	0.26
N. Bastion	57	27	16	316	0.41	2.5
S. Bastion	34	59	7	364	0.37	3.5
S.W. Face	43	54	3	560	0.26	2.1
S. Face	80	16	4	448	0.44	1.3

Cliff top

Transect	Rock lost from transect by period (m)				Transect length	Total lowering since 1933 (m)
	Post 1995	1992–1993	1974–1992	1900–1974		
1	0.173	0.315	0.147	0.219	15	0.853
2	0.04	0.082	0	0.351	18	0.473
3	0	0	0.085	0.065	24	0.15
4	0	0.056	0.064	0.204	10	0.324
5	0.016	0.224	0.144	0	10	0.384
6	0.016	0.235	0.032	0	7.5	0.283
7	0.012	0.046	0.030	0.077	27	0.164
% of total	10.2	31.1	19.1	39.6	111.5	

CTSDs around the wall landward of Head of Stanshi received a fresh spread of debris in the storm of 1/1/1992 (Fig. 12).

Nevertheless, although the gross form of The Grind is relatively long-established, a combination of evidence from photographs, lichen distribution and mapping indicates that significant changes have occurred at The Grind since ~1900 AD that have affected the cliff face, the cliff top platform and the backing ridges and storm deposits. The nature of the change at these locations illuminates the processes and rates of erosion on the cliff face, cliff-top and cliff-top platform.

4.1. Erosion of the cliff face

On the cliff face, even at the base of the cliff, very little edge-rounding of joint-bounded steps occurs, suggesting that little debris is carried by waves on to these cliffs, and that abrasion of the base of the cliff is limited. Cliff bases drop quickly into water depths of 10–20 m, so that debris falling from the cliff face is lost to deep water.

The sockets and scars of different sizes at all elevations on the 15–22 m high cliff faces at The Grind indicate that no part of the cliff face is out of reach of wave impact. However, the pattern of block loss varies with elevation on the cliff face, illuminating the processes responsible for block removal.

The *cliff base* close to the water line shows a few fresh, short, closed and offset or zig-zag fractures. These features sub-divide and post-date joint blocks and resemble closely the fractures that occur at the cliff-top and generated by wave impacts during recent storms. Near the water line and on the lower 5 m of the cliff, some sharp-edged, prismatic sockets occur (Fig. 11), occasionally up to 6 m^2 in surface area but mostly <1 m^2, that conform partly to the joint patterns in the ignimbrite. These sockets are sites where blocks have been removed seawards from otherwise planar rock faces.

On the *middle and upper cliff face* at The Grind >8 m above sea level many fresh or weathered scars indicate the loss of single slabs, particularly beneath dip-parallel, stepped overhangs. Socket form indicates the loss of mainly joint-bounded blocks 0.01–2 m^3 in size and of prismatic, cuboidal and slab forms. From the middle part of a number of faces of the cliff, particularly at the North and South Bastions there is a rising sequence of fresh, then weathered and then blackened surfaces. Inference of an age sequence based on these weathering sequences implies that block loss can migrate up the cliff face, with the loss of a lower block creating an overhang that subsequently exposes the next higher block to wave impact from below. At The Gateway, the incidence of freshly quarried surfaces increases upwards towards the cliff face and cliff-top junction where it reaches a maximum (Fig. 6A).

In planform, the cliff face projects outwards in zones of massive jointing, but vertical clefts penetrate zones of higher fracture density. Initial block removal from

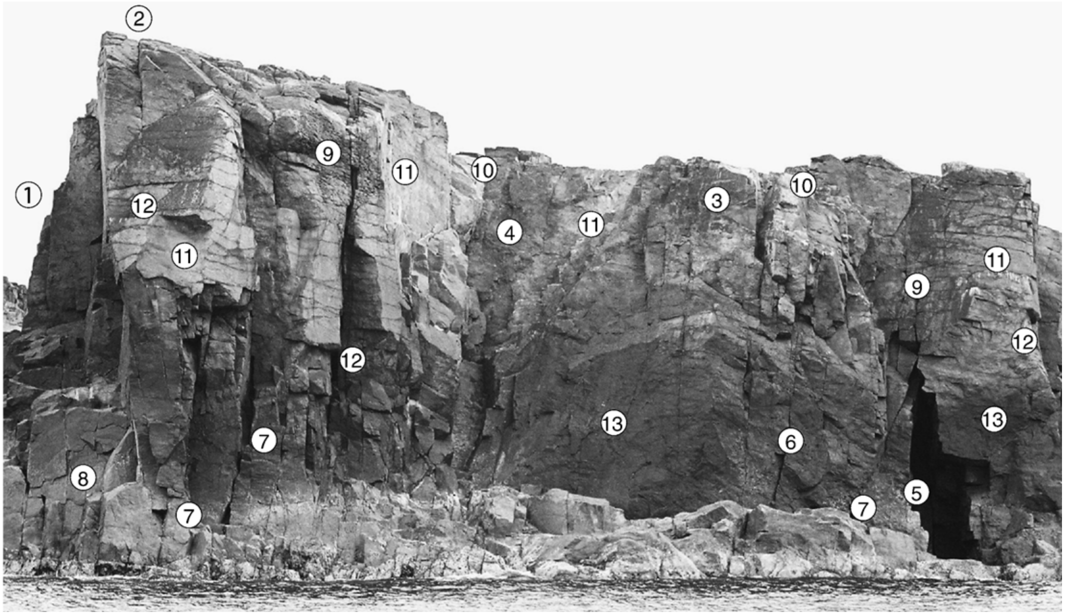

Fig. 11. Recent patterns of erosion on the SW Face at Grind of the Navir. 1) The Gateway. 2) South Bastion. 3) Buttress. 4) Cleft. 5) Cave. 6) Open joint. 7) Prismatic socket. 8) Hydro-fractures. 9) Crack propagation. 10) Fresh scar from 1992/1993. 11) Weathered scar from 1933 to 1991. 12) Stepped overhang. 13) Blackened cliff face, stable from before 1933.

planar cliff faces by waves involves the widening of steeply-inclined, closed fractures. Typically, fractures may locally branch or intersect to isolate small (0.001–0.10 m^3) prismatic rock chips and blocks. Wave action first removes these chips and then acts progressively to enlarge and extend the cavity upwards and inwards by block removal, creating a cleft or slot in the cliff face. Above clefts and caves on the south-west upper faces of The Grind, recent and apparently growing fractures extend towards the cliff top. These fractures in the upper cliff imply that high water pressures are developed in cliff-face cavities during wave impact which are capable of propagating cracks towards the cliff top. This is consistent with cave forms elsewhere on the Eshaness coast, where slots extend upwards from cave roofs along zones of fracturing, locally penetrating the cliff top as blowholes.

The evidence points to the importance of wave impact in driving cliff face erosion. The cliff face initially comprises tightly-fitted blocks of widely

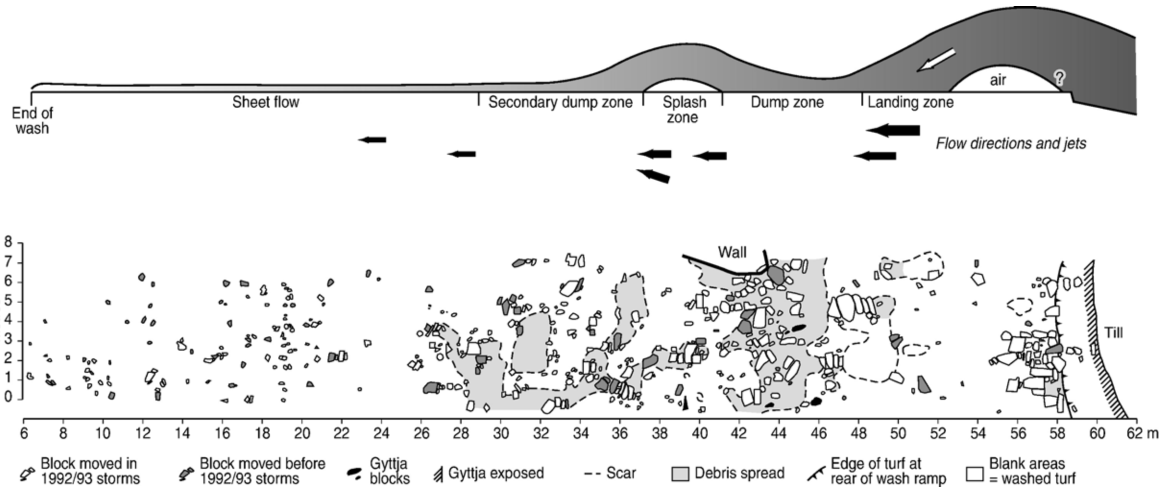

Fig. 12. Spreads of debris at 16 m above sea level on Head of Stanshi and inferred cliff-top wave dynamics in the 1992 storm.

varying dimensions defined by closed fractures which relate to both the original jointing and to wave-induced hydro-fracturing. Rock quarrying involves first the widening of fractures, followed by the loosening and removal outwards of small clasts. The opening of clefts appears to increase effective water pressures during wave impacts in these locations, promoting further fracturing and quarrying and the extension of small slot caves.

The distribution of blackened, weathered and fresh faces on the cliff indicate that about 30% of the total surface of the cliff faces at The Grind has experienced block loss since 1933. Average minimum rates of cliff face retreat, estimated using joint spacing on the adjacent cliff top and assuming loss of single blocks, are ~1.9 mm/yr. The actual figure is probably higher, as steps and overhangs on the cliff face may have a depth of 1–1.5 m and maximum joint spacing on the cliff top can exceed 3 m, but the patchwork of blackened surfaces across the faces make it unlikely that mean cliff face retreat has greatly exceeded 1.5 m over the last 70 years (~6 mm/yr), although larger rock falls may have occurred in places.

4.2. Erosion of the cliff top

Blackening suggests that large parts of the cliff-top platform have also experienced limited erosion during the last century (Fig. 9). In stark contrast, large expanses of fresh rock surfaces characterise The Gateway and pond area and archive photographs also indicate extensive recent erosion of this area (Fig. 10). Since ~1900, the major source of blocks on the cliff top has been a quarry zone represented by niches at the top of The Gateway and the rock surfaces on the cliff-top platform around and beneath the pond. Socket sizes for post-1993 erosion are 0.14–0.51 m^3 and for fresh surfaces from 1992–1993 are 0.46–1.65 m^3.

Few blackened surfaces survive on the northern side of the pond from before 1933 (Fig. 10). The greatest loss of rock has been from the niches at the head of The Gateway where up to 1.5 m of lowering has occurred (Fig. 10). Approximately 30% of the total erosion of the cliff top platform since 1933 occurred during the 1992 and 1993 storms. Mean rock surface lowering since 1933 is 0.35 m (Table 1).

The seaward faces of rock steps are prone to block quarrying (Fig. 6C). Observations at The Gateway in 2005 revealed new fracturing of *in situ* ignimbrite blocks forming the newly exposed faces of sockets (Fig. 6A). Typically, curved fractures are developed across the bottom corners of blocks or irregular fractures link ash cavities. The existence of fresh fractures in blocks where the open horizontal joint defining the block base is no more than 5 mm wide indicates that hydraulic lift forces generated beneath the blocks are sufficient to induce fracture or lifting of the block. Sites of failed lift are marked by blocks above horizontal joints held open by chock stones or displaced relative to bedrock joints (Fig. 6C).

4.3. Erosion and transport on the cliff top platform

Observations made soon after the storm of 12/01/2005 revealed patterns of impact marks formed as large blocks were carried across the cliff top platform (Fig. 5). The marks include chips, especially on the seaward-facing edges of rock steps, conchoidal fractures or crescentic marks from the impact of blocks and linear striations or scrapes, consistent with the blocks moving by saltation and sliding (Fig. 6B). The pattern and orientation of impact marks shows that blocks quarried from The Gateway were carried by high velocity water flow that traversed the pond area. The procession of striations towards Ridge 5 indicates that flow was deflected at the base of Ridge 5 to evacuate northward towards the inlet between The Grind and Head of Stanshi.

Video evidence, socket distribution, boulder orientation and the pattern of impact marks indicate that the storm of 12/01/2005 produced water flow over the pond area with sufficient depth and velocity to transport blocks and reach the base of Ridge 5 some 50 m landwards of The Gateway. The distribution of fresh scars suggests the water depth to have been a minimum of 2 m. Other scars and boulders related to the storm of 1992/1993 suggest more severe conditions, when water depths of >4.0 m overtopped the bounding ridges. It is clear that high water velocities are required to quarry and transport blocks 50–60 m inland as part of a flow that also surmounted the faces and crests of Ridges 5–7. Patterns of block movement inferred from boulder orientation and location from 1900 onwards conform to this general pattern of transport.

4.4. Deposition on the cliff top

In May 1992 fresh debris, comprising boulders, gravel spreads, and occasional lumps of gyttja and erratics, was observed covering the turf and earlier CTSDs up to 50 m inland to the rear of the Head of Stanshi. This debris had been largely sourced from erosion of the front of the nearby bluff at the rear of the cliff top platform (Fig. 12). Mapping of scour pits and debris distribution revealed dumps and spreads of gravel consistent with water flowing over the bluff, becoming airborne for ~6 m and plunging on to the turf. The lack of reworking of the debris suggests that only a few waves reached this part of the cliff-top during the storm of 01/01/1992 and none subsequently. The entire cliff-top at 12–15 m O.D. at Head of Stanshi must have been awash at this time.

In contrast, Ridges 1–4 carry mainly boulders with blackened surfaces. Boulder and ridge orientation in these Ridges indicate block transport and deposition to have occurred in westerly storms prior to 1933. The orientation of Ridges 5–7, together with that of individual boulders and imbricate clusters of boulders, indicates emplacement by waves accessing the cliff top via The Gateway. Clast orientation is consistent for all boulders irrespective of whether they have fresh, weathered or blackened surfaces (Fig. 7), indicating that wave dynamics over this part of the cliff-top platform have not changed significantly for at least 70 years.

On Ridge 5, blocks with blackened surfaces are confined to the landward slope with very fresh surfaces on the seaward slope, suggesting active recent erosion and reworking of the ridge face over the last 70 years. This is confirmed by photographic evidence which shows frequent changes in block disposition and ridge crest elevation from 1900 onwards (Fig. 8).

Ridge 6 carries no post-1993 debris but the abundant fresh debris across the entire ridge indicates wave reworking during the 1992–1993 storms. The ridge crest has been lowered by ≤ 0.8 m since 1900 (Fig. 8). Ridge 7 carries few fresh boulders up to 0.44 m^3 in size but boulders with blackened surfaces dominate. Photographs indicate that these boulders were already in place from 1900, suggesting that Ridge 7 has been largely stable since that time, with only localised reorganisation of boulders and minor lowering (Fig. 8). Ridge 8 is a significantly older feature with weathered and blackened boulder surfaces. Boulder orientations indicate deposition by waves approaching from the W or WNW (Fig. 7).

5. Discussion

5.1. Processes shaping the headland

The general nature of the waves and subsequent water flows which cause erosion, transport and deposition at The Grind can be inferred from morphological and sedimentological evidence and from direct observation. These properties help to constrain physical and mathematical models of the processes operating during storms on the cliff face and top (Hansom et al., submitted for publication).

Recent, irregular fractures that cross-cut joint blocks on the lower cliff face at The Grind indicate that forces generated during wave impact here exceed the estimated tensile strength of ignimbrite of about 1.5 MPa. Mathematical models indicate that pressures of 3.5 MPa are routinely exceeded on The Grind cliff face under 20 m high breaking waves, these pressures typically reaching a maximum about 1/3rd of the wave height below the crest i.e. at the upper third of the cliff face (Hansom et al., submitted for publication). Higher forces may be generated within cracks and recent work on waves on breakwaters shows that forces generated within 10 mm wide cracks can reach 55 MPa (Peregrine et al., 2004). Both observational and modelling evidence indicate that wave impacts at the cliff face of The Grind can generate forces sufficient for crack propagation in ignimbrite. Closed fractures in the rock of the cliff face are widened by the removal of rock chips, allowing small prismatic blocks to be then removed from otherwise planar rock surfaces. The loss of small blocks to seaward is directly analogous to the loss of masonry blocks seaward from sea walls and breakwaters (Marth et al., 2005). Measurements during wave impacts on Alderney Breakwater, Jersey, record the development of seaward pressures at the end of cracks of up to 25 MPa (Peregrine et al., 2004). Similar pressures within fractures at The Grind account for block removal from planar cliff faces, especially for loosened blocks where the effective overburden pressure is reduced.

The loss of slabs from the middle and upper cliff face during recent storms suggests that impact pressures on the face produce fracturing which then generates pressures within vertical joints sufficient to lever blocks from the face. The loss of smaller blocks appears to generate and maintain stepped overhangs and may indicate that water is injected at pressure into backing joints (Sunamura, 1992). The progressive block removal from the middle and upper cliff face also requires rapid movement of water up the cliff face, implying up-rush is sufficient to generate significant shear forces (Sunamura, 1992). In the aftermath of the 2005 storm, observation and video-footage shows waves of about 8 m in height generating jets of spray well above the cliff and large volumes of broken wave water surging over the cliff top platform to impact on Ridge 5. These observations suggest that joint-bounded blocks may be removed seawards from the cliff face by storm waves of deepwater heights that are much less than the cliff face height at The Grind.

The opening of clefts in the cliff face allows larger blocks to be dislodged by waves than would otherwise be the case. The observed fractures above the clefts and caves at The Grind imply crack propagation under high confined water pressures in closed and partially closed cavities during wave impact. It is clear from the frequency of caves and inlets on the Eshaness coast that the enlargement of cavities may progressively undermine parts of the cliff face, a key process in the retreat of the cliff face.

The presence of fresh, weathered and blackened sockets on the upper cliff face, at the apex of the cliff and on the cliff top platform indicates that waves arriving at The Grind have exceeded the 22 m maximum height of the cliff during storms. Gaps in the cliff face act to direct and channel wave impact on the cliff face and top; The Gateway is one such point. The quarry zone here shows recent multiple fractures that require generation of wave-induced pressures of >1.5 MPa in the storms of 1992, 1993 and 2005. The observational evidence for block removal, entrainment and transport requires that many boulders must first be flipped from sockets and carried 50–60 m across the cliff-top platform to arrive at Ridge 5. Block removal is concentrated at The Gateway but occurs more widely during major storms, when the entire cliff top may be awash. In the 1992–1993 storms, water depths were >3 m in the pond area, blocks were removed from sockets across the entire cliff-top platform and flow overtopped Ridges 5–7. The flow of wave water over the cliff top appears similar to that of greenwater flow produced by storm waves which overtop the bows of large ships, as investigated in the Safe-Flow project (Buchner and Voogt, 2004; Safe-Flow, 2004).

On this high energy coast, wave-induced rock fracture and block quarrying therefore has the potential to affect any part of the cliff face and its cavities, but particularly the upper cliff face and top. This appears to be a different situation from classic models of cliff erosion, where wave erosion is assumed to be concentrated at a basal notch and to decrease exponentially with height (Belov et al., 1999). The distribution of sockets also demonstrates extensive block quarrying by flow across the cliff top, a zone presumed to experience little or no erosion by waves in classic models of cliff evolution.

5.2. Patterns and rates of erosion

The distribution of lichen-covered and weathered rock surfaces at The Grind, together with the location of sockets on the ground and in old photographs indicate that erosion by waves in the past century has been variable in time and space.

Erosion has been concentrated at The Gateway where parts of the upper cliff face and, especially, the cliff top around the pond have suffered substantial block loss over the past century. Material quarried from the cliff top has been assembled into boulder ridges that themselves have been extensively reworked. The pattern of erosion is clearly closely controlled by the current coastal configuration.

The most significant changes on the cliff top were observed after the storms of 1992 and 1993, probably two of the largest storms to affect Shetland in the last century. These storm events accounted for 31% of the total erosion of bedrock from the pond area. Nonetheless, the evidence of block removal and transport on the cliff top platform in the decade after 1993 and the frequent changes in block disposition seen in photos imply that lesser scale block removal occurs during storms in most years, with widespread rearrangement of free-standing boulders.

Despite the intensity of the major 20th century storms, there have been only minor changes to Ridges 1–4 and 6–8 and to the CTSDs landward. These landforms either relate to storms of greater magnitude than those experienced since 1900, or erosion has altered the coastal configuration so that the locus of change has moved to a different area of the cliff top. Radiocarbon dates indicate that Ridge 5 was established at some time in the 18th or early 19th century. At nearby Villians of Hamnavoe, luminescence ages on CTSDs beyond the limit of wave wash in 1992–1993 are consistent with deposition during the great storms of 1634 and 1669 (Hall et al., 2006), storms which may also have had major impacts at The Grind.

The total volume of rock erosion represented by the debris incorporated into Ridges 5–7 on the rear of the cliff-top platform is estimated at ~1230 m^3, assuming 30% pore space. This is equivalent to a lowering of ~1.37 m^2 over the 900 m^2 pond area. Although this bedrock cavity may have existed prior to the onset of marine erosion, it is now 4–6 m deep within its bounding ridges, and so the boulder ridges include only part of the debris eroded. The loss of boulders to the adjacent inlet in the 2005 storm indicates one route by which debris is routinely lost from the cliff top platform. Lowering of the cliff top in the vicinity of the pond has likely proceeded at an average rate of 5 mm/yr over the last 70 years. Extrapolation of this rate allows the entire pond cavity to have been excavated over an 800–1200 yr time frame and is entirely consistent with the maximum known OSL-derived residence time of 1200 yr for CTSDs on this coast (Hall et al., 2006). This rate does not apply elsewhere on the cliff top platform bedrock ridges, where blackening by lichen indicates much more limited recent change.

Estimates of rates of cliff-face retreat at The Grind are difficult due to the complex geometry of the cliff face and the loss of rockfall debris to the submerged cliff base. Mean rates of retreat over the last 70 years lie in the range of 1.9–6.0 mm/yr. These retreat rates are consistent with the illustration of a cliff skyline very similar to that of today in mid-19th century engravings. Sunamura (1992) has collated global data on cliff recession and estimated average rates of retreat on granite cliffs at 0.001 mm/yr, several orders of magnitude less than in the ignimbrites at The Grind, confirming that rates of hard rock cliff erosion here are very high. However, similar rates of 0.4 mm/yr have been estimated for cliffs with CTSDs on Aran (Williams and Hall, 2004). It is likely that long-term rates of cliff retreat are higher than estimated as no major failure of the cliff face has occurred over the past century. Such rapid erosion is perhaps to be expected on an exposed headland on one of the highest energy coastlines in the world.

6. Conclusion

During Atlantic storms, offshore wave heights often exceed 20 m and deep water nearshore allows high-energy waves to arrive largely unmodified at several cliff sites in Scotland and Ireland (Hall et al., 2006). One such site is The Grind of the Navir in Shetland where sockets, impact marks and boulder ridges show that the cliff top at 15–22 m is awash with wave water when wave heights exceed 8 m, a condition met in most years. Detailed mapping of erosion scars, patterns of lichen growth and reference to ground photography over the past century allow the processes, patterns and rates of erosion to be assessed on different parts of the headland.

On the cliff face, particularly on the middle and upper faces, wave impact generates forces sufficient to fracture the ignimbrite bedrock and to allow removal of some blocks to seaward in a fashion similar to block loss from breakwaters. However most blocks appear to be moved upward and landward by upward moving water flow capable of removing blocks from stepped overhangs on the upper part of the cliff, this promoting further rock removal. Clefts in the cliff face extend inwards and upwards by crack propagation and block removal, leading to the development of slot caves. The opening of these cavities eventually leads to major collapse of parts of the cliff face.

During storms, flows over the cliff top and cliff top platform occur as a fast-moving bore that quarries blocks from rock steps. Socket sizes and block characteristics indicate that blocks of >1 m^3 are quarried from sockets and carried landwards for up to 60 m to be deposited in a series of boulder ridges at the rear of the cliff top platform. Sets of boulder ridges of different ages can be identified that are likely related to changes in cliff configuration over several centuries. One set of ridges has seen major changes during the major storms of the past century.

Rates of cliff face and cliff top erosion vary across the headland, with some areas experiencing no major erosion over the last 70 years. The average rate of cliff face retreat at The Grind is estimated at 1.9–6.0 mm/yr, whereas parts of the cliff top are known to have been lowered at rates of 5 mm/yr. Longer term cliff retreat rates are likely governed largely by major rock falls of relatively low frequency. Unlike conventional models of cliff erosion where erosion is concentrated by wave activity at the waterline, wave impacts on exposed headlands such as The Grind can occur on any part of the cliff face, but especially on the middle and upper faces, the cliff top and cliff top platform where most of the erosion takes place. This is a major departure from classic models of cliff erosion, where cliff development is driven by rapid erosion of the basal notch which then promotes failure of the cliff above. The distribution of cliff top and cliff top platform sockets also signals extensive block quarrying by wave impact and by high velocity bores at altitude over the cliff top, a zone presumed to experience little or no erosion by waves in classic models of cliff evolution.

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