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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