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An exploratory numerical model of rocky shore profile evolution

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ABSTRACT

Rocky shores occur along much of the world's coastline and include a wide range of coastal morphologies, such as intertidal shore platforms. Considerable research effort has been placed on trying to understand developmental processes on rocky shores, but progress has been forestalled because these landscapes develop slowly and preserve little evidence of evolution through time. This paper presents a new exploratory numerical model developed to study long-term shore profile evolution on rock coasts. The model purposely considers only a limited number of processes, each represented in a highly abstracted way. Despite these simplifications, the model exhibits a large range of emergent shore profile shapes. This behavior is enabled both by broader spatial representation of the driving erosion forces and the flexibility provided by a grid discretization scheme. Initial model testing shows the development of varied rocky profile geometries, ranging from steep plunging cliffs, cliffs with narrow benches, and cliffs with a variety of shore platform shapes. Most of the model geometries are similar to those observed in the field, and model behavior is robust and internally consistent across a relatively large parameter space. This paper provides a detailed description of the new model and its subsequent testing. Emphasis is placed on comparison of model results with published field observations in which morphometric relationships are described between shore platform gradient and tidal range, and platform elevation and platform width. The model adequately simulates these morphometric relationships, while retaining its ability to simulate a wide range of profile shapes. The simplicity of process representations, and the limited number of processes implemented, means that model outputs can be interpreted reasonably easily. Hence, an opportunity is now provided, following the testing described in this paper, to use the model to systematically investigate the broader controlling conditions on rock shore profile development.

1. Introduction

A wide range of landforms occur on rock shorelines: plunging cliffs, cliffs with notches, cliffs fronted by beaches, and rocky shores characterised by sea stacks, sea caves, and arches. However, most research, both fieldwork and modelling, has been focussed on shore platforms, which are low-gradient, usually intertidal, rocky foreshores that abut coastal cliffs. In general, two types of platforms are recognized: sloping platforms (1–5° gradient), sometimes referred to as type-A, mostly occur in meso-to megatidal environments and have a seaward-sloping surface that gradually becomes submerged without any marked break in slope; and sub-horizontal platforms (<1° gradient), sometimes referred to as type-B, mainly occur in micro- to meso-tidal environments and have an abrupt scarp at their seaward margin that sharply descends into sub-tidal areas (Trenhaile, 1987; Sunamura, 1992).

Numerous field-based studies have explored the complex interaction of environmental processes (e.g. tidal range, waves) and lithological controls that determine the presence and distribution of the different platform types around the world (e.g. Bartrum, 1926; Edwards, 1951; Gill, 1972; Tsujimoto, 1987; Trenhaile, 1999; Stephenson and Kirk, 2000b; Dickson, 2006; Kennedy and Dickson, 2006; Ogawa et al., 2011, 2012). However, fundamental questions remain concerning the processes that control morphological development (Stephenson, 2000). For instance, which erosion processes dominate the evolution of shore platform morphology, and how do processes-form interactions change over time? To what extent is morphological development dependent on extreme events versus gradual processes? To what extent is platform morphology inherited from previous sea-level positions? In addition to these particular questions of shore platform development, a number of more general questions also exist pertaining to rocky shore developmental trajectories. For instance, what particular combinations of boundary conditions and driving processes allow shore platforms to form on some rocky shores but not others? To resolve these types of questions it is necessary to go beyond the local site-specific descriptions that characterise many previous studies, to consider the full spectrum of controlling processes across a broad range of developmental conditions. This paper describes a numerical exploratory modelling approach that will help address these questions.

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Table 1
Summary of key processes on rock coasts that drive rock coast development and are incorporated into the exploratory model.

Process controls on rock coasts	Reference studies
Wave transformation:	
— Nearshore transformation of waves on rocky shore is highly complex. A large portion of incident energy is reflected where the rock profile descends into deep water, whereas on wide, shallow platforms there is substantial energy dissipation.	Sunamura (1992)
— It is generally assumed that exponential decay of wave height occurs following wave breaking on platform surfaces, but recent field measurements on sub-horizontal platforms with abrupt seaward scarps have drawn attention to complex wave attenuation behaviors and the role of different wave frequencies (e.g. incident vs. infragravity waves).	Sunamura (1992), Trenhaile (2000), Beetham and Kench (2011), Marshall and Stephenson (2011), Ogawa et al. (2011, 2012), Dickson et al. (2013)
Wave erosion:	
— Hydraulic forces associated with wave breaking against rock include shock pressures, water hammer, and compression of air in rock joints; such processes can remove rock fragments (wave quarrying). Structural properties such as discontinuities also plays important role in enhancing wave quarrying.	Trenhaile (1987), Sunamura (1992), Trenhaile and Kanyaya (2007), Cruslock et al. (2010), Naylor and Stephenson (2010)
— Mechanical action includes abrasion of rock where waves are armed with entrained sediments, but beach or cliff debris may either enhance or dampen cliff erosion depending on the volume of available sediment.	Robinson (1977), Valvo et al. (2006)
— Hydraulic and mechanical actions occur simultaneously, so distinguishing their relative importance is difficult.	Sunamura (1992)
Rock weathering:	
— Physical degradation of rock (e.g. by salt crystallisation) occurs on rocky shores through tidally controlled wetting and drying cycles. Weathering efficacy depends on lithological and environmental conditions, but laboratory experiments suggest that the greatest reduction in rock strength occurs at higher tidal levels and decreases with elevation within the intertidal zone.	Wentworth (1938), Stephenson and Kirk (2000b), Kanyaya and Trenhaile (2005), Porter et al. (2010a, 2010b, 2010c)
— Biological activity is also important in shore platform erosion and has been associated with both protective and destructive roles. The contribution relative to other formative processes is however not fully understood.	Trenhaile (1987), Stephenson and Kirk (1998, 2000b), Stephenson (2000), Naylor et al. (2012)
Sea level and tidal water fluctuations:	
— At different locations shore platform morphology may be partly inherited from historical sea-level positions, but only a few studies exist which have reliably obtained chronological data from rocky shores.	Trenhaile et al. (1999), Trenhaile (2002b), Blanco Chao et al. (2003), Choi et al. (2012), Regard et al. (2012)
— A positive correlation exists between mean spring tidal range and regional platform gradients, implying that tidal duration distribution controls the spatial distribution of rock profile erosion.	Trenhaile (1972, 1974, 1987, 1999)
Cliff mass failure:	
— Cliff mass failure can occur through many mechanisms, including deep-seated slumps, small and large rock fall, debris and mudflows, and cantilever collapse.	Trenhaile (1987), Sunamura (1992, 2015), Castedo et al. (2012, 2013), Rosser et al. (2013), Stephenson et al. (2013)

The erosional evolution of rocky coasts occurs over millennia, but little evidence of developmental stages is preserved. In recent years numerical models have been increasingly utilised to investigate long-term rock profile development. For example, the SCAPE (Soft Cliff and Platform Erosion) model (Walkden and Hall, 2005) has been developed and applied to numerous studies of soft-rock coasts (e.g. Dickson et al., 2007; Walkden and Dickson, 2008; Carpenter et al., 2014, 2015). Similarly, Castedo et al. (2012, 2013, 2015) has developed a new model

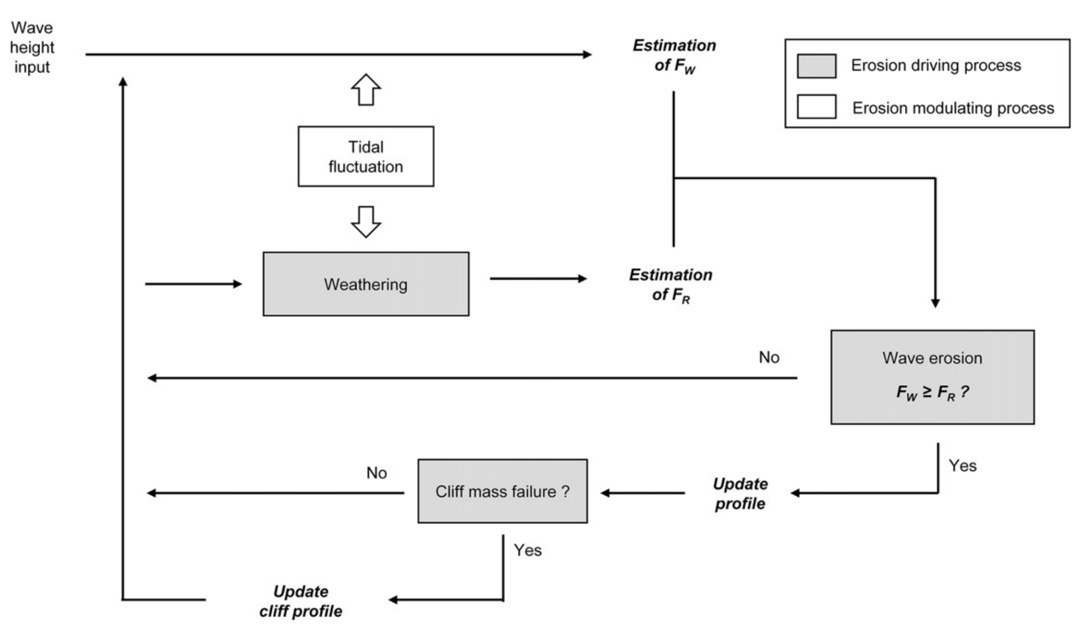

Fig. 1. Interactions between processes that contribute to shore profile development. Wave erosion, weathering and cliff mass failure are considered as an erosion driving process (grey box), while tidal water level fluctuation is employed as an erosion-modulating process (white box) which controls spatial variability of wave erosion and weathering.