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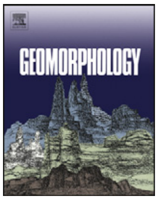

Modelling tidal notch formation by wetting and drying and salt weathering

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ABSTRACT

The formation and morphology of marine notches formed by tidal wetting and drying and salt weathering was modelled for 6 micro- to megatidal environments. The model used published tidal-elevation-dependent weathering and erosional data from 1- to 3-year experiments conducted on more than 2000 sandstone, argillite, and basalt samples from eastern Canada. The model analysed annual tidal predictions to convert the weathering data into slope-recessional units. Realistic model profiles, with notches at the high tidal level, were produced within the 3000–6000 year period since the sea attained its present level. There were up to 4 cycles of notch formation and collapse during this time in the rapidly eroding sandstones and a smaller number in the argillites. Notch morphology was affected by the tidal range, the rock type, and the initial slope gradient, but the maximum depth of the notch (before collapse) controlled only the number and frequency of the collapse events. Continuous positive and negative changes in RSL extended the notches in the vertical plane, according to the rate and direction (upwards or downwards) of these changes. A distinct series of notches can develop from episodic changes in RSL, but the survival of older notches, and consequently their utility as palaeosea-level indicators, depends upon such factors as their elevation with respect to the present tidal range.

1. Introduction

Notches, erosional indentations ranging from a few centimetres up to several metres in depth, are often seen at the foot of cliffs and other steep slopes in coastal regions. They are cut by marine weathering and erosional processes that are most effective within a narrow range of elevations, and in rocks that are strong enough to project out, unsupported, over the undercuts. Notches are usually deep and narrow in microtidal (tidal range < 2 m), low wave energy environments in the Tropics and less well defined and higher (the distance from the floor to the roof at the front of the notches) (Fig. 1) in the wave-dominated, mega- to high mesotidal mid-latitudes (Focke, 1978; Spencer, 1985a,b; Trenhaile, 1987; Sunamura, 1992; Rust and Kershaw, 2000; Kershaw and Guo, 2001; Wziatek et al., 2011; Moses, 2013).

Notch morphology varies according to the structure and lithology of the rock, tidal and wave regimes, the nature of the formative processes, and the presence of fixed biological organisms (Pirazzoli, 1986; Trenhaile, 1987; Sunamura, 1992; Trenhaile et al., 1998; Moses, 2013). These factors determine the elevations at which notches develop, and they have confounded attempts to use notches as palaeosea-level indicators and to reconstruct eustatic and tectonic history (Christiansen, 1963; Trudgill, 1976; Woodroffe et al., 1983; Pirazzoli, 1986; Tija, 1996; Nunn et al., 2002; Pedoja et al., 2011; Trenhaile et al., in press). The origin of notches has been inferred from potentially ambiguous field evidence and from assumptions based on the climate and type of rock, the distribution and life history of observed organisms, the prevailing wave and tidal regimes, and notch morphology. It is generally assumed that fairly shallow, irregular and discontinuous indentations in wave-dominated environments are wave quarried, whereas smoother forms fronted by sand or other beach material, and often running at high angles to the incoming waves, were formed by abrasion (Duperret et al., 2004; Budetta, 2011; Wziatek et al., 2011). Most workers attribute notches in tropical regions to chemical or biochemical corrosion, or to biological grazing and boring, especially on calcareous substrates (Pirazzoli, 1986; Trenhaile, 1987; Spencer, 1988), although abrasion and other forms of mechanical wave erosion are significant in some areas (Takenaga, 1968; Vita Finzi and Cornelius, 1973; Trudgill, 1976; Tija, 1985). Although many workers have opined that wetting and drying and salt weathering are important mechanisms in coastal environments (Jutson, 1918; Tricart, 1962; Coleman et al., 1966; Baggioni, 1975; Stephenson and Kirk, 2001; Porter et al., 2010a), there has been little consideration of their possible role in notch formation. Pirazzoli (1986) attributed some types of notch to 'sea corrosion', a collective term for marine physio-chemical and biological processes which, while not stated specifically, must include the effects of salt weathering and wetting and drying. Kelletat (2005) proposed that notches can be formed by salt weathering in sandy and coarse-grained rocks in areas with limited wave action and fairly low tidal ranges.

Abbreviations: (RSL), relative sea level; (HHT), highest high tide; (LHT), lowest high tide; (HLT), highest low tide; (LLT), lowest low tide; (Tr), tidal range.

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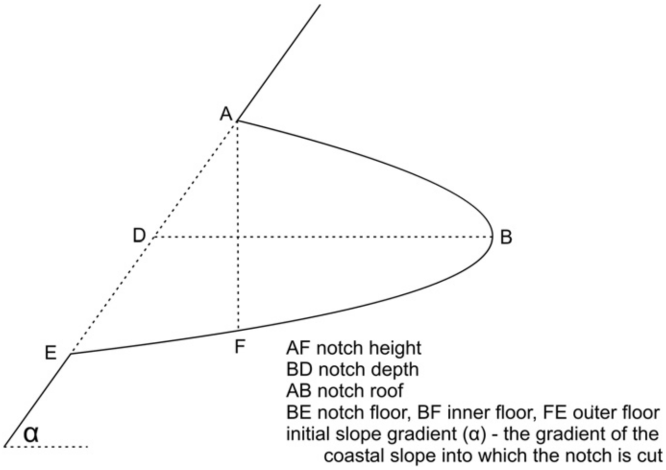

Fig. 1. Notch morphology and nomenclature used in this paper.

The efficacy of tidal wetting and drying and salt weathering has been demonstrated in experiments conducted on more than 2000 rocks from the coast of eastern Canada over periods ranging from 1 to 3 years (Porter et al., 2010a,b,c). These experiments showed how rates of weathering, and resulting erosion as the debris is removed, varies according to the type of rock and to its elevation within the intertidal zone, which determines the length and frequency of the wetting and drying periods. It has been shown, through geochemical analysis and laboratory experimentation, that these processes are largely responsible for notches in volcanic lahar deposits on the La Paz Peninsula in Mexico (Trenhaile et al., 2013; in press). It is reasonable to assume that the same processes have produced notches in non-calcareous rocks elsewhere in the Subtropics and in the estimated two-thirds of the Tropics that do not consist of carbonate substrates (Spencer and Viles, 2002). Furthermore, given the effect of these processes on rocky coasts in New Zealand, eastern Canada, and other regions (Stephenson and Kirk, 2001; Porter et al., 2010a) they must also contribute to notch formation in temperate and other environments, especially in sheltered locations lacking abrasive material. Although corrosion can occur where fresh water mixes with sea water (Moses, 2013), there has been no rigorous geochemical or other testing of the general assumption that deep notches in tropical limestones are produced in unmixed sea water by chemical corrosion or bioerosion. Until such work has been conducted one should not exclude the possibility that wetting and drying and salt weathering also have contributory or even dominant roles in the formation of notches in calcareous substrates.

There have been only a few attempts to model the formation of coastal notches. Pirazzoli (1986) developed a simple model, based on the assumption that erosion was at a maximum at mean sea level, to study the effect of cliff slope on notch development on sheltered, microtidal limestone coasts. This model indicated that cliff slope has a strong effect on notch shape and on the time that is required for notch development, which also increases with the tidal range. Another model was developed by Larson et al. (2011) for the formation of notches by wave impact and Trenhaile (1989) modelled cliff erosion and coastal evolution as a result of repeated cycles of notch undercutting, collapse, and reformation.

The purpose of this paper is to use the experimental weathering data of Porter et al. (2010a,b,c), combined with a realistic representation of tidal oscillations, to model the development of notches by erosion resulting from tidal wetting and drying and salt weathering, and possibly by some associated chemical weathering. The terms "weathering" and "erosion" are used interchangeably in parts of this paper because of the rapid, essentially instantaneous removal of weathered material on steep surfaces by gravity, tides, and wave impact, splash and spray.

2. Material and methods

Porter et al. (2010a,b,c) used a series of pumps, timers, and flood basins to expose more than 1200 rock samples to semi-diurnal tidal cycles, simulating that portion of the intertidal zone extending from the highest low tidal (HLT) level to the lowest high tidal (LHT) level. The initially desalinized samples were immersed in commercial, synthetic sea water in one set of experiments and, in order to isolate the effect of wetting and drying, in de-ionized water in a second set of experiments; the data from the synthetic sea water experiments were used in the present study because they best represent natural conditions. The salinity of the synthetic sea water was 35‰ and it contained 28 ions and elements in similar concentrations to their occurrence in natural sea water. These experiments were conducted over a 3-year period and used sandstone, basalt, and argillite samples from the coast of eastern Canada from, respectively, Burntcoat Head and Scots Bay on the northern coast of Nova Scotia in the Bay of Fundy, and Mont Louis in Gaspé, Québec, A second set of experiments, using synthetic sea water and de-ionized water and a further 840 samples of the same rocks, was conducted for one year; again, only the synthetic sea water experimental data were used in the present study. These experiments used longer periods of exposure and immersion to represent, respectively, more extreme elevations within the upper and lower intertidal zone, ranging from the LHT up to the highest high tidal (HHT) levels and from the HLT down to the lowest low tidal (LLT) levels (Tables 1, 2).

The sandstones, basalts, and argillites needed only 1–1.5 h to attain their maximum water content when immersed in water but they dried very slowly, frequently retaining from 33 to 50% of this water after 11 h of exposure in air (Trenhaile and Mercan, 1984; Kanyaya and Trenhaile, 2005). Therefore, it is the length of the exposure period rather than the duration of the period of immersion that is primarily responsible for variable rates of weathering. This conclusion is consistent with field data which indicate that weathering rates are highest in the upper intertidal zone (Porter et al., 2010a), and with experimental and field measurements that show that the greatest amounts of rock surface expansion and contraction in response to tidal wetting and drying, respectively, are also greatest in this zone (Trenhaile, 2006; Porter and Trenhaile, 2007).

Because of monthly and other long-term variations in tidal range and consequently in the height of the high and low tides, the time that a rock surface is exposed to the air varies spatially with the intertidal elevation and temporally with the amplitude of the tidal cycle (Fig. 2). The relationship between intertidal elevation and immersion frequency and length of the drying period is complex, reflecting the occurrence of mixed or diurnal tidal regimes, inequalities between consecutive semi-diurnal high (or low) tides, and bimonthly and longer-term variations in the height of the high and low tides. Therefore, at a particular elevation, a rock could be exposed and dried in air for several hours over a few consecutive spring tidal cycles, and then left exposed for a week or more by the neap high tides. Ignoring the effect of storm surges and other weather- and wave-related mechanisms on the water level, the

Table 1
Periods of immersion and exposure (Porter et al., 2010a).

Elevation	Subzone	Immersion period (time in water)	Exposure period (time out of water)
High intertidal zone	HT3	1.5 h	3 wk
	HT2	1.5 h	2 wk
	HT1	1.5 h	1 wk
Central intertidal zone	LHT	1 h	11 h
	MT	6 h	6 h
	HLT	11 h	1 h
Low intertidal zone	LT1	1 wk	1.5 h
	LT2	2 wk	1.5 h
	LT3	3 wk	1.5 h

LHT is the lowest high tidal level and HLT is the highest low tidal level. MT is mid-tide. HT1 to HT3 represent increasingly higher elevations in the upper intertidal zone and LT1 to LT3 represent increasingly lower elevations in the lower intertidal zone (h is hours and wk is weeks).