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Modelling coastal notch morphology and developmental history in the Mediterranean

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ABSTRACT

Coastal notches are used as paleo-sea level markers and to determine rates of tectonic uplift. This has been especially important in warm, microtidal seas. Modelling was used in this paper to test the hypothesis, developed in the Mediterranean, that the shape of notch profiles provides insights into changes in relative sea level (RSL) and modes of tectonic activity. Variables in the model included local factors such as the gradient of the initial slope, whether notches collapsed or remained stable, and rock strike, dip, and bed resistance to erosion. The main regional-scale variables included climatically induced changes in erosional efficacy and a variety of uniform and episodic, positive and negative changes in RSL. Model results suggest that attempts to use notch profiles to identify changes in climate and RSL must be accompanied by careful field observation and mineralogical analysis in order to extract the obfuscating effects of local factors. Similar notch profiles can be produced by different combinations of local and regional factors and, based on ambiguous field evidence, differentiating the morphological effect of changes in RSL from the effect of these other factors may continue to be problematic, especially where there has been low tectonic activity or stability.

1. Introduction

Coastal notches range from shallow, short-lived up to deep, long-lived indentations at the foot of steep to vertical cliffs. Notch occurrence, morphology, and longevity reflect the strength of the rock and its susceptibility to marine processes; wave and tidal regimes; the time that has elapsed since the notch began to form or since it last collapsed; and changes in relative sea level (RSL). Notch development is also influenced by the general morphology of the rock coast, including associated cliffs, intertidal shore platforms, and offshore zones, which affects the nature and efficacy of the erosional and depositional-constructional processes ([37,43] pp. 254–260, 2015; [41] pp 184–188; [22,28,29,46]).

Notches have been used to reconstruct Pleistocene and Holocene RSL history and, where the sea level component can be isolated in tectonically active regions, to deduce rates and amounts of uplift or subsidence [4,21,32,33,40]. Nevertheless, notches can develop at a variety of elevations relative to mean sea level according to site-specific morphogenic and geological conditions, and the nature and efficacy of the dominant formative mechanisms. It is generally accepted that notches in carbonate rocks in the Mediterranean and in parts of the Tropics, where the potential range of elevations for notch development is constrained by the occurrence of microtidal regimes and fairly low wave energy, provide the most precise indicators of former sea levels (Pirazzoli and Evelpidou, [39]).

Notches can be preserved by sudden positive or negative changes in RSL that are of sufficient magnitude, relative to tidal range and wave height, to remove them from the zone of effective marine erosion. These notches may be modified or eliminated later by subaerial, marine, or submarine (especially bioerosional) processes. More complex changes occur when slow, or small episodic, changes in RSL cause the erosional focus to migrate up or down notch backwalls [37,45].

There have been few attempts to model the effect of changing RSL on notch morphology. Trenhaile [44] used experimental salt weathering and wetting and drying data derived from non-carbonate substrates to model notch development in micro- to megatidal environments with episodic and slow but continuous changes in RSL. Pirazzoli [37] and Evelpidou et al. [11–13] developed conceptual models for the modification of notches by continuous and episodic changes in RSL. They considered only a limited range of RSL changes, however, and did not, for example, include the possible effect of notch collapse, climatically induced changes in erosional efficacy, and variations in the susceptibility of the rocks to the formative processes.

The purpose of this paper is to describe the use of a simple mathematical model to examine and extend Pirazzoli and Evelpidou's hypothesis that notch profile shape records, and can therefore be used to reconstruct, RSL history, and to distinguish

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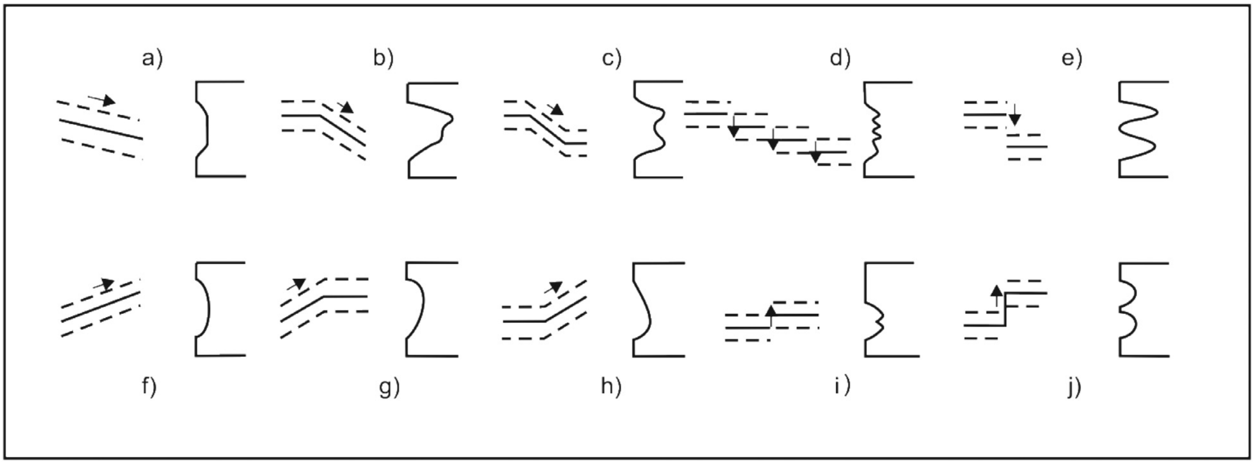

Fig. 1. Examples of conceptual model predictions of notch profiles with falling RSL (a–e), after [37]) and rising RSL (f), (h), (i), (j) after [11], and g) after [13]). The accompanying figures with arrows show the corresponding changes in RSL, whether continuously linear, interspersed with periods of stability, or episodic. The solid lines in these figures represent the mid-tidal levels, the dashed lines the high and low tidal levels, and the arrows the direction of RSL changes.

between instantaneous, coseismic and slower, more continuous changes in RSL (Fig. 1). Pirazzoli and Evelpidou's hypothesis was concerned with notches formed around the mid-tidal zone in limestones and in other types of rock in sheltered microtidal environments in the Mediterranean; that regional emphasis is retained in this paper. The purpose of this paper was not to replicate the morphology of these notches. Rather, the intention was to determine whether specific types of RSL history produce distinct morphological signatures in homogeneous and more variable carbonate substrates, and under constant and variable climatic conditions. Notches in this region have been termed, following Pirazzoli [37], tidal notches, and they have usually been attributed to physiochemical and biological processes. The present model uses erosional data collected from the Mediterranean by Furlani and Cucchi [16]. These authors also suggested that their erosional data were primarily the result of bioerosion and mixing corrosion processes, and they noted that the vertical distribution of erosion rates in their study was consistent with the shape of tidal notches in this region.

2. The Mediterranean

The Mediterranean Basin is astride the converging African and Eurasian plates. Tectonic activity, involving rapid transitions between subsidence, uplift, and stability, have characterized large areas of Italy, Greece, and Turkey, whereas other areas, including in the western Mediterranean and northern Africa, are essentially stable or experiencing slow crustal deformation [2]. Mean tidal range is about 0.4 m, although exceptional tides of up to 1.8 m can occur in the northern Adriatic Sea; tides are very low off southern Greece and southern Sicily, especially near amphidromic points where they are negligible. Despite a generally mild climate, storms can generate high waves in winter. Mean wave energy is highest in the western Mediterranean between Menorca and Sardinia-Corsica, and generally lowest in the eastern Mediterranean, especially along the coasts of the Adriatic, Greece, and Turkey. Sea level in the Mediterranean is rising at about 1.4 mm yr^{-1}. Antonioli et al. [2] proposed that notches first started to form when there was a significant reduction in the rate of RSL rise in the Mediterranean about 6800 years ago, and then migrated landwards and upwards as sea level rose to its present elevation.

3. The model

Although there are no precise data on notch erosion rates at different elevations in the Mediterranean, Pirazzoli [37] opined that they are highest at mean sea level and decrease towards the high and low tidal levels. Furlani and Cucchi [16] installed seven micro-erosion meter stations between 0.75 m above and below mean sea level on a vertical limestone slab in the Gulf of Trieste (Italy), where the mean spring tidal range is 0.86 m. Measurements were made over a five-year period, although the authors considered the most reliable were for the three-year period following the first two years of exposure, after the slab had become weathered and colonized by marine organisms (Fig. 2a)).

The model used a grid with a potentially infinite number of cells, although the number was limited in practice by the required amount of sea level change (vertical plane - elevation units) and the time over which notch formation was to be studied (horizontal plane - time units). Each cell was used to record the amount of erosion occurring during one time unit according to the elevation of that cell relative to the mean sea level. Relative erosion rates in the model, based on Pirazzoli's [37] comments and Furlani and Cucchi's [16] field data, decreased linearly from a maximum of 1 at the mid-tidal level to zero at elevations 10 vertical units above and 10 units below the mid-tidal level (Fig. 2b, Table 1). These erosion rates were used in most model runs and are therefore referred to as 'normal', although rates ranging from half to double the normal rate were used in some runs to investigate variations in rock resistance and process efficacy. Linear changes in erosion rates with elevation in the model were similar to those reported by Furlani and Cucchi, with the exception of the very slow erosion detected 0.5 m above mean sea level in the Gulf of Trieste, and the fastest rate being a little below the mid-tidal level in that area (Fig. 2a)).

Profile development was modelled by calculating the total amount of erosion occurring in the horizontal plane. Each run was made over about 31 time units (T1, T2, etc in Table 1), the total number of units varying slightly to accommodate an even number of episodic events (for example, 30 time units, or iterations, were needed for runs in which RSL dropped three times by 10 elevational units every 10 time units). Although the model employed a grid with nominal vertical and horizontal dimensions, each interval in the vertical plane would represent about 0.05 m for a 1 m tidal range (1/21) and 0.025 m for a 0.5 m tidal range (0.5/21). Given that notches in the model runs were typically represented by about 10 to 20 time units, if one assumes that modern notches in tectonically stable regions have been developing for the last 3,000 years, then each horizontal or time unit would represent a roughly 150- to 300-year period.

Notch height in this paper refers to the difference in elevation between the roof at the front of the notch and the floor of the