Numerical Modelling of Tidal Notch Sequences on Rocky Coasts

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Abstract: Tidal notches have had the potential to form at sea level from ~6,000 years BP in the Mediterranean basin and preserve a symmetrical shape comparable to a quadratic polynomial. Statically determined, the roots are defined by the tidal range. However, gradual variations of eustatic sea-level rise and coseismic uplift in tectonically active regions contribute to vertical shifts of the erosional base at coastlines. As a consequence, the cliff morphology gets modified through time resulting in widening, deepening and separation of notches and possible overprinting of older features. In order to investigate successive modifications of coastal cliff morphology we developed a numerical model that considers the erosion rate, the erosion zone relative to sea-level, the regional sea-level curve, and tectonic uplift rates. The results show, that the present-day notch sequence from top descending to sea-level is not inevitably of decreasing age. Furthermore, the initiation of notch formation is not necessarily linked to the date of a certain seismic event.

Key words: Tidal Notches, digital modelling, Sea-Level Curve, extensional tectonics, Holocene.

Introduction

Tidal notches are widely used as a sea-level marker. Notches form due to the contributions of ongoing horizontal erosion by chemical, physical and biological agents, they develop obvious ecological and morphological topographies that range from a few centimetres up to several metres deep. When these features are raised or submerged from present-day sea-level, palaeo-tectonic activity can be inferred. However, it remains unclear as to what present morphologies can reveal regarding the palaeo-magnitude and coseismic uplift/subsidence of historic earthquakes. Biological erosion dominates notch formation on limestone coasts (e.g. Evelpidou et al., 2012). Frequently submerged by periodic tides horizontal galleries of endolithic bivalves are most active in the midlittoral zone, which extends across the tidal range (Pirazzoli, 1986). Endolithic bivalves act as the primary notch-forming agent and their habitat is limited to the tidal zone so the duration of sustained relative sea-level controls how deep a notch indentation develops. However, eustasy, isostasy, and vertical tectonic movements exhibit considerable spatial and temporal variability throughout the Holocene (Lambeck et al., 2004).

Boulton and Stewart (2015) compared local sea-level curves with associated regional uplift estimates and concluded that the highest elevation tidal notch on uplifting coasts dates to ~6,000 years BP in the Mediterranean. At that time the rate of eustatic sea-level rise decreased to ~1 mm/yr and reached gravitational equilibrium with the continental lithosphere (Carminanti et al., 2003; Stocchi et al., 2005) (Fig. 1). Since the Mid-Holocene slow relative sea-level changes caused gradual changes of the erosional base at emerging coastlines. However, in seismically active regions, such as the extending Gulf of Corinth (central Greece), rapid displacements occur due to coseismic uplift of the coastlines that may not have exceeded the tidal range. As a consequence of both slow (eustatic) and rapid (tectonic) variations in the position of the erosional base, notch shape modification occurs. To distinguish between notch widening and new notch development is challenging (Fig. 2). It has to be expected, that the time period for notch formation might be short and the resulting indentation is only of minor scale, and that massive overprinting and degradation of older features has occurred since 6,000 years BP.

Fig. 1: Mid-Holocene sea-level curve for the Peloponnese, Greece (after Lambeck & Purcell, 2005). The gradient of sea-level rise and isostatic Holocene regional uplift (orange) are similar not until approximately 6,000 years BP.
In order to visualise the development of notch sequences incorporating eustatic and isostatic balances, erosion rates, coseismic uplift, and cliff steepness, we present a numerical model that simulates the migration of the erosional base through the Holocene. Well dated features can operate as inputs in order to verify the interpreted results or to indicate missed events due to notch degradation.

**Dynamic Notch formation**

In the first instance, the gradient of relative sea-level change determines whether a tidal notch will develop or not.

![Fig. 2: Logic tree for tidal notch sequence evolution.](image)

The static notch formation model incorporates only the erosion rate (ER) to estimate the notch depth. The dynamic model considers gradual sea-level (SL) changes due to unbalanced eustasy (E) and isostasy (a), and coseismic land displacements. Resulting cliff shapes contain widened notches (I), emerged notches (b), or a combination of both (c).

For the Mediterranean, estimates of limestone erosion rates range from 0.2 - 1.0 mm/yr (Pirazzoli and Evelpidou, 2013). Thus, balanced conditions between eustasy and isostasy have to persist for at least 200 years to develop a significant 0.20 m deep notch. The notch height would approximately equal the tidal range for which estimates range from 0.3 - 0.4 m (Evelpidou et al., 2012). The coefficients of a quadratic polynomial can cover the requirements to describe such shapes (Fig. 3). Thus, in a static model notch depth is specified by erosion rate [mm/yr] x time [yr] of a constant erosional base. Minor variations of sea-level change are not modelled here.

The dynamic model calculates the parabolic erosion for every year considering both rapid and slow relative sea-level changes and computes the cumulative sum of erosional impacts. Using a local sea-level curve and information regarding ongoing isostatic and dated coseismic uplift events as inputs to control the migration of the erosional base enables the model to describe the vertical cliff morphology at a given moment.

![Fig. 3: A quadratic polynomial describes the depth (f(x)) along a symmetrical notch profile. Floor (F) and roof (R) depict the roots separated by the tidal range (TR) along the x-axis. The erosion rate (ER) corresponds to c and determines the depth of the notch after one year. The coefficient b is null since the inflection point is at mean sea-level (SL). The coefficient a controls the gradient at f(0) and thus produces a curved or pointing shape.](image)

The model assumptions are as follows:

- The erosion rate is consistent through time
- Erosion only effects the cliff within the tidal range with maximum impact at mean sea-level and gradual decrease towards the roof and floor (e.g., Antonioli et al., 2015)
- The affected lithology is homogeneous
- The initial cliff surface is smooth

**Results**

The Mid-Holocene sea-level curve for Peloponnese (Greece) from Lambeck & Purcell (2005) shows a monotonically increasing shift (Fig. 1) and does not contain characteristics such as a mid-Holocene highstand (e.g., Kelletat, 2005) or punctuated variation (e.g., Goodman-Tchernov & Katz, 2015). When correcting this curve for the isostatic trend the resulting gradient indicates balanced conditions and suggests the period of notch formation was from ~6,500 years until today. In figure 4, a regional uplift rate of 1.2 mm/yr (Boulton & Stewart, 2015) is modelled. Using this uplift rate, relative sea-level change stagnated starting at ~ 6,000 years BP. However, today, a notch is present about 2 m above sea-level. However, slightly variable gradients within the past 3,000 years cause grazing towards the erosional zone and notch formation at the present-day sea-level. Vertical cliff sections above the present-day sea-level are...
significantly different in shape than those predicted without coseismic uplift events. Introducing coseismic uplift events creates a stepwise modification to the emerging coast function (Fig 5). Using the same regional uplift rate as before no submerged notches occur but vertical cliff sections above the present-day sea-level are significantly different in shape than predicted without coseismic uplift producing events. The most elevated notch is not as deep but significantly higher (at ~2.5 m) than the notch predicted in Figure 4. The uplift events lower the the erosional base. When sea-level is rising at ~1.2 mm/yr with a tidal range of 0.4 m, an uplift event of 0.22 m causes a prolongation of the erosional phase along a vertical section of sea cliff.

In the coseismic uplift model (Figure 5) initial notch formation begins prior to uplift event 2. Event 2 in figure 5 causes prolongation of the erosional phase of the initial notch. Contrarily, event 3 and 4 cause a lowering of the erosional base in a period of eustatic and isostatic balance (<6,000 BP). As a result, the erosional level significantly changes and results in the development of a new notch generation in response to each uplift event. In accordance to the applied sea-level curve no notch can be dated older than ~7,000 years BP.

A more likely scenario is presented in figure 6. The cliff slope is not vertical and the seismic recurrence interval chosen is more suitable for the Peloponnese (Gaki-Papanastassiou et al., 2007). Furthermore, earthquake magnitudes are lowered to M6.5 producing only 0.11 m of coseismic uplift. The first notch develops at almost 6,500 years BP at an equivalent modern elevation of 2.2 m. Event 2 causes a quasi-relative sea-level-stagnation since eustatic sea-level rise is slightly faster than the gravitational uplift at that time. At ~5,900 years BP the roof of the initial notch gets significantly degraded and a younger generation notch forms at about 2.6 m (modern ASL). At 5,400 years BP, event 3 causes a lowering of the erosional base of 0.11 m and thus only widens the notch. Successive displacements of the erosional base are caused by events 4 and 5, at 4,500 and 3,600 years BP, respectively. Also, event 5 shifts the erosional base back to a level which occurred already 3,000 years ago. Subsequent coseismic events are accompanied by gradual relative sea-level variations. As a result, individual notches are widened and more separated than those that formed earlier.

Local sea-level curves can be highly dynamic, c. 8,000 years BP the rise in relative sea-level was considerable at 12-20 mm/yr (see Fig. 1); yet, Lambeck et al. (2014) highlights that 75% of mid-Holocene sea-level rise occurred from 6,700 to 4,200 years BP. In this stage, relative sea-level changed at 1.2 mm/yr and thus equals the herein modelled regional (gravitational) uplift rate. The shift of the erosional base appears to be mainly controlled by coseismic uplift during this period. Since 3,000 years BP, relative sea-level rise has been comparatively slow with rates < 1 mm/yr. As a result, the modelled notch sequence demonstrates how difficult it is to identify the specific timing of when notch formation began (see also Goodmen-Tchernov & Kratz, 2015).

Discussion

Fig. 5: a) Added five seismic events (arrows) of M7 of which each produced a coseismic uplift of 0.22 m. b) Resultant notch sequence. Triangles indicate individual notch generations: The oldest generation already began to develop prior to event 2 (I). (II) and (III) show generations formed due to coseismic uplift (Events 3 and 4). (IV) is the result from coseismic uplift and eustatic/isostatic disbalance. (V) depicts the present-day notch massively stretched due to ongoing disbalance.

Fig. 4: Balancing eustatic and isostatic (1.2 mm/yr) agents (a) and the resulting notch profile (b) after 8 k yrs of a shifting erosional base in a tectonically stable setting. Cliff slope is 90°, Erosion rate is 0.5 mm/yr.
Modern cliff morphology contains indentations, nips, and deepened sections that are not true notches. This geomorphology is a product of continuous notch formation, repeated overprinting, bedrock heterogeniety, storm surge elevations. Gradual sea-level change in combination with tectonic activity shifts the erosional base along the vertical axis. Therefore, it does not necessarily follow that drawdown results in a chronological sequence from old to young (see Fig. 6).

**Fig. 6.** a) 10 regularly separated M6.5 EQ with 0.11 m coseismic uplift (arrows). b) Notch profiles at a certain time during evolution the of present day shape. Asterix points on shown correspondig profile. Triangles indicate individual notch generations. Model input: Cliff slope is 80°, erosion rate is 0.5 mm/yr, and isostatic uplift is 1.2 mm/yr.

**Conclusion**

Dependent on the region and associated local sea-level history, Holocene tidal notches can form beginning about 6,000-6,500 years BP in the Mediterranean Basin. Thereby, the very early stages of counterbalanced conditions might not result in the most elevated sea-level marker at present-day. As a consequence, a notch sequence from sea-level upwards does not necessarily adhere rigidly to a young to old chronology.

Stages of almost-stagnation between regional sea-level rise and regional uplift (since approximately 4,000 years) tend to produce more space between individual notch generations. However, resulting notch shapes appear widened in comparison to older features formed 6,000-4000 years BP.

The model presented makes clear how slow an rapid processes bias each other and enables researchers to have an enhanced understanding of the evolution of tidal notch sequences and thus contributes to palaeoseismological research.

**Acknowledgements:** T. M. Fernández-Steeger (RWTH Aachen University) is acknowledged for financial support and fruitful discussions. We thank Beau Whitney for his throughout review.

**References**


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