The geometry of tidal notches – What do they reveal about coastal tectonics?

Schneiderwind, Sascha (1), Kázmér, Miklos (2), Boulton, Sarah (3), Papanikolaou, Ioannis (4), Stewart, Iain (3), Reicherter, Klaus (1)

(1) Neotectonics & Natural Hazards, RWTH Aachen University, Lochnerstr. 4-20, 52056 Aachen, Germany. s.schneiderwind@nug.rwth-aachen.de
(2) Department of Palaeontology, Eötvös University, H-1117 Budapest, Pázmány Péter sétány 1/c, Hungary.
(3) School of Geography, Earth and Environmental Sciences, Plymouth University, Plymouth, Devon PL4 8AA, UK.
(4) Laboratory Mineralogy – Geology, Agricultural University of Athens, Iera Odos 75, Athina 118 55, Greece.

Abstract: *Tidal notches form at sea-level, predominantly on limestone coasts, during the Holocene. When present-day sea-level is different from distinct and stacked expressions coastal tectonic activities are inferred, in general. However, the relation between the offset of different notch generations and coseismic uplift produced from a single event remains a contentious issue. In order to review the evaluation of raised tidal notches in the frame of palaeoseismology, conceptional modelling of tidal notch sequence development provides new insights of morphological characteristics. High-resolution topographic data is able to provide the potential for the required accuracy to resolve those characteristics. The analysis of surface normal orientation and curvature enables the identification of tidal notches on steep cliffs and mapping of their spatial extent.*

Key words*: Tidal Notches, Holocene, Coastal Tectonics, t-LiDAR, Greece.*

Introduction

Tidal notches along steep rocky calcareous coastlines have been the subject of several studies in the past decades, mainly focussed on Holocene relative land movements sea-level variation and coastal tectonic processes. Resulting in obvious ecological and morphological topographies (Fig. 1) ranging from a few centimetres up to several metres deep, notches form at sea-level within the tidal range by continuous physical, chemical, and biological erosion (Pirazzoli, 1986). Assuming erosion rates between 0.2 – 1.0 mm/yr (Pirazzoli & Evelpidou, 2013), time periods of several decades to hundreds of years either in stable conditions or with balanced contributions of eustasy, isostasy and tectonics are required to form these distinct sea-level markers. Due to the rapidly rising post-LGM sea-level and slow crustal isostatic adjustments, such constant conditions were probably established not before 6 ka BP (Carminanti et al., 2003; Stocchi et al., 2005; Boulton & Stewart, 2015).

When the notches are found above or below the modern tidal range, coastal uplift or subsidence can be inferred, respectively. Warm, microtidal seas with active tectonics such as the Mediterranean provide beneficial conditions for studies that aim to unravel coastal tectonic activity (e.g. Pirazzoli et al., 1982, 1989, 1991; Rust & Kershaw, 2000; Stiros et al., 2000; Kershaw & Guo, 2001; Evelpidou et al., 2012a).

With a focus on Greek coastlines (Southwestern Crete and Eastern Gulf of Corinth), this paper aims to review existing knowledge about tidal notch formation, to provide new insights on reading exposures in terms of palaeoseismology, and to introduce a new methodology in order to extract evidence for coastal uplift in discrete events.

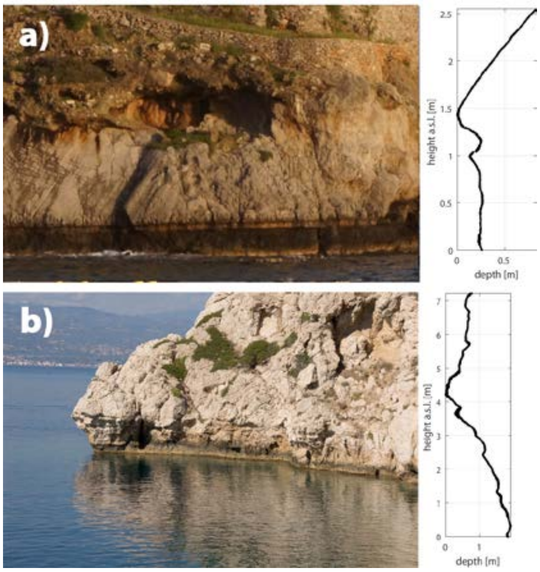

Fig. 1: Examples of palaeo sea-level markers and associated vertical profiles. a) Agio Pavlos (Southwestern Crete) raised by the 365 AD M8.5 earthquake. b) Heraion Lighthouse, Eastern Gulf of Corinth.

Tidal notch formation

The term 'tidal notch' refers to a horizontal erosion feature at sea-level (Kelletat, 2005) due to the coeval action of chemical, physical, and biological impacts (Antonioli et al., 2015). Pirazzoli (1986) established a descriptive vertical classification based on objectively determinable characteristics. According to this study, tidal notches indicate the location of the midlittoral zone, which is vertically limited by the tidal range of approximately 0.4 m in the Mediterranean Sea (Evelpidou et al., 2012b) (Fig. 2).

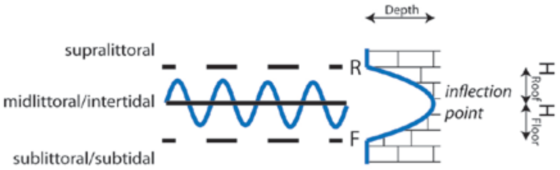

Fig. 2: Tidal notch formation at sea-level.

Chemical component

In the literature chemical erosion of calcareous cliffs is seen as a minor contributor only. Kelletat (2005) points out that dissolution of carbonates is not a common effect of seawater exposure, which is already saturated with $CaCO_3$. Only localised coastal sections might possess decreased saturation levels caused by submarine ground water discharge (Evelpidou et al., 2012b).

Physical component

Abrasion notches characterised by a well-rounded profile and a smooth surface are usually addressed separately. Their formation requires a nearby source of sand and pebbles that can be transported in suspension (Pirazzoli, 1986). Under such conditions the influence of biological erosion is likely decreased, if not completely extinguished since no organisms survive in these grinding environments (Kelletat, 2005).

A different type of physical erosion that occurs on limestone coasts is defined by the rock's resistance to wave action. Structural weaknesses such as cracks, fissures, joints, or faults can increase the potential of physical erosion. The rock is even more affected when turbulent water contains air that gets compressed when smashed against the rock and causes cavitation pitting (Antonioli et al., 2015).

Biological component

Biological erosion is commonly assumed to be the predominant agent in notch formation (Evelpidou et al., 2012b) and forms well-defined vegetational belts (Pirazzoli, 1986). The sublittoral zone of continuous immersion forms the habitat of grazing organisms like sea urchins that erode the underlying rock by abrading the surface with their hard teeth and radulas. Endolithic bivalves, such as the famous Lithophaga lithophaga as well as limpets and chitons live in galleries at mean sea level. The supralittoral zone is only affected at high tide. Here, bioerosion is mainly caused by epilithic algae and cyanobacteria.

The shape of tidal notches

The relative contribution of the aforementioned erosional mechanisms has not been quantified so far. Assuming a constant erosion rate along the tidal range and a periodical tide, the potential to graze a cliff within the tidal range is maximum at sea-level and decreases evenly towards zero at the upper and lower limit of tidal influence, respectively. One possible mathematical description for the decrease of effective erosion is a quadratic function with the tidal range and the maximum erosion rate as inputs. Previous observations and sketches (e.g. Laborel et al., 1999; Cooper et al., 2007; Evelpidou et al., 2012a,b; Pirazzoli & Evelpidou, 2013; Taboroši and Kázmér, 2013; Trenhaile, 2015) support the hypothesis of a first order symmetrical V-/U-shaped notch (Pirazzoli, 1986) profile (Fig. 1a) with its retreat point (hereafter: inflection point) at mean sea level. The time controls the depth of a tidal notch if lithological, biological and climatic conditions are uniform. Deviations from symmetrical shapes occur when the cliff exposure is not sheltered to the open sea and when the cliff is not vertical. Furthermore, if the lithology is not homogeneous or intersected by structural weaknesses asymmetric shapes develop.

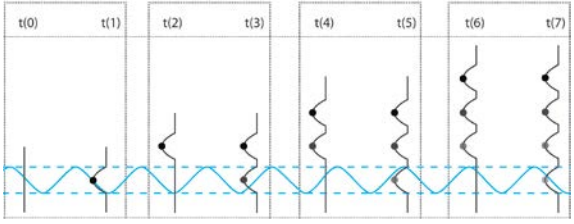

Fig. 3: General concept of raised notches. The initially straight cliff (t(0)) suffers continuous erosion within the tidal range (t(1)) with a maximum erosion rate at mean sea-level (dots). Rapid uplifting events (at t(2), t(4), and t(6)) raise the notches above the erosive zone.

Shape modification

In addition to exposure, and/or organic accretions (Pirazzoli, 1986), modification of the notches is also caused by processes that act differently in vertical and horizontal orientation. When sea-level rise and isostatic regional uplift occur at the same rate, a pseudo-stand still is produced and the erosional zone keeps its relative position along the cliff. Then the notch is only modified in its depth through time but keeps its height as long as the lithology is strong enough to support the weight of the overburden (Trenhaile, 2015). Vertical modification appears through slow and minor sea-level variations or due to rapid vertical land movements. Slow migration of the erosional zone only produces a widening of the existing notch while a rapid coast uplifting (or subsiding) event initiates the formation of a new notch (Fig. 3). When coastal uplift does not exceed the tidal range, the lower parts of the pre-existing notch will be overprinted. Furthermore, the amount of coseismic uplift in extensional tectonic settings ranges from ¼ to ½ of the net slip per event (e.g. Papanikolaou et al., 2010). Thus, even moderate to strong events produce only a few decimetres of uplift which is not likely to exceed the entire tidal range.

Conceptual notch sequence model

The main assumptions for notch modelling are a normal curve distribution of erosion with its maximum at mean sea-level and its tips at low and high tide, respectively (Fig. 4).

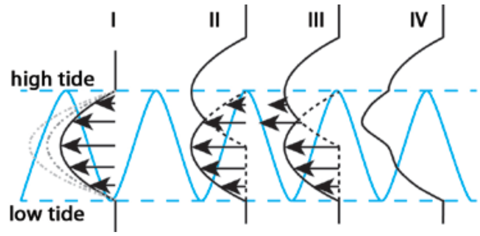

Fig. 4: Notch evolution incorporating a (I) normal distribution of erosion from low to high tide, and (II - IV) the effect of rapid land uplift which does not exceed the tidal range. (II) Raised older notch and theoretical erosion rate distribution. (III) Absolute erosion rates at the actual surface. (IV) Resulting cliff morphology exhibiting two notch generations.

Applying this model to the actual cliff's surface does not develop a classical ripple notch. Also, the resulting shape has its deepest indentation not at mean sea-level. The sum of afore and ongoing net erosion results in parts of the recent notch to be deeper than at mean sea-level. Furthermore, the resulting shape exhibits a significant potential for misinterpretation based on more than one uplifting events. Figure 5 shows the evolution of a notch sequence resulting from three earthquake events of the same magnitude and associated uplift each separated by the same time period.

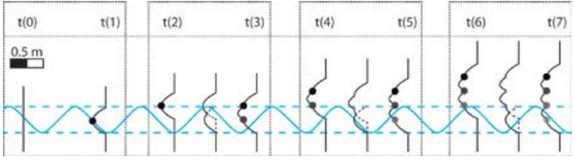

Fig. 5: Evolution of a notch sequence. M7 earthquakes at t(2), t(4), and t(6) produce successive coastal uplifts of 0.22 m. Grey dots indicate former inflection points.

As a result, raised inflection points are not located at the deepest indentations of the sequence. Further, uplifts of more than half the tidal range do not produce a successive deepening of the cliff exposure. The inflection points only migrate vertically but are still existent on the exposed cliff. If the amount of uplift is less than half of the tidal range no remnants of pre-existing notches are preserved (Fig. 6).

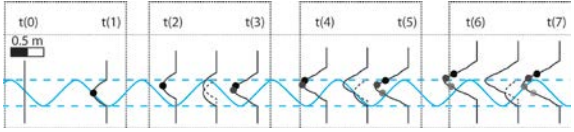

Fig. 6: Successive evolution of a notch sequence experiencing 3 earthquakes (t(2), t(4), and t(6)) of different magnitude (M6.5, M6.2, and M6.4) and uplift (0.11 m, 0.08 m, and 0.1 m). Grey dots indicate former inflection points

The usage of reasonable earthquakes and associated mean uplifts (in accordance with Wells & Coppersmith, 1994) produces a sequence with successive indentation into the cliff exposure, when still applying equal recurrence intervals. Furthermore, not only the lower parts of pre-existing notches but also their inflection points and even more towards the roof will degrade. As a result, the individual inflection points are only projections of previous relative mean sea-levels onto the successively incised exposure and do not show any distinct geometrical evidence for their existence.

In sheltered conditions the roof may be preserved and allow reconstructing the palaeoseismic history.

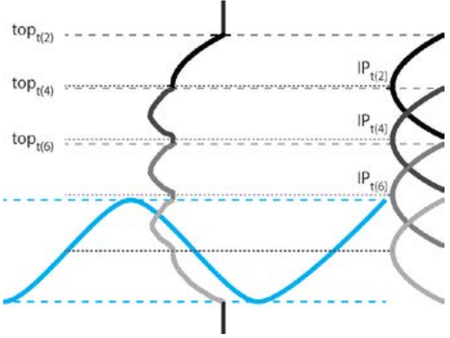

Fig. 7: Reading the sequence. The preserved top of each notch generation allows reconstructing associated inflection points (IP). This figure refers to the notch sequence of Fig. 5.

When assuming that the tidal range did not change through time and thus the parabolic shape intersects the levels of low and high tide, respectively, historic sea-levels can be reconstructed (Fig. 7). However, recognising this potentially minor feature might turn out to be challenging.

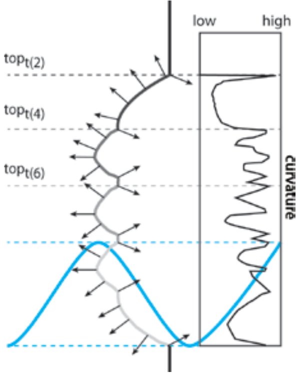

Fig. 8: Normal orientation and direction (arrows), and surface curvature along a vertical notch sequence.

High-Resolution Laser Scanning

High resolution terrestrial laser scanning (TLS) offers the opportunity to evaluate an exposure not just by single vertical profiles (e.g. Kázmér & Taboroši, 2012) but in a full 3D-extent. The high accuracy and precision of the resulting point cloud data enables to detect minor changes in surface curvature and normal orientation (Fig. 8). The majority of surface normals of the concave cross-section of the notch is oriented towards the cliff (Fig. 8). Only a few knickpoints face towards the sea. However, when pointing downwards these normal vectors are located at the roof of a notch. Furthermore, the curvature represents the bend of a surface within a given radius. Thus, the combination of normal orientation and the amount of curvature points to remnants of older notch generations. The third dimension provided by TLS allows comparing the evolution of the curvature along the exposure and thus, verifying evidence for a raised tidal notch (Fig. 9).

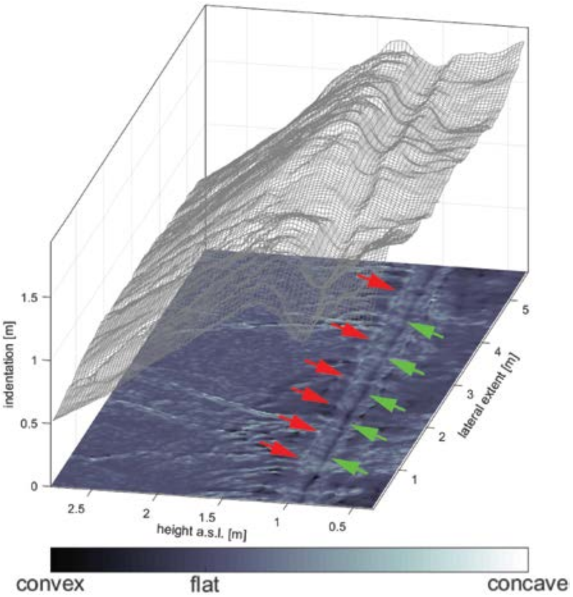

Fig. 9: Laser scan from a distinct tidal notch at Agio Pavlos (Southwestern Crete). Concave (red) and convex (green) patterns represent the roof and the center of the notch, respectively.

Conclusions

The symmetrical shape of tidal notches is the result of frequent immersion due to constant periodical tides. In sheltered conditions, a distinct notch floor and roof form at low and high tide, respectively. Ongoing erosion only affects the dethp of a notch but not its height. Conceptual modelling showed that, following these assumptions, complex sequences of raised notches carry information on palaeo sea-levels. However, remnants of overprinted older features are difficult to recognise. High-resolution surface data, such as from TLS, can provide the required accuracy to analyse the orientation of normals and the curvature along an exposure.

Acknowledgements: The Hellenic Navy Hydrographic Service provided tidal range data from Posidonia. Thanks to C. Hilgers and his team (RWTH Aachen University) for the loan of the TLS System. T. M. Fernández-Steeger (RWTH Aachen University) is acknowledged for financial support.

References

Antonioli, F., Lo Presti, V., Rovere, A., Ferranti, L., Anzidei, M., Furlani, S., Mastronuzzi, G., Orru, P.E., Scicchitano, G., Sannino, G., Spampinato, C.R., Paglirulo, R., Deiana, G., de Sabata, E., Sansò, P., Vacchi, M., and Vecchio, A., 2015. Tidal notches in Mediterranean Sea: a comprehensive analysis. Quaternary Science Reviews 119, pp. 66–84.

Boulton, S. J. and Stewart, I. S., 2015. Holocene coastal notches in the Mediterranean region: In-dicators of palaeoseismic clustering? Geomorphology 237, pp. 29–37.

Carminati, E., Doglioni, C.., Scrocca, D. (2003): Apennines subduction-related subsidence of Venice (Italy). Geophys. Res. Lett. 30 (13).

Cooper, F.J., Roberts, G.P., and Underwood, C.J., 2007. A comparison of 10 3 −10 5 year uplift rates on the South Alkyonides Fault, central Greece: Holocene climate stability and the formation of coastal notches. Geophys. Res. Lett. 34 (14).

Evelpidou, N., Vassilopoulos, A., Pirazzoli, P. A. (2012a): Submerged notches on the coast of Skyros Island (Greece) as evidence for Holocene subsidence. Geomorphology 141-142, pp. 81–87.

Evelpidou, N., Kampolis, I., Pirazzoli, P. A., Vassilopoulos, A. (2012b): Global sea-level rise and the disappearance of tidal notches. Global and Planetary Change 92-93, pp. 248–256.

Kázmér, M. and Taboroši, D., 2012. Rapid Profiling of Marine Notches Using a Handheld Laser Distance Meter. Journal of Coastal Research 283, pp. 964–969.

Kelletat, D.H., 2005. Notches. Encyclopedia of Coastal Science. Edited by M. L. Schwartz. Springer, Dordrecht.

Kershaw, S. and Guo, L., 2001. Marine notches in coastal cliffs: indicators of relative sea-level change, Perachora Peninsula, central Greece. Marine Geology 179 (3-4), pp. 213–228.

Laborel, J., Morhange, C., Collina-Girard, J., and Laborel-Deguen, F., 1999. Littoral bioerosion, a tool for the study of sea level variations during the Holocene. Bull. of the Geological Society of Denmark 45, pp. 164–168.

Papanikoloau, I., Foumelis, M., Parcharidis, I., Lekkas, E.L., and Fountoulis, I.G (2010): Deformation pattern of the 6 and 7 April 2009, Mw=6.3 and Mw=5.6 earthquakes in L'Aquila (Central Italy) revealed by ground and space based observations. Nat Hazards Earth Syst. Sci., 10, 73-87.

Pirazzoli, P. A. (1986): Marine notches. In Orson van de Plassche (Ed.): Sea-Level Research. Dordrecht: Springer Netherlands, pp. 361–400.

Pirazzoli, P. A., Laborel, J., Saliège, J. F., Erol, O., Kayan, İ., Person, A. (1991): Holocene raised shorelines on the Hatay coasts (Turkey): Palaeoecological and tectonic implications. Marine Geology 96 (3-4), pp. 295–311.

Pirazzoli, P. A., Montaggioni, L. F., Saliège, J. F., Segonzac, G., Thommeret, Y., Vergnaud-Grazzini, C. (1989): Crustal block movements from Holocene shorelines: Rhodes Island (Greece). Tectonophysics 170 (1-2), pp. 89–114.

Pirazzoli, P. A., Thommeret, J., Thommeret, Y., Laborel, J., Montag-Gioni, L. F. (1982): Crustal block movements from holocene shorelines: Crete and antikythira (Greece). Tectonophysics 86 (1-3), pp. 27–43.

Pirazzoli, P. A. and Evelpidou, N. (2013): Tidal notches: A sea-level indicator of uncertain archival trustworthiness. Palaeogeography, Palaeoclimatology, Palaeoecology 369, pp. 377–384.

Rust, D. and Kershaw, S. (2000): Holocene tectonic uplift patterns in northeastern Sicily: evidence from marine notches in coastal outcrops. Marine Geology 167 (1-2), pp. 105–126.

Stiros, S.C., Laborel, J., Laborel-Deguen, F., Papageorgiou, S., Evin, J., and Pirazzoli, P.A., 2000. Seismic coastal uplift in a region of subsidence: Holocene raised shorelines of Samos Island, Aegean Sea, Greece. Marine Geology 170 (1-2), 41–58.

Stocchi, P., Spada, G., Cianetti, S. (2005): Isostatic rebound following the Alpine deglaciation: impact on the sea level variations and vertical movements in the Mediterranean region. Geophys. J. Int. 162 (1), pp. 137–147.

Taboroši, D. and Kázmér, M., 2013. Erosional and Depositional Textures and Structures in Coastal Karst Landscapes. Michael J. Lace, John E. Mylroie (Eds.): Coastal Karst Land-forms, vol. 5. Dordrecht: Springer Netherlands (Coastal Research Library), pp. 15–57.

Trenhaile, A.S., 2015. Coastal notches: Their morphology, formation, and function. Earth-Sci Rev 150, 285–304.

Wells, D. L. and Coppersmith, K. J. (1994): New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America 84 (4), pp. 974-1002,A1-A4,B1-B11,C1-C49.