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Variations holocènes du niveau relatif de la mer d’après les encoches de marée submergées : approche méthodologique

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ABSTRACT

Underwater geomorphological survey may reveal evidence of submerged tidal notches. In this paper, we present the methodology with the aim to reveal past temporary standstills of relative sea-level. Some examples of tidal notch development and tectonic movements are provided from fossil submerged notches mainly from Greece. A vertical movement causes a displacement of the intertidal bioerosion zone. For this reason the tidal notch profile reflects changes that occurred in the relative sea-level. If the movement is rapid a new tidal notch will be formed. On the contrary, if the movement is slower than the intertidal bioerosion rate, the height of the notch will increase. For this reason underwater marks on carbonate cliffs may provide evidence of recent vertical shoreline displacements of gradual or co-seismic origin.

Keywords: tidal notches, sea-level changes, intertidal bioerosion

RÉSUMÉ

VARIATIONS HOLOCÈNES DU NIVEAU RELATIF DE LA MER D’APRÈS LES ENCOCHES DE MARÉE SUBMERGÉES : APPROCHE MÉTHODOLOGIQUE

Des relevés géomorphologiques sous-marins sont susceptibles de révéler l’existence d’encoches de marée submergées. Cet article propose une méthodologie pour déterminer des périodes temporaires de stabilité du niveau relatif de la mer dans le passé. Quelques exemples de développement d’encoches de marée fossiles en fonction de mouvements tectoniques sont fournis, principalement en Grèce. Un mouvement vertical provoque un déplacement de la zone de bioérosion intertidale. De ce fait, le profil de l’encoche de marée témoigne des variations du niveau relatif de la mer. Si le mouvement est rapide, il aboutit à la formation d’une nouvelle encoche de marée. Au contraire, si le mouvement est moins rapide que la vitesse de la bioérosion intertidale, il provoque une augmentation de la hauteur de la même encoche de marée. De ce fait, des traces préservées dans des roches carbonatées peuvent indiquer des changements récents de la ligne de rivage correspondant à des déplacements verticaux graduels ou d’origine co-sismique.

Mots-clés : encoches de marée, changements du niveau de la mer, bioérosion intertidale

1 - INTRODUCTION

In the midlittoral zone, parallel vegetational belts are more developed. Eroding Cyanobacteria, patellaceous gastropods (limpets) and chitons are more abundant (Laborel & Laborel-Deguen, 2005) contributing to the erosion of the underlying rock, by grazing the vegetational belts (Torunski, 1979), and in sites sheltered from strong wave action, they enable the development of a reclined U-shaped or V-shaped intertidal notch. The bioerosion rate is generally higher near the Mean Sea-level (MSL) where the vertex of the tidal notch is developed and gradually decreases towards the upper and lower limits of the intertidal range (fig. 1). The profile of a tidal notch is an excellent sea-level indicator, because it provides information about the former MSL position, the approximate duration in which MSL remained at the level of the notch vertex and it determines whether the vertical displacement was gradual or rapid, possibly co-seismic (Pirazzoli, 1986, 2005; Evelpidou et al., 2011b).

Micro-erosion measurements have shown that the deepening rate of a tidal notch profile may be very variable in the Mediterranean, since it ranges from less than 0.1 mm.yr\(^{-1}\) to more than 1 mm.yr\(^{-1}\), with averages of the order of 0.2 to 0.3 mm.yr\(^{-1}\) at some sites (Pirazzoli, 1986; Furlani et al., 2011a,b; Evelpidou et al., 2011b). This high variability may depend on seasonal changes in the environment (temperature, salinity, air pressure) that influence not only the intertidal vegetation and grazing...
organisms, but also the sea-level changes over seasonal or inter-annual scales.

All carbonate rocks are not equally sensitive to tidal-notch development: the slope of the rock layers and irregularities on the rock structure or surface may locally prevent the development of a tidal notch (Pirazzoli & Evelopidou, 2013). During the last two centuries tide gauges have shown that the global sea-level (sensu Kemp et al., 2011, or Jevrejeva et al., 2008) was rising at a faster rate than the possibilities of intertidal bioerosion (at least in the Mediterranean). As a consequence, new tidal notches have not been forming in most places, where the average tidal range is less than the sea-level rise during the last couple of centuries (Evelopidou et al., 2012a).

If raised notches have often been used to estimate past changes in sea-level and tectonic movements (e.g. Pirazzoli et al., 1982, 1989, 1994; Liew et al., 1993; Hantoro et al., 1994; Bard et al., 1996; Stewart et al., 1997; Stiros et al., 2000, 2009; Morhange et al., 2006), submerged notches, which are more difficult to observe, have been studied mainly occasionally by a few authors. Such underwater observations have been, most of the time, devoted to the measurement and interpretation of a single submerged tidal notch (e.g. Pirazzoli, 1980; Fouache et al., 2000; Benac et al., 2004; Antonioli et al., 2007; Nixon et al., 2009; Fauve et al., 2010a,b; Furlani et al., 2011a,b). Nevertheless, Holocene tectonics may include more than a single episode and it may be useful to extend underwater observations below the first submerged notch. This seems to have been attempted only in very few cases e.g. in the Kvarner region (Benac & Juračić, 1998).

In comparison, by applying the methodology described in this paper and an accurate analysis of the genesis of notch profiles, it has been identified more than one submerged shoreline along most of the northern coast of the Corinth Gulf (Evelopidou et al., 2011a), along the coast of Skyros Island (Evelopidou et al., 2012c), along Skopelos and Alonnisos Islands (Evelopidou et al., 2013a) and in the SE Cyclades (Evelopidou et al., 2013b). In all the cases studied, the vertical successions of submerged notches suggest the occurrence of rapid subsidence events, potentially of seismic origin.

The aim of this paper is to summarize the methodology that would be most useful to apply systematically in order to reveal past temporary standstills and the type of changes in the relative sea-level that have occurred in carbonate coastal zones based on submerged tidal notches.

2 - MATERIALS AND METHODS

Detailed, accurate and systematic survey along the coastal zone by boat is necessary in order to access all sites and to establish lateral continuity of observations. During the survey, the local lithology and tidal range are taken into account. For each site, the time and the GPS coordinates are collected. Underwater, the observed features are measured in relation to the apparent sea-level and the accuracy in depth measurements due to waves should be estimated. Finally, the observed features are photographed and video recorded.

Notch geometries (height, vertex and inward depth) are measured according to Pirazzoli (1986) (fig. 1). The accuracy can be improved by multiple measurements, while depths referred to the apparent sea-level at the time of the measurement are subsequently corrected by comparison with tide-gauge records at nearby tidal stations, also taking into account the real meteorological conditions (especially air pressure and wind).

The profile of the notches is recorded in detail during field work and afterwards interpreted as discussed in next paragraph. Submerged tidal notches cannot be dated directly, but their age can be indirectly estimated. After field work, reports from the observations are delivered first (fig. 2) as they are essential for initial interpretations and discussions, while, tables including tide corrections with sizes of submerged notch profiles may be prepared afterwards, resulting from the primary analysis of the collected data. These tables should include the following information: area, site, coordinates, notch measurements (corrected for tide and air pressure), genesis and illustrations. The notch measurements should include data regarding the roof depth from sea-level, the vertex from sea-level, the height and the inward depth of vertex. Additional information of the nearby area such as platforms, bottom, depth, etc, could be also provided.

The described table could also include further information deriving from the first order interpretation of the collected data. This information should include the
possible duration of development (centuries) deduced from the measurement of the inward depth (e.g. Evelpidou et al., 2011b; Evelpidou et al., 2012c; Evelpidou et al., 2013a) and the regional sea-level correlation (cm below present MSL).

3 - EXAMPLES OF INTERPRETATION OF NOTCH PROFILES

Data collection during fieldwork constitutes a key element for this type of studies. The notch geometries (fig. 1) and the mapping of the notch profile are the data to be further interpreted. Various tidal notch profiles for submerged notches, e.g. fig. 3, have been graphically

Fig. 3: Theoretical (A) and observed (B) type a’ notch profiles.
A/ Notch of type a’ profile (after Evelpidou et al., 2011a, 2012a,c), drown after a rapid, probably co-seismic subsidence. After this abrupt submergence the gradual sea-level rise, which took place during the last few centuries at a faster rate than bioerosion (indicated with oblique lines), kept submerging the area. B/ Submerged notch in Corfu Island (Ionian Sea). Its vertex is located at -51 cm and has an inward depth of 29 cm. The notch profile (type-a’) suggests the occurrence of a relatively stable sea-level during a period of 3-14 centuries, depending on the rate of bioerosion, to enable its full development.

Fig. 2: An example of a field work report for a specific studied site. Apart from the place name and exact location, date and time are very important in order to correct afterwards the measurements taken by comparison with the tide-gauge records and the meteorological conditions. In the specific example from Cephalonia Island (Ionian Sea), a double submerged notch below an elevated one have been identified and measured. Since this figure is an example of the report written during fieldwork, the depth measurements have not yet been tide and meteorology corrected.

Fig. 2: Un exemple de rapport de terrain pour un site spécifique étudié. En plus du nom et de la localisation précise du site, la date et l’heure sont très importantes, en vue des corrections ultérieures des mesures en tenant compte des enregistrements marégraphiques et des conditions météorologiques. Dans cet exemple spécifique de Céphalonie (Mer Ionienne), on a identifié et mesuré une double encoche submergée, au-dessous d’une encoche émergée. Puisque cette figure est un exemple de rapport établi pendant le terrain, les mesures n’ont pas encore été corrigées pour tenir compte de la marée et de la météorologie.
summarized in various papers, e.g. Evelpidou et al. (2011b; 2012a,b,c) and seven theoretical schemes of tidal notch profiles under different conditions, on a vertical carbonate cliff, have been distinguished and allow to qualitatively discriminate the way of subsidence e.g. co-seismic event, gradual relative sea-level rise, etc. A prime (’) has been added to previously compiled fossil notch types, i.e. which are not of present-day formation.

Type a’ (fig. 3A and B): reclined U-shaped notch profile. The height of the notch roof (H_r) is very similar to the height of the notch floor (H_f). A rapid subsidence, greater than the tidal range, resulted to an underwater preserved former notch. Type b’ (fig. 4a and b): two submerged former notches, which were preserved after two rapid subsidence events, greater than the tidal range. Type c’: a rapid subsidence, smaller than the tidal range, preceded and followed by a period of millennium of relative sea-level stability, produces a notch higher than the tidal range (fig. 5A and B). Two vertices appear, separated by an undulation in the notch profile, indi-

Fig. 4: Theoretical (A) and observed (B) type b’ notch profiles.
A/ Notch of type b’ profile (after Evelpidou et al., 2011a, 2012a,c), drown after two rapid, probably co-seismic subsidence events followed by the gradual sea-level rise which took place during the last few centuries, at a faster rate than bioerosion (indicated with oblique lines), kept submerging the area. B/ Two submerged notches in Keros Island (Cyclades, Aegean Sea). The upper notch, developed between -20 ± 10 and -65 ± 10 cm, is of type b’ profile, indicating that its submergence was rapid. The lower notch, between -190 ± 10 and -260 ± 10 cm, corresponds to a former sea-level at about 220 ± 20 cm below the present one.

Fig. 5: Theoretical (A) and observed (B) type c’ notch profiles.
A/ Notch of type c’ profile (after Evelpidou et al., 2011a, 2012a,c). B/ Submerged notches in Naxos island (Cyclades, Aegean Sea). The upper one (see arrow) corresponds to type c’ and suggests a seismic movement that displaced sea-level from the lower notch (NA2) to the upper one NA1.

Fig. 4 : Profils théorique (A) et observé (B) d’encoches de type b’.
A/ Profil d’encoche de type b’ (d’après Evelpidou et al., 2011a, 2012a,c), dessiné après deux cas, probablement co-sismiques, de subsidence rapide. Après cette double submersion, la montée graduelle du niveau de la mer qui a suivi pendant quelques siècles, à une vitesse dépassant la vitesse de la bioérosion (indiquée par des traits obliques) a poursuivi la submersion de la région. B/ Deux encoches submergées dans l’île de Keros (Cyclades, Mer Égée). L’encoche supérieure, développée entre -20 ± 10 et -65 ± 10 cm, présente un profil de type b’, indiquant une submersion rapide. L’encoche inférieure, située entre environ -190 ± 10 et -260 ± 10 cm, correspond à un ancien niveau marin à environ 220 ± 20 cm au-dessous du niveau actuel.

Fig. 5 : Profils théorique (A) et observé (B) d’encoches de type c’.
A/ Profil d’encoche de type c’ (d’après Evelpidou et al., 2011a, 2012a,c). B/ Encoches submergées à Naxos (Cyclades, Mer Égée). L’encoche supérieure, de type c’, suggère un mouvement sismique qui a déplacé le rivage de NA2 à NA1.
cating the former and the following MSL positions. Type d': a gradual relative sea-level rise, at a rate smaller than the bioerosion rate, produces a notch profile much higher than the tidal range but of limited inward depth (fig. 6A and B). Type e': in the case of a gradual relative sea-level rise during one millennium, followed by relative sea-level stability of the same duration, the notch height becomes greater than the tidal range, with $H_k < H_f$ (fig. 7A and B). Type e'': in the case of relative sea-level stability, followed by a gradual relative sea-level rise of the same duration, the notch height becomes greater than the tidal range, with $H_k < H_f$ (fig. 8A and B).

Fig. 6: Theoretical (A) and observed (B) type d' notch profiles. A/ Notch of type d' profile (after Evelpidou et al., 2011a, 2012a,c). B/ A submerged notch in Kineta area, in the Saronic Gulf. The notch is located at ~66 cm, with a height of 99 cm, much larger than the tidal range, and corresponds to type d' suggesting a gradual relative sea-level rise at a slower rate than the intertidal bioerosion.

Fig. 7: Theoretical (A) and observed (B) type e' notch profiles. A/ Notch of type e' profile (after Evelpidou et al., 2011a, 2012a,c). B/ A submerged notch in the north part of Corinth Gulf. This notch is located between about -40 ± 10 and -85 ± 10 cm, with an inward depth of about 45 cm. Its profile is dissymmetrical (e'-type), with the roof height smaller than the floor height. It suggests the occurrence of a gradual subsidence of about half a meter, followed by a period of relatively stable sea-level and then by a period of relative sea-level rise.
Sequences of tectonic events, including periods of relatively stable sea-level, interrupted by co-seismic vertical displacements and possibly by other periods of gradual relative sea-level rise, can be tentatively deduced from erosion profiles on carbonate cliffs. Especially the inward depth of the notch may be used to roughly assess the duration of the relative sea-level standstill. Tidal notches could be relatively dated if correlated with archaeological data and especially anthropic constructions functioning near MSL. For example, it is recognized that fish tanks may be considered as palaeo-sea-level markers that allow accurate evaluation of relative sea-level variations during the last two millennia. Finally, tidal notches may be dated based on historical earthquake records. When vertical displacements are of co-seismic origin, they generally occur at the time of earthquakes with magnitudes larger than 6.0, which for the Greek region are commonly associated with morphogenic faults, and thus produce direct surface faulting (Ambraseys & Jackson, 1990).

5 - DISCUSSION

In the field, it is relatively easy to confirm the continuity of emerged shorelines while the confirmation of the continuity of a submerged shoreline is more difficult. Submerged shoreline cannot be dated directly in the absence of other nearby datable sea-level indicators because bioerosion rapidly destroys submerged fossils, making the collection of samples to be dated almost impossible.

It has been shown by Pirazzoli & Evelpidou (2013) that, if tidal notches can be used to assess interpretations of relative sea-level change in places where they have been preserved, the lack of tidal notches cannot be relied upon to interpret the absence of a sea-level stillstand at that site, and it should be accepted that coastal archives may be incomplete. As a consequence, underwater correlation of submerged shorelines must often be based on a limited number of tidal notch profiles.

In Greece, the study of submerged tidal notches have clearly shown that subsidence in the Aegean area, far from being gradual as often believed by modelers, occurs as subsidence jerks of one or few decimetres, occurring with a frequency of a few centuries. Despite the lag of systematic datings, we can provide examples in several areas where subsidence predominates and inward depth measurements can permit to obtain estimates of average durations of development. Based on the reasonable assumption that bioerosion rate had an average rate of 0.6 mm.yr$^{-1}$ can be deduced that in the Sporades Islands six co-seismic subsidences of an average 25 cm occurred in Alonnisos and seven subsidences of an average 40 cm in Skopelos, with probable average return times of the order of four to five centuries (Evelpidou et al., 2013a). Similarly, in Ithaca Island six co-seismic subsidences of on average 20 cm have been detected with average return time of two to three centuries. The last co-seismic subsidence in Ithaca (about one decimetre) occurred in 1953 (Evelpidou, pers. obs.).

4 - AGE ESTIMATION OF SUBMERGED TIDAL NOTCHES

Submerged tidal notches cannot be dated directly because of the bioerosion that takes place after the submergence and destroys fossils. Their age, however, can be inferred from other sea-level indicators such as archaeological, stratigraphical (e.g. stratigraphic column out of coastal cores), or geomorphological (e.g. beachrocks).

Tidal notches may be dated based on nearby coastal cores (e.g. Nixon et al., 2009; Evelpidou et al., 2012c). They may also be indirectly dated based on their profile.
In the absence of direct radiocarbon dating this method could provide some useful information on the tectonic trend in certain areas while this cannot be applied to areas where co-seismic uplift movements can also occur, e.g. Corfu, Cephalonia, Eastern Attica, Karpathos, etc.

6 - CONCLUSION

A methodology is proposed aiming to reveal past temporary standstills of relative sea-level. This methodology may be applied in underwater marks of carbonate rocky areas and specifically in submerged tidal notches, which correspond to former sea-level positions, or to recent vertical shoreline displacements of seismic origin, under the assumption that the eustatic sea-level has remained almost stable during the last millennia.

The underwater geomorphological survey may reveal submerged tidal notches and allows the determination of subsidence rates in the investigated area while the profile of the notches can allow to qualitatively distinguishing the way of subsidence. Furthermore, proposals of how to relatively date submerged tidal notches and thus former shorelines, are provided.

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