# Chapter 12
# Sea-Level Indicators

**Niki Evelpidou and Paolo A. Pirazzoli**

**Abstract** Because changes in sea level may have a great impact on the distribution of mineral resources, the exploration and exploiting of these resources should not ignore the changes in sea level that may have occurred in the past in the area considered. The study of relative sea-level changes is an essential element of ocean observation and technological advances are often necessary to improve this study that includes the determination of levels (elevation or depth), chronological estimations, and the identification of appropriate sea-level indicators.

Indicators of fossil or present-day sea-level positions are the most important elements for a sea-level reconstruction, because they provide information not only on the former level but also on the accuracy of the reconstruction.

A classification is proposed of the main criteria that can be used to deduce appropriate sea-level indicators from geomorphological, stratigraphical, biological or archeological coastal data. Two cases studies are used as examples of sea-level reconstructions that may be useful to clarify the geology in certain areas, or to coastal engineering and coastal protection: (1) on the impact of the recent sea-level rise in the interpretation of sea-level indicators; and (2) on the foreseeable impacts of the predicted near-future sea-level rise on the coasts of NE Italy.

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## 12.1 Introduction

Because changes in sea level may have a great impact on the distribution of mineral resources, the exploration and exploiting of these resources should not ignore the changes in sea level that may have occurred in the past in the area considered. On the other hand, due to the fact that recent and ongoing sea-level changes have a great impact on the biologic resources in the near shore environment, the possibility of such changes should be considered by mariculture farms and coastal engineers. The study of relative sea-level changes is therefore an essential element of ocean observation and technological advances are often necessary to improve this study that includes the determination of levels (elevation or depth), chronological estimations, and the identification of appropriate sea-level indicators.

Levels may be determined in many manners (with satellites, oceanographic vessels, geophysical equipments, leveling techniques, tide-gauge devices, or even direct measurement by an observer). Chronological estimations may result from radiometric analysis of samples, comparison with stratigraphic sequences, archeological or historical data, assumptions on erosion or deposition processes, or even from glacio-isostatic or climate modeling.

Indicators of fossil or present-day sea-level positions are nevertheless the most important elements for a sea-level reconstruction, because they provide information not only on the former level but also on the accuracy of the reconstruction.

We propose in this chapter a classification of the main criteria that can be used to deduce appropriate sea-level indicators from geomorphological, stratigraphical, biological or archeological coastal data, followed by a couple of case-studies of sea-level reconstructions that may be useful to clarify the geology in certain areas, or to coastal engineering and coastal protection: (1) on the impact of the recent sea-level rise in the interpretation of sea-level indicators; and (2) on the foreseeable impacts of the predicted near-future sea-level rise on the coasts of NE Italy.

## 12.2 How Can Fossil Paleoshorelines Be Identified?

Fossil paleoshorelines can be identified and traced from geomorphological, biological, sedimentological, stratigraphical or archeological sea-level indicators.

The coastal geomorphological features that are used as sea-level indicators are the result of either erosional or depositional processes. Erosional features can only be preserved on hard, solid rocks and in some cases they constitute indicators of sea-level change. Such indicators are marine notches, potholes, abrasion platforms, etc. Among the depositional formations, marine terraces and beachrocks stand out as the most important sea-level indicators.

**Fig. 12.1** Uplifted wave cut notch at western part of Corfu island. Although it indicates that an uplift has taken place it is not a precise sea level indicator that could provide the exact magnitude of the uplift

### *12.2.1 Erosional Geomorphological Sea-Level Indicators*

Erosional processes along coastlines include the direct effects by waves, abrasion, salt weathering, bioerosion and chemical attack (Rampino 2005).

Marine notches on coastal cliffs near sea level may be produced by various processes. The imprecise term 'wave-cut', often found in the literature, generally refers to erosion by wave activity slightly above sea level. The effect of waves transporting sand or gravel, on the rock is abrasive, forming wave-cut platforms and notches, which are easily recognizable by their polished surfaces. The accuracy of abrasion features as sea-level indicators is often weak, depending mainly on exposure (Fig. 12.1).

Salt weathering takes place when salt crystals grow within pore spaces in rocks and is most effective in areas exposed to salt spray and subject to alternative wetting and drying. Salt weathering may produce a honeycomb pattern or a cavernous weathering called tafoni which should not be used however as sea-level indicator, because tafoni have also been observed in arid tropical areas remote from the sea (Fig. 12.2).

Biological erosion may be especially important in tropical or subtropical areas on carbonate coasts. Algae are probably the most important bioerosional agent on

**Fig. 12.2** Tafoni formations may not be used as sea-level indicator since they have been observed also in areas remote from sea. Tafoni of this figure have been formed in a granodiorite hill of Naxos island (Cyclades) and are not related to the sea level changes that have taken place in this area and are generally of subsidence (Evelpidou et al. 2013a)

rocky coasts. The substrate under algal mats is exposed to the products of metabolism and organic waste, which can directly etch the rocks. Algae also support grazing organisms such as gastropods and echinoids, which abrade rock surfaces. Boring and browsing organisms erode rocks most effectively in the intertidal zone. The rate of maximum undercutting (near MSL) varies with the rock type and the local climate and has been roughly estimated to be of the order of 1 mm/a (Laborel et al. 1999). However, this is only a first order value, as lower rates are generally observed in hard limestones, especially in non tropical areas. More detailed estimations show a range varying from 0.2 to 5 mm/a, depending on lithology, location, and probably duration of bioerosion (for references, see Pirazzoli 1986, Table 1; Laborel et al. 1999, Table 1; Evelpidou et al. 2011a, Table 1).

In the midlittoral zone, several types of notches can be useful as sea-level indicators, though with variable accuracy: tidal notches, surf notches and solution notches.

Tidal notches are well known as precise sea level indicators that usually undercut limestone cliffs in the mid-littoral zone (e.g. Pirazzoli 1986), and constitute the most important erosional geomorphological sea-level indicators. In microtidal areas sheltered from wave action, elevated or submerged notches are used to indicate former sea-level positions, with up to a decimetre confidence.

Bioerosion by endolithic organisms and surface feeders grazing upon epi- and endolithic algae are generally acknowledged to play an important role in tidal-notch development. The erosion rate is generally highest near mean sea level (MSL) and

**Fig 12.3** A well developed continuous tidal notch at Cephalonia island, which is emerged nowadays. During its formation the vertex was located near MSL, its base near the lowest tide and its top near the highest tide level

decreases gradually towards the upper and lower limits of the intertidal range. Accordingly, in places sheltered from continuous wave action, if MSL remains stable, tidal-notch profiles will be typically reclined U-shaped or V-shaped, with their vertex located near MSL, their base near the lowest tide and their top near the highest tide level (Fig. 12.3). In a moderately exposed site, continuous wave action may splash sea water onto the roof, thus shifting the top of the notch upwards, above the highest-tide level. When a tidal notch is uplifted or submerged, its profile may provide valuable information on whether the movement was co-seismic or gradual and eventually on the type of paleoseismic history, e.g. whether one or more events took place. Figure 12.4 depicts the three most common profiles for emerged and submerged tidal notches. Profile a and a′ corresponds to a rapid uplift and subsidence accordingly, greater than the tidal range, resulted to a preserved former notch. In Fig. 12.5a an example of a-type profile is shown from Qwambu, Huon Peninsula (Papua New Guinea) while in Fig. 12.5b an example of a′ type profile from Karpathos island (Greece) is shown. Profile b and b′ corresponds to two uplifted and submerged accordingly former notches, which were preserved after two rapid uplift and subsidence accordingly events, greater than the tidal range. In Fig. 12.6a repeated b-type profiles are shown from Tewai, Huon Peninsula (Papua New Guinea) while in Fig. 12.6b an example of b′-type profile from Kaminakia, Antikythira Island (Greece) is shown.

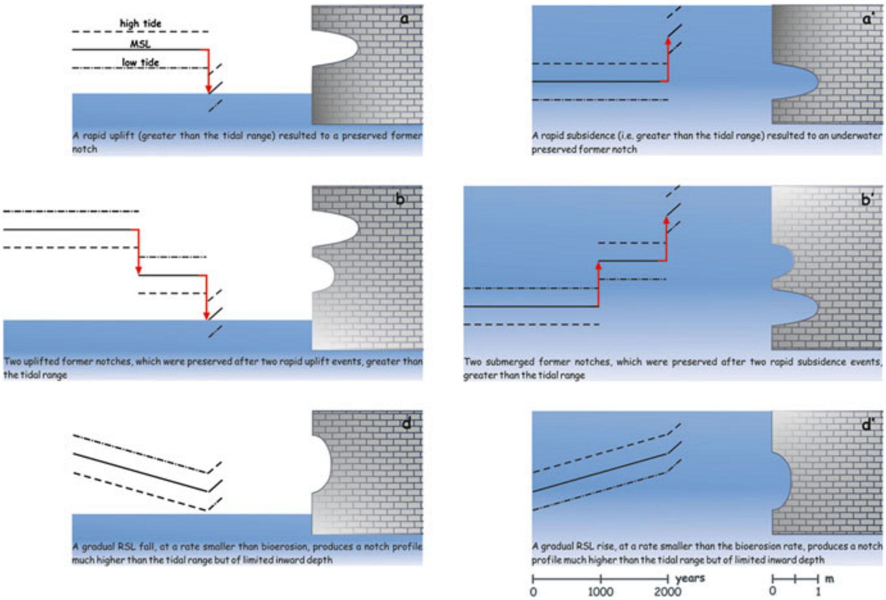



**Fig. 12.4** Various profile types of tidal notches providing information on the type of the event that uplifted or submerged this sea level indicator

Finally, profile d and d′ depict a gradual RSL fall and rise, at a rate smaller than bioerosion, which produces a notch profile much higher than the tidal range but of limited inward depth. In Fig. 12.7a an example of d type profile is shown from Cheng-Kung, eastern coast of Taiwan, while in Fig. 12.7b an example of d′-type profile from north Corinth gulf (Greece) is shown.

Carbonate coasts exposed in stronger wave action commonly have a distinctive morphology. In fact, as water turbulence increases, so does the height of the notch and organic incrustations may develop on the floor of the notch. These organic incrustations often comprise calcareous algae (*Lithophyllum*, *Lithothamnium*, *Porolithon*, *Neogoniolithon*) and vermetids (*Denropoma*, *Petaloconchus*, *Spiroglyphus*) (Kempf and Laborel 1968; Focke 1978a; Laborel 1979) (Fig. 12.5). These organisms protect the substrate rock and thus locally inhibit erosion. While erosion proceeds above the accretion level, a surf bench may begin to form protruding seawards, which may extend as high as 2 m above high-tide level (Focke 1978b). Surf notches may therefore develop on more exposed sites above high tide level. Fossil surf notches can be easily identified and distinguished from fossil tidal notches when a bioconstructed accretion exists near the notch floor. In this case, indications on the former sea-level may be provided by the organic accretion rather than by the notch developed above it.

Solution notches are frequent in carbonate rocks near sea level, in the case of fresh-water arrivals. Higgins (1980) even believes that solution notches in calcareous rocks occur *only* in proximity to coastal springs, where surface seawaters are locally diluted by freshwater.

**Fig. 12.5** (**a**) Holocene raised tidal notch of a-type, at Qwambu, Huon Peninsula (Papua New Guinea). Repeated Holocene coseismic uplifts occurred in this area, with recurrence of 1,000–1,300 years and average uplift of about 3 m (Chappell et al. 1996). C. Jouannic gives scale (Photo P.A.P. A898, 5 Aug. 1988). (**b**) Example of a' type profile from Karpathos island (Greece)

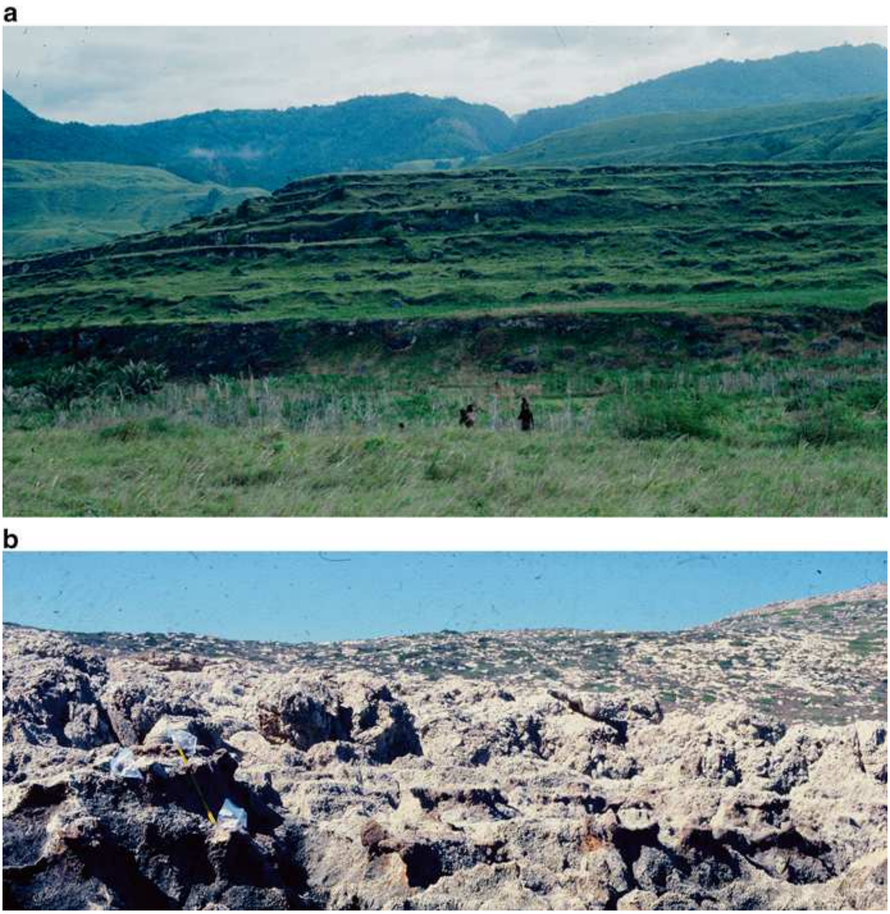
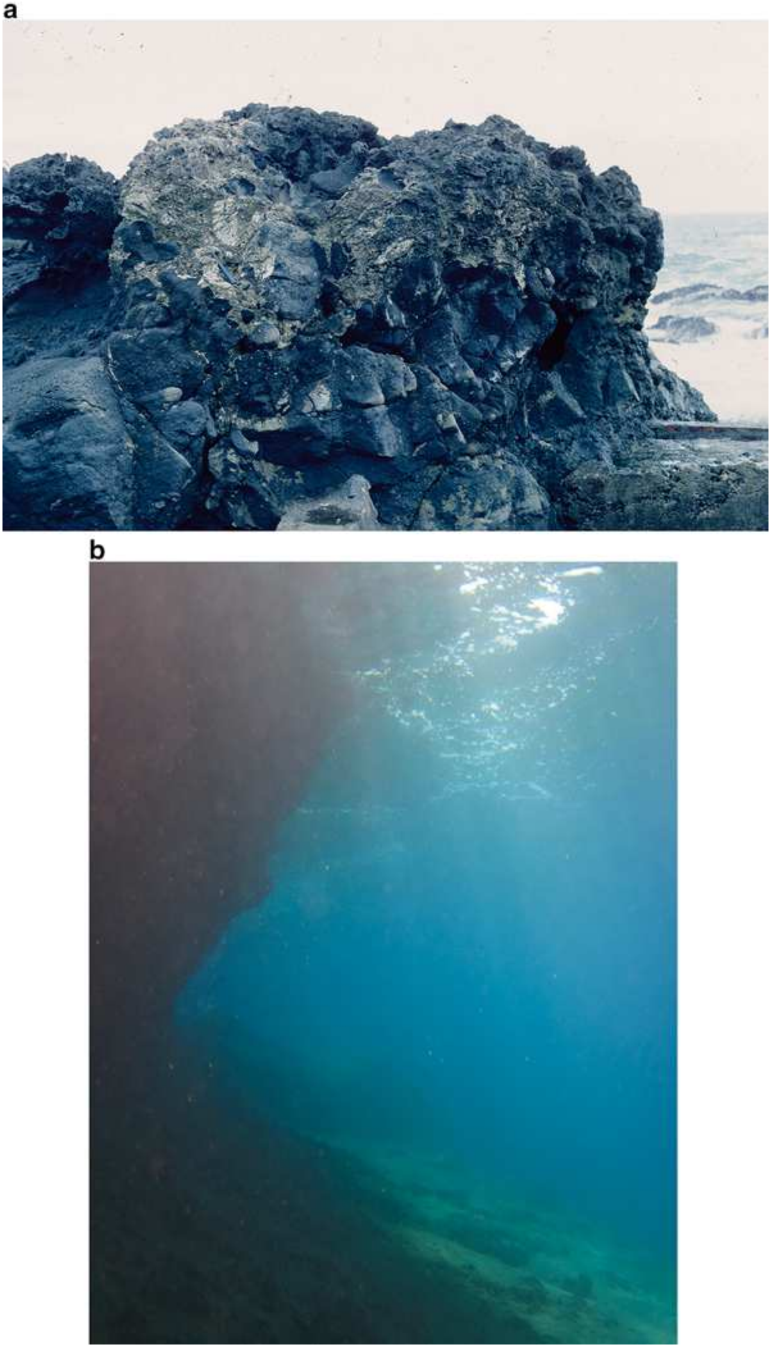


**Fig. 12.6** (**a**) Repeated b-type profiles in Tewai, Huon Peninsula (Papoua New Guinea). The repeated Holocene co-seismic uplifts with a recurrence of 1,000–1,300 years and average uplift of about 3 m caused the development of sequences of Holocene regressive terraces (Chappell et al. 1996). Persons in the foreground give scale (Photo P.A.P. A954, Aug. 1988). (**b**) b′-type tidal notch at Kaminakia, Antikythira Island (Greece). Tidal notches initially formed at sea level and submerged repetitively, have been subsequently raised all together co-seismically in AD 365. Former shorelines may be distinguished at about +2.20 m (its submergence has been dated 1,490 ± 70 BP), at +2.00 m (dated 1880 ± 70 BP and at +1.7 m (dated 2180 ± 70) (Pirazzoli et al. 1981) (Photo P.A.P. 5655, Sept. 1979)

### *12.2.2 Depositional Sea Level Indicators*

Beachrocks are hard, coastal sedimentary formations (Fig. 12.9), consisting of beach sediments that are rapidly cemented by the precipitation of carbonates (High-Magnesium Calcite or Aragonite) (Bricker 1971). The formation of beachrocks takes places in the intertidal zone, and constitutes a diachronic process. Since a



b

Fig. 12.7 (**a**) d-type tidal notch of height greater than the local tidal range bordering a raised coral reef reaching +3.5 m above MSL N of Cheng-Kung, eastern coast of Taiwan. Average tidal range = 1.1 m, Spring tidal range = 1.45 m. This area is characterized by irregular average uplift rates, varying between 2.5 and over 8.0 mm/a (Pirazzoli et al. 1993). At least part of the uplift of the coral reef probably occurred gradually (Photo P.A.P B737, 18 Jan. 1990). (**b**) d′-type tidal notch in north Corinth Gulf (Greece) lithification takes place on the coast, beachrocks (also in correlation with other sea level indicators) have often been used as indicators of sea level changes and neotectonic movements (e.g. Tatumi et al. 2003; Kelletat 2006; Desruelles et al. 2009; Mourtzas 2012; Stattegger et al. 2013).

There is still some debate concerning the reliability of beachrocks as sea level indicators. According to Hopley (1986), beachrocks are more reliable in areas with small tidal range as opposed to low-latitude areas and furthermore only the upper part of beachrocks constitutes a reliable indicator of the paleo-tidal level. Laboratory analysis of beachrock samples is necessary in order to determine the mineralogical composition of the cement and not confuse them with other lithified materials of the coast.

A marine terrace is any relatively flat surface of marine origin, bordered by a steeper ascending slope on one side and by a steeper descending slope on the opposite side (Pirazzoli 2007) (Fig. 12.10). The development of marine terraces is linked to Quaternary sea level changes associated with global climatic changes and/or to active tectonic processes. A steadily and rapidly rising coastline is the best mark for measuring major long term sea-level fluctuations and tectonic uplift, since marine terraces are the geological records of former sea levels. A series of uplifted marine terraces could be even correlated with different interglacial periods, when the uplift rate is rapid enough. Marine terraces may be very useful at extracting rates of long-term tectonic deformation.

Speleothem formations of karstic origin may also provide information for past sea level fluctuations, when they are covered by marine biogenic overgrowths. Although speleothems are typical continental features, developed only in subaerial conditions, when they are submerged by a rising sea level, they are covered by marine biogenic overgrowths. By dating this biogenic overgrowth, it is possible to determine the timing of cave flooding due to rising sea level and the establishment of marine conditions. Speleothems have often been used for sea level reconstructions (e.g. Lundberg and Ford 1994; Antonioli and Oliverio 1996; Alessio et al. 1996; Bard et al. 2002; Antonioli et al. 2004).

### *12.2.3 Sedimentological Sea Level Indicators*

In the study of coastal changes, environments such as coastal marshes and wetlands may provide powerful data as they are sensitive to environmental changes. In particular, sea level fluctuations affect low-lying coastal areas, and any change in sea level will be recorded by vegetation succession, changes in lithology and the microfossil assemblages within deposits. The most common method, for locating material that will provide information regarding sea-level change, is the use of a vibrating sampler. In such environments, the study of lithostratigraphy (sedimentary characteristics) and biostratigraphy (associated flora and fauna) allow to distinguish various sub-environments. Micropaleontological analysis allows distinguishing transitions between sub-environments within the sedimentary sequence.

In order to develop the chronology of the sedimentary sequence, the age of biomarkers and organic, peaty deposits can be established by radiocarbon dating. Biomarkers found in sedimentary sequences, through core analysis, should be related to sea level in a consistent and quantifiable way.

The reconstruction of sea level changes, through the use of drillings, stems from the combined interpretation of lithostratigraphy, biostratigraphy and chronostratigraphy. Such sea level reconstructions should take into consideration some limitations; compaction should be taken into account for the positional uncertainty of the dated samples and samples should be disturbed as little as possible.

### *12.2.4 Biologic Sea Level Indicators*

As the research of sea level changes developed and started taking into account multidisciplinary criteria, the use of fossilized biological remains has developed greatly recently. On a rocky coast, several zones may be distinguished, where littoral flora and fauna are developed in parallel horizontal layers: supralittoral, mid-littoral and infralittoral zones.

Species that live in very narrow depth ranges are considered as the most reliable sea level indicators (Laborel and Laborel-Deguen 2005); such are for instance, the corallines *Lithophyllum lynoides* and *Lithophyllum onkodes*, vermetid gastropods of genus *Dendropoma* and *Spiroglyphus* (Laborel 1986) and annelids such as *Idanthyrsus* and *Galeolaria* (Baker and Haworth 1999). In order to accurately determine a past sea level position, one needs to distinguish and measure the altimetric difference between the fossilized remains and their present day counterpart (Fig. 12.8).

Apart from fossilized biological indicators, it has recently been shown that bioerosional textures in limestone coastlines (Kázmér and Taboroši 2012; Taboroši and Kázmér 2013) may help to determine the chronological order of vertical displacements. For example, traces of sea urchins on a -today- uplifted tidal notch in Cephalonia allowed to determine a complex history of subsidence followed by uplift.

Apart from biological indicators found in rocky coasts, biological markers from core samples are also used to determine past sea level positions, provided that compaction is minimum and the sample is disturbed as little as possible.

### *12.2.5 Archeological Sea Level Indicators*

Geoarcheological analysis in coastal areas provides with valuable evidence for past sea levels, when it is possible to correlate the coastal structures with sea level.

The continuous presence of man during the last thousand years near the coasts has left numerous evidences, such as production structures, town structures and ports. The vast majority of archeological remains cannot provide evidence for the

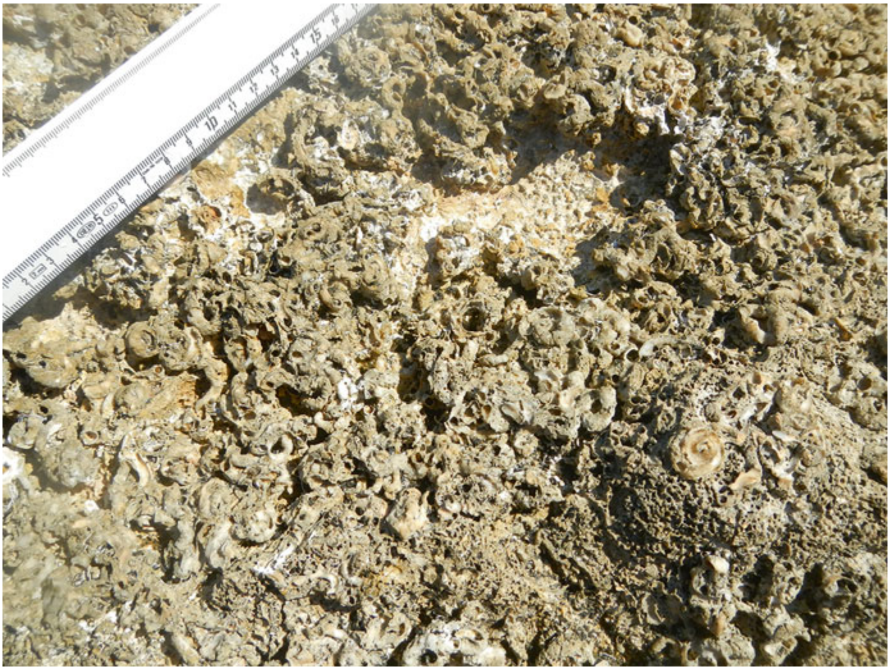


**Fig. 12.8** Continuous incrustations of Vermetids up to +60 cm at Karavomylos area (Cephalonia island)

location of sea level and can only be used in a few cases to obtain information on past sea level fluctuations. This is owed to the fact that a site on land, which has been uplifted, is difficult to be distinguished from a site that was initially built in a higher altitude. In addition, although submerged sites suggest that a relative sea level rise has occurred, it is difficult to quantify such a rise. Nevertheless, some structures were directly "connected" with sea level and during their function were partly submerged, depending on tide and marine conditions (harbor structures, breakwaters, quays, docks, fish tanks, etc.) (Flemming 1979-1980); these may be considered as reliable sea level indicators (Fig. 12.11). A review of various archeological sea level indicators and their accuracy has been provided by Auriemma and Solinas (2009).

In order to reliably reconstruct ancient sea level based on archeological remains, it is necessary to have a good understanding of the structure's usage and functionality and the local hydrographic and climatic conditions.

## 12.3 Dating Relative Sea Level Changes

Dating sea level changes may be direct or indirect, depending on the type of sea level indicator available, whether it is found emerged or submerged and, therefore, whether datable material is available.

**Fig. 12.9** Uplifted beachrock formation near Ancient Diolkos at Corinth Gulf. Scale is given by Niki Evelpidou

**Fig. 12.10** Marine terrace at Arkitsa area (North Euboean Gulf, Greece)

The easiest and most trustworthy method is radiocarbon dating of biomarkers. This is usually the case for uplifted fossil shorelines, or samples deriving from coastal cores; in the latter the accuracy of the relationship of the biological marker to mean sea level should be taken into account.

In the case of submerged sea level indicators, indirect ways may be used to date a past sea level; correlation with other dated sea level indicators (e.g. archeological or from coastal cores) found at about the same depth is commonly used.

Archeological remains used as sea level indicators are not always easily and accurately dated. For instance, buildings may be dated with more precision by their intrinsic and distinctive features in comparison to quarries or breakwaters, whose typology remained unchanged for centuries (Auriemma and Solinas 2009). A special exception are Roman fish tanks, whose use was very frequent along the

**Fig. 12.11** Punta della Vipera fish tank located near the town of Civitavecchia (Tyrrhenian coast of Italy). Features such as foot walks (crepidines), sluice gates, tops of channels, and moles may provide information regarding relative sea level at the time of construction

Tyrrhenian coasts of central Italy between the 1st c. BC and the 1st c. AD (Plinius, Naturalis Historia, IX; Columella, De Re Rustica, XVII; Varro, De Re Rustica, III).

A special mention should also be made to beachrocks, whose dating presents some difficulties. Beachrocks can be dated either by biogenic materials with radiocarbon, or by dating the cement. In the case of biogenic materials, it is possible to acquire an age much older than that of the beachrock lithification, because the time interval between the death of the organism and the cementation of the beachrock may have lasted very little time to even thousands of years. In the case of dating the cement, difficulties arise when trying to extract enough material and furthermore, the acquired age may be much younger due to subsequent alteration of the cement.

## 12.4 Case-Studies

### *12.4.1 The Impact of the Recent Sea-Level Rise on the Interpretation of Sea-Level Indicators*

Several recent studies (e.g. Jevrejeva et al. 2008; Kemp et al. 2011) have shown from tide-gauge records that the global sea level has risen during the last two centuries at an average rate of the order of 2 mm/a, i.e. about 20 cm.

One may wonder what the impact of this sea-level rise could be on the interpretation of several sea-level indicators available today in the coastal zone. For depositional geomorphological sea-level indicators, the impacts would be quite variable, depending on the features considered. The recent sea-level rise at the rate of 2 mm/a exceeds the possibilities of bioerosion in the intertidal zone. This means that, especially on carbonate rocks, the deepening of tidal notches is interrupted. As a consequence, in microtidal areas, no new tidal notches could have formed during the last two centuries, leading to the disappearance of this type of feature, as shown by Evelpidou et al. (2012). In contrast, tidal notches developed before the nineteenth century will be submerged and preserved in fossil form (they are called 'modern' tidal notches) at a depth of the order of about 20 cm. The reality of such a recent disappearance has been verified in most areas of the Mediterranean, where submerged 'modern' tidal notches testify of the local MSL position preceding the recent period of sea-level rise, e.g. in Greece, in the Cyclades and the Sporades Islands (Evelpidou et al. 2013a, b), or in several Ionian Island (in preparation).

On the other hand, the response of other types of notches will be completely different. In surf notches containing a biologic accretion the sea-level rise may be absorbed by an increase in the development of the organic accretion, which will remain the only relatively valuable sea-level indicator (if its position in the vertical biological zonation can be taken into account), while the surf notch developed above it and the notch roof will remain close or above the present sea level, with no value as sea-level indicator. Such an example is the notch observed undercutting the limestone cliff in the Orosei Gulf (Sardinia). A photo of this notch near the present sea level has been published by Antonioli et al. (2007, Fig. 12.6) with the caption "A well-developed tidal notch at Orosei Gulf, Sardinia, Italy". However, if it was a tidal notch, its position at the present sea level, after the recent sea-level rise, would have been abnormal. It seems that it was not taken into account that the almost horizontal base is capped, by an organic platform up to 10–20 cm thick; it is made, according to Carobene (1972), mainly by Serpulids and Lithotamnia, with the presence also of *Patella caerulea*, *Chama gryphoides* (L.), *Barbatia barbatia*, *Chthamalus stellatus* and *Balanus* sp. This notch is therefore not a tidal one, but a surf notch, in which the recent sea-level rise has been absorbed by a thickening of the organic accretion.

The situation is also different for solution notches, where a freshwater spring undercuts a limestone cliff at sea level. Accompanying a rise in sea level, dissolution by freshwater will tend to displace the roof of the notch that protrudes above the waterline continuously upwards, while the base of the notch, dissolved, will tend to be missing. For this isolated roof of a solution notch, protruding above the waterline (Fig. 12.12), the term "visor" has been proposed by Evelpidou et al. (2011b).

For marine terraces, the case of a small sea-level rise can probably be neglected, but for beachrocks the problem is completely different, especially in microtidal areas, because the upper level of beachrock cementation, which is the most significant sea-level indicator, will have been displaced upwards.

For biological sea-level indicators, a gradual upwards displacement of the biological vertical zonation should be taken into account.

In addition, for sea-level indicators deduced from archeological remains related to constructions in the sea (like harbors or fish tanks), where the biological marine

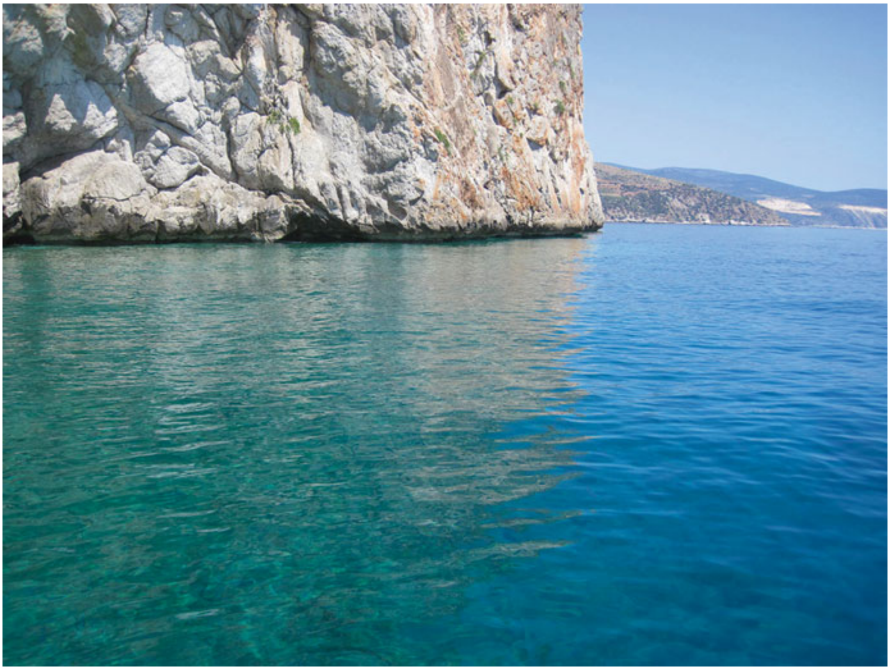


**Fig. 12.12** A visor developed by the dissolution of freshwater which tends to displace the roof of the notch, at North Corinth Gulf

zonation may leave fossils related to former sea levels, the impacts of a small sea-level rise should be taken into account, while this rise can most often be neglected in archeological remains unrelated to coastal activities.

### *12.4.2 Foreseeable Impacts of the Predicted Near-Future Sea-Level Rise on the Coasts of NE Italy*

The coasts of northeastern Italy in Roman times have been described by Pliny as a continuous, almost impassable sequence of lagoons, marshes and estuaries. The Po delta had not yet developed at that time and the openings of the various branches of this river to the sea were called the Septem Maria (seven seas) area. Most of the marshes have subsequently been filled by sediments or drained by man. Among the lagoon basins remaining today, the largest ones are the Lagoons of Marano and Caorle (the Grado Lagoon developed in late Roman times), the Lagoon of Venice, the Comacchio fisheries ("Valli") and the salt marshes ("Saline") of Cervia.

Due to the Sirocco, a persistent wet wind blowing from SSE (140–180°) along the longitudinal axis of the Adriatic, especially in the autumn and winter seasons, sea water tends to be channeled between the Apennines and the Dinaric Alps and

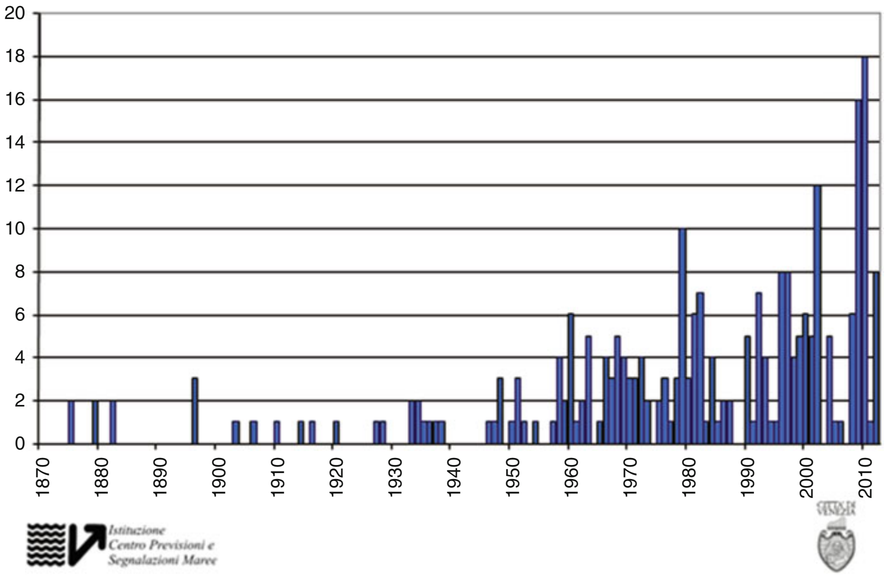



**Fig. 12.13** Annual frequency (number of flooding events = tides >1.10 m a. the local datum) in Venice, from 1872 to 2012). At the level of 1.10 m, 14 % of the city if flooded

pushed northwards, producing sea-level surges in all the Adriatic, with maximum values in its northern part, from where there is no possible way out (Pirazzoli and Tomasin 2008).

Flooding events, often reported in coastal areas, may result from sea-level surges or from river overflow. Great sea-level surges are generally related to deep atmospheric depressions and are often accompanied by heavy rain and in certain cases by river flood; therefore, during the most devastating coastal floods, it is usually difficult to distinguish the boundary between water coming from the sea from that of the river, even in inland areas.

Coastal areas of the NE Adriatic Sea, covering a surface of almost 2,400 $km^2$ along over 300 km of coast between Monfalcone and Cattolica, are depressed below sea level (Bondesan et al. 1995). Man-induced or natural subsidence has affected these areas, especially near the Po delta area, where an altitude of over 2.5 m was lost in some places during the past century. They are therefore exposed to the risk of flooding by sea-level surges and rivers.

According to the summary for Policymakers of the IPCC AR5, near-future relative sea-level changes between 30 cm and 1 m (depending on the emission of greenhouse gases scenario assumed) are expected to occur during this century. Among the areas at risk, the lagoon of Venice represents specific problems for coastal engineering.

In the historical city of Venice, flooding at street level is a frequent phenomenon (Fig. 12.13). During the great flooding of 1966 the tide reached the level of 1.94 m above the local datum. A special Italian law, in 1984, suggested constructing adjustable barriers at the lagoon inlets. The barriers should have been "experimental, gradual and reversible". The study of the barriers has been committed, in monopoly, to a group of private companies (*Consorzio Venezia Nuova*) who proposed to construct a project called Experimental Electromechanical Module (MoSE). The project consists of 79 mobile gates at the three inlets of the lagoon (Fig. 12.13).

Each gate 20 m long would lie on the seabed during normal time but would be raised by injecting compressed air. The mobile gates are expected to be closed when the height of the tide threatens to reach the level of 110 cm above the local datum. Each gate will oscillate independently with waves. Thus narrow passages for water will have to remain open at all times and the barrier will not be watertight.

Each gate would be connected with a hinge to an enormous submerged concrete caisson. Below the caisson, thousands of foundation stakes, several dozen meters long, would be capped by a continuous concrete slab across the inlet. Indeed, such a huge construction could not be "gradual and reversible", as requested by the law of 1984.

A commission of the Italian Ministry of the Universities and Research (MURST) estimated in 1999 the following scenarios of relative sea-level rise for the year 2100 in Venice: most probable: 16.4 cm; prudent (recommended for the MoSE project): 22 cm; pessimistic: 31.4 cm. These underestimations, which were ignoring the work of international sea-level experts (e.g. IPCC) constitute a wrong basic assumption for the MoSE project. They were immediately denounced (Pirazzoli 2002), but all criticism was ignored.

The foundation stone for the MoSE project was set in 2003 by the Berlusconi government, in spite of the opposition of the Municipality of Venice and the strong negative impacts feared for the environment.

The MoSE gates cannot face a sea-level rise because they do not form a watertight barrier. Their oscillations with waves will enlarge the spaces between the gates and will permit sea water to raise the lagoon level even when the gates are closed. Rainfall and river discharges will also raise the lagoon level. This has been demonstrated by simulating the occurrence of certain storms of the past with the flood gates assumed to be fully operational (Pirazzoli 2002; Pirazzoli and Umgiesser 2006). It was shown that problems would start for a sea-level rise of about 20–30 cm, or even today with a repetition of the 1966 event.

In 2006 a hydrodynamic study commissioned by the Municipality of Venice to the French Company PRINCIPIA R.D., has shown that for certain steep wave conditions ($Hs = 3.2$ m; $TP = 8$ s), not rare in the area, an unstable behavior is obtained for the MoSE gates (https://www2.comune.venezia.it/mose-doc-prg/->4.2). In these conditions of resonance, the flow of sea water into the lagoon through the gates would increase to a level that cannot be specified by modeling and the gates could even overturn. The MoSE experts ignored the results of this study and did not try to explain how the resonance phenomena could be avoided.

In short, the MoSE Project, for which the heart of the construction is just starting, is inadequate to the safeguard of Venice. If it is completed (at best in 2016), it will be necessary to demolish it shortly after its construction. It is therefore urgent that the Italian Government considers realistically the limits of this project and studies the possibilities, when flooding would become unavoidable, of conversion of what has already been constructed into the rapid building of a permanent water-tight dyke separating the lagoon from the sea.

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