Geological Society, London, Memoirs

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*Geological Society, London, Memoirs* 2014, v.40; p89-123.
doi: 10.1144/M40.7



**Notes**

# Chapter 7

# The rock coast of the Mediterranean and Black seas

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**Abstract:** Rock coasts and shore platforms are conspicuous landforms along the Mediterranean and Black Sea (MBS) coasts. These coasts have been fashioned by changes in sea level because of vertical movements of the land and variations in eustatic and isostatic sea-level. For this reason, the Quaternary evolution of MBS coasts has been extensively studied, even starting from geomorphological markers, while very few researches have addressed the processes related to their origin and evolution. Despite most of the Mediterranean coast being rocky, studies about rocky shore processes are almost completely lacking, except for limited areas. Data on sea cliff retreats have mainly been collected to study the susceptibility of cliff failures or to prevent landslides, in particular along shores used for tourism. Data on erosion rates and processes on shore platforms are generally scarce and restricted to limestone bedrocks. In this paper, we summarize the results of studies of rates and processes of rocky coasts of the countries overlooking the Mediterranean and Black Seas and review the current knowledge concerning rock coasts in the MBS area.

Rocky coasts represent most of the coastline bordering the Mediterranean and Black Sea (MBS; Figs 7.1 & 7.2) and are intimately related to the geological history of the landscape that overlooks the two basins. Despite the high percentage of rocky coasts in the MBS (more than 50%), published research literature is limited and it has received very little attention in textbooks and papers. The published research literature on rocky coasts in the MBS, as with the remaining world's rock coastlines, was almost completely neglected with respect to low-lying coasts (Emery & Kuhn 1982). Data regarding cliff retreat can be partly inferred from geotechnical reports produced by local public authorities or geoengineering papers (e.g. Budetta *et al.* 2000). Field measurements of shore platform erosion rates were completely missing until the 1980s along the MBS coasts and were rare along the Mediterranean after the 1980s, except for limited coastal sectors and limited types of bedrocks (e.g. Torunski 1979; Cucchi & Forti 1986). During the last decade process-based literature increased, but with only a few studies focused on the Mediterranean Sea rocky shores (e.g. Gómez-Pujol *et al.* 2006; Andriani & Walsh 2007; Furlani *et al.* 2009; Micallef & Williams 2009; Chelli *et al.* 2010*a*). In the last decade, much interest has been raised in tsunamis and their consequences (e.g. Soloviev *et al.* 2000; Mastronuzzi 2010). Along the Mediterranean rocky coasts, traces of large deposited boulders have been recognized (e.g. Scheffers & Kelletat 2003), but questions related to their origin remain.

Our aim is to provide an overview of the geomorphological issues and to review the rare results of the studies concerning the rates and processes of rocky coast evolution in the MBS. To this end, the MBS has been divided into five areas, following a clockwise continental and basin division, in particular: (a) northwestern European Mediterranean, from Gibraltar to Sicily (including the islands of the Tyrrhenian Sea); (b) northeastern European Mediterranean, from the Ionian Sea to Greece (including the islands of the Aegean Sea); (c) the Asian Mediterranean, in particular Turkey and the Middle East; (d) African Mediterranean coasts; and (e) Black Sea coasts. Owing to the larger amount of data concerning the northwestern and northeastern part of the Mediterranean, these chapters have been divided into subparagraphs, (i) an overview of rock coasts landforms within their geographical background and (ii) literature on processes operating on rock coasts: a review.

## MBS geographical background

The physical geographical features of the Mediterranean area (Fig. 7.1) has been widely described in Woodward (2009), while a general overview of the Black Sea coasts have been provided in Kos'yan (1993). The MBS are almost completely enclosed by land. The Mediterranean coastline extends approximately 46 000 km. It is connected to the Atlantic Ocean through the Gibraltar Strait, 14 km wide, in the west, and to the Sea of Marmara and the Black Sea through the Dardanelles and the Bosporus Straits in the east. The Sea of Marmara is often considered part of the Mediterranean Sea. In 1869 the Suez Canal was opened, an artificial sea-level waterway connecting the Mediterranean and the Red Sea. In the north it is surrounded by Europe and Anatolia, in the south by North Africa, and in the east by the Middle East coasts. Sometimes the Mediterranean is considered part of the Atlantic Ocean, although usually it is identified as a separate body of water. It covers roughly an area of 2.5 million km$^2$. Following the International Hydrographic Organization (1953) it can be divided into the western and eastern Mediterranean along an imaginary axis in correspondence with the Strait of Sicily and Tunisia. However, many papers identify an undefined 'central Mediterranean area' which covers the area of the Tyrrenian Sea and the Ionian Sea.

The Black Sea coastline extends about 4500 km. In the north it is surrounded by Europe, and in the south by Anatolia. It covers an area of about 415 000 km$^2$ (Shuisky 1993) and includes the Sea of Azov, in the northeastern sector.

*From*: Kennedy, D. M., Stephenson, W. J. & Naylor, L. A. (eds) 2014. *Rock Coast Geomorphology: A Global Synthesis*. Geological Society, London, Memoirs, **40**, 89–123. http://dx.doi.org/10.1144/M40.7

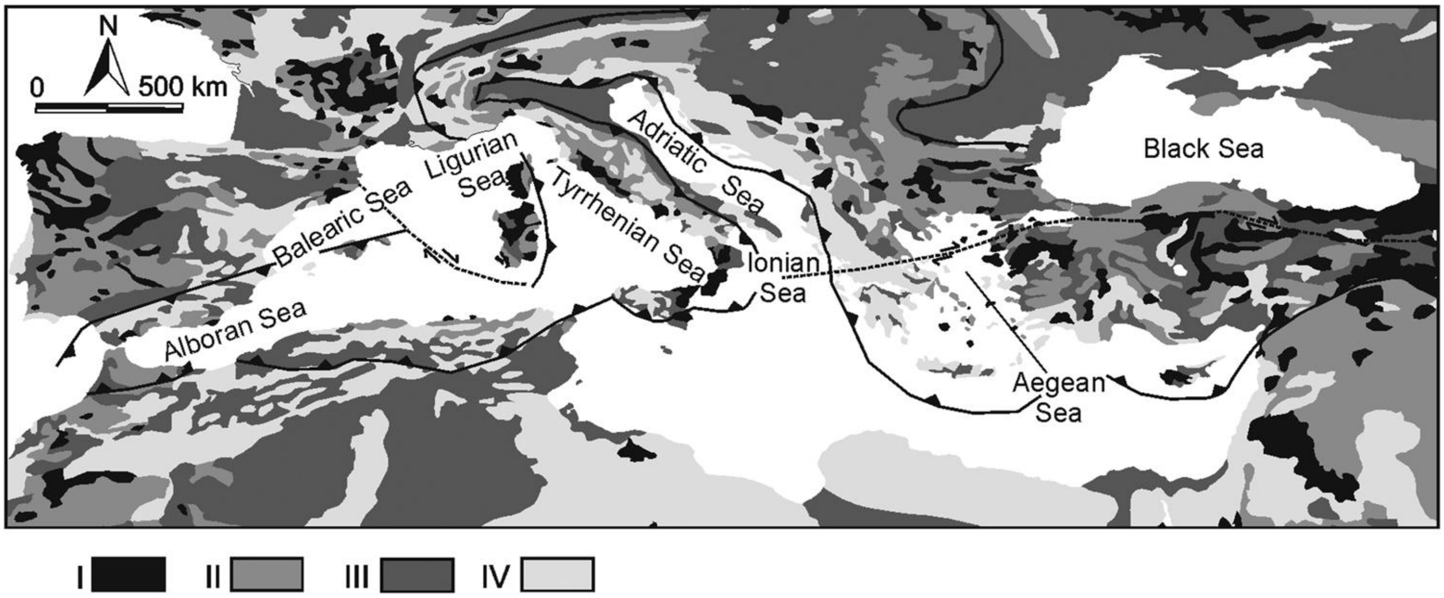



**Fig. 7.1.** Geological and structural map of the MBS area. The rocks are classified taking into account, broadly, their response to the geomorphological processes (mechanical and/or chemical). (I) Volcanic, plutonic and metamorphic rocks; (II) consolidated clastic rocks (clay- to mud- and siltstones, sandstones and conglomerate, marls and marlstones, volcano-sedimentary rocks); (III) semi- to unconsolidated sediments (mainly Cenozoic limestones, siliciclastic sediments and alluvial deposits); (IV) soluble rocks, carbonates and evaporites (modified from Dürr *et al.* 2005).

The Mediterranean Sea also includes large islands like Cyprus, Crete, Euboea, Rhodes, Lesbos, Chios and Cephalonia in the Aegean Sea; Corfu, Naxos and Andros in the eastern Mediterranean; Sardinia, Corsica, Sicily, Cres, Krk, Brač, Hvar, Pag, Korčula and Malta; and Formentera, Ibiza, Cabrera, Dragonera, Mallorca and Menorca (the Balearic Islands) in the western Mediterranean.

The coastal fringe of the MBS has a long and complex geological history, being involved in the collision of the African and Eurasian plates (Fig. 7.2). This history began about 250 Ma ago following the break-up of the Pangea and the formation of the Thethys, the forerunner to the Mediterranean Sea (Mather 2009).

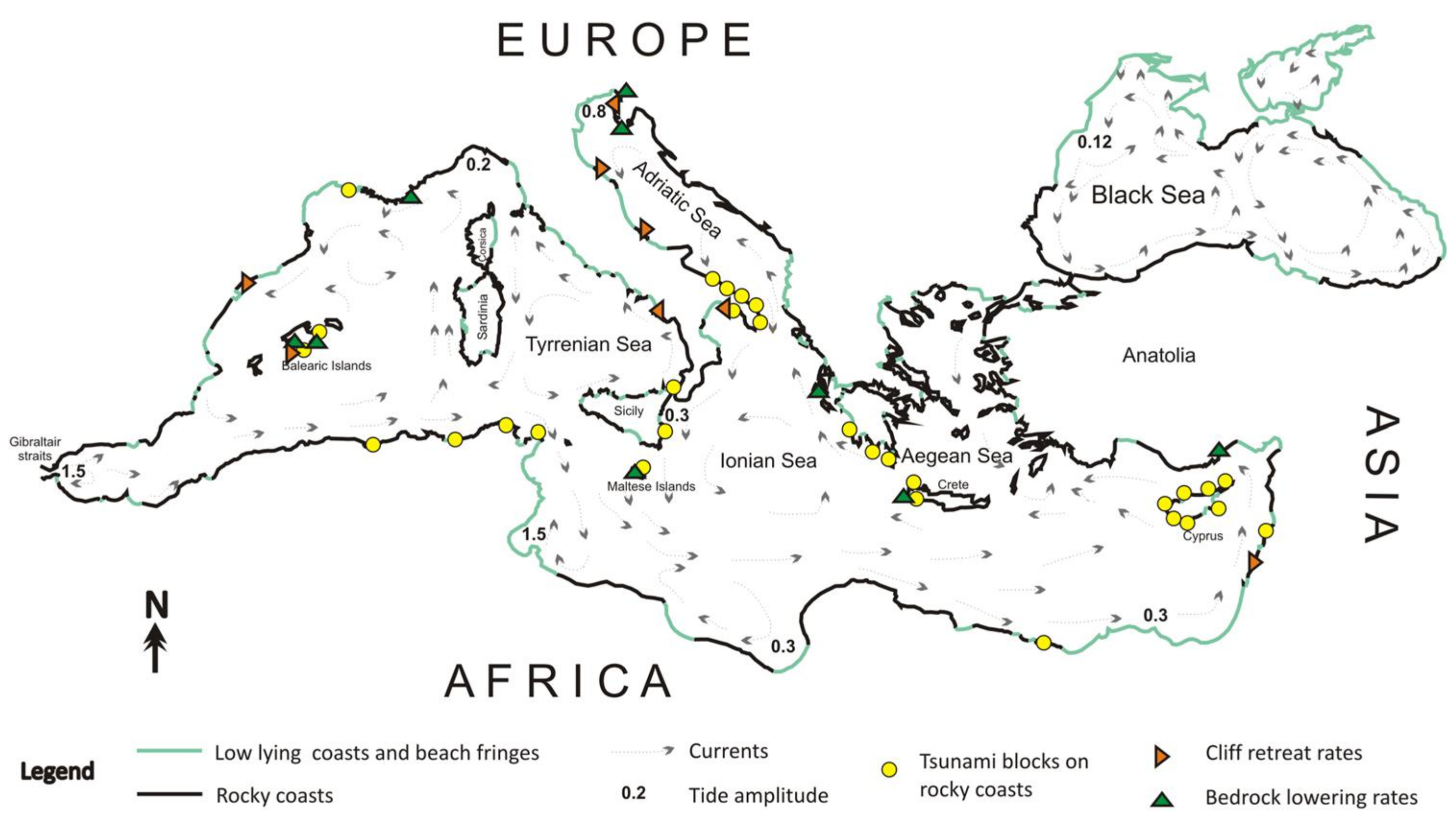



**Fig. 7.2.** Map of the Mediterranean and Black Sea (MBS) area showing (**a**) rocky coasts, low-lying coasts and beach fringes along the MBS coast; (**b**) surface water circulation in the MBS (after Vergnaud-Grazzini *et al.* 1988; Roussenov *et al.* 1995; Shuisky 1993), (**c**) sites of reported cliff retreat rates (from Tables 7.1 & 7.2), (**d**) sites of reported bedrock erosion rates in the Mediterranean area (from Table 7.3), (**e**) sites of reported tsunami blocks in the MBS (see Table 7.4).

The Mediterranean Sea flanks the westernmost sector of the Alpine–Himalayan orogenic belt. The geodynamic evolution of the Mediterranean Sea was driven by differential seafloor spreading along the Mid-Atlantic Ridge, which led to the closure of the Tethys Ocean and in the end to the Alpine orogenesis (Mather 2009). The Mediterranean hosts wide extensional basins and migrating tectonic arcs, in response to its land-locked configuration. The collisional history gradually reduced the connections of the Mediterranean, and consequently of the Black Sea, with the surrounding marine basins following the closure of the gateways. During the Miocene, the MBS was completely isolated and dried up. Then, the Mediterranean Sea was rapidly filled, 5.33 Ma ago following the Zanclean flood, during which water entered from the Atlantic Ocean through the Strait of Gibraltar (Garcia-Castellanos *et al.* 2009).

Vertical and horizontal crustal movements control the geological and geomorphological history of the area. The Mediterranean Sea includes zones of active subduction associated with volcanic activity and older zones of quiescent subduction (Mather 2009). Geodetical data (Calais *et al.* 2002; Nocquet & Calais 2004) suggest an overall north–south compression, with Africa globally moving northwards at 5 mm $a^{-1}$. The steep coastal reliefs and seismic activity generated by geodynamics drive many of the active erosional landscape processes within the area. The resultant geomorphic features on rock coasts include sea cliffs and shore platforms or marine notches, which can be at different altitudes (Mather 2009). The active nature of tectonics in the Mediterranean is revealed by the combination of raised and drowned shorelines. The spatial variation in uplift can be highlighted using different markers, such as notches, marine terraces or archaeological remains. The geomorphic expression of the regional tectonics in the landscape along the coast thus contains valuable data on the spatial and temporal variations in rates and styles of tectonic processes (Mather 2009). However, temporal changes in uplift rates have been very well defined from archaeological, sedimentological or geomorphological markers around the central and eastern Mediterranean (e.g. Pirazzoli *et al.* 1996*a*; Lambeck *et al.* 2004; Ferranti *et al.* 2006, Antonioli *et al.* 2009; Pavlopoulos *et al.* 2011; Vacchi *et al.* 2012*a*, *b*; etc.).

Rocky coastal landforms along the MBS coastline are in a tight relationship with sea-level history. A review of the last 300 ka in western-central Mediterranean comparing sea-level curves with observational data has been produced by Antonioli (2012), while Ferranti *et al.* (2006) reviewed information about MIS5.5 (*c.* 125 ka) shorelines in Italy and the whole Mediterranean area. They are spread in elevation from few metres up to more than 100 m a.s.l., owing to the relevant tectonic uplift that patchily affects the basin coastline. Information on MIS7 and 9 is available mainly from speleothems and that on MIS5 minor substages and on MIS3 is at the moment scarce or controversial. Rovere *et al.* (2011*a*, *b*) suggested that recurrent levels of abrasion platforms found underwater may have been formed during MIS7 or lower MIS5 stages. Pleistocene highstands have mainly been responsible for the formation of stepped flights of terraces along the rocky coastline of the Mediterranean. Holocene sea-level changes in Mediterranean Sea were modelled and later tested in the field by Pirazzoli (1991), Lambeck & Bard (2000), Lambeck *et al.* (2004, 2011), Lambeck & Purcell (2005) and Pavlopoulos *et al.* (2011). Stewart & Morhange (2009) described processes and markers of sea level changes in the Mediterranean. However, there is no general agreement on the evaluation of Holocene sea-level change rates. Three main components contribute to total sea-level change: the sea level response to the past glacial cycle, including the response to the most recent glacial unloading; the response to the ocean cycle (including meltwater, in ocean volume provided by thermal expansion); and the tectonic component. The isostatic response requires models for the past ice sheets, and these have been estimated from inversions of rebound data from the formerly glaciated regions, such as the recent Australian National University (ANU) ice models (Lambeck *et al.* 2011) calculated in particular for the central Mediterranean (Stocchi & Spada 2009). This complex interaction between the relative sea level (RSL) curve components results in an extremely varied pattern of sea-level change with different typologies of RSL curves that may be expected within short distances along the Mediterranean coast. Generally, curves based on observational evidence as well as those derived from modelling display a monotonous rise through the Holocene or are characterized by a moderate sea-level highstand around 5 ka BP followed by sea-level fall. Holocene shorelines may be significant in shaping the rocky shores only in rapidly uplifting tracts of the coastline, such as in Sicily (e.g. Antonioli *et al.* 2009) and Greece (e.g. Pirazzoli *et al.* 1994, 1996*a*, *b*, 2004), where they leave traces mostly in the form of raised notches.

The typical Mediterranean climate has hot, dry summers and mild and rainy winters (Rohling *et al.* 2009), while the Black Sea is situated in the region of transition between moderate and subtropical zones (Kos'yan 1993). The southern Crimean slopes, the southern Bulgarian coast and the Rumelian coast of Turkey have Mediterranean-type climate, while the Caucasian and Anatolian coasts can be included within the humid subtropics (Shuisky 1993).

Given the semi-enclosed configuration of the MBS, the oceanic gateways are critical in controlling water circulation and environmental evolution in the Mediterranean Sea. Water circulation patterns are driven by a number of interactive factors, such as climate and bathymetry, which can lead to the precipitation of evaporites. Evaporation greatly exceeds precipitation and river runoff in the Mediterranean and it mainly affects the water circulation within the basin (McElderry 1963). Pinet (1996) reported that evaporation is especially high in the eastern part and causes the water level to decrease and salinity to increase eastward. This pressure gradient pushes relatively cool, low-salinity water from the Atlantic across the basin. It warms and becomes saltier towards the east, then sinks in the region of the Levant and circulates westward, to spill over the Strait of Gibraltar. Seawater flow is eastward in the Strait's surface waters, and westward below (Rohling *et al.* 2009). McElderry (1963) reported a current of 2 knots, and it flows towards north in winter and south in summer. In the Black Sea the fresh-water balance is positive (Shuisky 1993). Surface circulation in the Black Sea is divided into two wind-, drift- and stream currents moving counterclockwise (Shuisky 1993).

In the Mediterranean Sea, tides have a mean vertical variation of about 0.4 m as a result of the narrow connection with the Atlantic Ocean (Pinet 1996). The Straits of Gibraltar are affected by ocean tides, thus mean amplitude is 1.5 m, but it quickly decreases eastwards (Fig. 7.1). Atmospheric conditions can often hide or increase tides, insomuch as in the Gulf of Gabes (Tunisia) and the northern Adriatic Sea tides have a maximum range of nearly 2 m. In the Black Sea, tides are very limited but they can be overlapped by seiches and seasonal variations in river discharge (Shuisky 1993), in particular the Danube River (Bondar 2007).

## The MBS rocky coasts

Rocky coasts border most of the MBS (Fig. 7.1). In particular, starting from the Gibraltar Strait, cliffed and rocky coasts occur along *c.* 1800 km of the Mediterranean Iberian Peninsula and the Balearic Islands coastline. They represent the 53% of the total coastline measured on the 1:100 000 EUROSION digital map (Lenôtre *et al.* 2004).

The northwestern Mediterranean coastal sector includes the coast of France and of the Italian regions Liguria, Tuscany and Latium. The Mediterranean coast of France is about 620 km long and is predominately bordered by cliffs and coves in its eastern part, east of the Rône delta. This landscape is rather similar to that of the western sector of Liguria. The Liguria region displays a mostly rocky coast (55% that can be increased up to *c.* 80% if we include those tracts that are artificially protected from erosion; Ferretti *et al.* 2003), whereas Tuscany and Latium have rocky promontories bracketing wide coastal plains; respectively 63 and 40% of their littoral is rocky (Ferretti *et al.* 2003). For Tuscany the estimate includes the coastline of the so-called Tuscan Archipelago (Elba Island and minor islands), that is mainly rocky and cliffed. The major islands in the central Mediterranean, Sardinia and Corsica have extensive tracts of rocky littorals. Seventy-nine per cent of the coast of Sardinia is rocky. Corsica displays wide coastal plains only on its western side, whereas the remaining coast is cliffed. The Sicilian shoreline is also mainly cliffed or rocky. The Calabrian and Basilicata Ionian coasts in the Gulf of Taranto are low-lying sedimentary types, while the remaining part is cliffed or rocky. The northwestern sector of the Adriatic Sea is bordered by flat coasts, but the southernmost sector and the eastern side are almost totally cut in Mesozoic or Cenozoic limestones (Fig. 7.2). The same applies to the whole southern Balkan peninsula and Turkish coast, while only the northern Albanian coasts are low-lying. Small pocket beaches or coastal plains are bracketed between rocky headlands, which border most of the eastern Mediterranean Sea. The physiography of coastal areas is conditioned by the absence of wide river catchments (apart from the Nile) and the reduced flow of air masses from the sea landward, owing to the presence of extensive reliefs facing the coast.

Erosional landforms dominate rocky coasts, even if they are often found associated with depositional landforms, such as tidal creeks, salt marshes, etc. (Huggett 2011). This paper is concerned, in particular, with landforms produced by erosive waves and weathering action on the cliff–platform system (Fig. 7.3).

Rocky coasts are usually divided in three main groups (Sunamura 1992, Bird 2000): sloping shore platform (type A), horizontal shore platform (type B) and plunging cliff. The sloping shore platform (type A), or seaward-sloping *sensu* Bird (2000), are gently sloping platforms, between 1° and 5° in slope (Fig. 7.4a). They are usually planation surfaces that extend between the high tide at the base of the cliff and roughly the low tide level (Bird 2000). Shore platfomrs type A are usually prominent features on soft rocks and high-energy coasts. Plunging cliffs (Fig. 7.4b) steeply pass at high depth below low tide level without any shore platform or other rocky shore outcrops (Bird 2000). Horizontal shore platforms usually have a low-tide cliff and can be subdivided into high-tide shore platforms and low-tide shore platforms (Fig. 7.4c). Type B platforms are flat or nearly flat benches and are often termed structural platforms if the upper flat surface is cut in resistant rocks. Supratidal composite shore platforms (Fig. 7.4d) are rocky shore outcrops variously inclined and gently plunge below low tide level.

In the MBS there are significant variations and transitions between the three groups, mainly related to the interaction of waves, weathering and relative sea-level changes, such as the gently sloping platforms along the eastern Adriatic coastline or the uplifted plunging cliffs with narrow shore platforms along the Greek and Turkish coast.

Particular mention should be accorded to limestone coasts, because bioerosion and the removal of the lithic substrate by the

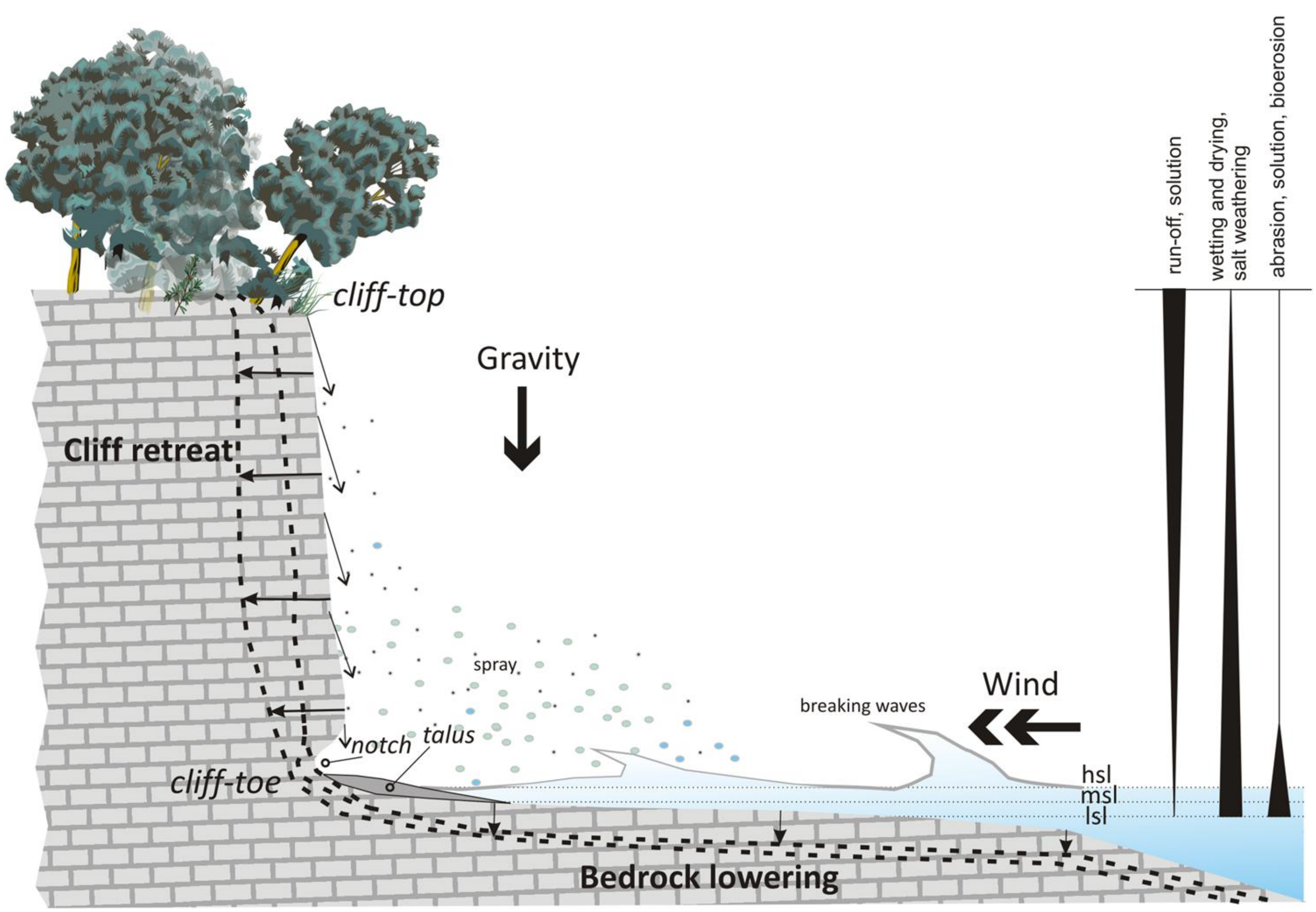



**Fig. 7.3.** Sketch of the cliff–platform system and the processes producing cliff retreat and shore platform lowering.

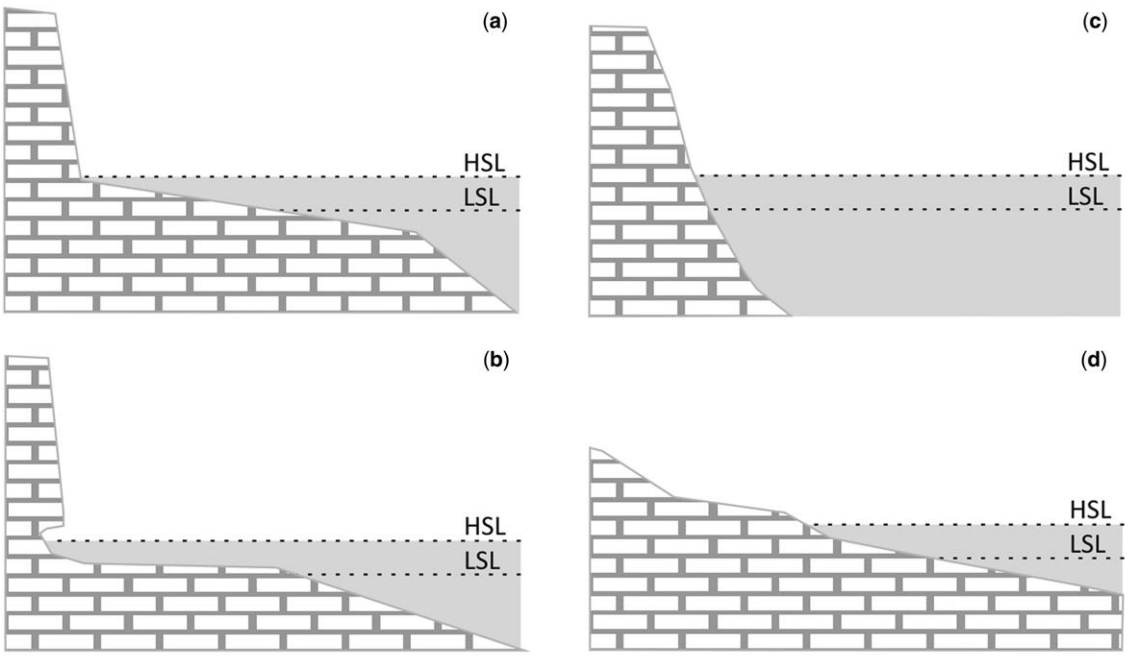



**Fig. 7.4.** Erosional landforms of the Mediterranean rocky coasts (modified and adapted to the MBS area, from Sunamura 1992; Bird 2000). (**a**) Sloping shore platforms (Type-A), (**b**) horizontal shore platforms, (**c**) plunging cliffs, (**d**) supratidal or composite shore platforms.

action of organisms is probably of greatest importance (Neumann 1966). The activities of organisms living on limestone substrates, following a precise distribution according to altitude with respect to the mean sea-level (Fig. 7.5), are directly responsible for the formation of the biokarst, widely studied also in the Mediterranean (e.g. Schneider 1976; Torunski 1979; Naylor & Viles 2002). The geographic location of the figures in the following paragraphs are reported in a map of the MBS area (Fig. 7.6).

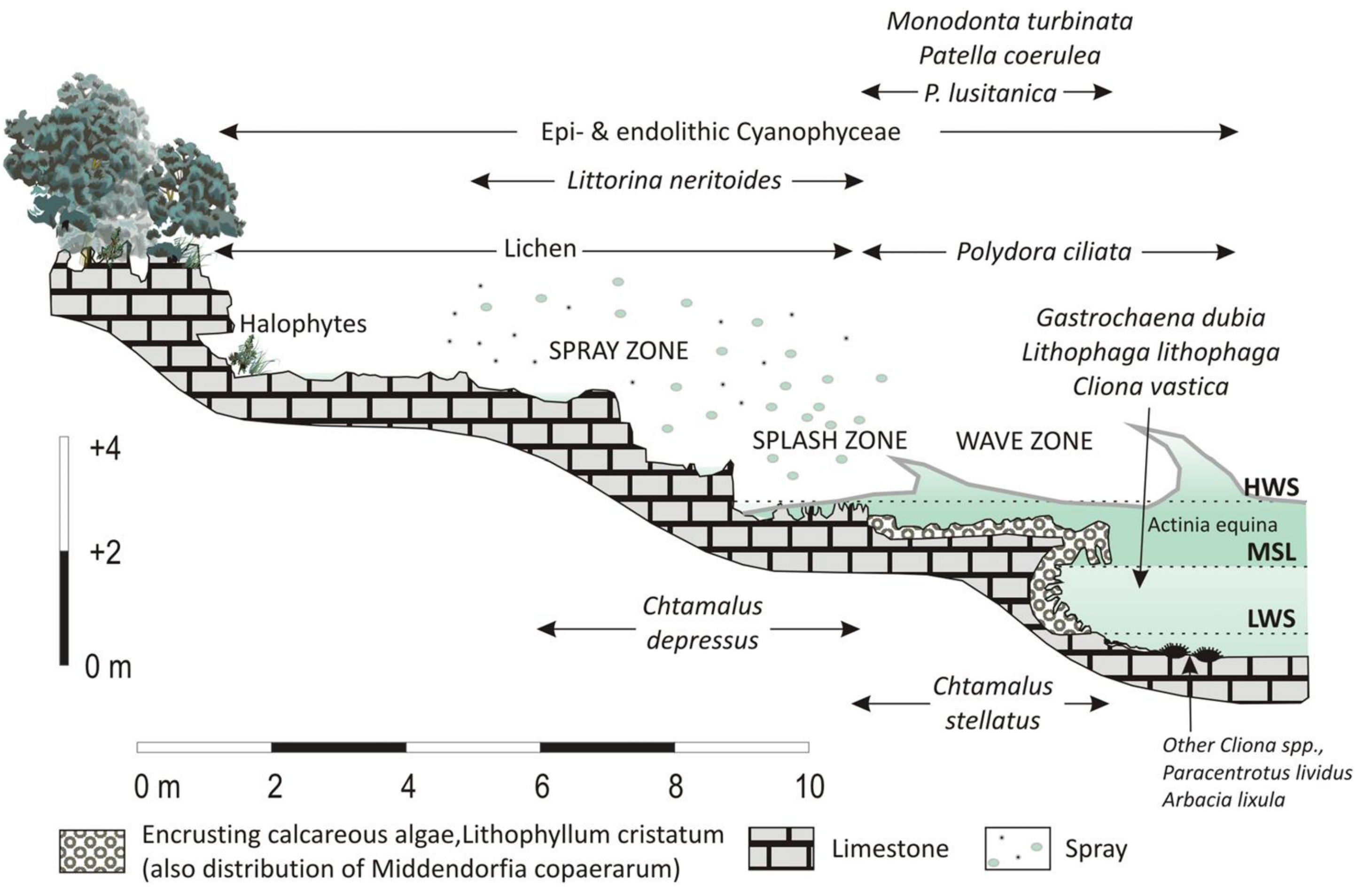



**Fig. 7.5.** Sketch of the the zonation of limestone coasts and distribution of littoral organisms in the Adriatic coast (modified from Schneider 1976).


**Fig. 7.6.** Location of the figures in the paper inside the MBS area.

## Northwestern Mediterranean rocky coasts

### *Overview of rock coasts landforms within their geographical background*

In Mediterranean Iberia and the Balearic archipelago, three-quarters of the rock coasts occur in conglomerates and/or soft-rock cliffs (mainly Upper Miocene Limestone and Quaternary rock outcrops). The remaining quarter of the rock coastline is shaped in hard rocks as granites or folded Jurassic limestone. Meteomarine conditions are characterized by low to moderate wave energy (Cañellas 2010), small tide ranges (from 0.9 m at Gibraltar to typically less than 0.2 m in the Balearic Sea), weak tidal currents and rivers with low or intermittent discharge (Bird 2010).

East of Gibraltar to the French border and through the Balearic Islands, different types of cliffs and associated features are found. The Mediterranean southern coast of the Iberian Peninsula has been described as a longitudinal coast controlled by the structure and the influence of the Betic chain internal zones (Solé 1994). Despite this, the coastline is mainly an accumulation coast – with many large sandy beaches or nip coasts related to Plio-Quaternary alluvial fans and eolianites – and it is backed by mountain ranges drained by numerous valleys. Intermittently these mountains reach the coast offering different types of cliffs, such as the Gibraltar sea walls that reach 400 m in height and are shaped in Jurassic limestone (Fig. 7.7a), and the Triassic marble cliffs (20–80 m in height) or the irregular cliff profiles shaped in Palaeozoic schists (*c.* 200 m in height) along the Granada coast. At Gata cape, the coast turns sharply to the NE and the lineal coast changes to an irregular coastline where Miocene volcanic rocks reach the coast. This results in a crenulated cliffed coastline with cliff heights ranging from 50 to 200 m (Fig. 7.7b). The rest of the eastern Almeria coast is characterized by a small sector of vertical cliffs cut in tabular Upper Miocene rock near Carboneras and large sectors of Palaeozoic schist cliffs with narrow shore platforms.

A series of headlands (e.g. Cope Cape and Tiñoso Cape) and bays characterizes the southern coast of Murcia. López-Bermúdez (1969) attributed a structural nature to most of the cliffs shaped in Palaeozoic schists, Triassic dolomites and sandstones that range from 5 to 30 m in height. Subhorizontal shore platforms are conspicuous features along the Murcia Palaeozoic cliffs (Fig. 7.7c).

The coast between the Mar Menor lagoon and the Ebro delta is characterized by a succession of beaches and sea cliffs (i.e. Cap de l'Horta, Serra Gelada, Penyal d'Ifac, Moraira, La Nau, Cap Sant Antoni, Penyiscola), mainly limestone, related to the external Betic chain and controlled by tectonics and lithology factors (Sanjaume 1985; Rosselló & Fumanal 2005). Thus vertical cliffs with narrow platforms and plunging cliffs (Fig. 7.7d) are better developed in Cretaceous Limestone at Sant Antoni cape or Moraira with cliffs reaching 100 and 160 m in height (Fumanal & Viñals 1988), whereas composite cliffs, with larger and continuous shore platforms, appear when marls and flysh units crop out at Cap Martí or at La Nau cape (La Roca *et al.* 2005). Triassic sandstones and limestone between Calp and Cap de les Hortes or flysh cliffs around el Campello result in composite cliffs. Sometimes they attain heights between 100 and 200 m and rest on narrow shore platforms. Both sectors are rich in coastal rock falls and screes (Sanjaume 1985). Between the cited locations there are several sectors with low cliffs shaped in limestone, marls and also Plio-Quaternary colluvial and alluvial deposits. Most of them are carpeted by Quaternary eolianites with well-developed coastal karren assemblages (Sanjaume *et al.* 1982).

Along the 552 km of the Catalonia coast, and after the low Jurassic stacks of Salou and Tarragona or the nips shaped in alluvial Quaternary deposits (Montoya 2008), the first significant cliffs

**Fig. 7.7.** Examples of cliffs along the Mediterranean Iberian Peninsula and Balearic Archipielago coastline. See explanation in text. (**a**) Gribraltar limestone cliffs, more than 400 m in height. (**b**) Cape of Gata schist cliffs. (**c**) Calnegre cliffs and shore platform in Murcia coast. (**d**) Cape of Sant Antoni, cliffs of 160 m in height shaped in Cretaceous limestone. (**e**) La Falconera, 130 m in height plunging cliff. (**f**) Crenulated coast and irregular cliffs shaped on Palaeozoic rocks at Cape of Creus. (**g**) Formentor cliffs in northern Mallorca (Balearic Islands), 400 m structural cliff shaped in Jurassic limestone. (**h**) Examples of calas, a characteristic rock coast macroform in Balearic Islands, in southeastern Mallorca.

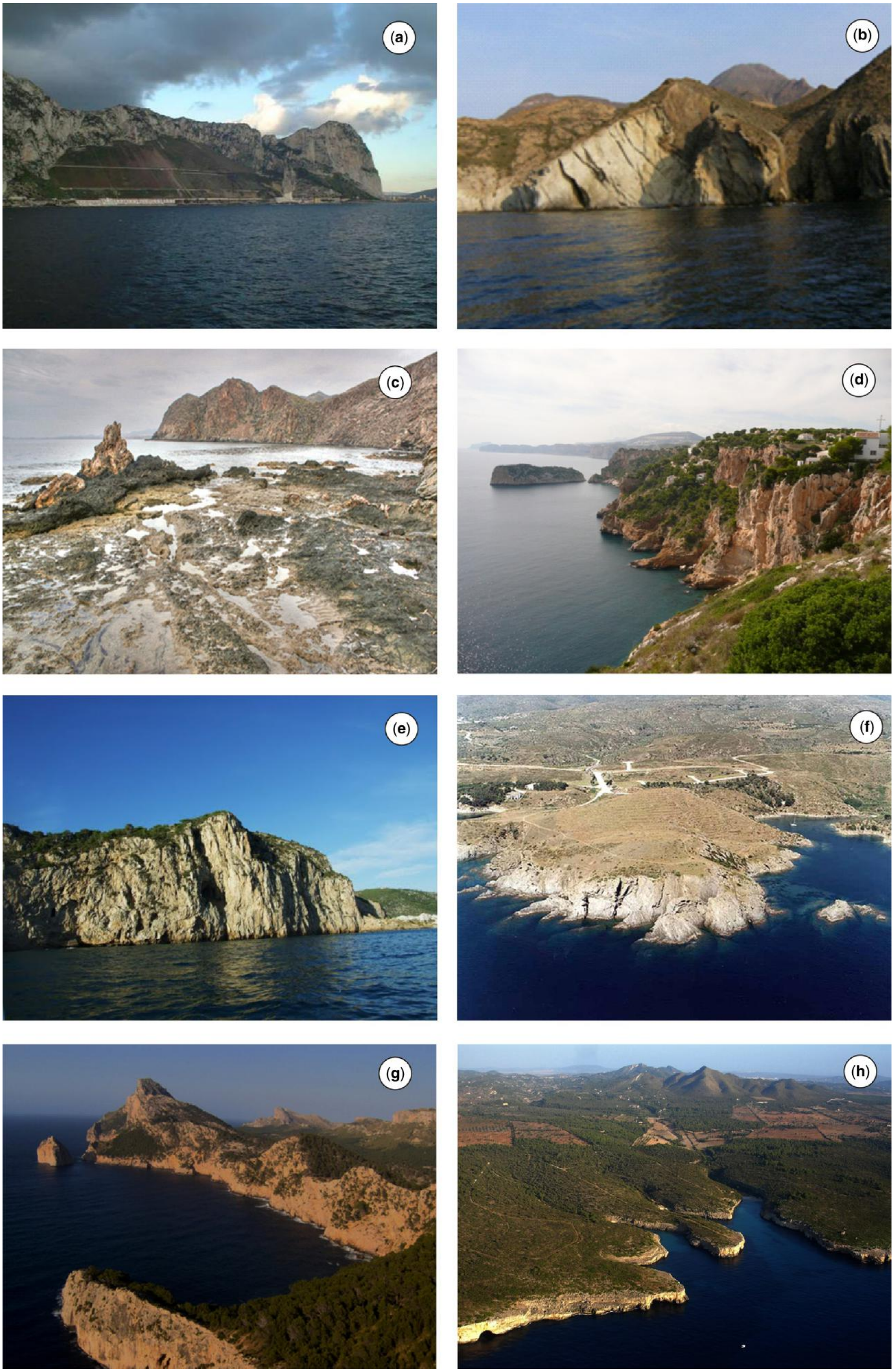

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

**Fig. 7.8.** Cliffs and shore platform shaped in granites around Blanes at Catalan Coastal Ranges (Iberian Peninsula).

appear close to Barcelona, when the limestone Garraf Mountains reach the coast (Calvet & Gallart 1973). Cliffs such as la Falconera, 130 m high (Fig. 7.7e), are quite representative of this Cretaceous Limestone formation with abundant caves and other karst features (i.e. blowholes, pinnacles, basin pools, etc.). Northward cliffs are related to the Coastal Catalan Range, where Palaeozoic granites and schists form composite and irregular cliffs with occasional but well-developed shore platforms (Fig. 7.8). Palaeozic schists build up the promontories of Cape of Roses and Cape of Creus, and cliffs are irregular and covered by honeycomb and tafoni features (Barbaza 1970). Differential erosion in shale and deformed schist control the development of shore platforms and result in a crenulated coastline that hosts abundant pocket beaches (Fig. 7.7f; Calvet & Gallart 1973). Some Pleistocene terraces have been identified corresponding to different marine levels (Butzer 1964; Solé 1962).

Cliffed coasts are characteristic of a large part of the Balearic Islands coastline. They are almost exclusively associated with deep water offshore and the −20 m isobath is generally found considerably less than 500 m from the shoreline (Butzer 1962). Cliff form is closely related to the large-scale morphological units of each island that are an extension of the external Betic chain. Thus the general picture for Mallorca and Eivissa is one of plunging cliffs with a large array of profiles developed on carbonate Mesozoic to Middle Miocene folded outcrops in which the cliff face varies locally from 3 to over 50 m in height, although maximum cliffs heights reach vertical walls of 275 m and composite cliffs of 400 m (Fig. 7.7g). Cliffs of these sectors extend from 5 to 10 m below sea level. Shore platforms are intermittently developed and closely related to lithological and structural control. For instance, they rarely appear in Liassic limestone because of rock hardness and the structural nature of most of the cliffs. At softer rock outcrops, such as Neogene turbidites or Rhaetian dolostones, a limited shore platform development can be appreciated (Gómez-Pujol *et al.* 2006). Post-orogenic Upper-Miocene coastal outcrops of calcarenite – appearing in southern and eastern Mallorca, southern Menorca and Formentera – present composite profile cliffs with step-like forms closely associated with former Pleistocene sea levels (Butzer 1962; Fornós *et al.* 2012). These steps are enhanced by the geometry of the Miocene strata and the differences in geomechanical properties between depositional units. Cliffs cut in this Upper Miocene rocks range from 2 to 20 m in height. Shore platforms are common, as well as notches and attached bioherms (*trottoir*) (Gómez-Pujol *et al.* 2006). The character of the northern Menorca coast is the only feature that departs from the Balearic scenario; Palaeozoic shales and Triassic sandstones appear in the north, resulting in a crenulated coast with composite cliff profiles. Calas (Fig. 7.7h), fluvio-karstic drowned valleys, are abundant features in both south and southeastern Mallorca and southern Menorca coast (Rosselló 2005; Gómez-Pujol *et al*. 2013). Additionally Pleistocene marine terraces appear widespread along the Balearic coasts and from the early 1960s (Butzer & Cuerda 1962) to the present (Zazo *et al.* 2003; Ginés *et al.* 2012) constitute a benchmark for Quaternary studies and sea-level stratigraphy in the western Mediterranean.

Coastal exokarstic landforms are quite common features at the Balearic Islands, owing to the presence of extensive coastal limestone outcrops as well as a suitable hydrodynamic and bioclimatic environment that promotes the development of karst processes. Pinnacles, basin pools, pits and notches, among others, can be seen, especially on the south and southeastern coast of Mallorca, the southern coast of Menorca and all around Formentera (Fig. 7.9a, b). Otherwise the presence of coastal karren in northern Mallorca, Menorca and Eivissa is less prominent owing to lithology. Coastal karren on the Balearic Islands are quite remarkable because of their morphological variety and occurrence on different rock types, but also as a subject of study on the effect of hydrodynamic gradients and the precipitation and temperature settings or on the biological influence in karst processes. Coastal karren together with plunging cliffs and Quaternary aeolianites exploited as rock quarries are the foremost representative feature of the Balearic Islands coastline (Gómez-Pujol & Fornós 2009).

The coastline of France facing the Mediterranean displays a small rocky tract by the Spanish border where cliffs are cut in the Cambrian and Ordovician formations of the eastern Pyrenees (Guilcher 1985). East of the Rône Delta the Mediterranean rocky coastline of France is called the French Riviera. The piedmont of those calcareous mountain ridges bordering southward the Western Alps (Monts des Maures, 779 m, and Massif d'Estérel, 616 m) dip into the sea, creating the stepped rocky landscape typical of this region. Rocky shores, thus, account for over 52% of the present Riviera shoreline (Anthony 1994). In spite of this, all the attention of researchers has been paid either to the small, gravelly pocket beaches sheltered inside coves within rocky promontories (Cohen & Anthony 2007), or the Quaternary marine terraces preserved almost at their eustatic elevation, owing to the

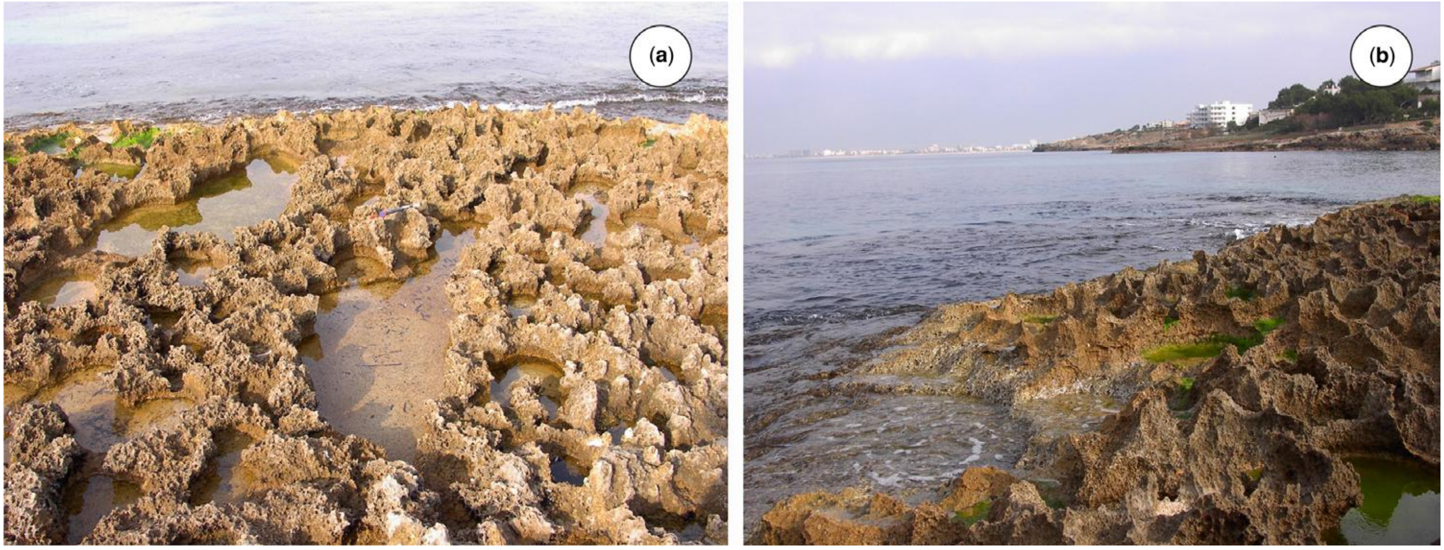



**Fig. 7.9.** Coastal karren is a distinctive feature of rock coasts at Balearic Islands. Examples on (**a**) longitudinal and (**b**) plan view forms distribution (platform, pinnacles, isolated and connected basin pools) shaped in Quaternary eolianites at Palma Bay (Mallorca).

negligible uplift rate (0.008 mm $a^{-1}$) that affected this coastal slope (Dubar *et al.* 1992). The Holocene sedimentary sequences of the small coastal plains present along the French Riviera have also been investigated by Morhange *et al.* (2003). Cliffs, narrow platforms or benches and the associated rocky landforms (e.g. mega boulders; Vella *et al.* 2011) are nevertheless widespread; the rocky sections of the coastline are shaped in different types of Mesozoic limestone, so that a tidal notch at present day sea level can develop, in continuity with a similar feature that was described in the Balzi Rossi locality (Fig. 7.10a), just beyond the Italian border (Pappalardo 2007). This tidal notch is associated with an intertidal shore platform in a staircase with Pleistocene marine terraces. A broadly similar tectonic setting, characterized by a subsiding shelf and a moderately uplifting coastal range (Ferranti *et al.* 2006), affects all the coastal sector from the French Riviera up to the central Tyrrhenian coast. The coast of Liguria is mostly cliffed and indented, with minor coastal plains. It displays particular features compared with the rest of the Italian coastline. In fact, the regional territory is an arch-shaped mountain ridge whose seaward slope is very steep so that its watershed is very close to the sea (5–30 km). For this reason, slope-over-wall profiles, characterized by steep slopes descending to basal cliffs, are the dominant coastal profile. Lithological and weathering conditions affect the extreme variability of landforms in the proximity of present-day sea level. From a geological point of view, the western part belongs to the Alps and is characterized by mainly calcareous units cropping out in western Liguria. In the central part, an ophiolitic complex marks the transition between the alpine and the Apenninic domains that crop out in the eastern part and are represented by different flysch units. The stratified nature of these rocks is evident when they are exposed on cliff faces and on small shore platforms or benches (Chelli *et al.* 2008). Marine caves, stacks and natural arches can be found along the coast, although not very frequently; the caves of Bergeggi (Fig. 7.10b) in western Liguria (Rovere *et al.* 2010; Fig. 7.10c) and of Palmaria Island at the easternmost edge (Chelli & Pappalardo 2008) deserve to be mentioned owing to their significance as past sea-level indicators (Fig. 7.10d).

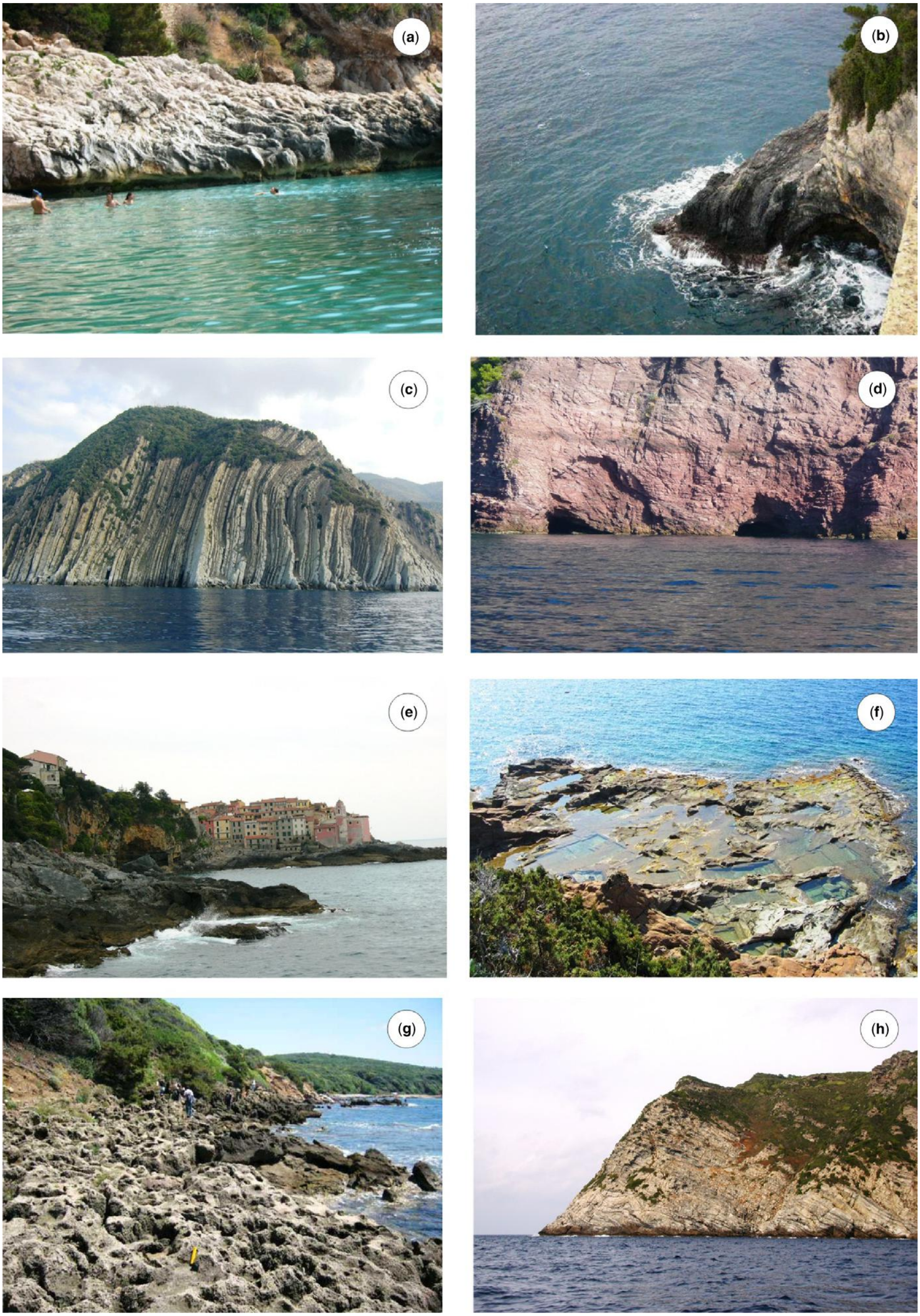
Coastal plains become prevalent along the coasts of Tuscany and Latium, where rocky promontories bounded by cliffs are more scattered. In Tuscany, south of Livorno, narrow shore platforms, carved in a sandstone bedrock, are in a staircase with a wide MIS5 marine terrace (De Fabritiis 2012).

The Tuscan Archipelago, formed by the Elba and six minor islands, displays a variety of coastal landforms, owing to the large variety of rock types and geological settings that characterize them. Among coastal features, cliffs are frequent and well developed, whereas inactive shore platforms are few and sometimes of uncertain interpretation (Aringoli *et al.* 2009). In particular Pianosa, where, like in Giannutri, karst landforms dominate, preserves relevant traces of Upper Pleistocene shorelines (Antonioli *et al.* 2011).

The Argentario Promontory is linked to the coast of Tuscany by means of two sand ridges (tombolo), that enclose the Orbetello lagoon. Archaeological evidence show that the promontory was an island at least until Roman times (D'Alessandro *et al.* 1979). In the area the Argentarola cave provides well chronologically constrained speleothems that give an insight into the penultimate interglacial sea-level oscillation amplitude (Dutton *et al.* 2009).

In Latium the scattered rocky tracts of the shore are mostly indented with numerous peninsulas bounded by low cliffs; bedrock is commonly composed of carbonate rocks into which honeycombs and globular erosional features are carved, and may be capped by thin layers of Quaternary beach-rock. North of the Tiber Delta, the connection between the shore and the low, beachrock shore platforms is often represented by a cliff lower than 3 m upon which archaeological deposits occur. In this area, rocky coastal landforms are frequently associated with traces of human settlement, from Prehistory up to Roman Times (Lambeck *et al.* 2004; Evelpidou *et al.* 2012), such as fish tanks, coastal quarries and Roman and pre-Roman harbours (Rovere *et al.* 2011*b*).

In the Circeo Promontory, a prominent feature in the coastal landscape also mentioned by Homer in the *Odyssey* (Book X, 135–137), relevant Palaeolithic and Mesolithic archaeological deposits were found in the numerous karst caves, some of which have been disturbed by the sea (Antonioli & Ferranti 1994). In the 'Grotta delle Capre' coastal cave, traces of MIS5.5 sea-level were found. It is interesting to note that the last interglacial tidal notch in the Circeo promontory, well-marked at an elevation of *c.* 9 m a.s.l., does not display a modern counterpart at present-day sea level. On the contrary, at Monte Orlando, near Gaeta, both a present-day notch and an MIS5.5 notch have been observed. Antonioli *et al.* (2006*a*) suggested that MIS5.5 notches along the Tyrrhenian coasts found in stable areas were formed during a single highstand. Their particular morphology, called 'double notch', resulted from a combination of isostatic motion and tidal erosion. Considering the limestone lowering rates suggested by Fornós *et al.* (2006), Furlani *et al.* (2009) and Antonioli & Furlani (2012), it can be inferred that MIS5.5 tidal notches in the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Mediterranean are well preserved because they were probably covered by late Pleistocene deposits, which prevented erosion.

The coastline of Campania includes three main tracts where the coast is mainly rocky, separated by wide low lying tracts. In northern Campania, steep and rocky shores, often with gravelly beaches or debris cones at their base, are present both north of the bay of Naples (in the Phlegrean district formed by volcanic rocks and in the islands of Ischia and Procida) and south of it, in the Sorrento Peninsula, a limestone promontory known for its holiday resorts. Cliffs formed by well-stratified carbonate rocks are typical of the facing island of Capri. In this area shorelines of the past interglacial are carved in the rocky promontories in the form of notches and marine terraces (Riccio *et al.* 2001). Typical landforms were classified by De Pippo *et al.* (2007): they recognized plunging cliffs and cliffs bordered by shore platforms or pocket beaches. Attention was paid also to submarine topography (De Pippo *et al.* 2004), which was investigated in order to reveal coastal landforms formed during past sea-level highstands and lowsands (De Pippo *et al.* 2004). Southward, the Cilento coast stretches over 100 km in length and is shaped in the form of cliffs alternating with slopes and beaches, in the framework of a complex geological structure characterized by flysch formations and Mesozoic dolomitic limestones (Mt Bulgheria; Ascione & Romano 1999). Promontories display retreating cliffs frequently subject to landslides and mid to late Pleistocene marine terraces, on top of which the main villages are developed. Some shore platforms occur especially in the area around Punta Licosa (Iannace *et al.* 2001). Coastal caves are also widespread, recording moments of speleothem formation between the different phases of marine ingression. Into the caves the traces of at least three different highstands can be observed from present day sea level and the elevation of 8 m a.s.l., which can be referred to the last interglacial (Esposito *et al.* 2003).

In the southernmost tract of the Campania coastline, in Basilicata up to the northernmost edge of Calabria, the Gulf of Policastro displays a discontinuous rocky coastal slope stepped by a flight of marine terraces elevated up to 400 m a.s.l. (Filocamo *et al.* 2010).

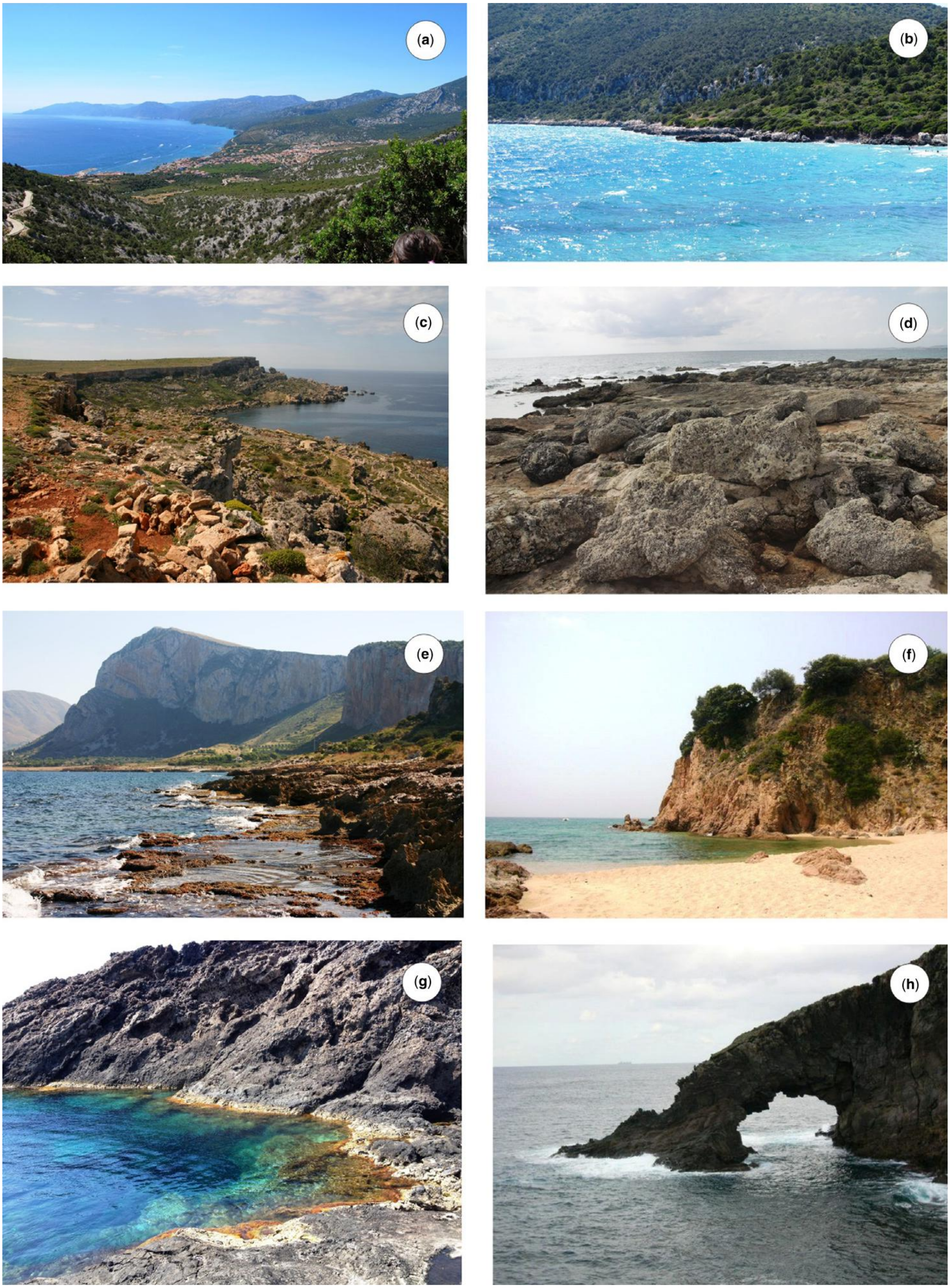
The west coast of Calabria displays three main rocky tracts, separated by wide coastal plains. The northernmost tract represents the steep, seaward slope of the so-called 'Coastal Range' (Sorriso-Valvo & Sylvester 1993), which is of great geodynamic interest as it preserves a stair of Quaternary marine terraces overlapped by significant marine and continental successions. They testify an enhanced uplift rate of the chain during early and middle Pleistocene, that becomes negligible in the late Pleistocene (Filocamo *et al.* 2009). A narrow coastal plain, 0.5–1 km wide, separates the mountain foothills from the sea, so that no particular rocky landforms are modelled. South of the wide Gulf of Sant'Eufemia, instead, the rocky promontory portending towards the sea with Capo Vaticano displays cliffs and stacks alternated to narrow beaches. Geologically the Capo Vaticano peninsula consists of granites and gneiss of the Palaeozoic basement, covered by tertiary carbonates, on top of which a staircase of eight raised erosional and depositional marine terraces are present that have been dated to 7.3–3.3 highstands (Bianca *et al.* 2011). The geodynamic history reconstructed for the area suggests that a very complex pattern of regional uplift and local faulting controls the morphological setting, even of the littoral currently subject to wave action and marine processes. It is worth noticing that cliffs in this area are not plunging, but display at their base a submerged and weakly seaward-dipping platform that is currently subsiding and was roughly at sea level 2.5 kyr ago, as testified by the presence of Greek harbour facilities (Stanley & Bernasconi 2012).

The southernmost edge of Calabria is, together with northwestern edge of Sicily, one of the fastest uplifting sectors of the central Mediterranean, where extensive studies have been traditionally performed on Quaternary shorelines (e.g. Antonioli *et al.* 2006*b*). Ferranti *et al.* (2008) studied two Holocene uplifted shorelines near Scilla, which were partly identified by relict shore platforms, a few metres elevated above present-day sea level, with which microforms such as potholes are associated. Although mostly neglected from the point of view of current morphological processes, areas of potential interest are widespread along this tract of coast, which is mostly cliffy. Being seismically very active (Ferranti *et al.* 2007), some attention was paid by researchers to hazards triggered by earthquakes and associated tsunamis (Bonavina *et al.* 2005; Bozzano *et al.* 2009), especially along cliff faces (De Blasio & Mazzanti 2010) and unstable steep slopes.

Relevant coastal landforms occur on the Aeolian islands, a volcanic archipelago facing the northeastern coast of Sicily, in particular in Lipari, where marine processes have cut volcanic structures, while Stromboli and Vulcano are intermittently active (Calanchi *et al.* 2007). Here sea-level change markers have been used to study the tectonic displacements of the area (Lucchi *et al.* 2004). Along the NE and SW portions of the volcanic edifice of Stromboli, at a depth of about 100 m, well-developed abrasion platforms, probably related to late Quaternary sea-level fluctuations, are present (Chiocci & Romagnoli 2004). They, though, lack any modern counterpart at present-day sea level.

The northern coast of Sicily is dominated by high cliffs, which can be considered as the westward continuation of the Calabrian Appennines in the island. Pocket beaches can be found in embayments. Rust & Kershaw (2000) examined the uplifted marine notches in northeastern Sicily and suggested that the roof of the uppermost notch can be considered a prominent and laterally persistent feature easily related to the boundary between subaerial and marine processes. The height of the roof varies between 5 m a.s.l. at the Messina Strait and 2.1 m a.s.l. at Capo Milazzo (Scicchitano *et al.* 2011). From Capo d'Orlando westward, sand and gravel beaches occur up to the limestone Cefalù promontory. Near Palermo, the coast shows an alternation of high cliffs and small pocket beaches (Agnesi *et al.* 2004). Antonioli *et al.* (2002) dated the emerged and submerged coastal sectors near the limestone promontory of Capo San Vito (Agnesi *et al.* 2004), at the NW corner of Sicily (Fig. 7.11e) and suggested the relative tectonic stability of the area. Southward, the Monte Cofano marble massif reaches a height of more than 600 m. Dolomite cliffs are present all around the archipelago of the Egadi Islands (Marettimo, Favignana and Levanzo islands). Along the southern Sicilian coast a system of headlands and bays, with pocket beaches of various size, extends south of Capo Passero, at the boundary between the Ionian Sea and the Sicily Channel. Then, a succession of promontories and bays extends north from the Torre di Vendicari. Along the southeastern coast of Sicily, Scicchitano *et al.* (2007) reported the occurrence of large boulder deposits related to 1169, 1693 and 1908 tsunami events (Fig. 7.11d). High limestone cliffs occur at Capo Murro di Porco. Then, an alternation of headlands, cliffs with different heights and bays continues until the Plain of Catania, where lava from Mt Etna reaches the coast, forming high cliffs. At Acitrezza, lava deposits from Etna form a small group of sea stacks (locally named *faraglioni*). Along the steep limestone cliffs in the Taormina area,

**Fig. 7.10.** Typical rocky shore landforms along the coastline of northwestern Mediterranean. (**a**) Present-day tidal notch in the limestone cliff of Balzi Rossi, at the border between France and Italy. (**b**). Shore platform and marine cave of Bergeggi promontory (western Liguria, Italy). (**c**) Cliff cut in bedded marls near Sestri Levante (Eastern Liguria, Italy). (**d**) Sea caves in a red shale cliff at Cinque Terre (Eastern Liguria, Italy). (**e**) The indented coastline of the eastern promontory of La Spezia Gulf with shore platforms and marine terraces in a staircase; in the background the village of Tellaro (eastern Liguria, Italy). (**f**) Roman quarries in a sandstone shore platform (Calafuria, central Tuscany, Italy); evidence of Holcene sea-level rise is provided by their current position below sea level. (**g**) Rockpools carved in the beach-rock capping a raised shore platform (Baratti Gulf, Tuscany, Italy). (**h**) Plunging cliff in sedimentary rocks of Gorgona Island, in the Tuscan Archipelago.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Rust & Kershaw (2000) reported the occurrence of uplifted marine notches, similar to those at Capo Milazzo. The authors interpret these as surf notches. At sea level, the organic rim is only few centimetres wide.

The volcanic island of Pantelleria is located over 100 km south of Sicily, but the central volcano, which rises up to over 800 m above sea level, has been inactive since 1891. Coastal caves, sea arches and other spectacular morphologies can be found around the island (Fig. 7.11h). Ustica is also completely volcanic (Fig. 7.11g). Lampedusa is a bare, low-relief island, 11 km long, while Linosa is the smallest of the Pelagic Islands, an inactive volcano; along its coast, sea caves occur.

Considering MIS5.5 sea-level markers, Ferranti *et al.* (2006) suggested that southern Tyrrenian coasts are generally stable, while vertical displacements occur around the Messina strait. The maximum uplift rate might be centred at the Etna volcano (Monaco *et al.* 2002). The present-day coastal morphology of the area is strongly affected by local tectonics. Sardinia and Corsica, which are separated by the narrow (only 15–20 km wide) Bonifacio Strait, after Sicily, are the second and the third largest islands, respectively, of the central Mediterranean Sea.

From a geological point of view, Sardinia and Corsica represent a portion of the European margin made by Hercynian basement, locally covered by Carboniferous to Permian continental deposits and Triassic to Cenozoic carbonate sediments. The northeastern portion of Corsica, the so-called 'Alpine Corsica', displays tectonic units made by Jurassic ophiolites and their Jurassic to Early Cretaceous sedimentary cover, overlain by Cretaceous–Oligocene flysch sequences (Molli 2008). Suites of rocks pertaining to two distinct Cenozoic volcanic cycles crop out extensively in Sardinia. Quaternary deposits are subordinate (Carmignani *et al.* 2001).

Sardinia and Corsica display prevalently rock coasts, characterized by cliffs, notches and shore platforms. These forms are shaped in different types of rocks as a consequence of the geological history of the islands. Geological features on the coastlines of the two islands are the main factors guiding landform development and erosive processes.

The coast along the Gulf of Orosei, in the central-eastern part of Sardinia, represents a key area for rock coast geomorphology. It is characterized by high cliffs, mainly cut in Jurassic dolostones and limestones, developed along 37 km from north to south, between the villages of Cala Gonone and Santa Maria Navarrese (Fig. 7.11a). Well-developed tidal notches, indicating present and past mean sea levels, are described along the entire carbonate coast, from a depth of 10 m b.s.l. to the height of 10.5 m a.s.l. (Carobene 1972, 1978; Carobene & Pasini 1982; Antonioli *et al.* 1999, 2007). The notch attributed to MIS5.5 is decreasing in height from north to south between 10.5 and 7.7 m a.s.l. and is continuous along the entire tract of limestone coast.

Shore platforms are present in different sections of the Sardinia coast (Fig. 7.11b). At San Pietro Island, facing the SW coast of Sardinia, shore platforms and marine terraces are present. Shore platforms are also reported along the western coast of Corsica in the Gulf of Valinco. Landslides are another type of process affecting the rock coast of Sardinia and Corsica. Rock or debris falls are quite widespread along the coastal cliffs and involve different rock types. Nevertheless, entire coastal tracts are affected by mass wasting. On the extreme northern side of Sardinia, in the neighbourhood of Castelsardo, Ginesu (1992) reported that the evolution of an entire coastal tract is due to landslides and deep-seated gravitational slope deformation. The area is characterized by rocks from the Oligocene–Miocene volcanic cycle (Carmignani *et al.* 2001), and include ignimbrites and tufaceous–cineritic rocks (Fig. 7.11f), in addition to aeolianites. Different types of landslides are the cause of coastline retreat depending on the interplay of rock types. Debris avalanches occur in cliffs in aeolianites where undermining is caused by waves, earth slumps where aeolianites overlie loamy ash substrates, and rock slumps involving cineritic and tufaceous rocks. In Corsica, the occurrence of rock falls contributes to the retreat of the coastline on the north side of the Propriano bay, in the western part of the island (Chelli *et al.* 2007).

Finally the coastline of the Maltese Islands (Malta, Comino and Gozo) consists of steep or vertical limestone cliffs, indented by bays, inlets and coves (Bird 2010). It is closely controlled by the combination of the geological structures and fluvio-karstic development (Paskoff & Sanlaville 1978). Bays in the north correspond to downlifted blocks in a horst–graben system, generally developing in an east–west direction. High cliffs occurring in the southern part of the island are related to the Pantelleria fault system. Paskoff & Sanlaville (1978) reported the presence of finger-like creeks near Valletta, which are drowned valleys that were previously excavated by fluvial processes. Most of the Maltese coast is high and shows different types of cliffs: plunging cliffs, mainly related to fault scarps, limestone cliffs with the soft Globigerina limestone and shore platforms at their base, and cliffs with large landslides (Fig. 7.11c), locally called *rdhum* (Said & Schembri 2010). The latter consist of limestones at the top and clays at their base. They have been extensively studied in the northwestern sector of Malta by Devoto *et al.* (2012).

### *Literature on processes operating on rock coasts: a review*

There are few data reporting the rates and modes of cliff retreat and shore platform erosion along the Mediterranean Iberian Peninsula and the Balearic Islands. Perhaps because the 60% of rock coasts from this regional section of the coast are located in the Balearic archipelago, most studies on rock coast erosion dynamics belong to this geographical area.

Cliff retreat has been measured over a range of time and spatial scales. Balaguer *et al.* (2001) characterize cliff retreat in south and SE Mallorca by field-based observations. Episodic retreat, after five years of surveying without any mass movement, relates to intensive and sporadic rainstorms between December 2001 and January 2002. Mass movements on hardest limestone mobilized 1431 $m^3$ and on a softer rock with more lithological variation the loss was 40 $m^3$. Rainfall intensity, fracture density and lithological variations seem to be the key factors determining macro-scale erosion along these cliffed coasts of Mallorca. Block quarrying is also a frequent process in cliff and shore platform erosion. Swantesson *et al.* (2006) detail the detachment of 2.24 $m^3$ at granite coasts in Catalan Coastal Range sectors and between 0.06 and 1.98 $m^3$ on a yearly basis. Larger values relate to folded Jurassic or Cretaceous limestone, whereas lower values relate to Upper Miocene calcarenites. Linking these values to long-term surveys

**Fig. 7.11.** Examples of cliffs and rocky coasts in the islands in the central Mediterranean. (**a**) View from north of the calcareous rock coast of the Gulf of Orosei (western Sardinia) extending from Cala Gonone (the settlement in the photograph) towards the south, to Santa Maria Navarrese. (**b**) Shore platforms characterize several coastal tracts of Sardinia. Here the outer margin of the shore platform near the Cartoe beach (Gulf of Orosei) is recognizable. Slope deposits hide the inner portion of the platform and the junction between the platform and the back cliff. The top of the inactive cliff is still visible even if deeply eroded by the weathering and karst processes. (**c**) Limestone rocks at the top of the cliffs lie on clays, producing large landslides (Malta island, western coast). This morphotype is locally called *rdhum*. (**d**) Tsunami blocks near Siracusa (Sicily). (**e**) Trottoirs along the coast at San Vito lo Capo (Sicily). (**f**) The cliff shaped in the volcanites cropping out along the Gulf of Valinco (Southern Corsica, France) displays a drowned shore platform at its foot. (**g**) Volcanic coast at Ustica (photograph courtesy of Sara Biolchi). (**h**) Natural arch locally named 'The Elephant' carved in the volcanic rocks along the Island of Pantelleria.

based on Ordnance Survey maps and aerial photography, Balaguer *et al.* (2008) indicate that from 1956 to 2008 there is no clear spatial and temporal pattern in decline or increase of cliff erosion rates. Most events are episodic in space and time. On the southern Catalonia coast, Montoya (2008) described rock falls of 2.4 $m^3$ from field studies and cliff retreat of 0.2 m $a^{-1}$ from aerial photograph comparisons.

In contrast, granular cliff face disintegration has been identified as a continuous but low-magnitude erosive agent in south and southeastern Mallorca (Balaguer & Fornós 2003). Erosion owing to this kind of process yields cliff retreat values between 0.03 and 0.12 mm $a^{-1}$. These processes are mainly related to salt weathering, cliff face rainfall cleaning and wind erosion, and at short time scales do not cause a significant change in the cliff profile.

Further studies focus on erosion rates and processes on shore platforms. Swantesson *et al.* (2006) and Fornós *et al.* (2006) measured shore platform downwearing rates on different shore platforms in Mallorca (limestone) and northeastern Catalonia (granites). In both locations micro erosion meter (MEM), traversing micro erosion meter (TMEM) and laser scanner techniques showed low erosion rates (0.021–0.323 mm $a^{-1}$). These values contrast with the bioerosion rates from different snails and limpets such as *M. neritoides* or *Patella* sp., which are abundant on the Mediterranean rock coast. Bioerosion rates range between 0.003 and 2.1 mm $a^{-1}$ and are related to the rock lithology and ecological constraints (Gómez-Pujol 2006).

Gómez-Pujol *et al.* (2006) compiled erosion rates and morphological analysis and concluded that many cliffs and shore platforms in the western Mediterranean are not related to the feedback mechanisms between waves, rock hardness and platform width, and slopes are not in equilibrium with contemporary processes. Therefore other factors such as geological control and inheritance (as sea level has changed repeatedly during the Quaternary and has reached the contemporary position many times) exert primary control over the morphology of present day rock coasts. Continuous bioerosion, granular disintegration and coastal karren are slowly modifying the gross cliff–platform morphology.

Both Rombenchi & Tarchiani (2001) in the Argentario area and Groppelli *et al.* (2001) identified two main factors contributing to sea cliff retreat; the former is wave action while the latter is related to geological features, such as the lithology and the structural and geomechanical setting.

During the last five years, a research project on shore platforms of the northern Tyrrhenian and Ligurian Seas, in Italy, has been carried out, with the purpose of identifying, surveying and genetically interpreting those landforms that are scattered along this coastal tract (Arozarena Llopis 2006; Chelli *et al.* 2010*a*, *b* and references therein). In this area, though, shore platforms do not display a typical morphology. They are not strictly intertidal features but develop from the low spring tide up to 2 m and in some cases up to 5 m a.s.l. Their surface generally has a low angle (but steeper than that of typical oceanic landforms), ending with a seawards cliff (Fig. 7.10e), resembling the type A of Sunamura (1992); frequently they are backed by a cliff but in some cases by a ramp or a vegetated slope.

An inventory of the shore platforms of this area has been carried out (Rosa 2010) based on the interpretation of aerial and satellite images and oblique photographs of the coastline. This has been organized in the form of a GIS database and is constantly implemented, storing on it all the data collected in fieldwork activities (topographic profiles, Schmidt hammer tests, petrographic and structural analyses of the bedrock etc.) as well as all morphometric analyses. This database is maintained in the framework of a collaborative project at the ENEA Santa Teresa Research Center, and implemented with data from researches carried out at Pisa and Parma Universities.

Recurrent patterns have been identified in the weathering microforms affecting the shore platforms surface and in biologic zoning of the intertidal and lower supratidal portions of the platforms. Weathering microforms are widespread in all bedrock types along this section of the coast. In sandstones microforms occur as rockpools and honeycombs (McBride & Picard 2004); granitoid rocks are mostly affected by honeycombs and tafoni (Elba Island; Aringoli *et al.* 2009); in limestones and shales potholes are prevalent, the shape and size of which is firmly controlled by the geological structure, by faults and fractures pattern.

Platforms surfaces are colonized by different biota, that form ubiquitous bands from low-tide sea level upwards. This biological zoning includes the upper limit of algas, then a band colonized by grazing gastropods, echinoids and fixed bivalves, a narrow band of cyrripeds (barnacles, 30 cm width in sheltered sites), that may turn into a wide area in exposed sites, and finally a continuous band of Cyanofites topped by a discontinuous lichen cover (*Verrucaria adriatica*) in the upper supratidal. The well-defined barnacle belt is constituted by a mixture of *Chthamalus montagui* and *Chthamalus stellatus* (Pannacciulli & Relini 2000). An attempt to disentangle the specific contribution of bioerosion/bioprotection in shaping shore platforms has been carried out (Rosa 2009; Chelli *et al.* 2012). In particular, the role of *Chthamalus* spp. and *Verrucaria* spp. was investigated. It represents the major sessile organisms along these limestone shores. The percentage surface cover of biota was measured over selected areas of the platform and each area was then tested with the Schmidt hammer. This analytical method was applied to a number of tracts of the platforms, displaying different coverage. Results demonstrate that only those parts of the rock covered by chtamalid barnacles display a reduction of rock hardness, on the order of 10% compared with uncovered rock at the same tidal elevation. Preliminarily this reduction in hardness was attributed to the bioerosive action of barnacles; new experiments based on a multivariate statistical analysis are in progress in order to test this hypothesis.

Rock hardness was tested on the rock surface by means of the Schmidt hammer also in order to highlight changes in the effectiveness of weathering processes. A rebound reference value was measured testing a fresh rock outcrop, hammering the platform at its uppermost edge. Different approaches were tried: the first approach was aimed at differentiating the lower part of the platform, from sea level to the upper limit reached by Cyanofites (B belt; Arozarena Llopis 2006) from the upper part (A belt). The results obtained from a large number of testing points in each belt were statistically processed and used to compare the two belts against each other and both against the fresh rock. The same type of sampling strategy was used to compare different orders of shore platforms (Biagioni *et al.* 2008): a first order, displaying an inner edge in the elevation range 2–5 m, and a second order, raised from present day sea level, in which the inner edge elevation of the single platforms clusters around the value of 10 m a.s.l. The two platforms orders proved to be statistically different applying Students's *t*-test to the rebound values obtained from each of them. Second-order platforms yield in general lower rebound values, and are thus more weathered than the first-order ones. This evidence was interpreted as a consequence of the fact that raised platforms are inherited landforms that have been exposed to subaerial weathering for a long time.

The second approach (Chelli *et al.* 2010*a*) was based on the analysis of testing points equally spaced and arranged in transects perpendicular to the shoreline. At the study sites facing the Ligurian Sea, where the bedrock is represented by different varieties of flysch (containing different percentages of calcium carbonate) and the coastline is more articulated, shore platforms display weathering profiles that highlight the maximum effectiveness of weathering processes in the intertidal and lower supralittoral (B belt). In the upper part of the supralittoral (A belt) a landward negative trend of weathering was observed, suggesting that shore platforms are weathered mainly by those subaerial processes that are driven by the proximity to the sea, such as wetting and drying and salt weathering. Along the coast facing the northern Tyrrhenian Sea (De Fabritiis 2012), which is less indented and thus more exposed, tests performed on the rocky coast south of Pisa, composed of sandstone, show that close to the sea rebound values are higher than in the B belt. This is due to the effectiveness of wave action that fosters plucking, the evidence of which can be observed on the rock surface.

Flat or gently dipping rock surfaces artificially created (Fig. 7.10f) along the coast (e.g. quarries) were tested in order to statistically differentiate them from natural shore platforms surfaces where fresh scars are evident. In this region coastal areas have been settled since the Iron Age and thus quarries have been exploited since then up to the end of the second millennium BC as the coast provided facilities for transport and trading of extracted materials. The age of a cave can be broadly inferred from traces left by different quarrying techniques. Schmidt hammer testing suggests that the effects of weathering are detectable already on surfaces that have been exposed for a century (Rosa 2009). In general the measured reduction in hardness of the rock owing to weathering with respect to the fresh rock ranges between 15 and 50%.

Some attempts were made to evaluate the contribution of wave action to overall platform shaping. A model was employed that was capable of simulating wave parameters at the shore starting from offshore wave gauge data. The energy of waves and the position where they break with respect to the shore were calculated along selected profiles normal to the coastline along the eastern promontory of La Spezia Gulf (Arozarena Llopis 2003), which is a very indented tract of coast with a carbonate bedrock (Spagnolo *et al.* 2008, Fig. 7.3e). Results demonstrate that, in that specific area, waves are unable to shape rocky shores as rock resistance exceeds by one order of magnitude the energy exerted by waves at the shore. A further study is in progress along the exposed, rectilinear coastline developed in a sandstone south of Pisa.

The data collected so far for the Ligurian and northern Tyrrhenian Seas coast suggest that the agents responsible for shaping the shore platforms in the intertidal and lowermost supratidal in this area are mainly weathering and bioerosion (Fig. 7.10g). The former is driven by geological structure and based on physical processes linked to the proximity to the sea, such as wetting and drying and salt weathering. All the investigated platforms are only partly in a steady state with current morphological agents: they should be considered as inherited landforms, genetically bound to a past highstand and thus formed in connection with a relative sea-level higher than today (Fig. 7.10h). At present, processes acting on them are mainly weathering and bioerosion, the ultimate effect of which will be platform destruction.

In a focused study of the rockpools along the Latium (Circeo) and Campania (Cilento) coast, De Pippo & Donadio (1999) suggested a morphological classification of these landforms based on their genesis and geometry. They identified 13 morphotypes falling into five categories. These are assessed with a genetic criterion, and include biogenic, erosional (owing to dissolution and abrasion), structural, artificial and polygenetic forms.

The morphometric index $I_p$ was worked out in order to classify these landforms. It derives from the ratio between the rockpool length or diameter and its depth. In the study areas it ranges from 0.6 to 6. The index value depends on the evolution stage and on the genetic agent: it increases as the bedrock structural conditions prevail on erosional agents in determining rockpools pattern.

Along the southern Tyrrhenian coast, rock instability of the sea-facing slopes is considered a major issue for geomorphological research. De Pippo *et al.* (2008, 2009) and Pennetta & Lo Russo (2011) worked out a method to quantify, rank and map the distribution of hazard in the Sorrento Peninsula and in the island of Capri. They highlight that observed cliff recession is related not only to wave action but also to slope processes. In particular, Pennetta & Lo Russo (2011) focused on the role of the bathymetry and morphology of the submerged areas near the cliffs. They concluded that mechanical wave erosion is very low and mass movements are absent in correspondence with plunging cliffs, while mass movement produces retreat on cliffs with basal shore platforms.

The rocky coast of Cilento was selected by Budetta *et al.* (2000) to investigate the relationship between rock mass strength and coastal erosion. Coastal erosion rates were quantified studying the variations, especially in restricted headland areas, occurring over two time spans, 30 and 45 years long, through remote sensing analysis. These comparisons suggest an average erosion rate of 0.5 m $a^{-1}$ in 30 years, and 0.8 m $a^{-1}$ in 45 years. The study of a notch incised by wave action on a concrete sea wall built to protect a terrace enabled the authors to calculate the wave energy able to cause cliff erosion, correlating the compressive strength of the rock mass forming the cliff and the long-term average erosion rate. In this way, an average wave energy of 24 MPa was calculated.

Owing to the high tourist value of the island, several studies have dealt with coastal retreat in Sardinia, approaching the problem from a geomorphologic perspective (Ginesu *et al.* 2012 and references therein). Also here, the coastal plain evolution and beach erosion have received more attention with respect to rock coasts.

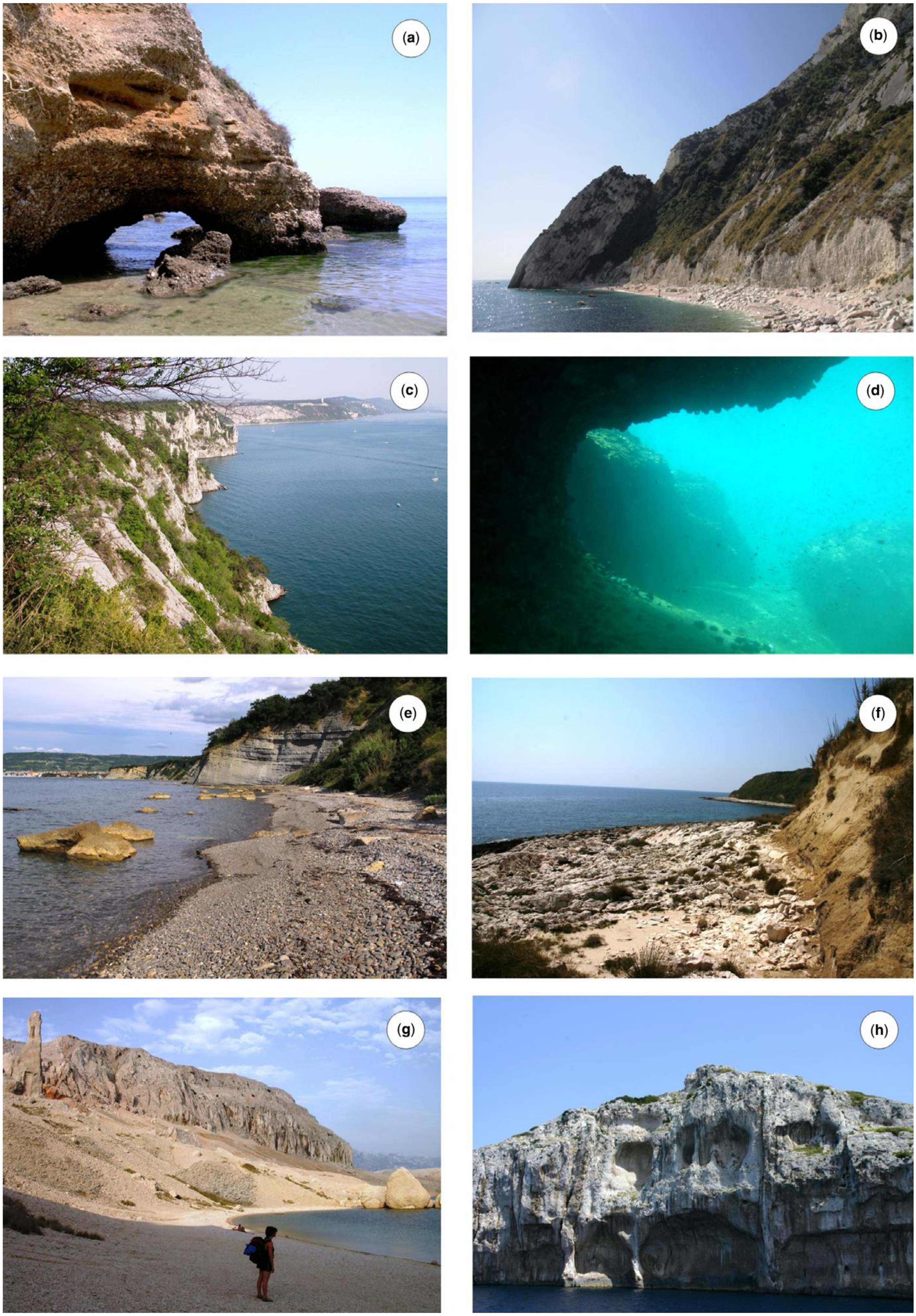
The karst and littoral processes are responsible for the coastal morphologies (De Waele 2004) and erosion is promoted by corrosion that is prevalent where mixing between fresh and salt water occurs, leading to hyperkarst phenomena (De Waele *et al.* 2001). Erosive sea caves, formed by wave action, are located along the coast where joints or structurally weak rocks crop out, while important coastal karst caves, reaching lengths of several kilometres (De Waele & Forti 2002), occur where the mixing phenomena between salt and fresh water exist.

The most intense and widespread karst-forming processes that caused the forms present on the Orosei Gulf coast are likely to have occurred during the mid Pleistocene (between isotopic stages 9 and 6, approximately 350 000–130 000 years BP; De Waele 2004). The existing morphologies are, at least in part, inherited and they started to form during one or more wet interglacial periods.

At Punta Funtanas, in western Sardinia, the processes responsible for the morphology of the coastal karst on both Miocene massive limestones and Quaternary aeolianites have been investigated (De Waele *et al.* 2009). Here the existence of favourable conditions such as dominant northwesterly wind, conditions of the sea and exposure, have allowed the development of a rich set of karst landforms including caves, cylindrical shafts, coastal karren, pipes and photokarren. For these areas, where a shore platform exists (De Waele *et al.* 2009), the rock surface close to the outer cliffs of the platforms (up to 10 m inland from those) is dominated by extremely irregular rough and sharp forms, whose continuity is broken by deep and often coalescing solution pans generally filled with water. This zone is subjected to marine splash and spray, allowing the development of blue-green algae that almost completely cover the surfaces. The remaining surface of the shore platform may be roughly subdivided into two parts with a line 20 m inland with respect to the outer cliff. Seaward of this line the rock surface is characterized by forms with smoother edges and great but shallower coalescing solution pans, in which water does not always persist. The surfaces are extensively pitted, leaving them relatively irregular. Landward of this imaginary line the rock surface comprises the remaining part of the shore platform where forms are well rounded, and pitted surfaces are smaller and less developed and leave space to smooth limestone surfaces in which the control of structural factors is clearly visible.

Shore platforms with flat rock surfaces are reported by Violante (2009), shaped in volcanic rocks. The development of shore platforms is the consequence of cliff retreat caused by quarrying and abrasion processes, with significant aid from bioerosion and weathering.

Near Capo Laurosu (southern portion of the Gulf of Valinco), Chelli *et al.* (2007) surveyed and described a shore platform gently dipping into the sea and shaped in granite. Physical


(a)
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(wetting-and-drying, salt weathering) and chemical processes are invoked by the authors for the development of this platform that represents the result of the progressive dismantling of the marine terrace that constitutes part of the headland. Rock pools and grooves characterized the surface of the shore platform. On the whole, the erosive processes acting on this portion of the coast are also underlined by the presence of sea stacks at some distance from the coast, that testify the general retreat of the coastline.

The occurrence of weathering forms is common in rocks of different types along the Sardinia and Corsica coasts. In Corsica, Mustoe (1982) reported that the wide variety of pits, hollows and boxwork patterns of indurated joints, reffered as 'tafoni', are widespread in rocks such as granite, sandstones, gneiss and schist. In Sardinia, Ginesu & Secchi (2009) observed the presence of tafoni along the coast of Gallura, the region representing the northeastern part of the island, where granitic rocks crop out extensively.

Reusch (1883) probably first used the term 'taffoni' dealing with the description of this weathering form in Corsica. Afterwards, Bourcart (1930) used the term 'tafoni' for the occurrence of dramatic weathered pockets on the island of Corsica (Turkington & Paradise 2005). Bourcart (1930) considered that salt weathering explained the honeycomb weathering in coastal environments, while Cailleux (1953) believed that such weathered surfaces in Corsica were preserved from the Pleistocene, when they were formed by localized frost shattering. Tafoni and forms owing to chemical weathering were also observed by Chelli *et al.* (2007) in the coastal area of Propriano Bay, where granitic rocks crop out.

In the minor islands of the central Mediterranean, and especially in the volcanic ones, there is a special need for studies on coastal processes. In fact a great potential is represented by the huge amount of evidence provided by volcanology and tectonics available for these areas, as well as by the large-scale bathimetric data collected in recent years.

Regarding Malta, Micallef & Williams (2009) used a rock profiling technique to investigate surface denudation rates on Maltese shore platforms. They suggested lowering rates ranging from 0.74 mm $a^{-1}$ to 9.16 mm $a^{-1}$ depending on the lithology.

Farrugia (2008) studied sea cliffs, in particular *rdhums*. Farrugia (2008) suggested that sea cliff erosion rates are accelerated by destabilization from engineering works during construction and increased load on the cliffs, and cliff retreat can be higher on the top of the cliff rather than at the toe, because of the morphology of the cliffs and the protection provided by collapsed blocks. At the top of the *rdhums*, deformation rates are up to 2.7 cm $a^{-1}$ (Mantovani *et al.* 2013).

Along the coasts of the northwestern Mediterranean were recognized tsunami-deposited blocks. Scheffrers & Kelletat (2003) reported the occurrence of blocks up to 23 t along the coastline of the Balears (Table 7.3). Scicchitano *et al.* (2007) found tsunami blocks scattered at 2–5 m a.s.l. between Augusta and Siracusa. Boulders are up to 182 t in weight and are arranged as isolated elements or in small groups of blocks, and are probably related to the earthquakes of 1169 and 1693. Antonioli *et al.* (2004) found tsunami blocks along the Scilla–Palmi coast, in Calabria – large blocks between 0.9 and 1.8 m a.s.l. located on an uplifted marine terrace (Table 7.3). Furlani *et al.* (2011*e*) reported storm wave and tsunami blocks in the northwestern sector of the island of Malta (Table 7.3).

## Northeastern Mediterranean rocky coasts

### *Overview of rock coasts landforms within their geographical background*

Three-quarters of the total length of the Mediterranean coastline is confined in the northeastern sector of the Mediterranean Sea (Stewart & Morhange 2009) and about 65% of it is rocky. This coastline represents the northern part of the Eastern Mediterranean and includes the Ionian, the Adriatic and the western coasts of the Aegean Sea.

An alternating succession of headlands and embayments of different sizes affect most of the Ionian coast along the Italian peninsula. In the Gulf of Taranto, the southern and western sides are bordered by steep slopes descending to a narrow coastal plain (Ciavola 2010). Limestones crop out with partly drowned dolines. Up to seven uplifted marine terraces have been recognized, the highest 400 m above mean sea-level (Ferranti *et al.* 2006). The east coast, beyond Taranto, is a generally low-lying hilly peninsula culminating in the Capo San Maria de Leuca. The whole of the Taranto area has a well-documented history of late Pleistocene coastal changes and tectonism (Belluomini *et al.* 2002).

While the northwestern Adriatic coastline is low-lying and dominated by plains related to the major rivers flowing from the Alps, the eastern and southern sectors of the Adriatic Sea are bordered by rocky coasts. From the southeastern border between the Adriatic and the Ionic Sea, the Apulian coast is almost completely rocky, with limestone sloping shores and cliffs sometimes alternating with wide pocket beaches (Mastronuzzi *et al.* 2002). From the town of Brindisi to the Gargano Promontory, high limestone rocky coasts and small pocket beaches occur (Bird 2010). In the coastal sector south of Bari a flight of steps of marine terraces, jointed by steep scarps, stretches from 150 m a.s.l. down to the sea-level; here, Maracchione *et al.* (2001) identify four different types of cross-shore profiles and work out a semiquantitative approach to relate coastal landforms to coastal dynamics. The coast of the Gargano Promontory is cut in biogenic calcarenites and shows evidence of Holocene uplift (Mastronuzzi & Sansò 2002), while northward the coast is mainly low lying up to the Gulf of Trieste. The Abruzzo coastline is dominated by soft rock cliffs (Fig. 7.12a) cut in gravels and sands; then, only Monte Conero and Monte San Bartolo display rocky shores. Monte Conero (Fig. 7.12b) was first described by Rovereto (1908). This headland is formed by high marls and limestones cliffs, breaking the long stretch of beaches dominating this coastal sector; at the base of the cliffs, carved in soft rock coasts, the coastal scenery is dominated by sea stacks and caves. A short tract of cliffed coast can be found near Pesaro, the Monte San Bartolo Promontory. Northwards, the eastermost termination of the Po plain, dominated by low-lying coasts and beach fringes, extends up to the Lagoon of Venice and Grado-Marano.

The eastern Adriatic coast generally follows the NW–SE strike, from the Gulf of Trieste (Italy, Slovenia and Croatia) to the Gulf of Kotor (Montenegro), with folded rock formations descending straight to the sea and forming high plunging cliffs or low-lying limestone coasts. In the so-called Classical Karst area, between Duino and Sistiana (Italy, Fig. 7.12c), 70 m-high plunging cliffs descend to the sea (Furlani *et al.* 2011*a*). Coastal limestone features in the Gulf of Trieste were studied by Forti (1985) and

**Fig. 7.12.** Examples of rocky shores along the Adriatic Sea. (**a**) Soft cliffs cut in Pliocene–Pleistocene conglomerates at Punta Aderci (Abruzzo). Stacks, sea caves and arches develop because of cliff retreat. (**b**) Monte Conero sea cliffs cut in marly limestones. (**c**) Plunging cliffs at Sistiana-Duino (Gulf of Trieste). A number of coastal springs occur along the coastal sector. They are mainly related with the Timavo River system, the main underground river of the Classical Karst. (**d**) The submerged notch occurring along most of the eastern limestone Adriatic coast. (**e**) Cliffs and shore platforms at Strunjan (Strugnano) along the Slovenian coast. (**f**) Cliffs cut in Pleistocene aeolian sands at Susak Island. The retreat of sandy cliffs exhumes underneath limestone beds. (**g**) Rocky coast at Pag Island (Croatia). At the base of limestone cliffs, landslides provide pebbles, cobbles and large limestone blocks. (**h**) Plunging cliffs at Dugi Otok (Croatia). The limestone cliff face is carved by features owing to karst processes related to differential corrosion.

Furlani *et al.* (2011*d*), such as the submerged notch (Fig. 7.12d). Southwards, the Trieste area and NW Istrian coasts are affected by drowned valleys, locally called Valloni (D'Ambrosi 1948), cut in Eocene flysch (Fig. 7.12e), with up to 80 m-high cliffs and extensive shore platforms at their foot, which extended for hundreds of metres below the mean sea-level (Furlani 2003).

The remaining part of the Croatian coast from the Istrian peninsula to the Kvarner Sea and the Dalmatian coast are dominated by limestones. The general shape of this coast is so distinctive that a 'Dalmatian type' was recognized by Shepard (1973). This type consists of elongated ria with chains and straits that follow the axes of parallel or perpendicular folding (Von Richtofen 1885; De Martonne 1948). Ria coasts are steep with a longitudinal structure and produce elongated islands, peninsulas, channels, straits and bays (De Martonne 1948). Sometimes they are referred to as fjords (e.g. Limski Fjord), but this is incorrect, as they were not produced by glaciation. Gregory (1915) observed that the coastal features along Dalmatian coasts are so similar to glacial features that, if they were situated in higher altitudes, they would be surely have been attributed to glaciation.

In general, the Eastern Adriatic coast is steep and rocky, with occasional pocket beaches of sand or gravel. The coasts of the Istrian peninsula and the Gulf of Rijeka to the east are steep and penetrated by narrow inlets along drowned valleys. Southeast from Rijeka the coast is also steep. There are occasional shingle beaches, usually at or near the mouths of steep valleys where streams bring down gravels during heavy rain events. All along the Eastern Adriatic coast a well-carved submerged notch (Fig. 7.12d) occurs (Pirazzoli 1980; Fouache *et al.* 2000; Benac *et al.* 2004, 2008; Antonioli *et al.* 2007; Faivre *et al.* 2010; Furlani *et al.* 2011*a*). In contrast, the authors surveyed the complete lack of a present-day one at sea level. Faivre *et al.* (2011) suggested that the submerged notch was carved after the Roman age, while Furlani *et al.* (2011*a*) and then Faivre *et al.* (2013) suggested that it could have been carved as a consequence of both tectonic stability and palaeoclimatic causes, possibly associated with the medieval warm period.

The outer coasts of the islands of Krk, Cres, Losinj and Pag (Croatia, Fig. 7.12g) islands are exposed to strong wave action, whereas the mainland coast is very sheltered. To the south, the islands of Rab and Pag (Fig. 7.12g) are elongated with valleys and inlets running along the NW–SE direction. Cliffs on the seaward side show karst dissection, with submerged notches, while on the inner shores slopes descend to sea level, incised by valleys that are essentially wadis. The lower slopes and coastal plains have a mantle of loess, locally eroded into low cliffs, which have yielded sandy and silty material for occasional bay beaches. The Kelebitski Canal divides the islands from the mainland. It continues SE to the mouth of the Zrmanja valley, ending in the almost enclosed Novigrad Lagoon, which has bouldery limestone shores. At Povljana, the steeper landward slope is a dry escarpment, with submerged springs flowing from the scarp foot. There are low cliffs, partly in the loess capping over dipping limestone, across which shore platforms have been cut, and locally the beach sand has been cemented into beachrock. Loess deposits completely cover the island of Susak, but its coasts are almost completely carved in the basal limestones (Fig. 7.12f).

The deep Paklenica canyon opens from the high mountain range to a conical debris fan, now incised by the river that swings southeastward. Low cliffs expose siliceous gravels, which locally form a shore-bench.

At Seline, low cliffs to the south expose a conglomerate cemented by calcareous material and a soft chalky limestone. There are high cliffs on the seaward side of offshore islands such as Kornati Islands (Fig. 7.12h). The deep Krka Valley opens into an estuarine inlet, Skradinski Buk, widening down to Sibenik. To the SE, few islands protect the continental coast, so the shore is much more exposed to Adriatic storm waves. This can be considered the true Dalmatian coast, extending SE to the Neretva River. To the SE, Brac, Hvar, Korcula and many smaller islands occur. Sandy or gravelly pocket beaches locally occur, and in some places small islands have been tied to the mainland, forming tombolos.

The island chains converge on the mainland coast towards Dubrovnik, where high plunging cliffs occur along the base of the steep coast to the SE, exposed to the open Adriatic Sea. Across the border with Montenegro, the relief is interrupted by a deep curving ria at Boka Kotorska (Gulf of Kotor).

The Albanian littoral can be divide into two major units; the Adriatic coastline is low lying while the Ionian is mainly composed of steep rocky coasts (Pano *et al.* 2007). The Gulf of Vijose occupies a trough behind the high Karaburuni Peninsula, which runs out NNW to Cape Gjuhezes, with the high outlying island of Sazan (Paskoff 1985). The seaward slopes of the Karabuni Peninsula are steep, and the nearshore sea deep, with exposure to strong southwesterly waves across the Ionian Sea. Cliffs up to 50 m high have been cut in the strongly folded Cretaceous limestones and sandstones. Karst topography has developed locally on limestone shores (Paskoff 1985). The steep coast follows the trend of the mountain range SE to Cape Kefali, a cliffed promontory beyond which the coast passes into the shelter of the island of Corfu.

Greek coasts are characterized by steep cliffs alternated with low-lying deltaic areas which can produce coastal features, such as tombolos (Fig. 7.13c). The Greek coastline represents the result of major structural lineaments that have influenced coastal geomorphology (Bird 2010). Folded and faulting structures developed following the Alpine orogenic uplift (Kronberg & Günther 1978). As a consequence, a horst and graben system produced an extremely rugged topography, mainly following a NW–SE direction, but also an east–west direction, as in the Gulf of Corinth. The tectonic setting of the Aegean Sea is very complex because of the collision of several continental plates, producing uplift or subsidence of former coastlines (Lagios & Wyss 1983). Greek coasts are mainly high and steep and retreat rates varied according to their lithology – since cliffs are cut in sedimentary (Fig. 7.13a, b), methamorphic or volcanic rocks (Fig. 7.13e) – and exposure (Bird 2010). Tziavos & Kraft (1985) suggested that retreat rates are higher in correspondence with limestones and metamorphic rocks. Marine terraces have been surveyed at 16–18, 30–40, 90–100 and 150–200 m along the Aegean coastline (Eisma 1978; Kraft *et al.* 1980).

Pirazzoli (1980) combined the occurrence of submerged limestone corrosion features, such as tidal notches, with dated archaeological remains, in order to define past sea level positions in the Aegean area (Fig. 7.13d). Afterwards, Stiros *et al.* (1992) on Euboea Island, Stiros *et al.* (1994) in Cephalonia, Pirazzoli *et al.* (1996*a*, *b*) in Crete, Stiros *et al.* (2000) in the Samos Island and other eastern Mediterranean sites, Kershaw & Guo (2001) in the Perachora Peninsula, Pirazzoli *et al.* (2004) in the Gulf of Corinth and recently Evelpidou *et al.* (2011) on Theologos (Greece) and Pavlopoulos *et al.* (2011) in different sites in the western Aegean Sea (Antikythira, Crete, Rhodes, Nisyros and Thrace region) surveyed the altitude of submerged or uplifted notches along Greek coasts. Pirazzoli *et al.* (1982) suggested the presence of nine to 10 uplifted shorelines in Crete and eight on Rhodes Island (Pirazzoli *et al.* 1989). Pirazzoli *et al.* (1994) following a systematic multidisciplinary survey of the coasts of the Ionian Islands, relating the occurrence of uplifted or submerged notches to dated palaeoseismic events on the Ionian Islands. In particular, radiocarbon dating suggested that uplift occurred in Corfu (two to three post-medieval age events), in Levkas, where metric up-and-down movements occurred since 2400 years ago, in Cephalonia (two co-seismic events occurred at 350–710 and 1953 AD), and the southeastern part of Zante, while submergence has been proposed in Ithaca. Pirazzoli *et al.* (1994) suggested that some movements could correspond with a period of regional tectonic paroxysm around the fifth century AD and it could be extended to several areas in the eastern Mediterranean Sea. While short time periods of observation prevent the quantification


**Fig. 7.13.** Examples of rocky shores along Greek and Turkey coasts. (**a**) Sandstone cliffs at Corfu Island (Ionian Sea, Greece). (**b**) High sea cliffs cut in clays (Xi beach, Kefalonia, Greece). (**c**) Tombolo at Balos (Western Crete, Greece). (**d**) Multiple uplifted notches in the Heraion Bay, South Corinth Gulf (Greece). (**e**) Volcanic cliffs at Apronisi (Santorini, Greece).

of bioerosive activity, they suggested that Phoronida worms, the bivalve *Brachidontes pharaonis* worms and the limpet *Patella* sp. act to destroy Plio-Quaternary conglomerates.

The island of Crete displays about 1000 km of mainly rocky coast (Scheffers & Browne 2010). Owing to the proximity to the Hellenic Trench, the island is tectonically active and was affected by earthquakes in the period between the mid-fourth and mid-sixth centuries (Pirazzoli *et al.* 1996*a*). The coastline is mainly rocky and steep since it is almost entirely mountainous. Small coastal plains occur along the northern side of the island or southern in correspondence to the mouth of the valleys (Scheffers & Browne 2010). Limestone cliffs are usually affected by the occurrence of tidal notches or rockpools whose genesis is due to bioerosion. Kelletat & Zimmerman (1991) report biogenic formations formed by vermetids and calcareous algae in the upper subtidal zone.

Evidence of differential uplift have been reported around the island (Peterek *et al.* 2003), mainly using tidal notches (Kelletat 1996; Pirazzoli *et al.* 1996*a*; Stiros 2001; Scheffers 2006), archaeological markers (Bruins *et al.* 2008) and biological markers (Pirazzoli *et al.* 1996*a*).

### *Literature on processes operating on rock coasts: a review*

Regarding rates and modes of cliff retreat and bedrock erosion, the available data are mainly concentrated along the Adriatic coasts as well as studies related to aspects of the coastal scenery, such as caves, stacks, sea arches, etc. Studies on the occurrence and distribution of tsunami or storm wave blocks are widely distributed along exposed rocky coasts.

Along the coasts of the Gulf of Taranto, cliff retreat rates were studied by Mastronuzzi & Sansò (1998). The mean cliff retreat rates is $0.5 \text{ m a}^{-1}$ and ranges between 0.06 and $0.8 \text{ m a}^{-1}$ (Table 7.1), depending on the limestone bedding. Lower rates were evaluated corresponding to the limestone beds dipping onshore, while higher rates were estimated corresponding to the occurrence of abrasion notches at the cliff foot. Andriani & Walsh (2007) provided a critical review of the processes and factors affecting cliff retreat and coastal morphology along the a sector of the Murgia coastline in Apulia (Italy). Gently sloping shore platforms are characterized by retreat rates of $0.2 \text{ m a}^{-1}$, while cliff recession is episodic and discontinuous in both time and space. Andriani & Walsh (2007) reported cliff retreat rates ranging between 0.01 and $0.1 \text{ m a}^{-1}$ in the period 1997–2003 (Table 7.1). Delle Rose & Parise (2004) studied sea cliffs in the Salento area, between Rocavecchia and Torre dell'Orso. Cliffs are cut in biogenic calcarenites, with basal notches. Sea caves or small enlarged fractures occur. Delle Rose & Parise (2004) described the geomorphological and hydrogeological setting of the coastal cave called 'Grotta della Poesia' and reported about 50 slope-failures from 1943 to 1996 along the sea cliffs. Cancelli *et al.* (1984) examined the factors influencing the stability of overconsolidated clay cliffs in the central western Adriatic Sea and studied the features of the main landslides occurring in the area. The first movements occurred at the cliff toe and continued upwards (Cancelli *et al.* 1984). Comparing historical topographic maps and aerial images D'Alessandro *et al.* (2001) suggested that cliff retreat rates range between 0.3 and $0.9 \text{ m a}^{-1}$ depending on the lithological and structural setting of the area and on the exposure to waves (Table 7.1). Lollino & Pagliarulo (2008) identified along the southern coastline of the San Nicola island, in the Tremiti islands, rockfalls and block slidings, probably induced by the rain infiltration in the joints and, in general, by subaerial weathering and driven by predisposing factors, such as the presence of the weak and erodible dolomitic calcarenite formation.

Colantoni *et al.* (2004) reported retreat rates ranging between 0.05 and $0.16 \text{ m a}^{-1}$ on the flysch cliffs along the promontory of San Bartolo, near Pescara. These rates were evaluated on the basis of the position of archaeological remains from the present-day coastline. Archaeological marker are useful since they allow the study of cliff recession over thousand of years. Furlani *et al.* (2011*b*) used archaeological and historical markers and the comparison of repeated photos during a 10-year survey to study sea cliff retreat along the Slovenian coast (Fig. 7.12e) and suggested mean rates ranging between 0.1 and $0.2 \text{ m a}^{-1}$ (Table 7.1). Major changes in the cliff face have been observed after large storm events. The combined action of sea cliff retreat and the relative sea-level rise measured in the NE Adriatic produce wide shore platforms persisting hundreds of metres off-shore (Furlani 2003). Xeidakis *et al.* (2006) studied the mechanisms of cliff erosion cut in soft rocks along the Greek north Aegean coastline.

Regarding bedrock erosion rates, available data in the Mediterranean Sea are mainly localized in the northeastern and central Adriatic Sea. Recently, Kazmer & Taboroši (2012) and Taboroši & Kazmer (2013) provided a practical guide for the field interpretation of bioerosional textures on limestones created by intertidal organisms. Schneider (1976) found that microorganisms produce specific boring patterns and classified the intertidal zone on the basis of the colouring of the surfaces by endolithic andepilithic cyanophytes, the morphological features of the limestone bedrock and the distribution of lichens and halophytes (Fig. 7.5). Torunski (1979) recognized six colour zones in the Gulf of Trieste and discussed about one year of TMEM data collected along the coast of the southeastern Gulf of Trieste in the intertidal zone (Table 7.2). Torunski (1979) and Furlani *et al.* (2009) reported seasonal variations in limestone lowering rates. They could be related to rainfall events, since the measured variations occur in different seasons and rainfall peaks are variously distributed during the year. Both bioerosion (Schneider 1976; Torunski 1979) and submarine freshwater (Higgins 1980) were considered responsible for intertidal erosion. Cucchi *et al.* (2006) and Furlani *et al.* (2009) suggested that coastal limestone lowering rates are about 10 times higher than lowering rates collected in the inland Karst (Table 7.2). This pattern could explain the genesis and evolution of tidal notches (Furlani *et al.* 2011*b*). The lack of present-day notches along the coasts of the Gulf of Trieste and the occurrence of an underwater notch could be due to the tectonic subsidence of the area or to climatic factors (Furlani *et al.* 2011*b*). For this purpose, an experimental limestone slab was set in the mid-intertidal zone (Furlani *et al.* 2010), in order to collect micro-erosion meter data on vertical limestone surfaces, to study erosion rates and notch development in the Gulf of Trieste and to evaluate the contribution of seawater and bioerosion effects. After five years of measurements on the limestone slab, Furlani & Cucchi (2013) suggest a 'notch trend' of erosion with maximum rates in the mid-intertidal zone up to about $0.3 \text{ mm a}^{-1}$. Even if bioerosion and bioconstruction are thought to be the most effective processes involved in the notch development (De Waele & Furlani 2013), Higgins (1980) suggested that little attention has been given to solution by fresh groundwater, even considering the one-to-one correspondence of marine notches with coastal and submarine springs. Furlani *et al.* (2009) suggested that, in the Gulf of Trieste, rates measured in the intertidal zone can be higher than rates measured on the Istrian coast because of the increased amount of freshwater in the Gulf. Furlani (2014), from the preliminary processing of morphological and hydrogeological data collected during a 250 km snorkel survey along the southern and western Istrian coast, suggested that the submarine notches occur in correspondence with the largest submarine springs.

At Falasarna (Crete), Naylor & Viles (2002) evaluated the nature and effects of short-term biological colonization. They found that exposed sites became colonized more quickly than the sheltered sites. Moreover, once algae covered the limestone surface, biological and chemical weathering were reduced.

Characteristic erosional landforms have been studied mainly on coastal limestone. De Waele *et al.* (2011) reported the presence of a large number of uniform cone-shaped dissolution pipe in the coastal karst of Apulia, Sardinia and Tunisia. They suggest that their perfect vertical development is evidence of the gravity control of their genesis, probably formed in a previous covered karst setting rather than in coastal environments. Other small karst features developed in the swash zone have been studied by

**Table 7.1.** *Rates of sea cliff retreat in the Mediterranean Sea*

| Location | Lithology | Erosion rate (m $a^{-1}$) | Interval (years) | Method | Reference | Notes |
|---|---|---|---|---|---|---|
| Catalunya (Spain) | Fluviatile Quaternary deposits | 0.2 | — | Aerial analytical photogrammetry | Montoya (2008) | — |
| Mallorca (Balearic Islands) | Calcarenite | $0.74 \times 10^{-3}$ | 235 k | Field survey | Fornós *et al.* (2005) | — |
| Mallorca (Balearic Islands) | Calcarenite | 40 $m^3$ | 1 | Field survey | Balaguer *et al.* (2008) | Cliff face fall with minimum cliff retreat |
| Mallorca (Balearic Islands) | Calcarenite | 143 $m^3$ | 1 | Field survey | Balaguer *et al.* (2008) | — |
| Mallorca (Balearic Islands) | Fluviatile–Eolianite Quaternary deposits | 0.09–0.56 | 46 | Aerial photograph survey | Balaguer *et al.* (2008) | — |
| Cilento, Campania (Italy) | Flysch | 0.5–0.8 | 30–45 | Aerial analytical photogrammetry | Budetta *et al.* (2000) | — |
| Apulia (Italy) | Limestone | 0.06–0.8 | 100 | Field survey | Mastronuzzi & Sansò (1998) | — |
| Murgia, Apulia (Italy) | Limestone | 0.01–0.1 | 1997–2003 | Field survey | Andriani & Walsh (2007) | — |
| Ortona–Vasto, Abruzzo (Italy) | Conglomerates, sands and pelites | 0.3–0.9 | 109 | Comparison of aerial photographs and maps | D'Alessandro *et al.* 2001 | — |
| Monte S. Bortolo (Pesaro), Italy | Sandstone and marls | 0.05–0.16 | 6 k | Archaeological remains | Colantoni *et al.* (2004) | Evaluated from the text |
| Slovenian coast | Flysch | 0.01–0.02 | 1999–2010 | Comparison of terrestrial photographs | Furlani *et al.* (2011*b*) | — |
| North of Khan Yunis (Israel) | — | 0.41 | 1956–1984 | Aerial analytical photogrammetry | Golik & Goldsmith (1984, 1985), from Zviely & Klein (2004) | — |
| North Gaza (Israel) | — | 0.3–0.9 | 1956–1984 | Aerial analytical photogrammetry | Golik & Goldsmith (1984, 1985), from Zviely & Klein (2004) | — |
| North of Ashkelon (Katza, Israel) | — | 1.07 | 1976–1984 | Aerial analytical photogrammetry | Golik & Goldsmith (1984, 1985), from Zviely & Klein (2004) | — |
| Jaffa (Israel) | — | 0.11–0.25 | 1945–1987 | Aerial analytical photogrammetry | Ron (1982), from Zviely & Klein (2004) | — |
| Jaffa (Israel) | — | 0.03–0.29 | 1987–1996 | GPS measurements | Greenstein (1997), from Zviely & Klein (2004) | — |
| Herzliya (Israel) | — | 0.2–0.4 | 1942–1996 | Comparison of aerial photographs | Nir (1992), from Zviely & Klein (2004) | — |
| Apolonia (Israel) | — | 0.09–0.36 | 1944–2000 | Comparison of aerial photographs | Ben-David (2001), from Zviely & Klein (2004) | — |
| Netanya (Israel) | — | 0.3–0.4 | 1945–1978 | Aerial analytical photogrammetry | Ron (1982), from Zviely & Klein (2004) | — |
| Netanya (Israel) | — | 0.5 | 1962–1994 | Comparison of aerial photographs and maps | Ben-David (1995), from Zviely & Klein (2004) | — |
| Shoshanat Hamakim (Israel) | — | 0.05–0.58 | 1939–1991 | Comparison of aerial photographs and maps | Nir (1992), from Zviely & Klein (2004) | — |
| Neurim (Israel) | — | 0.8–3.2 | 1992–1995 | Field measurements | Perath & Almagor (1996), from Zviely & Klein (2004) | — |
| Tel-Aviv and Beit-Yannay (Israel) | Eolianite (kurkars) | 0.15–0.22 | 1982 | Field measurements | Perath (1982), from Zviely & Klein (2004) | — |
| Beit-Yannay (Israel) | Eolianite (kurkars) | 0.15–0.3 | 1939–1991 | Comparison of aerial photographs and maps | Nir (1992), from Zviely & Klein (2004) | — |
| Michmoret and Givat Olga (Israel) | — | 0.24 | 1991–1996 | Field measurements | Schwartz (1997), from Zviely & Klein (2004) | — |
| Beit-Yannay (Israel) | Eolianite (kurkars) | 0.2 | 1918–2000 | Comparison of aerial photographs | Zviely & Klein (2004), from Zviely & Klein (2004) | — |

**Table 7.2.** *Rates of shore platform and coastal bedrock lowering in the Mediterranean Sea*

| Location | Lithology | Erosion rate (mm $a^{-1}$) | Interval (years) | Method | Reference |
|---|---|---|---|---|---|
| NE Adriatic | Limestone | 0.25–1 | — | Biological survey (*Littorina neritorides*) | Schneider (1976) |
| NE Adriatic | Dolomite/oolitic limestone | 0.01 | — | Biological survey (*Lithophaga* lithophaga) | Kleeman (1973) |
| NE Adriatic | Dolomite/oolitic limestone | 0.01 | — | Biological survey (*Lithophaga* lithophaga) | Kleeman (1973) |
| Gulf of Piran (Slovenia) | Intertidal Mesozoic limestones | 0.07–1.114 | 1976–1977 | TMEM | Torunski (1979) |
| Gulf of Trieste (Italy) | Intertidal Mesozoic limestones | 0.009–0.194 | 1980–1982 | MEM | Cucchi & Forti (1983) |
| NE Adriatic (Italy, Croatia) | Intertidal Mesozoic limestones | 0.001–0.34 | 1980–2005 | MEM, TMEM | Cucchi *et al.* (2006) |
| NE Adriatic (Italy, Croatia) | Intertidal Mesozoic limestones | 0.011–2.966 | 1980–2007 | MEM, TMEM | Furlani *et al.* (2009) |
| NE Adriatic (Italy, Croatia) | Intertidal Mesozoic limestones | 0.011–0.970 | 1980–2011 | MEM, TMEM | Furlani *et al.* (2011*a*) |
| Mallorca (Balearic Islands) | Supratidal Cretaceous Limestone | 0.007–0.482 | 1999–2001 | MEM, Laser Scanner (LS), biological survey | Swantesson *et al.* (2006) |
| Mallorca (Balearic Islands) | Supratidal Upper Miocene Reef Limestone | 0.003–0.814 | 1999–2001 | MEM, Laser Scanner (LS), biological survey | Swantesson *et al.* (2006) |
| Mallorca (Balearic Islands) | Supratidal Upper Miocene calcarenite | 0.003–2.095 | 1999–2001 | MEM, Laser Scanner (LS), biological survey | Swantesson *et al.* (2006) |
| Mallorca (Balearic Islands) | Supratidal Upper Miocene calcarenite | 0.004–0.369 | 1999–2001 | MEM, Laser Scanner (LS), biological survey | Swantesson *et al.* (2006) |
| Mallorca (Balearic Islands) | Supratidal Jurassic Dolomite breccias | 0.011–0.997 | 1999–2001 | MEM, Laser Scanner (LS), biological survey | Swantesson *et al.* (2006) |
| Mallorca (Balearic Islands) | Intertidal Upper Miocene Calcarenite | 0.80–1.18 | 2002–2005 | TMEM | Gómez-Pujol (2006) |
| Costa Brava (Catalonia) | Supratidal granites | 0.001–0.003 | 1999–2001 | MEM, Laser Scanner (LS), biological survey | Swantesson *et al.* (2006) |
| Marseilles (France) | Limestones | 0.4–0.88 | 900–1500 | Notch depth | Laborel *et al.* (1994) |
| Cephalonia (Greece) | Limestones | 0.76–1.28 | 39 | Notch depth | Stiros *et al.* (1994) |
| W Crete (Greece) | Limestones | 0.3–0.7 | 1500 ± 100 | Notch depth | Thommeret *et al.* (1981) |
| SE Turkey | Limestones | 0.25–1.0 | 1000 | Notch depth | Pirazzoli *et al.* (1991) |
| Mersin (SE Turkey) | Limestones | < 0.15 | 50 | Biological survey | Gul *et al.* (2008) |
| Malta | Middle Globigerina limestone | 9.16 | 3–5 | Rock profiling | Micallef & Williams (2009) |
| Malta | Lower Globigerina limestone | 0.74 | 3–5 | Rock profiling | Micallef & Williams (2009) |
| Malta | Upper Coralline limestone | 1.38 | 3–5 | Rock profiling | Micallef & Williams (2009) |
| Malta | Lower Coralline limestone | 0.77 | 3–5 | Rock profiling | Micallef & Williams (2009) |
| Malta | Middle Globigerina limestone | 9–14 | 1 | TMEM | This research |

**Table 7.3.** *Sites of reported tsunami boulders along the MBS coastline*

| Location | Lithology | Erosion rate ($m\ a^{-1}$) | Interval (years) | Method | Reference |
|---|---|---|---|---|---|
| Cape Sabla (Bulgaria) | Limestone | 0.01 | — | — | Simeonova (1985) |
| Cape Sabla (Bulgaria) | Limestone with underlying clays | 8 | — | — | Simeonova (1985) |
| Tauk-Liman, Cape Sabla (Bulgaria) | Limestone with underlying clays | 0.01 | — | Survey | Koštjak & Avramova (1977) |
| Balčik-Varna (Bulgaria) | — | 1 | — | — | Milev & Cencov (1977) |
| Kavarna (Bulgaria) | — | 15 | — | — | Simeonova (1976) |
| Crimean Peninsula (Russia) | Limestones | 0.3 | — | — | Shuisky (1985) |
| Crimean Peninsula (Russia) | Clays, silt | 9 | — | — | Shuisky (1985) |
| Primorsko-Atchtarsk, Azov Sea Coast | Clay | 12 | — | — | Sunamura (1992) (from Zenkovich (1967)) |
| Black Sea | Flysch | 0.02–0.03 | 20 | Surveys, photographs | Sunamura (1992) (from Zenkovich *et al.* 1965) |
| Black Sea | Flysch, shale | 0.01–0.02 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Coquinite | 0.002–0.005 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Crystallized limestone | 0.003 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Massive limestone | 0.3–0.5 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Limestone with loess | 2–3 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Limestone with loess | 0.61 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Quaternary loess | 0.5–1.0 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Quaternary conglomerate | 12 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Quaternary brown loam and clay | 1 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Quaternary clay | 2–3 | — | — | Sunamura (1992) (from Zenkovich (1965) |
| Black Sea | Diluvial deposits | 0.11 | — | — | Sunamura (1992) (from Zenkovich (1965) |

Furlani *et al.* (2011*b*) in Istria and Perica *et al.* (2004) in the Kornati area. They found significant differences in coastal karren development because of the interaction of waves, beddings, bed thicknesses and lithology. Both studies suggest development since historic times since fissure- and network-type karren are well developed in nearby coastal quarries. Morphometric and geomorphic parameters related to shore grykes have been collected by Furlani *et al.* (2010) along the northwestern Istrian coast. Considering the local tectonic setting of the area, the grykes seem to be subaerial karst forms subsequently enlarged by marine processes.

The coastal scenery of the northeastern Mediterranean Sea has many sea caves of different origin. Zezza (1981) studied the development of sea caves along the southeastern sector of the Gargano promontory, which are mainly related to joints and faults. Mastronuzzi & Sansò (2002) reported the occurrence of flat-topped caves cut in horizontally stratified Jurassic limestones and suggested evidence of Holocene uplift. Otonicar *et al.* (2010) reported the presence of a flank margin cave in Cres Island, developed in talus breccias facies, probably Pleistocene in age. Morphometric features and the Holocene evolution of partially submerged coastal caves along the Istrian peninsula and the Gulf of Trieste have been recently studied by Furlani *et al.* (2012). Morphological features related to the position of these caves with respect to the present-day sea level highlight the contribution of both subaerial and marine factors involved in their morphological evolution. The emerged and submerged parts of the caves correspond to different morphological zones. The submerged part is mainly affected by abrasion processes while the emerged zone is affected by subaerial processes. This produce a bell-shaped cross-section, in which the submerged parts of the caves are significantly larger than the emerged parts. Furlani *et al.* (2012) suggested that the early phases of the evolution were dissolutionally controlled, but most of the widening is marine-controlled and occurred during the late Holocene.

Along the coasts of the northeastern Mediterranean many sites with tsunami- or storm wave-deposited blocks have been reported (Scheffers & Kelletat 2003). The Apulian coast is interesting for the occurrence of large tsunami blocks related to earthquakes on the eastern Ionian coast (Gentile *et al.* 2003). A limestone block, 80 t in weight, slid 40 m onshore up to 1.8 m a.s.l. (Table 7.3), was reported by Mastronuzzi & Sansò (2000).

The Ionian coast of Apulian coast is interesting for the occurrence of large tsunami-deposited blocks related to submarine landslides triggered by the 5 December 1456 earthquake (Mastronuzzi & Sansò 2000). Other similar blocks are found along the Apulian Adriatic coast. Tsunami-deposited blocks with *Lithophaga* and *Cliona* borings up to 75 t in weight (Table 7.3) were identified along the western coast of the island of Crete by Scheffers & Scheffers (2007) and along the southern and western coasts of the Peloponnesus (Scheffers *et al.* (2008) and on the Island of Lesbos (Vacchi *et al.* 2012*a*).

## Rocky coasts in the Mediterranean Middle East

The Turkish Mediterranean coast is 5191 km long and is strongly affected by tectonic activity. From a structural point of view, the Turkish Mediterranean coast runs parallel to the Taurus folded mountain chain, with marine terraces at various levels indicating tectonic displacements. Owing to the complex tectonic setting of the area, studies of coastal geomorphology concern mainly late Quaternary displacement of coastal features rather than present-day processes.

The Turkey Aegean coast is very complex, since it is controlled by horst and graben structures or faults (Erol 1985). From a geomorphological point of view, the coastline is very indented, with alternating rocky cliffs and low-lying coasts (Erol 1985). The Saros Gulf and the Marmara Sea develop along the Anatolian fault, and cliffs are cut in volcanic and Neogene sediments. Southwards, Palaeozoic and Mesozoic formations compose the cliffy coastline. The southern Turkish, or the real Mediterranean Turkish, coastline develops parallel to the Taurus Mountains, with the large embayment at Antalya. Here, cliffs are cut in travertine. Dipova (2009) studied the instability problems related to the cliffs at Antalya and suggested that cliff retreat is very slow and significant only at geological scales. Sea caves on Antalya cliffs were studied by

Dipova & Okudan (2011). Three type of caves were recognized according to their origin: sea caves, tufa caves and flank margin caves. The first type is related to differences in rock resistance. Tufa caves are blind holes occurring behind tufa curtains and are sedimentary forms instead of corrosion forms, while flank margin caves are related to mixing corrosion between the sea and groundwater level. Dipova & Okudan (2011) suggested that the entrances of sea caves are concentrated between 0 and −5 m a.s.l. and the depth of the caves is about 5 m.

Very high cliff coasts occur in the central Mediterranean region. Cliffs are mainly cut in limestone and schists and cobble-boulder beaches occur at the base of the cliffs. Eastwards, the coast is dominated by the Çukurova Plain, related to the Seyhan and Ceyhan rivers and the Gulf of Iskenderun, rectangular in shape (Erol 1985).

Gul *et al.* (2008) studied biodegradation effects over different types of rocks in the coastal areas of Mersin, along the Turkish coast. From a geographical point of view, the island of Cyprus is part of the Middle East. It is the third largest island of the Mediterranean Sea (Nir 2010) and the coastline is very indented, since it is affected by several limestone and calcarenite headlands separated by beaches (Thrower 1960). Comparing the spatial and temporal distribution of hundreds of notches in the eastern Mediterranean area (Fig. 7.13d), Boulton & Stewart (2011) suggested a dominantly tectonic control on their genesis. The northern side of the island is very steep. Moving southwards, the island is composed of gently undulating hills up to the Troodos Mountains in the SW sector of the island (Nir 2010). Evidence of Quaternary differential uplift is documented by marine terraces at different altitudes above sea level (Nir 2010). Noller *et al.* (2005) suggested that archaeological and geological records testify a long history of tsunami activity in Cyprus and reported many sites indicating tusnamis boulder processes along the coastline.

The territory of the Middle East that faces the Mediterranean Sea represents the northwestern edge of the Palaeozoic cratons of Asia and the tablelands that occupy the coastal fringe are mostly constituted by the craton sediment blanket, dissected by the fracture systems connected to the African rifting. The most relevant rocky tracts are in northern Syria (the foothills of the Gebel Akra) and in Lebanon (the capital Beirut lays on a rocky promontory), with the exception of the sandy littoral where the ancient cities of Tyre and Sidon were built. By the border with Israel the promontory of Ras en-Naqurah displays its calcareous slopes and more southwards the Carmel Promontory marks the last rocky outcrop up to Sinai. All the Levantine coast, though, is punctuated by Quaternary sandstone ridges. These aeolianites, often very cemented and steeply dipping towards the sea, have been extensively studied in Israel, where they represent a typical feature of the coastal landscape (Porat *et al.* 2004; Sivan & Porat 2004). In Israel, we have the best chronologically constrained aeolian sequences of the whole Mediterranen; their ages fall in both the last interglacial and glacial periods. Consolidated aeolian dunes (locally named *kurkar*), are intercalated to red loamy units (*hamras*), strongly affected by pedogenesis; the ages of *kurkars* and *hamras* overlap (Sivan & Porat 2004).

Cliff retreat rates were widely measured along the Israel coast, as evidenced by Zviely & Klein (2004) and reported in Table 7.1. Katz & Mushkin (2012) suggested that cliff retreat rates decrease with increasing observation time; therefore cliff retreat rates are highly variable across annual and decadal time scales. Zviely & Klein (2004) compared aerial photographs collected in the period 1918–2000 at Beni-Yannay and concluded that mean cliff retreat rate of the crest is 0.2 m $a^{-1}$ for a total retreat of a maximum 25 m. Mushkin & Katz (2012) suggested that eolianite cliff retreat rates are up to 0.3 m $a^{-1}$ and the extreme winter storms play an important role in the local morphological structure of the cliffs.

The Syrian coast is generally rocky but low, carved in clayey limestones that are actively eroded under a very energetic wave climate. The tidal range is microtidal (0.20–0.40 m) and rainfall of 1000–1200 mm is concentrated in autumn. Stream discharge is thus relevant, and littoral drift becomes an effective erosive agent. Warm sea temperatures throughout the year enable the development of bioconstructions, mostly of Vermetids, along the rocky shores, that are frequently platform shaped, and sometimes covered by Quaternary beach rocks (Sanlaville *et al.* 1997).

Similar rocky landforms are present along the rocky tracts of the Lebanese coast. Here shore platforms are characterized by typical biota and weathering microform zoning, including a supralittoral belt in which the rocky surface is affected by marine karst microforms and rockpools, and a lower bench, bracketed by an inner and an outer cliff, colonized by Vermetid reefs (Sanlaville 1977). Within this general framework a great variety of rocky shore landforms are illustrated by Morhange *et al.* (2006*a*), including notches, benches and sea stacks. These are partly raised and have been interpreted as late Holocene elevated shorelines (Pirazzoli *et al.* 1996*b*; Morhange *et al.* 2006*a*, *b*).

Late Holocene boulders were identified and dated along the shorelines around the Tripoli islands and Byblos, in northern Lebanon by Morhange *et al.* (2006*b*). The authors assumed a tsunami origin for most of the boulders.

Levantine coastal aeolianites have been affected by human settlement since prehistory (Tsatskin & Ronen 1999). During Phoenician times they were extensively quarried in order to provide materials to build the cities along the coast. The extraction of blocks from these ridges created, starting from aeolianites ridges, impressive rock walls stretching for hundreds of metres along the seaside, which can reach many metres in height (Viret 2005). They were used as protective barriers for coastal quarries and more generally for different types of coastal settlement. Although their chronology is poorly known, available data indicate that they were a long-standing tradition, lasting at least until Roman times, as the age of shells cemented on a quarry face in Ziré Island (Lebanon) demonstrates (Morhange *et al.* 2006*a*). These man-made landforms are currently being re-shaped by natural agents (wave action and coastal weathering), so that traces of quarrying activity have largely been removed. Somewhere on the exposed rock walls a notch is visible at an elevation of 0.5 m a.s.l. Some authors consider it as a trace of former sea-levels, now raised owing to Holocene tectonic pulses (Morhange *et al.* 2006*a*), whereas others suggest that it is an erosional feature formed by storm waves (Viret 2005).

## African rocky coasts

The western sector of the Northern Africa includes the coasts of the Atlas Mountains in Morocco, Algeria and the northern sector of the Tunisian coastline up to Cap Bon (Bonniard 1934). The remainder of the North African coast is generally flat and the easternmost sector is occupied by the Nile Delta.

Although geographically belonging to Europe, and separated from Africa by a 15 km strait, Gibraltar will be considered here. The Rock of Gibraltar, a 426 m-high promontory shaped in Jurassic limestone, displays rocky coastal features, including platforms, cliffs and karstic caves partly reshaped by the sea. The eastern side of Gibraltar is exposed to easterly storms from the western Mediterranean, with a fetch of more than 1500 km (Flemming 1972). As a result it is subject to stronger wave energy than any other site in the Mediterranean, leading to a continuous coastal retreat. For this reason the eastern side displays an articulated slope profile, showing a design with two well-differentiated elements: a composite cliff and a basal shore platform (Rodríguez-Vidal *et al.* 2004). Multistoreyed cliffs display two or more steep surfaces (wave-cut faces) separated by gentler slopes, created by scree accumulation. They reflect the combined effects of subaerial (e.g. gravitational) and marine processes and progressive tectonic uplift during the Quaternary.

Shore platforms extend from approximately the mean high water mark, at the base of the receding, basal cliff, to an elevation below the mean low water mark. The zone of greatest wave erosion is therefore probably in the supratidal, above the neap high water level, where the most vigorous storm waves operate.

At least 143 caves, situated above present-day sea level, have been located (Rose & Rosenbaum 1991) and more are known to occur below (Fa *et al.* 2000), providing evidence of karstic base-level fluctuations associated with sea-level highstands. Speleothem deposits interbedded with cave floor sediments may provide evidence of ancient climatic change. Marine Gorham's and Vanguard caves are filled with aeolian sediments and palaeosols. Recent archaeological excavations have uncovered abundant remains of fauna and clear evidence of human occupation over the past 100 kyr (Pettitt & Bailey 2000).

The Mediterranean coastline of Morocco is shaped in the foothills of the Rif mountain chain (Maurer 1968), 2453 m in elevation, which geologically represents the prosecution of the Betic Cordillera in Spain. It stretches for 470 km, displaying a very indented coast with wide bays, and the rocky coast is exposed to waves and separated by narrow promontories flanked by small islands which are sometimes grouped in archipelagos. From the west the 'Hercules' pillar' on the African shore (facing the Rock of Gibraltar) is represented by the so-called 'El Acho', which is geographically part of the Ceuta Promontory (Punta de Almina in Spanish). The Peregil Island, inside the Gibraltar Strait, flanks it on the west. Towards the east the main promontories are Ras Tarf (Cabo Negro) with the small island of Ghomara, Cabo Nuevo (on the east by the small archipelago of Al-Houzama), Cabo Quilates, Ras el-Ouerk and finally, fronted by the Chafarinas Islands, the Cabo de l'Agua, after which, as the name suggests, the mouths of the main rivers of the Mediterranean coast of Morocco are located.

Towards the east, Algeria has a 1100 km-long coastline and it is almost totally rocky and cliff-shaped (Fig. 7.14a), poorly indented and exposed to wave action (Mahrour & Dagorne 1985). The mountain ridge that backs the coastline, named 'Tell', ranges in elevation between 1000 and 2000 m and is frequently flat-topped; when a watershed is evident, though, it is frequently close to the sea, so that the coastal fringe is remarkably narrow and steep. The rocky coast of Algeria is cut in different rocks, such as schists, quarzites, limestones and Quaternary deposits. Mahrour & Dagorne (1985) identify three types of erosional rocky coasts along the Algerian coastline: (a) rocky cliffy coasts, cliffs owing to present or inherited erosion processes, sometimes similar to dead cliffs; (b) structural rocky, cliffy coasts, when the cliffs have a structural origin, sometimes coupled with an uplifted shore platform or composed of plunging cliffs; and (c) low rocky coasts, or shore platforms at or below the present-day mean sea-level. Mahrour & Dagorne (1985) report the presence of recurrent algal rims and lapis.

Maouche *et al.* (2009) reported the occurrence of tsunami boulders along the coast between Tipaza and Dellys and evaluated the size, weight and distance from the shoreline of more than 100 boulders. The biggest blocks weighed up to 200 t (Table 7.3).

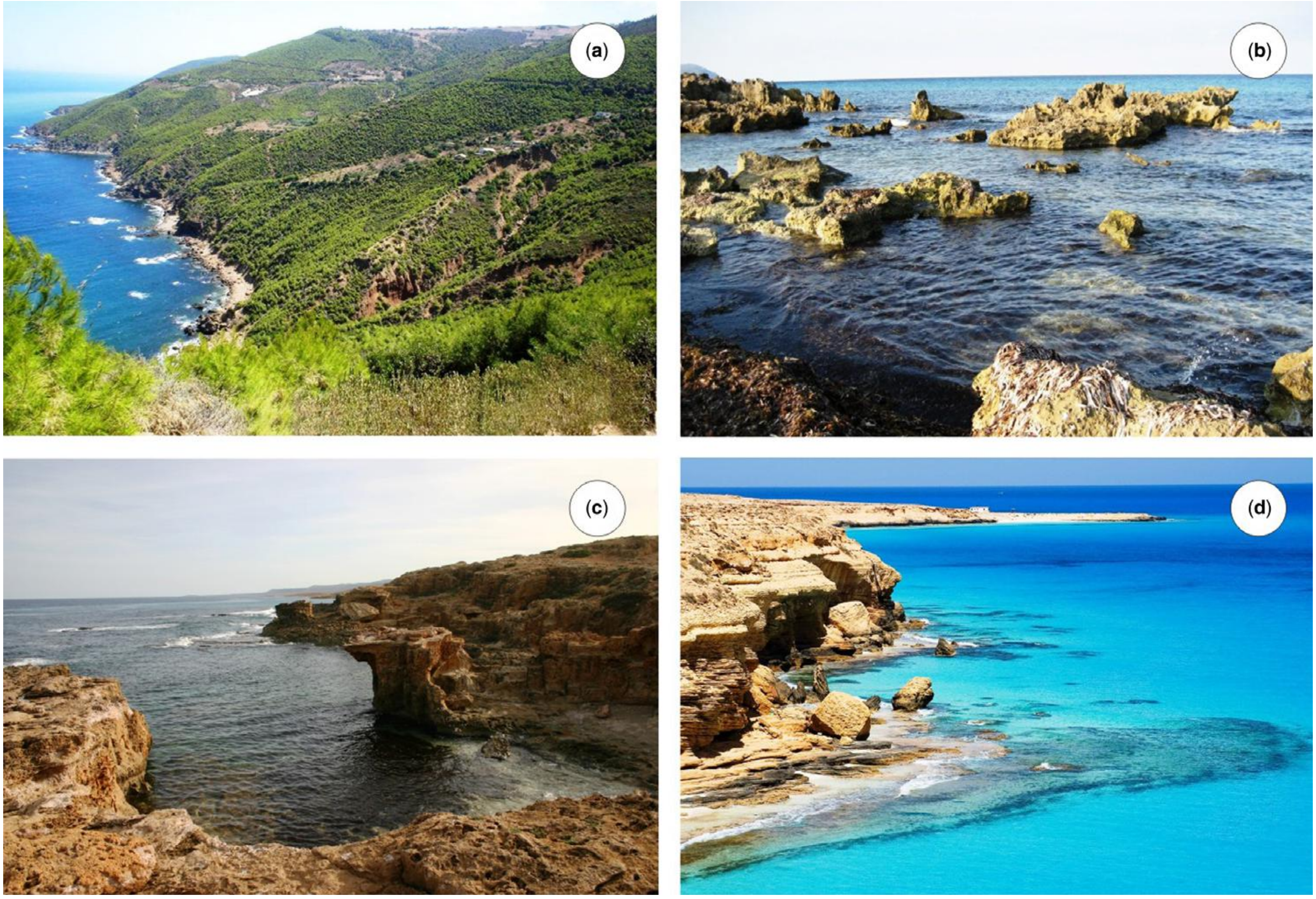


**Fig. 7.14.** Examples of rocky shores along the north African Mediterranean coast. (**a**) Cliff at Damous, Algeria. (**b**) Coastal features near Kelibia (Tunisia). (**c**) Cliffs and shore platforms in Libya (photograph courtesy of Franco Cucchi). (**d**) Cliffs and shore platforms at Agiba, Egypt.

Tunisia's northern coast mostly displays rocky tracts, especially from the border with Algeria up to Cap Blanc. It is shaped on the eastern edge of the northernmost ridge of the Atlas mountain chain, the so-called 'Tell', a mid-mountain relief made from Eocene sandstones. The Cap Serrat promontory interrupts this poorly indented coastline. Forty kilometres off-shore, La Galite island is a product of Cenozoic volcanic activity. This tract of coast ends towards the east with Cap Blanc; from here up to the easternmost rocky promontory of Tunisia (Fig. 7.14b), Cap Bon, a wide lowland (Gulf of Tunis) is scattered with rocky promontories resulting from the infilling of a former wide gulf during the late Holocene from increased river discharge, according to a model common to a great number of Mediterranean coastal plains (Vött 2007). Cap Bon displays a staircase of marine terraces and relevant outcrops of cemented aeolianites (Mauz *et al.* 2009; Elmejdoub *et al.* 2011).

The only modern study of rock coasts for Tunisia was by Oueslati (1993, 2004). A preliminary distinction was made between cliffs and flat rocky coasts. The former display remarkable features such as high and stepped cliffs, particularly close to the border with Algeria, up to Rass Ettarf and in the northwestern side of Cap Bon Peninsula. Typical of headlands, they represent the bottom of the steep slopes that face the sea, and are shaped differently according to the rock type. Headland elevations frequently reachs 10 m a.s.l. By comparison the eastern coast cliffs are less frequent and seldom exceed 5 m a.s.l. They can be found in the innermost part of the wide gulfs of Hammamet and Gabés; in this latter area the rock type, a Cenozoic chalk, fosters slope instability and high retreat rates of the cliff face. Although the climate is very dry in the south of the country and thus erosion owing to rainfall is scarce, rockfalls are frequent at the cliff toe and notches and sea stacks are widespread.

Low-lying rocky coasts, shaped in the form of typical shore platforms, dominate the northern sector of the coast of Tunisia, inside the bays and wherever the coastline is regular. Along the eastern side shore platforms are scattered and only those on the western side of Djerba Island deserve mention. Shore platforms in Tunisia are cut mainly in carbonate rocks, which may be tertiary limestone but also cemented Quaternary marine and aeolian deposits and pedogenic carbonate crusts. A detailed survey of many coastal profiles (Oueslati 2004) suggests that on some shore platforms weathering and bioerosion dominate, whereas on exposed platforms, wave action and abrasion are the dominant agents.

Morphologically two types of shore platforms can be differentiated (Oueslati 1993): both types display an intertidal and a supratidal part, separated by a low (1 m) cliff. The supratidal platform is in both cases a gently dipping plane, in which zonation of weathering types occurs. From the cliff top inland we can find a band with rockpools and potholes, another with marine karren microforms and an uppermost zone affected by honeycomb weathering. The intertidal portion may be narrow (from *c.* 0.5 to 10 m) and limited seawards by a plunging low tide cliff, or wide (up to tens of metres) and gradually dipping into the sea. Narrow shore platforms are typical of the northern coast where the tidal range is microtidal. Weathering is the agent of development, but bioerosion may also contribute, as the surfaces are densely colonized by marine biota. Wide platforms are more typical of some tracts of the eastern coast of Tunisia, such as in the Gulf of Gabés, where the tidal range reaches 2.5 m at spring tides. In this case the role of waves appears to be the key agent because of the scarcity of biota and the occurrence of sand in pools that suggest that abrasion is active.

May *et al.* (2010) presented evidence of tsunami block accumulations in the NE sector of Tunisia. Results presented by May *et al.* (2010) suggest that boulders were probably transported by tsunami-induced waves rather than storm waves.

The coastal fringe of Libya is 1900 km long and mostly sandy, especially in its central part, in which the Sahara Desert faces the Mediterranean Basin. A remarkable exception is represented by the eastern region of Cyrenaica, occupied in its northern part by a 880 m-high limestone plateau of Cenozoic age, known as the Gebel el-Akhdar (Green Mountain). This flat-topped relief degrades towards the sea by means of a number of steps, the lowest of which directly plunges into the sea along those tracts of the coastline where it is not indented (Fig. 7.14c). In particular, cliffs and terraces are widespread between the cities of Tokra (east of Benghazi) and Darna. The rocks of this plateau are extensively affected by both surface karst features and caves. The stepped morphology of the northern slope of the plateau is mainly structurally controlled, but its lowermost part could be shaped owing to the effects of Quaternary sea-level highstands.

The eastern part of the Egyptian coast is dominated by coastal plains and the Nile Delta; the central and western coasts are modified by the interaction of marine and continental processes which produce several coastal forms such as sea cliffs, drowned wadis and shore platforms (Embabi 2004). The central coast is dominated by promontories, so that this section is called the 'coast of headlands', which are related to structural lines (Fig. 7.14d) parallel to the coastline (Shukri *et al.* 1956), while in the western coast, to the border with Libya, a wide limestone bulge dominates.

Cliffs 40–60 m high occur at Ras El-Hekmah to the west for about 4 km (Embabi 2004). Twenty metre-high limestone cliffs extend for 7 km at Ed-Dab'aa and occur in two separated areas: El-Sira and Mersa Abu Samra. In Ras El-Hekmah and El-Dab'aa, a cliff–platform system has developed along the seaward side of the coastal ridge and extends for about 9 km. Lower cliffs, between 1 and 7 m in height, occur between Ras Abu Girab and Ras 'Alam El-Rum (Mo'awad 2003), between Alamain and Ras El-Shaqiq and between Wadi 'Agiba and Ras Abu Laho (Embabi 2004). Cliffs are generally straight and steep (up to 80°), cut by a notch at the cliff foot. Butzer (1960) reported the occurrence of uplifted notches at different heights. Several shore platforms along parts of the Egyptian coast are uplifted (Shukri *et al.* 1956; Mo'awad 2003).

The coastal scenery is populated by caves, stacks and other microforms studied by Mo'awad (2003) in the Ras El-Hekmah, in the Alamain area and at Umm El-Rakham (Embabi 2004).

## The Black Sea

Most of the Black Sea coasts are rocky, despite the occurrence of large river mouths, such as that of the Danube River. Retreat rates are available only for limited sectors of the western (Koštjak & Avramova 1977; Stanev & Simeonova 1979; Simeonova 1985) and northern (Shuisky 1970, 1974, 1979, 1985) coastline, while only qualitative data are available for the eastern and southern coast. Zenkovich (1958) contributed much to the study of the Black Sea coasts, while the American Society of Civil Engineers has published a collection of articles concerning them (Kos'yan 1993). Recently, Dolotov & Kaplin (2005) reviewed the Black Sea coastal geomorphology. The Black Sea coasts are rather uniform and slightly embayed. Erosional coasts predominate; in particular, in the eastern and southern sectors elevated mountainous coasts predominate (Dolotov & Kaplin 2005). Graded and erosional accumulative coasts are typical of the western and northern parts of the sea. In the eastern part erosional processes are active owing to an extremely narrow continental shelf, which sometimes nearly coincides with the coastline of the Caucasus. Slopes of the Great Caucasian Ridge interests most of the Caucasian coast, since the axis of the ridge is subparallel to the coastline.

The Bulgarian sector of the Black Sea coasts is mainly composed of rocky coasts. It consists mainly of cliffs cut in igneous formations in the south, folded flysch rocks in the central part and almost horizontal marls, sandstones, clays and limestones beds in the north. Simeonova (1985) studied sea cliff retreat cut in different igneous formations in the south, folded flysch rocks in the central part and almost horizontal marls, sandstones, clays and limestones beds in the north (Simeonova 1985). The stability of sea cliffs varies depending on the geology with average rates of 0.01 m $a^{-1}$ near Cape Sabla (Simeonova 1985) in limestone cliffs up to 8 m $a^{-1}$ corresponding to underlying clays (Table 7.4). Stanev & Simeonova (1979) considered the pattern of distribution and changes in the level of underground water as fundamental in studies concerning coastal landslides. Koštjak & Avramova (1977) report seasonal variations in block movements on the cliff. Corresponding to Balkan structures to the south, cliff retreats vary between few centimetres and 15 m $a^{-1}$ (Simeonova 1976).

The Rumanian coastline is mainly built by the sediments of the Danube River (Charlier & De Julio 1985), even if limited cliffed coasts with submerged rocky formations occur near Costanta. High erosional shores are typical also of the mountainous coasts of the southern Crimea Peninsula, as described by Shuisky (1985). The cliffs are cut in the steeply sloping flysch beds and ridges are noticed in the submarine bench. Shore destruction is accelerated by landslides occurring in clays. In the Karadag region (southern Crimea), cliffs are in part cut in volcanic rocks or related to faults. Volcanic rocks and limestones form caps on up to 100 m-high cliffs separated by shores represented by soft shales, clays and sandstones. Retreat rates during the past century are up to 0.3 m $a^{-1}$ (Shuisky 1985). On softer formations measured retreat rates are up to 9 m $a^{-1}$ (Table 7.4), in the long term similar to depositional coastlines (Shuisky 1970, 1974, 1979). Regarding the Sea of Azov, sea cliffs develop in correspondence with drowned valleys (Mamykhina & Khrustalev 1980) and are mainly cut in limestones or Cenozoic and Quaternary clays. Retreat rates range respectively between 0.4 and 6 m $a^{-1}$ (Shuisky 1974).

Moving eastwards, in the area between Anapa and Sukhumi, the northern sector of this area is composed of cliffs cut in soft clays and wide shore platforms (Zenkovich 1985). At Anapa, corresponding to the northern termination of the Caucasian range, cliffs up to 200 m and submarine platforms are cut mainly in flysch (Dolotov & Kaplin 2005) and develop for a total length of about 100 km southeastwards. East of sukhumi cliffs gradually lower and the coastline is dominated by the low-lying coasts of the Colchis Plain. Erosional and denudation coasts with steepy rocky cliffs are widespread along the Turkish Black Sea coasts. The southeastern Black Sea coast is composed of rocky promontories alternating with pocket beaches (Buachidze 1974). Here, steep cliffs develop parallel to the coastline and consist of Mesozoic–Tertiary igneous–sedimentary formations (Erol 1985). The western shoreline is bordered by the north Anatolian Mountains and consists mainly of rocky coasts cut in volcanic sediments (Erol 1985). Their elevation progressively lowers westwards up to the Bosphorus Strait, where the height is lower than 300 m (Dolotov & Kaplin 2005). High plateaus overlook the Bosphorous Strait with alternating volcanic headlands and sandy beaches (Erol 1985). Even the Sea of Marmara is part of the Anatolia fault system, therefore the coastline is structurally controlled with high cliffs (Ardel & Kurter 1957). The Dardanelles Strait, which connects the Sea of Marmara with the Aegean Sea, is composed of river valleys developed along fault lines and invaded by sea during Quaternary interglacials (Stanley & Blanpied 1980). Papadopoulos *et al.* (2011) presented data on tsunamis occurring from antiquity in the Black Sea and the Azov Sea, but no large block deposits were reported by the authors.

## Future research

This review demonstrates that rock coasts and shore platforms are conspicuous landforms along much of the MBS coast, but few studies have explored their erosion rates, rock decay processes and related forms. Quantitative data on cliff retreat and the erosion of shore platforms are scarce and restricted to a few localities. Studies about rocky shore processes are almost completely lacking, apart from a few exceptions in some areas. Although the Quaternary evolution of the Mediterranean coast has been extensively studied, even relying on geomorphological evidence, such as shore platforms and notches, very few studies have addressed the processes related to their origin and evolution. Geomorphological evidence provided in this chapter suggests that this area is potentially very promising for studies on rocky shores. Rocky coasts are widespread along the MBS and all the types of landforms characteristic of rock coasts are accounted for. Carbonate bedrocks are common tracts of many coastlines in the basin. This provides great potential to study those processes, typical of coastal karst under variable, but not extremely different, climate conditions. The low-energy setting of many sectors of the MBS allowed snorkel-surveying along the Istrian coasts in July 2012. This experience could be repeated along other rocky coast

**Table 7.4.** *Rates of sea cliff retreat in the Black Sea*

| Location | Weight | Height (m a.s.l.) | Distance to coastline (m) | Transport figure (t $m^2$) | $\rho_s$ (g $cm^{-3}$) | Reference |
|---|---|---|---|---|---|---|
| Mallorca (Spain) | 23 | 8 | 35 | 6,440 | — | Scheffers & Kelletat (2003) |
| Provence (France) | 33.5 | 2 | 39 | 2,613 | $\rho_s = 2.4$ | Vella *et al.* (2011) |
| Torre Sant'Emiliano, Apulia (Italy) | 75 | 4 | 35 | 10,500 | $\rho_s = 2.7$ | Pignatelli *et al.* (2009) |
| Torre Squillace, Apulia (Italy) | 70 | 1.8 | 40 | 5,040 | $\rho_s = 2.35$ | Pignatelli *et al.* (2009) |
| Torre Santa Sabina, Apulia (Italy) | 8 | 2 | 22 | 352 | $\rho_s = 1.62$ | Mastronuzzi & Sansò (2000) |
| Augusta, Siracusa, Sicily (Italy) | 182 | 45 | 2 | 16,380 | $\rho_s = 2.13$ | Scicchitano *et al.* (2007) |
| Sicily (Italy) | 50 | 2 | 5 | 500 | $\rho_s = 2.7$ | Antonioli *et al.* (2004) |
| Armier Bay (Malta) | 4.7 | 2 | 15 | 141 | $\rho_s = 2.2$ | Furlani *et al.* (2011*a*–*e*), this research |
| Mavros, Crete (Greece) | 40 | — | 60 | — | — | Scheffers & Scheffers (2007) |
| Balos, Crete (Greece) | 75 | 14 | 150 | 157,500 | — | Scheffers & Scheffers (2007) |
| Cape Skalas, Peloponnesus (Greece) | 40 | 14 | 150 | 21,000 | $\rho_s = 2.3$ | Scheffers *et al.* (2008) |
| Lesbos Island (Greece) | 17.6 | 0.4 | 8 | 56.32 | $\rho_s = 2.6$ | Vacchi *et al.* (2012*b*) |
| Cyprus | 30 | 10 | 100 | 30,000 | — | Scheffers & Kelletat (2003) |
| Tripoli islands (Lebanon) | 3.5 | — | 60 | — | $\rho_s = 2.2$ | Morhange *et al.* (2006*a*, *b*) |
| Senani (Lebanon) | 30 | — | 10 | — | — | Morhange *et al.* (2006*a*, *b*) |
| Byblos (Lebanon) | 20 | — | — | — | — | Morhange *et al.* (2006*a*, *b*) |
| 'Alam El Rom (Egypt) | 43 | 4 | 45 | 7,740 | $\rho_s = 3.0$ | Dalal & Torab (2013) |
| Cap Bon, Tunisia | 11 | 5 | 50 | 2,750 | $\rho_s = 2.2$ | May *et al.* (2010) |
| Algeri area (Algeria) | 375 | — | — | — | $\rho_s = 1.7$ | Maouche *et al.* (2009) |

sectors of the basin. The geological framework of this area is very well known, and particularly its tectonic setting as well as crustal mobility owing to glacio-isostatic rebound. This enables the investigation of geological contingency on current coastal processes; the presence of uplifted or drowned counterparts of present-day coastal landforms is a relevant opportunity for mutual exchange between coastal geomorphologists and Quaternary geologists. Future studies are needed that collect direct measurements in coastal settings, such as the emplacement of continuous monitoring stations, in order to record slow but significant surface variations in microtopography. Moreover, it will be useful to improve the use of remote sensing and photogrammetry techniques to study the evolution of features at different scales. Similarities can be highlighted between coastal tracts within the basin, concerning features such as rock type, crustal mobility, tidal range and type of colonizing biota. This is the case, for example, for seismically active coastal areas facing the southern Tyrrhenian and Aegean Sea, and carbonatic microtidal coasts of the French–Italian border compared with those of northern Tunisia. Such comparisons provides a great opportunity to carry out the same type of analysis in different study sites and then compare the results. Gaining awareness of the relevance of rocky littorals throughout the Mediterranean could be a valuable opportunity for mutual exchange between geomorphologists from different Mediterranean countries, and raise the profile of Mediterranean coasts within the wider rock coasts geomorphological community.

We are grateful to G. Mastronuzzi, University of Bari, for his willingness to discuss data about tsunami boulders along the Mediterranean coasts, A. Rovere, Columbia University, for his advices about the Ligurian coast. Moreover, we are grateful to the MEDFLOOD Project (MEDiterranean sea-level change and projection for future FLOODing, resp. A. Rovere (USA), S. Furlani (Italy), J. Benjamin (UK) and A. Fontana (Italy), sponsored by INQUA) and to the RoofOfRock IPA Adriatic CBC Programme 2007–2013 (PI, F. Cucchi, University of Trieste; S. Furlani, resp. WP3 – Platy limestone, geological definition and its use as mineral commodity). The authors acknowledge research funds from MICINN project CGL2010-18616/BTE of the Spanish Government.

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