ROCKY COASTS

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Contents

Summary

Although extending along about 80% of the coasts worldwide, rocky coasts are poorly known in comparison to sandy coasts. Processes acting on these kind of coasts are complex and their effects are generally slow, with the exception of some mass movements that can act at very short time rates. The main processes acting on rocky coasts are wave- and tide-dependent, although biological processes can be very important in rock abrasion, and chemical processes in the weathering of some rock types such as limestone, especially in warm climates.

Weathering is responsible for many geomorphological features characteristic of rocky shores and associated cliff retreat rates and mass movements.

The major rocky coast morphologies can be subdivided into three types—plunging cliffs, horizontal platforms, and sloping platforms.

1. Introduction

Worldwide, rocky coasts extend over 80% of continental and island margins. Though they can have different origins, and their lithology and age vary along the coasts, they are always subject to a strong wave-climate.

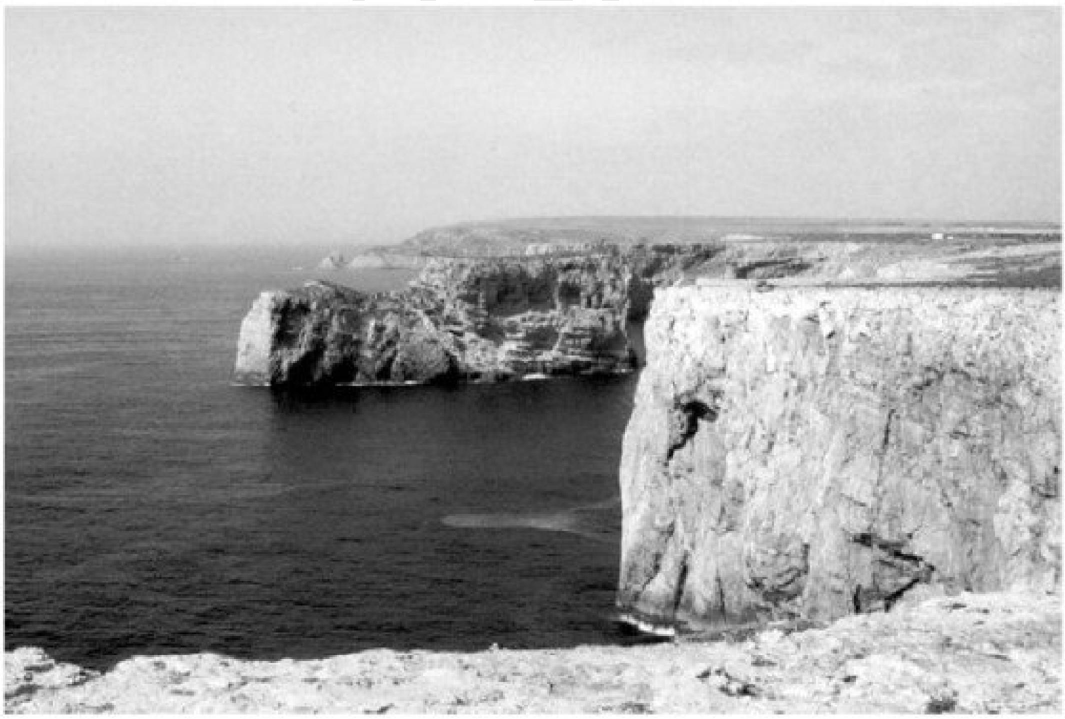

Figure 1. Plunging cliff, St. Vicente cape, south-west Portugal

Rocky coasts are reflective coasts with high, steep cliffs (see Figure 1) consisting of consolidated sediments (lithified coasts) or unconsolidated sediments (unlithified coasts) with different mechanical strengths and an abrasional shore platform at the base which can be covered by clastic deposits forming small pocket-beaches. The height of the cliff is controlled by the nature of the hinterland, i.e. the composition, the slope, and the resistance of the rocks to erosion by marine, continental, and anthropic agents. There are also other kind of rocky coasts that are low and do not present cliffs (see Figure 2).

Figure 2. Low rocky coast, north-west Corsica (courtesy of J. Favennec)

Rocky coasts, especially those that are made of unconsolidated sediments or rocks with joints, faults or bedding structures, can present accentuated cliff retreat rates, that can lead to very serious environmental impacts and difficult management problems.

2. Origin of rocky coasts

Rocky coasts can have different origins. They are often associated with tectonically-active convergent margins, but they can also be present on coasts without dominant tectonic movements, or they amy be associated with Pleistocene glaciers or glacial drift. Another variety of rocky coast is related to hard carbonate-rich sedimentary deposits.

2.1. Rocky coasts at tectonically-active convergent margins

This type of rocky coast is related to tectonic margins in the vicinity of subduction zones, along continental-margins. The start of such a mountain belt is related to the subduction of the oceanic lithosphere at or close to the continental margin. A trench, associated with the down-going oceanic lithosphere marks the ocean-ward side. Frictional heat generated along the upper-edge of the under-thrusting lithospheric slab at depths greater than 100 km, generates an upwelling of magma in an expanding dome within the growing orogenic belt that can rise high above sea level. The final result is a complex of faults, folds, and igneous intrusions and extrusions.

The Andes constitute the most spectacular example of a 9000 km and 5000 m high continental margin orogen. The coasts along the Andes and also those of the western edge of North America, like the California coast, are good examples of rocky shores with high relief, and a practically non-existent continental shelf.

2.2. Rocky coasts not related to active margins

There are many rocky coasts located along wide and flat continental shelves, e.g. the European shores, New Zealand's western coast, and Australia's southern and eastern coast. Some of these rocky coasts have inactive cliffs today, but they were active during the Pliocene or Quaternary higher sea-level stands.

A slight change such as tectonic uplift, sea level drop, or the formation of shingle beaches or barrier islands, can transform an active cliff into a fossil one. Today, fossil cliffs can be found along coasts with other coastal features in front of them like filled marine platforms or coastal plains. Some of these rocky cliffs are the consequence of local tectonics, such as those associated with the Spanish *rias*.

2.3 Rocky coasts associated with glacial activity

During the Pleistocene, glaciers played an important role in the generation of cliffed coasts. The moving ice masses eroded steep U-shaped valleys that were drowned when sea level rose again at the end of glaciation. This is the case of the high-latitude *fjords*, such as in Scandinavia and Greenland, but also the low rocky coasts of the ancient shield areas of the northern coast of Canada that began as glacier valleys.

Another type of cliffed coasts are those formed by glacial drift that transported enormous quantities of unsorted material (till), later deposited beneath and at the margins of the ice as end-moraines. When close to the sea, waves shape steep cliffs. Examples are Cape Cod in Massachusetts, USA, the Scarborough Bluffs of Lake Ontario, Canada, the East Anglia red crags in the UK, and the small cliffs in the former inland sea of the Netherlands (the Ijsselmeer) as well as the former islands of Urk and Schokland in the same area.

2.4. Carbonate rocky coasts

This is a particular type of rocky coast whose cliffs are lithified sandstones cemented by carbonates. They are the remnants of beaches and dunes formed during the Pleistocene, in which the grains were later welded by a carbonate cement, possibly formed by the chemical reaction of shell debris with ocean spray or percolating ground waters. This is the case of eolianites and of beach rocks that can be exposed today to sea erosion, like the cliffed coasts of Bermuda, the Yucatan coast and many Caribbean islands, or the southern coast of Mozambique.

3. Processes

The agents that act on rocky coasts are identical to those on other types of coasts i.e. waves, tides, currents, winds, and others like rain-wash and biological action. While the physical, chemical and biological processes are similar, their effects are rather different.

3.1. Physical processes

3.1.1. Wave-dependent processes

Wave energy is the most dynamic agent that can act on rocky coasts. There is a concentration of energy and thus erosion of the headlands, while in the embayments energy is dispersed, leading to an accumulation of sediments.

Nearshore, waves are depth-dependent and become refracted when depth becomes equal or inferior to half of the wave length. Rocky coasts are associated with shallow platforms with gentle slopes that enhance the breaking of incoming waves. These can display different breaker patterns—spilling, plunging, collapsing, and surging (in order of decreasing wave height for specified period and slope conditions), like on clastic shores. However, rocky headlands with steep subtidal slopes reflect the incoming waves with little or no loss of energy, thus reinforcing the next wave that becomes a standing wave. This kind of waveform, that never really breaks, is called *clapotis*.

When a wave reaches the steep rocky surface, it traps pressurized air that acts as an energy surplus (static + dynamic pressure) that attack the bare stone, producing characteristic features and pulling out particles that, together with gravel and sand from the longshore currents, contribute to the abrasion of the rocks, and hence to cliff retreat. This kind of abrasion is responsible also for some typical features found in rocky platforms (see 4.2.1).

The role of storms is not so important in rocky coasts as it is in clastic shores. However, storm surges with larger and steeper waves contribute to an increase of the dynamic pressure (as high as 20 tons per m^2) and so to stronger shocks and erosion. Notches can be larger and carved at higher levels.

3.1.2. Tidal dependent processes

The influence of tides on rocky coasts depends on tidal amplitude and the cross-shore profile, both conditioning the area that is reworked by waves. On coasts with a small tidal amplitude—microtidal coasts like the Mediterranean—the wave attack is produced in a restricted area at the base of the cliff (when this is vertical or very steep), generating typical features (see 4.2.1). Coasts with higher tidal amplitudes—mesotidal and macrotidal—like south Portugal and St. Malo in France, present broader exposed areas and less focused wave attacks.

3.1.3. Other physical processes

Other physical processes act on rocky shores, though not so spectacularly. This is the case of frost and salt weathering that generate volumetric changes within rock voids and fissures and hence their fracturing. Permeable or fissured rocks are the most vulnerable to this process.

When voids are filled with water (from rain, groundwater, or salt spray) that freezes, ice crystals will increase the pore pressure. Alternating freezing and thawing, especially if it is diurnal, leads to fracturing. This mechanism is most common in arctic regions.

Salt weathering, involving precipitation of salts in voids and expansion of salt crystals through hydratation or heating, is most active in coastal environments and in arid environments. This is the case in coastal deserts like the Atacama (Chile) and the Namib (Namibia), or those along the Red Sea.

Insolation weathering, i.e. thermal amplitudes produced by heating and cooling, is also responsible for expansion, contraction, and volumetric changes of the rock mass. Pressure release, exfoliation and granular disintegration are the consequences of volumetric changes, such as in Rio de Janeiro.

Mass movements are another major process acting on cliffed coasts that will be discussed later (5.3).

3.2. Biological processes

Plants and animals can contribute to the erosion of rocky coasts, above as well as below sea level.

Above sea level, the roots of trees and shrubs contribute to the slow failure of rocks. At both supratidal and intertidal levels, algae can penetrate 1mm into rocks, especially if they are densely distributed. These organisms are more widespread in porous rocks, such as limestones or reefs, or fissured rocks. Other pioneering colonizers are fungi and lichens that—in addition to being rock borers—allow subsequent occupation by grazing organisms when the rocks drop into the intertidal or subtidal zone. These organisms include snails, chitons, sea urchins, and sea stars that abrade the rock surfaces by mechanical rasping.

Other boring marine organisms are bivalves, sponges, worms, and spiny echinoids, that contribute to the weakness of the rock and its vulnerability to wave attack.

3.3. Chemical processes

Chemical weathering rates are related to climate and rock lithology. Water is undoubtedly the main agent, tropical regions being privileged areas for chemical weathering. Oxidation is the most rapid of the chemical reactions.

Lithology plays an important role. Limestones are easily weathered by carbonic acid-rich waters. However, many authors think that bio-erosion is the main kind of limestone erosion , once coastal water are oversaturated or saturated in calcium carbonate. But rock minerals such as feldspar and biotite, are also chemically weathered into clay minerals that constitute a large percent of muds, soils, and colluvium. Chemical weathering contributes to the occurrence of very typical erosional features (see 4.2.1).

Chemical rock building in contrast, occurs where shells and other carbonate particles are welded by a cement. Beach rocks and eolianites are example of this kind of chemical building.

4. Geomorphology

Rocky coast morphology is controlled by lithology, structural configuration, waves, climate, and minor relative changes in sea level, which are very different worldwide. The most spectacular rocky coasts are those that are associated with high and steep cliffs, either with or without marine platforms.

4.1. Major morphologies

Three major morphological types can be distinguished: sloping shore platforms (Type-A), horizontal shore platforms (Type-B), and plunging cliffs (see Figure 3).

Some coasts present very high and steep bluffs of unconsolidated sediments that, not being truly rocky coasts, are included due to their similar morphology. These bluffs are formed by erosion of older coastal deposits or glacial sediments. They tend to be fronted by beaches that develop from the interaction between lag material from cliff erosion and the wave action.

4.1.1. Sloping shore platforms (Type-A)

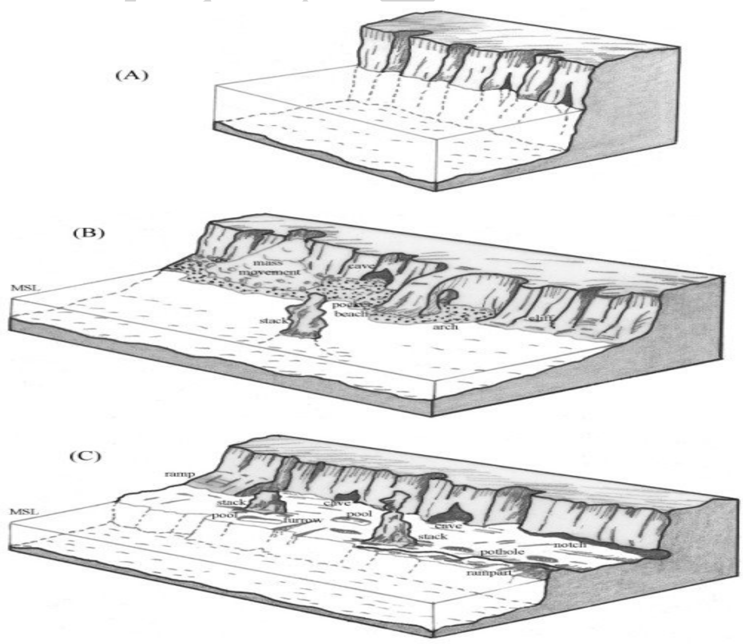

Figure 3. Schematic representation of cliff rocky coasts and main morphological features:
a) plunging cliff; b) sloping shore platform, c) horizontal shore platform.

The platform extends without significant topographic break, from the base of the cliff to the nearshore sea floor below low-tide level (see Figure 4).

Figure 4. Shore platform associated with a cliff, Alentejo coast, Portugal

This profile is more common in macrotidal environments and soft rocks. The base of the cliff is generally located at the run-up level, above mean sea-level in non-tidal environments, and above the high-water mark in tidal environments. Gravel or coarse sand beaches can be present. This kind of platform can be as wide as 5000m and as deep as 30m, like on the western Sakhalin coast.

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Biographical Sketch

Helena Maria L. P. Granja was born in 1953, in Porto, Portugal. She graduated in Geology at the University of Porto. She obtained an MSc at the University of Bordeaux I (France) in Oceanology and a PhD in Geology at the University of Minho. Presently she is Professor at the University of Minho (Portugal), where she teaches Stratigraphy, Geomorphology, and Environmental Geology. Formerly, she worked as a sedimentologist in the state Department of Environment, in Lisbon.

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She is involved in European projects concerned with the coastal zone and has published several papers in international journals related to her speciality. She supervises several post-graduate students in two main fields of research: Holocene coastal stratigraphy and sedimentology, and shore morphodynamics.