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A Global Synthesis with implications
for management of future coastal change

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Quaternary coastal morphology and sea level changes

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Quaternary staircased model of marine terraces and linked coastal formations (Gibraltar, Southern Iberia)

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Introduction

Gibraltar is a north-south peninsula with 6 km^2 in total land area. The Rock is an outcrop of Mesozoic carbonates and shales fissured by various faults and fractures, grouped in two main families: NE-SW and NW-SE, with a clear transcurrent component.

Coastal processes are important and these have been especially active in the eastern face of the Rock, where there is greater fetch. The combination of tectonic and eustatic fluctuations have caused change in the location of the coastal landforms. The lithification of the Quaternary deposits has led to the preservation of a varied group of sediments which represent processes that indicate a rapid and complex geomorphological development and neotectonic uplift history.

When tectonic uplift exceeds the rate of eustatic sea level rise, or when the sea level falls, then the coastal cliffs can be isolated from wave attack and preserved as relict features. At this stage subaerial processes may act, degrading the slope. Conversely, when the relative sea-level rise is positive, the cliffs can be reached more frequently by waves and therefore subject to greater erosion rates.

Sedimentary record

Smith (1846) and Ramsay and Geikie (1878) initiated the documentation of the Quaternary deposits on the flanks of the Rock and later detailed studies were made by Rose and Hardman (1994, 2000).

Quaternary sediments on the Gibraltar flanks have a widespread surficial distribution and are related to marine and continental deposits. Their systems have generated sand and cobble shore sediments, aeolian sands, scree breccias, and karstic products, like clays, fallen rocks and speleothems.

Tectonic uplift of marine highstands shows raised shorelines staircased throughout the Gibraltar slopes. Geomorphological techniques are required to establish a suitable chronological situation given the different location and height of these sediments and their spatial interrelation.

The relationships between beach, scree and dune sedimentary formations establish, after our geomorphological research and mapping, five main morphotectonic steps on the Rock (Fig. 1): marine terraces between 1 and 25 m (e.g. Governor's Beach), 30-60 m (e.g. Europa Flats), 80-130 m (e.g. Windmill Hill Flats), 180-210 m (e.g. Martin's Cave), and probably upper. Each terrace succession and its slope-aeolian linked sediments is backed by a steep relict sea cliff along its landward margin, so forming a composite cliff (Rodríguez-Vidal and Gracia, 2000). The hanging slopes appear much better developed on the eastern side of the Rock, since the littoral erosive processes here are much greater. In general, the age of higher morphotectonic steps are likely to be older than lower ones, and might range back into the Lower Pleistocene.

Uplifted marine terraces

Raised shorelines in Gibraltar are represented by marine sediments and landforms and are best developed to the south and east of the Rock. Current evidence suggests that there are traces of at least twelve former levels that are now raised above present MSL at heights of 1-3, 7-9, 15-17, 20-25, 30-40, 50-60, 80-86, 90-130, 180-190, about 210, and possibly 240-250 m or even 300 m. The cartographic and morphostratigraphic disposition of the terraces, their faunal content and their U-Th age (Lario, 1996; Zazo et al., 1999) provide tools for reasonable chronostratigraphic interpretation of the marine sequence, especially of the most recent terraces.

The last morphotectonic step in the Gibraltar emerged coast (Fig. 1) is related with Oxygen Isotope Stages 7, 5 and 1. Dated marine terraces linked with them are located at 25-20 m, 17-15 m and 10 m (OIS 7), 5 m (OIS 5c), 2-1.5 m (OIS 5a), and 1.5 m above present MSL (OIS 1). All of them represent emerged highstand positions of the

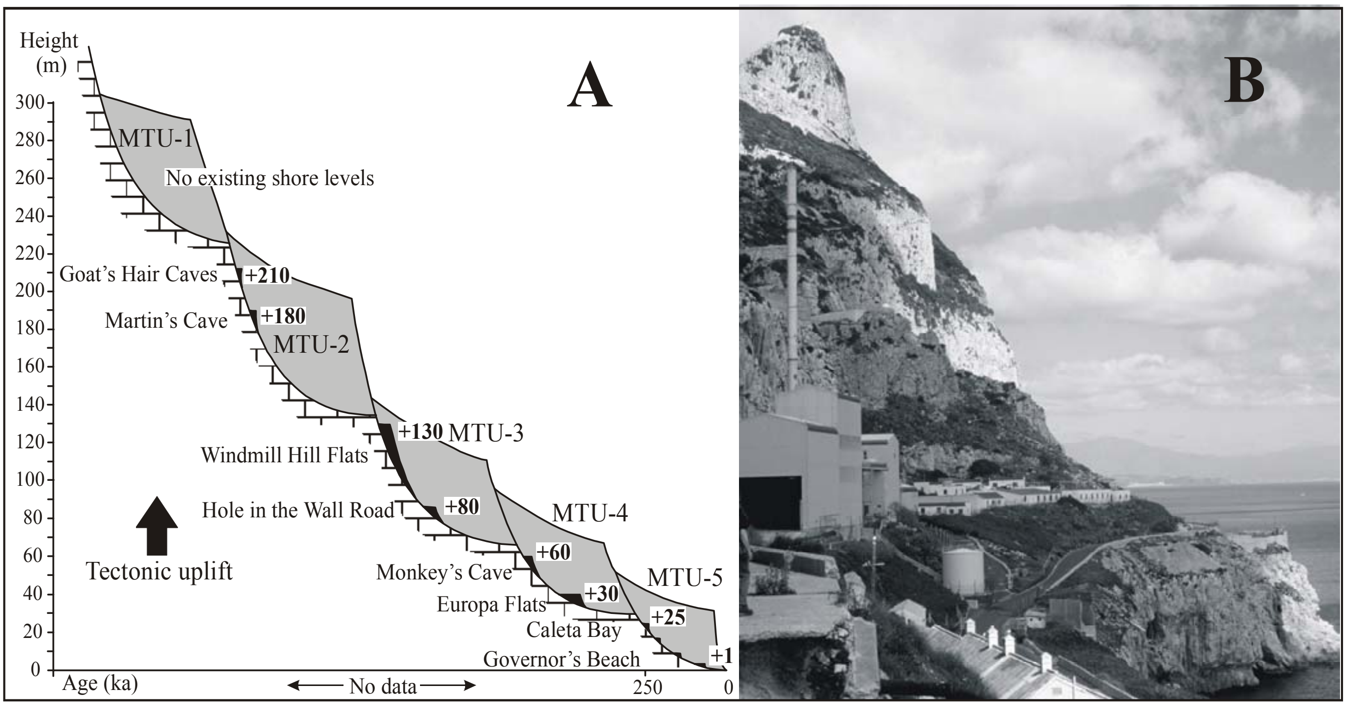

Figure 1. (A) Synthetic diagram of a morphotectonic transect on the Eastern flank of the Rock of Gibraltar. Five morphotectonic units (MTU) distinguished, with altitudinal localization of some examples of marine terraces that act as reference. **(B)** Hillside of composite cliffs on the SE coast Gibraltar, where each shelf separates a MTU with a complete morphosedimentary record (shore sediments – aeolian sands – scree breccias – karstic product).

interglacial sea levels (Hoyos et al., 1994, Zazo et al., 1994), although other highstand terraces (OIS 3) are probably submerged on the eastern coast of Gibraltar (Flemming, 1972).

Staircased slopes

In Gibraltar the most recent profiles (and also the vestiges of ancient hillsides) show very similar designs, with two, well-differentiated elements: a semi-vertical cliff top, and a rectilinear to concave basal slope. The former originates from gravitational processes: collapses and falls associated with intense fracturing of the calcareous mass, possibly affected by other secondary processes and factors, such as the network of surface-breaking endokarst conduits, root activity, mechanical weathering, etc.

This type of morphology is associated with the so-called "composite cliffs", whose polycyclic evolution is usually related to tectonoeustatic fluctuations and to the different rates of erosive retreat of the escarpments due to wave action (Trenhaile, 1987).

All the dates that have been obtained so far in the Quaternary marine deposits of Gibraltar, are situated in the morphotectonic step of lowest altitude (MTU-5, Fig. 1). This morphological episode is limited above by an old marine slope that evolved subsequently in a continental environment.

There were positive and negative sea-level changes during the time required for its development. The marine highstand positions are all emerged or fosilized by subsequent deposits. Lowstand positions are currently submerged and, for now, cannot be studied. The MTU-5 extends across emerged and submerged areas with a continental cliff limit and an undetermined submarine limit.

It is therefore not surprising that deposits of littoral origin of different age are found superimposed against each other or stepped in slopes in inverted chronological positions.

The gradual tectonic uplift of the Rock elevated the marine levels to positions that do not correspond with the originals but they are always found within the morphotectonic step MTU-5.

Only tectonic large scale events are able to elevate the whole morphosedimentary complex to levels that can never be reached by subsequent highstand positions. A stepped morphotectonic unit, of the type that have been charted on the Gibraltar slopes, is thus defined.

Conclusions

The geomorphological evolution is linked to the rapid Quaternary sea level changes and the slower ones of local tectonic origin.

The former create a morphosedimentary complex of marine, aeolian, gravitational and karstic origin, that are distributed over a cartographically well-defined altitude range; the latter separate the morphosedimentary complexes into several morphotectonic steps, in the form of high scarps of palaeocliff. In this way the rocky coast behaves like a composite cliff, with successive profiles of erosive cliff and sedimentary talus.

For this tectonoeustatic model to be valid it is necessary that there should be fluctuations in the rates of coastal uplift and that we should be in a tectonically active region, as is the case in the Strait of Gibraltar. Low uplift rates generate morphosedimentary units (MSU), stepped and offlapped. Higher rates isolate these units by way of main cliffs and form morphotectonic units (MTU), the most recent ones probably being dated between 250 ka and the present.

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