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The rock coast of continental Europe in the Atlantic

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Abstract: Rocky coasts occur along more than one-third (37%) of the Atlantic continental European coastline, approximately 3666 km, often forming vertical cliffs and characteristically gently sloping shore platforms. The continental European Atlantic rocky coasts show a great variability of rock types and structural contexts, as well as different wave climates and tidal ranges. Through a review of previously published data on cliff retreat rates and shore platform erosion measured on monthly, seasonal, annual and decadal timescales, this paper highlights the different processes and agents, their magnitude and frequency in shaping rocky coasts. In particular, the links between cliff retreat, shore platform evolution, present dynamics and inheritance (understood as whether platform and other rock coast features were shaped by a higher sea level than the present) comprise one of the major contributions from continental European Atlantic rocky coasts to a global understanding of rock coast coastal geomorphology.

From a geomorphological point of view there is not a general consensus about the meaning and the extent of the term Atlantic coasts. Despite being a passive margin, the complex geological setting and evolution of Europe's Atlantic coastline and the varied oceanographic and climatic zones provide a diverse range of coastal landforms. In contrast, Atlantic cultural geography, floristic and climatic regions are well established. For the purposes of this paper and in line with the regional appraisal covered in this book, the extent of the continental European Atlantic rocky coasts will be taken to those continental coastlines belonging to the European Atlantic watershed, which straddles more than 15° of latitude, from cape of Tarifa (southern Spain) to Pas de Calais (northwestern France).

In continental Atlantic Europe, rocky coasts appear widely along the shores of Spain, Portugal and France, often forming vertical cliffs and characteristically gently sloping shore platforms that extend at low water tens of metres (Kelletat & Scheffers 2005). Other rock coast macroforms such as *rias* are quite abundant on Galician coast (northwestern Spain), on Brittany coast (northwestern France) and are also representative of this physiographical region (Fig. 6.1). Measured on a 1:100 000 digital map (Lénotre *et al.* 2004), Atlantic cliffed and rocky coasts occur along more than one-third (37%) of the continental European coastline, approximately 3666 km (Fig. 6.2). About 48% of these cliffed coasts develop on hard rock outcrops (i.e. granites or limestone) and 52% on soft rocks, such as Upper Cretaceous chalk or Quaternary colluvial–alluvial sediments.

The west-facing European continental shore is exposed to Atlantic swell and also to waves generated by westerly and north-westerly winds. In general, wave energy decreases from north to south. Significant wave heights higher than 4 m are considered as storms and occur between 2 and 4% of the time along the South Portugal coast (Pires 1989; Nunes *et al.* 2009), essentially during winter months, whereas mean significant wave heights in

the Biscay Bay reach 2.64 m and extreme events of 6 m are common on an annual basis (Dupuis *et al.* 2006). Tidal range and the strength of tidal currents vary along a north–south gradient. Spring tidal range is highest around the Brittany coast, reaching more than 10 m, but in the south, near Gibraltar, spring tidal range is lower than 2 m.

Many authors have emphasized a lack of research tradition and publications on rocky coast morphology (Trenhaile 2000), and this is also true for the continental European Atlantic coasts (i.e. Moura *et al.* 2006). Nevertheless, recently a growing list of researchers on the subject is reflected in the increase of the published papers about rock coasts (Naylor *et al.* 2010). Currently different research groups, based on Europe continental Atlantic coasts, are giving impetus to the study of this subject and have contributed to highlighting major themes in rock coast research, such as inheritance or geological control on processes acting in shore platforms (Dasgupta 2011). Contemporary rock coast research in Continental Atlantic Europe is best considered from a thematic point of view, rather than from a national or professional approach. In each country groups are found that have concentrated on measurement of erosion rates (Costa *et al.* 2004; Henaff *et al.* 2006; Marques 2008; Del Río *et al.* 2009), while others have explored inheritance (Trenhaile *et al.* 1999; Blanco *et al.* 2003; Pierre 2007), cliff retreat or shore platform erosion mechanisms (Lahausse & Pierre 2003a, b; Nunes *et al.* 2011). Thus, at least four major topics have been addressed, namely: (a) cliff and shore platform morphology; (b) cliff retreat and shore platform downwearing; (c) the role of marine and subaerial processes on cliff and platform development such as abrasion; and (d) the role of geological control and inheritance.

The present paper aims to review the research conducted on Continental European Atlantic rocky coasts and in doing so identify main findings and possible areas of future research that will enhance the understanding rock coast morphodynamics.

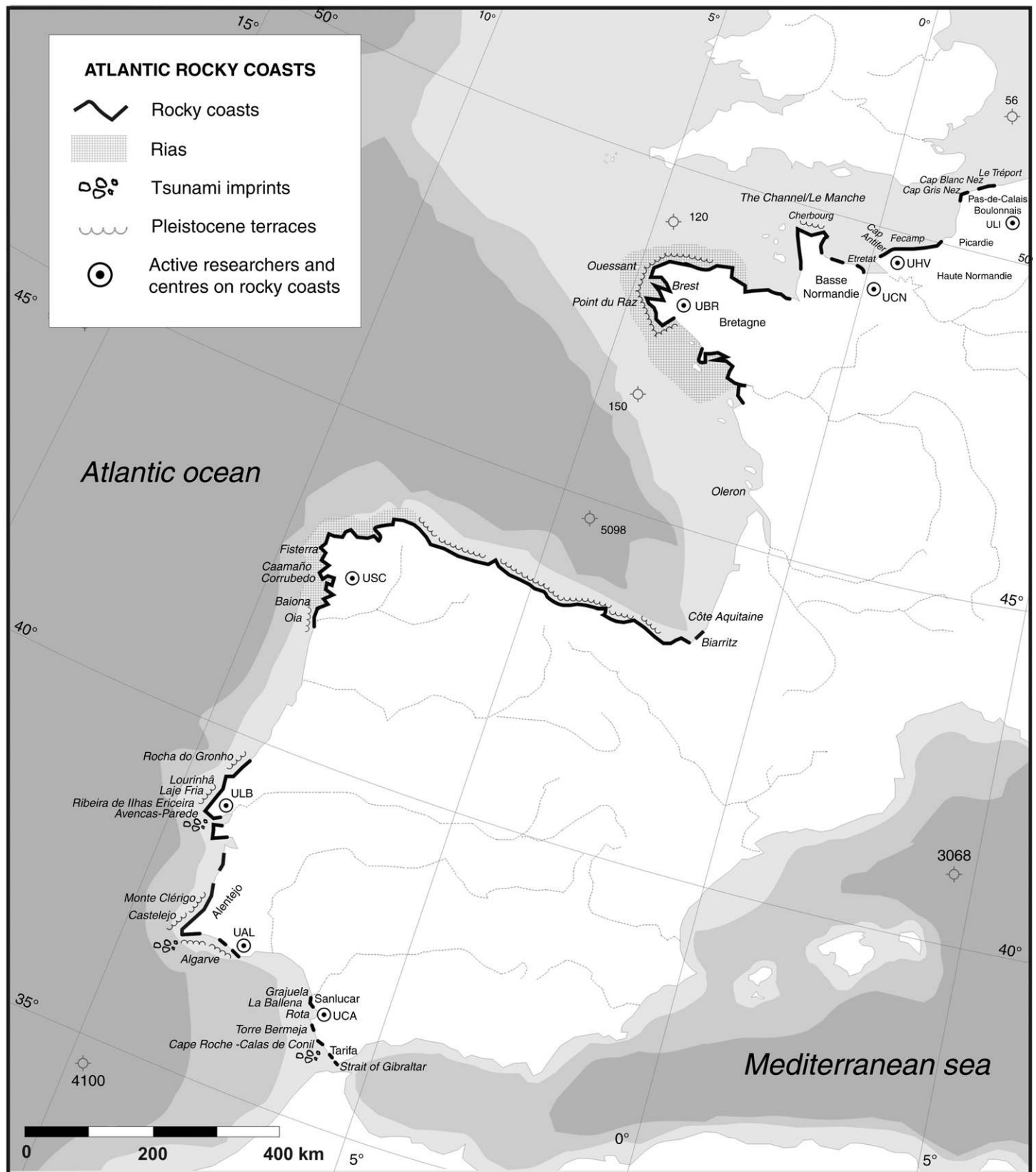


Fig. 6.1. The continental European Atlantic rocky coast: major morphological features and locations cited in the text. Dots indicate the active researchers and centres on rocky coasts: UCA, University of Cadiz; UAL, University of Algarve; ULB, University of Lisbon; USC, University of Santiago; UBR, University of Bretagne Occidentale; University of Caen Basse Normandie; UHV, University du Havre; ULI, University of Lille.

Cliff and shore platform morphology

In Continental Atlantic Europe there are more studies that focus on erosion rates and processes and modes of cliffs and/or shore platform retreat than on cliff and shore platform morphology.

Nevertheless there are further detailed field studies that provide significant information on this topic.

The work of Moura *et al.* (2006, 2011a, b) explores the threshold conditions for cliff and platform development in the Algarve south coast (Portugal). Results show that the cliff heights and profiles in

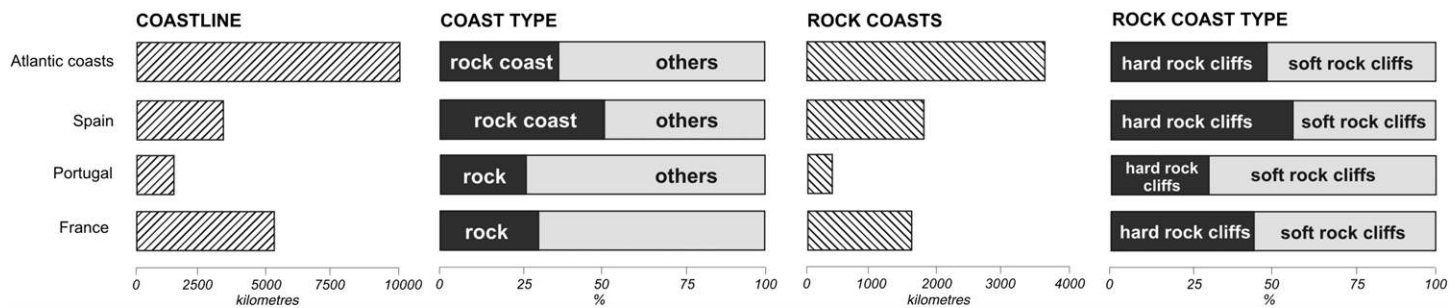


Fig. 6.2. Length and coast type along the European Atlantic coast.

that region are lithologically and structurally controlled, whereas shore platforms occur and show a strong correlation with the exposure to the prevailing wave direction. Wave attack is one of the main agents in shore platform sculpturing and platform width links, first, with the degree of wave exposure and, second, with lithology and structure control (Moura *et al.* 2006). Occurrence of shore platforms correlates positively with waves approaching from the west ($r^2 = 0.5$) and to greater degree with waves from the SE ($r^2 = 0.6$) with significant height of 2 m and peak period of 9 s. On the Algarve south coast, shore platforms range from 4 to 150 m in width and are typically subhorizontal. There are several raised platforms with previous evidences of former sea-levels. The South Algarve is partially a carbonate coast whose caves and microrelief are distinctive features. Marine cave genesis is mainly related to the rock layer structure and to differential erosion (Moura *et al.* 2011a, b). Coastal karren features and joint density contribute to the roughness aspect of Algarve shore platforms, nevertheless notch occurrence seems independent of the degree of exposure but mostly occurs in sandy substrata (Moura *et al.* 2011a, b). In contrast Wziątek *et al.* (2011) show that tidal notches were more common in sheltered cliffs, while surf notches prevailed in exposed and moderately exposed areas. In that sense, the spatial distribution of tidal notches appears to follow vertical variation of chemical resistance; nevertheless that trend is weaker for the most energetic sections of the coastline.

Most research on Spanish shore platform morphology and cliff shape has been conducted in Galicia, northwestern Spain. Owing to its lithological and structural diversity (granitic, metamorphic and basic rocks), the coast of Galicia, with the exception of the extreme southwestern and northeastern sections, has numerous indentations, including the great rias of the western coast and many smaller inlets and bays (Blanco-Chao & Pérez-Alberti 1996; Pérez-Alberti & Blanco-Chao 2005). The irregular shape of this coast and the nearby coastal mountains create a morphogenic environment that was dominated by cold processes during the last glacial stage (Blanco-Chao *et al.* 2002). In most of coastal Galicia there are landforms developed during several transgressive episodes that were fossilized by continental deposits in regressive stages. Coastal processes are therefore operating today on a host of inherited and relic landforms, including cliffs, shore platforms and boulder beaches (Pérez-Alberti *et al.* 1998a, b; Blanco-Chao *et al.* 2002). In the Caamaño area wide intertidal shore platforms are found (50–120 m) backed by a supratidal rock ledge, or by a steeper and narrower supratidal ramp extending up to several metres above the highest tidal level. The platforms have mainly developed in vertical to steeply dipping metamorphic strata with some granitic intrusions (Fig. 6.3). The platform gradients range from 0.3 to 0.8° and are backed by abandoned and grass-covered sea cliffs (Trenhaile *et al.* 1999). On the Baiona coast, extensive shore platforms up to 100 m in width



Fig. 6.3. The intertidal platform and supratidal ramp at Caamaño (NW Galicia, Spain).



Fig. 6.4. Shore platform with channels and coastal karren forms at Puys, Haute-Normandie.

have an irregular surface, mostly covered by ancient continental deposits, cliff debris and blocks of loose rocks (Trenhaile *et al.* 1999). Gastropods (*Patella* spp., *Littorina* spp.), crustaceans (*Balanus perforatus*, *Chthamallus stellatus*), molluscs (*Mytilus edulis*) and algae (*Lithophyllum lichenoides*) cover the lower parts of the platforms. The supratidal portion of the platform has steeper gradients (c. 3°), whereas in the intertidal zones the gradients are typically between 1 and 2° (Blanco-Chao *et al.* 2003). At Corrubedo, the granitic platform is generally between 100 and 150 m in width and 1 or 2° in slope. The platform surface is very irregular and many channels have been cut along joints. This results in linear or concave-linear profiles with a steeper ramp and with associated gradients of between 4 and 5° (Blanco-Chao *et al.* 2006). Boulder beaches back the platforms and exert a protective role controlling the geometry and slope of the platforms (Pérez-Alberti *et al.* 2013). Otherwise, a recent study in NW Spain by Feal-Pérez & Blanco-Chao (2013) explored the role of abrasion in rock coast surfaces at the micro- to the meso-scale (millimetre to centimetre), showing, by means of Equotip measures, that abrasion along near-vertical rock surfaces induces a decrease in rock strength with elevation above the sediment layer that carpets shore platforms. Additionally they established that abrasion encompasses two distinctive processes: first of all, the wave-induced sweeping and dragging of sand and gravel, and second, the projection of clasts against rock surfaces. This results in a variable rock surface roughness, strongly influenced by the properties of diverse rock minerals and the local fracture and cleavage patterns.

Studies on the chalk coast of northern France (Costa *et al.* 2004; Hénaff *et al.* 2006) show the importance of lithology and geological structure on platform–cliff morphology and how the spatial distribution of platform features created by external processes is adapted to a morphology that conforms to the structure. A characteristic zonation of chalk platform features can be described; the main elements are a gently sloping platform (250 m in width and approximately 1° slope), and landward to seaward, the cliff and the cliff foot, a shingle beach and then a rock platform where different units can be identified (Fig. 6.4). The cliffs are cut vertically into the chalk plateau and are approximately 50–100 m

height. Some inherited endokarstic features appear at the cliff foot or on the cliff face, including caves created and enlarged by the sea and karstic pipes near the top of the cliff (Hénaff *et al.* 2006). Because of the dynamic of the cliffs, sometimes massive accumulations of mass-movement debris locally cover the shore platforms and, as a consequence, they play an ambivalent role because they can assist wave attack acting on the cliffs (Costa *et al.* 2006; Duperret *et al.* 2004). Basal notching by waves is rarely observed, however occasional notches related to other processes, such as differential erosion of softer chalk layers, are common (Hénaff *et al.* 2002). Shore platforms gently slope seaward (1–1.3°) and according to Nesteroff & Melieres (1967), a common morpho-ecological zonation can be established. Even though the spatial zonation of each zone may vary from one area to another, successively they describe the abrasion or white zone, the grey or transition zone, the pinnacle zones (*lapies*), the flat pool zone and the external zone cut by runnels that drain to the low tide step cliff (Fig. 6.5). The white zone has a smooth and slightly undulating surface, mainly owing to mechanical abrasion caused by transverse and longitudinal movements by waves of sedimentary materials from the upper intertidal zone (Hénaff *et al.* 2002; Costa *et al.* 2006). The white zone is followed by a karren zone, with pinnacle, pits and hollows 1–10 cm deep closely related to the biological action of a variety of Cyanophytes, endolithic organisms, rock-boring species, grazers and Polychaete worms (Hénaff *et al.* 2006).

Cliff retreat and shore platform downwearing

Erosion of shore platforms and cliff retreat occurs at a variety of scales (Table 6.1). In Continental Atlantic Europe cliff retreat has been measured over a range of spatial and temporal scales, using different methods and techniques. In southwestern Spain, Del Río *et al.* (2009) measured the retreat of the top of cliff edge over the last 50 years, by means of detailed field inspections and digital photogrammetric techniques, between Tarifa and Sanlúcar cliffs. The cliffed coasts shaped on conglomerates, sandstones and cemented detritic deposits – namely Middle Miocene



Fig. 6.5. General overview of the chalk shore platform, coastal karren, boulder and gravel beaches and vertical cliffs at Les Grandes Dalles (Normandy, France).

to Plio-Pleistocene – are retreating at varying rates of up to 1.5 m a^{-1} , with values ranging from 0.2 to 2 m a^{-1} (Fig. 6.6). Lower cliff retreat corresponds to Oligo-Miocene detritic and calcareous materials, faulted and folded by the Alpine Orogenia. Despite shore platforms being a conspicuous feature of the southern Spanish Atlantic coast, there is a lack of studies on shore platform morphology and erosion in this area. In northern Spain, Pérez-Alberti *et al.* (2013) quantify retreat rates of 0.03 – 2.78 m a^{-1} for granitic cliffs and Blanco-Chao *et al.* (2006) measured platform downwearing rates ranging from 0.13 to 1.8 mm a^{-1} . Most of this erosion may reflect the way in which abrasion wears down the coarse-grained granites.

In Portugal cliff retreat has been measured over a range of rock types and locations (Fig. 6.7). For the period 1947–2000, Marques (2006) determined retreat rates of 0.003 m a^{-1} for cliffs cut in a Mesozoic alternation of marls and marly limestones and 0.008 m a^{-1} for cliffs cut in a Carboniferous alternation of shales and greywackes. In weak Miocene calcarenites retreat rates encompass values around 0.006 – 0.009 m a^{-1} (Marques, 1997; Teixeira, 2006). Marques (2008) explored the magnitude–frequency of sea cliff instabilities and showed no evidence of erosion trends in cliff evolution. On the other hand, Marques (2006) suggests a decrease in the cliff dynamics in retreat on the Alentejo coast (SW Portugal) since 1986, where the retreat rate for the period 1982–1989 ranges from 0.43 to 0.85 m a^{-1} . Epifânio *et al.* (2013) identified landslides as the main process in coastal cliffs of Lourinhã (Central Portugal), resulting in cliff retreat ranging from 0.013 to 0.130 m a^{-1} . In the Portuguese Estremadura coastal area, Neves (2004) measured downwearing on three platforms between May/June 2001 and May/June 2003: (a) at *Laje Fria*, cut in upper Jurassic fine-grained carbonate sandstone; (b) at *Ribeira de Ilhas*, cut in lower Cretaceous marly limestone; and (c) at *Areia Branca*, cut in clay-rich sandstone. At each studied platform, along a transversal profile, four TMEM (traversing micro-erosion meter) stations were installed with different exposure periods to marine and subaerial processes. Several results (*Laje Fria* – 0.063 mm a^{-1} ; *Ribeira de Ilhas* – 0.858 mm a^{-1} ; *Areia Branca* – 1.699 mm a^{-1}) were well correlated with the compressive strength of the shore platforms substratum, highlighting an important lithological control. Also interesting were the seasonal patterns, particularly noticeable at *Ribeira de Ilhas*, where summer downwearing data from the

stations located near maximum high-water spring level presented results 3–9 times higher than winter ones, indicating that the weathering processes can be more effective at this band than the waves abrasion, whereas the lower TMEM stations had similar results all year round. Surface swelling was also recorded. In Algarve (southern Portugal), Moura *et al.* (2012) show higher downwearing rates in calcarenite (0.25 – 2.97 mm a^{-1}) than in siltstone. These downwearing rates correlate positively with substrate porosity and burrows produced by borers, suggesting the role of bioeroders in surface lowering.

Studies of the French chalk coast, based on a variety of historical records, ordinance survey maps and aerial photography, suggest that recently cliff retreat has been increasing. For 120 km stretch of cliffs between Antifer and Le Treport (Picardy), decadal rates of retreat, calculated by Costa *et al.* (2003, 2004, 2006) using photogrammetric analysis for the period 1947–1995, give a mean rate of approximately 0.14 m a^{-1} , whereas for the period 1966–1995 the mean cliff retreat was approximately 0.28 m a^{-1} . On the other hand, NE of Fecamp (Haute Normandy), Hénaff *et al.* (2002) measured cliff retreat from cadastral surveys over the period from 1824 to 1986 and suggest erosion rates of 0.05 – 0.07 m a^{-1} (Fig. 6.8). For the same region and on the basis of cosmogenics, Regard *et al.* (2010, 2012) suggest that the cliff retreat rate since the mid-Holocene has been $0.25 \pm 0.05 \text{ m a}^{-1}$. Differences between these erosion values are due to the nature of the measurement techniques and also to factors at the local study sites that are different, despite the sites being part of the same region. The variations may be caused by measurement techniques not always being comparable, but mostly by local structural or exposure conditions sometimes being slightly different.

In addition Siegburg (1990) and Lahaussé & Pierre (2003a, b) argue that cliff retreat has experienced a decrease in cliff falls and subsequent retreat that results in retreat rates of 0.58 – 5 m a^{-1} for the period 1929–1963 and of 0.04 – 0.25 m a^{-1} for the period 1963–1993. On the Aquitanian coast cliff retreat on marly limestones or Triassic muddy sandstones ranges from 0.15 to 0.50 m a^{-1} (Aubie *et al.* 2011).

In France, the only published data on platform downwearing are for two locations on the Normandy coast (Foote *et al.* 2006). The average annual, retreat rate of 40 measurement sites throughout the years 1999–2002 is 4.80 mm a^{-1} , excluding the abrasion zone where the retreat is 3.32 mm a^{-1} . The authors stress that

Table 6.1. *Cliff retreat rates at European Atlantic Rocky coasts*

Location	Mean rate (m a ⁻¹)	Range (m a ⁻¹)	Time period	Rock type	Type of cliff retreat	Author
<i>Southwest Spain</i>						
Grajuela	n.a.	0.8–1.6	1956–2005	Gravels and sands	Rock fall	Del Río <i>et al.</i> (2009)
Ballena-Aguadulce	n.a.	0.5–1.2	1956–2005	Marls and sands	Rock fall and flow	Del Río <i>et al.</i> (2009)
Rota	0.8	max. 1.5	1956–2005	Marls and sands	Slide	Del Río <i>et al.</i> (2009)
La Barrosa	n.a.	0.2	1956–2005	Conglomerates and sands	Rock fall and slide	Del Río <i>et al.</i> (2009)
Calas de Conil	n.a.	0.2–0.7	1956–2005	Sandstones, sands and marls	Rock fall, slide, toppling	Del Río <i>et al.</i> (2009)
<i>South Portugal</i>						
South central Algarve	0.01	n.a.	1995–2004	Carbonate Miocene rocks	Rockfall and karst collapse	Teixeira (2006)
	0.006	0.002–0.0039	1947–1991	Weak Miocene calcarenites	Rock fall and karst collapse	Marques (1997)
West Algarve	0.004	0.003–0.017	1947–1991	Carboniferous shale and greywacke	Planar and rockfalls	Marques (1997)
	0.003	0.001–0.016	1947–1991	Jurassic marly limestones	Rockfalls and toppling	Marques (1997)
Forte Novo	0.019	0.006–0.028	1947–1991	Quaternary eolianites	Rockfalls	Marques (1997)
	0.4	<1.44	2009–2010	Plio-pleistocene red sands	n.a.	Nunes <i>et al.</i> (2011)
	n.a.	0.14–2.27	1991–2001		n.a.	Oliveira <i>et al.</i> (2008)
<i>Southwestern Portugal</i>						
Monte Clérigo	0.008	0.006–0.015	1947–2000	Carboniferous chales and greywacke	Planara mass movement and toppling	Marques (2003)
	0.004	n.a.	1999–2003	Carboniferous chales and greywacke	Planara mass movement and toppling	Marques (2006)
Castelejo	0.69	0.43–0.85	1982–1989	Carboniferous grauwacke and schists	Slides and rockfalls	Neves & Pereira (1999)
<i>Western Portugal</i>						
Avencas – Parede	0.017	0.001–0.017	1947–2000	Albian sandstones and Upper Cretaceous marly nodular limestones and limestones alternating with marls	Toppling	Marques (2006)
	0.017	n.a.	1999–2003		Toppling	Marques (2006)
Ribeira de Ilhas	0.003	n.a.	1947–1989	Lower Cretaceous near horizontal alternating layer of marly limestones, marls and sandstone	Planar	Marques (1998)
	0.005	0.003–0.013	1947–2000		Planar	Marques (2006)
Roca do Gronho	0.008	n.a.	1999–2003		Planar	Marques (2006)
	0.15	0.02–0.27	1958–2004	Cretaceous sandstone	Rockfall and toppling	Neves (2004)
	n.a.	3.4–8.9	1995–2005		Rockfall and toppling	Neves (2008)
<i>Northern Spain</i>						
Fisterra	0.37	0.03–2.78	1956–2008	Granites	n.a.	Pérez-Alberti <i>et al.</i> (2013)

platform erosion is greatest in autumn and winter, but there is considerable variation between years, which has been related to the incidence of stormy weather. Additionally, during the monitoring period there are several TMEM readings, which indicate rock surface swelling previous to rock surface erosions. Using a different approach, Regard *et al.* (2013) investigated the relationships between platform dynamics and cliff retreat along a section of the Channel Chalk coast. They concluded by comparing aerial photographs at 23 year interval that platform erosion owing to platform step retreat (0.28 mm a⁻¹) accounts for at least 20% of the platform erosion.

Modes of cliff retreat and shore platform erosion

Studies on Continental Atlantic Europe rock coasts focus on the role of marine or subaerial processes and modes of cliff retreat over short time periods. Although the debate still exists on the effectiveness of waves, only as a simple transport agent clearing

collapses and landslides and reactivating the cliff instability, or as a real erosion agent capable of creating cliff falls, is there a general consensus on the role of lithologic control and the intense rain episodes as the main drivers of cliff retreat (Duperret *et al.* 2002; Rohmer & Dewez 2013). Studies on the chalk coast of northern France attribute cliff failure and collapse to heavy winter rainfall (Duperret *et al.* 2002; Lahousse & Pierre 2003a, b; Letortu *et al.* 2011), and in particular to sequences of wet years that induce an increase in groundwater level in the coastal rock mass (Lageat *et al.* 2006). Pierre & Lahousse (2006) show that the mechanical behaviour of the rocks determines the modes of failure and the coupled rainfall and piezometric surface data showed a ‘piston flow’ mechanism. In some coastal locations of the northern Boulonnais, almost all of the retreat since 1939 occurred in November 2000 (Pierre & Lahousse 2003). It is suggested that, during periods of intense rainfall, high pore water pressure within rock – especially in chalky cliffs – is accompanied by a decline in effective shear strength that leads to or accentuates cliff collapse.

Table 6.1. (Continued)

Location	Mean rate (m a ⁻¹)	Range (m a ⁻¹)	Time period	Rock type	Type of cliff retreat	Author
<i>Île d'Oléron</i>						
Chassiron	n.a.	0.40–0.70	1959–1999	Jurassic Limestone	Rockfall	Arteaga (2008)
<i>Côte Aquitaine</i>						
Biarritz	n.a.	0.15–0.50	1954–2009	Oligocene limestone and marly limestone	Slides, rock fall	Aubie <i>et al.</i> (2011)
Bidart	n.a.	0.15–0.35	1954–2009	Eocene marls to Triassic muddy sandstones	Slides, rockfalls	Aubie <i>et al.</i> (2011)
Sant Jean de Luz	n.a.	0.10–0.15	1954–2009	Cretaceous marly limestone flysch	Slides, rockfalls, cave collapse	Aubie <i>et al.</i> (2011)
Hendaye	n.a.	0.10–0.15	1954–2009	Cretaceous marly limestone flysch	Slides, rockfalls, cave collapse	Aubie <i>et al.</i> (2011)
<i>Pays de Caux, Haute Normandie</i>						
Bénouville–Le Trèport	0.63	0.006–0.836	1824–1986	Upper Cretaceous Chalk	Slide, rock falls	Henaff <i>et al.</i> (2002)
	0.14	n.a.	1947–1995	Upper Cretaceous Chalk	Rock falls	Costa (1997)
	0.27	n.a.	1966–1995	Upper Cretaceous chalk	Rock falls	Costa <i>et al.</i> (2004)
Cap de la Hève	0.33	n.a.	1517–1667	Upper Cretaceous chalk	na	May & Heeps (1985)
	0.48	n.a.	1824–1904	Upper Cretaceous chalk	na	May & Heeps (1985)
Cap d'Antifer	n.a.	1.33–1.63	1834–1894	Upper Cretaceous chalk	na	May & Heeps (1985)
<i>Bouloinnais–Pas de Calais</i>						
Cap Blanc-Nez to Cap Gris-Nez	n.a.	0.58–5.00	1929–1963	Upper Cretaceous chalk	Rock falls	Siegburg (1990)
Cap Blanc-Nez	n.a.	0.04–0.25	1944–2000	Upper Cretaceous chalk	Rock falls	Lahausse & Pierre (2003b)

However, other authors such as Le Cossec *et al.* (2011) suggest that lithological factors, such as the position of soft or detachment layers control, the geometry of the coast and the shape of cliffs. Bezerra *et al.* (2011) show that, when the distribution of mass movements along the coast is analysed without considering the lithological variation, there is no relationship between the number and displaced volumes of mass movements and wave energy for each sector, with the majority of the movements and the greater volumes occurring in the least energetic sector. On the other hand, lithology and karst features (Moura *et al.* 2006; Nunes *et al.* 2011) coupled with storminess, in terms of both

rainfall and wave energy, seem to be responsible for cliff retreat in southern Portugal. This pattern is less clear for the neighbouring coast of southern Spain, where Del Río *et al.* (2009) and Del Río & Gracia (2009) suggest that the causes of cliff erosion are very complex and spatially varied, with most of the events occurring owing to a combination of wave attack at the base of the cliff and water erosion at upper part of the cliff. Additionally, they identify several examples of intensification of cliff recession by different anthropogenic factors, mainly discharge of surface water and increased load on cliff tops. In the western coast of Portugal, Neves (2008) also stressed the anthropogenic modification



Fig. 6.6. Cliff retreat and rock falls at Cape Roche (Cádiz, Southern Spain).



Fig. 6.7. Examples of prismatic rockfalls at Ericeira (Western Portugal) and cliffs cut in near-horizontal Lower Cretaceous alternating limestones and marls.

in the erosion history of a coastal cliff that resulted in an increase in the frequency and magnitude of mass movements (approximately 34 m in five events).

In northwestern Iberia Peninsula, Pérez-Alberti *et al.* (2009) identify rotational slides, rock falls and cliff collapses. Rotational slides seem related to basic, ultrabasic and schists rocks, as well as sedimentary cliffs. Rock falls occur mainly at intensively fractured granite cliffs and the collapses linked to structurally controlled sea caves. Cliff erosion can be triggered by intensive rainfall episodes, as accounted in the 2000–2001 autumn-winter season (Castillo-Rodríguez & Pérez-Alberti 2002).

Other authors further suggest that large cliff falls also occur in dry weather. Mortimore *et al.* (2004) and Pierre & Lahousse (2006) show that isolated cliff retreats larger than 100 000 m³, such as occurred in 1963 and 1993 at Cap Blanc Nez on the Channel

coast, are not related to rainfall. Others find controls more closely linked to the equilibrium state of the cliff, with high hydrostatic pressure triggering medium- to large-scale rockfalls, where the cliff is unstable. Got *et al.* (2010) or Senfaute *et al.* (2009) examine the micro-seismic signals recorded prior to rock-fall occurrence and stress their role in cliff collapse crisis. Nevertheless some of the examples addressed by Got *et al.* (2010) coincide with temperature falls, rainfall and frost occurrences.

In addition, shore platform downwearing rates measurements show that there are a great number of factors shaping platforms. Foote *et al.* (2006), for the chalk French coast, noted that higher downwearing rates occurred in both autumn and winter and suggest that the higher energy of waves associated with the winter storms enhance platform erosion. Additionally the same authors noted that, in the absence of severe frosts, the chalk

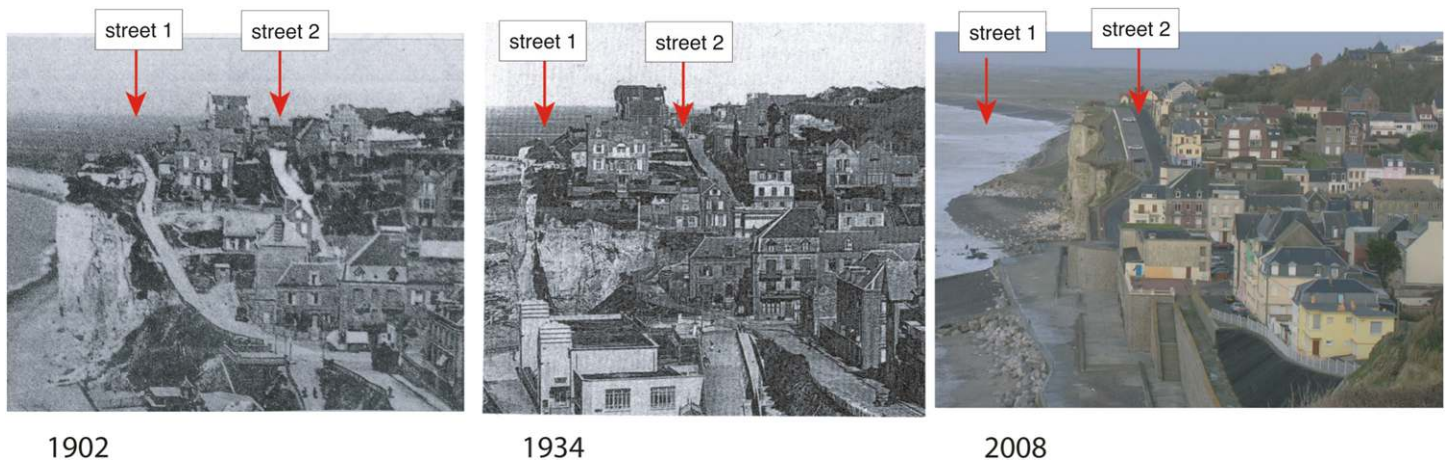


Fig. 6.8. Cliff retreat at Ault, Picardie (France). Note the position of the houses and streets in respect of the cliff line between the historical photos.



Fig. 6.9. Detail on abrasion evidences on shore platform surface at Porto Senin, Oia (NW Spain) related to beach blocks dynamics.

platforms are primarily the result of wave-driven erosion processes rather than subaerial weathering. Blanco-Chao *et al.* (2006, 2007) measured platform downwearing rates ranging from 0.13 to 1.8 mm a⁻¹ and proposed marine-driven processes as the main current platform-shaping agent. Latter studies suggest that abrasion (Fig. 6.9) is a temporally and spatially restricted erosive process that contributes to an increase in bedrock strength and leads to a decrease in the macro-scale roughness of the bedrock surface by means of sweeping and repeated impacts (Feal-Pérez & Blanco-Chao 2013). Moura *et al.* (2012) stressed the role of bioerosion and bioprotection in carbonate platform downwearing. These agents influence, attenuate or increase the effect of wave processes in platform shaping. There is a positive correlation between the volume of burrows from endolithic organisms and the downwearing rates, and inverse correlation with both rock hardness and carbonate content (Naylor *et al.* 2012). Burrows represent a significant alteration in the porosity of the rock, allowing vertical water percolation down to deeper portions of the substrate and therefore deepening and widening the weathering front available to be removed by waves (Moura *et al.* 2011a, b).

The role of the inheritance

Inheritance is a major issue in shore platform studies and complicates both shore platform morphology and processes (Trenhaile 2002). It refers to whether platform and other rock coast features were shaped by higher sea level than the present. Some of the most illustrative and recent studies on this issue have been developed on European Atlantic coasts showing evidence of formation of wide shore platforms in slowly eroding resistant rocks, at levels much higher than the present mean sea-level (Pérez-Alberti *et al.* 1998a, b, c; Blanco-Chao *et al.* 2003). Trenhaile *et al.* (1999) in northwestern Iberian Peninsula show that there would be little reason to state that the intertidal shore platform is entirely contemporary; this is suggested by features such as the occurrence of lichen and plants in the higher portion of the platform and ramp, the abandoned coastal cliffs, the presence of caves or a

cliff–platform junction above the elevations of highest tides, the remnants of beach deposits or dated Weichselian-age sediments on the upper part of the shore platform, and ramp gradients that are too high for the tidal range. These features suggest that the ramp was cut during the period of higher sea level during the last interglacial period, when there was insufficient time to attain a low equilibrium profile, while the rest of the platform was probably cut over several interglacial stages when the sea level was similar to what it is today (Trenhaile *et al.* 1999; Blanco-Chao *et al.* 2003). On the northern coast of France, in northern Boulonnais, Pierre (2007) was able to reconstitute the shoreline framework corresponding to the initial situation previous to the Holocene cliff retreat, through analysis of the distribution of the sub-boreal peat beds behind ancient coastal barriers – now exposed on the foreshore – and the characterization of a cliff-top Late Glacial deposit. Cliffs have been evolving under marine conditions only since the beginning of the Subatlantic and the straightening of the shoreline is of pre-Holocene age. Therefore, the developed fronting shore platforms consist of contemporary, partially inherited or even inherited units.

Rock coast research issues and prospects: a Continental European Atlantic perspective

As deduced from the discussion above, there is an important array of data on cliff retreat and platform downwearing collected for the continental European Atlantic rocky coast, although the length and spatial extent of datasets are less than at other locations with a deep knowledge, such as the English Chalk coast (e.g. Dornbursch *et al.* 2008; Moses & Robinson 2011), New Zealand Kaikoura platforms (Stephenson *et al.* 2010) or the Otway coast in southeastern Australia (Stephenson *et al.* 2012). The continental European Atlantic data focuses on either cliffs or shore platforms and shows significant variation in data collection, spatial scales of the studies and the temporal monitoring extent. Cliff retreat rates (Table 6.1) are usually a measure of the cliff-top edge and few studies address the change in the cliff face (i.e. fall and volume of debris, granular

disintegration); also shore platform downwearing studies focused on micro-erosion meter and TMEM are scarce and the temporal extent is discontinuous. Therefore continental European Atlantic Rocky Coasts contribute to the rock coast science through improving our knowledge of the mode of cliff retreat rather than the velocities and processes of shore platform erosion.

There are then four key points that emerge from our review that can serve as future research questions to be addressed by rock coast geomorphologists. First, there is a general consensus on the role of lithology and rainfall–groundwater in cliff retreat. However, because it is meaningless to extrapolate medium- and short-term retreat rates and patterns of cliff recession, there is no clear evidence on the acceleration–stabilization or deceleration of cliff retreat related to possible changes in storminess.

Second, there is a lack of studies linking cliff retreat and platform downwearing, and present knowledge suggests that at short and medium scales they respond to different agents and processes, stressing the role of subaerial processes in cliff dynamics and marine ones in platform evolution. It is clear from datasets that the rate of cliff retreat is much higher than that of platform erosion, but it is also true that most of the studies have concentrated on TMEM techniques (i.e. vertical erosion component) rather than on shore platform low-tide cliff retreat or meso-scale (i.e. metre-scale) shore platform erosion. However, techniques such as cosmogenic analysis can provide fundamental data on the joint, and not always synchronous, evolution of the coupled cliff–shore platform.

Third, boulder accumulations at the toe of the cliff or in the upper landward sections of shore platforms play a key role in cliff–shore platform retreat–erosion (i.e. Costa *et al.* 2006; Pérez-Alberti *et al.* 2012). These boulders occasionally play a protective role; however, generally they act as an abrasion agent. More research is needed in order to unravel the energy thresholds and hydrodynamics that govern and indicate the role of this agent in shore platform and cliff dynamics.

Fourth, one of the great challenges in continental European Atlantic coasts is the characterization and unravelling of inheritance in shore platform development. Examples in Galicia (NW Spain) and in Boulonnais (France) contribute to the determination of the age of rock coasts and their rate of development in two contrasted types of rock and morphogenic environments. These examples illustrate: (a) that shore platforms were inherited from one or more interglacial stages when the sea level was similar to today; and (b) fairly wide platform surfaces can develop within the few thousand of years of a single interglacial level.

These issues complicate theoretical and modelling approaches to rock coast erosion dynamics, and how to link these approaches with process-based methods that usually involve surveys of short timescales and limited spatial extent. However including recent advances in LiDAR and terrestrial laser scanning in field research, as well as dating techniques such as cosmogenics, could enable us to link shorter timescales with longer modelling and theoretical timescales, and local areas with large-scale studies. In addition, long-term monitoring programmes on both cliff retreat and shore platform erosion can improve our understanding of rock coast agents, processes, dynamics and evolution – especially if these long-term monitoring programmes combine measurements at different spatial and temporal scales and across different morphogenic environments.

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