Chapter 3

Non-Cultural Processes of Site Formation, Preservation and Destruction

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Introduction

The previous chapter described changes of sea level and climate at the global scale with an emphasis on the timescale of the last 20,000 to 120,000 years (Harff *et al.* this volume). Here we look more closely at how a relatively rising, constant, or falling sea level threatens to destroy a prehistoric deposit, and under what immediately local conditions it is likely to survive in a way that preserves information, preferably in the context of its terrestrial landscape, which can be interpreted by archaeologists. Later chapters will describe the coastal and shelf conditions favorable to prehistoric occupation, and the local oceanographic conditions, in different parts of European seas, both during the last marine transgression, and at present, as they determine the real and potential survival and discovery of prehistoric sites.

This chapter addresses the generic problem of how some prehistoric sites and remains on the sea floor are preserved through the vicissitudes of inundation by transgressing surf and subsequent submergence, and why others are destroyed. How do any sites survive in such a hostile environment? Can we predict where they will occur and survive? If we can predict their probable survival, can we find them by scientific or deterministic planned searching? Submerged prehistoric sites have been

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found on European coasts of all types in terms of geology and oceanographic conditions, so can we derive general rules for survival? This is gradually becoming possible, and we make a contribution, based on currently known sites, toward that objective. Predictive modeling has been tried with varying degrees of success and the specific examples will be mentioned in the regional chapters that follow.

Prehistoric archaeological sites and artifacts have been found and identified in the intertidal zone on coastal foreshores, and offshore in deeper water since at least 100 years ago (Reid 1913; Blanc 1940; Steers 1948: 339; Flemming 1968; 1983; Fischer 1995; Benjamin *et al.* 2011; Evans *et al.* 2014; Flemming *et al.* 2014). Since the beginning of proactive searches for submerged prehistoric sites in the 1960s, the question of the favorable conditions for their survival and detection has been a recurrent theme (e.g. Ruppé 1978; 1980; Gagliano *et al.* 1982; Flemming 2002).

Thousands of submerged prehistoric sites are known in the European seas scattered from the beach zone to the outer edges of the continental shelf (Jöns *et al.* 2016). Offshore prehistoric sites are found off all the coasts of Europe, though in very different spatial concentrations. In this book we will examine a small sample of sites in the chapters on regional sea areas, in order to study their geomorphological and hydrodynamic situation, but not to interpret the archaeology. Understanding how and why sites are destroyed or survive on the continental shelf, and their relationship to the surrounding landscape is an essential precursor and accompaniment to archaeological interpretation and will also assist in future discovery, research, conservation, and management.

The cultural significance of this substantial archaeological resource has been considered by Bailey (2011), Benjamin *et al.* (2011), and Evans *et al.* (2014) and the literature cited in those volumes, and the importance of the cultural research on this material will not be considered in any detail in the present work. Suffice it to say that the exposed continental shelf at glacial maxima added 40% to the land area of Europe, and that the human and pre-human occupation of this large land area has a profound impact on our understanding of how the European continent was occupied and exploited by successive hominins throughout the last million years and the origins of early maritime skills and exploitation of marine resources.

The earliest discoveries of offshore prehistoric sites were completely random and by chance (e.g. Burkitt 1932) and it was not until the late 1960s that scholars started trying to understand how and why prehistoric archaeological material survived on the seabed, and how further sites might be discovered by proactive prediction and search (e.g. Emery & Edwards 1966; Harding *et al.* 1969; Louwe Kooijmans 1970-71; Iversen 1973; Wreschner 1977; Fladmark 1975; Bowdler 1977; Ruppé 1980; Skaarup 1980; Masters & Flemming 1983; Pearson *et al.* 1986; Fischer 1995; Pedersen *et al.* 1997).

With the improved understanding of physical oceanography during and after the Second World War, especially in computing the statistics of wave climate and extremes, improvements in seabed acoustic mapping techniques (e.g. Stride 1963; Belderson *et al.* 1972; Fleming 1976; Kenyon *et al.* 1981; Stoker & Bradwell 2009) and a greater understanding of the chronology of Pleistocene glacially-driven sea-level changes (Shackleton & Opdyke 1973), it became possible to envisage purposeful searching for submerged continental-shelf prehistoric sites, and the construction of an integrated interpretation of prehistoric occupation of the shelf. It was optimistically expected that, given an understanding of the kinds of sites that occur in a region on the present land, knowledge of the local oceanographic conditions and wind fetch, a history of past climate change and sea level, and a map of the local continental shelf topography, it would be possible to create computer numerical models that would predict site occurrence, which could then be confirmed by acoustic survey and seabed sampling or diving. This would reduce the costs of search, and reduce the delay in waiting for chance finds. It would also reduce uncertainties, and hence costs, in licensing offshore concessions and the obligation to protect cultural heritage.

This goal has remained as the ideal, and indeed is part of the motivation of the present book. But the achievement of the ideal has turned out to be more difficult than expected in the 1970s and 80s. Predictive models have revealed areas of high probability and low probability for the discovery of sites (e.g. Pedersen *et al.* 1997; Benjamin 2010; Flemming *et al.* 2014: 63-65), but the application of them in a wide variety of coastal environments has not led to a deterministic ability to locate sites accurately. The conditions of the shallow seas in the Danish archipelago have proved uniquely productive of submerged prehistoric sites (e.g. Jessen 1938; Salomonsson 1971; Welinder 1971; Iversen 1973; Skaarup 1980; Andersen 2013) and it has been possible in this case to develop predictive models that save time when divers are searching the seabed. On the Mediterranean coast of Israel, reduced sand supply and periodic storms result in fresh exposures of prehistoric remains which are found by routine repeated surveys. In other parts of the European seas the discovery of exposed artifacts on the seabed or buried landscapes and artifacts in morpho-sedimentary structures has been more variable and problematic, and remains strongly influenced by chance industrial activity and intensive local knowledge of the seabed combined with repeated visual surveys.

The present chapter, indeed this whole book, approaches the problem from a Baconian rather than a Cartesian perspective. If we cannot predict the occurrence and survival of sites from a few logical first principles, can we assemble a mass of empirical data that provides the evidence for a set of useful pragmatic rules? Can we find patterns in large volumes of field data? Such rules or generalizations would show areas of parallel or similar conditions where sites are most likely to survive, and other areas where they are unlikely to survive. In due course, such experience may be used to strengthen rigorous predictive models, which can then be tested against the data and calibrated.

We have the evidence of thousands of sites that do survive (Fig. 3.1) and that have been discovered. While the precise geomorphological conditions have not always been reported, it is possible to see in a general way what conditions favor site survival and discovery. We can learn from this what factors may be important in future improved predictive models.

We are concerned with the empirical facts that describe, or can be deduced from, the processes of burial and survival in the sedimentary column of known archaeological deposits and terrestrial landscapes which have then been inundated by rising sea level. It is tempting to regard this as an extension of the study of taphonomy, which would be a convenient one-word definition of the topic: literally "the science of burial", but the strict definition and usage of taphonomy refers to the conversion of living matter to the fossilized lithic state (Efremov 1940; Lyman 2010), and is regarded as a component of paleontology. It would be unjustifiable to misappropriate this term wholesale, notwithstanding that it is used fairly widely by archaeologists in the general sense of the process of burial and subsequent preservation or deformation of all types of materials including inorganic artifacts. The phrases "site formation" "site formation processes" and "palimpsests" have considerable associated intellectual literature (e.g. Wood & Johnson 1978; Binford 1980; Schiffer 1987; Stein 2001; Bailey 2007; Holdaway & Wandsnider 2008), and it is clear that this concept is close to the concerns of this book. The term "site formation processes" includes the various cultural and behavioral attributes that lead to the deposition and accumulation of material remains in a certain way, or in certain patterns and frequencies, and the subsequent human activities which may disturb the initial deposits through site re-use and the creation of palimpsest effects. The changes after that point are termed "non-cultural site formation processes", and it is only the non-cultural processes that concern us here, although it is obvious that modern coastal and offshore industries can and do disturb archaeological sites. In practical terms, since we know that wave and current action have destroyed many, and probably the majority, of prehistoric sites which once existed below present sea level, the phrase "non-cultural site formation, survival, destruction and discovery" is most appropriate. The word "taphonomy" will be used from time to time as shorthand for this expression provided that no misunderstanding can occur. Where the word "taphonomy" has been used by the authors of other chapters, it has not been altered. At this stage we are concerned only with the mechanistic and sedimentary biogeochemical analysis of how sites survive, or do not, and we are not extending the interpretation to consider the way in which this biases the subsequent state of knowledge about the culture and behavior of the people who created the sites. That bias manifestly occurs and must be considered by others. The large number of seabed sites that have been lost is probably not a random and unbiased sample of all the sites that existed below present sea level. Similarly, in this book,

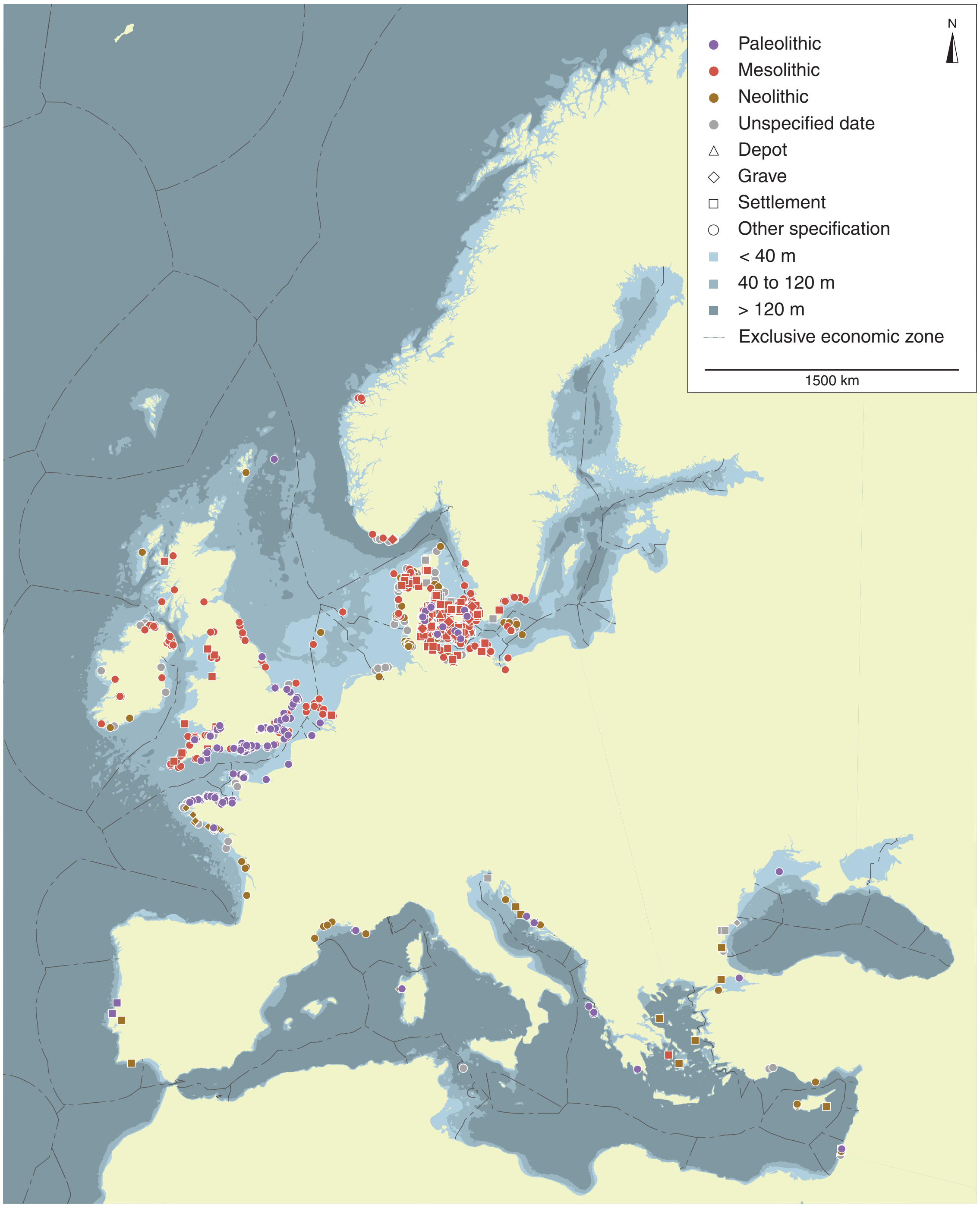

Fig. 3.1 Distribution of submerged prehistoric settlements and artifacts over 5000 years old on the coasts and in the coastal seas of Europe, reported to the SPLASHCOS database. Map courtesy of Hauke Jöns.

we are not attempting to understand or predict the cultural reasons why prehistoric peoples would choose one site rather than another for a settlement, kill site, camp, flint quarry or other activity. We are primarily concerned with understanding how or if a site, once formed, will survive marine inundation, or be destroyed. In addition, by obtaining or measuring the data that allows reconstruction of the terrestrial paleoenvironment, we hope to provide the means to a better understanding of patterns of living, foraging, hunting, mobility, migration, dispersal and adaptation to change.

The regional chapters that follow in this book analyze the geological, geomorphological, and oceanographic processes that are relevant to this problem in each area. Particular prehistoric sites will be referred to briefly, and readers wishing to obtain further details on these sites should consult the SPLASHCOS viewer (Jöns *et al.* 2016).

The sequence within the present chapter will be to examine the following themes:

1. the geology of the continental shelf, its origin, and the present shelf morphology and geomorphic forcing processes;
2. the effect of the sea-level changes described in Chapter 2 on the profile and sediments of the continental shelf;
3. how and why sites survive or are destroyed in the long, intermediate, or short term;
4. site formation and coastal landscapes and processes;
5. diagenesis of deposits in sub-aerial and coastal conditions;
6. case reviews of how sites survive in different example environments;
7. threats to known submerged prehistoric sites.

The Continental Shelf Profile, Landscape, and Factors Determining Site Survival on Different Timescales

The continental shelf is defined as the sea floor and underlying rocks from the coast seawards, having an outer edge and break of slope at a depth of 150 m below present sea level. The continental shelf is a global feature although, in places of rapid tectonic uplift and active or convergent margins, it may be extremely narrow or vestigial. Viewed simply, it is the cumulative effect over many millions of years of the marginal sinking blocks of continental crust and listric faulting on passive or divergent margins and thick sediment layers stacked on top of the sinking blocks by the sediment outflow from eroding and down-cutting rivers, glaciers, ice caps, and coastal erosion. Shepard (1963: 105–174) attempted to explain the origin and form of continental shelves before the development of plate tectonics theory, and provided an excellent descriptive summary, but the mechanism was much clearer once plate tectonic models showed the distinction between divergent margins which are spreading apart or diverging with an expanding oceanic crust area between them, and convergent margins where continental rocks are overriding the subducted oceanic crust or residual marine basins are being eliminated. The processes are summarized briefly by Seibold and Berger (1996: 45–57). A global review of the present state of knowledge of continental shelves is provided by Chiocci and Chivas (2014).

In the European-Mediterranean area both divergent and convergent margins exist and the distinction helps us to understand the extent of land which would be exposed at low Pleistocene sea levels. The Atlantic Margin of Europe from southern Spain to Norway is a divergent margin, spreading away from the Americas, with creation of new oceanic crust at the Mid-Atlantic Ridge. Thus there have been extensional tectonics, the formation of shallow marginal sea basins, and thick accumulation of sediments from the continental rivers, from glacial outwash, and coastal erosion. The result is a broad continental shelf off most coasts and hence a large area that was exposed at the times of glacial maxima and low sea level. In contrast, the Mediterranean sea basin as a whole is convergent and the distance between North Africa and southern Europe is reducing by about 5 mm/year (Sakellariou *et al.* this volume). The crustal response to the convergence and the decreasing distance between two continents is complex at the scale of 100 km to 1000 km, with active mountain building on many

Fig. 3.2 Map of Europe and the Mediterranean showing the continental shelf in gray, defined in this case as having a depth of <200 m. Reproduced with permission from GEBCO.

coasts, increasing depth of central basins, subduction of the relict oceanic crust under island arcs, lateral displacement of microplates, and active faulting and volcanics. The result is a narrow continental shelf on most Mediterranean coasts, typically less than 10 km, with exceptions in the Golfe du Lion, northern Adriatic, north and northwest Black Sea, and the Gulf of Sirte, North Africa (Fig. 3.2).

The topography of the wider divergent-margin European continental shelves is itself complex, although the undulating relief seldom exceeds 10 m to 30 m in amplitude. The average gradient is of the order of 1:1000 (0.1°) over many tens of kilometers, although rock outcrops, fossil beaches and shorelines, sand dunes, glacial moraines, river valleys, and other features can cause local highs and depressions, and even vertical cliffs. Figure 3.3 shows the bathymetry of a typical marginal sea, the North Sea, which is within the northwest European continental shelf. The details of the submerged or buried terrestrial features will be discussed in later chapters.

By contrast, Fig. 3.4 shows part of the continental shelf of eastern Spain (Mediterranean shelf), where a narrow shelf typically 10 km to 20 km wide is dissected by deep-water canyons approaching up to the modern shoreline.

Effect of sea-level variation on the shelf profile

During the last 4 million years the global sea level has been falling from an average position about 25 m to

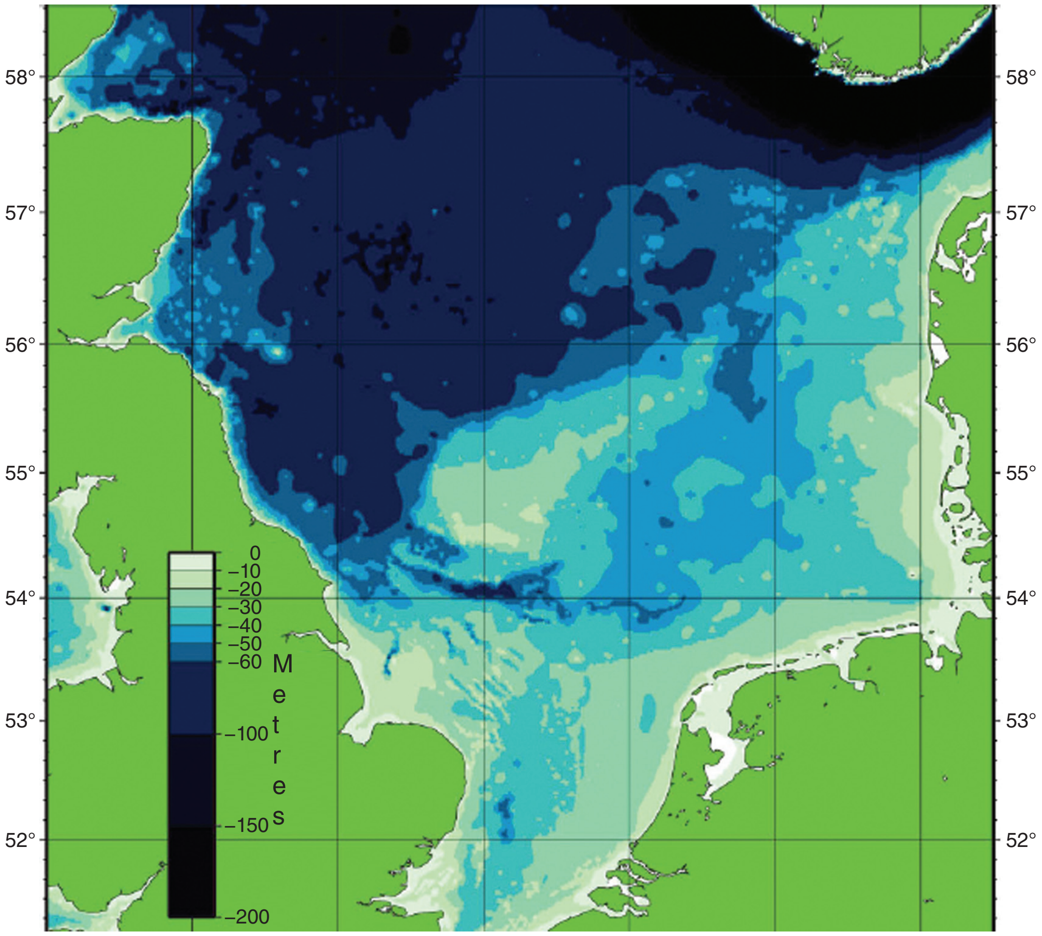

Fig. 3.3 Bathymetry of the North Sea (courtesy Geotek). Note that in the southern part of the sea the depth seldom exceeds 50 m, and that only in narrow depressions. This boundary of amplitude of relief extends over distances of 200 km to 400 km.

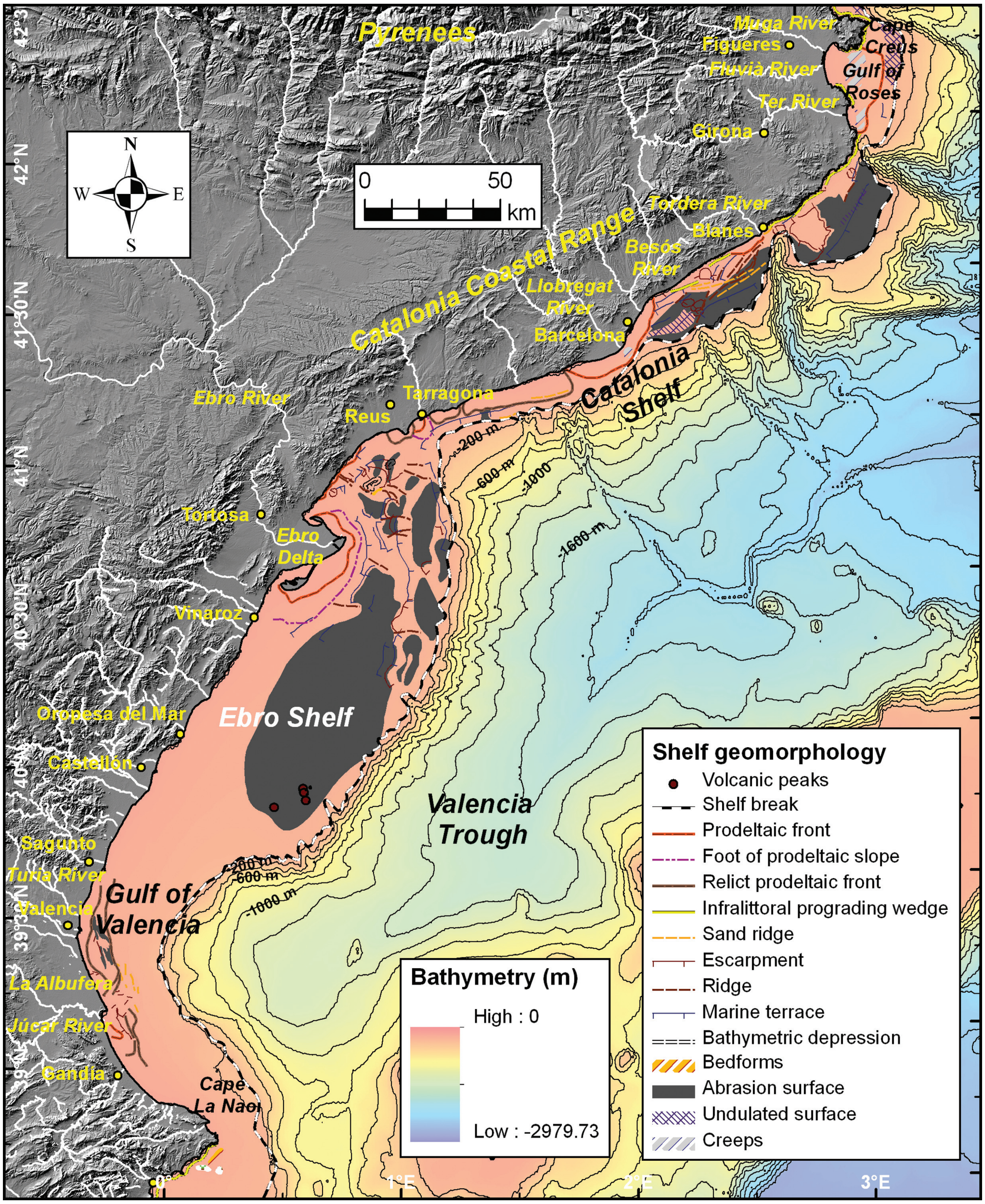

Fig. 3.4 The continental shelf of northeastern Spain, showing a narrow shelf and rapid descent into a deep trough. Lobo *et al.* (2014). Reproduced with permission from the Geological Society of London.

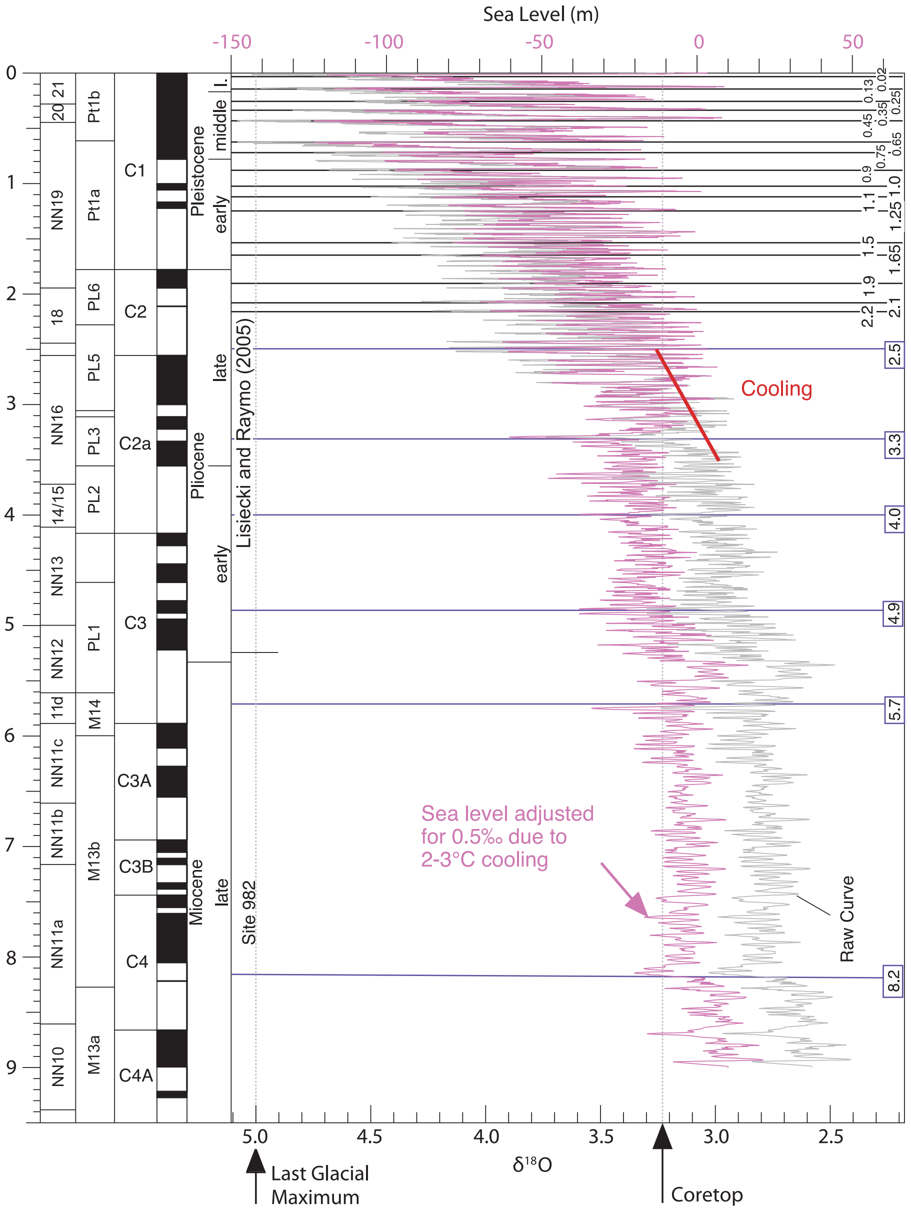

Fig. 3.5 Global sea-level trend for the last 9 million years. Miller *et al.* (2005). Reproduced with permission from the AAAS.

50 m above present sea level to 50 m below present sea level (Miller *et al.* 2005) with an oscillating vertical amplitude of the order of 50 m to 100 m (Fig. 3.5). The early higher levels created terraces and raised beaches and cliffs even in areas which have not experienced tectonic uplift. The larger glacial fluctuations of the last 1 million years, and especially the last 20,000 years, have been analyzed in the previous chapter.

Since the shoreward parts of the shelf and its hinterland above present sea level are generally erosional in origin, with visible cliff retreat in some places, it is logical to expect that almost all fragile features on the currently submerged inner shelf would be destroyed or eroded through time, while those further seawards would be buried by deposits of sediment transported seawards. On timescales of the order of 1 million years or more this is probably true, though fossil animal remains and, theoretically, early hominin traces, could be preserved in drowned valleys and depocenters which have been infilled with many tens of meters of sediments. Pliocene fossils of terrestrial fauna have been recovered by trawlers in the North Sea (Post 2010). Low-lying alluvial coastal floodplains and large deltas also provide environments within which Paleolithic deposits can be preserved below present sea level, either inland, or a short distance offshore.

To an approximation, the total time that the sea level has been between any two vertical intervals can be represented by a Gaussian curve (Flemming 1968) distributed symmetrically about present sea level, which is close to the average for the last few million years (Fig. 3.5) (Miller *et al.* 2005). The more time that the sea has cumulatively occupied a certain level, the further we would expect the coastal process to have eroded landwards relative to the mean gradient envelope of the land surface, taking into account the tectonic nature of the margin. Also, the more sediment would be expected to be transported seawards below the given sea level. This is a close approximation to what we see today, where a low-gradient shelf is incised into the continental gradient with a maximum landward extent at close to present sea level, and an increased gradient above that point.

In order to survive multiple glacial cycles, an archaeological deposit would benefit from originating in an area of gradual subsidence and becoming buried either by rapid or slow sediment accumulation in a depocenter. If the burial is deep, the anthropogenic signal is only likely to be discovered by marine industrial operations. This is supported by the discovery of anthropogenic materials dating from 340 ka (Wessex Archaeology 2011; Tizzard *et al.* 2014) in the sediments of the southern North Sea. Gaffney *et al.* (2007) have shown how re-interpretation of commercial geophysical seismic records can be used to identify sub-bottom buried terrestrial landscape topography, including rivers, creeks, shorelines, marshes, and near-coast islands (Gaffney *et al.* 2007). Sites with Mesolithic and Neanderthal skull fragments have been discovered in the southern North Sea (e.g. Hublin *et al.* 2009). Nevertheless, even this broad generalization has exceptions, and the hand axes found by Bruno Werz in Table Bay, South Africa, have probably survived several glacial cycles while buried in several meters of sand and earth on an open exposed low-gradient shore (Werz & Flemming 2001), and an assemblage of flints off Cap Lévi, near Cherbourg has a date range of 100 ka to 50 ka, suggesting several periods of inundation and re-exposure (Cliquet *et al.* 2011). Another example of long-term survival of hominin remains on the continental shelf outside Europe is the recovery by fishermen of an archaic hominin jawbone from a depth of 60 m to 120 m in the Taiwan Strait, provisionally dated to the timespan 450 ka to 10 ka (Chang *et al.* 2015). Because so few anthropogenic remains have been found offshore older than 100 ka, it has been necessary to include non-European examples to illustrate the conditions. In several of the following chapters on regional sea areas the authors have identified cumulative depocenters offshore where analogous archaeological materials could survive from before the Last Glacial Maximum (LGM).

Assessments of How and Why Sites Survive or are Destroyed in the Long, Intermediate, or Short Term

In general terms it is convenient to discuss the rates of potential erosion and destruction of the coastal zone on three timescales. These are (1) the multiple glacial cycles and stadials of the whole Quaternary with periods of 20,000 years to 1–2 million years; (2) the processes that occur within the fluctuations of sea level and climate in a single glacial stadial and Dansgaard-Oeschger (D-O) events, that is 100 years to 20,000 years; and (3) the processes that occur during periods of approximately constant sea level, from weeks to 100 years, or a few thousand years. The boundaries between these time periods are very flexible, but it is necessary to break the complexity down into manageable time segments, and we recognize that the rates of processes will vary significantly between regions and on differing geological substrates, with different rates of erosion, weathering, and geochemical processes.

The broadest timescale of multiple glacial cycles has been discussed in the previous section, and the number of known sites offshore that have survived for such durations, more than one complete glacial cycle or half-cycle, is still very small. An important systematic methodology for the analysis and interpretation of stratigraphic sequences has been developed by Catuneanu *et al.* (2011) which is useful in understanding the varied structure of the sedimentary accumulations of the continental shelf, but the scale and time resolution of the analysis tends to be in units of many millions of years, making it difficult to appreciate the finer analogous processes that have occurred within the Pleistocene. The section on coastal and shallow water siliciclastic settings (Catuneanu *et al.* 2011: 198 *et seq.*) is the most relevant to geoarchaeology. This approach can be refined, and there is every hope that more sites and drowned landscapes earlier than the LGM will be found, especially during commercial operations that extract sediments from the sea floor, but, for the time being, such finds are sparse.

Effects of coastal and shallow water processes on the timescale of 100 years to 20,000 years

We consider here the timescale which would embrace a stadial oscillation within a glacial cycle, a D-O event, or the deglaciation since the LGM, in terms of how coastal and other marine processes might preserve or destroy anthropogenic material and terrestrial landscapes. We assume that a prehistoric archaeological deposit consists initially of unconsolidated strata of terrestrial deposits, within which hominin/human indicators exist, or a single artifact such as a flint tool or carved antler. Within caves or underground karstic river channels, it is possible for hominin indicators to be cemented to the walls or floor of the cave by speleothem accumulations, or carved into the rock, but this will be treated later as a special case in Chapter 12 and associated Annex (Canals *et al.* — this volume). In most situations the anthropogenic material, before it is inundated, is in clastic deposits of soil, sand, gravel, or cohesive sediments such as mud, clay, or peat. In these cases direct destructive wave attack by waves of the order of 1 m to 2 m significant wave height (H_s) can, in general, partially erode the site with each single breaking wave on an exposed shore. Since H_s can be as much as 10 m in the Mediterranean, and 20 m in the Atlantic, it will be important to analyze how some prehistoric sites or terrestrial soils survive the first storm that strikes their location. This discussion will be conducted later in the section on the shortest time period.

As will be shown in the consideration of short-term processes in the next section, the preservation of sites in the very short term depends greatly on the local topography upon which the sea impinges, the response and behavior of the lateral sediment transports on the coastline, and equilibrium gradient of the shore. Masters and Flemming (1983) showed by reviewing the preserved seabed prehistoric sites known at that date that topographic features such as lagoons, local rock outcrops, small offshore islands, sand spits and barriers, sheltered estuaries, and stable dissipative low-gradient beaches, etc., could provide protection for prehistoric sites in shallow water, or on the beach for many centuries. Thus, in the present section, we need to consider to what extent these defensive barriers and protective shields can be destroyed on a longer timescale.

It is difficult to specify general rates of change and rates of destruction or preservation on this timescale, and complex models would be needed in each specific location to test the propositions put forward here. For example, the rates of change, and the three-dimensional response of a low-gradient sediment-rich coast to rising sea level, are discussed in the previous chapter (Zhang *et al.* 2010; 2011; 2012; Harff *et al.* this volume). But the topographic feature that protects a site could be a massive granite rock ridge, as in the case of La Mondrée, Fermanville, at Cap Lévi near Cherbourg (Scuvée & Verague 1988; Cliquet *et al.* 2011), a low-gradient oceanic sandy beach as in the case of Table Bay, Cape Town (Werz & Flemming 2001) and on the Atlantic coast of Florida (Cockerell & Murphy 1978), a large rocky near-coastal island such as the Isle of Wight protecting the Solent Channel, or a network of postglacial sandy islands, as in the case of the southern Baltic (Lübke 2001; 2002a,b; 2003; Harff & Lüth 2007; 2011; Harff *et al.* 2007).

If the protecting screen is hard rock or a rocky coastal island, the sheltered site(s) could be preserved for more than one glacial cycle. Cohesive mud and clay has proved to be a good preserving medium (Aldhouse-Green *et al.* 1992; Bell & Neumann 1997). If the screen is provided by a sediment gradient, peat, or a sand spit screening a lagoon, ria valley or estuary, the site may be buried and preserved, or a change of sea level could radically alter the sediment supply to unconsolidated landforms, and destroy the archaeology at the same time.

There is a great deal of work and research modeling to be done here. It is worth considering that the processes operating on this timescale are distinct from the effects over many glacial cycles, and from those at the very short term. The latter will be discussed in the next section. On this intermediate timescale, also, prehistoric archaeological deposits need to survive centuries or millennia of exposure to terrestrial weather, precipitation, and geomorphological processes, but these are the same in generic form to those applying to sites found on the present landmass, and will be discussed later only in the context of the coastal environment immediately prior to inundation.

Processes in the short term: weeks to 100–1000 years

It is not possible here to expand in detail on the mechanisms of waves in shallow water, or the different ways in which shoaling waves of different wavelengths impact on coasts of different offshore gradients. These factors are outlined in relatively simple terms in standard textbooks such as Davis and Fitzgerald (2004), and more academically by Holthuijsen (2007). Coastal processes and geomorphology are described in more detail by works such as Carter (1988) and Davidson-Arnott (2010). The point which needs emphasizing and elucidating here is that, in order to survive marine inundation as a primary deposit, an unconsolidated prehistoric archaeological deposit must be protected by natural circumstances to such an extent that the wave forces striking it directly in an erosive manner are very weak indeed, or almost zero. Put bluntly: how does an unconsolidated prehistoric site withstand the impact of the first storm waves that strike the shore at the same level in its neighborhood as the sea level rises? Even if the level is rising at several meters per century, the site will be potentially exposed to the dynamic oscillations of breaking waves for the order of 100 years. A protective situation can be created either by the three-dimensional topographic protection of the coastline preventing large waves reaching the site, or by the offshore gradient interacting with the waves so that their internal water movements are dissipative at the seabed and are not erosive, and the beach+foreshore is in equilibrium, or by longshore drift and beach progradation providing an overlying screen, or bar and lagoon. These processes are often combined. As the shore adjusts geomorphologically to the impact of the rising sea, some sites are preserved by the local response, while another site a few kilometers along the shore can be destroyed by the same regional wind-wave-current regime.

A further way in which this protection can be enhanced is when the archaeological stratum is already buried in several meters of soil, sand, peat or rock-fall before the sea rises over it, and the cover is sufficiently thick that the wave action does not erode down to the archaeological deposit. This certainly can occur, but then it is unlikely that the archaeological material will be discovered until either the overburden is eroded away, or excavation for industrial purposes brings the archaeology to light. Events of this kind include the discovery of the so-called Viking Flint (Long *et al.* 1986); the A240 Paleolithic site (Tizzard *et al.* 2014); the dredging of Early Neolithic material at Port-Leucate harbor, Roussillon, France (Geddes *et al.* 1983); and the dredging of the Yangtze Maasvlakte 2 harbor (Moree & Sier 2014). This possible sequence of events should be borne in mind when offshore industrial activities are being planned.

In the more general case, the deposit is not adequately protected by overburden, and is in direct contact with the surface of the sea or shallow sea water. Even in the most unlikely circumstances, for example Atlantic waves breaking on a rocky foreshore, fragments can be trapped between massive boulders for centuries, as in the case of jewelry from Armada wrecks on the coast of Ireland. At a constant sea level a clastic beach or coastline can reach an equilibrium form which may change slightly with the seasons, or before and after storms, but which remains almost constant for decades or centuries. On a longer timescale, as described above, cliffs may erode, sand spits and deltas build forwards, but archaeological sites in areas which do not suffer massive and constant erosion will be safe, even if they become buried. Masters and Flemming (1983) brought together archaeologists and oceanographers to consider this problem in 1981, and a chapter in that book by Flemming (1983: 135–173) reviewed the 31 submerged prehistoric sites, or suspected sites, known at that time from the published literature. It was apparent from that review (Flemming 1983: 161–163) that a major factor in defining the characteristics of every site was the protective topography of the coastline within a few hundred meters horizontally around the site. All sites were in shallow water, less than 10 m, except for two sites at about 20 m in Florida sinkholes (Murphy 1978; Clausen *et al.* 1979). The favorable sites were classified into six categories: (1) Ria, lagoon, and estuarine; (2) Sheltered alluvial coasts; (3) Exposed equilibrium or accumulating beaches; (4) Submerged sea caves; (5) Karstic caves and sinkholes; and (6) Islands and archipelagos. The common factor in all cases except case (3) is the protection provided by limited wind fetch, with the fetch restricted to a few kilometers or less by the local topography.

There are thus two propositions which seem self-evidently probable on brief consideration, but which are probably unsound, and which need careful checking to see whether they are universally or even sometimes applicable. The first is that given a constant sea level, the majority of, if not all, prehistoric sites will be destroyed quite quickly by a combination of wave action and currents; the second proposition, which is not exactly a correlate of it, but is consistent, is that when a site is transgressed by rising or falling sea level it is most likely to survive if the rate of change of vertical level is rapid.

A striking conclusion from the 1983 review, especially given the debate in recent years about the importance of maximum rate of change of sea level in order to preserve sites, is that all the known open-sea coastal sites known at that date are in very shallow water, in locations where the relative sea level has been constant to within 1 m or 2 m for the last 5000 years. That is, thousands of years of storms at a near-constant sea level had not destroyed them yet, although we cannot know how many sites have already been lost. It is possible that we are seeing some sites in a narrow window between their exposure and subsequent destruction. Repeated observation of some sites has revealed varying rates of continued slow destruction, even in locations sheltered from waves. For example, tidal currents can erode cohesive deposits even when there is very effective protection from large waves, as in the case of Bouldnor Cliff (Momber *et al.* 2012: 261). Seabed vegetation such as eelgrass stabilizes the sediments and reduces erosion, but if pollution damages the vegetation, then erosion increases (Fischer 2011). We can add to the early evidence cited above the results of the SPLASHCOS survey, which is a register of submerged prehistoric sites, using data that had been accumulated for decades previously by local experts (Jöns *et al.* 2016). A large number of prehistoric sites in the SPLASHCOS Database are at present in water shallower than 5 m or are in the intertidal zone, with the waves and tidal currents washing over them every day (Fig. 3.6). As noted above, we may be seeing some sites for a short period between exposure and erosion, but many others appear to be stable in spite of their closeness to present sea level. Since storm waves can cause oscillatory water motion at the seabed down to depths of many meters this analysis includes all sites down to 5 m. The SPLASHCOS Database in March 2014 contained records of over 2400 prehistoric sites, and of these 331 were submitted with the depth information accurately quantified. Of these 331 the number reported as occurring in water shallower than 5 m is 238, that is 71%. Although the database reports a few sites which occur in depths of 20 m to 100 m or more, it is thus apparent that the great majority are in shallow water. Table 3.1 shows the distribution of the 238 sites by country, and they are well distributed in many different climates, geological zones, and environments. Furthermore, the Danish data which describe many sites that are known to be very shallow had not yet been entered in the database.

It follows that an inundated prehistoric site, usually of unconsolidated — although possibly cohesive — terrestrial soils and gravels intermixed with anthropogenic materials, can, in the right circumstances, survive at or close to the sea level, and can survive in this position when the sea level remains constant for several thousand years. If the sea level is rising and coastal and shallow marine sediments are redistributed, this period of initial survival can be followed either by burial or by inundation at a depth and location such that the residual currents and

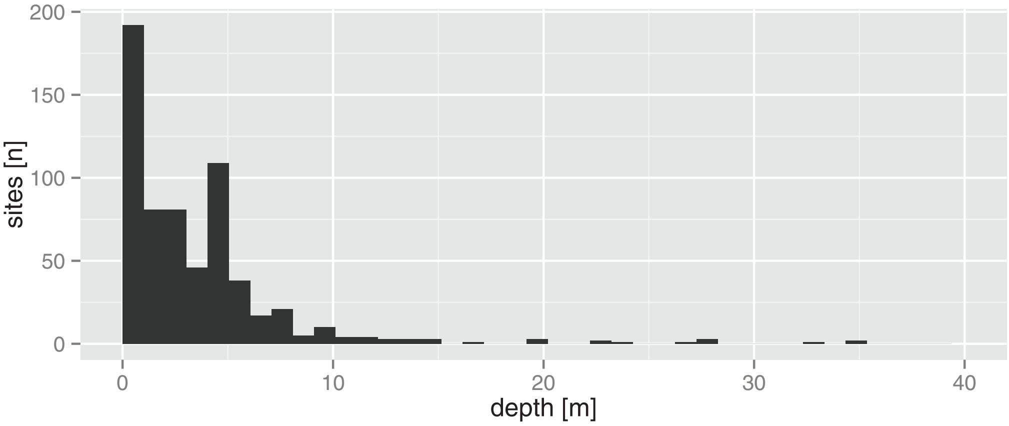

Fig. 3.6 Histogram of the submerged prehistoric sites from the SPLASHCOS Action showing number of sites for which the depth is known in bands of 1 m depth. The number of submerged prehistoric sites for which the depth is known is N = 632. The most common depth band is at less than 1 m, or intertidal, and most sites are shallower than 5 m. The peak in the band 4.01 m to 5.0 m is probably due to the common tendency to pick round numbers. The number of sites at depth 5 m or shallower is 509, that is 80% of the total. Data and graphic from Mennenga Moritz and Hauke Jöns. Reproduced with permission.

wave action are sufficiently attenuated by the topography to ensure survival. While a relatively rapid rise of sea level may not protect sites by sufficiently reducing the time exposed to breaking waves, a rapid rate of rise after transgression may result in rapid burial, which promotes survival in the longer term. The conditions for complete and undisturbed survival are determined by chances of local topography, but the same can be said of the survival of stratified prehistoric sites on land. Some survive, but many are lost. The study of the stability or fragility of known submerged prehistoric sites is now a matter of great interest.

We must assume that many sites are indeed destroyed by rising sea level, or during a constant sea-level stillstand, but the easy assumption that they are all destroyed, and that no site can survive close to a constant sea level, must be rejected. Something other than a rapid rate of change of sea level is providing the additional protection, and this is the complex three-dimensional response of the coast to the forces of waves and tides, as discussed above.

The second common assertion (e.g. Belknap 1983; Belknap & Kraft 1985; Waters 1992; Ballard 2008: 184-185; TRC Environmental 2012) is that, since it is assumed to be obvious that sites at or close to sea level are liable to be destroyed by waves, then it follows that a site is more likely to survive the process of inundation if the sea level is changing quickly, say 2.5 m per century in a peak surge of glacial melting, a meltwater pulse (Stanford *et al.* 2011), rather than the long-term deglaciation average of about 0.6 m to 1.0 m per century since the LGM. The first part of this assumption is often true, though far from always, as shown in the previous paragraphs. The question is, given conditions which do expose a site to erosion during marine transgression, will a faster rate of rise save it from destruction? There is one set of circumstances where this can be correct, and that is where prehistoric deposits are already buried by many meters of overlying terrestrial or later marine sediments, so that the incoming marine forces have to erode a large distance inland and then downwards before damaging the archaeological layer. While the specific quantification of this process will vary from site to site, it is apparent that a deeply buried site could survive for longer, and that a rapid rise of sea level would help survival. However, if a site is that deeply buried, it may not be discovered later when it is also deep under the sea.

In the more general case where an unconsolidated prehistoric deposit is located on the land surface, and the stratigraphic layers are a few meters thick, a single storm wave of a height of 2 m to 5 m striking the deposit would,

TABLE 3.1 NUMBER OF SUBMERGED PREHISTORIC SITES REPORTED WITH A KNOWN DEPTH BELOW MEAN SEA LEVEL (OR BELOW MEAN HIGH TIDE IN TIDAL SEAS), AND DISTRIBUTED BY COUNTRY, AND SHALLOWER THAN 5 M DEEP IN THE SEA.

Country where depth data is available	Sites depth <=5.0m	Total sites (with depth data)
Belgium	3	3
Bulgaria	8	19
Croatia	9	11
Cyprus	0	2
Denmark	83	113
France	74	84
Germany	54	68
Greece	2	2
Israel	17	20
Italy	5	6
Netherlands	0	3
Northern Ireland (UK)	25	26
Norway	17	17
Portugal	4	4
Rep. of Ireland	16	17
Sweden	26	42
Turkey	11	20
UK – England	138	156
UK – Scotland	12	14
UK – Wales	5	5

other things being equal, begin to erode the deposit, and an extensive area could be eroded or scattered within a few years at most. Since the waves can exert erosive force to a depth of several meters, it would be irrelevant whether the site was exposed to the wave action for 100 years of rapid sea-level change, or 500 years of slow sea-level change. The site would be destroyed in both cases. A rapid rate of sea-level rise is therefore not, in most cases, a sufficient factor promoting survival of prehistoric deposits. Cohesive sediments such as compacted mud, clay, or peat may resist erosion for a short while, but on a timescale of hundreds of years do not provide protection.

Rapid vertical rise of sea level cannot of itself significantly increase the chance of a site surviving inundation. However, if it is combined with a low gradient, rapid horizontal transgression of the surf zone, protective topography, and is followed by a prolonged period of shallow-water coastal processes, it does enhance survival. Ballard (2008: 184–185) proposes that a combination of thick overburden and relatively rapid rise of transgressing sea level could achieve this effect. This is a possible scenario, as noted above at the intermediate timescale. Indeed, the proposition in the previous section is that the structural protection provided by landscape coastal forms will survive for longest if it is not attacked repeatedly at slightly different levels over tens of thousands of years. This is another way of saying that the survival is more likely if the sea level does not keep re-occupying the same vertical interval, creating an integrated and cumulative level of destruction, and passes it by with a rapid rate of change relative to the intermediate timescale.

The apparently simple proposition that sites are most likely to survive during the phases of the post-LGM rise of sea level that were most rapid has not yet been put to the test, and there are difficulties in establishing such a correlation empirically. The two most cited periods when rapid rise might lead to well-preserved prehistoric sites are Meltwater Pulses 1A and 1B at approximately 90 m depth 15,000 years ago, and 50 m depth 11,000 years ago respectively (ignoring local glacio-isostatic adjustment and local tectonics). As demonstrated above, very few sites have been found deeper than 50 m, and the population density in the Paleolithic was probably much lower than in later periods. Thus the chances of acquiring the statistical sample to demonstrate this assertion are poor. The implications of rate of rise of sea level are discussed by Belknap and Kraft (1981; 1985), and by TRC Environmental Corporation (2012: 20 *et seq.*), but the significant effect of local topography is also recognized.

It follows from this preliminary discussion that for most prehistoric sites in most locations, the apparent coincidence of the sea level and the site deposit for a given time, longer or shorter (on this timescale), is not the defining factor in survival or destruction. Other combinations of factors create the protective screen that ensures that a surprising number of sites do indeed survive for many thousands of years close to a constant sea level. As we have shown, those factors are the local coastal topography, refraction and diffraction of wave energy, gradient of land or gradient of the beach, the offshore seabed gradient, the fetch over which the wind can blow straight onto the site, and a variety of other site-specific characteristics which can, almost counter-intuitively, allow one site to be protected for millennia, while destroying another nearby site in a year or less.

One of the most common formulae for assessing the quantitative effect of rising sea level is the application of the Bruun Rule (Bruun 1962). This suggests that, as the sea level rises, the sediments at or just above the sea level are eroded and deposited down-slope, according to a simple formula, and a new beach gradient established. If this were universally true, no prehistoric deposits would survive transgression, unless very deeply buried. In contrast to the over-simplified Bruun Rule, quantification of coastal geomorphological changes must be based on three-dimensional source-to-sink transport models. The two-dimensional Bruun Rule neglects longshore transport and should not be recommended for the purposes of this book. An alternative to the Bruun concept was given by Deng *et al.* (2014) with the so-called Dynamic Equilibrium Shore Model (DESM). The basic concept of the model is a dynamic equilibrium of the coastal cross-shore profiles adapting to sediment mass balancing in a semi-enclosed coastal area, in which the unknown parameters of the cross-shore profile shapes are calculated by numerical iterations.

The discussion above has already cast doubt on the automatic assumptions implied by the Bruun Rule. At this point it is worth quoting fully (with the authors' permission) the abstract from a paper by Cooper and Pilkey (2004). It is difficult to state the case more succinctly or effectively:

> *In the face of a global rise in sea level, understanding the response of the shoreline to changes in sea level is a critical scientific goal to inform policy makers and managers. A body of scientific information exists that illustrates both the complexity of the linkages between sea-level rise and shoreline response, and the comparative lack of understanding of these linkages. In spite of the lack of understanding, many appraisals have been undertaken that employ a concept known as the "Bruun Rule". This is a simple two-dimensional model of shoreline response to rising sea level. The model has seen near-global application since its original formulation in 1954. The concept provided an advance in understanding of the coastal system at the time of its first publication. It has, however, been superseded by numerous subsequent findings and is now invalid.*
>
> *Several assumptions behind the Bruun Rule are known to be false and nowhere has the Bruun Rule been adequately proven; on the contrary several studies disprove it in the field. No universally applicable model of shoreline retreat under sea-level rise has yet been developed. Despite this, the Bruun Rule is in widespread contemporary use at a global scale both as a management tool and as a scientific concept. The persistence of this concept beyond its original assumption base is attributed to the following factors:*
>
> 1. *appeal of a simple, easy to use analytical model that is in widespread use;*
> 2. *difficulty of determining the relative validity of 'proofs' and 'disproofs';*
> 3. *ease of application;*
> 4. *positive advocacy by some scientists;*
> 5. *application by other scientists without critical appraisal;*
> 6. *the simple numerical expression of the model;*
> 7. *lack of easy alternatives.*
>
> *The Bruun Rule has no power for predicting shoreline behavior under rising sea level and should be abandoned. It is a concept whose time has passed. The belief by policy makers that it offers a prediction of future shoreline position may well have stifled much-needed research into the coastal response to sea-level rise. (Cooper & Pilkey 2004:157).*

The data and discussion of the previous sections of this chapter are compatible with the position taken by Cooper and Pilkey (2004). Furthermore, the statement by Cooper and Pilkey is consistent with the approach to numerical modeling of coastal geomorpho-dynamics

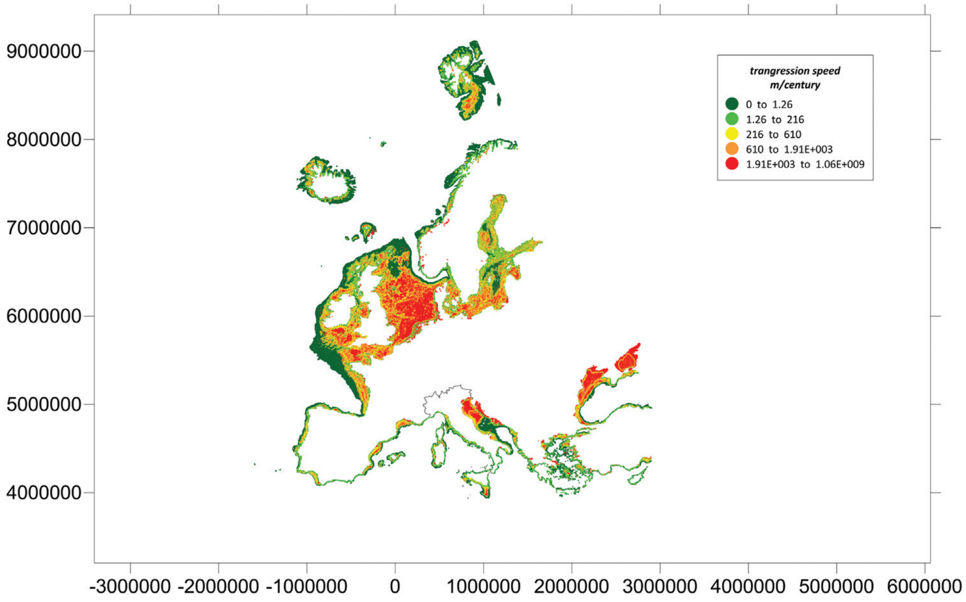

Fig. 3.7 The rate of horizontal transgression of the rising sea level post-LGM in meters/century is obtained by computing the gradient of the region and the rate of rise of sea level. The gradient also determines wave characteristics in shallow water and the rate at which sediments can be transported down-slope. Graphic by F. Chiocci is fig. 2.10 from Flemming *et al.* (2014).

summarized in Chapter 2 (Zhang *et al.* 2010; 2011; 2012; Harff *et al.* this volume).

The significance of seafloor gradient and rate of transgression of the rising sea level is shown in Fig. 3.7. The plot is obtained by combining the generalized curve for relative rate of rise of sea level with the local average gradient to produce the rate of horizontal transgression in meters per century. The variation in local gradients from near-vertical to near-horizontal has a dramatic effect on the rate of horizontal transgression. After marine transgression, during sea-level rise over a low gradient, a prehistoric site will be located in a shallow-water environment, and potentially sheltered by local undulations of the topography. During sea-level fall, those conditions will apply when the water is shallow before the site is exposed to the terrestrial conditions, and after exposure the site will be in a low-gradient landscape, and hence probably low rates of terrestrial erosion. The majority of sites reported to the SPLASHCOS Database (as shown in Fig. 3.1) are concentrated in the areas of low gradient and sediment accumulation. Relatively fewer sites have been found so far on the coasts of steeper gradient, although this is partly due to the necessary correlate that the total area of submerged shelf is small. The potential for discovery of sites on a steep rocky shelf is further reduced by the fact that deeper water necessarily means an older site, extending back into the Paleolithic, when population densities were probably lower, and hence fewer sites are likely to have existed before inundation. The strip within which Mesolithic and Neolithic sites could have existed is generally less than half the shelf width on a steep gradient.

Site Formation and Coastal Landscapes and Processes

Geomorphological processes on the shore and close to the coast combine with wave and current action to generate changes and forces tending to destroy or bury prehistoric sites. Processes will be described very briefly. We consider in sequence:

high latitude rock weathering
glacial erosion and transport
high latitude, eolian erosion and transport

mid latitude rock weathering
fluvial erosion and transport
early diagenesis
substrate and coastal physiography

High latitude (>50°N) rock weathering

In high latitudes the physical weathering of rock largely dominates in comparison to chemical weathering. Frost weathering is a common mechanism where temperature frequently falls below zero °C. Discontinuities like pores, cracks, joints and bedding planes make it easy for water to penetrate, and ice wedgings go deep into the rocks. Hence, a large amount of sediment is produced due to the rock breakdown. This mechanism is more efficient where successive freezing and thawing occurs due to seasonal or diurnal temperature contrasts. The amount of sediment produced by frost weathering that is then available to be eroded and transported depends on the geological substrate. Physical weathering is more effective in coarse textures (e.g. granite, gneiss) than in fine textures like basalts (Konishchev & Rogov 1993; Schaetzl & Anderson 2005). For instance, the breakdown of the very old and deformed crystalline rocks of the Baltic Shield produced a remarkable volume of detrital sediment throughout the Quaternary. Those glaciogenic sediments are currently exposed in the cliffs of the southern region of the Baltic basin and cover the Baltic Sea floor (where they also occur as eskers) and on the eastern margin of Scotland.

In contrast, the weathering products of chalk are very different from the granular disintegration of the crystalline rocks. Chalk texture is also vulnerable to frost weathering and furthermore, the landscape morphological features tend to be preserved as a fossilized surface. This is because secondary porosity is developed into the chalk due to frost action and the water infiltration is then higher than surface runoff so that the valleys become dry with no fluvial erosion. This is observable in the chalks along the English Channel (French 2007).

Thermokarst is a process of thawing of permafrost in high latitude regions and was developed on the continental shelves of periglacial areas during the LGM marine regression. It then influenced coastline evolution during the Holocene transgression. Thermokarst geoforms such as lakes and depressions formed ca. 11 ka to 8.5 ka and evolved into coastal lagoons leading to the development of an indented coastline physiography during the Laptev Sea shelf flooding (Romanovskii *et al.* 2000).

Glacial erosion and transport

The Quaternary glaciations were mainly a Northern Hemisphere phenomenon and ice sheets extended far southward in Europe during the LGM, covering the Norwegian continental shelf and part of the North Sea basin (Williams *et al.* 1993). Glaciers have larger transport capacity than rivers due to the greater viscosity of ice relative to water in liquid phase. As a consequence, glaciers transport large amounts of heterometric material from boulders to mud. However, the distance of the glacier transport, up to tens of kilometers, is less than that produced by rivers. Glaciers drain regions where snow accumulates and since they attain either altitudes or latitudes where temperature lies below the freezing point, the coarser sediments deposit in a chaotic way (moraines). Glaciers may reach continental margins where the deposits may potentially accumulate, either as submerged glacial features, or so as to construct paleoshorelines. Submerged moraines, drumlins and eskers are morphological features related to glacial activity and their occurrence, dimension and orientation on northern shelves are good proxies for paleocoastlines. Drumlins and esker genesis relate to changes in the net ice flow and drainage under the ice respectively, with the former being parallel to the ice flow. Thus, when occurring underwater as are the eskers reported in the Baltic Sea, they mean that the region was exposed during previous glacial times and this can be used to facilitate reconstruction of the coastal landscape. The evolution is determined by the successive glaciers as they retreat and spread. However, moraines are successively eroded, transported and deposited, making it often difficult to establish clear relative chronologies. Large amounts of coarse fluvio-glaciogenic sediments transported onto the exposed shelf during the LGM formed a barrier complex during the postglacial sea-level rise and may be preserved to survive wave erosion, as happened in the northeastern English Channel (Mellett *et al.* 2012).

Eolian erosion and transport

Wind was an important geomorphic agent during the Pleistocene cold events, acting over unvegetated surfaces on the exposed shelves in periglacial areas during the LGM low sea level (Lowe & Walker 1984). Chalk outcrops along the English Channel are veneered by loess accumulated mainly during the last glaciation (French 2007). Silt blown by the wind in periglacial arid regions is entrained from glaciogenic deposits like eskers, braided channels, glacial outwash plains and lake shores (van Huissteden *et al.* 2001; Dietrich & Seelos 2010). Sand dunes or sand sheets in cold dry environments as in the southeastern Netherlands were deposited during the Mid and Late Pleistocene between ca. 14 ka and 12 ka during the permafrost degradation and increased aridity (Kasse 1997). Submerged beach deposits off the coast of Normandy and Brittany in depths of 50 m to 90 m and as far out as the Hurd Deep consist of conglomerates cemented by loess (Antoine *et al.* 2003; Murton & Lautridou 2003; Lefort *et al.* 2011; 2013). The majority of the more widespread distribution of loess which blew south from the English coast onto the floor of the English Channel has been eroded by the rising sea level since the LGM.

Mid latitude (50°N–30°N) rock weathering

Rock weathering in mid latitudes includes all the weathering mechanisms both chemical and physical, and the extent and rate are highly dependent on the substrate properties and climatic conditions. These show high variability influenced by several variables, among them the distance from the sea, and the relationship between the dominant wave direction and the elevation, orientation and topography of coastal mountains. Karstification in carbonate rocks is the paradigmatic example of the relationship between lithology and weathering process. Dissolution acting in limestone and dolomite leads to the development of dissolution landscapes. Karstic landscapes may have great social impact due to the lack of surface drainage and patches of soil, which are formed by the insoluble residue (sand, silt and clay) of carbonate rocks confined inside solution cavities. Karstic caves provide attractive refuges and were successively over time occupied by human and animals. Nevertheless, detrital load transported by streams traversing limestone and dolomite lithologies does not represent an important sedimentary contribution to continental shelves since the major component of these rocks (Ca^{2+}) is highly soluble. On the contrary, karstic landscapes act as a trap for detrital sediment in karstic depressions and underground conduits. During high discharge events those sediments may be transported by subterraneous streams and reach the coast. Coastal karst is successively fossilized and exhumed due to mean sea-level variations and, during erosional phases, large amounts of detrital sediment contribute to feed the adjacent beaches and shelf. Rocks of phaneritic texture like granite and gneiss vulnerable to hydrolysis provide large amounts of detrital sediments to be transported by rivers.

Fluvial erosion, transport and coastline evolution

Fluvial landscapes are the most widespread in mid latitude areas, and continental margins are the main reception areas of the materials eroded from the mainland. The thickness of the sedimentary coverage of the continental shelves is a balance between the sedimentary input, the marine climate and the space for accommodation (Catuneanu *et al.* 2011), the latter governed mainly by tectonics and sediment compaction. Some detrital sediments over the shelves are inherited from past lowstands of sea level in areas where the contemporaneous fluvial sedimentary load is insufficient to cover them. Moreover, the shelf morphology together with the sedimentary input to the coast determines the coastline position. As a result, for the same uniform global changes of sea level, the coastline behavior and evolution are highly dependent on several variables other than the sea level.

The thickness of detrital sediments transported onto the shelf has a dual role in the preservation of human remains and landscape structures. When the deposition rate is high, both structures and traces of human activity are quickly buried, thus becoming better protected from erosive processes such as wave and current action later. However, the thick sedimentary coverage hinders both their detection and recovery. This aspect is well illustrated in the Danube Delta where, due to the combined effect of the delta subsidence and the high sedimentation rate, the Late Prehistory layer should be now buried at depths greater than 4 m to 5 m (Dimitriu 2012). The thickness of sediments accumulated during the Pliocene and the Pleistocene epochs increases eastwards from 100 m in the Danube Delta proximal area to 1 km in its deep-sea cone (Dinu *et al.* 2005). Thus, the compaction of such thick sedimentary sequences may cause the subsidence of the delta, which in turn influences the regional relative mean sea level. Detrital sedimentary input may be a first order factor in determining coastline evolution of confined sea basins. This is well illustrated in the Black Sea, a marginal sea that receives the massive sedimentary load of rivers draining the Alpine orogenic chains, among them the Danube, the Dnieper and the Don (e.g. Winguth *et al.* 1997; Dinu *et al.* 2005; Dimitriu 2012; Rosyan *et al.* 2012). Similarly, the semi-enclosed Mediterranean basin exhibits several environmental indicators favorable to the preservation of morpho-sedimentary features underwater, such as its marine climate, sub-aerial climate and sedimentary input from the drainage basin catchment area.

The perisutural basin of the Po River Plain that received the drainage from the Alps and Apennines is filled by up to 800 m of sediments accumulated during the Pliocene and Quaternary, from which up to 40 m thickness accumulated during the last ca. 19 kyr (Dinelli *et al.* 2012). Large amounts of sediments from the Po Plain on the Adriatic sea shelf led to the formation of barrier-lagoon systems, which migrated landward during the postglacial sea-level rise, and two of those barrier-lagoon systems are now submerged and preserved due to a rapid sea-level rise (up to 60 mm/year) and a marine climate different from the present (Storms *et al.* 2008). The coastline was ca. 20 km to 30 km landward from the present one at ca. 7 ka during the maximum Holocene transgression. After that maximum transgression, the sea-level rise decelerated and the large amount of sediments transported by the Po River led to the seaward migration of the coastline due to delta progradation (Amorosi *et al.* 2003). This trend still continues at least since 1600 AD with different migration rates and some episodes of landward migration (Marabini 1997). Thus, while the global trend of the coastline is landward retreat (until reaching a geomorphic limit) in response to the mean sea-level rise, in areas with strong sedimentary input to the coastline the trend can be in the opposite direction. Morphosedimentary bodies like sand bars, barriers and dunes formed on the continental shelves due to strong sedimentary supply may be preserved depending on marine conditions, rate of sea-level rise and early diagenesis.

Early diagenesis

The underwater genesis and preservation of morpho-sedimentary bodies has several requisites: (1) sediment available to be transported by waves, currents and wind to form spits, barriers and dunes; (2) rapid sea-level rise and; (3) early diagenesis of the sand. The combination of these environmental variables is identified as responsible for the preservation of submerged shorelines even on a steep and high-energy shelf (Salzmann *et al.* 2013). Although early diagenesis is often reported as restricted to subtropical conditions (Salzmann *et al.* 2013), it may occur in temperate climate at mid latitudes showing marked seasonality depending on the carbonate content of sands e.g. Cornwall, UK (Howie 2009), the Bay of Biscay (Arrieta *et al.* 2011), and the Algarve in southern Portugal (Moura *et al.* 2007; 2011).

Sandstones of high content of carbonate (up to 80%) both from shells and from erosion of the adjacent carbonate rocky cliffs occur submerged in the southernmost continental shelf of Portugal forming a series of paleo-spit bars and barriers roughly parallel to the current coastline (Infantini *et al.* 2012). During glacial sea-level falls and continental shelf exposure to aerial conditions, sandy bodies (barrier, beachrocks and eolianites) were rapidly cemented due to the high content of calcium carbonate and the well-marked seasonality. The high porosity of the sand allows an easy circulation of fresh water during the wet season and the consequent dissolution of the carbonate fraction. During the hot and dry season the water evaporates rapidly and therefore carbonate precipitates as chemical cement leading to the formation of carbonate sandstones (Arrieta *et al.* 2011). Cementation of beach sands may be as rapid as within 30 years, potentiated by biological activity, such as that reported in Corsica on an artificial shore produced by debris discharge of asbestos (Bernier *et al.* 1997). However, beachrock should be used carefully as a proxy for reconstruction of coastlines because of the rate of sea-level variations in macrotidal sites where tidal range can reach several meters. Eolianites may also be used to reconstruct paleocoastline evolution based on the variation of the sand recruitment area to form dunes (Moura *et al.* 2007).

Eolian dunes accumulated extensively over the Northern Hemisphere continental shelves during the cold and dry climate anomalies of the Younger Dryas and the 8.2 ka Event (Alley & Ágústsdóttir 2005 and the cited literature). Like beachrock and sandy barriers, eolianites may also be preserved underwater and the potential for preservation is directly correlated to the rapidity of diagenesis and sea-level rise.

Substrate and coastal physiography

Rocks are metastable phases that undergo weathering when exposed to sub-aerial conditions. Landscapes evolve more or less rapidly depending on the climatic conditions and substrate. Carbonate rocks are extremely vulnerable to chemical attack producing typical karstic landscapes where caves are frequent. Wet conditions, joints, faults, crevices and thin bedding layers favor the genesis of karstic caves. Caves are propitious morphological features to preserve human remains on land, often close to the coast, and many archaeological sites have been reported in karstic caves on land (e.g. Joris 2002; Ontañón 2003; Karkanas *et al.* 2007; Carrión *et al.* 2008; Kuhn *et al.* 2009; Nakazawa *et al.* 2009). However, the preservation and discovery of prehistoric material in submerged karstic environments has been problematic (see, for example, the discussion of this subject by Billaud in Canals *et al.* this volume, Annex, and Flemming and Antonioli (2017)). The sub-aerial evolution of karst includes the collapse of dolines and caves to produce karstic breccias, and several archaeological remains have been found within breccias resulting from cave collapses (e.g. Yeshurun *et al.* 2007). Besides karstic landscapes being the most favorable geomorphic context to produce caves, several other lithologies other than carbonate ones can produce caves or at least small cavities if affected by fractures or eroded dikes and sills.

Karstic aquifer behavior (porous and fractured) permits the influx of large amounts of fresh water to the coast conducted through galleries or fractures, producing freshwater springs in the marine environment. For instance, in arid or semi-arid regions such as the Mediterranean basin and Atlantic south Iberian coast, karstic aquifers represent the main groundwater drainage network (PNUE 2004). This process should play an important role in providing freshwater resources on the exposed continental shelf during lowstands. Whereas freshwater tables fell on the continental areas as a consequence of relative mean sea-level (RMSL) fall and climatic aridity, the availability of surface fresh water increased on the emerged shelf (Faure *et al.* 2002).

Differential erosion producing different types of topographic relief is very frequent in carbonate landscapes due to the occurrence of conspicuous outcropping harder dolomites relative to mechanically and chemically less resistant limestones and marls. Coastal promontories are often sculpted around dolomites more resistant to wave attack whereas bays are cut into softer limestones. This leads to a highly crenulated coastline physiography as on the southern coast of Portugal, where waves and littoral current propagation show a strong morphological control (Bezerra *et al.* 2011; Moura *et al.* 2007; 2011; this volume; Horta *et al.* 2013; Rocha *et al.* 2013).

Crenulated coasts provide a geomorphic context which favors the genesis of spit bars anchored in headlands and, in warm Mediterranean climates, beachrock in the more sheltered bays. Headlands are natural obstacles to longshore drift and sediments are deposited downdrift due to current deceleration (Jackson *et al.* 2005; Backstrom *et al.* 2009; Jackson & Cooper 2010; Silva *et al.* 2010). Beach behavior within a headland-beach system is of fundamental interest for coastal evolution since it represents a buffer to wave attack on the backing cliff (Benavente *et al.* 2002). In these various ways the nature and structures of the substrate have a major influence on coastal processes.

Selected Case Examples

It is not practical to provide an exhaustive set of geomorphological examples for how sites have survived in different locations for different periods of time. More examples and types of prospective location will be described in subsequent chapters. The following selection provides brief geomorphological data on sites in increasing age.

Golfe du Morbihan, Brittany, France, 5000 BP to 4500 BP

Standing stone circles occur on the shore of the island of Er Lannic in a massive flooded ria bay. The lowest standing menhir is situated about 6 m below mean high water spring (MHWS), with very restricted wind fetch, but high tidal range (Giot 1968; Giot *et al.* 1979; Prigent *et al.* 1983: 307; Cassen *et al.* 2011).

Pavlopetri, southern Greece, 5000 BP

At Pavlopetri (Harding *et al.* 1969; Henderson *et al.* 2011), there are 8 hectares of well-preserved Early Bronze Age ruins dated 5000 BP to 3000 BP that have survived on the sea floor sloping down from the beach to a depth of over 3 m, and probably associated with a shoreline at –5 m. The location of the town is at the head of the large Bay of Vatika, which is screened in all directions from maximum storm-fetch waves by headlands and islands, so that the maximum wave height reaching the location is less than 2 m, based both on local observation and numerical wind-wave refraction+shoaling models. A submerged ridge of fossil eolianite dune curves out from the shore, breaking the surface at several locations, and terminating in the island of Pavlopetri, which is about 80 m × 50 m in size. The submerged town is in the triangular sea area between the ridge and the present shoreline. Wave action within this sheltered zone is very limited, seldom exceeding 0.5 m in amplitude and with short wavelength. Moving bands of seabed sand banks have covered large parts of the town at different dates in the last 45 years, and the exposed areas seem to be increasingly damaged by boring species and corrosion. The topography has protected the ruins to an extraordinary degree, but biological action and casual souvenir collecting by tourists suggests that the site may be unrecognizable in another hundred years.

Southwest Baltic, Danish and German coasts

Many hundreds of submerged prehistoric sites have been found with the earliest settlements about 8000 years old (Fischer 1995; 2002; 2011; Lübke 2002a,b; 2003; 2004; Harff & Lüth 2011; Jöns 2011; Lübke *et al.* 2011). The Baltic as a whole is sheltered from Atlantic oceanic storm waves, and has minimal tides. The southwest Baltic archipelago further restricts wind fetch to a few kilometers, and sites studied on the sea floor were usually protected by islands, sand banks or peninsulas, now submerged, before site inundation. Re-working of the coastal sediments during sea-level rise further protected some sites, while eroding others. Freshwater conditions have preserved wooden objects such as tool shafts, canoes, paddles, fish weirs, and hut posts.

Western UK and Severn Estuary, 8000 BP to 6000 BP

The intertidal mudflats of western England have revealed a wide range of prehistoric materials and imprints of Mesolithic to Bronze Age origin, 8000 BP to 6000 BP (Aldhouse-Green *et al.* 1992; Bell & Neumann 1997; Bell 2007). The finds include human footprints of children and adults, and the hoof-prints of cattle, sheep and pigs as well as wooden remains, trackways, posts, and fish traps. The substrate is laminated silt that retains fossilized seasonal variations, overlain by mobile layers of soft mud and sediments that are partially eroding. The gradients are extremely low, and the archaeological signals survive in spite of the high spring tidal range of 14 m and exposure to storm waves from the west.

Atlit-Yam, Israel, Pre-Pottery Neolithic, 8000 BP

The stretch of coast between Dor and Haifa is bordered by calcified eolianite dune ridges known as *kurkar* which are closely parallel to the shore, both on land and offshore (Galili *et al.* 1993; 2004). The offshore kurkar ridges have protected the settlements from wave action on the site during inundation, and the remains were subsequently buried by the longshore drift of sand supplied by the Nile River. Mid-twentieth-century damming of the Nile has reduced the sand supply, so that Early Neolithic villages are now being exposed in water depths of the order of 10 m to 15 m. Local fishermen, and professional and amateur diving archaeologists inspect the shallow seabed frequently to detect remains revealed after storms. Finds include hearths, charcoal, human burials, freshwater wells, hut foundations, food remains, and other organic materials.

Bouldnor Cliff, Isle of Wight, UK, 8000 BP

The submerged Mesolithic site is at a depth of 11 m on the north shore of the Isle of Wight, protected from the storm waves of the English Channel and the wind-wave fetch from the Atlantic to the south-west by a narrow channel. The Solent is 4.5 km across in the region of the site so that locally generated wind waves are limited. There are strong tidal currents which continue to erode the archaeological strata which are embedded in peat and clay. The site has been monitored for 20 years so that the erosion is documented (Momber 2006; Momber *et al.* 2012). The archaeological remains include timbers, cut wood, worked lithics, string, a hearth, and seeds of grain.

Rotterdam Port, the Netherlands, North Sea, 30,000 BP to 10,000 BP

During the extension of Rotterdam port known as Yangtze Maasvlakte 2, layers of alluvial sediments 10 m to 20 m thick were dredged out of the coastal waters of the North Sea, and Mesolithic and Paleolithic remains up to 30,000 years old were identified and partially recovered (Weerts *et al.* 2012; Moree & Sier 2014). Site distribution was reconstructed on the buried dune ridges. This extensive project confirms both the concentration of prehistoric Mesolithic communities on the estuarine and deltaic dunes, adjacent to marine and freshwater resources, and the potential for preservation of such sites as they were deeply buried in deltaic sediments during sea-level rise.

Cap Lévi, Anse de La Mondrée, France, 100 ka

Paleolithic flint artifacts were recovered in the late 1970s by divers on the east side of the granite ridge and rocky islet known as Biéroc, projecting from Cap Lévi near the village of Fermanville, east of Cherbourg (Scuvée & Verague 1988). Subsequent analysis of the lithics and dating of sediments has shown that the site at a depth of 18 m to 20 m was occupied sporadically between approximately 100 ka to 50 ka (Cliquet *et al.* 2011). Collections of flint cores, worked tools, and débitage show that flints were knapped on the site. The tidal currents reach speeds of 5 knots, but the high granite ridge prevents scour at the seabed, and equally protects the deposits from the wind waves and Atlantic storms driven in from the west.

A240 concession, East Anglia, UK, North Sea, 300 ka to 250 ka

Dredging for aggregate gravels in 2009 revealed Acheulean handaxes and Levallois flakes from a concession area defined as A240, 11 km off the coast of East Anglia in the North Sea, at a depth of 16 m to 35 m. The area was protected from further commercial extraction, and archaeological tests and examination were conducted by Wessex Archaeology (Tizzard *et al.* 2014). Core samples revealed stratified river gravels, estuarine, coastal and terrestrial sediment layers, showing marine transgressions and regression, and lithic tools were recovered from a layer that could be dated to approximately 250 ka. While some lithics may be derived from older layers, the majority owe their survival to burial in a steadily accumulating marine basin, protected from the open Atlantic Ocean, and with regional low gradients making erosion minimal at the site. At the date of writing (2016), this site constitutes the oldest seabed archaeological site in European seas.

Value of Understanding the Submerged Landscape: Sites in Context

Although the first indication that a submerged prehistoric site exists is often the chance retrieval of artifacts, such deposits cannot be understood without considering the context in terms of the overall stratigraphy of the anthropogenic components, and their relationship to the topography and ecology of the immediate surroundings. This is a commonplace of archaeological investigation, but in the offshore situation it needs to be stressed because it usually entails the survey and sampling of the seabed for hundreds of meters, or several kilometers, around the site, requiring acoustic survey systems and seabed sampling equipment. Analysis of sites in environmental and landscape context reveals patterns that facilitate further site prediction, and provides understanding of foraging and hunting strategies, as well as prehistoric access to raw materials and fresh water. The regional chapters which follow Chapter 4 provide sources of data facilitating the reconstruction of drowned landscapes.

Environmental and Industrial Threats to Known Sites and Preserved Submerged Landscapes

Known submerged prehistoric sites are at risk from coastal erosion in shallow locations, from seabed erosion in open water, and from industrial excavation or tourist and professional looting. In addition, we can assume that there are thousands of offshore prehistoric deposits, either exposed on the sea floor, or buried in the sedimentary column, that are unknown as yet, and are similarly at risk. Thousands more have already been destroyed. The preceding discussion has shown how unexpectedly robust prehistoric sites are in the marine environment, but that discussion was structured to counter the supposition that nothing at all will survive inundation. In practice, we must recognize the precarious balance of environmental forces, such that some sites do survive and can be studied, while others will certainly be destroyed, and it is probably not possible to save them.

In shallow coastal waters out to a depth of about 10 m, many sites are found by fishermen, sports divers, and amateur archaeologists, all of whom report finds to the authorities (Flemming *et al.* 2014). Research agencies and academic bodies can then usually respond and conduct investigations. In deeper water, finds to a depth of 20 m to 30 m can still be examined by divers using compressed air, but deeper than 40 m requires specialists in mixed gas diving. At depths of 30 m to 40 m or more, and tens of kilometers offshore, work by research or conservation agencies become expensive, and surveys to find prehistoric sites are rare. However, bottom trawl nets recover paleontological materials (see for example Mol *et al.* 2008), while aggregate dredging and pipelaying extract massive samples from the sea floor, within which prehistoric traces may be found. Thus, in spite of the risk of damage, and provided that there is routine communication with archaeological experts, the offshore industries help to locate, and ultimately protect, prehistoric traces on the continental shelf that would never otherwise be found. A reciprocal relationship is needed whereby offshore operators are required to assess the potential for prehistoric materials and to monitor discoveries in their concession areas. The Regional Seas chapters of this book document coastal change processes, whether accumulation or erosion, and hence the potential threat to known sites.

Conclusion

Given suitable local topography and oceanographic exposure, field evidence shows that prehistoric remains can survive for hundreds, or even a few thousand, years in the shallow surf zone at constant sea level. The protecting factors are topographic, morphodynamic, and progradational, and examples have been provided. This observation and deduction contradicts the common assumption that sites cannot survive close to a steady sea level, and can only survive when they are deeply buried and the sea level is changing rapidly.

For longer periods, prehistoric archaeological and paleontological remains have the greatest potential to survive on the seabed, and through multiple glacial cycles of sea-level change, if they have been deposited in a sedimentary depocenter with a steady rate of sediment accumulation. The prime example of this on the scale of the whole Quaternary is the central to southern North Sea. On the timescale of the last glacial cycle, the southern Baltic has provided long-term accumulation and protection for the survival of thousands of sites.

The preservation of underwater landscapes, particularly paleoshorelines in constructive environments, is favored by: (1) high sedimentary input to the coast; (2) calm marine climate with low wave and current energy; (3) early diagenesis and; (4) sea level not repeatedly re-occupying the same or a similar level. Crenulated coasts where headlands act as natural obstacles to longshore drift are favorable environments for the genesis of sandy barrier complexes, and hence burial or screening of prehistoric sites.

At the intermediate timescale of hundreds of years to tens of thousands of years, the probability that a site will survive is determined by the ability of its protective topographic screen to resist multiple transgressions and regressions, with wave attacks delivered at different levels and possibly from different directions and in different climates through multiple cycles of sea-level change. The cumulative time that the sea surface stays at, or re-occupies, the same vertical zone within ±10 m of the site increases the probability that it will be destroyed.

Analysis of the effect of rising sea level on a coastal landscape must be conducted with fully three-dimensional modeling, replicating the lateral processes of coastal erosion and transport of sediments.

The selected examples outlined above provide an illustration of the wide range of environmental and geo-dynamic situations in which submerged prehistoric sites have survived.

The drowned sites, landscapes, and ecosystems discussed in following chapters are all from the European and Mediterranean seas, and hence in mid latitude to near-polar environments. All the circumstances discussed in this chapter, and indeed throughout this book, will not be applicable directly to tropical or fully polar environments, where different processes occur.

References

Aldhouse-Green, S., Whittle, A., Allen, J. R. L. *et al.* 1992. Prehistoric human footprints from the Severn Estuary at Uskmouth and Magor Pill, Gwent, Wales. *Archaeologia Cambrensis* 141:14-55.

Alley, R. B. & Ágústsdóttir, A. M. 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. *Quaternary Science Reviews* 24:1123-1149.

Amorosi, A., Centineo, M. C., Colalongo, M. l., Pasini, G., Sarti, G. & Vaiani, S.C. 2003. Facies architecture and Latest Pleistocene–Holocene depositional history of the Po Delta (Comacchio area), Italy. *Journal of Geology* 111:39-56.

Andersen, S. H. 2013. *Tybrind Vig: submerged Mesolithic settlements in Denmark*. (Jutland Archaeological Society Publications). Aarhus University Press: Højbjerg.

Antoine, P., Catt, J., Lautridou, J. -P. & Sommé, J. 2003. The loess and coversands of northern France and southern England. *Journal of Quaternary Sciences* 18:309-318.

Arrieta, N., Goienaga, N., Martínez-Arkarazo, I. *et al.* 2011. Beachrock formation in temperate coastlines: Examples in sand-gravel beaches adjacent to the Nerbioi-Ibaizabal Estuary (Bilbao, Bay of Biscay, North of Spain). *Spectrochimica Acta Part A, Molecular and Biomolecular Spectroscopy* 80:55-65.

Backstrom, J. T., Jackson, D. W. T. & Cooper, J. A. G. 2009. Shoreface morphodynamics of a high-energy, steep and geologically constrained shoreline segment in Northern Ireland. *Marine Geology* 257:94-106.

Bailey, G. N. 2007. Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology* 26:198-223.

Bailey, G. N. 2011. Continental shelf archaeology: where next? In Benjamin, J., Bonsall, C., Pickard, C. & Fischer, A. (eds.) *Submerged Prehistory*. pp. 311-331. Oxbow Books: Oxford.

Ballard, R. (ed.) 2008. *Archaeological Oceanography*. Princeton University Press: Princeton, New Jersey.

Belderson R. H., Kenyon, N. H., Stride, A. H. & Stubbs, A. R. 1972. *Sonographs of the Sea Floor: A Picture Atlas*. Elsevier Publishing Co.: Amsterdam.

Belknap, D. F. 1983. Potentials of discovery of human occupation sites on the continental shelf and nearshore coastal zone. In *Proceedings of the Fourth Annual Gulf of Mexico Information Transfer Meeting*. 15th – 17th November 1983, New Orleans, pp. 382-387.

Belknap, D. F. & Kraft, J. C. 1981. Preservation potential of transgressive coastal lithosomes on the U.S. Atlantic Shelf. *Marine Geology* 42:429-442.

Belknap, D. F. & Kraft, J. C. 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. In Oertel, G. F. & Leatherman, S. P. (eds.) *Marine Geology (Special Issue — Barrier Islands)* 63:235-262.

Bell, M. 2007. *Prehistoric Coastal Communities. The Mesolithic in western Britain*. CBA Research Report 149. Council for British Archaeology: York.

Bell, M. & Neumann, H. 1997. Prehistoric intertidal archaeology and environment in the Severn Estuary, Wales. *World Archaeology* 29:95-113.

Benavente, J., Del Río, J., Anfuso, G., Gracia, F. J. & Reyes, J. L. 2002. Utility of morphodynamic characterisation in the prediction of beach damage by storms. *Journal of Coastal Research (Special Issue 36, International Coastal Symposium Proceedings Northern Ireland)*. pp. 56-64.

Benjamin, J. 2010. Submerged prehistoric landscapes and underwater site discovery: Reevaluating the 'Danish Model' for international practice. *Journal of Island & Coastal Archaeology* 5:253–270.

Benjamin, J., Bonsall, C., Pickard, C. & Fischer, A. (eds.) 2011. *Submerged Prehistory*. Oxbow Books: Oxford.

Bernier, P., Guidi, J. -B. Böttcher, M. E. 1997. Coastal progradation and very early diagenesis of ultramafic sands as a result of rubble discharge from asbestos excavations (northern Corsica, western Mediterranean). *Marine Geology* 144:163-175.

Bezerra, M. M., Moura, D., Ferreira, Ó. & Taborda, R. 2011. The influence of wave action and lithology on sea cliff mass movements in central Algarve coast, Portugal. *Journal of Coastal Research* 27:162-171.

Binford, L. R. 1980. Willow smoke and dog's tails: Hunter gatherer settlement systems and archaeological site formation. *American Antiquity* 45:4-20.

Blanc, A. C. 1940. Industrie musteriane e paleolithiche superiore nelle dune fossile e nelle grotte litorannee del Capo Palinuro. *R.C. Reale Accademia d'Italia* 10(7):1.

Bowdler, S. 1977. The coastal colonisation of Australia. In Allen, J., Golson, J. & Jones, R. (eds.) *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia*. pp. 205-246. Academic Press: London.

Bruun, P. 1962. Sea-level rise as a cause of shore erosion. *Journal of the Waterways, Harbors and Coastal Engineering Division* 88:117-130.

Burkitt, M. C. 1932. A Maglemose Harpoon dredged up recently from the North Sea. *MAN* 32:118.

Carrión, J. S., Finlayson, C., Fernández, S. *et al.* 2008. A coastal reservoir of biodiversity for Upper Pleistocene human populations: palaeoecological investigations in Gorham's Cave (Gibraltar) in the context of the Iberian Peninsula. *Quaternary Science Reviews* 27:2118-2135.

Carter, R. W. G. 1988. *Coastal Environments: An Introduction to the Physical, Ecological and Cultural Systems of Coastlines*. Academic Press: London.

Cassen, S., Baltzer, A., Lorin, A., Fournier, J. and Sellier, D. 2011. Submarine Neolithic Stone Rows near Carnac (Morbihan), France: Preliminary results from acoustic and underwater survey. In Benjamin, J., Bonsall, C., Pickard, C. & Fischer, A. (eds.) *Submerged Prehistory*. pp. 99-110. Oxbow Books: Oxford.

Catuneanu, O., Galloway, W. E., Kendall, C. G. St C. *et al.* 2011. Sequence stratigraphy: Methodology and Nomenclature. *Newsletters on Stratigraphy* 44:173-245.

Chang, C. -H., Kaifu, Y., Takai, M. *et al.* 2015. The first archaic *Homo* from Taiwan. *Nature Communications* 6:Article number 6037.

Chiocci, F. L. & Chivas, A. R. (eds) 2014. *Continental Shelves of the World: Their Evolution During the Last Glacio-Eustatic Cycle*. Memoirs (41). Geological Society: London.

Clausen, C. J., Cohen, A. D., Emiliani, C., Holman, J. A. & Stipp, J. J. 1979. Little Salt Springs, Florida: a unique underwater site. *Science* 203:609-614.

Cliquet, D., Coutard, S., Clet, M. *et al.* 2011. The Middle Palaeolithic underwater site of La Mondrée, Normandy, France. In Benjamin, J., Bonsall, C., Pickard, C. & Fischer, A. (eds.) *Submerged Prehistory*. pp. 111-128. Oxbow Books: Oxford.

Cockerell, W. A. & Murphy, L. 1978. 8 SL17: Methodological approaches to a dual component marine site on the Florida Atlantic coast. In Barto-Arnold, J. (ed.) *Beneath the Waters of Time — Proceedings of the 9th Conference on Underwater Archaeology*. pp. 175-182. Texas Antiquities Committee Publication No. 6.

Cooper, J. A. G. & Pilkey, O. H. 2004. Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change* 43:157-171.

Davidson-Arnott, R. 2010. *Introduction to Coastal Processes and Geomorphology*. Cambridge University Press: Cambridge.

Davis, R. A., & Fitzgerald, D. M. 2004. *Beaches and Coasts*. Blackwell Publishing: Oxford.

Deng, J., Zhang, W., Harff, J. *et al.* 2014. A numerical approach for approximating the historical morphology of wave-dominated coasts — A case study of the Pomeranian Bight, southern Baltic Sea. *Geomorphology* 204:425-443.

Dietrich, S. & Seelos, K. 2010. The reconstruction of easterly wind directions for the Eifel region (Central Europe) during the period 40.3-12.9 ka BP. *Climate of the Past 6*:145-154.

Dimitriu, R. G. 2012. Geodynamic and hydro-geological constraints regarding the extension of the prospective archaeo-cultural area within the northern Romanian coastal zone. *Quaternary International* 261:32-42.

Dinelli, E., Ghosh, A., Rossi, V. & Vaiani, S.C. 2012. Multiproxy reconstruction of Late Pleistocene-Holocene environmental changes in coastal successions: microfossil and geochemical evidences from the Po Plain (Northern Italy). *Stratigraphy* 9:153-167.

Dinu, C., Wong, H.K., Tambrea, D. & Matenco, L. 2005. Stratigraphic and structural characteristics of the Romanian Black Sea shelf. *Tectonophysics* 410:417-435.

Efremov, J. A. 1940. Taphonomy: a new branch of Paleontology. *The Pan-American Geologist* 74:81-93.

Emery, K. O. & Edwards, R. L. 1966. Archaeological potential of the Atlantic continental shelf. *American Antiquity* 31:733-737.

Evans, A., Flatman, J. & Flemming, N.C. (eds.) 2014. *Prehistoric Archaeology on the Continental Shelf: a Global Review*. Springer: New York.

Faure, H., Walter, R. C. & Grant, D. R. 2002. The coastal oasis: ice age springs on emerged continental shelves. *Global and Planetary Change* 33:47-56.

Fischer, A. (ed.) 1995. *Man and Sea in the Mesolithic. Coastal settlement above and below present sea level.* Oxbow Books: Oxford.

Fischer, A. 2002. Food for feasting? An evaluation of explanations of the neolithisation of Denmark and southern Sweden. In Fischer, A. & Kristiansen, K. (eds.) *The Neolithisation of Denmark — 150 Years of Debate*. Sheffield Archaeological Monographs 12. pp. 343-393. J.R. Collis Publications: Sheffield.

Fischer, A. 2011. Stone Age on the Continental Shelf: an eroding resource. In Benjamin, J., Bonsall, C., Pickard, C. & Fischer, A. (eds.) *Submerged Prehistory*. pp. 298-310. Oxbow Books: Oxford.

Fladmark, K. R. 1975. *A Palaeoecological Model for Northwest Coast Prehistory*. National Museums of Canada: Ottawa.

Fleming, B. W. 1976. Side-scan sonar: a practical guide. *International Hydrographic Review* 53:65-92.

Flemming, N. C. 1968. Derivation of Pleistocene marine chronology from morphometry of erosion profiles. *Journal of Geology* 76:280-296.

Flemming, N. C. 1983. Survival of submerged lithic and Bronze Age artefact sites: a review of case histories. In Masters, P. & Flemming, N. C. (eds.) *Quaternary Coastlines and Marine Archaeology*. pp. 135-174. Academic Press: London and New York.

Flemming, N. C. 2002. *The scope of Strategic Environmental Assessment of North Sea areas SEA3 and SEA2 in regard to prehistoric archaeological remains*. UK Department of Trade and Industry: London.

Flemming, N. C. & Antonioli, F. 2017. Prehistoric archaeology, palaeontology, and climate change indicators from caves submerged by change of sea level. In Campbell, P. (ed.) *The Archaeology of Underwater Caves*. pp. 22-38. Highfield Press: Southampton.

Flemming N. C., Çağatay M. N., Chiocci F. L. *et al.* 2014. *Land Beneath the Waves: Submerged Landscapes and Sea Level Change. A Joint Geoscience-Humanities Research Strategy for European Continental Shelf Prehistoric Research*. Chu N.-C. & McDonough N. (eds.) Position paper 21 of the European Marine Board: Ostend, Belgium.

French, H. M. 2007. *The Periglacial Environment* (3rd Ed). John Wiley & Sons: Chichester.

Gaffney V., Thomson, K. & Fitch, S. (eds.) 2007. *Mapping Doggerland: The Mesolithic Landscapes of the Southern North Sea*. Archaeopress: Oxford.

Gagliano, S. M., Pearson, C. E., Weinstein, R. A., Wiseman, D. E. & McClendon, C. M. 1982. *Sedimentary Studies of Prehistoric Archaeological sites: Criteria for the Identification of Submerged Archaeological Sites of the Northern Gulf of Mexico Continental Shelf*. National Park Service: Baton Rouge, LA.

Galili, E., Weinstein-Evron, M., Hershkovitz, I. *et al.* 1993. Atlit-Yam: A prehistoric site on the sea floor off the Israeli coast. *Journal of Field Archaeology* 20:133-157.

Galili, E., Lernau, O. & Zohar, I. 2004. Fishing and coastal adaptations at Atlit-Yam — A submerged PPNC Fishing village off the Carmel coast, Israel. *'Atiqot* 48:1-34.

Geddes, D. S., Guilaine, J. & Monaco, A. 1983. Early Neolithic occupation of the submerged continental plateau of Roussillon (France). In Masters, P. M. & Flemming, N. C. (eds.) *Quaternary Coastlines and Marine Archaeology*. pp. 175-188. Academic Press: London.

Giot, P.-R. 1968. La Bretagne au péril des mers holocènes. In Bordes, F. & de Sonneville-Bordes, D. (eds.) *La Préhistoire, problèmes et tendances*. pp. 203-208. CNRS: Paris.

Giot, P. -R., L'Helgouac'h, J. & Monnier, J. -L. 1979. *Préhistoire de la Bretagne*. Ouest-France: Rennes.

Harding, A. F., Cadogan, G. & Howell, R. 1969. Pavlopetri: an underwater Bronze Age town in Laconia. *The Annual of the British School at Athens* 64:113-142.

Harff, J. & Lüth, F. (eds.) 2007. *SINCOS — Sinking Coasts: Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea*. Bericht der Römisch-Germanische Kommission: Special Issue 88.

Harff, J. & Lüth, F. (eds.) 2011. *SINCOS II — Sinking Coasts: Geosphere Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea II. Bericht der Römisch-Germanische Kommission*: Special Issue 92.

Harff, J., Lemke, W., Lampe, R. *et al.* 2007. The Baltic Sea coast — A model of interrelations among geosphere, climate, and anthroposphere. *Geological Society of America Special Papers* 426:133-142.

Henderson, J. C., Gallou, C., Flemming, N. C. & Spondylis, E. 2011. The Pavlopetri Underwater Archaeology Project: investigating an ancient submerged town. In Benjamin, J., Bonsall, C., Pickard, C., & Fischer, A. (eds.) *Submerged Prehistory*. pp. 207-218. Oxbow Books: Oxford.

Holdaway, S. & Wandsnider, L. (eds.) 2008. *Time in Archaeology: Time Perspectivism Revisited*. pp. 13-30. University of Utah Press: Utah.

Holthuijsen, L. H. 2007. *Waves in Oceanic and Coastal waters*. Cambridge University Press: Cambridge.

Horta, J., Moura, D., Gabriel, S. & Ferreira, O. 2013. Measurement of pocket beach morphology using geographic information technology: the MAPBeach toolbox. *Journal of Coastal Research* (Special Issue 65):1397-1402.

Howie, F. M. P. 2009. Beachrock development along the north coast of Cornwall. *Geoscience in South-West England* 12:85-94.

Hublin, J. -J., Weston, D., Gunz, P. *et al.* 2009. Out of the North Sea: the Zeeland Ridges Neandertal. *Journal of Human Evolution* 57:777-785.

Infantini, L., Moura, D. & Bicho, N. 2012. Utilização de ferramentas SIG para o estudo da morfologia submersa da Baía de Armação de Pêra. In Almeida, A. C., Bettencourt, A. M., Moura, D., Monteiro-Rodrigues, S. & Alves, M. I. C. (eds.) *Environmental Changes and Human Interaction along the Western Atlantic Edge*. pp. 227-241. APEQ: Coimbra.

Iversen, J, 1973. *The Development of Denmark's Nature Since the Last Glacial*. Geological Survey of Denmark V. series No. 7-c.

Jackson, D. W. T. & Cooper, J. A. G. 2010. Application of the equilibrium planform concept to natural beaches in Northern Ireland. *Coastal Engineering* 57:112-123.

Jackson, D. W. T., Cooper, J. A. G. & del Rio, L. 2005. Geological control of beach morphodynamic state. *Marine Geology* 216:297-314.

Jessen, K. 1938. Some west Baltic pollen diagrams. *Quartär* 1:124-139.

Jöns, H. 2011. Settlement development in the shadow of coastal changes — case studies from the Baltic Rim In Harff, J., Björck, S. & Hoth, P. (eds.) *The Baltic Sea Basin*. pp. 301-336. Springer-Verlag: Berlin-Heidelberg.

Jöns, H., Mennenga, M. & Schaap, D. 2016. *The SPLASHCOS-Viewer. A European Information system about submerged prehistoric sites on the continental shelf. A product of the COST Action TD0902 SPLASHCOS (Submerged Prehistoric Archaeology and Landscapes of the Continental Shelf).* Accessible at splashcos-viewer.eu/

Joris, C. 2002. The Magdalenian assemblages from Ardèche (France) in the Mediterranean Basin context. *L'Anthropologie* 106:99-134.

Karkanas, P., Shahack-Gross, R., Ayalon, A. *et al.* 2007. Evidence for habitual use of fire at the end of the Lower Paleolithic: Site-formation processes at Qesem Cave, Israel. *Journal of Human Evolution* 53:197-212.

Kasse, C. 1997. Cold-climate Aeolian sand-sheet formation in North-Western Europe (c. 14–12 ka); a response to permafrost degradation and increased aridity. *Permafrost and Periglacial Processes* 8:295-311.

Kenyon, N. H., Belderson, R. H., Stride, A. H. & Johnson, M. A. 1981. Offshore tidal sandbanks as indicators of net sand transport and as potential deposits. In Nio, S. D., Schuttenhelm, R. T. E. & van Weering, T. C. E. (eds.) *Holocene Marine Sedimentation in the North Sea Basin*. pp. 257-268. Blackwell Publishing Ltd: Oxford.

Konishchev, V. N. & Rogov, V. V. 1993. Investigation of cryogenic weathering in Europe and Northern Asia. *Permafrost and Periglacial Processes* 4:49-64.

Kuhn, S. L., Stiner, M. C., Guleç, E. *et al.* 2009. The early Upper Paleolithic occupations at Üçağizli Cave (Hatay, Turkey). *Journal of Human Evolution* 56:87-113.

Lefort, J. -P., Danukalova, G. A. & Monnier, J.-L. 2011. Origin and emplacement of the loess deposited in northern Brittany and under the English Channel. *Quaternary International* 240:117-127.

Lefort, J. -P., Danukalova, G. & Monnier, J.-L. 2013. Why the submerged sealed beaches, last remnants of the low stands of the Upper Pleistocene regression, are better expressed in the western than in the eastern English Channel? *Geo-Eco-Marine* 19:5-16.

Lobo, F. J., Ercilla, G., Fernández-Salas, L. M. & Gámez, D. 2014. The Iberian Mediterranean shelves. In Chiocci, F. L & Chivas, A. R (eds.) *Continental Shelves of the World: Their Evolution During the Last Glacio-Eustatic Cycle (Geological Society Memoir No. 41)*. pp. 147-170. Geological Society: London.

Long, D., Wickham-Jones, C. R. & Ruckley, N. A. 1986. A flint artefact from the northern North Sea. In Roe, D. A. (ed.) *BAR International Series (No. 296) Studies in the Upper Palaeolithic of Britain and North West Europe*. pp. 55-62. British Archaeological Reports: Oxford.

Louwe Kooijmans, L. P. 1970-71. Mesolithic bone and antler implements from the North Sea and from the Netherlands. *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek* 20-21:27-73.

Lowe, J. J. & Walker, M. J. C. 1984. *Reconstructing Quaternary Environments*. Longman: London.

Lübke, H. 2001. Eine hohlendretuschierte Klinge mit erhaltener Schäftung vom endmesolithischen Fundplatz Timmendorf-Nordmole, Wismarbucht, Mecklenburg-Vorpommern. *Nachrichtenblatt Arbeitskreis Unterwasserarchäologie* 8:46-51.

Lübke, H. 2002a. Steinzeit in der Wismarbucht: ein Überblick. *Nachrichtenblatt Arbeitskreis Unterwasserarchäologie* 9:75-87.

Lübke, H. 2002b. Submarine Stone Age settlements as indicators of sea-level changes and the coastal evolution of the Wismar Bay area. *Greifswalder Geographische Arbeiten* 27: 202-210.

Lübke, H. 2003. New investigations on submarine Stone Age settlements in the Wismar Bay area. In Kindgren, H., Knutsson, K., Larsson, L., Loeffler, D. & Åkerlund,

A. (eds.) *Mesolithic on the Move — Proceedings of the Sixth International Conference on the Mesolithic in Europe*, 4th – 8th September 2000, Stockholm, pp. 69-78.

Lübke, H. 2004. Spät- und endmesolithische Küstensiedlungsplätze in der Wismarbucht — Neue Grabungsergebnisse zur Chronologie und Siedlungsweise. *Bodendenkmalpflege in Mecklenburg-Vorpommern (Jahrbuch 2004)* 52:83-110.

Lübke, H., Schmölcke, U. & Tauber, F. 2011. Mesolithic Hunter-Fishers in a Changing World: a case study of submerged sites on the Jäckelberg, Wismar Bay, northeastern Germany. in Benjamin, J., Bonsall, C., Pickard, C. & Fischer, A. (eds.) *Submerged Prehistory*. pp. 21-37. Oxbow Books: Oxford.

Lyman, R. E. 2010. What taphonomy is, what it isn't, and why taphonomists should care about the difference. *Journal of Taphonomy* 8:1-16.

Marabini, F. 1997. The Po River Delta evolution. *Geo-Eco-Marina* 2:47-55.

Masters, P. M. & Flemming, N. C. (eds.) 1983. *Quaternary Coastlines and Marine Archaeology*. Academic Press: London.

Mellett, C. L., Hodgson, D. M., Lang, A., Mauz, B., Selby, I. & Plater, A. J. 2012. Preservation of a drowned gravel barrier complex: A landscape evolution study from the north-eastern English Channel. *Marine Geology* 315-318:115-131.

Miller, K. G., Kominz., M. A., Browning, J. V. *et al.* 2005. The Phanerozoic record of global sea-level change. *Science* 310:1293-1298.

Mol, D., Vos, J. de, Bakker, R. *et al.* 2008. *Mammoeten, neushoorns en andere dieren van de Noordzeebodem*. Wetenschappelijke Biblioteek: Diemen.

Momber, G. 2006. Mesolithic occupation: 11m below the waves. In Hafner, A., Niffler, U. & Ruoff, U. (eds.) *The New View: Underwater Archaeology and the Historic Picture*. pp. 56-63. Archaeologie Schweiz: Basel.

Momber, G., Bailey, G. & Moran, L. 2012. Identifying the archaeological potential of submerged landscapes. In Henderson, J. (ed.) *Beyond Boundaries — Proceedings of the 3rd International Congress on Underwater Archaeology*. 9th – 12th July 2012, London, pp. 257-268.

Moree, J. M. & Sier, M. M. (eds.) 2014. *Twintig meter diep! Mesolithicum in de Yangtzehaven — Maasvlakte te Rotterdam. Landschapsontwikkeling en bewoning in het Vroeg Holoceen. BOORrapporten 523*. Bureau Oudheidkundig Onderzoek Rotterdam (BOOR): Rotterdam.

Moura, D., Veiga-Pires, C., Albardeiro, l., Boski, T., Rodrigues, A. L. & Tareco, H. 2007. Holocene sea level fluctuations and coastal evolution in the central Algarve (southern Portugal). *Marine Geology* 237:127-142.

Moura, D., Gabriel, S. & Jacob, J. 2011. Coastal morphology along the Central Algarve rocky coast: Driver mechanisms. *Journal of Coastal Research* (Special Issue 64):790-794.

Murphy, L. 1978. 8 SLO 19: Specialised methodological, technological and physiological approaches to deep water excavation of a prehistoric site at Warm Mineral Springs, Florida. In Barto-Arnold, J. (ed.) *Beneath the Waters of Time — Proceedings of the 9th Conference on Underwater Archaeology*. pp. 123-128. Texas Antiquities Committee Publication No. 6.

Murton, J. B. & Lautridou, J-P. 2003. Recent advances in the understanding of Quaternary periglacial features of the English Channel coastlands. *Journal of Quaternary Science* 18:301-307.

Nakazawa, Y., Straus, L. G., González-Morales, M. R., Solana, D. C. & Saiz, J. C. 2009. On stone-bolling technology in the Upper Paleolithic: behavioral implications from an Early Magdalenian hearth in El Mirón Cave, Cantabria, Spain. *Journal of Archaeological Science* 36:684-693.

Ontañón, R. 2003. Sols et structures d'habitat du Paléolithique supérieur, nouvelles données depuis les Cantabres: la Galerie Inférieure de La Garma (Cantabrie, Espagne). *L'Anthropologie* 107:333-363.

Pearson, C. E., Kelley, D. B., Weinstein, R. A. & Gagliano, S. M. 1986. *Archaeological Investigations on the Outer Continental Shelf: A Study Within the Sabine River Valley, Offshore Louisiana and Texas*. Coastal Environments, Inc: Baton Rouge.

Pedersen, L. D., Fischer, A. & Aaby, B. 1997 (eds.). *The Danish Storebaelt since the Ice Age: Man, Sea and Forest*. Storebaeltsforbindelsen: Copenhagen.

PNUE (Programme des Nations Unies pour l'Environment) 2004. *L'eau des Méditerranéens: Situation et perspectives*. MAP Technical Report Series No. 158. PNUE/PAM: Athens.

Post, K & Kompanje, E. J. O 2010. A new dolphin (Cetacea, Delphinidae) from the Plio-Pleistocene of the North Sea. *Deinsea* 14:1-14.

Prigent, D., Vissent, L., Morzadec-Kerfourn, M. T. & Lautridou, J-P. 1983. Human occupation of the submerged coast of the Massif Armoricain and postglacial sea level changes. In Masters, P. M. & Flemming, N. C. (eds.) *Quaternary Coastlines and Marine Archaeology*. pp. 303-324. Academic Press: London and New York.

Reid, C. 1913. *Submerged Forests*. Cambridge University Press: Cambridge.

Rocha, M., Silva, P., Michallet, H., Abreu, T., Moura, D. & Fortes, J. 2013. Parameterizations of wave nonlinearity from local wave parameters: a comparison with field data. *Journal of Coastal Research* (Special Issue 65):374-379.

Romanovskii, N. N., Hubberten, H. -W., Gavrilov, V. *et al.* 2000. Thermokarst and land-ocean interactions, Laptev sea region, Russia. *Permafrost and Periglacial Processes* 11:137-152.

Rosyan, R. D., Goryachkin, Yu. N., Krylenko, V. V., Dolotov, M. V., Krylenko, M. V. & Godin, E. A. 2012. Crimea and Caucasus accumulative coasts dynamics estimation using satellite pictures. *Turkish Journal of Fisheries and Aquatic Sciences* 12:385-390.

Ruppé, R. J. 1978. Underwater site detection by use of a coring instrument. In Barto-Arnold, J. (ed.) *Beneath the Waters of Time — Proceedings of the 9th Conference on Underwater Archaeology*. pp. 119-121. Texas Antiquities Committee Publication No. 6.

Ruppé, R. J. 1980. The archaeology of drowned terrestrial sites: a preliminary report. *In Bureau of Historical Sites and Properties Bulletin 6*. pp. 35-45. Division of Archives, History and Records Management: Tallahassee.

Salomonsson, B. 1971. Malmotraktens förhistoria. In Bjurling, O. (ed.) *Malmö Stads Historia I*. pp. 15-170. Allhems Forlag: Malmö.

Salzmann, L., Green, A. & Cooper, J. A. G. 2013. Submerged barrier shoreline sequences on a high energy, steep and narrow shelf. *Marine Geology* 346:366-374.

Schaetzl, R. J. & Anderson, S. 2005. *Soils: Genesis and Geomorphology*. Cambridge University Press: Cambridge.

Schiffer, M. B. 1987. *Formation Processes of the Archaeological Record*. University of New Mexico Press: Albuquerque, NM.

Scuvée, F. & Verague, J. 1988. *Le gisement sous-marin du Paléolithique moyen de l'anse de La Mondrée à Fermanville, Manche*. CEHP-Littus: Cherbourg.

Seibold, E. & Berger, W. H. 1996. *The Sea Floor*. Springer: Berlin and New York.

Shackleton, N. J. & Opdyke, N. D. 1973. Oxygen isotope and palaeomagnetic stratigraphy of Equatorial Pacific core V28-238: oxygen isotope temperature and ice volumes on a 10^5 and 10^6 year scale. *Quaternary Research* 3:39-55.

Shepard, F. P. 1963. *Submarine Geology* (2nd Ed). Harper and Row: New York.

Silva, R., Baquerizo, A., Losada, M. Á. & Mendoza, E. 2010. Hydrodynamics of a headland-bay beach — nearshore current circulation. *Coastal Engineering* 57:160-175.

Skaarup, J. 1980. Undersoisk stenhalder. *Tiddskriftet* 1:3-8.

Stanford, J. D., Hemingway, R., Rohling, E. J., Challenor, P. G., Medina-Elizalde, M. & Lester, A. J. 2011. Sea-level probability for the last deglaciation: A statistical analysis of far-field records. *Global and Planetary Change* 79:193-203.

Steers, J. A. 1948. *The Coastline of England and Wales*. Cambridge University Press: Cambridge.

Stein, J. K. 2001. A review of site formation processes and their relevance to geoarchaeology. In Goldberg, P., Holliday, V. T. & Ferring, C. F (eds.) *Earth Sciences and Archaeology*. pp. 37-51. Springer: New York.

Stoker, M. & Bradwell, T. 2009. Neotectonic deformation in a Scottish fjord, Loch Broom, NW Scotland. *Scottish Journal of Geology* 45:107-116.

Storms, J. E. A., Weltje, G. J., Terra, G. J., Cattaneo, A. & Trincardi, F. 2008. Coastal dynamics under conditions of rapid sea-level rise: Late Pleistocene to Early Holocene evolution of barrier-lagoon systems on the northern Adriatic shelf (Italy). *Quaternary Science Reviews* 27:1107-1123.

Stride A. H. 1963. Current-swept sea floors near the southern half of Great Britain. *Quaternary Journal of the Geological Society* 119:175-197.

Tizzard, L., Bicket, A. R., Benjamin, J. & De Loecker, D. 2014. A Middle Palaeolithic site in the southern North Sea: investigating the archaeology and palaeogeography of Area 240. *Journal of Quaternary Science* 29:698-710.

TRC Environmental Corporation 2012. *Inventory and analysis of archaeological site occurrence on the Atlantic outer continental shelf.* U.S. Dept. of the Interior: New Orleans.

van Huissteden, Ko (J.), Schwan, J. C. G. & Bateman, M. D. 2001. Environmental conditions and paleowind directions at the end of the Weichselian Late Pleniglacial recorded in aeolian sediments and geomorphology (Twente, Eastern Netherlands). *Netherlands Journal of Geosciences* 80:1-8.

Waters, M. R. 1992. *Principles of Geoarchaeology: A North American perspective*. University of Arizona Press: Tuscon.

Weerts, H., Otte, A., Smit, B. *et al.* 2012. Finding the needle in the haystack by using knowledge of Mesolithic human adaptation in a drowning delta. In Bebermeier, W., Hebenstreit, R., Kaiser, E., & Krause, J. (eds.) *Landscape Archaeology — Proceedings of the International Conference (Special Volume 3).* 6th – 8th June, Berlin, pp. 17-24.

Welinder, S. 1971. Ő́verâda — A pitted ware culture site in eastern Sweden. *Meddelande från Lunds historiska museum* 1969-70:5-98.

Werz, B. E. J. S. & Flemming, N. C. 2001. Discovery in Table Bay of the oldest handaxes yet found demonstrates preservation of hominid artefacts on the continental shelf. *South African Journal of Science* 97(May/June):183-185.

Wessex Archaeology 2011. *Seabed Prehistory: Site Evaluation Techniques (Area 240) Synthesis*. Wessex Archaeology: Salisbury.

Williams, M. A. J., Dunkerley, D. L., De Deckker, P., Kershaw, A. P. & Stokes, T. J. 1993. *Quaternary Environments*. Edward Arnold: London.

Winguth, C., Wong, H. K., Panini, N., Dinu, C., Georgescu, P. & Ungureanu, G. 1997. Upper Quaternary sea level changes in the northwestern Black Sea: Preliminary results. *Geo-Eco-Marina* 2:103-113.

Wood, W. R. & Johnson, D. L. 1978. A survey of disturbance processes in archaeological site formation. *Advances in Archaeological Method and Theory* 1:315-381.

Wreschner, E. E. 1977. Neve-Yam. A submerged Late Neolithic settlement near Mount Carmel. *Eretz Israel* 13:260-271.

Yeshurun, R., Bar-Oz, G. & Weinstein-Evron, M. 2007. Modern hunting behavior in the early Middle Paleolithic: Faunal remains from Misliya Cave, Mount Carmel, Israel. *Journal of Human Evolution* 53:656-677.

Zhang, W. Y., Harff, J., Schneider, R. & Wu, C. 2010. Development of a modeling methodology for simulation of long-term morphological evolution of the southern Baltic coast. *Ocean Dynamics* 60:1085-1114.

Zhang, W. Y., Harff, J. & Schneider, R. 2011. Analysis of 50-year wind data of the southern Baltic Sea for modelling coastal morphological evolution — a case study from the Darss-Zingst Peninsula. *Oceanologia* 53:489-518.

Zhang, W. Y., Schneider, R. & Harff, J. 2012. A multi-scale hybrid long-term morphodynamic model for wave-dominated coasts. *Geomorphology* 149-150: 49-61.