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| Abstract: | <p>The link between episodic sand invasion and changes in climate conditions (enhanced storminess) has been previously evidenced along the Atlantic coasts of Europe from stratigraphical, geomorphological and chronological investigations of recent aeolian sand-dune deposits. While well-constrained timing templates of dune accretion during Holocene were reconstructed in Portugal, Spain and Ireland, available data about the French Atlantic coast are limited to the Aquitaine dune complex (SW France). This lack of data is mainly due to the absence of well-developed palaeosoils interbedded within the aeolian sand deposits, especially in Brittany where only thin humic layers are preserved within the coastal dune sediment sequences. An alternative approach is here applied to the coastal dunes of Brittany by also integrating available and partly revised archaeological dataset, excavated from the end of the 19th century, and used as chrono-stratigraphical markers to reconstruct at a regional scale the periods of coastal dunes mobility during the last ca. 7,000 years. This analysis was further completed with historical data about the last few centuries. 221 sites have been selected to provide chrono-stratigraphic data about 78 coastal sand-dune systems. Four main episodes of aeolian activity identified during the mid- to late-Holocene period are dated at 4,250-4,100 cal BP (phase 1), 3,250-2,400 cal BP (phase 2), 1,050-700 cal BP (phase 3), and 350-110 cal BP (phase 4). Despite some methodological limitations, archaeological remains appear to be relevant chronological indicators and may be used to reconstruct ancient periods of coastal dune mobility.</p> |
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Opposed Reviewers:

Highlights

- Archaeological remains was used to reconstruct the coastal dune chrono-stratigraphy
- Four main sand-drift events have been identified for the mid- to late-Holocene period
- Coastal sand dune systems have been affected by episodic morphological changes



Holocene evolution of coastal dunes in western France: regional reconstruction from archaeological and historical data

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Abstract

The long-term evolution of coastal sand-dune systems is known to be controlled by variations in sediment supply, relative sea level (RSL), wind energy, vegetation cover and anthropogenic forcing. The link between episodic sand invasion and changes in climate conditions (enhanced storminess) has been previously evidenced along the Atlantic coasts of Europe from stratigraphical, geomorphological and chronological investigations of recent aeolian sand-dune deposits. While well-constrained timing templates of dune accretion during Holocene were reconstructed in Portugal, Spain and Ireland, available data about the French Atlantic coast are limited to the Aquitaine dune complex (SW France). This lack of data is mainly due to the absence of well-developed palaeosoils interbedded within the aeolian sand deposits, especially in Brittany where only thin humic layers are preserved within the coastal dune sediment sequences. An alternative approach is here applied to the coastal dunes of Brittany by also integrating available and partly revised archaeological dataset, excavated from the end of the 19th century, and used as chrono-stratigraphical markers to reconstruct at a regional scale the periods of coastal dunes mobility during the last ca. 6,000 years. This analysis was further completed with historical data (historical syntheses, archives, old maps, historical photos) about the last few centuries. 221 sites distributed along the western coasts of France have been selected to provide accurate information in terms of dune stratigraphy and chronology. A conceptual tool routinely used in archaeology, the Harris matrix, was employed to synthesise these chrono-stratigraphic data about 78 coastal sand-dune systems. Four main episodes of aeolian activity identified during the mid- to late-Holocene period are dated at 4,250-4,100 cal BP (phase 1), 3,250-2,400 cal BP (phase 2), 1,050-700 cal BP (phase 3), and 350-110 cal BP (phase 4). Despite some methodological limitations, archaeological remains appear to be relevant chronological indicators and may be used to reconstruct ancient periods of coastal dune mobility. Finally, an evolutionary model is established about the sand-dune morphological changes that occurred during the mid-to late-Holocene period along the Western France coasts, whereas the nature of the driving mechanisms of sand movement initiation is also discussed.

Keywords: Coastal dune, Holocene, western France, archaeology, chronology, sand-drift event.

1. Introduction

The formation, stabilization, and mobility of coastal sand-dune systems are controlled by a combination of several driving mechanisms such as coastal sediment supply and distribution, relative sea level (RSL) changes, wind speed, storm-induced erosion and vegetation cover stability (Hesp, 2011), as well as by anthropogenic pressures on these drivers. Numerous morpho-stratigraphic and geochronological studies have attempted to define the respective contribution of these factors to the morphological behaviour of coastal dunes at different spatial and temporal scales. Along the Atlantic coasts of Europe, periods of coastal dune mobility have been well reconstructed for the Holocene period in Portugal (Clarke and Rendell, 2006; Costas et al., 2012), Ireland (e.g. Wilson et al., 2004), and the Great Britain (e.g. Wilson et al., 2001; Sommerville et al., 2007). Such reconstructions remained limited about the French Atlantic coasts, as being restricted to geochronological investigations of dune systems in the Aquitaine region (SW France, e.g. Clarke et al., 2002; Bertran et al., 2020; Stéphan et al., 2019c).

Most of these studies have demonstrated that the morphodynamic of Holocene coastal dunes is characterized by a succession of sand-drift events associated to the deposition of aeolian sand inland alternating with periods of dune stabilization that led to the formation of organic sandy soils. Periods of dune stability have been reconstructed by the radiocarbon dating of dune paleosoils interbedded within aeolian sand deposits (e.g. Wilson et al., 2001, 2004; Clemmensen et al., 2009), while Optically Stimulated Luminescence (OSL) dating has been used on sandy material to date sand-drift events (e.g. Sommerville et al., 2007; Costas et al., 2012). A few works have also relied on the analysis of archaeological remains and available historical data to consolidate the local chronologies of coastal dune morphological changes (e.g. Sommerville et al., 2007; Bampton et al., 2017).

Along the western coasts of France, the dune sedimentary sequences still stay to be accurately dated despite some dating works have been attempted over the last decades (Regnault et al., 1995; Haslett et al., 2000; Meurisse-Fort, 2008; Van Vliet-Lanoë et al., 2014a, 2014b, 2016). The absence of well-developed palaeosols within aeolian sand deposits limited the use of radiocarbon dating, except for several interbedded organic-rich humic layers, while no OSL dating was attempted on aeolian sand deposits.

Since the end of the 19th century, numerous archaeological remains have been discovered, excavated and documented within the coastal sand-dune complexes of Brittany. These remains attest to a long-lasting human occupation of coastal sandy environments covering cultural periods that range in age from the Neolithic to the Modern periods. Consequently, the analysis

1 of archaeological remains as chrono-stratigraphic markers appears as an alternative method to
2 identify the stability/mobility phases of dune complexes in this area. Furthermore, a great
3 number of historical sources indicate coastal sand inundations during the last centuries are well-
4 documented. Numerous detailed descriptions of sand-drift events inundating villages, churches
5 and cultivated fields during the 18th century are available for the northern coast of Brittany
6 ([Charpentier, 2009](#)). [Lageat et al. \(2019\)](#) also present a review of all archived catastrophic
7 flooding and sand-blow events that occurred in the region during the 18th century.

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13 The aim of this paper is to establish the accurate chronology of coastal dune mobility periods
14 based on the re-evaluation of available archaeological and historical data in Brittany. First, a
15 geoarchaeological database (GAD) was constructed in order to get a complete inventory of
16 archaeological discoveries about the coastal sand-dune systems. The archaeological remains
17 considered in this study concern the different cultural periods over the last 7,000 years, starting
18 from the beginning of the Neolithic up to the present. Second, the archaeological observations
19 previously made during the excavation operations have been systematically reviewed to extract
20 relevant stratigraphic and chronological data. Third, the Harris diagram was used to estimate
21 the periods of sand deposition on a large number of dune complexes. This approach was
22 complemented by a review of historical data and furthermore by a series of radiocarbon dates
23 devoted to beach/dune systems. Finally, all these data were compiled to reconstruct the main
24 periods of coastal dune mobility in western France during the mid- to late-Holocene.
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37 **2. Environmental setting of the study area**

38 **2.1. Coastal dune morphology**

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42 The geological context in Brittany, West Armorican Massif, is dominated by Proterozoic and
43 Paleozoic series that recorded the Variscan orogenic events ([Le Corre et al., 1991](#); [Ballevre et](#)
44 [al., 2013](#)). The diversity of the rocks largely accounts for the varying coastal morphology with
45 alternating hard cliffs on rocky headlands, sandy or gravelly beach/dune systems in bays, and
46 estuarine mouths in the lower parts of incised river valleys. As a result, a great number of
47 sedimentary cells is present and display a large diversity in terms of lithology, morphology,
48 hydrodynamic and sedimentology ([Stéphan et al., 2019a](#)).
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56 Brittany coastal dunes stretch over 310 km long, i.e. 12.6% of the present-day coastline
57 ([Guilcher and Hallegouet, 1991](#); [Stéphan et al., 2019a](#)) ([Fig. 1a](#)). In northern Brittany, dune
58 complexes are less numerous and they occupy small-sized bays sheltered between rocky
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headlands (Meur, 1993). Normally, the morphology of coastal dunes corresponds to a single sandy ridge isolating lagoons and/or salt marshes from the sea. The dunes culminate between 5 and 6 m above the highest astronomical tide level (HAT). The mean grain size ranges from 200 to 315 μm (Stéphan et al., 2019a). In the southern and western parts of Brittany, dune massifs cover larger areas, usually stretching over several kilometres long. The topography of the largest dune field is characterized by transgressive dunes that are now completely stabilized by vegetation. For example, in the Audierne Bay (Fig. 1a), a >11 km-long dune barrier stretches along the coastline whilst sandy deposits extend up to 2 km inland (Hallégouët and Bodéré, 1993). In SW Brittany, several perched dune complexes are now disconnected from current beaches and occupy coastal slopes up to 25-30 m above sea level (Haslett et al., 2000).

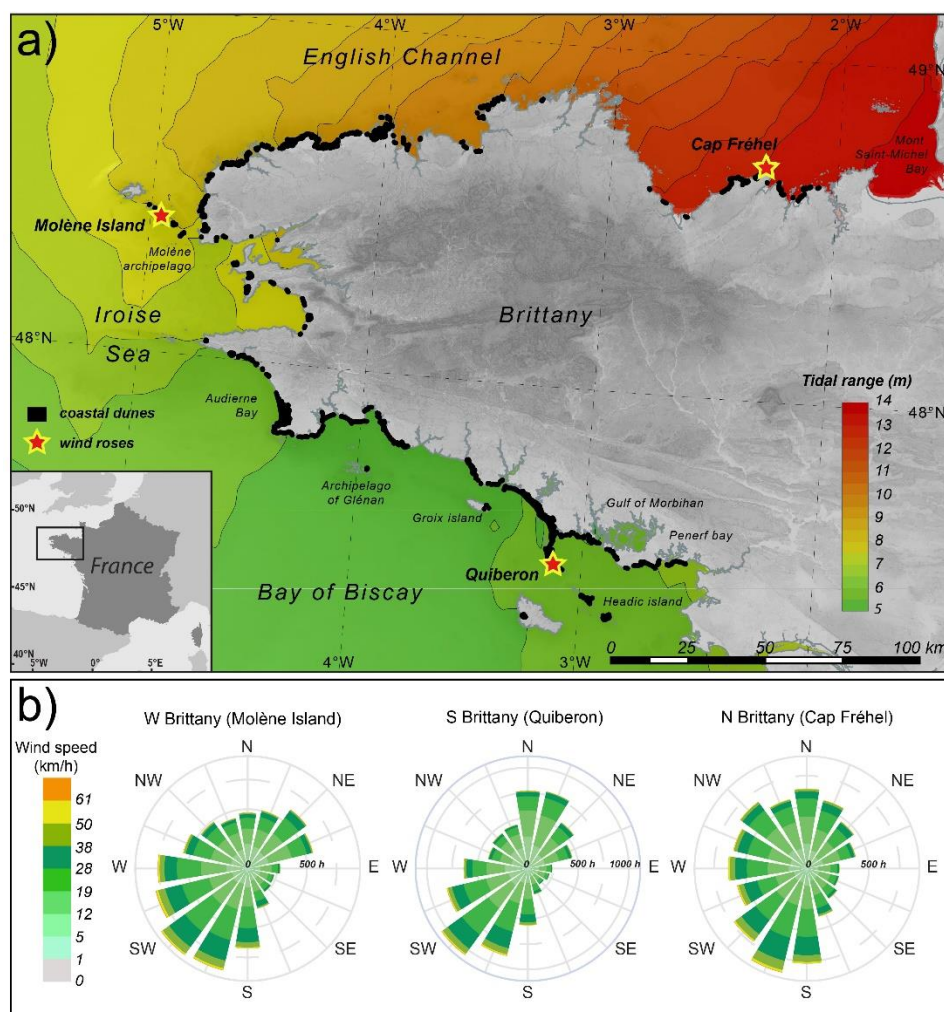


Fig. 1. (a) Distribution of the coastal sand-dune systems in western France (source: 1:50 000 geological map, BRGM, <http://infoterre.brgm.fr>); (b) Wind roses from 30 years of modelled wind data for the north, south and west coasts of Brittany (source: <https://www.meteoblue.com>). Tide data is obtained from the Service Hydrographique et Océanographique de la Marine, SHOM-Brest.

1 During the 20th century, the intensification of human activities along the coasts led to a large
2 range of morphogenetic impacts on dune barriers. Farmers massively exploited calcareous
3 marine sand on beaches for soil amendment (Guilcher and Hallégouët, 1991; Hallégouët and
4 Hénaff, 1995; Yoni and Hallégouët, 1998; Blanken, 2020). Coastal sands were also exploited
5 in many quarries for industry purposes. During the 1970s and 1980s, the rapid extension of
6 urbanized areas along the coasts led to the installation of residential housing and its
7 infrastructures and facilities close to the coastal dunes (Le Berre et al., 2017). Coastal
8 urbanisation and sand extraction led to the incidental discovery of many archaeological sites.
9 Between the 1960s and the 1980s, the rapidly increasing number of tourist on beaches led to a
10 strong degradation of the dune vegetation and a remobilization of the sand, caused by trampling,
11 camping, riding, driving, motorcycling, etc.
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20 Besides, over the last few decades, the vast majority of coastal dunes have experienced a
21 shoreline retreat in Brittany (Stéphan et al., 2019a), especially when severe storm events are
22 combined with high spring tide levels (Suanez et al., 2016; Stéphan et al., 2019a). The erosion
23 trend of many beach/dune systems reflects a scarcity of coastal sand supplies that have been
24 aggravated by human actions during the last three centuries. Due to the high elevations of the
25 dune ridge, erosional processes led to the formation of scarps on the dune front, in turn
26 favouring the discoveries of buried archaeological remains.
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34 From the 1980s onward, the creation of the Coastal Conservancy (Conservatoire du Littoral) in
35 1975, conducted after the National Trust of Britain, facilitated the practice of “soft
36 management” of dune environments. This public agency either bought or received coastal lands
37 and delegated their management to public councils or private nature conservation societies
38 (Deboudt et al., 2008). Marram grass plantations and wooden fences were installed on the most
39 degraded dunes. These soft solutions were very efficient in preventing aeolian erosion and
40 blowouts and in channeling pedestrian flows through the coastal dunes (Guilcher and
41 Hallégouët, 1991). Where legislation protects the coastal environment, smaller number of
42 archaeological artefacts are discovered. However, a few archaeological sites have been the
43 subject of specific scientific research programs and have provided fruitful data (e.g. Beg ar
44 Loued site, Molène Island, W Brittany: Paillet and Nicolas, 2019; Le Douet site, Hoëdic Island,
45 S Brittany: Large, 2014).
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56 Currently, many coastal dunes are a part of the natural protected areas in Brittany. The dunes
57 are stabilized by dense vegetation cover and only the foredunes are partly mobile (Meur, 1993;
58 Suanez et al., 2012). During the summer period, the upper beaches are colonized by annual
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halonitrophilous species (e.g. *Atriplex laciniata*, *Cakile maritima*, *Salsola kali*). The vegetation of the foredunes is mainly composed of psammophilous herbaceous species such as *Ammophila arenaria* or *Agropyrum junceum* (Meur, 1993; Favennec, 1998). In the inner parts of the dune complexes are colonized by dense grasslands with a wide variety of plant species. The more sheltered and partially decalcified sectors are colonized by vegetation dominated by eagle ferns (*Pteridium aquilinum*), gorse (*Ulex* spp.), and heather (*Erica* spp., *Calluna vulgaris*). Finally, some dunes have a wooded cover mainly composed of coniferous trees such as maritime pine (*Pinus pinaster*) and Lambert cypress (*Cupressus macrocarpa*).

2.2. Holocene coastal changes

The post-glacial RSL changes were recently reconstructed along the western coast of France, based on a reappraisal of 66 sea level index points (Stéphan and Goslin, 2014; García-Artola et al., 2018). Slight differences in the rates of RSL rise were attributed to glacio-isostatic adjustments and reflect the migration of the European peripheral forebulge from the northeast to the northwest of Brittany during the Holocene (Goslin et al., 2015; García-Artola et al., 2018). A similar pattern of RSL change was depicted from spatio-temporal statistical model predictions for north, west and south Brittany. The rate of marine transgression slowed down at 7,000 cal BP, with RSL positions at -6.50 ± 1.1 m, at -7.35 ± 0.9 m, at -5.75 ± 1 m in north, west and south Brittany, respectively (García-Artola et al., 2018). In response to the RSL rise slowdown, modern coastline and costal barriers formed, with basal *Phragmites* peats occupying the base of the coastal sequences. In Brittany, these deposits have been dated in the range 7,000–4,500 cal BP and suggest a large extension of swampy environments behind relatively stable coastal barriers (Morzadec-Kerfourn, 1974; Goslin et al., 2013; Stéphan et al., 2015). Estuaries infilled with tidal flat and salt-marsh sediments (Menier et al., 2010; Penaud et al., 2020). With the stabilization of the RSL in the mid- to late-Holocene, alongshore sediment transport favoured the development of coastal spits and associated salt-marshes in low-lying coastal areas (Lespez et al., 2010; Stéphan and Laforge, 2013; Stéphan et al., 2015). In some embayed beaches, sand supply locally favoured the coastal sand-dune movement on surrounding slopes, as evidenced by the perched dunes dated to ca. 5,280 cal BP and ca. 4,350 cal BP at Pen Hat beach (Meurisse-Fort, 2008) and Gwendrez beach (Haslett et al., 2000), respectively. Between 2,900 and 2,700 cal BP, subtidal sedimentary prisms and coastal barriers recorded deep morphosedimentary changes. Sharp erosional contacts and/or sedimentary hiatuses were systematically observed in the coastal sedimentary sequences, indicating increased hydrodynamics and barrier breaching (Fernane et al., 2014; Goslin et al., 2013, 2015;

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Stéphan et al., 2015; Ehrhold et al., 2021;). After ca. 2,700 cal BP, marsh sedimentary sequences record continuous accretion to the present day, suggesting a new period of coastal barrier stabilization (Stéphan, 2011; Stéphan et al., 2015). However, coastal sand-dune systems appear to have experienced several phases of destabilization over the past 3,000 years. Based on the analysis of 18 sediment cores distributed along the coast of Brittany, Van Vliet-Lanoë et al. (2016) recently identified four periods of aeolian sand movement during the following periods: ca. 3,050-2,300 cal BP (Phase 1), ca. 1,600-1,150 cal BP (Phase 2), ca. 1,150-750 cal BP (Phase 3) and from ca. 600 cal BP (Phase 4).

2.3. Wind, wave and tide conditions

In western France, the coastal hydrodynamic pattern jointly depends on tides, wind and wave conditions. The climate of Brittany is characterized by temperate oceanic conditions with generally mild, wet winters and cool summers. Westerly- and south-westerly-directed winds are dominant (Fig. 1b). Wind speeds are strongly seasonally-modulated, with winter wind speeds almost 50% higher than summer values offshore (Bentamy and Croize-Fillon, 2014). The mean wind speed values are about 9 m/s and 5.50 m/s during the winter and summer seasons, respectively. During severe winter storm events, wind speeds can reach 50 to 60 m/s. On average, winds are mostly westerly-directed in winter. In spring, dominant winds are north-westerly- and south-westerly-directed in S and N Brittany, respectively, whereas they are mostly north-westerly-directed over the area during summer and fall (Bentamy and Croize-Fillon, 2014).

As similarly displayed by wind conditions, the wave climate is energetic and strongly seasonally-modulated, especially in western Brittany where high-energy winter swells and storm waves come from the W-NW with significant wave height frequently exceeding 5 m. Wave refraction and diffraction are significant near the coast due to the presence of numerous islands and reefs.

The coast is typically a meso- to macro-tidal environment with a highly variable tidal range from the NE to the W (Fig. 1a). The maximum tidal range reaches up to 14 m during spring tides in the Mont-Saint-Michel Bay and gradually decreases westward with a maximum ranging from 6.9 m to 7.6 m in the Iroise Sea. Along the southern coast of Brittany, the tidal range goes from 6.1 m in the Bay of Penerf to a minimum value of 3.3 m in the Gulf of Morbihan (Fig. 1a).

3. The Geoarchaeological Database (GAD) : methodology

3.1. General presentation

A geoarchaeological database (GAD) (see supplementary table 1) grouping all archaeological remains discovered in the coastal dunes of western France has been created from three main sources of information which are: (i) the national archaeological geodatabase (called "*carte archéologique nationale*") that has inventoried archaeological discoveries in France since the 1975s (Chaillou and Thomas, 2007; Lorho, 2014); (ii) archaeological operation archives (reports and notes taken in the field during excavations); and (iii) scientific papers published in local and national journals from the end of the 19th century. Three main criteria were utilised: (i) the location of the archaeological remains, (ii) their stratigraphic position within the aeolian sand deposits, and (iii) their age or chronological attribution (Fig. 2a and 2b).

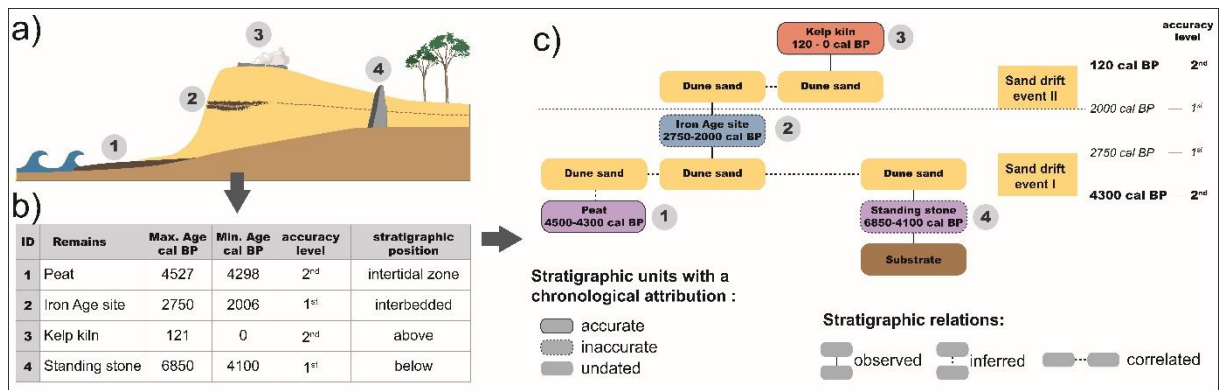


Fig. 2. Methodological approach applied in the present work. (a) Distribution of archaeological, historical and sedimentological remains associated to a theoretical coastal dune complex; (b) Organization of the geoarchaeological database (GAD); (c) Harris matrix deduced from available stratigraphical data. The numbers refer to newly-discovered remains.

3.2. Site location

In this study, we have only considered the archaeological finds located within the Holocene coastal sandy formations, whose spatial extension inland is provided by the 1:50,000 geological maps edited by the BRGM (Geological and Mining Research Institute). Most of the locations of discoveries made before the 1980s are poorly described and the geographical position of the archaeological sites was deduced from iconographic sources available in publications (maps, plans, photographs) and from local place names. For the most recent discoveries, the location of archaeological remains is based on more precise GPS or DPGS measurements. The local geographic coordinates have been converted into the international WGS84 system. The GAD includes 221 archaeological sites covering cultural periods from the Neolithic to present. These

remains are located within 78 dune complexes, evenly distributed along the northern, western and southern coasts of Brittany (Fig. 3, Tab. 1).

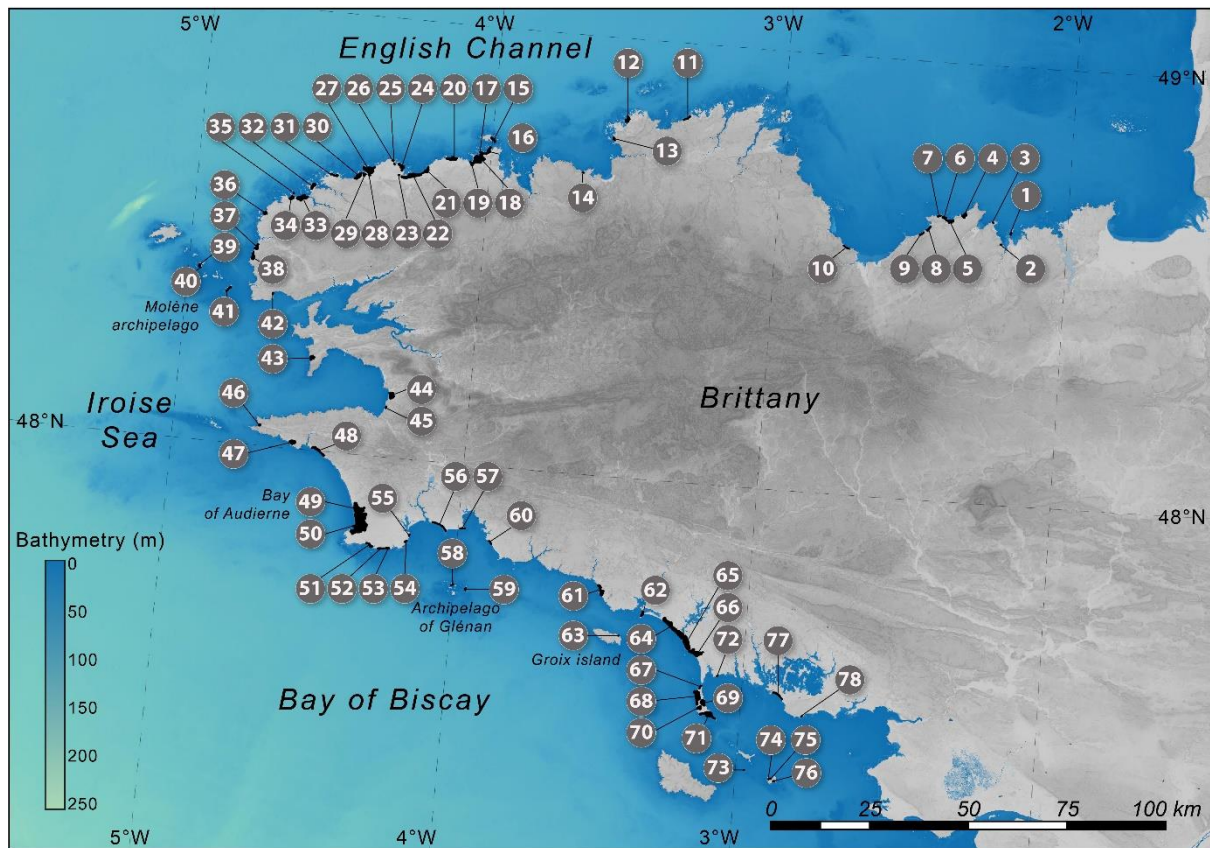


Fig. 3. Location map of the studied coastal sand-dune systems. The numbers refer to sites listed in Table 1.

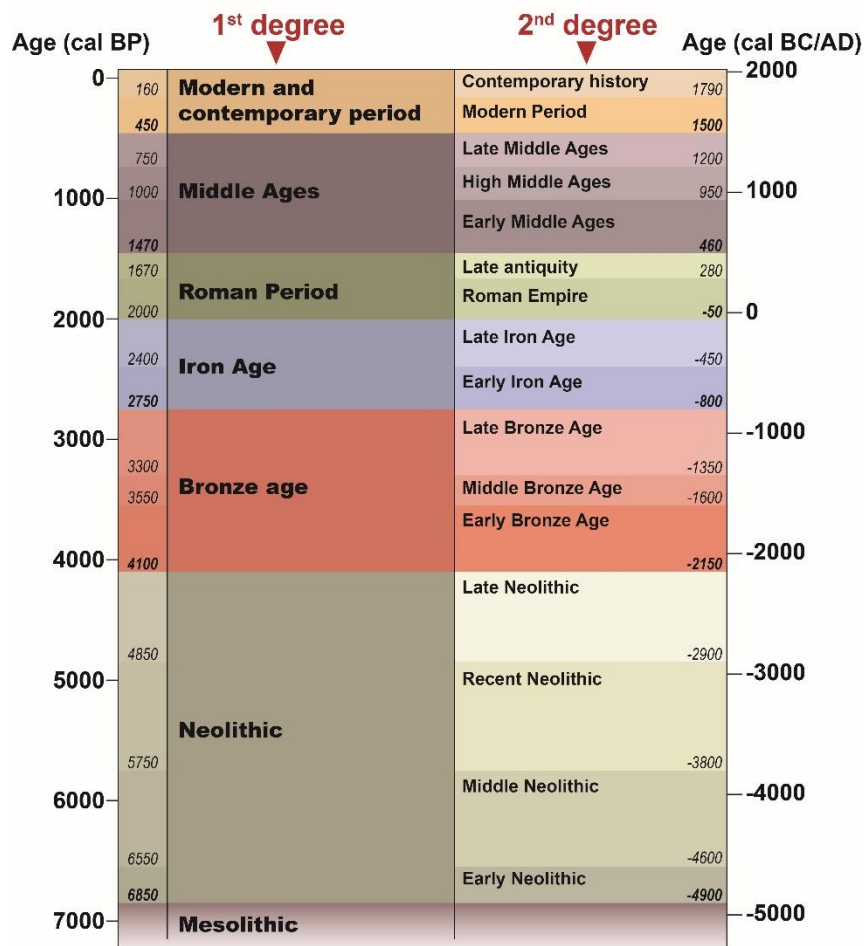
3.3. Stratigraphic position within the sandy sequences

Stratigraphic positions of the archaeological remains within the aeolian sand deposits were systematically integrated into the database according to three main configurations which are below, interbedded between and above (an) aeolian sand deposit(s) (Fig.2b). Only archaeological sites with a clearly established stratigraphic context were included. Sites without significant sandy deposits (thickness < 0.2 m) were not taken into account.

3.4. Chronological attribution

Ages of the remains were determined from a reappraisal of available archaeological data (absolute dating, architectural elements, type of monuments, and presence of ceramic, lithic and/or metallic materials). Based on the quality of these data, two degrees of chronological precision were attributed. The first precision degree characterizes poorly documented remains whose ages can only be related to the major cultural periods recognized in Brittany (Fig. 4). In

1 this case, chronological attributions show large uncertainties, especially for the Neolithic
 2 ($\pm 1,500$ years) and Bronze Age (± 700 years) periods. The second precision degree characterizes
 3 well-documented remains, with detailed archaeological information and, in some cases,
 4 absolute dating data (AMS- ^{14}C and OSL dates, archaeomagnetism). Ages of the remains were
 5 then related to different subdivisions of the major cultural periods in Brittany (Fig. 4). This
 6 second temporal division offers chronological attributions of a three centuries or less.
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44 **Fig. 4.** Chronological boundaries of archaeological and historical periods in western France.
 45 Chronological attributions of remains are subdivided into two precision degrees corresponding
 46 to major cultural periods (first degree) and to subdivisions of the latter (second degree).
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49 3.5. Additional data

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 51 Three types of additional data were integrated into our GAD: (i) archaeological, (ii)
 52 sedimentological, and (iii) historical (see supplementary table 1 and 2). First, some
 53 archaeological discoveries carried out on the beaches of the studied beach/dune systems were
 54 taken into account as the remains systematically corresponded to ancient terrestrial sites
 55 (habitats, burial sites) that were buried under the present-day coastal dunes. Therefore, they
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constitute temporal markers that pre-date the aeolian sand deposits and which are used for calibrating the first phases of coastal dunes mobility. Additional chrono-stratigraphic markers are supplied by accurately dated (radiocarbon) intertidal organic-rich peat deposits outcropping on the beaches of the studied beach/dune systems where they are commonly associated with the development of back-barrier marshes (Morzadec-Kerfourn, 1969, 1974; Visset and Bernard, 2006; Goslin, 2014). In direct contact with the bedrock, these deposits form the base of coastal sedimentary sequences, pre-dating the overlying aeolian sand deposits. Third, historical data (archives, old maps, historical photos) available from the last three centuries have been used to chronologically constrain the most recent phases of dune mobility. The Cassini map (produced between 1683 and 1744) and the Etat-Major map (edited between 1820 and 1866) were used to identify the extension of the dunes during this period. However, with regards to the criteria above, they are considered to be 1st degree chronological markers (not very precise) (Fig. 4) because the dune morphologies are not represented with sufficient detail as to distinguish between mobile and fixed dunes. For the last few decades, aerial photos produced by the *Institut Géographique National* (IGN) have been examined to complete the observations. Locally, images of coastal landscapes represented on old postcards were also studied. Lastly, we used recent historical syntheses that provide an in-depth analysis of coastal dune dynamics over the last centuries in Brittany (Charpentier, 2009; Lageat et al., 2019).

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3.6. Radiocarbon dates

AMS-¹⁴C dates available in literature were included in the GAD because they provide information on the chronology of archaeological sites (92 dates) and on the age of peat deposits (14 dates) located in the intertidal zone (see supplementary table 3). About organic sediments, conventional radiocarbon ages were calibrated with OxCal v.4.4.4 software (Ramsey, 2021) using the IntCal20 calibration curve (Reimer et al., 2020). Three dates obtained on marine shells in the Hoedic Island site were calibrated using the Marine20 curve (Heaton et al., 2020). Besides, the marine reservoir correction database was used (Reimer and Reimer, 2001) to determine the average reservoir age along the coasts of Brittany. An error-weighted mean of five ΔR values from sites located within ca. 150 km of the archaeological sites concerned yielded an average ΔR of -95 ± 62 years (Tisnérat-Laborde et al., 2010). Calibrated radiocarbon ages were reported in calendar years before present (cal BP) relative to 1950 AD with an uncertainty of 2 sigma. Despite a large number of dates (n=106), no statistical analysis of the chronological distribution of ages was attempted due to the over-representation of some archaeological sites documented by a large number of AMS-¹⁴C dates (e.g. 36 AMS-¹⁴C dates

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for Beg ar Loued site on Molène Island, 21 AMS-¹⁴C dates for Groah Denn site on Hoedic Island).

3.7. Archaeological-based dune stratigraphic reconstruction: Harris matrix

A Harris matrix (Harris, 1989) has been applied to each dune complex under study in order to reconstruct the local chronology of dune mobility periods (Fig. 2b). Conceptualized in the 1970s, the Harris matrix is widely used in archaeological research to document and represent stratigraphic relationships during excavations (e.g. Kobyliński, 1993; Trócoli, 1993; Dye and Buck, 2015). The Harris matrix is a sequence diagram that represents the relative temporal succession of all stratification units observed within an archaeological site (e.g. sedimentary layers, constructions, removal or erosional surfaces). In this paper, we consider each coastal dune as an archaeological site, i.e. as a coherent set of long-lasting deposits resulting from various natural and anthropogenic events. The archaeological remains are considered as uniform stratigraphic features in relation to the bedrock and to the lower and/or upper sand dune layers. Three main stratigraphic relationships are represented (Fig. 2b): (i) superposition of layers observed in the field; (ii) lateral correlation between layers of the same nature (especially dune sand layers), and (iii) stratigraphic relationships not observed in the field, but inferred from the nature and location of the stratigraphic units (e.g. foreshore sites pre-dating the formation of coastal dunes). Chronological data (age of archaeological sites and AMS-¹⁴C dates) were integrated into the Harris matrix to infer the maximum age of each aeolian sand layer. The beginning of a sand-drift event was defined from the age of the archaeological remains subsequently buried by the corresponding aeolian sand deposit. The end of a sand-drift event corresponds to the human settlements at the top of the corresponding aeolian sand deposit.

4. Results

This section describes the information provided by several of the archaeological discoveries in the coastal dunes of Brittany according to cultural periods (Fig. 4 and 5). Then, the Harris matrix applied to several dune complexes is described to illustrate the approach used to reconstruct the

dune chrono-stratigraphy. Finally, an evolutionary temporal template of dune mobility phases is proposed based on the compilation of the corresponding Harris matrices.

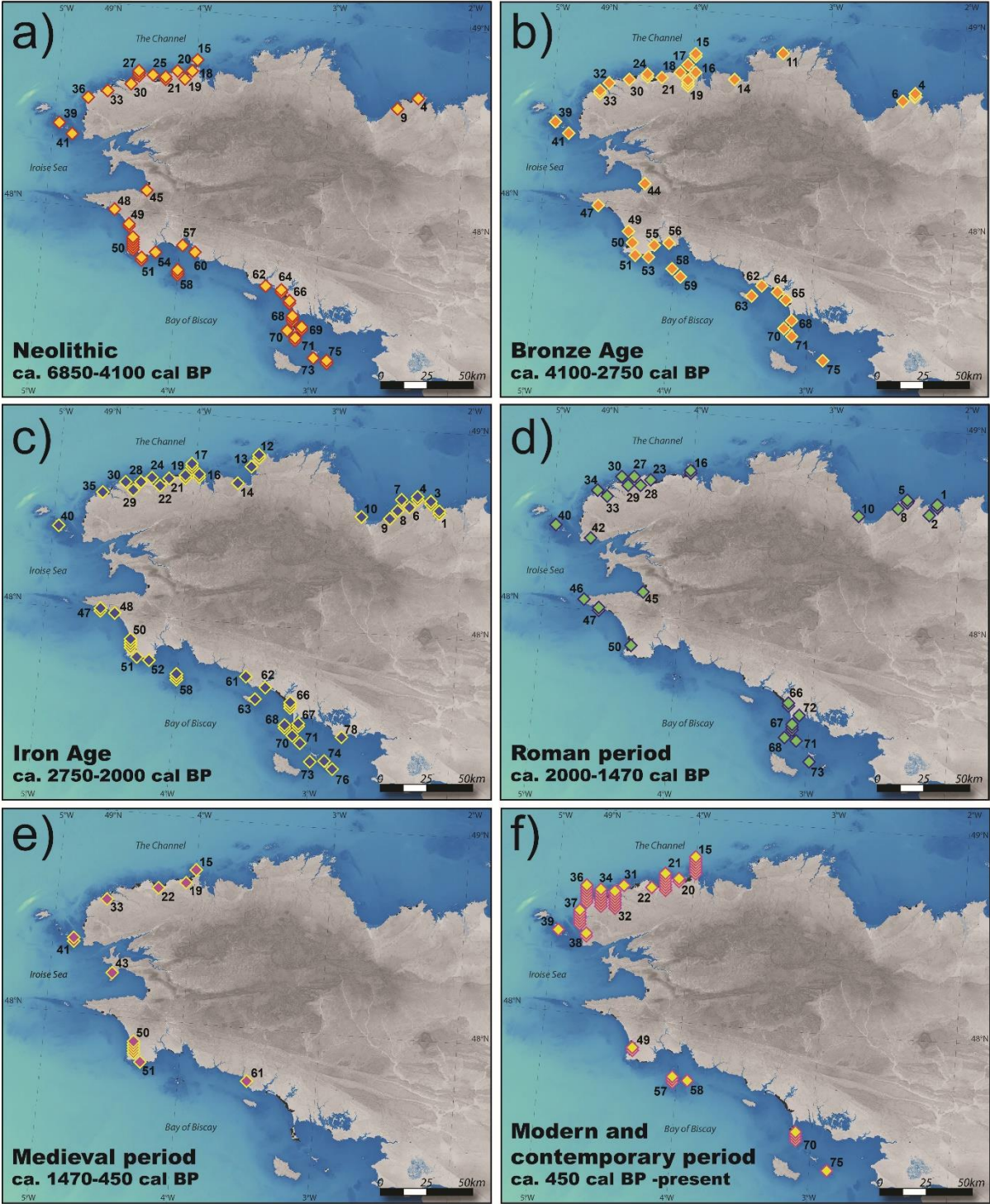


Fig. 5. Location maps of archaeological remains for : (a) the Neolithic period; (b) Bronze Age period; (c) Iron Age period; (d) Roman period; (e) Medieval period; (f) Modern and contemporary periods. The numbers refer to coastal dune sites listed in Table 1.

4.1. Coastal dune archaeological remains

4.1.1. Neolithic period (ca. 6,850-4,100 cal BP)

The Neolithic archaeological remains correspond either to megalithic monuments (n=28) found at the base of dune sedimentary sequences, or to lithic and ceramic material found within the underlying clayey-silty palaeosols (n=12). Because of their basal stratigraphic positions, the Neolithic remains can be considered only as *terminus post-quem* that provide information on the earliest aeolian sand-drift events. The Neolithic megaliths discovered in the coastal dunes of Brittany correspond to either (i) burial monuments of the mound/cairn type (n=17), or (ii) a series of standing stones (n=8). The available archaeological data suggest that these monuments are associated with long periods of human occupation and multiple reuses subsequent to their construction. Without numerous AMS-¹⁴C dates, ages of the megalithic monuments are difficult to precisely establish from the archaeological data.

4.1.2. The Bronze Age period (ca. 4,100-2,750 cal BP)

Most of the Bronze Age sites date to the Early Bronze Age (ca. 4,100 to ca. 3,550 cal BP) and were found at the base of aeolian sand deposit sequences (n=33) within silty-clayey paleosoils. They represent *terminus post-quem* to the overlying aeolian sand deposits. These remains mainly correspond to stone cists (individual burials: Briard, 1984; Blanchet et al., 2019) discovered along the dune fronts affected by marine erosion. At Port-Blanc (Penvénan, N Brittany, site no.11 on Fig. 5b), after episodes of shoreline retreat, numerous cists forming part of a necropolis have been discovered since the 1930s (Merlet, 1935; Giot, 1960; Le Roux, 1975). These burials were dug in paleosoil covered by a ca. 2 m-thick aeolian sandy deposit (Fig. 6a and 6b). At Port-Mélite (Groix Island, S Brittany, site no.63 on Fig. 5b), a similar burial cist contained a well preserved female skeleton which yielded a radiocarbon age of 3,888–3,692 cal BP (Le Roux, 1969; Nicolas et al., 2015; Nicolas, 2016). The burial was dug into silty paleosoil in turn overlaid by a 0.5 m-thick aeolian sand deposit.

Four discovered archaeological sites are interbedded within the aeolian sand deposits. On the Kerminihy dunes (Erdeven, S Brittany, site no.65 on Fig. 5b), numerous scatters of coastal flint debitage have been found in an extensive sand quarry (Chapuy, 1973, 1975). Large quantities of lithic material and ceramic fragments indicated temporary settlements between the Final Neolithic and the Early Bronze Age (4,850–3,550 cal BP; Chapuy, 1976). This archaeological level is interbedded with two aeolian sand deposits. As the remains are not associated with a humic horizon, these data suggest a human presence during a phase of aeolian sand deposition.

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On the Saint-Nicolas Island dune (Glénan archipelago, SW Brittany, site no.58 on Fig. 5b), the remains of a wall dating from the Early Bronze Age are interbedded with two sand-dune deposits, indicating perennial occupation during dune stabilization (see section 4.2). On the Béniguet Island (Molène archipelago, SW Brittany, site no.41 on Fig. 5b), a shell-midden dated to the Early Bronze Age (4,140–3,908 cal BP) is also interbedded within aeolian sand deposits (see section 4.2). Its upper part clearly shows a layer of humic sand, which also indicates stabilization of the dune massif during this period (Cudennec, 2019; Paillet and Nicolas, 2022).

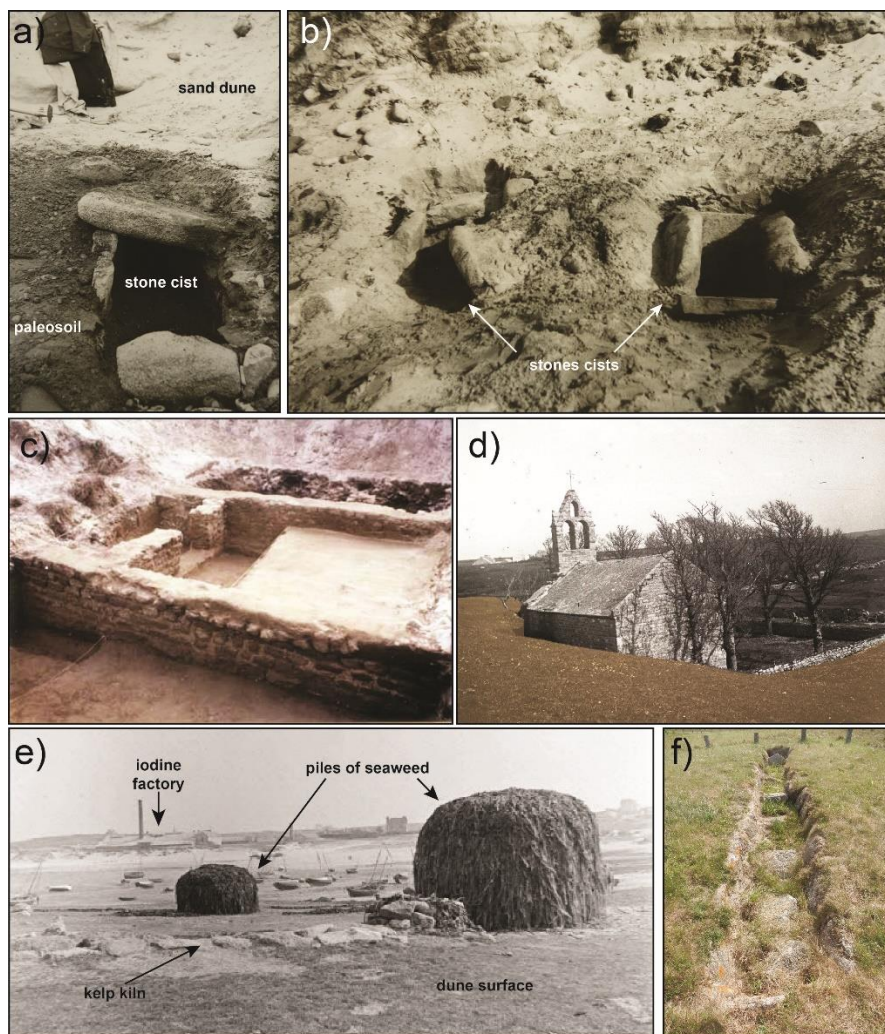


Fig. 6. Examples of archaeological remains discovered in the coastal dunes of Brittany. (a, b) Stone cists discovered around 1923 in the coastal dune of Port-Blanc (Penvénan, N Brittany) (source: *Archives du service Régional d'Archéologie*, Rennes); (c) *Villa maritima* dated to the High Roman Empire during excavation on the dune of Sables d'Or les Pins (Fréhel, N Brittany) (source: Langouët, 1979); (d) Photograph of the Saint-Egarec church around 1924 (Lampaul-Plouarzel, W Brittany) (source: Yroise, *Bibliothèque numérique patrimoniale de Brest*); (e) Kelp kilns and iodine factory at Porspaul in Lampaul-Plouarzel around 1938 (author: Pierre Toulgouat; source: *Museum of European and Mediterranean Civilizations - MUCEM*); (f) Kelp kiln at Porspaul in Lampaul-Plouarzel in 2016 (author: Yves Gruet; source: *Service Régional de l'Inventaire du Patrimoine en Bretagne*).

4.1.3. *The Iron Age period (ca. 2,750-2,000 cal BP)*

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2 A total of 54 archaeological sites attributed to the Iron Age have been inventoried within 35
3 coastal dune complexes in Brittany (Fig. 5c). A large number of these remains are interbedded
4 within aeolian sand deposits (n=20) and were mainly dated at the Late Iron Age (ca.
5 2,400–2,000 cal BP). The sea salt industry developed along the Brittany coasts during this
6 period is documented by remains, called “*briquetages*”, containing large quantities of terracotta
7 waste, containers and characteristic oven remains (Daire, 2003). For example, the Moulin de la
8 Rive site (Locquirec, W Brittany, site no.14 on Fig. 5c), corresponds to a vast complex of
9 habitats and sea salt production workshops attributed to the end of the Late Iron Age
10 (2,100–2,000 cal BP) (Giot et al., 1958, 1986). The archaeological levels are interbedded with
11 two layers of aeolian sand, reaching 2.5 m- and 1.5 m-thick for the lower and upper deposit,
12 respectively.
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4.1.4. *Gallo-Roman period (ca. 2,000-1,470 cal BP)*

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24 For the Gallo-Roman period, the most characteristic archaeological remains discovered in the
25 coastal dunes correspond to *villae maritimae* dated to the High Roman Empire (between ca.
26 1,970 and 1,660 cal BP). On the dunes of Sables-d'Or-les-Pins (Fréhel, NE Brittany, site no.5
27 on Fig. 5d), such a *villa* associated to a thermal complex was dated at ca. 1,775–1,755 cal BP
28 (Fig. 6c). The abandonment appears to have been caused by a fire dated to ca. 1,680 cal BP
29 (Langouët, 1979). Archaeological excavations shown that the residences were built on a
30 paleosoil covered by a 2.3 m-thick aeolian sand deposit (Langouët, 1979; Bizien-Jaglin et al.,
31 2002; Le Bot, 2003). At the Légenèse site (Carnac, S Brittany, site no. 72 on Fig. 5d), a similar
32 thermal complex dated between 1,850 and 1,650 cal BP was discovered after an episode of
33 shoreline retreat (Le Rouzic, 1910). The foundations of this *villa* overlaid aeolian sand deposits.
34 The site was also abandoned after a fire and the remains were later buried under an aeolian sand
35 deposit about 2.5 m-thick (Le Bot, 2003).
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4.1.5. *The medieval period (ca. 1,470-450 cal BP)*

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49 Only 12 medieval archaeological sites distributed within 8 dune complexes have been
50 discovered on the coastal dunes of Brittany (Fig. 5e). Two medieval habitats have been
51 particularly well documented. The site of Pen-er-Malo (Guidel, S Brittany, site no.61 on Fig.
52 5e) shows a group of 6 dry-stone houses built on a basal paleosoil overlaid by aeolian sand
53 deposits (Bertrand, 1972, 1975). The archaeological remains were radiocarbon-dated between
54 972 and 567 cal BP. The abandonment of the houses has been attributed to a sand inundation
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1 that buried the entire hamlet (Bertrand, 1972, 1975). At the Tronoën site (Plomeur, SW
2 Brittany, site no.50 on Fig. 4) two houses dates at ca. 950 to 750 cal BP were buried beneath
3 aeolian sand deposits (see section 4.2.5). The most accurate data for this period comes from a
4 necropolis located at Saint-Urnel (Plomeur, SW Brittany, site no.50 on Fig. 5e) where three
5 levels of burials are interbedded in an aeolian sand deposit (see section 4.2.5).
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10 *4.1.6. Modern and contemporary periods (ca. 450-0 cal BP to present)*

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12 Between the 16th and 17th centuries, the destruction of arable land, houses and churches by
13 aeolian-sand inundation is reported in many archival documents. In the village of Tréménac'h
14 (Plouguerneau, NW Brittany, site no.31 on Fig. 5f), the first invasions of aeolian sand occurred
15 during the mid-16th century (Lageat et al., 2019). In 1722, nearly two-thirds of the area was
16 inundated by sand dunes (Lageat et al., 2019). Historical sources indicate that the church was
17 abandoned in 1728 after being buried under 3 m-thick deposit of wind-blown sand (Perennec,
18 2004; Charpentier, 2009; Reille-Taillefert, 2010). On the Batz Island (NW Brittany, site no.15
19 on Fig. 5f), the church of Sainte-Anne, built around the 10th century, was severely damaged
20 under the weight of dune sands and abandoned in the 17th century (Moret, 1993; Charpentier,
21 2009; Lageat et al., 2019). Similarly, the chapel of Saint-Guevroc (Tréfléz, NW Brittany, site
22 no.22 on Fig. 5f), built between the 15th and 16th centuries, was quickly abandoned because of
23 its burial under sand deposits. In 1869, the church was almost invisible under the sandy cover
24 (Madeleneau, 1875). Other localities in western Brittany (e.g. Landeda, Santec) also
25 experienced sand inundation during the 18th century (Charpentier, 2009). In the village of
26 Lampaul-Plouarzel (NW Brittany, site no.37 on Fig. 5f), historical documents dating from the
27 18th century mention the frequent destruction of agricultural crops due to the deposition of
28 aeolian sands (Charpentier, 2009). The migration of the mobile coastal dunes reached the
29 church of the village in 1760. The religious authorities then decided to move the services to
30 another church because the building may have collapsed under the weight of the sand. From
31 the 19th century, numerous historical archives indicate a progressive stabilization of coastal
32 dunes. In 1838, a new church was built on the ruins of the old church of Lampaul-Plouarzel
33 (Thomas, 1889) (Fig. 6d). In the area of Tréfléz, the church of Saint-Guevroc was unearthed in
34 1872 and rebuilt from 1895 to 1898 once the dunes were stabilized (Menant, 1985). The
35 stabilization of the dunes from the 19th century is also indicated by the presence of numerous
36 seaweed ovens built on the surface of the coastal dunes to produce soda (Arzel, 1987) (Fig. 6e
37 and 6f). In this study, 47 seaweed ovens were inventoried and provide evidence of local stability
38 of coastal dunes since the 19th century.
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4.2. Chrono-stratigraphical reconstructions of coastal dune complexes

4.2.1. Dunes of the Molène Island

The recent excavation of a Bronze Age habitat in the coastal dunes of the Molène Island (W Brittany, site no.39 on Figs. 3 and 7) provided numerous precise archaeological and stratigraphic data. The different phases of human occupation have been reconstructed based on 36 AMS-¹⁴C dates (Pailler and Nicolas, 2019). The earliest evidence of occupation was attributed to the Early Neolithic, but the most abundant remains are associated with two oval houses composed of dry stone walls (Fig. 7b) dated to the Early Bronze Age. The oldest house was occupied between ca. 4,150 and ca. 3,900 cal BP and the youngest one between ca. 3,950 and ca. 3,700 cal BP (Pailler and Nicolas, 2019).

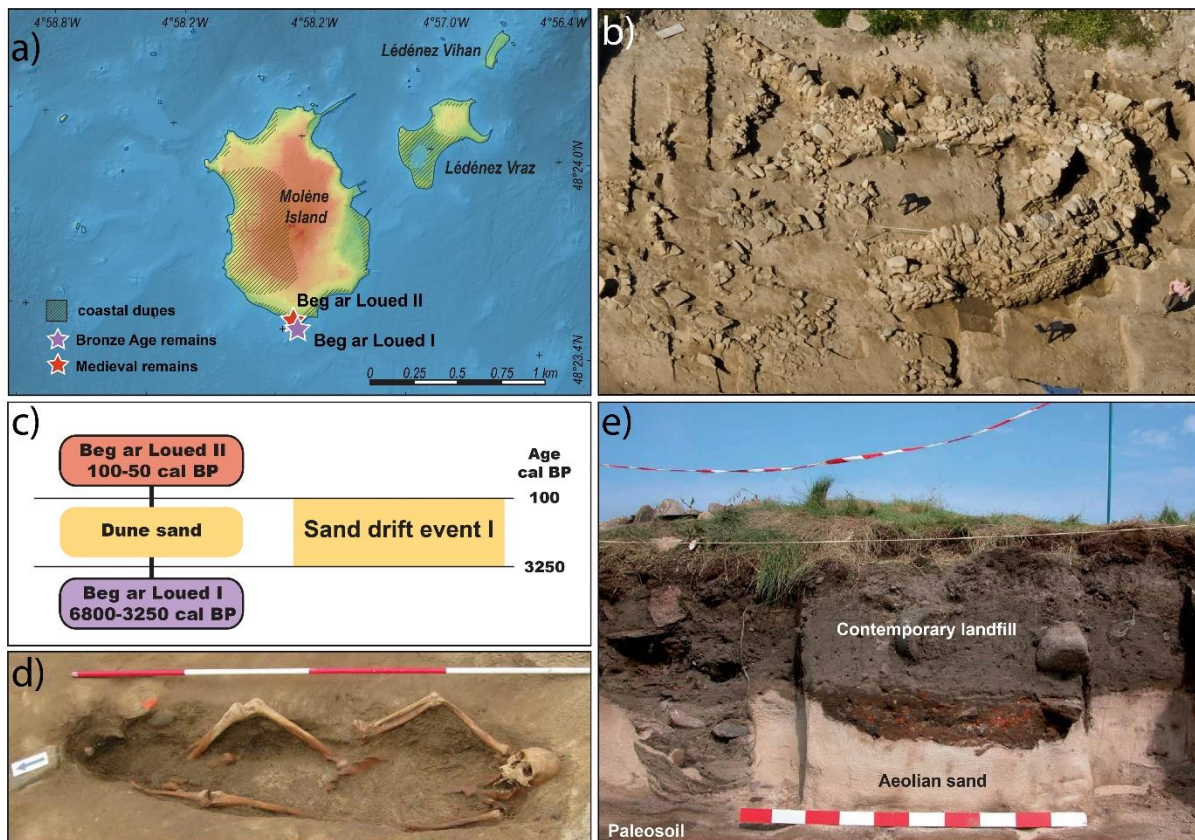


Fig. 7. Coastal dunes of Molène Island (W Brittany, site no.39). (a) Location map of the archaeological remains; (b) Aerial photography of the dry stone oval houses of Beg ar Loued I site during excavation (author : *Marine nationale*; source: Pailler and Nicolas, 2019); (c) Harris matrix based on observations at the Beg ar Loued I and II archaeological sites; (d) Modern tomb discovered in aeolian sand during excavation of the Beg ar Loued site (source: Pailler and Nicolas, 2019). (e) Stratigraphic section in the northwestern part of the Beg ar Loued site (author: Y. Sparfel; source: Pailler and Nicolas, 2019).

After abandonment, the ruins of these houses were used as sheep barns between ca. 3,800 and ca. 3,250 cal BP. The stratigraphic data reveal that much of the site was subsequently buried by a 1 m-thick aeolian sand deposit. Several contemporary remains associated with hunting, seaweed harvesting, and agricultural activities have been found at the top of these sandy sequences (Fig. 7e). A well-preserved human skeleton dated from the 18th to 19th centuries was also discovered in a pit dug into the dune and the buried soil. From these data, a single sand-drift event was identified between ca. 3,250 and 200 cal BP (Fig. 7d).

4.2.2. Dunes of Goulvars

In the Goulvars site (Quiberon, S Brittany, site no.70 on Figs 3 and 8), the stratigraphic sequence was reconstructed from the analysis of 6 archaeological sites. Two Neolithic megalithic sites (Conguel and Roc'h Priol sites) and an Early Bronze Age stone-cists cemetery (Beg er Vil site) are associated with the clayey palaeosol at the base of the aeolian deposits.

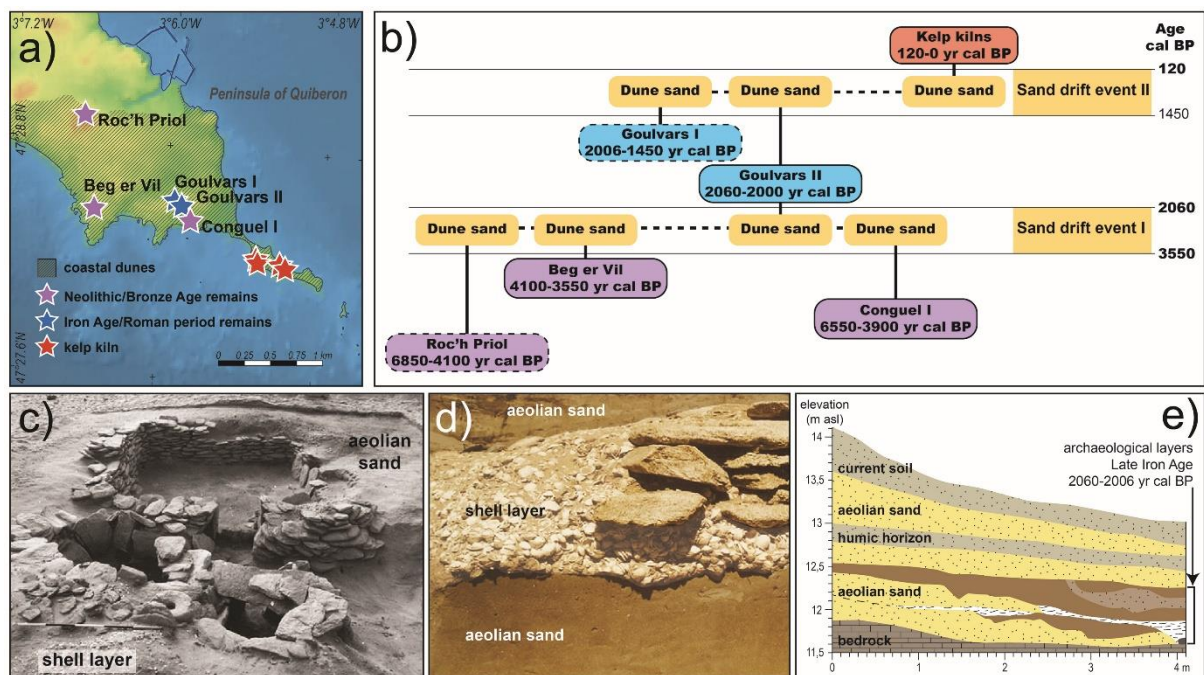


Fig. 8. Coastal dunes of Goulvars (Quiberon, S Brittany, site no.70). (a) Location map of the archaeological remains; (b) Harris matrix based on observations of archaeological sites discovered in the dune complex; (c) Photography of the Goulvars II site (house S11) during the excavation stage (source: Hyvert, 1987); (d) Photography of the stratigraphic section of the M3 wall and the marine shell deposits interbedded in the eolian sand at the Goulvars II site (source: Hyvert, 1985); (e) Simplified stratigraphic section of the Goulvars II site, after Hyvert (1985).

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A late Iron Age settlement (Goulvars II site; ca. 2,060-2,000 cal BP) was discovered interbedded within sandy sediments indicating the stabilisation of the dune complex at this period. Several dry-stone houses whose foundations were dug in underlying aeolian sand deposits occur beneath two layers of white aeolian sands (Figs 8c, 8d and 8e). The latter are 2.5 m-thick and are separated by an undated humic horizon (Fig. 8e). From these records, the first sand-drift event is identified between the Early Bronze Age and the Late Iron Age, i.e. in the range ca. 3,550 and 2,060 cal BP. A further Roman-age settlement (Goulvars I site) has been discovered at the base of the aeolian stratigraphic sequence. This is the most recent site positioned below the sand deposit and it represents *terminus post-quem* for the second sand-drift event. At the top of the Goulvars dunes, 4 kelp kilns indicate the stabilisation of the massif during the 19th century. From these data, a second sand-drift event has been identified between the Roman and the Contemporary period ca. 1,450-120 cal BP.

4.2.3. *Dunes of the Béniguet Island*

On the Béniguet Island (Le Conquet, W Brittany, site no.41 on Fig. 3), a loessic paleosoil is overlaid by 3 shell-middens interbedded within aeolian sand deposits (Cudennec, 2019; Paillet and Nicolas, 2022; Fig. 9). The basal shell-midden has been radiocarbon-dated from 4,404–4,150 cal BP, i.e. the end of the Neolithic period (bell beaker culture). This anthropogenic deposit is overlaid by a 0.3 m-thick aeolian sand layer, at the top of which an intermediate shell-midden has been dated to the Early Bronze Age, from 4,140 to 3,908 cal BP. This succession of sedimentary deposits suggests a sand-drift episode between ca. 4,250 and ca. 4,000 cal BP (Fig. 9c). A humic aeolian sand deposit, about 0.2 m-thick and without archaeological remains, overlies this second shelly level. Its upper part is composed of a 1.05 m-thick layer of white aeolian sand, and an upper shell-midden dated between 1,286 and 1,123

cal BP, indicating a second sand-drift event between ca. 4,000 and ca.1,200 cal BP (Fig. 9c).

Finally, the top of the sedimentary sequence is formed by a layer of humic aeolian sand.

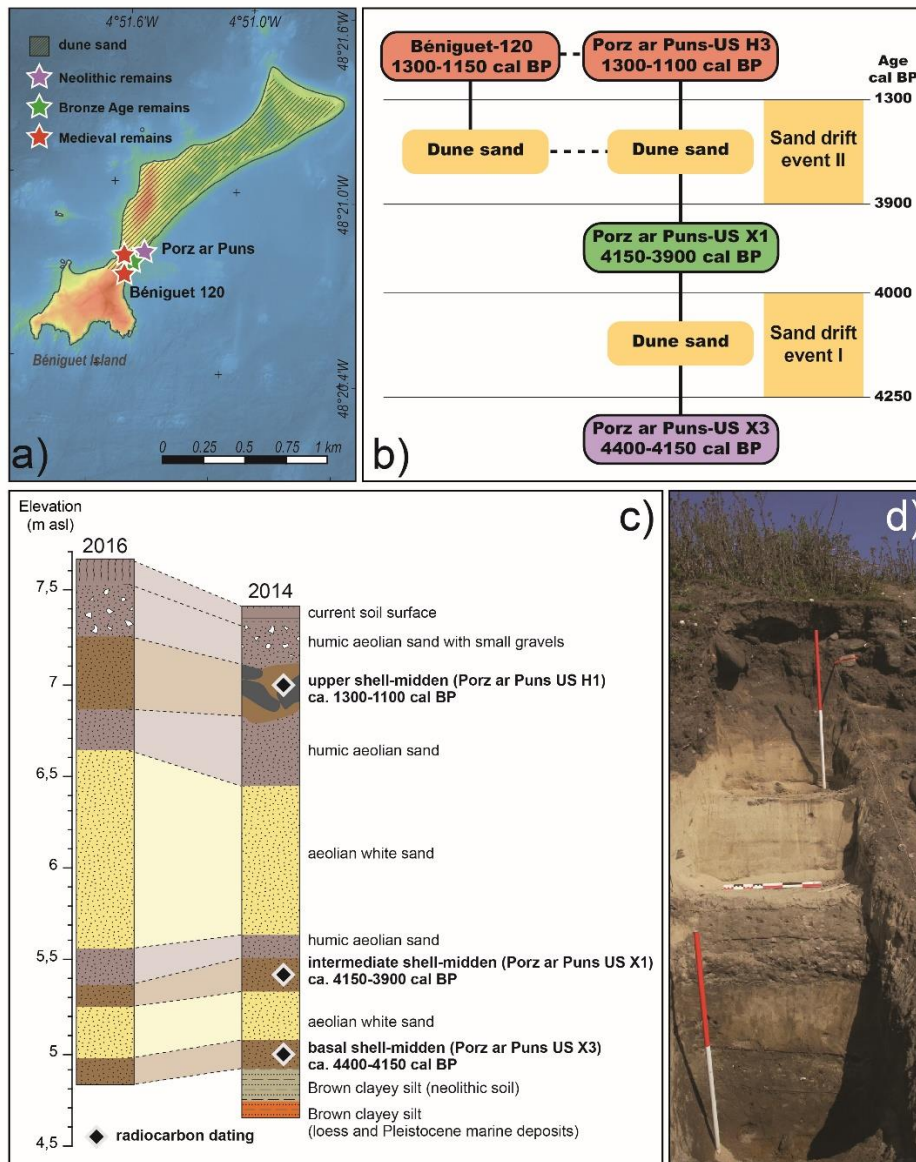


Fig. 9. Coastal dunes of Béniguet Island (Le Conquet, W Brittany, site no.41). (a) Location map of the archaeological remains; (b) Harris matrix based on observations at the archaeological sites on Béniguet Island; (c) Stratigraphic sections observed in 2014 and 2016, after Cudennec, (2019) and Paillet and Nicolas (2022); (d) Photography of the stratigraphic section observed in 2014, (source: Cudennec, 2019).

4.2.4. Dunes of the Saint-Nicolas Island

The stratigraphic sequence of the aeolian sand deposits of the Saint-Nicolas Island (Fouesnant, W Brittany, site no.58 on Fig. 3) was reconstructed from the analysis of 6 archaeological sites named Saint-Nicolas I, II, III, IV, V and VI, respectively (Fig. 10).

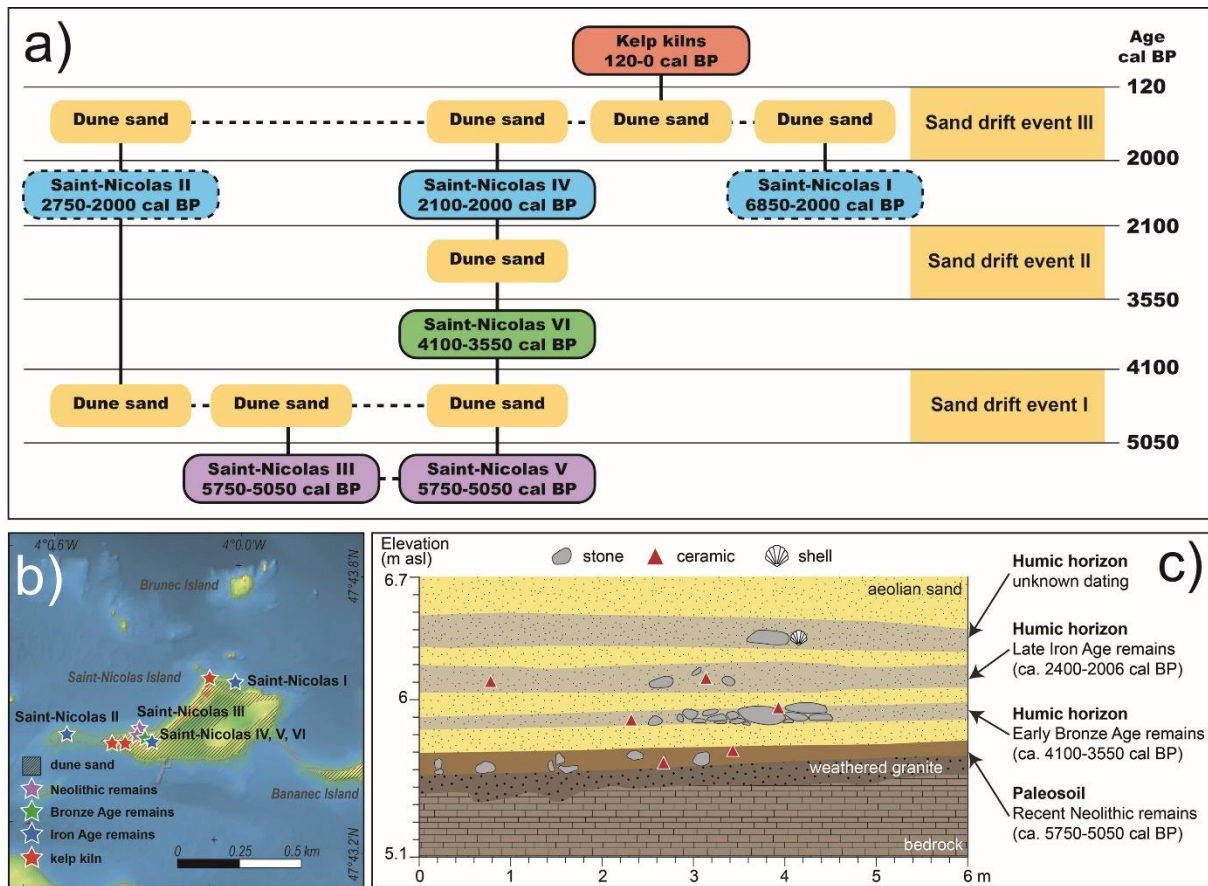


Fig. 10. Coastal dunes of Saint-Nicolas Island (Fouesnant, W Brittany, site no.58). (a) Harris matrix based on observations of archaeological sites discovered in the dune complex; (b) Location map of the archaeological remains; (c) Stratigraphic section of the Saint-Nicolas IV, V and VI sites, after Hamon (2007).

The most detailed data has been obtained from the Saint-Nicolas IV, V, VI sites (Hamon, 2006, 2007), where a basal paleosoil is overlaid by 4 successive sand dune deposits with interbedded humic horizons containing a high number of archaeological materials (Fig. 10c). The paleosoil situated at the base of the sequence contained numerous ceramic and lithic remains attributed to the Recent Neolithic (ca. 5,750–5,050 cal BP). A Late Neolithic settlement has been also discovered in the basal palaeosol of Saint-Nicolas III site (Hamon, 2006). This deposit is overlaid by a 0.15 m-thick aeolian sand layer, at the top of which the first humic horizon contains a dry stone wall and ceramics characteristic of the Early Bronze Age (ca. 4,100-3,550 cal BP), both indicating a stabilisation of the dune complex during this period. This succession of sedimentary deposits indicates that the first sand-drift episode occurred between ca. 5,050 and ca. 4,100 cal BP (between Late Neolithic and Early Bronze Age). This sequence is overlaid by a 0.18 m-thick aeolian sand layer at the top of which a second humic horizon that contains fragments of ceramics dating from the Late Iron Age (ca. 2,400-2,000 cal BP). Two other

1 settlements located at the north of the island have been attributed to the same period (Saint-
2 Nicolas I and II sites). One of which has been discovered in a humic horizon interbedded in the
3 dune sands. These data indicate a second period of dune stabilization during the Late Iron Age.
4 A second sand-drift event is consequently identified between ca. 3,550 and 2,100 cal BP
5 (between Early Bronze Age and Late Iron Age). These remains are covered by two successive
6 aeolian deposits with an interbedded humic horizon. A stone construction associated with
7 fragments of *Pecten maximus* shells is present within this humic layer, but no dating was carried
8 out. Finally, the upper humic horizon corresponds to the current dune soil. Four kelp kilns
9 observed on this island indicate the stabilization of the dune complex in the 19th century. Since
10 the dating of the interbedded humic horizon is not yet available, only one sand-drift event can
11 be identified between the Late Iron Age and the 19th century (ca. 2,000 and 120 cal BP).
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21 ***4.2.5. Dunes of the Audierne Bay***

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23 Among all the studied dune complexes, those of the Audierne Bay (Plomeur, SW Brittany, site
24 no.50 on **Figs 3 and 11**) contain the largest number of archaeological remains (n=15). Neolithic
25 megalithic monuments as well as Bronze Age stone cist has been discovered in a clayey
26 paleosoil forming the base of the aeolian sequences (**Fig. 11c**). There, 4 Iron Age settlements
27 have been identified, two of which were interbedded in the aeolian deposits. The oldest well-
28 dated remains are a Late Iron Age necropolis (La Torche, Plomeur: [Kayser 1984, 1986, 1987](#)),
29 which indicates that the dune was stabilised between 2,400 and 2,000 cal BP (**Fig. 11d**). From
30 these data, the first sand-drift event at this site is identified as occurring between 3,550 and
31 2,400 cal BP, i.e. between the end of the Early Bronze Age and the beginning of the Late Iron
32 Age. An extensive medieval necropolis has been excavated in the Saint-Urnel site (Plomeur
33 locality, **Fig. 11e and 11f**). The sedimentary sequence shows aeolian sand deposits with three
34 interbedded levels of burials (levels I to III in **Fig. 11e**) ([Giot and Monnier, 1977](#)). Level I is
35 associated with remains of wooden and dry stone constructions built on a ca. 0.9 m-thick sand
36 layer. A humic horizon at the top of this sandy deposit indicates that the dune was stabilised by
37 vegetative cover from 1,708 to 979 cal BP. Level II is observed in a sedimentary deposit ca. 0.4
38 m-thick that encloses alternating layers of humic horizons and white sand, indicating an
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episodic invasion of aeolian sand. A AMS-¹⁴C date on bones provided ages ranging from 1,065 to 691 cal BP. Level II is overlaid by a ca. 0.7 m-thick homogeneous aeolian sand deposit.

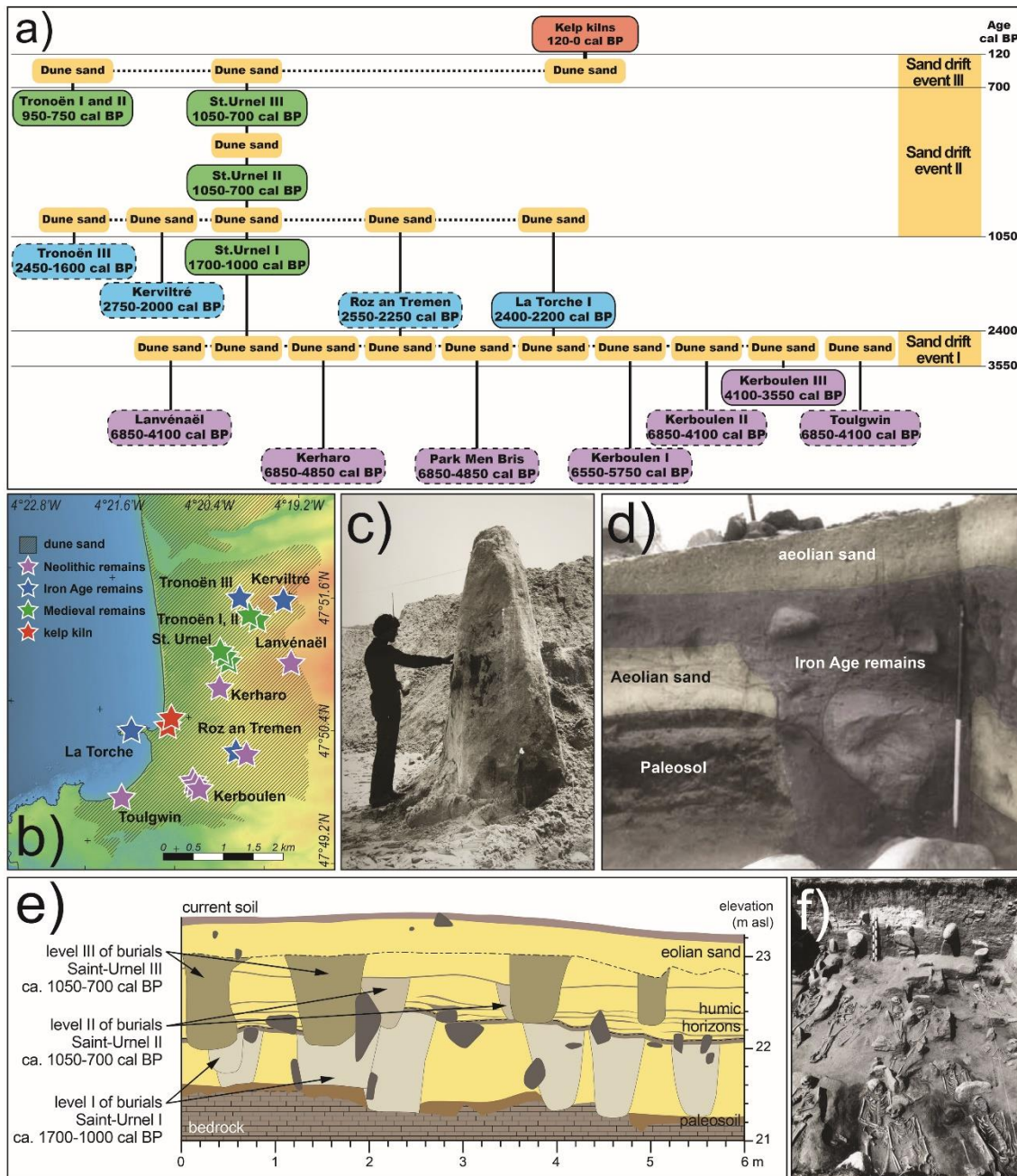


Fig. 11. Coastal dunes of the Audierne Bay (Plomeur, W Brittany, site no.50). (a) Harris matrix based on observations of archaeological sites discovered in the dune complex; (b) Location map of the archaeological remains; (c) Photography of the Kerharo standing stone when it was discovered in 1978 (unknown author; source: *Service Régional de l'Archéologie Bretagne*); (d) Photography of the Iron Age settlement of La Torche during the excavation stage (source: [Kayser 1987](#)); (e) Stratigraphic section of the Saint-Urnel site, after [Giot and Monnier \(1977\)](#); (f) Photography of the Saint-Urnel necropolis during the excavation stage (source: [Giot and Monnier, 1975](#)).

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2 Finally, the level III occurring at the top of this sandy layer yields ages between 1,059 and 692
3 cal BP. AMS-¹⁴C dates from levels II and III are quite similar, suggesting the continuous use
4 of this necropolis despite the increasing invasion of dune sands. Consequently, a second sand-
5 drift event has been identified during this period between ca. 1,050 and 700 cal BP. Level III
6 of the Saint-Urnel necropolis is overlaid by a layer of aeolian sand about 0.4 m-thick. Another
7 medieval settlement has also been investigated at the Tronoën site where two dry stone houses
8 dated from ca. 950 to 750 cal BP are buried beneath a sandy cover ca. 0.5 m-thick (Villard,
9 2008). At the top of this last aeolian deposit, i.e. at the present-day dune soil, 2 kelp kilns have
10 been identified, indicating the stabilisation of the complex during the 19th century. A third
11 sand-drift event is then defined between 700 and 120 cal BP.
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21 **4.3. Regional chronology of coastal dunes mobility**

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23 Archaeological and historical data supplied by most of coastal dunes in Brittany (n=60) are too
24 limited to identify more than one sand-drift event at a regional scale. Two sand-drift events
25 have been accurately documented at only 14 studied sites, whereas three coastal dune sites are
26 sufficiently well-documented to highlight three successive chronologically well-constrained
27 sand-drift events (Tab. 1). Although these events cover a wide time-period ranging from 6,700
28 to 50 cal BP, the compilation of all these data clearly shows 4 main periods of coastal dune
29 mobility (Fig. 12).
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37 A first period is identified at the end of the Neolithic, between ca. 4,250 and ca. 4,100 cal BP,
38 although being evidenced by a limited number of archaeological sites. The beginning of this
39 period is in the time-range 4,404–4,150 cal BP from one AMS-¹⁴C date obtained on a paleosoil
40 at the base of the aeolian sand deposit sequence on the Béniguet Island site (W Brittany). The
41 end of this period of dune mobility is supported by Early Bronze Age (ca. 4,100 to ca. 3,550
42 cal BP) archaeological remains interbedded within aeolian sand deposits on the Saint-Nicolas
43 Island (SW Brittany).
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50 A second period of coastal dune mobility is recognized between the end of the Bronze Age and
51 the beginning of the Iron Age, between ca. 3,250 and ca. 2,400 cal BP. Numerous Early Bronze
52 Age sites have been discovered at the base of dune deposit sequences (e.g. Port Blanc I site,
53 Penvénan) or correspond to the final use of Neolithic megalithic tombs (e.g. Conguel I site,
54 Quiberon). The most recent date for the beginning of this period comes from the Beg-ar-Loued
55 habitat site (Molène Island) and it ranges 3,446 to 3,251 cal BP. This radiocarbon dating is used
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to define the beginning of this mobility phase. The end of this period takes place during the Late Iron Age (ca. 2,400–2,000 cal BP), as suggested by the numerous remains of settlements discovered on top of the sandy deposits of this period (e.g. Mesperleuch site, Plouhinec; La Torche site, Plomeur).

A third phase of dune mobility is highlighted during the Middle Ages, between ca. 1050 and ca. 700 cal BP. However, this phase is only identified on the coastal dune of the Audierne Bay where burial levels II and III of the Saint-Urnel necropolis provide dates for the beginning and end of this period, respectively.

A fourth period of dune mobility is identified between ca. 350 and ca. 110 cal BP from historical data. The beginning of this period is represented by the abandonment of the church of St-Anne (Batz Island, no. 15 on Fig. 3) in the 17th century caused by the invasion of the coastal dune sands. For this last period, the end is defined by the reconstruction of the chapel of Lampaul-Plouarzel in 1838.

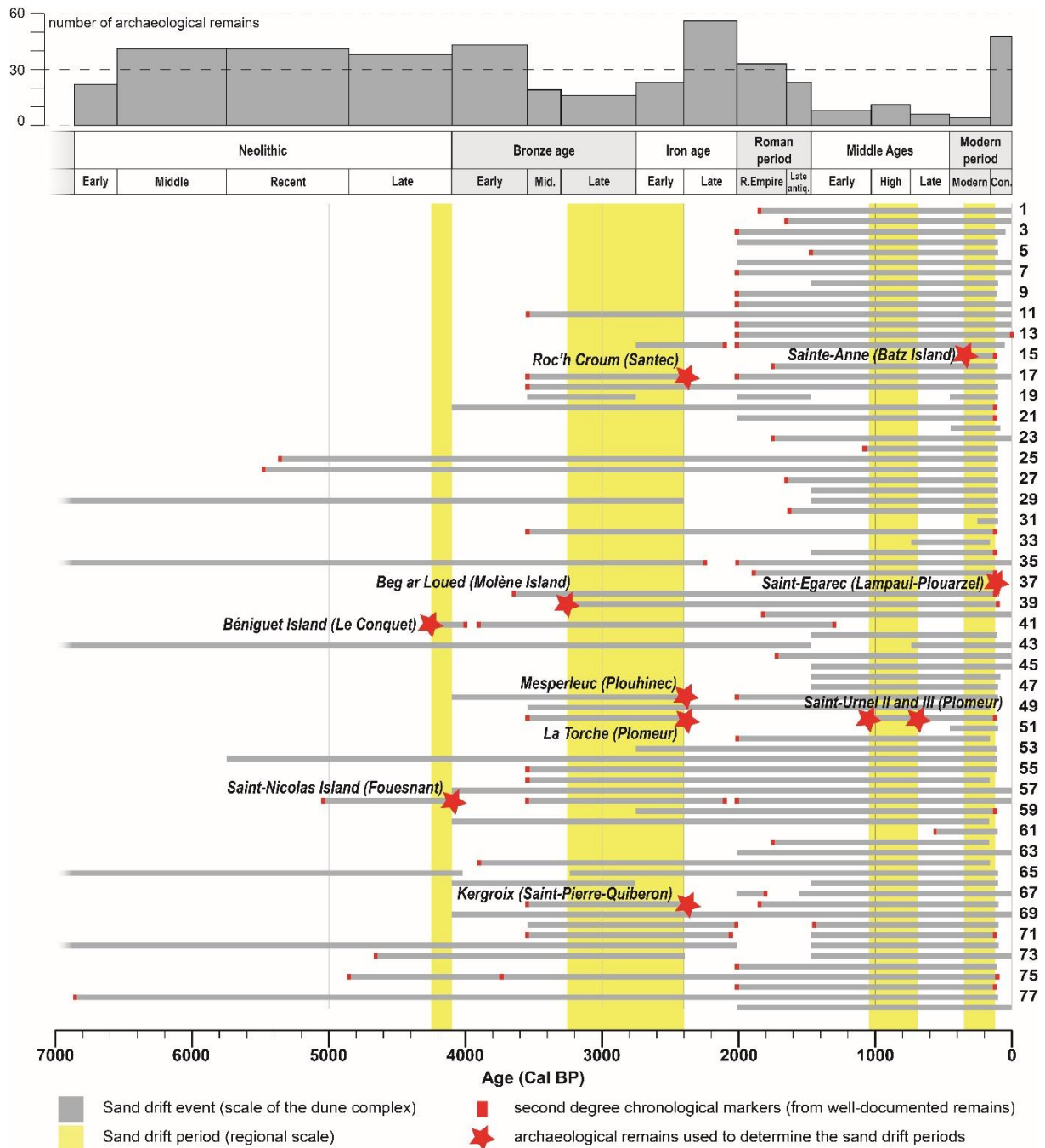


Fig. 12. Compiled data about sand-drift events obtained for each dune massif (for numbers refer to **Tab. 1** and **Fig. 3**). Yellow bands represent major sand-drift periods identified at a regional scale.

5. Discussion

5.1. Methodological issues

The geoarchaeological approach used in this study is based on the analysis and synthesis of abundant scientific literature devoted to archaeological sites and further completed by an

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extensive historical dataset. Such an approach is only made possible in countries, which benefit from a long-lasting tradition of archaeological and historical researches that permit a large amount of data to be re-examined in order to question regional-scale environmental changes. Along the UK coastlines, for instance, numerous excavations of multi-period archaeological sites in machair and coastal dunes areas were coupled with abundant historical references to weather events in chronicles, hagiographies and laws in order to finely reconstruct the dynamics of coastal sand-dune systems in Holocene times (e.g. [Wilson and Braley, 1997](#); [Wintle et al., 1998](#); [Gilbertson et al., 1999](#); [Wilson et al., 2001, 2004](#); [Sommerville et al., 2003, 2007](#); [Griffiths, 2015](#)).

One of the difficulties in analysing archaeological and historical data is the great heterogeneity of the available information, which concerns diverse cultural periods and various types of corresponding material (e.g., temporary camps, perennial habitats, cult and funerary sites, sites related to the exploitation of marine resources). For archaeological purposes, chronological attributions are primarily based on the nature of the remains which makes it possible to associate objects with material cultures. Absolute dating (AMS-¹⁴C, dendrochronology, archaeometry, etc.) is only used to confirm initial interpretations and to precise the chronological attribution. In Brittany, the succession of material cultures is now accurately established and the chronological division into cultural periods and sub-periods has become much more precise since the pioneer archaeological work more than a century ago (e.g. [Boujot and Cassen, 1992](#); [Milcent, 2012](#); [Menez and Lorho, 2013](#); [Blanchard, 2017](#); [Stéphan et al. 2017](#); [Nicolas et al. 2019](#)). Consequently, a systematic reappraisal of the earliest available dataset has been carried out in order to correct potentially erroneous interpretations, especially about previous chronological attributions (e.g. [De Closmadeuc, 1886](#); [Du Chatellier, 1907](#)). Despite these efforts, the age of many remains is still very imprecise, due to their nature or poor state of preservation. This has justified to take into account two degrees of dating precision for all the studied archaeological sites.

About the coastal dunes systems in Brittany, some archaeological remains are clearly associated with organic levels interbedded within the aeolian sand deposits (e.g. sites of Saint-Nicolas Island, Fouesnant). Thus, they represent useful chrono-stratigraphic markers in the absence of absolute dating. However, stratigraphic data are poorly detailed in the archaeological literature. Prior to the 2000s, the remains discovered in the coastal dunes of Brittany were most often excavated and analysed without any considerations about their sedimentary and stratigraphic contexts (e.g. [Du Chatellier, 1896](#); [Quinio, 1971](#); [Langouët, 1980](#)). Therefore, observations and

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interpretations were strictly devoted to archaeological issues. The Harris diagram used in the present work aims to partly fill this stratigraphic/chronological gap. Despite its frequent use in archaeological studies (e.g. [Kobyliński, 1993](#); [Trócoli, 1993](#); [Dye and Buck, 2015](#)), this tool had never been used to reconstruct the chrono-stratigraphy of coastal dunes. From available archaeological and historical information, this method is highly relevant to estimate the age of aeolian sand deposits and then to establish the accurate chronology of sand-drift events. This approach is applied here to coastal sand dune systems in Brittany using archaeological remains as chrono-stratigraphic markers of dune stabilization. We assumed that past human coastal communities favoured fixed dunes for permanent settlement. Therefore, a re-examination of previous archaeological dataset was also carried out to reinterpret the duration of human occupation in the coastal dunes of Brittany. These periods of occupation are very variable from sites to sites, ranging from temporary visitations (e.g. site of Kerminihy, Erdeven) to human settlements covering a few hundred years to several millennia (e.g. site of Goerem, Gâvres). In the case of perennial settlements, it is possible to associate the presence of archaeological remains with periods of dune stabilisation. About temporary settlements, it much less clear whether they fit in time with periods of dune stabilization or mobility.

The adaptive ability (or resilience) of past human communities to manage environmental stress ([Bradt Möller et al., 2017](#)) may have induced an abandonment of human settlements long after the initiation of sand dune migration. Data obtained from the Saint-Urnel medieval site clearly show that populations continued to use the necropolis despite sand inundation. Similarly, religious monuments buried by aeolian sands from the 15th and 16th centuries were regularly maintained for several decades before being permanently abandoned. Such a mismatch between the environmental constraint (sand invasion) and the societal response (abandonment) is much more difficult to argue for Prehistoric or Protohistoric periods because attempts to stabilize the coastal dunes have left no known archaeological evidence.

5.2. Regional comparison

Between 4,250 and 4,100 cal BP, the oldest phase of dune mobility ([Fig. 12](#)) has been identified from a limited number of sites located only on the southern (e.g. sites of Saint-Nicolas Island, Hoëdic Island, Ile aux Chevaux and Kerminihy beaches) and the western coasts of Brittany (Beniguet Island).

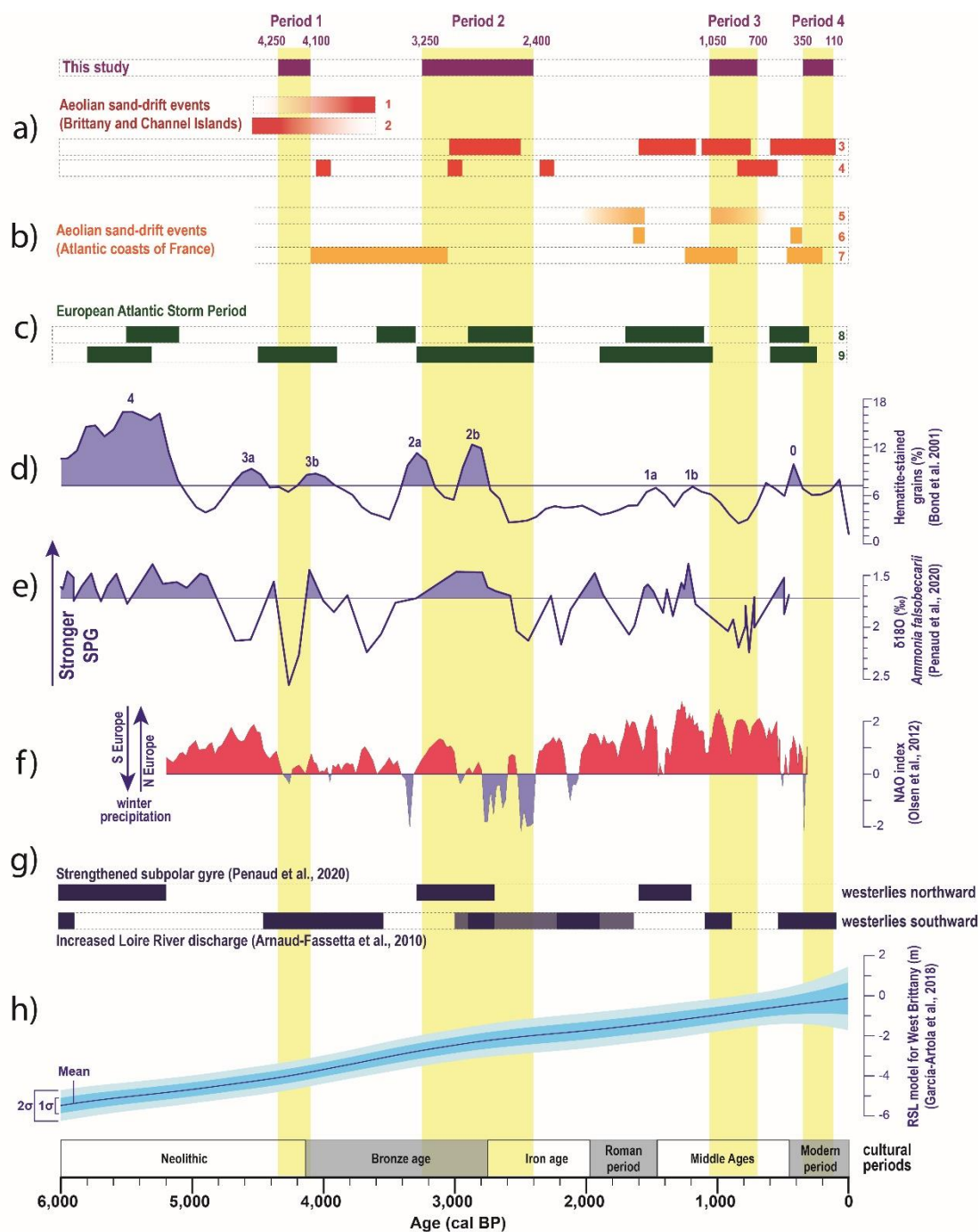


Fig. 13. Aeolian sand-drift events on the Brittany and Atlantic coasts of France and North Atlantic climate records: Yellow and purple bands represent aeolian sand-drift events identified in this study. (a) Aeolian sand-drift events identified in Brittany and the Channel Islands: 1. Verger Bay, Cancale, North Brittany (Regnault et al., 1995) 2. Beach of Guendrez, Plouhinec, West Brittany (Haslett et al., 2000) 3. Dunes building phases in Brittany (Van Vliet-Lanoë et al., 2016) 4. Herm Island, Channel Islands (Bailiff et al., 2014); (b) Aeolian sand-drift events identified on the Atlantic coasts of France : 5. Picardy, North France (Meurisse et al., 2005) 6. Aquitaine, South-West France (Bertran et al., 2020) 7. Aquitaine, South-West France (Clarke et al., 2002); (c) European Atlantic Storm Periods: 8. European Atlantic storm events from Pouzet et al. (2018) 9. Holocene storm periods in northern Europe from Sorrel et al. (2012); (d) Hematite-stained quartz percentages record from stacked North Atlantic Ocean

1 cores with Bond events numbered (Bond et al., 2001); (e) $\delta^{18}\text{O}$ curve acquired on *Ammonia*
2 *falsobeccarii* benthic foraminifera from CBT-CS11 core, Northern Bay of Biscay, North-East
3 Atlantic Ocean (Penaud et al., 2020), negative anomalies has been established in reference with
4 the average of the considered dataset: blue (more IRD or stronger SPG) ; (f) North Atlantic
5 Oscillation (NAO) index (Olsen et al., 2012) (red : positive NAO-like conditions, blue :
6 negative NAO-like conditions); (g) Strengthened subpolar gyre in Bay of Biscay, North-East
7 Atlantic Ocean (Penaud et al., 2020) and increased river activity of Middle Loire River
8 (Arnaud-Fassetta et al., 2010); (h) RSL model for West Brittany (García-Artola et al., 2018).
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10 This phase of aeolian sand deposition has also been recognized by previous studies on the
11 western coast of Brittany (Fig.13a). A AMS- ^{14}C date from the base of a perched dune in the
12 Audierne Bay provided an age between 4,545 and 4,160 cal BP (Haslett et al., 2000). On the
13 northern coast of Brittany, a shell-midden interbedded within aeolian sand deposits was dated
14 between 3,600 and 2,400 cal BP at the Anse de Verger site (Cancale) (Regnault et al., 1995)
15 and attested to dune mobility before 3,600 cal BP. More recently, a phase of aeolian activity
16 has also been documented at around 4,000 cal BP on the Herm Island (English Channel) by
17 Bailiff et al. (2014). Finally, only 7 coastal dune systems recording a period of mobility between
18 4,600 and 3,600 cal BP have yet been evidenced along the coasts of Brittany. The paucity of
19 such dated aeolian sites likely results from the poor preservation of supratidal sedimentary
20 deposits. Around 4,150 cal BP, the RSL was approximately -3.86 ± 0.7 m below the present-
21 day level (García-Artola et al., 2018; Stéphan et al., 2019b) (Fig.13h). Since this time, it is
22 likely that many coastal dune systems were affected by marine erosion induced by the still rapid
23 RSL rise so that sandy sedimentary material was in turn extensively redistributed during later
24 phases of coastal dune mobility.
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38 The second phase of coastal dune mobility is identified between 3,250-2,400 cal BP, i.e. from
39 the Middle Bronze Age to the end of the First Iron Age (Fig. 12). These results are consistent
40 with previous geomorphological and sedimentological observations along the coasts of Brittany
41 (Giot, 1970; Guilcher and Hallégouët, 1991) (Fig. 13a). Based on the analysis of several
42 sedimentary cores, Van Vliet-Lanoë et al. (2016) identified a mobility phase of dune massifs
43 between 3,050 and 2,300 cal BP (Fig. 13a). On the Herm Island, two distinct phases of aeolian
44 activity were recognized around 3,000 and around 2,300 cal BP, respectively (Bailiff et al.,
45 2014) (Fig. 12). These results suggest several pulses of dune mobility during a ca. 800 years-
46 long-lasting phase. The thickness of aeolian sand deposited during this second phase is relatively
47 significant, reaching up to 2.5 m at the Moulin de la Rive site. These deposits also cover
48 extensive areas and were observed on archaeological sites located far away onshore from the
49 current coastline. At Saint-Urnel (Plomeur; Fig. 11), the medieval necropolis is located more
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than 1 km away from the present coastline and lies on aeolian sand deposits attributed to this second period of dune mobility (Giot and Monnier, 1977). At Kerhilio (Erdeven, S Brittany, site no.66 on Fig. 3) a paleosoil dated at the Late Iron Age and interbedded with 2 aeolian sand deposits was uncovered at about 900 m inland (Blanchet, 2003). These observations highlight the local extent of sand inundation and suggest the development of transgressive dune fields that migrated over great distances away from the coastline. The 3,000–2,500 cal BP period has long been recognized as a phase of dramatic changes for morpho-sedimentary systems along the coasts of western France. In NW Brittany, erosional surfaces and sedimentary hiatuses recorded in marine and coastal sedimentary sequences reflect enhanced hydrodynamic conditions between 3,000 and 2,500 cal BP (Fernane et al., 2014; Stéphan et al., 2015; Ehrhold et al., 2021). Contemporaneous disruptions of coastal sedimentary environments along the English Channel (Billeaud et al., 2009; Sorrel et al., 2009; Lespez et al., 2010; Tessier et al., 2012) and the Atlantic coasts of France (Pontee et al., 1998; Clavé et al., 2001; Stéphan et al., 2019c; Tastet and Pontee, 1998) as regarded as the morphogenic impact of intense storms (Pouzet et al., 2018).

The third period of dune mobility recognized in this study between 1,050 and 700 cal BP (Fig. 12) is only argued from the Saint-Urnel site (Plomeur) in the Audierne Bay. Supplementary stratigraphic evidences at Saint-Nicolas Island (Fouesnant, Fig. 10) and Goulvars (Quiberon, Fig. 8) also suggests a destabilization of coastal dunes between 2,000 and 350 cal BP. Stratigraphical data clearly show a layer of aeolian sand deposited between 2,000 cal BP (end of the Late Iron Age) and 350 cal BP, i.e. the Little Ice Age (LIA) period. Although no absolute dating or chronological markers are available on these both sites, the sand deposition during the medieval period is likely as several aeolian sand deposits have been dated by Van Vliet-Lanoë et al. (2016) between 1,150 and 750 cal BP (Fig. 13a). On the Herm Island, aeolian sand deposits dated at around 1,200 cal BP are genetically related to an early dune mobility phase during the LIA period (Bailiff et al., 2014) (Fig. 13a). On the Picardie coast (northern France), coastal dunes appear to have been reactivated between 1,060 and 720 cal BP (Meurisse et al., 2005). Dunes on the Aquitaine coast (SW France) also show an increasing mobility between 1,250 and 850 cal BP (Clarke et al., 2002) (Fig. 13b). Other dune complexes of the European Atlantic coasts also show a period of increased sand movement around 900 cal BP in Denmark (Clemmensen et al., 2009) and between 1,100 and 1,000 cal BP in N Ireland (Wilson, 1990). However, the phase of dune mobility recorded between the late Roman and early medieval periods (ca. 1,700–1,150 cal BP) along the European Atlantic coasts (Gilbertson et al., 1999;

Meurisse et al., 2005; Clemmensen et al., 2009; Van Vliet-Lanoë et al., 2016) was not clearly identified in this study.

The most recent phase (phase 4) of dune mobility was evidenced here between ca. 350 and 110 cal BP, i.e. during the LIA period (Fig. 12), is consistent with previous works in Brittany (Guilcher and Hallegouet, 1991; Meur, 1993; Van Vliet-Lanoë et al., 2016; Lageat et al., 2019). However, the timing of the onset of this mobility phase is still poorly defined with our dataset. Based on the analysis of several sedimentary cores collected from the coasts of Brittany, Van Vliet-Lanoë et al. (2016) suggest that dune movement started around 600 cal BP and continued through a series of sand-drift pulses until present (Fig. 13a). One of these pulses appears to be centered on the 18th century, as noted by Lageat et al. (2019) from the analysis of the historical records. On Herm Island, OSL dating revealed a period of sand-drift between ca. 750 and 350 cal BP that has been attributed to an early LIA phase (Bailiff et al., 2014) (Fig. 13a). Along the Atlantic coasts of France, sand movements dating from this period have also been recorded in Picardie (Meurisse et al. 2005) and Aquitaine (Clarke et al., 2002; Bertran et al., 2020) (Fig. 13b). On the coastal sand-dune systems of Brittany, the LIA phase is associated with very thick sand deposits which can reach several meters at the Saint-Egarec church (Lampaul-Plouarzel, Fig. 6) and at the Saint-Guévroc church (Tréfléz, site no.22 on Fig. 3). These sandy deposits cover very large areas, as shown by the position of the buried houses and churches relative to the current shoreline. The abovementioned Saint-Egarec church and the Tréménéac'h church (Plouguerneau, NW Brittany, site no.31 on Fig. 3) are located at about 400 m and 350 m from the present coastline, respectively. In the Audierne Bay, the aeolian sand cover extends more than 2 km inland. The initiation and migration of transgressive coastal sand-dune systems during the LIA period have been recognized as the last major phase of aeolian sand mobilization on many western European coasts (e.g. Clarke and Rendell, 2006; Jackson et al., 2019). These large-scale transgressive dune systems inherited from the LIA period have also been observed in Denmark (Clemmensen et al., 1996, 2009, 2015; Clemmensen and Murray, 2006; Aagaard et al., 2007), in Britain (Gilbertson et al., 1999; Bailey et al., 2001; Wilson et al., 2001; Wilson, 2002; Bateman and Godby, 2004; Sommerville et al., 2007; McIlvenny et al., 2013; Bampton et al., 2017), in northern Ireland (Wilson and Braley, 1997; Wilson et al., 2004;) and in Portugal (Clarke and Rendell, 2006; Costas et al., 2012).

5.3. Driving mechanisms of coastal dune mobility

According to Hesp (2011), the development of coastal dunes requires two basic environmental prerequisites: (i) a supply of suitable grain-sized beach sediment from aeolian transport and (ii)

1 wind speeds capable to initiating saltation transport of particles towards the supratidal stage. At
2 long time-scales (decades, century to millennia), several intricate driving mechanisms have
3 long been identified about the coastal dune mobility process, such as RSL changes, climate and
4 anthropogenic forcing (Christiansen et al., 1990; Klijn, 1990; Wilson and Braley, 1997).
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7 8 **5.3.1. Relative sea level changes** 9

10 RSL changes are a key factor in the morphodynamics of coastal dune systems by controlling
11 sediment supply and redistribution processes (Hesp, 2011). According to previous works, sand-
12 drift events are commonly associated with marine transgressive pulses that could promote high
13 rates of sand supply and/or reworking of pre-existing dunes by marine erosion (e.g. Aagaard et
14 al., 2007; Szkornik et al., 2008). Conversely, some other works have shown that a regressive
15 trend in RSL can lead to coastal dune formation and landward sand-drift events by exposing
16 large intertidal sandy areas to wind deflation (e.g. Christiansen and Bowman, 1986;
17 Clemmensen et al., 1996; Wilson et al., 2001). In Brittany, the RSL curve produced by
18 Morzadec-Kerfourn (1969) suggested a significant RSL decrease around 3,000 cal BP. The
19 period of coastal dune mobility identified at the end of the Bronze Age period was initially
20 interpreted as the result of processes linked to this marine regression (Giot, 1970; Guilcher and
21 Hallégouët, 1991). However, a recent re-examination of RSL index points produced in Brittany
22 clearly demonstrated the absence of a regressive trend in RSL over the last 7,000 years (Stéphan
23 and Goslin, 2014; Goslin et al., 2015; Stéphan et al., 2015). In addition, statistical modelling
24 performed on RSL records showed that RSL rise rates gradually decreased during the mid- and
25 late-Holocene (García-Artola et al., 2018) (Fig. 13h). The analysis of some back-barrier
26 sediment infillings demonstrated that the RSL rise favoured the landward migration of coastal
27 barriers in NW Brittany (Morzadec-Kerfourn, 1974; Stéphan et al., 2015). This landward
28 translation of beach/dune systems was associated to a vertical accretion of back-barrier swampy
29 environments that created an accommodation space for aeolian sand deposits and the episodic
30 mobility of transgressive dunes.
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49 **5.3.2. Storminess** 50

51 Because the wind forcing is a primary driving mechanism of coastal dune erosion and mobility
52 (Hesp, 2011), the chronology of mid- to late-Holocene sand-drift events was frequently
53 associated with enhanced coastal storminess (e.g. Clarke and Rendell, 2006; Costas et al.,
54 2012). Five main “storm periods” have been recognized along the north-east Atlantic coasts
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1 over the last 7,000 years (Sorrel et al., 2012; Van Vliet-Lanoë et al., 2014b; Pouzet et al., 2018)
2 which further coincide with phases I, II, and IV of coastal dune mobility in Brittany (Fig. 13c).
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4 A study of a lake sediments from southwest Greenland (Olsen et al., 2012) (Fig. 13f) suggested
5 a shift from predominantly positive to negative NAO-like conditions over the period
6 4,500–2,000 cal BP. In particular, a significant strengthening of NAO- conditions was shown
7 first around 4,300 cal BP, and then between 3,400 and 2,000 cal BP, which corresponds to
8 phases I and II of dune mobility, as identified in this study (Fig. 13f). A negative decadal NAO
9 mode is associated with cold and dry winter conditions over northern Europe due to a southward
10 shift of the westerly wind belt (Van Vliet-Lanoë et al., 2014b; Lambert et al., 2020; Penaud et
11 al., 2020). In parallel, storm events are considered more intense due to the abrupt atmospheric
12 front between tropical and Arctic air masses (Trouet et al., 2012; Van Vliet-Lanoë et al., 2014b).
13 A similar negative decadal NAO mode is revealed during the LIA (Trouet et al., 2012), also
14 characterized by an increase in storm strength (Fig. 13c). Based on the analysis of a set of
15 historic aerial photographs, Mathew et al. (2010) documented the development of an extensive
16 transgressive dunefield produced by a catastrophic overwash on Greenwich Dunes, Prince
17 Edward Island National Park (Canada). These authors clearly show that the subsequent
18 stabilization of the beach-dune system took place 8 decades after an intense storm event. It is
19 thus assessed here that, moreso than the frequency, the intensity of storms is an essential
20 parameter in the dynamics of dune systems in Brittany.
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35 **5.3.3. Climate and vegetation cover interaction**

36 With regards to well-vegetated dunes, Jackson et al. (2019) point out that the morphological
37 impact of storms alone does not explain the widespread destabilization of coastal dune
38 complexes over several decades or centuries. Massive aeolian sediment transport also implies
39 a significant degradation of the vegetation cover due to climatic and/or anthropogenic factors.
40 In the North Atlantic Ocean, Bond et al. (2001) identified several ice-rafted debris (IRD) events
41 reflecting advections of colder surface waters eastwards from the Labrador Sea and southwards
42 from the northern sea (Fig. 13d). In the Bay of Biscay, IRD events are closely associated with
43 a strengthening of the subpolar Gyre (SPG) dynamic, which in turn results in colder climatic
44 conditions along the Brittany coast (Penaud et al., 2020) (Fig. 13e). These periods of local
45 climate cooling roughly correspond to mobility phases I, II, and IV identified in this study.
46 Jackson and Cooper (2011) demonstrated that North Atlantic coastal dune vegetation is highly
47 sensitive to changes in climate conditions. Decreases in temperature and changes in soil salinity
48 both alter the growth of dune plants such as *Ammophila arenaria* (Chergui et al., 2018) and
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1 reduce the development of the vegetation cover. Such climate changes directly reduce the role
2 of vegetation in dune stabilization. Based on these considerations, [Jackson et al. \(2019\)](#)
3 proposed a conceptual model of the transgressive behaviour of dune massifs during the LIA
4 period for the western European coasts. According to this model, the vegetation cover of dune
5 systems was progressively destroyed under the combined action of increased storm strength
6 and decreased temperatures. Large quantities of sands thus moved landward from the coastal
7 dunes by aeolian deflation, rapidly leading to the formation of highly mobile transgressive
8 systems. Similar processes may have affected the coastal dunes of Brittany during phases I, II
9 and IV identified in this study. Only phase III identified between 1,060 and 700 yr cal BP is
10 associated with significantly higher temperatures in western Europe which corresponds to the
11 Medieval Warm Period ([Lamb, 1965](#); [Bradley et al., 2003](#)). However, more recent studies have
12 shown that this period of climate warming was discontinuous and spatially heterogeneous
13 ([Bradley et al., 2003](#); [Guiot et al., 2010](#)). Tree ring analysis in the European Alps and
14 Scandinavia has indicated cool conditions between 900 and 800 cal BP ([Büntgen et al., 2006](#);
15 [Grudd, 2008](#); [Corona et al., 2010](#)) with reconstructed temperatures similar to the LIA. Phase III
16 was recorded only at the Saint-Urnel dune in the Audierne Bay and may not be representative
17 of the dynamics of coastal dunes in Brittany as a whole.

31 **5.3.4. Detritism and fluvial sediment input**

32 An increase in detritism has been suggested to explain the development of coastal dunes in
33 Brittany through episodic inputs of fluvial sediments to the coast during the mid- to late-
34 Holocene period ([Van Vliet-Lanoë et al., 2016](#)). Significant palynological evidences in western
35 France highlighted that the major retreat of mixed temperate forest is recorded between 4,500
36 and 4,000 cal BP, i.e. at the start of the Bronze Age ([David, 2014](#); [Fernane et al., 2015](#); [Penaud
37 et al., 2020](#)). In Normandy, evidences of detrital sedimentation has been observed since the
38 Bronze Age in many coastal valleys ([Lespez, 2012](#)). The landscape opening was then
39 intensified at the Bronze-Iron Age transition and, with more significance, at the start of the
40 Middle Age ([Penaud et al., 2020](#)), leading to soil erosion and episodic inputs of river sediments
41 to the coastal waters ([Marguerie, 1992](#); [Larue et al., 1996](#); [Germain-Vallée and Lespez, 2011](#);
42 [Penaud et al., 2020](#)). However, fluvial sediment supplies to the coast seems to have been
43 modulated by variations in the hydrological regime of coastal rivers. A synthesis of the fluvial
44 activity in the middle and lower Loire valley highlighted several periods of higher flood
45 frequency and/or magnitude during the Holocene, reflecting wetter conditions over the Loire
46 watersheds ([Arnaud-Fassetta et al., 2010](#)). These periods correspond in part to phases of dune
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1 mobility identified in this study (Fig. 13g). Strengthened of the Loire River discharge occurred
2 during time intervals characterized by a southward deflection of westerlies (Penaud et al., 2020)
3 (Fig. 13g). Surprisingly, this situation would provide favourable conditions for coastal dune
4 mobility in Brittany.
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7 In Brittany, the size of coastal rivers and the watersheds areas are very limited and not conduce
8 to abrupt detritic events. Furthermore, the incised morphology of the lower parts of these river
9 valleys favoured the trapping of fluvial sediments as shown by the thickness of some Holocene
10 deposits (Menier et al., 2006). These valleys are connected to the sea by small-size estuaries
11 where large thicknesses of sediment were deposited during the Holocene (Jouet et al., 2003;
12 Gregoire et al., 2017; Ehrhold et al., 2021). On the foreshore, seismic data show that the valleys
13 extend into the subtidal domain by submarine incised-valleys partially filled by a sequence of
14 fluvial, estuarine, and marine sedimentary deposits (e.g. Sorrel et al., 2009, 2010; Menier et al.,
15 2010; Traini et al., 2013). Currently, a limited number of lower coastal valleys are completely
16 filled and represent a former corridor for sediment transport along the land-sea continuum in
17 Brittany. Based on a historical analysis of coastline changes, Stéphan et al. (2019a) recently
18 noted that a large majority of beach/dune systems in Brittany have experienced a retreat process
19 during the last decades due to a depletion of sediment supply, with the exception of sites located
20 near some infilled estuarine mouths. In these areas, the foredunes have shown significant
21 progradation reflecting a positive sediment budget. The authors suggested episodic sediment
22 supply associated to the migration of tidal sandbars from the estuarine mouths to the nearby
23 beaches. Such processes have also been inferred to explain the phases of dune mobility recorded
24 at the mouth of the Gironde River over the last 2,000 years (Stéphan et al., 2019c).
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41 ***5.3.5. Disturbances due to human activities***

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43 The archaeological and historical data examined in this study provides little evidence of
44 possible human disturbances on the coastal dunes of Brittany. For the Neolithic and Bronze
45 Age periods, most of the archaeological remains were discovered within paleosoils currently
46 overlain by the dune sand covers. These sites correspond to perennial or temporary occupations
47 initially located far behind the coastline, so that they do not provide any data on a possible use
48 or frequentation of coastal dunes, except for some flintknapping activity as seen at Kerminihy
49 or, not so far from Brittany, at La Caouillerie in Cotentin peninsula (Rousseau et al., 2014). For
50 the Late Iron Age and Roman periods, archaeological data indicate numerous perennial
51 settlements in dune environments, often with long-lasting occupation of several centuries. The
52 stratigraphy of archaeological sites generally shows anthropogenic deposits with a series of
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1 interbedded thin sandy layers that reflect episodic aeolian sand-blows during the human
2 occupation period (e.g. Moulin de la Rive, Locquirec, [Giot et al., 1986](#); Goulvars, Quiberon,
3 [Hyvert, 1985, 1986, 1987](#)). These sedimentary sequences may reflect the local impact of human
4 pressure on the vegetation cover (e.g. trampling) leading to a spatially limited remobilization
5 of coastal dunes. During the medieval period, few scattered human occupations are suggested
6 along the coast of Brittany ([Cassard, 2015; Tonnerre, 2015](#)), quite limiting the potential impact
7 of human activities on dune environments. However, between the 11th and 14th centuries, the
8 significant expansion of the European population resulted in a strong human footprint on local
9 ecosystems (e.g. [Mouthon, 2017](#)). In western France, this period is associated with significant
10 clearings (e.g. [Marguerie, 1992; Lambert et al., 2020; Penaud et al., 2020](#)) and coincides with
11 the dune mobility phase III identified in this study. From 800 cal BP, a study conducted in the
12 Bay of Brest highlighted the major threshold when anthropogenic-related unoff forcing exceeds
13 natural trends related to precipitation regimes, either above Loire watersheds or Brittant
14 watersheds ([Lambert et al., 2020](#)). In the medieval subsistence society, demographic pressure
15 may have led to the increasing use of marginal land such as sand dunes as a resource. Locally,
16 spatial expansion of cultivated areas could have caused a deterioration of dune vegetation cover
17 and consequently the potential for enhanced aeolian impacts. In the Hebrides islands,
18 [Sommerville et al. \(2007\)](#) put forward a somewhat similar hypothesis to explain dune mobility
19 as a result of cultivation of marginal dune lands by coastal populations.
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35 From the 18th century onwards, numerous historical sources provide information on the
36 practices responsible for the mobility of the dunes. In 1752, a law voted by the regional
37 authorities forbade the use of coastal dunes as grazing areas, under penalty of fine and
38 imprisonment due to the sand inundations caused by this practice ([Charpentier, 2009; Lageat et](#)
39 [al., 2019](#)). In Landeda (NW Brittany), a "dune warden" is appointed each year to enforce this
40 ban ([Charpentier, 2009](#)). Measures are also taken by local authorities to fix the sand-dune
41 system or slow its landward migration. Santec (NW Brittany) is illustrative of the efforts
42 undertaken by coastal populations to stabilize the dunes. Starting in 1760, rows of fens were
43 installed along the dunes, and regularly raised ([Goury Aîné, 1828](#)). From 1807, a "dune police
44 force" was created in order to supervise the activities practiced on the dunes and their
45 surroundings. Behind the dune front, the massif was seeded with maritime pines, gorse, and
46 broom ([Goury Aîné, 1828](#)). The circulation paths were delimited and the non-vegetated spaces
47 were covered with seaweed in order to enrich the land and prevent sand-blows.
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60 **5.4. Pattern of Holocene coastal dune changes**

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In Fig. 17, we propose an evolutionary temporal sketch, subdivided into five stages, about morphological changes of coastal sand-dune systems and Human settlements during Holocene times along coastal areas in Brittany.

Stage 0 corresponds to an initial state around 7,000 BP during which the slowing RSL rise led to the formation of the first coastal barriers in Brittany (Stéphan and Goslin, 2014; García-Artola et al., 2018). The Neolithic period (6,850-4,100 cal BP; stage 0; Fig. 14) is represented by numerous archaeological sites distributed along the coast (Giot et al., 1998), but human settlements appear to have been systematically located behind coastal systems, such as dunes and marshes.

Between 4,250 and 4,100 cal BP (stage 1, Fig. 14), the primary phase of coastal sand-dune mobility is recorded, related to the combined effect of decreasing temperatures and an enhanced storminess in the NE Atlantic. Coastal dunes were stabilized by the vegetative cover from the Early Bronze Age (4,100-3,550 cal BP), as indicated by archaeological evidence associated with humic horizons interbedded within aeolian sand deposits.

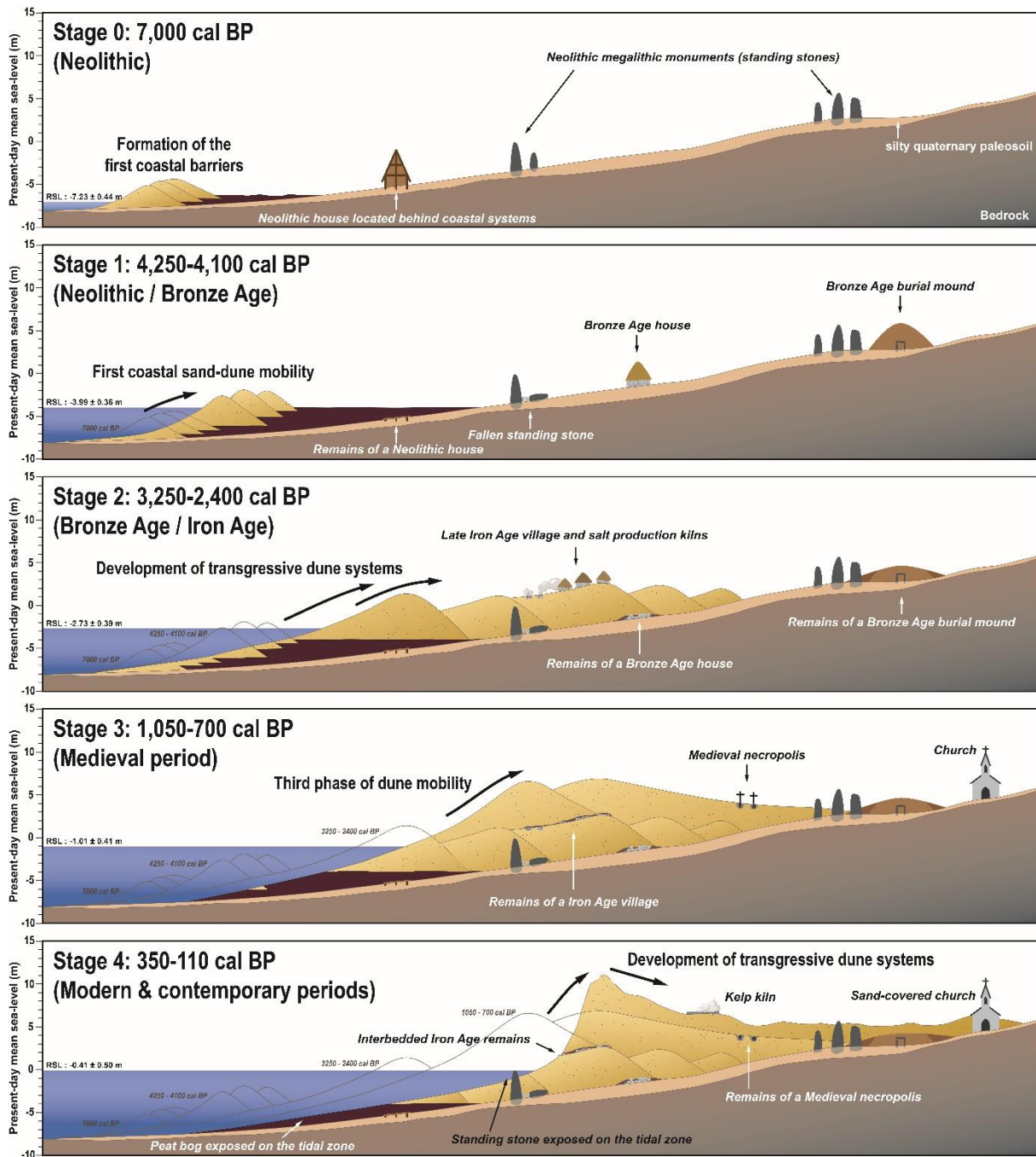


Fig. 14. Evolutionary temporal sketch of sand-dune systems and Human settlements during the last 7 000 years along the coasts of Brittany.

Between 3,200 and 2,400 cal BP (stage 2; Fig. 14), a destabilization of the coastal dunes results in the establishment of large transgressive systems that affected the entire coast of Brittany. Archaeological remains dating from the Middle/Final Bronze Age (3,550-2,750 cal BP) and the First Iron Age (2,750-2,400 cal BP) periods are absent in dune environments, reflecting a decline in coastal occupations that can be attributed to a deterioration in climatic conditions (Stéphan et al., 2019b, 2013), even if we cannot exclude other human factors or archaeological

1 biases. The 3,300-2,800 cal BP interval (Bond event 2; Fig. 13d) characterized by “NAO+,
2 SPG+” (Fig. 13d, e, f) also corresponds to decreased influence of the warm and salty poleward
3 current (Penaud et al., 2020). Penaud et al. (2020) suggested that coastal societies might have
4 turned towards land since palynological data south of Brittany reflect major phases of upland
5 clearance on western France watersheds. From the Late Iron Age onwards (2,400-2,000 cal
6 BP), the dunes were stabilized and numerous occupations, mainly related to sea salt extraction,
7 were established.

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13 A third phase of dune mobility is suspected between 1,050 and 700 cal BP (stage 3, Fig. 14),
14 but the corresponding data only concern the Audierne Bay and may reflect local dynamics
15 linked to site-specific processes. During this period, human occupations were very dispersed
16 along the coasts of Brittany and settlements were located far back from the coastal areas.

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21 The last period of dune mobility, dated between 350 and 110 cal BP (stage 4, Fig. 14),
22 corresponds to the LIA climatic deterioration. The destabilization of sand-dune systems
23 concerned all European Atlantic coasts (e.g. Clarke and Rendell, 2006; Jackson et al., 2019). In
24 Brittany, the development of large transgressive systems and their migration several kilometres
25 inland led to the inundation of many villages, churches, and cultivated land by aeolian sands.
26 The dune massifs were stabilized and vegetated during the second half of the 19th century.

27 28 29 30 31 32 33 34 35 **Conclusions**

36
37 In this paper, the dynamics of Holocene coastal dune systems has been reconstructed for
38 western France based on geomorphological, archaeological and historical data. This study
39 shows that in the absence of radiocarbon-datable interbedded paleosoils and OSL dating of
40 sandy deposits, archaeological remains represent useful chronological indicators of coastal
41 dune mobility. From the re-examination of 221 archaeological sites previously studied by
42 archaeologists over the past 150 years, successive phases of sand movement are dated on 78
43 coastal sand-dune systems in Brittany, by using the Harris diagram method. For the first time,
44 a regional chronological framework is proposed for Brittany based on a representative set of
45 dune systems well distributed along the western coasts of France. Our results emphasize the
46 episodic nature of the major morphological changes leading to the formation of dune
47 complexes. Four periods of major aeolian sand-drifts are identified: 4,250-4,100 cal BP (period
48 1), 3,250-2,400 cal BP (period 2), 1,050-700 cal BP (period 3), and 350-110 cal BP (period 4).
49 During periods 1, 2, and 4, sand movements are associated with an enhanced North Atlantic

1 storm regime (Sorrel et al., 2010; Pouzet et al., 2018), indicating the primary role of extreme
2 storm events in dune destabilization. These periods also coincide with rapid climatic changes,
3 marked by a decrease in annual temperatures and an increase in precipitation in western France
4 (Arnaud-Fassetta et al., 2010; Penaud et al., 2020). These conditions seem to be favourable to
5 the mobility of coastal dunes, especially through a degradation of the vegetation cover.
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9 From a methodological point of view, the use of archaeological remains as chrono-stratigraphic
10 indicators has shown several limitations, notably because of the scarcity of available
11 archaeological data for specific periods, particularly between the end of the Roman period and
12 the Middle Ages. Pionner discoveries of Neolithic and Bronze Age remains rarely document
13 stratigraphic contexts and chronological attributions lack precision because no radiocarbon
14 dating is available. Consequently, the regional chronological framework provided in this study
15 about the spatio-temporal evolution of coastal dune sand systems could be further refined by
16 the use of OSL dating.
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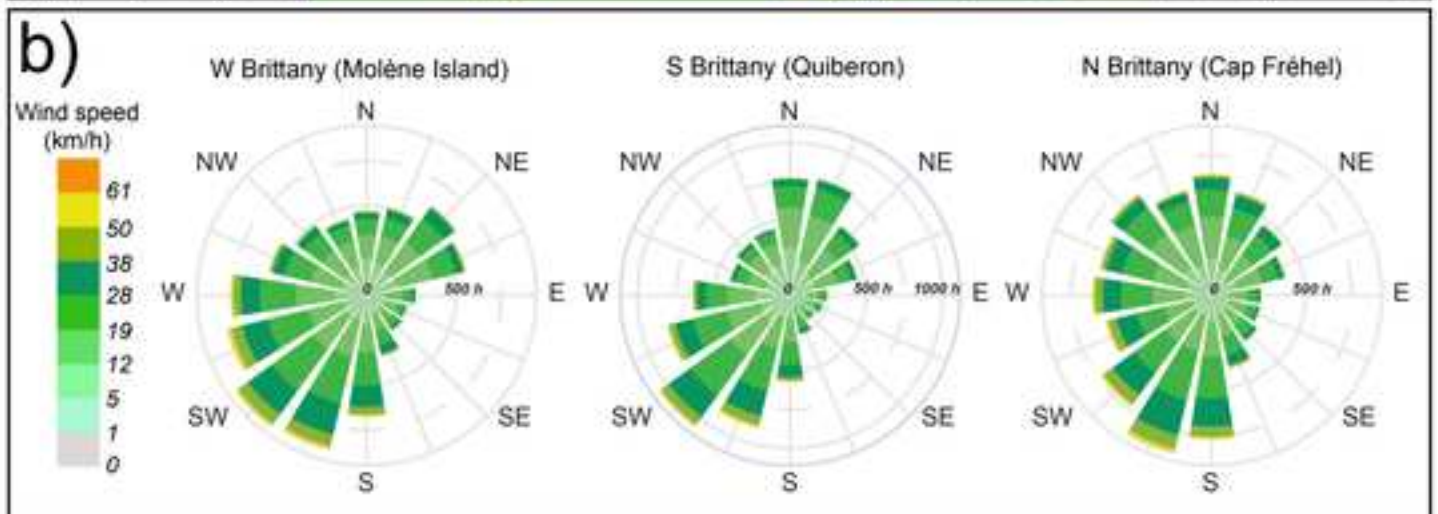
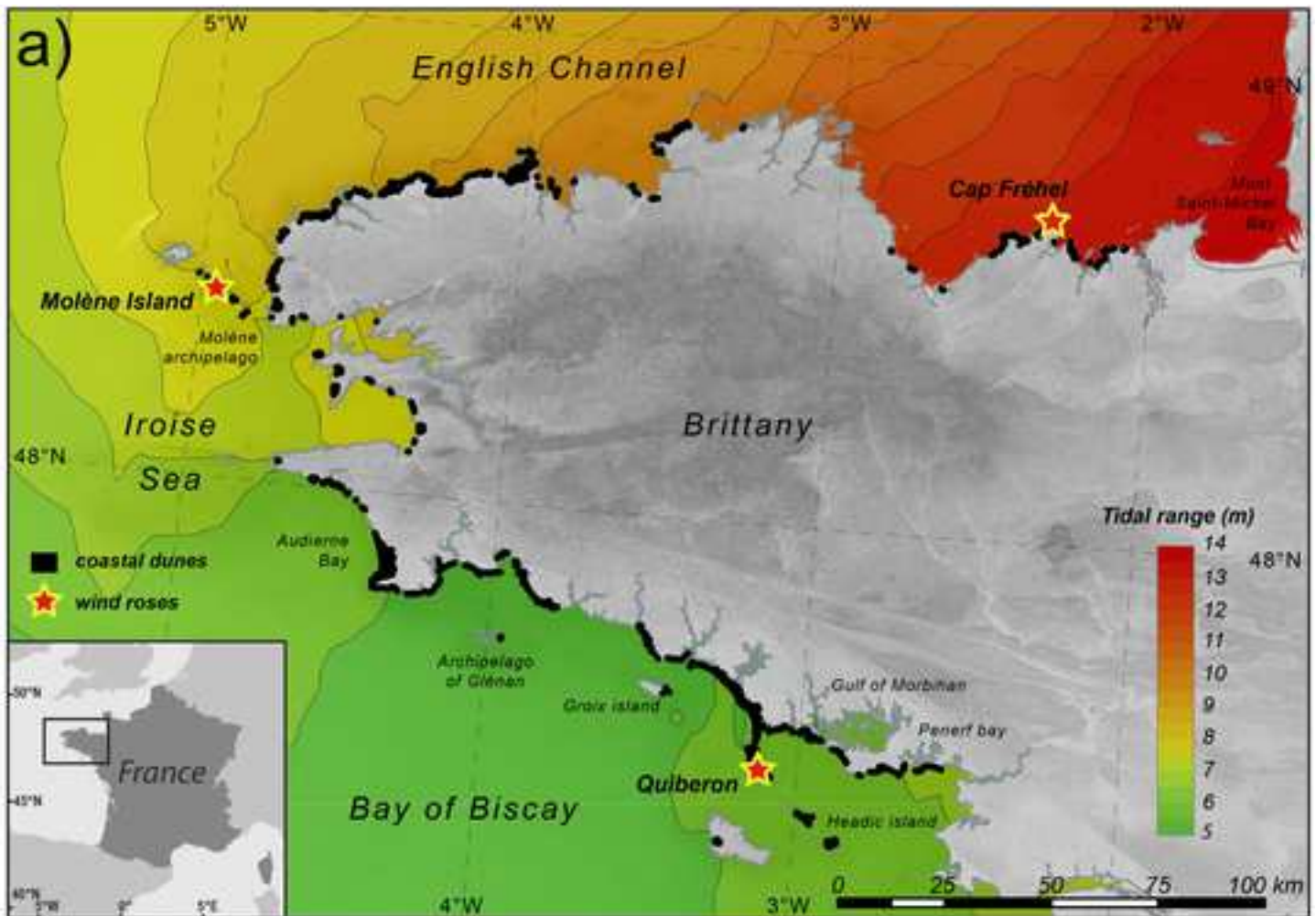
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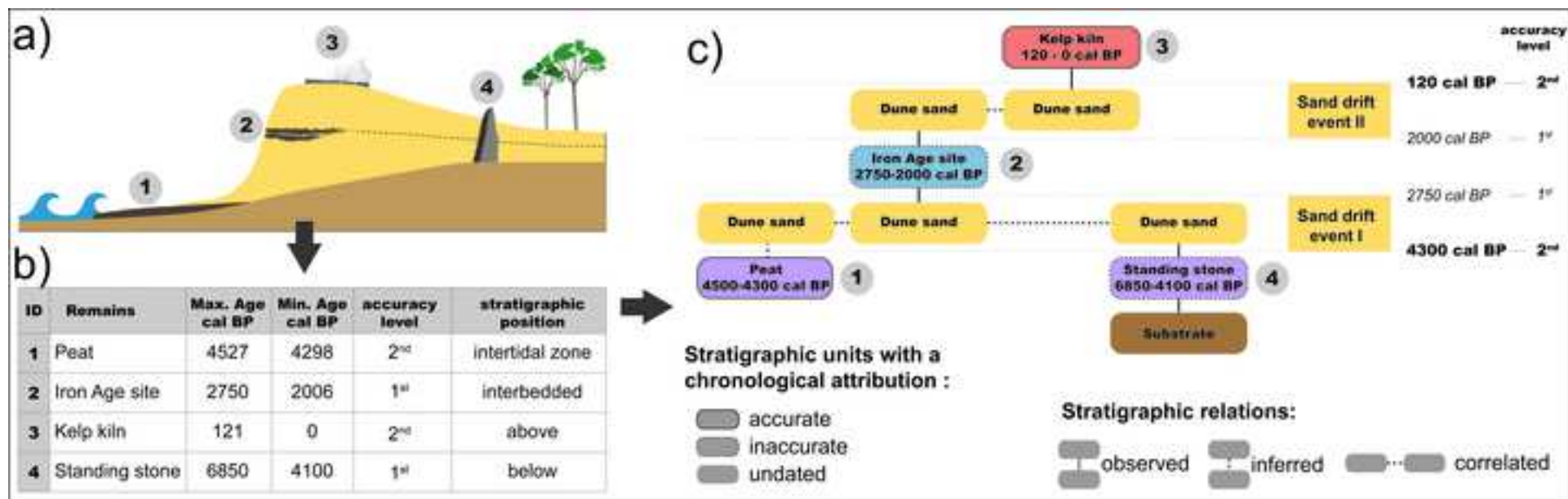
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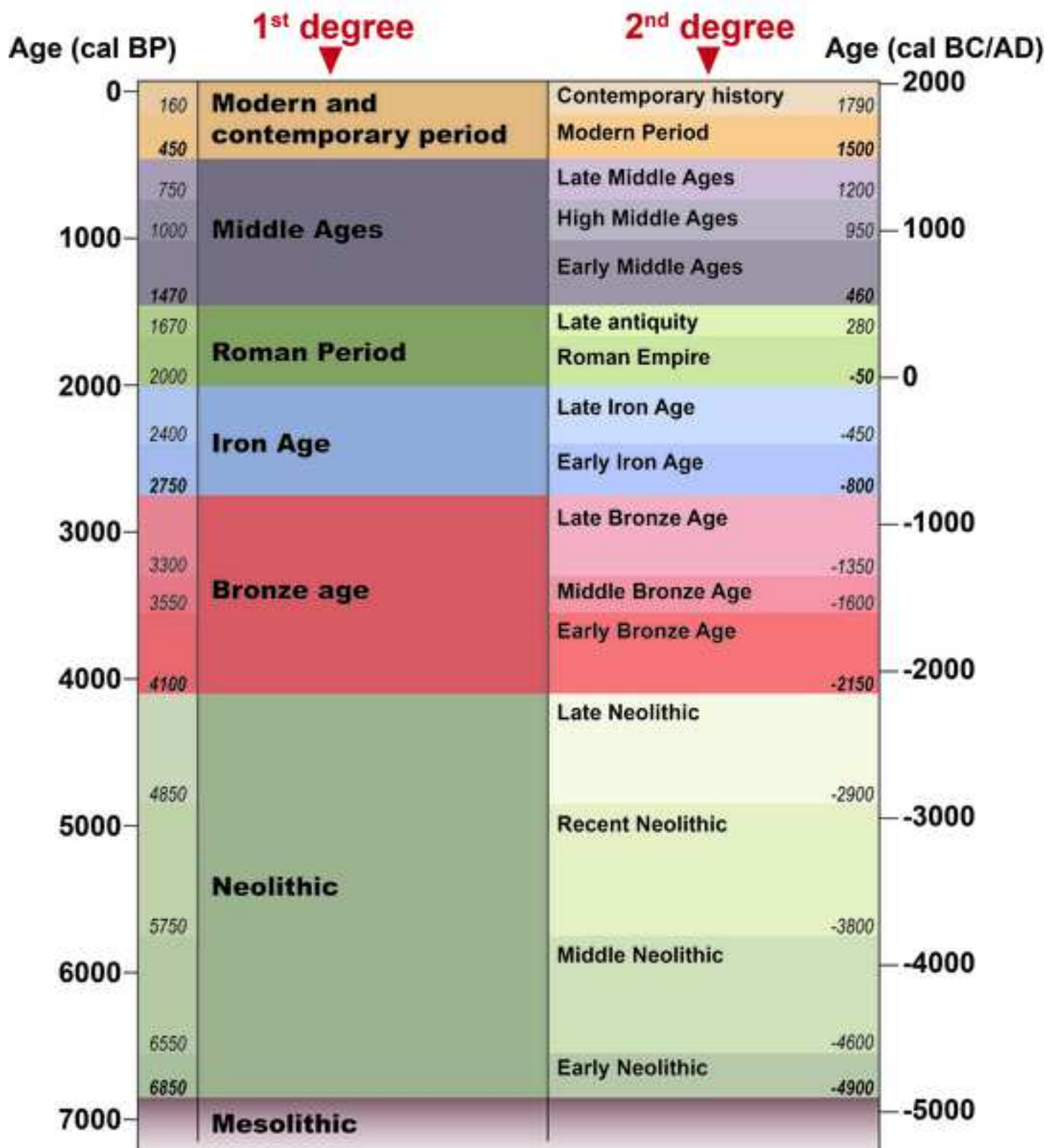
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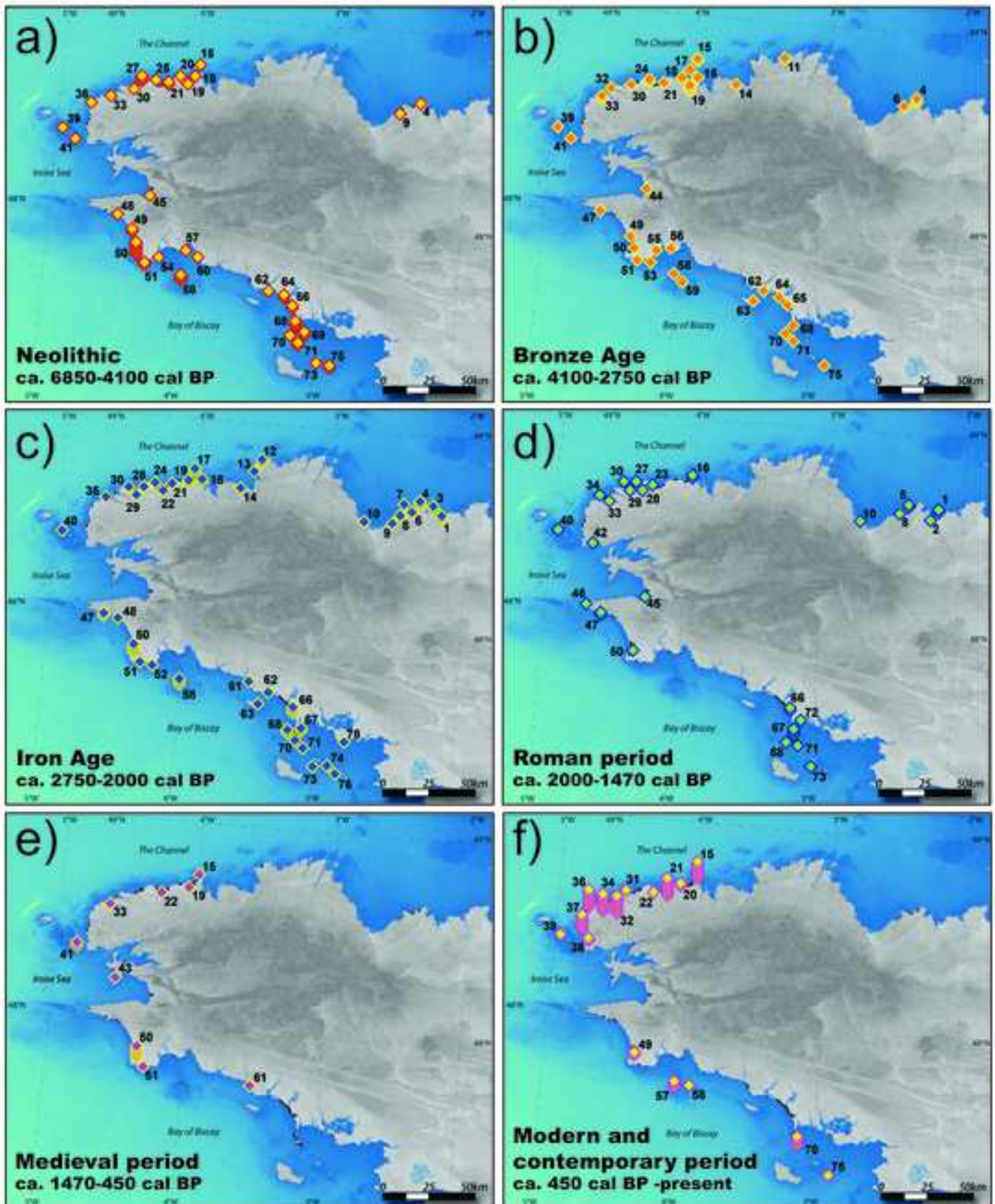
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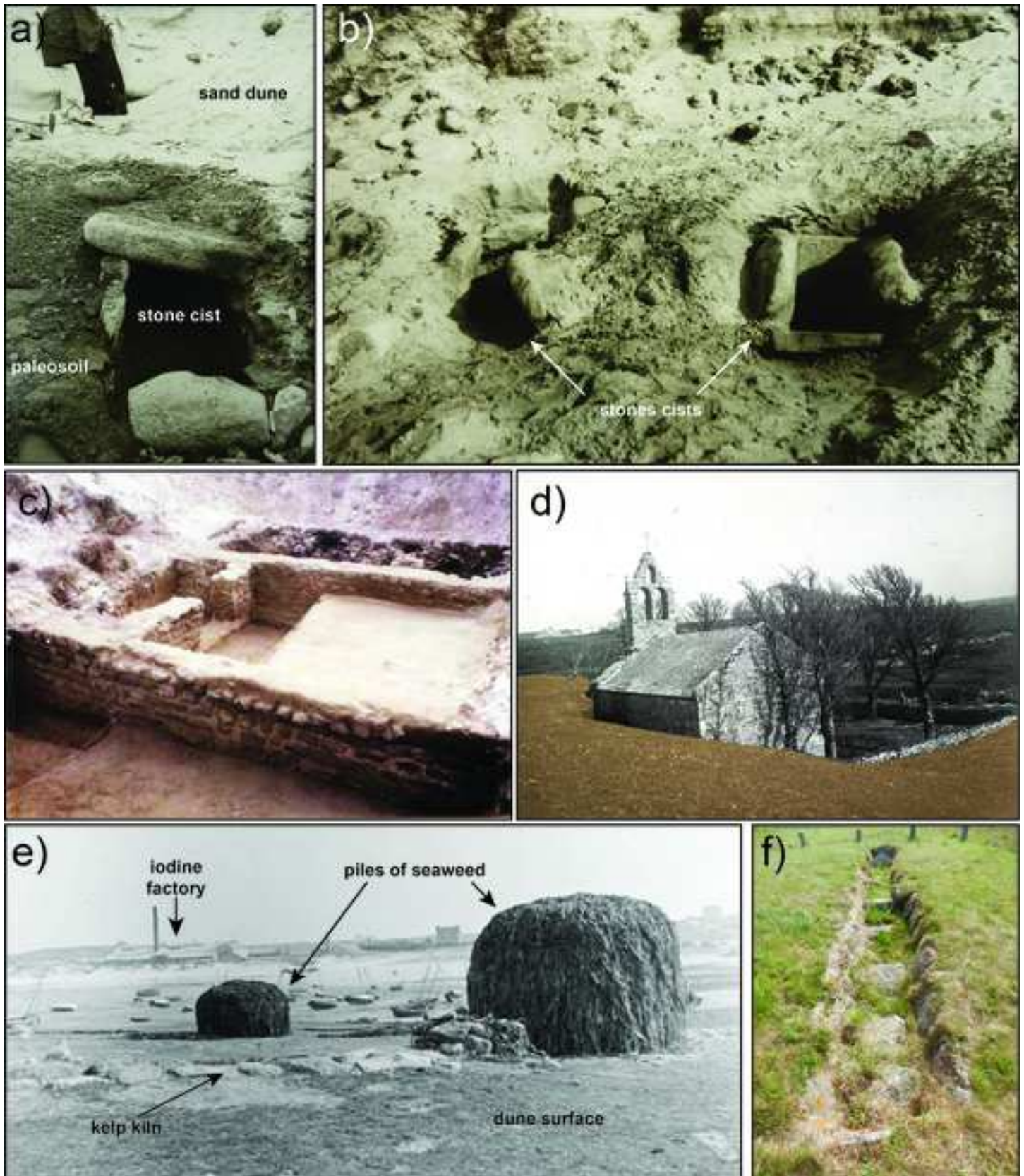


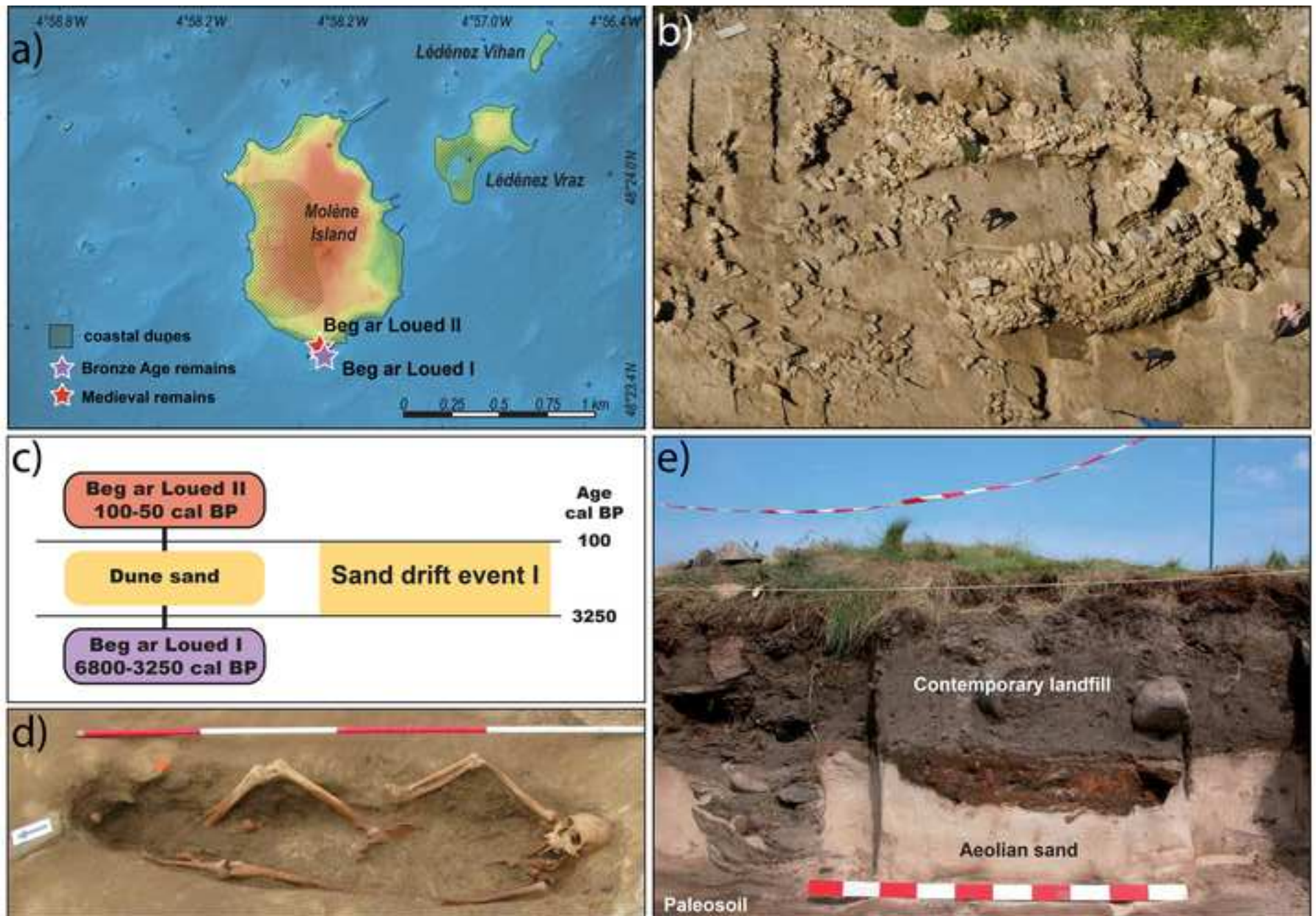


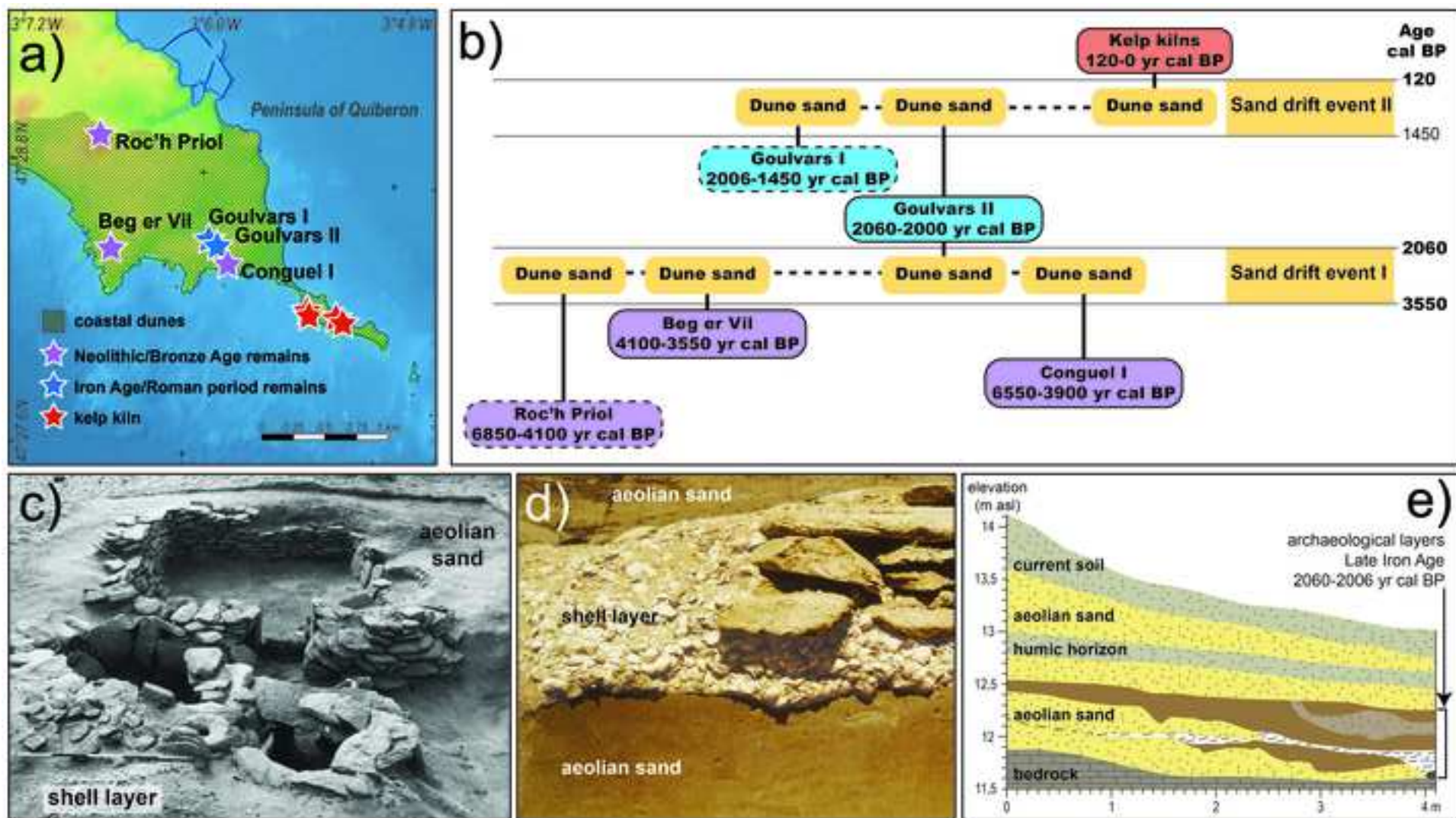


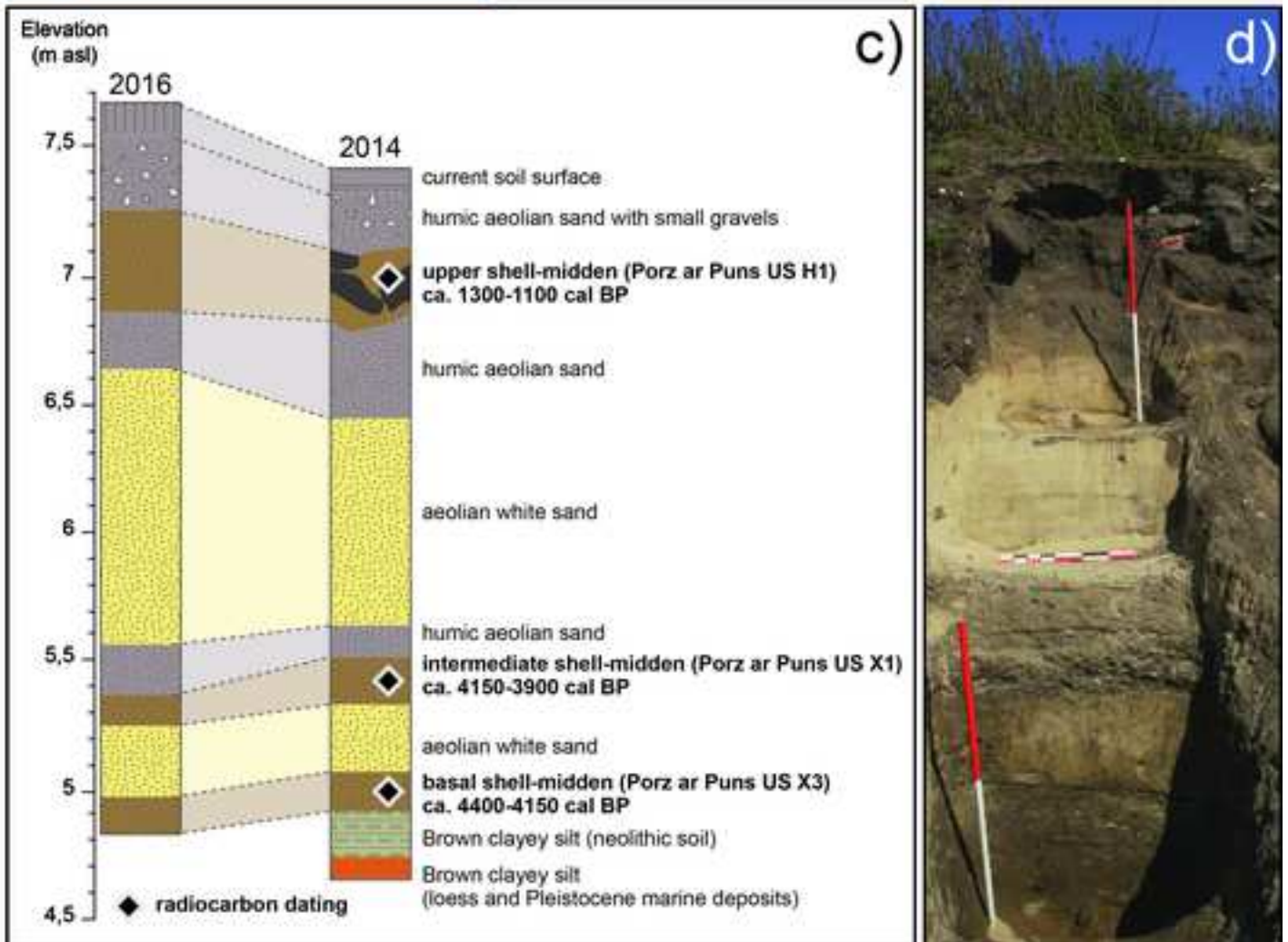
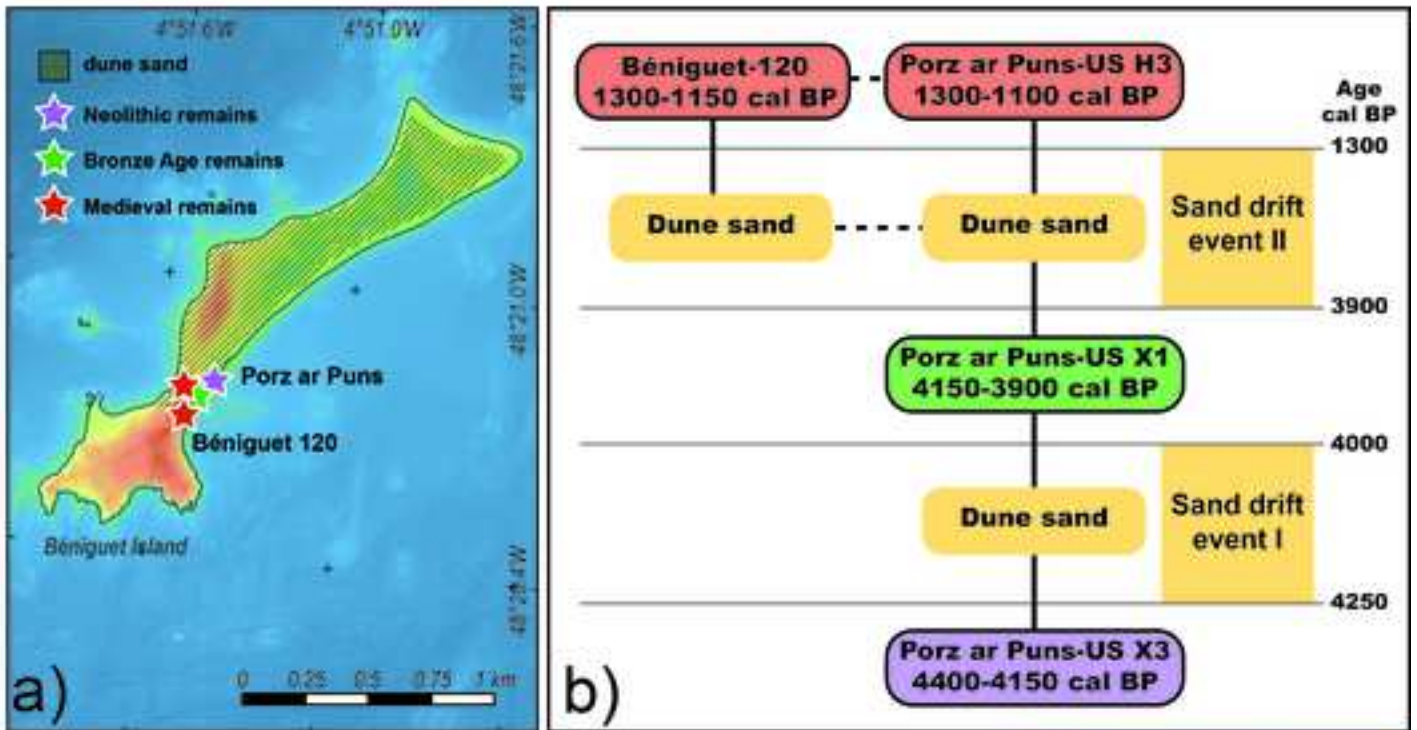


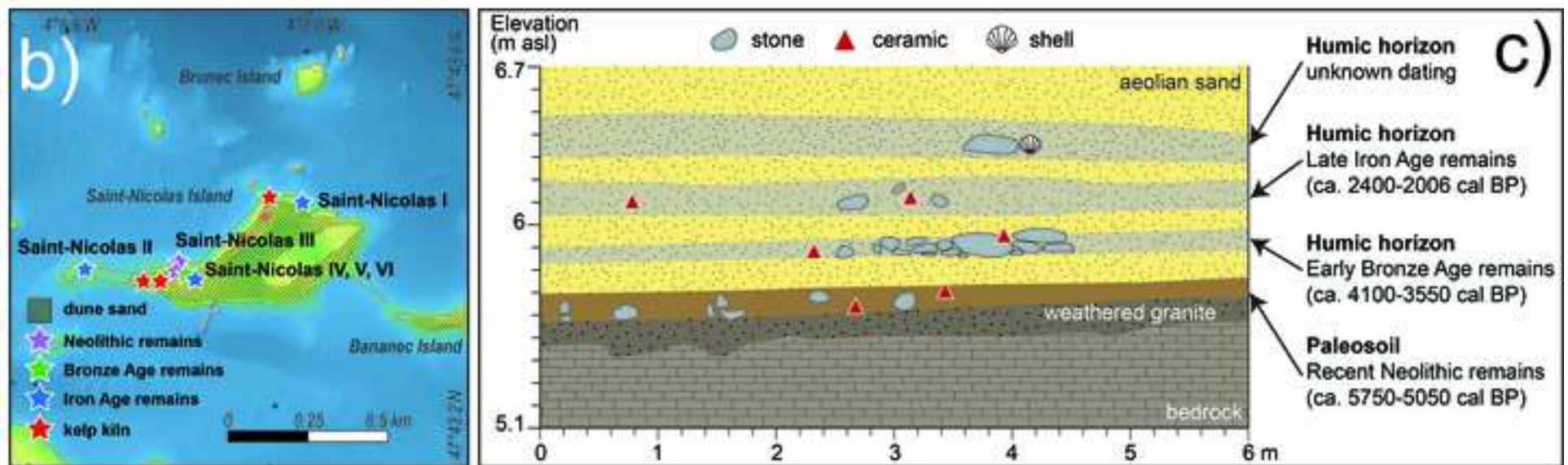
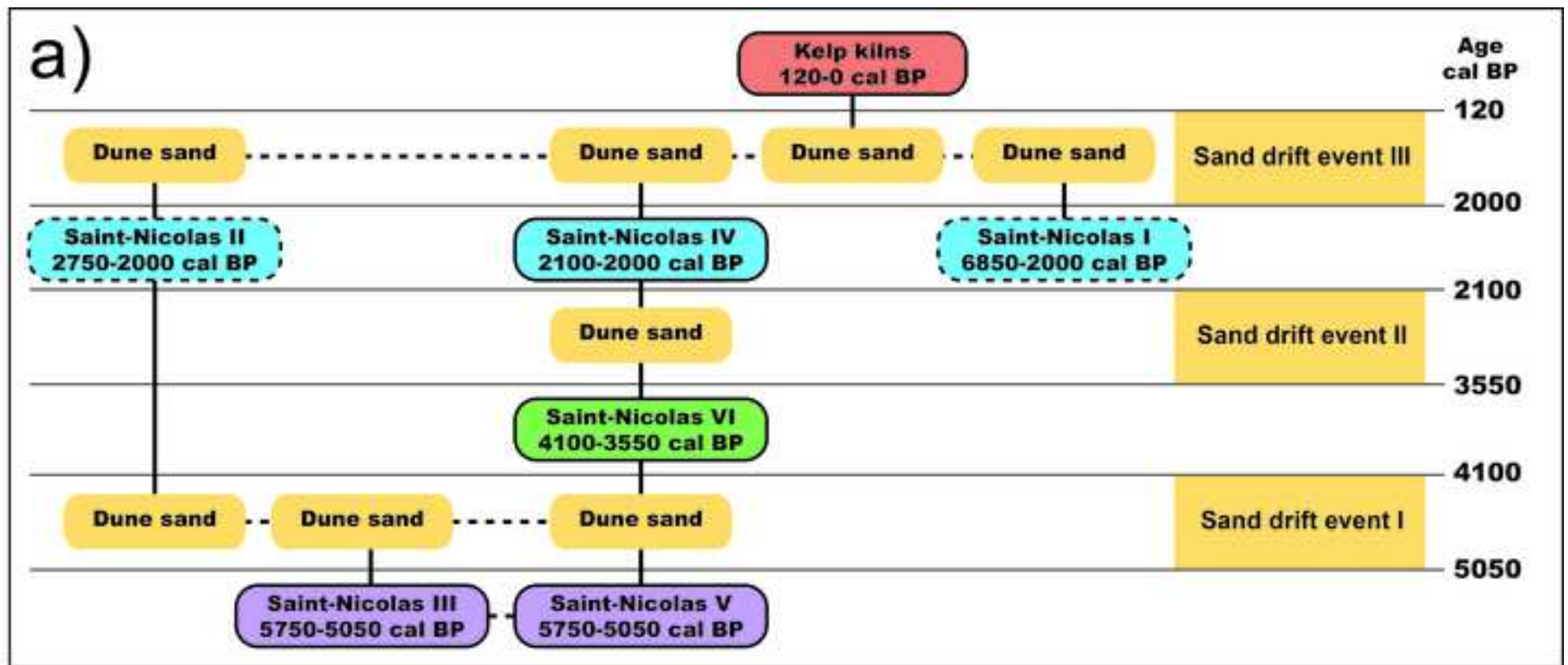


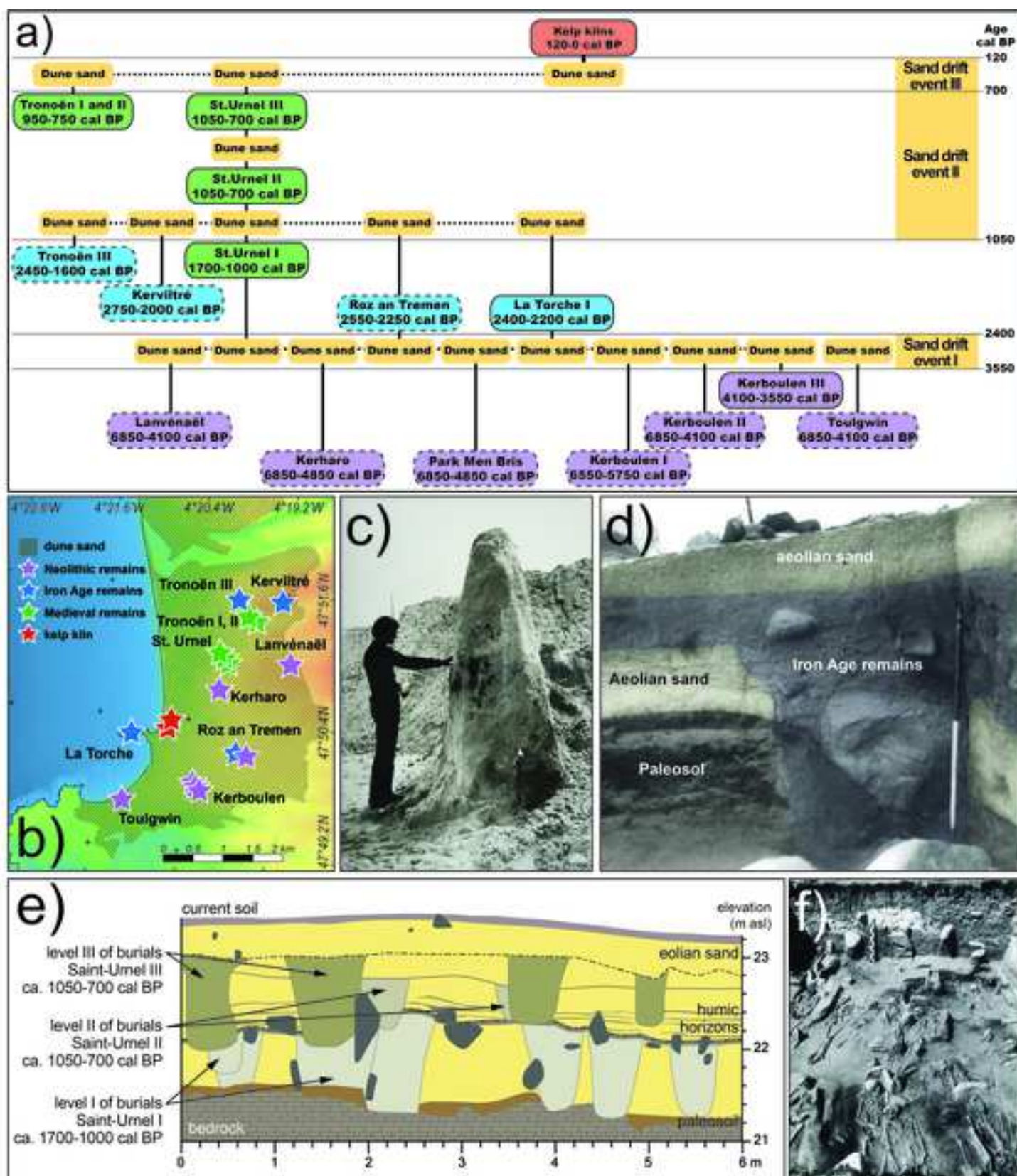


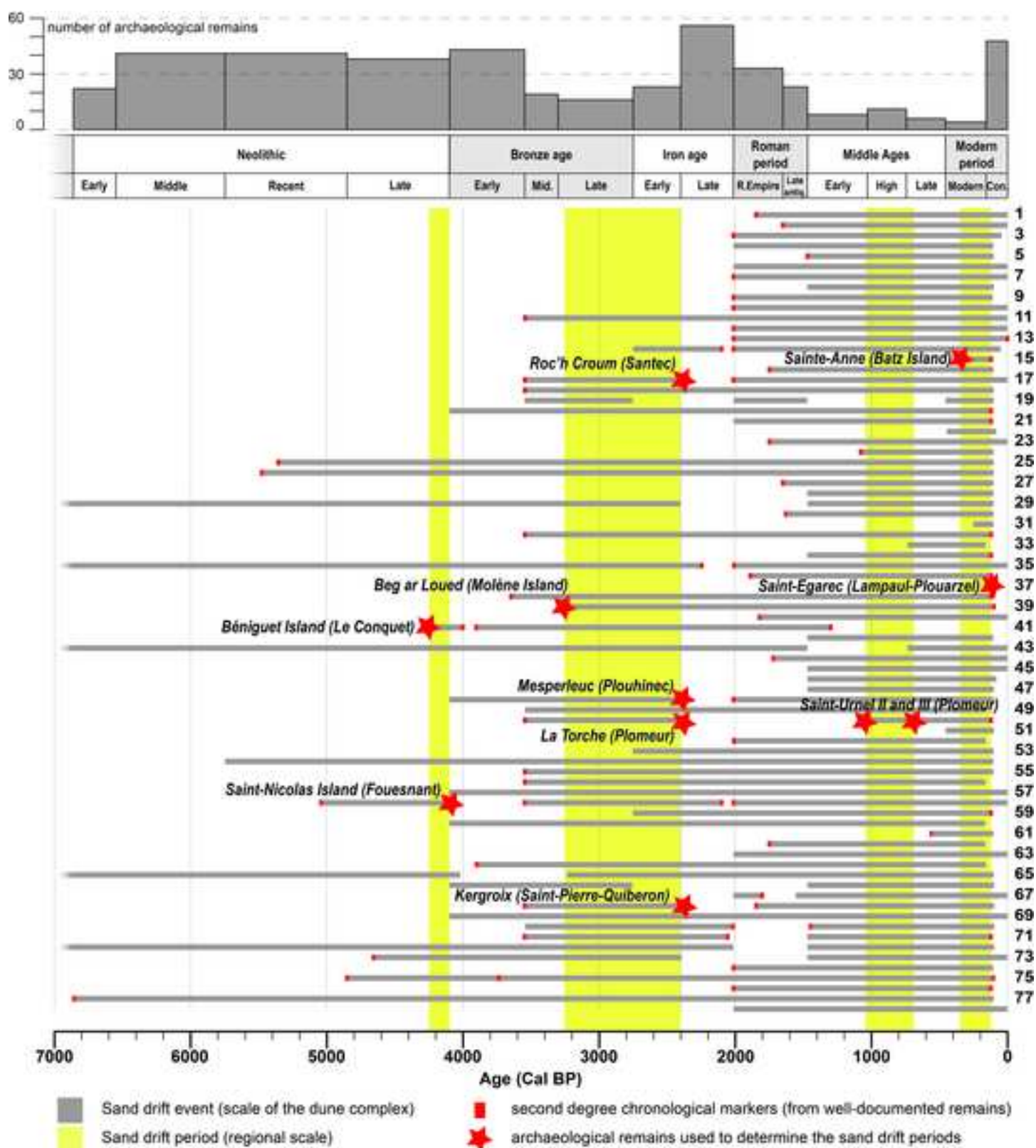


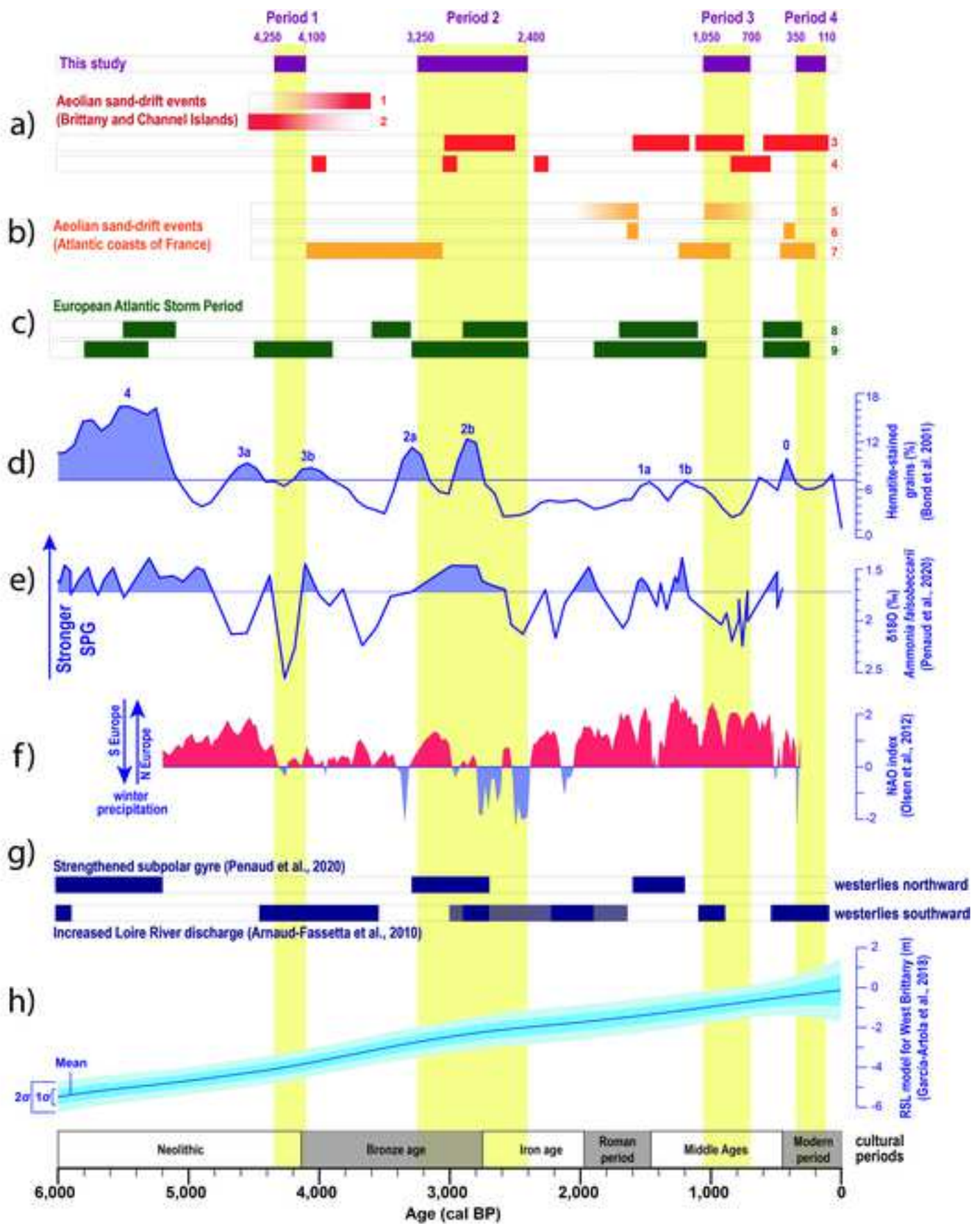












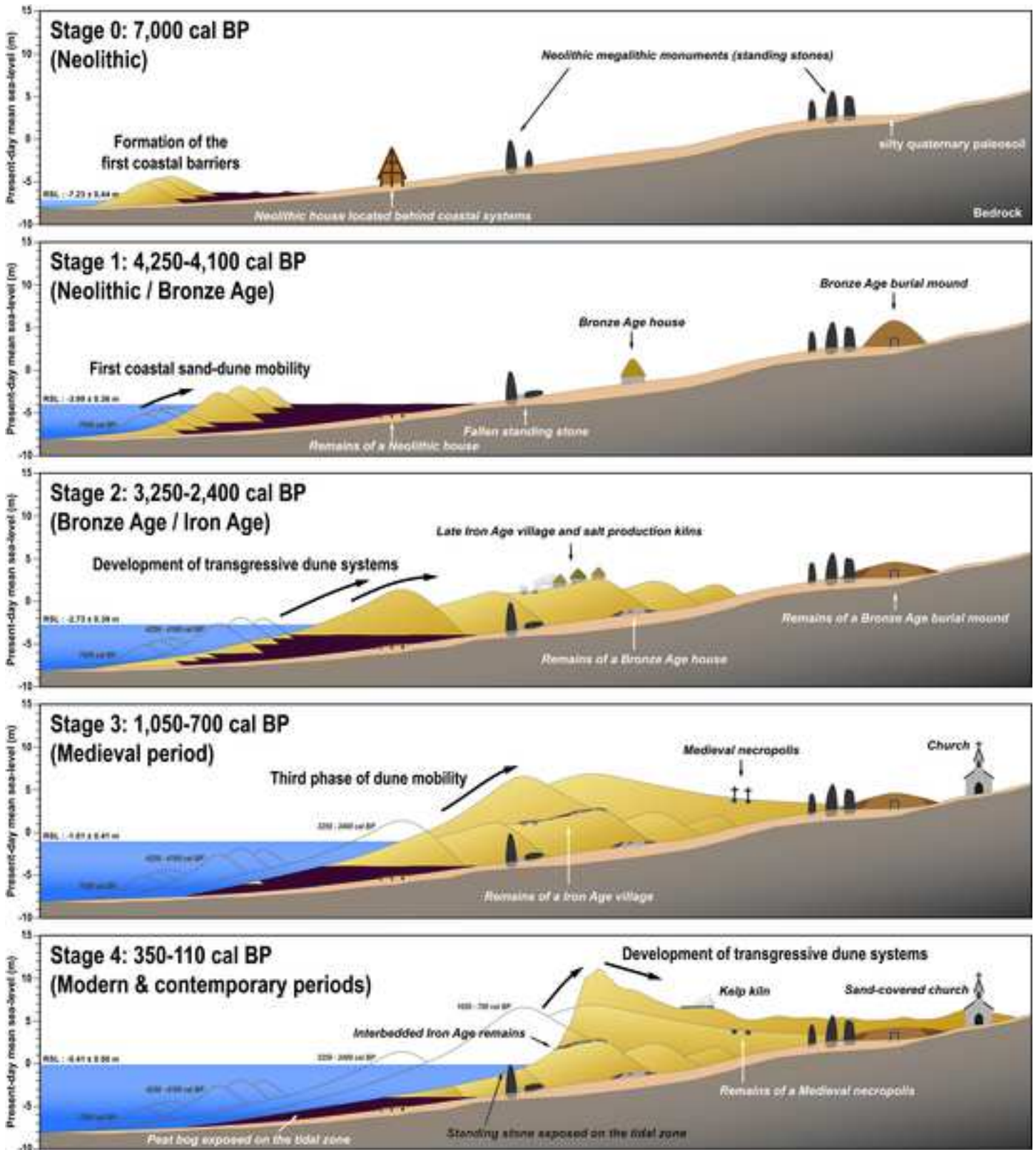


Table 1. Chronological boundaries of sand drift events deduced from

| Coastal dune ID | Name of coastal dunes | Location |
|------------------------|------------------------------|---------------------|
| 1 | Ébihens Island | North Brittany |
| 2 | Beach of Quatre Vaux | North Brittany |
| 3 | Beach of La Mare | North Brittany |
| 4 | Bay of Croc | North Brittany |
| 5 | Les Sables d'Or | North Brittany |
| 6 | Les Hôpitaux | North Brittany |
| 7 | Beach of Guen | North Brittany |
| 8 | Beach of Caroual | North Brittany |
| 9 | La Ville Berneuf | North Brittany |
| 10 | Beach of Rosaires | North Brittany |
| 11 | Les Dunes | North Brittany |
| 12 | Landrelles | North Brittany |
| 13 | Trozoul | North Brittany |
| 14 | Moulin de la Rive | North-West Brittany |
| 14 | Moulin de la Rive | North-West Brittany |
| 15 | Aod Venn | North-West Brittany |
| 16 | Plage de Pouldu | North-West Brittany |
| 17 | Roc'h Croum | North-West Brittany |
| 17 | Roc'h Croum | North-West Brittany |
| 18 | Mechou Rouz | North-West Brittany |
| 19 | Theven | North-West Brittany |
| 19 | Theven | North-West Brittany |
| 19 | Theven | North-West Brittany |
| 20 | Theven-Kerbat | North-West Brittany |
| 21 | Kernic | North-West Brittany |
| 22 | Keremma | North-West Brittany |
| 23 | Tréguéiller | North-West Brittany |
| 24 | Beach of Lividic | North-West Brittany |
| 25 | Le Scluz | North-West Brittany |
| 26 | Chardons Bleu | North-West Brittany |
| 27 | Mentoul | North-West Brittany |
| 28 | La Grève | North-West Brittany |
| 29 | Trerohan | North-West Brittany |
| 29 | Trerohan | North-West Brittany |
| 30 | Le Vougot | North-West Brittany |
| 31 | La Grève Blanche | North-West Brittany |
| 32 | Sainte-Marguerite | North-West Brittany |
| 33 | Corn ar Gazel | West Brittany |
| 34 | Teven | West Brittany |
| 35 | Bec Island | West Brittany |
| 35 | Bec Island | West Brittany |
| 36 | Saint-Gonvel | West Brittany |

| | | |
|----|----------------------|---------------------|
| 37 | Beach of Porspaul | West Brittany |
| 38 | Porz Tévigné | West Brittany |
| 39 | Beg ar Loued | West Brittany |
| 40 | Le Bourg | West Brittany |
| 41 | Béniguet Island | West Brittany |
| 41 | Béniguet Island | West Brittany |
| 42 | Le Trez Hir | West Brittany |
| 43 | Lostmarc'h | West Brittany |
| 43 | Lostmarc'h | West Brittany |
| 44 | Tréguier Vihan | West Brittany |
| 45 | Plage de Kervel | West Brittany |
| 46 | Bay of Trépasses | West Brittany |
| 47 | Beach of Trez Goarem | West Brittany |
| 48 | Mesperleuc | West Brittany |
| 48 | Mesperleuc | West Brittany |
| 49 | Parc ar Hastel | West Brittany |
| 50 | La Torche | West Brittany |
| 50 | La Torche | West Brittany |
| 50 | La Torche | West Brittany |
| 51 | La Grève Blanche | South-West Brittany |
| 52 | Léhan | South-West Brittany |
| 53 | Beach of Kersaux | South-West Brittany |
| 54 | Beach of Lodonnec | South-West Brittany |
| 55 | Beach of Langoz | South-West Brittany |
| 56 | Mousterlin | South-West Brittany |
| 57 | Beg-Meil | South-West Brittany |
| 58 | Saint-Nicolas Island | South-West Brittany |
| 58 | Saint-Nicolas Island | South-West Brittany |
| 58 | Saint-Nicolas Island | South-West Brittany |
| 59 | Penfret Island | South-West Brittany |
| 60 | Corn-Pao | South-West Brittany |
| 61 | Pen er Malo | South Brittany |
| 62 | La Grande Plage | South Brittany |
| 63 | Port Mélite | South Brittany |
| 64 | Magouëro | South Brittany |
| 65 | Kerminihy | South Brittany |
| 66 | Kerhillio | South Brittany |
| 66 | Kerhillio | South Brittany |
| 67 | Keriaker | South Brittany |
| 67 | Keriaker | South Brittany |
| 68 | Kergroix | South Brittany |
| 68 | Kergroix | South Brittany |
| 69 | Le Petit Rohu | South Brittany |
| 70 | Goulvars | South Brittany |
| 70 | Goulvars | South Brittany |
| 71 | Beg er Vil | South Brittany |
| 71 | Beg er Vil | South Brittany |
| 72 | Beach of Légenèse | South Brittany |

| | | |
|----|--------------------|----------------|
| 72 | Beach of Légenèse | South Brittany |
| 73 | Island of Chevaux | South Brittany |
| 73 | Island of Chevaux | South Brittany |
| 74 | Port Blanc | South Brittany |
| 75 | Le Douet | South Brittany |
| 76 | Stefland | South Brittany |
| 77 | Kerjouanno | South Brittany |
| 78 | Port-Saint-Jacques | South Brittany |

om archaeological, historical and sedimentological data for western France

| Locality | Beginning | | accuracy level |
|-----------------------|--------------|-----------------------|----------------|
| | age (cal BP) | deduced from | |
| Saint-Jacut-de-la-Mer | 1850 | archeological data | 2nd |
| Saint-Cast-le-Guildo | 1650 | archeological data | 2nd |
| Saint-Cast-le-Guildo | 2006 | archeological data | 2nd |
| Fréhel | 2006 | archeological data | 1st |
| Fréhel | 1474 | archeological data | 2nd |
| Erquy | 2006 | archeological data | 1st |
| Erquy | 2006 | archeological data | 2nd |
| Erquy | 1474 | archeological data | 1st |
| Pleneuf-Val-Andre | 2006 | archeological data | 2nd |
| Plerin | 2006 | archeological data | 2nd |
| Penvenan | 3550 | archeological data | 2nd |
| Plomeur-Boudou | 2006 | archeological data | 2nd |
| Trébeurden | 2006 | archeological data | 2nd |
| Locquirec | 2006 | archeological data | 2nd |
| Locquirec | 2750 | archeological data | 1st |
| Batz Island | 350 | archeological data | 2nd |
| Santec | 1750 | archeological data | 2nd |
| Santec | 2006 | archeological data | 2nd |
| Santec | 3550 | archeological data | 2nd |
| Santec | 3550 | archeological data | 2nd |
| Plougoulm | 2006 | archeological data | 1st |
| Plougoulm | 3550 | archeological data | 1nd |
| Plougoulm | 458 | archeological data | 1st |
| Cleder | 4100 | archeological data | 1st |
| Plouescat | 2006 | archeological data | 1st |
| Tréfléz | 450 | archeological data | 1st |
| Plounéour-Trez | 1750 | archeological data | 2nd |
| Plounéour-Trez | 1072 | sedimentological data | 2nd |
| Brignogan-Plage | 5327 | archeological data | 2nd |
| Brignogan-Plage | 5472 | sedimentological data | 2nd |
| Kerlouan | 1650 | archeological data | 2nd |
| Guisseny | 1474 | archeological data | 1st |
| Guisseny | no data | archeological data | no data |
| Guisseny | 1474 | archeological data | 1st |
| Guisseny | 1620 | archeological data | 2nd |
| Plouguerneau | 250 | archeological data | 1st |
| Landeda | 3550 | archeological data | 2nd |
| Lampaul-Ploudalmezeau | 737 | archeological data | 1st |
| Lampaul-Ploudalmezeau | 1474 | archeological data | 1st |
| Lampaul-Ploudalmezeau | 2006 | archeological data | 2nd |
| Lampaul-Ploudalmezeau | no data | archeological data | 1st |
| Landunvez | 1873 | sedimentological data | 2nd |

| | | | |
|-----------------------|---------|-----------------------|---------|
| Lampaul-Plouarzel | 190 | archeological data | 2nd |
| Plouarzel | 3640 | sedimentological data | 2nd |
| Molène Island | 3251 | archeological data | 2nd |
| Molène Island | 1810 | archeological data | 2nd |
| Le Conquet | 4404 | archeological data | 2nd |
| Le Conquet | 3908 | archeological data | 2nd |
| Plougonvelin | 1474 | archeological data | 1st |
| Crozon | 737 | archeological data | 1st |
| Crozon | no data | archeological data | no data |
| Ploéven | 1716 | sedimentological data | 2nd |
| Plonevez-Porzay | 1474 | archeological data | 1st |
| Cléden-Cap-Sizun | 1474 | archeological data | 1st |
| Esquibien | 1474 | archeological data | 1st |
| Plouhinec | 4100 | archeological data | 1st |
| Plouhinec | 2006 | archeological data | 2nd |
| Tréguennec | 3550 | archeological data | 1st |
| Plomeur | 3550 | archeological data | 2nd |
| Plomeur | 1065 | archeological data | 2nd |
| Plomeur | 690 | archeological data | 2nd |
| Guilvinec | 458 | archeological data | 1st |
| Treffragat | 2006 | archeological data | 2nd |
| Plobannalec-Lesconil | 2750 | archeological data | 1st |
| Loctudy | 5750 | archeological data | 1st |
| Loctudy | 3550 | archeological data | 2nd |
| Fouesnant | 3550 | archeological data | 2nd |
| Fouesnant | 4100 | archeological data | 1st |
| Fouesnant | 2006 | archeological data | 2nd |
| Fouesnant | 3550 | archeological data | 2nd |
| Fouesnant | 5050 | archeological data | 2nd |
| Fouesnant | 2750 | archeological data | 1st |
| Trégunc | 4100 | archeological data | 1st |
| Guidel | 567 | archeological data | 2nd |
| Gâvres | 1750 | archeological data | 2nd |
| Groix Island | 2006 | archeological data | 1st |
| Plouhinec | 3900 | archeological data | 2nd |
| Erdeven | 3300 | archeological data | 1st |
| Erdeven | 4100 | archeological data | 1st |
| Erdeven | 1474 | archeological data | 1st |
| Saint-Pierre-Quiberon | 1550 | archeological data | 1st |
| Saint-Pierre-Quiberon | 2006 | archeological data | 1st |
| Saint-Pierre-Quiberon | 1850 | archeological data | 2nd |
| Saint-Pierre-Quiberon | 3550 | archeological data | 2nd |
| Saint-Pierre-Quiberon | 4100 | archeological data | 1st |
| Quiberon | 3550 | archeological data | 1st |
| Quiberon | 2006 | archeological data | 2nd |
| Quiberon | 1474 | archeological data | 1st |
| Quiberon | 3550 | archeological data | 2nd |
| Carnac | no data | archeological data | no data |

| | | | |
|---------------|------|--------------------|-----|
| Carnac | 1474 | archeological data | 1st |
| Houat Island | 1474 | archeological data | 1st |
| Houat Island | 4648 | archeological data | 2nd |
| Hoedic Island | 2006 | archeological data | 2nd |
| Hoedic Island | 3716 | archeological data | 2nd |
| Hoedic Island | 2006 | archeological data | 2nd |
| Arzon | 6850 | archeological data | 1st |
| Sarzeau | 2006 | archeological data | 1st |

!.

| age (cal BP) | End deduced from | accuracy level |
|---------------------|-------------------------|-----------------------|
| 0 | aerial photography | 1st |
| 0 | aerial photography | 1st |
| 40 | postcard | 1st |
| 102 | Etat-Major map | 1st |
| 102 | Etat-Major map | 1st |
| 0 | aerial photography | 1st |
| 0 | aerial photography | 1st |
| 102 | Etat-Major map | 1st |
| 102 | Etat-Major map | 1st |
| 0 | aerial photography | 1st |
| 0 | aerial photography | 1st |
| 0 | aerial photography | 1st |
| 0 | aerial photography | 2nd |
| 40 | postcard | 1st |
| 2100 | archeological data | 2nd |
| 121 | archeological data | 2nd |
| 101 | Etat-Major map | 1st |
| 0 | aerial photography | 1st |
| 2400 | archeological data | 2nd |
| 101 | Etat-Major map | 1st |
| 1474 | archeological data | 1st |
| 2750 | archeological data | 1st |
| 101 | Etat-Major map | 1st |
| 121 | archeological data | 2nd |
| 121 | archeological data | 2nd |
| 80 | archeological data | 2nd |
| 0 | aerial photography | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 2400 | archeological data | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 121 | archeological data | 2nd |
| 164 | Cassini map | 1st |
| 121 | archeological data | 2nd |
| 0 | aerial photography | 1st |
| 2250 | archeological data | 2nd |
| 121 | archeological data | 2nd |

| | | |
|------|---------------------|-----|
| 121 | Historicals sources | 2nd |
| 121 | archeological data | 2nd |
| 100 | archeological data | 2nd |
| 0 | aerial photography | 1st |
| 3908 | archeological data | 2nd |
| 1298 | archeological data | 2nd |
| 101 | Etat-Major map | 1st |
| 0 | aerial photography | 1st |
| 1475 | archeological data | 1st |
| 0 | aerial photography | 1st |
| 0 | aerial photography | 1st |
| 84 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 2400 | archeological data | 2nd |
| 101 | Etat-Major map | 1st |
| 167 | Cassini map | 2nd |
| 2400 | archeological data | 2nd |
| 690 | archeological data | 2nd |
| 121 | archeological data | 2nd |
| 101 | Etat-Major map | 1st |
| 167 | Cassini map | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 101 | Etat-Major map | 1st |
| 167 | Cassini map | 2nd |
| 0 | aerial photography | 1st |
| 121 | archeological data | 1st |
| 2100 | archeological data | 2nd |
| 4100 | archeological data | 2nd |
| 121 | archeological data | 2nd |
| 167 | Cassini map | 1st |
| 101 | Etat-Major map | 1st |
| 161 | Map of Cassini | 1st |
| 0 | aerial photography | 1st |
| 161 | Cassini map | 1st |
| 102 | Etat-Major map | 1st |
| 2750 | archeological data | 1st |
| 102 | Etat-Major map | 1st |
| 0 | aerial photography | 1st |
| 1800 | archeological data | 2nd |
| 102 | Etat-Major map | 1st |
| 2400 | archeological data | 2nd |
| 0 | aerial photography | 1st |
| 2400 | archeological data | 2nd |
| 102 | Etat-Major map | 1st |
| 121 | archeological data | 2nd |
| 2060 | archeological data | 2nd |
| 2006 | archeological data | 1st |

| | | |
|------|--------------------|-----|
| 102 | Etat-Major map | 1st |
| 0 | aerial photography | 1st |
| 2400 | archeological data | 1st |
| 102 | Etat-Major map | 1st |
| 111 | Etat-Major map | 2nd |
| 121 | archeological data | 2nd |
| 102 | Etat-Major map | 1st |
| 0 | aerial photography | 1st |

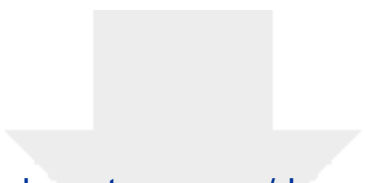
Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

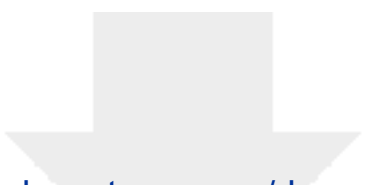
CRedit author statement.

Aneta Gorczynska: Conceptualization, Methodology, Writing- Original draft preparation, Data curation, Visualization, Investigation. Pierre Stéphan: Conceptualization, Methodology, Writing- Original draft preparation, Supervision. Bernard Le Gall: Writing- Reviewing and Editing, Supervision. Yvan Pailler: Conceptualization, Writing- Reviewing and Editing, Supervision. Guillaume Guérin: Writing- Reviewing and Editing. Clément Nicolas: Writing- Reviewing and Editing. Aurélie Penaud: Writing- Reviewing and Editing. Ophélie David: Writing- Reviewing and Editing. Muriel Vidal: Writing- Reviewing and Editing.




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