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Late Pleistocene Landscape and Settlement Dynamics of Portuguese Estremadura

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ABSTRACT

Here we report the results of an integrated geoarchaeological survey to study Palaeolithic human settlement dynamics in the coastal region of Portuguese Estremadura. The region has been an important focus of human occupation across multiple glacial-interglacial cycles, including periods of well-documented abrupt climate instability during MIS 3 and 2. The pedestrian survey covered a roughly 10 km wide strip of land between São Pedro de Muel and Peniche. The survey intensively targeted three landscape settings with Pleistocene-age surfaces and sediments: the coastal bluffs with exposed aeolian, fluvial, and colluvial sands; the Caldas da Rainha diapiric valley and associated fluvial/estuarine fills; and, Cretaceous chert-rich limestone uplands that bound the inland margin of the study area. We discovered dozens of new Palaeolithic sites, analyzed numerous Pleistocene sedimentary sections, and applied widespread OSL-dating to establish age control that allowed us to build a regional geomorphic history to contextualize Late Pleistocene human settlement across the region.

KEYWORDS
Palaeolithic; archaeological survey; geomorphology; OSL dating; Portugal

Introduction

In 2005, we began a systematic archaeological survey along the Estremadura coast of Portugal to study human adaptations to Pleistocene climatic instability and environmental change in the coastal zone, which is now recognized as a key setting for understanding Middle and Upper Palaeolithic settlement dynamics (Finlayson 2004; Finlayson and Giles Pacheco 2000; Finlayson and Carrion 2007). Our research focused on the last glacial cycle, Marine Isotope Stages (MIS) 5–2, a period of dramatic environmental changes, which includes the last interglacial stage (MIS 5e), the initial descent into glacial conditions (MIS 5–4), a highly unstable period punctuated by Greenland stadial/interstadial (Dansgaard-Oeschger events) and Heinrich events (MIS 3), the Last Glacial Maximum (LGM), and Termination I, ending with the Younger Dryas climatic reversal (MIS 2). These events are of critical importance in both archaeological and paleoenvironmental studies, as previous work shows that they exerted strong controls on the physical and biological landscape experienced by Middle and Upper Palaeolithic populations, whether Neanderthals or modern humans, in Iberia (Barton et al. 2013; Bicho, Haws, and Almeida 2011; Bicho et al. 2017; Haws 2012; Schmidt et al. 2012; Tuffreau and Roebroeks 2002; van Andel and Davies 2003; van Andel and Tzedakis 1996). The primary goals of this project were to discover new Palaeolithic sites and build a record of human settlement in the region, to establish a baseline chronology of Palaeolithic human and geomorphic response to climate and sea level change, to characterize the paleoenvironments that Palaeolithic people inhabited, and to test hypotheses concerning Palaeolithic coastal landscape use and models of coastal landform evolution.

To meet these goals, we designed an integrated geoarchaeological survey to locate and map artifacts and build a geomorphic history of the study area using radiometric dating techniques (luminescence, AMS radiocarbon, and U-Th dating). We then integrated these data with high-resolution paleoenvironmental records (ice cores, deep sea sediment cores, and speleothems) to address questions of landscape change during the Late Pleistocene.

Previous studies linking Late Quaternary paleoclimatic events and terrestrial deposits were hindered by problems with limited absolute dating and radiocarbon calibration prior to 30,000 B.P. and the relatively large uncertainty of luminescence age estimates. Advances in both radiocarbon and optically-stimulated luminescence (OSL) dating have improved the temporal resolution, but limitations remain (Briant and Bateman 2009; Higham, Jacobi, and Bronk Ramsey 2006; Jacobs and Roberts 2007; Jöris and Street 2008; Reimer et al. 2013; Wood et al. 2016). These limits are especially problematic given the short duration of paleoclimatic episodes such as Dansgaard-Oeschger (D-O) and Heinrich events (HEs) (Whittington and Hall 2002). As Aubry and colleagues note, “the exact impact of Heinrich Events (and Stadials) on terrestrial systems and the open-air sedimentary record is still not clearly established” (Aubry et al. 2015, 2). This stems from research and preservation biases, as well as a lack of age control.

One of our goals was to avoid potential geomorphic biases in the archaeological record and to establish the spatial and temporal scales over which hypotheses about human settlement and resource use can be tested. Before making interpretations of patterned behavior, we needed empirically derived maps of artifact locations across the region and a better

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spatio-temporal resolution of the regional geology and geomorphology. As Bintliff (2000, 200) cautions, "Relying on the known extensive knowledge can be a recipe for failing to uncover unexpected details of the surface archaeology." In fact, very little was known about the surface archaeology and Quaternary geomorphology of the study area when we began. No systematic pedestrian survey had been undertaken in the study area, and the existing geological maps were prepared before the development of many radiometric techniques. These maps were drawn at a 1:50,000 scale that barely represented the Quaternary deposits in most of the survey area. For example, the Pleistocene deposits at Praia Rei Cortiço, where we found a Middle Palaeolithic site buried beneath almost 20 m of Pleistocene fluvial and aeolian deposits, are rendered invisible at the 1:50,000 scale.

The Study Region

Portuguese Estremadura is a coastal region encompassing 8,700 km^2 between 40°07' and 38°24' N. The region extends northward from the Setúbal peninsula to the Mondego River and eastward to the Tagus (*Tejo*) valley and Portuguese central range (Marks et al. 1994; Ribeiro, Lautensach, and Daveau 1987). Estremadura has a varied geography marked by a Jurassic limestone massif and karstic caves, surrounded by plains and valleys filled by Miocene and Quaternary sands (Daveau 1980). Oceanic influence allows for a mild climate and a mix of Thermo and Meso-Mediterranean bioclimatic zones (Quézel 1985).

The survey focused on the coastal strip from São Pedro de Muel to Peniche (Figure 1). The geology and topography of the study area are strongly influenced by salt diapirs, strike-slip faults, and other active neotectonic features (Alves et al. 2003; Cabral et al. 2018; Cunha 2019; Cunha, de Vicente, and Martín-González 2019; Galve et al. 2020). The coast north of Nazaré is characterized by a vast, raised bedrock platform overlain by Pliocene and Quaternary deposits as far north as São Pedro de Muel (Cunha 2019; Cunha, Barbosa, and Pena dos Reis 1993; Pais et al. 2012; Ramos 2008; Vieira 2009). A coastal dune field, mapped as an older Pleistocene belt and a younger Holocene belt, covers the coastal cliffs and extends up to 15 km inland (André, Rebelo, and Cunha 1997, 2001; André et al. 2009; Cunha et al. 2006; França and Zbyszewski 1963). South of Nazaré, the coast is

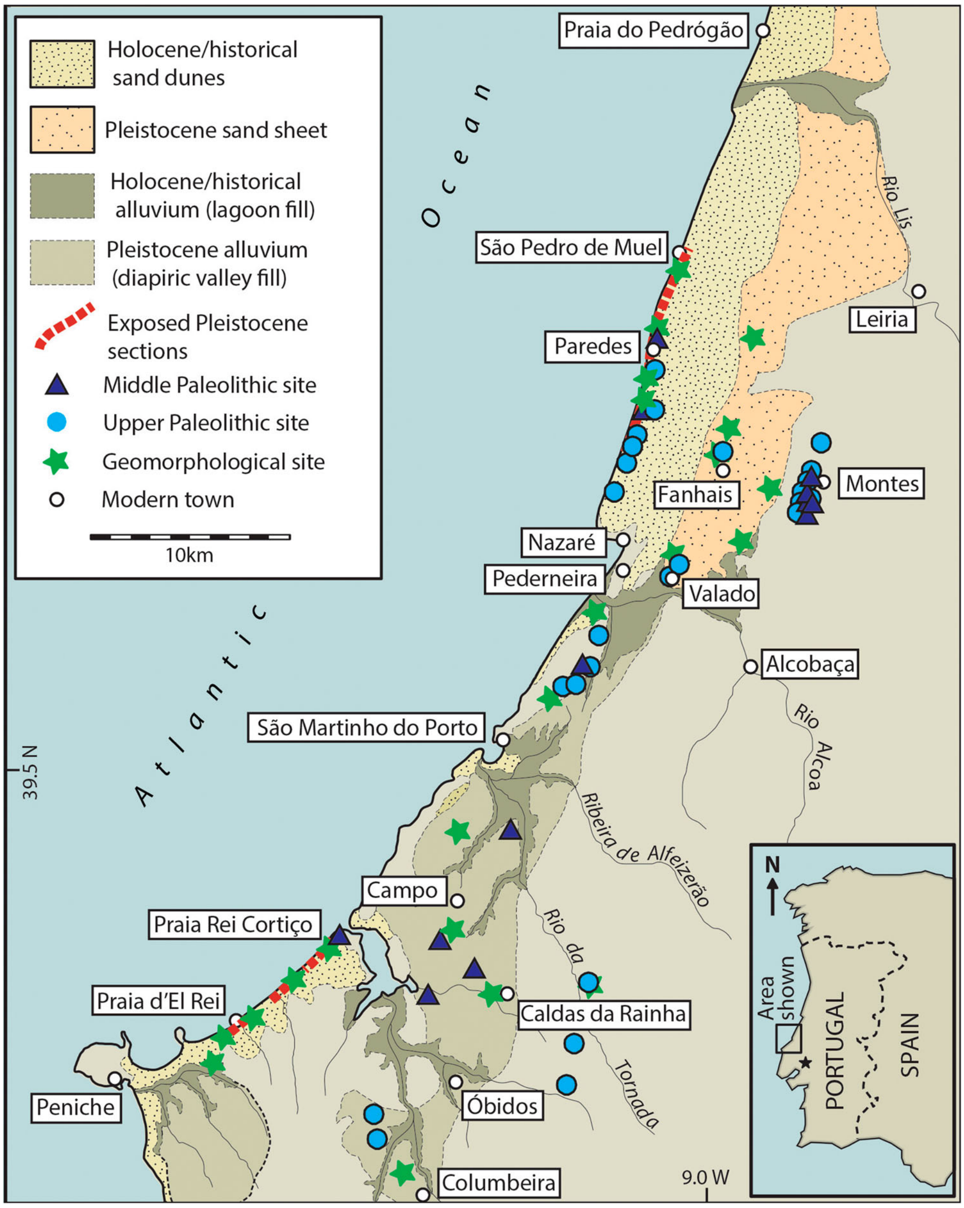

Figure 1. Map of study area and sites mentioned in the text.

occupied by steep Mesozoic bedrock cliffs with a mantle of Pliocene and Quaternary marine, fluvial, aeolian, and colluvial sands and gravels. Landward of the cliffs lies the Caldas da Rainha valley, an unroofed diapir that runs parallel to the coast and has been occupied by tidal lagoons during relative sea level high stands of the Pleistocene and Holocene (Dinis et al. 2006). The largest of these, the Lagoa de Óbidos, is a structurally-controlled estuary that dominates the southern part of the diapiric valley. Thick Quaternary valley fills occupy its tributaries and other paleovalleys etched into the bedrock. The diversity of modern coastal landforms (barrier beaches, bedrock cliffs and platforms, bays, and estuaries) is mirrored in stratigraphic evidence of ancient depositional environments preserved in the study area.

Palaeolithic archaeology

Previous works established that Estremadura contains abundant Pleistocene-aged surfaces and Palaeolithic archaeological sites (Almeida et al. 2003; Breuil and Zbyszewski 1945; Carvalho et al. 1989; Fernandes, Moreira, and Raposo 2008; Haws et al. 2011; Marks et al. 1994; Straus, Bicho, and Winegardner 2000; Thacker 2000, 2001; Zilhão 1997, 2000). Settlement locations include the beach, near-shore tidal flats, coastal bogs, streams, interfluves, dunefields, caves, and rockshelters. Despite their near-coastal setting, most of the Palaeolithic sites are open-air localities without organic preservation. A relatively small number of cave and rockshelter sites contain sporadic evidence of coastal resource use during the Palaeolithic (Cardoso 2006; Bicho 2000; Bicho and Haws 2008).

Estremadura occupies an important coastal ecotone, where a rich marine upwelling zone meets a series of productive Mediterranean biomes (Abrantes 1988, 1991, 2000; Allen 2010; Fiuza 1983; Quézel 1985; Rivas-Martínez et al. 2001). Similar ecotone settings are well-documented as preferred locations for ethnographically-known foragers (Lee and Daly 1999; Westley and Dix 2006). Late Pleistocene hunter-gatherers utilized this landscape with varying degrees of intensity through time, likely associated with pulses in upwelling intensity and oceanic productivity (Haws 2003; Bicho and Haws 2008). Such pulses of occupation are apparent in evidence from the adjacent Rio Maior, Lis, and Alcabrichel drainage basins (Carvalho et al. 1989; Zilhão 1997; Straus, Bicho, and Winegardner 2000; Thacker 2000).

Artifact classes in Estremadura show no distinctions that may be regarded as social boundary indicators (Thacker 2000; but see Zilhão 1997, 2000 for an alternative view). The absence of strong regional differentiation in Palaeolithic artifact style and the palimpsest nature of most of the material records preclude a clear demarcation of territory. The presence of coastal items in caves and rockshelters up to 50 km inland suggests a large exploitation territory ranging from the shoreline to upland valleys along the entire Estremaduran strip (Bicho and Haws 2008). The size of Estremadura is well within Whallon's (2006) maximal band radius, corresponding to an area possibly occupied by a few minimal bands. Recently, Aubry and colleagues (2012) have analyzed lithic raw material sourcing data in GIS to link the Côa Valley rock art sites with settlements in Estremadura. The nonlocal chert in Estremadura and occurrence of Estremaduran chert in the Côa Valley sites suggests movement within ethnographically-known annual exploitation territories of hunter-gatherers. Thus, one large social group likely occupied Estremadura at any given time, with smaller ones regularly interacting and moving seasonally between the actual coast and inland valleys.

Methods

Understanding human adaptations to Pleistocene climatic instability and environmental change requires an appreciation for long, medium, and short-term behavioral and geomorphic processes that form the archaeological record. Humans respond to changing environmental conditions through technological, subsistence, and settlement decision-making. The organizational properties of these components can be studied best through a landscape approach, which helps mitigate conceptual problems associated with site-based archaeology (Dunnell 1992; Mithen 1998; Thacker 2000; Zvelebil, Green, and Macklin 1992). We use the archaeological landscape concept to identify broader, long-term patterns in artifact accumulation, organizational properties of settlement, and the duration and intensity of landscape occupation (de Lange 2008; Dewar and McBride 1992; Donohue and Lovis 2006).

As part of a sedimentary process, the archaeological record forms through a series of human actions, subsequent deposition, and modification due to continuous geomorphic processes. Developing a landscape history using a geomorphological approach is necessary to help understand the formation of the archaeological record, particularly in complex geomorphic settings (Holdaway and Fanning 2008; Wells 2001). Holdaway and Fanning (2008, 172) have observed that land surfaces form as a "result of individual erosion and deposition events operating at different temporal and spatial scales," and that "(r)egional discontinuity in deposition is the norm, leading to a patchwork distribution of land surfaces differing markedly in age." This type of discontinuous landscape formation applies directly to Portuguese Estremadura, where a diversity of landforms and lack of absolute age-control have limited our understanding of regional landscape history.

Shott (2003, 60) noted that, "(a)ssemblages cannot be understood without knowing the time span over which they accumulated." Many open-air Palaeolithic localities lack typologically diagnostic artifacts, and radiometric dating has been crucial to provide better temporal controls on settlement intensity and geomorphic context. In past studies, age control for open-air sites has largely been achieved through typological attribution of artifacts and, in limited cases, radiocarbon dating of features. In a circular fashion, the archaeology has been used to date landscapes and then landscape age has been used to explain settlement patterns. In this case, we developed independent age control by age-dating sediments and inferring archaeological age in conjunction with technological associations.

Thus, a critical step in our survey was to establish baseline chronologies for geomorphic activity and human occupation in the study area. OSL dating of landforms and weathering surfaces has been essential to establishing independent age control for the Quaternary landscape and open-air Palaeolithic archaeology of Estremadura. We age-dated key features of the Pleistocene landscape in which archaeological processes unfolded: coastal dune fields, paleowetlands, fluvial terraces, valley fills, and paleosols. Most Quaternary deposits in the study area are sandy and pebbly, with poor preservation of organic matter or microfossils. OSL dating was applied with good results in similar settings along the Portuguese coast (Carvalhido et al. 2014; Ramos et al. 2012; Thomas et al. 2008). OSL was successful in this region because the surface sediments are rich in medium to coarse grained quartz sand, and the luminescence signal was reliably reset by exposure to subtropical sunlight on surfaces with limited vegetation cover under mostly semiarid to subhumid Pleistocene climates. Radiocarbon dating in the study area, on the other hand, has been hindered by poor organic matter preservation in the highly oxidizing sandy sediments and by deep penetration of modern roots and illuvial humus. Therefore, our study relied heavily on OSL dating to provide age control (Benedetti et al. 2009).

Archaeological survey

We used a multi-scale survey methodology similar to that employed by Holdaway and Fanning (2008). Following Stern (2008, 366), our survey covered a wide geographic extent with broad stratigraphic intervals needed for long-term landscape archaeology. Effectively, this was a stratified survey to specifically target extant Quaternary landscapes. At the regional scale, the survey covered major landforms, including the coastal bluffs, Pleistocene dunefields, fluvial terraces, and limestone uplands with caves, shelters, and chert sources. The targeted landforms occur along the exposed coastal bluffs between São Pedro de Muel and Peniche, the calcareous uplands of Montes, the sands of the Caldas da Rainha diapiric valley, and the surrounding limestone massif with known caves such as Casa da Moura, Gruta Nova de Columbeira, and Lapa do Suão (Figure 1). The diapiric valley includes Pleistocene terraces along the margins of the three ancient lagoons of Pederneira, Alfeizerão, and Óbidos that formed during the Holocene marine transgression and silted in during historic times (Dinis et al. 2006).

The survey crew consisted of archaeologists and geomorphologists, along with students from the participating universities. A crew of 6–8 walked a broad transect along the top of the coastal bluffs where Pliocene and Pleistocene sediments outcropped between São Pedro do Muel and Peniche, a roughly 50 km stretch of coastline. The width varied from a few meters to several tens of meters, depending on the extent of the exposures. The crew also walked transects in the valleys and uplands adjacent to the coastal dunes. These tracts covered clearings, pine and eucalyptus plantations, and agricultural fields, including vineyards and orchards of varying widths and lengths. The field tracts typically ranged from 10–50 m wide × 10–100 m long. The tracts were georeferenced using handheld Garmin GPS devices that had a 1–5 m standard error. In the last field season, we employed a total station to create a detailed map of artifacts to demonstrate the downslope movement of artifacts and palimpsest creation in the Montes uplands. Site testing in 1× 1 m units was limited to localities that had extensive surface artifacts. We used a bucket auger in several areas to trace buried landscape features such as paleosols and determine the extent and depth of artifact distributions. In all cases, a sample of surface artifacts was collected for technological and typological analyses at the Universidade do Algarve. Three sites, Praia Rei Cortiço, Mira Nascente, and Ribeiros de Lagoa Seca, were extensively excavated after determining that they were in imminent danger from marine erosion and construction activities.

OSL and radiocarbon dating

Sediment samples for OSL dating were collected from geomorphological profiles and archaeological sites. Prior to sampling, approximately 30 cm of sediment was removed from the exposure wall to ensure sample quality. For each sample, a PVC tube wrapped with opaque, black electrical tape was driven into the profiles using a soft mallet to collect sand. Samples were analyzed at the Luminescence Dating Lab at the University of Illinois-Chicago and, subsequently, Baylor University. Equivalent doses were determined by the multiple aliquot regenerative dose method under green (514 nm) or blue (470 nm) excitation (Jain, Botter-Jensen, and Singhvi 2003). The coarse-grained (150–250 mm) quartz fraction of each sample was analyzed. The environmental dose contribution of surrounding sediments was determined from samples collected in a 20 cm radius surrounding the sample tube and the cosmic dose component from Prescott and Hutton (1994) based on latitude, longitude, elevation, and burial depth of samples. Water content (generally 10–15%) was estimated from particle size characteristics, assuming periodic wetting in the vadose zone.

Charcoal, peat, and organic sediment samples were collected and sent for AMS radiocarbon analysis at the Center for Applied Isotope Studies at the University of Georgia and Beta Analytic in Miami, Florida. Both labs utilized the acid-base-acid (ABA) pretreatment protocol.

Geomorphological characterization

Field methods included description of sediment and soil profiles and sampling for laboratory analyses, including a full range of sedimentological, pedological, paleobotanical, geomagnetic, and geochemical techniques. These include particle size by sonic sifter and laser diffraction methods, pollen and plant macrofossil identifications where preservation allowed (Minckley et al. 2015; Taylor et al. 2018), geochemical discrimination of depositional environments using sand grain counts and heavy mineral separations, clay mineralogy by XRD analysis, and elemental analysis by XRF analysis (Benedetti et al. 2009). Analysis of δ^{13}C ratios in modern estuarine/floodplain sediments (reflecting plant adjustments to salinity gradients) provided a baseline for comparison to ancient organic deposits. We also used ground penetrating radar (GPR) to map paleosurfaces and subsurface hydrology (Conyers et al. 2013). Additionally, U-Th dating and δ^{13}C, δ^{18}O, and δ^{234}U analyses of speleothems from caves in the study area provided a record of paleoprecipitation and coarse-grained vegetation changes over the last 200,000 years (Denniston et al. 2018).

Results

The survey identified of a series of colluvial deposits on coastal bluffs, aeolian dunes, alluvial valley fills, peat deposits, buried soils, and associated Palaeolithic archaeological artifact occurrences. These deposits revealed considerable geomorphic and temporal variability. Figures 2–4 show the location of the archaeological sites and geomorphological profiles mentioned in the text. Extensive application of OSL dating in the Pleistocene sand deposits and artifact mapping, collection, and analysis indicate that nearly all of the sandy Pleistocene surface deposits in the study area date between MIS 6–2 (roughly

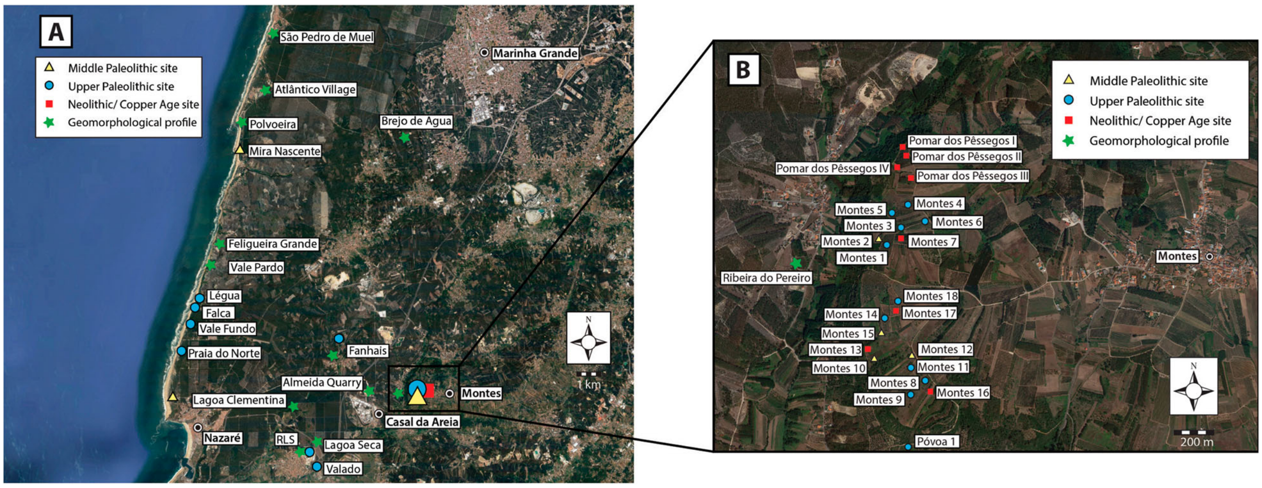

Figure 2. Northern study area sites (A) near Pataias with Montes inset (B). Background image from Google Earth.

200-12 kya; Table 1), suggesting widespread reorganization of this landscape over the period of Middle and Upper Palaeolithic occupation. Here, we report the results to date and their implications for understanding human response to environmental change during the Pleistocene.

The results presented here focus on summarizing the Late Pleistocene archaeological record in its geomorphic setting and stratigraphic context. Detailed geomorphological (Benedetti et al. 2009), pollen (Minckley et al. 2015), GPR (Conyers et al. 2013), and speleothem (Denniston et al. 2018) results have been published previously and are used as supporting evidence here.

Age control

We found excellent agreement between OSL age estimates and radiocarbon age estimates on charcoal from the same stratigraphic levels (Benedetti et al. 2009). Additionally, we established firm age control at several sites through replicate sampling of key strata. For example, at Mira Nascente, the artifact-bearing stratum is a sand deposit that dates to around 40,000–42,000 B.P., based on a suite of 5 OSL and radiocarbon samples. While the error for each individual sample is fairly large (1σ range of about 1000–5000 years for OSL ages of 10–70 kya), as a composite, the samples yield a useful age probability distribution for correlation with paleoclimate records. Terrestrial evidence from Estremadura compares favorably with ice core and deep-sea sediment records tuned to the GICC05 timescale using the INTIMATE protocol (Rasmussen et al. 2014), which gives accurate age estimates for Dansgaard-Oeschger and Heinrich events off Portugal and can be used for land-sea correlation in Iberia (de Abreu et al. 2003; Turon, Lézine, and Denèfle 2003; Sánchez Goñi et al. 1999, 2008, 2018; Vautravers and Shackleton 2006).

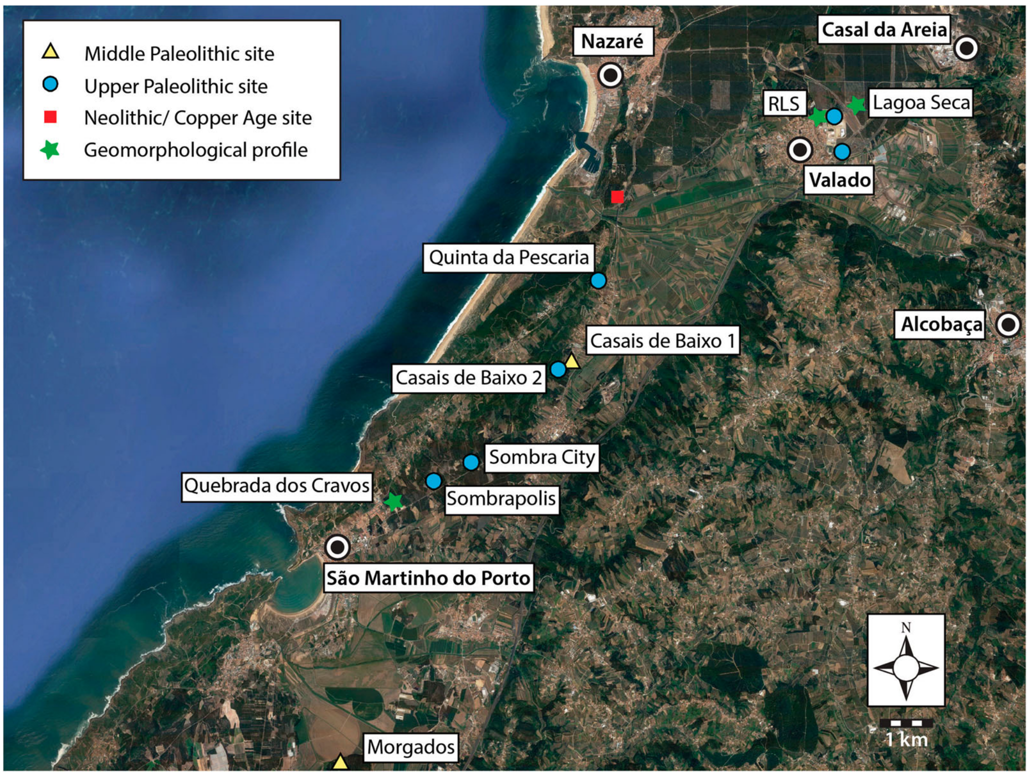

Figure 3. Central study area sites between Nazaré and São Martinho do Porto. Background image from Google Earth.

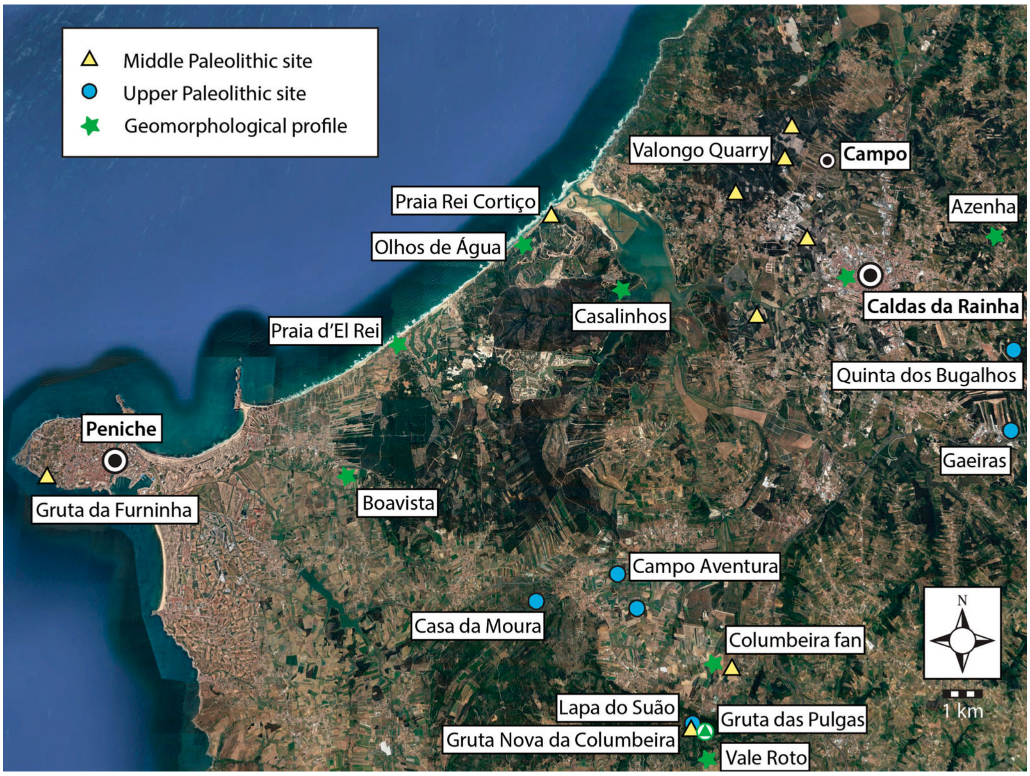

Figure 4. Southern study area sites near Caldas da Rainha and Peniche. Background image from Google Earth.

For example, the age of the artifact deposit at Mira Nascente is just prior to the H4 event, while the overlying cross-bedded sand dates to just after H4, demonstrating a disconformity associated with H4 (Benedetti et al. 2009). Although individual samples may not yield ages that can be conclusively linked to a specific climatic event, an argument can still be built around clusters of ages that are centered on specific Heinrich events or non-Heinrich intervals. At present, this multi-sample approach is one of the only ways to address short-lived geomorphic events and human settlements prior to the glacial maximum.

We employed a similar approach in linking aeolian and fluvial sections to paleoclimate events. Repeated cycles of sand mobilization and dune building in the study area between 11–70 kya are indicated by OSL ages that cluster around Heinrich and D-O events. At present, nearly every dated sample falls within the $\pm 1\sigma$ range of a cold phase (see also Costas et al. 2012). Although the precise relationship between erosive episodes and climate events is obscured by the uncertainty associated with OSL ages, it appears that the occurrence of HEs at 5000–7000 year intervals (along with higher frequency D-O cycles) may have precluded formation of mature soils and favored geomorphic instability throughout MIS 2, 3, and 4. This pattern helps explain the sparse/altered nature of most Palaeolithic archaeological finds associated with dunes, coastal bluffs, and fluvial terraces in the period 10,000–100,000 B.P. The exceptions are stratigraphically-intact buried sites like Mira Nascente and Praia Rei Cortiço. By contrast, the end of the Pleistocene brought a period of prolonged forest expansion, pedogenesis, and geomorphic stability. The Early to Middle Holocene is marked by a well-developed spodosol soil profile that is found today on undisturbed parts of the landscape. Surface and buried exposures of this paleosol are valuable indicators of Pleistocene-aged geomorphic surfaces that often preserve Palaeolithic archaeological evidence.

Paleovegetation

The Pleistocene vegetation history of Estremadura is mainly known from regional-scale pollen in offshore sediment cores. Records of vegetation change in western Iberia over the last glacial cycle show periodic fluctuations between arid steppe vegetation during cold, dry events and open woodlands of mixed temperate and Mediterranean species during warmer and more humid ones (Sánchez Goñi et al. 2000; Roucoux et al. 2005; Vautravers and Shackleton 2006; Daniau et al. 2007; Gómez-Orellana, Ramil-Rego, and Muñoz Sobrino 2007). At the local scale, pollen and plant macrofossils are found in the study area. We sampled several of these dated between MIS 5 and 2. Pollen analyses for Praia Rei Cortiço were conducted at the University of Wyoming and for Mira Nascente by Marjeta Jeraj at the University of Wisconsin. Minckley and colleagues (2015) published a pollen record of vegetation changes during MIS 5 from Praia Rei Cortiço. This paleowetland preserves a relatively short-term record of vegetation response to climate fluctuations during the Last Interglacial. The channel fill deposit at Mira Nascente records the presence of both rocky shore and marsh vegetation during a humid phase of late MIS 3. Across the region, inter-dunal lakes and wetlands were present during humid phases of the Late Pleistocene (Granja, de Groot, and Costa 2008). In northern Portugal, tree stumps of *Pinus sylvestris* have been exposed along the coast and dated to the Pleniglacial (García-Amorena et al. 2007).

Geoarchaeological survey

The integrated survey identified Palaeolithic artifacts in varying concentrations across three major landforms in the study region. These include the coastal bluffs with Pleistocene sands, the diapiric valley fills, and the calcareous uplands,

Table 1. Sample data for optically-stimulated luminescence ages in this study. Ages in bold are considered reliable.

Site	Unit ID	Lab Reference	Equivalent Dose (Grays)[a]	U (ppm)[c]	Th (ppm)[c]	K_2O (%)[c]	H_2O (%)[d]	Cosmic Dose (mGrays/yr)[e]	Total Dose (mGrays/yr)	OSL Age (yr)[f]
São Pedro de Muel	SP2	UIC2069[h]	41.66 ± 0.74	0.5 ± 0.1	1.5 ± 0.1	1.13 ± 0.01	10 ± 3	0.016 ± 0.002	1.17 ± 0.07	**35,530 ± 2,785**
	SP3b	UIC2066[h]	62.52 ± 0.11	0.9 ± 0.1	2.9 ± 0.1	1.63 ± 0.01	10 ± 3	0.016 ± 0.002	1.77 ± 0.08	**35,260 ± 2,590**
	SP3d	UIC2068[h]	56.08 ± 0.50	0.7 ± 0.1	2.2 ± 0.1	1.32 ± 0.01	10 ± 3	0.015 ± 0.001	1.42 ± 0.07	**39,450 ± 2,980**
	SP3f	UIC2067[h]	71.51 ± 0.83	0.8 ± 0.1	2.2 ± 0.1	1.50 ± 0.01	10 ± 3	0.015 ± 0.002	1.54 ± 0.07	**46,660 ± 3,570**
Brejo de Agua	BA1	UIC3032	12.32 ± 0.89	0.6 ± 0.1	1.6 ± 0.1	0.82 ± 0.01	10 ± 3	0.15 ± 0.01	1.07 ± 0.06	**11,610 ± 820**
Atlântico Village	AV1	UIC2323[h]	2.30 ± 0.20	0.9 ± 0.1	2.0 ± 0.1	0.91 ± 0.01	10 ± 3	0.16 ± 0.02	1.24 ± 0.06	**1,850 ± 200**
Polvoeira	PV2c	UIC2070[h]	62.69 ± 0.45	0.6 ± 0.1	1.5 ± 0.1	1.77 ± 0.01	10 ± 3	0.015 ± 0.002	1.73 ± 0.08	**36,250 ± 2,840**
	PV4	UIC2071[h]	57.40 ± 1.38	0.7 ± 0.1	1.9 ± 0.1	0.75 ± 0.01	10 ± 3	0.014 ± 0.001	0.92 ± 0.05	**62,220 ± 4,660**
Mira Nascente	MN2	UIC1875[h]	50.10 ± 0.16	0.6 ± 0.1	1.4 ± 0.1	1.36 ± 0.01	10 ± 3	0.028 ± 0.003	1.39 ± 0.07	**36,030 ± 2,750**
	MN2	UIC1863[h]	61.79 ± 0.15	0.6 ± 0.1	1.2 ± 0.1	1.91 ± 0.02	10 ± 3	0.016 ± 0.002	1.82 ± 0.09	**33,905 ± 2,690**
	MN3b	UIC1864[h]	50.22 ± 0.05	0.8 ± 0.1	1.5 ± 0.1	1.14 ± 0.01	10 ± 3	0.016 ± 0.002	1.24 ± 0.07	**40,450 ± 2,980**
	MN3c	UIC1923[h]	47.89 ± 1.00	2.0 ± 0.1	2.7 ± 0.1	1.09 ± 0.01	20 ± 5	0.015 ± 0.002	1.39 ± 0.07	**34,300 ± 2,630**
	MN4	UIC1868[h]	>140.08 ± 0.08	0.6 ± 0.1	1.2 ± 0.1	1.25 ± 0.01	10 ± 3	0.015 ± 0.002	1.27 ± 0.07	>110,050 ± 8,460
	MN5	UIC2065[h]	139.69 ± 0.68	0.6 ± 0.1	1.8 ± 0.1	0.85 ± 0.01	15 ± 5	0.012 ± 0.001	0.93 ± 0.05	**150,920 ± 12,575**
Vale Pardo	VP2	UIC2324[h]	86.10 ± 2.31	0.8 ± 0.1	1.8 ± 0.1	1.11 ± 0.01	10 ± 3	0.16 ± 0.02	1.37 ± 0.07	62,855 ± 4,590
	VP3	UIC2326[h]	42.98 ± 2.10	1.0 ± 0.1	1.9 ± 0.1	1.18 ± 0.01	10 ± 3	0.16 ± 0.02	1.48 ± 0.07	**29,100 ± 2,415**
	VP3	UIC3033	25.71 ± 1.80	0.8 ± 0.1	1.9 ± 0.1	0.67 ± 0.01	10 ± 3	0.11 ± 0.01	0.88 ± 0.05	**29,055 ± 1920**[g]
	VP4	UIC3034	>290	1.9 ± 0.1	9.6 ± 0.1	2.37 ± 0.02	15 ± 3	0.05 ± 0.01	2.94 ± 0.14	>99 ka
Ribeiro do Pereiro	RP1	UIC2571	14.34 ± 0.17	0.5 ± 0.1	0.7 ± 0.1	1.14 ± 0.01	10 ± 3	0.16 ± 0.02	1.26 ± 0.06	**11,425 ± 855**
Fanhais	FN1	UIC1876	43.34 ± 0.08	0.5 ± 0.1	1.0 ± 0.1	1.51 ± 0.01	10 ± 3	0.028 ± 0.003	1.58 ± 0.08	**27,490 ± 2,070**
Casal da Areia (Almeida Quarry)	AQ1	UIC2327	29.15 ± 0.24	0.8 ± 0.1	2.1 ± 0.1	2.27 ± 0.02	10 ± 3	0.028 ± 0.003	2.26 ± 0.12	**12,985 ± 1,005**
	CA2	BG3976	41.62 ± 1.62	0.61 ± 0.01	1.22 ± 0.01	0.91 ± 0.01	10 ± 3	0.08 ± 0.01	0.96 ± 0.05	**43,540 ± 3405**
Lagoa Seca	LGS-T3	BG3582	15.13 ± 0.99	0.5 ± 0.1	1.2 ± 0.1	1.08 ± 0.01	10 ± 3	0.16 ± 0.02	1.17 ± 0.06	**12,905 ± 1050**
Valado dos Frades	VFII-A	UIC3016	13.36 ± 0.82	0.6 ± 0.1	1.8 ± 0.1	0.98 ± 0.02	10 ± 3	0.10 ± 0.01	1.16 ± 0.06	**11,480 ± 820**
	VFII-A	UIC3015	0.26 ± 0.03	0.5 ± 0.1	2.8 ± 0.1	1.00 ± 0.01	10 ± 3	0.15 ± 0.01	1.27 ± 0.07	**205 ± 30**
	VFII-C	UIC2998	0.28 ± 0.04	0.5 ± 0.1	1.3 ± 0.1	1.07 ± 0.01	10 ± 3	0.16 ± 0.02	1.27 ± 0.07	**230 ± 40**
Quebradas dos Cravos	QC1	UIC2328	168.40 ± 4.56	0.8 ± 0.1	1.8 ± 0.1	1.31 ± 0.01	10 ± 3	0.18 ± 0.02	1.56 ± 0.08	**108,265 ± 8,020**
Cafurno	CF1	UIC2572	29.08 ± 0.13	0.7 ± 0.1	1.3 ± 0.1	1.16 ± 0.01	10 ± 3	0.16 ± 0.02	1.36 ± 0.07	**21,445 ± 1520**
Azenha	AZ1	UIC2325	38.54 ± 0.79	0.8 ± 0.1	1.9 ± 0.1	0.93 ± 0.01	10 ± 3	0.16 ± 0.02	1.23 ± 0.06	**31,440 ± 2,180**
Cabeço da Amoreira	CAM-1	UIC2997	38.76 ± 2.34	1.6 ± 0.1	7.3 ± 0.1	2.56 ± 0.03	10 ± 3	0.13 ± 0.02	3.10 ± 0.15	**12,480 ± 845**
Valongo (Campo) Quarry	VQ1	UIC2400	>168.20 ± 2.81	0.6 ± 0.1	1.6 ± 0.1	0.72 ± 0.01	10 ± 3	0.028 ± 0.003	0.87 ± 0.05	>193,910 ± 14,360
	VQ3	UIC3021	61.37 ± 4.41	0.8 ± 0.1	3.2 ± 0.1	0.86 ± 0.01	10 ± 3	0.14 ± 0.01	1.24 ± 0.06	**49,520 ± 3690**
Caldas da Rainha	CQ2	UIC2573	>199.91 ± 2.25	0.9 ± 0.1	1.4 ± 0.1	0.49 ± 0.01	10 ± 3	0.14 ± 0.01	0.83 ± 0.05	>241,905 ± 15,780
Casalinhos (Óbidos)	CL0-1	UIC3028	68.62 ± 3.80	0.7 ± 0.1	2.0 ± 0.1	0.67 ± 0.01	10 ± 3	0.16 ± 0.02	0.99 ± 0.05	**69,120 ± 4550**
Praia de Rei Cortiço	PC1[b]	UIC3352	0.46 ± 0.08	0.8 ± 0.1	3.4 ± 0.1	0.37 ± 0.01		0.15 ± 0.01	0.83 ± 0.04	**545 ± 100**
	PC2	UIC2399[h]	33.58 ± 0.27	1.0 ± 0.1	5.6 ± 0.1	1.70 ± 0.01	10 ± 3	0.16 ± 0.02	2.23 ± 0.12	**15,060 ± 980**
	PC3	UIC3361	42.70 ± 0.90	0.7 ± 0.1	1.5 ± 0.1	0.54 ± 0.01		0.04 ± 0.04	0.83 ± 0.04	**51,165 ± 3865**
	PC3	UIC2608[i]	65.87 ± 2.80	0.8 ± 0.1	1.8 ± 0.1	0.75 ± 0.01	10 ± 3	0.028 ± 0.003	0.95 ± 0.05	**69,380 ± 5660**
	PC3	UIC2607[i]	72.51 ± 2.92	0.7 ± 0.1	1.7 ± 0.1	0.88 ± 0.01	10 ± 3	0.063 ± 0.006	1.06 ± 0.05	**68,320 ± 5530**
	PC4	UIC3353	68.04 ± 3.86	2.3 ± 0.1	8.3 ± 0.1	1.94 ± 0.01		0.04 ± 0.01	2.69 ± 0.14	25,315 ± 1595
	PC4	UIC3360	48.49 ± 2.91	0.7 ± 0.1	1.4 ± 0.1	0.43 ± 0.01		0.04 ± 0.01	0.58 ± 0.03	**79,800 ± 5695**
	PC4	UIC2398[h]	71.63 ± 2.58	0.9 ± 0.1	1.4 ± 0.1	0.47 ± 0.01	10 ± 3	0.028 ± 0.003	0.71 ± 0.04	**101,010 ± 7,870**
	PC5	UIC2606[i]	111.17 ± 3.08	1.3 ± 0.1	4.1 ± 0.1	0.70 ± 0.01	10 ± 3	0.021 ± 0.002	1.17 ± 0.06	**95,370 ± 6470**
	PC5	UIC3022	61.97 ± 4.12	1.7 ± 0.1	4.3 ± 0.1	0.79 ± 0.01	15 ± 3	0.02 ± 0.01	0.93 ± 0.05	**66,950 ± 4790**
	PC5	UIC3023TT	NC	5.9 ± 0.1	5.6 ± 0.1	0.56 ± 0.01	15 ± 3	0.02 ± 0.01	2.04 ± 0.10	NC
	PC5	UIC3019	No quartz							Non-datable
	PC5	UIC2915[i]	89.34 ± 6.65	0.6 ± 0.1	1.5 ± 0.1	0.79 ± 0.01	10 ± 3	0.020 ± 0.002	0.80 ± 0.04	**111,250 ± 8800**
	PC6	UIC2852[i]	>236	1.3 ± 0.1	2.4 ± 0.1	1.83 ± 0.01	10 ± 3	0.03 ± 0.01	2.01 ± 0.10	>117,670
	PC6	UIC3363	saturated	1.6 ± 0.1	5.5 ± 0.1	1.95 ± 0.02		0.03 ± 0.01	2.22 ± 0.12	In-calculable
	PC7	UIC3351	68.22 ± 4.09	1.3 ± 0.1	4.1 ± 0.1	0.83 ± 0.01		0.05 ± 0.01	1.28 ± 0.07	53,370 ± 3290

(*Continued*)

Table 1. Continued.

Site	Unit ID	Lab Reference	Equivalent Dose (Grays)[a]	U (ppm)[c]	Th (ppm)[c]	K_2O (%)[c]	H_2O (%)[d]	Cosmic Dose (mGrays/yr)[e]	Total Dose (mGrays/yr)	OSL Age (yr)[f]
PRC-South	PRC-S1	UIC3583[j]	4.27 ± 0.31	1.1 ± 0.1	1.7 ± 0.1	0.48 ± 0.01	15 ± 3	0.18 ± 0.02	0.71 ± 0.03	**5,985 ± 430**
	PRC-S2	UIC3584[j]	7.66 ± 0.51	1.2 ± 0.1	4.4 ± 0.1	0.43 ± 0.01	15 ± 3	0.14 ± 0.01	0.81 ± 0.04	**9,415 ± 650**
Olhos de Agua	OA1	UIC3024	60.94 ± 3.93	4.2 ± 0.1	10.6 ± 0.1	1.73 ± 0.02	15 ± 3	0.14 ± 0.01	2.56 ± 0.12	23,670 ± 1640
Vale Benfeito	VB1	UIC3020	7.86 ± 0.48	3.8 ± 0.1	4.8 ± 0.1	1.57 ± 0.02	15 ± 3	0.16 ± 0.02	2.48 ± 0.12	**3,180 ± 270**
Praia del Rei	PRS1	UIC2999TT	253.40 ± 12.21	0.7 ± 0.1	2.2 ± 0.1	1.63 ± 0.02	10 ± 3	0.02 ± 0.01	1.69 ± 0.06	**150,325 ± 13,410**
	PRS2	UIC3000	>200	2.0 ± 0.1	7.6 ± 0.1	1.52 ± 0.02	10 ± 3	0.03 ± 0.01	2.25 ± 0.11	**>89 ka**
	PDR-2[b]	UIC3354	34.66 ± 1.69	1.3 ± 0.1	4.0 ± 0.1	0.71 ± 0.01		0.19 ± 0.02	1.32 ± 0.07	**26,350 ± 2005**
	PDR-3	UIC3355	110.68 ± 6.64	0.5 ± 0.1	1.3 ± 0.1	1.44 ± 0.01		0.15 ± 0.01	1.54 ± 0.08	**71,850 ± 5530**
Boavista de Ferrel	BV-1	UIC3017	2.25 ± 0.14	1.3 ± 0.1	4.2 ± 0.1	2.20 ± 0.03	10 ± 3	0.18 ± 0.02	2.57 ± 0.12	**880 ± 70**
	BV-2	UIC3035	10.18 ± 0.62	1.4 ± 0.1	2.9 ± 0.1	1.96 ± 0.02	10 ± 3	0.17 ± 0.02	2.30 ± 0.11	**4435 ± 310**
	BV-3	UIC3038	61.87 ± 3.80	1.8 ± 0.1	5.8 ± 0.1	2.80 ± 0.03	10 ± 3	0.16 ± 0.02	3.27 ± 0.16	**18,895 ± 1440**
	BV-4	UIC3036	108.82 ± 7.41	3.6 ± 0.1	13.4 ± 0.1	3.36 ± 0.03	10 ± 3	0.15 ± 0.02	4.64 ± 0.23	**23,450 ± 2170**
	BV-5	UIC3037	>220	4.5 ± 0.1	7.9 ± 0.1	3.15 ± 0.03	12 ± 3	0.14 ± 0.01	4.19 ± 0.21	>53 ka
	BV-6	UIC3018	>190	2.0 ± 0.1	4.2 ± 0.1	3.12 ± 0.03	12 ± 3	0.12 ± 0.01	3.37 ± 0.17	>56 ka
	BV-7	UIC3031	0.03 ± 0.01	1.7 ± 0.1	5.9 ± 0.1	0.48 ± 0.01	10 ± 3	0.19 ± 0.02	1.34 ± 0.07	**20 ± 10**
Columbeira fan	PF1	UIC3030	>159	2.6 ± 0.1	9.8 ± 0.1	0.35 ± 0.01	10 ± 3	0.13 ± 0.01	1.60 ± 0.08	>99 ka
Gruta das Pulgas	LP1	UIC2996	>211	0.7 ± 0.1	2.4 ± 0.1	0.90 ± 0.01	10 ± 3	0.04 ± 0.01	0.99 ± 0.06	>184 ka
Vale Roto	UVR1	UIC3029	97.00 ± 6.98	1.8 ± 0.1	4.5 ± 0.1	2.78 ± 0.03	10 ± 3	0.16 ± 0.02	3.17 ± 0.16	**30,600 ± 2440**
Forte da Barralha	FB1(Block)	UIC3001	78.53 ± 7.22	0.5 ± 0.1	1.3 ± 0.1	0.88 ± 0.01	5 ± 2	0.21 ± 0.02	1.20 ± 0.06	**65,665 ± 6120**

[a] Equivalent dose determined by the multiple aliquot regenerative dose method under green (514 nm) or blue (470 nm) excitation (Jain, Botter-Jensen, and Singhvi 2003). Blue emissions are measured with 3 mm thick Schott BG-39 and one 3 mm thick Corning 7-59 glass filters that block > 90% luminescence emitted below 390 nm and above 490 nm in front of the photomultiplier tube. The coarse-grained (150–250 µm) quartz fraction is analyzed.
[b] Single aliquot regenerative dose method (Murray and Wintle 2003); blue light excitation after infrared (880 nm) excitation.
[c] U, Th, and K_20 determined by ICP-MS at Activation Laboratory Ltd., Ontario.
[d] Average water content estimated from particle size characteristics assuming periodic wetting in the vadose zone.
[e] Cosmic dose rate component from Prescott and Hutton (1994) based on latitude, longitude, elevation, and burial depth of samples.
[f] All errors are at 1σ, and ages are calculated from A.D. 2000. Analyses performed by Luminescence Dating Research Laboratory, Department of Earth & Environmental Sciences, Univeristy of Illinois-Chicago.
[g] Errors are at 1σ, and ages are calculated from A.D. 2010.
[h] Dates published in Benedetti and colleagues (2009).
[i] Dates published in Minckley and colleagues (2015).
[j] Dates published in Taylor and colleagues (2018).

some of which have known caves with Palaeolithic occupations. The Pleistocene landscape is present in exposures of the sands under the coastal dunes and in the diapiric valley fills, but these deposits did not form during a single geomorphic episode.

The rapidly-eroding coastal cliffs have exposed Pleistocene sediments overlooking the Atlantic shore. Artifact scatters regularly occur at the top of these cliffs where the Holocene dunes have blown away (Supplemental Material 1). Most of these scatters are Late Upper Palaeolithic (Figure 2A). Some cliffs preserve thick Pleistocene deposits with occasional artifacts eroding out of their original buried context. Two excavated Middle Palaeolithic localities, Praia Rei Cortiço and Mira Nascente, date to MIS 5 and 3, respectively (Haws et al. 2010).

The diapiric valley has undergone slow neotectonic uplift, while being filled and flushed of sand numerous times during Quaternary sea level cycles. As a result, variably-aged remnants of fluvial and estuarine fills outcrop in various places. At Valongo quarry, near Campo, a thick sandy fill returned minimum OSL ages of ca. 193 kya and ca. 241 kya in the middle portion of the exposed sediments (Figure 3, Supplemental Material 2, Table 1). The upper portion in an adjacent pit gave a finite OSL age of MIS 3. In the central part of the valley, fluvial deposits on a pediment upslope from Quebrada dos Cravos dated to MIS 5. Artifacts from the Lower, Middle, and Upper Palaeolithic are present in the exposed surface sands across the diapiric valley and its tributaries. The Lower and Middle Palaeolithic artifacts are mostly located along the margins of the southern part of the valley, where the older terrace remnants are preserved (Figure 4). Upper Palaeolithic artifacts are found throughout the valley, for example at Valado, Sombra City, Sombrapolis, and Campo Aventura (Supplemental Material 3).

In the upland zone near Montes, the survey identified numerous artifact scatters on the surface of calcareous sediments weathered from the Cretaceous limestone bedrock. This Cenomanian period limestone found throughout the region contains chert nodules of reddish brown, light yellow brown, and dark gray colors. The weathering of the bedrock has brought nodules to the surface, where people exploited them from the Middle Palaeolithic to the Neolithic. Plowing for orchards and vineyards has made artifact deposits visible across the uplands from Alpedriz to Cós (Supplemental Material 4). Sites were found walking rows of apple, peach, nectarine, and plum trees or in fields that were freshly prepared for new saplings.

The survey mapped and collected several artifact scatters, testing three to determine whether subsurface archaeology exists (Figure 2B). Middle Palaeolithic artifacts from several localities, referred to as Montes 2, 10, 12, and 15, have diagnostic technological characteristics. Most appear to have been struck from discoidal cores. No definitive Levallois elements were identified. The Upper Palaeolithic artifact localities, Montes 1, 3–6, 8, 9, 11, 14, and 18, have characteristic blades and bladelets, with lots of cortical flakes, few cores, and retouched pieces. Nodules were probably prepared at the source and transported away for future use. The most abundant artifact scatters can be attributed to the Neolithic or Copper Age. These assemblages have diagnostic technological characteristics such as large blade cores, straight blades with parallel dorsal scars, and simple, small platforms.

Generally, the Middle Palaeolithic artifacts are completely patinated with a creamy white color. The later Upper Palaeolithic and Neolithic artifacts are much less patinated, preserving their original color. Well-preserved artifact edges and removal scars from all ages suggest that while many artifacts are in secondary position, they have not moved far from their original location.

Despite the paucity of stratigraphically-sealed archaeological sites in the study area, the survey enabled us to identify patterns in landscape use and settlement intensity in response to environmental change in the coastal zone of Estremadura. Major gaps occur in the Late Pleistocene record, but sedimentary vestiges preserved in the coastal cliffs and diapiric valley allowed us to fill some of them. We used radiometrically dated archaeological and geomorphological localities to stitch together a regional history of human occupation in its paleoenvironmental context (Table 2, Figure 5). The surface archaeology is linked where the techno-typological attribution permits a comparable temporal resolution. This is more common in the Upper Palaeolithic, when the pace of technological change narrows the potential windows of time.

Pre-MIS 5 Archaeology?

Sand and cobble deposits exposed near Caldas da Rainha and Óbidos contain bifaces, cleavers, Levallois and discoidal cores, and flakes (Figures 6, 7). The majority of the finds occur on the terraces along the northern edge of the silted-in portion of the Lagoa de Óbidos. Many additional Acheulean and Middle Palaeolithic sites were documented by Fernandes, Moreira, and Raposo (2008) in similar contexts along the margins of the Lagoa de Óbidos. The co-occurrence may be a palimpsest of Acheulean and Middle Palaeolithic artifacts, or it could indicate Early Middle Palaeolithic deposits (ca. 200–165 kya according to Pereira et al. 2019). None of the finds have associated radiometric dates, making a precise age estimation all but impossible. A few OSL ages offer hints of MIS 6 and older sediments, but all of the well-dated artifact assemblages date to MIS 5 and later.

MIS 5 Landscapes, Archaeology, and Paleoecology: Praia Rei Cortiço (PRC)

The site of Praia Rei Cortiço (PRC) contains roughly 25 m of Upper Pleistocene and Holocene sediments filling a paleovalley that drained northward into the Óbidos estuarine complex (Figure 8) (Benedetti et al. 2009). Middle Palaeolithic artifacts were found in the northern part of the valley within a colluvial deposit of pebbly sand (PC5) near the base of the section where a 1.28 m thick paleowetland deposit lies directly atop the Cretaceous bedrock (Haws et al. 2010, 2011). The age of the archaeological level is constrained by OSL dating of overlying aeolian sands (80 ± 6 and 101 ± 8 kya), pebbly colluvium within the artifact concentration (95 ± 6 kya), and fluvial sands underlying the artifacts (111 ± 9 kya). These ages place the occupation within the Last Interglacial Complex (LIC), likely during MIS 5c or Greenland Interstadial (GI) 23. The setting is interpreted as a gentle slope above a freshwater marsh surrounded by open woodland (Minckley et al. 2015).

The PRC wetland (PC5) formed in a paleovalley connected to the Óbidos estuary, one of several structurally-controlled valleys on the margins of the Caldas da Rainha diapir subject

Table 2 Radiometric dates obtained from localities in the study area organized by time period.

Period	Setting	Study site	Age	Method	Lab ID
Holocene					
	Eolian sand	Valado	205 ± 30	OSL	UIC 3015
	Eolian sand		230 ± 40	OSL	UIC 2998
	Eolian sand	PRC 1	545 ± 100	OSL	UIC 3352
	Eolian sand	Boavista	20 ± 10	OSL	UIC 3031
	Paleosol (Ab)	Boavista	880 ± 70	OSL	UIC 3017
	Paleosol (Ab)	PRC 2a	3,970 ± 40	^{14}C	Beta 234368
	Paleosol (Ab)	Vale Pardo	2,610 ± 40	^{14}C	Beta 222201
	Paleosol (Ab)	Feligueira Grande	2,150 ± 40	^{14}C	Beta 208227
	Paleosol (Eb?)	Atlantico Village	1,850 ± 200	OSL	UIC 2323
	Paleosol (Eb?)	Boavista	4,435 ± 310	OSL	UIC 3035
	Peat	Vale Benfeito	3,180 ± 270	OSL	UIC 3020
	Peat	PRC-South	5,985 ± 430	OSL	UIC 3583
	Peat	PRC-South	9,415 ± 650	OSL	UIC 3584
Pleistocene					
Late MIS 2					
	Eolian sand (C)	Brejo de Agua	11,610 ± 820	OSL	UIC 3032
	Eolian sand (C)	Ribeiro do Pereiro	11,425 ± 855	OSL	UIC 2571
	Eolian sand (C)	Casal da Areia	12,985 ± 1005	OSL	UIC 2327
	Eolian sand (C)	Valado	11,480 ± 820	OSL	UIC 3016
	Eolian sand (C)	Lagoa Seca	12,905 ± 1050	OSL	BG 3582
	Eolian sand (C)	Cabeço da Amoreira	12,480 ± 845	OSL	UIC 2997
	Fluvial gravel	PRC 2b	15,060 ± 980	OSL	UIC 2399
LGM	Eolian sand (C)	Cafurno	21,445 ± 1520	OSL	UIC 2572
	Eolian sand (C)	Boavista	18,895 ± 1440	OSL	UIC 3038
			23,450 ± 2170	OSL	UIC 3036
Early MIS 2	Eolian sand (C)	Fanhais	27,490 ± 2070	OSL	UIC 1876
		Praia del Rei	26,350 ± 2005	OSL	UIC 3354
Late MIS 3	Eolian sand?	Vale Pardo	29,100 ± 2415	OSL	UIC 3033
(after H4)		Mira Nascente 2	33,905 ± 2690	OSL	UIC 1863
			36,030 ± 2750	OSL	UIC 1875
		S. Pedro de Muel 2	35,530 ± 2785	OSL	UIC 2069
		SPM 3b	35,260 ± 2590	OSL	UIC 2066
		SPM 3d	39,450 ± 2980	OSL	UIC 2068
		Polvoeira	36,250 ± 2840	OSL	UIC 2070
	Fluvial sand	Azenha	31,440 ± 2180	OSL	UIC 2325
	Paleosol (C)	Vale Roto	30,600 ± 2440	OSL	UIC 3029
Early MIS 3		SPM 3f	46,660 ± 3570	OSL	UIC 2067
(before H4)		MN 3	40,450 ± 2980	OSL	UIC 1864
			37,540 ± 600	^{14}C	Beta 234375
	Eolian sand (C)	Casal da Areia	43,540 ± 3405	OSL	BG 3976
	Alluvial sand (C)	Valongo Quarry	49,520 ± 3690	OSL	UIC 3021
		PRC 3	51,165 ± 3865	OSL	UIC 3361
MIS 3/4	Raised beach	Forte da Barralha	65,665 ± 6120	OSL	UIC 3001
		Polvoeira	62,220 ± 4660	OSL	UIC 2071
	Eolian sand? (C)	Vale Pardo	62, 855 ± 4590	OSL	UIC 2324
MIS 4	Eolian sand (C)	Casalinhos	69,120 ± 4550	OSL	UIC 3028
		PRC 3	68,320 ± 5530	OSL	UIC 2607
			69,380 ± 5660	OSL	UIC 2608
		Praia del Rei	71,850 ± 5530	OSL	UIC 3355
MIS 5	Eolian sand	PRC 4	79,800 ± 5695	OSL	UIC3360
			101,010 ± 7870	OSL	UIC 2398
	Colluvium	PRC 5	95,370 ± 6470	OSL	UIC 2606
	Fluvial sand		111,250 ± 8800	OSL	UIC 2915
	Eolian sand	Quebrado dos Cravos	108,265 ± 8020	OSL	UIC 2328
MIS 6	Gravelly mud	MN 5	150,920 ± 12575	OSL	UIC 2065
	Gravelly mud	Praia del Rei	150,325 ± 13410	OSL	UIC 2999TT

to fluctuating water levels during late Quaternary climatic and sea-level change (Dinis et al. 2006; Freitas et al. 2003). Pollen data indicate a five-part sequence of vegetation change in this 1.8 m thick deposit (Figure 9). Initially, an open marsh, heath-dominated environment formed in pollen zone PC5–I (Minckley et al. 2015). Relatively low *Pinus* percentages suggest patchy or distant conifer woodlands. Open water habitat is evidenced by sedges and water milfoils, taxa locally found in sub-aerial habits. The early marsh converted, at least locally, to birch/hazel woodlands in PC5–II, possibly due to reduced effective moisture that dried the surface, allowing tree establishment. PC5–III suggests open, mixed conifer-hardwood woodlands interspersed by wetland habitats (Minckley et al. 2015). PC5–III includes both the driest (e.g., no pollen preservation from 84–87 cm) and wettest (e.g., peak *Myriophyllum alterniflorum* at 47 cm) intervals of the record. This section represents prolonged floristic stability. Pine forests rapidly established prior to the driest period (84–87 cm) and persisted for most of the record. Data from PC5–IV suggests significant environmental change related to water availability. High abundance of Ericaceous pollen, low, but persistent *Artemisia*, low pine abundance, and abrupt changes in dominant arboreal taxa suggest increasingly arid conditions. The switch from closed-forest to open environment was progressive, likely due to gradually reduced moisture. PC5–V represents continued aridification, with establishment of steppe-like conditions.

The archaeological site was found in a buried colluvial deposit in PC5 that traces laterally southward at the base of the coastal bluff into the peat wetland described above (Supplemental Material 5). The 2008 and 2012 excavations at this locality recovered a total of 971 lithic artifacts. Flakes,

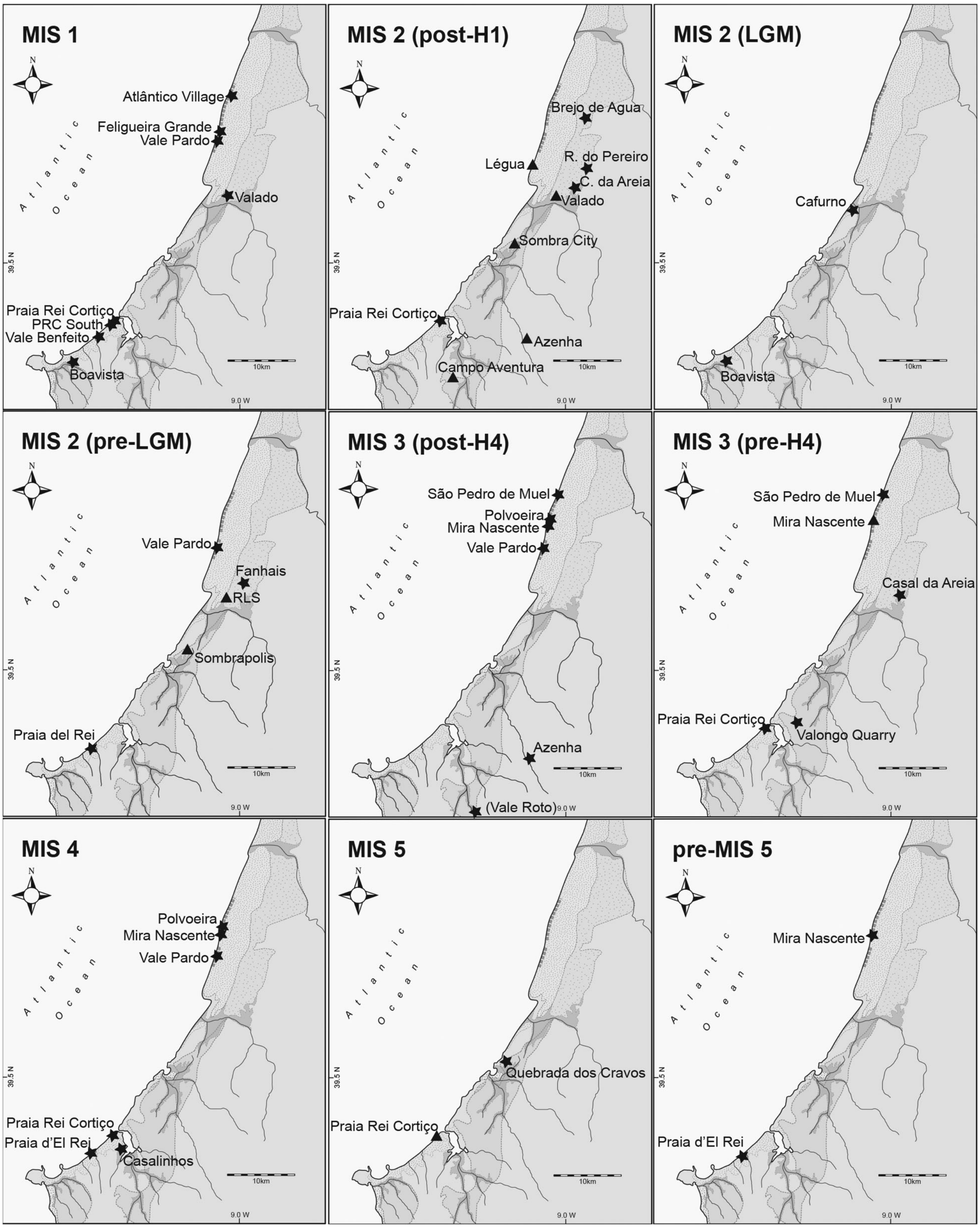

Figure 5. Maps of studied archaeological and geomorphological sites by temporal phase.

fragments, and chips make up the majority of the assemblage (Table 3). Technological analysis indicates the production of typical and atypical Levallois flakes, Levallois points, and a few pseudo-Levallois points (Figure 10, Table 4). Only a few retouched pieces were recovered, including a sidescraper and a few denticulates and notches. The assemblage also includes several centripetal and unidirectional cores. The raw material is dominated by quartzite, with low percentages of quartz and chert. The overwhelming frequency of quartzite and quartz suggests locally available sources within several tens to several hundreds of meters away. The nearest known primary chert sources are about 25 km away.

Artifact refitting shows that most of the chert may be from a single core or nodule. Several pieces of a core that broke during the final Levallois removal were found in a small cluster (Figure 11). Additional refits from several meters away include a second set of Levallois flakes that was burned inside a large combustion feature. In contrast, few quartzite pieces refit, which may suggest that part of the site was eroded away by the sea prior to discovery and testing.

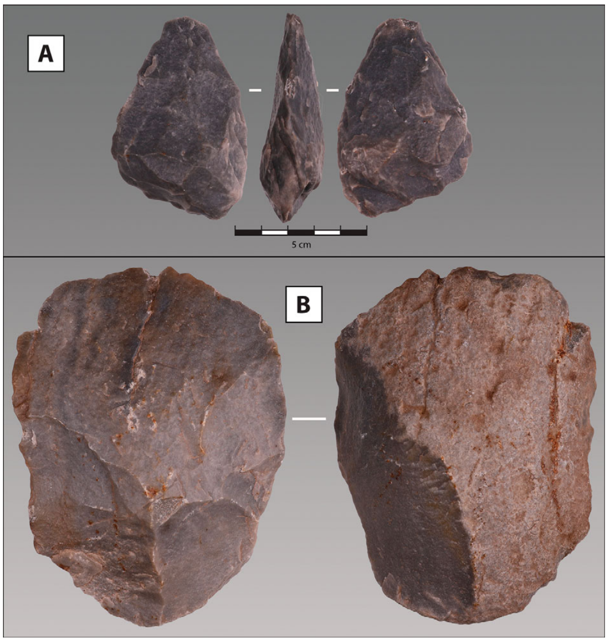

Figure 6. LP–MP artifacts from fields adjacent to the Caldas da Rainha industrial zone: A) biface, B) cleaver.

The evidence from PRC shows that Neanderthals exploited a diverse range of coastal habitats, including terrestrial and riparian landscapes and littoral seascapes (Gamble 1999). The proximity of the PRC wetland to the coast suggests a linkage to a greater estuarine complex that these people lived within. We hypothesize that freshwater supplies were relatively abundant for most of the existence of the PRC wetland, based on the reconstructed precipitation of southern Europe during the LIC (Brewer et al. 2008). However, toward the end of the LIC, freshwater availability may have concentrated in wetland environments like those preserved in the PRC paleovalley, creating a coastal ecotone with a powerful attraction to Neanderthals inhabiting the region.

Late MIS 5/4: Early Glacial Eolian Activity

The Early Glacial and MIS 4 is represented at several localities in the study area. OSL ages from the lower deposits at Polvoeira and Vale Pardo, Valongo quarry near Campo, Casalinhos near the Lagoa de Óbidos, and the coastal sections of Praia Rei Cortiço and Praia d'El Rei suggest extensive eolian and colluvial activity during MIS 4, which was a prolonged period of severe climate indicated by deep sea records off the coast of Portugal. The cessation of speleothem growth further indicates reduced precipitation and arid conditions across much of the region (Denniston et al. 2018).

Unfortunately, none of the MIS 4 deposits in the study area yielded archaeology. In fact, very few Middle Palaeolithic lithic assemblages in the region derive from secure age-controlled stratigraphic contexts (e.g., Cardoso, Zbyszewski, and André 1992; Cardoso 2006). For MIS 4, this is especially problematic. Many sites and localities are plagued by age estimates with very large error ranges. Previously excavated caves in the study area, such as Furninha and Columbeira, are thought to have occupations dated to MIS 4, but these lack firm radiometric dates (Cunha et al. 2017; Figueiredo et al. 2017). A single U-Th date of 80.8 kya (+42.4 kya, -31.2 kya) from Furninha has a massive standard error and is therefore useless for dating the archaeological deposits (Bicho and Cardoso 2010). At Columbeira, an estimated U-Th date of 87.1 ± 6.3 kya on bone suggests a late MIS 5 age for level 8, with upper layers possibly dated to MIS 4 (Zilhão et al. 2011).

Across the region, similar problems persist. U-Th dates place Oliveira levels 27–26 in MIS 5 and levels 13–8 in MIS 3 (Hoffmann et al. 2013). The intervening levels 25–14 likely date to MIS 4, but none of the U-Th dates fall within this range (Zilhão et al. 2013). Thus, the problem of MIS 4 human occupation in caves may also be related to issues of dating techniques and materials.

In open air settings, OSL dating is providing chronological control for Middle Palaeolithic sites. Recently reported luminescence and U-Th dates from the T5 and T6 terraces of the lower Tagus River staircases provide bracketing ages for the Middle Palaeolithic industries found in several stratigraphic levels. The dates of 136–73 kya encompass an MIS 5 and 4 range for T5, while the dates of 63–32 kya place the T6 terrace firmly in MIS 3 (Cunha et al. 2008, 2012, 2019).

MIS 3 Landscapes, Archaeology, and Paleoecology: Mira Nascente

Mira Nascente is located about 10 km north of Nazaré in eroding coastal bluffs between Polvoeira and Vale Paredes. The site is situated about 30 masl in a Late Pleistocene sand unit separated by disconformity from the Lower Pleistocene to Pliocene marine to deltaic unit (Cabral et al. 2018). The sand unit outcrops for about 1 km between Paredes and Polvoeira. Luminescence and radiocarbon dates place the occupation at around 42 kya, during MIS 3 and just prior to the H4 event (Benedetti et al. 2009; Haws et al. 2010). The artifact-bearing stratum at Mira Nascente is a medium-to-fine white sand layer (MN3) that is capped by a weak paleosol (Figure 12C). It is overlain by coarse-grained yellowish sands with prominent low-angle crossbeds (MN2) and likely reflects interdunal wetlands and proximal (near source) dune sands. The pollen analyses suggest humid conditions with a mix of coastal heath and herbaceous vegetation. Marsh habitats existed in the low-lying areas with nearby stands of temperate deciduous and Mediterranean evergreen trees and shrubs. The presence of thermophilous trees, such as *Alnus* and *Quercus,* suggests a period of arboreal expansion consistent with interstadial conditions.

Initial excavations at Mira Nascente during 2005–2006 revealed a low density, high-resolution artifact cluster that reflects important differences in raw material economy between this coastal locality and more inland ones (Haws et al. 2010). Most of the 432 stone artifacts were made on reddish-brown chert, likely from the Cenomanian formation that does not visibly outcrop within 10 km of the site. The assemblage is mostly reduction debris from centripetal Levallois cores, including Levallois flakes and points (Figure 13, Tables 5, 6). The artifacts are situated in the lower part of the white sand layer, and the majority occur in a ca. 15 cm thick band. Artifact refitting has demonstrated that there has been little vertical displacement of the assemblage (Figure 14, Supplemental Material 6). This is corroborated by the lack of patina, sharp flake edges, and well-defined flake scars, suggesting rapid burial after discard. Initial use-wear analyses identified wear on several flakes consistent with soft tissue and some bone cutting, most likely from processing fish (Haws et al. 2010). Most flakes exhibit no visible traces of use-wear, a further indicator of the brief duration of artifact

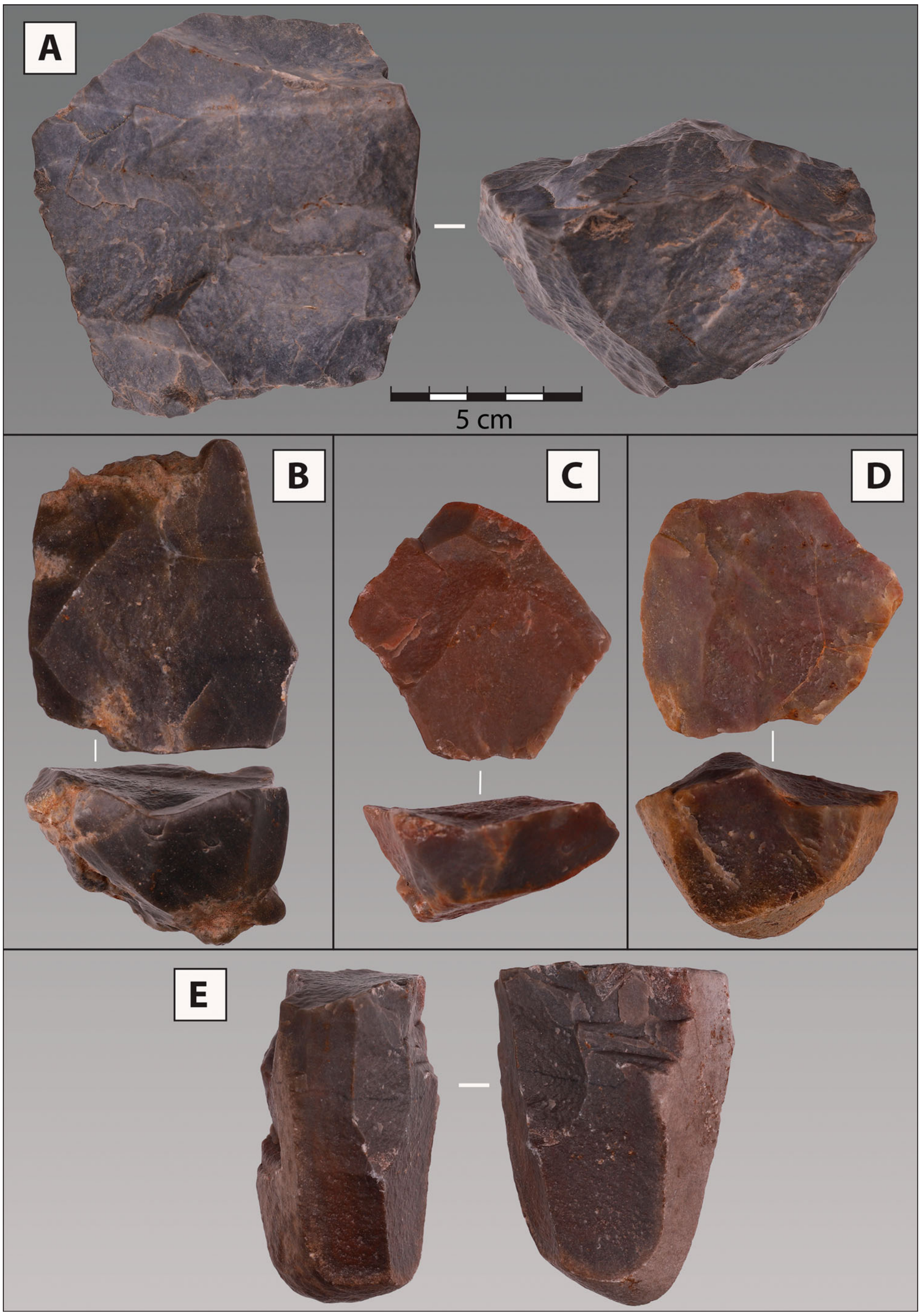

Figure 7. Discoidal cores collected near Caldas da Rainha: A) discoidal core from a field between Caldas da Rainha and the Lagoa de Óbidos, B) Levallois core from a field between Caldas da Rainha and the Lagoa de Óbidos, C) Levallois core D) Levallois core from a field near Columbeira, E) blade core from same field as C). C and E were found in the same field as Figure 6 biface and cleaver.

manufacture, use, and discard. Thus, the assemblage represents a unique, high-resolution example of Neanderthal behavior in Portugal. The lithic assemblage also demonstrates a high degree of flexibility in land use strategies by Neanderthals during the Late Middle Palaeolithic.

The geological and spatial context of the artifacts, extraordinarily well-preserved flake edges, and refits suggest a discrete occupation with spatially organized activity areas. Although the site did not yield hearths, the concentrations of artifacts indicate that much of the site is still buried. In 2006, a second locality in the white sand deposit 150 m north of the main artifact concentration yielded a Middle Palaeolithic sidescraper (Supplemental Material 7A). In 2008, the survey team excavated five test pits in the white sand outcrop at 10 m intervals. One test pit yielded a large Middle Palaeolithic flake tool (Supplemental Material 7B). Additional visits and surface collection yielded another scraper (Supplemental Material 7C) and a crested blade that indicates an Upper Palaeolithic component may be preserved above. These finds demonstrate multiple occupations of this locality in the Late Middle Palaeolithic and that the use of coastal wetlands was part of recurrent settlement patterns, not simply a rare occurrence (see also van Andel and Runnels 2005).

MIS 2 Landscape History and Archaeology

During the 2005–2013 field work, the survey team identified numerous Upper Palaeolithic artifact scatters along the exposed coastal bluffs where Pleistocene sands outcrop.

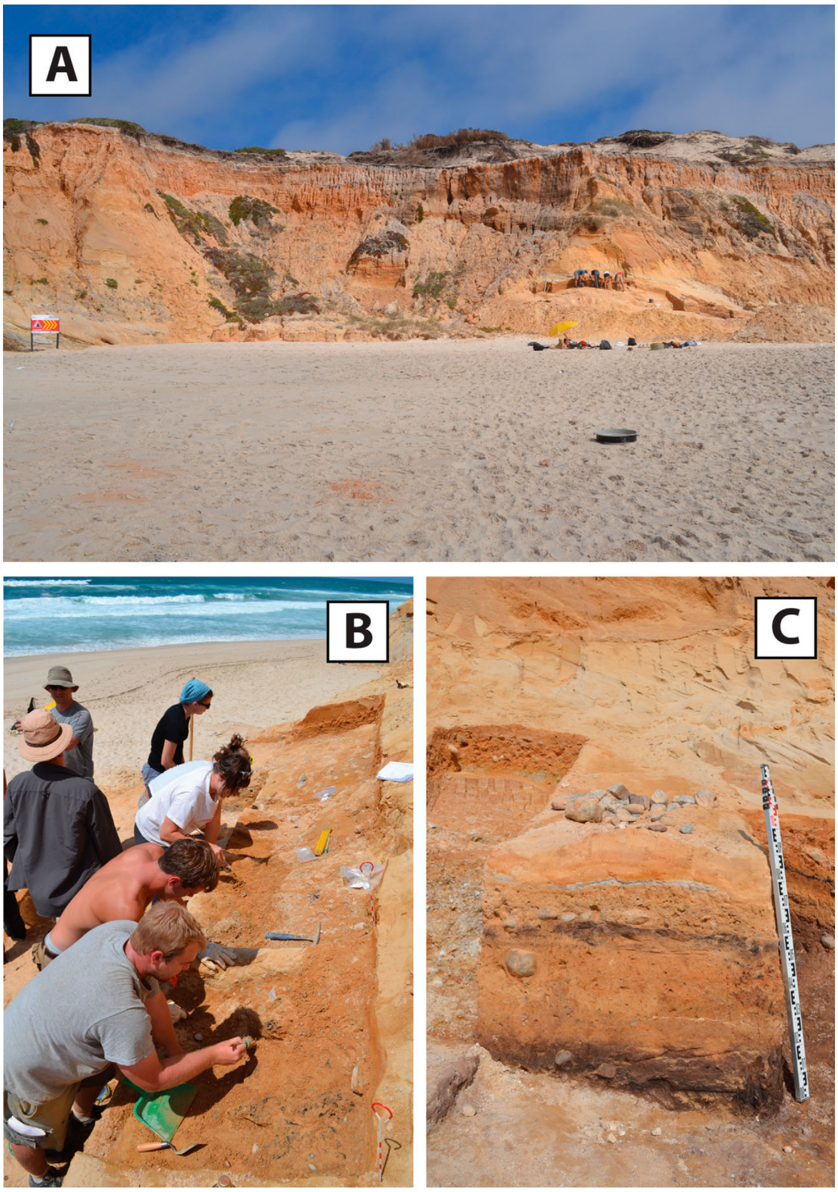

Figure 8. Praia Rei Cortiço.

Most artifact scatters and finds have no diagnostic indicators of a particular technocomplex. A few can be attributed on technological grounds, such as the blank and burin production techniques, to earlier Upper Palaeolithic phases, likely Gravettian. The same sands outcrop in the Caldas da Rainha valley where the survey recorded several additional Late Upper Palaeolithic localities. Many of the artifacts show affinities with Late Magdalenian sites in the Rio Maior valley.

Although a couple of sites, Ribeiros de Lagoa Seca and Sombrapolis, had buried deposits, most of the sites did not contain stratigraphically-sealed deposits. Artifacts are typically found in the sands above or even lying on the deflated surface in contact with a well-developed Bh spodosol. Many had artifacts that were displaced by bioturbation, plowing, or construction disturbance.

Coastal dunes

Several artifact scatters along the bluffs north of Nazaré could be attributed to the Upper Palaeolithic (see Figure 2). In the coastal dune outcrops, a few sites had diagnostic artifacts or indicated the presence of buried artifacts that warranted further investigation. Definitive Upper Palaeolithic artifacts were found on deflated surfaces at Praia do Norte, Vale Fundo, Falca, Légua, and Feligueira Grande. Praia do Norte extends from the cliffs at Nazaré to Vale Fundo. Several localities were recorded where Pleistocene sands were exposed along this stretch of coastal dunes and bluffs. Three of the localities, Praia do Norte I, II, and III, had Upper Palaeolithic artifacts on the deflated surface, but nothing could be assigned to a specific technocomplex. The exposed sands at Vale Fundo had several Upper Palaeolithic flakes and three tools, including a transverse burin on truncation, a dihedral burin, and a notched piece, lying on the surface. Subsurface testing did not yield any artifacts. Falca is located at the edge of an eroded slope along the cliffs. Although the artifacts are wind-polished, the edges are still sharp, suggesting a buried occupation may be preserved under the dunes. At Légua, lithic debris found on a deflated sand and pebble surface included flakes, bladelets, and a bladelet core, likely Magdalenian, based on similarities with other radiometrically-dated assemblages in the Rio Maior valley, such as those from the Cabeço do Porto Marinho

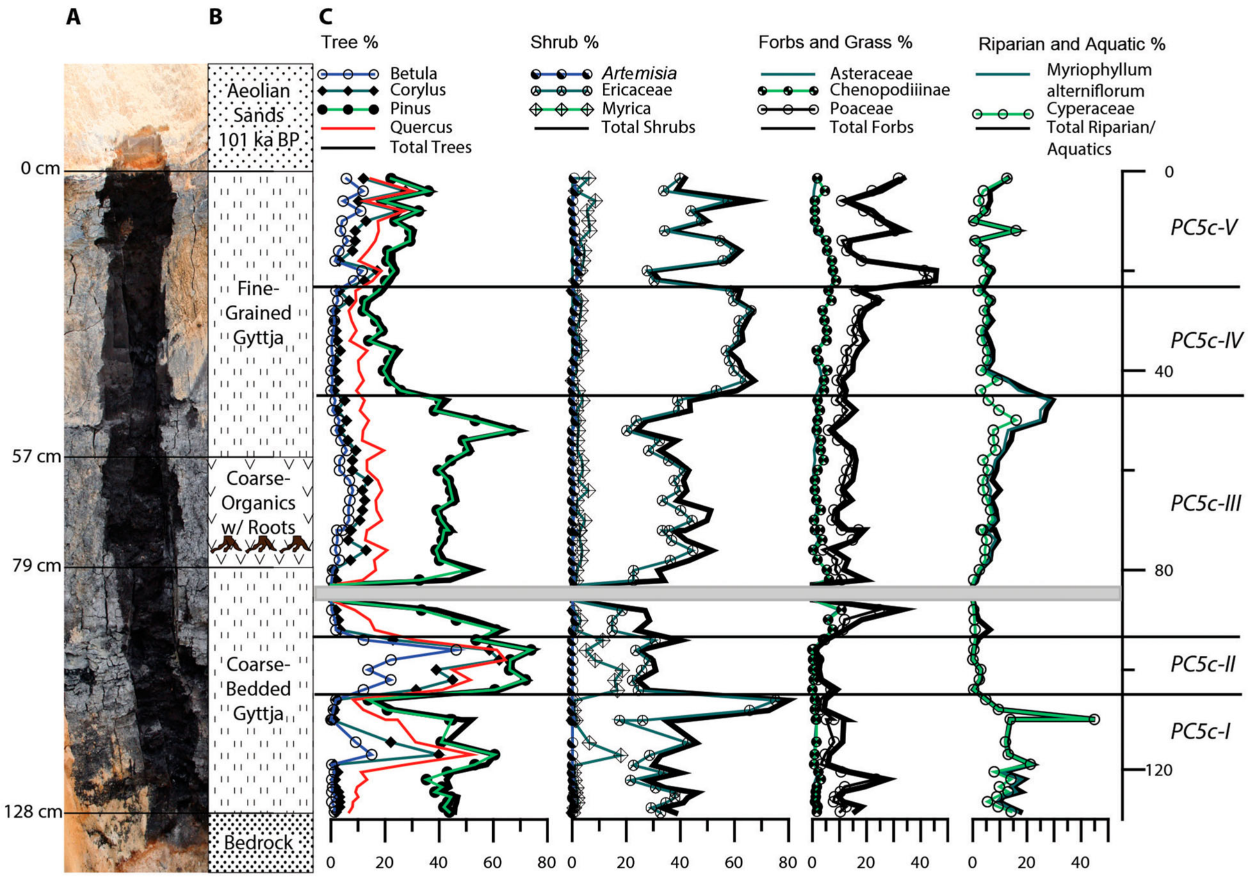

Figure 9. Praia Rei Cortiço pollen.

open-air site. Légua may have intact deposits under the adjacent dunes, but no testing was attempted. The exposed sands at Feligueira Grande produced an Upper Palaeolithic core and various bladelets. The site, called Vale Furado I, has lithic artifacts dispersed across a deflated surface in the Pleistocene sands.

A few kilometers north, surface finds at Vale Pardo appeared to be eroding from under a paleosol that produced a radiocarbon date of 2,610 ± 40 B.P. on the buried A horizon. A series of test pits laid out along the exposed paleosol all yielded lithic artifacts about 40–45 cm below the buried A horizon in the E horizon. Only undiagnostic pieces, such as small flakes and chips, were found in test pits, but their stratigraphic position suggests an occupation layer may be preserved. Alternatively, the artifacts may simply have settled into a stone line due to bioturbation (e.g., Johnson 1989, 2002). Several charcoal concentrations were found, but none had artifacts in association. We concluded that their spacing suggested they were burned roots of plants growing on the paleosol. Below the E horizon, we encountered two Pleistocene-age fluvial or aeolian sand layers that yielded OSL dates of ca. 29 kya and 63 kya, respectively (Benedetti et al. 2009). A single flake with a characteristic *chapeau du gendarme* platform typical of Mousterian industries was found on the surface about 25 m north of the test pits, but additional artifact finds have not confirmed a Middle Palaeolithic occupation.

Valley fills

Pedestrian survey of the Pleistocene sands filling the Caldas da Rainha diapiric valley also showed evidence of MIS 2 landforms and archaeology. Several tracks were walked along a long transect covering the Pleistocene sediments of a stream valley with Pleistocene exposures to the north of Fanhais. At least three Palaeolithic artifact scatters were found on terraces above the stream. An OSL date of 27 kya from Fanhais suggests an early MIS 2 sand mobilization. The artifacts are

Table 3. Lithic counts by class from Praia Rei Cortiço.

			Quartz						
	Quartzite	Chert	Milky	Fine	Coarse	Schist	Granite	Sandstone	Total
Pebbles	6							1	7
Cores	11	1							12
Flakes	175	15	25	16	2		1		234
Blades	9	1		1					11
Bladelets	2			3					5
Points	6	2							8
Core edges	4								4
Fragments	309	5	39	66					419
Chips	129	6	78	54	2	2			271
Total	651	30	142	140	4	2	1	1	971

Figure 10. Praia Rei Cortiço Levallois flakes.

Table 4. Lithic counts by type from Praia Rei Cortiço.

			Quartz				
	Quartzite	Chert	Milky	Fine	Coarse	Sandstone	Total
Typical Levallois Flake	23	4					27
Atypical Levallois Flake	5	2			1		8
Levallois Point	4	2					6
Pseudo-Levallois Point	2						2
Transversal Straight Sidescraper	1						1
Tranchet				1			1
Notch	8		1				9
Denticulate	3						3
Distal notch	2						2
Miscellaneous	1		1	1			3
Anvil	1						1
Hammerstone	12					1	13
Total	62	8	2	2	1	1	76

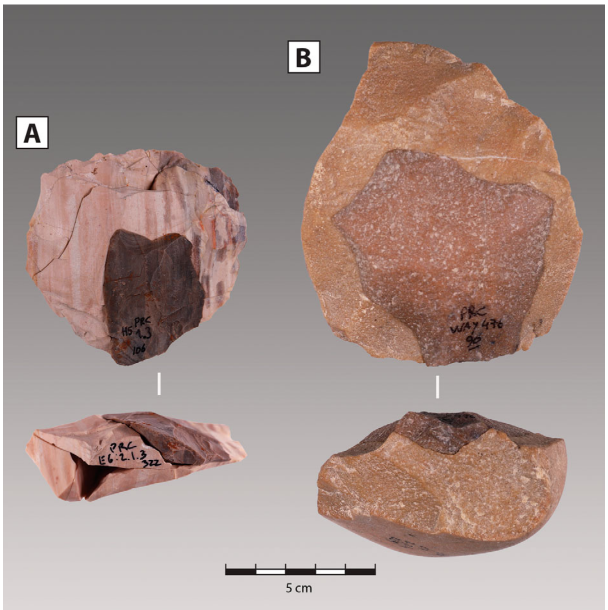

Figure 11. Praia Rei Cortiço cores: A) Levallois core on chert. Refit flake was burned in a combustion feature; B) Levallois core on quartzite.

not diagnostic of any particular Upper Palaeolithic technocomplex. In the lower valley, along the edge of a pine plantation at Valado, we found surface lithic artifacts diagnostic of the Late Magdalenian. These were mainly flakes, including a scraper with affinities to ones from Bocas rockshelter, a Late Magdalenian site located about 20 km east (Bicho 1992).

A second locality was found after the pine plantation was cleared to prepare a new business and industrial complex a few hundred meters north of Valado. The survey team visited the clearing to inspect a cut into the Holocene dunes that cover the Pleistocene sands. The profile exposed the modern soil on top of the Holocene dunes and the buried paleosol that formed in the Middle and Late Holocene. This locality produced a series of OSL dates from the last century back to the Late Pleistocene (Table 1).

Pedestrian survey of the clearing identified a substantial artifact scatter where heavy machines had removed most of the sands down to the clayey bedrock mapped as Jurassic. A subsequent test led to a full emergency excavation (Supplemental Material 8). The site, known as Ribeiros de Lagoa Seca (RLS), is located about 100 m east of the dated profile in sands below the Bh horizon of the paleosol. Remnants of the Bh horizon were left between machine furrows. The lithic artifacts were found in a 20–40 cm thick bed of yellowish-brown sands with clay lamellae (Figure 15).

Based on the surface distribution and excavated material, it appears that the site was quite extensive, covering an area of over 100 m^2. Considering the presence of Roman, Neolithic, and Palaeolithic materials, this locale likely had several occupations that were destroyed by the construction. It therefore appears to be a palimpsest with artifacts from different time periods partially mixed with each other in the construction debris.

The Upper Palaeolithic artifacts found in situ, stratigraphically below the disturbed sediments, show clear technological affinities with the Gravettian in Portugal. These typically include an emphasis on blade and bladelet production from large prismatic cores. However, the nearest OSL dates from the C horizons at Lagoa Seca (12,905 ± 1050 kya) and Valado (11,480 ± 820 kya) suggest a Magdalenian age. The presence of primary débitage and cortical and secondary artifacts

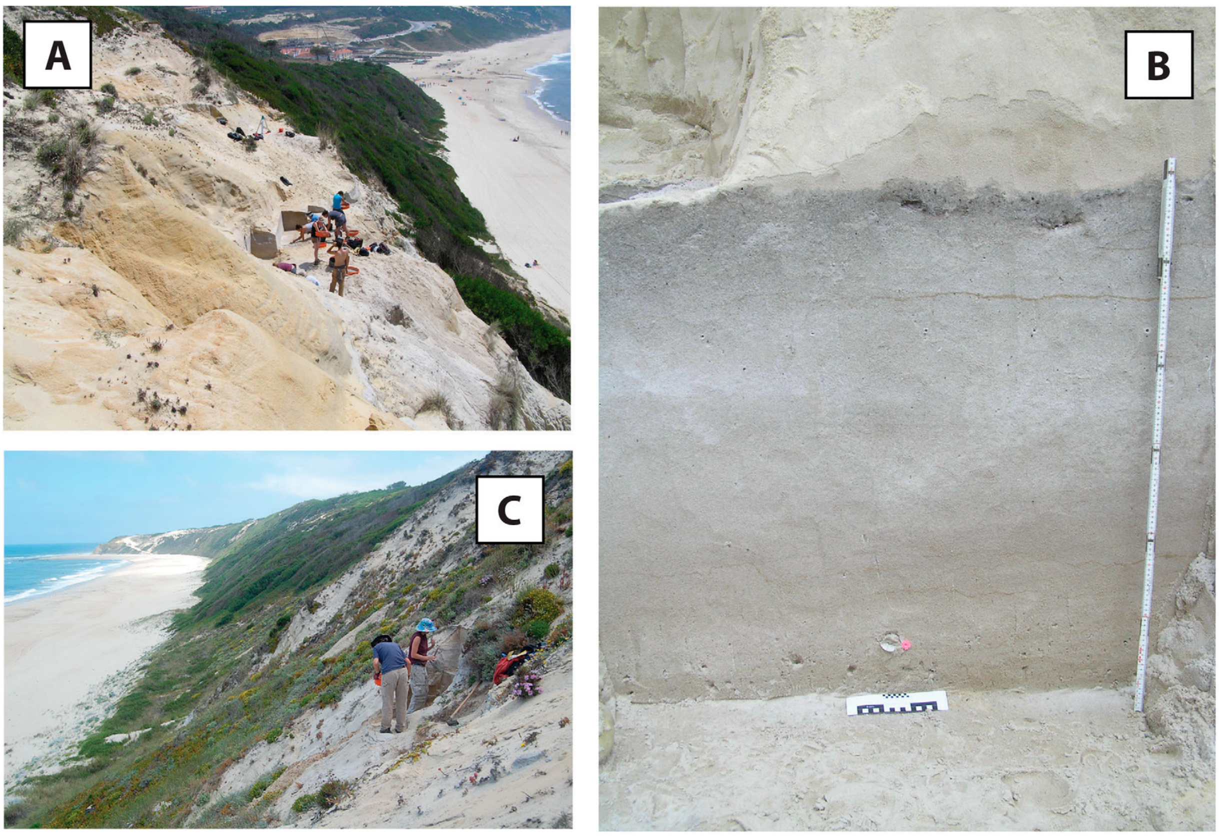

Figure 12. Mira Nascente: A) Mira Nascente site, B) white sand profile showing paleosol at the top with artifact in situ exposed in lower profile, C) Mira Nascente North test locality.

Figure 13. Mira Nascente Levallois flakes and points.

Table 5. Lithic counts by class from Mira Nascente.

	Chert	Quartz	Quartzite	Total
Flakes	61	5		66
Flake fragments	15	1	1	17
Blades	6			6
Bladelets	3	1		4
Fragments	1		1	2
Chips	281	44	3	328
Cores	4		1	5
Retouched tools	1			1
Core trimming Flakes	2			2
Hammerstone		1		1
Total	374	52	6	432

Table 6. Lithic counts by type from Mira Nascente.

	Chert		Quartz		Total	
Mira Nascente Tools	#	%	#	%	#	%
1: Typical Levallois Flake	2	15.38			2	15.38
2: Atypical Levallois Flake	1	7.69			1	7.69
3: Levallois Point	6	46.15			6	46.15
5: Pseudo-Levallois Point	1	7.69			1	7.69
43: Denticulate			1	7.69	1	7.69
51: Tayac Point	1	7.69			1	7.69
9: Straight Simple Sidescraper	1	7.69			1	7.69
Total	12	92.31	1	7.69	13	100.00

and blades, together with the lack of cores and retouched tools, suggests the presence of a workshop to prepare cores for transport (Figure 16, Table 7). This pattern is peculiar, since the nearest sources of raw materials are 4 km west, at Nazaré, and 4 km east, near Montes. Some caution is needed in making any firm conclusions, given the almost complete destruction of the site. The lack of cores and tools could be due to the removal of extensive areas of the site.

Several additional lithic artifact patches were found several tens of meters away, suggesting a recurrent use of the place. Ground penetrating radar showed the presence of a buried stream channel adjacent to the site (Conyers et al. 2013). Water availability would have been a significant attractor for human settlement location during the Late Pleistocene. The nearby Lagoa Seca, about 200 m away, is one of several spring-fed lakes along the margin of the Pleistocene sands and Holocene dunes field. These lakes were likely streams during the Pleistocene and Early Holocene, when lower sea levels created a steeper coastal water table gradient and an increased hydrostatic head on inland aquifers (e.g., Faure,

Figure 14. Mira Nascente chert core refit.

Figure 15. Ribeiros de Lagoa Seca.

Walter, and Grant 2002). The resulting pressure release would have increased groundwater flow to the coast through channels like those at Ribeiros de Lagoa Seca. Encroaching coastal dunes associated with Holocene marine transgression probably blocked the flow, creating the lakes on the present landscape. The base of a pollen core from one such lake, Lagoa Clementina, is radiocarbon dated to 3,400 B.P., confirming that sedimentation likely began in the mid-Holocene.

In the middle segment of the diapiric valley, between Famalicão and São Martinho do Porto, we discovered three additional Upper Palaeolithic sites: Sombra City, Sombrapolis, and Quebrada dos Cravos. Sombra City is located in a cleared pine stand that exposed the Pleistocene sands. We found two relatively large scatters of Late Magdalenian artifacts, including backed bladelets and bladelet cores (Supplemental Material 9). The lithic artifacts are technologically consistent with a Magdalenian attribution. The assemblage is mainly chert, but quartz and quartzite were also used for production of flakes. Auger tests failed to identify buried, intact deposits at the site.

Figure 16. Ribeiros de Lagoa Seca artifacts: A) chert flake with patina, B) refitted chert flakes, C) chert blades and bladelets.

Sombrapolis is located in a cleared eucalyptus plantation about 1 km south of Sombra City. This locality produced several bladelets, flakes, and chips in a small (< 2 m) area (Figure 17). The artifacts had minimal patina and sharp edges, suggesting that they had been buried and brought to the surface by the deep plowing of the eucalyptus plantation. Subsurface testing revealed a fairly rich assemblage may be preserved. The lithic assemblage is comprised of bladelets, blade fragments, flakes, and burins that may have been used to produce the bladelets (Figure 18). The assemblage is tentatively assigned to the Gravettian, based on similarities in burin production techniques with other dated sites, such as those from Picos (Marks et al. 1994) or Cabeço do Porto Marinho (Zilhão 1997).

Quebrada dos Cravos is located a couple of hundred meters south in a similar setting, but situated along the margins of a small stream. The site yielded lithic artifacts in two areas separated by an erosional gully. The southern concentration was lying on a deflated surface on top of Miocene (?) sands. The other concentration was found in surficial Pleistocene sands that had been reworked by recent bulldozing activity. This locality produced a small surface assemblage of lithic artifacts, but no diagnostic pieces for attribution to a particular Upper Palaeolithic technocomplex. An OSL date from an intact sand deposit upstream yielded an age of 108 kya, but this is not directly associated with the artifacts.

In the southern part of the Caldas da Rainha valley, Late Upper Palaeolithic artifacts occur in concentration at Campo Aventura and as isolated finds in the exposed Pleistocene sands (Figure 19). The Campo Aventura site is located in sands exposed in agricultural fields on a gentle slope above

Table 7. Lithic counts by class from Ribeiros de Lagoa Seca.

	Chert	Quartzite	Total
Flake	101	3	104
Blade	29		29
Bladelet	27		27
Crest	2		2
Burin spall	1		1
Chip	685		685
Fragment	53		53
Core front	1		1
Core	2	1	1
Total	901	4	905

Figure 17. Sombrapolis bladelets.

the silted-in portion of the Lagoa de Óbidos. The survey team collected surface artifacts, but subsurface testing was not possible due to planting. The lithic assemblage is mostly composed of flakes, with a small number of blades, bladelets, and retouched pieces. Bladelets were made from chert cores, while quartzite was used for flakes. On technological grounds, the assemblage is attributed to the Magdalenian.

Calcareous uplands

In the upland zone near Montes, the survey identified numerous artifact scatters that could be attributed to the Upper Palaeolithic (Supplemental Material 10). More than a dozen of these contained sufficient artifacts to recorded as sites, although given the nature of the surface archaeology, the

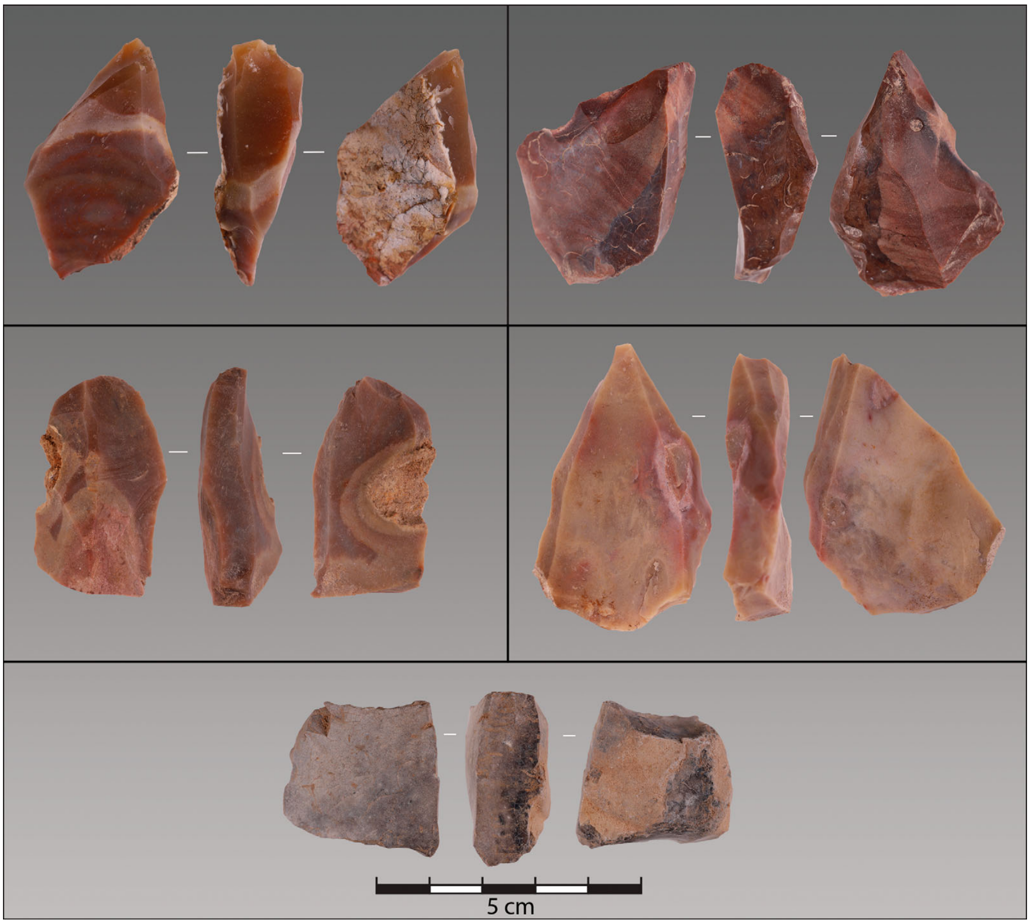

Figure 18. Sombrapolis burins.

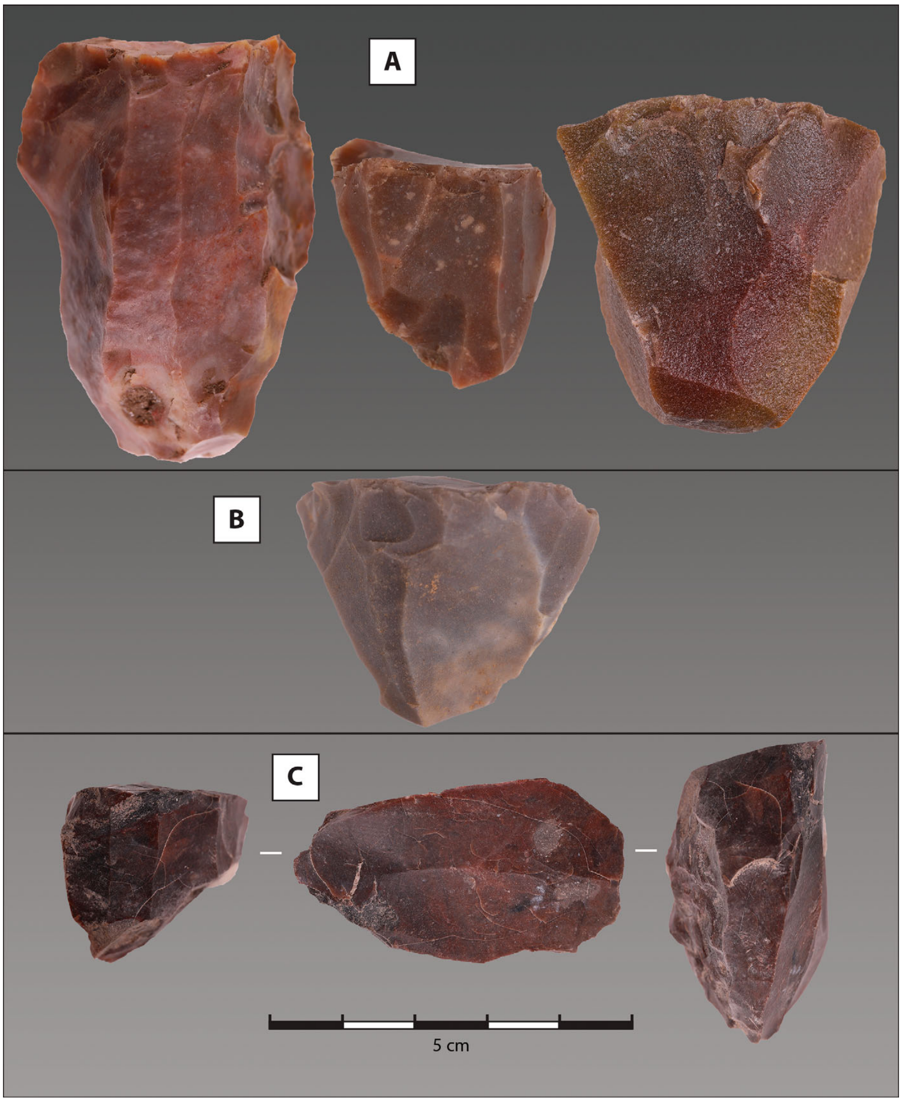

Figure 19. Late Magdalenian cores from the southern diapiric valley: A) Campo Aventura, B) bladelet core from a eucalyptus plantation north of the A15 across from the known site of Casal da Olaria 2 (Fernandes, Moreira, and Raposo 2008), C) isolated find ca. 1 km southeast of Campo Aventura.

designation of "sites" is subjective (e.g., Dunnell 1992). Montes 1–6, 8, 9, 11, 14, and 18 all have artifacts that are attributed to the Upper Palaeolithic on technological grounds. Of these, Montes 1 has artifacts that could be Early Upper Palaeolithic, but most do not have diagnostic elements that could indicate a particular phase. Póvoa 1, found on a fan below the Montes uplands, likely dates to the Magdalenian.

Discussion

Environmental forcing, human settlement patterns, and archaeological visibility

Three major episodes of geomorphic activity have impacted the landscape, preservation, and visibility of the archaeological record: MIS 3 climate instability, MIS 2 aeolian erosion and deposition (e.g., Costas et al. 2012), and Late Holocene hydroclimatic variability (Taylor et al. 2018) and sand mobilization, the latter mostly related to anthropogenic disturbance or coastal erosion (e.g., André, Rebelo, and Cunha 2001; André et al. 2009; Cunha et al. 2006). The close association of OSL ages in the study area with Heinrich and Dansgaard-Oeschger events, and the Younger Dryas, suggests a strong bioclimatic control on geomorphic activity in the study area. Aeolian dune field emplacement and expansion seem to have occurred during the cold/arid stadials during MIS 3 and 2, as documented in other areas of central Portugal (e.g., Cunha et al. 2012, 2019). A similar explanation was proposed by Clarke and Rendell (2006), who reported a strong link between coastal dunes in western Europe and states of the North Atlantic Oscillation. These data are also consistent with a model first proposed by Knox (1972) and later built upon by various authors in developing the field of biogeomorphology (Hugenholtz and Wolfe 2005; Vandebergh 1995; Viles et al. 2008). As originally developed by Knox (1972), this biogeomorphic response model predicts maximum hillslope erosion, and thus sediment delivery to river floodplains should follow the transition from an arid phase to a humid phase when erosive rains fall on minimally vegetated slopes. Paleovegetation reconstructions from deep sea sediment cores off the Portuguese margin (e.g., Salgueiro et al. 2010; Sánchez Goñi and Harrison 2010) show that abrupt climate events produced rapid shifts between arid periods of depressed vegetation cover and more temperate periods of forest expansion in Iberia. The MIS 3 climatic instability likely resulted in a highly active landscape with rapidly adjusting vegetation and landform systems and little pedogenesis. This landscape is largely preserved as buried deposits that are exposed in the coastal cliffs, which are in rapid retreat due to ongoing sea level rise. Thus, the coast is a rich source of archaeological information, in comparison to inland surfaces that have been extensively impacted by deforestation, agriculture, and development. MIS 2 landscapes are thought to be generally erosive and not aggradational, as lowered sea levels led to downcutting of streams and increased slope erosion, with deposition out on the now-submerged coastal plain or near the shelf (Daveau 1993; Dias et al. 2000). In places, the active landscape permitted rapid burial of both short term (hours/days) and medium-term (days/weeks) occupations. In much of the area covered by Pleistocene sands, continuous aeolian activity and bioturbation reworked the sands and obscured the spatial distribution of task activities. Along the exposed coastal cliffs, artifacts were visible in blowouts or at the contact edge of the Pleistocene sand. In these places, small scatters of wind-polished artifacts in deflated areas represent time-averaged and/or redeposited assemblages. In the Holocene sand dunes, where recent dynamic geomorphic activity has hidden the material traces of the past, we encountered large areas with no visible surface archaeological record.

In places like the Caldas da Rainha diapiric valley, fluvial and colluvial sands filled the valleys during the Late Pleistocene. Palaeolithic artifacts in various concentrations are located in these deposits, most of which have been impacted largely by recent agricultural activities. Middle Palaeolithic artifacts appear wind-polished and water worn, indicating that they are no longer in primary contexts. Upper Palaeolithic artifacts may still be in place, but deflation and bioturbation have altered their original positions. Despite these impacts, a number of significant finds shed light on Palaeolithic settlement and land use in the region.

Landscape and settlement dynamics of the coastal region of central Estremadura

Our work along the coast builds on previous studies of Middle Palaeolithic settlement in the region (Cardoso 2006; Pereira, Haws, and Bicho 2013; Zilhão 2001), yielding new data that widens our perspective on landscapes inhabited by Neanderthals. At Mira Nascente and Praia Rei Cortiço, we found Middle Palaeolithic artifacts in a new landscape setting (coastal wetlands) with good age-control. While the assemblages are rather small, they suggest important differences in land-use and lithic technological organization between the cave and river terrace locales.

The paleoenvironmental and archaeological records from Praia Rei Cortiço fill a major void in our knowledge of MIS 5 environments on the Iberian Peninsula and, in particular, the Atlantic coast margin. The paleobotanical sequence represents a unique and significant high-resolution diachronic record of vegetation response to climate change and Neanderthal occupation during the transition from interstadial to glacial conditions. The PRC pollen data shows considerable local-scale variability compared to the deep-sea pollen record and reveals a new picture of Neanderthal adaptation to Last Interglacial paleoenvironments on the Iberian Peninsula (Minckley et al. 2015).

Lithic technology and settlement patterns do not appear to have changed significantly during the Middle Palaeolithic, likely reflecting inherent flexibility in long-term human adaptation to climatic instability (Papagianni 2008) and the resilience and biodiversity of Mediterranean ecosystems in general. By late MIS 3, this situation changed with the arrival of modern humans and their Upper Palaeolithic technology (Haws 2012).

As many of the previously reported late Middle Palaeolithic sites have been re-dated using state of the art radiocarbon and luminescence methods (e.g., Cunha et al. 2019), the H4 event appears to have been a significant threshold past which Neanderthals did not survive (Higham et al. 2014; Sepulchre et al. 2007). Mira Nascente is now one of the latest Middle Palaeolithic sites in western Iberia. Dated just prior to H4, the site and its setting have further potential to enlighten our understanding of the processes involved in Neanderthal extinction and modern human colonization.

Possible hints of an Early Upper Palaeolithic pulse in settlement come from sites like Sombrapolis, Ribeiros de Lagoa Seca, and the Montes uplands. Late MIS 3 and MIS 2 climatic instability may have had significant impacts on human settlement patterns. The coastal dune field was mobile throughout late MIS 3 and the MIS 2 sea-level lowstand, coincident with increased upwelling intensity and reduced terrestrial biomass productivity. The nearby Lagar Velho rockshelter, dated to MIS 2, has marine mammal remains and shell ornaments demonstrating links to the shore during the Gravettian (Moreno-Garcia and Pimenta 2002; Zilhão and Almeida 2002).

There does not appear to be any evidence for Solutrean occupation in the survey area. During the LGM, open-air settlement is sparse on the coastal dune fields and valley fills. A few Solutrean sites exist in similar geological contexts to the south at Vale Almoinha, where a radiocarbon date of 21,000 B.P. indicates the continued mobilization of sand through the LGM (Zilhão 1997). Most Solutrean occupations occurred in caves or rockshelters, such as Lagar Velho, found in sheltered valleys.

In contrast, the most visible pulse in Upper Palaeolithic settlement appears to occur during the Magdalenian, which may be due to regional population growth through time or geomorphic evolution of the landscape that has erased or obscured most of the earlier record. Magdalenian sites are found all along the Estremadura coast in the Late Pleistocene sands (Bicho and Haws 2012). At Oitavos, near Lisbon, a consolidated dune dated by OSL to 15.7–13.1 kya below a paleosol and 12.9–10.8 kya above suggests two phases of dune building (Prudêncio et al. 2007). The main phase began during or just after the H1 cold event when the sea level was rising but the sand supply to the ocean would have been decreasing with the spread of forests during the Bölling and Allerød interstadials. Additionally, the sands could have been mobile during the Younger Dryas. OSL ages of 12.9–11.4 kya in the study area and numerous Magdalenian sites in the coastal dunes and valley fills demonstrate a Late Glacial settlement focus near the shore. Magdalenian sites tend to occur in the sands along tributary streams at sites like Valado and Sombra City, and possibly Campo Aventura and Quebrada dos Cravos.

Conclusions

The survey identified numerous clusters of Middle Palaeolithic artifacts in secondary contexts. These are usually associated with stream cobbles in fluvial settings, primarily in the southern half of the Caldas da Rainha valley. In the uplands near Montes, several Middle Palaeolithic localities were identified, but no precise age estimation is possible. Chert raw material availability likely attracted people to this locale over vast time spans.

The Praia Rei Cortiço paleovalley, located near Óbidos, preserves a lengthy MIS 6–1 sedimentary sequence in the exposed coastal cliffs. Near the base of the section, we discovered an archaeological site, Praia Rei Cortiço, dated to MIS 5. This site is situated on a colluvial slope above an ancient swamp and presents a unique landscape setting for known Middle Palaeolithic sites in the region.

Along the coastal cliffs north of Nazaré, our team analyzed a series of vertically discrete stratigraphic profiles that preserve remnant MIS 3 and 4 landforms at a relatively fine spatial and temporal resolution. In this context, we discovered Mira Nascente, a Middle Palaeolithic site in a unique, near-shore aeolian dune context along a channel margin. OSL and radiocarbon dates of 40–42 kya place the occupation in MIS 3, just prior to the H4 event.

Across much of the study area, we recovered artifacts of different technocomplexes dispersed across what appears to be a uniform sand sheet that might imply long-term landscape stability, but OSL-dating and geomorphic mapping revealed evidence for multiple episodes of valley filling, dune formation, and stability during MIS 3 and 2. These results are consistent with a model of episodic dune field activity controlled by climate and sea level fluctuations. Millennial-scale cycles of abrupt and rapid climate shifts, mainly Dansgaard-Oeschger and Heinrich events, created relatively short periods of landscape stability, and Palaeolithic people utilized these landscapes in varying degrees of intensity. This study shows how, through systematic archaeological survey, geomorphic mapping, and radiometric dating, we can untangle what might otherwise be dismissed as an undecipherable spatial palimpsest.

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

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