Archaeological and Anthropological Sciences (2026) 18:25
https://doi.org/10.1007/s12520-025-02400-6

RESEARCH

Early evidence of earthquake management through mobility and social network adjustments at Vale Boi (SW Iberia)

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Received: 11 June 2025 / Accepted: 22 December 2025

Abstract
Tectonic processes profoundly influenced the dispersal, evolution, and archaeological record of our Paleolithic ancestors. However, in-depth reconstructions of human resilience against seismic events come mostly from contexts dating to the last 13,000 years. Here, we present geophysical, geological, geochronological, and archaeological data from the open-air site of Vale Boy in southwestern Iberia, revealing how foragers mitigated earthquake impacts between ~30,000 and 24,000 years ago. At Vale Boi, faulting formed sedimentary traps that were recurrently exploited by hunter-gatherers and periodically buried by rockfalls, likely triggered by ≥5.7 Mw earthquakes. Despite seismic destruction, hunter-gatherers repeatedly returned to the site, drawn by its strategic access to key resources. They mitigated seismic risks by increasing their mobility and even abandoning Vale Boi, as seen during the Gravettian and at the early/late Proto-Solutrean transition. When seismic and climatic stressors co-occurred (Heinrich Event 2), they did not abandon the site. Instead, they adopted strategies to limit their exposure to rockfall hazard while securing access to increasingly vital coastal and estuarine resources. Until the early Proto-Solutrean, tightly knit social networks supported the survival of Vale Boi foragers during periods of high stress, such as the aftermath of seismic rockfalls. During the late Proto-Solutrean, an expansion of super-regional connections might have functioned as a proactive buffer against future tectonic shocks. Our findings demonstrate that forager resilience to seismic events relied on flexible adjustments in mobility and social connectivity. Despite limitations deriving from its single-site focus, this study underscores the value of deep archaeological sequences for disentangling human responses to intertwined geological and ecological pressures.

Keywords Human resilience · Upper Paleolithic · Geophysics · Micromorphology · Bayesian modelling · Lithic refitting

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Published online: 20 January 2026

Introduction

Tectonic processes have long been recognised as fundamental agents shaping the evolution, dispersal, and behavioural variability of human populations (Bailey et al. 1993; King et al. 1994; King and Bailey 2006; Gracia et al. 2008; Bailey 2010). Faulting, uplift, and subsidence produced the basins and topographic gradients that structured resource distribution, hydrological regimes, and migratory routes, while also influencing the preservation of archaeological deposits through the creation of natural sediment traps (Bailey et al. 1993; King et al. 1994; Bailey and Flemming 2008; Bailey 2010; Haws et al. 2010; Rossi et al. 2020). Tectonically active landscapes offered both opportunities and risks: they generated ecologically rich ecotones attractive for settlement, but also exposed human groups to sudden, catastrophic events such as earthquakes, volcanic eruptions, and tsunamis (Kontopoulos and Koutsios 2010; Fouache and Pavlopoulos 2011; Fountoulis et al. 2013; Barbieri et al. 2023). Understanding how prehistoric foragers[1] coped with such short-term geological hazards is therefore essential to reconstructing the dynamics of resilience in early human societies – meaning their ability to absorb disturbance, reorganize, and persist through change (Halstead and O'Shea 1989; Folke 2006; Riede 2014; Wren et al. 2025) – which remains an underexplored dimension of Pleistocene archaeology.

Earthquakes in particular profoundly affected past human communities across time, altering landscapes, destroying habitats, and transforming settlement patterns (Riede 2008, 2014). Archaeological records show that past hunter-gatherers increased their mobility following major tectonic events (Torrence et al. 2000; Riede 2008; Oetelaar and Beaudoin 2016; Salazar et al. 2022; Damlien et al. 2024). Some of these communities even avoided earthquake–affected settlements for periods lasting up to thousands of years, as seen in Chile and New Guinea during the late Holocene. These prolonged abandonments surely exceeded the duration of post-quake resource depletion, and have thus been interpreted as long-term preventive strategies to minimize the impact of future, highly destructive quakes (Torrence et al. 2000; Salazar et al. 2022). Studies in tectonically active regions also show that post-disaster strategies frequently included diversification of resource procurement, modification of storage and transport systems, as well as the restructuring of relational networks to facilitate recovery (Halstead and O'Shea 1989; Torrence et al. 2000; Riede 2008; Oetelaar and Beaudoin 2016; Salazar et al. 2022). These cases reveal that human resilience emerges through a limited but flexible repertoire of behavioural mechanisms—mobility, economic diversification, and social networking—that mitigate environmental uncertainty (Halstead and O'Shea 1989; Folke 2006; Riede 2014; Riede et al. 2017).

Almost all well-documented cases of past forager responses to seismic impacts post-date 13 ka and focus on rare (10s-ka cycle), highly magnitude earthquakes compounded by tsunamis or volcanic eruptions (Torrence et al. 2000; Riede 2008; Oetelaar and Beaudoin 2016; Jeffrey et al. 2017; Salazar et al. 2022; Walker et al. 2024; Damlien et al. 2024). Whether earlier foragers possessed a similar capacity to anticipate and respond to mid-magnitude earthquakes – events that are far more common and still potentially destructive - is largely unknown. Progress on this question has been limited by the rarity of Pleistocene sites that preserve both continuous archaeological sequences and geological evidence for repeated seismic instability.

Vale Boi fills this gap. Situated in southwestern Portugal, the site provides a unique opportunity to examine how recurrent seismic and tectonic activity intersected with Paleolithic stays. Occupied from the Gravettian (32.5–31.7 ka cal BP) to the Epipaleolithic (10.1–9.5 ka cal BP), and later in the early Neolithic (Regala et al. 2014), Vale Boi lies within the convergence zone between the African and Eurasian plates (Fig. 1a). It is positioned at the crossroad of Quaternary faults capable of 5.7–7.2 M_w earthquakes (Dias et al. 2010; Figueiredo et al. 2011, 2018; Teves-Costa et al. 2019), making it especially well-suited for investigating long-term human response to seismic risk. Using geological and geophysical methods, we traced Pleistocene faults across the site and revealed that they generated both sedimentary traps and seismic rockfalls. When integrated with geochronological and archaeological datasets, these results reveal adjustments in mobility and social connectivity among Gravettian and Proto-Solutrean foragers following tectonic events. Through this integrated approach, our study reconstructs one of the earliest examples of seismic risk management in human history and expands existing models of Paleolithic resilience beyond climatic or ecological determinism.

Geological and tectonic context

The archaeological site of Vale Boi (37°05′23″N 8°48′33″W) is located 2.6 km inland from the Atlantic Ocean, on the eastern flank of the eponymous creek, along the slope of a mountain that reaches 60 m of elevation above current sea level (acsl, Fig. 1a–c) (Bicho et al. 2012a). This relief

[1] In this study, we use the terms *foragers* and *hunter-gatherers* interchangeably. When referring to human groups described in the original publications as primarily engaged in gathering marine resources or in hunting game, we retain the terms *fisher-gatherers* and *hunters*. We follow this terminology because it is widely used in the literature, while recognizing that such categories are debated within anthropology and can oversimplify or bias our understanding of Paleolithic societies (Grimm et al. 2025, p. 2).

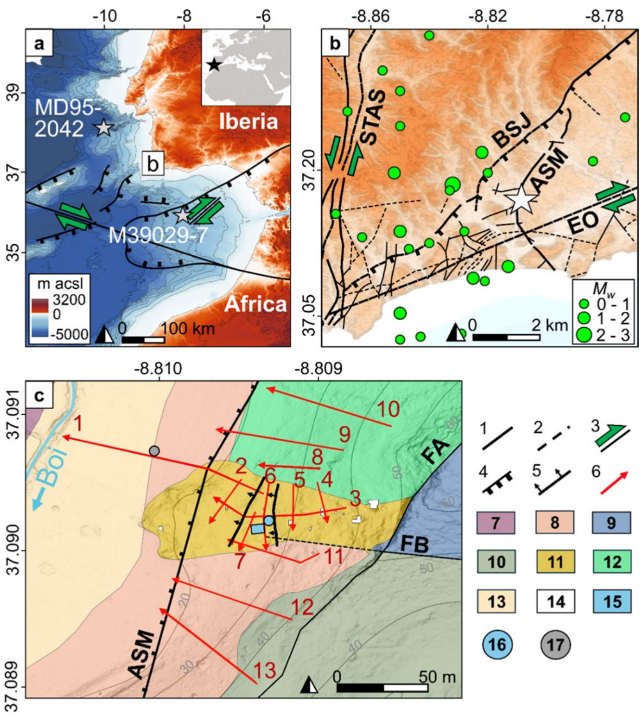


Fig. 1 Geological context of Vale Boi. (**a**) The subduction zone between Iberia and Africa, based on data from (Serpelloni et al. 2007; Zitellini et al. 2009; Gebco Compilation Group 2024). Grey stars depict the location of marine cores MD95-2042 and M39029-7. (**b**) Hillshade map from (SRTM 2013) depicting modern epicenters (as green circles) and faults surrounding the site of Vale Boi (depicted as a white star), based on (Rocha et al. 1975; Manupella 1992; IGME 2022; IPMA 2024). In bold, the main Quaternary systems in the study region (**STAS**, **EO**, **BSJ**, and **ASM**. Further details in the main text). (**c**) Geological map of Vale Boi, based on data presented in this paper as well as previously published cartography (Rocha et al. 1975; Manupella 1992). Faults displayed in subpanels (**a–c**): (**1**) unclear/unknown style; (**2**) potential; (**3**) strike-slip; (**4**) reverse, marked on hanging block; (**5**) normal, marked on hanging block. Data displayed in (**c**): (**6**) Electrical Resistivity Tomography profiles; (**7**) Triassic sandstones of Silves; (**8**) Jurassic Carbonated–Marls of Silves; (**9**) Limestones of Espiche and (**10**) Almadena; (**11**) Pleistocene sediments rich in fault breccia; (**12**) colluvial fan and (**13**) alluvial deposits of likely Holocene age; (**14**) archaeological excavations; (**15**) trench excavated at the Terrace; (**16**) Core A; (**17**) Core B. The three maps are projected in the WGS84–EPSG:4326 coordinate reference system

is made from Jurassic marls and limestones (Rocha et al. 1975; Manupella 1992) (Figs. 1c and Online Resource S1d–h). The site is situated some 150 km north from the subduction zone between the African and Eurasian plates (Fig. 1a) and it is surrounded by modern earthquake epicenters as well as reverse and strike-slip Quaternary structures (Fig. 1b). São Teotónio–Aljezur–Sinceira (Figueiredo et al. 2018), Barão de São João (Dias et al. 2010), and Espiche–Odiaxere (ID PO023) (IGME 2022) are the major fault systems located in a 6 km radius from Vale Boi (STAS, BSJ, and EO in Fig. 1b). Though currently exhibiting weak seismicity (Rocha et al. 1975; Manupella 1992; IGME 2022; IPMA 2024) (Fig. 1b), they are capable of earthquakes with estimated maximum magnitudes of 6.2 to 7 M_w (Dias et al. 2010; Figueiredo et al. 2011, 2018; IGME 2022). Along the mountaintop above the archaeological site runs a fault of Triassic age (Rocha et al. 1975; Manupella 1992) (FA in Figs. 1c and 2a and a). This is truncated by a more recent 7 km long fault that extends from Ponta de Almádena to Barão de São Miguel (ASM in Fig. 1b and c). Data presented in this paper clarify the mode and period of activity of this structure, as well as its impact on the archaeological site and prehistoric foragers.

Archaeological background

The archaeological site of Vale Boi was discovered in 1998 during survey (Bicho et al. 2003). Test pitting and systematic excavations confirmed the presence of archaeological stratification in three areas situated along a 20 m–wide and 75 m–long hillside strip, which are referred to as Rockshelter, Slope, and Terrace (Fig. 2a – cc´, Fig. 3). Materials unearthed from excavations of these areas include abundant and well–preserved marine and terrestrial fauna (Manne et al. 2012; Manne 2014), ornaments (Regala et al. 2014), portable art (Bicho et al. 2012b), and lithic artefacts (Marreiros et al. 2015; Cascalheira et al. 2017; Horta et al. 2019). A solid geochronological framework for these assemblages is provided by over 50 radiocarbon ages (Regala et al. 2014). At the foot of the slope, the Terrace represents the site area with the deeper archaeological sequence (Fig. 2). This consists of Gravettian (32.5 to 25.6 ka cal BP), Proto-Solutrean (25.4 to 23.2 ka cal BP), Solutrean, Epipaleolithic (10.1 to 9.5 ka cal BP), and Neolithic assemblages (8.5 to 6.7 ka cal BP) (Regala et al. 2014) (Gravettian and Proto-Solutrean dates are re-modelled in this study).

Forager resilience strategies at Vale Boi

In hunter-gatherer contexts, resilience manifests through behavioral flexibility across four adaptive domains: mobility, economy, storage, and social networking (after Halstead and O'Shea 1989). The text below summarizes published data from Vale Boi relevant to exploring these domains. In Table 1, we list the specific archaeological proxies we used in this study, integrating previously published datasets with new results.

Mobility

Published Summed Probability Density (SPD) of calibrated radiocarbon dates shows that Vale Boi was occupied during Heinrich Events (HE) 3 and 2, but abandoned during HE 1 (Cascalheira et al. 2017). The Gravettian at

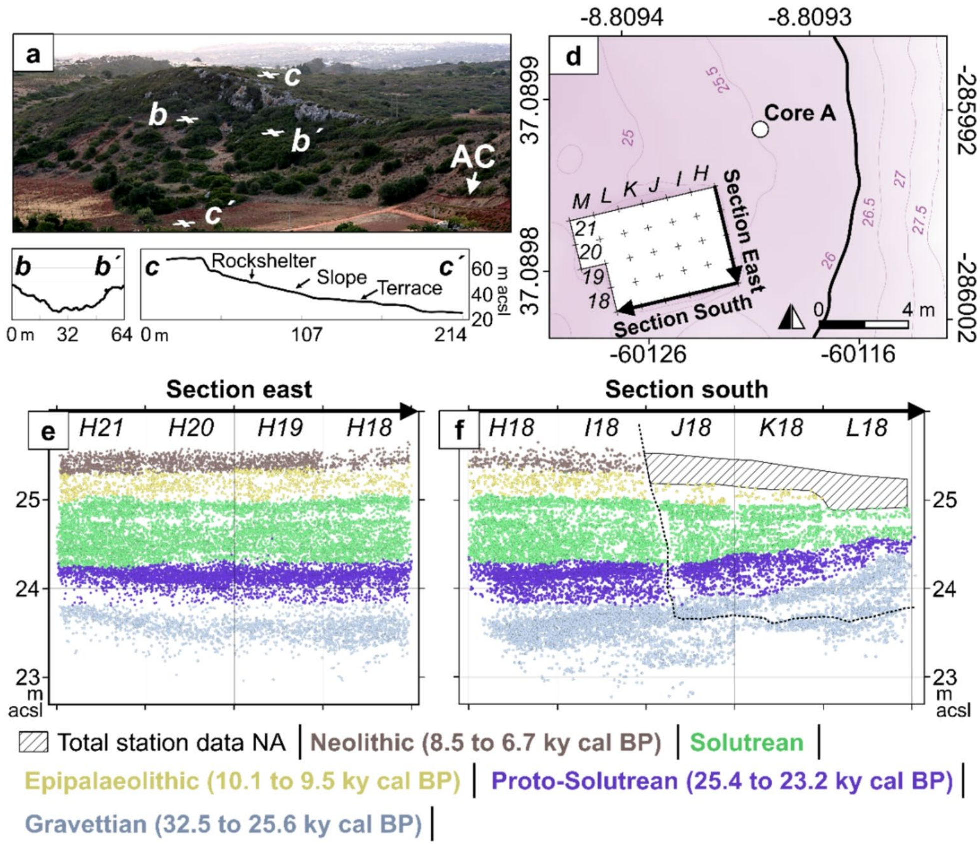


Fig. 2 The Terrace of Vale Boi. (**a**) Photo overview and topography profiles (***bb´*** and **cc´**) depicting the archaeological area of Vale Boi. (**d**) Archaeological trench at the Terrace with labelled excavation squares, each measuring 1 × 1 m. The black solid line depicts a normal fault. In pink, isolines as m above current sea level. (**e**) Total station points of archaeological materials from squares H21, H20, H19, and H18. (**f**) Total station points of archaeological materials from squares H18, I18, J18, and L18. Archaeological attribution of the assemblages as per Belmiro et al. (2021). Note that the Gravettian and Proto–Solutrean assemblages dip towards the hilltop. The dashed line marks the limit between the 2003–2010 excavations (above the line) and the 2012–2019 campaigns (below the line). The Neolithic deposit in J18, K18 and L18 were excavated in 5 cm spits without a systematic use of total station, therefore we excluded those total station points from subpanel f

this site saw phases of low SPD and decreased find density (Bicho et al. 2013; Cascalheira et al. 2017; Belmiro et al. 2021), yet the stressors driving these drops in occupations remain unclear. Analysis of the Whole Assemblage Behavioural Index (WABI) and subsistence catchments reveals that settlement system and landscape use remained stable during the late Upper Palaeolithic (Cascalheira et al. 2017). Except for earlier Gravettian occupations, deposits at the Terrace exhibit high lithic densities and low retouch frequency (< 10%), consistent with long-term residential use (Bicho et al. 2013; Cascalheira et al. 2017). Deer and horse dominated hunting throughout the Upper Paleolithic, with all skeletal parts represented, pointing to kills near the site (Manne et al. 2012; Manne 2014). The hunting of neonate and adult ungulates indicates human occupations in spring and early summer (Manne et al. 2012; Bicho et al. 2013; Manne 2014). Aquatic resources were also foraged from nearby river, lacustrine, and marine habitats (Manne et al. 2012). Together, these data suggest Vale Boi functioned as a central residential base with a daily mobility radius of ~20 km (Bicho et al. 2013; Cascalheira et al. 2017; Belmiro et al. 2025). Raw material procurement supports this inference. Most raw materials were either collected as pebbles along the Boi Creek (Pereira et al. 2016) or from outcrops within 20 km (Belmiro et al. 2025). Non-local types (up to 200 km away) make up 40–65% (in weight) of the chert used during the Gravettian and early Proto-Solutrean, dropping to 20% during the late Proto-Solutrean and Solutrean occupations (Belmiro et al. 2025). This decline has been linked with a more continuous presence of foragers in Vale Boi´s region since the late Proto-Solutrean (Belmiro et al. 2025). Dolerite, in contrast, was exclusively used by early and late Proto-Solutreans (Belmiro et al. 2021), probably sourced from outcrops up to 50 km away (Rocha et al. 1975; Manupella 1992). The absence of dolerite debitage suggests that finished pieces or blanks were imported, marking a slight shift in landscape and site use during HE 2 (Belmiro et al. 2021).

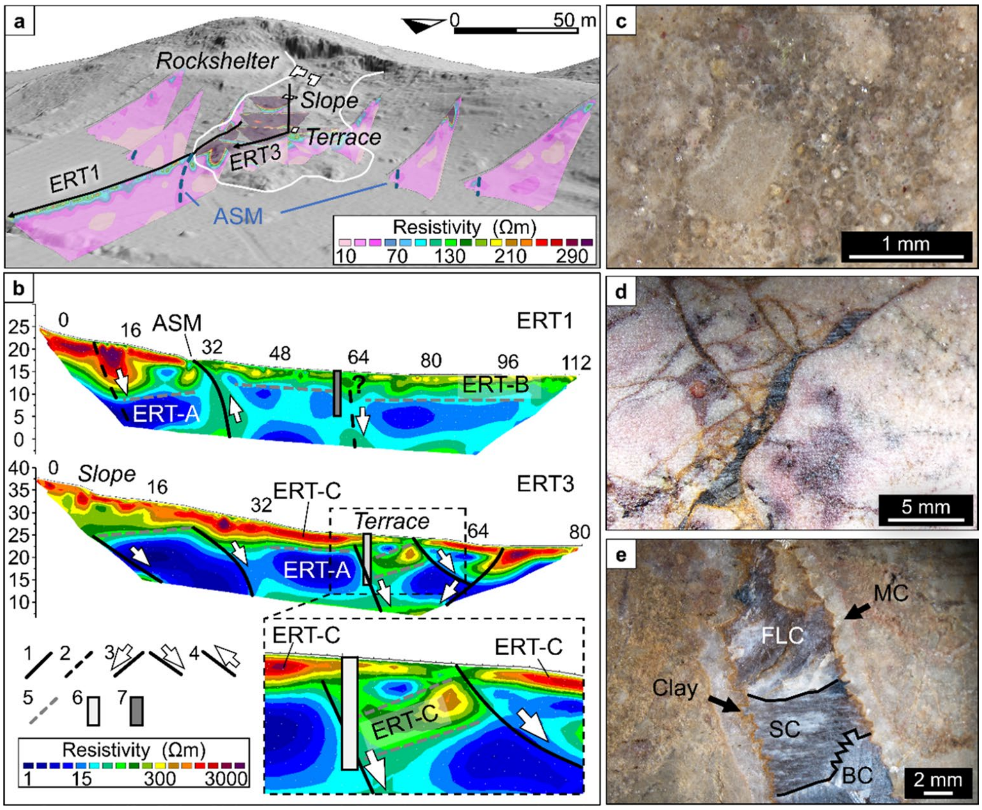


Fig. 3 Tectonic deformations in Electrical Resistivity Tomography (ERT) and coring data. (**a**) 3D view of the ERT data we collected at Vale Boi. The fault of Ponta de Almádena–Barão de São Miguel (**ASM**) is labelled with a dashed blue line within the ERT profiles. (**b**) The profiles ERT1 and ERT3 along with their location and orientation are depicted in subpanel (**a**). On the ERT profiles we labelled (**1**) faults of unclear/unknown style; (**2**) potential faults; (**3**) normal and (**4**) reverse faults; (**5**) beds deformed by faulting; (**6**) core A; and (**7**) core B. (**c**) Stereoscopic photomicrograph showing fault breccia with preserved oolites taken from a depth of 5 m in Core A. (**d** and **e**) Stereoscopic photomicrograph showing fault breccia with sigmoidal veins taken from depths of 3 and 5 m in Core A. In (**e**) note the various infilling consisting of micrite (**MC**), clay (**Clay**), fan–like sparitic calcite (**FLC**), stretched calcite (**SC**), and blocky calcite (**BC**), evidencing multiple cracking and sealing episodes (Bons et al. 2012; Zhao and Li 2022)

Table 1 Proxies of resilience used in this study include both published and newly generated results

Resilience Strategies	Proxies from Vale Boi
Mobility	Whole Assemblage Behavioural Index (Cascalheira et al. 2017)
	Catchment of food resources (Manne et al. 2012; Manne 2014)
	Raw materials (Belmiro et al. 2025)
	Summed Probability Density and Kernel Density Estimate of ^{14}C ages (Cascalheira et al. 2017; and in this paper)
	Spatial analysis of archaeological finds (in this paper)
Food Economy	Spectrum of hunted and foraged food resources (Manne et al. 2012; Manne 2014)
Storage	Evidence of bone grease rendering (Manne et al. 2012; Bicho et al. 2013; Manne 2014)
Social network	Lithic typo-technology (Marreiros et al. 2016; Bradtmöller et al. 2016; Cascalheira et al. 2017; Belmiro et al. 2021)
	Non-utilitarian goods (Bicho et al. 2012b; Regala et al. 2014)

Food economy

Throughout the Upper Paleolithic, hunted species composition remained stable, dominated by red deer, horse, and rabbit, with occasional aurochs, wild boar, ibex, European ass, and large birds (Manne et al. 2012; Manne 2014; Cascalheira et al. 2017). Marine resources show a similar pattern, with limpets, scallops, and clams, followed by smaller amounts of winkles, grooved carpet, cockles, and freshwater nerite, with only rare evidence of fish or small cetaceans (Manne et al. 2012and L. André personal comm. 2025). A decline in the frequency and diversity of marine shells after the late Proto-Solutrean has been linked to the ~130 m sea-level fall during the Last Glacial Maximum, which increased the site's distance from the coast (Manne et al. 2012). However, further analyses are necessary to confirm that this pattern is not simply a preservation bias.

Storage

Bone grease rendering is interpreted as a major investment in food storage, enabling the accumulation of animal fat as a storable energy source (Oetelaar and Beaudoin 2016). At Vale Boi, ungulate bones, particularly fat-rich skeletal elements, were systematically fragmented in all the Upper Palaeolithic deposits (Manne et al. 2012; Manne 2014; Cascalheira et al. 2017; Horta et al. 2019). Pitted greywacke anvils, common throughout the Terrace sequence, likely served as bone-smashing implements (Manne et al. 2012; Cascalheira et al. 2017), while recurrent fire-cracked quartz fragments suggest heat-in-liquid grease-extraction techniques (Manne et al. 2012). Together, faunal and lithic data indicate that bone-grease rendering was a long-standing adaptive strategy for Vale Boi's hunter-gatherers, helping them cope with limited game availability in the region (Manne et al. 2012; Bicho et al. 2013; Manne 2014).

Social network

Shifts between regionalization and standardization in lithic typo-technology and non-utilitarian goods may reveal changes in hunter-gatherer connectivity (Whallon 2006; Riede 2008; Fitzhugh et al. 2011; Damlien et al. 2024). At Vale Boi, quartz and chert were knapped unidirectionally into blanks and flakes using prismatic cores with platform preparation (Belmiro et al. 2021). Quartz was often struck expediently along natural edges (Cascalheira et al. 2017), while chert was preferred for formal tool production (Belmiro et al. 2021). The Gravettian record lacks classic *fossil directeurs*, such as Gravette and Microgravette points, but features distinctive bipointed double-backed bladelets unique to southern Iberia (Marreiros et al. 2016). Though the presence of non-local raw material may indicate contacts with other groups (Belmiro et al. 2025), the typo-technological signature of the Gravettian of Vale Boi more likely reflects a relative isolation from broader interaction networks (Marreiros et al. 2016; Bradtmöller et al. 2016). By contrast, late Proto-Solutrean and Solutrean assemblages contain super-regional lithic types (Vale Comprido and Solutrean points, Belmiro et al. 2021) and engraved plaquettes with widely shared decorative motifs (Bicho et al. 2012b), reflecting intensified long-distance connections. Non-utilitarian goods, however, also highlight continuity in local traditions. Shell beads occur in all Upper Palaeolithic layers (Regala et al. 2014). While species selection varied over time, all shells were collected locally, and bead-making techniques remained consistent, indicating stable systems of knowledge transmission and enduring symbolic practices (Regala et al. 2014).

To sum up, available data from Vale Boi indicate that:

(i) Since the late Proto-Solutrean, foragers decreased their mobility and camped more frequently at the site (Belmiro et al. 2025), though the higher mobility and sparser record of Gravettian occupations may reflect responses to stressors (Bicho et al. 2013; Cascalheira et al. 2017; Belmiro et al. 2021).
(ii) Food economy remained broadly stable throughout the Upper Palaeolithic (Manne et al. 2012; Manne 2014; Cascalheira et al. 2017). Marine resources might have been consumed less during the Solutrean, though preservation bias remains to be addressed.
(iii) Intensive efforts to store food persisted throughout the Upper Paleolithic (Manne et al. 2012; Manne 2014; Cascalheira et al. 2017).
(iv) The late Proto-Solutrean marked the transition towards intensive long-distance networking, previously interpreted as an adaptive response to climatic shifts (Belmiro et al. 2021).

Data presented in this paper reveal potential tectonic stressors during the Gravettian and Proto-Solutrean as well as clarify the taphonomy of seashell remains, challenging the hypothesis of a major shift in the exploitation of marine resources during the late Upper Paleolithic.

Materials and methods

We applied a suite of methods to reconstruct site formation processes with emphasis on tectonic dynamics: these include geophysical prospections, coring, lithological descriptions, and micromorphology. To explore forager response to tectonic impacts, we integrated published findings with newly generated data from the Terrace (Table 1), as this exhibits the most complete archaeological sequence unearthed at Vale Boi. We expanded previous analyses of the vertical density of archaeological finds (Cascalheira et al. 2017) to test hypotheses on mobility and subsistence shifts (see Archaeological Background). We also performed lithic refitting to identify in situ occupations within layers deformed by tectonic processes and buried by seismic rockfalls. Finally, we generated a new Bayesian age model, together with SPD and Kernel Density Estimate modelling (KDE) of radiocarbon ages, to establish a robust geochronological framework for in situ occupations and detect phases of decreasing site visits.

Electrical resistivity tomography (ERT)

ERTs 1–8 were acquired using a Geometrix Stratavisor NX resistivity meter connected to a chain of 48 electrodes with an electrode spacing of 1 m, requiring the use of a roll-along technique for ERTs 1 and 3. We collected the remaining profiles ERTs 9–13, using a Lippmann 4–point light 10 W attached to a chain of 20 electrodes with an electrode spacing of 4 m. All ERT measurements were performed using a pole-dipole array, to allow for deeper data acquisition. We inverted and interpreted the measured resistivities with Res-2Dinv 3.5. We evaluated the inversion results as pseudo 3D, together with LiDAR as well as coring data, in the software Blender 3.6.

Coring

Cores were drilled using Fraste Multidrill PL rotary equipment. Sediment samples, measuring 77 mm in diameter, were retrieved without the use of liners, from incremental depths of 1.2 m. Core A was drilled down to a maximum depth of 12 m, while Core B reached 9.7 m of depth. Drilling in both cores was halted after breaching through consolidated bedrock.

Lithological descriptions

Geological exposures, core sediments, and profiles from the archaeological excavation at the Terrace were cleaned, documented with photographs, and described following standardized protocols, which are detailed in Online Resources ST 1.1 and ST 2.1.2.

Micromorphology

With the help of plaster bandages, six micromorphological block samples were extracted from Section South at the Terrace, covering GLs 2–7. Samples were sun-dried, impregnated with a mixture of styrene, resin, and hardener, let consolidate for about ten days in the fume hood, cut with a rock saw, and shipped to Spectrum Petrographics Inc for thin section production. For this study, a total of 11 thin sections (50 × 75 mm, 30 mm in thickness) were analyzed and described using stereo– and petrographic microscopes in plane polarized (PPL) and crossed polarized light (XPL). Further details concerning micromorphological methods and analysis are reported in Online Resource ST 2.2.

Vertical trends in archaeological finds

We examined changes in the vertical density of the archaeological finds unearthed from 2003 to 2019. The analysis focused on the most common classes of archaeological materials occurring at the Terrace, namely lithics, bones, and marine shells. Finds were assigned to the corresponding GLs based on excavation fieldnotes and plotting of total station data. To minimize the risks associated with this retrospective attribution of the archaeological materials, we restricted the analysis to the most laterally continuous Paleolithic deposits preserved at the Terrace, namely GLs 3, 4, 5, 6, 7, 10, and 11. Previous studies detected two distinct occupational phases with different archaeological signatures within GL 5 (Belmiro et al. 2021, 2025). To harmonize with this discrepancy, we treated the top and bottom of GL 5 as two separate units. We calculated both the total density and the relative percentages of the archaeological finds (Online Resource Tables S21 and S23). We evaluated these results against our geoarchaeological data, also using Spearman's rank correlation, to tease apart taphonomic biases and shifts in hunter-gatherer behaviors.

Refitting of lithic artifacts

Lithic refittings were applied to most raw materials. Chert and chalcedony were exclusively refitted for Excavation Layers (EL) 4 and 4E to 7, while all raw materials excluding quartz were refitted for ELs 4B to 4D (correlation between EL and GL is explained in Online Resource ST 2.1). The refittings were aided by the visual characterization of non-chert raw materials such as greywacke and dolerite, and though a systematic study of chert and chalcedony raw materials. This study included the macroscopic description of chert and chalcedony using a 10x hand lens and a Nikon SMZ25 stereomicroscope and petrographic characterization through thin sections of several identified types. The combination of these methods allowed us to separate raw materials into units, which greatly aided in the success of the refitting process. The refits were complemented by technological studies, while knapping strategies were identified based on the technical attributes of the cores and the blank production. This allowed us to further classify and interpret the nature of the refits (whether technological/anthropical or conjoint/natural) (Tables S11 and S12). A detailed description of the refitting methods, analysis, and relevant references are provided in Online Resource ST 2.4.

Age modelling of ^{14}C ages

For the age modelling published in this paper, we considered only reliable published ^{14}C determinations performed on charcoal and shell samples from the Proto-Solutrean and Gravettian assemblages (Online Resources ST 2.5 and Tables S13 and 14). We considered only the shell specimens that XRD analysis indicated as not recrystallized (more details in Online Resource ST 2.5). This selection left us with 20 radiocarbon ages (Online Resource Table S13). Based on total station point, we grouped the ^{14}C ages by GL. For layers with multiple ages, we ordered the dates based on their relative elevation above the bottom sedimentary contact (DeltaZ in Online Resource Table S14). We preferred this approach to the use of absolute elevation because of the inclined geometry of the layers.

For the Bayesian modelling, we defined boundaries corresponding to the sedimentary contacts of the GLs. Exceptions are phases "Lower GL5" and "Top-GL 5/GL4a" to better constrain early and late Proto-Solutrean stays. Calibration and Bayesian modelling were performed with the software OxCal 4.4. The curve IntCal 20 (Reimer et al. 2020) was used to calibrate determinations performed on charcoal samples. Seashell specimens were calibrated using the curve Marine20 (Heaton et al. 2020) and a ΔR of 196 ± 90, based on the closest marine core available (Soares 1993; Reimer and Reimer 2001). Bayesian modelling of the 20 selected radiocarbon ages produced a model with eight ages showing poor Agreement ($A < 60$, in Online Resources Table S15 and S16). The good preservation indicated by the XRD screening and the formation history of the site suggest that these are likely inverted ages. To date in situ occupations at the Terrace, we excluded ages showing $A < 60$ and posterior outlier probability higher than 15% (Online Resource Table S17). As a result, we obtained a final model (Fig. 4) that shows good Agreement ($A_{model} = 104.2$ and $A_{overall} = 102.8$) and convergence above 97% for all the dates (Online Resources Table S18 and S19).

We coupled SPD and KDE of the modelled ^{14}C ages to reduce the risk of misinterpreting artifacts introduced during calibration (Ramsey 2017). We used the KDE_Model command in OxCal (Ramsey 2017), with default parameters (code in Online Resources Table S20).

Results

Evidence of faulting from geophysical and coring data

At the bottom of our Electrical Resistivity Tomography (ERT) profiles, we detected a lithological unit that is at least 20 m thick and composed of highly conductive layers (< 10 Ωm) alternating with more resistive beds (50 to 400 Ωm. ERT–A in Fig. 3). Sedimentary exposures as well as Cores A and B reveal that ERT–A is made from bedded marls (Online Resources Figs. S1–S3 and Table S1–S3). Along the passage from the valley floor to the hillside, these beds are vertically displaced along a moderately resistive (50–70 Ωm) sub–vertical feature, which dips westwards with an angle of approximately 70–60° (Fig. 3b). We interpret this feature as a reverse fault (Davis et al. 2011; Nabi et al. 2020). Based on our geological survey and previously published cartography (Rocha et al. 1975; Manupella 1992), this fault corresponds to ASM (Figs. 1c and 3a–b).

Geophysical and coring data show that the bedded marls delimit a 0.9 ha depression, which is recognizable in today´s topography (*bb´* and *cc´* in Fig. 2) and encompasses the three archaeological areas (11 in Fig. 1c). It is filled with a 1–8 m-thick layer made from boulders of crackle–mosaic breccia, which exhibit locally preserved fossils (Figs. 3c–d) (Mort and Woodcock 2008; Shukla and Sharma 2018). To our knowledge (Rocha et al. 1975;

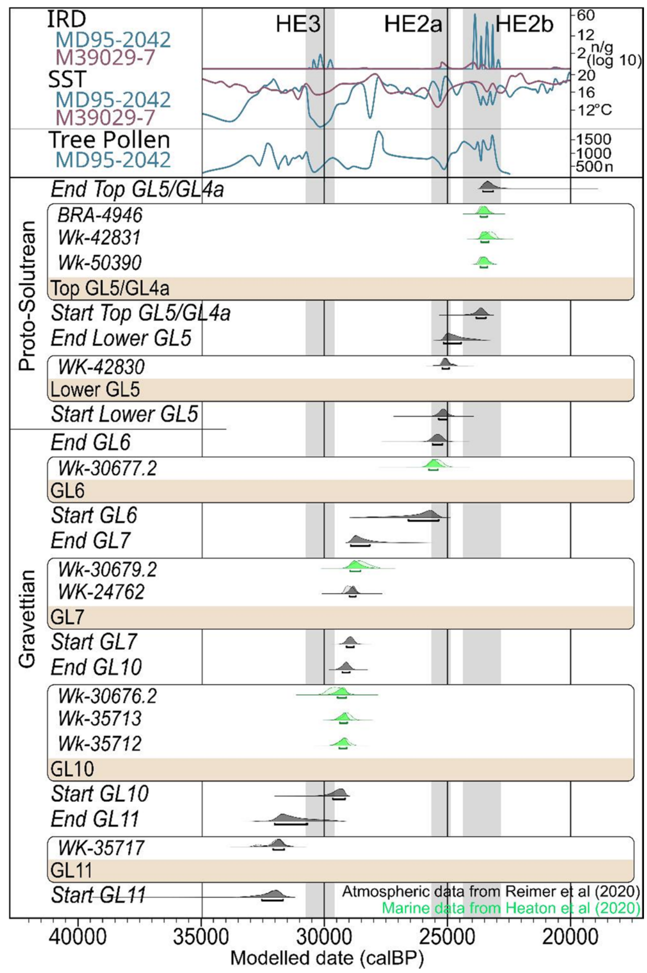


Fig. 4 Bayesian modelling of ^{14}C ages from Gravettian and Proto-Solutrean deposits at the Terrace. Calibration and Bayesian modelling were performed with the software OxCal 4.4. Charcoal samples were calibrated with the curve IntCal 20 (Reimer et al. 2020). Seashell specimens were calibrated with the curve Marine 20 (Heaton et al. 2020), using a ΔR of 196 ± 90, based on the closest marine core available (Soares 1993; Reimer and Reimer 2001). Radiocarbon ages from the terrace are correlated with Ice Rafted Debris (IRD) (Eynaud et al. 2009; Löwemark 2016) and Sea Surface Temperatures (SST) from marine cores MD95-2042 and M39029-7 (Salgueiro et al. 2010, 2014), as well as tree pollen counts from MD95-2042 (Sanchez Goñi 2014). Age model of both cores from (Lisiecki et al. 2021). The location of the cores is depicted in Fig. 1a.

Manupella 1992), the only formations with preserved fossils at Vale Boi are Jurassic limestones situated at the mountain top (Online Resources Figs. S1f–g). Therefore, before brecciation, these rockfall boulders eroded from the uphill limestone outcrops. Brecciation was caused by repeated extensional deformations, as evidenced by synthaxial sigmoidal veins observed in Core A (Figs. 3d–e) (Bons et al. 2012; Zhao and Li 2022) and parallel normal faults identified in the ERT data (Fig. 3b). These faults caused the subsidence and uphill tilting of both bedded marls and rockfall boulders underneath the Terrace (ca. 40°) and Slope areas (ca. 10°), opening sedimentary traps that enabled the accumulation and preservation of Pleistocene sediments and archaeological remains (Bailey et al. 1993; King et al. 1994; King and Bailey 2006).

Evidence of tectonic rotations and rockfalls within the terrace sequence

The lowermost layer exposed in the archaeological trench excavated at the Terrace corresponds to the brecciated and tectonically rotated limestone rockfall detected by ERT and coring (GL 12 in Figs. 3 and 5). This unit dips towards the hilltop with a maximum inclination of approximately 35° and was buried by rockfall layers (GLs 11, 10, 7, 8, and 5) alternating with rarer mud (GLs 6, 5a, 4a) and debris flows (GLs 4–1. Figures 5 and 6. Online Resources ST 2.1–2.2 and Table S5). GLs 4a – 11 also underwent tectonic rotation, as indicated by their uphill inclination (10° – 12°; Fig. 5a and a*dd´*, and 7b). Tectonic activity diminished (or halted) after the deposition of GL 4a, which dips towards the mountaintop with an angle of just 4°. In contrast, the upper contact of GL 4 is 1° inclined towards the valley bottom (Figs. 5a and 6b). Based on these observations, we propose that the Terrace sequence was deformed during two separate phases of rotation. The first occurred after the deposition of GL 12, while the second took place after the sedimentation of GL 5. The latter slowed down during the accumulation of GL 4a and halted during the deposition of GL 4. The hypothesis that the Terrace underwent multiple rotations is further supported by the cracked–&–sealed sigmoidal veins (Bons et al. 2012) identified in the core–retrieved breccia at the bottom of the archaeological sequence (Fig. 3e).

Human occupations between rockfalls and tectonic rotations at the terrace

Lithic refitting, radiocarbon dating, and micromorphology confirm multiple in situ human occupations embedded within the tectonically tilted rockfalls at the Terrace (Figs. 6–8). Gravettian foragers performed domestic activities above the rockfall blocks of GLs 10 and 7, as evidenced by nine technological refits (blank–blank and core–blank in Figs. 6 and 7. Online Resources Table S9), dating between 29.4 and 29.1 and 25.6–25.2 ka cal BP (Wk-30676.2 and End GL6 in Fig. 4). At the upper contact of GL 7 and within GL 6, elongated fragments of limestone, sandstone, marl, lithic artifacts, and unsorted bones crushed in situ (Miller et al. 2013) delimit stacked trampling surfaces (Fig. 8).

Our results suggest a gap in lithic refitting within GL 5 (Fig. 6b and Online Resource Table S9), potentially corresponding to a previously observed decline in chert and rise in quartz raw materials (Belmiro et al. 2021), for which no refitting was attempted. Nonetheless, seashells confirm that early Proto-Solutrean hunter-gatherers camped on the rockfall boulders of lower GL 5, between 25.4 and 24.4 ka cal

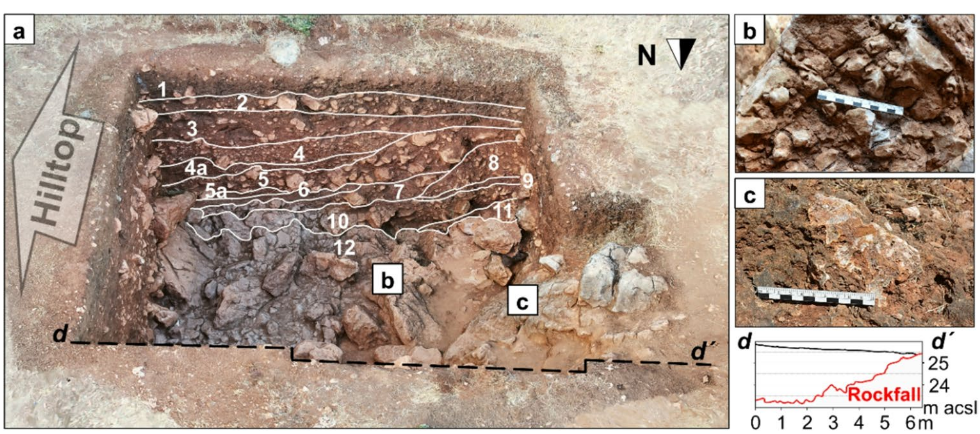


Fig. 5 Seismic rockfalls and upslope tectonic tilting at archaeological excavation. (**a**) Southward view of the trench dug at the Terrace (photogrammetric model compiled at the end of the archaeological excavation, in 2019). White lines and numbers indicate the Geological Layers (**GLs**) distinguished in the southern section of the trench. Archaeological excavation halted on a massive rockfall layer, which, to the west, appears brecciated (**b**, **c**). (***dd´***) Topography of modern ground surface (black line) and rockfall (red line) along the northern section of the trench. Note the uphill inclination of both the faulted rockfall (***dd´***) and the above–lying GLs 5–11 (**a**)

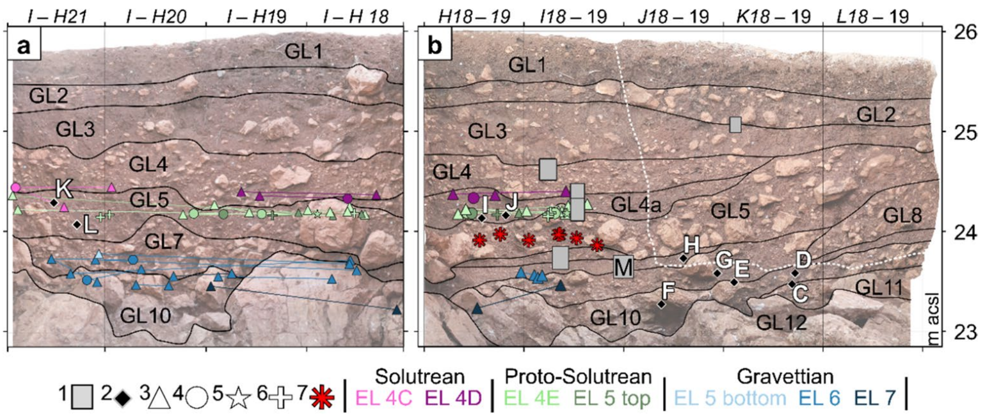


Fig. 6 In situ human occupations at the Terrace. (**a**) Section east and (**b**) Section south from the Terrace showing Geological Layers (**GLs**, depicted in black), and micromorphological samples (**1**). (**a**) shows ^{14}C ages (**2**) and refitting lithics (**3**– **6**) from the excavation squares H18 – 21 and I 18 – 21. (**b**) depicts ^{14}C ages (**2**), refitting lithics (**3**– **6**), and remains of Littorina littorea (**7**) from the excavation squares H18 – 19, I18 – 19, J18 – 19, K18 – 19, and L18 – 19. The location of both sections and the corresponding excavation squares are shown in Fig. 2. Refitting pieces are displayed as blanks (**3**), cores (**4**), shatters (**5**), and blank fragments (**6**). Note that the refitting lithic from Excavation Layer (EL) 5 comes from the upper contact of the Gravettian EL 6. This suggests that this lithic artifact is likely part of the Gravettian assemblage. For this reason, in this figure, EL 5 is indicated as Gravettian and not as Proto-Solutrean. In our study, only the assemblages excavated after 2011 were investigated for refitting analysis, corresponding to the listed excavation squares (left and below dotted white line in**b**). Plotted ^{14}C ages: Wk–35717 (**C**), Wk–35712 (**D**), Wk–35713 (**E**), Wk–30676.2 (**F**), Wk–30679.2 (**G**), Wk–30677.2 (**H**), Wk–42831 (**I**), BRA–4946 (**J**), Wk–50390 (**K**), Wk–42830 (**L**). For the positioning of the remaining radiocarbon dates see Online Resource Figure S8

BP (start and end of Lower GL 5 in Fig. 4). This interpretation is ensured by the fact that *Littorina littorea* remains at the Terrace were retrieved only between and above the boulders of GL 5 (Belmiro et al. 2021), aside from a lower shell fragment that was possibly displaced by post-depositional tectonic rotation (7 in Fig. 6b).

Evidence of in situ late Proto-Solutrean domestic activities consist of nine technological lithic refits buried between the top of GL 5 and the bottom of GL 4a (Figs. 6 and 7), dating between 23.8 and 23.1 ka cal BP (between Start and End Top GL5/GL4a in Fig. 4). In situ Solutrean stays are indicated by three refits at the bottom of GL 4, which exhibit a lower vertical dispersion than earlier Proto-Solutrean and Gravettian connections (Fig. 6), as they were discarded above smaller limestone blocks and were disturbed by lower rates of tectonic rotation.

Vertical trends in find density and taphonomy

Within the eight most laterally continuous deposits preserved at the Terrace, the total density of archaeological finds seems to decrease as the coarse sediment fraction increases (Fig. 9). This trend appears supported by a strong negative Spearman correlation ($\rho = -0.70$, $p=0.054$). Though just above the significance threshold, likely due to the small sample size ($n=8$), the test suggests that layers rich in gravel and boulders provided less space for the accumulation of archaeological material. We conclude that total find density cannot be used as a proxy for site use intensity.

From GL 11 to Lower GL 5, relative bone density declines progressively (Fig. 9), while rates of bone weathering remain consistent (Fig. 8b and c; Online Resource Fig. S5, ST 2.2 and ST 2.3). This pattern indicates that foragers gradually processed and discarded fewer animal carcasses at the Terrace. During the Gravettian (up to GL 6), this behavior coincided with intensive use of non-local chert and dolerite (Belmiro et al. 2025), suggesting increased forager mobility. The persistent presence of neonatal ungulates indicates shorter or less frequent stays in spring–summer (Manne et al. 2012; Manne 2014). During the early Proto-Solutrean (Lower GL 5), bone discard reached its minimum, whereas the use of non-local raw materials (Belmiro et al. 2025) and the disposal of marine seashells remained stable (Fig. 9). These trends suggest a phase of heightened mobility and comparatively more intensive consumption of marine resources.

In Top GL 5, bone density rises again while preservation indices remain similar (Fig. 9. Online Resource ST 2.2–2.3). This increase, together with a drop in non-local chert (Belmiro et al. 2025), suggests longer or more frequent late Proto-Solutrean stays.

In GLs 4 and 3 (Solutrean), both bones and shells decrease sharply (Fig. 9). Micromorphology shows the first appearance of clay-illuviation pedofeatures at the Terrace (Online Resource Fig. S6), indicating warmer and seasonally wetter conditions that most likely enhanced the dissolution of biogenic remains (Online Resource Fig. S5) (Fedoroff 1997;

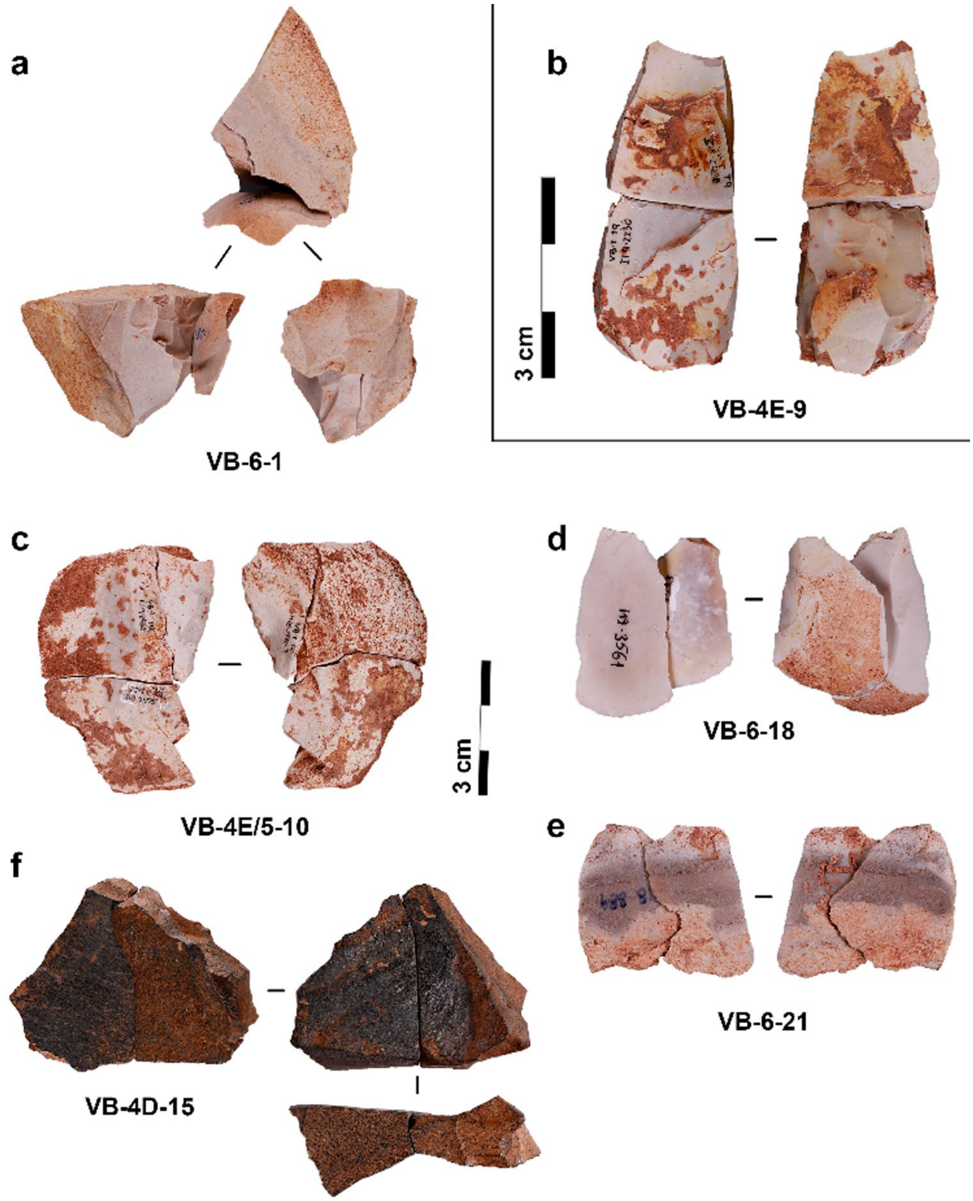


Fig. 7 Representative lithic refits from the Terrace. (**a**) Core-blank refitting on chert from the Gravettian Excavation Layer (EL) 6. (**b**) Core-fragment refitting on chert from the Proto-Solutrean EL 4E; (**c**) Blank-blank refitting on chert from the Proto-Solutrean EL 4E/5; (**d** and **e**) Blank-blank refitting on chert from the Gravettian EL 6; (**f**) Retouched blank-retouched blank refitting on greywacke from the Solutrean EL 4. In bold, the identifier of each refitting. Correlation between EL and Geological Layers (GLs) in Online Resource Table S8

Torrent 2005; Gunal and Ransom 2006; Herrmann et al. 2022).

Overall, although biased by geogenic site formation processes, find-density patterns at the Terrace reliably track changes in forager behaviors across Gravettian and Proto-Solutrean phases.

Phases of less intensive site visits

Bayesian, SPD, and KDE modelling of radiocarbon ages highlight three possible intervals of decreased activity (Figs. 4 and 10):

1. A 2.9–2.0 ka gap separates GL 11 from occupations above the rockfall GL 10. We consider this break reliable, as it is constrained by specimens with minimal vertical and horizontal offset (Fig. 6). Although this hiatus partly coincides with HE 3, the hypothesis that this abandonment was triggered by climatic deterioration is not supported by regional and site-scaled environmental data (more details in the discussion section).
2. A possible 2–2.5 ka hiatus between GL 7 and 6 appears in SPD and KDE but may reflect insufficient dating, as micromorphology and artifact densities show continued use (Figs. 6 and 8, and 9).
3. A 1.5–0.6 ka hiatus divides early and late Proto-Solutrean occupations. It was likely during this break that the Terrace underwent a phase of tectonic rotation during which the rockfall GL 5 was tilted towards the hilltop (Figs. 6b and 10).

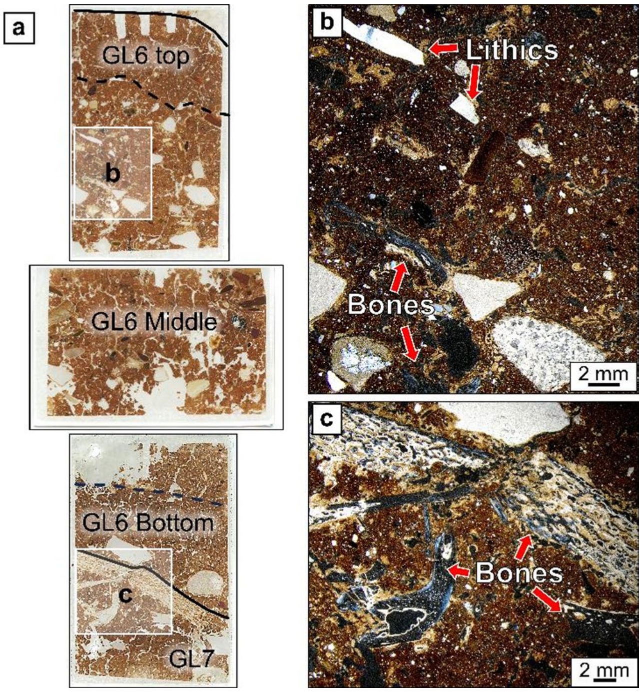


Fig. 8 Micromorphological evidence of in situ human occupations at the Terrace. (**a**) Thin section scans from the contact between GL 7 and GL 6 exhibiting bedded deposits. Slides produced from block labelled as (**M**) in Fig. 5. (**b**) Photomicrograph from (**a**) exhibiting stacked surfaces delimited by lithic fragments made from quartz (**Lithics**) and bones (**Bones**), in crossed-polarized light (XPL). (**c**) XPL photomicrograph from (**b**) showing a trampled bone fragment, which was also extensively replaced by calcium carbonate

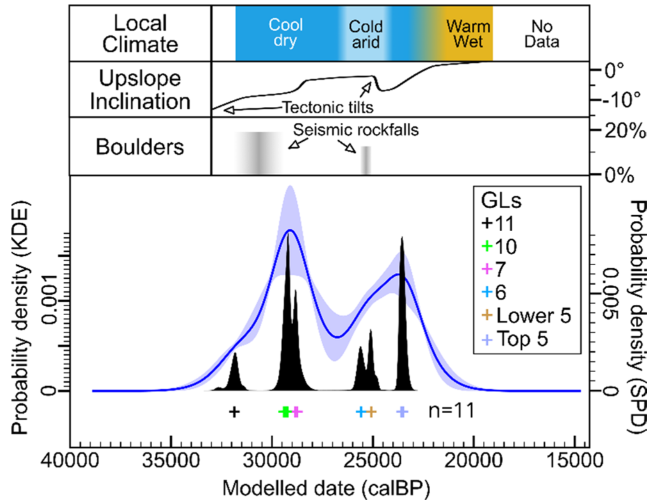


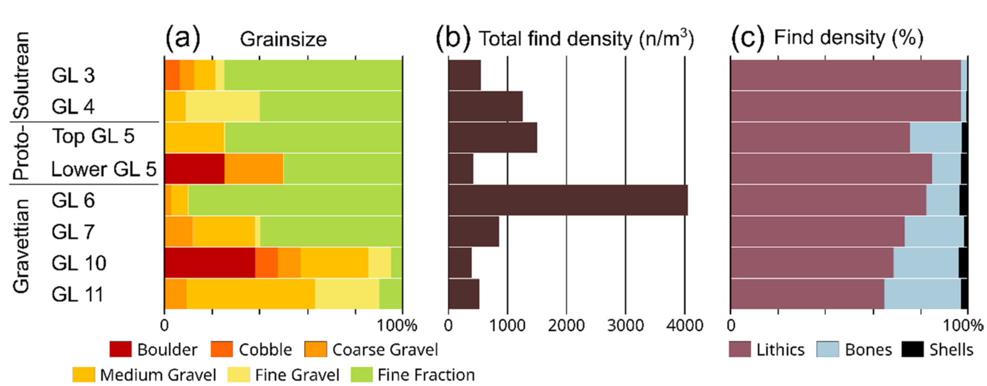
Fig. 10 Gaps in radiocarbon dating versus tectonic processes and climatic oscillations at the Terrace. At the bottom of the figure, a comparison between the Summed Probability Distribution (SPD, in solid black) and Kernel Density Estimate modelling (KDE) of the modelled radiocarbon ages plotted in Fig. 4. The median of each age is plotted as a cross, with colours indicating the respective Geological Layers (GLs) as indicated in the legend. This plot was generated with the software OxCal 4.4. The subpanel "Boulders" displays the relative amount of boulder limestone blocks accumulated at the Terrace. Subpanel "Upslope Inclination" shows shifts in the inclination of the Terrace deposits (°). Subpanel "Local Climate" depicts our climatic reconstruction based on micromorphological results presented in this paper, combined with previously reported seashell and faunal data from the Terrace (Manne et al. 2012; Manne 2014; Belmiro et al. 2021). The Heinrich Event 2 (HE 2) corresponds with the phase labelled as "Cold arid"

Discussion

Tectonic and seismic activity at Vale Boi and their regional implications

Based on our geophysical, coring, and stratigraphic data, we propose that during the late Pleistocene ASM acted as a reverse fault, likely part of the larger BSJ system (Dias et al. 2010) (Fig. 1b). Minor normal faults at Vale Boi were probably triggered by drag deformations along ASM (Online Resource Fig. S9a) (Grasemann et al. 2005; Breesch et al. 2009). Tectonic movements caused the depression of part of the hillside, which was subsequently filled with the rockfall GL 12, before 32.5–31.7 ka cal BP (Fig. 4). Rockfall remained the predominant sedimentary process until 25.2–24.4 ka cal BP (end Lower GL 5 in Fig. 4). Previous works showed that rockfall activity increases with higher temperatures, or with sudden and intensive

Fig. 9 Shift in lithology and find density at the Terrace. (**a**) Grain size; (**b**) Total find density; (**c**) Relative find density of lithic artifacts, bones, and shells



rainfalls (Zêzere et al. 2015; D'Amato et al. 2016). Micromorphological (Online Resources ST 2.2–2.3), malacological, and zooarchaeological data (Manne et al. 2012; Manne 2014) show that at the Terrace rockfalls occurred during dry and cool phases, ruling out the possibility that this sedimentary process was controlled by climate. Based on seismic-induced mass-wasting records in Portugal (Vaz and Zêzere 2016), we propose that earthquakes triggered rockfalls at the Terrace. The lack of seismic deformation microstructure in our thin sections does not contradict this interpretation, since such features typically develop only where the affected surface and subsurface exhibit marked contrasts in density or permeability (Gaggioli 2024). These conditions are not present at the Terrace, which explains their absence. Previous studies show that earthquakes can dislodge boulders of 1–2 m^3 by 40 to 360 m downslope (Koukouvelas et al. 2015). Among the rockfalls unearthed at the Terrace, which is located 72 m from the limestone cliff above Vale Boi, GLs 12, 10, and 5 exhibit boulders that are at least 1 m^3 in size (Figs. 5 and 6b). Therefore, we interpret these deposits as seismically triggered. Bayesian modelling of GLS11–5 suggests that seismic events at the site occurred every 3.6 ky, between 32.5 and 31.7 and 25.2–24.4 ka cal BP (Fig. 4).

Based on shifts in the geometry of the deposits, we proposed that the archaeological sequence accumulated at the Terrace underwent two separate phases of tectonic rotation, after the deposition of GL 12 and after GL 5. This deformation was possibly due to earthquakes or post-seismic stress transfer (Albano et al. 2021). Rockfalls and slip movements on slopes like Vale Boi's (up to 40°) can be triggered by earthquakes as weak as 5.7 M_w with epicenters as far as 100 s km (Bull 1996; Marzorati et al. 2002; Vaz and Zêzere 2016; Wallace et al. 2017). ASM has a total length of 7 km. Based on the regression analysis of surface rupture length on moment magnitude (Wells and Coppersmith 1994), ASM can generate earthquakes with a maximum 6.1 M_w. We conclude that seismic activity along ASM likely triggered the rockfalls and tectonic rotations observed at the Terrace. Alternatively, these features may have been caused by the neighboring BSJ and STAS, which can generate earthquakes up to 6.2 M_w and 6.8–7 M_w (Dias et al. 2010; Figueiredo et al. 2011, 2018).

Previous works proposed that past earthquakes caused cave collapses in the Algarve, hindering the development of large karstic systems and possibly deeply burying evidence of Paleolithic cave use (Regala 2021; Barbieri et al. 2023). Our findings provide the first direct evidence of seismic events capable of such destruction while the region was inhabited by Upper Paleolithic hunter-gatherers. While modern and historical seismic rockfalls have been reported mainly north of Lisbon (Vaz and Zêzere 2016), our study reveals that on-shore earthquakes can trigger this mass-wasting process also in the Algarve. These findings should be considered in future hazard studies, particularly in the western Algarve, where carbonate cliffs prone to collapse are widespread and visited by millions of tourists each summer (Teixeira 2014).

Resilience strategies in response to tectonic events at Vale Boi

The Vale Boi sequence allows the first reconstruction of hunter-gatherer resilience to recurrent seismic events older than 13 ka. Using Halstead and O'Shea's (1989) four adaptive domains—mobility, food economy, storage, and social networks—we can link specific behavioral adjustments to phases of tectonic and seismic instability.

Mobility

SPD indicates a 2.9–2 ka gap between GL 11 and the forager occupations above the seismic boulders of GL 10 (Fig. 10). This hiatus partly overlaps with HE 3. Nevertheless, sea surface temperatures (SST) from the nearby core M39029-7 (Fig. 4), as well as seashell (Online Resource ST 2.3) and faunal data from the Terrace (Manne 2014) show mild and stable conditions at Vale Boi and along the southern Portuguese coast. This makes it unlikely that this abandonment was a response to climatic stress. Similarly, the massive GL 10 rockfall might have made camping at Vale Boi less desirable. However, it seems unlikely that the effects of such landscape disruption lasted for millennia. Instead, this gap might reflect a long-term strategy to mitigate seismic hazards by relocating to other areas of southern Portugal less affected by seismic mass-wasting, to reduce the risks of casualties and key campsite destruction. Comparable long-term shift in settlement dynamics has been documented in Holocene contexts where tsunami and earthquake hazards shaped settlement memory (Salazar et al. 2022).

At the transition from late Gravettian to early Proto-Solutrean, seashell density remains relatively stable, bone density reaches its minimum (Fig. 9), while SPD and KDE show a relatively continuous human presence (GLs 6 and Lower 5 in Fig. 10). These data suggest a phase of shorter or less frequent stays rather than complete abandonment. The introduction of imported dolerite tools (Belmiro et al. 2021) and the continued use of far-sourced cherts (≤200 km; Belmiro et al. 2025) reinforce this interpretation. Early Proto-Solutrean foragers encountered two simultaneous stressors. First, they occupied the Terrace (shortly) after the seismic rockfall of Lower GL 5 (Fig. 6b). Second, their chronology overlaps with HE 2 (Fig. 4), a climatic event that, unlike HE 3, brought marked environmental deterioration to Vale Boi's refugium. This is reflected in the first and only appearance of *Littorina littorea* remains at the Terrace – a shell species capable of withstanding sub-zero water temperatures (Murphy 1979) – as well as drops in sea surface temperatures and peaks in ice-drafted debris in nearby marine cores (Fig. 4). Therefore, we hypothesize that hunter-gatherers limited the duration and/or frequency of their stays at the Terrace to mitigate both sudden seismic risks and broader climatic decline (more details under the next subsection "Food economy").

SPD and KDE indicate a 1.5–0.6 ka gap separating the early and late Proto-Solutrean occupations (Fig. 10). This hiatus coincided with high tectonic rotation rates that caused slope instability. Similar to the Gravettian gap, this interruption in occupation may reflect a long-term strategy to mitigate tectonic hazard (Salazar et al. 2022). Further research is necessary to test these alternatives. Compared with the Gravettian, Proto-Solutrean foragers had stronger incentives to move away from the unstable Vale Boi. The leading motive was the improved climate across southern Iberia, as shown by the increase in tree pollen count and sea surface temperature in marine core records (Fig. 4).

SPD and KDE peaks (Fig. 10), the high density of accumulated bones (Fig. 9), the increased frequency of lithic refits over time (9/0.7 ka contrasting with 9/4 ka for the Gravettian), and the more intensive use of local raw materials (Belmiro et al. 2025) mark a sharp increase in the frequency of forager visits at the Terrace during the late Proto-Solutrean. It is probably not coincidental that this reduction in mobility was paralleled by subsiding tectonic activity and the onset of a cool and dry climate at Vale Boi (Online Resource ST 2.3).

Food economy

At Vale Boi, previous works suggested a change in food economy during the Solutrean, which sees a sharp decline in seashell remains (Manne et al. 2012; Manne 2014). Our results, however, indicate that this drop reflects the more intensive dissolution of this material class (Online Resource Fig. S5), rather than a change in foraging behavior. Our study also shows that, while bone density dropped, seashell density remained consistent across late Gravettian and early Proto-Solutrean (Fig. 9). This pattern may reflect increased consumption of seafood, possibly linked to HE 2, and may explain why these foragers returned to this site despite seismic and rockfall hazards. During HE 2, environmental conditions across southwestern Portugal deteriorated (Fig. 4), possibly leaving local early Proto-Solutrean groups with very limited landscape options and depleted game populations (Belmiro et al. 2021). Under these stressors, returning to Vale Boi might have been an effective resilience strategy to access a key campsite for shellfish gathering along the Atlantic coast and Boi estuary. At the same time, restricting the duration of stays at the Terrace was probably an adjustment to mitigate seismic-related hazards. In sum, our data suggest that, although abandonment was often the default hunter-gatherer response to external pressure (Riede 2014; Riede et al. 2017), geographically extensive (Wren et al. 2025) and overlapping stressors may at times have made intermittent human presence the most viable survival strategy.

Storage

The practice of storing caloric reserves through rendering and drying of animal fats continued at the Terrace independently from tectonic and seismic activity, as previously evidenced by the constant presence of fragmented fat-rich bones, pitted greywacke anvils, and fire-cracked quartz through all the excavated layers (Manne et al. 2012; Bicho et al. 2013; Manne 2014).

Social network

Before and after seismic rockfalls, the Gravettian and early Proto-Solutrean assemblages of Vale Boi continued to be characterized by expedient lithic solutions and a lack of super-regional typo-technological markers, suggesting limited interaction with hunter-gatherers beyond southwestern Portugal (Marreiros et al. 2018; Belmiro et al. 2021). Such a close-knit regional network likely facilitated the sharing of reliable information, helped alleviate anxiety, improved economic recovery, and supported decision-making about evacuation and relocation, as observed among modern communities impacted by seismic destruction (Hoffman and Oliver-Smith 2002; Pu et al. 2021; Lagap and Ghaffarian 2024). Although it is difficult to demonstrate that strong regional ties were intentionally maintained, they almost certainly afforded Vale Boi foragers advantages in coping with high-stress events such as the aftermath of seismic rockfalls.

After a phase of tectonic tilting and subsequent abandonment (Fig. 10), the late Proto-Solutrean assemblage from the Terrace shows the appearance of Vale Comprido points and engraved plaquettes bearing motifs widespread across Iberia (Bicho et al. 2012b; Belmiro et al. 2021). These archaeological markers indicate a post-tectonic expansion of super-regional connections, which might have been intentionally fostered to buffer future episodes of resource scarcity (Wren et al. 2025) and, in the case of Vale Boi, to prepare for the possible loss of key campsite locations due to earthquake damage.

Conclusion

The Vale Boi sequence documents how recurrent, mid-magnitude earthquakes reshaped both landscape dynamics and human behaviors in southwestern Iberia between ~32 and 24 ka cal BP. Faulting along ASM generated sedimentary traps that preserved a deep, though laterally discontinuous, archaeological sequence and exposed foragers to periodic rockfalls and slope tilting. These events, probably triggered by ≥5.7 Mw earthquakes (Bull 1996; Vaz and Zêzere 2016), produced alternating phases of destruction, abandonment, and reoccupation detectable in the Terrace deposits.

Despite recurrent seismic disturbance, Gravettian and Proto-Solutrean hunter-gatherers consistently returned to Vale Boi. They did so by actively managing rather than merely enduring environmental risk, through a flexible resilience repertoire comparable to that described in later Holocene forager contexts (Torrence et al. 2000; Oetelaar and Beaudoin 2016; Salazar et al. 2022; Damlien et al. 2024). Following major earthquakes, hunter-gatherers increased mobility and even abandoned the site but maintained access to key local resources, as indicated by overall long-term stability in subsistence and storage systems (Manne et al. 2012; Bicho et al. 2013; Manne 2014). When seismic and climatic stressors coincided – notably during HE 2 – foragers visited the Terrace for short stays to limit seismic risks and maintain access to increasingly vital coastal and estuarine resources. These behaviors demonstrate enduring place attachment and knowledge of safe reoccupation windows—hallmarks of collective environmental memory. As tectonic activity waned, mobility decreased and social networks expanded, reflected in the spread of super-regional lithic types and symbolic motifs (Bicho et al. 2012b; Marreiros et al. 2016; Belmiro et al. 2021). This transition suggests that cooperative ties functioned as a proactive buffer against future shocks, echoing resilience models proposed by Halstead and O'Shea (1989) and by recent ecological frameworks (Folke 2006; Wren et al. 2025).

Our interpretations necessarily remain tentative. They derive from a single site, where depositional processes, tectonic events, and behavioral changes are tightly interlinked but not always easily separable. Further work is required to identify additional sites in southern Portugal with chronologies comparable to Vale Boi—both with and without evidence of seismic destruction—to evaluate how representative the patterns described here may be (Riede 2014). Such comparative data will help test whether the behaviors inferred at Vale Boi reflect local contingencies, broader regional adaptations, or elements of a more general Upper Paleolithic risk-management strategy.

Though needing further validation, our results extend the record of human seismic resilience by nearly twenty millennia and complement earlier discussions of tectonics as a structuring force in human evolution (Bailey et al. 1993; King and Bailey 2006). Vale Boi suggests that risk-management behaviours – including flexible mobility, resource buffering, and social cooperation – were already integral to middle Upper Palaeolithic lifeways. The capacity to anticipate and adapt to geological hazards emerges here as a deep-rooted element of human behaviour.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s12520-025-02400-6.

Acknowledgements We thank L. André (ICArEHB) for sharing his preliminary taxonomic results from the Terrace; A. Gomes (ICArEHB) for the help with the collection of micromorphological samples; R. Dias (ERA, Arqueologia, Conservação, e Gestão do Patrimonio) for the acquisition of LiDAR data at Vale Boi; P. and J. Carrasco García (Técnicas Geofisicas S.L) for the acquisition of ERTs 1 – 8; and the equipe of R. Castro (GeoAlgar) for the drilling of Cores A and B. A. Barbieri (PTDC/HAR-ARQ/27833/2017 and 2002.08622.CEECIND) and J. Cascalheira (DL57/2016/CP1361/CT0026) are funded by the Portuguese Ministry for Science and Technology. N. Bicho received funding for fieldwork and analyses at Vale Boi from the Portuguese Ministry for Science and Technology (ALG-01-0145-FEDER-27833) and Fundos FEDER through Programa Operacional Regional do Algarve - CRESC Algarve2020 (PTDC/HAR-ARQ/27833/2017). For the purpose of Open Access, the authors have applied a CC-BY public copyright license to any Author's Accepted Manuscript (AAM) version arising from this submission.

Author contributions AB: project administration; conceptualization; acquisition and analysis of geological, geophysical, and micromorphological data; analysis of vertical trends in find density; Bayesian SPD, and KDE age modelling; interpretation of all analyses. JSM, JB and JG: refitting analysis. PF: interpretation of tectonic features in cores. PH and JC: sampling for micromorphological analysis. JC: compilation of database for Bayesian modelling. NB: project administration. All authors: manuscript writing, review, and editing.

Funding Open access funding provided by FCT|FCCN (b-on).

Data availability All raw ERT data are available online (https://osf.io/ae69v/?view_only=1d594a8754ea4bf18cac0df5a5a7f04f). All the other data supporting this study are presented in the manuscript or in the Supplementary Material

Declarations

Competing interests The authors declare no competing interests.

References

Albano M, Barba S, Bignami C et al (2021) Numerical analysis of interseismic, coseismic and postseismic phases for normal and reverse faulting earthquakes in Italy. Geophys J Int 225:627–645. https://doi.org/10.1093/gji/ggaa608

Bailey G (2010) The red Sea, coastal Landscapes, and hominin dispersals. In: Petraglia MD, Rose JI (eds) The evolution of human populations in arabia: Paleoenvironments, prehistory and genetics. Springer Netherlands, Dordrecht, pp 15–37

Bailey GN, Flemming NC (2008) Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. Quat Sci Rev 27:2153–2165. https://doi.org/10.1016/j.quascirev.2008.08.012

Bailey G, King G, Sturdy D (1993) Active tectonics and land-use strategies: a palaeolithic example from Northwest Greece. Antiquity 67:292–312. https://doi.org/10.1017/S0003598X00045361

Barbieri A, Regala FT, Cascalheira J, Bicho N (2023) The sediment at the end of the tunnel: geophysical research to locate the pleistocene entrance of Gruta Da companheira (Algarve, Southern Portugal). Archaeol Prospect 30:117–134. https://doi.org/10.1002/arp.1881

Belmiro J, Bicho N, Haws J, Cascalheira J (2021) The Gravettian-Solutrean transition in Westernmost iberia: new data from the sites of Vale Boi and Lapa do Picareiro. Quat Int 587–588:19–40. https://doi.org/10.1016/j.quaint.2020.08.027

Belmiro J, Terradas X, Dominguez-Bella S, Cascalheira J (2025) Within and beyond: chert procurement patterns during the upper palaeolithic in Southwesternmost Iberia. J Paleo Arch 8:8. https://doi.org/10.1007/s41982-025-00209-2

Bicho NF, Stiner MC, Lindly JM et al (2003) Preliminary results from the upper paleolithic site of Vale Boi, Southwestern Portugal. J Iber Archaeol 5:51–65

Bicho N, Cascalheira J, Marreiros J (2012a) On the (L)edge: The Case of Vale Boi Rockshelter (Algarve, Southern Portugal). In: Bergsvik KA, Skeates R (eds) Caves in Context. Oxbow Books, pp 65–81

Bicho N, Vallejo MDS, Sánchez MC (2012b) A solutrean zoomorphic engraved plaquette from the site of Vale Boi, Portugal. Quartär 59:153–164. https://doi.org/10.7485/QU59-6

Bicho N, Manne T, Marreiros J et al (2013) The ecodynamics of the first modern humans in Southwestern Iberia: the case of Vale Boi, Portugal. Quat Int 318:102–116. https://doi.org/10.1016/j.quaint.2013.06.029

Bons PD, Elburg MA, Gomez-Rivas E (2012) A review of the formation of tectonic veins and their microstructures. J Struct Geol 43:33–62. https://doi.org/10.1016/j.jsg.2012.07.005

Bradtmöller M, Marreiros J, Pereira T, Bicho N (2016) Lithic technological adaptation within the gravettian of the Iberian Atlantic region: results from two case studies. Quat Int 406:3–24. https://doi.org/10.1016/J.QUAINT.2015.08.075

Breesch L, Swennen R, Vincent B (2009) Fluid flow reconstruction in hanging and footwall carbonates: compartmentalization by cenozoic reverse faulting in the Northern Oman mountains (UAE). Mar Pet Geol 26:113–128. https://doi.org/10.1016/j.marpetgeo.2007.10.004

Bull WB (1996) Prehistorical earthquakes on the Alpine fault, New Zealand. J Geophys Res Solid Earth 101:6037–6050. https://doi.org/10.1029/95JB03062

Cascalheira J, Bicho N, Manne T, Horta P (2017) Cross-scale adaptive behaviors during the Upper Paleolithic in iberia: the example of Vale Boi (Southwestern Portugal). Quat Int 446:17–30. https://doi.org/10.1016/j.quaint.2017.01.002

D'Amato J, Hantz D, Guerin A et al (2016) Influence of meteorological factors on rockfall occurrence in a middle mountain limestone Cliff. Nat Hazards Earth Syst Sci 16:719–735. https://doi.org/10.5194/NHESS-16-719-2016

Damlien H, Nyland AJ, Redmond JJ (2024) Lithic technology before and after the Storegga tsunami (8200 cal BP): dissolving large-scale regional trends to identify social impact of crisis in western Norway. Holocene. https://doi.org/10.1177/09596836241274987

Davis GH, Reynolds SJ, Kluth CF (2011) Structural geology of rocks and regions. Wiley, Ltd

Dias RP, Terrinha P, Carvalho J et al (2010) Sismotectonica do Algarve. In: Matias L, Vicente L (eds) Estudo do Risco sísmico e de tsunamis do Algarve. Laboratorio Nacional de Energia e Geologia, pp 10–28

Regala FT (2021) A O património espeleo-arqueológico do Algarve: Inventariação, caracterização e salvaguarda de cavidades cársicas com potencial arqueológico. Universidade do Algarve

Eynaud F, de Abreu L, Voelker AHL et al (2009) (Appendix 1) stable oxygen isotope record of globigerina bulloides, and abundances of neogloboquadrina pachyderma and ice-rafted debris in sediment core MD95-2042. Geochem Geophys Geosyst 10(7):Q07U05. https://doi.org/10.1029/2009GC002398. In supplement to: Eynaud, F et al. (2009): Position of the Polar Front along the western Iberian margin during key cold episodes of the last 45 ka

Fedoroff N (1997) Clay illuviation in red mediterranean soils. CATENA 28:171–189. https://doi.org/10.1016/S0341-8162(96)00036-7

Figueiredo PM, Cabral J, Rockwell TK (2011) Plio - pleistocene tectonic activity in the southwest of portugal. In: 2nd INQUA-IGCP 567 International Workshop Proceedings, Vol. 2: Earthquake Geology and Archaeology: Science, Society and Critical facilities. The Natural hazards Laboratory, National and Kapodistrian University of Athens, pp 30–33

Figueiredo PM, Rockwell TK, Cabral J (2018) Pleistocene Activity, morphotectonics and seismotectonics of the São Teotónio- Aljezur-Sinceira fault System, Southwest Portugal. In: Canora C, Martín F, Massana E et al (eds) Tercera reunión ibérica sobre fallas activas y paleosismología. Alicante, España. pp 39–42, pp 11–13. junio de 2018

Fitzhugh B, Phillips S, Gjesfjeld E, Whallon R, Lovis W, Hitchcock R (2011) Modeling Variability in Hunter-Gatherer Information Networks: An Archaeological Case Study from the Kuril Islands. Information and its Role in Hunter-Gatherer Bands. The Cotsen Institute of Archaeology at UCLA

Folke C (2006) Resilience: the emergence of a perspective for social–ecological systems analyses. Glob Environ Change 16:253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

Fouache E, Pavlopoulos K (2011) The Interplay between Environment and People from Neolithic to Classical Times in Greece and Albania. In: Martini IP, Chesworth W (eds) Landscapes and Societies: Selected Cases. Springer Netherlands, Dordrecht, pp 155–166

Fountoulis I, Mavroulis S, Vassilakis E, Papadopoulou-Vrynioti K (2013) Shoreline displacement and Pineios river diversions in NW Peloponnese (Greece) as result of the geology, active tectonics and human activity during the last 100 Ky. zfg_suppl 57:97–123. https://doi.org/10.1127/0372-8854/2013/S-00146

Gaggioli AM (2024) The geoarchaeology of seismically triggered soft sediment deformation structures (SSDS). J Archaeol Sci 165:105961. https://doi.org/10.1016/j.jas.2024.105961

Gebco Compilation Group (2024) GEBCO 2024 Grid. https://www.gebco.net/data-products-gridded-bathymetry-data/gebco2024-grid#formats

Gracia FJ, Rodríguez-Vidal J, Cáceres LM et al (2008) Diapiric uplift of an MIS 3 marine deposit in SW spain: implications for late pleistocene sea level reconstruction and palaeogeography of the Strait of Gibraltar Guadalete river Cádiz. Quat Sci Rev 27:2219–2231. https://doi.org/10.1016/j.quascirev.2008.08.013

Grasemann B, Martel S, Passchier C (2005) Reverse and normal drag along a fault. J Struct Geol 27:999–1010. https://doi.org/10.1016/J.JSG.2005.04.006

Grimm SB, Bradtmöller M, Lavi N, Nyland AJ (2025) Under pressure? Living with climate change and environmental hazards in the past and now. In: Bradtmöller M, Grimm SB, Nyland AJ, Lavi N (eds) Under pressure? Living with climate change and environmental hazards in the past and now. Springer Nature Switzerland, Cham, pp 1–14

Gunal H, Ransom MD (2006) Clay illuviation and calcium carbonate accumulation along a precipitation gradient in Kansas. CATENA 68:59–69. https://doi.org/10.1016/j.catena.2006.04.027

Halstead P, O'Shea J (eds) (1989) Bad Year Economics: Cultural Responses to Risk and Uncertainty. Cambridge University Press, Cambridge

Haws JA, Benedetti MM, Caroline L et al (2010) Coastal wetlands and the neanderthal settlement of Portuguese estremadura. Geoarchaeology: Int J 25:709–744. https://doi.org/10.1002/gea.20330

Heaton TJ, Köhler P, Butzin M et al (2020) Marine20—the marine radiocarbon age calibration curve (0–55,000 cal BP). Radiocarbon 62:779–820. https://doi.org/10.1017/RDC.2020.68

Herrmann N, Stadtmann R, Meister J, Kirchner A (2022) Importance of substrate genesis for Mediterranean soil evolution – an example from a limestone hillslope in the estremadura (W-Portugal). CATENA 218:106566. https://doi.org/10.1016/j.catena.2022.106566

Hoffman S, Oliver-Smith A (2002) Catastrophe and culture. The Anthropology of Disaster

Horta P, Cascalheira J, Bicho N (2019) The role of lithic bipolar technology in Western iberia's upper paleolithic: the case of Vale Boi (Southern Portugal). J Paleolithic Archaeol 2:134–159. https://doi.org/10.1007/s41982-019-0022-5

IGME (2022) QAFI: Quaternary Active Faults Database of Iberia. https://info.igme.es/QAFI. Accessed 26 Aug 2024

IPMA (2024) Boletim sismológico preliminar do Continente e Da Madeira (Janeiro 2003 - Outubro 2023). Instituto Português do Mar e da Atmosfera. I.P. - Divisão de Geofísica, Lisbon

Jeffrey SS, McCoy FW, Suka R (2017) Evidence for three earthquakes at Mochlos in the Neopalatial peiod, c. 1700 − 1430 BC. Minoan Earthquakes: Breaking the Myth through Interdisciplinarity. Leuven University Press, pp 307–325

King G, Bailey G (2006) Tectonics and human evolution. Antiquity 80:265–286. https://doi.org/10.1017/S0003598X00093613

King G, Bailey G, Sturdy D (1994) Active tectonics and human survival strategies. J Geophys Res Solid Earth 99:20063–20078. https://doi.org/10.1029/94JB00280

Kontopoulos N, Koutsios A (2010) A late Holocene record of environmental changes from Kotihi lagoon, Elis, Northwest Peloponnesus, Greece. Quat Int 225:191–198. https://doi.org/10.1016/j.quaint.2008.10.001

Koukouvelas I, Litoseliti A, Nikolakopoulos K, Zygouri V (2015) Earthquake triggered rock falls and their role in the development of a rock slope: the case of Skolis Mountain, Greece. Eng Geol 191:71–85. https://doi.org/10.1016/J.ENGGEO.2015.03.011

Lagap U, Ghaffarian S (2024) Digital post-disaster risk management twinning: a review and improved conceptual framework. Int J Disaster Risk Reduct 110:104629. https://doi.org/10.1016/j.ijdrr.2024.104629

Lisiecki LE, Jones AM, Rand DS, Lawrence CE (2021) Age models and dating methods for ten Iberian Margin sediment cores. In: Lisiecki, LE (2021): Age models for ten Iberian Margin sediment cores during the last glacial cycle (0-150 ka BP) [dataset bundled publication]. PANGAEA. https://doi.org/10.1594/PANGAEA.939730

Löwemark L (2016) Geochemistry and grain size analyses of sediment core M39/1_29 − 7 (M39029-7). In supplement to: Löwemark, L (2001): Biogenic traces as palaeoceanographic indicators in Late Quaternary sediments from the SW Iberian margin [thesis]. Berichte-Reports, Institut für Geowissenschaften, Universität Kiel, 14, 138 pp. https://doi.org/10.2312/reports-ifg.2001.14

Manne T (2014) Early upper paleolithic bone processing and insights into small-scale storage of fats at Vale Boi, Southern Iberia. J Archaeol Sci 43:111–123. https://doi.org/10.1016/j.jas.2013.12.003

Manne T, Cascalheira J, Évora M et al (2012) Intensive subsistence practices at Vale Boi, an Upper Paleolithic site in southwestern Portugal. Quat Int 264:83–99. https://doi.org/10.1016/j.quaint.2012.02.026

Manupella G (1992) Carta Geológica Da região do Algarve, Escala 1:100'000. Serviços Geológicos de Portugal, Lisboa

Marreiros J, Bicho N, Gibaja J et al (2015) Lithic technology from the Gravettian of Vale Boi: new insights into Early Upper Paleolithic human behavior in Southern Iberian Peninsula. Quat Int 359:479–498. https://doi.org/10.1016/j.quaint.2014.06.074

Marreiros J, Bicho N, Gibaja J et al (2016) Early gravettian projectile technology in Southwestern Iberian Peninsula: the double backed and bipointed bladelets of Vale Boi (Portugal). In: Iovita, R., Sano, K. (eds) Multidisciplinary Approaches to the Study of Stone Age Weaponry. Vertebrate Paleobiology Paleoanthropology 147–158. https://doi.org/10.1007/978-94-017-7602-8_10

Marreiros J, Gibaja J, Bicho N (2018) Lithic use-wear analysis of the early gravettian of Vale Boi (Cape St. Vicente, Southern Portugal): insights into human technology and settlement in southwestern Iberia. Archaeol Anthropol Sci 10:631–645. https://doi.org/10.1007/s12520-016-0382-4

Marzorati S, Luzi L, Amicis MD (2002) Rock falls induced by earthquakes: a statistical approach. Soil Dyn Earthq Eng 22:565–577. https://doi.org/10.1016/S0267-7261(02)00036-2

Miller CE, Goldberg P, Berna F (2013) Geoarchaeological investigations at Diepkloof rock Shelter, Western Cape, South Africa. J Archaeol Sci 40:3432–3452. https://doi.org/10.1016/j.jas.2013.02.014

Mort K, Woodcock NH (2008) Quantifying fault breccia geometry: Dent Fault, NW England. J Struct Geol 30:701–709. https://doi.org/10.1016/j.jsg.2008.02.005

Murphy DJ (1979) A comparative study of the freezing tolerances of the marine snails *littorina littorea* (L.) and *nassarius obsoletus* (Say). Physiol Zool 52:219–230. https://doi.org/10.1086/physzool.52.2.30152565

Nabi A, Liu X, Gong Z, Ali A (2020) Electrical resistivity imaging of active faults in palaeoseismology: case studies from Karachi Arc, southern Kirthar Fold Belt, Pakistan. NRIAG J Astron Geophys 9:116–128. https://doi.org/10.1080/20909977.2020.1722524

NSRT Shuttle Radar Topography Mission (SRTM) (2013) Distributed by OpenTopography. https://doi.org/10.5069/G9445JDF

Oetelaar GA, Beaudoin AB (2016) Evidence of cultural responses to the impact of the Mazama Ash fall from deeply stratified archaeological sites in Southern Alberta. Quat Int 394:17–36. https://doi.org/10.1016/j.quaint.2014.08.015

Pereira T, Bicho N, Cascalheira J et al (2016) Territory and abiotic resources between 33 and 15.6 ka at Vale Boi (SW Portugal). Quat Int 412:124–134. https://doi.org/10.1016/j.quaint.2015.08.071

Pu G, Chang-Richards A, Wilkinson S, Potangaroa R (2021) What makes a successful livelihood recovery? A study of China's Lushan earthquake. Nat Hazards 105:2543–2567. https://doi.org/10.1007/s11069-020-04412-y

Ramsey CB (2017) Methods for summarizing radiocarbon datasets. Radiocarbon 59:1809–1833. https://doi.org/10.1017/RDC.2017.108

Regala FT, Cascalheira J, Marreiros J et al (2014) Shell bead production in the upper paleolithic of Vale Boi (SW Portugal): an experimental perspective. J Archaeol Sci 42:29–41. https://doi.org/10.1016/j.jas.2013.10.029

Reimer PJ, Reimer RW (2001) A marine reservoir correction database and on-line interface. Radiocarbon 43:461–463. https://doi.org/10.1017/S0033822200038339

Reimer PJ, Austin WEN, Bard E et al (2020) The IntCal20 Northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62:725–757. https://doi.org/10.1017/RDC.2020.41
Riede F (2008) The Laacher See-eruption (12,920 BP) and material culture change at the end of the Allerød in Northern Europe. J Archaeol Sci 35:591–599. https://doi.org/10.1016/j.jas.2007.05.007
Riede F (2014) Towards a science of past disasters. Nat Hazards 71:335–362. https://doi.org/10.1007/s11069-013-0913-6
Riede F, Oetelaar GA, VanderHoek R (2017) From crisis to collapse in hunter-gatherer societies: A comparative investigation of the cultural impacts of three large volcanic eruptions on past hunter-gatherers. Crisis to collapse. The archaeology of social breakdown. UCL Presses Universitaires de Louvain, pp 23–39
Rocha RB, Lopes JC, Dãmaso LG, António HP (1975) Carta geologica de Portugal 1:50'000 - Folha 52A Portimão
Rossi IR, Karavanić I, Butorac V (2020) Croatia: submerged prehistoric sites in a karstic landscape. In: Bailey G, Galanidou N, Peeters H et al (eds) The archaeology of europe's drowned landscapes. Springer International Publishing, Cham, pp 347–369
Salazar D, Easton G, Goff J et al (2022) Did a 3800-year-old M w 9.5 earthquake trigger major social disruption in the Atacama Desert? Sci Adv 8:2996. https://doi.org/10.1126/sciadv.abm2996
Salgueiro E, Voelker AHL, de Abreu L et al (2010) Sea surface temperature and export production reconstructions of sediment core MD95-2042. In supplement to: Salgueiro, E. (2010): Temperature and productivity changes off the western Iberian margin during the last 150 ky. Quat Sci Rev 29(5–6):680–695. https://doi.org/10.1016/j.quascirev.2009.11.013
Salgueiro E, Naughton F, Voelker AHL et al (2014) Summer sea surface temperature and export production sediment core M39029-7. In supplement to: Salgueiro, E. (2014): Past circulation along the western Iberian margin: a time slice vision from the Last Glacial to the Holocene. Quat Sci Rev 106:316–329. https://doi.org/10.1016/j.quascirev.2014.09.001
Sanchez Goñi MF (2014) Pollen profile on sediment core MD95-2042 [dataset]. PANGAEA. https://doi.org/10.1594/PANGAEA.838159
Serpelloni E, Vannucci G, Pondrelli S et al (2007) Kinematics of the Western Africa-Eurasia plate boundary from focal mechanisms and GPS data. Geophys J Int. https://doi.org/10.1111/j.1365-246X.2007.03367.x
Shukla MK, Sharma A (2018) A brief review on breccia: it's contrasting origin and diagnostic signatures. Solid Earth Sci 3:50–59. https://doi.org/10.1016/j.sesci.2018.03.001
Soares AM (1993) The14C content of marine shells: Evidence for variability in coastal upwelling of Portugal during the Holocene. In: Isotope techniques in the study of past and current environmental changes in the hydrosphere and the atmosphere. pp 471–485
Teixeira SB (2014) Coastal hazards from slope mass movements: analysis and management approach on the Barlavento Coast, Algarve, Portugal. Ocean Coastal Manage 102:285–293. https://doi.org/10.1016/j.ocecoaman.2014.10.008
Teves-Costa P, Batlló J, Matias L et al (2019) Maximum intensity maps (MIM) for Portugal Mainland. J Seismol 23:417–440. https://doi.org/10.1007/s10950-019-09814-5
Torrence R, Pavlides C, Jackson P, Webb J (2000) Volcanic disasters and cultural discontinuities in Holocene time, in West New Britain, Papua New Guinea. In: McGuire WJ, Griffiths DR, Hancock PL, Stewart IS (eds) The Archaeology of Geological Catastrophes. Geological Society of London, pp 225-244
Torrent J (2005) Mediterranean soils. In: Hillel D (ed) Encyclopedia of soils in the environment. Elsevier, Oxford, pp 418–427
Vaz T, Zêzere JL (2016) Landslides and other geomorphologic and hydrologic effects induced by earthquakes in Portugal. Nat Hazards 81:71–98. https://doi.org/10.1007/s11069-015-2071-5
Walker J, Nyland AJ, Bergsvik KA et al (2024) A multiproxy approach to understanding the impact of the Storegga tsunami upon Mesolithic hunter-fisher-gatherers across different regions of western Norway. Quat Sci Rev 324:108433. https://doi.org/10.1016/j.quascirev.2023.108433
Wallace LM, Kaneko Y, Hreinsdóttir S et al (2017) Large-scale dynamic triggering of shallow slow slip enhanced by overlying sedimentary wedge. Nat Geosci 10:765–770. https://doi.org/10.1038/ngeo3021
Wells DL, Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull Seismol Soc Am 84:974–1002. https://doi.org/10.1785/bssa0840040974
Whallon R (2006) Social networks and information: non-"utilitarian" mobility among hunter-gatherers. J Anthropol Archaeol 25:259–270. https://doi.org/10.1016/j.jaa.2005.11.004
Wren CD, Romanowska I, Riede F (2025) Bad year econometrics: agent-based modeling of risk management strategies under varying regimes of environmental change. Sci Adv 11:eadr0314. https://doi.org/10.1126/sciadv.adr0314
Zêzere JL, Vaz T, Pereira S et al (2015) Rainfall thresholds for landslide activity in Portugal: a state of the Art. Environ Earth Sci 73:2917–2936. https://doi.org/10.1007/s12665-014-3672-0
Zhao B, Li R (2022) Formation mechanism of bedding-parallel antitaxial fibrous veins in shale: a review. J Struct Geol 161:104653. https://doi.org/10.1016/J.JSG.2022.104653
Zitellini N, Gràcia E, Matias L et al (2009) The quest for the Africa–Eurasia plate boundary west of the Strait of Gibraltar. Earth Planet Sci Lett 280:13–50. https://doi.org/10.1016/J.EPSL.2008.12.005