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Landscape and geology as controls on Bronze Age human dispersal: a case study from Sardinia (Italy)

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ABSTRACT
The interaction of human dispersal patterns with landscape features can in many cases provide useful information on the sustenance strategies of past communities. Mapping the present landscape is a necessary step in recognizing the nature, impact, and diffusion of the processes which drive the behaviour of past populations and modify palaeolandscapes. We constructed a map of the land units in the southwestern corner of Sardinia and compared them with the distribution of known Bronze Age megalithic towers called nuraghes. The vast majority of nuraghes are near the plains or at mid elevations close to the river network, in areas with the highest landscape diversity. The occurrence of nuraghes also seems to be related to elevated outcrops giving the advantage of a raised position and stable foundations. Denudation processes, Late Holocene sea level rise, and anthropogenic disturbance seem to be the most important factors driving changes in the palaeolandscape.

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1. Introduction

The spatial organisation of a population is a function of both socio-economic and environmental causes (French, 2010). The interaction of these factors has a major role in defining resource management and land use practices from local communities to whole societies (Howey et al., 2016; Kintigh et al., 2014). In this sense, the geological substrate and its landforms, as main providers of natural resources, have a clear influence on landscape management practices. This aspect becomes of vital importance in the study of past cultures: the association of human dispersal with certain landscape features can in many cases provide useful information on the sustenance strategies of past communities, as well as on specific adaptations to local conditions (Brandolini & Carrer, 2020; Carrero-Pazos, 2019; Costanzo et al., 2021; DiNapoli et al., 2019; Mariani et al., 2019).

In the reconstruction of spatial patterns of human settlements, we must consider the role of landscape also on a temporal level. The evolution of the physical territory has a potentially profound impact on the conservation and value of the archaeological record. Dynamic processes in changing landscapes can conceal or destroy the archaeological evidence and possibly mislead interpretations. Conversely, the absence of visible traces might instead stem from coeval palaeolandscape features which at the time discouraged local human exploitation. From this point of view, the areas showing low site densities can provide useful information for the creation of accurate dispersal models. The reconstruction of palaeolandscape changes is an effort greatly helped by the detailed assessment of current land units. Mapping the present landscape is a necessary step in recognising the nature, impact, and diffusion of geomorphological processes, which in turn inform on their action in the past. Areas of relevant and drastic changes can highlight cultural heritage losses from erosive processes or the potential for the investigation of sites buried by sedimentation. Stable areas which underwent only minor changes in time can instead be a more reliable source of information on past land management strategies. Such an approach heavily relies on the use of geomorphological and geological data. Landscape features are in fact strongly linked to the underlying geology, which must be considered when dealing with the relationships with human settlements. Many authors have recently started to adopt similar approaches, usually following a combination of information from both the geological bedrock and the geomorphological setting or selected features (Aucelli et al., 2020; Dall'Aglio et al., 2017; Ghilardi, 2021; Gioia et al., 2019, 2020).

The landscape evolution of the island of Sardinia (Italy) during the Holocene has strongly influenced the populations settled there. Among these, the Nuragic civilisation, developed between the XVIII and the

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VIII century BCE, is the most interesting case. Despite the flourishing trade with other Mediterranean cultures, this society heavily relied on the island for their sustenance and prosperity (Dyson & Rowland, 2007; Lilliu, 1999; Webster, 2015). Not much is known about the land occupation strategies of the Nuragic people and how they interacted with a physical territory high in diversity landscape and characterised by an uneven distribution of resources (Vanzetti et al., 2013). The purpose of this work is therefore to construct a map of the land units in the southwestern corner of Sardinia and compare them with the distribution of known Nuragic settlements. The retrieved information will provide valuable insights on the implications of palaeolandscape changes when interpreting past occupation patterns. They will also inform on the role of the physical landscape in shaping human-landscape interactions in Mediterranean Bronze Age.

1.1. Geographical and geological setting

The study area includes the portion of Southwestern Sardinia (39°45′48″N–38°51′54″N and 8°12′55″E–9° 03′18″E) surrounded by the sea to the West and South, including the Sant'Antioco and San Pietro islands, and by the Campidano valley, the largest tectonic valley in Sardinia (Casula et al., 2001), to the East (Figure 1). Outcrop lithologies vary between sedimentary, magmatic, and metamorphic rocks ranging in age from the Palaeozoic to the Quaternary (Barca et al., 2011; Lecca et al., 2017). Most of the landscape is occupied by metamorphic rocks deformed during the Variscan orogenesis (Palaeozoic) and by granitic rocks emplaced between 340 and 280 Ma (Carmignani et al., 2001, 2004). The Palaeozoic basement is cut into a northern and southern portion by the Cixerri valley which runs West to East into the Campidano valley. Above the metamorphic basement lies a thick Mesozoic–Cenozoic sedimentary succession linked to the evolution of the present-day western Mediterranean area. The most important lithologies are marine Mesozoic limestones outcropping to the Southwest and Paleogene terrigenous conglomerates also to the Southwest and in the Cixerri valley. The Cenozoic volcano-sedimentary succession relates to the tectonic rotation and placement of the Corsica-Sardinia block (Carminati et al., 2012). It is mainly characterised by rhyolitic-rhyodacitic ignimbrites and by andesitic and basaltic-andesitic lava flows distributed around the Palaeozoic basement in many locations (Cioni et al., 2001; Pioli & Rosi, 2005). Quaternary deposits are mostly represented by continental and in lesser quantity by lagoon and marine-littoral successions. Aeolian deposits mostly attributed to the Last Glacial Maximum (MIS2) (Andreucci et al., 2009; Coltorti et al., 2010; 2015) are widespread along the coast and occasionally interbedded with alluvial deposits and paleosols. The current climate is Mediterranean with dry, hot summers and mild winters. The area is swept by strong winds, particularly the cold Mistral from the Northwest and the hot Scirocco from the South. The water network is mainly ephemeral with a torrential regime.

1.2. Archaeological setting

During the Bronze Age, Sardinia was home to the Nuragic civilisation settled between the XVIII and the VII century BCE. For a thousand years the Nuragic people maintained the hegemony on the whole extent of the island without relevant interference from outsiders (Lilliu, 1999, 2001; Webster, 2015). During the Early Iron Age, their control of the land was progressively challenged by Phoenician colonies and then by the Punic conquest which ended the Nuragic period in the VI Century BCE. The Nuragic economy was based on agriculture, animal husbandry, fishing, and metallurgy, with widespread trade routes with the eastern and western Mediterranean and Northern Europe (Cámara Serrano & Spanedda, 2014; Freund & Tykot, 2011; Ling et al., 2014) and especially with continental Italy, where ore metals and manufactured products were exchanged on a regular basis (Lo Schiavo et al., 2005; Russell, 2020; Usai & Lo Schiavo, 2009). Nevertheless, there is still wide uncertainty on many aspects related to the socio-economic structure of the Nuragic communities (Cámara Serrano & Spanedda, 2014; Perra, 2009; 2014).

The most striking element of the Nuragic culture is the nuraghe. This structure is a conical, several-storied, dry-stone tower. Two main types have appeared in time: the early 'corridor' nuraghe or proto-nuraghe and the later 'tholos' nuraghe, the latter built as a single tower or as the complex union (Figure 2(a)) of multiple towers (Depalmas, 2018; Depalmas & Melis, 2010). Nuraghes are very widespread on Sardinia: more than 7000 structures and remains have been identified (Figure 2(b)). In the Final Bronze Age (1200-1000 BCE) the construction of nuraghes slowly stopped as the population moved into increasingly complex villages (Depalmas, 2003; 2009; Dyson & Rowland, 2007). The function of nuraghes is still a matter of considerable discussion (Bonzani, 1992; Depalmas, 2018; Usai, 1995).

2. Methods

In order to obtain a reliable comparison between the presence and distribution of Nuragic structures and the geological features of the landscape (Figure 3), we decided to use two main parameters: the main morphological units present in the landscape and the lithologies of the rock formations. The result is a

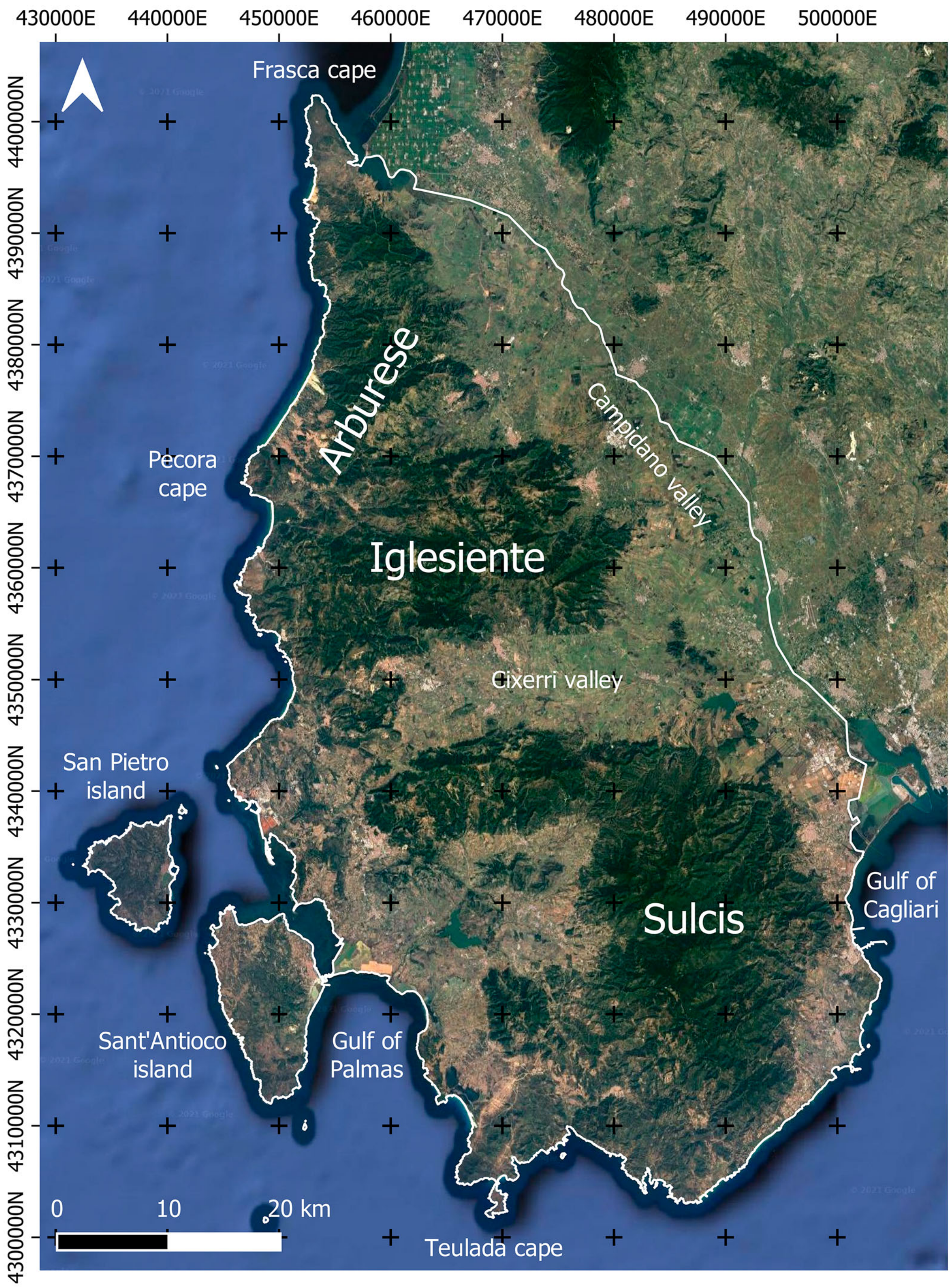

Figure 1. Extent of the study area (in white) with the main landscape features.

land units map of the area which can fully represent the variability of the territory in a way more suitable for human land use. The construction of the Main Map relied mainly on remote sensing elaborations. Data analysis used several datasets combining the available topographic, geological, and archaeological cartographies inside a QGIS geodatabase. Recent (6 August 2020) multispectral images with up to 10 m spatial resolution (ESA Copernicus Satellite 2A, tiles T32SMJ, T32SNJ, T32TMK, source: https://scihub.copernicus.eu/) composed in false colours (visible + near infrared) and projected to UTM Zone 32N provided the reference background for remote observations. The topography of the area and the raw data used for terrain analysis came from a 10 m Digital Elevation Model (DEM) retrieved from the Sardinia region online portal (Regione Autonoma della Sardegna, 2021) and reprojected to UTM Zone 32N. From it we calculated slope and hillshade models used for the construction of the Main Map. From the same source, we retrieved the water network drawn in the Main Map. A 1:25,000 (Regione Autonoma della Sardegna, 2021) and a 1:50,000 (CARG project: ISPRA, 2021) scale geological maps provided the lithological data and geological and structural settings used for remote observations. The comparison between the terrain and geological data from cartography and remote observation allowed to construct the

Figure 2. (a) The nuraghe Seruci (Gonnesa, SU) an example of well preserved complex nuraghe in the study area; (b) Spatial distribution of nuraghes in Sardinia (source: nurnet.net).

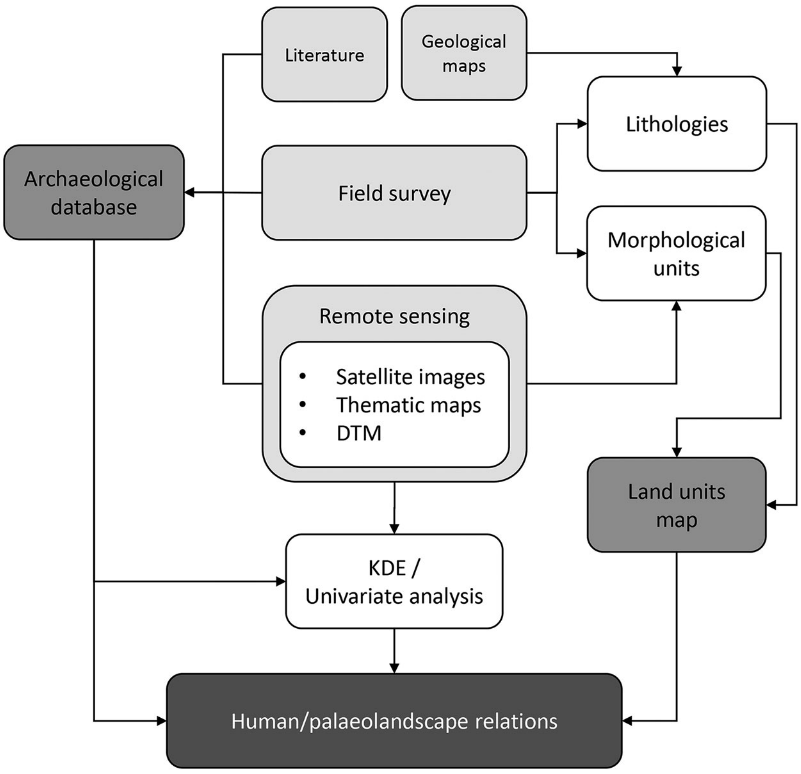

Figure 3. Model of the workflow employed in this study.

landscape units drawn in the Main Map. Field surveys carried out in specific locations allowed to verify the validity of the mapped units.

A publicly available online database (source: https://www.nurnet.net/) provided the main archaeological data: the nature and localisation of all Nuragic structures in the study area. Of these, we selected only the information pertaining to nuraghes, excluding other structures (villages, sacred wells, etc.) and not counting for differences between typologies of nuraghe. We verified the accuracy of the information retrieved from the database through comparisons with literature and the remote observation of the visible structures via satellite images. We also employed field validation in selected cases. In all instances when the database locations did not agree with satellite and field validations within a 50 m radius, the former were corrected accordingly. The intensity of the

Nuraghes sites was explored through the Kernel Density Estimation (KDE), a nonparametric density-based approach that creates a visual representation of intensity showing local variations (hotspots and coldspots) from the mean value of λ (Baddeley et al., 2015). In spatial statistics, the (homogeneous) intensity λ defines the expected number of points per unit area. The property of homogeneity in a point process means that the points have no preference for any spatial locations, a condition that is very unlikely to be observed in nature. When the intensity is spatially varying the number of points per unit area is determined by the function $\lambda(u)$, where u is the location observed in the point process (Baddeley et al., 2015). The standard deviation value (smoothing bandwidth or sigma) that we adopted to calculate the KDE corresponds to three times the mean distance to the nearest neighbours, as suggested by Nakoinz and Knitter (2016).

The digital elevation model was used as a covariate to perform the univariate analysis of the intensity of archaeological sites observed through the command rhohat in the spatstat R package. Assuming that the intensity of a inhomogeneous point process is a function of the covariate Z then: $\lambda(u)=\rho(Z(u))$, where ρ is the function that explains how the intensity of points depends on the value of the covariate. The generic R method plot returns a plot of the nonparametric estimation of the function $\rho(z)$ against covariate values z, together with 95% confidence envelope assuming an inhomogeneous (Poisson) point process (Baddeley et al., 2015).

3. Results and discussion

3.1. The many landscapes of SW Sardinia

Mapping the main land units in the area put into light the complexity of this landscape (Main Map). The largest land units are the two mountain areas to the North and the South. Here patterns of narrow valleys and ridges, often of structural origin, represent the main landforms. Different lithologies do anyway have an influence on morphologies. Metamorphic substrates (purple on the Main Map) tend to form more incised landscapes with many smaller peaks and straighter slopes (Figure 4(a)). Granites (red on the Main Map) instead often develop massif-like areas with a more convex profile and the characteristic rougher surface due to differential weathering (Figure 4(b)). Limestones (light blue on the Main Map) generally show a rugged morphology.

At mid elevations, different features drive the evolution of the landscape. The wide extensions of outcropping ignimbrites and andesites (light red and orange on the Main Map) left during past volcanic activity develop complex irregular landscapes of low hills and valleys, with different shapes according to the nature of the volcanic process. The presence of andesitic lavas such as in the Mt Arcuentu area

Figure 4. (a) landscape of metamorphic mountains with forested, narrow valleys and rugged peaks in the background; (b) granite mountains showing more convex slopes and denudation processes; (c) a structural cuesta composed of basaltic lavas over less resistant lithologies; (d) panorama of the Iglesiente and Arburese mountain areas from the Campidano valley; to the front, several isolated hills.

produces more regular convex–concave hills, while the morphology of pyroclastic flows as on Sant'Antioco and San Pietro islands is characterised by cuestas (Figure 4(c)). Basaltic lava flows are less represented in this part of Sardinia and tend to produce large plateaus such as the Capo Frasca promontory to the North. Towards the plains, in the areas mostly covered by later deposits, the past effusive activity left a constellation of smaller, isolated hills (dotted colours and vertical bars on the Main Map), in many cases the remains of volcanic domes (Figure 4(d)).

Most of the lower landscape is dominated by fluvial processes: here, starting from the Pliocene, multiple generations of alluvial fans (green on the Main Map) intersect each other and form a continuous low angle piedmont that fills most of the Campidano and Cixerri valleys. A proper alluvial plain is not present. Fluvial activity has repeatedly cut into the oldest fans multiple times during the Pleistocene, leaving a series of terraced deposits (dark green on the Main Map) on the sides of valleys. The western portion of the lowland is also interested by coastal dynamics, which interact with fluvial processes along the gulf of Palmas in the areas closer to the coastline. Sea level changes impacted deeply on the morphology of the whole coast during the Quaternary, forming during the Holocene a diverse landscape of beaches, rocky coasts, and high cliffs (Figure 5(a)). Numerous coastal lagoons are also present. Many of these environments were still in formation during the Bronze Age. The most visible contribution of aeolian processes is the deposition of wind-blown sand and dust. Dune fields and aeolianites (dark yellow on the Main Map) formed during the Late Pleistocene cover many areas and spots on the western coast: in the South wide deposits extended over the open plains, in the North, as for example near capo Pecora and capo Frasca, smaller fields are enclosed by mountains (Figure 5(b)).

The most diverse location is the western flatter portion of the Sulcis region, between the cities of Carbonia and Santadi. Here, metamorphic peaks enclose an area occupied by volcanic hills (light red and orange on the Main Map) surrounded by different deposits. At the foot of the mountains, a strip of land is filled with small alluvial fans (light green in the Main Map; Figure 5(c)). In front of the hills in the larger plains, a mix of aeolian and fluvial sediments (vertical green and yellow bars on the Main Map) changes towards the sea into a pattern of saltwater lagoons and beach deposits (light yellow on the Main Map).

3.2. Settlement distribution patterns: a link to land use?

Provided the limitations due to the changes in landscape since the Bronze Age, we can try and describe the evidence of trends in the settlement distribution of the Nuragic people and relate them to land occupation strategies and the use of resources.

As highlighted by the KDE, when we look at the distribution of nuraghes on the territory, there are some clear patterns corresponding to well-defined landscape features. The vast majority of nuraghes are near the plains or, less frequently, at mid elevations in correspondence with the river network (Figure 6). Unsurprisingly, the role of water is vital at site level, and all existing nuraghes are found within a short distance from rivers, springs and wells (Depalmas & Melis, 2010; Melis, 1998). Many settlements stay formally inside high elevation

Figure 5. (a) rocky cliffs of ignimbrites on the Western coast of Sant'Antioco island; (b) coastal dune field south of Frasca cape; (c) landscape of flat alluvial deposits and low hills in the Southwestern part of the map; in the background to the right the outer part of the Sulcis mountains.

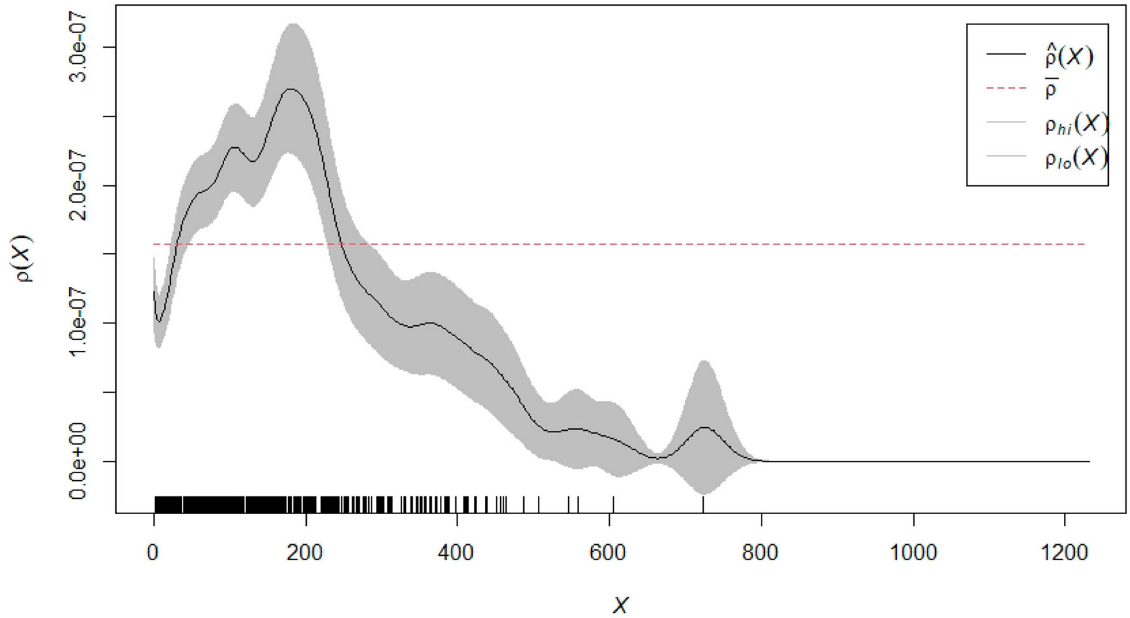

Figure 6. Univariate analysis of intensity of archaeological sites with elevation. X represents elevation, ρ(X) is the function that explains how the intensity of points depends on the elevation value. In grey the 95% confidence interval. Notice the strong correlation with lower elevations, especially between 100 and 200 m a.s.l.

areas, but at the boundary between the plains and the mountains, which are instead almost completely empty of sites. Mountain environments during the Bronze age were likely a difficult terrain to navigate, covered by forests (Beffa et al., 2016; Pedrotta et al., 2021) and even now subject to widespread erosive processes which prevent the formation of fertile soil. It is likely that these populations overwhelmingly preferred living down below where resources were more available, and that later denudation events destroyed the evidence of an already small presence of settlements. Conversely, the KDE shows how the area most densely settled is also the most diverse in terms of landscapes and potential resources (Figure 7(a)). Here the presence of gentle slopes and valleys allows thicker and more developed soils and a higher potential for agriculture and pastures. The proximity to the coast brings many advantages for fishing communities, but also for long-range ship transport and trade. It is possible to assume how the variety of substrates and physical environments could allow the exploitation of different resources and in turn allow more resilient and effective survival strategies (Zerboni et al., 2020).

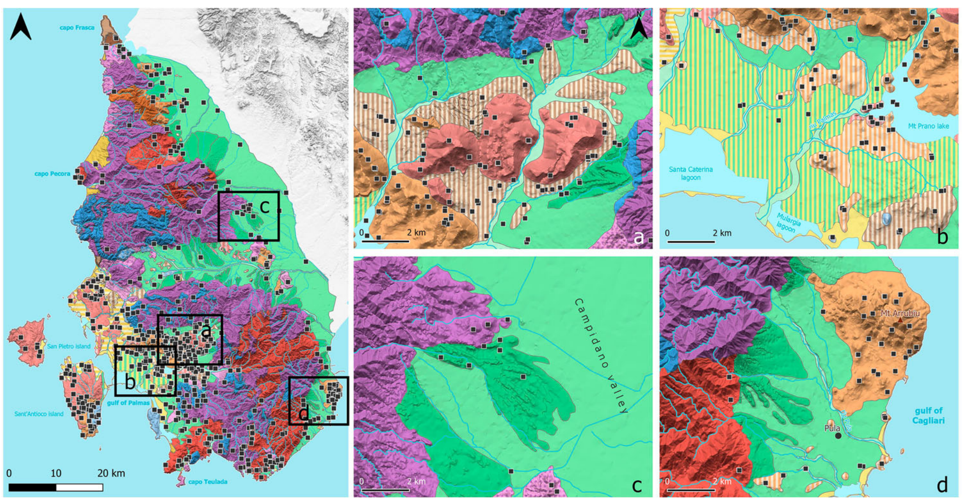

Figure 7 . Extracts of the Main Map highlighting the relations of different nuraghes with the landscape: (a) high concentration of nuraghes along hillslopes (vertical bars) and elevated positions (reds and oranges) in the Southwestern side of the map; (b) groups of nuraghes at the borders of the Gulf of Palmas coastal plain (yellow and green vertical bars). Inside the latter only isolated nuraghes appear on elevated mounds (brown and red vertical bars); (c) scattered nuraghes on the most stable terraced alluvial fans (dark green) along the Campidano valley; (d) clusters and isolated nuraghes on volcanic outcrops (orange) along the Gulf of Cagliari.

The occurrence of nuraghes also seems to be related to the presence of a stable rock surface. Most structures are located above outcrops and stable lithologies, often directly around the sediments of the plains and lowlands. In the most densely settled areas around the coastal plains most structures are built on volcanic outcrops or directly around them. The larger hills can group many towers, often around their sides or on secondary peaks and plateaus. Smaller hills and isolated outcrops also often host a single tower. Alluvial and coastal deposits are instead completely avoided. In fact, the coastal plains themselves are completely empty except for the nuraghes over higher and more stable positions (Figure 7(b)). In Southern Sardinia nuraghes along the coast are rare and not well investigated (Spanedda et al., 2007). The coastline itself is in a more retrograde position compared to the Bronze Age, now submerged (Antonioli et al., 2007; Vacchi et al., 2018). Along the Campidano valley to the Northeast and inside the Cixerri valley the scarcity of outcropping rock led the Nuragic people to use the higher platforms produced by the erosion of the oldest and most stable alluvial fans (Figure 7(c)). Slightly different is the situation to the West. The area occupied by ignimbrites inland and on the islands (light red on the Main Map) does not host significant unconsolidated deposits; it is anyway possible to see how small summits and platforms still host the majority of nuraghes, though in a less strict pattern.

The choice of building on elevated outcrops gives the advantage of both a raised position and usually a more stable ground, at least where most of the lower lands are made by unconsolidated deposits. Usually, the most invoked reason for this behaviour is land control (Cicilloni et al., 2015; De Montis & Caschili, 2012; De Reu et al., 2011): the higher visibility and possibly defence advantage over the surrounding pastures and crops provided by reaching the higher ground is certainly a strong motivation (Creighton, 2012; Jaeger, 2016; Zarifis & Brokou, 2002). Another possible reason is instead related to building technique: nuraghes are very heavy megalithic structures and need to sit on a substrate strong enough to bear their weight without risking ground failures. The unconsolidated loose deposits of the plains are not the most suitable choice, hence the preference for compact rock instead. Also, the occurrence of clusters of towers around certain landmarks, such as Mt Arrubiu along the gulf of Cagliari in the Southeast (Figure 7(d)) can be related to the source of the building materials. In fact, the majority of nuraghes are made by local stone blocks quarried in the vicinity and transported for very short distances. Logistic constraints would push for the exploitation of building spots around available quarries. In any case, the absence of clearly unstable substrates does not change the preference for raised positions, so it is possibly a matter of adaptation and flexibility of the Nuragic populations to different landscape settings.

3.3. Landscape evolution as a threat to the archaeological record

While in general land units at this scale remain mostly the ones we see today, many processes have in time produced significant changes that must be considered in the reconstruction of palaeolandscapes. In this sense, it is useful to look at the areas there the scarcity of nuraghes is most significant and recognise possible factors which could have not only kept settlers away, but also destroyed the evidence of their presence.

The most impactful is probably the action of slope processes. This area of Sardinia clearly bears the marks of highly active denudation processes concentrated in the mountain areas. Slopes typically show very thin and poorly developed soil covers with widespread bare rock especially on higher elevations. Erosion was likely helped by several human-driven deforestation events, which happened multiple times since prehistory to the Modern Age (Beffa et al., 2016; Di Rita & Melis, 2013; Pedrotta et al., 2021). The current prevalence in mountain plant cover of open forests and macchia formations still preserve the soils only partially. In these conditions, the threat to the archaeological record is evident. It is quite possible that existing structures disappeared because of landslide events and general transport from erosion, thus impairing our understanding of their settlement strategies.

The other major threat to archaeological structures is, at the opposite, at the lowest elevations. Here, along the coast, sea level changes during the Holocene heavily impacted the landscape and caused a drastic redefinition of the coastline and surrounding environments. From the Bronze Age to the present this process was not as dramatic, but still relevant (Vacchi et al., 2016). Sea levels in Southwestern Sardinia during the Bronze age have been measured between -6.8 ± 1.0 m and -2.2 ± 1.0 m (Vacchi et al., 2016), which affected both structures potentially located along the shoreline and settlements further inland. The interaction between marine transgression and fluvial deposition caused many fragile coastal environments, such as saltwater lagoons, to shift and disappear (Melis et al., 2017, 2018). This, together with the burial or submersion of at least a part of the Bronze Age settlements (Berlinghieri et al., 2020; Del Vais et al., 2006; Depalmas, 2002), influences our view of human-landscape interactions.

Last, there is the matter of human activity. The conscious destruction and reuse of structures by later populations is a common and sometimes institutionalised process, especially in Roman times (Barker & Marano, 2017), and this area makes no exception, especially in the flatter areas. The needs of local farmers and city dwellers required clear spaces, infrastructures and building materials, and it is not unlikely that many nuraghes were lost in the past for these reasons (Russu, 2012; Webster, 1991).

4. Conclusions

The features of the physical landscape seem to drive Nuragic human dispersal in different and sometimes unexpected ways. The close relation of settlement density with landscape diversity, and in turn with the variety and availability of natural resources, is another confirmation of how land use diversification can be a successful strategy for complex societies. It can therefore be interesting to consider the effect of geodiversity and landscape diversity on past sustenance strategies to build more accurate dispersal models. The interaction with the terrain also plays a complex role. The search for the higher ground is usually dictated by social and strategic reasons. Nevertheless, the presence of available building materials and of safe foundations is vital to host heavy dry-stone megalithic structures. This glimpse of the interplay between social and environmental factors in settlement choice highlights another topic worthy of consideration. More studies would be needed to provide rigorous comparisons to disentangle their effects in guiding survival strategies and land use.

While often difficult and necessarily approximate, the identification and mapping of the main processes pushing palaeolandscapes towards change can greatly support the study of human-landscape interactions. Their help in interpreting settlement density and locations can characterise natural interferences with the conservation of the archaeological record, as well as where and how our reconstructions can be the most accurate.

Software

The software used for all elaborations and the construction of the Main Map is QGIS, versions 3.14 and 3.16. GoogleEarthPro™ was also employed as support for remote sensing observations.

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Data availability statement

Authors agree to make data and materials supporting the results or analyses presented in their paper available upon reasonable request.

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References

Andreucci, S., Pascucci, V., Murray, A. S., & Clemmensen, L. B. (2009). Late Pleistocene coastal evolution of San Giovanni di Sinis, west Sardinia (Western Mediterranean). *Sedimentary Geology*, *216*(3–4), 104–116. https://doi.org/10.1016/j.sedgeo.2009.03.001

Antonioli, F., Anzidei, M., Lambeck, K., Auriemma, R., Gaddi, D., Furlani, S., Orrù, P., Solinas, E., Gaspari, A., Karinja, S., & Kovačić, V. (2007). Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data. *Quaternary Science Reviews*, *26*(19–21), 2463–2486. https://doi.org/10.1016/j.quascirev.2007.06.022

Aucelli, P. P. C., Valente, E., Di Paola, G., Amato, V., Cesarano, M., Cozzolino, M., Pappone, G., Scorpio, V., & Rosskopf, C. M. (2020). The influence of the geological–geomorphological setting on human settlements and historical urban development: The case study of Isernia (southern Italy). *Journal of Maps*. https://doi.org/10.1080/17445647.2020.1794989

Baddeley, A., Rubak, E., & Turner, R. (2015). *Spatial point patterns: Methodology and applications with R* (pp. 828). CRC Press.

Barca, S., Melis, E., Calzia, P., Patta, E. D., Rizzo, R., & Serri, R. (2011). *Note illustrative della Carta Geologica d'Italia 1: 50.000 Foglio 547-Villacidro*. ISPRA-Servizio Geologico d'Italia.

Barker, S. J., & Marano, Y. A. (2017). Demolition laws in an archaeological context. Legislation and architectural re-use in the Roman building industry. In P. Pensabene, M. Milella, & F. Caprioli (Eds.), *Decor. Decorazione e architettura nel mondo romano. Atti del convegno internazionale Roma, 21–24 maggio 2014* (pp. 833–850). Thiasos Monografie.

Beffa, G., Pedrotta, T., Colombaroli, D., Henne, P. D., van Leeuwen, J. F., Süsstrunk, P., Kaltenrieder, P., Adolf, C., Vogel, H., Pasta, S., Anselmetti, F. S., Gobet, E., & Tinner, W. (2016). Vegetation and fire history of coastal north-eastern Sardinia (Italy) under changing Holocene climates and land use. *Vegetation History and Archaeobotany*, *25*(3), 271–289. https://doi.org/10.1007/s00334-015-0548-5

Berlinghieri, E. F. C., Antonioli, F., & Bailey, G. (2020). Italy: The archaeology of palaeoshorelines, coastal caves and seafaring connections. In G. Bailey, H. Jöns, N. Galanidou, H. Peeters, & M. Mennenga (Eds.), *The archaeology of Europe's drowned landscapes* (pp. 321–340). Coastal Research Library Volume 35. Springer.

Bonzani, R. M. (1992). Territorial boundaries, buffer zones and sociopolitical complexity: A case study of the Nuraghi on Sardinia. In R. H. Tykot & T. K. Andrews (Eds.), *Sardinia in the Mediterranean: A footprint in the sea. Studies in Sardinian archeology presented to Miriam S. Balmuth* (pp. 210–220). Monographs in Mediterranean Archaeology 3. Sheffield Academic Press.

Brandolini, F., & Carrer, F. (2020). Terra, Silva et Paludes. Assessing the role of Alluvial geomorphology for Late-Holocene settlement strategies (Po Plain – N Italy) through point pattern analysis. *Environmental Archaeology*. https://doi.org/10.1080/14614103.2020.1740866

Cámara Serrano, J. A., & Spanedda, L. (2014). L'organizzazione sociale nuragica. Note e ipotesi. In A. Moravetti, E. Alba, & L. Foddai (Eds.), *La Sardegna Nuragica – storia e materiali* (pp. 151–159). Carlo Delfino Editore.

Carmignani, L., Barca, S., Oggiano, G., Pertusati, P. C., Salvadori, I., Conti, P., Eltrudis, A., Funedda, A., & Pasci, S. (2001). *Geologia della Sardegna: note illustrative della Carta Geologica della Sardegna a scala 1:200.000*. Memorie descrittive della Carta Geologica d'Italia, Volume 60. Istituto Poligrafico e Zecca dello Stato.

Carmignani, L., Funedda, A., Oggiano, G., & Pasci, S. (2004). Tectono-sedimentary evolution of southwest Sardinia in the Paleogene: Pyrenaic or apenninic dynamic? *Geodinamica Acta*, *17*(4), 275–287. https://doi.org/10.3166/ga.17.275-287

Carminati, E., Lustrino, M., & Doglioni, C. (2012). Geodynamic evolution of the central and western Mediterranean: Tectonics vs. igneous petrology constraints. *Tectonophysics*, *579*, 173–192. https://doi.org/10.1016/j.tecto.2012.01.026

Carrero-Pazos, M. (2019). Density, intensity and clustering patterns in the spatial distribution of Galician megaliths (NW Iberian Peninsula). *Archaeological and Anthropological Science*, *11*, 2097–2108. https://doi.org/10.1007/s12520-018-0662-2

Casula, G., Cherchi, A., Montadert, L., Murru, M., & Sarria, E. (2001). The Cenozoic valley system of Sardinia (Italy): Geodynamic evolution from new seismic and field data. *Marine and Petroleum Geology*, *18*(7), 863–888. https://doi.org/10.1016/S0264-8172(01)00023-X

Cicilloni, R., Mossa, A., & Cabras, M. (2015). Studio dell'insediamento protostorico in un'area della Sardegna centro-occidentale tramite strumenti GIS ed analisi multivariate. *Archeologia e calcolatori*, *26*, 149–168.

Cioni, R. A., Salaro, L. A., & Pioli, L. A. (2001). The Cenozoic volcanism of San Pietro Island (Sardinia, Italy). *Rendiconti del Seminario della Facoltà di Scienze dell'Università di Cagliari*, *71*, 149–63.

Coltorti, M., Melis, E., & Patta, D. (2010). Geomorphology, stratigraphy and facies analysis of some Late Pleistocene and Holocene key deposits along the coast of Sardinia (Italy). *Quaternary International*, *222*(1/2), 19–35. https://doi.org/10.1016/j.quaint.2009.10.006

Coltorti, M., Pieruccini, P., Montagna, P., & Zorzi, F. (2015). Stratigraphy, facies analysis and chronology of quaternary deposits at Capo S. Marco (Sinis Peninsula, west Sardinia, Italy). *Quaternary International*, *357*, 158–175. https://doi.org/10.1016/j.quaint.2014.03.033

Costanzo, S., Brandolini, F., Idriss Ahmed, H., Zerboni, A., & Manzo, A. (2021). Creating the funerary landscape of Eastern Sudan. *PLoS ONE*, *16*(7), e0253511. https://doi.org/10.1371/journal.pone.0253511

Creighton, O. H. (2012). *Early medieval castles. Aristocracy and authority, AD 800–1200*. Bloomsbury.

Dall'Aglio, P. L., De Donatis, M., Franceschelli, C., Guerra, C., Guerra, V., Nesci, O., Piacentini, D., & Savelli, D. (2017). Geomorphological and anthropic control of the development of some Adriatic historical towns (Italy) since the Roman age. *Quaestiones Geographicae*, *36*(3), 111–123. https://doi.org/10.1515/quageo-2017-0028

Del Vais, C., Depalmas, A., Fariselli, A. C., & Melis, R. T. (2006). Il paesaggio costiero della Penisola del Sinis (OR) tra preistoria e storia: aspetti archeologici e ambientali. In *Atti del I Simposio "Il monitoraggio costiero mediterraneo. Problematiche e tecniche di misura* (pp. 309–322). CNR-IBIMET.

De Montis, A., & Caschili, S. (2012). Nuraghes and landscape planning: Coupling viewshed with complex network analysis. *Landscape and Urban Planning*, *105*(3), 315–324. https://doi.org/10.1016/j.landurbplan.2012.01.005

Depalmas, A. (2002). Approdi e insediamenti costieri nella Sardegna di età nuragica. In N. Negroni Catacchio (Ed.), *Paesaggi d'acque. Preistoria e Protostoria in Etruria. Atti del Quinto Incontro di studi. Sorano-Farnese, 12–14 maggio 2000* (pp. 391–402). Centro Studi di Preistoria e Archeologia.

Depalmas, A. (2003). Scelte insediative e aspetti del popolamento nella Sardegna di età nuragica. *Historia Antiqua*, *11*, 13–21.

Depalmas, A. (2009, novembre 23–28). Il Bronzo Finale della Sardegna. In *La preistoria e la protostoria della Sardegna. Atti della XLIV Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria. Cagliari-Barumini-Sassari* (pp. 141–153). Istituto Italiano di Preistoria e Protostoria.

Depalmas, A. (2018). Dal nuraghe a corridoio al nuraghe complesso. In T. Cossu, M. Perra, & A. Usai (Eds.), *Il tempo dei nuraghi. La Sardegna dal XVIII all'VIII secolo aC* (pp. 54–60). Ilisso.

Depalmas, A., & Melis, R. T. (2010). The nuragic people: Their settlements, economic activities and use of the land. In P. I. Martini & W. Chesworth (Eds.), *Landscapes and societies. Selected cases* (pp. 167–186). Springer.

De Reu, J., Bourgeois, J., De Smedt, P., Zwertvaegher, A., Antrop, M., Bats, M., De Maeyer, P., Finke, P., Van Meirvenne, M., Verniers, J., & Crombé, P. (2011). Measuring the relative topographic position of archaeological sites in the landscape, a case study on the Bronze Age barrows in northwest Belgium. *Journal of Archaeological Science*, *38*(12), 3435–3446. https://doi.org/10.1016/j.jas.2011.08.005

DiNapoli, R. J., Lipo, C. P., Brosnan, T., Hunt, T. L., Hixon, S., Morrison, A. E., & Becker, M. (2019). Rapa Nui (Easter Island) monument (ahu) locations explained by freshwater sources. *PLoS ONE*, *14*(1), e0210409. https://doi.org/10.1371/journal.pone.0210409

Di Rita, F., & Melis, R. T. (2013). The cultural landscape near the ancient city of Tharros (central West Sardinia): Vegetation changes and human impact. *Journal of Archaeological Science*, *40*(12), 4271–4282. https://doi.org/10.1016/j.jas.2013.06.027

Dyson, S. L., & Rowland, R. J. (2007). *Archaeology and history in Sardinia from the Stone Age to the Middle Ages:*

Shepherds, sailors, and conquerors. UPenn Museum of Archaeology.

French, C. (2010). Archaeology. People, societies, and landscapes. *Science*, *328*(5977), 443–444. https://doi.org/10.1126/science.1186019

Freund, K. P., & Tykot, R. H. (2011). Lithic technology and obsidian exchange networks in Bronze Age Nuragic Sardinia (Italy). *Archaeological and Anthropological Sciences*, *3*(2), 151–164. https://doi.org/10.1007/s12520-010-0047-7

Ghilardi, M. (2021). Geoarchaeology: Where geosciences meet the humanities to reconstruct past human–environment interactions. an application to the coastal areas of the largest Mediterranean Islands. *Applied Sciences*, *11*(10), 4480. https://doi.org/10.3390/app11104480

Gioia, D., Bavusi, M., Di Leo, P., Giammatteo, T., & Schiattarella, M. (2020). Geoarchaeology and geomorphology of the Metaponto area, Ionian coastal belt, Italy. *Journal of Maps*, *16*(2), 117–125. https://doi.org/10.1080/17445647.2019.1701575

Gioia, D., Del Lungo, S., Sannazzaro, A., & Lazzari, M. (2019). Geological and geomorphological controls on the path of an intermountain Roman road: The case of the Via Herculia, Southern Italy. *Geosciences*, *9*, 398. https://doi.org/10.3390/geosciences9090398

Howey, M. C., Palace, M. W., & McMichael, C. H. (2016). Geospatial modeling approach to monument construction using Michigan from AD 1000–1600 as a case study. *Proceedings of the National Academy of Sciences*, *113*(27), 7443–7448. https://doi.org/10.1073/pnas.1603450113

ISPRA, Istituto Superiore per la Protezione e la Ricerca Ambientale. (2021). Carta Geologica d'Italia alla scala 1:50000. Retrieved July 31, 2021, from https://www.isprambiente.gov.it/Media/carg/index.html

Jaeger, M. (2016). *Bronze Age fortified settlements in Central Europe*. Studien zur Archäologie in Ostmitteleuropa, Band 17. Dr Rudolf Habelt GmbH.

Kintigh, K. W., Altschul, J. H., Beaudry, M. C., Drennan, R. D., Kinzig, A. P., Kohler, T. A., Limp, W. F., Maschner, H. D., Michener, W. K., Pauketat, T. R., & Peregrine, P. (2014). Grand challenges for archaeology. *American Antiquity*, *79*(1), 5–24. https://doi.org/10.7183/0002-7316.79.1.5

Lecca, L., Demuro, S., Carboni, S., Cossellu, M., Kalb, C., Nicola, P., & Tilocca, G. (2017). *Note illustrative della Carta Geologica d'Italia 1: 50.000 Foglio 566-Pula*. ISPRA-Servizio Geologico d'Italia.

Lilliu, G. (1999). *La civiltà nuragica*. Carlo Delfino Editore.

Lilliu, G. (2001). La Sardegna tra il XVII e il XIV secolo a.C. Linee di sviluppo e relazioni esterne. In C. Giardino (Ed.), *Culture marinare nel Mediterraneo centrale e occidentale tra il XVII e il XV secolo a.C.* (pp. 257–305). Ricerche di Storia, Epigrafia e Archeologia Mediterranea 4. Bagatto Libri.

Ling, J., Stos-Gale, Z., Grandin, L., Billström, K., Hjärthner-Holdar, E., & Persson, P. O. (2014). Moving metals II: Provenancing Scandinavian Bronze Age artefacts by lead isotope and elemental analyses. *Journal of Archaeological Science*, *41*, 106–132. https://doi.org/10.1016/j.jas.2013.07.018

Lo Schiavo, F., Giumlia-Mair, A., Sanna, U., & Valera, R. (Eds.). (2005). *Archaeometallurgy in Sardinia: From the origins to the early Iron Age*. Monographies Instrumentum 50. Éditions Monique Mergoil.

Mariani, G. S., Brandolini, F., Pelfini, M., & Zerboni, A. (2019). Matilda's castles, northern Apennines: Geological and geomorphological constrains. *Journal of Maps*, *15*(2), 521–529. https://doi.org/10.1080/17445647.2019.1625823

Melis, R. T. (1998). La ricostruzione paleo-ambientale come strumento di indagine archeologica. In G. Tanda (Ed.), *Sedilo. I monumenti. I monumenti nel contesto territoriale comunale* (pp. 9–20). Antichità Sarde. Studi e Ricerche 3/III. Soter Editrice.

Melis, R. T., Depalmas, A., Di Rita, F., Montis, F., & Vacchi, M. (2017). Mid to late Holocene environmental changes along the coast of western Sardinia (Mediterranean Sea). *Global and Planetary Change*, *155*, 29–41. https://doi.org/10.1016/j.gloplacha.2017.06.001

Melis, R. T., Di Rita, F., French, C., Marriner, N., Montis, F., Serreli, G., Sulas, F., & Vacchi, M. (2018). 8000 years of coastal changes on a western Mediterranean island: A multiproxy approach from the Posada plain of Sardinia. *Marine Geology*, *403*, 93–108. https://doi.org/10.1016/j.margeo.2018.05.004

Nakoinz, O., & Knitter, D. (2016). *Modelling human behaviour in landscapes: Basic concepts and modelling elements*. Springer International Publishing.

Pedrotta, T., Gobet, E., Schwörer, C., Beffa, G., Butz, C., Henne, P. D., Morales-Molino, C., Pasta, S., van Leeuwen, J. F., Vogel, H., & Zwimpfer, E. (2021). 8,000 years of climate, vegetation, fire and land-use dynamics in the thermo-mediterranean vegetation belt of northern Sardinia (Italy). *Vegetation History and Archaeobotany*. https://doi.org/10.1007/s00334-021-00832-3

Perra, M. (2009). Osservazioni sulla evoluzione sociale e politica in età nuragica. *Rivista di Scienze Preistoriche*, *LIX*, 355–368.

Perra, M. (2014). Politica, economia e società nel mondo dei nuraghi. In A. Moravetti, E. Alba, & L. Foddai (Eds.), *La Sardegna Nuragica - storia e materiali* (pp. 151–159). Carlo Delfino Editore.

Pioli, L., & Rosi, M. (2005). Rheomorphic structures in a high-grade ignimbrite: The Nuraxi tuff, Sulcis volcanic district (SW Sardinia, Italy). *Journal of Volcanology and Geothermal Research*, *142*(1–2), 11–28. https://doi.org/10.1016/j.jvolgeores.2004.10.011

Regione Autonoma della Sardegna. (2021). Sardegna Geoportale. Retrieved July 31, 2021, from http://www.sardegnageoportale.it

Russell, A. (2020). Nuragic networking? Assessing globalization and glocalization in a late Bronze Age Sardinian context. In A. Kouremenos & J. M. Gordon (Eds.), *Mediterranean archaeologies of insularity in an age of globalization* (pp. 27–52). Oxbow Books.

Russu, A. G. (2012). A note concerning the nuraghe Barrabisa, Palau (SS): First summary of research. In C. Burgess, P. Topping, & F. Lynch (Eds.), *Beyond Stonehenge. Essays on the Bronze Age in honour of Colin burgess* (pp. 213–214). Oxbow Books.

Spanedda, L., Cámara Serrano, J. A., & Puertas García, M. E. (2007). Porti e controllo della costa nel golfo di Orosei durante l'età del bronzo. *Origini. Preistoria e Protostoria delle civiltà antiche*, *XXIX*, 119–144.

Usai, A. (1995). Note sulla società della Sardegna nuragica e sulla funzione dei nuraghi. In N. Christie (Ed.), *Settlement and Economy in Italy 1500 BC-AD 1500: Papers of the Fifth Conference of Italian Archaeology* (pp. 253–259). Oxbow Books.

Usai, A., & Lo Schiavo, F. (2009, novembre 23–28). Contatti e scambi. In *La preistoria e la protostoria della Sardegna. Atti della XLIV Riunione Scientifica dell'Istituto Italiano* *di Preistoria e Protostoria. Cagliari-Barumini-Sassari* (pp. 271–286). Istituto Italiano di Preistoria e Protostoria.

Vacchi, M., Ghilardi, M., Melis, R. T., Spada, G., Giaime, M., Marriner, N., Lorscheid, T., Morhange, C., Burjachs, F., & Rovere, A. (2018). New relative sea-level insights into the isostatic history of the Western Mediterranean. *Quaternary Science Reviews*, *201*, 396–408. https://doi.org/10.1016/j.quascirev.2018.10.025

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A., & Rovere, A. (2016). Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: Sea-level variability and improvements in the definition of the isostatic signal. *Earth-Science Reviews*, *155*, 172–197. https://doi.org/10.1016/j.earscirev.2016.02.002

Vanzetti, A., Castangia, G., Depalmas, A., Ialongo, N., & Leonelli, V. (2013). Complessi fortificati della Sardegna e delle isole del Mediterraneo occidentale nella protostoria. *Scienze dell'Antichità*, *19*, 83–123.

Webster, G. (1991). Monuments, mobilization and Nuragic organization. *Antiquity*, *65*(249), 840–856. https://doi.org/10.1017/S0003598X0008056X

Webster, G. (2015). *The archaeology of Nuragic Sardinia*. Monographs in Mediterranean Archaeology 14. Equinox Publishing.

Zarifis, N., & Brokou, D. (2002). GIS and space analysis in the study of the hospitallers' fortifications in the Dodecanese. *BAR International Series*, *1016*, 149–156.

Zerboni, A., Perego, A., Mariani, G. S., Brandolini, F., Al Kindi, M., Regattieri, E., Zanchetta, G., Borgi, F., Charpentier, V., & Cremaschi, M. (2020). Geomorphology of the Jebel Qara and coastal plain of Salalah (Dhofar, southern Sultanate of Oman). *Journal of Maps*, *16*(2), 187–198. https://doi.org/10.1080/17445647.2019.1708488