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LATE BRONZE AGE COLLAPSE AT USTICA ISLAND (SICILY - ITALY): THE DROUGHT HYPOTHESIS

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ABSTRACT**:** Ustica is a small island in the southern Tyrrhenian Sea. During the Middle Bronze Age, hundreds of inhabitants were primarily concentrated in the fortified citadel of Villaggio dei Faraglioni. The site was suddenly abandoned between 1250 and 1200 BCE, and the entire island remained uninhabited for eight centuries. Several hypotheses have been put forward to explain this abandonment, including the occurrence of a natural catastrophe or an unexpected hostile invasion. Here, we explore an alternative explanation: the impact of climate change, with a particular focus on drought. Ustica remained uninhabited during a period of global and regional climatic deterioration, coinciding with sunspot minimum and stratospheric sulfate injection, from unknown explosive volcanic eruptions. Both northern and southern offshore areas of Sicily recorded prolonged and strengthened northerly atmospheric activity, which cooled sea surface temperatures and enhanced the water column vertical mixing. Stable isotope data from speleothems in northern Spain and central Italy indicate pronounced drought episodes following Ustica's abandonment at 3.15 ka BP, coinciding with a predominantly positive North Atlantic Oscillation phase. Locally, reduced precipitation levels are evidenced by significant dryness in Sicily between 3.2 and 3.0 ka BP, as reflected in lake level fluctuations. The severe drought affecting Sicily and Ustica between 3.2 and 3.0 ka BP appears to be the culmination of a broader aridification trend that had been ongoing at both global and regional scales since the 4.2 ka BP event. Water shortages may have led to sanitary issues, crop failures, and famine. Though speculative, our hypothesis provides a more plausible explanation for the well-preserved pottery and defensive walls at Villaggio dei Faraglioni, than scenarios involving natural catastrophes, invasions, or looting.

Keywords: Central Mediterranean; societal impact of climate change; Event 3.2 ka; archaeology; paleoclimate.

1. INTRODUCTION

There are numerous reports on the significant influence of climate change on the rise and fall of civilizations. For instance, the Justinianic Plague, which marks the decline of the Roman Empire, has been linked to a prolonged period of climate deterioration (Zonneveld et al., 2024). Similarly, the rise of the Roman Empire may have been facilitated by a sustained climatic optimum, characterized by the highest sea surface temperatures in the Mediterranean over the past 2,000 years (Margaritelli et al., 2019), before the anthropogenic CO_2 emission.

The Mediterranean region is particularly sensitive to climate fluctuations. Ongoing global warming is progressing at an accelerated rate in the Mediterranean Sea, approximately 20% faster than the global ocean average (MedECC, 2021; Marriner et al., 2022). Even past natural climatic oscillations were significantly amplified, as seen during the Dansgaard-Oeschger events of the last glacial period (Incarbona et al., 2013; Martrat et al., 2004; Sprovieri et al., 2012). Moreover, the Mediterranean is the cradle of Western civilization, as well as, at least in part, North African, Near Eastern, and Middle Eastern civilizations. Ancient Egyptians, Greeks, and Romans flourished in this region, and the distribution of UNESCO World Heritage sites vividly reflects their highest density along Mediterranean coasts.

Ustica is a small island in the southern Tyrrhenian Sea (Fig. 1), with a long history dating back to the Neolithic, in the 6th millennium Before Common Era (BCE). Its historical trajectory closely follows that of Sicily, particularly Palermo, located only about 30 nautical miles away. During the Middle Bronze Age (MBA), Ustica was densely inhabited. The largest settlement of that period was Villaggio dei Faraglioni, which, after about two centuries of intense activity, was suddenly abandoned around 1250-1200 BCE (Spatafora, 2009; Spatafora & Mannino, 2008). Thereafter, the island remained uninhabited for a long time, until a new settlement was established at Rocca della Falconiera in the third century BCE. This prolonged phase of abandonment is difficult to explain, as it coincides with the Phoenician and Greek colonization of Sicily, despite Ustica's strategic location along trade routes connecting the Etruscans and Sardinia (Spatafora & Mannino, 2008).

Several hypotheses have been put forward to explain Ustica's abandonment during the Late Bronze Age, primarily attributing it to a sudden natural catastrophe, such as an earthquake, or an unexpected invasion and subsequent looting (Spatafora & Mannino, 2008). However, the catastrophe hypothesis is contradicted by archaeological evidence, which shows no signs of significant structural damage to the village's defensive walls and huts, no massive destruction of pottery, and no evidence of extensive fire (Foresta Martin & Furlani, 2021).

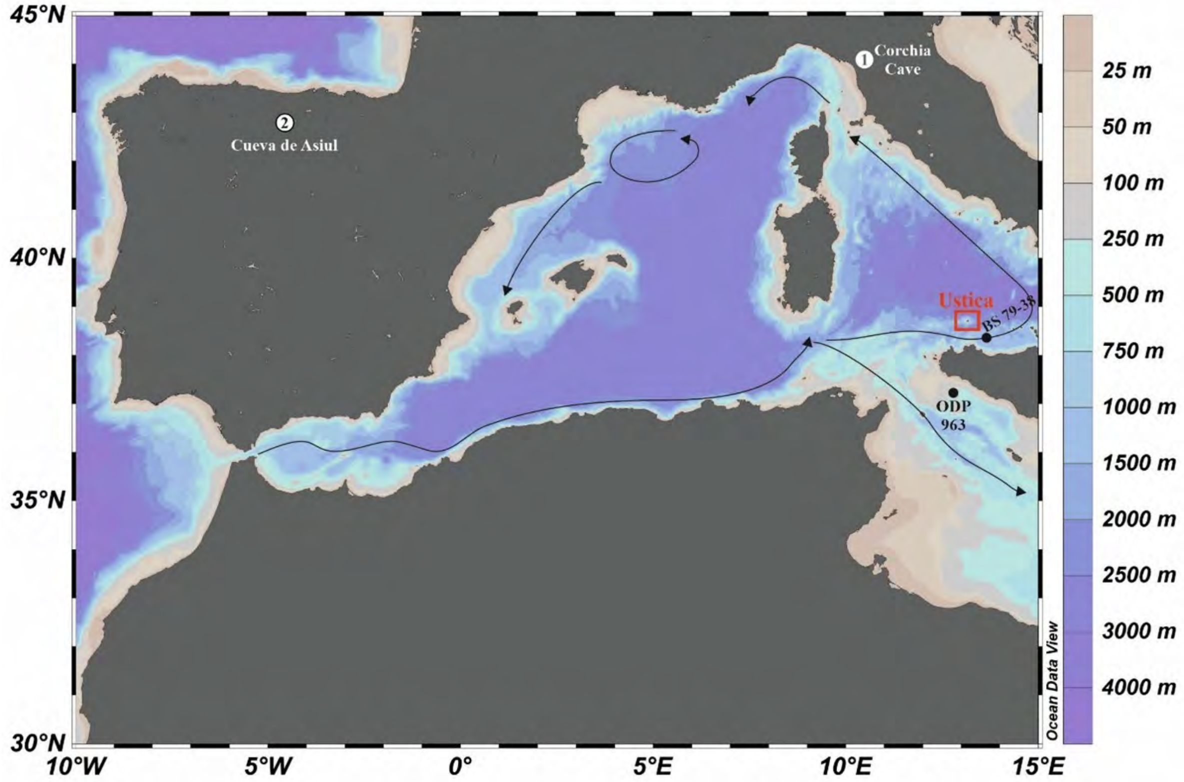


Fig. 1 - Bathymetric map of the western-central Mediterranean Sea (generated with Ocean Data View 4.0, Schlitzer, 2025) showing the location of Ustica Island (red rectangle). Black arrows indicate the Modified Atlantic Water (MAW) path (modified from Pinardi & Masetti, 2000). Black dots mark the locations of sedimentary cores from the Tyrrhenian Sea and the Sicily Channel (Sbaffi et al., 2001; Incarbona et al., 2008). Circles 1 and 2 indicate the locations of Corchia and Asiul caves, respectively (Smith et al., 2016; Isola et al., 2019).

In this study, we explore an alternative explanation: the impact of climate change, with a particular focus on drought. This hypothesis is not entirely new (Foresta Martin & Furlani, 2021), but here it is reassessed considering paleoclimatic advances made in the region over the past quarter-century. This review evaluates recent paleoclimatic proxy data from the Middle and Late Holocene to support a broad range of archaeological research and applications.

2. STUDY AREA

2.1. Ustica geology, archaeology and history

Ustica is a deep-sea volcano formed by the activity of a left-transtensional fault system, resulting from the anticlockwise rotation of the Italian Peninsula and the opening of the Tyrrhenian Basin, likely during the earliest Middle Pleistocene (De Vita et al., 1995, 1998). After several hundred thousand years of underwater volcanic activity, during which a high seamount was built, the island emerged approximately 500 ka ago. Volcanic activity continued with a complex sequence of subaerial eruptions, including effusive, Strombolian, and explosive phases, and ended around 130 ka with a hydromagmatic eruption that formed the Monte Falconiera crater (De Vita & Foresta Martin, 2017). Glacio-eustatic sea-level fluctuations led to the formation of several marine terraces dated to the Middle and Late Pleistocene (de Vita & Orsi, 1994; Buccheri et al., 2014; De Vita & Foresta Martin, 2017), (Fig.2).

The first settlements on the island were established during the Middle Neolithic, between the 6th and 5th millennia BCE (Mannino, 1998; Speciale et al., 2021). More abundant and significant archaeological remains from the Eneolithic, Early Bronze Age and Middle Bronze Age have been identified at different sites, testifying to the island's continuous human presence during prehistory (Foresta Martin & Furlani, 2021; Spatafora & Mannino, 2008). The Middle Bronze Age (1400-1200 BCE) marks the peak of population density on the island and the foundation of the fortified Villaggio dei Faraglioni on the northern cusp of the island. The rationality of the urban planning of the village, the fortification system and the diverse and sophisticated pottery recovered, suggests the development of a complex socio-economic structure within a prosperous community (Spatafora & Mannino, 2008; Russolillo et al., 2024). Around 1250-1200 BCE Villaggio dei Faraglioni was suddenly abandoned, and the entire island remained uninhabited for approximately 800 years (Spatafora & Mannino, 2008; Foresta Martin & Furlani, 2021; Russolillo et al., 2024). A new settlement was established in Ustica on the top of the Falconiera crater (Fig. 2) during the Hellenistic-Roman period, around the 3rd century BCE, likely in the time of the First Punic War (Spatafora & Mannino, 2008; Foresta Martin & Furlani, 2021).

Throughout Ustica's prehistory, from the Neolithic to the Middle Bronze Age, water supply was a challenge due to the scarcity of natural springs. Water was primarily obtained from dripping sources in sea caves and rain-

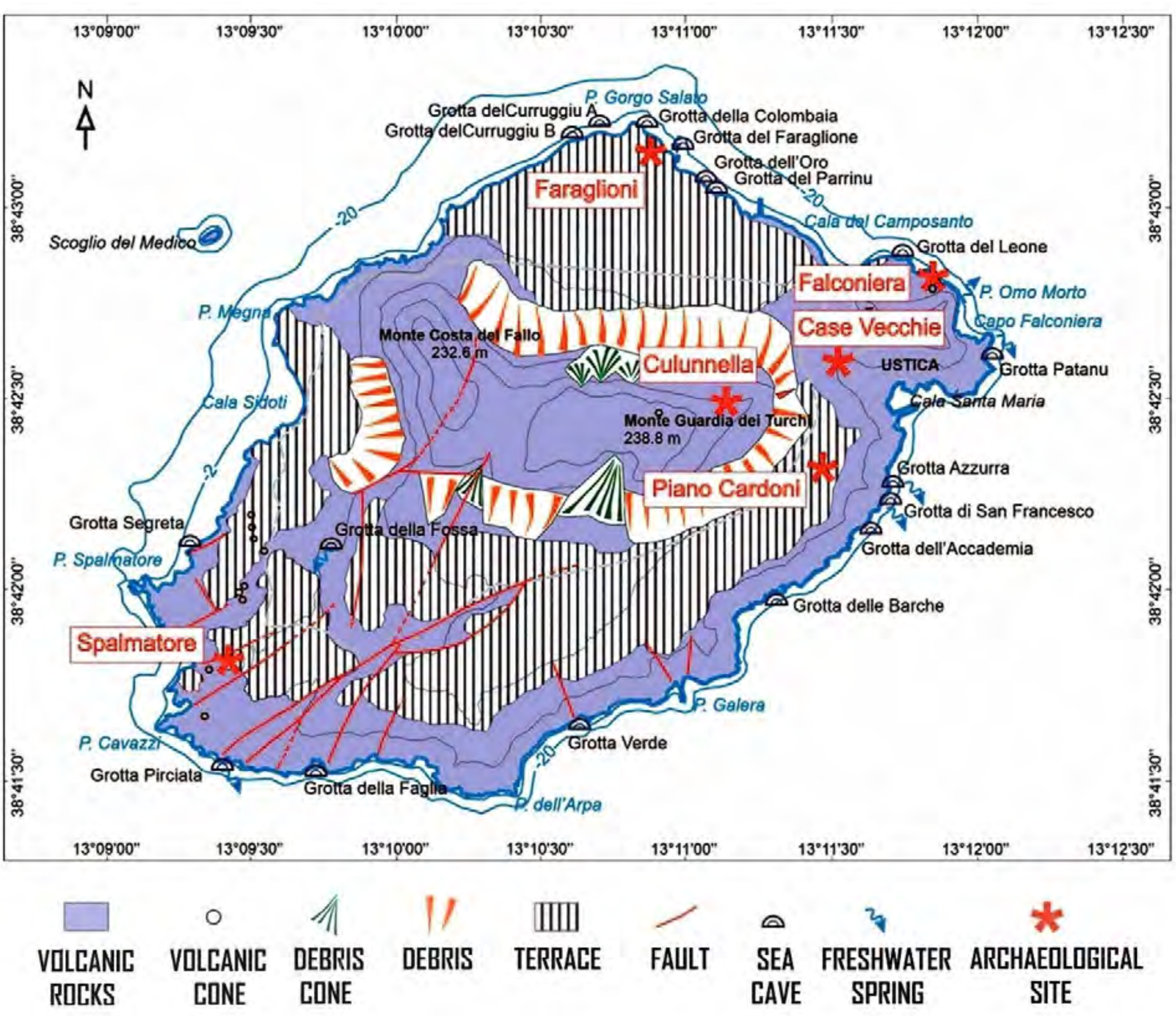


Fig. 2 - Simplified geomorphological map of Ustica island. The asterisks indicate the main archaeological settlements discovered so far. The Villaggio dei Faraglioni MBA site is in the coastal northern cusp of the island. Modified from Foresta Martin & Furlani, 2021.

water harvesting (Foresta Martin & Furlani, 2021). Sea caves may have provided up to 100 liters of dripping water per day (Foresta Martin & Furlani, 2021). Rainwater, which also fed the cave drippings, is more difficult to be quantified as it depends on seasonal and decadal cycles and regional atmospheric patterns. Following Ustica's reoccupation in the Hellenistic-Roman period, a far more advanced system for rainwater collection was developed, including an extensive network of cisterns for water storage, similar to those found in other Mediterranean settings (Yannopoulos et al., 2016). The island remained again inhabited since the 13th century, during the Middle Ages, except for a small community with an agricultural and pastoral vocation was established around a Cistercian monastery, in the Case Vecchie area (Fig. 2). This settlement, however, was short-lived due to the growing frequency of incursions by North African pirates, which compelled the inhabitants of Ustica to abandon the island, rendered increasingly unsafe by raids and abductions (Barraco Picone, 2007). Following almost five centuries of abandonment, in the second half of the 18th century, a new community, composed of settlers from Lipari, established a permanent presence on Ustica at the behest of the Bourbon government, founding the present-day town of Ustica near Cala Santa Maria (Fig. 2), on its southeastern coast (Barraco Picone, 2007). Throughout the 19th and 20th centuries the growing need for drinking water was supplied by tank ships, whereas today it is provided by a desalination plant.

2.2. Mediterranean climate framework

Both mid- and low-latitude climate systems exert a seasonally variable influence on the Mediterranean region. In summer, subtropical high-pressure fields establish stable, dry and warm conditions across the Mediterranean (Lionello, 2012). In winter, the North African subtropical high weakens and shifts southward, allowing cold polar/continental air outbreaks and rainy westerlies to penetrate the Mediterranean basin (Lionello, 2012; Rohling et al., 2015).

The North Atlantic Oscillation (NAO) is a mode of decadal atmospheric variability that largely controls precipitation in the European-Mediterranean region. During positive NAO phases, when the pressure gradient between the Azores High and the Icelandic Low is stronger, wet westerlies bring winter precipitation to central and northern Europe, while southern Europe and North Africa experience drought. This pattern reverses during negative NAO phases (Hurrell, 1995; Wanner et al., 2001). Persistent positive or negative NAO phases have been identified over longer timescales, based on proxy data, for preindustrial climate and societal changes such as the Roman Period, the Medieval Climate Anomaly, and the Little Ice Age (Luterbacher et al., 2001, 2004; Trouet et al., 2009), as well as for the Holocene (Olsen et al., 2012; Smith et al., 2016).

Although the Mediterranean Sea's thermohaline circulation does not significantly impact the global climate system, the outflow of salty intermediate-depth water through the Strait of Gibraltar may have enhanced water density and contributed to North Atlantic Deep Water formation during Heinrich stadials, potentially aiding in the resumption of the Atlantic Meridional Overturning Circulation (Rogerson, 2012; Rogerson et al., 2010). Nonetheless, palaeoceanographic data from deep Mediterranean Sea sediments provide valuable insights into past climate regimes and events. Among other indicators, variations in sea surface temperature, calcareous plankton productivity and seafloor ventilation reflect water column dynamics associated with different atmospheric patterns. The paleoclimatic proxy data relevant to this study are presented in detail in the next section (3. Materials and Datasets).

3. MATERIALS AND DATASETS

3.1. The Faraglioni Village chronology

Since the early 1970s, thirteen excavation campaigns have been conducted at the Faraglioni Village under the direction of three different archaeologists: four by Giovanni Mannino between 1974 and 1980; four by Robert Ross Holloway between 1990 and 1999; and a further five by Francesca Spatafora from 2000 to 2018 (Spatafora, 2023; Spatafora personal communication, 2025).

The extensive body of scientific literature resulting from these excavations broadly agrees in identifying a settlement that persisted for approximately two or three centuries, from 1450-1400 BCE to 1200-1150 BCE. This chronology is supported by a rich and diverse assemblage of tableware and storage pottery, whose shapes and decorative styles align with the Thapsos-Milazzese cultural facies of eastern Sicilian MBA. "Thapsos" refers to the eponymous site on the Magnisi Peninsula near Syracuse, while "Milazzese" relates to the homonymous village on Panarea in the Aeolian Islands (Spatafora, 2016; Spatafora & Mannino, 2008).

Among the most characteristic ceramics of this cultural tradition are high-footed cups (which in Ustica feature a ribbed stylistic variant), 'teglie' with internal handles, vases and amphorae of different sizes (Figs 3 and 4). Thapsos-Milazzese facies can be securely dated due to their close association with imported Mycenaean pottery from the Aegean, for which robust radiocarbon absolute chronology have been established (Alberti, 2013 and references therein).

Interestingly, in Ustica the presence of unequivocal Mycenaean imports is limited to a single fragment of a stirrup jar (Fig. 5) and a few glass beads recovered during Holloway's excavations (Holloway, 1995). This scarcity has sparked debate among archaeologists as to whether it reflects the absence of Mycenaean materials in the areas excavated thus far, or a genuine lack of trade connections between Ustica and the Aegean world.

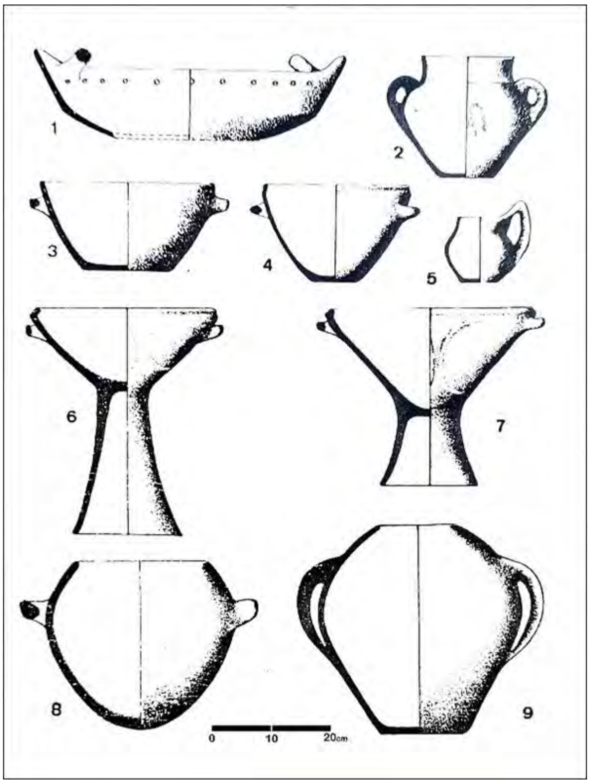


Fig. 3 - The main vascular forms of the abundant pottery recovered during the excavations at the Villaggio dei Faraglioni in Ustica. All stylistically recall the pottery of the Thapsos-Milazzese facies, typical of the MBA, but with some stylistic variants exclusive to Ustica. 1: "Teglia" (large flat plan), with internal handles. 2, 3,4: Medium-fine ware vessel with two handles. 5: Jug with one handle. 6: Cup with high trumpet foot and double handle. 7: Cup with short trumpet foot and double handle. 8, 9: Small two-handled amphorae. Modified from Mannino, 1982.

Holloway (1995) submitted eight samples from the Faraglioni Village to the Laboratory of Isotopic Geochemistry at the University of Arizona in Tucson for radiocarbon (^{14}C) analysis, whose results are shown in Table 1. Due to the advances in the calibration curves over the last 30 years, we carried out a new calibration of Holloway's radiocarbon datings by OxCal v4.4.4, with the atmospheric data by Reimer et al. (2020). No significant mismatch exists between the two different calibrations (Table 1): most of results overlaps the traditional archaeological chronology, with a settlement which persisted from 1450-1400 BCE to 1200-1150 BCE; two calibrated ages fall outside the expected archaeological timeframe. Different authors complain lacking information on examined materials and suggest that the site may have been shortly re-occupied (Leighton, 2004; Spatafora, 2009); one calibrated age indicate a much earlier occupation of the site. It may be an outlier and in any case its meaning is beyond the aim of the present paper that deals with the Late Bronze Age abandonment.

Even the chronological development of the urban plan of the Faraglioni Village towards a more orderly and rational layout, characterized by a main road axis flanked by a sequence of huts and courtyards, with secondary streets arranged orthogonally, provides an indication, albeit indirect and approximate, of its construction period. It is the shared view of the archaeologists who have worked on the site that this more advanced layout, stratigraphically datable to the final phase of the Village's existence, is connected to contemporary urban planning practices in Eastern Sicily, notably at Thapsos, which were themselves influenced by Mycenaean housing culture (Fig. 6) (Holloway, 1995; Spatafora & Mannino, 2008).

3.2. Holocene climatic cycles

In our study, archaeological and demographic data were converted from BCE or CE to BP, where year 0 corresponds to 1950 CE.

The Holocene, the current interglacial period that began 11.7 ka ago, was long considered climatically stable, characterized by a long-term cooling trend, with only one major climatic deterioration event at 8.2 ka (Alley et al., 1997). Bond et al. (1997, 2001) were the first to identify a complete sequence of Holocene suborbital fluctuations, known as Bond cycles, based on peaks of ice-rafted detritus (IRD) deposited in the high-latitude North Atlantic. These cycles exhibit the same 1,470-year periodicity as the last glacial Dansgaard-Oeschger events. However, unlike Dansgaard-Oeschger events, episodes of Atlantic Meridional Overturning Circulation (AMOC) slowdown do not perfectly align with Bond cycles, nor does solar variability provide a definitive explanation (Bond et al., 2001; Oppo et al., 2003).

Bond cycles closely resemble Rapid Climatic Changes (RCCs), a series of climatic anomalies recorded at more than 50 sites worldwide (Mayewski et al., 2004). Rather than being strictly cooling events, RCCs represent local climatic anomalies, such as droughts, intensified atmospheric circulation, or glacier advances (Mayewski et al., 2004). Focusing on the mid-to-late Holocene, which is particularly relevant for archaeological and historical studies, a well-established link exists between RCCs and sunspot minima. These minima were often accompanied by explosive volcanic eruptions that released sulfur, which subsequently transformed into highly reflective sulfate aerosols in the atmosphere (Maasch et al., 2005; McGregor et al., 2015).

The following section introduces the paleoclimatic proxy data presented in Figs 7 and 8 to ensure a smooth discussion. All data are shown according to their original age models, with dating uncertainties generally within a few hundred years.

IRD peaks in the North Atlantic were deposited during the coldest phases of both the last glacial period and the Holocene, when Northern Hemisphere ice sheets expanded, leading to their destabilization and the subsequent release of massive numbers of icebergs (Bond et al., 1997, 2001; Hemming, 2004).

Fig. 4 - Pottery recovered during excavations at the Villaggio dei Faraglioni, on display at the 'Seminara' Archaeological Museum in Ustica. From left, top: cups on a high foot; big pot supported by two 'alari'; large containers for storing grain, cereals and oil. Photo by FFM.

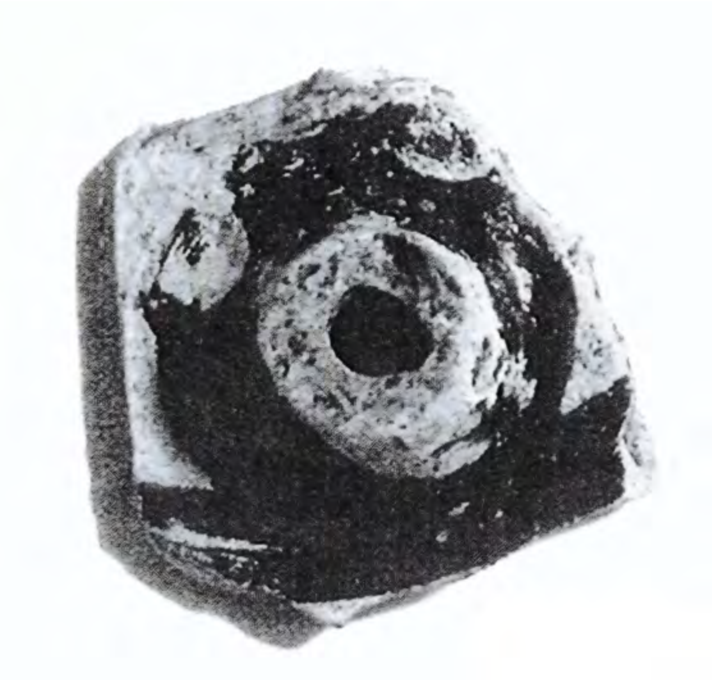
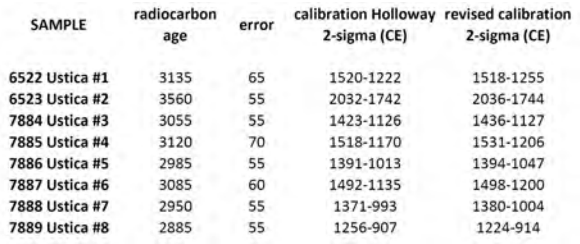


Fig. 5 - The only Mycenaean vase fragment found so far at the Faraglioni Village of Ustica. The find dates back to the excavations carried out by Holloway in the first half of the 1990s. From Holloway, 1995.



SAMPLE	radiocarbon age	error	calibration Holloway 2-sigma (CE)	revised calibration 2-sigma (CE)
6522 Ustica #1	3135	65	1520-1222	1518-1255
6523 Ustica #2	3560	55	2032-1742	2036-1744
7884 Ustica #3	3055	55	1423-1126	1436-1127
7885 Ustica #4	3120	70	1518-1170	1531-1206
7886 Ustica #5	2985	55	1391-1013	1394-1047
7887 Ustica #6	3085	60	1492-1135	1498-1200
7888 Ustica #7	2950	55	1371-993	1380-1004
7889 Ustica #8	2885	55	1256-907	1224-914

Tab. 1 - Revised calibrations of radiocarbon datings at Villaggio dei Faraglioni by Holloway (1995). From the left: sample laboratory code; radiocarbon age and its uncertainty; calibration by Holloway (1995) in years BCE; revised calibration by OxCal v4.4.4 (Bronk Ramsey, 2021), with the atmospheric data by Reimer et al. (2020).

Sea Surface Temperature (SST) estimates are derived from different ‘paleothermometers,’ i.e., various analytical techniques. Among fossil organic compounds, alkenones are the most commonly used, while in inorganic geochemistry, the Mg/Ca ratio in calcite shells is the primary method.

Solar magnetic activity decreases during periods of low sunspot numbers, leading to an increased flux of galactic cosmic rays in the Earth's outer atmosphere, which enhances the production of ^{14}C and ^{10}Be (Finkel & Nishiizumi, 1997; Hughen et al., 2000; Stuiver et al., 1998). The total solar irradiance (TSI, in W/m²) reconstruction used in this study is based on measurements of cosmogenic ^{10}Be in ice cores (Steinhilber et al., 2009).

Net primary productivity estimates in the Sicily Channel are based on a regional calibration between the percentage values of the coccolithophore species *Florisphaera profunda* in 43 surface sediment samples and ten years of net primary production data at the same sites, derived from satellite imagery. Chlorophyll estimates obtained via remote sensing were converted into milligrams of carbon per square meter per day (mgC m^{-2} d^{-1}) using the standard algorithm of the Vertically Generalized Production Model (Behrenfeld & Falkowski, 1997). The regression equation follows a logarithmic function, with R=0.84 (Incarbona et al., 2008).

High concentrations of non-sea-salt K^+ in Greenland ice cores serve as a proxy for intensified atmospheric circulation in the Northern Hemisphere and an expanded Polar Vortex (Mayewski et al., 1997; Meeker & Mayewski, 2002).

Local cave investigations have established a link between oxygen isotope variations in speleothems and regional rainfall levels. Light and heavy $\delta^{18}O$ values correspond to wet and dry conditions, respectively. Decadal - and centennial-scale variations in the Cueva de Asiul speleothem moisture record align with European reconstructions of NAO variability over the past 2.5 kyr (Smith et al., 2016).

4. DISCUSSION

The centuries-old abandonment phase of Ustica Island, occurring between 3.2-3.15 and 2.25 ka BP, aligns perfectly with the Bond cycle B2, a Rapid Climate Change (RCC) interval, and the Mediterranean Sea Surface Temperature (SST) cooling event known as the 3.2 ka event (Bond et al., 1997, 2001; Marriner et al., 2022; Mayewski et al., 2004) (Figs. 7A-B). This indicates that the island remained uninhabited during a period of global and regional climatic deterioration. As with other late Holocene RCCs, this phenomenon is associated with three distinct phases of sunspot minima, including the Homeric minimum between 2.8 and 2.55 ka BP (Martin-Puertas et al., 2012; Steinhilber et al., 2009) (Fig. 7C), as well as with stratospheric sulfate injections from unknown explosive volcanic eruptions (Sigl et al., 2022), which contributed to global cooling (McGregor et al., 2015). Evidence of glacier advances in Central Asia, the Southern Hemisphere, North America, and Scandinavia (Denton & Karlén, 1973; Haug et al., 2001) confirms the widespread nature of this phenomenon, which is thought to have been extremely rapid and effective (Krishnamohan et al., 2019; McGregor et al., 2015).

At a regional scale, the phase of Ustica’s abandonment coincides with a ~2°C cooling recorded in the Tyrrhenian core BS 79-38 (Sbaffi et al., 2001) (cooling event C2 in Fig. 7D), located just a few nautical miles away (Fig. 1A), and with an increase of ~15 gC m² yr^{-1} in net primary productivity at the Sicily Channel ODP 963 Site (Incarbona et al., 2008) (Fig. 7E). The combination of these two proxies, from both northern and southern Sicily offshore locations, suggests the arrival of pro-

Fig. 6 - Two aerial perspectives of the Villaggio dei Faraglioni. On the left, in the view from the north-east, the two stacks and the high cliff coast are highlighted. On the right, from the north-west, the orderly urban layout of the town can be appreciated, characterized by a main road with huts and courtyards at its edges. Drone photo respectively by INGV and V. Ambrosanio.

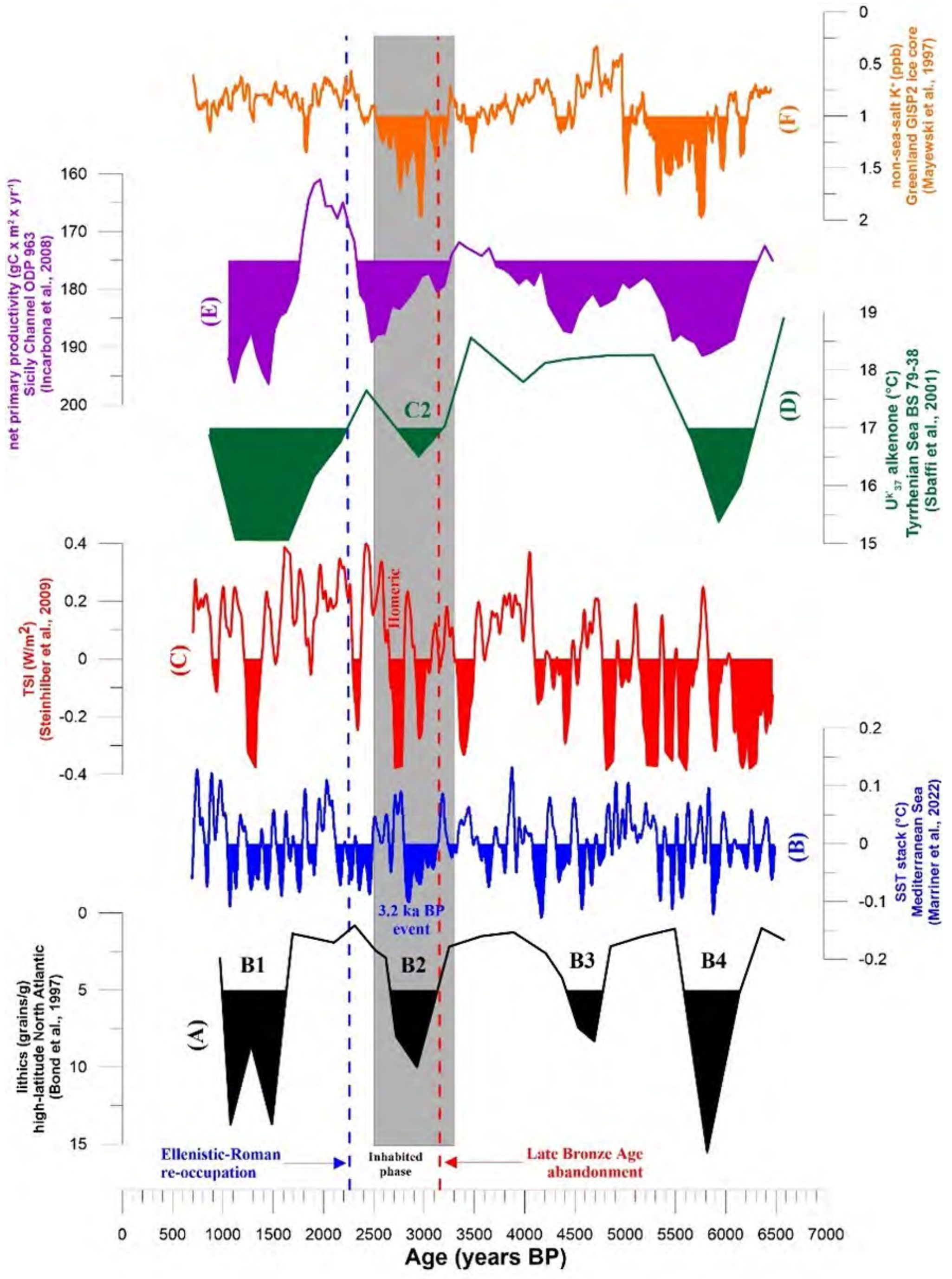


Fig. 7 - Late Bronze Age abandonment (red dashed line) and Ellenistic-Roman re-occupation (blue dashed line) at Ustica Island and selected paleoclimatic records. (A) Ice rafted detritus (grains/g) from North Atlantic, note the reversed axis. The black line has an infilling above 5 grains/g (Bond et al., 1997. B1-B4 are Bond cycles. (B) Mediterranean SST (°C) stack. The blue line is a running average of xx points, with an infilling below 0 (Marriner et al., 2022). The cooling of the 3.2 ka BP event is labelled (C) Total solar irradiation (W/m^2). The red line is a running average of xx points, with an infilling below 0 (Steinhilber et al., 2009). The Homeric sunspot minimum is shown. (D) Sea surface temperatures (°C) in the Tyrrhenian Sea core BS 79-38 (Sbaffi et al., 2001). The green line has an infilling below 17°C. The cold event C2 is shown. (E) Net primary productivity estimates (mgC x $^{m-2}$ x d^{-1}) in the Sicily Channel ODP Site 963, note the reversed axis. The purple line has an infilling above 175 mgC x $^{m-2}$ x d^{-1} (Incarbona et al., 2008). (F) K$^+$ (ppb) in Greenland GISP2 ice cores, note the reversed axis. The orange line is a running average of xx points, with an infilling below 1 ppb (Mayewski et al., 1997). The light grey shadow indicates the Rapid Climate Change of the Late Bronze Age (Mayewski et al., 2004). All curves are plotted *versus* age expressed in years BP. Late Bronze Age abandonment and Ellenistic-Roman re-occupation ages were converted into years BP.

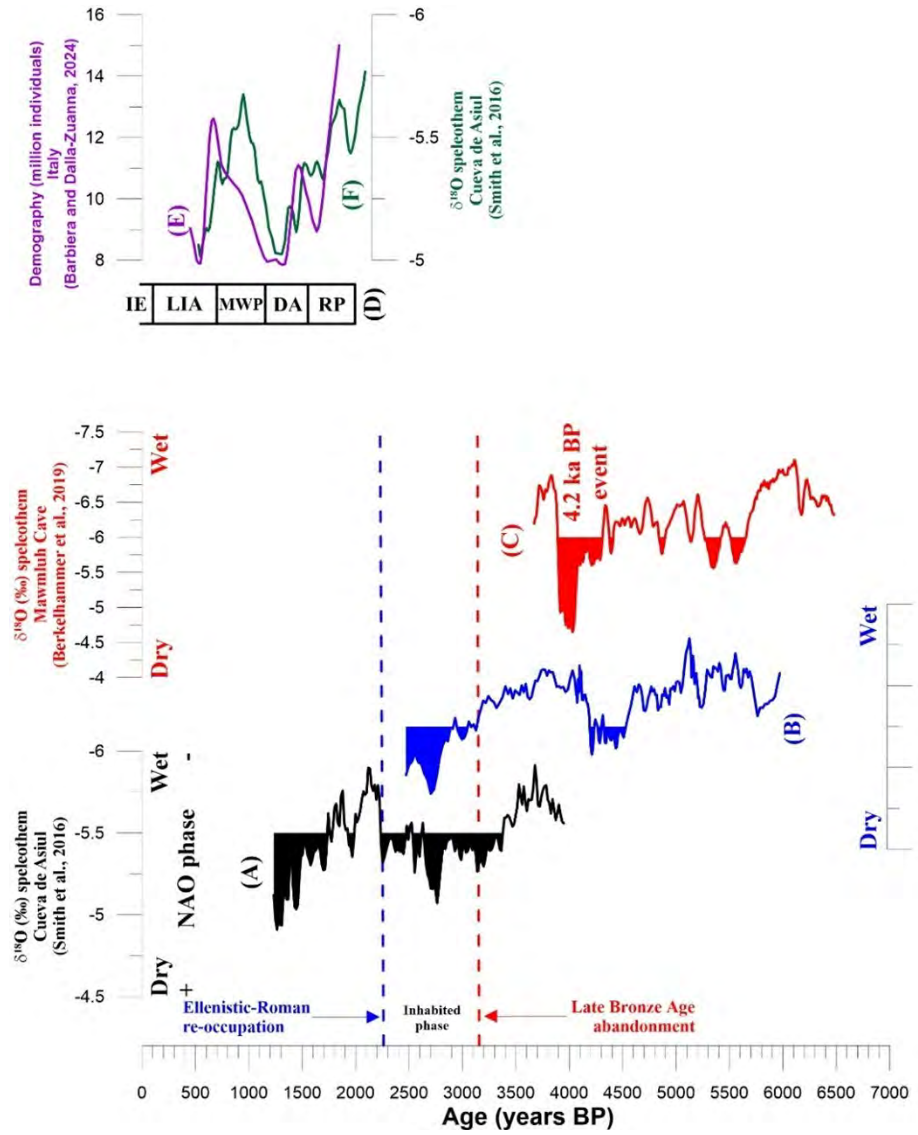


Fig. 8 - Late Bronze Age abandonment (red dashed line) and Ellenistic-Roman re-occupation (blue dashed line) at Ustica Island and selected paleoclimatic records. (A) d^{18}O values (‰) in Cueva de Asiul speleothem, note the reversed axis. The black line has an infilling above 5.5 ‰ (Smith et al., 2016). Higher and lower values are respectively associated with dry and wet phases and with prevalent positive and negative NAO phases. (B) d^{18}O values (‰) in Corchia Cave speleothem, note the reversed axis. The blue line is a running average of 3 points, with an infilling above 4.75 ‰. Higher and lower values are respectively associated with dry and wet phases (Isola et al., 2019). (C) d^{18}O values (‰) in Mawmluh Cave speleothem, note the reversed axis. The red line is a running average of 7 points, with an infilling above 6.0 ‰. Higher and lower values are respectively associated with dry and wet phases (Berkelhammer et al., 2012). (D) Preindustrial/Industrial changes in climate and society, following Abram et al. (2016), Büntgen et al. (2016) and Margaritelli et al. (2016). Roman Period; Dark Age; MCA: Medieval Climate Anomaly; LIA: Little Ice Age; IE: Industrial Era. Ages of these periods were converted into years BP. (E) Population variations in Italy (million individuals) between the Imperial Roman period and the Middle Ages in purple line (Barbiera & Dalla-Zuanna, 2024). (F) d^{18}O values (‰) in Cueva de Asiul speleothem, note the reversed axis. The green line is a running average of 5 points. Higher and lower values are respectively associated with dry and wet phases (Smith et al., 2016). All curves are plotted *versus* age expressed in years BP. Late Bronze Age abandonment and Ellenistic-Roman re-occupation ages were converted into years BP.

longed northerly atmospheric outbreaks, which cooled sea surface water and promoted vertical mixing in the water column, thereby fueling nutrient availability in the photic zone (Cortina-Guerra et al., 2021; Incarbona et al., 2008, 2010a, 2016, 2019). The strengthening of atmospheric circulation in the Northern Hemisphere is further supported by the K^+ record from Greenland ice cores (Fig. 7F), a proxy for the expansion and activity of the Siberian High (Mayewski et al., 1997; 2004).

Focusing on atmospheric patterns and precipitation levels, stable isotope records from speleothems in both Cueva de Asiul (Northern Spain) and Corchia Cave (Central Italy) reveal pronounced drought episodes beginning with Ustica's abandonment at 3.15 ka BP (Isola et al., 2019; Smith et al., 2016), which were particularly severe during the Homeric minimum (Fig. 8A-B). Specifically, the speleothem record from Northern Spain suggests that a predominantly positive NAO phase was established (Fig. 8A), leading to arid conditions in southern Europe (Smith et al., 2016). The Central Italian speleothem record indicates reduced precipitation levels (Fig. 8B) (Isola et al., 2019), which likely affected the southern Tyrrhenian Sea as well. A marked drought episode in Sicily between 3.2 and 3.0 ka BP is further supported by paleohydrological data from Lake Pergusa (Magny et al., 2007; Sadori & Narcisi, 2001) and by a definitive water level drop at Lake Preola (Magny et al., 2011). Vegetation opening is evident in different Sicily sites, but it may be due, at least partly, to the increased agricultural and pastoral activities in the Island during the Late Bronze Age (e.g. Bisculm et al., 2012; Calò et al., 2012; Noti et al., 2009; Tinner et al., 2009).

It is worth noting that the pronounced drought affecting Sicily and Ustica between 3.2 and 3.0 ka BP appears to be the culmination of an aridification trend that began on a global and regional scale with the 4.2 ka BP event (Bini et al., 2019). The 4.2 ka BP event represents a major reorganization of the global climate system and marks the beginning of the Meghalayan Stage within the Holocene Series (Walker et al., 2018). Among other impacts, the significant weakening of the East Asian and Indian Summer Monsoons (Fig. 8C) has been linked to societal collapses in Mesopotamia, India, the Tibetan Plateau, and China (Blanco-González et al., 2018; d’Alpoim Guedes et al., 2016; Guo et al., 2018; Ponton et al., 2012; Zhang et al., 2018). In the central Mediterranean, this megadrought event is documented by speleothem records (Isola et al., 2019; Zanchetta et al., 2016), while a decline in arboreal pollen suggests forest opening south of 39°N, similar to Ustica’s geographic setting (Di Rita & Magri, 2019; Tinner et al., 2016). We propose that this long-term aridification trend may have culminated abruptly during the Late Bronze Age, causing severe drought on Ustica. Water scarcity may have led to sanitary issues, such as contamination from animal waste and epidemic outbreaks, and/or crop failure and famine. Although speculative, this hypothesis provides a more plausible explanation for the well-preserved defensive walls, domestic architecture and pottery at Villaggio dei Faraglioni than scenarios involving natural disasters or hostile invasions.

Climate deterioration and drought have long been considered primary drivers of the Late Bronze Age Collapse (~1200 BCE) across the Eastern Mediterranean and Near and Middle Eastern societies. Mycenaean, Aegean, and Anatolian populations fragmented into small settlements, the Hittite Empire collapsed, and both the Assyrian Empire and Egypt’s New Kingdom experienced decline (Drake, 2012; Hazell et al., 2022; Manning et al., 2023; Weiss, 1982). This broad geographical region suffered from socio-economic and political instability, conflicts, migrations, and depopulation. Ustica serves as an especially suitable case study for evaluating the impacts of climate change, as its small geographic extent and limited resources meant that abandonment was the only viable response to climate deterioration and drought.

One might question why Ustica was abandoned specifically between 1200 and 300 BCE, despite multiple previous and subsequent episodes of climate deterioration (Fig. 7). To address this, we must consider Holocene climate evolution. Between 10.5 and 6.0 ka BP, the North African desert nearly disappeared (last Green Sahara phase) due to the northward shift of the Intertropical Convergence Zone, which brought monsoon rainfall over a much wider catchment. At the same time, the Nile River discharged massive volumes of freshwater into the Eastern Mediterranean, leading to the formation of an organic-rich seafloor layer (Grant et al., 2017; Rohling et al., 2015; Tierney et al., 2017). While monsoon rains never reached Mediterranean coastal areas, their intensification coincided with more frequent winter storm tracks from North Atlantic low-pressure systems (Dixit et al., 2020; Toucanne et al., 2015; Wagner et al., 2019). However, peak precipitation in southern Europe may have been slightly delayed, sustaining high moisture availability throughout the Middle Holocene (Capraro et al., 2023; Magny et al., 2013; Peyron et al., 2013; Tinner et al., 2009; Zanchetta et al., 2007). Thus, while earlier climatic deteriorations (e.g., B4 in Fig. 7) provided sufficient rainfall to sustain Ustica’s population, the 4.2 ka BP event marked the first significant regional aridification episode.

The Hellenistic-Roman reoccupation of Ustica followed a general climatic improvement and, crucially, advancements in rainwater harvesting techniques, mitigating the effects of later droughts, including those of the Dark Ages (DA) and the Little Ice Age (LIA, Fig. 8D). Severe droughts occurred in Sicily during the LIA, as documented in historical records (Incarbona et al., 2010b; Piervitali & Colacino, 2001) and may have contributed to make the island uninhabitable between the 13th and 18th century, which is indeed ascribed to pirate raids by historians. While no ancient demographic estimates exist for Ustica or Sicily, data from the Italian Peninsula (6th-15th century CE) (Barbiera & Dalla-Zuanna, 2024) (Fig. 8E) reveal a striking correlation between population climate variability played a decisive role in Ustica’s Late Bronze Age collapse.

5. CONCLUSION

The hypothesis of severe drought as the cause of the eight-century-long abandonment of Ustica Island has been tested by leveraging advances in Mediterranean paleoclimatology. The unoccupied phase of Ustica Island, between 3.2-3.15 and 2.25 ka BP, coincides with a global and regional period of climatic deterioration. This phase is associated with three distinct sunspot minimum periods (Martin-Puertas et al., 2012; Steinhilber et al., 2009) (Fig. 7C) and explosive volcanic eruptions (Sigl et al., 2022), which contributed to global cooling (McGregor et al., 2015). This interval is also characterized by SST cooling in the southern Tyrrhenian Sea and increased primary productivity in the Sicily Channel (Sbaffi et al., 2001; Incarbona et al., 2008), suggesting that prolonged atmospheric perturbations led to cooler sea surface temperatures and enhanced vertical mixing in the water column.

Climatic deterioration is coupled with severe drought, as inferred from speleothem oxygen isotope records in North Spain and central Italy, as well as lake level drops in Sicily (Isola et al., 2019; Magny et al., 2007, 2011; Sadori & Narcisi, 2001; Smith et al., 2016). A predominantly positive NAO phase may have contributed to aridification across southern Europe, the Near East, and the Middle East, where numerous societies declined or collapsed (Drake, 2012; Hazell et al., 2022; Manning et al., 2023; Weiss, 1982).

The drought in Sicily and Ustica between 3.2 and

3.0 ka BP may represent the culmination of an aridification trend that began on both regional and global scales following the 4.2 ka BP event (Bini et al., 2019), likely leading to epidemic outbreaks and famine. Analyzing the Holocene climatic evolution of the region suggests that previous episodes of climate deterioration still provided sufficient rainfall to sustain Ustica's population. After the Hellenistic-Roman reoccupation (3rd century BCE), significant advancements in rainwater harvesting techniques mitigated the effects of subsequent droughts, including those during the Dark Age (DA) and the Little Ice Age (LIA) (Fig. 8D). However, the close correlation between population fluctuations in Italy and North Spain speleothem oxygen isotope records (Barbiera & Dalla-Zuanna, 2024; Smith et al., 2016) over the 6th to 15th centuries CE (Fig. 4E-F) highlights the pervasive influence of climate variability, even on more advanced societies. This relationship in historical times further supports the hypothesis that climate change played a critical role in the Late Bronze Age Collapse at Ustica Island.

This case study underscores the importance of an interdisciplinary approach that integrates paleoclimatic and archaeological records to understand past societal responses to environmental change.

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