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A B S T R A C T

The Holocene colonisation of islands by humans has invariably led to deep-seated changes in landscape dynamics and ecology. In particular, burning was a management tool commonly used by prehistoric societies and it acted as a major driver of environmental change, particularly from the Neolithic onwards. To assess the role of early human impacts (e.g. livestock grazing, forest clearance and the cultivation of marginal land) in shaping "pristine" island landscapes, we here present a 350-year record of fire history and erosion from Malta, straddling the earliest peopling of the island. We show that recurrent anthropogenic burning related to Neolithic agro-pastoral practices began ~7500 years ago, with well-defined fire-return intervals (FRI) of 15–20 years that engendered erosion and rapid environmental degradation. As early as the Neolithic, this study implies that, in sensitive insular contexts, just a few generations of human activities could rapidly degrade natural islandscapes.

1. Introduction

The arrival of even small human populations to uninhabited lands can lead to permanent vegetation shifts, extended biomass burning and increased erosion (Butzer, 2005; Rull et al., 2015). Islands, in particular, are extremely sensitive to these widespread ecological transformations (Burjachs et al., 2017), especially when fire is used as a tool of landscape modification and management (Jouffroy-Bapicot et al., 2016). Early human societies used fire in technology, social organisation, subsistence, to manipulate the environment, for clearing occupation areas, and even in warfare (Pausas and Keeley, 2009; Glikson, 2013). With a surface area of just 246 km^2, Malta constitutes a unique laboratory to explore the ecological dimensions of early human impacts - and associated environmental tipping points - in a Mediterranean island context (Guilaine, 2003; Broodbank, 2013; French et al., 2018). The island has a long and complex history of human occupation, stretching back at least ~7500 years cal. BP (Cassar, 1997). These early settlers formed communities and introduced agriculture (Bonanno, 2011). They were able to manage the transfer of animal stocks and domesticated plants that necessitated robust sea-craft and navigational skills, as well as bring knowledge of managing "founding stocks" of animals (Bonanno, 2011). By 4100 BCE, the island had developed a rich Neolithic culture, most enduringly expressed by

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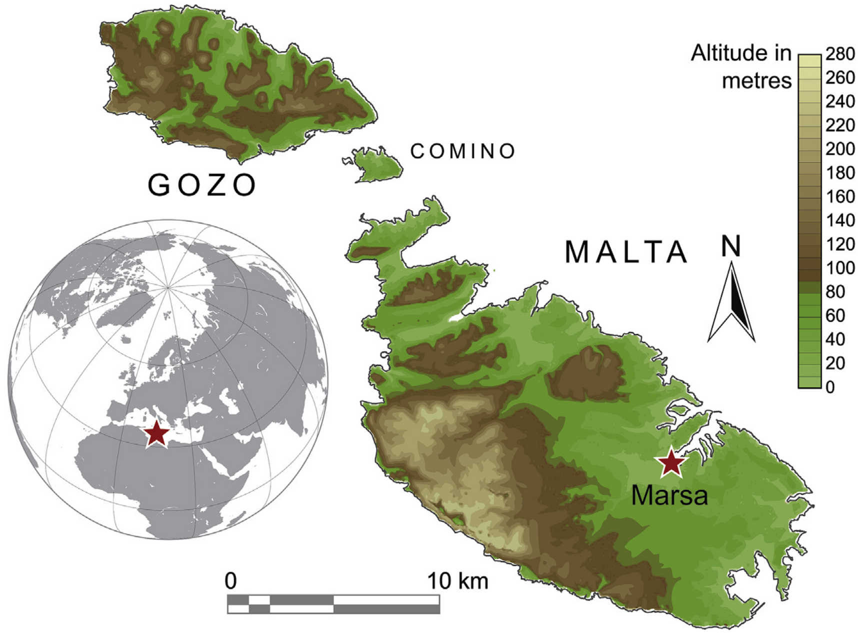

Fig. 1. Location map of Malta and the core site on the Marsa floodplain.

its megalithic architecture, unparalleled elsewhere in the Mediterranean at this time (Evans, 1971; Vella, 2013).

Here, we couple high-resolution palaeoecological and geochemistry data to provide a new perspective on human impacts and ecosystem dynamics in Mediterranean island contexts, at the time of Malta's earliest peopling. Our study focuses on a fine-grained sediment archive from the Marsa floodplain, Malta's largest catchment area that drains ~20% of the island (Fig. 1). These new records of regional land-use supplement site-specific archaeological data, which, at present, are extremely sparse for this key, yet poorly understood, period of Malta's prehistory. In particular, Malta's small island status – it is a mere 27 km long – allows us to probe and better understand the possible impacts of Neolithic societies on a "pristine" Mediterranean environment, within the context of wider debate on the Early Anthropocene Hypothesis (Ruddiman, 2007) and human-driven changes in Mediterranean fire regimes during the early Neolithic (Vannière et al., 2016).

2. Methods

A continuous sediment core was extracted from the Marsa floodplain in 2011 (Fig. 1; Figs. SM1-2), using a mechanised percussion coring system. The floodplain lies at the head of a well-protected coastal ria. The Marsa catchment is Malta's largest, with a surface area of 50 km^2, draining ~20% of the island. The geology of the watershed is dominated by limestones of Miocene age (Pedley et al., 1976) that are dissected by an intricate system of *widens*, short Mediterranean-type watercourses that carry water and sediment during the wet season and flash-flood events. Today, the Marsa watershed is heavily artificialised, with a shallow soil cover (20–60 cm) made-up of terra rosa, xerorendzinas and carbonate raw soils (Lang, 1960). The soils are easily eroded under a climatic regime of long dry summers and a wet season in which rain frequently falls in heavy showers. At present, rainfall averages 529.6 mm per annum and is characterised by a marked seasonal distribution, with ~70% of the total falling between October to March (Chetcuti et al., 1992). In many areas, the valley sides and floors have been eroded to bare rock. Similar to other islands and coastal areas in the Mediterranean region, the vegetation of Malta is influenced by the intense heat and low precipitation experienced during the summer months, as well as the human activity that has increased in the area over the last millennia (Grove and Rackham,

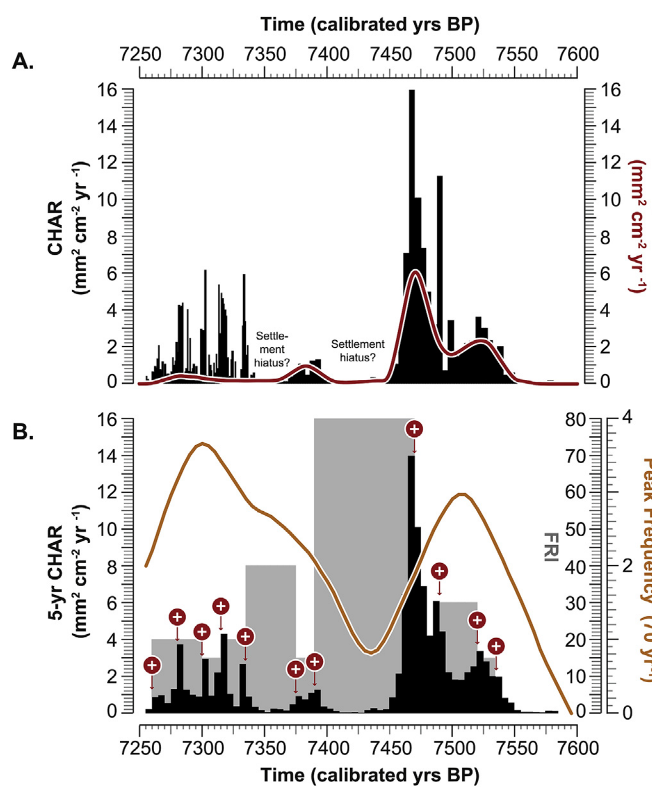

Fig. 2. (A) Charcoal Accumulation Rates (CHAR) and (B) Background Charcoal Accumulation Rates (BCHAR) and Fire-Return Intervals (FRI) from the Marsa floodplain, for the period 7600 to 7250 cal years BP. The encircled crosses denote statistically-defined fire events. Fire was intentionally used to create open, matorral vegetation communities, conducive to both grazing and cultivation.

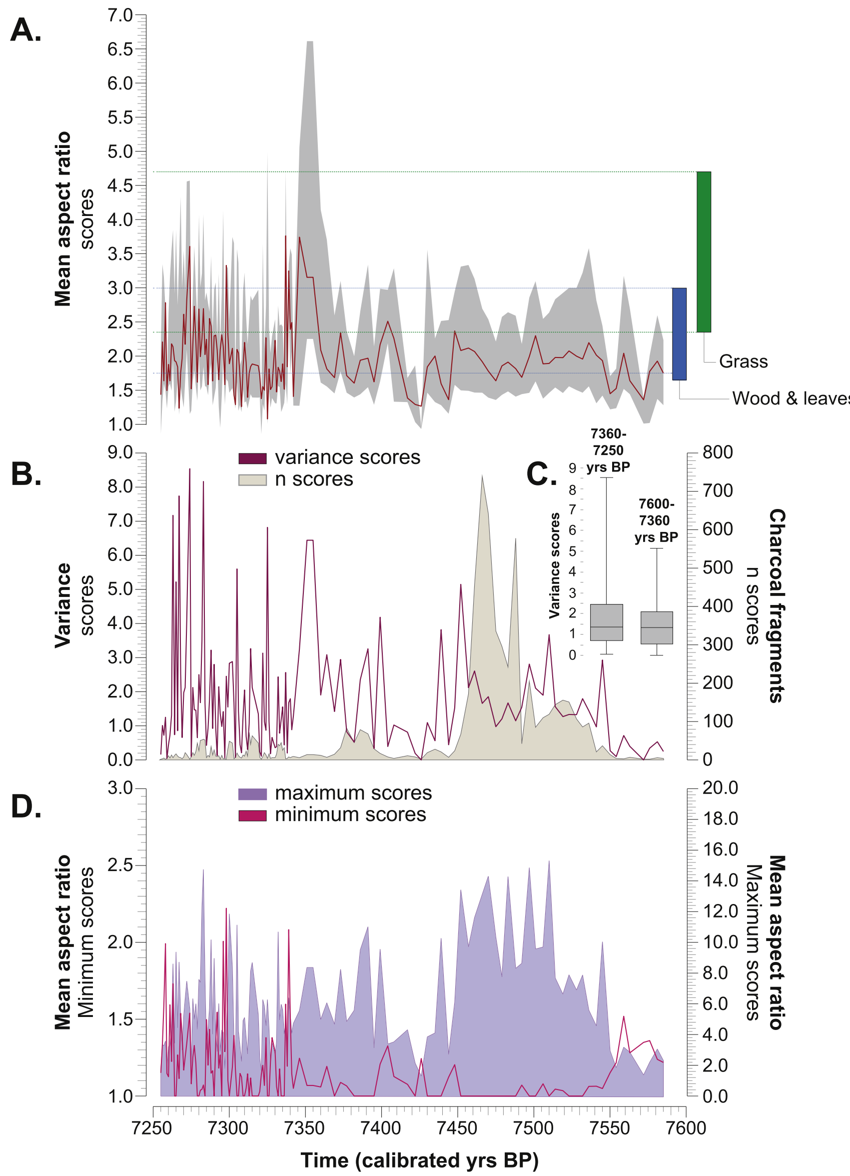

Fig. 3. (A) Mean aspect ratios (AR) of charcoal fragments from the Marsa record. The red line denotes the mean AR score and the upper and lower boundaries of the grey envelope the 25th and 75th percentiles. (B) AR variance scores plotted against the charcoal number. (C) Boxplots of the AR variance between 7600 and 7360 yrs BP and 7360-7250 years BP. (D) Minimum and maximum mean AR scores. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2001; Carroll et al., 2012; Gambin et al., 2016). The three main semi-natural vegetation types presently found on the island are maquis (*Ceratonia siliqua*, *Olea europaea*, *Pistacia lentiscus*, *Rhamnus alaternus* and *R. oleoides*), garrigue (*Thymbra capitata*, *Erica multiflora*, *Euphorbia melitensis*, *Teucrium fruticans* and *Anthyllis hermanniae*) and steppe (*Lygeum spartum* (clay slopes) *Hyparrhenia hirta*, *Andropogon distachyus*, *Brachypodium retusum*, *Stipa capensis*, *Aegilops geniculata*, *Carlina involucrata*, *Notobasis syriaca*, *Galactites tomentosa*, *Asphodelus aestivuus*, and *Urginea pancration*); along with some smaller community types, such as woodland and coastal wetlands, as well as freshwater, sand dune and rocky habitats which are all important for the rare endemic species that can be found within them (Schembri, 1997).

The core was described, wrapped and labelled in the field, then exported to the CEREGE geoscience facility in Aix-en-Provence, where core sections were longitudinally split. We performed high-resolution measurements (0.5 cm) for Fe, Ti and Ca using an XRF core scanner (ITRAX, Cox Analytical Systems) with a Chromium X-ray source (35 kV, 35 mA) and a 30 s count time. On the basis of the core's radiocarbon chronology, we pinpointed the period around 7500 cal years BP (Fig. SM3; Table SM1) that, according to the archaeological record, corresponds to the earliest peopling of Malta. The core section in question was sampled at continuous 1-cm intervals ($n = 141$ samples), with each sample representing a time period of between 1 and 4 years. This exceptionally short temporal resolution is ideal for resolving rapid human impacts, management techniques and landscape degradation at the onset of Malta's Neolithic history. Variations in the influx of charcoal particles were used to provide the primary record of past fires. 1-cm^3 samples were prepared using classic charcoal preparation techniques (Vannière et al., 2008). Samples were gently washed through a 150 μm sieve. Charcoal fragments were subsequently extracted - in water and using a pipette in order to avoid breakage - under a binocular microscope and placed in a petri dish. Digital photographs and the image-processing computer program ImageJ were used to precisely quantify the surface area of charcoal

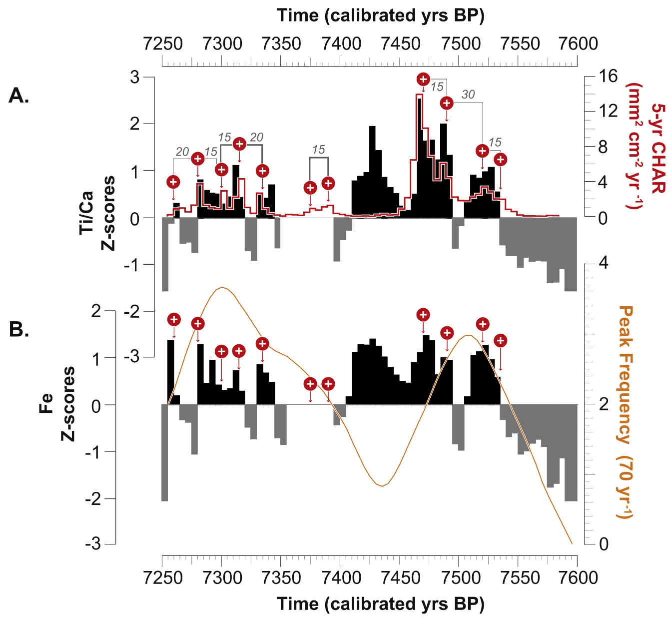

Fig. 4. Geochemical indicators of erosion, namely z-transformed Ti/Ca (A) and Fe (B). These are plotted against the 5-yr CHAR (A) and 70 yr-1 Peak Frequency (B) on the left. The encircled crosses denote statistically-defined fire events.

fragments per 1 cm^3 of sediment aggregate. All charcoal data are reported in mm^2/cm^3 of sediment (Fig. SM4). There was a robust correlation between the surface area of charcoal samples and the number of pieces in each chronostratigraphic level ($r^2 = 0.99$), which supports our methodology based on computer-aided image processing. Peaks in charcoal are assumed to represent fire episodes that occurred within or near the Marsa watershed (i.e. at the landscape scale). The image-processing computer program ImageJ was used to calculate charcoal Aspect Ratios (AR) from digital photographs (AR = charcoal [Major Axis]/[Minor Axis]). We analysed 6888 charcoal fragments (Fig. SM5). AR values ranged from 1 to 15.314 (Fig. 2).

All data were analysed using CHAR Analysis, PAST (version 2.17c) and XL-Stat2017. The charcoal concentrations were converted into charcoal accumulation rates (CHAR in $mm^2/cm^{-2}/yr^{-1}$) based on the sedimentation rate estimated from the age-depth model. The CHAR record was resampled and normalised to a timescale of 5 yr cm^{-1}, corresponding to the mean sedimentation rate of the record (5 yr/cm^{-1}). The data were subsequently log-transformed to homogenise variance (Figs. 2–4). The Background component (BCHAR) was estimated with a local polynomial (100-yr moving window), allowing the calculation of the Peak Component (Cpeak=(log)CHAR-(log)BCHAR). Fire episodes were detected using a threshold within the range of values with the lowest sensitivity to the number of peaks detected, derived by plotting a frequency distribution histogram of the peak component. The fire frequency was smoothed using a 70-yr moving window. The process is fully described in the literature (Higuera et al., 2009). The peak component (fire-episode detection) is indicated on a linear age-scale.

Periodicities in the CHAR, Fe and Ti/Ca signals were investigated using a sinusoidal regression (phase Free) to determine the long-term trends and further examined using a wavelet analysis (wavelet transform) with Morlet as the basis function, and spectral analysis (Fig. 5).

3. Results

The charcoal record from Marsa supports the occurrence of extensive human-induced ecological changes and burning of vegetation stands at the time of the earliest peopling of Malta, around 7500 cal years BP (Fig. 2). Charcoal volumes ranged from 0 to 63.8 mm^2/cm^3 (739 pieces/mm^2/cm^3), with a mean of 3.95 mm^2/cm^3 (49.75 pieces/mm^2/cm^3) and a median of 1 mm^2/cm^3 (13 pieces/mm^2/cm^3). All charcoal volumes were converted into Charcoal Accumulation Rates (CHAR) and then analysed using the method of charcoal signal decomposition developed by Higuera et al. (2009). Statistical analyses detected eleven fire episodes between 7600 and 7250 cal years BP, with a maximum frequency of 3.67 and a minimum of 0.01 fire episodes every 70 yr^{-1}. The early peopling of the Marsa watershed is expressed by four well-defined influxes of charcoal: (1) a first, more minor, peak (CHAR ~3.5 $mm^2/cm^{-2}/yr^{-1}$) centred on ~7535 cal years BP, followed by a second inflection of similar amplitude ~15 years later; and (2) a third pronounced and two-pronged peak spanning ~7490 to 7465 cal years BP (maximum CHAR ~16 $mm^2/cm^{-2}/yr^{-1}$). Four fire episodes attest to close and regular fire-return intervals (FRI) of ~15 years, beginning ~7535 cal years BP. Two fire episodes are recorded between ~7390 and 7375 cal years BP, with a further five at ~7335, 7315, 7300, 7280 and 7260 cal years BP.

The landscape dimensions of early anthropogenic fire activity were explored using high-resolution XRF data. Specifically, Fe counts and Ti/Ca ratios were employed as proxies for watershed soil erosion during the early peopling of Malta, between 7600 and 7250 cal years BP. These geochemical tracers have been shown to be valuable tools in tracking erosion processes (Brisset et al., 2013). To be consistent with the CHAR record, the geochemical data were resampled at regular 5-year intervals and z-score transformed (Fig. 4).

For the period 7600 to 7350 cal years BP, concurrent with the human-induced fire episodes at ~7535, 7520, 7490 and 7470 cal. BP, we observe a major change in the geochemical regime. These data suggest that, as the soils lost protection from the vegetation cover, they were rapidly eroded by runoff, with pronounced erosion pulses centred on ~7530, 7515, 7490 and 7470 cal years BP (Fig. 4). For the period ~7600 to 7450 cal years BP, we observe a good correlation between the 5-yr CHAR record and the geochemical tracers of erosion (Ti/Ca, $r = 0.79$; Fe, $r = 0.7$), which attests to a near instantaneous response of Malta's fragile island landscape to vegetation clearance by burning. A third pulse in Fe and Ti/Ca values ~7425 cal years BP, not accompanied by a peak in charcoal concentrations, implies that erosion continued for several decades in the absence of a well-developed vegetation cover.

4. Discussion

Within the Marsa catchment, our data point to extensive human-induced biomass burning (BCHAR) and an unprecedented increase in fire frequency, probably driven by Malta's earliest colonists. We assume that this was done with the aim of clearing the natural landscape for livestock grazing and the cultivation of land, as attest palaeoecological records from elsewhere in the central Mediterranean (Colombaroli et al., 2008; Colombaroli and Tinner, 2013). After ~7470 cal years BP, a FRI of 80 years evokes the possibility of either an occupation hiatus or a decline in the need to burn surrounding areas. The end of this hiatus is marked by two fire episodes between ~7390 and 7375 cal years BP. These events are followed by a further possible break in occupation of ~40 years. More sustained activity in the area is characterised by five regularly-spaced fire episodes at ~7335, 7315, 7300, 7280 and 7260 cal years BP. These human-induced palaeofire cycles of 15–20 years mesh tightly with observed mean fire-return intervals in present human-modified ecosystems of the western Mediterranean (Mouillot et al., 2003; Pausas and Fernández-Muñoz, 2012).

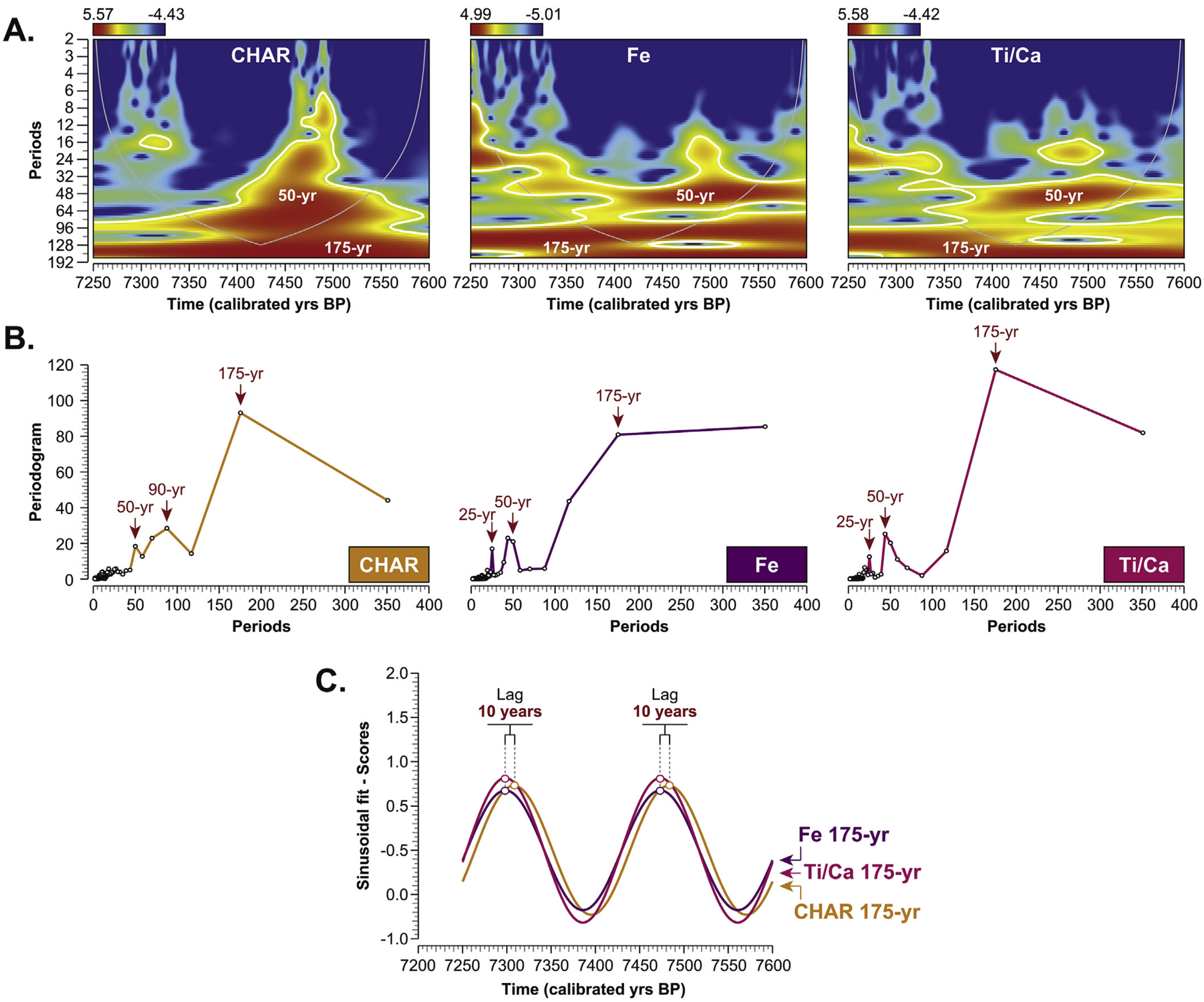

Fig. 5. Wavelet analyses (A), periodograms (B) and sinusoidal fits (C) of the CHAR, TI/Ca and Fe datasets. These underscore a lag in the landscape response to vegetation burning.

Such cycles are consistent with time-dependent shrub-vegetation growth and the accumulation of dry biomass from the understorey vegetation of these ecosystems, reaching maturity every 15–20 years.

Broadly, the CHAR record between 7250 and 7600 cal years BP indicates that the regular cyclicity of Marsa's palaeofire regime was driven by intensifying Neolithic land-use. Climate data from nearby Sicily suggest that this period was relatively "dry", which could have accentuated human-induced fire activity through an increase in dry biomass (Tinner et al., 2009; Magny et al., 2011). Current archaeological data suggest that Malta's early settlers probably originated from Sicily. These populations have been identified through the distinctly decorated pottery known as Stentinello Ware (Sagona, 2015). Whether due to push factors caused by demographic pressures in their homeland and/or due to the pull factor of new unexploited land, a group (or groups) of persons probably undertook the sea-crossing of just over 80 km. They brought with them all the necessary personnel, tools, technological knowledge, seeds and livestock needed to establish a community (or communities) based on agriculture and animal husbandry (Bonanno, 2011). Archaeological layers from this period of early human occupation on Malta show that these early settlers maintained socio-cultural ties with Sicily (Vella, 2008). Such contact would have provided access to a "support network" that could, should the need arise, provide much needed replenishments to the fledgling colony. In turn, this would have led to a scenario in which agriculture — and hence the need for land clearance and management — could be more easily sustained.

In the main, archaeological evidence for the earliest phases of human occupation on Malta has come from two sites: Għar Dalam, a cave just off St George's Bay in the south east of Malta and Skorba, an inland site in the central-northern part of the island. Importantly, some of the pottery found in these early levels is, despite its close semblance to that originating from Sicily, made of local clay, which is easily sourced in various parts of the island (Tanasi and Vella, 2011). The significance of this must not be underestimated. Local clay was being harvested, shaped and decorated in particular styles but it also had to be fired. Nothing is known about the type of kilns used during the early Neolithic period of Malta, as none have yet been discovered. However, with the right techniques and knowledge, pottery can also be produced using pit-firing (Maggetti et al., 2011). Whatever the case, the production of local ware from an emerging and expanding community over the period of study must have contributed somewhat to the exploitation of existing trees and vegetation cover, as evoked by recent palynological studies (Carroll et al., 2012; Djamali et al., 2013).

Experimental studies have demonstrated that charcoal morphometrics can be used to trace the type of fuel burnt during fire events (Jensen et al., 2007). In this instance, we used digital image treatment to calculate charcoal Aspect Ratios (AR, i.e. charcoal [Major Axis]/[Minor Axis]) in order to probe trends in the fuel types used by Malta's earliest Neolithic colonists. Crawford and Belcher (2014), for instance, have shown that wood and leaves generally generate ARs <3, whereas grass tends to produce charcoal with ARs >3. We analysed 6888 charcoal fragments in 141 chronostratigraphic levels (Fig. 3); the maximum AR value was 15.314 and the minimum was 1. Palynological results from the Burmarrad catchment evoke a transition from "natural" to "human-modified" fuel sources, essentially characterised by the burning of forest stands before 7360 cal yrs BP in contrast to a mixed pyrophytic shrub-grassland, comprising *Asphodelus*, *Erica*, *Quercus ilex*, *Pinus*, *Pistacia* and *Sanguisorba*, after this time (Djamali et al., 2013). In the Marsa record, overall charcoal influx between 7600 and 7360 cal yrs BP was 76% greater than in the later phase 7360 to 7250 cal yrs BP. Lower aspect ratio variance in the former period suggests that Malta's pioneer colonists burned a relatively narrow range of fuel stocks (i.e. tree stands, Fig. 3).

For the period 7350 to 7250 cal years BP, the charcoal data show well-defined fire-return intervals of 15–20 years. These results point to the establishment of regular patterned burning related to Neolithic practices in the Marsa catchment. Following the initial landscape disturbances around 7500 cal years BP, erosion pulses slightly lag behind fire episodes (Fig. 5). The wavelet transforms (basis function Morlet) and spectral analyses both display two main periodicities of 175-yr and 50-yr in the fire regime. Using the major 175-yr cycle as a reference period for the long-term trends (Fig. SM6), the sinusoidal regression (phase Free) depicts a clear lag of 10 years between peaks in fire and erosion ($P < 0.001$), suggesting that burning activities played a key role in the degradation of soils.

Our data imply that early Neolithic farming and herding activities on Malta developed in coastal areas and lowlands, much like Sicily at this time (Natali and Forgia, 2018). Although some recent publications do cover environmental and agricultural matters (Bonanno and Vella, 2015) such data remains sparse and relatively unexplored. Of notable interest are ceramic zoomorphic handle fragments, depicting bovine heads, from both Għar Dalam and Skorba (Sagona, 2015). Nonetheless, at present, there are no published archaeological data pertaining to the type of agriculture adopted by Malta's first human populations. This constitutes an important avenue for future research.

5. Conclusion

Global change has sharpened focus on the vulnerability of Mediterranean islands to past, present and future climate modifications (Vogiatzakis et al., 2016). Profound human impacts and climate risk are notable challenges to small islands, such as the Maltese archipelago, because their pressure absorption ability is lower than for continents. Because Malta is bound by its insularity, it is a particularly relevant unit of analysis to probe how past environmental changes and intense human pressures have impacted islandscapes and ecological systems, and contextualise future global change in Mediterranean island settings (e.g. McLaughlin et al., 2018).

The high-temporal resolution of data obtained from the Marsa floodplain allows us to elucidate a heavy human imprint that closely mirrors early human occupation of the island of Malta. These new results provide evidence for deep-seated modification of Malta's landscapes at the time of the earliest peopling of the island, with wider implications for our understanding of anthropogenic disturbances in "pristine" island contexts, as well as ecological tipping points (Reyer et al., 2015).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.03.001.

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