Supplementary Information for:

Climatic subdivision of Heinrich Stadial 1 based on centennial-scale paleoenvironmental changes observed in the western Mediterranean area

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SUPPLEMENTARY INTRODUCTION

Heinrich Stadial 1 (HS1) is one of the most recent and coldest Heinrich Stadials of the last glaciation, described in several marine sedimentary records close to the study area (Salgueiro et al., 2014; Naughton et al., 2016). In this region, some marine records with high sedimentation rates presented two and three-phase division of HS1. For example, two phases were described in Iberian margin marine sedimentary records (Naughton et al., 2009; Salgueiro et al., 2014; Sánchez Goñi et al., 2018) and Neil River Basin (Castañeda et al., 2016), with similar wet conditions during the first phase and arid climate during a second phase. Other paleoclimate studies based on different proxies recorded a three-phase division for HS1, such as those from the Alboran Sea (Fletcher and Sánchez Goñi, 2008; Bazzicalupo et al., 2018), northwestern Mediterranean (Sierro et al., 2005), Iberian margin (Naughton et al., 2016) and off NW Africa (Bouimetarhan et al., 2012). However, these studies showed different paleoenvironmental reconstructions for these three phases (early, middle and late HS1), which are shown in Table S1.

Table S1. Marine records presenting a division of HS1 in three phases (Sierro et al., 2005; Fletcher and Sánchez Goñi, 2008; Bouimetarhan et al., 2012; Naughton et al., 2016; Bazzicalupo et al., 2018). Marine and continental reconstructions of the early, middle and late HS1 have been schematized below. Note the diversity in the interpretations for the three phases identified within HS1.

Study	Location	Record	Environmental reconstruction	Proxy	Early HS1 (HS1a)	Middle HS1 (HS1b)	Late HS1 (HS1c)
Fletcher and Sánchez Goñi (2008)	Alboran Sea	MD95-2043	Marine	*N. pachyderma-s* (cold water indicator)	Cool	Cold	Cool
			Continental	Vegetation	Cold/humid	Arid	Cool/less arid
Bazzicalupo et al. (2018)	Alboran Sea	ODP-976	Marine	Calcareous plankton	Cold	Fresher water	Cooler
			Continental	Vegetation	Increase aridity	Maximum aridity	Cold/arid
Sierro et al. (2005)	Northwestern Mediterranean	MD99-2343	Marine	δ^{18}O *G. bulloides* (SST, iceberg meltwater)	Cold	Cool	Cold
Naughton et al. (2016)	Iberian margin	MD03-2697	Marine	Alkenone-based SST and % *N. pachyderma-s*	Extreme cooling	Warmer (still cool)	Cooling (warmer than HS1a)
			Continental	Vegetation	Extreme cold/wet	Warmer (still cool)/increase aridity	Warming/wet
Bouimetarhan et al. (2012)	Off NW Africa	GeoB9508-5	Continental	Vegetation	Dryness	Wetter	Extreme dry

REGIONAL AND LOCAL SETTINGS

Padul is located at the foothill of the Sierra Nevada, which is an approximately 85 km long E-W aligned mountain range located in southern Spain. The precipitation in the

Sierra Nevada is highly controlled by the humidity carried from the westerlies and the North Atlantic Oscillation (Jiménez-Moreno and Anderson, 2012; Lionello, 2012).

The Padul wetland (724 m a.s.l.) is located in the western margin of the Sierra Nevada range, 20 km south of Granada city (Andalusia, Spain) (Fig. 1) and covers an area of 4 km^2 in the Padul-Nigüelas basin. The NW-SE elongated Padul-Nigüelas endorheic basin developed as a consequence of extensional activity of the main normal fault that delimits the NE edge of the basin (Santanach et al., 1980). It bears an estimated sedimentary sequence of about 100 m in the depocenter of the basin (Ortiz et al., 2004). The Padul area is at present characterized by a semiarid Mediterranean climate with high temperature and low precipitation during summertime (summer drought), presenting a mean annual temperature of 14.4ºC and mean annual precipitation of 445 mm (AEMET, 2016).

METHODS

Chronology

The 42.64 m-long Padul-15-05 sediment core was drilled in the Padul wetland lakeshore (37°00´39´´N, 3°36´14´´W) in July 2015. The chronological control of the Padul-15-05 core is based on 43 Accelerator Mass Spectrometry (AMS) radiocarbon dates, 4 Amino Acid Racemization (AAR) dates from gastropods (hydrobiid *Milesiana schuelei*) and two different sediment accumulation rates (SAR) for both peat and carbonate/marl lithologies for the bottom part of the core (Camuera et al., 2018). The age-depth control for the new Padul-15-05 record between 20 and 11 kyr BP (4.88 – 3.52 m depth) was built using 10 AMS radiocarbon dates, from a total of 15 radiocarbon samples analyzed (Table S2). Five dates were rejected because they provided ages that are too young due to root penetration from above (1 sample), and ages too old due to reservoir effect (2 samples from gastropods and 2 samples from bulk carbonates). This record presented high sediment accumulation rates (SAR, 0.151 mm/yr) during this time period and therefore permitted us to perform high-resolution multiproxy analyses for regional paleoclimate reconstructions.

The age-depth model was developed using the R-code package Clam 2.2 software (Blaauw, 2010), under the IntCal13.14C calibration curve (Reimer et al., 2013) at 95% confidence level. Note that 6 new radiocarbon dates between 415.46 and 460.35 m depth (15658 – 19481 cal yr BP) were analyzed in this study and added to the age model for an accurate delimitation of HS1.

Table S2. AMS-standard radiocarbon ages of the Padul-15-05 record between 4.88 - 3.52 m depth (according to the age-depth model, between 20000 and 11000 calibrated years BP). In red are the dates that were rejected for the age model.

	Material	**Depth (cm)**	**Age (^{14}C yr BP ± 1σ)**	**Calibrated age (cal yr BP) 95% confidence interval**	**Median age (cal yr BP)**
Poz-74348	Plant remains	375.62	9120 ± 50	10199 - 10412	10305
Poz-79815	Org. bulk sed.	377.83	10310 ± 50	11847 - 12388	12144
Poz-79817	Gastropods	411.02	13910 ± 60	16588 - 17088	16838
Poz-79818	Gastropods	414.89	14130 ± 50	17001 - 17419	17210
BETA-506210	Bulk carbonate	415.46	13060 ± 40	15400 - 15852	15658
BETA-506209	Org. bulk sed.	420.59	13630 ± 40	16238 - 16639	16365
Poz-77574	Org. bulk sed.	423.65	13580 ± 80	16113 - 16654	16384
Poz-79819	Org. bulk sed.	432.82	13500 ± 60	16047 - 16494	16270
Poz-19821	Org. bulk sed.	437.92	13910 ± 70	16570 - 17113	16841
Poz-79822	Org. bulk sed.	448.12	14640 ± 70	17618 - 18011	17814
Poz-77575	Org. bulk sed.	452.2	14890 ± 80	17898 - 18325	18111
BETA-506207	Org. bulk sed.	457.29	14480 ± 50	17473 - 17863	17650
BETA-506208	Org. bulk sed.	457.29	14780 ± 50	17815 - 18157	17980
BETA-506205	Bulk carbonate	460.35	16140 ± 60	19256 - 19661	19481
BETA-506206	Bulk carbonate	460.35	16080 ± 60	19210 - 19592	19410

Palynological analysis

For this study a total of 92 pollen samples were analyzed between 4.88 and 3.52 m depth (20 - 11 kyr BP) with a resolution of ~77 years for the last part of the Last Glacial Maximum (LGM) and HS1 (20 – 15.6 kyr BP) and ~131 years for the BA, YD and the beginning of the Holocene (15.6 – 11 kyr BP), augmenting the resolution with respect to the previous study on the entire Padul-15-05 core about vegetation and climate changes during the last ~197 kyr (Camuera et al., 2018; 2019). Pollen extraction was done following a modified methodology of Faegri and Iversen (Faegri and Iversen, 1989). After the final extraction of the pollen residue, a minimum of 300 terrestrial pollen grains per sample were identified using a Zeiss transmitted light microscope under a magnification of 400x.

The Mediterranean forest includes *Quercus* total, *Olea*, *Phillyrea* and *Pistacia*. The xerophyte pollen group includes *Artemisia*, *Ephedra* and Amaranthaceae. Pollen Climate Index (PCI) includes *Quercus* total, *Olea*, *Fraxinus*, *Phillyrea*, *Acer*, *Betula*, *Alnus*, *Ulmus*, *Taxus*, *Salix*, *Pistacia*, *Corylus* and *Carpinus*. Finally, the Precipitation Index (I_p) is expressed as: I_p = [*Quercus* deciduous / (*Artemisia* + *Ephedra* + Amaranthaceae + *Quercus* deciduous)]. Pollen percentages were calculated based on the terrestrial pollen sum excluding aquatic plants (Cyperaceae, *Typha*, *Myriophyllum*, *Utricularia* and *Potamogeton*).

The Mediterranean forest group taxa have previously been shown to be a good indicator of climate changes in the Mediterranean region (Fletcher and Sánchez Goñi, 2008). The PCI is based on the mesothermic/steppic taxa ratio (Combourieu Nebout et al., 1999; Joannin et al., 2011), and has been useful in identifying climate changes mainly related to temperature in this region. However, some taxa included in the PCI respond not only to temperature, but also to different precipitation conditions, hence a more precise reconstruction of the precipitation in this area has been obtained using the *Ip* (Fletcher et al., 2010).

Inorganic geochemistry

Inorganic geochemical composition of the Padul-15-05 core was analyzed every 1 cm (~70 years resolution between 20 – 11 kyr BP) in a continuous XRF Avaatech core scanner from the CORELAB at the University of Barcelona (Spain). From a total of 34 elements analyzed, Si was taken as the most representative data for climate reconstruction in this study (Fletcher et al., 2010; Camuera et al., 2018). This element has been used as Si normalized (Si_{norm}), represented by the silicon data divided by the sum of the total counts (in cps) from the most important elements as: Si_{norm} = Si / (Si, K, Ca, Fe, Zr, Br, Sr, Al, Rb, Cl, Zn, Mn, S, Pb, U, Ni, Ti). However, calcium data present very high values in carbonate lithologies. Therefore, a normalized Si values excluding Ca from the total counts have also been represented in order to observe more accurate changes in carbonate sediments. Elements with low representation, negative values and/or elements providing background values have been excluded.

Spectral analysis and filtering

The spectral analysis was developed on the raw xerophyte data from Padul with the PAST 3.19 software (Hammer et al., 2001) using the REDFIT procedure of Schulz and Mudelsee (2002) under the rectangular window function, and the standard value of 2 for the segments parameter and value of 3 for the oversample parameter. Two spectral analyses were run on xerophytes, including the age range between 20 – 11 kyr BP and for HS1 (18.4 – 15.6 kyr ago). A periodicity of ~2000 years (f = 0.0004990; >95% Confidence Interval) was obtained in the spectral analysis for the age range between 20 – 11 kyr BP. Cyclicities of ~800 years (f = 0.001384 – 0.001211), ~500 years (f = 0.002075 – 0.001905) and ~200 years (f = 0.005181 – 0.004273) (all above >90% CI) were identified in both spectral analysis (Fig. 4a, b). The spectral analysis run on *Ip* for the age range between 20 and 11 kyr BP also show a periodicity of ~2000 years (f = 0.00049955; >95% CI) and ~800 years (f = 0.0013321 – 0.00011656; >95% CI) (Fig. 4c).

A spectral analysis was also run on the raw ^{10}Be flux values (10^6 atoms cm^{-2} yr^{-1}) from GRIP (Adolphi et al., 2014) using the same REDFIT procedure as on xerophyte data from Padul under the rectangular window function and the standard value of 2 for segments and oversample parameters, with the purpose of observe cyclicities related to solar activity. A periodicity of ~800 years was obtained from the ^{10}Be flux data with a confidence interval of ~90% (Fig. 4d).

The obtained periodicities of ~2000 and ~800 years were filtered using the Analyseries 2.0 software (Paillard et al., 1996) for the comparison of cyclicities between different records (Fig. 5).

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