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Human adaptation to changing coastal landscapes in the Eastern Adriatic: Evidence from Vela Spila cave, Croatia

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Abstract

In this paper new palaeogeographic and archaeological data from the prehistoric cave Vela Spila on the island of Korčula in Croatia are combined with new realizations of two glacial isostatic adjustment models in order to present relative sea-level change scenarios confronting the inhabitants of the cave at different time slices and to show how they experienced and adapted to

23 sea-level and climate change from the Late Pleistocene through the Holocene. Our results show that
 24 from the Late Upper Palaeolithic until the Mesolithic, humans in the study area would have
 25 experienced tens of metres of sea-level rise, at rates in some cases up to 12 mm per year, and, owing
 26 to the relatively flat morphology of the now submerged plains, hundreds of meters of horizontal
 27 coastline change in the plains to the north and south of the island. This evidence supports the
 28 hypothesis that the rapid loss of these plains likely contributed to the human abandonment of the
 29 cave after the Palaeolithic for about five thousand years, followed by significant changes in lifestyle
 30 and diet in the Mesolithic. Our results have important implications for the study of how past human
 31 groups, especially in vulnerable coastal areas, were affected by sea level, climate, and other
 32 environmental changes. Vela Spila represents a case study of how changing environment and rising
 33 seas can force significant alterations in human societies, even when there is no risk of inundation to
 34 the settlement itself.

35 **1 Introduction**

36 Since prehistory, humans have adapted their settlement and mobility patterns in response to
 37 environmental change (Blute, 2008; Bini et al., 2018; Butzer, 2005), using their decision-making
 38 skills (Nunn, 2020), or even engineering skills (Galili et al., 2019) to overcome challenges created
 39 by modifications to coastlines and their related ecosystems. The Eastern Adriatic region represents a
 40 key area to investigate the relationship between environmental changes and cultural responses. The
 41 ‘Great Adriatic Plain’ periodically exposed during the Pleistocene provided suitable conditions for
 42 human settlement; its loss to rising sea level during the Late Pleistocene and Early Holocene
 43 precipitated a significant restructuring of plant, animal, and human communities (Boschian and
 44 Fusco, 2007; Miracle, 2007). The palaeoecological and archaeological evidence of the region is
 45 reviewed by Pilaar Birch and Linden (2018).

46 Sea-level change has been a major cause of environmental change; it has modified coastal
47 landscapes by dramatically and cyclically altering coastal plains around shallow sea basins, and by
48 influencing the distribution of islands and their distance from the mainland. The outline and area of
49 many present-day islands were different during the Late Pleistocene owing to the last ice age and
50 the relative sea-level (RSL) changes associated with it; the islands' current isolation is unusual
51 during the last 70 ka (Weigelt et al., 2016). Consequently, the distribution of human and animal
52 communities in coastal areas (Carroll et al., 2012; Garg et al., 2018; Hewitt, 2000; McLaughlin et
53 al., 2018) was profoundly affected, resulting in major behavioural and cultural change. A robust
54 reconstruction of shoreline position at different time slices of the Late Pleistocene and Holocene is
55 essential for understanding human settlement and animal dispersal patterns.

56 Following the seminal work by van Andel (1989), reconstructing ancient coastlines in order to
57 elucidate their influence on hominin dispersal and cultural behaviour became an important research
58 goal. In archaeological literature, the reconstruction of ancient coastal landscapes has focused on
59 comparing present-day bathymetric surfaces with global eustatic curves (Dobson, 2014). However,
60 past RSL can be reconstructed more precisely by combining geophysical and geological techniques
61 (Pirazzoli, 2013; De Boer et al., 2014; Shennan et al., 2015).

62 Sea-level reconstructions must be combined with bathymetric data, which have also been widely
63 used to identify landforms, assess palaeoenvironments and palaeoshorelines, and address
64 archaeological questions in the central Mediterranean. Bathymetric mapping and archaeological
65 research have been combined in Sardinia (Palombo et al., 2017) for this purpose. In the Tyrrhenian
66 Sea west of Italy, seismic profiles have been used to detect terraces that may be associated with
67 ancient sea stands (Casalbore et al., 2017). Extensive single- and multibeam data were used
68 (Trincardi et al., 2014) to identify several drowned landforms in the western Adriatic. Bathymetric
69 data from Malta (Foglini et al., 2016) have shown drowned karstic features and river landforms, and
70 can answer questions about prehistoric fauna migration and human settlement. In the NW Adriatic,

71 prehistoric settlement surfaces and lagoon deposits have contributed to landform and RSL
72 reconstructions (Fontana et al., 2017). In the eastern coast of the Adriatic dozens of submerged
73 coastal prehistoric sites have been located, from Istria to southern Dalmatia, and excavations have
74 been initiated on several of those sites (Bekić, 2017; Bekić et al., 2015; Benjamin et al., 2011;
75 Benjamin and Bonsall, 2009; Čelhar et al., 2017; Koncani Uhač and Čuka, 2015; Radić Rossi,
76 2008). The majority of the sites belong to relatively recent prehistoric times (Bronze Age and Iron
77 Age), while only very few of them belong to Copper Age or Neolithic periods. Further excavation,
78 interdisciplinary investigation (collaboration of archaeologists and geologists), and analyses are
79 required before they can be used as accurate indicators of local sea-level change in prehistoric times
80 (Rossi, 2017)

81 This study integrates palaeoenvironmental and archaeological evidence from Vela Spila, a cave
82 situated on the island of Korčula, close to the central Dalmatian coast in Croatia (Fig 1) with a new
83 synthesis of bathymetric datasets. We Palaeogeographic reconstructions were created at time slices
84 relevant for key cultural events during cave occupation phases from the Late Upper Palaeolithic to
85 the Neolithic. The main goal of this work is to investigate the relationship between the shoreline
86 position and the cave. The results provide an understanding of how inhabitants of the cave
87 experienced and adapted to sea-level and climate changes since the Late Pleistocene.

88 This study incorporates both existing and new data and approaches that are discussed in light of
89 current research. In particular:

90 1) Novel archaeological evidence provided in this study compliments previous work on Vela Spila
91 (Branscombe et al., 2020; Cristiani et al., 2014; Farbstein et al., 2012; Radić, 2018; Rainsford et al.,
92 2014). Vela Spila (Fig 2) is one of the richest and most promising archaeological sites in the Eastern
93 Adriatic region, with a Late Pleistocene to Holocene stratigraphic sequence spanning the Late
94 Upper Palaeolithic (LUP) to the Bronze Age. The deposits include exceptionally well-preserved
95 cultural, human, animal, and vegetal remains that document important environmental and biological

96 changes during the Pleistocene-Holocene, and cultural changes during the Palaeolithic-Mesolithic
97 and Mesolithic-Neolithic transitions.

98 2) Data used in the current study to reconstruct bathymetry around Vela Spila represent a synthesis
99 of available bathymetric datasets for the area, and thus an improvement on the datasets used by
100 previous authors such as Sikora et al. (2014), which used satellite bathymetric data combined with
101 GIS analysis to reconstruct river drainage during the lowstand of the Last Glacial Maximum
102 (LGM). Bathymetric data, as a source of palaeolandscape data, are applicable to our study area
103 because of the karstic nature of the Eastern Adriatic - rainwater sinks into the endokarst instead of
104 creating high sediment flux onto the seabed (Pikelj and Juračić, 2013). Consequently, LGM
105 landforms and topography are still visible in bathymetric data, aside from limited fluvial
106 sedimentation.

107 3) Bathymetric data for the seabed around Korčula are combined with two updated geophysical
108 models of glacial-hydro-isostatic adjustment (GIA) realized specifically for the area under
109 investigation in order to reconstruct palaeogeographic phases; all previous authors used in the best
110 case older, less refined models, and Sikora (2014) used a global model. This implies differences of
111 tens of kilometres in the position of the shoreline at specific times. The use of GIA models is valid
112 for this subregion of the Eastern Adriatic because tidal notches documented by Faivre and Butorac
113 (2018) show relatively slower rates of subsidence here than in areas to the north, at least for the
114 Late Holocene.

115 Vela Spila represents a relevant case study on how changing environment and rising seas can force
116 significant changes in human societies, even when there is no direct risk of inundation for the
117 settlement itself.

118 **2 Regional setting**

119 **2.1 Adriatic sea**

120 The Adriatic Sea (Fig 1) is a NW-SE elongated basin of approximately 800 by 200 km that
 121 separates the Italian peninsula from the Balkans (Trincardi et al., 2014). This basin can be divided
 122 into three sub-basins: the northern, which is 35 m deep on average, the middle with an average
 123 depth of 140 m, and the southern with maximum depths reaching 1200 m (Artefiani et al., 1997).
 124 This paper is focused on the island of Korčula, which lies on the eastern coast between the middle
 125 and southern basins. The Eastern Adriatic bedrock is about 8,000 m of limestone and/or dolomite
 126 (Vlahović et al., 2005, 2002) formed in shallow sedimentation basins between the Mid-Late
 127 Triassic, Mesozoic and Palaeogene, followed by relatively thin Eocene flysch outcrops. The
 128 tectonic deformation pattern of the Eastern Adriatic is characterised by a complex system of faults,
 129 thrust faults and overthrusts formed since the Miocene and developed along the so-called
 130 Dinaric Strike with NW-SE orientation (Vlahović et al., 2005, 2002). The typical relief pattern of
 131 mountain and hill ridges parallel to the coastline (Fig 1) derives from this tectonic compressional
 132 motif, followed by extensional processes and eventually repeated flooding during the Quaternary
 133 sea-level fluctuations. The westernmost Dinarides were submerged by the postglacial RSL rise
 134 (Kelletat, 2005) and now form the Croatian islands and the typically rocky Dalmatian Coast (Felja
 135 et al., 2015; Pikelj and Juračić, 2013). Significantly for this study area, the Eastern Adriatic coast
 136 and its hinterland are karstic and dominated by typical karst landforms, with few significant rivers
 137 discharging sediments into the sea, so that the present-day bathymetry closely reflects LGM
 138 landforms (Pikelj and Juračić, 2013). This is confirmed in the immediate study area by research
 139 (Giglio et al., 2020) in the waters around the present-day Neretva delta, which shows river
 140 sedimentation rates quickly approaching 0 mm/a (mm per year) within 10 km offshore. This aspect

141 of the coast contrasts with the wide and flat morphology of the north-eastern Adriatic, which was an
 142 alluvial plain dominated by sandy river discharge when the LGM RSL was 120 m below present
 143 (Trincardi et al., 2014). Though these submerged morphological features in the western Adriatic
 144 have been identified by multibeam imagery (Trincardi et al., 2014), including drowned karst
 145 landscapes (Taviani et al., 2012), public high-resolution data are less available for the rocky Eastern
 146 Adriatic.

147 **2.2 Central-southern Dalmatia**

148 Korčula is an island in central-southern Dalmatia, separated from the Pelješac peninsula by a
 149 narrow channel about 40-45 m deep. Like most Dalmatian islands (Kelletat, 2005), it represents the
 150 top of a submerged ridge formed by tectonic overthrusting and uplift of reliefs which, in the case of
 151 the southern islands, are rotated counterclockwise with reference to the dinaric strike. The island
 152 landscape is rugged, controlled by the nature of the underlying Mesozoic limestones and dolomitic
 153 limestones, and also characterised by several deep and elongated *polje* oriented along the structural
 154 motif and by deep karstic depressions, whose bottoms are filled by *terra rossa/crvenica* soils
 155 (Bonacci et al., 2012). The coasts are almost always steep and rocky. The channel between Korčula
 156 and Hvar -the island immediately to the north – is at most about 70 m deep and represents the
 157 prolongation of the Neretva river valley towards the Adriatic basin (Sikora et al., 2014). On the
 158 westernmost tip of the island, a narrow, winding and shallow inlet protects the Vela Luka harbour.
 159 In the now submerged zones between islands, areas at greater depth closer to the LGM lowstand of
 160 -120 m (Peltier and Fairbanks, 2006) or -115 m (Sikora et al., 2014) had less exposure time to
 161 erosion and other landscape forming processes than areas situated near highstand levels. As a result,
 162 most morphology of these submerged areas consist of broad, flat areas; a fact often compounded by
 163 the presence of alluvial sediments in areas near palaeo rivers.

164 2.3 Vela Spila

165 Vela Spila (Fig. 2) is a large cave situated 121 m above sea level on the western side of Spilski Rat,
 166 a low hill overlooking Vela Luka harbour. The cave's single, semi-ellipsoidal chamber, about 50 m
 167 by 30 m wide and 17 m high, opens in Cenomanian radiolaritic limestone whose layers dip
 168 southwards (Cristiani et al., 2014). The whole inside surface of about 1000 m² is at present always
 169 well-lit through a wide entrance facing west and two large holes in its ceiling.

170 The outside landscape has been strongly affected by human activities over long time scales,
 171 probably since the cave was first inhabited during the Late Glacial. Most hillsides have extensive
 172 19th century terraces for viticulture or growing olive trees, though many are now abandoned. Good
 173 quality data about outside soils and their evolution through the end of the Late Glacial to Middle
 174 Holocene are difficult to collect in these conditions: the typical features are thick stone walls
 175 sustaining *terra rossa* backfills, alternating with patches of barren denuded limestone. Cave data are
 176 in this case the best way to acquire information about climate and environment evolution in the area
 177 since they are undisturbed by agricultural activity during the last two millennia.

178 2.4 Regional relative sea level

179 Global eustatic sea level has risen roughly 120 m since the LGM (Fairbanks, 1989; Peltier and
 180 Fairbanks, 2006). GIA models (Lambeck and Purcell, 2005; Peltier, 2004; Peltier et al., 2015) have
 181 been used to estimate timing and magnitude of these changes. Datable biological, geological and
 182 archaeological proxies have been used to calibrate these models and provide more precise
 183 chronological indications of past RSL (Rovere et al., 2016).

184 In the Eastern Adriatic area, fossil remains of *Lithophyllum* sp. and an ancient harbour (Faivre et al.,
 185 2013; Vacchi et al., 2016) provide sea-level indicators in close proximity to the study area. Salt
 186 marsh foraminifera have also been studied (Shaw et al., 2018) to reconstruct RSL in the last
 187 millenium, and suggest a subsidence rate of 0.45 +/- 0.6 mm/a in Jadrtovac, ~ 100 km northwest of

188 Korčula. A dataset of speleothem dates from submerged caves exists (Juračić and Surić, 2010) but
 189 most of these samples predate the LGM; a specimen from ca. 9.2 cal ka BP is relevant to the current
 190 study, though these indicators constitute only a maximum possible elevation for RSL. Vacchi et al.
 191 (2016) used the ICE-5G (VM2) GIA model (Peltier, 2004) of the last 15 ka to predict a RSL rise of
 192 less than 1 m since 4 ka BP, preceded by a much faster increase. However, they also noted that the
 193 sea-level points indicate an RSL approximately 1 m lower than the model during the last 3 ka, and
 194 hypothesize a general subsidence trend in the wider area. The observational data in this study area
 195 (Faivre et al., 2013; Vacchi et al., 2016), however, were mostly limited to the last 3 ka BP.
 196 Unfortunately for central-southern Dalmatia no valuable index points from coastal depressions are
 197 available to constrain relative sea level, like the ones obtained by Brunović et al. (2019) for the
 198 north-eastern Adriatic. In this area Antonioli et al. (2007) applied a methodology similar to the one
 199 used in this work using a GIA model by Lambeck & Purcell (2005) that predicts roughly similar
 200 changes for the last 12 ka in Istria (north-eastern Adriatic), but with the stabilizing point occurring
 201 at ca. 6 ka BP instead of 4 ka BP.

202 **3 Materials and methods**

203 **3.1 Bathymetric data**

204 This study utilizes a combination of publicly available bathymetric data sources. These include
 205 digitized nautical charts, and SRTM15_PLUS data from NOAA ERDDAP (Sandwell et al., 2014a),
 206 which is a 15'' version of the Shuttle Radar Topography Mission (SRTM) dataset containing
 207 bathymetric data from a combination of sources, chiefly from satellite altimetry gravity elevations
 208 (Smith and Sandwell, 1997). The bathymetric data have been combined with topographic digital
 209 elevation data of 1'' resolution (~30 m) from the SRTM. Table 1 lists these datasets and their
 210 characteristics.

DATASET	Projection	Horizontal Datum	Vertical Datum	Resolution	Type	Citation
NASA SRTM Shuttle radar	Geographic	WGS84	EGM96	1'' or ~22 m at latitude (emerged areas only)	Raster (with vector coastline)	(NASA, 2000)
SRTM15_PLUS	Geographic	WGS84	Unspecified	15'' or ~340 m at latitude	Raster	(Olson et al., 2014, 2016; Sandwell et al., 2014a)
Chart soundings	Geographic	Lat/Lon	Presumed to be mareograph derived lowest astronomical tide	Varies: 10 ⁻¹ or 10 ⁻² m distance between points in harbours or channels. 10 ⁻³ m distances in deep seas Non homogeneous	Vector	(Croatian Geoportal, 2019; Državni Hidrografski Institut, 1998)

211 *Table 1. Overview of the bathymetric and topographic datasets.*

212 The bathymetric and nautical sounding datasets were combined into a single point cloud using
 213 QGIS so that the high resolution SRTM 1'' and nautical chart data supersedes the SRTM15_PLUS
 214 15'' data in emerged areas, and a raster interpolation was created using the GRASS GIS algorithm
 215 v.surf.rst. Satellite bathymetry, with its high vertical resolution but poor horizontal resolution, was
 216 also eliminated within ~500 m of all coastlines to favour the more accurate nautical chart soundings
 217 available in those areas.

218 **3.2 Uncertainties**

219 The vertical datum for the Croatian chart soundings used in this DEM are based on HRSDM71, i.e.
 220 Mean Lower Low Waters of Spring Tide from tide gauges at Dubrovnik, Split, Bakar, Rovinj and
 221 Koper (epoch 1971.5) (Domijan et al., 2005; HHI, 2019). A ± 0.5 m is a cautious uncertainty for
 222 these whole-number elevations. The satellite altimetry data is heavily post processed to remove
 223 wave noise (Sandwell et al., 2014b; Smith and Sandwell, 1997), and come from electromagnetic
 224 pulse return times between satellites and the ocean surface at time of sampling, but uncertainties

surrounding the geoid height, GPS technologies, and the ship soundings used for calibration make calculating an overall vertical uncertainty difficult. See Tozen et al. (2019) for further discussion of error distributions. In any case, the ~0.5 km spatial resolution of the satellite derived bathymetry in the SRTM15 dataset and the heterogenous spatial resolution and unspecified XY precision of nautical chart soundings mean that XY errors far outweigh the vertical Z uncertainties created by harmonizing the datasets used in the DEM in this area where the largest recorded tidal ranges are less than 0.5 m (tide-forecast.com, 2019). The present study excludes datapoints within 1 km of coastlines, and gives precedence to chart soundings when they conflict with the satellite data. We The SRTM15_PLUS dataset in the study area was also validated with the chart soundings and it was noted that in most deep areas (~100 m) the predicted depths correspond well (less than 10 m disparity) with available chart soundings.

3.3 GIA modelling

For this work, new realizations of GIA models calculated specifically for Korčula were used. Previous regional studies based on an GIA models (Lambeck and Purcell, 2005), have used calculations of GIA for Istria (Antonioli et al., 2007) and Vis (Vacchi et al., 2016) but these span only the last 12-14 ka BP, while Vela Spila's archaeological record goes back to ca. 20 ka BP. The GIA results were obtained by solving the sea-level equation with the program SELEN developed by Spada and Stocchi (2007). In its current implementation, SELEN (version 4) accounts for the migration of shorelines and rotational effects on sea level (Spada and Galassi, 2017). The realizations derive from two different GIA models, based on different assumptions about the melting chronologies of Late Pleistocene ice sheets, and the viscosity profile of the mantle. The first model is the ICE-6G_C (VM5a) of Peltier et al. (2015) while the second has been progressively developed by K. Lambeck and co-workers at the Australian National University (ANU) (for more information, see e.g., Lambeck et al. (2003) and subsequent refinements). These two realizations

are henceforth referred to as I6G_S4 and ANU_S4, where S4 is an abbreviation for SELEN (version 4). Since calculating and illustrating an uncertainty for a GIA model is difficult owing to the large number of variables, assumptions, and parameters that comprise the final prediction (Melini and Spada, 2019), having two models allows us to use the difference between them as an envelope of uncertainty. The RSL reconstructions, the bathymetric digital elevation map, and the archaeological stratigraphy were analysed together in order to reconstruct the palaeogeographic and environmental conditions during the relevant archaeological phases. A literature review for sea-level indicators in the region was also undertaken in order to provide verification for the models.

3.4 Archaeological data

The most relevant palaeoenvironmental aspects inferred from the observation of the Vela Spila sediments have been summarised from published work (Branscombe et al., 2020; Čečuk and Radić, 2005; Cristiani et al., 2014; Farbstein et al., 2012; Rainsford et al., 2014) and complimented with unpublished observations made in the four cave key trenches (Fig 3) during the systematic excavations carried out since 2010. Chronology used in this study is partly derived from published radiocarbon dates collected (Table 2) from previously unpublished dates and published sources (Čečuk and Radić, 2005; Farbstein et al., 2012; Rainsford et al., 2014; Srdoč et al., 1989), and partly from the typology of the archaeological remains, the chronology of which is assessed confidently in Dalmatia (Kaczanowska and Kozłowski, 2018; Komšo, 2008; Kozłowski and Kaczanowska, 2004; Miracle and Forenbaher, 2005). In this study, dates referring to specific C^{14} results use cal a or cal ka BP, whereas dates specifying general periods, GIA models, archaeological typology, or other methods use a or ka BP.

4 Results

4.1 Palaeoenvironmental evidence from archaeological stratigraphy

The most relevant palaeoenvironmental changes from Vela Spila sediments are outlined here from bottom to top in order to relate them to shoreline changes. The general stratigraphy of the Vela Spila archaeological deposit is presented in Fig 4. The cave bedrock was not found in any of the excavated trenches, despite maximum excavation depths of about 5 m below the present-day cave floor, so the question of the oldest occupation of the cave is still open. Table 2 lists the collected ^{14}C for this site, with calibration results summarised in Fig. 5 and referenced below in the text as well.

Lab Code	^{14}C Age (a BP)	2-sigma calibrated age (a BP)	Method	Material dated	Reference	Attribution	Context
Z-3987	16200±200	19,530- 19,190	Std	WC	This paper*, Rainsford <i>et. al.</i> 2014	Palaeolithic	LUP A
VERA- 2338	16140±60	19665- 19255	AMS	WC	Farbstein <i>et al.</i> 2012: TAB. 1	Palaeolithic	LUP A
VERA- 2339	15690±70	19130- 18775	AMS	AB	Farbstein <i>et al.</i> 2012: TAB. 1	Palaeolithic	LUP A
z-3993	14500±100	17950- 17410	Std	WC	Farbstein <i>et al.</i> 2012: TAB. 1	Palaeolithic	LUP C
z-3992	14100±100	17587- 17105	Std	WC	Farbstein <i>et al.</i> 2012: TAB. 1	Palaeolithic	LUP D
z-3991	13300±100	16280- 15700	Std	WC	Farbstein <i>et al.</i> 2012: TAB. 1	Palaeolithic	LUP E
z-3988	12800±100	15660- 14925	Std	WC	This paper*, Rainsford <i>et. al.</i> 2014	Palaeolithic	LUP G
z-3990	12700±100	15500- 14655	Std	WC	This paper	Palaeolithic	LUP G
z-3989	12700±100	15500- 14655	Std	WC	Farbstein <i>et al.</i> 2012: TAB. 1	Palaeolithic	LUP G
VERA- 2345	12290±40	14490- 14050	AMS	AB	Farbstein <i>et al.</i> 2012: TAB. 1	Palaeolithic	NYT
VERA- 2346	12269±40	14410- 14025	AMS	WC	Čečuk & Radić 2005: 34	Palaeolithic	NYT
Wk- 27370	12457±57	14995- 14230	AMS	AB	This paper*, Rainsford <i>et. al.</i> 2014	Palaeolithic	LUP I
VERA- 2343	8290±35	9425-9135	AMS	AB	This paper	Mesolithic	Meso A
VERA- 2344	8230±35	9395-9030	AMS	WC	Čečuk & Radić 2005: 62	Mesolithic	Meso A
VERA- 2341	8200±30	9270-9030	AMS	WC	Čečuk & Radić 2005: 62	Mesolithic	Meso A

z-3995	8200±70	9400-9005	Std	WC	This paper*, Rainsford <i>et. al.</i> 2014	Mesolithic	Meso B
z-3986	8200±70	9400-9005	Std	WC	This paper*, Rainsford <i>et. al.</i> 2014	Mesolithic	
OxA-18171	8110±37	9235-8985	AMS	HB	Forenbaher <i>et al.</i> 2013: 591	Mesolithic	Meso B
Wk-24217	8004±41	9010-8715	AMS	HB	This paper		Burial 2/1986
z-3994	7410±70	8375-8045	Std	WC	This paper*, Rainsford <i>et. al.</i> 2014	Mesolithic	Meso D
Wk-24216	7350±39	8305-8025	AMS	AB	This paper*, Rainsford <i>et. al.</i> 2014	Mesolithic	Meso D
Z-1967	7300±120	8375-7930	Std	WC	Čečuk & Radić 2005: 62	Early Neolithic?	Meso D?
VERA-2342	7175±35	8045-7935	AMS	AB	This paper	Mesolithic	Meso D?
VERA-2340	7200±30	8155-7950	AMS	WC	Čečuk & Radić 2005: 62	Mesolithic	Meso D?
Z-1968	7000±120	8030-7595	Std	WC	Čečuk & Radić 2005: 82	Early Neolithic?	Early Neo?
Wk-24219	6735±35	7665-7515	AMS	AB	This paper	Neolithic	Neo C
Wk-24218	6678 ± 34	7610-7485	AMS	AB	This paper*, Rainsford <i>et al.</i> 2014	Neolithic	Neo C
z-1742	5430±100	6410-5950	Std	WC	Srdoč <i>et al.</i> 1989: 86	Neolithic ?	Neo?

Table 2. Radiocarbon age dataset from Vela Spila. Std: standard method; AMS: accelerator mass spectrometry; WC: wood charcoal; AB: animal bone; HB: human bone. *Uncalibrated date published for the first time in this paper.

278 4.1.1 Palaeolithic

279 The lowermost unit of the sequence (Fig. 4) exposed so far is represented by a 3 m-thick talus
280 made up of unsorted frost slabs with an open-work fabric, and with no traces of human occupation.
281 Even if geochronometric dates are not available for this unit, it can be attributed to the LGM
282 because of its sedimentological characteristics and of the radiocarbon age of the overlying units
283 (Farbstein et al., 2012). This type of sediment is consistent with a cold climatic spell typically
284 connected with an RSL lowstand.

285 The sediments testifying to the first human occupation of the cave directly overlie the LGM
286 talus and include Upper Palaeolithic remains ¹⁴C constrained to approximately 19.7-14.0 cal ka BP
287 (Fig. 5, Table 2). These strata are composed of frost slabs that decrease in quantity and become finer
288 upwards to the top of the Late Upper Pleistocene units. Alternations of discontinuous fine and

coarse-grained layers and/or gravelly lenses, as well as some blocks, testify to warmer and colder climate fluctuations, and to localised deposition of gravel from inhomogeneous gelifraction of the ceiling. The silty loamy fine fraction of the sediments suggests colluvial inputs of windblown sediments previously deposited outside the cave or, when more clayey and reddish, of material deriving from the dismantling of soils. The top of the sequence is marked by a horizon of large limestone slabs overlain by a 15 cm-thick layer of sub-primary tephra locally deformed by frost action, ascribed to the Neapolitan Yellow Tuff (NYT) ejected from a volcano in the Campi Flegrei near Naples (Radić et al., 2007), ^{14}C dated to 12.3 ± 0.04 ka BP (14.5–14.1 cal ka BP; Tab. 2; Fig. 5) (Čečuk and Radić, 2005; Farbstein et al., 2012), which fits reasonably well the 14.9 ± 0.4 ka BP $^{40}\text{Ar}/^{39}\text{Ar}$ age of the tephra (Deino et al., 2004) and much better its modelled age 14.3–13.9 cal ka BP date obtained by Bayesian method (Blockley et al., 2008).

The anthropic component of these layers –abundant organic matter, charcoal, bone and stone tools deriving from intense occupation of the cave – is dominant over non-anthropoc material and gives the sediment a very dark, blackish colour value. Archaeological materials include Late Upper Palaeolithic lithics of Epigravettian tradition (Farbstein et al., 2012; Rainsford et al., 2014), sharing strict analogies with other technocomplexes of Dalmatia and its hinterland, e.g. Pupičina peć (Miracle, 2007), Šandalja II (Janković et al., 2012; Karavanić, 2003; Richards et al., 2015), Vlakno (Cvitkušić et al., 2018; Vukosavljević and Perhoč, 2017), Zemunica (Šošić Klindžić et al., 2015), Kopačina (Vukosavljević et al., 2011; Vukosavljević and Perhoč, 2017), Badanj (Whallon, 1999), Crvena Stijena (Basler, 1975; Kozłowski and Kaczanowska, 2004). The large mammal fauna is dominated by *Cervus elaphus* (red deer), followed by the dry environment taxon *Equus hydruntinus* (European ass). Other less frequent taxa are *Capreolus capreolus* (roe deer), *Bos/Bison* (wild cattle/bison), *Sus scrofa* (wild boar) and *Lepus* sp. (hare). A few specimens of *Canis lupus* (wolf), *Felis lynx* (lynx), *Felis silvestris* (wild cat), *Vulpes vulpes* (red fox) are also present. Smaller vertebrate remains (e.g., rodents, birds, bats, reptiles, fish) are not abundant in the Pleistocene

314 layers. The rich and abundant faunal assemblage suggests a landscape characterised by wide-open
 315 areas with wooded patches that was resource-rich, productive and able to sustain a large community
 316 of hunters-gatherers.

317 4.1.2 *Abandonment phase*

318 A complex and not yet fully understood human occupation gap of approximately 4.6 ka
 319 occurred between the latest Late Upper Palaeolithic and the earliest Mesolithic phases (Radić,
 320 2018). At the foot of the southern wall of the cave, the Mesolithic layers overlie the NYT tephra
 321 directly. Conversely, at the centre of the cave huge limestone blocks, up to 2.5 m large, rest on the
 322 NYT and are partially covered by about 1.4 m of limestone rubble mixed with reddish silty loam –
 323 with no cultural remains. The base of Mesolithic layers is here about 1 m lower than at the foot of
 324 the wall and overlies the rubble, apparently without sedimentary gaps. This situation suggests that
 325 throughout the Late glacial the topography of the inside of the cave had been pre-determined by the
 326 shape of the LGM scree, which had partly filled the cave from the western entrance and along the
 327 southern wall. The central area was strongly depressed, so that the accumulation of the Late Upper
 328 Palaeolithic layers did not level it completely. Later on, the deposition of ceiling breakdown blocks
 329 was triggered by frost in some still undated –posterior to NYT – cold phase of the Late Glacial and
 330 was followed by rubble and colluvium of reddish silty loam during the subsequent climate
 331 improvement. The fine component of these sediments include mica flakes and other minerals
 332 typical of the mineral suite of loess or loess-like sediments of the Adriatic area, and their grain-size
 333 supports this (Cremaschi, 1990; Wacha et al., 2011a, 2011b). These sediments can be found only in
 334 the central part of the cave, for the following two reasons: i) large breakdown blocks and rubble
 335 accumulated only under the ceiling opening, which is located above this area; ii) colluvium flowing
 336 into the cave from the western entrance, and probably also from the ceiling opening, was
 337 preferentially deposited in the topographic low.

4.1.3 Mesolithic

This topographic setting also influenced the deposition of the Mesolithic layers. Thickness and composition of sediments including the Mesolithic cultural remains are variable throughout the cave; the bottom areas of the cave are rich in ash and charcoal remains, whereas the central part of the cave was still slightly depressed when people started occupying the site again around 9.4 cal ka BP. In the centre these layers are somewhat thick (about 1.3 m) and largely composed of fine sediment deriving from the runoff of reworked red soils and/or windblown sediments, whereas they are much thinner (about 20-60 cm) and stony at the foot of the southern wall. These characteristics suggest that the topography of the cave (Fig. 3) inside was different from the present-day one, with a large depression at its centre, and that different areas of the cave were used for specific purposes by humans.

The age of the Mesolithic occupation is ca. 9.4 to 8.0 cal ka BP (Farbstein et al., 2012; Rainsford et al., 2014). Faunal remains from these layers indicate a reduction of the typical Late Pleistocene open environment mammal taxa, with a shift towards associations preferring good vegetative shrubby or woody cover, represented here mostly by *Vulpes vulpes* (fox), *Capreolus capreolus* (roe deer), *Sus scrofa* (wild boar). Among the infrequent remains of other small-size taxa are those of *Erinaceus roumanicus* (Northern white-breasted hedgehog) (Mauch Lenardić et al., 2018).

The decrease in mammal taxa size and a smaller number of ungulate remains testify to a generalised reduction of high-quality food resources, which was replaced by the exploitation of marine taxa. The Mesolithic units include remains of *Delphinidae* sp. (dolphin) and *Monachus monachus* (monk seal), as well as abundant *Scomber japonicus* (mackerel) and other fish taxa (Rainsford et al., 2014). These marine vertebrates are associated with extremely abundant molluscs like *Patella caerulea* and *Patella rustica* (limpet) and Trochidae, mostly *Phorcus turbinatus*

(turbinate monodont) (Branscombe et al. 2020). Several other marine mollusc taxa– mostly adapted to rocky coasts – are also well represented, even if less abundant than the aforementioned ones; continental molluscs are also common, as in most Adriatic area sites (Rizner et al., 2009), and mostly represented by *Eobania vermiculata* (chocolate band snail). Other Mesolithic sites of Dalmatia and neighbouring areas that share similar techno-typological and economic characteristics are Pupičina peć (Miracle, 2007, 2002, 2001), Abri Šebrn (Miracle et al., 2000), Nugljanska peć (Pilaar Birch and Miracle 2015), Vela Spilja Lošinj (Pilaar Birch and Miracle 2017), Vlakno cave (Vukosavljević et al., 2014; Cvitkušić et al., 2018), Zemunica (Šošić Klindžić et al., 2015). The remarkable amount of marine resource remains found in the cave, including large quantities of mackerel bones, pierced *Columbella* (dove snail) shells, and a relatively few large fish bones (possibly associated with deep-sea fishing), indicates an economic shift towards the sea.

4.1.4 Neolithic

The age of the Holocene sediments (including the earliest Neolithic remains of Vela Spila ascribed to the Impressa Ware cultural horizon) is bracketed between 8.0 and 6.0 cal ka BP (Čečuk and Radić, 2001). During the Neolithic there was virtually no deposition of clastic sediments derived by soil erosion from the outside of the cave, which is interpreted as a sign of extended vegetation on the slopes, favoured by mild climatic condition and evenly distributed rainfall. Depositional rates were however high inside the cave, because penning of domesticated animals, mostly sheep and goats, produced large quantities of dung that was intentionally burned. Typical sediments of this phase are the so-called “layer-cake” or *fumier* sequences (Boschian and Miracle, 2007), characterised by long successions of cyclically alternating black and white layers including ash, charcoal and other products of herbivore metabolism. From the Neolithic onwards, depositional environments in caves change in this way all over the Mediterranean area (Angelucci et al., 2009), demonstrating the new role of caves within a complex agropastoral system. Similar *fumier*

386 sequences were excavated in other caves on both sides of the Adriatic Sea, e.g. in several north
 387 Adriatic Karst sites (Boschian and Montagnari-Kokelj, 2000), at Pupičina peć (Boschian, 2006;
 388 Forenbaher and Miracle, 2006) in Istria, at Zemunica Peć (Šošić Klindžić et al., 2015) in central
 389 Dalmatia, and at Grotta dei Piccioni and Grotta S. Angelo (Boschian and Iaconis, 2008) in central
 390 Italy.

391 Neolithic deposits contain abundant bones of domestic animals (mostly sheep and goats), few
 392 wild animal bones, some terrestrial and marine mollusc shells, many potsherds, chert from the
 393 Gargano Peninsula (c. 125 km to the southwest) and obsidian from Lipari (c. 500 km to the
 394 southwest). Evidence of soil erosion is again apparent in the sequence corresponding with the Late
 395 Neolithic onwards. In this case erosion is interpreted as evidence of human activities (agriculture
 396 and pastoralism) which caused deforestation.

397 A long-lasting and intensive Neolithic occupation of the site is represented by a complete
 398 sequence of cultural facies and characteristic pottery of all major styles occurring in the eastern
 399 Adriatic area during this period (Forenbaher et al., 2013), testifying to the sociocultural and
 400 economic aspects of the Neolithic transition (Zvelebil and Lillie, 2000) and the further evolution of
 401 the Neolithic towards Copper Age and Early Bronze Age.

402 Throughout the period of occupation subsistence depended heavily on herding. Faunal
 403 assemblages are dominated by domestic animal remains; primarily sheep and goats, while cattle and
 404 pigs are less common. Also present in relatively small quantities are terrestrial and marine molluscs,
 405 while fish remains are quite rare.

406 Despite systematic attempts to recover seeds through flotation of soil samples, direct evidence
 407 of agriculture remains scarce, but this should not be interpreted as indicating an absence of plant
 408 cultivation. Productive arable land tends to be located some distance away from the heavily
 409 karstified areas where caves abound, and a similar absence of cultivars was observed in other caves
 410 in the region (Borojević et al., 2008; Forenbaher and Miracle, 2006). After the Neolithic, the

archaeological sequence continues through the Copper and Bronze Ages (Radić, 2018), with rich ceramic assemblages and sediments of mostly *terra rossa* colluvium and anthropic components represented by variable amounts of organic matter and stable sediments.

4.2 Sea-level change and palaeogeography around Vela Spila

According to the model predictions (Fig. 6), RSL was 101-107 m below present at the start of Vela Spila's Upper Palaeolithic occupational phase, and then climbed at a rate of about 5 to 6 mm/a. Combining the isostatic model with the bathymetric analysis, it is possible to infer that the landscape around the Island of Korčula changed remarkably over the site's prehistoric phases (Table 3). Contemporaneous with the first detected Upper Palaeolithic occupation (starting at ~19.7 cal ka BP, Fig. 7A), the cave was ~8-9 km from the sea and 221-228 m above it, while the area south of western Korčula consisted of a broad plain where the present-day Lastovo island group appeared as a cluster of hills. 7-16% of the land within 20 km of the site (a day's round-trip travel at a comfortable walk) was inundated. Korčula was still also connected to the mainland in the east via the Pelješac Peninsula and Hvar Island to the north. To the SW of the present bay of Vela Luka, a 0-30 m deep sea existed, and to the NW Vis and Biševo were also not yet islands. South of Vela Luka bay, a natural depression indicated by the bathymetric data might have been filled by a small, shallow lake or marsh a few meters deep and a couple kilometres wide. To the N and NE of present day Korčula, the palaeo-Neretva river flowed in an alluvial plain between Hvar and Korčula, shown in GIS reconstructions carried out by Sikora et al. (2014).

Archaeological phase	Start (ka BP)	End (ka BP)	RSL at start (m)	RSL at end (M)	RSL change (m)	Average rate of change (mm/a)	Average Horizontal Coastline Change (m/a)	Vertical RSL Change in human lifetime (m)	Horizontal coastline change in human lifetime (m)
Palaeolithic	19.7	14.0	-107 to -100	-74 to -72	29 to 33	5 to 6	5	0.2	160

Abandonment	14.0	9.4	-74 to -72	-30 to -16	44 to 55	10 to 12	14	0.4	492
Mesolithic	9.4	8.0	-30 to -16	-13 to -7	9 to 17	7 to 12	0.5 in Vela Luka Bay	0.2 to 0.4	18 in Vela Luka Bay
Neolithic	8.0	6.0	-13 to -7	-3 to -1	6 to 10	3 to 5	0.1 in Vela Luka Bay	0.1 to 0.2	4 in Vela Luka Bay

Table 3. Palaeogeographic changes by archaeological period at Vela Spila. In the Mesolithic and Neolithic, coastal migration around the island becomes insignificant so the rates of incursion into the long, valley-like Vela Luka Bay are noted instead. N.b. the distinction between mm/a (mm per year) and m/a (meters per year).

431 By the end of the Palaeolithic occupation at 14.0 ka BP (Fig. 7B), ca. 5 ka later, RSL had risen
 432 29 to 33 m (Table 3), the coastline had advanced 4-10 km into Vela Luka Bay, and Vis and Biševo
 433 were likely already islands. At this point, about 40% of land within 20 km of the site was flooded.
 434 When the cave was abandoned, sometime after the NYT eruption between 14.9 and 13.9 cal ka BP
 435 (Blockley et al., 2008; Deino et al., 2004), any nearby lake or depression south of Vela Luka Bay
 436 had already become part of the Adriatic Sea, which had been advancing eastward up to 4 m/a
 437 (meters per year) in this area.

438 According to our models, the most dramatic RSL rise and landscape change around Korčula
 439 occurred during the roughly 5 ka (14.0-9.4 cal ka BP) period when the cave was abandoned. RSL
 440 rose ~44 to 55 m at an average of about 10–13 mm/a and the coastline advanced eastward by as
 441 much as 10 to 12 m/a or more to the north and south of the island (Table 3). Land connections to
 442 areas north and south of Korčula, such as present day Lastovo and Hvar, were probably severed
 443 during the first millennium of the abandonment phase.

444 Much of the coastlines of the islands advanced to within 1 km of their present position by ca.
 445 12 ka BP, after which horizontal changes in coastlines became much smaller: above the ~70 m
 446 isobath, slopes around the island tend to be much steeper (Fig. 8). A land bridge between the
 447 Pelješac Peninsula and Korčula may have persisted until between 12 and 10 ka BP, at which time
 448 the geography of the area became quite similar to the present-day. When the cave was finally
 449 reoccupied at the start of the Mesolithic at ~8.0 ka BP (Fig. 7C, Fig. 9), the surrounding landscape

450 had been totally transformed. About 80% of nearby lands were flooded. 30-50 m deep seas were 2
 451 km away from the cave to the north and south, and a shallow (10-20 m) bay was only 1-2 km to the
 452 west. No land connections with other present-day islands existed, though many of the smaller islets
 453 around Korčula may still have been connected to it at times. By ca. 8.0 ka BP, at the beginning of
 454 the Neolithic, most of the northern and southern coasts of the island were even closer to the present-
 455 day shoreline, though some islets may still have been connected, and the inner part of Vela Luka
 456 harbour had not been fully submerged.

457 **5 Discussion**

458 **5.1 Last Palaeolithic occupants facing rapidly inundating planes**

459 The Palaeolithic people at Vela Spila experienced average RSL change rates of 5–6 mm/a,
 460 although the ANU_S4 realization does predict some phases of higher rates. The rate of RSL change
 461 increased to 10–12 mm/a during the abandonment phase (Table 3). Hence the Late Upper
 462 Palaeolithic coastline was relatively stable compared to that of the subsequent abandonment phase.
 463 The cave was only 8–9 km distant from the sea, and the lack of shells in the archaeological
 464 stratigraphy during this phase of inhabitation is not necessarily a consequence of distance from the
 465 cave but, more likely, a preference for the terrestrial species which had been the traditional Upper
 466 Palaeolithic food resource (Miracle, 2007; Mussi and Palombo, 2001; Stewart et al., 2003) and
 467 would still have been widely available at this point, given that they occupy a large part of the diet.
 468 The palaeo-Neretva's plain north of Korčula became submerged during the abandonment phase at
 469 Vela Spila, and in those millennia the high rates of RSL change may not have left time for the
 470 formation of submerged landforms such as palaeocoastlines or palaeodeltas (Sikora et al., 2014).

471 During the Palaeolithic phase, only a relatively small area of potential hunting grounds was
 472 inundated in the plains north and south of Korčula. Still, the coastline moved east at a rate of nearly

473 5 m/a, so that in the average human lifespan of 35 years, a person would have witnessed ca. 160
 474 meters of horizontal coastal change. The rate of change experienced by the Upper Palaeolithic
 475 foragers in the Central Adriatic was 6-7 times greater than the present-day estimates of ongoing
 476 RSL change (Church et al., 2013; Neumann et al., 2015). It is most likely that this landscape change
 477 stressed littoral habitats and limited potential human exploitation of marine resources; however,
 478 sediments and cultural remains show that human frequentation continued to be intensive in the
 479 cave. Following on the Palaeolithic occupation at Vela Spila, the abandonment phase (from ca. 14.0
 480 to 9.4 cal ka BP) appears to have seen even more intense changes in the surrounding
 481 palaeogeography.

482 **5.2 Environmental reasons for abandoning the cave: rising sea or climate?**

483 The deposition into Vela Spila of in-washed NYT tephra (Fig. 4) coincided or preceded
 484 approximately the end of the Late Upper Palaeolithic occupation and the beginning of a long gap in
 485 the human record (14.0–9.4 cal ka BP), at the start of which the RSL was 74–72 m below present.
 486 Since the eruption took place about 300 km SW of Vela Spila, it is worth speculating what role, if
 487 any, this event may have played in inducing Upper Palaeolithic people to abandon the cave.
 488 Cryoturbation features involving specifically the NYT sediment in the cave suggest that deposition
 489 was associated or immediately followed by a cold spell, though it cannot be ascertained if it was
 490 consequential to the eruption.

491 Rapid landscape changes caused by a high RSL rise rate may have had a greater influence on
 492 human behaviour and settlement pattern change during this phase; predicted RSL changes were
 493 much faster than during the Upper Palaeolithic cave occupation. Humans would have witnessed
 494 nearly 0.40 m of RSL rise, corresponding to about 500 m of horizontal coastline displacement
 495 during a 35-year average lifespan, i.e. about 14 m of horizontal eastward coastal change per year
 496 immediately north and south of Korčula. This suggests a highly unstable or marshy littoral zone,

497 rapid flooding of the traditional foraging grounds of the Upper Palaeolithic groups, and stress on the
498 ecosystem at all trophic levels. Particularly rapid change (about 20 m rise) took place during the
499 centuries following the Meltwater Pulse 1A (MWP-1A), which has been dated to 14.7–14.3 ka BP
500 (Deschamps et al., 2012).

501 Volcanic eruptions such as the NYT on the other hand usually have an impact on climate for
502 only a few years, so that their consequences are not easily detected in $\delta^{18}\text{O}$ isotope or other climate
503 proxies (Aufgebauer et al., 2012). The NYT eruption also coincides with the end of a colder climate
504 phase highlighted at Lake Ohrid (Vogel et al., 2010), and with increased winter precipitation
505 (Bordon et al., 2009; Aufgebauer et al., 2012). If the settlement was already in a marginal position
506 due to climate changes and to the landscape changes highlighted by this study, a sequence of
507 particularly unfavourable years due to an eruption may have contributed to pushing the Late Upper
508 Palaeolithic people to a tipping point that eventually resulted in abandonment of the site.

509 The first two thousand years of the Vela Spila occupation gap overlap with, in addition to the
510 NYT and Meltwater Pulse 1A, the Bølling–Allerød warming, and were followed by the Younger
511 Dryas major dry/cold event (Gkinis et al., 2014), which is recorded throughout the Balkans in
512 various lacustrine sequences (Cvetkoska et al., 2014). At many Late Upper Palaeolithic sites in the
513 Eastern Adriatic region the Bølling–Allerød warming is associated an increase in of human
514 settlement (Miracle, 2007), and the same pattern is largely true on the Italian side of the Adriatic
515 (Mussi 2001). The occupational sequence at Vela Spila is in stark contrast to this wider pattern.

516 Younger Dryas effects in the Adriatic Plain are indicated at Vela Spila by the occurrence of
517 partially altered loess-like sediments colluviated into the cave. The precise timing of this
518 colluviation is currently unknown; it probably was partly during the Younger Dryas, but mostly
519 during the early Holocene. It is, however, unclear that the Bølling–Allerød or Younger Dryas
520 climate changes played a direct role in forcing the Late Upper Palaeolithic foragers to leave the site,
521 although the Younger Dryas is correlated with cultural change and adaptation throughout Europe

(Aura et al., 2011; Burdukiewicz, 2011; Mussi and Peresani, 2011; Weber et al., 2011). Instead, the rapid RSL rise concurrent with the meltwater pulse 1A and Bølling–Allerød may have been the environmental trigger for the abandonment of Vela Spila, since the cave had already been abandoned by the time of the Younger Dryas at ca. 12 or 13 ka BP (Gkinis et al., 2014).

5.3 Stabilising coastlines and the Mesolithic

Benjamin et al. (2017) suggest that the Northern Hemisphere cooling during the Younger Dryas slowed the RSL rise in the Mediterranean as in other areas in the world. The GIA models in this work (Fig. 6) also predict a decrease in RSL rise rates following the Younger Dryas, but only few local relative sea-level indicators are available for verification. By ca. 9.4 ka BP, when the model predicts RSL rates were starting to level off, Mesolithic groups re-occupied the cave and continued dwelling in it for the following ~ 1.5 ka. The corresponding units of the cave sequence show evidence of the Preboreal and Boreal humid climate conditions indicated by colluvia. In this period RSL continued rising quickly from between -30 to -16 below present, up to between -13 m and -7 m – i.e. a rise of 9 m to 17 m in approximately 1.5 ka (Table 3), which gives a rate of 7 to 12 mm/a, though this is a slower rate of change than during the abandonment phase. The sea was only about 1-2 km distant from the cave at the onset of the Mesolithic, compared to 8-9 km in the Upper Palaeolithic.

The Mesolithic assemblage is dominated by the remains of shellfish, fish and other marine creatures. The exploitation of marine resources by Mesolithic people is widespread in the Mediterranean and the Atlantic, though the Mediterranean is supposed to be less productive (Colonese et al., 2011). In general, resource depression and human population pressure have been considered the main reason for shifting toward marine resources (Colonese et al., 2011), even if there are major differences between regions. However, it does not appear that the exploitation of

546 fish and shellfish was ever the most important food resource in the Adriatic region; isotopic studies
 547 on human remains show that “while the Mesolithic people of the Adriatic coast consumed some
 548 marine protein, terrestrial protein constituted a significant part of the diet” (Lightfoot et al., 2011, p.
 549 82). The balance between the need for resource diversification and expedience of marine resources
 550 due to the approaching coastline is not always clear or consistent. As the Mesolithic progresses,
 551 there is a decline in the use of fish and an increase in shellfish and snails at Vela Spila, along with a
 552 decrease in terrestrial fauna remains. Fishing seems to shift from open-sea to inshore taxa
 553 (Rainsford et al. 2014). This is partially in contrast with data from the northern Adriatic where the
 554 coastline approached later: here, fishing shifts from freshwater to marine taxa and Early Mesolithic
 555 intensive snail exploitation is substituted by consumption of marine species (Boschian and Pitti,
 556 1984; Cremonesi et al., 1984).

557 These data suggest that, in the northern Adriatic, the need for resource diversification was the
 558 driving force towards marine food well before landscape modification due to RSL rise. In contrast,
 559 the same need started more or less contemporaneously at Vela Spila, but was immediately oriented
 560 towards marine resources because of the earlier advance of the coastline. The decrease in other
 561 resources is testified by the disappearance of red deer and other large ungulates from the Mesolithic
 562 layers, presumably because of the early Holocene palaeoenvironmental turnover, and because
 563 Korčula had become an island where faunal replacement was impossible as access to more
 564 productive hunting grounds decreased.

565 The transition between Mesolithic and Neolithic started in the Eastern Adriatic at ca. 8.0 ka BP
 566 (Forenbaher et al., 2013). Radiocarbon determinations and cultural assemblages from Vela Spila are
 567 consistent with this date. The Mesolithic-Neolithic transition shortly follows the 8.2 ka event, which
 568 was a disruption in thermohaline Atlantic circulation owing to meltwater input from North America
 569 (Alley and Ágústsson, 2005). The 8.2 ka BP event is associated with an estimated drop in winter
 570 temperatures of more than 4° C, at least in Northeastern Greece (Pross et al., 2009) and the sea-

level impact of the event in the study area is approximately 1 m (Kendall et al., 2008), although this perturbation is too rapid and small to appear in the GIA models. Furthermore, because the coastlines were already near their present-day position abutting the high relief slopes of the island (Fig. 8), the RSL rise itself would not have been significant for the inhabitants unless they had built immobile coastal infrastructure, of which no evidence exists. Likewise, no clear fingerprint of the 8.2 event exists in the archaeological record of the site. By the end of the Neolithic at ca. 6.0 ka BP, RSL had risen to within 3 meters of present level, and sea-level changes from then on were much slower (Fig. 6).

6 Conclusions

In this work we direct evidence from a detailed, extensively excavated archaeological stratigraphy was used to understand human reactions to changing rates of RSL rise and horizontal coastline shift in a coastal landmass that becomes an island.

In the Late Upper Palaeolithic the abandonment of Vela Spila cave was triggered by environmental events that caused the area to be less attractive for humans. In particular, high rates of sea-level rise likely stressed the least observant inhabitants in Vela Spila more sharply than other environmental factors (e.g. climatic forcing) by submerging hunting grounds and reshaping marine and terrestrial ecosystems in the rapidly disappearing Great Adriatic Plain, where the coastline advanced tens of meters per year.

The coastline positions around Korčula island become stabilized only by ~12 ka BP as the rising seas surpassed the 70 m isobath and encountered the steep morphology of the island's sides (Fig. 8), though rapid RSL rise continued. This state, together with other environmental factors, may have fostered the re-occupation of the cave at ca. 9.4 cal ka BP. In the Mesolithic, it was the new insularity of the island that forced humans to exploit all resources available (e.g. seafood and

594 smaller fauna like foxes, rather than larger animals such as red deer). The disadvantages of this
 595 insularity were initially overcome by skilled seafaring and later, more effectively, by the onset of
 596 agriculture and pastoralism that accompanied, after 8 ka BP, a substantial slowing down of sea-level
 597 rise.

598 This study also emphasizes the importance of potential future research projects aimed at
 599 gathering underwater data, for example by more detailed bathymetric surveys or sediment coring in
 600 relevant areas around Vela Luka bay such as the plains to the north and south, the palaeo Neretva,
 601 and the strait between Korčula and the Pelješac, which could reveal additional drowned landforms
 602 and improve resolution for sea-level change histories and the environmental transformation of
 603 Korčula from mainland to island.

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999 Figures captions

1000 Fig 1. Map of the Adriatic Sea and study area. A: general map of the Adriatic Sea, divided into
 1001 three sub-basins, and surrounding areas. B: Korčula and surrounding Islands. Tectonic information:
 1002 Korbar, 2009; Surić et al., 2014. Map and relief data: GEBCO and GADM.

1003 Fig 2. Vela Spila and surroundings. Top: View from the cave towards the SW, showing Vela
 1004 Luka town and harbour (photo from P.T. Miracle). Middle left: View of Vela Luka bay looking
 1005 northeast. Hvar and the mainland in background. Vela Spila is in the centre hill of the image (photo
 1006 from G. Boschian) Middle right: Another view from Vela Spila, but looking west out Vela Luka bay.
 1007 The innermost harbour is visible (photo from F. Rinaldi). Bottom: Interior photomosaic of Vela
 1008 Spila. The most recently excavated trenches are on the left (photo from G. Boschian).

1009 Fig 3. Plan of Vela Spila cave, with locations of archaeological excavations. 1: dripline of
 1010 entrance and of windows in ceiling; 2: excavations pre-2000; 3: excavations 2000-2018; A-A'
 1011 location of the profile in fig. 4.

1012 Fig 4. General stratigraphy of the Vela Spila archaeological deposit. From left to right: cultural
 1013 horizons and informal Quaternary stratigraphy, photo and main lithostratigraphic subdivisions of
 1014 vertical profile (A-A' in fig. 3). NYT: Neapolitan Yellow Tuff; red lines: erosive boundaries. Note
 1015 the wavy limits of NYT and overlying units, due to frost action in sediment.

1016 Fig 5. Summary of calibrated dates from Vela Spila. Note the absence of archaeological
 1017 material for dating during the abandonment phase.

1018 Fig 6. Sea level reconstructions for Vela Luka. Sea-level realizations for the Vela Luka area of
 1019 Korčula. Dashed line: I6G_S4 realization of the ICE-6G_C (VM5a) (Peltier et al., 2015). Dotted
 1020 line: ANU_S4 realization of Lambeck/ANU (Lambeck et al., 2003; Lambeck and Purcell, 2005).
 1021 Sea-level indicators from Faivre et al. (2013), Juračić and Surić (2010), and Mljet lakes (Govorčin
 1022 et al., 2001; Wunsam et al., 1999) shown in green. Archaeological periods for the site reconstructed
 1023 with 14C dates from Table 2. Exact period delineations are an abstraction, in reality date
 1024 uncertainties and gradual cultural shifts mean the transitions were nuanced.

1025 Fig 7. Palaeogeography and sea-level change at Vela Spila. Palaeogeographic reconstruction of
 1026 the area around Korčula at different phases of Vela Spila's settlement history. A) Start of the
 1027 Palaeolithic ca. 19.7 cal ka BP. B) Start of the abandonment phase ca. 14.0 cal ka BP. C) Start of the
 1028 Mesolithic ca. 9.4 cal ka BP. Vela Spila location shown by red dot. Light blue shows ICE6G
 1029 predicted RSL; dark blue shows Lambeck/ANU predicted RSL. Dotted blue line indicates probable
 1030 location of palaeo-Neretva river according to Sikora et al.(2014). For each time-slice, a red line or
 1031 lines indicates distance to sea from Vela Spila. The crosshatched circle indicates the percent of land
 1032 within a 20 km radius from the cave that is inundated. Map elevations interpolated from datasets
 1033 listed in Table 1.

1034 Fig 8. Slope vs. depth in Western Korčula. Profile of 15 km transects AB and CD from Fig 5C,
 1035 showing the higher slopes that predominate above the 70 m isobath (note, Y axis in left panels is
 1036 exaggerated). Right panel shows slope in degrees vs. depth below sea level along transect CD.
 1037 Slopes increase above -70 m. This morphology results in negligible horizontal coastline change
 1038 after ca. 12 ka BP.

1039 Fig 9. A zoomed in view of the palaeo shorelines at the start of the Mesolithic (~9.4 ka BP) at
 1040 Vela Spila, overlaid on modern orthophotos (Croatian Geoportal, 2019). ANU and ICE models for
 1041 sea-level are shown. The situation of the site on a hill at ~121 m ASL above the harbour valley is
 1042 evident. To the south and southeast, where the town of Vela Luka is now situated the western end of
 1043 the flat karstic depression known as Blatsko Polje can be seen.

1044

Figure 1

[Click here to access/download;Figure;Fig1_regional_map_double_column.tif](#)

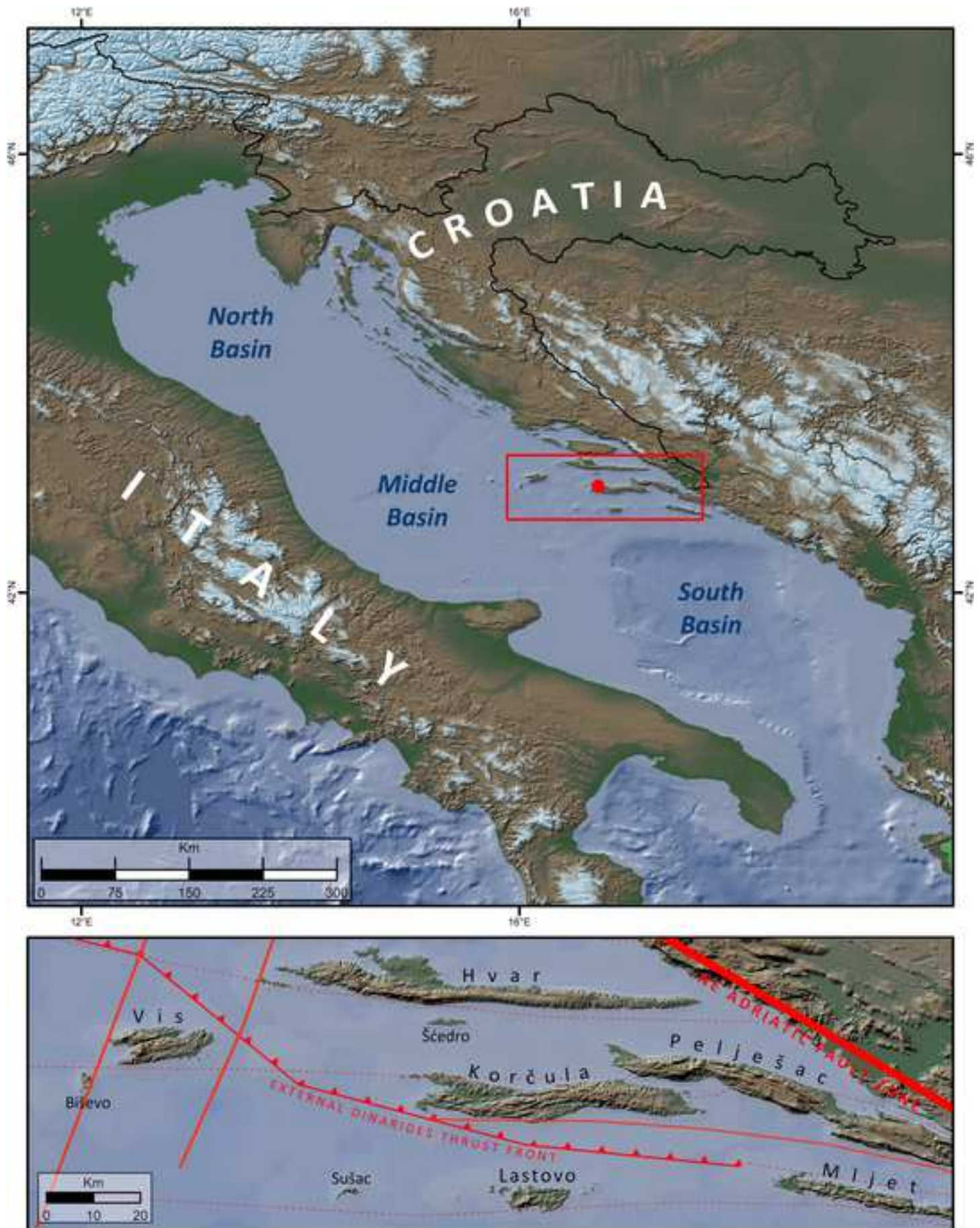


Figure 2



Figure 3

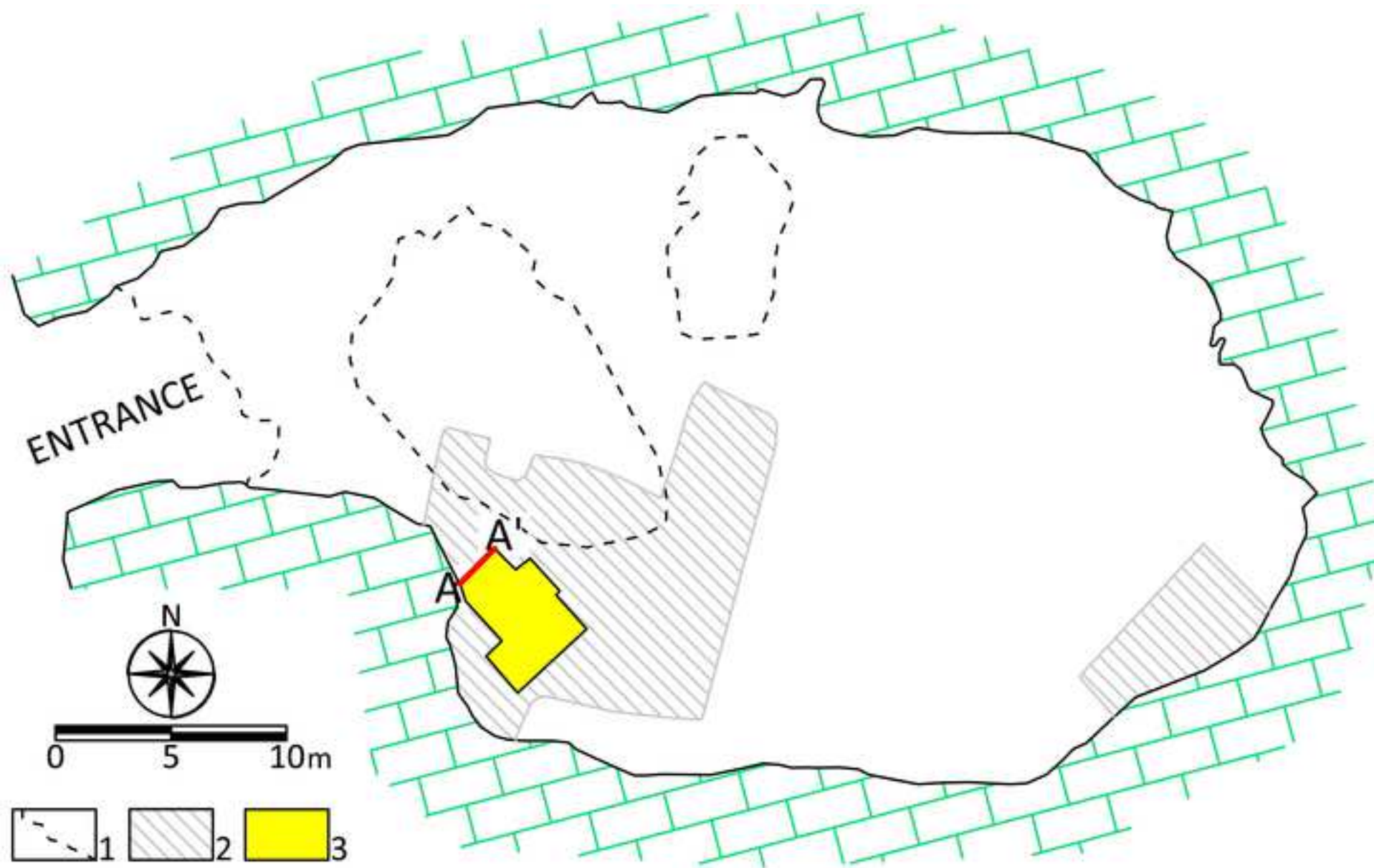


Figure 4

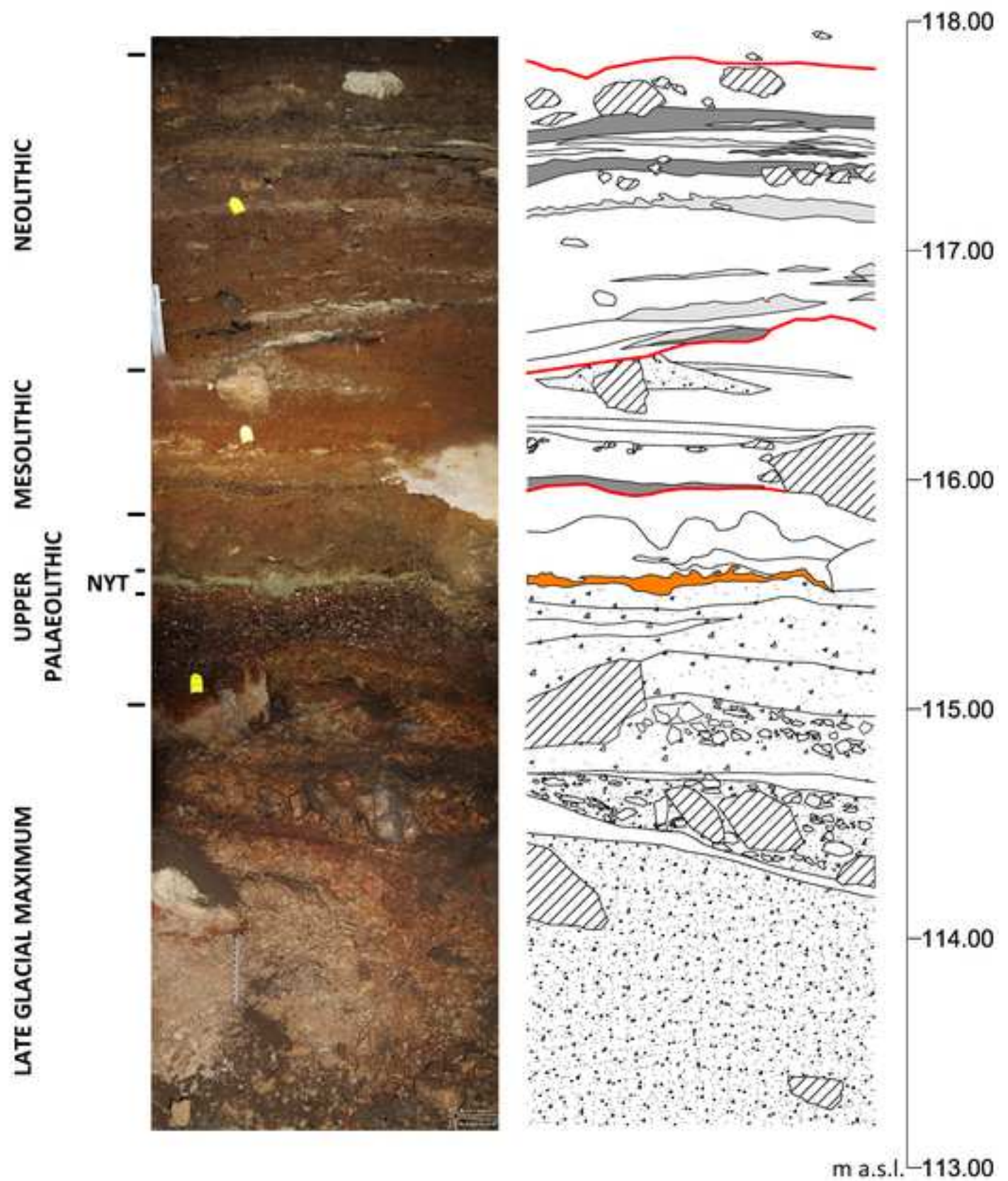


Figure 5

OxCal v4.3.2 Bronk Ramsey (2017); r5 IntCal13 atmospheric curve (Reimer et al 2013)

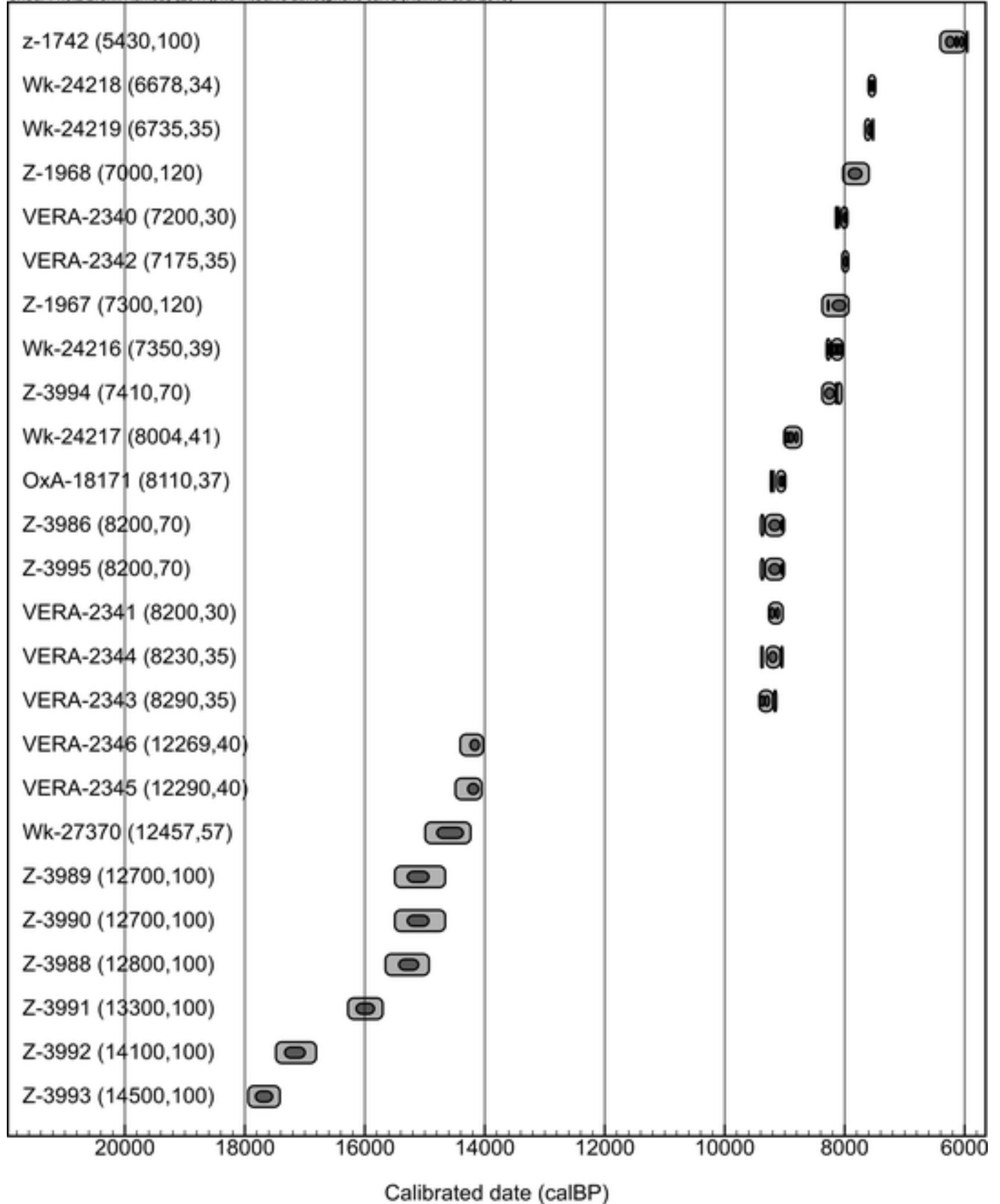
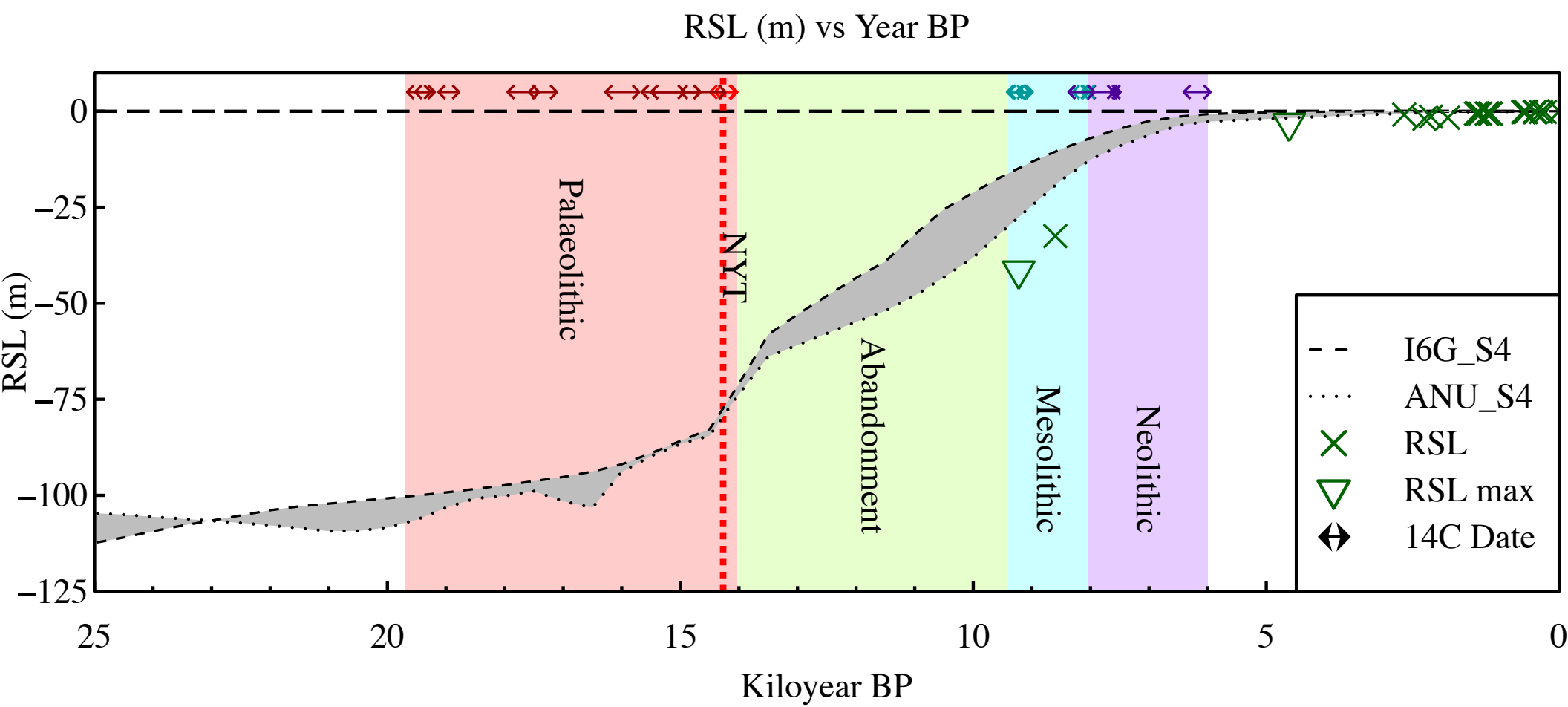


Figure 6



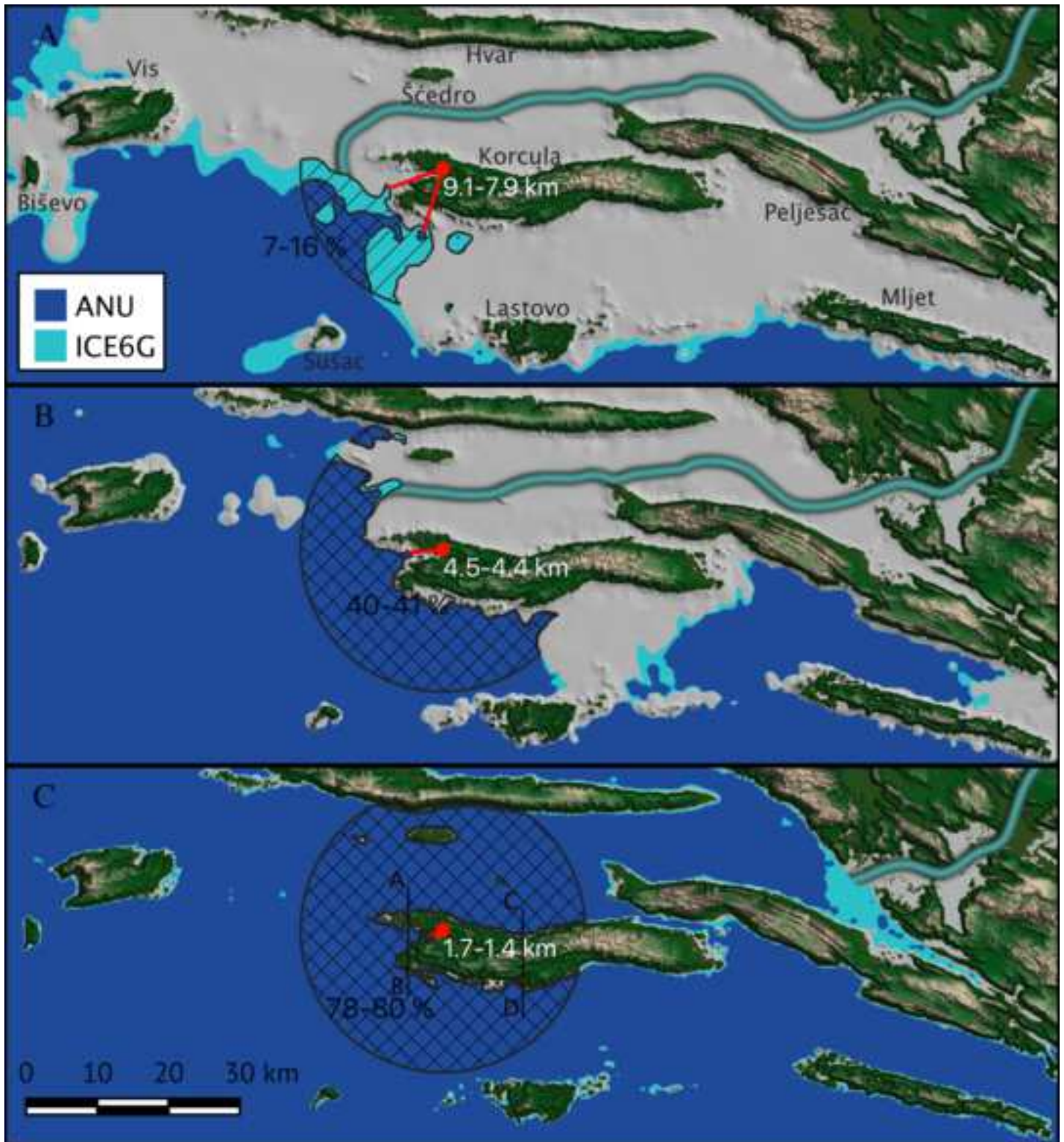


Figure 8

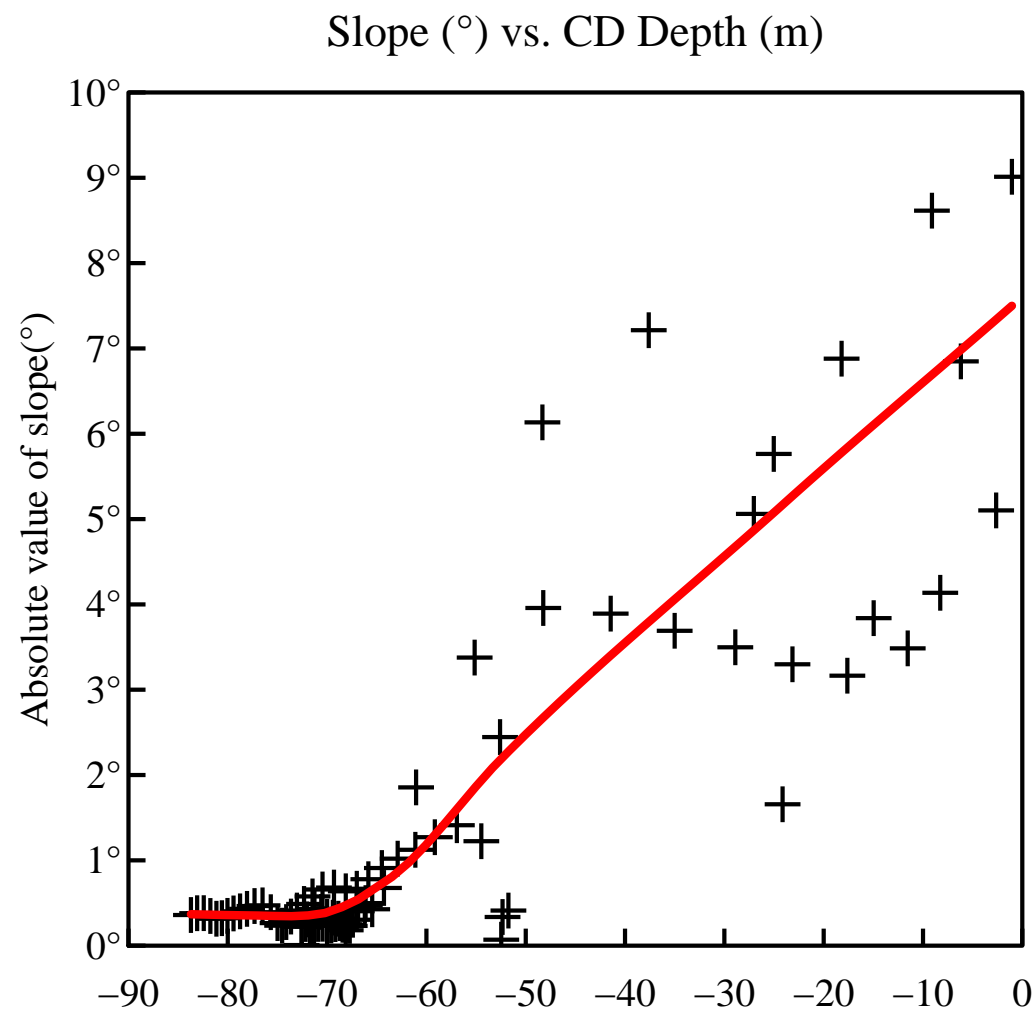
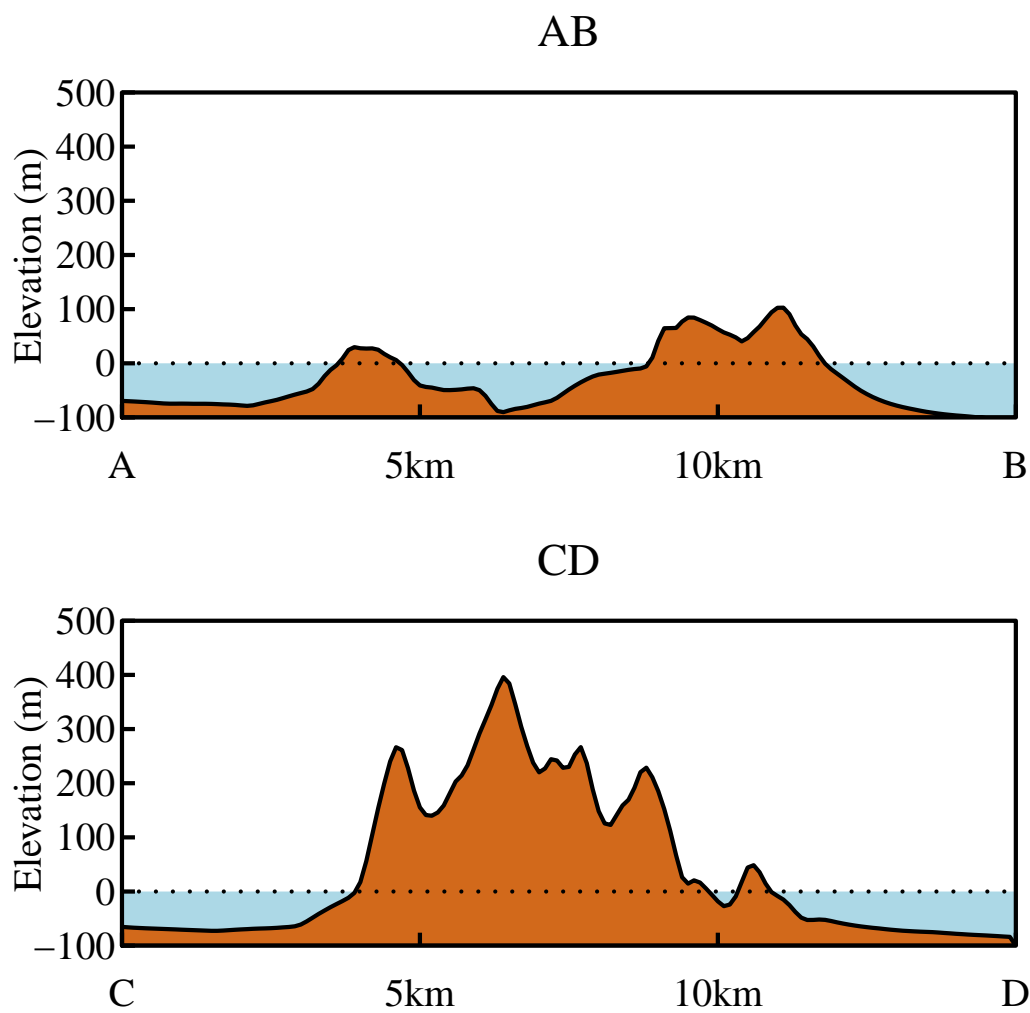


Figure 9



Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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