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

Published Version:

Human adaptation to changing coastal landscapes in the Eastern Adriatic: Evidence from Vela Spila cave, Croatia / Dean, Silas; Pappalardo, Marta; Boschian, Giovanni; Spada, Giorgio; Forenbaher, Stašo; Juračić, Mladen; Felja, Igor; Radić, Dinko; Miracle, Preston T.. - In: QUATERNARY SCIENCE REVIEWS. - ISSN 0277-3791. - STAMPA. - 244:(2020), pp. 106503.1-106503.18. [10.1016/j.quascirev.2020.106503]

Availability:

This version is available at: https://hdl.handle.net/11585/771653 since: 2022-02-14

Published:

DOI: http://doi.org/10.1016/j.quascirev.2020.106503

Silas Dean, Marta Pappalardo, Giovanni Boschian, Giorgio Spada, Stašo Forenbaher, Mladen Juračić, Igor Felja, Dinko Radić, Preston T. Miracle, *Human adaptation to changing coastal landscapes in the Eastern Adriatic: Evidence from Vela Spila cave, Croatia*, Quaternary Science Reviews, Volume 244, 2020, 106503.

The final published version is available online at: https://doi.org/10.1016/j.quascirev.2020.106503

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

Silas Dean[1], Marta Pappalardo[1]*, Giovanni Boschian[2], Giorgio Spada[3], Stašo Forenbaher[4], Mladen Juračić[5],
Igor Felja[6], Dinko Radić[7] Preston T. Miracle[8]

[1]Department of Earth Sciences, University of Pisa, Italy
[2]Department of Biology, University of Pisa, Italy
[3]Dipartimento di Scienze Pure e Applicate, Università di Urbino 'Carlo Bo', Urbino, Italy
[4]Institute for Anthropological Research, Zagreb, Croatia
[5]Croatian Academy of Sciences and Arts, Croatia
[6] University of Zagreb, Faculty of Science, Dept. of Geology, Croatia
[7]Centar za kulturu, Vela Luka, Croatia
[8] Department of Archaeology, University of Cambridge, UK
*Corresponding author

KEYWORDS: Sea-level change; Environmental change; Human settlement patterns, Bathymetry; Prehistoric archaeology; Late Pleistocene-Holocene; Central Adriatic coast; Croatia

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

1 Introduction

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

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

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

Sea-level reconstructions must be combined with bathymetric data, which have also been widely used to identify landforms, assess palaeoenvironments and palaeoshorelines, and address archaeological questions in the central Mediterranean. Bathymetric mapping and archaeological research have been combined in Sardinia (Palombo et al., 2017) for this purpose. In the Tyrrhenian Sea west of Italy, seismic profiles have been used to detect terraces that may be associated with ancient sea stands (Casalbore et al., 2017). Extensive single- and multibeam data were used (Trincardi et al., 2014) to identify several drowned landforms in the western Adriatic. Bathymetric data from Malta (Foglini et al., 2016) have shown drowned karstic features and river landforms, and can answer questions about prehistoric fauna migration and human settlement. In the NW Adriatic, prehistoric settlement surfaces and lagoon deposits have contributed to landform and RSL reconstructions (Fontana et al., 2017). In the eastern coast of the Adriatic dozens of submerged coastal prehistoric sites have been located, from Istria to southern Dalmatia, and excavations have been initiated on several of those sites (Bekić, 2017; Bekić et al., 2015; Benjamin et al., 2011; Benjamin and Bonsall, 2009; Čelhar et al., 2017; Koncani Uhač and Čuka, 2015; Radić Rossi, 2008). The majority of the sites belong to relatively recent prehistoric times (Bronze Age and Iron Age), while only very few of them belong to Copper Age or Neolithic periods. Further excavation, interdisciplinary investigation (collaboration of archaeologists and geologists), and analyses are required before they can be used as accurate indicators of local sea-level change in prehistoric times (Rossi, 2017)

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

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

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

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

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

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

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

2 Regional setting

2.1 Adriatic sea

The Adriatic Sea (Fig 1) is a NW-SE elongated basin of approximately 800 by 200 km that separates the Italian peninsula from the Balkans (Trincardi et al., 2014). This basin can be divided into three sub-basins: the northern, which is 35 m deep on average, the middle with an average depth of 140 m, and the southern with maximum depths reaching 1200 m (Artegiani et al., 1997). This paper is focused on the island of Korčula, which lies on the eastern coast between the middle and southern basins. The Eastern Adriatic bedrock is about 8,000 m of limestone and/or dolomite (Vlahović et al., 2005, 2002) formed in shallow sedimentation basins between the Mid-Late Triassic, Mesozoic and Palaeogene, followed by relatively thin Eocene flysch outcrops. The tectonic deformation pattern of the Eastern Adriatic is characterised by a complex system of faults, thrust faults and overthrusted tiles formed since the Miocene and developed along the so-called Dinaric Strike with NW-SE orientation (Vlahović et al., 2005, 2002). The typical relief pattern of mountain and hill ridges parallel to the coastline (Fig 1) derives from this tectonic compressional motif, followed by extensional processes and eventually repeated flooding during the Quaternary sea-level fluctuations. The westernmost Dinarides were submerged by the postglacial RSL rise (Kelletat, 2005) and now form the Croatian islands and the typically rocky Dalmatian Coast (Felja et al., 2015; Pikelj and Juračić, 2013). Significantly for this study area, the Eastern Adriatic coast and its hinterland are karstic and dominated by typical karst landforms, with few significant rivers discharging sediments into the sea, so that the present-day bathymetry closely reflects LGM landforms (Pikelj and Juračić, 2013). This is confirmed in the immediate study area by research (Giglio et al., 2020) in the waters around the present-day Neretva delta, which shows river sedimentation rates quickly approaching 0 mm/a (mm per year) within 10 km offshore. This aspect of the coast contrasts with the wide and flat morphology of the north-eastern Adriatic, which was an alluvial plain dominated by sandy river discharge when the LGM RSL was 120 m below present (Trincardi et al., 2014). Though these submerged morphological features in the western Adriatic have been identified by multibeam imagery (Trincardi et al., 2014), including drowned karst landscapes (Taviani et al., 2012), public high-resolution data are less available for the rocky Eastern Adriatic.

2.2 Central-southern Dalmatia

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

2.3 Vela Spila

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

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

2.4 Regional relative sea level

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

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

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

3 Materials and methods

3.1 Bathymetric data

This study utilizes a combination of publicly available bathymetric data sources. These include digitized nautical charts, and SRTM15_PLUS data from NOAA ERDDAP (Sandwell et al., 2014a), which is a 15” version of the Shuttle Radar Topography Mission (SRTM) dataset containing bathymetric data from a combination of sources, chiefly from satellite altimetry gravity elevations (Smith and Sandwell, 1997). The bathymetric data have been combined with topographic digital elevation data of 1” resolution (~30 m) from the SRTM. Table 1 lists these datasets and their 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; Drẑavni Hidrografski Institut, 1998)

Table 1. Overview of the bathymetric and topographic datasets.

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

3.2 Uncertainties

The vertical datum for the Croatian chart soundings used in this DEM are based on HRSDM71, i.e. Mean Lower Low Waters of Spring Tide from tide gauges at Dubrovnik, Split, Bakar, Rovinj and Koper (epoch 1971.5) (Domijan et al., 2005; HHI, 2019). A ±0.5 m is a cautious uncertainty for these whole-number elevations. The satellite altimetry data is heavily post processed to remove wave noise (Sandwell et al., 2014b; Smith and Sandwell, 1997), and come from electromagnetic 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 palaeoenviromental 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; Kozlowski 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 palaeoenviromental 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	14C 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 *et. al.* 2014	Palaeolithic	LUP A
VERA-2338	16140±60	19665-19255	AMS	WC	Farbstein *et al.* 2012: TAB. 1	Palaeolithic	LUP A
VERA-2339	15690±70	19130-18775	AMS	AB	Farbstein *et al.* 2012: TAB. 1	Palaeolithic	LUP A
z-3993	14500±100	17950-17410	Std	WC	Farbstein *et al.* 2012: TAB. 1	Palaeolithic	LUP C
z-3992	14100±100	17587-17105	Std	WC	Farbstein *et al.* 2012: TAB. 1	Palaeolithic	LUP D
z-3991	13300±100	16280-15700	Std	WC	Farbstein *et al.* 2012: TAB. 1	Palaeolithic	LUP E
z-3988	12800±100	15660-14925	Std	WC	This paper*, Rainsford *et. al.* 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 *et al.* 2012: TAB. 1	Palaeolithic	LUP G
VERA-2345	12290±40	14490-14050	AMS	AB	Farbstein *et al.* 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 *et. al.* 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 *et. al.* 2014	Mesolithic	Meso B
z-3986	8200±70	9400-9005	Std	WC	This paper*, Rainsford *et. al.* 2014	Mesolithic	
OxA-18171	8110±37	9235-8985	AMS	HB	Forenbaher *et al.* 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 *et. al.* 2014	Mesolithic	Meso D
Wk-24216	7350±39	8305-8025	AMS	AB	This paper*, Rainsford *et. al.* 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 *et al.* 2014	Neolithic	Neo C
z-1742	5430±100	6410-5950	Std	WC	Srdoč *et al.* 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.*

4.1.1 Palaeolithic

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

The sediments testifying to the first human occupation of the cave directly overlie the LGM talus and include Upper Palaeolithic remains ^{14}C constrained to approximately 19.7-14.0 cal ka BP (Fig. 5, Table 2). These strata are composed of frost slabs that decrease in quantity and become finer 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}Ar/^{39}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-anthropic 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. Pupićina 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; Kozlowski 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 layers. The rich and abundant faunal assemblage suggests a landscape characterised by wide-open areas with wooded patches that was resource-rich, productive and able to sustain a large community of hunters-gatherers.

4.1.2 *Abandonment phase*

A complex and not yet fully understood human occupation gap of approximately 4.6 ka occurred between the latest Late Upper Palaeolithic and the earliest Mesolithic phases (Radić, 2018). At the foot of the southern wall of the cave, the Mesolithic layers overlie the NYT tephra directly. Conversely, at the centre of the cave huge limestone blocks, up to 2.5 m large, rest on the NYT and are partially covered by about 1.4 m of limestone rubble mixed with reddish silty loam – with no cultural remains. The base of Mesolithic layers is here about 1 m lower than at the foot of the wall and overlies the rubble, apparently without sedimentary gaps. This situation suggests that throughout the Late glacial the topography of the inside of the cave had been pre-determined by the shape of the LGM scree, which had partly filled the cave from the western entrance and along the southern wall. The central area was strongly depressed, so that the accumulation of the Late Upper Palaeolithic layers did not level it completely. Later on, the deposition of ceiling breakdown blocks was triggered by frost in some still undated –posterior to NYT – cold phase of the Late Glacial and was followed by rubble and colluvium of reddish silty loam during the subsequent climate improvement. The fine component of these sediments include mica flakes and other minerals typical of the mineral suite of loess or loess-like sediments of the Adriatic area, and their grain-size supports this (Cremaschi, 1990; Wacha et al., 2011a, 2011b). These sediments can be found only in the central part of the cave, for the following two reasons: i) large breakdown blocks and rubble accumulated only under the ceiling opening, which is located above this area; ii) colluvium flowing into the cave from the western entrance, and probably also from the ceiling opening, was 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 Pupićina 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* sequences were excavated in other caves on both sides of the Adriatic Sea, e.g. in several north Adriatic Karst sites (Boschian and Montagnari-Kokelj, 2000), at Pupićina peć (Boschian, 2006; Forenbaher and Miracle, 2006) in Istria, at Zemunica Peć (Šošić Klindžić et al., 2015) in central Dalmatia, and at Grotta dei Piccioni and Grotta S. Angelo (Boschian and Iaconis, 2008) in central Italy.

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

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

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

Despite systematic attempts to recover seeds through flotation of soil samples, direct evidence of agriculture remains scarce, but this should not be interpreted as indicating an absence of plant cultivation. Productive arable land tends to be located some distance away from the heavily karstified areas where caves abound, and a similar absence of cultivars was observed in other caves 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).

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

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

Much of the coastlines of the islands advanced to within 1 km of their present position by ca. 12 ka BP, after which horizontal changes in coastlines became much smaller: above the ~70 m isobath, slopes around the island tend to be much steeper (Fig. 8). A land bridge between the Pelješac Peninsula and Korčula may have persisted until between 12 and 10 ka BP, at which time the geography of the area became quite similar to the present-day. When the cave was finally reoccupied at the start of the Mesolithic at ~8.0 ka BP (Fig. 7C, Fig. 9), the surrounding landscape had been totally transformed. About 80% of nearby lands were flooded. 30-50 m deep seas were 2 km away from the cave to the north and south, and a shallow (10-20 m) bay was only 1-2 km to the west. No land connections with other present-day islands existed, though many of the smaller islets around Korčula may still have been connected to it at times. By ca. 8.0 ka BP, at the beginning of the Neolithic, most of the northern and southern coasts of the island were even closer to the present-day shoreline, though some islets may still have been connected, and the inner part of Vela Luka harbour had not been fully submerged.

5 Discussion

5.1 Last Palaeolithic occupants facing rapidly inundating planes

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

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

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

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

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

Rapid landscape changes caused by a high RSL rise rate may have had a greater influence on human behaviour and settlement pattern change during this phase; predicted RSL changes were much faster than during the Upper Palaeolithic cave occupation. Humans would have witnessed nearly 0.40 m of RSL rise, corresponding to about 500 m of horizontal coastline displacement during a 35-year average lifespan, i.e. about 14 m of horizontal eastward coastal change per year immediately north and south of Korčula. This suggests a highly unstable or marshy littoral zone, rapid flooding of the traditional foraging grounds of the Upper Palaeolithic groups, and stress on the ecosystem at all trophic levels. Particularly rapid change (about 20 m rise) took place during the centuries following the Meltwater Pulse 1A (MWP-1A), which has been dated to 14.7–14.3 ka BP (Deschamps et al., 2012).

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

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

Younger Dryas effects in the Adriatic Plain are indicated at Vela Spila by the occurrence of partially altered loess-like sediments colluviated into the cave. The precise timing of this colluviation is currently unknown; it probably was partly during the Younger Dryas, but mostly during the early Holocene. It is, however, unclear that the Bølling–Allerød or Younger Dryas climate changes played a direct role in forcing the Late Upper Palaeolithic foragers to leave the site, 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 fish and shellfish was ever the most important food resource in the Adriatic region; isotopic studies on human remains show that “while the Mesolithic people of the Adriatic coast consumed some marine protein, terrestrial protein constituted a significant part of the diet” (Lightfoot et al., 2011, p. 82). The balance between the need for resource diversification and expedience of marine resources due to the approaching coastline is not always clear or consistent. As the Mesolithic progresses, there is a decline in the use of fish and an increase in shellfish and snails at Vela Spila, along with a decrease in terrestrial fauna remains. Fishing seems to shift from open-sea to inshore taxa (Rainsford et al. 2014). This is partially in contrast with data from the northern Adriatic where the coastline approached later: here, fishing shifts from freshwater to marine taxa and Early Mesolithic intensive snail exploitation is substituted by consumption of marine species (Boschian and Pitti, 1984; Cremonesi et al., 1984).

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

The transition between Mesolithic and Neolithic started in the Eastern Adriatic at ca. 8.0 ka BP (Forenbaher et al., 2013). Radiocarbon determinations and cultural assemblages from Vela Spila are consistent with this date. The Mesolithic-Neolithic transition shortly follows the 8.2 ka event, which was a disruption in thermohaline Atlantic circulation owing to meltwater input from North America (Alley and Ágústsdóttir, 2005). The 8.2 ka BP event is associated with an estimated drop in winter 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 smaller fauna like foxes, rather than larger animals such as red deer). The disadvantages of this insularity were initially overcome by skilled seafaring and later, more effectively, by the onset of agriculture and pastoralism that accompanied, after 8 ka BP, a substantial slowing down of sea-level rise.

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

7 Acknowledgements

The authors of this paper would like to recognize the EU project no. 692249 “Smart Integration of Genetics with Sciences of the Past in Croatia: Minding and Mending the Gap” (http://mendthegap.agr.hr/) for providing most of the travel and workshop opportunities for many of the authors to perform research for this paper. Archaeological excavations and analyses were also supported by the British Academy (SG101073), the University of Cambridge, and St John’s College, Cambridge.

8 Works Cited

Alley, R.B., Ágústsdóttir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149. https://doi.org/10.1016/j.quascirev.2004.12.004

Andel, T.H.V., 1989. Late Quaternary sea-level changes and archaeology. Antiquity 63, 733–745. https://doi.org/10.1017/S0003598X00076869

Angelucci, D.E., Boschian, G., Fontanals, M., Pedrotti, A., Vergès, J.M., 2009. Shepherds and karst: the use of caves and rock-shelters in the Mediterranean region during the Neolithic. World Archaeology 41, 191–214. https://doi.org/10.1080/00438240902843659

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

Artegiani, A., Paschini, E., Russo, A., Bregant, D., Raicich, F., Pinardi, N., 1997. The Adriatic Sea General Circulation. Part II: Baroclinic Circulation Structure. J. Phys. Oceanogr. 27, 1515–1532. https://doi.org/10.1175/1520-0485(1997)027<1515:TASGCP>2.0.CO;2

Aufgebauer, A., Panagiotopoulos, K., Wagner, B., Schaebitz, F., Viehberg, F.A., Vogel, H., Zanchetta, G., Sulpizio, R., Leng, M.J., Damaschke, M., 2012. Climate and environmental change in the Balkans over the last 17 ka recorded in sediments from Lake Prespa (Albania/F.Y.R. of Macedonia/Greece). Quaternary International, Temporal and spatial corridors of Homo sapiens sapiens population dynamics during the Late Pleistocene and Early Holocene 274, 122–135. https://doi.org/10.1016/j.quaint.2012.02.015

Aura, J.E., Jordá, J.F., Montes, L., Utrilla, P., 2011. Human responses to Younger Dryas in the Ebro valley and Mediterranean watershed (Eastern Spain). Quaternary International 242, 348–359.

Basler, Đ., 1975. Crvena stijena: zbornik radova. Zajednica kulturnih ustanova, Nikšić.

Bekić, L., 2017. Šimuni, novo podvodno brončanodobno nalazište u Zadarskoj županiji. Diadora: glasilo Arheološkog muzeja u Zadru 31, 41–50.

Bekić, L., Pešić, M., Scholz, R., Meštrov, M., 2015. Podvodna arheološka istraživanja na prapovijesnom nalazištu Pakoštane–Janice. Diadora: glasilo Arheološkog muzeja u Zadru 29, 7–22.

Benjamin, J., Bekić, L., Komšo, D., Uhač, I.K., Bonsall, C., 2011. Investigating the submerged prehistory of the eastern Adriatic: Progress and prospects. Submerged prehistory 193–206.

Benjamin, J., Bonsall, C., 2009. An underwater archaeological survey in the northern Adriatic Sea. International Journal of Nautical Archaeology 38, 163–172.

Benjamin, J., Rovere, A., Fontana, A., Furlani, S., Vacchi, M., Inglis, R.H., Galili, E., Antonioli, F., Sivan, D., Miko, S., Mourtzas, N., Felja, I., Meredith-Williams, M., Goodman-Tchernov, B., Kolaiti, E., Anzidei, M., Gehrels, R., 2017. Late Quaternary sea-level changes and early human societies in the central and eastern Mediterranean Basin: An interdisciplinary review. Quaternary International 449, 29–57. https://doi.org/10.1016/j.quaint.2017.06.025

Bini, M., Pappalardo, M., Rossi, V., Noti, V., Amorosi, A., Sarti, G., 2018. Deciphering the effects of human activity on urban areas through morphostratigraphic analysis: The case of Pisa, Northwest Italy. Geoarchaeology 33, 43–51. https://doi.org/10.1002/gea.21619

Birch, S.E.P., Linden, M.V., 2018. A long hard road… Reviewing the evidence for environmental change and population history in the eastern Adriatic and western Balkans during the Late Pleistocene and Early Holocene. Quaternary International, Impacts of gradual and abrupt environmental changes on Late glacial to Middle Holocene cultural changes in Europe 465, 177–191. https://doi.org/10.1016/j.quaint.2016.12.035

Blockley, S.P., Ramsey, C.B., Pyle, D.M., 2008. Improved age modelling and high-precision age estimates of late Quaternary tephras, for accurate palaeoclimate reconstruction. Journal of Volcanology and Geothermal Research 177, 251–262.

Blute, M., 2008. CULTURAL ECOLOGY. Encyclopedia of Archaeology. https://doi.org/10.1016/B978-012373962-9.00098-4

Bonacci, O., Ljubenkov, I., Knezić, S., 2012. The water on a small karst island: the island of Korčula (Croatia) as an example. Environ Earth Sci 66, 1345–1357. https://doi.org/10.1007/s12665-011-1345-9

Bordon, A., Peyron, O., Lézine, A.-M., Brewer, S., Fouache, E., 2009. Pollen-inferred Late-Glacial and Holocene climate in southern Balkans (Lake Maliq). Quaternary International, Rhythms and Causalities of the Anthropisation Dynamic in Europe between 8500 and 2500 cal BP: Sociocultural and/or Climatic Assumptions 200, 19–30. https://doi.org/10.1016/j.quaint.2008.05.014

Borojević, K., Forenbaher, S., Kaiser, T., Berna, F., 2008. Plant use at Grapčeva cave and in the eastern Adriatic Neolithic. Journal of Field Archaeology 33, 279–303.

Boschian, G., 2006. Geoarchaeology of Pupićina cave, in: Miracle, P., Forenbaher, S. (Eds.), Prehistoric Herders of Northern Istria: The Archaeology of Pupićina Cave. Archaeological Museum of Istria, Pula, pp. 123–162.

Boschian, G., Fusco, F., 2007. Figuring Out No-One's Land Why Was the Karst Deserted in the Late Glacial?, in: Whallon, R. (Ed.), Late Paleolithic Environments and Cultural Relations Around the Adriatic. Archaeopress, Oxford, pp. 15-+.

Boschian, G., Iaconis, M., 2008. Geoarchaeology of the deposits of Grotta dei Piccioni and Grotta Sant'Angelo (Abruzzo, Central Italy), in: Boschian, G. (Ed.), Proceedings of the 2nd International Conference on Soils and Archaeology, Atti Società Toscana Scienze Naturali, Mem. pp. 181–188.

Boschian, G., Miracle, P., 2007. Shepherds and caves in the karst of Istria (Croatia). Atti della Società Toscana di Scienze Naturali 173–180.

Boschian, G., Montagnari-Kokelj, E., 2000. Prehistoric shepherds and caves in the Trieste Karst (Northeastern Italy). Geoarchaeology 15, 331–371. https://doi.org/10.1002/(SICI)1520-6548(200004)15:4<331::AID-GEA3>3.0.CO;2-H

Boschian, G., Pitti, C., 1984. I livelli mesolitici della Grotta dell’Edera, in: Il mesolitico sul Carso Triestino, Quaderni della Societá per la Preistoria e Protostoria della Regione Friuli-Venezia Giulia. Italo Svevo, Trieste, pp. 143–210.

Branscombe, T.L., Bosch, M.D., Miracle, P.T., 2020. Seasonal Shellfishing across the East Adriatic Mesolithic-Neolithic Transition: Oxygen Isotope Analysis of Phorcus turbinatus from Vela Spila (Croatia). Environmental Archaeology 1–14.

Burdukiewicz, J.M., 2011. Late Glacial hunter-gatherer reactions to the Younger Dryas cooling event in the southern and eastern Baltic regions of Europe. Quaternary International 242, 302–312.

Butzer, K.W., 2005. Environmental history in the Mediterranean world: cross-disciplinary investigation of cause-and-effect for degradation and soil erosion. Journal of Archaeological Science 32, 1773–1800. https://doi.org/10.1016/j.jas.2005.06.001

Carroll, F.A., Hunt, C.O., Schembri, P.J., Bonanno, A., 2012. Holocene climate change, vegetation history and human impact in the Central Mediterranean: evidence from the Maltese Islands. Quaternary Science Reviews 52, 24–40. https://doi.org/10.1016/j.quascirev.2012.07.010

Casalbore, D., Falese, F., Martorelli, E., Romagnoli, C., Chiocci, F.L., 2017. Submarine depositional terraces in the Tyrrhenian Sea as a proxy for paleo-sea level reconstruction: Problems and perspective. Quaternary International, Quaternary coastal and marine studies in Central Mediterranean 439, 169–180. https://doi.org/10.1016/j.quaint.2016.02.027

Čečuk, B., Radić, D., 2005. Višeslojno pretpovijesno nalazište - Vela Luka, Otok Korčula. Višeslojno pretpovijesno nalazište - Vela Luka, Otok Korčula, Korčula.

Čečuk, B., Radić, D., 2001. Vela Špilja - preliminarni rezultati dosadašnjih istraživanja, in: Čečuk, B. (Ed.), Arheološka istraživanja na području otoka Korčule i Lastova. Hrvatsko arheološko društvo, Zagreb, pp. 75–118.

Čelhar, M., Parica, M., Ilkić, M., Vujević, D., 2017. A Bronze Age underwater site near the islet of Ričul in northern Dalmatia (Croatia). SKYLLIS-Zeitschrift für maritime und limnische Archäologie und Kulturgeschichte 17, 21.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., Unnikrishnan, A.S., 2013. Sea Level Change, in: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 1137–1216.

Colonese, A.C., Mannino, M.A., Mayer, D.B.-Y., Fa, D.A., Finlayson, J.C., Lubell, D., Stiner, M.C., 2011. Marine mollusc exploitation in Mediterranean prehistory: an overview. Quaternary international 239, 86–103.

Cremaschi, M., 1990. Stratigraphy and palaeoenvironmental significance of the loess deposits on Susak Island (Dalmatian archipelago). Quaternary International 5, 97–106.

Cremonesi, G., Meluzzi, C., Pitti, C., Wilkens, B., 1984. Grotta Azzurra: scavi 1982 (nota preliminare), in: Il mesolitico sul Carso Triestino, Quaderni della Societá per la Preistoria e Protostoria della Regione Friuli-Venezia Giulia. Italo Svevo, Trieste, pp. 21–37.

Cristiani, E., Farbstein, R., Miracle, P., 2014. Ornamental traditions in the Eastern Adriatic: The Upper Palaeolithic and Mesolithic personal adornments from Vela Spila (Croatia). Journal of Anthropological Archaeology 36, 21–31. https://doi.org/10.1016/j.jaa.2014.06.009

Croatian Geoportal, 2019. Topografska karta u mjerilu 1:25000.

Cvetkoska, A., Levkov, Z., Reed, J.M., Wagner, B., 2014. Late Glacial to Holocene climate change and human impact in the Mediterranean: The last ca. 17ka diatom record of Lake Prespa (Macedonia/Albania/Greece). Palaeogeography, Palaeoclimatology, Palaeoecology 406, 22–32. https://doi.org/10.1016/j.palaeo.2014.04.010

Cvitkušić, B., Radović, S., Vujević, D., 2018. Changes in ornamental traditions and subsistence strategies during the Palaeolithic-Mesolithic transition in Vlakno cave. Quaternary International, Quaternary of Croatia 494, 180–192. https://doi.org/10.1016/j.quaint.2017.08.053

De Boer, B., Stocchi, P., Van De Wal, R., 2014. A fully coupled 3-D ice-sheet-sea-level model: algorithm and applications. Geoscientific Model Development 7, 2141–2156.

Deino, A.L., Orsi, G., de Vita, S., Piochi, M., 2004. The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera – Italy) assessed by 40Ar/39Ar dating method. Journal of Volcanology and Geothermal Research, The Neapolitan Volcanoes: Vesuvius, Campi Flegrei and Ischia 133, 157–170. https://doi.org/10.1016/S0377-0273(03)00396-2

Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A.L., Henderson, G.M., Okuno, J., Yokoyama, Y., 2012. Ice-sheet collapse and sea-level rise at the Bølling warming 14,600 years ago. Nature 483, 559–564. https://doi.org/10.1038/nature10902

Dobson, J.E., 2014. Aquaterra Incognita: Lost Land Beneath The Sea. Geographical Review 104, 123–138. https://doi.org/10.1111/j.1931-0846.2014.12013.x

Domijan, N., Leder, N., Čupić, S., 2005. Visinski datumi Republike Hrvatske (Vertical datums of the Republic of Croatia), in: Zbornik radova trećeg hrvatskog kongresa o katastru s međunarodnim sudjelovanjem. Croatia.

Drẑavni Hidrografski Institut, 1998. Jadransko More, charts MK17, MK-19, MK-20, MK-21, MK-22, MK-23, MK-24, 535.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642. https://doi.org/10.1038/342637a0

Faivre, S., Bakran-Petricioli, T., Horvatinčić, N., Sironić, A., 2013. Distinct phases of relative sea level changes in the central Adriatic during the last 1500 years — influence of climatic variations? Palaeogeography, Palaeoclimatology, Palaeoecology 369, 163–174. https://doi.org/10.1016/j.palaeo.2012.10.016

Faivre, S., Butorac, V., 2018. Recently submerged tidal notches in the wider Makarska area (Central Adriatic, Croatia). Quaternary International 494, 225–235. https://doi.org/10.1016/j.quaint.2017.07.020

Farbstein, R., Radić, D., Brajković, D., Miracle, P.T., 2012. First Epigravettian Ceramic Figurines from Europe (Vela Spila, Croatia). PLOS ONE 7, e41437. https://doi.org/10.1371/journal.pone.0041437

Felja, I., Fontana, A., Furlani, S., Bajraktarević, Z., Paradžik, A., Topalović, E., Rossato, S., Ćosović, V., Juračić, M., 2015. Environmental changes in the lower Mirna River valley (Istria, Croatia) during Upper Holocene. Geologia Croatica 68, 209–224. https://doi.org/10.4154/GC.2015.16

Foglini, F., Prampolini, M., Micallef, A., Angeletti, L., Vandelli, V., Deidun, A., Soldati, M., Taviani, M., 2016. Late Quaternary coastal landscape morphology and evolution of the Maltese Islands (Mediterranean Sea) reconstructed from high-resolution seafloor data. Geological Society, London, Special Publications 411, 77–95.

Fontana, A., Vinci, G., Tasca, G., Mozzi, P., Vacchi, M., Bivi, G., Salvador, S., Rossato, S., Antonioli, F., Asioli, A., Bresolin, M., Di Mario, F., Hajdas, I., 2017. Lagoonal settlements and relative sea level during Bronze Age in Northern Adriatic: Geoarchaeological evidence and paleogeographic constraints. Quaternary International 439, 17–36. https://doi.org/10.1016/j.quaint.2016.12.038

Forenbaher, S., Kaiser, T., Miracle, P.T., 2013. Dating the East Adriatic Neolithic. European Journal of Archaeology 16, 589–609. https://doi.org/10.1179/1461957113Y.0000000038

Forenbaher, S., Miracle, P.T., 2006. Pupićina Cave and the spread of farming in the eastern Adriatic, in: Miracle, P., Forenbaher, S. (Eds.), Prehistoric Herders of Northern Istria: The Archaeology of Pupićina Cave. Archaeological Museum of Istria, Pula, pp. 483–523.

Galili, E., Benjamin, J., Eshed, V., Rosen, B., McCarthy, J., Horwitz, L.K., 2019. A submerged 7000-year-old village and seawall demonstrate earliest known coastal defence against sea-level rise. PLoS ONE 14. https://doi.org/10.1371/journal.pone.0222560

Garg, K.M., Chattopadhyay, B., Wilton, P.R., Malia Prawiradilaga, D., Rheindt, F.E., 2018. Pleistocene land bridges act as semipermeable agents of avian gene flow in Wallacea. Molecular Phylogenetics and Evolution 125, 196–203. https://doi.org/10.1016/j.ympev.2018.03.032

Giglio, F., Romano, S., Albertazzi, S., Chiarini, F., Ravaioli, M., Ligi, M., Capotondi, L., 2020. Sediment Dynamics of the Neretva Channel (Croatia Coast) Inferred by Chemical and Physical Proxies. Applied Sciences 10, 807. https://doi.org/10.3390/app10030807

Gkinis, V., Simonsen, S.B., Buchardt, S.L., White, J.W.C., Vinther, B.M., 2014. Water isotope diffusion rates from the NorthGRIP ice core for the last 16,000 years – Glaciological and paleoclimatic implications. Earth and Planetary Science Letters 405, 132–141. https://doi.org/10.1016/j.epsl.2014.08.022

Govorčin, D.P., Juračić, M., Horvatinčić, N., Onofri, V., 2001. Holocene sedimentation in the Soline Channel (Mljet Lakes, Adriatic Sea). Natura Croatica 10, 247–258.

Hewitt, G., 2000. The genetic legacy of the Quaternary ice ages. Nature 405, 907–913. https://doi.org/10.1038/35016000

HHI, 2019. Hrvatski Hidrografski Institut [WWW Document]. Hrvatski Hidrografski Institut. URL http://www.hhi.hr/en/mareo (accessed 12.28.19).

Janković, I., Ahern, J.C.M., Karavanić, I., Stockton, T., Smith, F.H., 2012. Epigravettian Human Remains and Artifacts from Šandalja II, Istria, Croatia. PaleoAnthropology. Official Publication of the Paleoanthropology Society. 2012, 87–122.

Juračić, M., Surić, M., 2010. Late Pleistocene–Holocene environmental changes–records from submerged speleothems along the Eastern Adriatic coast (Croatia). Geologia Croatica 63, 155–169.

Kaczanowska, M., Kozłowski, J.K., 2018. The Mesolithic lithic industries of the eastern Adriatic zone. Folia Quaternaria 191–215.

Karavanić, I., 2003. L'industrie aurignacienne de la grotte de Šandalja II (Istrie, Croatie) dans le contexte de la région de l'Est de l'Adriatique. L'Anthropologie 107, 577–602. https://doi.org/10.1016/j.anthro.2003.10.003

Kelletat, D.H., 2005. Dalmatian Coasts. Encyclopedia of coastal science, Encyclopedia of earth sciences series.

Kendall, R.A., Mitrovica, J.X., Milne, G.A., Törnqvist, T.E., Li, Y., 2008. The sea-level fingerprint of the 8.2 ka climate event. Geology 36, 423–426. https://doi.org/10.1130/G24550A.1

Komšo, D., 2008. Mezolitik u Hrvatskoj. Opusc. Archaeol. Rad. Arheol. zavoda 30, 55–92.

Koncani Uhač, I., Čuka, I., 2015. M., 2015–Doprinos poznavanju podmorskog eneolitičkog nalazišta u uvali Zambratija, Histria archaeologica 46. Pula 25–73.

Kozlowski, J.K., Kaczanowska, M., 2004. Gravettian/Epigravettian sequences in the Balkans and Anatolia. Mediterranean Archaeology and Archaeometry 4, 5–18.

Lambeck, K., Purcell, A., 2005. Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas. Quaternary Science Reviews 24, 1969–1988. https://doi.org/10.1016/j.quascirev.2004.06.025

Lambeck, K., Purcell, A., Johnston, P., Nakada, M., Yokoyama, Y., 2003. Water-load definition in the glacio-hydro-isostatic sea-level equation. Quaternary Science Reviews 22, 309–318. https://doi.org/10.1016/S0277-3791(02)00142-7

Lightfoot, E., Boneva, B., Miracle, P.T., Šlaus, M., O'Connell, T.C., 2011. Exploring the Mesolithic and Neolithic transition in Croatia through isotopic investigations. Antiquity 85, 73–86. https://doi.org/10.1017/S0003598X00067442

Mauch Lenardić, J., Oros Sršen, A., Radović, S., 2018. Quaternary fauna of the Eastern Adriatic (Croatia) with the special review on the Late Pleistocene sites. Quaternary International 494, 130–151. https://doi.org/10.1016/j.quaint.2017.11.028

McLaughlin, T.R., Stoddart, S., Malone, C., 2018. Island risks and the resilience of a prehistoric civilization. World Archaeology 50, 570–600. https://doi.org/10.1080/00438243.2018.1515656

Melini, D., Spada, G., 2019. Some remarks on Glacial Isostatic Adjustment modelling uncertainties. Geophys J Int 218, 401–413. https://doi.org/10.1093/gji/ggz158

Miracle, P., 2007. The Late Glacial" Great Adriatic Plain":" Garden of Eden" or “No Man’s Land” during the Epipalaeolithic? A view from Istria (Croatia), in: Late Paleolithic Environments and Cultural Relations around the Adriatic, BAR International Series. Archaeopress, pp. 41–51.

Miracle, P., 2002. Mesolithic meals from Mesolithic middens, in: Miracle, P., Milner, N. (Eds.), Consuming Passions and Patterns of Consumption. McDonald Inst of Archeological, pp. 65–88.

Miracle, P., 2001. Feast or famine? Epipalaeolithic subsistence in the northern Adriatic basin. 1 28, 177–197. https://doi.org/10.4312/dp.28.10

Miracle, P., Galanidou, N., Forenbaher, S., 2000. Pioneers in the hills: Early Mesolithic foragers at Šebrn Abri (Istria, Croatia). European Journal of Archaeology 3, 293–329. https://doi.org/10.1179/146195700807860837

Miracle, P.T., Forenbaher, S., 2005. Neolithic and Bronze-Age Herders of Pupićina Cave, Croatia. Journal of Field Archaeology 30, 255–281.

Mussi, M., Palombo, M.R., 2001. Les carnivores du Pliocène supérieur et du Pléistocène de la péninsule italienne: quelles implications pour le peuplement humain. Brugal, J. Ph., Fosse, P.(eds), Actes du XIVe Congrès UISPP «Hommes & Carnivores au Paléolithique», Liège 597–609.

Mussi, M., Peresani, M., 2011. Human settlement of Italy during the Younger Dryas. Quaternary international 242, 360–370.

NASA, 2000. Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global Elevation Data.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. PLOS ONE 10, e0118571. https://doi.org/10.1371/journal.pone.0118571

Nunn, P.D., 2020. In Anticipation of ExtirpationHow Ancient Peoples Rationalized and Responded to Postglacial Sea Level Rise. Environmental Humanities 12, 113–131. https://doi.org/10.1215/22011919-8142231

Olson, C.J., Becker, J.J., Sandwell, D.T., 2016. SRTM15_PLUS: Data Fusion of Shuttle Radar Topography Mission (SRTM) Land Topography With Measured and Estimated Seafloor Topography (NCEI Accession 0150537).

Olson, C.J., Becker, J.J., Sandwell, D.T., 2014. A new global bathymetry map at 15 arcsecond resolution for resolving seafloor fabric: SRTM15_PLUS. AGU Fall Meeting Abstracts 2014, OS34A-03.

Palombo, M.R., Antonioli, F., Lo Presti, V., Mannino, M.A., Melis, R.T., Orru, P., Stocchi, P., Talamo, S., Quarta, G., Calcagnile, L., Deiana, G., Altamura, S., 2017. The late Pleistocene to Holocene palaeogeographic evolution of the Porto Conte area: Clues for a better understanding of human colonization of Sardinia and faunal dynamics during the last 30 ka. Quaternary International 439, 117–140. https://doi.org/10.1016/j.quaint.2016.06.014

Peltier, W.R., 2004. Global Glacial Isostasy and the Surface of the Ice-Age Earth: The Ice-5g (vm2) Model and Grace. Annual Review of Earth and Planetary Sciences 32, 111–149. https://doi.org/10.1146/annurev.earth.32.082503.144359

Peltier, W.R., Argus, D.F., Drummond, R., 2015. Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. Journal of Geophysical Research: Solid Earth 120, 450–487. https://doi.org/10.1002/2014JB011176

Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews, Critical Quaternary Stratigraphy 25, 3322–3337. https://doi.org/10.1016/j.quascirev.2006.04.010

Pikelj, K., Juračić, M., 2013. Eastern Adriatic Coast (EAC): Geomorphology and Coastal Vulnerability of a Karstic Coast. Journal of Coastal Research 289, 944–957. https://doi.org/10.2112/JCOASTRES-D-12-00136.1

Pirazzoli, P.A., 2013. Geomorphological Indicators, in: Encyclopedia of Quaternary Science. Elsevier, pp. 377–384. https://doi.org/10.1016/B978-0-444-53643-3.00133-3

Pross, J., Kotthoff, U., Müller, U.C., Peyron, O., Dormoy, I., Schmiedl, G., Kalaitzidis, S., Smith, A.M., 2009. Massive perturbation in terrestrial ecosystems of the Eastern Mediterranean region associated with the 8.2 kyr B.P. climatic event. Geology 37, 887–890. https://doi.org/10.1130/G25739A.1

Radić, D. (Ed.), 2018. Island of Korčula: From the earliest times to the end of prehistory. Centar za kulturu “Vela Luka,” Vela Luka, Croatia.

Radić, D., Lugović, B., Marjanac, L., 2007. Neapolitan Yellow Tuff (NYT) from the leistocene sediments in Vela Spila on the island of Korčula: a valuable chronostratigraphic marker of the transition from the Palaeolithic to the Mesolithic. Opvscvla archaeologica 31, 20.

Radić Rossi, I., 2008. Arheološka baština u podmorju Kaštelanskog zaljeva. Archaeologia Adriatica 2, 489–506.

Rainsford, C., O’Connor, T., Miracle, P., 2014. Fishing in the Adriatic at the Mesolithic–Neolithic transition: Evidence from Vela Spila, Croatia. Environmental Archaeology 19, 311–320. https://doi.org/10.1179/1749631414Y.0000000018

Richards, M.P., Karavanić, I., Pettitt, P., Miracle, P., 2015. Isotope and faunal evidence for high levels of freshwater fish consumption by Late Glacial humans at the Late Upper Palaeolithic site of

Šandalja II, Istria, Croatia. Journal of Archaeological Science 61, 204–212. https://doi.org/10.1016/j.jas.2015.06.008

Rizner, M., Vukosavljević, N., Miracle, P., 2009. The paleoecological and paleodietary significance of edible land snails (Helix sp.) across the Pleistocene-Holocene transition on the eastern Adriatic coast, in: MESO 2005: The 7th International Conference on the Mesolithic in Europe.

Rossi, I.R., 2017. Proučavanje promjena morske razine na arheološkim nalazištima u priobalju. Vjesnik za Arheologiju i Povijest Dalmatinsku 110.

Rovere, A., Stocchi, P., Vacchi, M., 2016. Eustatic and Relative Sea Level Changes. Curr Clim Change Rep 2, 221–231. https://doi.org/10.1007/s40641-016-0045-7

Sandwell, D.T., Becker, J.J., Smith, W.H.F., 2014a. SRTM15_PLUS Estimated Topography, 15 seconds, Global, v1.

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E., Francis, R., 2014b. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. Science 346, 65–67. https://doi.org/10.1126/science.1258213

Shaw, T.A., Plater, A.J., Kirby, J.R., Roy, K., Holgate, S., Tutman, P., Cahill, N., Horton, B.P., 2018. Tectonic influences on late Holocene relative sea levels from the central-eastern Adriatic coast of Croatia. Quaternary Science Reviews 200, 262–275. https://doi.org/10.1016/j.quascirev.2018.09.015

Shennan, I., Long, A.J., Horton, B.P. (Eds.), 2015. Handbook of Sea-Level Research. John Wiley & Sons, Ltd, Chichester, UK.

Sikora, M., Mihanović, H., Vilibić, I., 2014. Paleo-coastline of the Central Eastern Adriatic Sea, and Paleo-Channels of the Cetina and Neretva rivers during the last glacial maximum. Acta Adriatica 55, 3–18.

Smith, W.H.F., Sandwell, D.T., 1997. Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings. Science 277, 1956–1962. https://doi.org/10.1126/science.277.5334.1956

Šošić Klindžić, R., Radović, S., Težak Gregl, T., Šlaus, M., Perhoć, Z., Altherr, R., Hulina, M., Gerometta, K., Boschian, G., Vukosavljević, N., Ahern, J.C.M., Janković, I., Richards, M., Karavanić, I., 2015. Late Upper Paleolithic, Early Mesolithic and Early Neolithic from the cave site Zemunica near Bisko (Dalmatia, Croatia) 12, 3–46.

Spada, G., Galassi, G., 2017. Extent and dynamic evolution of the lost land aquaterra since the Last Glacial Maximum. Comptes Rendus Geoscience 349, 151–158.

Spada, G., Stocchi, P., 2007. SELEN: A Fortran 90 program for solving the “sea-level equation.” Computers & Geosciences 33, 538–562. https://doi.org/10.1016/j.cageo.2006.08.006

Srdoč, D., Obelić, B., Horvatinčić, N., Bronić, I.K., Sliepčević, A., 1989. Rudjer Bošković Institute radiocarbon measurements XI. Radiocarbon 31, 85–98.

Stewart, J.R., Van Kolfschoten, M., Markova, A., Musil, R., 2003. The mammalian faunas of Europe during oxygen isotope stage three. Neanderthals and modern humans in the European landscape during the last glaciation 60, 103–130.

Taviani, M., Angeletti, L., Campiani, E., Ceregato, A., Foglini, F., Maselli, V., Morsilli, M., Parise, M., Trincardi, F., 2012. Drowned karst landscape offshore the Apulian margin (Southern Adriatic Sea, Italy). Journal of Cave and Karst Studies 74, 197–212. https://doi.org/10.4311/2011JCKS0204

tide-forecast.com, 2019. Tide Times and Tide Charts Worldwide [WWW Document]. Meteo365.com. URL https://www.tide-forecast.com (accessed 7.27.19).

Tozer, B., Sandwell, D.T., Smith, W.H.F., Olson, C., Beale, J.R., Wessel, P., 2019. Global Bathymetry and Topography at 15 Arc Sec: SRTM15+. Earth and Space Science 6, 1847–1864. https://doi.org/10.1029/2019EA000658

Trincardi, F., Campiani, E., Correggiari, A., Foglini, F., Maselli, V., Remia, A., 2014. Bathymetry of the Adriatic Sea: The legacy of the last eustatic cycle and the impact of modern sediment dispersal. Journal of Maps 10, 151–158. https://doi.org/10.1080/17445647.2013.864844

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

Vlahović, I., Tišljar, J., Velić, I., Matičec, D., 2005. Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics. Palaeogeography, Palaeoclimatology, Palaeoecology 220, 333–360. https://doi.org/10.1016/j.palaeo.2005.01.011

Vlahović, I., Tišljar, J., Velić, I., Matičec, D., 2002. The Karst Dinarides are Composed of Relics of a Single Mesozoic Platform: Facts and Consequences. Geologia Croatica 55, 171–183.

Vogel, H., Wagner, B., Zanchetta, G., Sulpizio, R., Rosén, P., 2010. A paleoclimate record with tephrochronological age control for the last glacial-interglacial cycle from Lake Ohrid, Albania and Macedonia. J Paleolimnol 44, 295–310. https://doi.org/10.1007/s10933-009-9404-x

Vukosavljević, N., Perhoč, Z., 2017. Lithic raw material procurement of the Late Epigravettian hunter-gatherers from Kopačina Cave (island of Brač, Dalmatia, Croatia). Quaternary International, Prehistoric hunter-gatherers and farmers in the Adriatic and neighboring regions 450, 164–185. https://doi.org/10.1016/j.quaint.2016.09.017

Vukosavljević, N., Perhoč, Z., Altherr, R., 2014. Pleistocene-Holocene transition in the Vlakno Cave on the island of Dugi otok (Dalmatia, Croatia)–lithic perspective. Prilozi Instituta za arheologiju u Zagrebu 31, 5–72.

Vukosavljević, N., Perhoč, Z., Čečuk, B., Karavanić, I., 2011. Late Glacial knapped stone industry of Kopačina Cave. Vjesnik za arheologiju i povijest dalmatinsku 104, 7–54.

Wacha, L., Frechen, M., Crnjaković, M., 2011a. The loess chronology of the Island of Susak, Croatia. Quaternary Science International 60, 153–169.

Wacha, L., Pavlaković, S.M., Novothny, Á., Crnjaković, M., Frechen, M., 2011b. Luminescence dating of Upper Pleistocene loess from the Island of Susak in Croatia. Quaternary International 234, 50–61.

Weber, M.-J., Grimm, S.B., Baales, M., 2011. Between warm and cold: Impact of the Younger Dryas on human behavior in Central Europe. Quaternary International 242, 277–301.

Weigelt, P., Steinbauer, M.J., Cabral, J.S., Kreft, H., 2016. Late Quaternary climate change shapes island biodiversity. Nature 532, 99.

Whallon, R., 1999. The lithic tool assemblages at Badanj within their regional context, in: Bailey, G.N., Adam, E., Panagopoulou, E., Perles, C., Zachos, K. (Eds.), The Palaeolithic Archaeology of Greece and Adjacent Areas, Monograph of the British School at Athens. Presented at the Proceedings of the ICOPAG Conference, British School at Athens, Athens.

Wunsam, S., Schmidt, R., Müller, J., 1999. Holocene lake development of two Dalmatian lagoons (Malo and Veliko Jezero, Isle of Mljet) in respect to changes in Adriatic sea level and climate. Palaeogeography, Palaeoclimatology, Palaeoecology 146, 251–281.

Zvelebil, M., Lillie, M.C., 2000. Transition to agriculture in Eastern Europe, in: Price, T.D. (Ed.), Europe’s First Farmers. Cambridge University Press, New York.

Figures captions

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

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

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

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

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

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

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

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

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

Figure 1

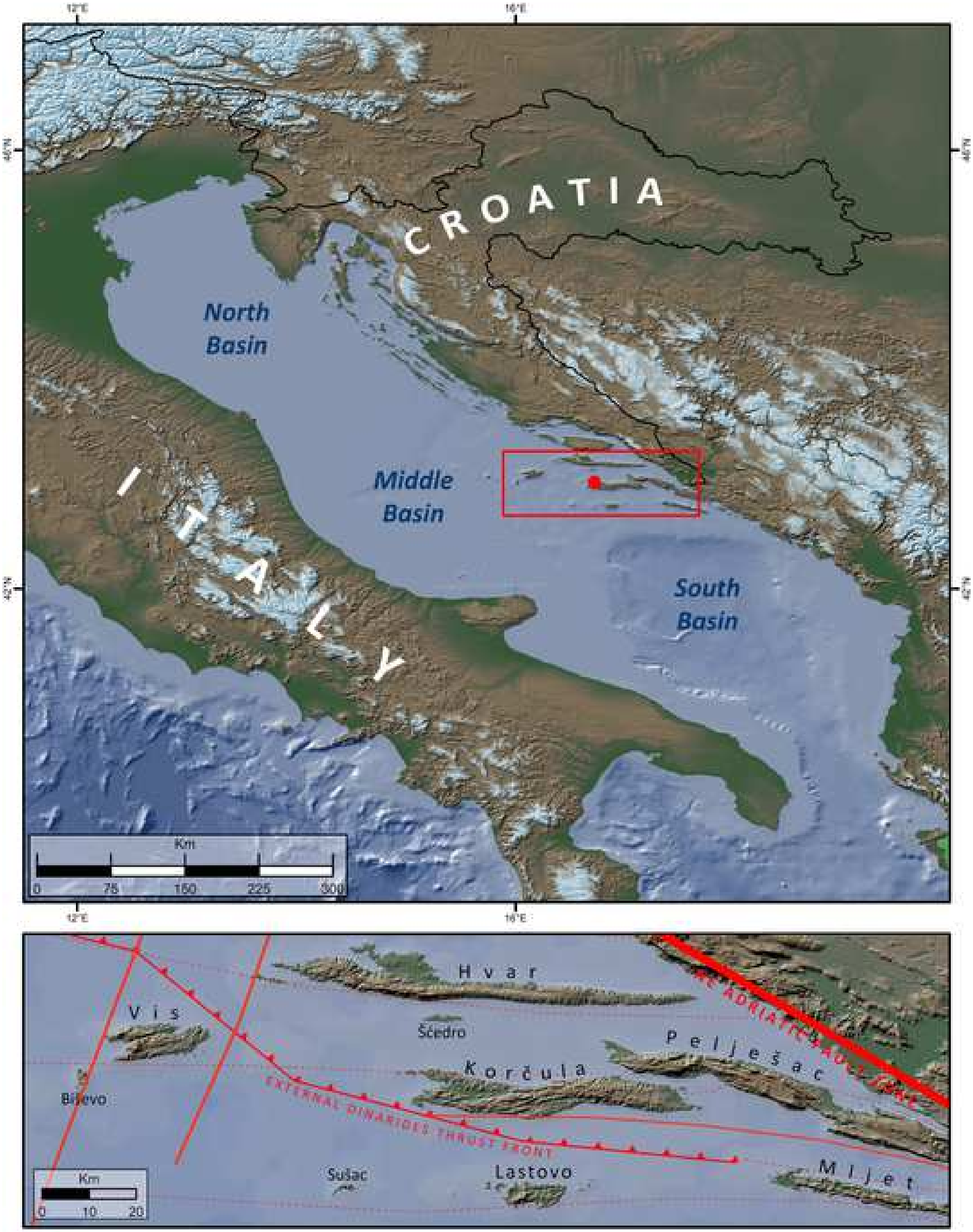

12°E
16°E
46°N
42°N
CROATIA
North Basin
Middle Basin
South Basin
ITALY
Km
0
75
150
225
300
Hvar
Vis
Šćedro
Pelješac
Korčula
Biševo
NE ADRIATIC FAULT ZONE
EXTERNAL DINARIDES THRUST FRONT
Sušac
Lastovo
Mljet
Km
0
10
20

Figure 2

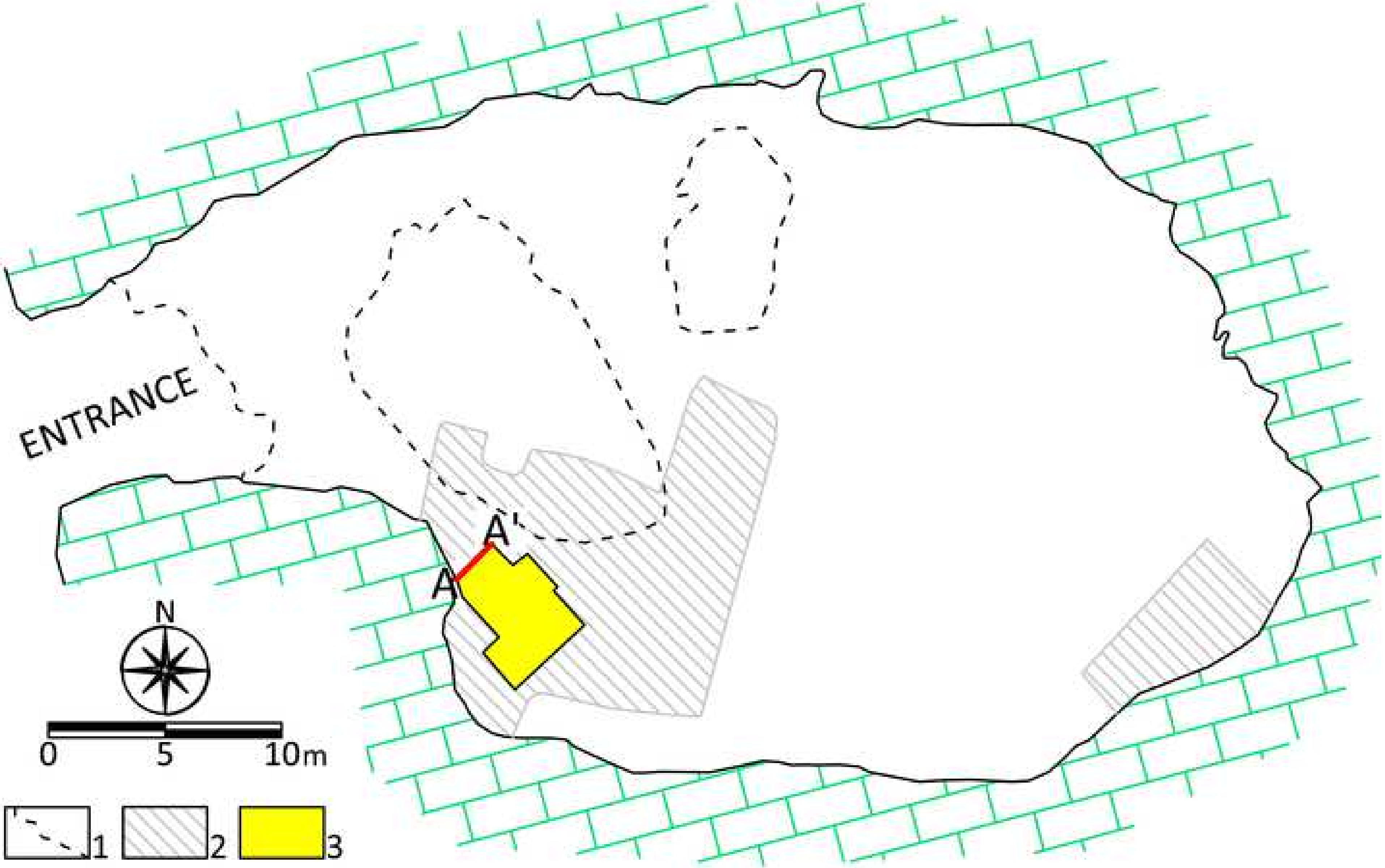
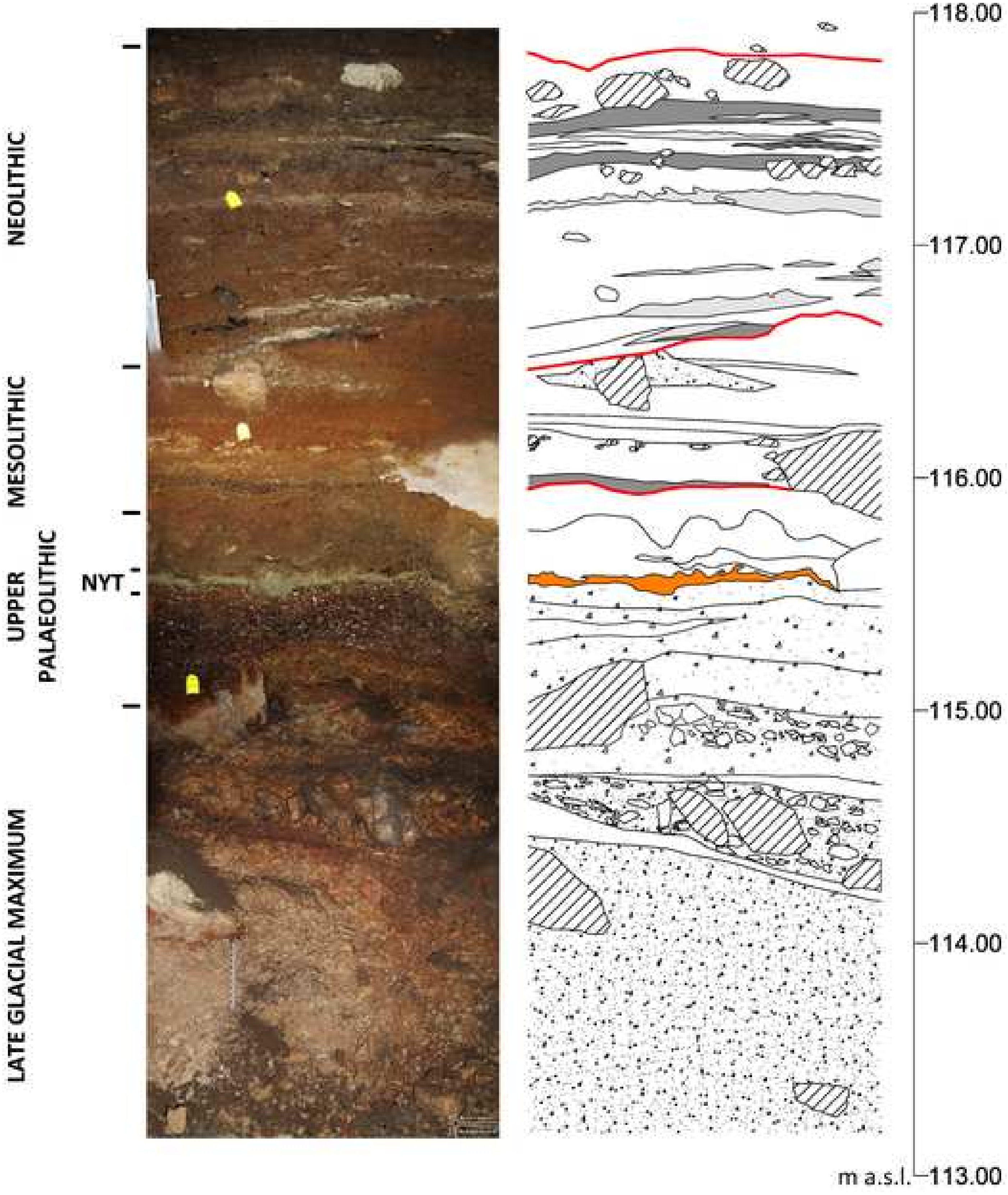

ENTRANCE
A
A'
N
0
5
10m
1
2
3

Figure 4


NEOLITHIC
MESOLITHIC
UPPER PALAEOLITHIC
NYT
LATE GLACIAL MAXIMUM
118.00
117.00
116.00
115.00
114.00
m a.s.l.
113.00

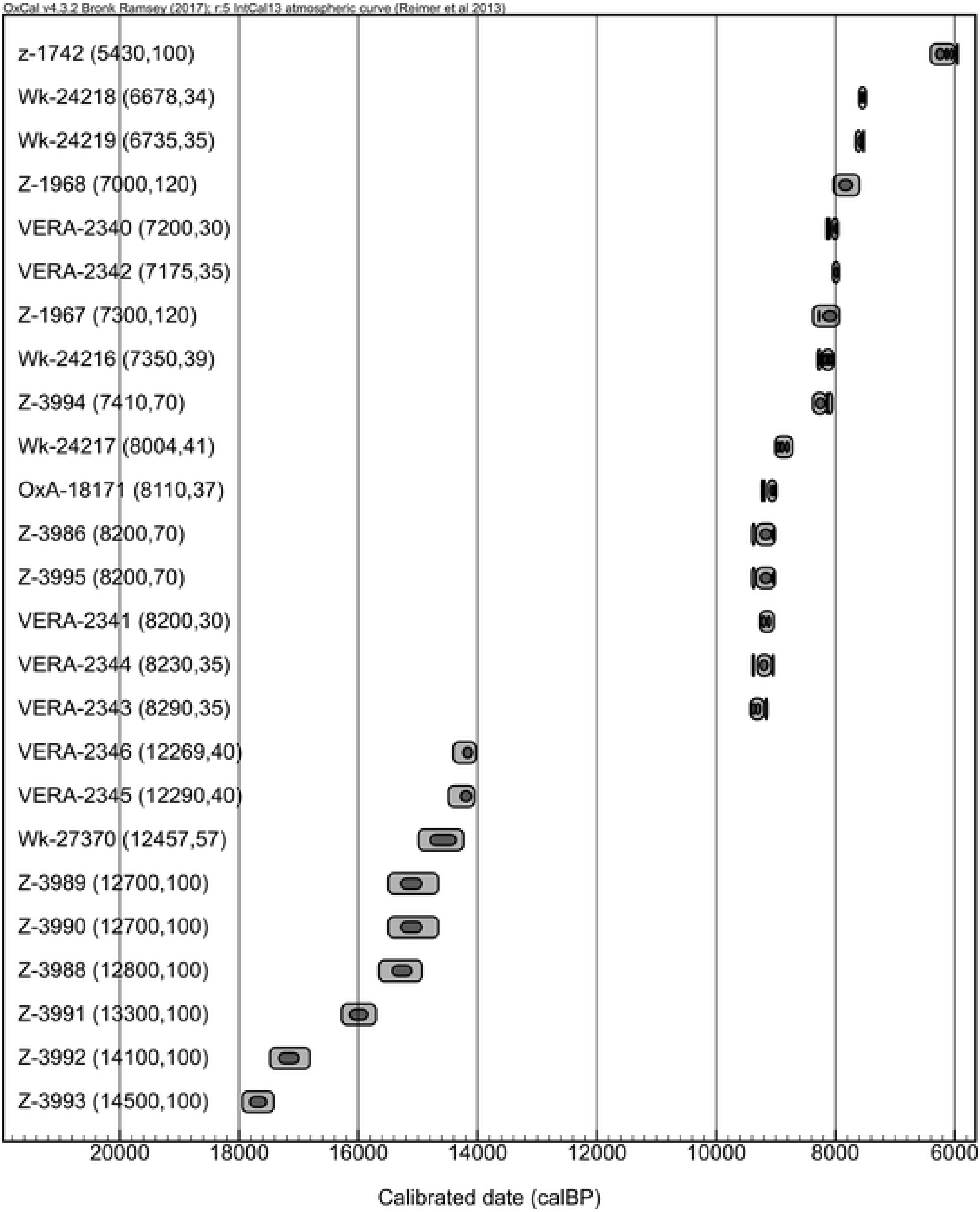

OxCal v4.3.2 Bronk Ramsey (2017); r:5 IntCal13 atmospheric curve (Reimer et al 2013)
z-1742 (5430,100)
Wk-24218 (6678,34)
Wk-24219 (6735,35)
Z-1968 (7000,120)
VERA-2340 (7200,30)
VERA-2342 (7175,35)
Z-1967 (7300,120)
Wk-24216 (7350,39)
Z-3994 (7410,70)
Wk-24217 (8004,41)
OxA-18171 (8110,37)
Z-3986 (8200,70)
Z-3995 (8200,70)
VERA-2341 (8200,30)
VERA-2344 (8230,35)
VERA-2343 (8290,35)
VERA-2346 (12269,40)
VERA-2345 (12290,40)
Wk-27370 (12457,57)
Z-3989 (12700,100)
Z-3990 (12700,100)
Z-3988 (12800,100)
Z-3991 (13300,100)
Z-3992 (14100,100)
Z-3993 (14500,100)
20000
18000
16000
14000
12000
10000
8000
6000
Calibrated date (calBP)

Figure 6

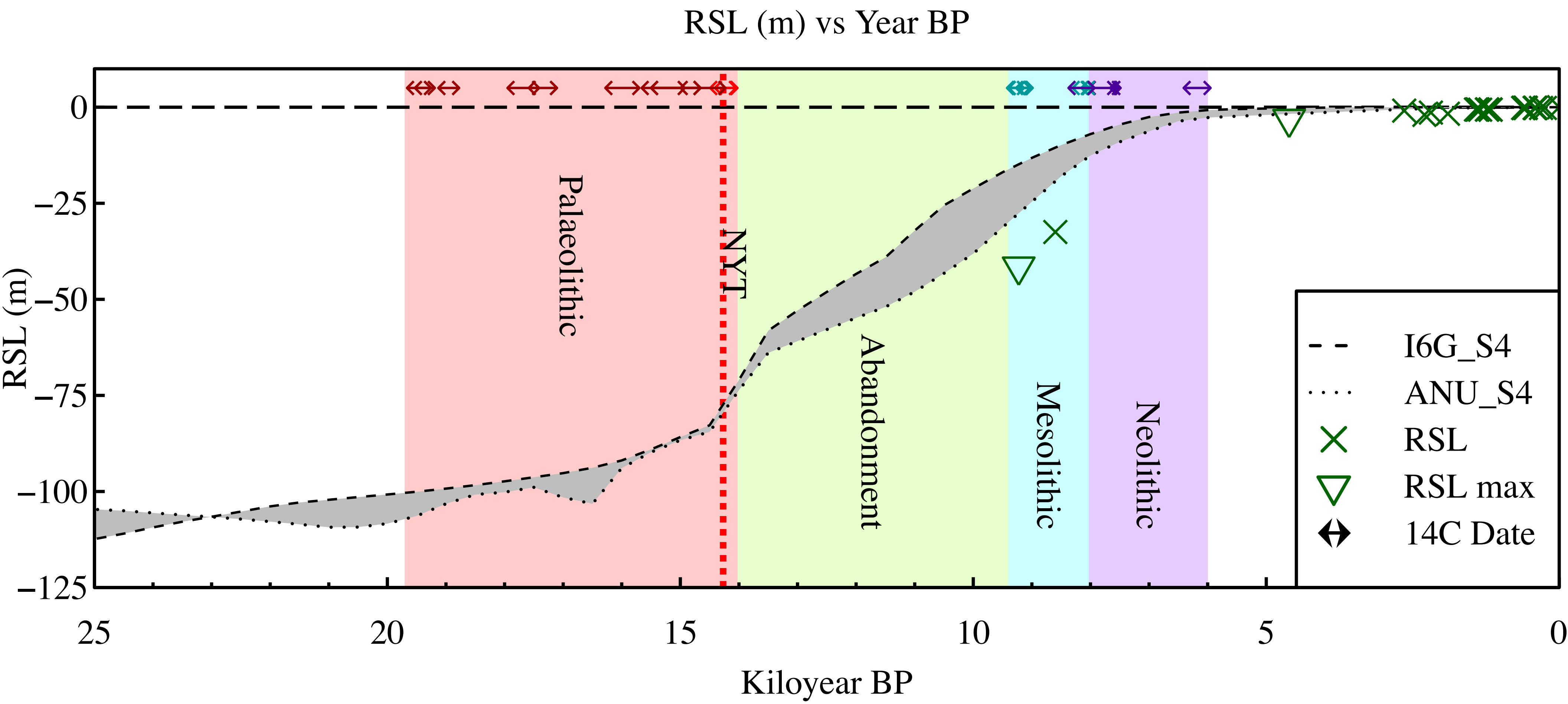

RSL (m) vs Year BP
RSL (m)
0
−25
−50
−75
−100
−125
25
20
15
10
5
0
Kiloyear BP
Palaeolithic
NYT
Abandonment
Mesolithic
Neolithic
I6G_S4
ANU_S4
RSL
RSL max
14C Date

Figure 7

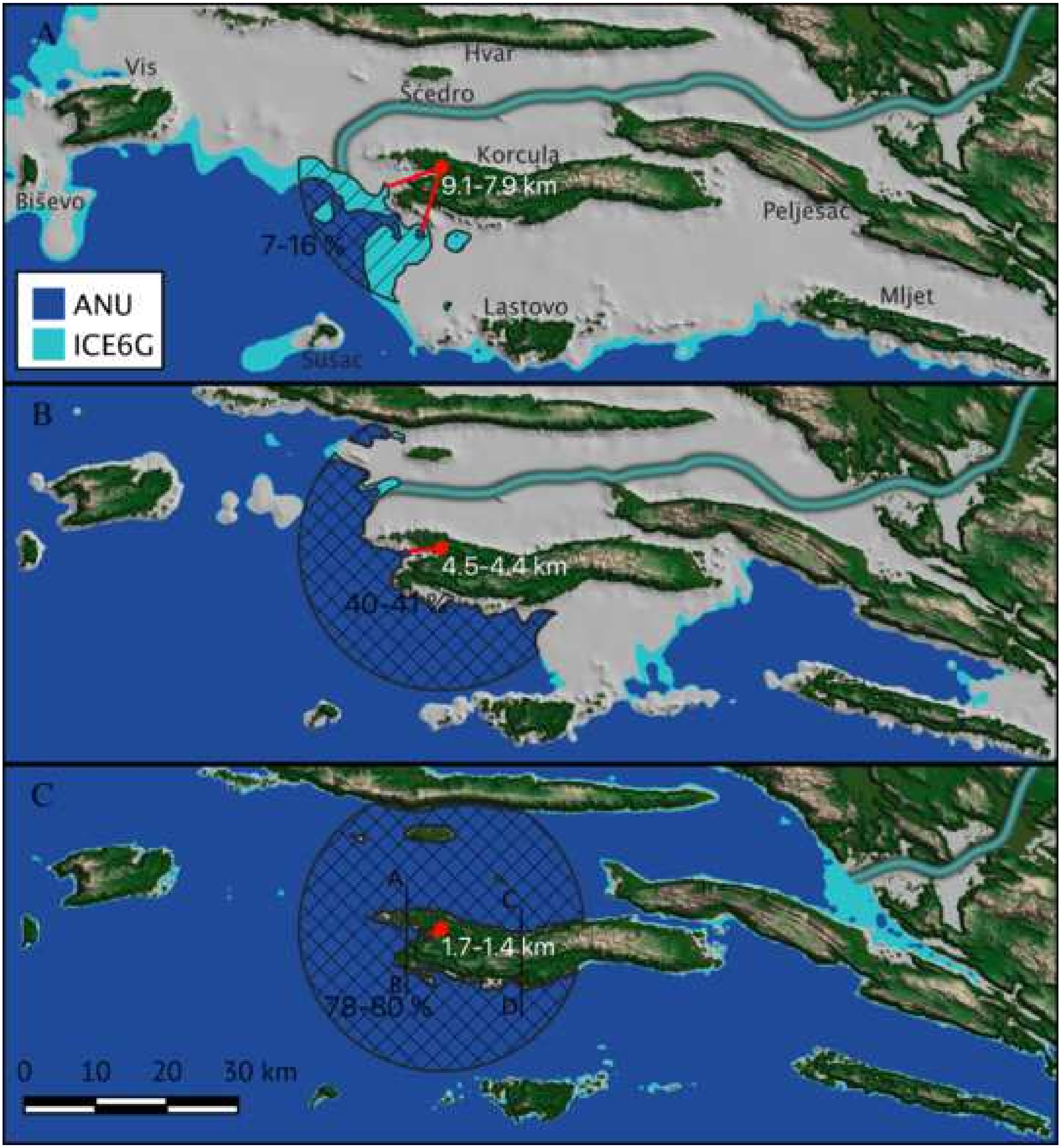
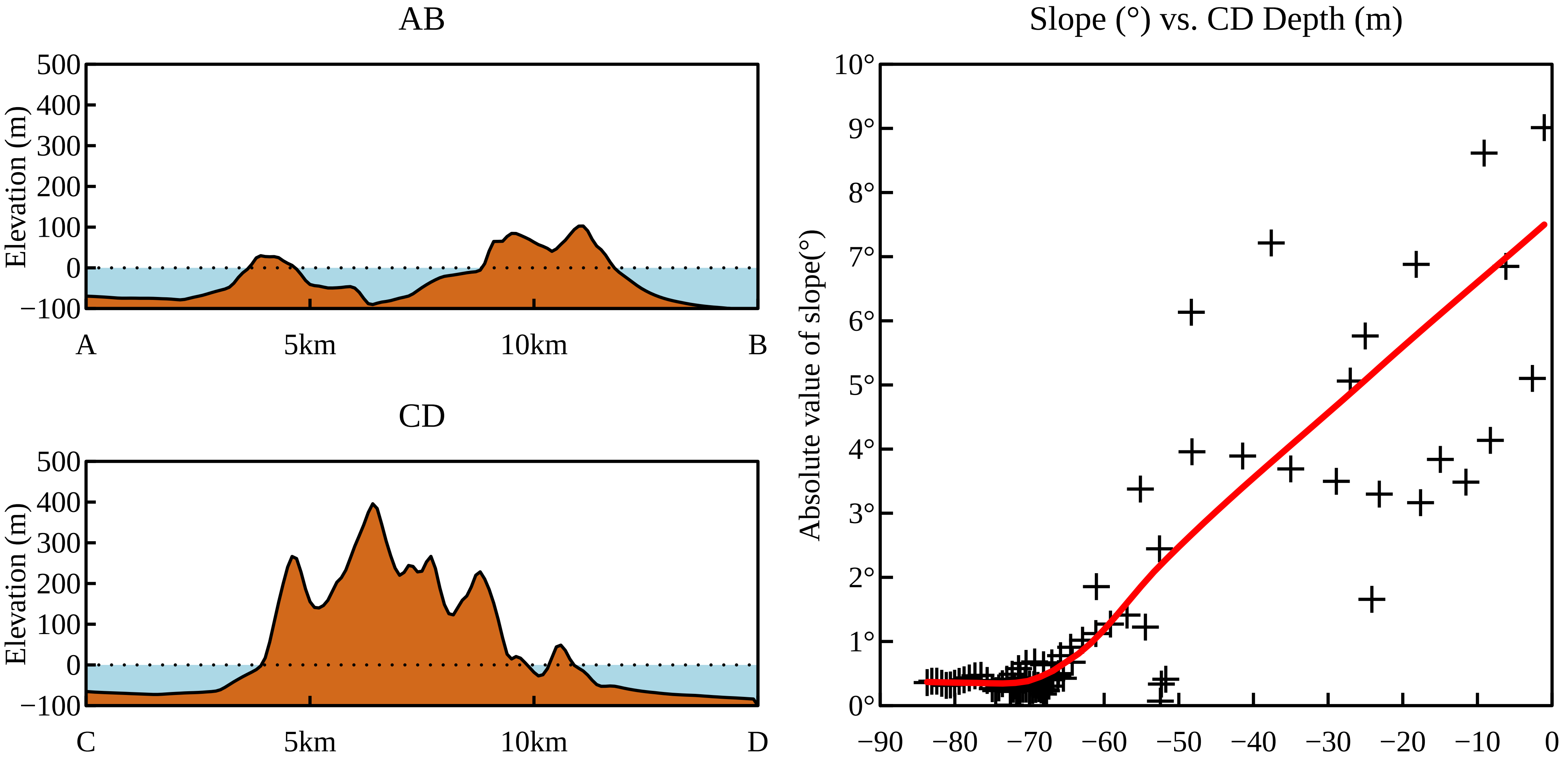
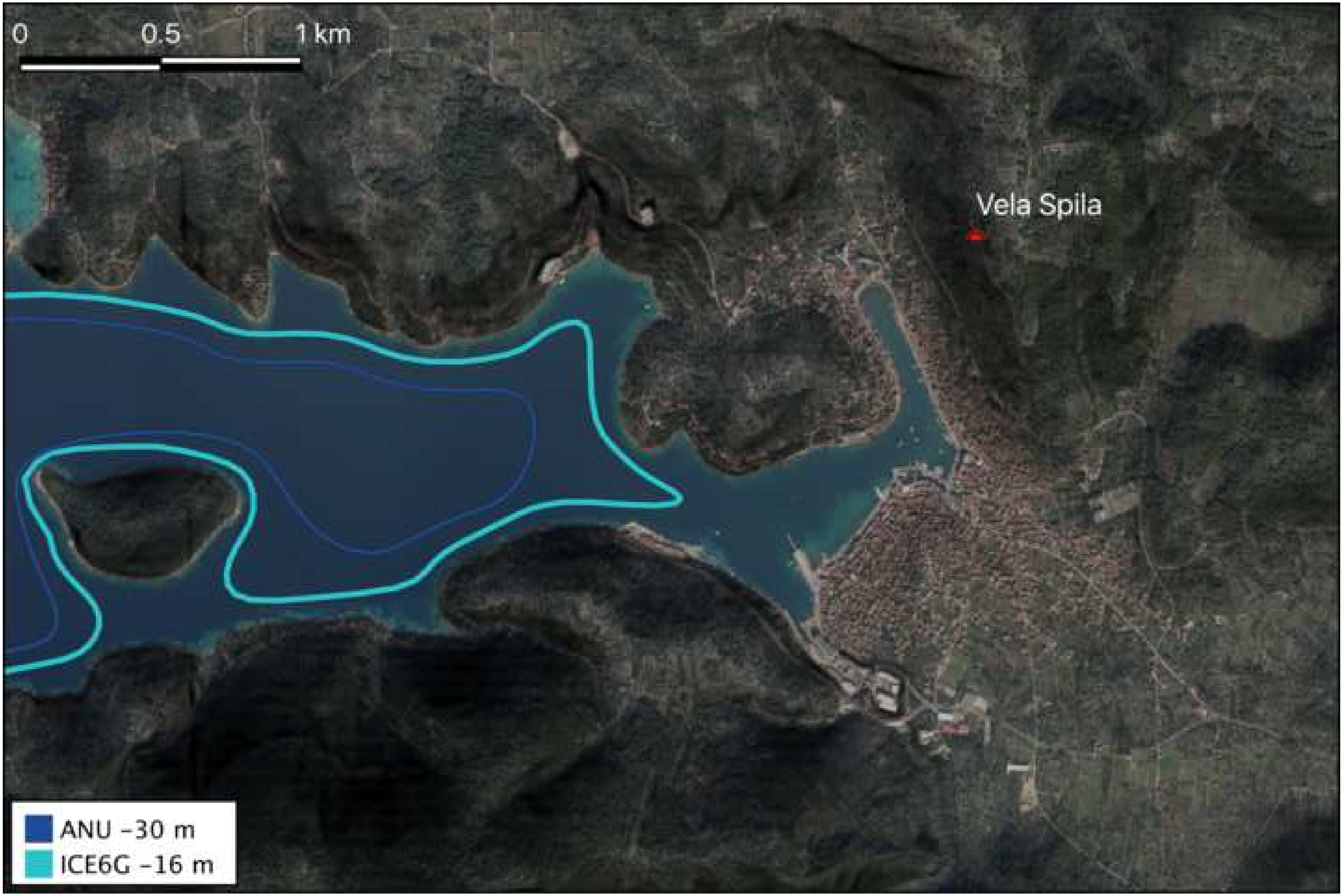

A
Vis
Hvar
Šcedro
Korcula
9.1-7.9 km
Biševo
Peljesac
7-16 %
ANU
ICE6G
Lastovo
Mljet
Susac
B
4.5-4.4 km
40-41 %
C
A
C
1.7-1.4 km
B
D
78-80 %
0 10 20 30 km

Figure 8


AB
Elevation (m)
500
400
300
200
100
0
−100
A
5km
10km
B
CD
Elevation (m)
500
400
300
200
100
0
−100
C
5km
10km
D
Slope (°) vs. CD Depth (m)
Absolute value of slope(°)
10°
9°
8°
7°
6°
5°
4°
3°
2°
1°
0°
−90
−80
−70
−60
−50
−40
−30
−20
−10
0


0
0.5
1 km
Vela Spila
ANU -30 m
ICE6G -16 m

Conflict of Interest

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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Statement

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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: