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Sequence stratigraphy and relative sea level variations in Kaštela Bay, Dalmatian coast, Croatia, and implications for the submerged palaeolandscapes and archaeology of the late Pleistocene, marine isotope stage 3 and marine isotope stage 2

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ABSTRACT

Relative sea level, palaeoclimate, and palaeohydrology are critical variables for contextualising past hominin behaviours and the resulting archaeological record. This is especially important in submerged palaeolandscape reconstructions of drowned continental shelves formerly inhabited by past hominin populations. We report significant results of one such palaeolandscape reconstruction along the Dalmatian coast of Croatia, Adriatic Sea, near the city of Split, as part of the Life on the Edge (LOTE) project. The LOTE project aims to develop refined palaeolandscape reconstructions of submerged landscapes in multiple study regions, including along this portion of the Dalmatian coastline. Reconstructed seismic surfaces have been combined with refined relative sea level predictions accounting for isostasy and corrected for sedimentation since these were last subaerial, allowing for a more accurate assessment of the palaeolandscape. The results presented here indicate the presence of a preserved, formerly subaerial landscape likely dating to Marine Isotope Stage 3 (57,000 cal BP to 29,000 cal BP). At least two hominin species occupied the region during this part of the late Pleistocene epoch. Our findings indicate that the region of Kaštela Bay comprised multiple habitats that offered diverse, abundant resources that were likely highly attractive to either, or both, of these hominin populations.

1. Introduction

1.1. Study aims

Relative sea level (RSL), palaeoclimate, and palaeohydrology are key variables included when interpreting the archaeological record for past hominin populations. Modelling these variables is a critical component for submerged palaeolandscape reconstructions of drowned continental shelves formerly inhabited by such past populations. A majority of palaeolandscape reconstructions rely on bathymetric data to assess the extent of the subaerial landscape during marine regressions. In marine basins where sedimentation and erosion are minimal and tectonics passive, this is a reasonable approach (e.g. Faught, 2004). However, many marine basins, including those with proximity to onshore regions with dense, early human occupations, do not meet these conditions (Clark et al., 2014; Fitch et al., 2005; Gaffney et al., 2007; Marcott et al., 2009; Missiaen et al., 2021; Törnqvist et al., 1996). In these cases, effects of sediment deposition, isostatic adjustments, and tectonic histories are critical to accurately reconstructing the submerged palaeolandscape during any given period when these were subaerial and available for human occupation (Balsillie and Donoghue, 2011; Fitch et al., 2012; Fitch, 2022; Gaffney et al., 2007; Gaffney and Fitch, 2022; Kim et al., 2023; Missiaen et al., 2021)

This study presents a palaeolandscape reconstruction of Kaštela Bay on the Dalmatian coast of Croatia for the period during which this bay was a subaerial landscape suitable for habitation. This reconstruction is derived from recent marine seismic surveys carried out in 2023 and 2024. Surfaces from this dataset have been delineated and synthesized

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with current assessments of local and regional RSL curves derived using measures of isostasy instead of relying solely on modern bathymetry and eustatic sea level curves. This study therefore avoids the problems introduced into submerged palaeolandscape reconstruction by use of simple bathymetry alongside RSL curves that do not take into account local and regional variability (Fitch, 2022; Fitch et al., 2011, 2012; Gaffney et al., 2007; Gaffney and Fitch, 2022; Missiaen et al., 2021; Balsillie and Donoghue, 2011).

The LOTE project aims to refine submerged palaeolandscape reconstructions across multiple study regions, including along this portion of the Dalmatian coastline. This overall aim is supported by updated application of local and regional depositional and tectonic histories to Kaštela Bay, the Belgian continental shelf along the southern North Sea, Cardigan Bay, and offshore Japan. The research here offers insights into submerged palaeolandscapes available to hominin populations in southeastern Europe during periods when glacial and interstadial conditions made much of western Eurasia inhospitable. Kaštela Bay was then part of a larger southern European landscape that functioned as a climate refugium from which these populations expanded as climate conditions ameliorated at the end of the Pleistocene (Rathmann et al., 2024).

1.2. Regional tectonic and environmental setting

Kaštela Bay is a shallow embayment oriented along an east to west axis on the Dalmatian coast of the Adriatic Sea (Fig. 1). It is bounded to the east by the Split peninsula and to the west by the island of Čiovo. A narrow channel at its far western end allows access to the rest of the Adriatic, whilst the bay's outlet is located between the eastern end of Čiovo and Split peninsula. This outlet is in turn protected by the island of Brač. Because of its geomorphology, the Bay is protected from higher energy marine forces, increasing the likelihood that intact sediments and archaeological materials have been preserved within the bay since the Holocene marine transgression. These characteristics make Kaštela Bay a high potential target region to address multiple questions surrounding submerged landscapes, including methods for site detection and prospection.

The Dalmatian coastline of Croatia is a tectonically active marine margin formed by complex plate tectonics associated with the collision of the African and the Eurasian plates, as well as interactions of microplates in the eastern Mediterranean, from the Mesozoic Era to the Miocene epoch. The coastline is dominated by the Dinaric Alps, which were formed by carbonate deposition in increasingly shallow marine contexts on the Adria microplate, which then collided with the Eurasian plate. This collision resulted in subduction of the Adria plate, uplift of carbonates deposits resulting in an overturned syncline structure, and deposition of flysch deposits along the subduction margin. Reverse faulting is found throughout the region and individual faults generally follow a northwest to southeast orientation (see Radić Rossi et al. 2020 and references therein).

The carbonate bedrock consists of both limestone and dolomite and has been subject to intense karstification processes. This has resulted in a complex coastline along with abundant karst features such as dolines, springs, and caverns. This trend continues offshore, where bathymetric data have been used to estimate the watersheds for the palaeochannels of the Cetina and Neretva rivers, including potential palaeolakes now submerged between Brač and the mainland and between Brač and Hvar (Sikora et al., 2014). Submerged springs have been documented in the region as well as submerged caverns (Fritz and Bahun, 1997; Radić Rossi et al., 2020).

The modern coastline emerged shortly after 6000 years ago as the Holocene marine transgression slowed. Both fault orientations and the orogeny of the Dinaric Alps have resulted in a coastline fringed by islands that follow a general northwest-to-southeast coastline axis, termed a Dalmatian type coast. The channels and sounds between the islands and the mainland would have been low-lying coastal plain zones prior to submergence. The combination of easy access to the palaeo-Adriatic and abundant freshwater resources provided by karst springs (some of which still flow in Kaštela Bay) (Fritz and Bahun, 1997; Sikora et al., 2014) likely made this submerged palaeolandscape highly attractive to early hominin populations.

1.3. Human habitation during the Pleistocene

Hominin occupation of the western Palearctic of Eurasia was constrained by glacial and climate cycles of the Pleistocene. The Adriatic region in particular played a crucial role in hominin occupations during the coldest periods of the Pleistocene. The Alps and Dinaride mountains surrounding the area blocked and redirected harsh weather, fostering a more temperate, stable climate. Even during glacial periods, the region remained comparatively mild even though large parts of northern Europe became inhospitable. As a result, the region ensured the persistence of ecosystems and allowed human communities to persist, migrate, adapt, and develop (Vujević, 2016; Radić Rossi et al., 2020). Furthermore, during maximum marine regressions such as those at the last glacial maximum (LGM), around 24,000 years ago, the full extent of the Northern Adriatic basin was an exposed coastal plain, facilitating the movement of species and hunter-gatherer communities across the landscape.

Croatia and the Adriatic plain have been occupied by multiple hominin species since the Lower Palaeolithic (Table 1). The earliest, albeit scant, evidence for human occupation dates to the Lower Palaeolithic and is associated with the Acheulian stone tool technology. The most prominent Croatian site that has yielded Acheulian materials is Šandalja I near Pula (Fig. 1, site 1, above), located in a karst cave system in Istria, whilst other lower Palaeolithic sites such as Donje Pazarište, Punikve and Golubovec are defined by surface finds (Malez, 1979; Karavanić and Janković, 2006: 22) (Fig. 1, sites 2–4, above). No Acheulian or Lower Palaeolithic sites have been identified on the central and southern Dalmatian coast, from Šibensko-Kninska County, to Splitsko-Dalmatinska County, or to Dubrovacko-Neretvanska County furthest to the south.

The number of documented sites increases across Croatia during the Middle Palaeolithic, including on the central and southern Dalmatian coast. Today, around forty Mousterian sites are known on the eastern Adriatic coast broadly, including the Croatian coastline. On the central and southern Dalmatian coast of Croatia itself, these include some caves. However, most are open-air sites defined by surface finds in the Dalmatian hinterlands and islands near sources of raw material (Vujević, 2011, 2016; Vujević and Perhoč, 2024; Karavanić and Vukosavljević, 2019; Karavanić et al., 2014a, 2014b, 2016a, 2016b, 2023). There are only a few systematically excavated sites in Dalmatia proper: the caves Mujina Pećina near Kaštela (Karavanić and Bilich-Kamenjarin, 1997; Rink et al., 2002; Karavanić et al., 2008, 2016b, 2021a), Mala Pećina and Velika Pećina in Kličevica near Benkovac (Karavanić and Ćondić, 2006; Karavanić et al., 2014a, 2016a, 2016b, 2021a; Vujević and Perhoč, 2024) (Fig. 1, sites 5–7); and the open-air sites: Malo Polje – Krban (Karavanić et al., 2023) and the underwater site of Kaštel Štafilić–Resnik (Karavanić et al., 2009, 2014a, 2016a, 2021b; Barbir et al., 2022) (Fig. 1, sites 8 and 9). The oldest dates from these caves precede the arrival of anatomically modern Homo sapiens (AMH) in Europe and are associated with both the Mousterian industry and Neanderthal populations.

Marine Isotope Stages (MIS) 4, 3, and 2, represent glacial and interstadial periods during which Mousterian sites associated with Neanderthal populations in Europe are well documented. Neanderthals spread rapidly throughout the Mediterranean during MIS3 (57,000 to 29,000 years ago) (Rasmussen et al., 2006; Shackleton and Opdyke, 1973). Around 37,000 years ago, climate conditions began to deteriorate during the transition to MIS2, a full glacial period (29,000 to 11,700 years ago). Increasingly harsh conditions forced hominin groups to retreat towards climate refugia in southeastern and southwestern

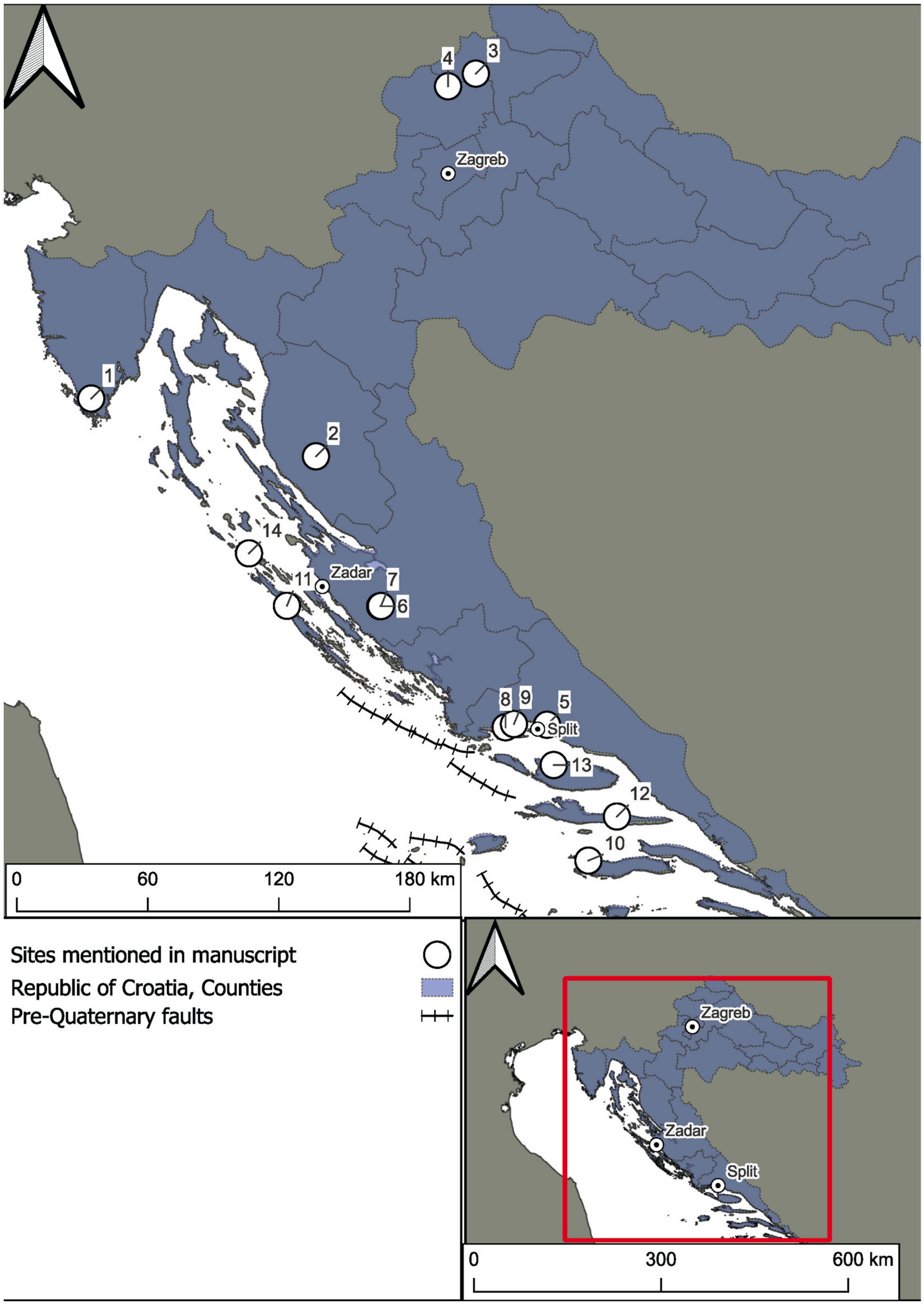

Fig. 1. Overview of the study region showing faulting along the seabed of the Adriatic and the locations of known Palaeolithic sites. Sites are numbered and are as follows: 1 - Šandalja I and II, cave site, Lower Palaeolithic, Upper Palaeolithic, Istarka County; 2 -Donje Pazarište, open Air site, Lower Palaeolithic, Licko-Senjska County; 3 – Punikve, open air, Lower Palaeolithic, Varaždinske County; 4 – Golubovec, 0pen air site, Lower Palaeolithic Krapinsko County; 5- Mujina Pećina, cave site, Middle Paleolithic, Splitsko-Dalmatinska County; 6 - Velika i Mala Pećina cave site, Middle Palaeolithic, Zadarska County; 7 - Velika Pećina in Kličevica, cave site, Middle Palaeolithic, Zadarska County; 8 - Malo polje Krban open air site, Middle Palaeolithic, Splitsko-Dalmatinska; County 9 - Kaštel Štafilić – Resnik, open air (submerged), Middle Paleolithic, Splitsko-Dalmatinska County; 10 -Vela Spila on Korčula, cave site, Upper Palaeolithic, Splitsko-Dalmatinska County; 11 – Vlakno, cave site, Upper Palaeolithic, Zadarska County; 12 - Badanj in Pokrivenik, cave site, Upper Palaeolithic (Epigravettian), Splitsko-Dalmatinska County; 13 - Kopačina, cave site, Upper Palaeolithic (Epigravettian), Splitsko-Dalmatinska County; 14 – Zemunica, cave site, Upper Palaeolithic, Zadarska County.

Table 1
Hominin occupations in the region of the Dalmatian coast.

Period	Archaeological visibility	Culture	Chronozone	Croatian sites and counties mentioned in text	Map reference (Fig. 1)	References
Lower Palaeolithic	Low (5–20)	Acheulian	>MIS5	Šandalja I (Istarka) Donje Pazarište (Licko-Senjska) Punikve (Varaždinske) Golubovec (Krapinsko)	1 2 3 4	Paunović et al., (2001); Karavanić and Janković (2006)
Middle Palaeolithic	Moderate (20–50)	Mousterian	MIS5, 4, 3	**Cave sites:** Mujina Pećina (Splitsko-Dalmatinska), Velika Pećina in Kličevica (Zadarska) **Open air sites:** Trogir-Kaštela area (Splitsko-Dalmatinska), Malo polje Krban (Splitsko-Dalmatinska) **Submerged:** Kaštel Štafilić – Resnik (Splitsko-Dalmatinska)	5 6 7 8 9	Barbir et al., (2022); Karavanić and Bilich-Kamenjarin (1997); Karavanić and Ćondić (2006); Karavanić and Janković (2006); Karavanić and Paraman (2022); Karavanić et al., (2008), 2014a, 2016a, 2016b, 2021a; b, 2023; Vujević (2011), 2013; Vujević and Perhoč (2024)
Upper Palaeolithic	Low (5–20) Very low (1–5)	Aurignacian Gravettian	MIS3 Transition from MIS3 to MIS2	Šandalja II (Istarka)	1	Paunović et al., (2001); Karavanić and Janković (2006); Peresani et al. (2021) Paunović et al., (2001); Karavanić and Janković (2006); Vujević (2016); Radić Rossi et al. (2020)
	Low (5–20)	Early Epigravettian	LGM	Šandalja II (Istarka), Badanj in Pokrivenik (Splitsko-Dalmatinska) Vlackno (Zadarska), Vela Spila (Splitsko-Dalmantinska)	10 11 12	Obelić et al., (1994); Miracle (1995); Forenbaher (2002); Farbstein et al., (2012); Cvitkušić et al., (2018); Vukosavljević and Karavanić (2017); Vujević (2021); Dean et al., (2020); Vukosavljević et al., (2011)
	Significant rise after the Bølling-Allerød	Late Epigravettian	Oldest Dryas Bølling-Allerød, Younger Dryas	**Cave sites:** Vlakno on Dugi otok (Zadarska), Kopačina on Brač (Splitsko-Dalmantinska), Vela spila on Korčula (Splitsko-Dalmantinska), Zemunica near Bisko (Zadarska)	11 13 12 14	Vukosavljević et al., (2014); Vukosavljević and Karavanić (2017); Cvitkušić et al., (2018); Farbstein et al., (2012)

Europe, as far away as the Black Sea (Van Andel et al., 2003; Bocquet-Appel et al., 2000, 2005; Rathmann et al., 2024). Mousterian sites on the eastern Adriatic coast are consistent with this pattern. Radiocarbon dates range from 60,000 to 39,000 years before present (Rink et al., 2002; Karavanić, 2009; Karavanić et al., 2014b, 2018: 159; 2021a), but the most intensive occupations were concentrated between 45,000 and 39,000 years before present (Vujević, 2016: 20).

Several factors suggest that the most promising locations for Mousterian archaeological sites along the Adriatic coast are likely now submerged. First, known Mousterian sites tend to cluster on or near the modern coastline even though the modern littoral was likely inhospitable during colder periods. In contrast, the northern half of the Adriatic basin that is now submerged never experienced permanent snow cover, even during the LGM, and remained well-watered thanks to the Palaeo Po River and its tributaries. The steep topography of the Dinarides supported diverse ecological zones within a short distance from one another due to altitudinal effects (Šegota, 1979:26–28; Karavanić et al., 2018; Peresani et al., 2021). Such a configuration could have supported similarly multiple diverse flora and fauna, including hominins (Cancellieri, 2016; Dean et al., 2020; Karavanić et al., 2018; Mussi, 2001; Rathmann et al., 2024; Sikora et al., 2014).

One hypothesis is that Neanderthal populations deliberately chose compact and heterogenous Mediterranean environments to best support subsistence needs (Soffer, 2000; Finlayson, 2004; Vujević and Perhoč, 2024). Available archaeological evidence is generally found in restricted areas, such as around Zadar and Kaštela, and islands (Paunović et al., 2001; Karavanić and Janković, 2006; Karavanić et al., 2014b; Vujević, 2011, 2016; Vujević and Perhoč, 2024; Radić Rossi et al., 2020; Karavanić et al., 2023). It is also likely that documented sites represent only one component of their original territories.

The transition from the Middle to Upper Palaeolithic is poorly understood along the Adriatic, with this transition being archaeologically visible only in northern Croatia (Karavanić and Smith, 1998; Ahern et al., 2004; Janković et al., 2006). This period saw the entry of AMH into Europe bringing with them Aurignacian culture during MIS3. Only a few assumed open-air sites around Zadar region and its hinterlands provide evidence of early Upper Palaeolithic on the Adriatic coast during MIS3, but not within the region of Kaštela Bay in central Dalmatia. Generally, they contain Mousterian material intermingled with smaller percentage of Aurignacian material (Karavanić and Janković, 2006; Vujević, 2009, 2016). It may be the case that both hominin species undertook similar approaches to resource use, leading to occupational overlap at open air locations, but there is no evidence for a similar pattern of cave usage (Vujević, 2016). However, across the eastern Adriatic coast, its surrounding hinterland, and the central and southern Dalmatian coast specifically, not a single site spans this Middle to Upper Palaeolithic transition during MIS3 and there is a drastic decline in number of documented sites. Furthermore, there is clear a chronological gap between Middle and Upper Palaeolithic sites on the central and southern Dalmatian coast (see: Papagianni, 2009; Karavanić, 2009; Karavanić et al., 2016b: 2018; Mihailović and Whallon, 2017).

One particularly notable site located on the Adriatic coastline, albeit not in central Dalmatia itself, that does contain Aurignacian materials is the cave site at Šandalja II in the Istrian Peninsula[1] (Istarka County) (Fig. 1, site 1, above). The lower levels at Šandalja II are attributed to Aurignacian by lithic material whilst the upper levels are defined as Epigravettian (Malez, 1979; Karavanić et al., 2023; Karavanić and Janković, 2010; Karavanić and Vukosavljević, 2019; Karavanić et al., 2013). Additionally, radiocarbon dating of the site puts Aurignacian levels several millennia later than the last Mousterian dates on eastern Adriatic (Malez and Vogel, 1969; Srdoč et al., 1979; Obelić et al., 1994; Oros Sršen et al., 2014; Richards et al., 2015). However, due to inconsistencies in these dates, the validity of site has been questioned (see: Ruiz-Redondo et al., 2024 and references therein).

Climate conditions worsened during the end of MIS3 and during the onset of the last glacial maximum (LGM) during MIS2. As a result, during the LGM (24,000–21,000 years ago), much of Europe was sparsely inhabited (Mussi, 2001). Climate conditions on the Dalmatian coast inferred from studies of aeolian dust, dune formations, and regional pollen assemblages were more arid (Ludwig et al., 2021; Peresani et al., 2021; Wacha et al., 2019) and sea surface temperatures were very low (Favaretto et al., 2008). There is a clear gap in archaeological evidence along the eastern Adriatic coast during and just after LGM. Moreover, few Upper Palaeolithic sites can be dated before 13,000 BP. Along the central Dalmatian coast, the only sites with layers attributed to these periods are Vela Spila on the island of Korčula, Vlakno on the island of Dugi Otok (Zadarska County) and Badanj cave in Pokrivenik on the island of Hvar (Splitsko-Dalmatinska County) (Forenbaher, 2002; Cvitkušić et al., 2018; Vujević, 20165; Peresani et al., 2021; Vukosavljević and Karavanić, 2017; Dean et al., 2020) (Fig. 1, sites 10–12).

Nevertheless, the presence of this limited number of sites suggests that the Adriatic region was not completely abandoned. However, it is only that during the later phases of Epigravettian that the number of sites began to rise in the Adriatic region (Mussi, 2001; Vujević, 2016; Vukosavljević and Karavanić, 2017; Peresani et al., 2021).

Two main environmental zones can be delineated during and after the LGM: the northern Adriatic plain and the karst hinterland. The plain comprised an arid semi-desert short grass steppe, with occasional woody cover near fluvial systems, wetlands, and protected valleys (Ludwig et al., 2021; Peresani et al. 2021; Wacha et al., 2019). The karst hinterland was an arboreal mosaic, the taxa of which were controlled by altitudinal effects (Miracle, 1995; Peresani et al., 2021). Mussi (2001) argues that the plain had a hostile environmental and climatic conditions characterized by strong winds and a lack of shelter. Therefore, Palaeolithic communities had to live along its borders and make frequent use of caves. However, most other authors agree that the harsh LGM conditions encouraged Upper Palaeolithic populations to prefer the Adriatic plain that was rich in resources rather than the inhospitable karst hinterlands (Shackleton et al., 1984; Miracle, 1995, 2007; Peresani et al., 2021). The latter better coincides with archaeological evidence.

As RSL rose after the LGM, the Adriatic plain was flooded and warming climate conditions allowed a return of flora and fauna to the karst hinterlands (Asioli et al., 2001; Bazzicalupo et al., 2022; Favaretto et al., 2008; Ludwig et al., 2021). Likewise, an increase in the number of sites into mountainous regions aligns with the Bølling-Allerød interstadial (14,700 cal BP to 12,900 cal BP). This suggests that that Upper Palaeolithic communities who previously occupied the Adriatic plain began to settle in what were once the outer reaches of their territory (Vukosavljević, 2012). Several of the known Epigravettian sites are found in Istria and the Kvarner islands (Karavanić and Janković, 2006; Komšo and Pellegatti, 2007; Ruiz-Redondo et al., 2019; Percan et al., 2020). On the central Dalmatian coast in Splitsko-Dalmatinska county around Kaštela Bay, the most notable sites include caves on islands: Kopačina on Brač (Obelić et al., 1994; Miracle, 1995; Vukosavljević et al., 2011), Vela spila on Korčula (Farbstein et al., 2012; Dean et al., 2020), Vlakno on Dugi otok (Vukosavljević i sur. 2014; Vujević, 2016; Cvitkušić et al0.2018) and inland at Zemunica cave (Šošić et al., 2015) (Fig. 1, sites 10, 13, and 14).

The eastern Adriatic coast took on its current shape around 5000 to 6000 cal BP, during the mid-Holocene. Deglaciation and flooding pushed human communities to the periphery of their former territory, into the mountain areas, limiting their movements, changing the environment and compelling them to change their survival strategies (Miracle, 1995, 2007). Furthermore, with time, communication routes between the two shorelines of the Adriatic were severed, forcing

[1] There are additional confirmed and potential Mousterian and Aurignacian sites on the Istrian Peninsula. However, due to the geographical scope of this study being limited to Dalmatia, they are not included in this paper. Šandalja II is an exception due to its significance.

communities to rely more on local, inland resources (Vujević, 2016).

1.4. Climate, relative sea level and palaeotopographic landscape changes

Sea levels during the late Quaternary reflect a response to changes in Earth's climate, which at the LGM, was significantly colder than present with global mean surface temperatures 5–7 °C cooler. During glacial and interglacial cycles, the growth and decay of ice sheets and glaciers caused RSL to rise and fall tens to hundreds of meters driven primarily by barystatic and thermosteric processes related to increasing or decreasing global ocean mass and volume (e.g., Horton et al., 2018; Gregory et al., 2019). In the Mediterranean, changes in RSL also reflect the regional response to processes associated with glacial isostatic adjustment (GIA) and barystatic gravitational effects related to the loading and unloading of ice and ocean mass and vertical response of the solid Earth (e.g., Peltier et al., 2022) and the spatially variable redistribution of meltwater from ice sheets and glaciers (e.g., Lin et al., 2021). Furthermore, local processes related to the complex tectonic framework

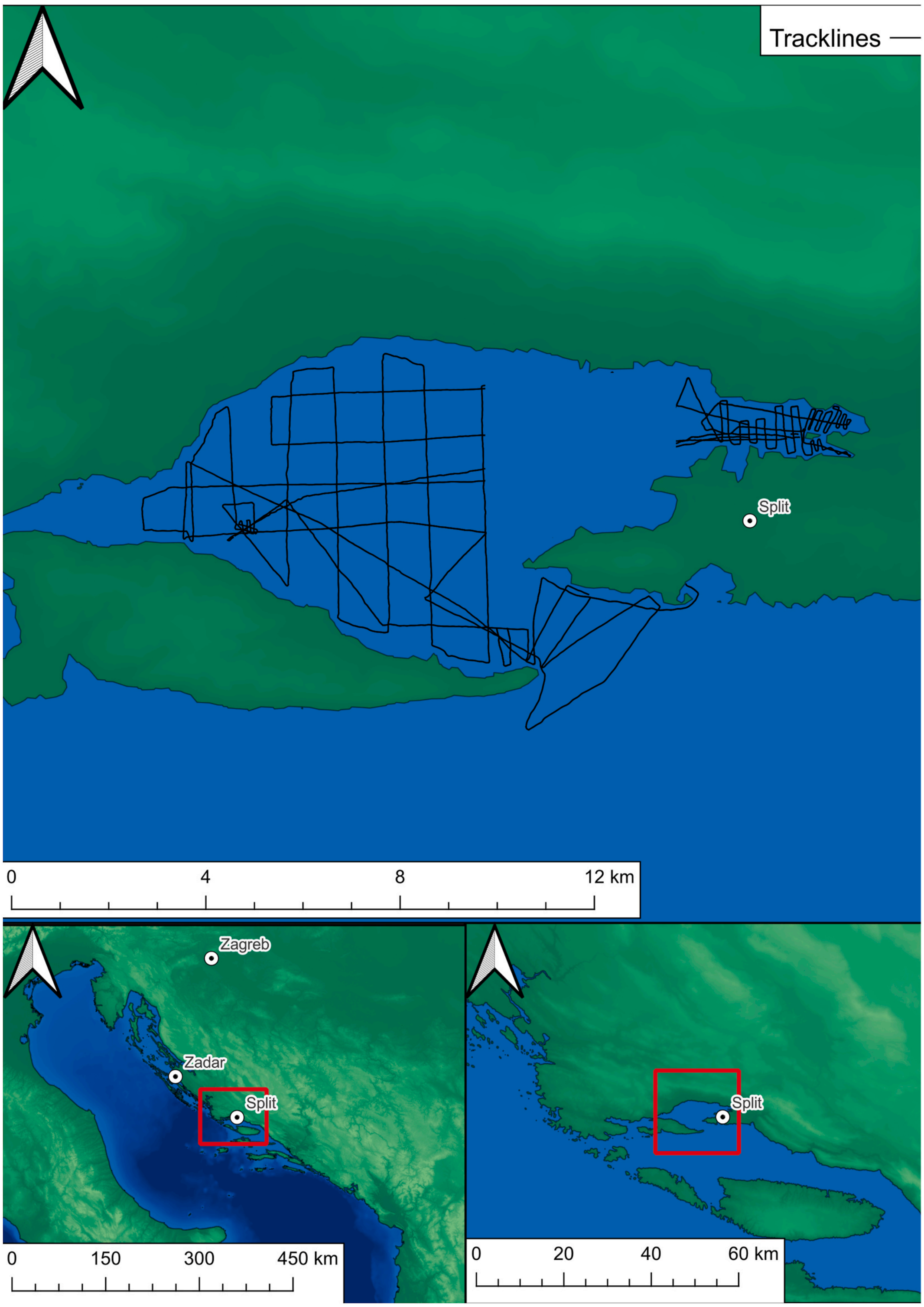

Fig. 2. Overview of Kaštela Bay showing seismic survey tracklines, from 2023 to 2024.

of the region also caused variability in sea level (e.g., Vacchi et al., 2016; Shaw et al., 2018). Significant efforts have been made towards reconstructing and understanding RSL changes in the Mediterranean, which underscore the region's complex spatial variability due to these processes (e.g., Lambeck and Purcell, 2005; Roy and Peltier, 2018; Pirazzoli, 2005; Antonioli et al., 2011; Vacchi et al., 2016).

During glacial periods, the growth of ice sheets and glaciers covered large portions of the northern hemisphere in North America and Eurasia (Peltier et al., 2022). As a result, global mean sea level during the LGM for example, was ~130 m below present level exposing shallow continental shelves (e.g., De Groeve et al., 2022). As global climate warmed and the large volumes of water stored in ice sheets melted, the position of global coastlines were transformed impacting migration routes of flora and fauna which became disconnected along with ancestral hominin populations inhabiting coastal regions (e.g., Benjamin et al., 2017; Kim et al., 2023).

2. Methods

2.1. Seismic survey

Marine seismic survey was undertaken at a regional scale followed by higher resolution survey over targets identified during the regional survey (Fig. 2). The regional survey was done to understand prevailing geological and environmental conditions and the high-resolution study was done to map individual targets of interest. The survey vessel was equipped with an Innomar Quattro system for the first round of survey and an Innomar Six Pack was deployed for the second round. Both instruments were pole mounted on the starboard side and submerged 1m below the water surface.

The transducers were deployed in a rectangular array (2x2 and 2x3) for single channel use to optimise power and depth of penetration in sediments. Positional information was provided by a Garmin GLO2 unit via a high-speed Bluetooth interface directly into the Innomar recording unit. This provided positional information from a combination of GPS, GLONASS and BeiDou satellites. This positional data was corrected utilising differential positional information obtained through the unit's satellite link, producing sub-meter accuracy. Throughout both surveys good satellite coverage was observed and the data recorded within the seismic files is regarded as reliable for archaeological purposes. The position data was recorded in the Innomar system as both WGS84 Lat/Long and UTM 33N. Motion correction for the data was also provisioned using a Seatex Motion Reference Unit which was mounted in the bridge of the boat and its location and offset with respect to the sensor head recorded. This motion correction information was transmitted via a RS232 interface into the Innomar unit and recorded within the seismic files.

Trackline spacing varied depending on geological and archaeological conditions across Kaštela Bay. The regional survey lines averaged 1000 m (1 km) apart, to constrain the regional landscape (Fitch et al. 2011) and to identify specific features of interest where higher resolution surveys were then focused and tighter line spacing was used. Two specific areas of higher interest lay within the harbour on the eastern side of the Bay proximal to Sjeverna Luka and on the west side of Kaštela Bay, between Trogir on the mainland and the island of Čiovo (Čiovo Otok) (Fig. 2). Line spacing off Sjeverna Luka was between 150 and 175 m, whilst line spacing offshore Trogir was approximately 60 m with some variation due to the need to capture bathymetric features of irregular form. A complete network of data was acquired across the bay and trackline distance totaled 189,545.72 m (189.55 km) (Fig. 2).

The seismic data were recorded utilising the Innomar SeisWin application. SeisWin acquired data outputs of the parametric echo sounder, the positional data, and the motion correction information. The high frequency component was set to 100Khz whilst the low frequency was set to 10Khz. Lower frequencies of 5Khz and where necessary 8Khz were utilised along supplementary lines added to the main survey grid to aid depth penetration and resolution of the sediments in areas of interest.

2.2. Seismic data processing

Seismic data were initially processed using the Innomar ISE3 software. All seismic data from 2023 to 2024 were imported in a single project in UTM 33N projection. Each profile was then converted from the proprietary Innomar.SES file type to standard SEGY file type using Big Endian byte order at 32-bit resolution. These converted data were compiled into a single project that included both 2023 and 2024 data within the IHS Markit Kingdom 2024 software. Profiles were processed using automatic gain control (AGC) as well as a bandpass filter that varied low pass, low cut, high pass, and high cut frequencies per analytical needs. Data were reviewed line by line and the seabed horizon was traced using a combination of manual delineation, 2D Hunt, and 2D Seeker + picking algorithms using a 0.001 s window. Peak, trough, negative to positive, and positive to negative signatures were all used to locate the horizon depending on the nature of each profile.

Interpreted horizons were gridded in Kingdom using two-way travel time (TWTT) and exported as.csv files. These.csv files were then imported into QGIS 3.34 where they were converted to point shapefiles. TWWT travel time was recalculated to depth below sea level by using the field calculator to multiple the z values in the TIN surfaces by 1500, representing the speed of sound in water. These depths were compiled into a field designated as ELEV and refactored as integer values. Raster files for bathymetry from EMODNET and topography from EURODEM were then added to the map. The pixels to points tool was used to convert these rasters to point shapefiles, again assigning elevation/depth below sea level, to a field named ELEV. The survey area was clipped out of the bathymetric point shapefile using the difference tool. Finally, all three of the point shapefiles were merged and interpolated as a TIN. The final surfaces were visualised in QGIS so that local RSL curves accounting for isostasy could be utilised.

2.3. RSL predictions and paleotopography maps

Predictions of RSL from 50 ka BP to the present were provided using two ice models (ANU-ICE and ICE-7G-NA; Argus et al., 2014; Lambeck et al., 2014; Peltier et al., 2015) and coupled with the same 3D Earth model (HetM_L140; Li et al., 2018; Li and Wu, 2019). The temporal resolution of models prior the LGM are lower due to the lack of constraint on the ice model (Lambeck et al., 2014; Peltier et al., 2015). However, the resolution over the main period of interest was deemed sufficient for archaeological visualisation and modelling. These models were applied to both the picked seismic surface and the modern bathymetry to visualise the effect of sea level on the landscape and to contextualise of the archaeological record within its contemporary landscape.

We reconstructed the RSL history and generated palaeotopography maps to demonstrate spatial and temporal land area changes in response to RSL changes during and after MIS3 and MIS2. The paleotopographic maps were generated following Peltier (2004) and use both ANU-ICE (Lambeck et al., 2014) and ICE-6G_C (Argus et al., 2014; Peltier et al., 2015) global ice history models and HetM-LHL140 3D Earth model (Li et al., 2018; Li and Wu, 2019):

$$(\theta,\lambda,t) = S(\theta,\lambda,t) + \left[T_p(\theta,\lambda) - S(\theta,\lambda,t_p)\right]$$

Where, θ,λ , and t represent latitude, longitude and time, respectively; $T(\theta,\lambda,t)$ is the paleotopography at time t; $T_p(\theta,\lambda)$ is the present topography from ETOPO1 (Amante and Eakins, 2009), $S(\theta,\lambda,t_p)$ and $S(\theta,\lambda,t)$ are the present-day sea level and sea level at time t respectively, which are predicted by GIA models ICE-6G_C (HetM-LHL140) and ANU-ICE (HetM-LHL140), respectively. The HetM-LHL140 3D Earth model includes lateral variations both in the lithospheric thickness and mantle viscosity (Li et al., 2018; Li and Wu, 2019).

2.4. Diver survey

Diver surveys were carried out to test targets identified during regional surveys and mapped at higher resolution by targeted surveys. Diver surveys employed circle searches and transects oriented along E-W and/or N-S axes using the anchor point of the boat as a temporary datum location. Navigation was by diver compass, using dead reckoning methods that estimated distance using what are termed “fin cycles”. Fin cycles to estimate distance are calculated by using a metre tape to measure the distance travelled by a diver who has kicked with each fin. Contact with the temporary datum at the anchor was established by using dive reels for additional safety as well as to further constrain distances.

Hand fan test units were dug every 5 fin cycles, which correlated to 5–7 m intervals. Hand fan test units were dug to 20–30 cm, depending on the friability of marine and sub-seabed sediments. The depth, location, and sedimentary characteristics of stratigraphic units observed in these test units were documented using diver slates and, where possible, photography. Archaeological sampling was carried out where human-modified materials were detected after their locations were documented.

3. Results

3.1. Seismic data

Signal to noise ratio for seismic data was generally acceptable during seismic interpretation and analysis. Six horizons were interpreted across the survey area (Table 2, Fig. 3). In addition to the seabed horizon (labelled H0), the bedrock horizon (labelled H1) could be clearly seen in most profiles. Additional horizons were traced across each profile, numbered from H2 to H4, with H2 being the deepest above the H1 bedrock horizon, and H4 the shallowest horizon beneath the seabed. An additional horizon, labelled HTect as a shorthand for ‘tectonic horizon’ could also be seen in some areas of Kaštela Bay but was not consistent. It was also absent in the regional profiles interpreted from the Brač channel, where the correlative unconformity comprised the upper boundary of a seismic unit consisting of parallel to sub-parallel reflectors more consistent with estuarine or pluvial sediments. HTect and its correlative unconformity in Brač channel appeared beneath H4 and above H3, where present.

Examination of seismic profiles across the Bay indicated different degrees of preservation of buried stratigraphy. Generally, the central and southern portions of the Bay contain better preserved seismic units than those in the northwestern and north-central part of the Bay offshore Trogir where only a thin veneer of sediment was visible outside of palaeochannel areas (see Fig. 2, above). Carbonate bedrock appears to directly underlie this veneer in the northwestern and north central portion of the bay. Areas where deep seismic stratigraphy is preserved tend to be within palaeochannel features, which in turn appear to be at least partially controlled by the orientation of local fault lines.

Deposits in the eastern bay off Sjeverna Luka (see Fig. 2) are thicker, especially where two smaller palaeochannels flowing from east to west join one another. Within these channels, deep seismic stratigraphy shows parallel reflectors consistent with multiple episodes of deposition in low energy conditions. HTect overlies H3 within the channel features and is peppered with larger parabolic reflectors. This unit is consistent with colluvium deposited by tectonic events sufficient to create slope failures carrying all particle sizes, up to boulders, into these bathymetric lows.

Not all potential fault features have resulted in the development of palaeochannels. Several bathymetric highs and nearby submerged springs have been detected in the bay that appear to be associated with previously mapped faults (Fritz and Bahun, 1997) (Fig. 4). One of these faults parallels the northwest coastline of the bay, striking at approximately 45°, and the other strikes at 90° along an axis that traverses Split peninsula, westward to Čiovo. Acoustic penetration was not sufficient during the 1997 work to fully resolve the seismic stratigraphy of the submerged springs and nearby bathymetric highs associated with these two faults (Fritz and Bahun, 1997), but acoustic penetration during the LOTE study was more successful.

The profiles over bathymetric highs associated with the one fault and nearby submarine springs sites showed complex seismic stratigraphy with multiple onlapping, sigmoidal reflectors extending downslope into nearby palaeochannels. Whilst such reflector geometry is typically associated with deltaic deposits, the lack of any clear large fluvial system nearby from which they might originate argues against a prograding delta feature at this location. Instead, these seismic horizons are thought to be more consistent with travertine deposits, which can form along fault lines in karst contexts, and which are common across the region. These deposits are also associated with springs, either hot or cold.

Whilst noting that no radiometric dates exist for any samples taken from hand cores yet, it is reasonable at this point to at least comment on the evidence for the presence of at least one parasequence in the study region (Middleton, 1973; Nichols, 2009; Catuneanu, 2017). H4, just below H0, likely represents the youngest preserved flooding surface and may thus date to the early and middle Holocene marine transgression. Below H4, HTect is visible in the northeastern portion of the Bay, suggesting that any tectonic event(s) that created this deposit post-date exposure of the H3 surface below it. H3 tends to delineate the upper bounds of deposits consistent with fluvial channels and fluvial margins, but it is discontinuous across the bay, suggesting it experienced both subaerial and later marine erosional forces. As such, it likely represents subaerial surfaces dating to a glacial period. H2 underlies H3 and is also discontinuous across the Bay. Palaeochannel morphology, where visible in H2, is more consistent with shallower hydraulic gradients such as those created by marine transgression events, and therefore, H2 is interpreted as a transgressive stage sequence tract. Below H2 lies H1, where carbonate bedrock attenuates the acoustic signal.

3.2. RSL predictions and paleotopography maps

RSL was predicted for Split, on the mainland of the southeastern shore of Kaštela Bay. The two models generally agree in the timing and pace of marine transgression after the LGM but differ in timing and magnitude of marine regression and transgression before the LGM (Fig. 5). The models for Split were applied to the data from Kaštela Bay based on proximity and ages in cal BP were calibrated from IntCal 20 (Reimer et al., 2020). ANU-ICE suggests an RSL of around 75 m below modern sea level at 48,000 cal BP, whereas ICE-7G-NA predicts an RSL of around 85 m below modern sea level at 48,000 cal BP, with significant implications for palaeolandscape reconstruction.

Additionally, examination of seismic profiles within palaeochannels in the bay as well as within the sound between the mainland and Brač revealed that as much as 12 m of sedimentation above H3 has occurred since it was last subaerial (Fig. 6). It is assumed that this represents post-submergence deposition into the marine basin that developed during the Holocene marine transgression. When models for the coastline positions were generated using EuroDEM and EMODNET bathymetry, significant

Table 2
Interpreted seismic horizons.

Horizon	Interpreted surface
H0	Seabed, modern flooding surface
H1	Carbonate bedrock
H2	Possible transgressive stage surface tract
H3	Sequence boundary/subaerial surface
HTect	Colluvial materials
H4	Flooding surface

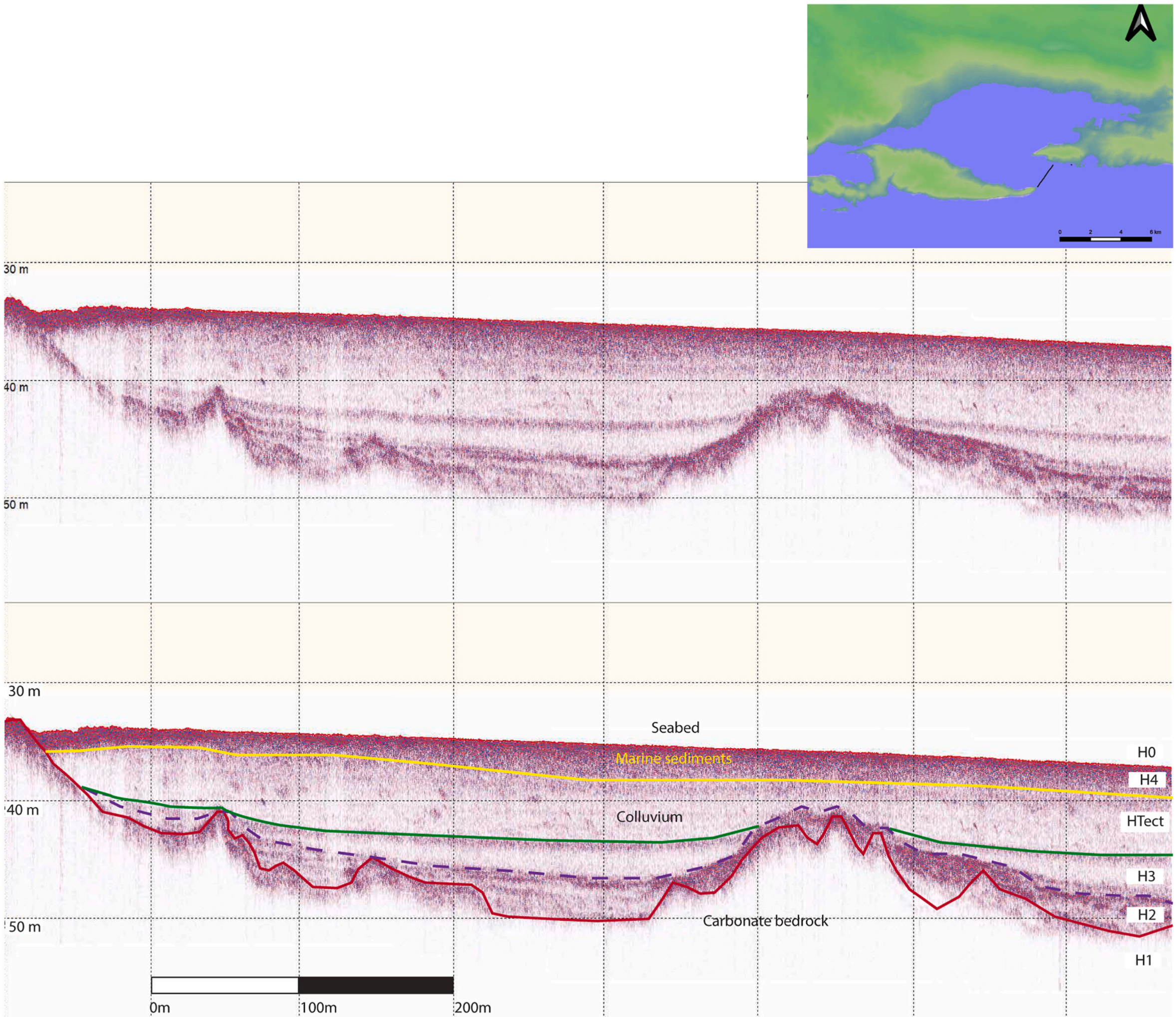

Fig. 3. Profile view of the horizons delineated within Kaštela Bay.

differences arose between visualisations that corrected for the stratigraphic units overlying H3 in Kaštela Bay, and those that did not. Without having corrected for these sediments, the ICE-7G_NA model shows no flooding of Kaštela Bay at 48,000 cal BP at all, whilst the ANU-ICE model indicates the presence of a paleolake within Kašela Bay (Fig. 7).

Unfortunately, the density of seismic lines was not sufficient in this area to generate a useable model outside of Kaštela Bay to reconstruct the Brač channel directly from the geophysical data. Instead, information on the depth of sediment above the putative MIS3 landscape was approximated by digitally backstripping this sedimentation to create a probable land surface during MIS3 (Table 3). Whilst this approach cannot be used to create fine-grained models, it is helpful in indicating general trends within the area and highlighting the issue of burial and sedimentation associated with the submerged landscape.

Correction for sedimentation was achieved by using EMODNET and EuroDEM geotiffs which were contoured in QGIS. Contours that offset by 12 m from than the two modelled RSLs estimated were selected as representative of the maximum depth to the original land surface prior to sedimentation (Table 3). These contours were converted to polygon features. Next, polygon features from the surfaces within Kaštela Bay were derived from contours representative of the actual RSLs predicted by both sea level models, as this part of the region did not require backstripping. Polygons from both inside and outside Kaštela Bay were then merged to show the estimated coastline positions corrected for the post-submergence sediment deposition. Finally, uncorrected polygons were derived from EMODNET and EuroDEM geotiffs for comparison (Fig. 6).

Once post-submergence sedimentation is accounted for, potential coastline positions for 48,000 cal BP are very different from the uncorrected positions (Fig. 6). The ANU-ICE model shows paleolakes at 48,000 cal BP within and outside Kaštela Bay. Assuming the presence of fluvial connections between these features, which have been inferred in past studies of bathymetry (Sikora et al., 2014), it is reasonable to hypothesize connection to the Adriatic Basin. This could result in significantly different salinities for these bodies of water, as well as generally a greater abundance of water resources across the regional landscape.

Results from the ICE-7G-NA model, however, were significantly different. Using the ICE-7G-NA model and before correcting for sediment deposition, Kaštela Bay and Brač Channel were subaerial coastal plain with only a few small lake features. Corrected reconstructions show only minor changes in these hypothetical hydrological conditions. Both uncorrected and corrected reconstructions do not show potential linkages to the Adriatic Basin such as that as might be inferred from the corrected ANU-ICE model.

3.3. Diver survey

Diver survey was carried out offshore Trogir at the bathymetric high associated with a possible fault, as low visibility conditions precluded such investigations offshore Sjeverna Luka. Survey locations were also chosen based on seismic data suggesting the potential presence of

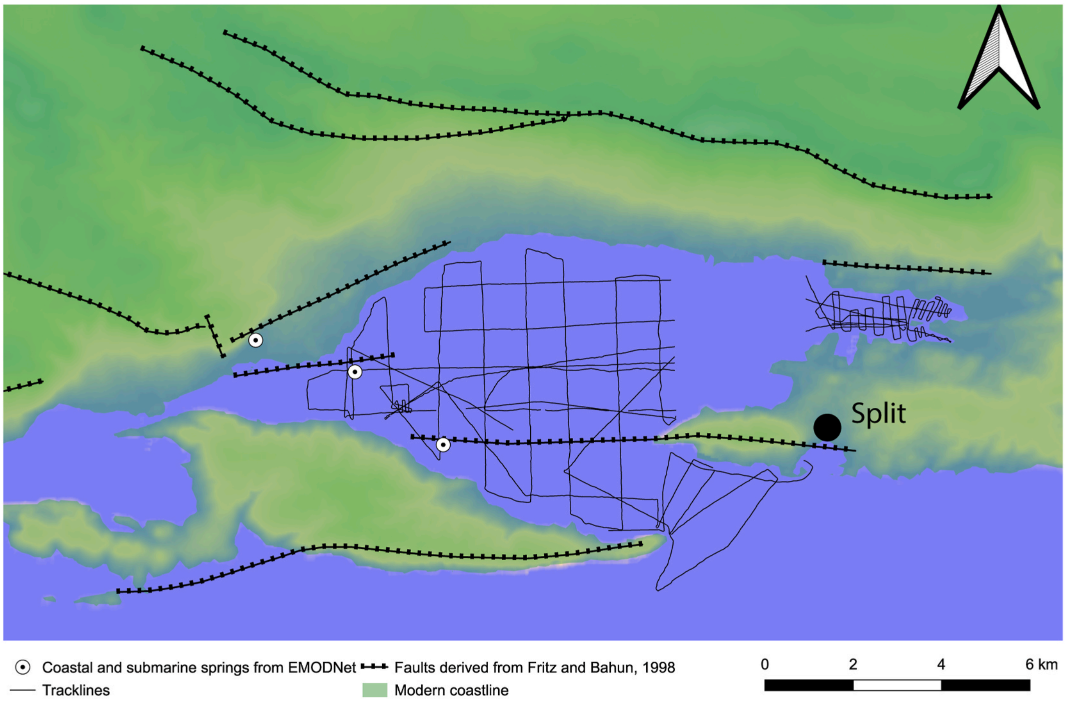

Fig. 4. Tracklines contextualised by locations for faults and spring locations derived from EMODNet and Fritz and Bahun (1997).

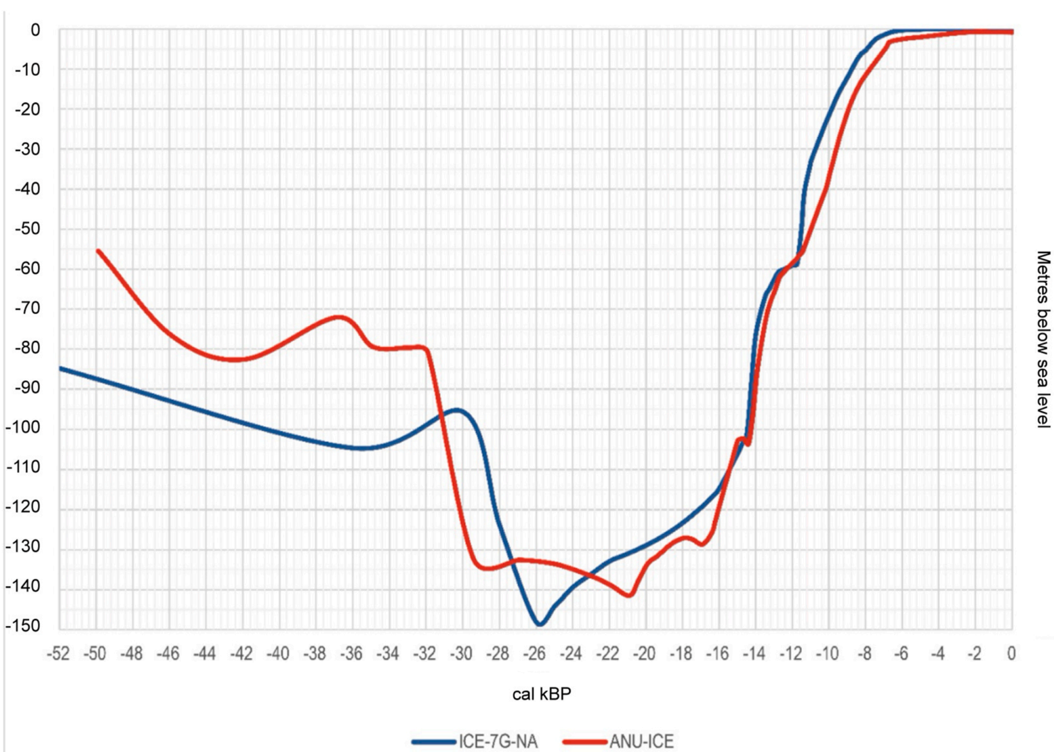

Fig. 5. RSL predictions using the ANU-ICE and ICE_7G-NA models for Split. Ages converted from kBP to cal BP using Intcal20 (Reimer et al., 2020).

acoustic resonance anomalies. These anomalies, which appear in the water column, are a topic currently under intensive investigation, as some, but by no means all, studies suggest it may correlate to anthropogenic lithics (Fitch and Hale, 2024; Grøn et al., 2021; Morris et al., 2022). Seismic survey data indicated that the 13–14 m isobath was the most likely depth to be productive and the search area was located where the bathymetry deepened from 10 to 15 m (Figs. 8 and 9).

The first series of dives was carried out on May 6th, 2025. Three different dive targets were investigated. Each target was investigated using circle search survey, with four divers deployed approximately 3–4 m apart along a line connected to the anchor line. Searching was carried out by moving the line clockwise in a circle by maintaining the anchor line as a centre point. This allowed all four divers to carry out visual searches of the seabed from their respective positions along the line and

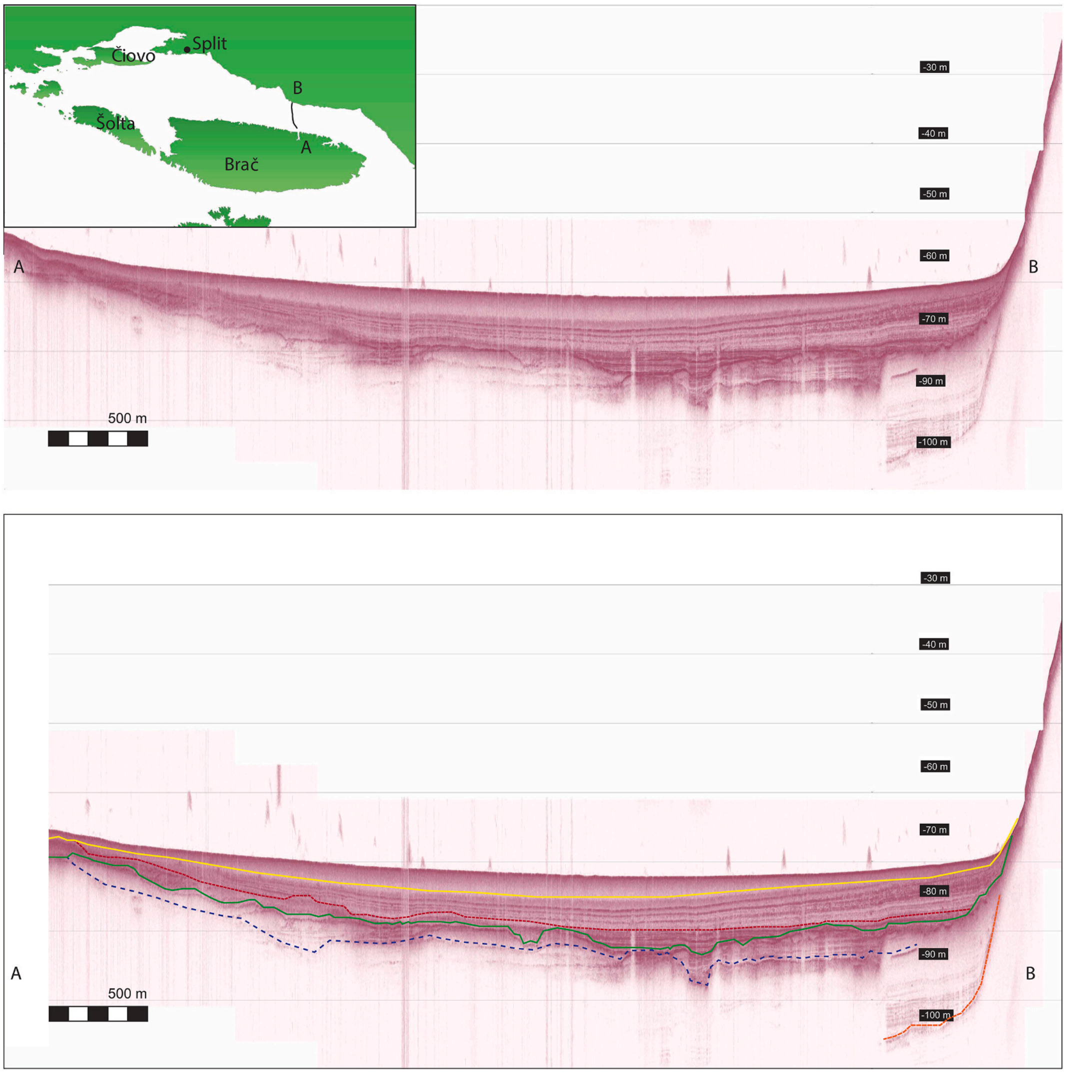

Fig. 6. The channel between Brač and the mainland showing multiple seismic stratigraphic units.

thus investigating a larger swatch of area than can be surveyed using linear transects. to.

Circle survey at the first dive target, designated DT01, showed abundant sea grass beds but no indication of anthropogenic materials (though such could be hidden by sea grass beds). A shift to dive target two, designated DT02, around 830 m to the west-southwest, revealed a sandy seabed with preserved stratigraphy lying around 20 cm below the seabed, across the entire circle search area. A third locale, designated DT03, was investigated visually with no excavation, at approximately 30 m northeast from DT02. DT03 yielded a lithic item during circle search that showed some flake scarring; this item was recovered from seabed sediments (Figs. 9 and 10) (see Fig. 11).

A sediment core was taken on May 10th, 2024, by a team of four divers approximately 50 m northeast of the area where the potentially anthropogenic lithic item was recovered on May 6th (Fig. 8). This location was at the −13-m isobath and comprised only sandy seabed. The sediment core was driven using a slide hammer and a sledgehammer to approximately 1 m below seabed. It was then capped, pulled by hand, and sealed at the bottom. The core was then reserved for future analysis at the University of Split. Additional diver survey was carried in proximity to the core location and was designated DT04, but limitations on visibility made productive observation difficult and the survey was not expanded more than about 5 m from the core location.

The second set of diver surveys was carried out on May 11th, 2024. at the same location where the sediment core was recovered on May 10th, 2024. Diver observation during coring indicated that the wider area was, like the core location, comprised of sandy seabed and thus a better candidate for focused transect survey. Accordingly, divers descended the anchor line at DT05 and deployed along an east to west transect. Hand fan test units were dug along this transect at approximately every 3–4 m until marine sediments gave way to the same stratigraphic unit observed at DT02. A transect was surveyed due east bearing 90° for 50 m from DT04 and due west bearing 270° for 50 m from DT04. A water jet dredge was then deployed at the bottom of the anchor line to sample a larger test unit. However, 1 h of dredging only revealed stratigraphy and did not recover any artefactual materials. The dredging did confirm the stratigraphic observations made at DT02, however, indicating some level of depositional continuity in this area.

After the first two dives, the boat anchor dragged and the vessel had to be repositioned; the position to where the anchor dragged was recorded as DT06 in the interest of full record keeping, though no survey was carried out at this location.

Once the boat had been re-positioned at the location of DT04, a third diver survey was carried out. This survey transect, extending approximately 95 m west of the first survey transect and the first dredge unit. This survey comprised a transect survey along an east to west transect during which divers carried out hand fanning every 3–4 m. The visual and hand fanning survey resulted in recovery of one clearly

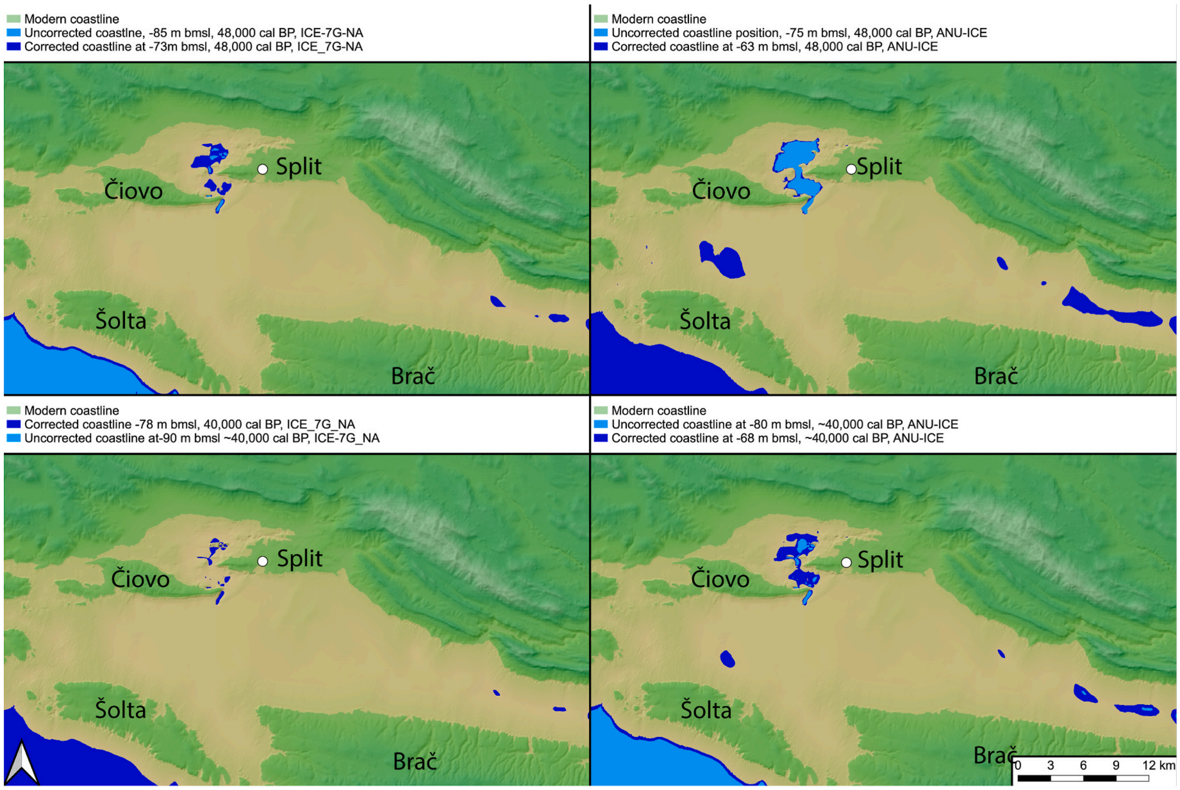

Fig. 7. ANU-ICE and ICE-7G_NA RSL models for 48,000 cal BP, showing projected subaerial landscapes based on uncorrected bathymetric data, and bathymetric data corrected for 12 m of sediment deposition.

Table 3
Correction depths following RSL models, for minimum and maximum sedimentation depths. Ages converted from kBP to cal BP using IntCal20 (Reimer et al., 2020).

Correction depth	−12 m
ANU-ICE, RSL, 48,000 cal BP (−75 bmsl)	−63 bmsl
ICE-7G-NA, RSL, 48,000 cal BP (−85 bmsl)	−73 bmsl

anthropogenically modified lithic (Figs. 8 and 9) at a location designated DT07. This item was recovered within the upper portion of a greyish-brown silty fine sand overlain by the marine materials at the seabed, approximately 25 cm below seabed. Unlike the lithic item recovered at DT03, It was embedded within this stratigraphic unit, not overlying it.

Hand fan test units at every set of dive targets as well as the test excavation unit revealed two stratigraphic units at all locations that were tested. Marine sediments at the seabed consisted of coarse sands, very coarse sands, shell fragments, and gravels. Underlying this at 20–30 cm below the sandy seabed lay a second stratigraphic unit. This unit, whilst friable, was clearly more consolidated than the overlying marine sands. It was composed of very fine sand to silt with signs of burrowing, along with minor shell hash inclusions. The presence of marine boring and shell inclusions suggests that it most likely constitutes a condensed stratigraphic section formed from lag deposits eroded from a deflated subaerial surface.

One lithic item was recovered at the seabed at DT03, and the second lithic item was recovered within the upper portions of the stratigraphic unit underlying it at DT07. These lithics both show some evidence of wave-rounding. This in turn suggests exposure to the wave zone during and after submergence. However, both items could be identified as anthropogenically modified, with the most likely association being Mousterian. The first lithic appears to be a utilised flake and the second lithic item is consistent with a used Mousterian centripetal core.

4. Discussion

4.1. Surface reconstruction

Reconstruction of the extent of surface exposed indicates that the waterline position within Kaštela Bay would have shifted somewhat during MIS3 and been drawn down entirely during the LGM when the shoreline was at roughly the −120 to −130 m isobath. The fullest extent of this marine regression lasted from around 30,000 cal BP to around 18,000 cal BP. Between the beginning of MIS3 at 57,000 cal BP, and 30,000 cal BP, however, the region of Kaštela Bay would have been comprised of uplands, a coastal plain basin encompassed by those margins, and either lake features or perhaps even an estuarine basin lying between the mainland and the island of Brač and between the islands of Brač and Hvar, where it met the palaeo Adriatic sea (see Fig. 7), depending on the time period and RSL positions.

It is important to note that the magnitude of RSL at MIS3 is still under debate. Far-field coral-reef sites reconstruction (Cabioch and Ayliffe, 2001; Peltier and Fairbanks, 2006; Siddall et al., 2008) and marine oxygen isotope (δ^{18} O) (Siddall et al., 2008; Waelbroeck et al., 2002) show the RSL fluctuated between 60 and 90 m below present, whilst intermediate-/near-field sites data (Pico et al., 2018; Yokoyama et al., 2022) indicate RSL ranged between 25 and 50 m below present. This discrepancy indicates the need for more high-precision and continuous records to better constrain the MIS3 RSL and refine the GIA model. With respect to the study area here, additional palaeoenvironmental datasets are to be sought to offer evidence concerning how regional hydrology impacted the RSL fluctuations.

Although RSL during the first part of MIS3, from 57,000 to 48,000, cannot be estimated with full accuracy, palaeolandscape reconstructions for the period from 48,000 cal BP to 30,000 cal BP are achievable, with the hypothetical positions for the coastlines shown in Fig. 7, above. These results also have implications for potential archaeological site

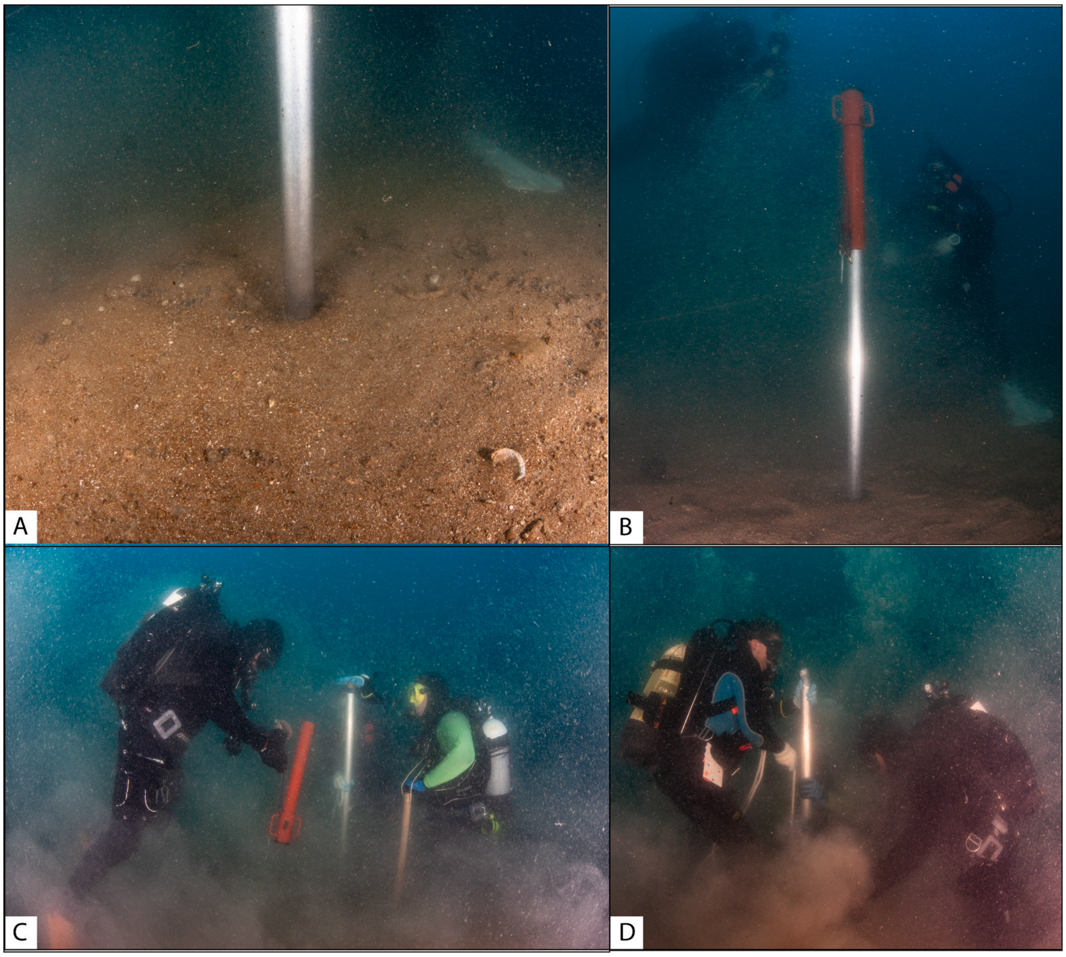

Fig. 8. Diver sediment coring. A: sandy seabed; B: early part of driving the core; C: Core reaches refusal and is capped; D: hand pulling the core.

patterns, specifically in areas that are now submerged. The geomorphology and hydrology predicted by the ANU-ICE RSL curve likely gave rise to multiple diverse ecological zones ranging from relatively arid steppe/coastal plain, to coastal plain dotted with freshwater, brackish, and even saline water bodies that likely also supported wetlands, at around 48,000 cal BP. Diverse ecological zonation of this latter type is a known driver for floral and faunal diversity and abundance, including human populations. However, the ICE-7G-NA RSL curve indicates a much different situation, with minimal flooding and resulting hydrological features for the same time period. Depending on which model is more accurate, the nature of MIS3 hominin occupations during this time period would have varied.

Moreover, the trend for both RSL curves during the end of the Mousterian, roughly defined here as 40,000 cal BP following current understanding of the extirpation of Neanderthal populations, is one of marine regression (Fig. 7). A brief, minor transgression is suggested around 42,000 cal BP by the ANU-ICE curve (Fig. 12) but by 40,000 cal BP, the ANU-ICE model posits a corrected RSL of around −68 m below modern sea level (Fig. 7). At the same time, the ICE-7G-NA model posits a corrected RSL of around −85 m below modern sea level, identical to the uncorrected estimates for 48,000 cal BP. Regardless of which model is correct, hominin populations in the region of Kaštela Bay would have experienced increasing levels of aridity during the end of the Mousterian, with only a brief respite around 42,000 cal BP, assuming the ANU-ICE model is correct. These conditions in turn would have likely tethered them more tightly to freshwater resources. Future archaeological prospection for submerged Mousterian sites in the region would benefit from more robust assessments of the palaeo-hydrology within and near Kaštela Bay.

Currently, palaeoenvironmental data is insufficient to offer dispositive interpretations for which model is more correct; should ANU-ICE be more accurate, conditions in the region of Kaštela Bay would be expected to have been less arid than if the ICE_7G-NA model is more correct, especially given the brief reprieve that would have resulted from the slight marine transgression around 42,000 cal BP. The lack of connectivity to the Adriatic Basin by 48,000 cal BP in the latter scenario would have had significant impacts on regional hydrology and thus general ecological conditions, with concomitant impacts on hominin behaviour. In either case, however, continuing marine regression would have eliminated connectivity to the Adriatic and left the region of Kaštela Bay increasingly arid, with the only freshwater resources most likely limited to freshwater springs such as those documented by EMODNet (Figs. 4 and 7).

4.2. Paleoenvironmental reconstruction

As discussed above, palaeoclimate conditions varied during the Middle and Upper Palaeolithic, and the reconstructed landscape presented above would have experienced significant shifts in ecology during MIS3. MIS3 conditions were less cold and dry than the LGM during MIS2, but more dynamic. Henrich events, of which there were three (Heinrich Events 5, 4, and 3) generally led to colder, drier, semi-desert conditions across the Mediterranean (Bond et al., 1992; Di Stefano et al., 2015; Fletcher and Sánchez Goñi, 2008) and an increase in arid-tolerant taxa such as Artemisia and Chenopodiaceae, at the expense of Mediterranean forest taxa. Some oak forest recovery can be detected during

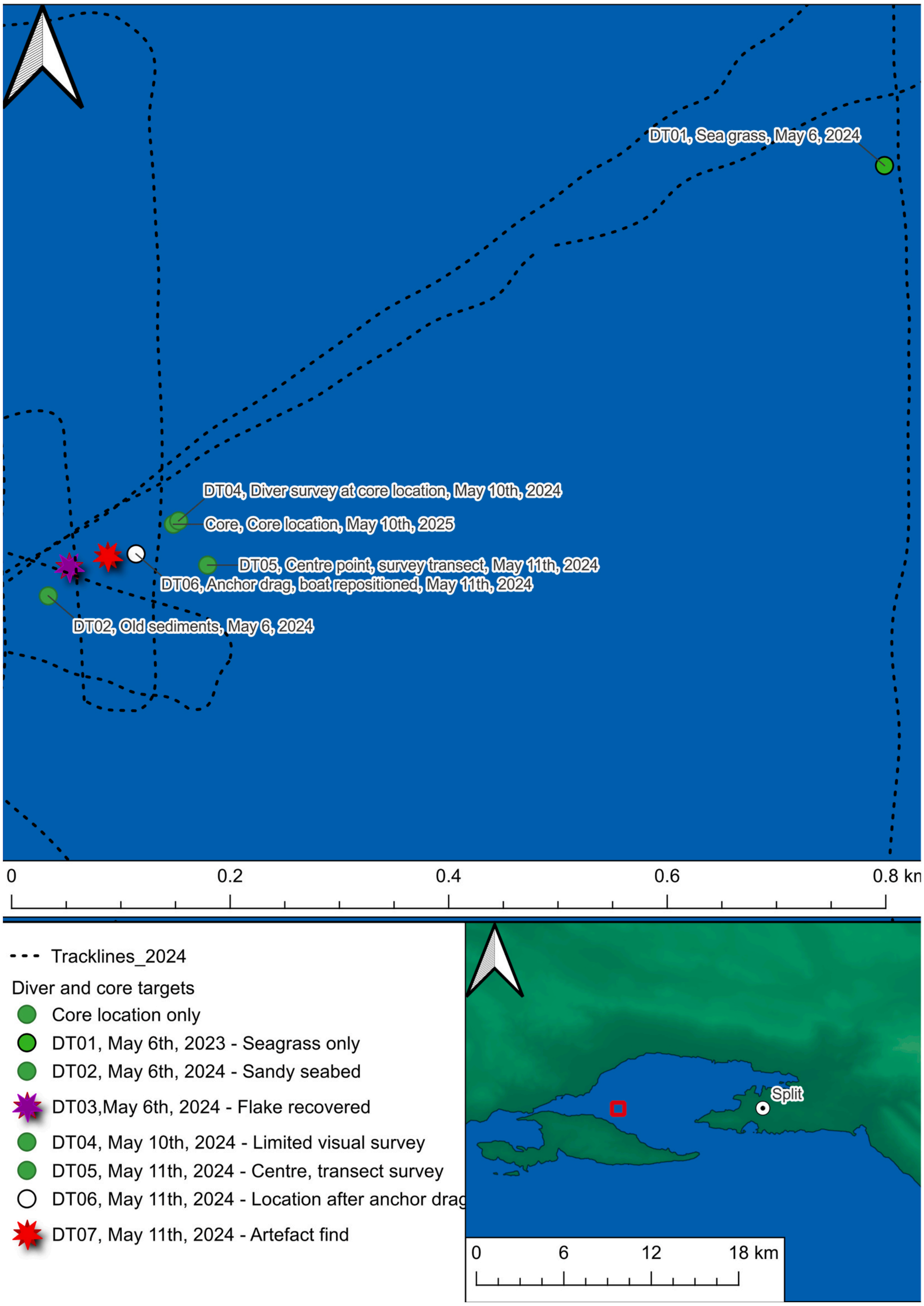

Fig. 9. Coring and dive targets, offshore Trogir.

intervening stadial periods, however, suggesting that rainfall and temperatures increased during these times, at least temporarily (Fletcher and Sánchez Goñi, 2008). Even during cold episodes, however, thermal springs would have created micro-refugia capable of supporting some deciduous tree cover such as Corylus, Fagus, Quercus, Tillia, and Ulmus (Peresani et al., 2021: 132-134). Such springs often correlated to travertine deposits (Brogi et al., 2020; Dramis et al., 1999; Pentecost, 1995; Pentecost and Viles, 2007).

As climate deteriorated during the LGM, the area of Kaštela Bay experienced increasing aridity whilst coastlines retreated, and glaciers and ice caps expanded in the Alps and Dinarides. Dune fields are documented on the island of Vis and regional pollen records indicate an increase in xerophytic shrub and herb taxa such as Artemisia and Chenopodiaceae (Wacha et al., 2019). The lowest lying areas of the Bay were likely part of the inferred semi-desert and desert biomes interpreted from pollen records across the region, whilst the modern coastal zone likely comprised a piedmont zone capable of supporting some *Betula* and *Pinus*. Higher altitudes would have been icefield, rocky

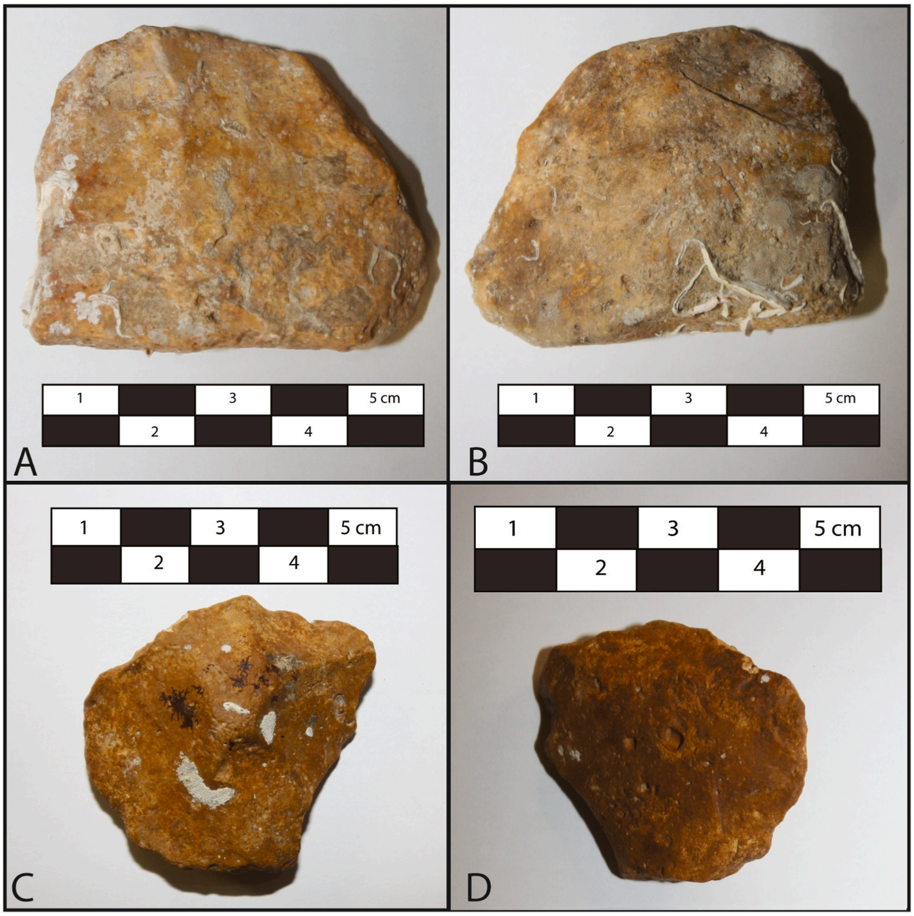

Fig. 10. Human modified lithic recovered from Kaštela Bay. Panel A and Panel B show the lithic recovered from DT02 on May 6th, 2024 while Panels c and D show the lithic recovered on May 11th, 2024.

steppe, and where water sources were present, cold herb communities (Peresani et al. 2021:132–134). As during MIS3, thermal springs, if present, would have acted as micro-refugia with some deciduous tree cover (Peresani et al. 2021:132–134). It is worth noting that the arboreal taxa found at such locations include mast bearing taxa. Along remaining watercourses, such as those that may have lain between the mainland, Brač, and Hvar, increased water supplies could have supported intermittent tree cover such as Alnus, Betula, and Pinus, whilst wetlands associated with fluvial margins could support Alnus, Betula, and Populus swamp (Peresani et al. 2021:132–134).

An overview of the known Palaeolithic sites in relation to hypothetical ecozones suggests several implications for future archaeological prospection, though it is critical to note that this distribution pattern reflects the state of archaeological research and could change if more sites are identified (Fig. 12). However, given this caveat, assuming 12 m of sedimentation since this landscape was submerged, each of these sites was likely located within reach of multiple ecosystems.

Additionally, the findspots for the Mousterian materials recovered during this project are associated with a travertine deposit that may have been a thermal spring. Even if this feature did not include hot springs, it almost certainly provided access to water resources, which in turn would have allowed arboreal taxa to persist here. Such taxa would have provided access to potential mast crops, an attractor for hominin populations as well as other fauna. Moreover, three of the four known sites had viewsheds of the embayment area, and the fourth, Kopačina, overlooked the palaeo Brač channel within which Pleistocene palaeochannels have been documented, suggesting orientation to water resources, including when these water bodies retained some connection to the palaeo-Adriatic.

Finally, as aridity deepened, marine regression progressed, and water resources became scarcer on the landscape, it seems likely that spring features and any other remaining sources for freshwater would have become increasingly critical for the hominin populations in this region. Site patterns appear to correlate well with this, as all identified sites lie within 5 km of a spring site documented either along the modern coastline or within the Bay itself. Given the presence of known submerged springs in Kaštela Bay, future prospections for submerged archaeological deposits would be well served to identify and closely examine submerged spring features along with any potential travertine deposits.

The seismic survey results have yielded a landscape map for Kaštela Bay that allows for several observations. First, the MIS3 and 2 landscape of the bay, when subaerial, comprised a diverse landscape with significant geographic variation across the bay. Mapping alongside seismic profile analyses also indicate substantial differences in preservation potential across the bay. The information provided by the seismic data in the areas likely to have better preservation will be critical when developing future testing to recover environmental data sufficient to advance our understanding of both palaeoecological changes during the Quaternary and RSL curves for this portion of the Adriatic.

These data also underscore the need to account for the effects of local tectonics, bedrock composition, and geohydrological conditions when developing palaeolandscape reconstructions. Preliminary reconstruction of the late Palaeolithic landscape around Kaštela Bay suggest that known Palaeolithic sites as well as the newly detected findspot for Mousterian materials offshore Trogir were chosen based on their proximity to multiple ecological zones ranging from higher altitude zones all the way to the coastline, with a potential orientation towards that

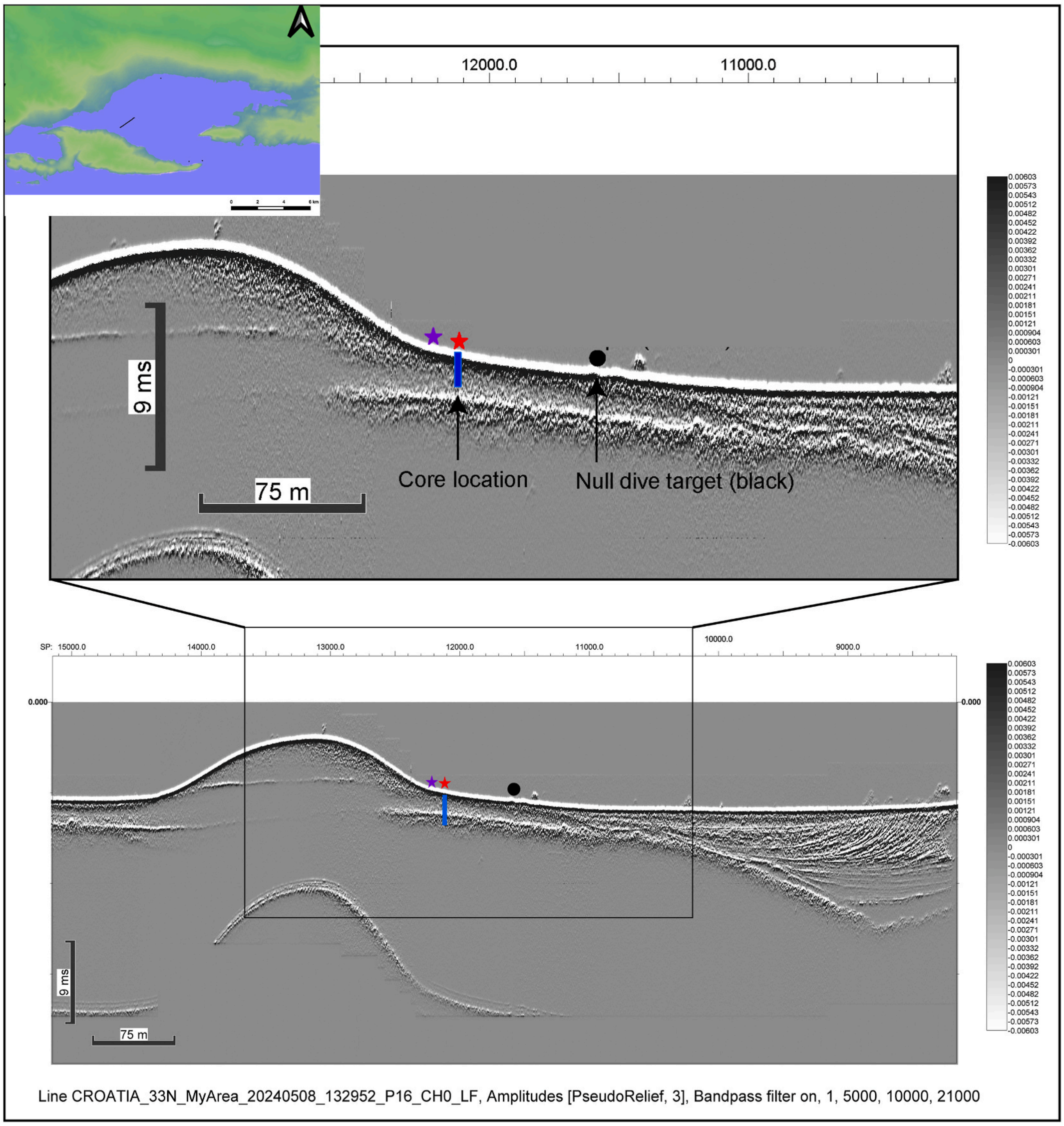

Fig. 11. Profile view of Line (20240508_132952_p16_CH0_LF showing seismic stratigraphy (not annotated here) associated with multiple cycles of marine transgression and regression as well as the locations of hand cores, null dive targets, and artefact find spots. Profile overview below, inset detail above. The red star designates the first lithic find spot, and the purple star designates the second lithic find spot. Only one null dive target is shown to demonstrate the difference between bathymetry at positive versus negative dive targets.

coastline zone. This tightly telescoped mosaic of different ecological zones across the region of Kaštela Bay would have provided access to multiple and diverse resources despite periods of increased aridity and cold.

Questions of the degree of artefact transport must be addressed when assessing their bathymetric and stratigraphic contexts. The Mousterian materials show signs of edge-rounding likely consistent with some degree of transport. However, past empirical studies of artefact transport at other submerged landscapes indicate that whilst edge rounding can occur, actual movement is minimal in terms of physical distance. This has been confirmed in both on-site analyses of submerged anthropogenic deposits as well as with multiple flume studies (Benjamin et al., 2022; Cook Hale et al., 2022; Marks, 2006). More confidence can be gained from the fact the second artefact was recovered from within the stratigraphic unit below the seabed sediments and thus were not within the modern mobile seabed sediments. Thus, it seems reasonable to infer that these items were recovered from locations that are not substantially distant from where they were originally deposited.

Following this, we can observe that these newly detected Mousterian materials were recovered from a bathymetric feature created by travertine deposits likely associated with spring features that may have been thermal features. The specific feature detected here most likely formed along a fault that has been previously tracked running from east to west along Split peninsula across the Bay to the island of Čiovo (Fritz and Bahun, 1997). The presence and location of such freshwater resources are significant when considering areas for archaeological prospection and modelling. Such now-submerged springs which would have represented reliable water sources in the past to human groups in addition to supporting more floral and faunal taxa than the surrounding areas.

More broadly, results of palaeolandscape reconstruction from ground-truthing interpreted seismic stratigraphy provides a strong framework with which to examine the effects of sea level change. The seismically derived land surface shows the landscape at the end of MIS3 and the slide into the LGM to be considerably different from the bathymetry. This is a critical issue, as palaeolandscape reconstructions based on post-transgression sedimentary infill will fail to capture the true depth of the formerly subaerial surfaces, leading to reconstructions that may, for example, position the coastline considerably seaward of its true location and in turn fail to grasp the correct extent of the coastal

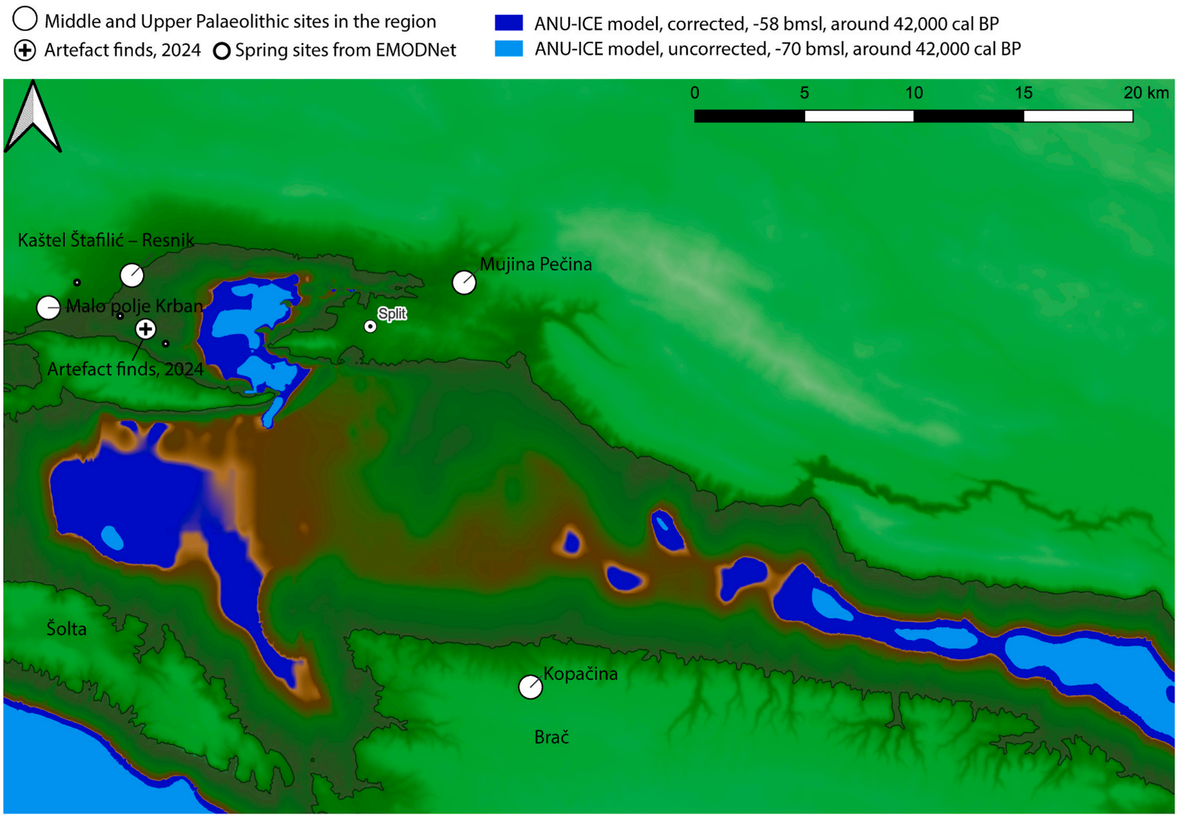

Fig. 12. Landscape reconstructions for the end of the Mousterian showing the brief marine transgression at around 42,000 cal BP as well as the locations of known sites around Kaštela Bay and coastal and submarine springs.

plain zone.

Additional benefit can be found through the combination of the mapped contemporary land surface and sea level data. Currently most visualisations of sea level data for submerged landscapes are often still performed on pseudo-landscapes when visualising sea level curve data. As seen in this research, whilst using bathymetry may produce results which are indicative on a broad scale global, they are problematic when used at a regional or local level due to bathymetry ignoring the effects of erosion and deposition between the time under investigation and the present. Synthesis of seismic surfaces with regional archaeological trends, including archaeological materials recovered during this study, point towards rather different potentials for detecting more such Mousterian sites in this region.

4.3. *Diver survey analysis*

Diver survey was useful for achieving several objectives: it allowed for visual identification of seabed conditions, supported coring efforts, and allowed for shallow, minimally invasive assessments of the stratigraphy at and just below (<1 m) below the seabed. Finally, it led to the recovery of two anthropogenically modified lithic items consistent with Mousterian technology offshore Trogir, as well.

Diver survey has limitations that must be considered for future work. First, it is depth limited. Divers can only safely dive to 30–40 m using regular air mixes, though other gas mixtures can increase depth and temporal ranges. However, use of these gas mixtures requires additional specialised training as well as access to the means to obtain them, which cannot be guaranteed in all locations. Second, it is limited by visibility conditions. Whilst divers can carry out close range manual tasks such as hand coring or hand fan excavation with minimal visibility, it is difficult to document these results using photography or videography. Third, it is limited by depth of sub-seabed excavation, which is in turn controlled by sediment conditions and available technology. Dredging can only remove a certain amount of sediment before wall collapse becomes a danger; the depth at which this becomes a risk is controlled by the nature of the sediment and its corresponding angle of repose.

4.4. *Implications for submerged palaeolandscapes study and early Homo sapiens in Europe*

Synthesis of seismic results with the RSL predictions for the area of Kaštela Bay indicate that this palaeolandscape was subaerial from approximately 48,000 years ago until approximately 13,000 years ago. This represents a time slice when multiple events of significance to human evolution and occupation in western Eurasia occurred. These include the entry of modern *Homo sapiens sapiens* into western Eurasia, admixture with extant Neanderthal populations, multiple incidents of population turnover, withdrawal to climate refugia during the LGM, subsequent re-expansion after the termination of the LGM, and admixture with new populations entering Europe from the Near East (Fu et al., 2016; Rathmann et al., 2024). The area of Kaštela Bay moreover is part of a region that comprised a critical spatial context for many of these developments (Fu et al., 2016; Rathmann et al., 2024). It is well-understood that submerged portions of the continental shelf contain evidence for such key developments in human evolution and expansion across the globe (Bailey and Flemming, 2008).

As such, the development of a more refined palaeolandscape reconstruction for this portion of southern Europe represents a significant step forward towards recovery of archaeological materials left behind by ancient human populations, some of which may represent cultural adaptations heretofore undocumented and invisible (Ford and Halligan, 2010). Moreover, this portion of the coastline likely constituted a refugium within a refugium (Klein et al., 2021) situated as it was within reach of the coastline, multiple freshwater sources, and a dynamic but somewhat more forgiving ecology than the harsher, colder, drier interior (Bazzicalupo et al., 2022; Peresani et al., 2021).

4.5. Next steps

Future surveys can build on these results by seeking data to answer multiple questions. The most obvious next step is to intensively examine the findspot for Mousterian materials offshore Trogir to determine the extent of the site, degree of preservation, and human activities that can be inferred from archaeological materials. The bathymetric high upon which these materials were recovered should also be geologically sampled to determine if this is, in fact, a travertine deposit, as well as whether it was deposited by thermal springs or not. Additional similar bathymetric highs within the Bay should be targeted for intensive geophysical and diver surveys (if possible) to assess them for additional archaeological materials. Finally, coring campaigns focused on recovery of deep terminal Pleistocene and early to middle Holocene sediments can offer multiple lines of proxy evidence to refine palaeoenvironmental reconstructions during the Middle and Upper Palaeolithic. In so doing, these studies can offer previously inaccessible data on the relationships between hominin populations and the coastal zone of the central Adriatic.

5. Conclusions

Seismic surveys and targeted diver surveys have allowed for the development of a more accurate palaeolandscape reconstruction for the landscape of Kaštela Bay during MIS3. This landscape was considerably different in topography from the modern seabed bathymetry due to millennia of post-submergence sediment deposition. Accordingly, had palaeolandscape reconstruction relied only on RSL curves and modern bathymetry, it would have underestimated the possible extent of flooding between the islands and within the Bay itself. This in turn would have led to inaccurate estimations of potential ecological zones for these chronozones and thus would have been entirely ineffective for developing target areas for diver surveys.

The validity of this approach is supported by targeted diver surveys. These have resulted in recovery of anthropogenically modified flint tools likely of Mousterian association. Whilst these findings are preliminary and require additional data collection to support the palaeoecological reconstructions proposed here, they do provide validation of the stepwise methods deployed in this study. They also underscore the need for submerged landscape and archaeological site detection to carefully document methods and applications to support replicability, especially in multidisciplinary studies.

Planned follow-up research by the project will focus on high-resolution mapping of the locations where artefacts were recovered in 2024, as well as testing of new targets that are deemed high probability due to their hypothetical ecological conditions based on this revised palaeolandscape reconstruction that takes sedimentation alongside local and regional sea level history into account. Additionally, the area where artefacts have been recovered should be sampled for palaeoenvironmental proxies such as pollen, organic materials suitable for radiometric dating, and geological samples suitable for testing to determine if the putative travertine deposit at this locale was a thermal spring or not. Finally, additional possible travertine deposits will be identified and tested to determine if these specific landforms were attractors for the hominin populations that clearly made use of Kaštela Bay's emergent coastal plain during MIS3.

Author contributions

Simon Fitch – Project PI. Lead on the Geophysical Survey. Undertook geophysical processing and analysis of the Geophysical survey data used in the project. Wrote text on survey, geophysics and co-wrote text on landscapes and project. Lead editor of text, Slavica Bosnjak – Assisted in acquisition of survey data and lead on the text on archaeological background/Croatia archaeological perspective and find description. Assisted with the paleoenvironmental reconstructions. Jessica Cook Hale – Lead on the dive survey and wrote dive results and produced paleoenvironmental reconstructions. Worked on the geophysical analysis. Led the writing on landscape. Co-edited the text and lead on the production of figures. Vedran Barbarić – Assisted with the archaeological and geophysical surveys and worked with Bosnjak to produce the background to Croatia and its archaeology. Timothy A. Shaw – Undertook the sea level modelling and produced sea level curves. Co-wrote the text on relative sea-level. Provided comments to the text. Tanghua Li - Undertook the sea level modelling and produced sea level curves. Co-wrote the text on relative sea-level. Provided comments to the text.

Declaration of competing interest

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

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Data availability

A link to the data and/or code is provided as part of this submission.

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