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KARST LANDFORMS AND PREHISTORIC SETTLEMENT PATTERNS: A CASE STUDY FROM KORČULA ISLAND (CROATIA)

Abstract: Dean S., Pappalardo M., Felja I., Juračić M. & Boschian G., *Karst landforms and prehistoric settlement patterns: a case study from Korčula Island (Croatia).* (IT 0391-9838, 2020).

This study is aimed at testing if and how a detailed assessment of geomorphological features in the territory nearby can complement palaeoenvironmental evidence revealed by the archaeological stratigraphy from a cave site. In the test site, located in the western part of the Adriatic island of Korčula (central Dalmatian coast, Croatia), the stratigraphy of the prehistoric cave settlement of Vela Spila reveals a tight relationship between postglacial environmental changes and human settlement patterns. In this work the territory outside the cave was investigated from a geomorphological point of view. A 1:25000 scale geomorphological map of the western part of the island was created through remote sensing and field survey. Two cores were drilled in Blatsko Polje, a large karst depression shaping the western part of the island to verify if the sediment record trapped in the depression was a suitable candidate for future palaeoenvironmental studies. The geomorphological context was also related to archaeological evidence from surface archaeological surveys in Western Korčula. The result of these combined methods shows a karst landscape typical of the Dalmatian coast and highly influenced by the island's underlying structural and tectonic characteristics, with several landforms such as debris flows and pocket valleys indicating possible episodes of wetter, more erosive conditions both before and after the last ice age. The sediment cores from the Blatsko Polje, which is now artificially drained, show previous phases of intermittent flooding and a drier episode that led to the area being exploited more by humans in the Neolithic (8-4 ka BP). This is indicated both by the placement of archaeological sites of different phases around the Polje, and by finds of lithics, pottery, and microfauna in the cores themselves. Geomorphological analysis supports evidence of a tight relationship between environmental changes and human settlement patterns inferred from the cave stratigraphy and provides some information on the features of the landscape exploited by the cave dwellers. Finally, the polje infill proved to be a potential palaeoenvironmental archive (albeit an unusual one), that would warrant future investigation with higher resolution core sampling.

Key words: Geomorphological map, Polje, Human settlement, Environmental change, Dalmatian coast.

Riassunto: Dean S., Pappalardo M., Felja I., Juračić M. & Boschian G., *Morfologie carsiche e schemi insediativi preistorici: un caso di studio nell'Isola di Curzola (Croazia).* (IT 0391-9838, 2020).

Questo studio si propone di verificare quanto efficacemente le informazioni paleoambientali dedotte dall'analisi di una stratigrafia archeologica in grotta possano essere integrate dalla caratterizzazione geomorfologica di un opportuno areale contiguo al sito di indagine puntuale. Nell'area di studio, ubicata nel settore occidentale dell'Isola di Curzola, lungo la costa della Dalmazia centrale (Croazia), la stratigrafia del deposito archeologico della grotta di Vela Spila mostra una stretta relazione tra le modificazioni ambientali postglaciali e gli schemi insediativi. La geomorfologia dell'area è stata indagata attraverso la realizzazione, basata sul telerilevamento combinato con indagini di terreno, di una carta geomorfologica alla scala 1:25 000 che comprende la porzione occidentale dell'Isola di Curzola. Due carotaggi sono stati realizzati nei sedimenti del Blatsko Polje, un'ampia depressione carsica che occupa un'ampia porzione dell'area di studio, allo scopo di verificare l'adeguatezza, per future indagini a carattere paleoambientale, dei depositi accumulati all'interno della depressione. Il contesto geomorfologico è anche stato messo in relazione con indagini archeologiche di superficie. Il risultato di questa indagine combinata evidenzia un paesaggio tipico del carsismo dalmata influenzato dai caratteri tettonici e strutturali dell'Isola, nel quale sono presenti alcune forme, come *debris flow* e valli a tasca, che testimoniano possibili episodi di clima umido e intensa attività erosiva sia antecedenti che successivi all'ultima glaciazione. La stratigrafia dei depositi contenuti nella depressione del Blatsko Polje, che oggi è drenato artificialmente, suggerisce che durante il Neolitico (8000-4000 anni fa) il fondo del polje era prevalentemente asciutto e sfruttato per le attività umane. Questa ricostruzione è basata su analisi spaziali delle tracce di insediamenti umani attorno al polje e dal contenuto dei sedimenti in termini di industrie litiche, frammenti ceramici e microfaune. L'analisi geomorfologica conferma il legame tra modificazioni ambientali e dinamiche insediative umane già emerso dall'indagine stratigrafica in grotta,

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e contribuisce a tratteggiare i lineamenti del paesaggio all'esterno della grotta stessa. Infine, i sedimenti del polje, sebbene eterogenei per facies sedimentaria, hanno dimostrato di avere delle discrete potenzialità come archivio paleoambientale, e meriterebbero di essere oggetto, in futuro, di indagini stratigrafiche a maggior risoluzione.

Termini chiave: Carta geomorfologica, Polje, Insediamento umano, Modificazioni ambientali, Costa Dalmata.

INTRODUCTION

Adaptation to karst landscape is typical of ancient cultures of the Mediterranean (Lewin & Woodward, 2009). This is particularly relevant in the Dinaric karst, where a peculiar cultural landscape related to the dominance of karst landforms has developed over time (Gams & Gabrovec, 1999; Aničić & Perica, 2003). The karst landscape differs by areas depending on bedrock lithology, morphology and structure, and depending on local climate (Ford & Williams, 2007). Being near the so called "Classical Karst" (Cvijić, 1960), the landscape of Dalmatia includes the typical landforms of the mid-latitude temperate karst, but with some features that depend on non-climatic factors. As suggested by Ford (2006), the tectonics, the bedrock structure, and sea-level fluctuations that have affected the area since the Miocene desiccation phase (Vlahović & *alii*, 2002; Korbar, 2009) are responsible for huge poljes with shore-parallel axes that are the dominant local morphological feature.

The aim of this paper is to document the main geomorphological features in western Korčula (fig. 1), and investigate how prehistoric settlement patterns adapted to those landforms and to postglacial Holocene environmental changes in the karst landscape. The study area is relevant to address this topic because:

1 - It is a key area in the study of westward migration of human cultures since the Upper Palaeolithic (Butzer, 2005), and the western part of the island of Korčula (fig. 2) is particularly suitable because of its rich heritage of long-term settlement from the Upper Palaeolithic to the Iron Age (Radić, 2018).

2 - The so called Dalmatian-type coasts are a unique form of karst coastal landscape, with typical landforms such as zigzag coastlines resulting from submerged shore-parallel folds (Fairbridge, 1968), karst estuaries, and coastal karst dolines (Kelletat, 2019; Pikelj & Juračić, 2013; Felja & *alii*, 2015; Brunović & *alii*, 2019).

3 - In this area, most landscape changes were driven by sea-level rise between c. 20-12 ka BP, due to the shallow, flat intra-island bathymetry and steep island shores (Dean & *alii*, 2020).

This paper cross-checks evidence from detailed geomorphological mapping and basic stratigraphic description of sediments from cores drilled in a large karst polje (Blatsko Polje) with available archaeological evidence from surface surveys, to provide clues about the relationship between human settlement patterns and proximal environmental changes in the central-western part of Korčula Island (fig. 2b). Moreover, the Blatsko Polje infill was investigated in order to reveal if it has a potential archive of palaeoenvironmental information that could in the future complement the archaeological data from the Vela Spila cave sedimentary record. In fact, there was no previous evidence on the presence in Blatsko Polje of a typical lacustrine/lagoonal palaeoenvironmental archives similar to those investigated elsewhere in the region (Sadori & *alii*, 2015; Mazzini & *alii*, 2016; Hajek-Tadesse & *alii*, 2018; Ilijanić & *alii*, 2018). The results of this work suggest that a detailed assessment of geomorphological features in the territory nearby can complement palaeoenvironmental evidence revealed by the archaeological record from a cave site, helping to investigate the relationship between cave dwellers and the landscape outside.

BACKGROUND

The area of the Adriatic Sea, along with sub-alpine Italy and the Tyrrhenian Sea extending to Calabria and Sicily, is thought to be a promontory of the African Plate, or a small microplate called Adria, which separated from Africa in the Cretaceous (Sani & *alii*, 2016). The bedrock in the eastern Adriatic Carbonate Platform is comprised of up to 8 km of limestone and/or dolomite formed in shallow sedimentation environments before and during Adria's separation from Africa (Vlahović & *alii*, 2002). The tectonic deformation pattern of the Eastern Adriatic is characterised by a complex system of faults, thrust faults and overthrusted tiles (fig. 1B and) formed since the Miocene and developed along the so-called "Dinaric Strike" with NW-SE orientation (Vlahović & *alii*, 2002, 2005; Korbar, 2009). The typical relief pattern of mountain ridges and valleys parallel to the coastline derives from this tectonic compressional motif, followed by extensional processes and eventually repeated, partial flooding during the Quaternary sea-level fluctuations. The westernmost edges of the Dinarides now form the Croatian Islands, but in Central Dalmatia these islands are rotated ~45° counter clockwise with reference to the Dinaric Strike. (Picha, 2002)

The Eastern Adriatic is dominated by karst landforms (Pikelj & Juračić, 2013; Zupan Hanja, 2019). The karst in the study area is referred to as the Dinaric Karst, which is developed on the up to 8 km thick carbonate platform formed by Mesozoic and Palaeogene limestone and dolostone (Kranjc, 2004; Vlahović & *alii*, 2005; Zupan Hajna, 2019), with some bauxite present in areas. Flysch (marl and sandstone in alternation) deposited in the Eocene is also preserved in some synclines, which occasionally leads to areas of fluvial relief with streams, developed soil and vegetation. Typical morphological features in this area are different types of karst valleys (Goudie, 2003; Bočić & *alii*, 2015; Bočić, 2016) and depressions, such as dolines, poljes and uvalas (Milanović, 2004; Ćalić, 2011; Bonacci, 2013) as well as karst peaks (hums), while few surface watercourses are present. There are several larger rivers in Central and Southern Dalmatia such as the Neretva, Cetina, and Krka (Zupan Hajna, 2019), but they all differ in geomorphology and sediment supply (Felja & Juračić, 2018). Karst landscape formation has taken place on the megayear scale, which is shown by karst features such as caves with speleothems and springs found as deep as 70 m underwater (Gunn, 2004; Surić & *alii*, 2005).

FIG. 1 - Study area A: The Adriatic Sea and eastern Adriatic Coast. B: Korčula and surrounding islands with tectonic information adapted from Korbar (2009). Red square indicates area mapped for current study.

Korčula (fig. 1B) is an elongated island ~50 km east to west, and 6-7 km wide in most places. Most of the island is hilly, peaking at 569 m asl on the highest point in the central part of the island. Its coastline is highly indented with small bays locally called uvala (a word distinct from the geomorphological term). The western side of Korčula overlooks the largest indentation of the coastline, Vela Luka Bay, a triangular west-facing inlet which is 6 km wide north to south at its mouth, and about 7 km long east to west. At the end of the bay is the winding, shallow channel that protects Vela Luka harbour. In the east, Korčula is separated from the mainland by the Pelješac Channel, which is a narrow channel about 40-45 m deep, and 2 km across. The channel between Korčula and Hvar – the island to the north (Korčula Channel), is approximately 15-20 km wide and at most 70 m deep and represents the prolongation of the palaeo Neretva river valley towards the Adriatic basin (Sikora & *alii*, 2014). The island of Lastovo is approximately 15 km to the south of the central part of the island, and Vis is approximately 35 km to the WNW (fig. 1B).

Vlahović & *alii* (2005) describe a number of carbonate geological formations typical of sedimentation on a carbonate platform, and both the geological map (Korolija & *alii*, 1975) and the hydrological surveys carried out on the island (Bačani & *alii*, 2006; Bonacci & *alii*, 2012) confirm an anticlinal structure with an axis running from east to west. The principal fault system is perpendicular to this main structure.

The island's coasts are generally steep and rocky, except for a few bay-head pebble beaches. The distinct surface drainage network is largely absent on the island, but several springs and ponors were identified by a hydrological survey (Bačani & *alii*, 2006) inland and along the coast. Western Korčula is dominated by the presence of several large, closed depressions, the largest of which is Blatsko Polje. The ter-

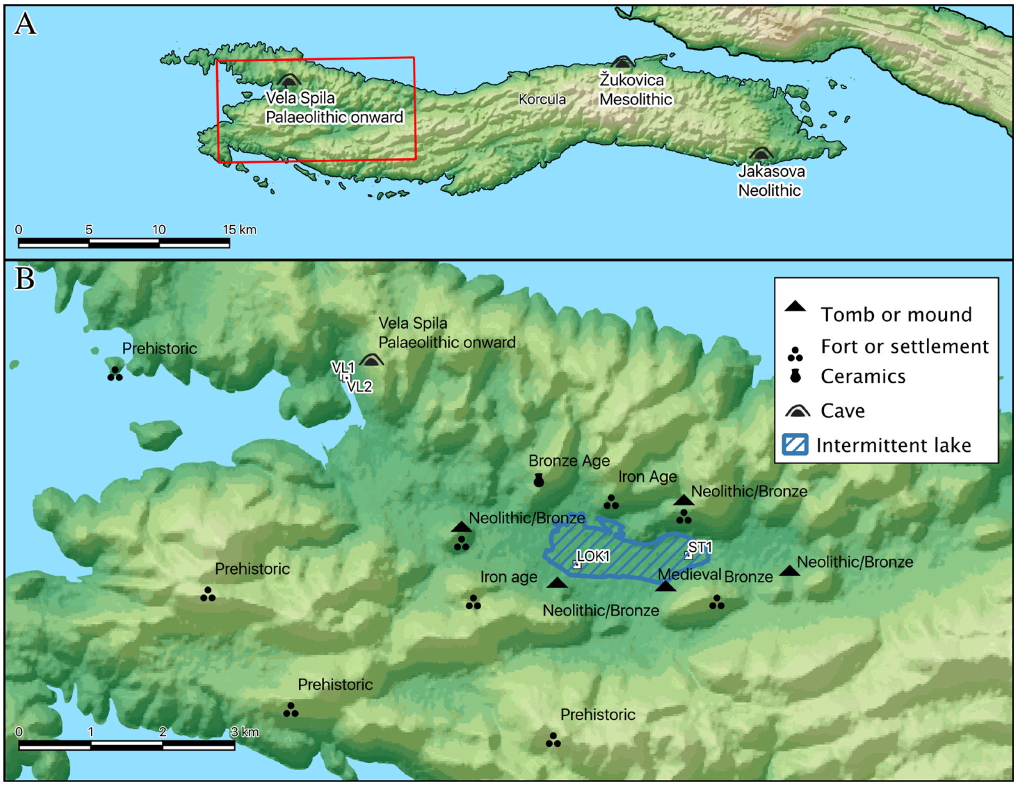

Fig. 2 - Archaeology on Korčula. A: The site of three excavated prehistoric sites on Korčula. B: A number of sites around Blatsko Polje (the low-relief area in the middle of western Korčula) from Radić (1999). Cores drilled in September 2017, including ST1 and LOK1 mentioned in this study, are marked in white. The blue polygon indicates the extent of a seasonal lake mapped in Blatsko Polje during the 19th century military survey of the island (Timár & *alii*, 2006).

minology (Goudie, 2003) separating different types of karst depressions is not universally agreed upon, see for example Gams (1978), Gunn (2004), Ćalić (2011), Ford & Williams (2013), Sauro, 2019 for a variety of definitions. Poljes are usually considered flat- bottomed, polygenetic landforms formed in karst regions with developed karst hydrology. They are preferentially produced by limestone dissolution limited to a groundwater base level along tectonic structures and filled with residual products of limestone chemical weathering mobilized by runoff down the surrounding slopes.

Blatsko Polje is a typical karst polje which was occasionally flooded until 1911. The intermittent lake was drained by the construction of canals and tunnels for moving water into the sea on the north. The western side of the island, including Blatsko Polje and much of the Vela Luka bay (fig. 2B), is the focus of our study, which is represented in the geomorphological map (Appendix A). The area was selected because of the outstanding prehistoric heritage that is preserved here in close association with geological archives suitable to provide clues about proximal environmental changes. The archaeological record includes Vela Spila Cave (fig. 2B), which has the potential to record changes at a higher resolution than other proxies such as global climate records or GIA models. Ongoing excavations are summarized in several works (Dean & *alii*, 2020 Farbstein & *alii*, 2012, Radić, 2018), and indicate Palaeolithic inhabitation from as early as c. 19.7 ka BP above a layer of scree presumably from the Last glacial maximum (LGM), though subsequent excavation may reveal older inhabited strata. Tephra identified as the Neapolitan Yellow Tuff (Radić & *alii*, 2007) coincides, without any clear causal relationship, with the end of the Palaeolithic phase. After c. 14.5-14.1 ka BP, the cave remained abandoned until c. 9.5 ka BP, when Mesolithic groups reoccupied the cave. Between 8.4-8.0 ka BP, the Neolithic settlement becomes evident in the record, and the cave remained settled until modern times.

In addition to Vela Spila, two other archaeologically excavated caves exist on Korčula (fig. 2A). On the southeast end of the island, Jakasova Cave was inhabited in the Neolithic; and Žukovica Cave close to the north coast on the eastern part of the island was inhabited in the Mesolithic (Radić, 2018). The island is also covered with approximately 20 hill forts (Radić, 2018) built around the beginning of the Bronze age (c. 4 to 5 ka BP) in response to social changes. Many gomile, or burial mounds, from the late Neolithic and early bronze age are present as well. Three groups seem to have inhabited the island after the end of the Neolithic, in the eastern, central, and western parts of the island. Overlooking Blatsko Polje, an Iron Age fortified settlement and necropolis (7th to 1st c BC) called Kopila has been excavated, yielding extensive artefacts and burials. (Radić, 1999, 2018)

METHODS

Geomorphological assessment

A 1:25000 scale geomorphological map of the area (Appendix A) was made using 0.5 m resolution orthophotos and topographic maps provided through WMS/WMTS by the Croatian State Geodetic Administration Geoportal (geoportal.dgu.hr) accessed through QGIS. This configuration was used to identify landforms in conjunction with pre-existing studies of the island. A variety of additional source layers were also consulted to address current and past environmental conditions, including the national 1:5000 basemap from the same geoportal, official geological maps (Korolija & *alii*, 1975) and an historical 19th century survey maps by the Austro-Hungarian empire (Timár & *alii*, 2006).

The map was created by digitizing landforms in QGIS. This enabled us to obtain quantitative data on features that are reported in the tables shown in the results section.

In addition, a field campaign of survey and observation was carried out in the western part of the island to look for relevant features and assess conditions on the surface and below sea level. The survey included ~68 km of coastline and interior, and ~7 km of underwater studies. On Korčula, the snorkel surveys included part of Vela Luka bay, 4 small uvala bays on Korčula/Proizd, and a snorkel circumnavigation of Ošjak Island in Vela Luka bay. Four scuba dives were performed in two other uvalas on Korčula. Swims and dives in uvalas on Vis and Lastovo islands also took place for comparison with Korčula.

The geomorphological map includes lithologies from an official geological map by Korolija & *alii* (1975) and symbols adopted for map features adhere closely to the ISPRA guidelines published by the Geological Service of Italy for geomorphological maps (Campobasso & *alii*, 2018).

As mentioned above, authors on karst geomorphology have not always adhered to a consistent nomenclature, and the long standing terminological debates have not been resolved so far; for a variety of definitions, e.g. see Gams (1978), Gunn (2004), Ćalić (2011) and Ford & Williams (2007). For this study we employ definitions adapted from Sauro (2019) and Ford & Williams (2007) where doline refers to depressions that appear to be solely formed by limestone dissolution (solution doline), i.e. simple, round depressions. Uvala is complex polygenetic depression formed by different processes along with geological structures. Polje is the largest karst depression with a flat floor and developed karst hydrology. Most of the poljes were formed within geological structures, where their bottoms were levelled by corrosion at the water table and enlarged by lateral corrosion.

Coring and laboratory methods

In order to retrieve a broad stratigraphic description of the Polje infill two cores (ST1 and LOK1) were drilled in Blatsko Polje in September 2017. Locations were chosen (fig. 2B) under the guidance of archaeologists Dinko Radić, Preston Miracle and Stašo Forenbaher, in places where in the past archaeological materials had been collected at the surface. An Atlas Copco Cobra breaker with a set of metre-long steel open-tube augers of 6 cm and 5 cm diameter with extender rods capable of penetrating as deep as 15 m were used to retrieve sediment, which was then described and sampled on site.

Core locations were recorded with conventional GPS, and elevations estimated from the Croatian 1:5000 scale base map and the 1:25,000 topographic map (Croatian Geoportal, 2019). At least one sediment sample was taken within each sedimentary unit recognised.

Samples were sieved through a set of 7 standard ASTM sieves (4-0.063 mm mesh) with one Φ interval to obtain fractions from fine gravel to very fine sand. The fraction that passed the 0.063 mm sieve (mud) was collected in suspension, from which a subsample has been taken for analysis with a sedigraph using the standard procedure (Micromeritics, 2002) to obtain fractions from very coarse silt to clay. The material retained on sieves was dried and weighed and the data obtained by both techniques were merged to obtain the overall grain size range. Sediments were classified according to the Folk scheme (Folk, 1954). The results were entered into GRADISTAT 6.0 to calculate statistics and diagrams (Blott & Pye, 2001). The GRADISTAT spreadsheets were then used in a custom R program created for this study to generate plots and logs. Sieved samples from cores ST1 and LOK1 were also subjected to a binocular microscope analysis for micro-faunal finds. All cores were also analysed for macro-faunal remains during initial description and flotation was used to look for seeds and other macro-floral remains.

RESULTS

Map and survey

The geomorphological mapping of the study area (Appendix A) revealed various features. Fluvial features include 107 gullies (small watercourses, possibly relict in some cases, or of occasional or torrential nature), and 10 debris flows. Structural landforms included 7 hogbacks/cuestas, and three selective erosion scarps and crests, in addition to 109 saddles or passes. Tectonic features include an anticline, four reverse fault scarps, one strike-slip fault scarp, and three possible fault facets. Karst features include 48 dry valley courses and one pocket valley, as well as three dolines, three major poljes, and 21 uvalas. The location of an estavela, three intermittent springs, a ponor, and five submarine springs were taken from the hydrological survey of the island (Bačani & *alii*, 2006). 111 hums or peaks formed by karst processes were identified, including 11 that are more isolated or distinct from the surrounding topography. The grain size of the different pocket beaches cannot be ascertained with certainty from orthophotos, but those subjected to on-the-ground observation contained pebbles/cobbles, and it is likely that most of the others contain coarse sediments also. On the geomorphological map (Appendix A), the only feature where relict/active status is possibly applicable would be fluvial gullies. All of those on the map are likely intermittently active, but without additional closer surveys it is difficult to ascertain from orthophotos if any are active, so relict/active landforms are not delineated on the map. The following three tables (table 1-3) display the geomorphological landforms identified from the ground survey, orthophotos, and previous hydrological surveys. The tables are sorted into point features such as the summits of hums, linear features such as gullies, and areal features such as karst depressions. In addition to these three geometric categories, they are also sorted by geomorphic agent. Examination of these tables indicates the most dominant geomorphological agents in the area.

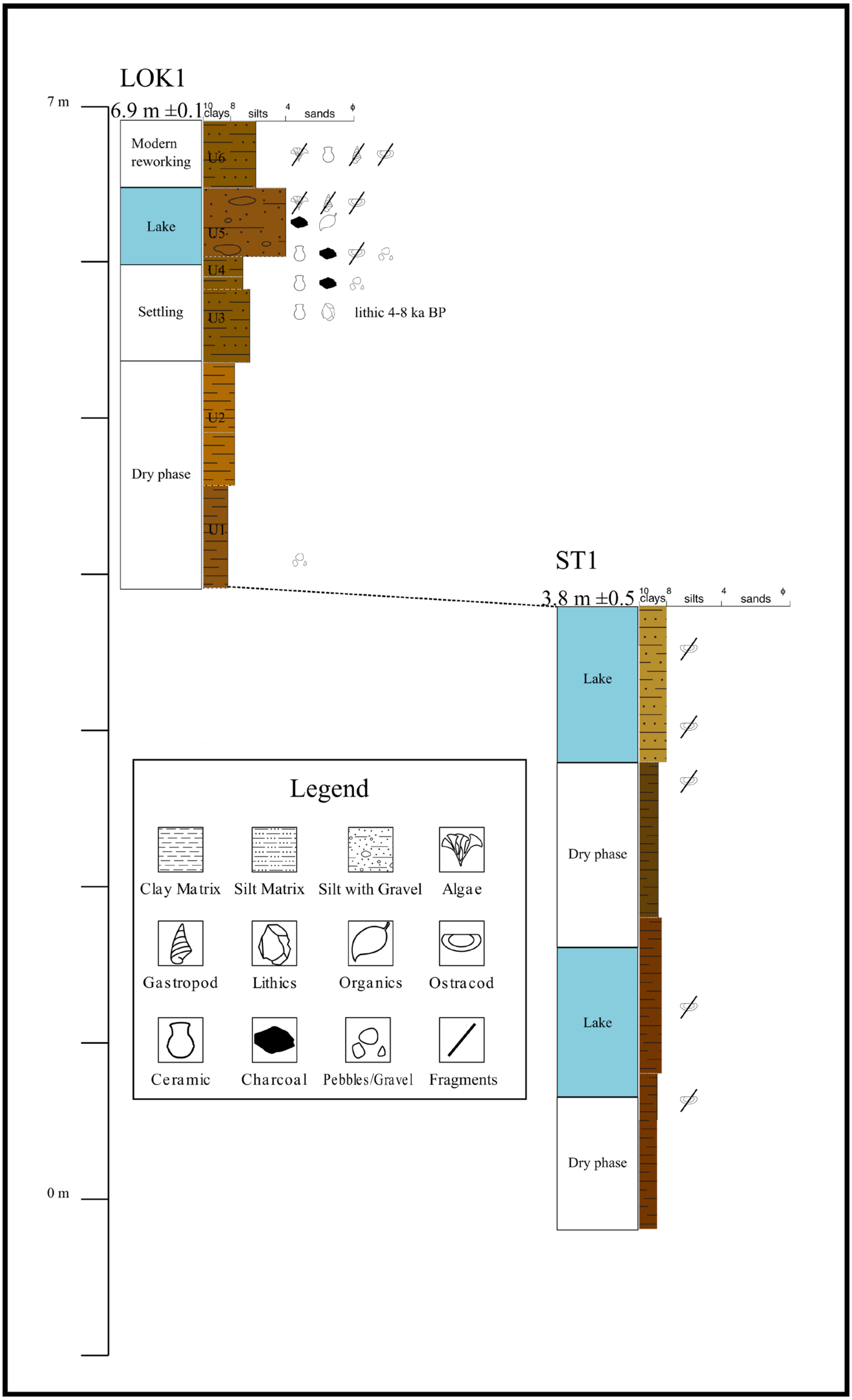

FIG. 3 - Diagrams of both cores drilled in Blatsko Polje for the current study. Core elevations are shown relative to the land survey datum HVRS71. Core ST1 was drilled in the bottom of a 2m trench, so the most recent portion of the record (modern reworking) present in LOK1 is not present in ST1. Note the Neolithic blade found in LOK1. Slashes through finds indicate fragments only.

TABLE 1 - Line features.

Agent	Feature	Count - feature	Average – length (km)	Std dev of length (km)	Average – slope (°)	Std dev – slope (°)
Fluvial	Gully	107	0.26	0.15	13	4.45
Karst	Dry valley	48	0.95	0.58	9	3.85
	Pocket valley	1	1.06	0.00	4	N/a
Structural	Cuesta	2	1.21	0.52	0	0.98
	Hogback	5	0.70	0.56	7	7.50
	Selective erosion crest	1	0.44	0.00	10	N/a
	Selective erosion scarp	2	0.29	0.21	1	16.67
Tectonic	Anticline	1	1.76	0.00	1	N/a
	Reverse fault scarp	4	1.28	0.86	3	6.31
	Strike-slip fault scarp	1	1.64	0.00	2	N/a

TABLE 2 - Area features.

Agent	Feature	Count - feature	Average area (ha)
Fluvial	Debris flow	10	8.04
Karst	Hum	11	26.64
	Doline	3	1.33
	Polje	3	98.96
	Uvala	21	9.85
Tectonic	Fault facet	3	12.48

TABLE 3 - Point features.

Agent	Feature	Count - feature
Coastal erosion	Pocket beach	24
Karst	Hum	111
	Cave entrance	1
	Estavela	1
	Intermittent spring	3
	Submarine spring	5
	Ponor	1
Structural	Saddle	109

A significant portion of the island was covered by viticulture terraces in the late 19th century when activity increased in the Balkans to compensate for the phylloxera blight in France (D. Radić, personal communication 2018). Many of these were subsequently abandoned when the blight reached the Balkans as well. Though the growth of trees makes it difficult to perfectly assess from aerial photos, terrace coverage may exceed 50% of the hillslopes in the study area and particularly around Blatsko Polje. As a result, many natural geomorphological process traces may be masked or erased. On the other hands, these terraces have had the likely impact of inhibiting erosion during intensive 20th century agriculture, so that the relief largely maintains its preindustrial character. These terraces are not presented on the geomorphological map in order to focus on preindustrial landforms.

Core results

The stratigraphy of the cores drilled in Blatsko Polje is described starting from the borehole that penetrated deepest into the polje infill, from bottom to top (fig. 3, and appendices B and C)

ST1 - This core (fig. 3, and Appendix B) was drilled from an elevation of 3.8 ± 0.5 m, in c. 2 m deep trench near Studénac Well (E 16.7726; N 42.9453), down to a depth of 4 m below the surface, beyond which the corer failed to penetrate. This core constitutes a diffuse transition of poorly-sorted silty clay at the bottom to clayey silts at the top. The colour changes distinctly from the bottom to the top of the core but only diffuse boundaries are present. The core retains nearly the same sedimentological properties, though the colour shifts from dark reddish-brown (5YR 3/3) at the bottom to dark brown 5YR 3/2 around 300 cm, and to dark yellowish-brown 10 YR 3/6 around 200 cm. In this section of the core, ~350-250 cm, rare fragments of ostracods were found in the sediment. 100 – 0 cm of sediment is heterogeneously compacted in crumbly aggregates. From approximately 115 to 0 cm, rare ostracod fragments were found.

LOK1 - This core (fig. 3 and Appendix C) was drilled at an elevation of 6.9 ± 0.1 m in the locality of Lokvica (E 16.7533; N 42.9444), inside a pumping station within a vineyard, down to a depth of 3 m, after which the corer became stuck in the extremely plastic sediment and drilling could not proceed. The sedimentary record includes 6 units. Unit 1 (300-245 cm) consists of very compacted and poorly sorted red (7.5YR 4/6) silty clay with occasional oxide spots and limestone cobbles. The unit, like all the others above, has a mild HCl reaction. The sediment coarsens upward diffusely to unit 2 (245-155 cm), which is also a very compacted silty clay with similar colour (7.5YR 4/5), but with a lower clay fraction. This unit coarsens upward into unit 3 (155-108 cm), again a very compact sandy silt with minor proportions of clay. Well rounded manganese and iron-based oxide spots were evident in the matrix, which is a brown colour (10YR 4/2). Many tiny pieces of pottery are present and at 125- 120 cm a broken but well-preserved flint knife was found in the auger (fig. 4). The sediment gradually fines upward to unit 4 (108-87 cm), clayey silt with small charcoal and pottery fragments, of a brownish colour (10YR 4/2). A few angular, very coarse pebbles were present. Rare fragments of ostracods were encountered in the top part of this unit. The sediment coarsens upward clearly to unit 5 (87-43 cm), a very poorly sorted sediment consisting of sand, silt and clay in equal proportions and with a brown colour (7.5YR 4/4). Coarse and very coarse angular limestone pebbles are present occasionally. The sediment is very compact and poorly sorted in prismatic aggregates with frequent roots and scattered small charcoals. Many ostracod and gastropod fragments were found in this sediment, as well as a few fragments of the freshwater green algae of the genus Chara. The bottom part of the unit contained red oxides mottles, which become less frequent upwards. Unit 5 fines upward diffusely to Unit 6 (43-0 cm), a sandy silt in prismatic aggregates with a colour of 10YR 4/3. There are no pebbles but several modern pottery fragments. Many ostracod and gastropod fragments were found in this sediment, as well as a few Chara sp fragments, since the area was a lake until the early 20th century (Radić, 1999). Unit 6 represents agricultural soils disturbed by modern anthropogenic practices, since the core was retrieved in an active vineyard.

FIG. 4 - This 4 cm long piece of a flint blade was situated ~1.25 m below the surface in core LOK1. This artifact was identified by Stašo Forenbaher of the Institute for Anthropological Research, Croatia, as a Neolithic artifact, which in Vela Spila ranges from c. 8.0-4.0 ka BP.

DISCUSSION

Types of landforms

STRUCTURAL LANDFORMS AND HUMS - The broad forms of the island are structural and reflect the typical features of the Dalmatian coastline delineated in geomorphological literature for the area (Kelletat, 2019), with several kilometres-long features such as fault scarps, anticlines, cuestas, and hogbacks creating the overall form of the landscape for karst processes to act on.

Although hums were considered as karst landforms on the geomorphological map (Appendix A) because they are created by limestone dissolution processes, their placement appears closely related to structural factors. Most hums in the study area were separated from other peaks and valleys by structural passes reported on the map. Overall, when examining the positions of hums with relation to both the karst valleys (see below) and faults noted on the geological map and hydrological survey map (Korolija & *alii*, 1975; Bačani & *alii*, 2006), it is clear that their occurrence is due to the underlying structural-tectonic features of the island.

Elevation of hum summits does not show a general pattern, as their peaks are evenly distributed between 25 and 250 m (fig. 5). This suggests that no long-term base levels imposed by sea highstands from past interglacials have determined the elevation of these features. There are several relatively isolated hums, protruding from the bottom of the polje, which seems anomalous within the context of this landscape. Isolated hums are usually, but not always, associated with tropical landscapes, evolving from cockpit karst developed to the water-table, or sometimes from uplifted corrosion planes (Monroe, 1970; Ford & Williams, 2007) rather than the temperate or the Mediterranean climate that Dalmatia experiences in the Holocene. They are most likely relic features dating back to warmer and more humid climate phased occurred during the Pliocene or even in the Miocene (Vlahović & *alii*, 2002).

KARST VALLEYS - The landscape south and particularly north of the polje is dominated by a series of valleys, which mostly terminate in either the coast, the polje itself, or another, smaller closed karst depressions. There is a particular concentration of these along the northern coast. Their orientations are shown in fig. 6. A slight preponderance of valleys seems to be oriented N to S, perpendicular to the major tectonic faults and structures of the island and parallel with minor faults posited on the geological map (Korolija & *alii*, 1975). Juračić & *alii* (2009), discussing the Kvarner area between Istria and Dalmatia, refer to these landforms which terminate at coastlines as "torrent valleys", while calling more substantial estuaries formed by actual rivers "fluvio-karstic valleys". Juračić & *alii* (2009) point out that overall morphology is comprised of karst landforms submerged by relative sea-level (RSL) that rose rapidly until c. 6 ka BP, at which time the stabilization of RSL led to the filling of the mouths of many rivers and valleys. Very few of these valleys have any indication of active stream courses in recent time, though more detailed investigation might correct this picture. Despite the apparent lack of active water flows in most of the valleys, they do often terminate in pocket pebble beaches within the bays locally called uvalas, which indicates intermittent fluvial or debris flow activity since the valleys were formed. The submerged sea-floor of these bays beyond the near-shore pebbles is usually covered by biogenic sediments (Pikelj, personal comm). Also Bačani & *alii* (2006) noted several submarine springs in these coastal uvalas, and noticeably colder, stratified water, indicative of a spring, was indeed encountered at the surface during a snorkel survey of uvalas in this study. This suggests that solution channels formed by karst processes along structural features may lie under many of the valleys courses. In the geomorphological map (Appendix A) therefore these features are categorized as dry valleys, since the primary transport of water may occur beneath

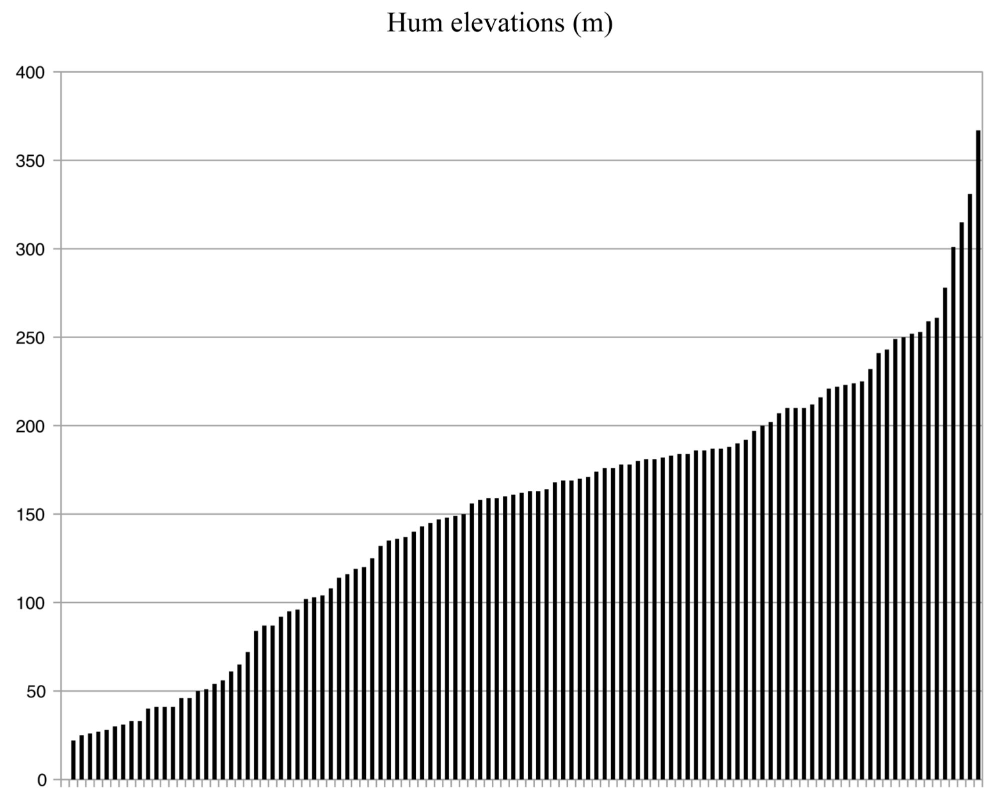

Fig. 5 - Elevations of hums mapped in the west Korčula study area. There is no evident clustering of hum elevations.

the surface, with slow debris flows or very occasional fluvial discharge at the surface perhaps intensified in periods of wetter climate responsible for the pocket pebble/cobble beaches. In the interior of the island, when these features reach the base of the polje, debris fans sometimes occur, indicating again at least intermittent or periodic activity during under different climate conditions. These debris flows may have been formed, or at least increased, during a wetter period such as deglaciation or the transition to the Holocene, when materials weathered or eroded by climate fluctuations washed downslope by increased runoff and precipitation. Phases of increased runoff e.g. during the Lateglacial are testified by the sedimentary record of the neighbouring cave Vela Spila (Dean & *alii*, 2020) and more generally by palaeoclimatic records from other Mediterranean mountain ranges (e.g. Columbu & *alii*, 2015).

In addition to dry valleys, smaller channels are visible from the orthophotos, which were classified as gullies in this study. The contour lines of the Croatian base map indicate the presence of these features, but they are much more spatially limited, with their effect on contour lines being merely tens of metres, rather than hundreds as in the case of the karst valleys. These features seldom are aligned along faults, and have non-linear courses more frequently than the dry valleys. Gullies are on average almost 4 times shorter than dry valleys (tab. 1). The high standard deviation among the latter is a result of the fact that the full course of many of the valleys on the north coast is obscured by sea-level rise.

The snorkel swim of coastal uvalas indicated typically cobble/pebble beaches in the vertices of these features within a few metres of water depth, with sides sloped by ~25° and scattered large collapsed boulders of limestone bedrock down to 3-5 m depth. In the centre of these bays below the 3-5 m isobaths, sea grass of *Posidonia* sp. is generally ubiquitous in the sandy carbonate sediments. Below the 10 m isobath, scuba dives on Korčula indicate that slope of the uvalas increased noticeably moving seaward to almost cliff-like slopes of more than 45°. Since the scuba dives indicated steep slopes with collapsed blocks at their bases at deeper isobaths, and the relief of karst features can be influenced by climate and rate of RSL change (which determines the base level for karst plains) (Ford & Williams, 2007), the morphology of the submerged parts of the uvala could indicate distinct phases of these processes: It is possible a gradual decrease in RSL, such as that experienced leading up to a glacial maximum could possibly have rejuvenated the karst and allowed for shaping of steep slopes within the uvalas.

Absence of coastal features

A striking aspect of Korčula is the widespread absence of coastal features at the macro level, aside from the pebble/cobble pocket beaches mentioned above. Most of the coastline is rocky, with limestone ramps denuded of vegetation in proximity to the sea, and with a slope determined by the dip of the bedding. At smaller scales, in areas where fetch is greater (such as the north coast of the island rather than

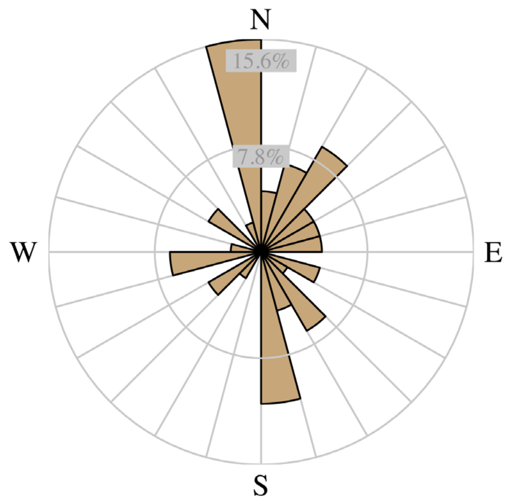

FIG. 6 - Orientations of karst dry valleys mapped in the study area. Note the slight preponderance of NS oriented valleys, perpendicular to the overall dominant structure of the island.

inside Vela Luka Bay), coastal rocks have a rougher and irregular texture due to karren- type weathering micro features generally termed "spitzkarren" (De Waele & Furlani, 2013), which are related to biokarst processes and weathering by seawater (Lundberg, 2009; Taboroši, D. & Kázmér, 2013). Remarkable is the absence of tidal notches (De Waele & Furlani, 2013) in Korčula, not even at contemporary sea level, except on an isolated section of coast near a fault, as documented by Faivre & Butorac (2018). Globally these findings correspond with the general conception of the Dalmatian coast (Kelletat, 2019) and other recent research (Juračić & *alii*, 2009; Pikelj & Juračić, 2013), wherein rapid sea-level rise submerges existing karst features, without allowing time for the formation of coastal features. Several submarine terrace-like formations, however, were observed along the coast by snorkel in Vela Luka Bay, particularly around the islet of Ošjak and they may be traces of sea-level stands or pauses during deglaciation, but a quantitative relationship to a particular palaeo RSL cannot yet be established for these phenomena owing to the unavailability of sufficiently high-resolution bathimetric data.

Palaeoenvironment in Blatsko Polje

The sediments retrieved in the cores taken in Blatsko Polje consist mostly of very poorly sorted silts and clays of the terra rossa variety typical to the island and karst Mediterranean regions, which contain mostly fine-grained hematite and kaolinite as residuals of limestone dissolution (Durn, 2003). Although they are visibly uniform, with few distinct units or horizons, minor granulometry variations reflect changes in sediment sources related to climatic and environmental fluctuations (Durn & *alii*, 2018). In core LOK1, scattered limestone clasts from bedrock were retrieved approximately 1 m below the top of the core. They were interpreted as the product of runoff along slopes surrounding the polje and thus considered proxies for phases of increased rainfall. Infills of karst depressions can form not only from the insoluble residue of limestone and dolomite dissolution (Yaalon, 1997), but also from a suite of exotic materials. In the study area, these may include tephra from the Southern Italy volcanic complex (Vogel & *alii*, 2010), Saharan dust (Varga & *alii*, 2016), loess from the Po Plain (Cremaschi, 1990) or from Balkan proglacial areas (Hughes & *alii*, 2010) as well as aeolian and clastic materials from other sources. Although the grain size of the terra rossa infill of Blatsko Polje is not inconsistent with possible aeolian sources, the necessary geochemical analyses are beyond the scope of this paper.

As regards other palaeoclimate proxies, layers containing freshwater microfauna in the form of fragmented ostracod shells are present in both cores. Ostracod species identification was not possible due to the fragmented and poor condition of the microfauna. The lacustrine nature of the top unit of LOK1 (Unit 6) corroborates local histories of a seasonal lake that was drained in the early 20th century (Radić, 1999). Details of the hydrological conditions and pumping infrastructure that keeps the area dry are discussed in Bonacci & *alii* (2012) and Bačani & *alii* (2006). Maps from the Second Military Survey of the Habsburg Empire in Dalmatia (1851-1854) (Timár & *alii*, 2006) also show the lake stretching from the eastern extremity of the polje where core ST1 was drilled, to the west as far as Puhovac and Lisac hum where LOK1 was located (fig. 2B). It is clear that the modern lake at times encompassed both drilling points, just as pictured in the Habsburg map, but this phase is not found in the sedimentary record of ST1, because it was drilled in a 2m deep trench (fig. 3). Radić (1999) states that the area was flooded in ancient times as well, since no archaeological sites are present in the polje itself, though the polje is surrounded (fig. 2B) with hill forts and gomile (grave mounds) from Prehistoric times to the Iron Age.

More numerous microfauna, including ostracod and gastropod fragments, are in the upper part of LOK1 (Unit 5 and top of Unit 4). This is likely because sufficiently humid climate conditions combined with poor drainage of the polje bottom characterised the area after the Neolithic or possibly since the latter part of it. The only chronological constraint available, i.e. the in situ flint knife, is located at the top of Unit 3. This artifact was identified by Stašo Forenbaher of the Institute for Anthropological Research, Croatia, based on tool typology, to be from the Neolithic, which in Vela Spila ranges from c. 8.0-4.0 ka BP. Unit 4, which is bracketed between the lake phase and the Neolithic flint, and contains tiny fragments of charcoal and pottery, therefore represents a phase of intense settlement or at least exploitation of the polje bottom which may be approximately dated to the end of the Holocene climatic optimum. This unit contains scattered angular and subangular pebbles that can also be related to a phase of increased runoff from the slopes surrounding the polje. Non indicative pottery fragments, but no charcoal, were also found in Unit 3, which likely represents the earliest phases of Neolithic settlement in the area. In this unit the absence of lithics and the presence of diffuse oxide spots testify to climate conditions consistent with the Holocene climatic optimum.

The lack of lacustrine microfauna in LOK1 below the top part of Unit 4 shows that at this time the polje was probably drier and therefore perhaps used for human activities; though no settlements have yet come to light, Neolithic artefacts have been tilled up occasionally in the fields. That the polje would have been dry in prehistoric times is not surprising since the sea level influences the base level of karst poljes and RSL was still 9-17 m below present at the start of the Neolithic (Dean & *alii*, 2020), so the base level for draining would be lower. Conversely, Units 1 and 2 are completely barren of traces of human settlement as well as of lacustrine microfauna.

Since ST1 is at a lower elevation and drilled at the bottom of a 2 m deep drainage ditch, the equivalent record as in LOK1 is mostly missing in this deeper core. The sediment granulometry results indicate that ST1 is more uniform with a very low sand fraction throughout the whole core, indicating potentially a low energy depositional environment. Probably the polje was partially filled in during MIS 3 and 2, since the formation of the karst features such as dry valleys and hums, and the runoff of associated materials took much longer than the Holocene (Ford & Williams, 2007).

Starting between the 2nd and 3rd metre in ST1 (Appendix B), the renewed presence of lacustrine microfauna may correlate with an earlier phase of seasonal flooding in the polje, predating the presumed dry Neolithic. This would necessitate an extremely wet phase where deposition of materials and water into the polje would be too rapid for karst drainage during at least some seasons, and where water was stopped from quickly draining by new or preglacial sediments in the polje. For a rough estimation of the age of sediments, a linear sedimentation rate to LOK1 can be applied, assumed that the Unit 4 corresponds to 4 – 8 ka BP. This suggests that almost the entire observed record in LOK1 core is probably of Holocene age but in any case not older than the Late Glacial, and the sediments in ST1 are likely from the LGM and part of the Late Glacial. No obvious facies changes are visible in the cores to suggest sudden changes in sedimentation rate, though the assumption of a linear rate is still a limitation since the only constraint is provided by the flint knife in LOK1 which is not directly dated. If however we accept this simplification and extend it downward to ST1, seasonal lake phases in that core may have occurred during MIS2.

Environmental influences on settlement patterns

The archaeological sites around the polje consist mainly of hill forts and burial stone mounds (gomile) reviewed in Radić (1999), though the dating of some of these sites may be precarious. For example, the site of an earlier hill fort could subsequently have been used for Late Neolithic/ Bronze tomb mounds. Besides, these remains are mostly piles of stones, so usually few directly datable materials exist, those that were present having long since been looted or destroyed when the island was being terraced in the 19th century. Given the available data as it now stands, however, there seem to be a number of hill forts and mounds on peaks around the polje dating from the Late Neolithic/Copper/ Early Bronze Age (c 5.0 – 3.0 ka BP) and Iron Age. Some of the hill forts are designated as simply "prehistoric" and maybe from the late Neolithic or speculatively, even older, when complex political situations involving three groups arose on the island (Radić, 2018). These tend to be on hums outside the polje, in areas that would have overlooked the sea, and this suggests that the polje became more important towards the latter part of the Neolithic and the Bronze Age. It suggests that the land was more useful or important in the context of the Neolithic cultural technocomplex, so that the people in the area saw fit to build more fortifications overlooking it. This could correspond to the drier phase detected in the two polje core records, and climatically, to a transition to a drier Mediterranean climate at 6.5-5.5 BP hypothesized by Lončar & *alii* (2017) from a decrease in speleothem growth rates in Mljet.

The Vela Spila archaeological record supports this view as well. The cave stratigraphy indicates that during Palaeolithic occupation, the main food resources were represented by terrestrial megafauna species whose habitat was the broad plain extending east, south and north of western Korčula, connecting the island to the mainland and the islands of Hvar, Lastovo, Mljet, Vis and Biševo (Dean & *alii*, 2020). To the N and NE of present-day Korčula, the palaeo-Neretva river flowed in an alluvial plain between Hvar and Korčula, according to GIS reconstructions carried out by Sikora et al. (2014). During the Mesolithic settlement phase, no land connections with other present-day islands existed, and much of the diet consisted of marine resources (Lightfoot & *alii*, 2011; Radić, 2018) and some small to the medium-sized game, mostly fox (Mauch Lenardić & *alii*, 2018), which is not uncommon in Mediterranean cultural contexts of that period (Colonese & *alii*, 2011). Since the island was detached from the mainland though, these animals were not being adequately replaced; instead, during the Neolithic the cave was used to keep domestic animals as a replacement for the lost wild megafauna (Radić, 2018). This pastoralism is more consistent with the exploitation of the Blatsko Polje area and its surroundings.

CONCLUSIONS

This work demonstrates the potential of a combined geomorphological and stratigraphic approach to provide palaeoenvironmental evidence that, cross-checked with archaeological data, can help explain patterns of human settlement seen in the study area. The landscape of this Dalmatian island and the homogeneous infill of its main morphological feature, Blatsko Polje, proved to be a useful tracer of geoarchaeological interest. This study shows:

1 - Some of the isolated conical hums, especially those within Blatsko Polje, may represent traces of different climates that affected the area during the Pliocene or possibly the Miocene.

2 - The few debris flows flanking Blatsko Polje also indicate wetter climates in the past, when precipitation was high enough to overwhelm groundwater infiltration rates, and carry solid particles downslope. At present, most of the valleys leading to these debris cones appear to be dry and terraced or used as roads.

3 - The lack of coastal features documented here accords well with the archetypal Dalmatian coast, where steep relief and rapid sea-level rise have not given time for significant coastal features to form (Kelletat, 2019). The implication of this is that the submerged zones are nearly identical to the emerged zone, and the dry valleys that now terminate in the sea continue underwater, with debris in the form of pebbles and cobbles that have been transported down the valleys to the present-day small bays or "uvalas" of local terminology.

4 - The sedimentological analysis of the polje infill demonstrates that this visually very homogeneous sediment can indeed record traces of human occupation in the area to compliment data from cave sequences and explain the organization of ancient populations. Moreover, sediments in the polje have been accumulating for a long time (several tens thousands of years), driven consistently by karst dissolution but also runoff, aeolian deflation and possibly other mechanisms. The polje infill is a potential palaeoenvironmental archive that would warrant future investigation with higher resolution core sampling.

5 - The settlement pattern suggested by archaeological evidence from Vela Spila cave and from open-air sites around Blatsko Polje indicates that up to the Mesolithic or early Neolithic the polje was not preferred for human exploitation of natural resources, whereas during and after the Neolithic, the geographical and environmental conditions (in addition to region-wide social changes) favoured intensive exploitation of flat, inland drained areas like Blatsko Polje. The orientation of sites changing from outward-facing on peripheral hums closer to the sea, to inward areas overlooking the polje reflected ongoing environmental changes in addition to social changes.

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