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Čedomir BENAC [1], Neven BOČIĆ [2*] & Mladen JURAČIĆ [1]

GEOMORPHOLOGIC CHANGES OF THE VELEBIT CHANNEL DURING LATE PLEISTOCENE AND HOLOCENE (NE ADRIATIC)

Abstract: Benac Č., Bočič N. & Juračič M., *Geomorphologic changes of the Velebit Channel during Late Pleistocene and Holocene (NE Adriatic).* (IT ISSN 0391-9838, 2022).

The Velebit Channel and its marginal basins in the northeastern Adriatic Sea were analyzed in order to reconstruct the geomorphological evolution of this area during the Late Pleistocene and Holocene (130 ka, MIS 5 to MIS 1) using detailed seabed maps, new data on sea-level changes, and submarine investigation. Submerged parts of the canyon, paleodeltas, traces of ancient lakes, and a large polje were discovered by analyzing these maps. Significant climate fluctuation during the Late Pleistocene and Holocene caused large variations in the Adriatic sea-level. On the very indented karst relief, the paleogeographic changes were quite impressive. The paleoflow of the Zrmanja River incised a canyon in the present Velebit Channel. A reconstruction of the paleoflow of the Zrmanja River shows that it could be traced at least 140 km from the current mouth during the Last Glacial Maximum. The transition from the marine to terestric/freshwater/lacustrine environment in the southeastern part of the Velebit Channel and in the marginal basins took place when the sea level dropped and oscillated between -20 m and -50 m (110-70 ka B.P.) after reaching a maximum of +5 m in 125 ka B.P. (MIS 5e). The basin in the northwest remained connected to the Kvarnerić marine basin at sea-level between -50 m and -80 m (70-30 ka B.P.). The sea completely receded from the Velebit Channel and Kvarnerić basin became polje during the Last glacial maximum (30-20 ka B.P.) when the sea level fluctuated between -100 and -120 m, whereas lakes probably remained in the deep depressions. During rapid sea-level rise between 19 and 7 ka B.P. the sea flooded a large part of the Zrmanja paleoriver valey and canyon (all of the Velebit Channel) and the sea penetrated into marginal basins. At the beginning of the stagnation of the Adriatic Sea level 7 ka B.P. a fine example of drowned fluviokarst relief was formed and the dynamics of water in the karst underground became similar to the present.

Key Words: Adriatic Sea, Sea-level change, Karstification, Fluviokarst, Canyon, Polje.

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Sažetak: Benac Č., Bočič N. & Juračič M., *Geomorfološke promjene Velebitskog kanala tijekom kasnog pleistocena i holocena (Sjeveroistočni Jadran).* (IT ISSN 0391-9838, 2022).

Jugoistočni dio Velebitskog kanala i rubni bazeni analizirani su kako bi se rekonstruirala geomorfološka evolucija ovog područja tijekom kasnog pleistocena i holocena (130 ka, MIS 5 do MIS 1) korištenjem detaljnih karata morskog dna, novih podataka o promjenama razine mora i istraživanjem podmorja. Značajne klimatske fluktuacije tijekom kasnog pleistocena i holocena uzrokovale su velike varijacije u razini Jadranskog mora. Na vrlo razvedenom krškom reljefu paleogeografske promjene bile su vrlo impresivne. Paleotok rijeke Zrmanje usjekao je kanjon u današnji Velebitski kanal. Rekonstrukcija paleotoka rijeke Zrmanje pokazuje da je tijekom posljednjeg glacijalnog maksimuma bio najmanje 140 km duži nego što je danas. Prijelaz iz morskog u kopneni/jezerski okoliš u jugoistočnom dijelu Velebitskog kanala i u rubnim kotlinama dogodio se kada je razina mora nakon postizanja maksimuma oscilirala između -20 m i -50 m u razdoblju od 110-70 ka B.P., nakon što je bila dosegla najvišu razinu od +5 m 125 ka B.P. (MIS 5e). Bazen na sjeverozapadu ostao je povezan s Kvarnerićem na razini mora između -50 m i -80 m (70-30 ka B.P.). More se potpuno povuklo iz Velebitskog kanala i Kvarnerića tijekom posljednjeg glacijalnog maksimuma (prije 30-20 ka) kada je razina mora fluktuirala između -100 i -120 m. Kvarnerić je postao krško polje a jezera su vjerojatno ostala u dubokim depresijama. Tijekom brzog porasta razine mora između 19 i 7 ka more je poplavilo veliki dio doline i kanjona paleorijeke Zrmanje (cijeli Velebitski kanal) te prodrlo u Paški i Ljubački zaljevi i Novigradsko more. Na početku stagnacije razine Jadranskog mora prije 7 ka formiran je lijep primjer potopljenog fluviokrškog reljefa, a dinamika vode u krškom podzemlju postala je slična današnjoj..

Ključne Riječi: Jadransko more, Promjene morske razine, Okršavanje, Fluviokrš, Kanjon, Krško polje

INTRODUCTION

Reconstruction of submerged paleorelief, paleohydrology, and paleoenvironments in Pleistocene and Holocene is rapidly evolving (Mattei & *alii*, 2022). However, reconstructions of paleohydrology in karst areas are not so common (Sikora & *alii*, 2014). An attempt to reconstruct the evolution of the Velebit Channel and the Kvarnerić basin in the karstic northeastern part of the Adriatic Sea since Late Pleistocene is presented, because so far, no scientific research has been published, and this work might contribute to the understanding of the morphological evolution of the Croatian part of the Adriatic coast. This, now submerged, area is archeologically rather interesting because all of the Northern Adriatic was a refugium for humans, animals and plants during glacial times, and especially during Last Glacial Maximum (LGM) (Pilaar Birch & Vander Linden, 2018). Caves in kanyon setting, and rims of karst poljes should have been optimal for human settlement.

The study area is located in Kvarner area (*sensu lato*). The Cres-Lošinj and Krk-Rab-Pag island chains divide it into Rijeka Bay, Kvarner Bay (*sensu stricto*), the Kvarnerić basin, and the Vinodol-Velebit Channel (Benac & Juračić, 1998; fig. 1).

The geomorphological evolution of the Adriatic Sea has been analysed in several works (D'Ambrosi, 1969; Brambati & Venzo, 1967; Pigorini, 1968; Morelli & *alii*, 1969; Van Straaten, 1970; Prelogović & Kranjec, 1983; Trincardi & *alii*, 1994; Correggiari & *alii*, 1996). However, in these papers, northern Croatian coast was considered only sporadically or not at all.

However, the seabed and geomorphological evolution of Kvarner has been somewhat better explored (Juračić & Pravdić, 1981; Benac & Šegota, 1990; Benac & Arbanas, 1990; Benac, 1996a; Benac, 1996b, Benac & Juračić, 1998; Juračić & *alii*, 1999). The sediments of the Vinodol-Velebit Channel bottom were described in the framework of the investigation in the Kvarner area (Škrivanić & Magdalenić, 1979; Alfirević, 1979).

A new detailed investigation were conducted in southeastern marginal basins: Novigrad and Karin seas (Hasan, 2017; Hasan & *alii*, 2020) and in the Lošinj Channel between Cres and Lošinj islands (Brunović & *alii*, 2020).

So far, no data have been published on the geomorphological evolution of the Velebit Channel. In this work, coupling detailed seabed maps, data on sea-level changes and new submarine investigation it was possible to reconstruct the morphological evolution of the central and southeastern part of the Velebit Channel which includes currently submerged part of the Zrmanja riverbed (Zrmanja paleoriver) and related marginal basins: Pag and Ljubač bays and the Novigrad Sea during the Late Pleistocene and Holocene.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The prominent feature of so called "Dinaric karst area", of which the eastern Adriatic coast is part, is a cradle of karst landforms research (Cvijić, 1893) and here were described the most prominent karstic features (*dolina*, *polje*, *ponor*…), and it is characterised by the predominant absence of surface watercourses and drainage networks

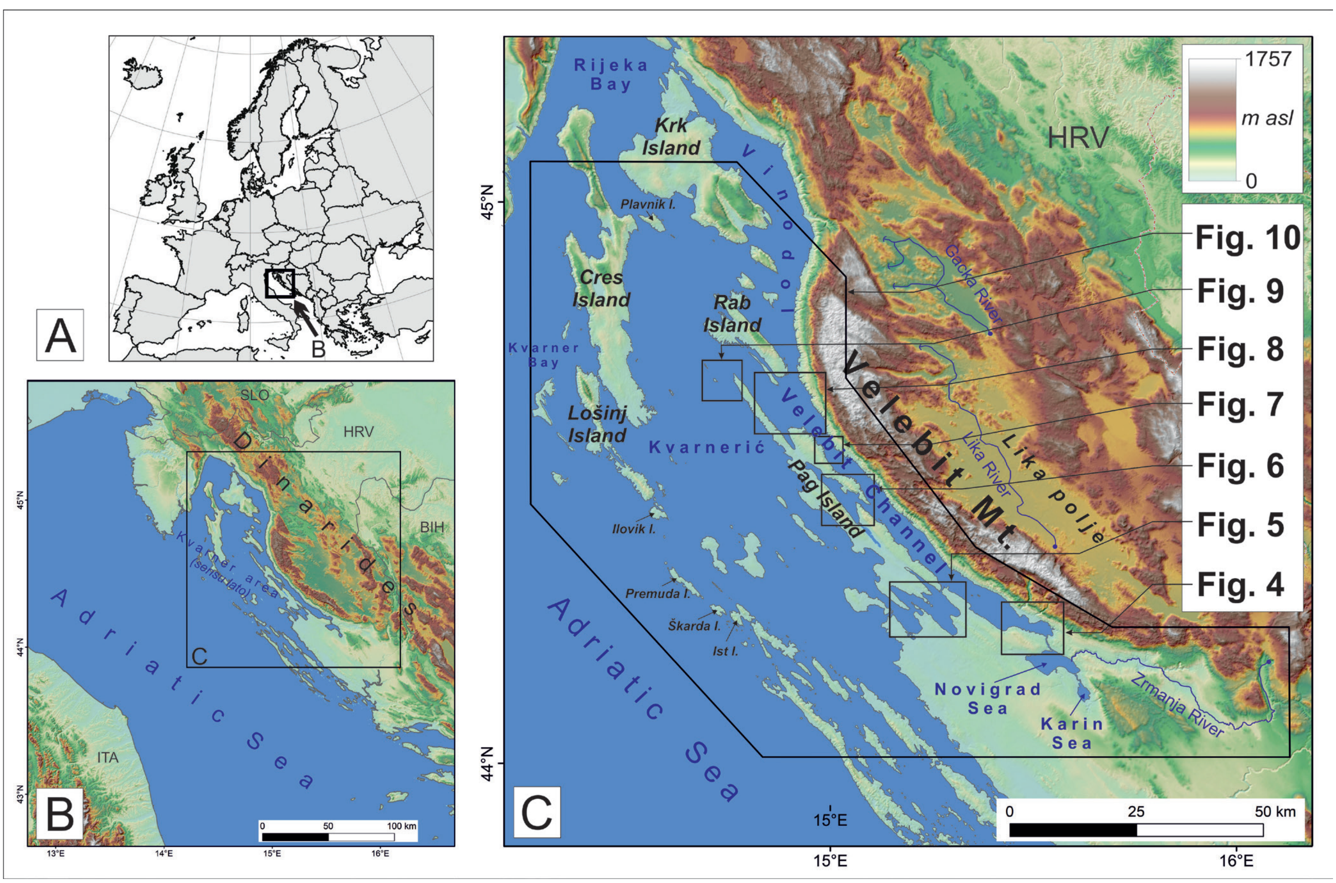

FIG. 1 - Geographical location of the study area with marked areas shown on figures 4-10.

(Herak, 1972). Nevertheless, some river valleys (canyons) are deeply incised in the carbonate bedrock (Bognar & *alii*, 2012; Bonacci, 2015). Such is the Zrmanja River, which surrounds the southern edge of the Velebit Mt. This 145 km long mountain reaches heights between 1500 and 1700 m. The northern Velebit is a large, faulted anticline with Middle Triassic dolomite rocks in its core and Jurassic and Cretaceous limestone rocks in its limbs. In contrast, the southern Velebit is composed of the reversely elevated southwestern limb of an anticline. Its Late Carboniferous and Permian clastic and carbonate rocks are reversely uplifted above the Triassic-Jurassic rocks. The coastal slopes of Velebit Mt. are very steep in inclination and mostly formed in Oligocene-Miocene tectogenic limestone breccias, known as Velebit breccia. These rocks overlie Upper Cretaceous rudist limestones and outcrops are visible in a few isolated zones (HGI, 2009).

The coastal slopes have a typical fluviokarst appearance. Numerous dry karst valleys are deeply cut into the carbonate rocks. The Canyons of the Velika Paklenica and Mala Paklenica torrent flows are particularly pronounced in the coastal relief.

The Zrmanja River course is 69 km long and springs at the eastern end of the Velebit Mt. in the Zrmanja Vrelo spring (335 m a.s.l.) and flows into the Novigrad Sea (fig. 1). In the lower tract the Zrmanja River receives a high discharge tributary (Krupa River) as well as some high discharge springs that bring water from swallow holes (ponors) in the Lika polje (Biondić & Biondić, 2014). Most of the Zrmanja River flow is carved into the canyon. Its watershed includes an area of about 1387 km^2 and the mean annual discharge is 39 m^3s^{-1} (Bonacci, 1999). A range of discharge is between 0.95 and 160 m^3s^{-1} and the entire Novigrad Sea is considered as its estuary (Viličić, 2011).

In contrast, Pag Island is levelled and the highest peak reaches only 250 m. The Pag Island has moderately to slightly inclined folds of Dinaric strike (NW-SE) with secondary folded limbs, and with upright to slightly inclined faults mostly in fold limbs. Two anticlines are composed of Upper Cretaceous rudist limestones in the core. The syncline is located in the central part of the island. This syncline is composed of Palaeogene flysch in the core and foraminiferal limestone in the limbs (Magdalenić, 1984; HGI, 2009). The southwestern coast of the Velebit Channel, which belongs to Pag Island, is mostly very steep. Dry karst valleys are rare.

The southwestern coast of the Novigrad Sea is formed in Upper Cretaceous rudist and dolomitic limestones. Northern coasts are formed in Oligocene-Miocene limestone breccias, and the southeastern part in Palaeogene marly limestones and conglomerates (Promina formation) (HGI, 2009).

CLIMATE AND SEA-LEVEL CHANGES

Palynological analyses of sediments in the Lošinj Channel show a transition from a subtropical to a cooler climate during MIS 5 (Brunović & *alii*, 2020). A cold and dry environment with periodic warmer periods was recognised in the loess and paleosoil in Susak Island during MIS 3 (Mikulčić Pavlaković & *alii*, 2011; Wacha & *alii*, 2018).

Based on geomorphological traces of glaciation, e.g. extraction of morphological features and sediment accumulations (cirques, glacial valleys, different types of moraines etc.) assumed that the northern and central Velebit was affected by glaciation at altitudes above 1300 m (Bognar & Faivre, 2006).

Therefore, during LGM (MIS 2), the snowline or equilibrium line altitude (ELA) was at least at 900 meters above the recent mean sea level (m.s.l.). Therefore, numerous accumulation and erosion traces of glacial deposits are located at altitudes of approximately 900 to 1400 meters on Velebit Mt. (Velić & *alii*, 2017). The zone of geomorphological traces of the Pleistocene glaciation covers around 75 km^2 (Bočić & *alii*, 2019). Glaciers on northern Velebit Mt. reached their maximum extent during the last glacial cycle between MIS 5 and 4 and the maximum area covered by glaciers was estimated to be about 116 km^2 (Žebre & *alii*, 2021). Records of wet climatic periods at the end of Pleistocene and early Holocene were found in the sediments in the Kvarner area (Schmidt & *alii*, 2001).

The study of paleoclimatic, paleoenvironmental, and archaeological data in the Mediterranean area, shows significant sea-level changes since the last glacial (MIS 6, approximately 132 ka B.P.) (Benjamin & *alii*, 2017) in line with the global trend (Waelbroeck & *alii*, 2002). During the last interglacial (MIS 5.e) sea-level was several meters above the present sea-level. After that, the sea-level began to fall and fluctuated between -20 m and -50 m between 110 ka and 75 ka B.P. (MIS 5d to 5a). Due to global cooling and increasing ice cover, sea-levels fluctuated between -50 m and -80 m between 70 ka and 30 ka B.P. (MIS 4 and MIS 3). During the last glacial maximum or LGM (30 ka - 20 ka B.P.), the sea-level dropped to a depth of -100 to -120 m (Benjamin & *alii*, 2017) (fig. 2).

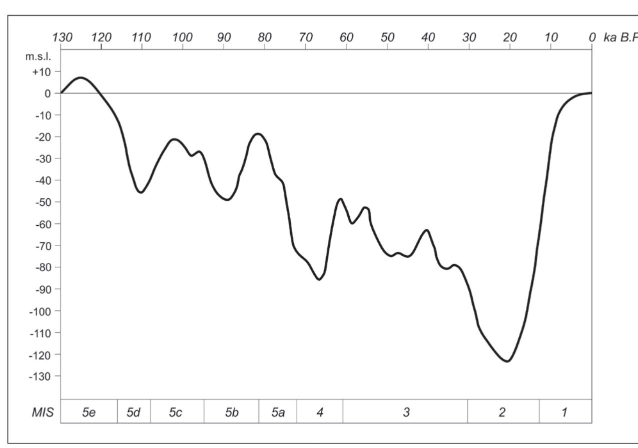

Fig. 2 - Global sea-level changes during the Late Pleistocene and Holocene (after Waelbroek & *alii*, 2002) adapted for the Mediterranean area (after Benjamin & *alii*, 2017).

Since the end of LGM a rapid global sea-level rise started. Near the eustatic peak of the Holocene sea-level rise, there was a period of equilibrium between the regional tectonic subsidence and hydro-isostatic emergence in the northern Adriatic area. These two opposite phenomena caused the relative sea-level to remain stable for several thousand years (Pirazzoli, 2005), and stagnation of the rise of the sea-level occurred in the last 7000 years (Lambeck & *alii*, 2004; Surić, 2009). Results of speleothem dating in the eastern Adriatic Sea show general agreement with sea-level curves from other coasts in the central Mediterranean (Surić & Juračić, 2010).

METHODS

The main source for research on seabed morphology were bathymetric charts published through the Navionics web service (NAVIONICS, 2022). This service provides comprehensive nautical charts obtained from multiple official, government, and private sources, displayed in a user-friendly layout. These charts are combined with SonarChart^{TM} HD Bathymetry, innovative bathymetric charts which are created using Navionics proprietary systems that augment existing content with sonar data contributed by the boating community (NAVIONICS, 2022). A zoom level with equidistance of 10 m was used to create an overview map. A detailed zoom level with equidistance of 1 m down to 50 m depth and 2 m at greater depths was used for a detailed analysis of the submarine relief and geomorphological maps. The maps were transferred as rasters into ArcGIS 10.7 in a series of sheets. These maps were then georeferenced and isobaths of -10, -30, -50, -70, -90 and -110 m were manually vectorized. The maximum horizontal deviation of the vectorized line from the original was 100 m, which we consider to be very precise in relation to the size of the studied area. These data were used for the geomorphological analysis of the particularly highlighted areas (fig. 1) and as a basis for the geomorphological maps presented (figs. 4-9).

A digital raster relief model of the seabed with a resolution depth of 90 x 90 m, taken from the General Bathymetric Chart of the Oceans web service (GEBCO, 2022), was used to create an overview map of the wider area. To determine the surface relief features at individual locations, a digital relief model with a resolution of 5x5 m was created based on altitude data from the State Geodetic Administration of the Republic of Croatia. All digital depth and elevation models were processed in ArcGIS 10.7.

The seabed of the Croatian part of the Adriatic Sea was not geologically mapped (HGI, 2009). However, a geological seabed map at a scale of 1: 250,000 is available for the Kvarner area (GEOPORTAL, 2022). This map, though, shows only the marginal northwestern part of the Vinodol-Velebit Channel, the area not analyzed in this paper.

Therefore, for the purposes of research in this paper, the boundaries between the zones of submerged bare karst and those covered with Holocene/Recent sediments were determined in part on the survey of individual sites by scuba diving. Three main types of deposits can be distinguished depending on erodibility and geomorphological processes: karstic rock mass (Upper Cretaceous rudist limestones, Paleogene foraminiferal limestones, Oligocene-Miocene limestone breccias), siliciclastic rock mass (Palaeogene flysch and Promina formation), and various types of coarse- to fine-grained fluvial, lacustrine and marine Pleistocene to Holocene semi-consolidated sediments.

Some remotely operated vehicle (ROV) observations in several places in Kvarner were also used and confirmed the data presented on the Navionics maps (NAVIONICS, 2022). Video documentation of the sea bottom relief was conducted using the Blueye Pioneer inspection class ROV model manufactured by Blueye Robotics. The ROV has a built-in FHD camera with a light-sensitive wide-angle lens, which allows recording at night, at great depths, or in poor visibility conditions. The ROV is operated via a control device (smartphone, tablet, or laptop) connected to the ROV surface router. The surface router and the ROV are physically connected via an interconnecting cable. While one person controls the ROV, other researchers can be wirelessly connected to the surface router and observe the ROV images in real-time.

For this investigation, the ROV dive and video documentation of the sea bottom was conducted from a boat anchored in the middle of the surveyed area near the coast. The ROV was lowered into the sea and imaging began immediately from the sea surface. The ROV was operated according to a predetermined movement and recording plan.

Unpublished images of sub-bottom acoustic profiling were used to analyse the geological structure and geomorphological features of the seabed (HHI, 2000). Since the studied area is quite large, in other zones the boundary between rocky karst bottom and recent sediments was determined by comparing the zones of the similar slope of the seabed, based on the long-term diving experience of the authors of this paper (fig. 3).

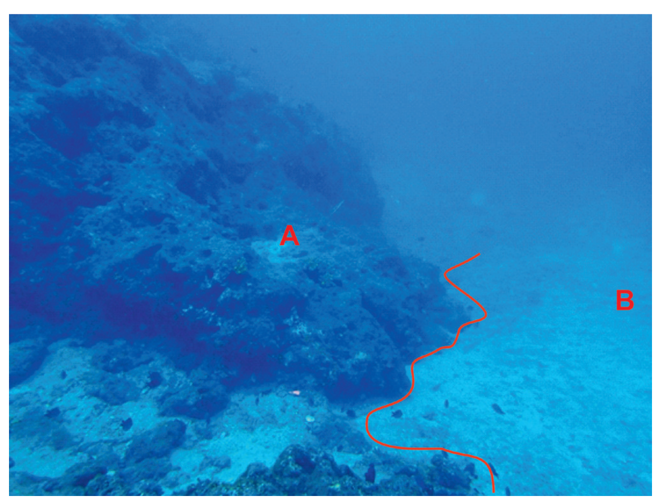

Fig. 3 - An illustrative example of the contact of rocky slope (A) and flat bottom covered with fine-grained sediment (B) (photo: Č. Benac).

GEOMORPHOLOGICAL ANALYSIS

SE Velebit Channel and Novigrad Sea

Today's Zrmanja River flows into the Novigrad Sea (fig. 1), but the geomorphological traces of its flow are also visible in the submarine relief. Between the Novigrad Sea and the southeastern part of the Velebit Channel (fig. 4), there is a narrow canyon-shaped elongated channel. This is the Novsko ždrilo, a partially submerged canyon 3.7 km long. It is between 150 and 260 m wide at sea level, i.e. 320 to 600 m at the level of the surrounding relief. The maximum height of the canyon sides in relation to the sea level is about 97.5 m on the west side and 95.5 m on the east side. The average height of the canyon sides concerning the sea level is about 67.5 m on the west side and about 60 m on the east side. According to bathymetric charts, the maximum depth of the submerged part of the canyon is 44 m (NAVIONICS, 2022).

Further downstream from the exit of the Novsko ždrilo strait, an 8.9 km long completely submerged canyon continues in the WNW-ESE direction. Its width is mostly 250-300 m, and the maximum depth is 41 m. Several elongated depressions are visible in the canyon (fig. 4). Northwest of that canyon are two alluvial fans, whose contours are visible on bathymetric charts (NAVIONICS, 2022). The Velebit channel widens to the northwest, and the depth of the bottom gradually increases to over 60 m in places.

Ljubač Bay

Ljubačka vrata strait is a connection between Velebit Channel and Ljubač Bay. This strait is a partially submerged canyon. Its total length is 2.2 km. The width of the canyon at M.S.L. ranges from 170 m in the narrowest part to about 530 m in the widest part in the north. The maximal depth of the submerged part of the canyon is 60-62 m (fig. 5).

The Ljubač Bay, i.e. a former relief depression, was drained by surface streams from valleys consisting mostly of flysch sedimentary rocks. However, it seems that a surface stream also came from the neighboring Nin Bay, i.e. the former Nin relief depression.

This is indicated by the completely submerged smaller canyon between Nin and Ljubač bays. The length of this canyon is 1 km, and its width is about 250 m. The maximum depth of the sea in the canyon is 23 m, and the canyon itself has cut into the submerged relief at a depth of about -10 m, which means that the maximum depth of the canyon incision is approximately 13 m. Also, a smaller submerged canyon-like form can be seen between the sea passage between Pag and the Veli Sikavac islands. It is about 500 m long and has a maximum depth of 22 m (fig. 5).

Pag Bay

The submarine relief of Pag Bay also indicates the high probability of surface runoff towards the Velebit Channel, i.e. to the valley of the Zrmanja paleoriver (fig. 6). Most of the depression of today's Pag Bay is formed on flysch bedrocks that allowed surface drainage.

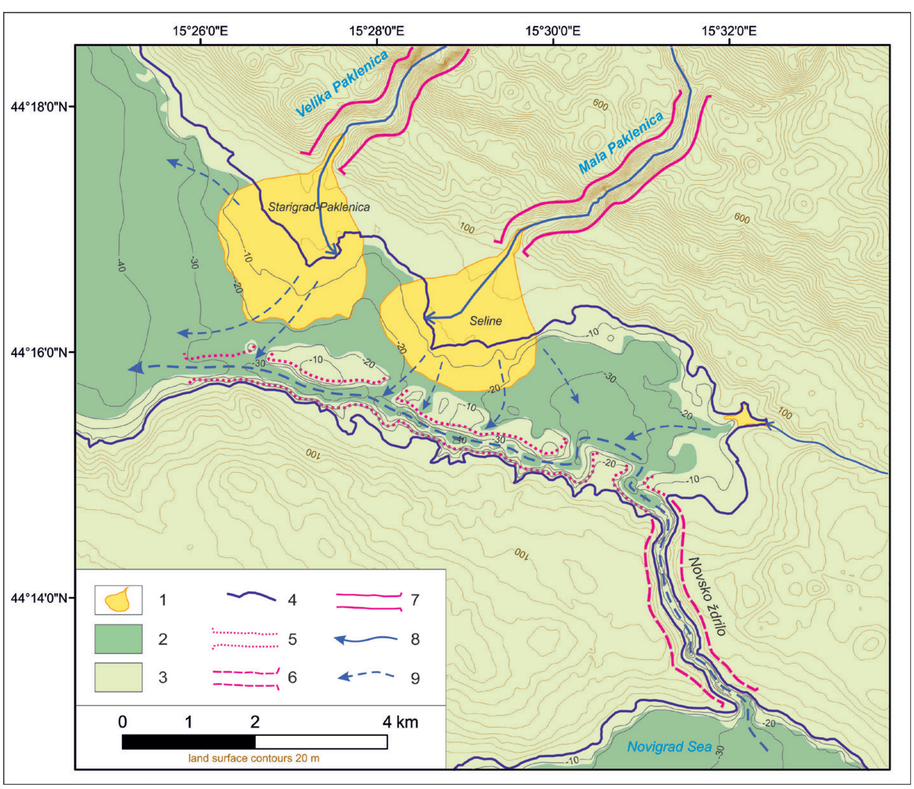

FIG. 4 - Geomorphological sketch map of subaereal and submerged landforms of the Velebit Channel and the Novigrad Sea: 1) alluvial fan; 2) marine sediments; 3) carbonate bedrock; 4) recent coastline; 5) submerged canyon; 6) partially submerged canyon; 7) canyon; 8) surface flow; 9) presumed paleoriver flow during lowstanding sea-level.

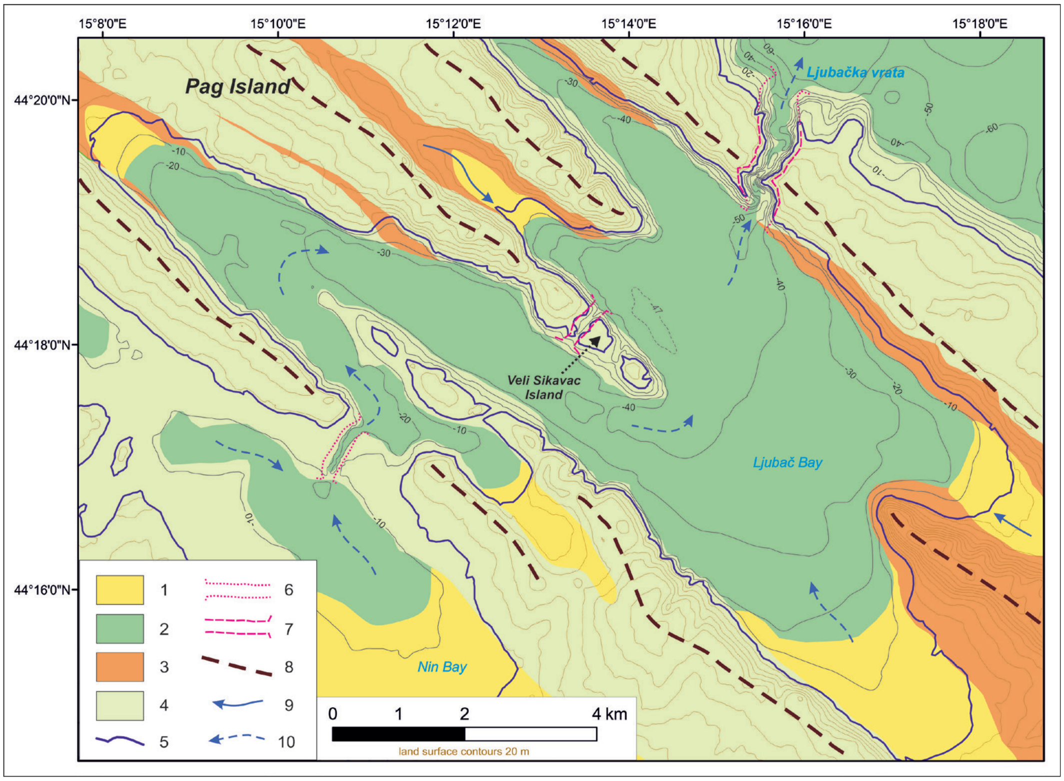

FIG. 5 - Geomorphological sketch map of subaereal and submerged landforms of the Ljubač Bay: 1) alluvial-proluvial sediments; 2) marine sediments; 3) flysch rocks; 4) carbonate rocks; 5) recent coastline; 6) submerged canyon; 7) partially submerged canyon; 8) main ridges; 9) surface flow; 10) presumed flow during lowstanding sea-level.

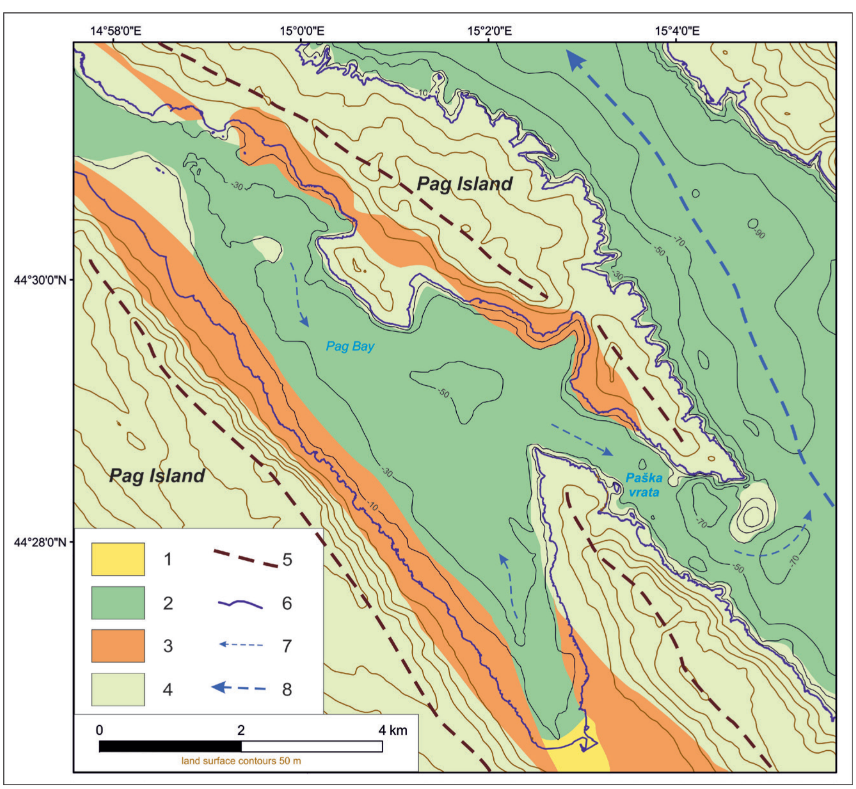

FIG. 6 - Geomorphological sketch map of subaereal and submerged landforms of the Pag Bay: 1) alluvial-proluvial sediments; 2) marine sediments; 3) flysch rocks; 4) carbonate rocks; 5) main ridges; 6) recent coastline; 7) presumed surface flow during lowstanding sea-level; 8) presumed riverbed of the Zrmanja paleoriver.

The Pag Bay, i.e. a former relief depression, was drained by surface streams from valleys consisting of flysch sedimentary rocks in its central part. However, a surface stream also came from an elevation on the northwest and southeast side. The bottom of the central part of Pag Bay is deeper than 50 m, and the entrance of Paška vrata strait is deeper than 70 m (fig. 6).

The central and northwestern parts of the Velebit Channel

The Velebit Channel is 2 to 4 km wide in its central part. The depth of the bottom is in some places greater than 70 m (fig. 7A) The trace of the paleo riverbed in the sediment body is visible on geological cross-section which was drawn on the basis of echo sounding data (fig. 7B).

The Velebit channel is up to 8 km wide in the northwestern part, and the depth of the bottom is in places greater than 90 m. On the northeast coast, dry karstic valleys are visible. They are cut into carbonate bedrock, and traces of submerged beds are visible up to 40 m deep on bathymetric charts (NAVIONICS, 2022). Submerged rocky shallows are located in the strait between Rab Island and the mainland (fig. 8A). The sediment body is more than 100 m thick and erosional disconformity is visible in the geological cross-section which was drawn on the basis of echo sounding data (fig. 8 B).

In NW direction from the NW cape of the Pag Island there is a trough-like elongated form visible on the sea bottom. It stretches towards the northwest and it is about 8 km in length and up to 500 m in width. Compared to the level of the surrounding seabed, it is about 15 meters lower, and the deepest places reach a depth of about -90 m. Southwest of the the NW cape of the Pag Island the strait between the Pag Island and the islets of Laganj and Dolfin is narrower than 2 km. Here the sea bottom is deeper than 90 m in some places (fig. 9).

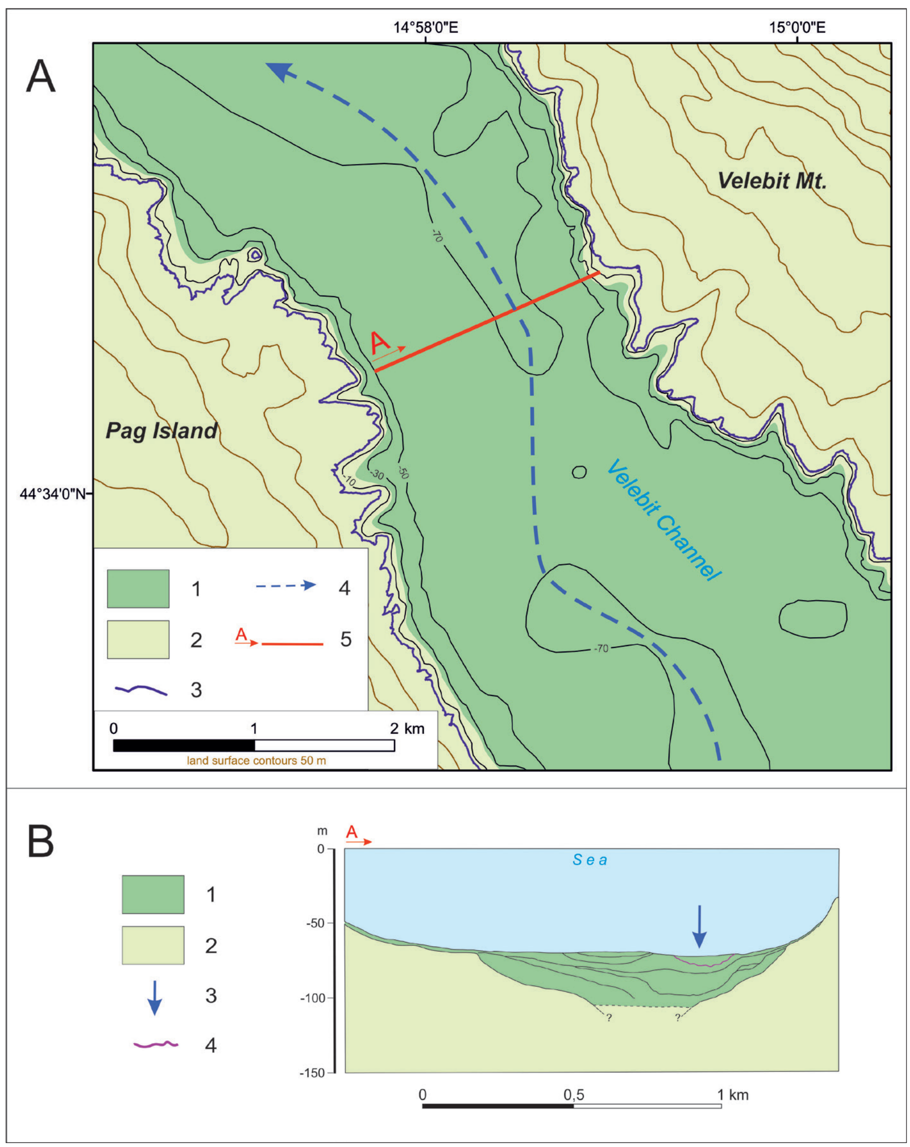

FIG. 7 - A) Geomorphological sketch map of subaerial and submerged landforms of the central part of the Velebit Channel: 1) marine sediments; 2) carbonate rocks; 3) recent coastline; 4) paleo riverbed; 5) trace of sub-bottom cross-section; B) geological cross-section (after Benac & *alii*, 1995): 1) marine sediments; 2) carbonate rocks; 3) position of the paleo riverbed; 4) contours of paleo riverbed.

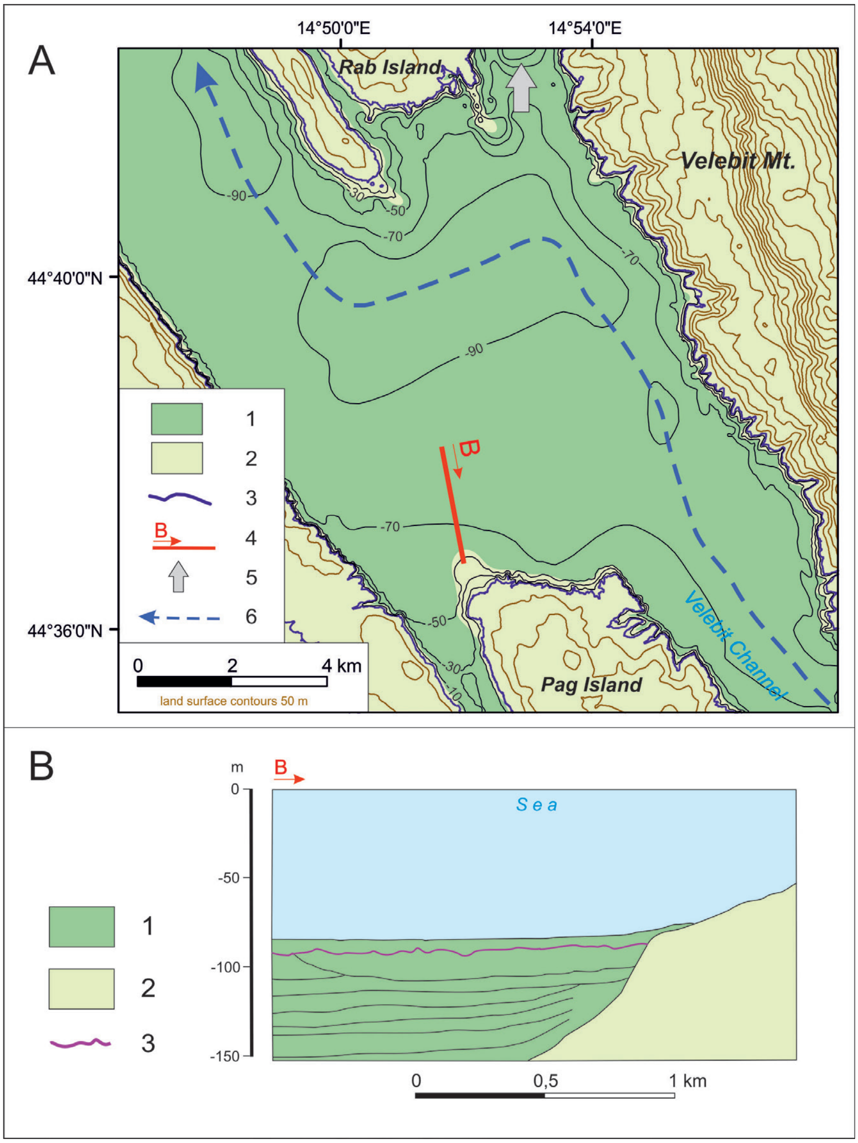

FIG. 8 - A) Geomorphological map of subaerial and submerged of NW part of the Velebit Channel: 1) marine sediments; 2) carbonate rocks; 3) recent coastline; 4) trace of sub-bottom cross-section; 5) location of shallows; 6) paleo riverbed; B) geological cross-section (after Benac & *alii*, 1995): 1) marine sediments; 2) carbonate rocks; 3) erosional disconformity.

DISCUSSION

Geomorphological evolution

The Kvarner area including the Vinodol-Velebit Channel is seismotectonically active (Prelogović & *alii*, 1998). The youngest phase is characterized by approximately N-S oriented compression and approximately E-W oriented tension in a strike-slip stress regime, which caused dextral re-activation of NW-SE striking faults in northwestern external Dinarides. This phase correlates with the recent regressive/transgressive phase (Žibret & *alii*, 2016). NW-SE and NE-SW striking dextral and sinistral faults, as well as NW-SE and NE-SW striking normal faults indicate a change in the paleostress field during the Neogene–Quaternary, with predominant transpression and radial extension in Vinodol Valley and nearby northwestern Vinodol-Velebit Channel (Palenik & *alii*, 2019). Therefore, the deep canyons might have been tectonically predisposed. During MIS 5, tectonic uplift may have occurred in the Kvarner area (Surić & *alii*, 2014). However, there are several indicators of recent tectonic subsidence of the Vinodol-Velebit Channel (Benac & *alii*, 2008a; Mariner & *alii*, 2011).

In order to try to reconstruct the evolution of the valley of the Zrmanja paleoriver the long-standing dichotomy between fluvial and karst geomorphic processes was tackled (Benac & *alii*, 2013; Phillips, 2017) but under conditions of alterations of transgression and regression of the sea.

Among the most important factors for the geomorphological evolution of the studied area is the position of the erosional base, which in this case depends primarily on the eustatic dynamics, i.e. on the position of the local sea-level in the Adriatic basin. The Messinian Salinity Crisis, which ended 5.32 Ma ago and caused deep erosion and karstification, was of great importance for the entire Mediterranean basin (Mocochain & *alii*, 2006). The impact of this event on the evolution of relief in the Adriatic basin has not yet been studied, but it has certainly had a major influence. During

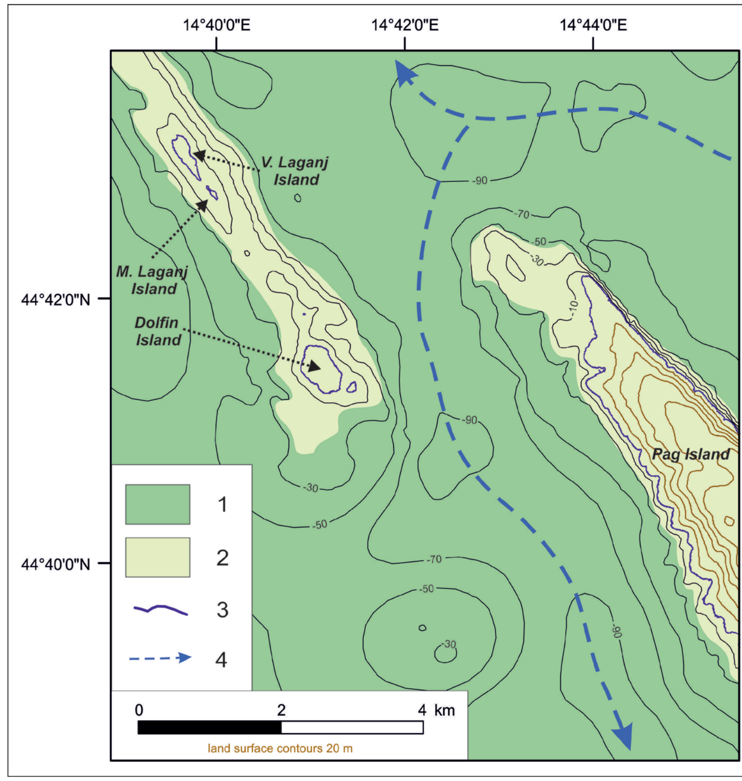

Fig. 9 - Geomorphological sketch map of of subaerial and submerged northwestern cape of the Pag Island: 1) marine sediments; 2) carbonate rocks; 3) recent coastline; 4) presumed flow of the Zrmanja paleoriver.

the Pliocene, the sea-level was generally slightly higher than today (Dumitru & *alii*, 2019; Grant & *alii*, 2019), which had an impact on the cessation of exogenous processes and favorable conditions for marine sedimentation in the Velebit Channel. Pleistocene sea-level changes had more pronounced dynamics which were particularly emphasized in the Late Quaternary (Benjamin & *alii*, 2017). Most probably sediments deposited above present sea level in older Pleistocene in the northern Adriatic including Kvarner were erased/eroded during subsequent glacials/stadials.

In addition to eustatic dynamics, paleoclimatic conditions also influenced the chemical aggressiveness of water. Water become acidified by dissolved carbon dioxide during its passage through the atmosphere, vegetation, and soil before making contact with the limestone (Williams, 2004) which is better expressed during warmer and wetter periods. The fluviokarstic phase, with prevalent surface drainage, probably diminished in the Pliocene in the Kvarner area. Therefore, during the Pleistocene, underground runoff through karst aquifers could prevail, and surface flows in numerous karst ravines could have been active only periodically, as is the case today (Benac & *alii*, 2013; Šegina, 2021). In contrast, during the glacial periods, mechanical rock weathering and regolith accumulation were more pronounced. However, during the glacial to interglacial transition, large amounts of water were released from the ice caps, which could cause significant fluvial erosion, as well as surface and underground karstification (Adamson & *alii*, 2014) but also alluvial fans accumulation at the foot of the mountains (Adamson & *alii*, 2017). Thomas & *alii*, (2018) also found that climatic variations quantitatively influenced the intensity of karstification.

Karstification and denudation of karst relief are generally considered to be one of the slowest geomorphological processes and depend on several factors. Some of the most important are geological fabric including the presence or absence of sediment covers and features of the local climate (Ford & Williams, 2007). The long-term denudation rate of the North Dalmatian Plain, including its local variability has been estimated to be 18.91 ± 0.81 m/Ma (Krklec & *alii*, 2022). Therefore, it can be assumed that denudation in karst areas was not significant during the late Pleistocene and therefore the relief formed in carbonate rocks was not significantly changed.

Landscape changes since last Interglacial

The depression of the present Velebit Channel was probably formed before the Late Pleistocene. Reliable evidence has not been found, but echo-sounding cross-sections indicate deep sedimentary basins (figs. 7, 8). The sea-level was several meters above the present m.s.l. during the last interglacial (MIS 5e) in the Mediterranean Sea (Benjamin & *alii*, 2017) (fig. 2). However, traces of higher sea-levels were not found in the Kvarner area including the Velebit Channel (Benac & Juračić, 1998) nor on the northeastern coast of the Adriatic Sea (Surić & Juračić, 2010). Therefore, the paleogeographic conditions in the wider area of the Velebit Channel at the beginning of the Late Pleistocene should have been similar to the present conditions.

After the last interglacial, sea-level began to fall, and was fluctuating between -20 m and -50 m i.e. from 110 ka to 75 ka B.P. (MIS 5.d -5.a) (fig. 2). The change in paleogeographic conditions was already pronounced at the -30 m level. Traces of submerged beds of present-day dry karstic valleys are visible up to -40 m on the northeast coast of the Velebit Channel (figs. 7, 8). Several phases of lacustrine facies were also found in the Lošinj Channel in the same period (Brunović & *alii*, 2020).

Environmental changes from marine to lacustrine were also possible in the shallower southeastern part of the Velebit paleochannel, but also in the depression where the present-day Ljubač and Pag bays and the Novigrad Sea are located (figs. 4, 5, 6). In some places, this could have a decisive influence on the interruption or establishment of connections between paleo-Velebit Channel paleobasins and the aforementioned marginal ones.

In this period, the sea retreated from a large part of the depression of the present Novigrad Sea, from depression where the present-day Ljubač and Pag bays are, and from the southeastern part of the Velebit Channel. Freshwater outflow and periodic connections to the sea were possible through canyons cut into the carbonate rocks (fig. 4).

Marine area become significantly smaller when the sea-level fluctuated between -50 m and -80 m i.e. from 75 ka to 30 ka B.P. (MIS 4 and MIS 3) (fig. 2). Karstic elevation between the Rab Island and the mainland emerged, and the surface water connection with the northwestern part of the Velebit Channel was interrupted (fig. 7). Bathymetric data strongly suggest that the northern part of the paleochannel was connected to the Kvarnerić marine basin through a strait between Pag and Dolfin islands (fig. 9).

Sea-level changes during the Late Pleistocene had a significant impact on the morphological evolution of the studied area. The deep straits or paleocanyons between paleobasins considerably influenced marine transgression and regression

One can presume that submerged canyons or present narrows between Pag and Ljubač bays, the Novigrad Sea and the southeastern part of the Velebit Channel were deepened during the terrestrial phase in the LGM (30 ka to 20 ka to B.P.). The erosion processes were more intense in the zones formed in the flysch rock mass. As a result the shape and depth of paleobasins such as Pag and Ljubač bays may have been substantially deepened in this period (figs. 4, 5, 6) and, due to the intensive sedimentation of this material, the downstream part of the Zrmanja paleoriver was shallowed (figs. 7, 8).

Depths of canyons between paleodepressions could also vary due to neotectonic and recent tectonic movements. Therefore, the interpretation of the sequence of geomorphological evolution is very complex. The detailed bathymetric map of the Novsko ždrilo canyon connecting the Velebit Channel with the Novigrad Sea show a maximal depth of 44 m and show features that are probably submerged calc-tufa barriers (Hasan & *alii*, 2020). The alluvial fans of the Velika and Mala Paklenica torrent flows have been formed/enlarged during the terrestrial phase in the LGM (fig. 4).

The global fall of the sea-level was strongly felt in the northern Adriatic Sea and in the Kvarnerić basin when the sea-level dropped to a depth of -100 to -120 m during the LGM (30 ka - 20 ka B.P.) (fig. 2). Erosional disconformity, visible in the echo-sounder cross-section in the northwest part of the Velebit Channel is a strong evidence of terrestrial environment during LGM (fig. 8). Kvarenrić basin has become a large polje, as well as southern part of the adjacent Lošinj Channel (Brunović & *alii*, 2020). The Po paleoriver and its tributaries flowed through the alluvial plain in the northern Adriatic up to the Jabuka depression (Ronchi & *alii*, 2018). Poljes are the index features of the Dinaric karst (Cvijić, 1895; Herak, 1972; Ford & Williams, 2007; Dean & *alii*, 2020), and Kvarnerić basin is a fine example of drowned large polje.

Paleohydrology

Waters from the catchment area of Gacka and Lika rivers that swallow in Lika polje flow through the karst underground into the Velebit Channel. Therefore, there are numerous coastal and submarine springs (vrulje) on the northeast coast of the channel (Biondić & Biondić, 2014). Submarine springs indicate that they were formed and were active as coastal springs during sea-level lowstand. However, periodic torrents have also probably significantly increased the discharge of the Zrmanja paleoriver. Mostly impermeable flysch rock mass plays an important role in the groundwater dynamics of the Dinaric karst (Biondić & Biondić, 2014). The flysch zone that extends through the central part of Pag Island and towards the southeast is a hydrogeological barrier that prevents, an probably prevented the development of large underground flows through Pag Island towards the Kvarnerić basin to the southwest (Magdalenić, 1984). According to the most probable paleoclimate scenario, the precipitation decrease from the present level was up to 10 % between MIS 4 and MIS 5, during the maximum expansion of glaciers on the Northern Velebit Mt. (Žebre & *alii*, 2021). Therefore, it is very probable that the Zrmanja paleoriver existed at the peak of the LGM and reshaped its canyon cut into the carbonate bedrock.

The main directions of groundwater flows have formed zones of intense karstification. That zones are located, for example, at a depth of 50 m below m.s.l. in the Bokanjačko blato depression near the town of Zadar (Fritz, 1979). Carbonate bedrock beneath the Pleistocene sediments is located at a depth of 45 m below m.s.l. in Lake Ponikve on Krk Island (Šegina, 2021). The deepest known entrance of a submerged cave in the Kvarner area is at 48 m below m.s.l. (Benac & *alii*, 2008b). The deepest point in Vrana Lake on Cres Island is 61.5 m below m.s.l. (Šegota & Filipčić, 2000). The maximum depth of karstification reaches -70 m in the Kvarner area according to Benac & Juračić (1998). These data correspond to paleo marine terrace at depths of 50 to 55 m (Miccadei & *alii*, 2011) and also to presumed paleo terraces at depths of 50 and 70 m (Miko & *alii*, 2021) which are a reliable indicator of sea-level stagnation.

Based on the reconstruction of the paleocoastline and paleochannels during the LGM on the Central Eastern Adriatic coast, it was assumed the sea-level was approximately 115 m lower than today. The total length of the Neretva riverbed was about 136 km longer, and the Cetina riverbed was assumed to be approximately 154 km longer than today (Sikora & *alii*, 2014).

The valley of the Zrmanja paleoriver can be traced along the Velebit Channel at a distance of approximately

140 km. The location of the paleo-riverbed is not visible on the ancient flood plains, unlike the canyons or straits. As a result, the shape and depth of paleobasins may have changed during the Late Pleistocene (figs. 4, 5, 6, 7, 8). This indicates that the length of this river was at least 200 km long, which is three times longer than its present-day lenght. However, there are not enough data on whether the Zrmanja paleoriver during LGM flowed on the surface to the Po paleoriver through straits between Ilovik and Premuda islands or Škarda and Ist islands. The other plausible possibility is that the Zrmanja paleoriver was a sinking river with ponors (swallow holes) in the polje in the present-day Kvarnerić basin (fig. 10). The rim of the Kvarnerić paleo-polje is a zone where possible archeologic submarine stone-age sites might be expected, as well as in submerged caves on the flanks of submerged canyons.

Since the end of the LGM, the sea-level rose very rapidly during the period between 19 ka and 7 ka B.P. (fig. 2). The seawater entered the Kvarnerić basin, probably through straits and submerged canyons between the Škarda and Ist islands. We presume that the flooding of the Velebit Channel was rapid. Three data on the sea-level rise in the region in Hasan (2017): onset of marine conditions were found at -36.5 m 11.4 ka B.P. in the southernmost part of the Velebit Channel; at -28.3 m 10.2 ka B.P; and -17.4 m 10.0 ka B.P. in the Novigrad Sea, indicate a rapid sea-level rise in the area at the beginning of the Holocene.

The sea flooded the entire Velebit Channel at the beginning of the relative stagnation of the Adriatic Sea level 7 ka B.P (fig. 2). The sea also flooded Pag and Ljubač bays as well as the Novigrad Sea. The present shape of the delta of Velika and Mala Paklenica torrents were formed after the last sea-level rise and during Holocene stagnation (fig. 4).

Seabed maps of limited accuracy were used in this investigation. Therefore, in future research, it would be necessary to use methods based on surveying by co-registration of side-scan sonar and multibeam echosounder images. In this way, it will be possible to obtain high-resolution seabed topography and surface details (Shang & *alii*, 2019). These data are especially important at the locations of partially or completely submerged karst canyons, which were the main connections between the basins during the Late Pleistocene and Holocene in the Velebit Channel. Acoustic sub-bottom profiling should be used to determine the thickness and characteristics of sediment cover, as well as the position and relief of bedrock (Tsai & Lin, 2022).

CONCLUSION

The present-day Velebit Channel was probably formed before the late Pleistocene as suggested by the presence of relatively deep sedimentary basins within the Channel. By analysing geographic (bathymetric) maps showing a detailed relief of the seabed, we were able to determine, with moderate accuracy, the boundaries of the submerged karst and deeper sedimentary basins, as well as the little-known connections between them. In this way, we were able to reconstruct paleogeographic conditions in the study area during the Late Pleistocene and Holocene.

The highly rugged terrestrial and submarine karst relief was formed in relatively resistant and low-erodible carbonate rocks. This relief probably little changed during the late Pleistocene and Holocene. Deep straits or canyons are the link between the depressions within the Velebit Channel, as well as with the marginal basins: the Pag and Ljubač bays and the Novigrad Sea. Therefore, even relatively small changes in sea level did significantly change paleogeographic conditions.

While the sea-level fluctuated between -20 m and -50 m i.e. between 110 ka and 70 ka B.P. (MIS 5.d - 5.a) the regression took place in the marginal basins: the Novigrad Sea, the Ljubač Bay, and in the Pag Bay, but also in the extreme SE part of the Velebit Channel. The connection to the open sea was possible only through deep canyons cut into the carbonate bedrock. Therefore, these isolated water bodies could have had a specific evolution of paleoenvironmental conditions.

When the sea-level fluctuated between -50 m and -80 m i.e. between 75 ka and 30 ka B.P. (MIS 4 and MIS 3) the sea gradually retreated from the southeastern part of the Velebit Channel to the northwest. Marine connection between the central part of the Velebit Channel and the northern part between Rab Island and the mainland was interrupted. The remaining connection to Kvarnerić was possible only through the passage between the Pag and Rab islands and the strait to the southeast between the Dolfin Islet and the Pag Island. The previously submerged karst elevations emerged and the Kvarnerić basin became much smaller.

When the sea-level dropped to a depth between -100 to -120 m i.e. during LGM (30 ka to 20 ka B.P.) the sea completely withdrew from the Velebit Channel leaving only the Zrmanja paleoriver flow, and Kvarnerić became paleo-polje. Lakes could have been preserved in the deepest parts. The mostly impermeable flysch rock mass which extends in the centre of Pag Island prevented the water from flowing southwest through the karst underground.

After the end of the Last Glacial Maximum, the sea-level rose very rapidly between 19 ka and 7 ka B.P. and rapidly flooded the Velebit Channel. At the beginning of the relative stagnation of the Adriatic Sea level since 7 ka B.P., the sea had already flooded the entire Velebit Channel including the Pag and Ljubač bays, and the Novigrad Sea. Groundwater dynamics in the karst underground similar to the present was established.

The Velebit channel and Kvarnerić basin are a fine examples of drowned karst relief, where zones of unchanged karst paleorelief (fluviokarst canyons) are preserved, along with zones covered with recent/subrecent sediments in downstream part of the Zrmanja Paleoriver and the Kvarnerić paleo-polje. The area, especially the rim of Kvarnerić paleo-polje, and canyon flanks are a zone of promising submarine archeologic stone-age sites.

However, the seabed of Kvarner as a whole, including the southeastern part of the Velebit Channel, is a poorly explored area. Therefore, any new spatially and temporally sound research result could help in further reconstruction of geomorphological evolution, not only of the Kvarner area but also of the Croatian coast and seabed of the Adriatic Sea.

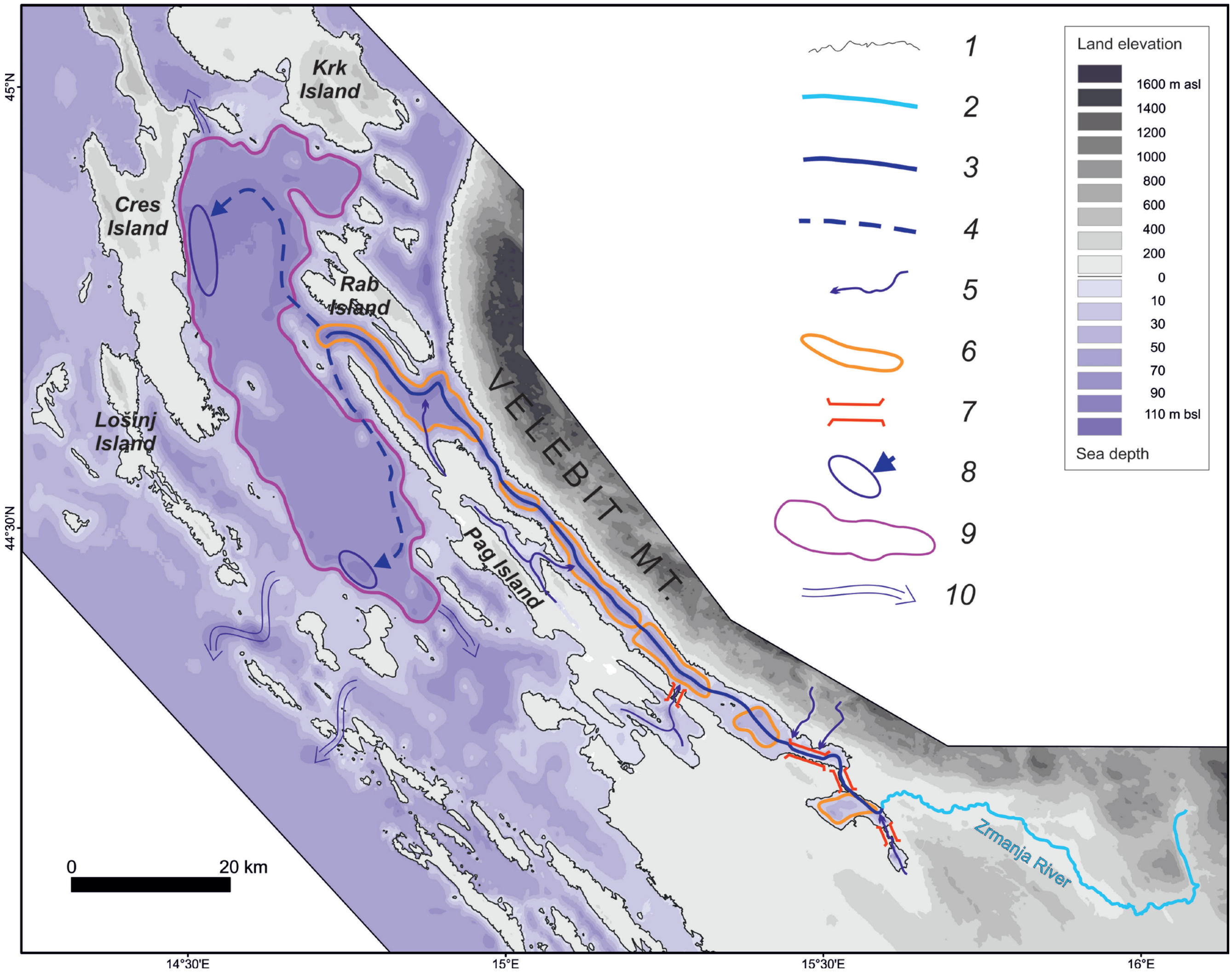

FIG. 10 - Main submerged geomorphological phenomena associated with the Zrmanja paleoriver: 1) recent shoreline; 2) recent Zrmanja riverbed; 3) valley of the Zrmanja paleoriver; 4) possible continuations of the Zrmanja paleoriver; 5) main tributaries; 6) presumed flood plains; 7) submerged canyon; 8) assumed ponor zones; 9) Kvarnerić depression with a possible karst polje; 10) possible surface connections of the karst polje and neighbouring lower terrains.

Future research should be focused on surveying through both: side-scan sonar and multibeam echo-sounding images, and methods of acoustic sub-bottom profiling. In this way, it will be possible to obtain high-resolution seabed topography and surface details including characteristics and thickness of the sedimentary cover, and bedrock relief.

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