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GEOMORPHOLOGICAL INDICATORS OF SEA LEVEL CHANGES DURING UPPER PLEISTOCENE (WÜRM) AND HOLOCENE IN THE KVARNER REGION (NE ADRIATIC SEA)

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Abstract:

This paper presents the data on the influence of the sea level change during the last 150000 years on the morphogenetic events in the Kvarner region (the north eastern part of the Adriatic Sea).

Some geomorphologic indicators with possible influences on sea level changes, such as the sea bottom morphology, the submarine zone sediments disposition, karsification depths, cave development depths and others have been analysed. The present land, coastal, and submarine relief in the Kvarner region was formed as a consequence of tectonic movements, different lithology, climatic changes, and sea level fluctuations during the late geological history, but also because of the erosional and accumulation processes caused by these changes. The remnants of the older morphogenetic phases have mostly been destroyed. The riverbeds were cut into the bedrock to –60 m because of the sea level fall during the Würm. The carbonate rocks were karstified 70 m below the recent sea level.

The present sediment distribution in the Kvarner submarine zone is a consequence of several morphogenetic phases correlated with the sea level changes during the Late Pleistocene. Due to much lower sea level in some periods of the Würm glacial the connections between the Rijeka Bay, Kvarnerić, Vinodol and Velebit channels and the open Adriatic were reduced or even interrupted. In the depressions of the Rijeka Bay, Vinodol and Velebit Channel during periods of lower sea level, lakes could be formed and only the Kvarnerić Bay could have remained connected to the Central Adriatic basin. In this period the Cres-Lošinj archipelago elevations were a morphologic barrier that divided the open Adriatic sedimentation zone from the relatively isolated Kvarner region. Therefore the sea bottom is considerably deeper eastern (-70 to-90 m) than western of the Cres and Lošinj islands (-40 to -50 m). That is also the reason for the bottom sediments western of Cres-Lošinj archipelago to be mainly sandy, while those on the eastern side to be more silty. Due to the lower sea level, the terrigenous material deposition occurred deeper and farther away from the present coastline, in areas where terrigenous influence is negligible today.

According to the traces of ancient riverbeds in the Kvarnerić region the sea level at the peak of Würm was more than 100 m below present position. Marine terraces on

-45 m and tidal notches on –19 m might have been formed during periods of the slower sea level rise or even its temporal stagnation during the Würm-Holocene transgression.

Key words:

Quaternary,Würm, Holocene, sea level, Adriatic Sea, Kvarner

GEOMORFOLOŠKI INDIKATORI PROMJENE MORSKE RAZINE TIJEKOM GORNJEG PLEISTOCENA (VIRMA) I HOLOCENA U PODRUČJU KVARNERA

Izvadak:

U radu se prikazuje utjecaj promjene morske razine tijekom posljednjih 150.000 godina na morfogenetska zbivanja u području Kvarnera (sjeveroistočni dio Jadranskog mora).

Analizirani su oni geomorfološki indikatori koji bi mogli ukazivati na promjene morske razine: morfologija dna, raspored sedimenata u podmorju, dubine okršavanja, dubine razvoja spilja i slično. Recentno kopno, obalni i podmorski reljef u području Kvarnera su posljedica tektonskih pokreta, različitog litološkog sastava, klimatskih promjena i fluktuacije morske razine tijekom mlađe geološke prošlosti, ali također i posljedica erozijskih i akumulacijskih procesa prouzročenih tim promjenama. Tragovi starijih morfogenetskih etapa uglavnom su uništeni. Zbog snižavanja morske razine tijekom virma korita vodotoka usječena su u podlogu do -60 m. Karbonatne stijene su okršene 70 m ispod današnje razine mora.

Današnji raspored sedimenata u podmorju Kvarnera posljedica je nekoliko morfogenetskih etapa sukladnih promjenama morske razine tijekom gornjeg pleistocena. Tijekom niže razine mora u nekim razdobljima virmskog glacijala veze između Riječkog zaljeva, Kvarnerića i Vinodolskog i Velebitskog kanala i otvorenog Jadrana bile su reducirane ili čak prekinute. U razdobljima niže morske razine u depresijama Riječkog zaljeva, Vinodolskog i Velebitskog kanala mogla su preostati jezera, a jedino je Kvarnerić mogao ostati povezan s morskim bazenom srednjeg Jadrana. U tom razdoblju uzvišenja Cresko-lošinjskog otočja bila su morfološka barijera koja je odvajala sedimentaciju u zoni otvorenog Jadrana od relativno izoliranog akvatorija Kvarnera. Zato su dubine mora znatno veće istočno od Cresa i Lošinja (-70 do –90 m) od onih na zapadu (-40 do –50 m), te su sedimenti zapadno od Cresko-lošinjskog arhipelaga pretežno pjeskoviti, a istočno više muljeviti. Zbog obalne linije koja je bila niže i dalje od današnje, taloženje krupnozrnatih terigenih sedimenata zbivalo se dublje i dalje od recentne obalne crte, u području gdje je utjecaj terigene sedimentacije danas zanemariv.

Sudeći prema usječenim dolinama vodotoka koji su tekli do bazena Kvarnerića, more je na vrhuncu virma bilo preko 100 m niže. Tragovi marinskih terasa na –45 m i plimskih potkapina na –19 m mogli bi biti posljedica sporijeg rasta ili čak stagnacije morske razine tijekom virmsko-holocenske transgresije.

Ključne riječi:

kvartar, virm, holocen, morska razina, Jadransko more, Kvarner

INTRODUCTION

The sea level is a global boundary with the weathering and the erosional processes prevailing above it, whereas the accumulation of sediments occurs below it. In accordance to the sea level changes during the geological history, the intensity and location of erosion, karstification and accumulation of sediments changed too (COWELL & THOM, 1997). Therefore, the sea level changes must have left traces on the coastal and submarine relief in the Kvarner region (fig. 1).

There are a few similar interpretations of the morphological evolution of the Adriatic Sea (D'AMBROSI, 1969; VAN STRAATEN, 1970; COLANTONI et al., 1979; PRELOGOVIĆ & KRANJEC, 1983; BRAMBATI, 1990; CORREGGIARI et al., 1996; JURAČIĆ, et al., 1999). According to these interpretations the present land, coastal and submarine relief in the Kvarner region is a consequence of tectonic movements, different lithology, climatic changes and sea level fluctuations during the late geological history, but also a consequence of erosional and accumulation processes caused by these changes. The recent investigations enabled to presume with greater reliability the global sea level changes during the last 150.000 years, namely from the Riss-Würm interglacial age till the preset days (FAIRBANKS, 1989; BARD H. et al., 1996; LOWE & WALKER 1997).

This paper presents an attempt of linkage of the relief forms and sediment distribution data in the Kvarner region with the sea level changes in that period. Geomorphologic indicators that could refer to the sea level changes were analysed, such as the sea bottom morphology, the pattern of sediments distribution on the seafloor, depths of karstification, depths of cave formation and others. The new data were collected, as well as the existing published data of the geological structures and geomorphologic peculiarities of the Kvarner region submarine zone were evaluated. The final objective of this paper is to present (on the basis of the present knowledge) the presumed morphological evolution of the Kvarner region since Riss-Würm interglacial.

Apart from its scientific value, the knowledge of the morphological evolution of the Kvarner region might be useful for the solution of the hydro geologic problems in coastal zone and the islands, as well as of the geotechnical ones.

AREA OF INVESTIGATION

Kvarner region (Kvarner *sensu lato*) is a part of the Adriatic Sea located between the Istrian peninsula and the Vinodol-Velebit coast. The island chains Cres-Lošinj and Krk-Rab-Pag divide it in the Rijeka Bay, the Kvarner Bay (*sensu stricto*), Kvarnerić and the Velebit and Vinodol Channel (fig. 1).

In the terrestrial part of the Kvarner region Lower Cretaceous limestones, Cretaceous carbonate breccias, Upper Cretaceous intercalated limestones and dolomites, along with Upper Cretaceous rudist limestones are presents. Paleogene deposits include foraminiferal limestones and clastic deposits (flysch - marls, sandstones and breccias in alternation) along with carbonate breccias (ŠIKIĆ et al., 1969; 1972; ŠUŠNJAR et al., 1970; MAGAŠ, 1968; MAMUŽIĆ, 1968; MAMUŽIĆ et al.,1969; 1970). Carbonates dominate, whereas flysch outcrops are restricted. Quaternary deposits partly cover this bedrock substrate. Red soil (*terra rossa*) is often found on limestones, whereas on flysch, a cover of weathered material and slope deposits is found.

According to geotectonic concept of the Adriatic and Dinarics structural formation (HERAK, 1986), the Kvarner region had a very dynamic tectonic evolution. The Kvarner region and the Istrian peninsula belong to the "Adrijatik" geodynamic unit, which is bordered by "Dinarik" unit on northeast. In a broader area the "Dinarik" unit overthrusts the "Adrijatik".

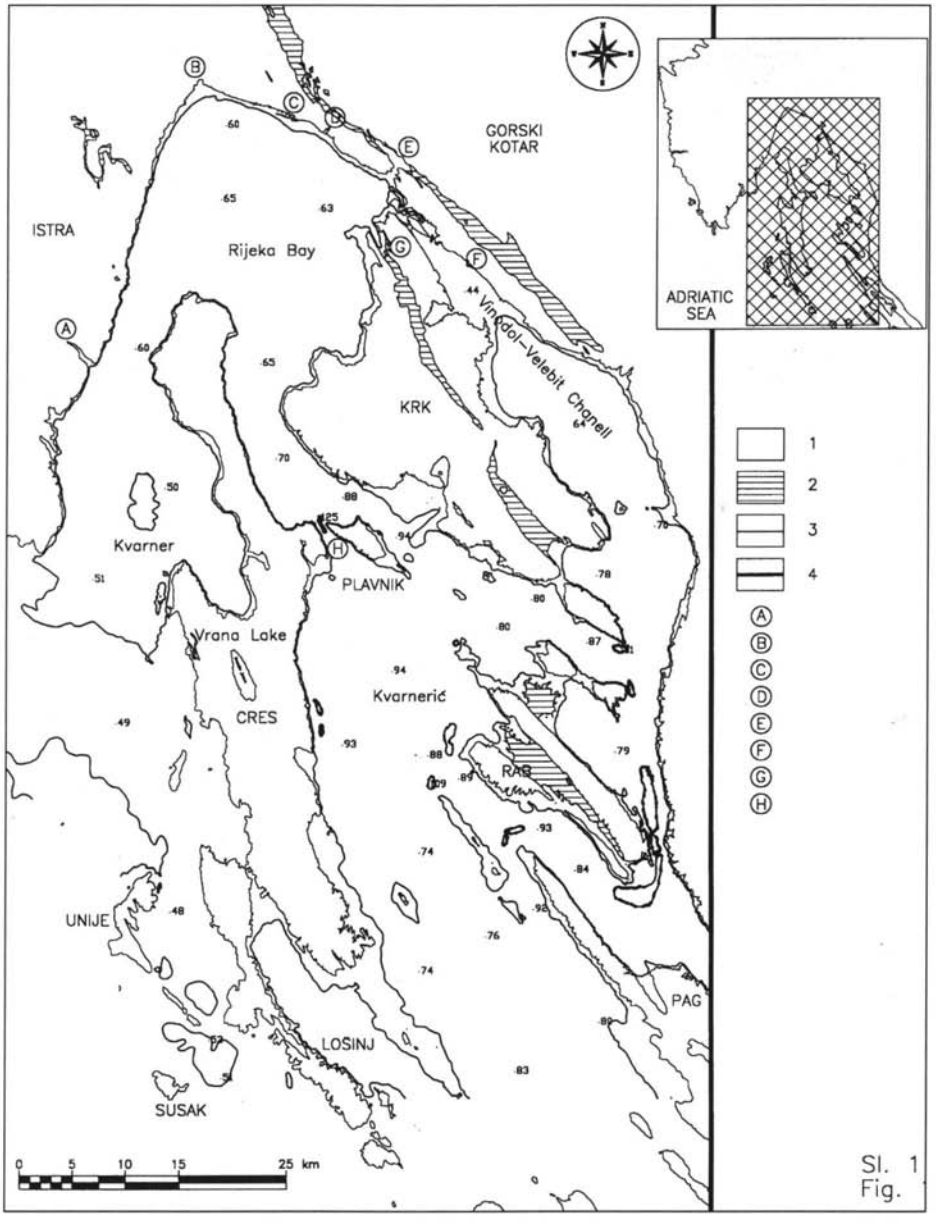

Fig. 1 - Lithologic and topographic map of Kvarner

1-Cretaceous and Paleogene carbonate rocks; 2-Peleogene flysch; 3-isobath –50 m; 4-isobath –100 m; A-Plomin Bay; B-Preluka; C-Rijeka; D-Martinšćica; E-Bakar Bay; F-the mouth of Dubračina River; G-Omišalj Bay; H-Krušija strait

Sl.1 Litološko-topografska karta Kvarnera

1-karbonatne stijene krede i paleogena; 2-fliš paleogena; 3-izobata –50 m; 4-izobata –100 m; A-Plominski zaljev; B-Preluka; C-Rijeka; D-Martinšćica; E-Bakarski zaljev; F-ušće Dubračine; G-Omišaljski zaljev; H-prolaz Krušija

Tectogenesis of the Kvarner region is in direct connection to the Adriatic carbonate platform subduction beneath the Dinarics during the Tertiary. Uneven intensity of subduction of the Istrian peninsula and of the Kvarner region (divided by the horizontal dextral Kvarner fault) beneath the Dinarides caused sinusoidal twist of structures with the Dinaric strike (NW-SE) into the meridional strike of the western part of the Kvarner region (MATIČEC, 1998). Neotectonic movements from the Lower Pliocene to the present played a dominant role in the actual relief formation. They appeared in the form of vertical and horizontal movements of different sign and intensity (PRELOGOVIĆ et al., 1981). These vertical movements resulted in sinking of the bottom of the Rijeka Bay, the Kvarnerić and the Vinodol and Velebit Channels, tilting towards southwest of the Kastav plateau, and the substantial uplift of the Učka ridge, Gorski Kotar mountains, of the Velebit Mountain, and of some parts of the Cres, Krk and Rab islands.

Due to these tectonic movements Cretaceous and Paleogene sedimentary rocks were folded and subsequently reverse faulting and overthrusting occurred. The main structures strike NW-SE. The actual diversity of relief in the Kvarner region is a consequence of contrasting lithology, reshaping of pre-existing structures and formation of new structures, along with the geomorphologic processes (MIHLJEVIĆ, 1998). The distinction between denudation-tectonical and denudation-accumulation morphostructural type could be made. Geomorphologic characteristics of the relief, tectonic structures, and high seismi city indicate very active recent tectonic activity (PRELOGOVIĆ et al., 1995; 1998).

At the seafloor of Kvarner area (*sensu lato*) three main sea bottom types are found: a) rocky bottom without sediments cover; b) bottom covered by coarse grained sandy and gravely sediments and; c) bottom covered by fine-grained muddy sediments (JURAČIĆ et al., 1999). However, fine-grained muddy sediments prevail at the seafloor of the Kvarner region. They are found in the Rijeka Bay, in the northern part of Kvarner Bay, in Kvarnerić, and in Vinodol and Velebit channels. Coarse (sandy) sediments are found near southern coast of Krk Island, around Rab and Susak islands, and southeastern of Cres-Lošinj archipelago towards the open part of the Adriatic Sea (JURAČIĆ et al., 1999).

GLOBAL SEA LEVEL CHANGES DURING THE LATE QUATERNARY

The global sea level changes during whole Pleistocene are not yet precisely reconstructed. The sea level at the glacial peaks is considered to be from 100 to 150 m below the actual one, while during the period of the interglacials could be few meters above the present sea level (SEIBOLD & BERGER, 1996). It is presumed that the Adriatic sea level oscillated accordingly during Pleistocene up to 150 m (VAN STRAATEN, 1970). The transgressive-regressive sequences in Pleistocene sediments of the Adriatic indicate such sealevel oscillations (TRINCARDI et al., 1994; TARI KOVAČIĆ, 1995; CORREGGIARI et al., 1996).

On the basis of geomorphologic and paleoclimatologic analyses a relatively accurate curve of the sea level fluctuations, during the last 150.000 years *i.e.* since the end of Riss glacial (CHAPPELL & SHACKLETON, 1986; TOOLEY, 1993, BARD et al., 1996) was acquired. At the peak of the Riss-Würm interglacial, some 135.000 to 120.000 years BP, the global sea level was similar to the recent one or up to 5 m higher. It was followed by the gradual sea level decrease which lasted up to 30.000 years BP. Therefore, during the relatively long time span of some 90.000 years, in accordance with climatic oscillations sea level fluctuated with amplitudes from 20 to 30 m

coming at least twice to 50 or 60 m below the present sea level.

Most researchers agree that during Würm climatic cold peak (25.000 to 20.000 years BP) the sea level was 100 m below the present surface, and most probably with terrestrial conditions in the major part of the northern Adriatic (D'AMBROSI, 1969, VAN STRAATEN, 1970; ŠEGOTA, 1982; CORREGGIARI et al., 1996). The recent results indicate that during last Würm stadial, there was a rapid global sea level drop to –120 or even –130 m (FAIRBANKS, 1989; STANLEY, 1995). The sea probably retreated from the northern Adriatic shelf, while the PaleoPo river with its tributaries flowed to the coastline at the northern rim of the Jabuka pit (Middle Adriatic depression MAD) (MORELLI et al., 1969; TRINCARDI et al., 1994; CORREGGIARI et al., 1996).

Some 18.000 years ago, along with the onset of the global heating, a fast rise of the sea level started. Due to melting of the glacial cover, sea level rose very fast and in steps between approximately 17.000 and 6.000 years whereas afterwards, the rise substantially decelerated. Fast rises occurred before approximately 14.200 yBP (MWP-1A), 11.500 yBP (MWP-1B) and before 7.600 yBP (calendar years, BLANCHON & SHAW, 1995). However stagnation of sea level rise occurred during Younger Dryas (from 11.000 to 10.000 years BP) and afterwards 8.400 to 8.000 years BP (FAIRBANKS, 1989; ALLEY et al., 1997). The average rise velocity was 37 mm/yr until 14.000 years BP. Afterwards, between 14.000 and 11.000 yBP the sea level rise velocity was only 10 mm/yr. After Younger Dryas event sea level rise again rose to 25 mm/yr (LOWE & WALKER, 1997). During last 6.000 years, the sea level rise has decelerated, and during Holocene the global sea level had never been higher then present one (KIDSON, 1986).

INDICATORS OF SEALEVEL CHANGES IN THE KVARNER REGION

In the Kvarner region, at the sea bottom a number of indicators have been discovered, suggesting different sea level positions during the last 150.000 years.

Among the erosive ones, the abrasion terraces (wave-cut platforms), incised V-shaped river valleys, karstification, bioerosion effects (tidal notches) can be singled out, while the present sediment distribution is the accumulative sea level indicator.

Geographic map of the Kvarner area shows at first sight puzzling differences in water depth, which seem to have logical foundation. In the open Adriatic west to the Cres-Lošinj archipelago the water depths are of only 40-50 m, while east, the depths in the Kvarnerić Bay reach more than 70-90 m (Fig. 1). The Kvarner area is a typical submerged karst relief. It shows numerous sea bottom elevations, more precisely, the submerged parts of the island structures as well as the isolated rocky elevations. The Rijeka Bay is a flat plain some 60 m deep. In a very narrow channel that serves as a link between the Rijeka Bay and the Vinodol Channel the depth reaches 60 m. In the considerably wider area of the Vinodol Channel the depth does not exceed 40 m. In relatively narrow straits between Krk and Rab islands, as well as between Rab and Pag islands, the sea floor exceeds the depth of 100 m. The greatest depth of 125 m was found in the strait of Krušija, between Cres and Plavnik islands (Fig. 1).

The important indicator of lower sea level in the Kvarner area is the abrasion part of the marine terrace formed in the limestone bedrock in front of the town of Rijeka. Its width is up to 50 m, while its present position is on the average depth of -50 m (BENAC & ŠEGOTA, 1990). The abrasion platform continuation was determined with the help of

geophysical surveying in the vicinity of the Martinščica Bay (ARBANAS & BENAC 1998). In the northern part of the Rijeka Bay, in front of the Preluka Bay on depth of -50 m and -66 m, two marine terraces in the partially consolidated Pleistocene sediments have been discovered. Today, they are covered with younger Holocene sediments (JURAČIĆ et al., 1998).

The basis of the Holocene sediments was determined on the depth of - 50 m in the Bakar Bay (MAGDALENIĆ et al., 1992) as well as in the Plomin Bay and Omišalj Bay (BENAC, 1994). In the Plomin Bay the marine wave-cut terrace in subrecent sediments is found on depth of - 45 m.

The ancient Rječina river channel as well as dry ravines on the locations of Potok (in the city of Rijeka) and Martinščica are cut into carbonate bedrock up to the depth of -60 m (BENAC, 1996).

Ancient river valley of the Dubračina river which flows into the Vinodol channel near the town of Crikvenica was also incised in a carbonate bedrock nearly to 40 m depth, and is now filled with Holocene alluvial sediments (BENAC et al., 1992).

On today's submerged parts of slopes around the Bakar and Plomin Bay the talus breccias are very frequent. The reddish color of their cement presents a clear sign that they have been formed in subaeral conditions. The Holocene sediment basis in numerous ravines in the area of the Kvarner Bay is also some 10 meters below the present sealevel. The overall Kvarner region submarine morphology indicates the existence of the submerged karst relief (fig.1). The karstification basis corresponds to the sealevel. Therefore the base-level erosion goes together with the intensive karstification which reaches the depth of -70 m in the western part of the Krk Island and the central part of the Cres Island (PAVIČIĆ, personal communication 1999), while the maximum submerged karst relief depth in the area of Kvarner exceeds 100 m. The sealevel stagnation caused also the groundwater level stagnation in the coastal zone. That phenomenon could cause formation of horizontal cave system. The largest submarine spring in front of the Ika settlement is determined at the depth of -22 m, while the one in the Bakar Bay is at -24 m (BENAC, 1994). Approximately on the same depth, but in different locations, a number of entrances of submerged caves has been detected, *e.g.* in front of the Kostrena settlement on the northern coast of the Rijeka Bay, on the northeastern side of the islet of St. Marko in the Čavlina Bay, as well as near Vrbnik on the Krk Island (ARKO-PIJEVAC et al., 1999).

The bottom of the Vrana Lake on the island of Cres which was formed in the karst depression is 40 m below mean sea level, while its deepest ponor-like depression reaches - 61 m (BIONDIĆ et al., 1995).

The living organisms in the littoral zone form in carbonate rocks, especially in limestones, the special microrelief form, the tidal notch (PIRAZZOLI, 1986). The notches are

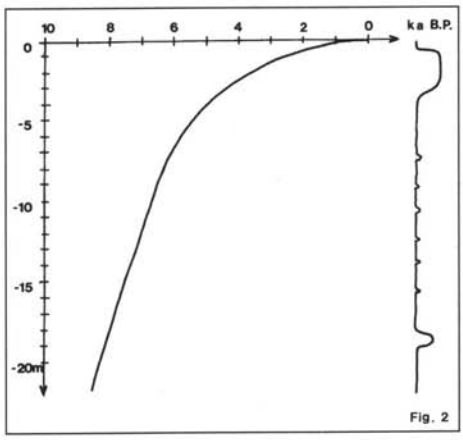

Fig. 2. - Comparision of tidal notches levels on submarine rocky scarps (NE coast of Krk island) and sealevel changes (according to FAIRBANKS, 1989)

Sl. 2 - Usporedba razina plimskih potkapina na podmorskim liticama (NE obala otoka Krka) i promjene morske razine (prema FAIRBANKS, 1989)

visible in numerous slopes and vertical rocky scraps in the Kvarner submarine zone in -19 m to -18 m depths. They are approximately 1 m high and 0,5 m deep. Above them, in the present infra-littoral zone the tidal notches of the flat concave shape up to 1,5 m deep and 3,5 m high are also visible on numerous spots (fig. 2).

Indicators of the lower sealevel in the Kvarner region are also coarse-grained sediments of the terrestrial origin, that are distant from the recent coastline and on the seafloor deeper than 40 or 50 m. This is well below the present wave base, and the actual terrigenous sedimentation is negligible. Such terrigenous, mostly sandy sediments are predominantly dispersed along zones of the intensive eroding of flysch rocks. Greater zones of sands and gravely sands can be found near outcrops of clastic rocks (flysch and loess) for example, in the southern part of the Krk Island (Baška and Stara Baška settlements) and around Rab and Susak islands (JURAČIĆ et al., 1999). Similarly, in the area of the open Adriatic west to the Cres and Lošinj islands, coarse-grained sediments cover the seafloor. They are probably of fluvial origin, transported by rivers from the Alps. However, during the Holocene transgression they were redeposited as coastal sands.

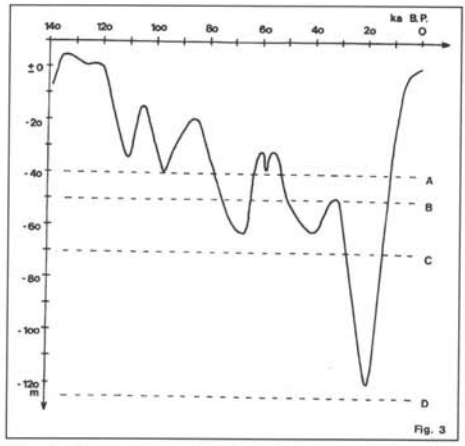

Fig. 3 Comparison of sealevel change during last 140000 years (according CHAPPEL & SHACKLETON, 1986; TOOLEY, 1993) and morphologic traces in the Kvarner area

A-bottom level of the Vrana lake (Cres island) and sumberged channel of the Dubračina river; B-base level of Holocene sediments in the Plomin Bay and the Bakar Bay, ancient river channel of the Rječina River and ancient abrasion terrace in the front of Rijeka city; C-maximum depth of karstification ; D-maximum depth of sea bottom in Kvarner area (Krušija strait)

Sl. 3 Usporedba promjene morske razine tijekom posljednjih 140.000 godina (prema CHAPPEL & SHACKLETON, 1986; TOOLEY, 1993) i morfoloških tragova u području Kvarnera

A-položaj dna Vranskog jezera (otok Cres) i potopljenog korita Dubračine; B-položaj podloge holocenskih sedimenata u Plominskom i Bakarskom zaljevu, fosilnog korita Rječine i fosilne abrazijske terase ispred Rijeke; C-maksimalna dubina okršavanja; D-najveća dubina dna u Kvarneru (prolaz Krušija)

DISCUSSION AND CONCLUSIONS

Intensive morphogenetic processes caused by tectonic movements and rapid sealevel changes, as well as climatic changes, provoked the present shape of the Kvarner region. The traces of older morphogenetic phases in this particular area during Lower and Middle Pleistocene are mostly destroyed or unrecognizable in the relief. On the basis of the geological surveys, geological and geomorphological indicators of the sealevel in the area of the Kvarner Bay and today's considerably well studied global sealevel changes during Upper Pleistocene, the geomorphologic evolution of the Kvarner Bay area from the Riss-Würm interglacial age to the present time, that is to say, in the last 150.000 years, can be reconstructed as follows.

During the peak of the Riss-Würm interglacial age, between 135.000 and 120.000 years, when the global sealevel was similar to the present one, the sea probably penetrated in the area of the recent Kvarner region (fig. 3).

Although the absolute sealevel was slightly above the present one, it probably did not reach the present coastline. The

reason for that was probably something-higher position of the land in that time, due to the tectonic subsidence of the Kvarner region since then (PRELOGOVIĆ & KRANJEC, 1983).

The wave cut marine terrace found in the submarine zones of the Rijeka and Kostrena settlements on depths from -50 to - 60 m, could have been formed during sealevel stagnation in the Riss-Würm interglacial (BENAC & ŠEGOTA, 1990). It is known that marine terraces can appear only in the conditions of relatively long sealevel stagnation, depending on rock resistance and destructive wave forces (GRIGGS & TRENHAILE, 1997). Today the marine erosion rate is relatively small in carbonate rocks in the coastal zone of the Rijeka Bay (BENAC, 1992). For formation of the marine terrace of the established width up to 100 m, several thousand years should be necessary. Therefore, the formation of the marine terrace could happen only exceptionally during the Würm glacial because of the strong sealevel oscillation in that period. The reason for that was relatively sheltered form of the Rijeka Bay, even at that time, where destructive wave forces were weak. By analysis of the sealevel change curve (fig.3), abrasion or wave-cut terrace could happen on top of the Riss-Würm interglacial age. The original level of the terrace has been changed, as a result of the tectonic subsidence (BENAC & ŠEGOTA, 1990). However, there is a possibility of its formation during the older interglacial ages or in the Würm, while the sealevel was roughly 50 m below the present one. On the Italian side of the Adriatic, using the geophysical surveying, the submerged terraces have been discovered on similar depths of some -60 m (VAN STRAATEN, 1970). Using the bottom boring in front of Venice, the Riss-Würm interglacial sediments were found on depths of -60 m to - 78 m (SERANDREI BARBERO, 1975).

After the Riss-Würm interglacial, in the period between 120.000 - 30.000, the sea level gradually decreased and oscillated between -20 m and - 60 m (fig. 3). By the sealevel decrease, as an absolute base level, the relief energy increased substantially, and erosion increased. Water channel incision was rather strong, most frequently reaching the depth of -50 to -60 m. As the Rijeka Bay and the Vinodol Channel bottoms are relatively shallow (-40 to -60m), they became local erosional base during the sea regression. Marine terraces were detected in the northern part of the Rijeka Bay formed in the semi-consolidated sediments on the depth between -50 and - 60 m, and today covered with younger Holocene sediments (JURAČIĆ et al., 1998). They could also have been formed during the sealevel stagnation in particular periods in Würm. However, the possibility of their formation at the beginning of Holocene should not be excluded, because of the sealevel stagnation during the Younger Dryas.

During time span of about 90.000 years (from 120.000 to 30.000 BP) while the sealevel decreased to the - 60 m depth, carbonate rock mass was also karstified. According to the results of water permeability measurements, the zone of increased karstification reaches the depth of -70 m in the western part of the Krk Island and the central part of the Cres Island (PAVIČIĆ, personal communication 1999). These results correspond to the results obtained in the Ravni kotari region (FRITZ, 1984). If compared depths of incised valleys with the karstification depth, their congruence is obvious. In regard to climatic changes, the karstification rate could sometimes be greater than the river erosion and the other way round (PAVIČIĆ & RENIĆ, 1992).

Due to the sealevel stagnation, some levels could become more karstified than others. The submerged caves are very frequent on depths between -20 m and -24 m. Their

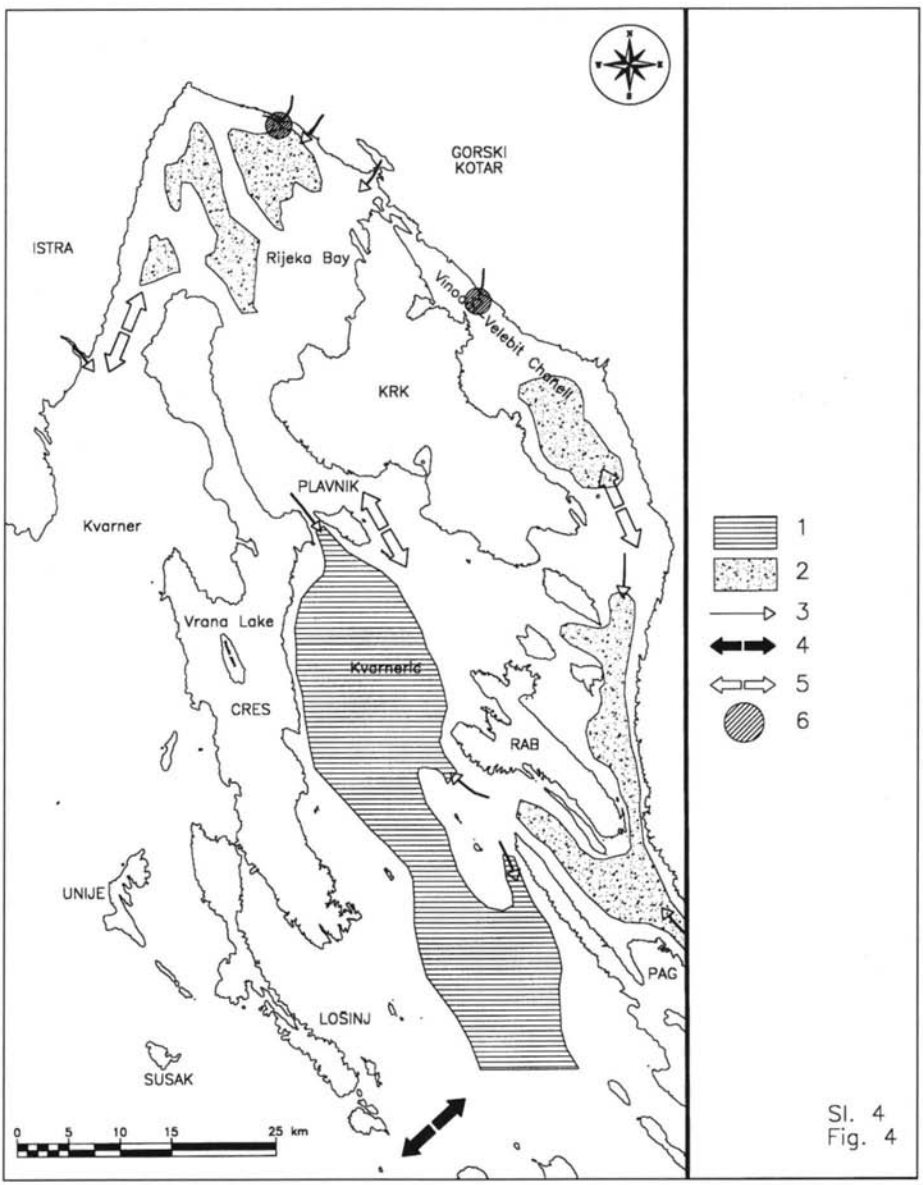

Fig 4. Morphological evolution of the Kvarner area during Würm glacial age

1-probable position of marine basin (90000-18000 yr B.P.); 2-probable position of periodical lakes (90000-18000 yr B.P.); 3-probable position of superficial waterflows (30000-18000 yr B.P.); 4-possible constant connection with marine basin in the Middle Adriatic; 5-periodically connected with marine basin; 6-intensive recent sedimentation

Sl. 4 Morfološka evolucija Kvarnera tijekom virmskog glacijala

1-vjerojatni položaj morskog bazena (90.000-18.000 g. B.P.); 2- vjerojatni položaj povremenih jezera (90.000-18.000 g. B.P.); 3-vjerojatni položaj površinskih tokova (30.000-18.000 g. B.P.); 4-moguća stalna veza s morskim bazenom u srednjem Jadranu;5-povremena prekinuta veza s morskim bazenom (90.000-18.000 g. B.P.); 6-izražena recentna sedimentacija

morphogenesis is closely connected to tectonic movements, and therefore the differences between certain islands from the Kvarner area are obvious (Božičević, 1992).

One can presume that paleorelief in Würm in general outlines resembled the present one, and therefore a relatively accurate reconstruction of depositional environments in that particular period is possible. By sealevel fall below -50 m, the water exchange between the Kvarner Bay and Rijeka Bay through the Vela Vrata strait became difficult or even impossible. The water exchange between the Velebit channel and the Kvarnerić Bay was also hampered (fig. 4).

In the isolated depressions of the Kvarner area, water could become brackish with time, and freshwater lakes could appear. The evidence of the freshwater or brackish environment has not been found yet. However, the considerable quantity of water flowing even today on surface or underground, towards the Rijeka Bay, the Vinodol and Velebit channels, as well as the results of the submarine geological surveys, support the hypothesis that brackish or freshwater lakes could have existed in the period of the lower sealevel Benac et al., 1995) (fig. 4).

The described sealevel changes during the Würm period are very important for the understanding of differences in water depths and sediment distribution in the Kvarner area. The majority of the terrigenous material sedimented in the northern Adriatic came with the river from the Alps. Today the sea current system carries that material along the Italian coast. During the Würm period and the lower sealevel, the rivers filled the northern Adriatic alluvial plain with terrigenous sediments. Istrian peninsula, as well as the islands of the Cres-Lošinj archipelago protected the eastern part of the Kvarner area from covering-up. This could explain the present differences in bottom depth, where the depths east of Cres and Lošinj islands vary from -70 m to -90 m, with maximum of -125 m, while on the west of the Cres-Lošinj archipelago the depth reaches only -40 m to -50 m (fig. 1). The difference is also in the type of sediment cover. West of the Cres and Lošinj islands sediments are predominantly sandy and belong to the Padane petrographic province, while east of it, sediments are more silty, and belong to the Kvarner petrographic province (Škrivanić & Magdalenić, 1979, Juračić et al., 1999).

At the same time, due to the lower sea level, the former coastline in the Kvarner area was seaward from the present one, and therefore the local coarse-grained sediments deposition around sources of terrigenous material (flysch and loess) occurred seaward from the present coastline, in the areas where recent terrigenous sedimentation is negligible, namely, south of the Krk Island, in front of the Baška and Stara Baška settlements, and around the Rab Island.

At the top of the Würm glacial some 20.000 - 25.000 years ago, the Adriatic sea level was lowered to at least -100 m, with great probability that the lowering reached -120 m, or even - 130 m. The sea withdrew completely from the open part of the northern Adriatic, and west to the Cres-Lošinj archipelago the alluvial plain existed, where the river Po and its tributaries probably flew towards the Jabuka pit. The winds blew over this plain carrying fluvial sediments to the Kvarner area (Bognar, 1998). In depressions of the present day Rijeka Bay (Benac, 1996) and in the Velebit channel most probably lakes remained. The deeper Kvarnerić Bay could have been connected with the marine basin in the central and southern Adriatic for the longest period of time. The freshwaters from the Rijeka Bay probably flew out through the narrow strait between Plavnik and Cres islands, where depth 125 m has been measured, or they sank in swallow hole. It is important to stress that at the top of

Würm the climate was considerably colder and arid (LOWE & WALKER, 1997), and therefore streams could not incise their valleys in grater extent. On the basis of depths that exceed 100m in the Pag channel, between Rab and Pag islands, one could presume that surface streams from the Vinodol Channel and Velebit Channel (the paleoZrmanja River) flew that way. The existence of the submerged river valleys was detected by echo-sounding (BENAC et al., 1995) (fig. 4).

The sea began to flood the northern Adriatic area, and in this respect the Kvarner area some 18.000 years ago. The rapid rise was between 17.000 and 6.000 years BP. Hydrographic and sedimentary conditions similar to the present ones appeared only after decrease in sealevel rise some 6.000 years ago. The sea covered the karst relief, and due to the fact that input of terrigenous material was relatively small, higher karstic rocky areas remained uncovered. However, in the deeper parts of the paleorelief started the sedimentation of those small quantities of terrigenous material that enters into the sea. Because of such a rapid rise marine erosion could not have been expressed on the ancient coasts, shaped predominantly in relatively strong and resistant carbonate rock. As the sealevel rise in the Mediterranean area was not even (PIRAZZOLI & PLUET, 1991), a temporarily stagnation could have left remnants of the marine erosion on the certain levels. The platforms in the Plomin Bay and Vinodol Channel bottoms at - 45 m depth could have been formed during the Younger Dryas, some 11.000 to 10.000 years ago (FAIRBANKS, 1989; LOWE & WALKER, 1997) (fig. 5).

Tidal notches are visible on the submarine rocky steeps, on numerous locations in the Kvarner area, at depths of -19 to - 18 m (fig. 2). They could have formed during the stagnation, or slow sealevel rise, some 8.400 - 8.000 years BP (ALLEY et al, 1997). Their small height and depth (1,0 m, or 0,5 m) suggests it. In comparison, the subrecent to recent tidal notches on the Kvarner area coasts are concave in shape, up to 3,5 m high and 1,5 m deep, as a consequence of the slow sealevel rise during last millenniums (PIRAZZOLI, 1980; BENAC, 1989).

During Holocene sealevel rise the sea flooded river valleys, causing formation of estuaries. Slow sealevel rise during the last 6.000 years created the conditions for filling of the earlier formed estuaries (SEIBOLD & BERGER, 1996). Transport and deposition of alluvial sediments at river mouths caused the seaward shift of the coastline. This is especially visible on the mouths of the Raša, Rječina and Dubračina rivers, where marine sediments were found in borings upstream of the present river mouths (BENAC et al.,

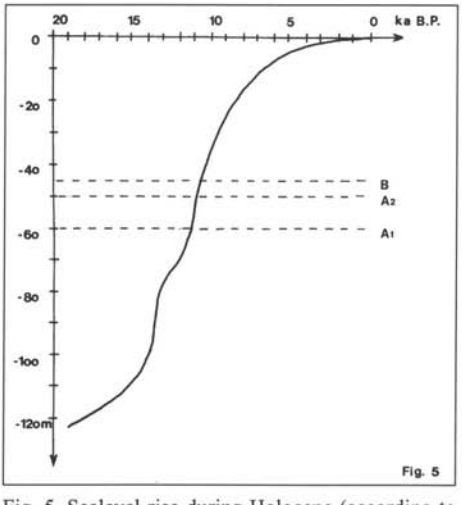

Fig. 5. Sealevel rise during Holocene (according to FAIRBANKS, 1989)
A1 and A2 position of submerged marine terraces in Rijeka Bay (formed in Pre-Holocene sediments)
B- position of submerged marine terraces in the Plomin Bay and Vinodol Channel (formed in recent sediments)
Sl.5 Rast morske razine tijekom holocena (prema FAIRBANKS, 1989)
A1 i A2 položaj potopljenih marinskih terasa u Riječkom zaljevu (stvorenih u pretholocenskim sedimentima)
B-položaj potopljenih marinskih terasa u Plominskom zaljevu i Vinodolskom kanalu (stvorenih u recentnim sedimentima)

1992). In the remaining marine part of the Kvarner area recent sedimentation is small causing the preservation of the Würm paleorelief.

The Kvarner region is relatively better investigated and described area in comparison to the rest of Croatian coast. However, there are still not enough strong proofs to document in detail its geomorphologic evolution. The reasons for that are inadequately examined neotectonic movements and sealevel oscillations. Therefore, every new result, deeply rooted in time and space, would present an important step towards the better understanding of the geomorphological evolution. That might considerably change the present reconstruction, not only regarding the Kvarner area relief evolution, but also the Adriatic Sea evolution as a whole.

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SAŽETAK

GEOMORFOLOŠKI INDIKATORI PROMJENE MORSKE RAZINE TIJEKOM GORNJEG PLEISTOCENA (VIRMA) I HOLOCENA U PODRUČJU KVARNERA

ČEDOMIR BENAC i MLADEN JURAČIĆ

U radu se analizira utjecaj promjene morske razine na morfogenetska zbivanja u području Kvarnera (sjeveroistočni dio Jadranskog mora) tijekom posljednjih 150.000 godina. Kvarner čine Cresko-lošinjsko otočje, otoci Krk i Rab, nekoliko manjih nenaseljenih otočića i hridi, kao i pripadajuće obale Istre i Vinodola. Između kopna i otoka nalaze se akvatoriji Riječkog zaljeva, Kvarnera u užem smislu, Kvarnerića, Vinodolskog i Velebitskog kanala. Na geografskoj karti Kvarnera vidljive su velike razlike u dubinama podmorja koje se ne čine logičnima (sl.1). Dubina otvorenog dijela Jadrana, zapadno od Cresko-lošinjskog otočja svega je od 40 do 50 m, a dubina Kvarnerića je od 70 do 90 m. Riječki zaljev je zaravnjen na dubini oko 60 m. U Vinodolskom i Velebitskom kanalu dobina je od 40 m do 70 m. U relativno uskim prolazima između otoka Krka i Raba, te Raba i Paga dubine su također mjestimično veće od 100 m. Najveća dubina od 125 m izmjerena je u prolazu Krušija između otoka Cresa i Plavnika.

U građi kvarnerskog prostora sudjeluju bituminozni vapnenci donje krede, prijelazne kredne karbonatne breče, gornjokredni dolomiti i vapnenci u izmjeni, te rudistni vapnenci. Od paleogenskih naslaga zastupljeni su foraminiferski vapnenci i sitnoklastične naslage (fliš) te karbonatne breče. Karbonatne naslage su prostorno dominantne, dok je rasprostranjenost fliša ograničena. Ove naslage čine osnovnu stijensku masu koja je na kopnu djelomično pokrivena mlađim tvorevinama.

Podvlačenje Jadranske karbonatne platforme pod Dinaride u izravnoj je svezi s tektogenezom Kvarnerskog područja. Neotektonski pokreti od donjeg pliocena do danas imali su presudnu ulogu u oblikovanju današnjih struktura. Odražavali su se u horizontalnim i vertikalnim pokretima različitih predznaka i intenziteta.

Današnja raznolikost reljefa na kopnu i u podmorju posljedica je litološkog sastava, preoblikovanja postojećih i stvaranja novih struktura kao i geomorfoloških procesa. Morfološke odlike reljefa i strukturni sklop naslaga kao i izražena seizmičnost, također ukazuju na vrlo živu recentnu tektonsku aktivnost.

Tijekom transgresije na vrhuncu risvirmskog interglacijala, između 135.000 i 120.000 godina globalna morska razina bila je slična današnjoj ili nešto viša (sl. 3). Jedini do sada poznati dokaz stagnacije mora u području današnjeg akvatorija Kvarnera je abrazijska terasa. Danas se nalazi na dubini –50 m zbog tektonskog spuštanja kvarnerskog prostora.

U relativno dugom razdoblju od približno 90.000 godina (između 120.000 i 30.000 godina) morska razina oscilira između -20 m i -60 m. Spuštanjem razine mora bitno je pojačana erozija. Posebice je bilo izraženo usjecanje vodotoka. Povlačenjem mora dna Riječkog zaljeva i Vinodoskog kanala postala su lokalne erozijske baze. Fosilna korita Rječine, kao i podloga sada neaktivnih rječnih dolina Potok i Martinšćica, smještene u okolici Rijeke usječena su do dubine od -60 m. Fosilno korito Dubračine koja kod Crikvenice utječe u Vinodolski kanal usječeno je u stijensku podlogu gotovo do -40 m, a to je i baza sedimentima holocenske starosti (sl. 1).

Bušenjem je također otkriveno više geomorfoloških indikacija niže razine mora. Na danas potopljenim dijelovima padina u dolini Rječine i Bakarskom i Plominskom zaljevu česte su siparne breče. Crvenkasta boja njihovog veziva jasan je znak da su formirane u terestičkim uvjetima. Podloga holocenskih sedimenata u brojnim jarugama na području Kvarnera nalazi se nekoliko desetaka metara ispod sadašnje morske razine. Na dubini od –50 m ustanovljena je podloga holocenskih sedimenata u Bakarskom zaljevu, kao i u Plominskom i Omišaljskom zaljevu. Dokazi stagnacije mora tijekom virma su i dvije abrazijske terase, danas pokrivene mlađim sedimentima. Ustanovljene su u sjevernom dijelu Riječkog zaljeva na dubini -50 i -60 m. Apsolutna dubina dna jezera Vrana na otoku Cresu je –40 m, a udubljenje u njemu seže do -61 m.

Zbog pomaknute obalne linije, terigeni sedimenti taložili su se daleko od recentne obalne crte, gdje je utjecaj terigene sedimentacije danas zanemariv. Tako se može objasniti nastanak većeg dijela pjeskovitih sedimenata koje nalazimo na dubinama većim od 40 ili 50 m. Pretežno pjeskoviti sedimenti posebice su rasprostranjeni uz zone intenzivnog erodiranja fliških naslaga. Zato se veće zone pijesaka i šljunkovitih pijesaka nalaze oko izvora terigenog materijala (fliša i lesa): južni dio otoka Krka (Baška i Stara Baška), oko otoka Raba i Suska. Zapadno od Cresko-lošinjskog otočja odvijala se istovremeno intenzivna sedimentacija materijala čiji su glavni izvor bile rijeke koje su pritjecale iz Alpa. Ti su sedimenti također pretežno pjeskoviti.

Sa spuštanjem erozijske baze povezana je i zona intenzivnog okršavanja koja seže do dubine -70 m na zapadnom dijelu otoka Krka i u središnjem dijelu otoka Cresa. Zbog stagnacije morske razine neki horizonti su jače okršeni. Otvor najveće vrulje u Iki ustanovljen je na dubini -22 m, a one u Bakarskom zaljevu na -24 m. Približno na istim dubinama otkriveni su i otvori potopljenih spilja ispred Kostrene na sjevernoj obali Riječkog zaljeva, na sjeveroistočnoj strani otočića Sv. Marko, u uvali Čavlena kao i kod Vrbnika na otoku Krku.

Na vrhuncu virma razina Jadranskog mora spustila se do najmanje -100 m, a vjerojatno do -120 m pa čak i do –130 m. More se posve povuklo iz otvorenog dijela sjevernog Jadrana, a zapadno od otočkog niza Cres-Lošinj bila je naplavna riječna ravnica preko koje su puhali vjetovi donoseći les na područje Kvarnera. U depresijama na sadašnjem dnu Riječkog zaljeva, a možda i Velebitskog kanala vjerojatno su preostala jezera. Hipsometrijski niže smješten akvatorij Kvarnerića, najdulje je ostao povezan s morskim bazenom u srednjem i južnom Jadranu. Vode iz Riječkog zaljeva praznile su se vjerojatno kroz uski prolaz između Plavnika i Cresa, gdje je izmjerena najveća dubina od –125 m ili su tamo ponirale. Vode iz Vinodolskog i Velebitskog kanala (ondašnja Zrmanja) tekle su kroz Paška vrata između Raba i Paga (sl. 4). To je vidljivo i po dubinama preko 100 m u tom području (sl. 1). Postojanje danas potopljenih riječnih korita potvrđeno je i hidroakustičkim mjerenjima.

More je počelo plaviti sjeverni Jadran, pa tako i područje Kvarnera prije nešto više od 18.000 godina. Hidrografski i sedimentacijski uvjeti slični današnjima nastali su tijekom holocena. More je potopilo krški reljef, a budući da je donos materijala s kopna bio relativno malen, izdignuta kamenita područja su ostala nepokrivena. Međutim u udubljenim dijelovima paleoreljefa počelo je taloženje onog dijela materijala koji ipak dospijeva s obale. Holocenski rast morske razine bio je vrlo brz, ali prije skokovit nego kontinuiran što je smanjilo mogućnosti stvaranja tragova marinske erozije u stjenovitom reljefu podmorja.

Unatoč brzom rastu mora razina je povremeno stagnirala. Dokazi usporavanja rasta morske razine krajem virma ili početkom holocena su abrazijske terase na dubini oko -45 m u Plominskom zaljevu i Vinodolskom kanalu (sl. 5). Tragovi potopljenih plimskih potkapina (tidal notch) nastalih pojačanom bioerozijom u karbonatnim stijenama, vidljivi su posvuda na vrlo strmim do vertikalnim podmorskim liticama na dubini –19 m do –18 m. Visine su oko 1 m i dubine oko 0,5 m. Njihova pojava je jasan znak kratkotrajnog usporavanja dizanja morske razine (sl. 2).

More je tijekom holocena potopilo riječne doline i stvorilo estuarije. Usporavanjem rasta morske razine na tim se lokacijama počinje događati suprotan proces: oplićavanje dna i pozitivno pomicanje obalne crte zbog taloženja sedimenata. Taj proces je osobito izražen na ušćima Raše, Rječine i Dubračine gdje su bušenjem ustanovljeni tragovi marinskih sedimenata uzvodno od sadašnjih ušća.

Kvarner je relativno bolje istraženo, a u znanstvenim radovima i bolje obrađeno područje u odnosu na veći dio hrvatske obale Jadranskog mora. Međutim, još nema dovoljno čvrstih dokaza, na temelju kojih bi se mogao odrediti pouzdan slijed morfološke evolucije. Razlog tomu su nedovoljno istraženi neotektonski pokreti i oscilacije morske razine. Zato je nedovoljno pouzdano datiranje nastanka morfoloških oblika samo na temelju komparacije s globalnim pokazateljima fluktuacije morske razine, a bez bez određivanje apsolutne starosti njihovog nastanka. Svaki novi, prostorno i vremenski čvrsto utemeljen rezultat istraživanja pomoći će u rekonstrukciji morfološke evolucije.

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