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RECONSTRUCTION OF PALEOENVIRONMENT IN THE BAY OF KOPER (GULF OF TRIESTE, NORTHERN ADRIATIC)

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ABSTRACT

Geomorphologically, the Bay of Koper (Gulf of Trieste, northern Adriatic) is a wide submerged valley of the Rižana river. Five boreholes drilled in the inner part of the Bay of Koper were used to reconstruct the paleoenvironment of the Bay in the Holocene. These changes are clearly related to the global changes of sea level. The cross-section of the Holocene sediment in the Bay indicates that the early Holocene - late Glacial sediment, dated to about 10-11000 years BP, occurred in the southern part of the Bay when the sea started to enter the Rižana valley. When the southern part of the valley was submerged, the eastern part was still influenced by the Rižana fluvial deposits. Marine sedimentation prevailed over fluvial sedimentation at depth of 26 m during the most intensive sea transgression. Studied boreholes also indicate simultaneous sea level rise and sedimentation process in the Bay during the Holocene. These data are in accordance with the general of sea-level rise in the northern Adriatic in Holocene.

Key words: recent sediment, paleoenvironment, Bay of Koper, Gulf of Trieste, Adriatic Sea

INTRODUCTION

The Bay of Koper covers about 35 km^2 and is, as a component of the larger Gulf of Trieste, the northernmost part of the Mediterranean. Geomorphologically, it is a submerged Rižana valley. At present it is a wide submarine plateau up to 20 m deep which is, according to the data obtained from some boreholes in the Port of Koper and its vicinity, composed of a few tens of meters of Quaternary sediment (Ogorelec *et al.*, 1988). Towards the west, *i.e.* along the Izola - Debeli rtič line, the Bay grades towards the open part of the Gulf of Trieste (Fig. 1). There, recent Quaternary sediment reaches, according to the seismic data obtained by Italian researchers, thickness of up to 230 meters (Rossi *et al.*, 1968). In spite of the riverine inflows of the Rižana river and the Badaševica stream, the Bay of Koper is quite closed, with fairly limited water circulation. The boundary between oxidation and reduction sedimentary environments is located in surficial sediment a few millimeters below the surface. Study of the bottom relief has shown that Koper Bay has a fairly steep coast which, however, at depths between 5 and 10 meters quickly grades into a very gently sloping underwater plain. The coast is composed of Eocene flysch layers with characteristically alternating solid sandstone and soft marl. The flysch coast gives to the Bay its characteristic form, particularly between Izola and Koper, at Cape Ronek and between Valdoltra and Debeli rtič. The coast is gentle only between Koper and Ankaran.

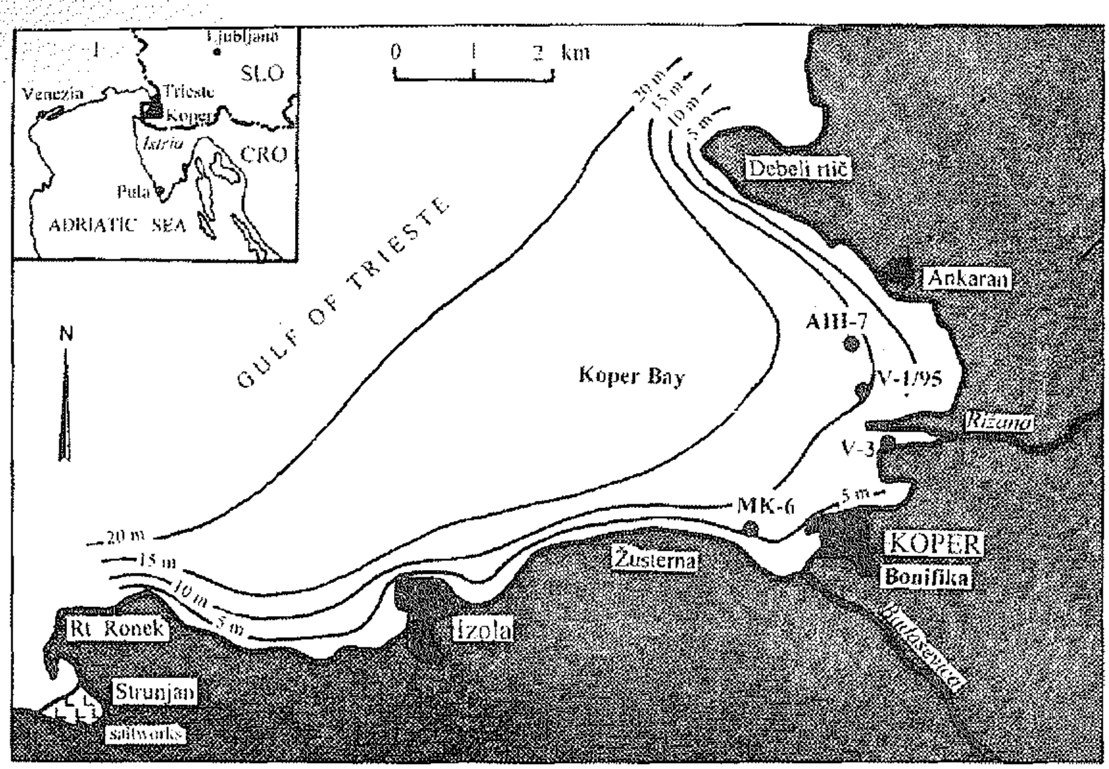

Fig. 1: Bathymetry and the position of studied boreholes in the Bay of Koper (Gulf of Trieste, northern Adriatic).
Sl. 1: Koprski zaliv: batimetrija in lokacije raziskanih vrtin.

Characteristic of the Bay are low winter (averaging 8 °C in February) and rather high summer water temperatures (averaging 24 °C in July). In late autumn and during winter, isothermia takes place. Shalowness, the mixing of water due to the strong winds (especially the so-called bora), and sediment resuspension caused by maritime traffic are the reasons for the high turbidity of these coastal waters. The concentration of suspended matter in the sea water column ranges between 1 and 18 mg/l and on average 60% is inorganic (Ogorelec *et al.*, 1991). Greater amount of suspended matter has been noted in the Rižana river mouth and this has been also confirmed by lower Secchi disc visibility. In the Rižana river mouth it reaches a depth of about 3 meters and in the central part of Koper Bay between 8 and 10 meters.

Recently, through multidisciplinary and systematic research carried out by geologists from the Geological Survey Ljubljana, chemists and biologists from the Marine Biological Station Piran and Jožef Stefan Institute Ljubljana, and paleontologists from the Research Center of the Slovene Academy of Sciences and Arts Ljubljana, we have obtained a fairly clear picture on the composition of the marine sediment in the southern (Slovene) part of the Gulf of Trieste (northern Adriatic). This study initially covered the Sečovlje saltwotks (Ogorelec *et al.*, 1981), successively the sediment of the Koper Bay (Ogorelec *et al.*, 1987), the open part of the Gulf of Trieste (Ogorelec *et al.*, 1991; Faganeli *et al.*, 1991), and a boreholes in Koper Bay (Ogorelec *et al.*, 1984; Faganeli *et al.*, 1987; Faganeli *et al.*, 1991). The sediment of Piran Bay was studied in detail by Ranke (1976) in the early 70's. These studies also implemented previous geographical and archaeological studies of the Slovene sea, its coast and Šavrinsko Primorje in the hinterland (Žumer, 1984; Kozličić, 1984; Župančič, 1986; Šegota & Filipčić, 1991).

The aim of this paper is to present a reconstruction of the paleoenvironment in the Bay of Koper through the latest geological period as well as the basic characteristic of marine sediment and the processes occurring in it. This description is particularly important for the appropriate study of sedimentary biogeochemical processes and pollution. Sampling and analytical methods are described elsewhere (Ogorelec *et al.*, 1987; 1991; Faganeli *et al.*, 1987; 1991).

SURFICIAL SEDIMENT OF THE BAY OF KOPER

Considering the grain size distribution, mineral composition and carbonate content the surficial sediment of the Bay of Koper can be divided into three distinct zones (Fig. 2): coastal sediment (zone A), sediment of the inner part (zone B), and sediment of the open part of the Bay (zone C). Along the coast there is a strip ranging from a few tens of meters to 300 meters large (zone A) com-

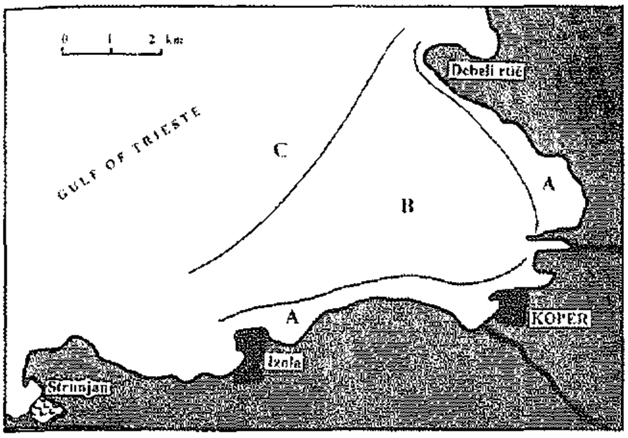

Fig. 2: Zonation of surficial sediment in the Bay of Koper. A - Coastal sediment, B - sediment of the inner part of the Bay, C - sediment of the open part of the Bay.
Sl. 2: Porazdelitev con površinskega sedimenta Koprskega zaliva: A - obrežni sediment, B - sediment notranjega dela zaliva, C - sediment odprtega dela zaliva.

posed of dark gray - green silt and sandy silt with up to 40% of sand and with less than 15% of clay (below 2 μm). The mean grain size ranges between 0.05 and 0.1 mm, while the contents of carbonates, composed of calcite, dolomite and shells of various organisms, are between 20 and 30%. The distribution of the clay in zone A is conditioned by the wave motion along the coast and its transportation to somewhat deeper and calmer parts of the Bay. Sand (above 63 μm) is composed of lithic fragments of coastal flysch rocks, shells of various organisms (shellfish, mollusks, foraminifers, sea urchins, and others), seagrass, wood, small tars of bitumen and, to a lesser extent, particles of anthropogenic origin (brick, glass, plastic, concrete, *etc.).*

In the inner part of the Bay (zone B, Fig. 2), including the majority of the Bay below the sea water depth of about 5 meters, the sediment becomes finer and more homogenous. The sediment is clayey silt with up to 40% of clay and up to 3% of sand. Its mean grain size is below 0.1 mm, while the carbonate content reaches about 30%. Towards the western part of the Bay the carbonate content increases. Here, in coarse fraction shells and skeletons of various organisms also prevail.

Towards the open part of the Bay (zone C, Fig. 2) the sediment is coarser (about 20% of sand with grains above 63 μm) because of lower contents of the clay component reaching less than 15%. Its mean grain size ranges between 10 and 40 μm, and the carbonate content between 30 and 45%. The high carbonate content is closely associated with numerous particles of organic skeletons. Clay is partially rewashed by the current flowing between Izola and Debeli rtič.

Mineralogically, the entire Koper Bay belongs to a uniform "mineral province", from where the minerals originate. This is the result of the input of particles originating from run-off mostly from the Rižana river, and erosion of the coast, built of flysch layers of Šavrinsko Primorje and Cretaceous-Paleogenic limestones of the Western Čičarija. The most abundant minerals in the recent sediment of Koper Bay are quartz and calcite. Quartz is present in all fractions, its content ranges from 20 to 35% and originates from flysch sandstones and marls. Also, calcite is mostly of terrigenous origin but its rather large part is associated with organic skeletons. Dolomite, as the second carbonate mineral, is much less common reaching only about 5%. Clay is composed of illite, chlorite and illite/montmorillonite, the latter as a mineral with mixed composition. In the central part of the Bay the total content of clay minerals reaches about 30%. Among authigenic minerals, pyrite should be mentioned together with calcite and organic skeletons. Pyrite is formed in the anoxic environment below the sediment-water interface by anoxic degradation of sedimentary organic matter. It occurs in up to 0.2 mm large framboids and its content is estimated at below 3%.

The organic carbon content in the surficial 5 cm sediment layer ranges between 0.5 and 2.7% averaging about 1.5%. Higher Corg. contents are found in fine clayey silt in the central part of the Bay, but lower (1.5%) in coarse sediment at the Bay entrance, and in the area along the shore (0.5%) influenced by tides and sediment resuspension. The sedimentary organic matter, deduced from the δ^{13}Corg. values, originates in the central part of the Bay from plankton and benthic microalgae ($\delta^{13}C$= -21‰., Faganeli*et al.*, 1991) while in the near shore area it has a significant imprint from macrophytes ($\delta^{13}C$= -18‰, Faganeli*et al.*, 1997).

The pollution of surficial sediment with heavy metals has been established using the results of geochemical analyses of samples from short cores at selected locations (Ogorelec *et al.*, 1987; Faganeli *et al.*, 1991). Concentrations of heavy metals in 30-40 cm long cores exhibit small variations and sometimes lower metal contents have been noted in the surficial 5 cm layer of sediment than below. This can be explained by the sediment resuspension, and homogenization as a result of the bioturbation processes mostly by polychaets and bivalves. The areal distribution of heavy metals is also more or less uniform. This is especially evident in copper, cobalt, arsenic and antimony distribution, while some small differences have been noted for zinc, lead and mercury. Zinc and lead, as pollution indicators, are slightly more concentrated in the inner part of the Bay, while mercury inversely shows increased concentrations towards the open part of the Bay. The higher mercury concentrations in the open part of the Bay are associated with the vicinity of the Soča river inflow which is the main source of mercury into the Gulf of Trieste, in spite of the fact that the Idrija mine has been closed for nearly 20 years. The average heavy metal contents in surficial sediments of the Bay of Koper are (Ogorelec *et al.*, 1987, Faganeli *et al.*, 1991): As 12 ppm, Hg 0.12 ppm, Cd 0.15 ppm, Mn 450 ppm, Co 10 ppm, Ni 100 ppm, Cr 160 ppm, Pb 45 ppm, Cu 30 ppm, Sb 0.3 ppm, Fe 3.15% and Zn 75 ppm. The heavy metal content in the surficial sediments of Koper Bay appears in general to be similar to that established in the unpolluted marine sediments. These values can be compared with the values from subsurficial layers of the 43 m deep borehole MK-6 in the Bay of Koper (Fig. 1, Faganeli *et al.*, 1991) and 40 m deep borehole V-6 in the Sečovlje saltworks (Ogorelec *et al.*, 1981), which could be considered as the natural geochemical background values for the eastern part of the Gulf of Trieste. Only the differences in the mercury content are noteworthy due to the greater distance from the Soča river outflow. The results show that the sediment of the Bay of Koper is not severely contaminated by heavy metals despite evident cultural impact. This would indicate that the sediment in the Bay is not a successful geochemical sink for pollutants as was also recently observed for areal distribution of PAH (Faganeli *et al.*, 1997).

THE STUDIED BOREHOLES

The sediment below the surface in the inner part of Koper Bay was studied using several boreholes (Ogorelec *et al.*, 1984, 1991; Faganeli *et al.*, 1987, 1991). These boreholes were located in the cargo port of Koper: (V-3, 41 m deep, at a depth of 4.5 m), in the ferry port (V-1/95, 45 deep, at a depth of 12 m), 200 metres off Žusterna (MK-6, 43 m deep, at a depth of 7 m), at Bonifika (24 m, on land), at the old Koper railway station (V-3/97, 28 deep, on land) and off Ankaran (A III-7, 20 m deep, at a depth of 13 m). The described locations are shown in Fig. 1. Boreholes Bonifika, V-1/95 and A III-7 are described in this paper for the first time.

Boreholes V-3 and V-1/95, drilled off port of Koper near the outflow of the Rižana river, reached the flysch basement at depths of approximately 40 and 50 meters, respectively. The cores can be divided into two parts (Figs. 3 and 8). The bottom 20 and 24 m, respectively, represent the alluvial deposit of the Rižana river with alternating layers of sand, silt and gravel. In borehole V-1/95 two thinner horizons of dark clayey silt with numerous organic particles appear at depths of 41 and 43 m below the present sea level, respectively, which are most probably the remains of a peat bog. They actually represent a paleomarsh environment at the former mouth of the Rižana river. A similar "peat" horizon was also noted in borehole V-6 drilled in the Sečovlje saltworks at a depth of 26.5 m (Ogorelec *et al.*, 1981). The upper 19 and 25 m of the sediment, respectively, which had been deposited in the marine environment consists of dark gray silt with uniform grain size and mineral composition. It contains many foraminifers, shells, mollusks and fragments of sea urchin remains. The mineral composition of marine deposit consists of quartz, calcite, illite, chlorite, illite/montmorillonite, feldspars, dolomite and pyrite while in fluvial deposit pyrite is absent. Vertical distribution of Corg. contents in the marine sequence of borehole V-3 exhibits higher values (1-1.6%) than in fluvial and brackish (<1%) probably because of lower biological productivity in these environments compared to marine, and lower sorption of organic matter on coarse fluvial particles (Hedges & Keil, 1995).

In borehole MK-6, drilled in the location of the planned Koper marina off Žusterna, no alluvial deposit has been noted. The sediment is approximately homogeneous composed of gray clayey silt with mean grain size below 10 μm, similar to that appearing in the surface of the central part of Koper Bay. It contains several fossil remains, particularly foraminifers, mollusks and ostracods. On the basis of foraminiferal species Cimerman *(pers. comm.)* concluded that the horizon between 26 and 36 m below the surface was deposited in a brackish environment (Fig. 8). The mineral composition is throughout rather uniform consisting predominantly of illite, chlorite, illite/montmorillonite, quartz, calcite, feldspars, dolomite and pyrite. Vertical distribution of Corg. contents showed higher values (1-2%) in the marine sequence, and lower (<1%) in the brackish sequence of the core. The δ^{13}Corg. values in the marine sequence varied between -20 and -24‰ while in the brackish sequence the δ^{13}Corg. values were lower (-26‰).

The borehole Bonifika (Fig. 4 and 8), drilled in the area between the new Koper commercial center and the sports center, reached a homogeneous orange-brown flysch mould at a depth of 12 m, and at a depth of 24 m a compact flysch basement. Down to the depth of 12 m the sediment is homogeneous dark gray silt containing remains of various shellfish, mollusks, echinoderms, foraminifers and ostracods. Occasionally, there are present various tiny mollusks of the species *Bittium reticulatum*, e.g. at a depth of 2 m where they represent up to 60% of the fraction above 63 μm, and *Barleera rubba*, and a shellfish *Cardium* sp. On the basis of ostracod and foraminiferal species, Cimerman *(pers. comm.)* described the alternation of marine and brackish environments. In the marine deposit the clay minerals, e.g. illite, chlorite and illite/montmorillonite prevail over quartz, calcite, feldspars and dolomite. The authigenic mineral is pyrite. The residual clay is, on the other hand, composed of illite and illite/montmorillonite, chlorite, quartz, feldspars and calcite while dolomite and pyrite are absent. Vertical distribution of Corg. contents shows values around 1.5% (1-3%) in the marine sequence while in the alternating brackish and marine environment the Corg. contents varied between 0.5 and 1.8%, respectively.

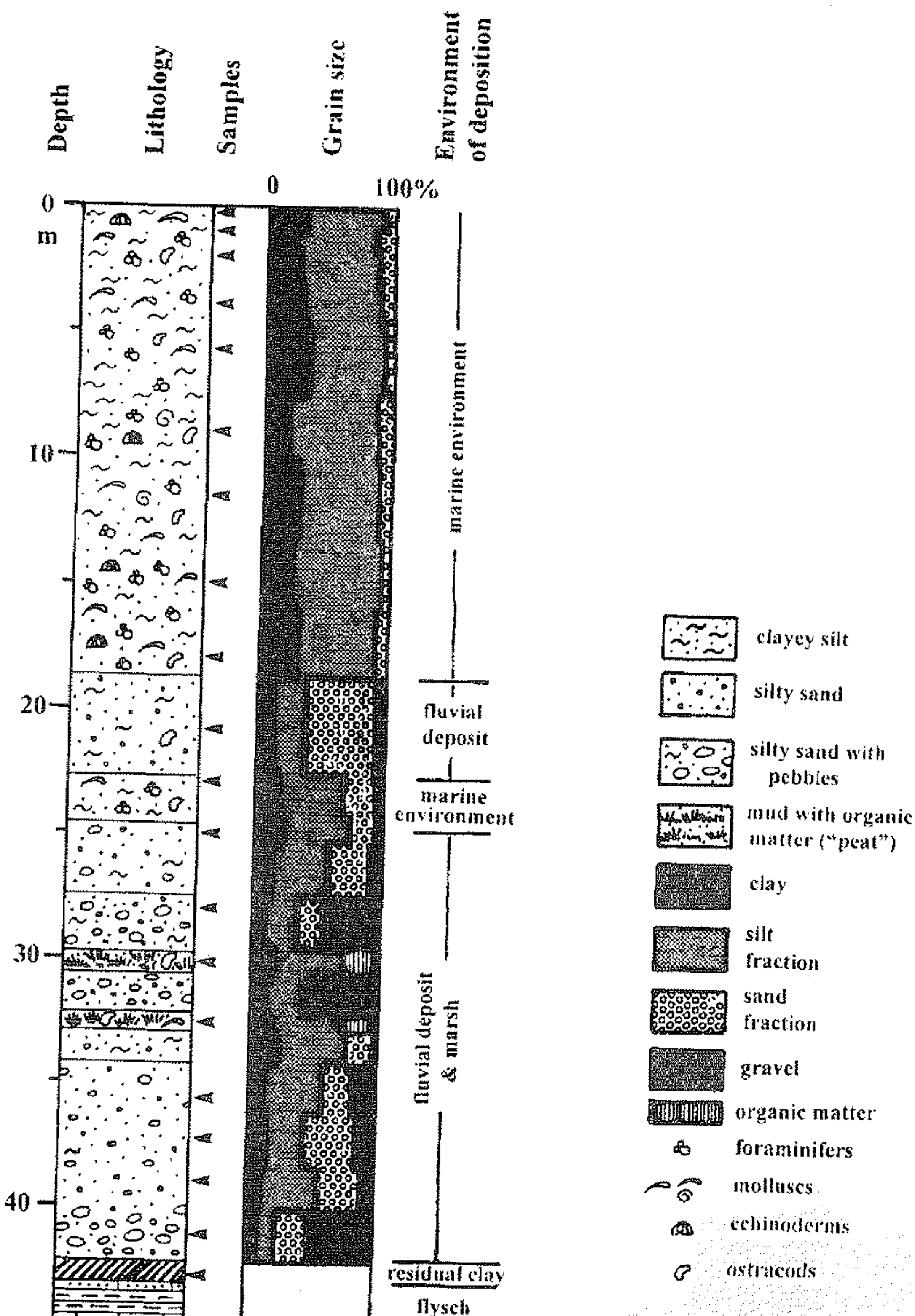

Fig. 3: Borehole V-1/95: lithological succession and grain size distribution.
Sl. 3: Litologija in zrnavost sedimenta vrtine V-1/95 v Koprski luki.

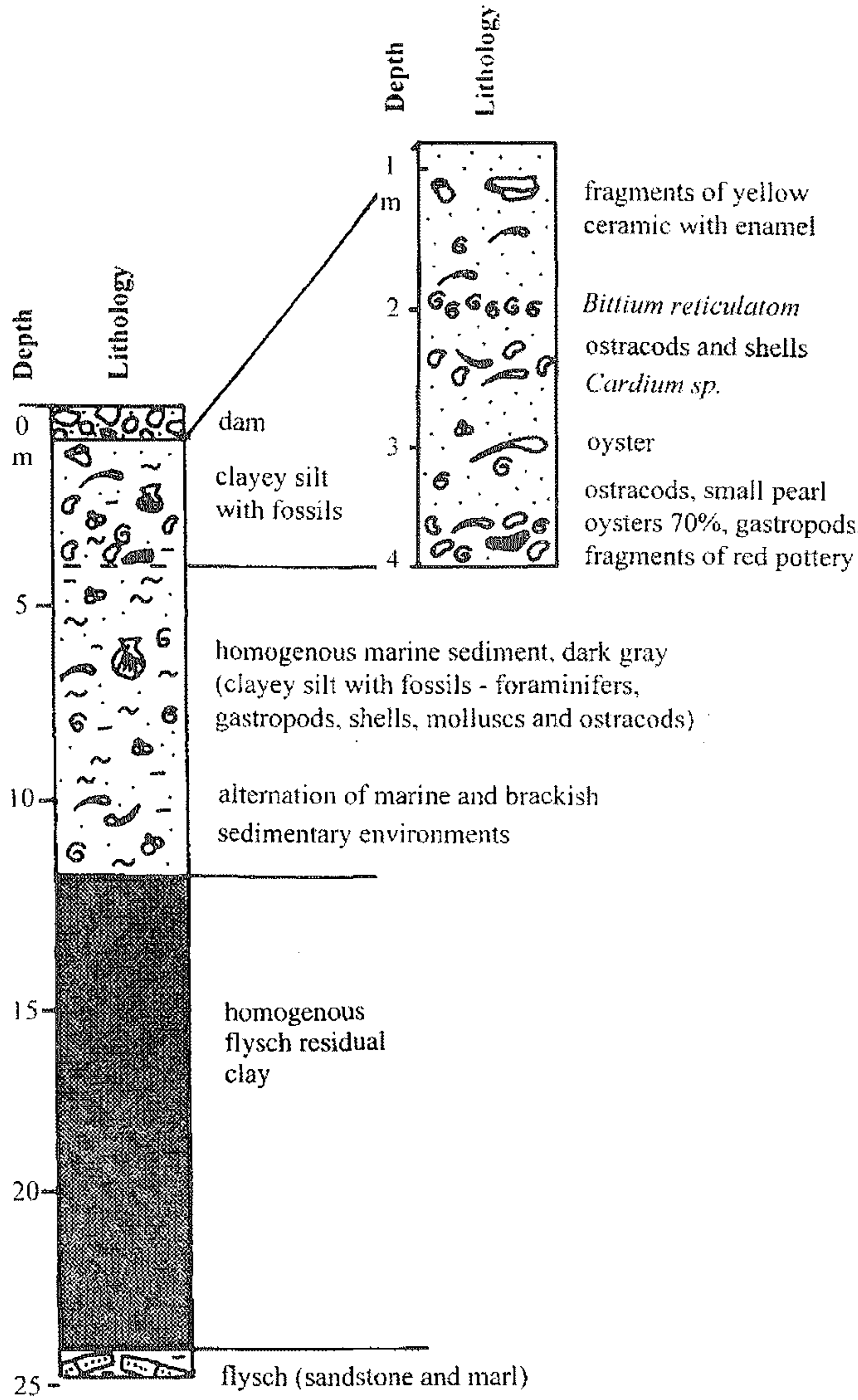

Fig. 4: Borehole Bonifika: lithological succession.
Sl. 4: Litologija vrtine Bonifika v Kopru.

In borehole A III-7 (Fig. 8), drilled in the sea bottom off Ankaran at a depth of 13 m for geomechanical purposes due to the planned expansion of the Port of Koper, the flysch mould was reached at a depth of 17 m. The sediment above the flysch mould is thoroughly homogeneous, *i.e.* dark gray silt with mean grain size around 10 µm. The clay content ranges between 24 and 38% and the content of the fraction above 63 µm ranges between 2 and 6.5%. This fraction consists mainly of mollusks and foraminifers. The mineral composition shows that the clay minerals, *e.g.* illite, illite/montmorillonite and chlorite, prevail over calcite, quartz and dolomite. Detrital grains of quartz and particles originating from coastal flysch layers are rare. Pyrite and part of calcite are authigenic minerals. The carbonate contents range between 25 and 36%.

RECONSTRUCTION OF PALEOENVIRONMENT OF THE BAY OF KOPER

Various historical sources clearly indicate that the coastline of Koper Bay was in the past very different than at present. The "embryo" of the town of Koper was the ancient settlement of Formio, in the Late Roman period known as Caprae (Šašel, 1989). At the end of the Middle Age it was a well formed town, densely populated, located on an islet and connected with the mainland by an artificial causeway (Fig. 5). At the edge of the eastern part of the Bay the Venetians constructed numerous small salt-pans in the 17th and 18th centuries, similar to those in Piran Bay near Sečovlje, and Strunjan (Fig. 6). In the mid-nineteenth century the salt-pans were abandoned as a result of the expansion of farmland.

Studying the described boreholes enable us to reconstruct the relief and sedimentation environment in Koper Bay through a longer geological history from the late Pleistocene to the Holocene. These conditions, however, are closely related to the relative global rise of the sea level. The most widely used dating method to establish the rate of sea level rise in the last postglacial period is ^{14}C analysis of samples and sediment from various depths. Especially appropriate for this purpose are the layers rich with organic matter (*e.g.* peat) and fossils. Peat layers were presumably formed in marshy plains at the mouths of former rivers and would therefore represent an approximate level of the sea in the past. The other, although less accurate but still widely used method in paleoenvironmental research, is the so-called palynological method based on the study of pollen. Studying the structure and association of pollen, a picture of vegetation and climate in a certain period can be deduced. Particularly important are the data from the pollen of agricultural plants, such as olive tree and grape in Istria, and maize in the most recent period, which could indicate the nature of human settlement in various places.

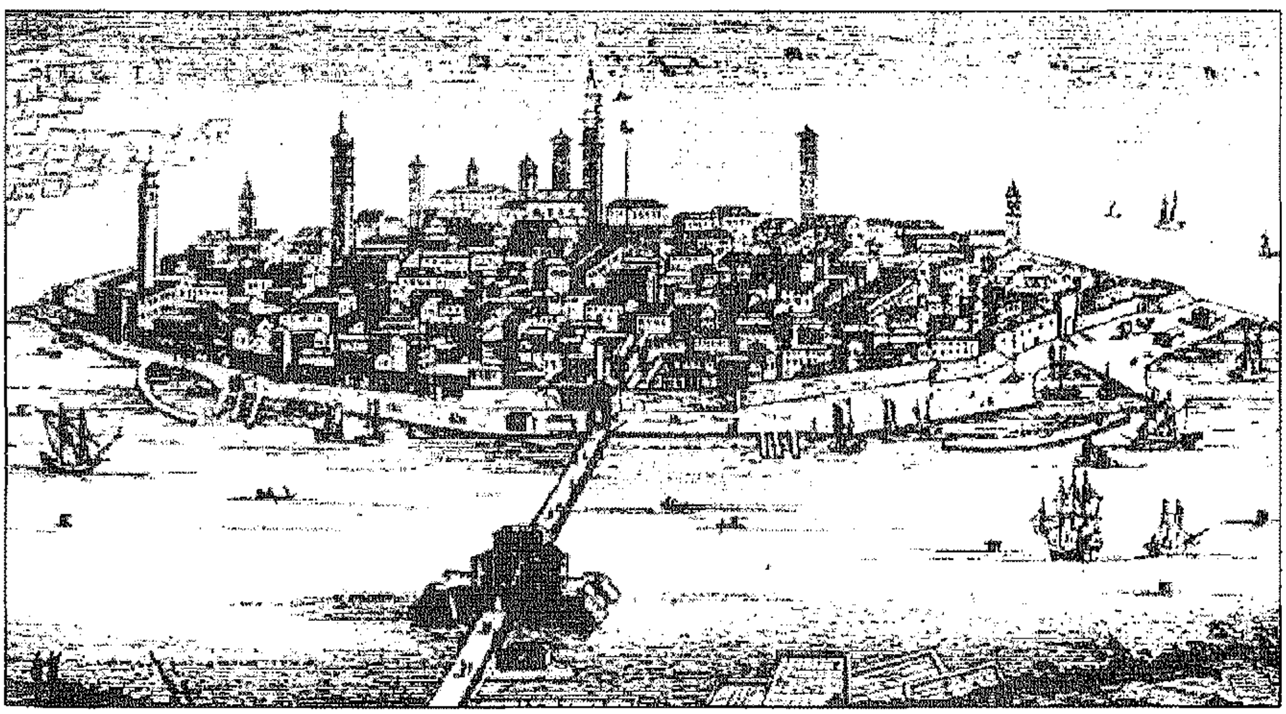

Fig. 5: View of the 18th century town of Koper.
Sl. 5: Panorama Kopra v 18. stoletju.

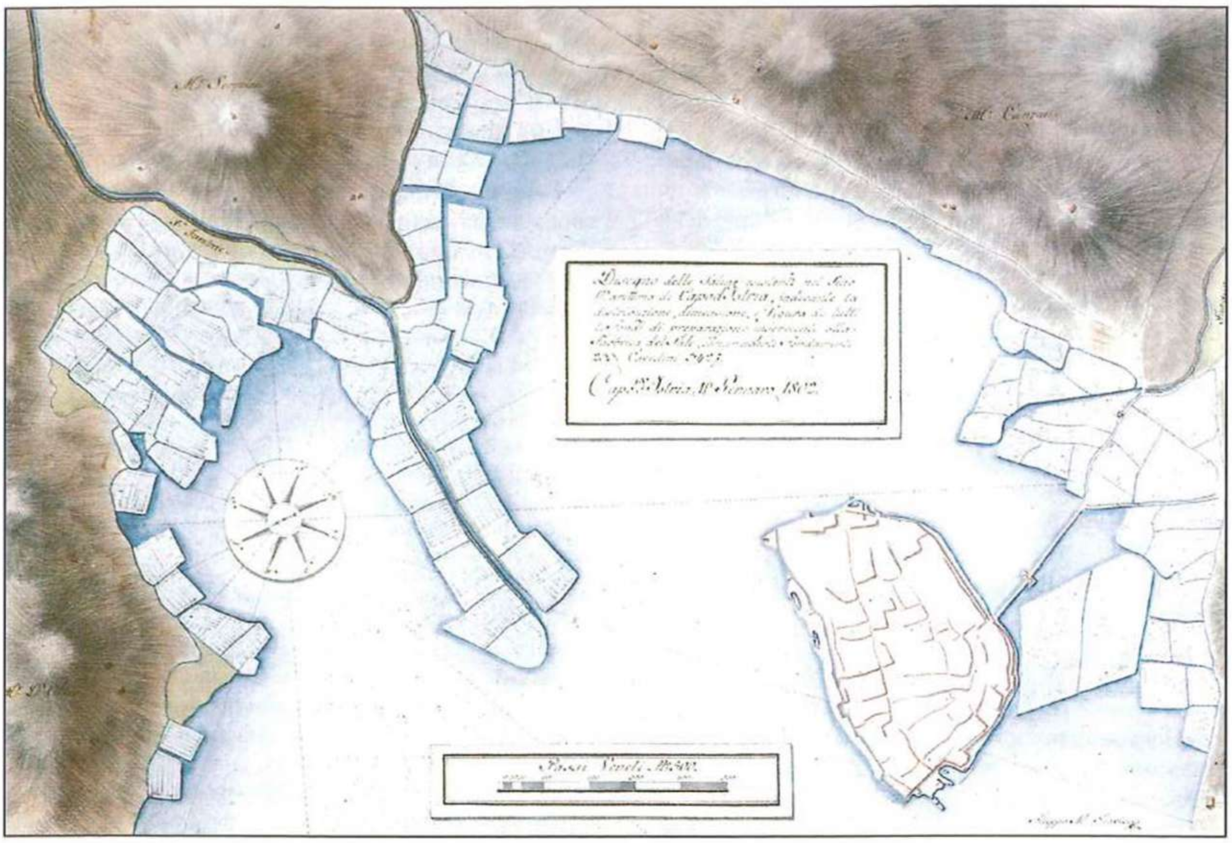

Fig. 6: Map of the inner part of the Bay of Koper with a view of saltworks from 1809 (Šašel, 1989).
Sl. 6: Zemljevid notranjega dela Koprskega zaliva iz leta 1809, na katerem so vidne številne soline (Šašel, 1989).

The problem of sea level changes in the Holocene has been intensively studied by a number of researchers: on the eastern Adriatic coast and Istria by Šegota (1968, 1973), Kozličić (1987), and Šegota & Filipčić (1991), on the Italian side of the northern Adriatic by Bortolami *et al.* (1977), Fontes & Bortolami (1973), Marocco (1989, 1991), Marocco *et al.* (1984), Tosi (1994) and recently by Correggiari *et al.* (1996), Marocco *et al.* (1996) and Bondesan *et al.* 1985). Their findings are consistent with the general curve of the global rising of the sea level, constructed on the basis of the ^{14}C dating and Th/U relations (Fairbanks, 1989, 1990). This curve (Fig. 7) indicates that 18000 years ago, during the sea transgression after the last glacial period, the relative sea level was about 120 m lower than at present. The Adriatic Sea located north of the Ancona - Zadar line was thus land (van Straaten, 1970). The rise of the sea level was initially relatively fast, the sea surface rose by 10 and even more meters in 1000 years. Some 5000 years ago, however, the rate of rise slowed considerably and in the last 2000 years the sea level has risen only another 2 meters, on average 1 mm yr^{-1}. The data obtained by Šegota & Filipčić (1991) and Kozličić (1987) are also quite consistent with the extrapolation of mareographical data from Pula (D'Ambrosi, 1951). The extension of the northern Adriatic Sea was the largest some 5000 years ago. In that time the Venice, Caorle and Grado lagoons were submerged by the sea (Marocco, 1991; Marocco *et al.*, 1996; Correggiari *et al.*, 1996).

Fig. 8 shows a cross-section of the Holocene sediment in the inner part of Koper Bay on the basis of five studied boreholes. The Bonifika borehole was drilled on land, the others at sea at different depths, ranging between 4.5 and 13 m. The sea level should be, therefore, taken into account to correctly correlate these boreholes. The MK-6 borehole is, however, not located south of the others, *e.g.* Bonifika (see the position of boreholes in Fig. 1), but westward in the open part of the Bay distorting the topographical view of the sea floor in the area around the town of Koper. The deepest and the oldest Holocene sediment in the inner part of Koper Bay was found in the borehole MK-6 off Žusterna at a depth of 48 m below the present sea level. This was expected since this borehole is the nearest to the open part of the Gulf of Trieste, from where the sea entered into the Bay. This occurred some 10 to 11 thousand years ago, when the sea began to advance quickly towards the Po plain and further north. This dating was per-

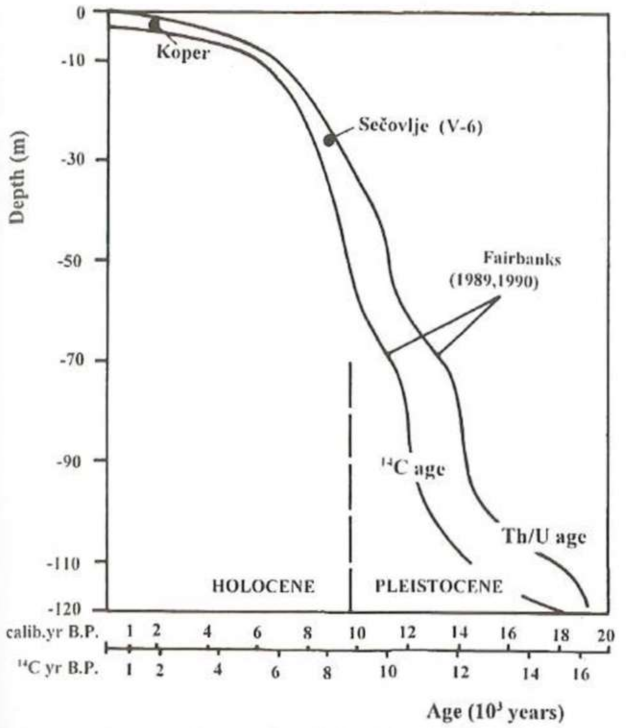

Fig. 7: Curve of sea level in the last 20000 years (Fairbanks, 1991; Correggiari** et al.**, 1996); ^{14}C of wood in peat layer from the borehole V-6 (Sečovlje saltworks) and pelecypods in Koper town wall are added for comparison.

Sl. 7: Krivulja gibanja morske gladine v zadnjih 20000 letih (Fairbanks, 1989, Correggiari** et al.**, 1996 1990); za primerjavo sta dodana vzorca lesa iz plasti šote iz vrtine V-6 v Sečoveljskih solinah in školjk pod mestnim obzidjem v Kopru izmerjena z metodo ^{14}C.

formed on the basis of the sea level curve movement (Fig. 7, Fairbanks, 1990) and the reconstruction of the movement of the Adriatic Sea in the late Quaternary (Correggiari *et al.*, 1996). In the period when the southern part of Koper Bay was already submerged by the sea, the inner (eastern) part of the Koper depression was filled up by fluvial sediments from the Rižana river inflow. This deposit is observable in layers of thick gravel (Fig. 3, borehole V-1/95, and Fig. 8), clayey sand and fine gravel. The thinner, some 0.5 m thick horizons of clayey silt rich in organic matter ("peat'), which in borehole V-1/95 occur at depths of 41 and 43 m below the present sea level, respectively, indicate the presence of episodical marshy areas in the Rižana river mouth

The most intensive sea transgression in the Bay was noted at a depth of 26 m. At that time the marine environment completely prevailed over the fluvial and brackish environment. This depth is completely in accordance with the "peat" layer in the V-6 borehole, which was, according to ^{14}C analysis, dated to 9180±120 years BP (Ogorelec *et al.*, 1981). In the same period, i.e. in the same sea level, when in the V-3 borehole, fluvial sedimentation changes into marine sedimentation, the sediment of the brackish environment in the MK-6 borehole also changes into marine environment. The area covered by Bonifika and Koper islet was at that time still a part of the land.

From a depth of 26 m upward, measured to the present sea level, only finely grained and homogenous clayey silt occurs over the entire Koper Bay. The numerous fossil skeletons, particularly shellfish and foraminifers indicate the marine sedimentation in this layer. This depth temporally corresponds to about 9000 years BP when the general sea transgression occurred during the transition from the late Glacial to Holocene. On the basis of sediment thickness and ^{14}C datings we can determine the approximate sedimentation rate in Koper Bay. For thicker sediments it ranges, on average, between 4 and 2.5 mm yr^{-1} and for upper meters of the sediment between 1.5 and 1 mm yr^{-1}. Assuming, in view of the general global rising of sea level (Fig. 7), that the sea transgression in the inner part of Koper Bay started on the flysch basement at a depth of 47 m (borehole MK-6) more than 10000 years ago, the sedimentation rate would then be approx. 4 mm yr^{-1}. For the upper 21 m of marine sediment the rate would be about 2.2 mm yr^{-1}. The rate from the borehole V-6 in the Sečovlje saltworks, measured on the basis of ^{14}C analysis of piece of wood in the "peat" layer, shows for the sediment depth of 26.5 m an average sedimentation rate of 3 mm yr^{-1}. The sedimentation rates calculated in the port of Koper (boreholes V-3 and V-1/95) range between 2.5 mm yr^{-1} for the upper marine part, and about 4 mm yr^{-1} for the whole (fluvial and marine) sediment. This difference is due to the faster sedimentation of the basin with more coarse riverine deposits than with pelitic marine sediment. The rate of 2.5 mm yr^{-1} is obtained if 22 m of the marine sediment is considered and the depth of the fluvial-marine sediment contact is located at a depth of 26 m below the present sea level and dated approximately to 9000 years BP. Similar accumulation rates, betwen 2 and 6 mm yr^{-1}, were reported by Marocco (1991) for sediments in the Tagliamento delta.

A somewhat slower sedimentation rate in the last 2000 years in the Bay of Koper is confirmed by isotopic datings and archaeological excavations. During the excavations performed at the so-called Great Gate in Koper, (Župančič, 1985) at a depth of 1.24 m, a layer of shells of the species *Cardium* sp. was found and they were ^{14}C dated to 1367±83 years BP, indicating that the sedimentation rate was about 1 mm yr^{-1}. This data is in accordance with the recent deposition rate in the Venice lagoon (Favero & Stefanon, 1980), lagoons of Marano, Grado and Caorle (Marocco, 1991, Marocco *et al.*, 1996) and with the average rise of the sea level in the last 2000 years, showing a synchronous rise of sea level with sedimentation.

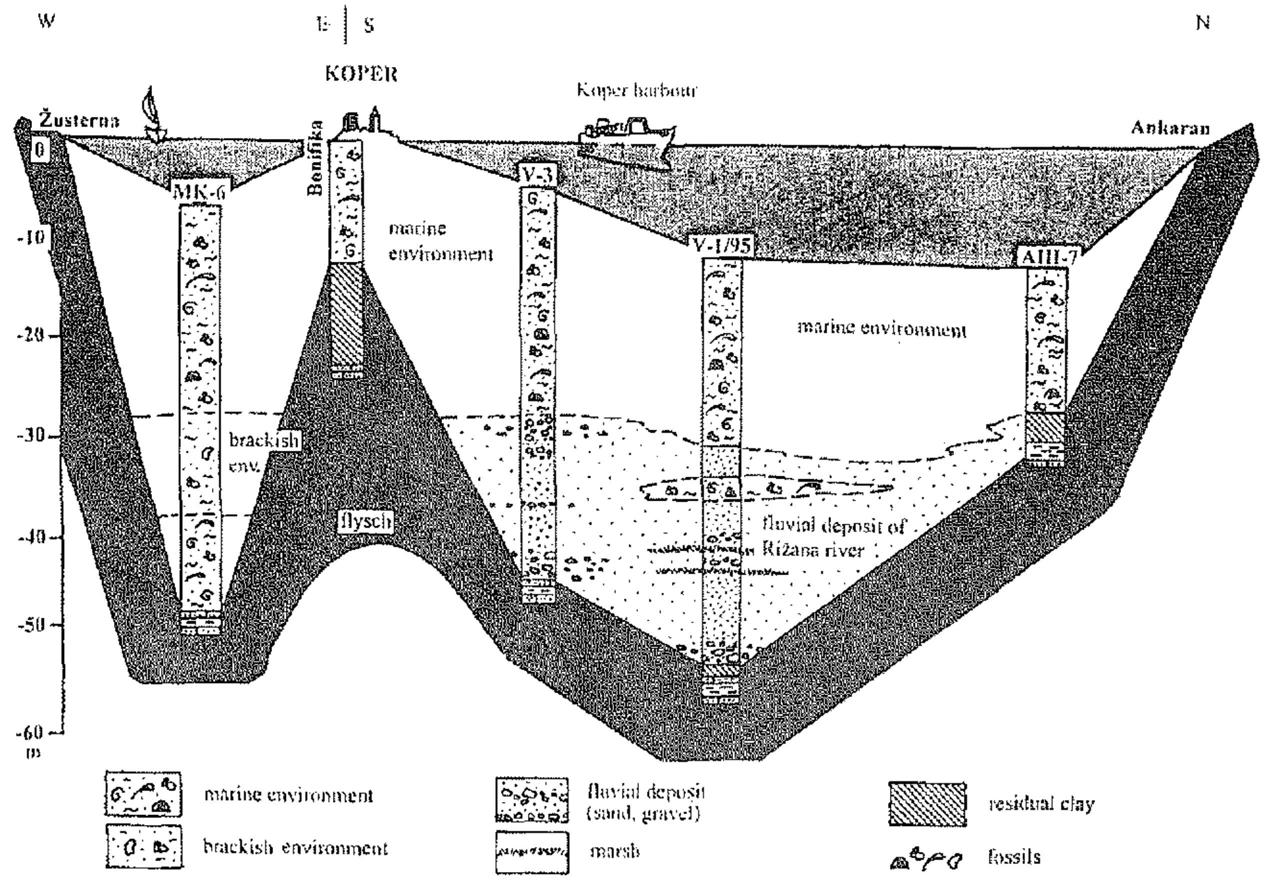

Fig. 8: Interpretation of Holocene sedimentary environment in the inner part of the Bay of Koper based on studied boreholes.
Sl. 8: Interpretacija sedimentacijskih okolij notranjega dela Koprskega zaliva v holocenskem obdobju po podatkih raziskanih vrtin.

A somewhat higher sedimentation rate, however, has been determined in various localities in the southern part of the Gulf of Trieste, and in Koper Bay, using ^{210}Pb analyses (Faganeli *et al.*, 1991). The recent sedimentation rate of about 5.5 mm yr^{-1} was estimated for the surficial layer of the borehole MK-6. This discrepancy should be attributed to the higher porosity of surficial sediment and that during diagenesis a compaction of the sediment occurs leading to lower sedimentation rate. Also, ^{210}Pb has a shorter half-life than ^{14}C and, hence, these nuclides are tracers of processes occurring in different time scales (tens vs. thousands of years).

The palynological investigations (Ogorelec *et al.*, 1984, Šercelj, *pers. comm.*) of sediment from boreholes V-3 and V-6/79 in the Sečovlje saltworks (Ogorelec *et al.*, 1981) divided the cores into three parts. In the sandy riverine deposits in the borehole V-3 from the depth interval between 43 and 26 meters pollen was not present. As a result of transgression the marine sediment at this depth contains oak and elm pollen as a characteristic vegetation of the early Holocene, Preboreal and Boreal. At depths of 18 and 16 m, the vegetation is already typical of the warmer period with its prevailing beech *(Fagus)* forest (boreal climate) and pine *(Pinus)* pollen. At a depth of 10.8 m the olive tree *(Olea)* and grape *(Vitis)* pollen occur, for the first time and in somewhat greater quantities. These are agricultural plants, which were introduced to Istria by man, most probably in the Early Roman period. At that time the forest vegetation greatly changed becoming poor, presumably as a result of deforestation and the introduction of pasture. The olive tree and grape pollen at a depth of 10.8 m indicate a high sedimentation rate, up to 5 mm yr^{-1}, in this part of the Bay, which is in accordance with the previously mentioned data from the borehole MK-6 (4 mm yr^{-1}) and recent sediment.

CONCLUSIONS

And finally, how will the Bay of Koper likely look in the future? An answer to this question depends on a number of factors, particularly on the trend and rate of the rise or fall of sea level, on tectonics and climate. In view of present predictions by climatologists, who claim even further global warming, we can expect a faster rate of rise of sea level. A warmer climate, on the other hand, enhances the general abrasion of the coast and denudation of land, a higher bioproduction of organic skeletons and, thus, a higher sedimentation rate. However, sedimentation will most probably still be balanced with the rise of sea level. In the eastern part of the Bay between Koper and Ankaran the expansion of the port will continue, which means that practically the entire coast will be urbanized. However, the steep flysch coast so characteristic of the Bay between Debeli rtič and Valdoltra as well as between Koper and Izola will probably remain intact.

REKONSTRUKCIJA PALEOOKOLJA V KOPRSKEM ZALIVU

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POVZETEK

Namen pričujočega članka je, da prikažemo rekonstrukcijo okolja v Koprskem zalivu (sl. 1) skozi najmlajše geološko obdobje ter osnovne značilnosti usedlin in procesov, ki se odvijajo v njih. Po zrnavosti, litologiji in geokemijskih lastnostih lahko površinski sediment Koprskega zaliva razdelimo v tri cone (sl. 2): obrežni sediment (cona A), sediment notranjega dela zaliva (cona B) in sediment odprtega dela zaliva (cona C). Opisane značilnosti sedimenta so pomembne za študij biogeokemijskih procesov in onesnaženja zaradi prisotnosti človekove dejavnosti.

Sediment pod površino smo v notranjem delu Koprskega zaliva raziskali z več vrtinami. Te so locirane v koprski tovorni luki: (V-3, globoka 41 m, na globini morja 4,5 m), tankerski luki (V-1/95, globoka 45 m, globina morja 12 m), dvesto metrov pred Žusterno (MK-6, globoka 43 m, globina morja 7 m), v Bonifiki pri Kopru (globoka 24 m, na kopnem) ter pred Ankaranom (A III-7, globoka 20 m, globina morja 13 m). Lokacije vseh teh vrtin so prikazane na sliki 1. Vrtine Bonifika, V-1/95 in A III-7 opisujemo v tem prispevku prvič.

Sediment vrtin V-3 in V-1/95, ki sta izvrtani na morju pred koprsko luko blizu izliva Rižane, sta na približno 40. in 50. metru prevrtali flišno podlago. Razdelimo ju lahko v dva dela (sl. 3 in 8). Spodnjih 20 in 24 metrov predstavlja rečni nanos Rižane. Menjavajo se plasti peska, mulja in proda. V vrtini V-1/95 se na 41. in 43. metru pojavljata dva tanjša horizonta temnega glinastega mulja s številnimi organskimi drobci, ki po vsej verjetnosti predstavljajo ostanke šotišča oziroma nakazujeta paleomočvirsko okolje ob nekdanjem ustju Rižane (sl. 3).

V vrtini MK-6, ki je bila izvrtana na predvideni lokaciji koprske marine pred Žusterno, rečnega nanosa ne opazujemo. Tu gre v celoti za precej homogen sediment, siv glinasti mulj s srednjo zrnavostjo pod 10 mm, kakršen nastopa na površini osrednjega dela Koprskega zaliva. V celotnem zaporedju se v večjem ali manjšem obsegu pojavljajo fosilni ostanki, predvsem foraminifere, moluski in ostrakodi. Po foraminifernih vrstah ugotavljamo, da je bilo v globini med 26. in 36. metrom pod morsko gladino v času nastanka sedimenta bolj brakično okolje (sl. 8).

Vrtina z oznako Bonifika, izvrtana na lokaciji med novim koprskim trgovskim centrom in športnim središčem, je v globini 12 m prešla v homogeno flišno preperino oranžno-rjave barve, na globini 24 m pa v kompakten fliš (sl. 4 in 8). Do globine 12 metrov je sediment zopet homogen temnosiv glinasti mulj z lupinami školjk, polžev, ehinodermov, foraminifer in ostrakodov. Mestoma so številni drobni polži vrste Bittium reticulatum, *nadalje polž* Barleera rubba *ter školjka* Cardium *sp. Tudi tu po ostrakodni in foraminiferni favni ugotavljamo menjavanje morskega in brakičnega okolja.*

Vrtina A III-7 (sl. 8), ki je bila izvrtana v morju pred Ankaranom v geomehanske namene zaradi širitve koprske luke, je na flišno preperino zadela na globini 17 metrov. Morje je tam globoko 13 metrov. Sediment nad flišno preperino je vseskozi homogen, temnosiv glinasti mulj s srednjo zrnavostjo okrog 10 µm. Glinasto frakcijo sestavljajo predvsem fosili - moluski in foraminifere, zelo redka pa so detritična zrna kremena in drobci flišnih plasti z obale.

Že iz zgodovinskih virov in slik lahko razberemo, da je obalna črta v Koprskem zalivu v preteklosti potekala drugače kot danes. Zametek Kopra je bila naselbina Formio iz antičnega obdobja, kasneje, v rimskem obdobju znana kot Caprae. Koncem srednjega veka je bil Koper že izoblikovano mesto, strnjeno na majhnem otočku in s kopnim povezano z umetnim nasipom (sl. 5). Ob robu vzhodnega dela zaliva so v 17. in 18. stoletju Benečani uredili številna manjša solna polja, kakršna so bila pri Sečovljah in Strunjanu (sl. 6). Sredi 19. stoletja so bila ta polja zaradi širitve kmetijskih površin opuščena.

Za ugotavljanje hitrosti dviga morske gladine v zadnji poledeni dobi so najbolj razširjene datacije z metodo izotopske sestave ^{14}C na vzorcih in sedimentu iz različnih globin. V ta namen so uporabne predvsem plasti, ki so bogate z organsko snovjo (npr. šota) in fosili. Šotne plasti naj bi nastajale na močvirskih ravnicah ob ustjih nekdanjih rek in bi torej predstavljale približni nivo morske gladine v preteklosti. Druga, sicer časovno manj natančna, a zelo razširjena metoda, s katero raziskujemo paleookolje, je palinološka, ki temelji na študiju peloda rastlin. Po sestavi in združbi peloda lahko sestavimo sliko o vegetaciji in klimi v nekem obdobju. Posebno pomembni so podatki o pojavih peloda kulturnih rastlin, kot so v Istri oljka in trta, v najmlajšem obdobju pa še koruza. Po njih lahko sklepamo na naselitve določenih prostorov. Za krivuljo dviga morske gladine v svetu konstruirane na osnovi starostnih datacij ^{14}C in razmerij Th/U (sl. 7) velja, da je bila morska gladina pred 18000 leti, v času würmske poledenitve, okrog 120 metrov nižja kot je danes. Tako je bil Jadran severno od linije Ancona-Zadar kopno. Dvig morja je bil sprva relativno hiter, saj se je morska gladina dvigovala povprečno za 10 in več metrov v 1000 letih. Pred približno 5000 leti pa se je to dvigovanje precej upočasnilo, tako da se je morje od rimskega obdobja dalje v zadnjih 2000 letih dvignilo le še za okrog 2 metra, kar pomeni v povprečju 1 mm/leto. Največji obseg morja v severnem Jadranu je bil pred približno 5000 leti, ko je to segalo še približno 50 km v notranjost delte Pada, pod vodo pa so bile tudi beneška laguna in laguni pri Maranu in Gradežu.

Na sliki 8 je prikazan presek skozi holocenske sedimente v notranjem delu Koprskega zaliva na osnovi petih vrtin. Vrtina Bonifika je bila izvrtana na kopnem, ostale vrtine pa na morju z različno globino vode, ki se giblje od 4,5 do 13 m. Zato moramo pri korelaciji teh vrtin upoštevati njihove prave položaje glede na današnjo gladino morja. Pri vrtini MK-6 moramo opozoriti tudi, da ta ni locirana južno od ostalih vrtin (npr. Bonifike, glej sl. 1), ampak zahodno proti odprtemu delu zaliva, kar popači topografijo morskega dna v predelu okrog Kopra.

Najglobji (najstarejši) holocenski sediment v notranjem delu Koprskega zaliva zasledimo v vrtini MK-6 pred Žusterno na globini 48 m pod sedanjo morsko gladino. To je bilo pričakovati, saj je ta vrtina najbližja proti odprtemu delu Tržaškega zaliva, od koder je prodiralo morje. Zato jo je tudi najpreje preplavilo. To je bilo pred približno 10 do 11000 leti, ko je morje hitro pričelo prodirati proti Padski nižini in naprej proti severu. To datacijo postavljamo na osnovi rekonstrukcije pomikanja Jadranskega morja v poznem kvartarnem obdobju.

V istem obdobju, ko je južni del Koprskega zaliva že zalilo morje, je notranji, vzhodni del takrat še koprske udorine zasipaval rečni nanos Rižane. Tega zastopajo sprva plasti debelega proda (sl. 3, vrtina V-1/95 in sl. 8), više navzgor pa zaglinjenega peska in drobnejšega proda. Tanjša, okrog 0,5 metra debela horizonta glinastega mulja oziroma "šote", ki se v vrtini V-1/95 pojavljata na globinah 41 in 43 m pod današnjim nivojem morske gladine, kažeta na občasne zamočvirjene predele ob ustju Rižane.

Najmočnejši morski transgresijski sunek v Koprskem zalivu zasledimo na globini 26 m pod sedanjo morsko gladino. Takrat je morski sediment popolnoma prevladal nad rečnim in brakičnim. Ta globina se popolnoma ujema s podatkom, da imamo v isti globini v vrtini V-6 v Sečoveljskih solinah plast "šote", ki je bila z izotopsko analizo ^{14}C datirana s starostjo pred 9180±120 leti. V istem obdobju oziroma nivoju, ko v vrtini V-3 rečna sedimentacija preide v morsko, preide tudi v vrtini MK-6 sediment brakičnega okolja v morskega. Prostor bonifike in koprskega otoka je bil v tem času še vedno del kopnega.

Od 26. metra navzgor, merjeno do današnje kote morske gladine, se v celotnem Koprskem zalivu javlja le še zelo drobnozrnat in homogen glinasti mulj. Številni fosilni skeleti, predvsem školjke in foraminifere kažejo na njegovo sedimentacijo v morskem okolju. Časovno ustreza ta nivo približno pred 9000 leti, kar ga uvršča v obdobje splošne morske transgresije na prehodu iz würma v holocen. Po debelini sedimenta in nekaterih njegovih starostnih datacijah z ^{14}C lahko sklepamo na približno hitrost sedimentacije v Koprskem zalivu. Ta se za debelejše morske pakete giblje med 4 in 2,5 mm/leto, za vrhnje metre sedimenta pa v poprečju med 1,5 in 1 mm/leto.

Če predpostavimo glede na splošno svetovno krivuljo dviga morske gladine (sl. 7), da je morska transgresija v notranjem delu Koprskega zaliva zajela flišno podlago na globini -48 m (vrtina MK-6) pred dobrimi 10000 leti, dobimo hitrost sedimentacije približno 4 mm/leto. Samo za vrhnjih 21 m sedimenta, ki je morskega izvora, pa znaša *ta hitrost okrog 2,2 mm/leto. Podatek iz vrtine V-6 v Sečoveljskih solinah, izmerjen na osnovi analize "šote" z metodo ^{14}C, nam daje za 26,5 m sedimenta povprečno hitrost sedimentacije 3 mm/leto.*

Izračuni hitrosti sedimentacije v koprski luki (vrtini V-3 in V-1/95) se gibljejo med 2,5 mm/leto za vrhnji morski sediment in okrog 4 mm/leto za skupni rečni in morski sediment. Ta razlika je lahko razložljiva zaradi hitrejšega zasipavanja bazena z bolj debelozrnatim rečnim nanosom kot pa pelitskim morskim sedimentom. Do podatka 2,5 mm/leto pridemo, če upoštevamo 22 m morskega sedimenta in datiramo globino kontakta rečni - morski sediment na globini 26 m v čas pred približno 9000 leti.

Počasnejšo sedimentacijo v zadnjih 2000 letih lahko v Koprskem zalivu zagovarjamo z izotopskimi datacijami in arheološkimi izkopavanji. Meritve ^{14}C školjk vrste Cardium sp., ki so jih izkopali pri velikih vratih v Kopru na globini 1,24 m, so pokazale starost 1367±83 let, kar kaže na približno hitrost sedimentacije 1 mm/leto. Ta podatek se ujema z enako hitrostjo zasipavanja Beneške lagune ter lagun Marano, Gradež in Caorle v zadnjem obdobju ter s povprečnim dvigom morske gladine v zadnjih 2000 letih, kar kaže na usklajeno dvigovanje morske gladine in sedimentacije.

Na večjo hitrost sedimentacije pa kažejo raziskave recentnega površinskega sedimenta, izmerjene na več lokacijah v južnem delu Tržaškega zaliva in tudi v Koprskem zalivu, analizirane z metodo ^{210}Pb. Te kažejo na hitrost usedanja približno 5 mm/leto. Upoštevati pa moramo, da je recentni sediment še zelo porozen in da pride v diagenezi do njegove kompakcije in s tem do vsaj polovico nižje hitrosti sedimentacije, pa tudi da sta ^{210}Pb in ^{14}C indikatorja procesov, ki potekajo v različnih časovnih skalah.

Palinološke raziskave v sedimentu iz vrtine V-3 in že prej iz vrtine V-6/79 v Sečoveljskih solinah so dale podlago za kronološko delitev sedimenta na tri dele. V peščenem rečnem nanosu vrtine V-3 od podlage na 43. metru do 26. metra sediment ne vsebuje peloda. S transgresijo se na tej globini že pojavi pelod hrasta in bresta kot značilna vegetacija zgodnjega holocena, preboreala in boreala. V globini 18 m in 16 m pa je vegetacija že toplodobna s prevladujočim bukovim gozdom (borealna klima) in s pelodom borovca. Na globini 10,8 m se prvič pojavita in sicer v večjih količinah oljka in vinska trta. To sta kulturni rastlini, ki jih je v Istro naselil človek, najverjetneje v zgodnjem rimskem obdobju. Gozdna vegetacija se je v tem času precej spremenila in osiromašila, verjetno zaradi krčenja gozda in uvajanja pašnih površin. Pelodi oljke in trte v globini 10,8 m kažejo na visoko hitrost sedimentacije, tudi do 5 mm/leto v tem delu zaliva, kar bi se nekako skladalo s preje omenjenimi podatki za vrtino MK-6 (4 mm/leto) in za recentni sediment.

In za zaključek, kako bo Koprski zaliv izgledal v prihodnosti? Odgovor na to vprašanje je odvisen od več dejavnikov, predvsem od trenda in hitrosti dvigovanja ali nižanja morske gladine, nadalje tektonike in klime. Glede na današnje prognoze klimatologov, ki napovedujejo še nadaljnjo otoplitev je pričakovati še pospešeno dvigovanje morja. Toplejša klima pa pospešuje splošno abrazijo obale in denudacijo zemlje v porečju, višjo bioprodukcijo organskih skeletov ter s tem višjo stopnjo sedimentacije. Po vsej verjetnosti pa bo zasipavanje še naprej uravnoteženo s porastom morske gladine. V vzhodnem delu zaliva med Koprom in Ankaranom se bo nadaljevalo širjenje luke, tako da bo praktično vsa obala z izlivom Rižane odvisna od človeka, še dolgo pa bodo ostale strme flišne stene, ki dajejo zalivu med Debelim rtičem in Valdoltro ter med Koprom in Izolo tako značilno podobo.

Ključne besede: recentni sediment, paleookolje, Koprski zaliv, Tržaški zaliv, Jadransko morje

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