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Origin and distribution of surface sediments in the Grgur Channel, Adriatic Sea, Croatia

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ABSTRACT

Granulometric, mineralogical and morphological investigation of the sea-bottom sediments in the Grgur Channel has revealed five sediment types, the most frequent of which are muds containing some amount of coarse fractions (sand and gravel). The coarsest fractions are predominantly composed of recent shell fragments. Unexpected well rounded carbonate gravel was found SE of Prvić Island in 83 m of water. This gravel was presumably transported, shaped and deposited during a sea-level lowstand, by stream and/or in a beach environment. Fine-grained fractions have a siliciclastic composition and suggest a predominant terrigenous origin. One part of the fine-grained fraction originates from the recent subaerial weathering of flysch outcrops, and the other from previously active (during a lower sea-level), subaerial erosion of presently submerged flysch outcrops.

As a result of the rapid Late Pleistocene–Holocene transgression, the investigated sediments are now below the present wave-base. Due to a presumed very low or even negligible rate of recent sedimentation in the study area, older sediments in the Grgur Channel remain uncovered and bioturbated by burrowing organisms. Therefore, analyzed surface sediments from the Grgur Channel are considered as a mixture of recent and subrecent deposits.

From this investigation, a new seabed sediments map of the Grgur Channel was produced, as an improvement on the existing sedimentological map of the Kvarner area.

Keywords: Late Pleistocene, Holocene, gravel, depositional environments, Kvarner

1. INTRODUCTION

Seabed sediments of the Adriatic Sea have been intensively investigated since the 1960s, but the previous studies were sporadic. Sediments of the northern, middle and western parts of the Adriatic Sea were investigated by Italian and other researchers (BRAMBATI & VENZO, 1967; BRAMBATI et al., 1983; BRAMBATI et al., 1988a, b; PIGORINI, 1968; VAN STRAATEN, 1970), while the eastern part remained poorly explored. However, LORENZ (1863) published an initial map of the seabed and surface sediments of the Kvarner region. Further investigation in this region was only resumed more than a century later (ALFIREVIĆ, 1964, 1980; ŠKRIVANIĆ & MAGDALENIĆ, 1979; JURAČIĆ & PRAVDIĆ, 1981; HIJRM, 1985; JURAČIĆ et al., 1997, 1999).

The seabed sediment map produced by LORENZ (1863) showed that the Grgur Channel bottom is mostly covered with clay, except for narrow zones along the Prvić, Grgur and Goli Island coastline, where a barren rocky bottom is present and/or covered with angular clasts and pebbles. ALFIREVIĆ (1980) indicated that coarse sandy sediments prevail along the Goli Island coasts; loamy-clayey sediments were registered in the area between Grgur and the Velebit channel, while the Grgur channel remained unexplored. According to the general map of the Adriatic Sea seabed sediments (HIJRM, 1985), the Grgur Channel is covered with clayey sands. In the more detailed map of the seabed sediments of the Kvarner region (JURAČIĆ et al., 1999) the Grgur Channel bottom sediments are classified as sandy muds.

The sea-floor sediment sampling and this study were carried out within a project entitled "*Preservation of biodiversity in Adriatic Sea"*, in order to eventually establish a marine park in the Prvić, Grgur and Goli Island area (ZAVODNIK et al., 2005). The main aim of this paper is to determine the pattern and origin of the surface sediment distribution, in order that investigation of sediment properties might also enhance the understanding of general sedimentation mechanisms in the channel area of the eastern Adriatic coast under the recent and subrecent climate conditions. Another purpose of this study is to supply detailed data for a new sediment map of the Kvarner area (and the eastern Adriatic coast in whole), by publishing a refined surface sediment distribution map of the Grgur Channel.

2. STUDY AREA

The Prvić, Goli and Grgur Islands belong to the Krk – Rab – Pag island chain that separates Kvarnerić Bay and the Velebit – Vinodol Channel within the Kvarner area (Kvarner *sensu lato*). About 4 km long and 3 km wide, the Grgur Channel is located between the islands of Prvić, Goli and Grgur (Fig. 1). Water depths in the Channel increase abruptly up to 70 m off the coast, and gradually deepen toward the central part (95 m). In the NE and SE part of the Channel, two seafloor depressions occur (Fig. 1). The maximum depth of the Channel at 107 m occurs in one of these, south of Prvić Island (HHI, 1997).

Regarding solid rock geology, the Kvarner area belongs to the NW part of the Adriatic Carbonate Platform (AdCP). It is characterized by predominantly shallow-marine carbonate deposits, ranging in age from the Lower Jurassic to the top of the Cretaceous. The end of AdCP shallow marine deposition was marked by a regional emergence between the Cretaceous and Palaeogene, but deposition controlled by synsedimentary tectonics continued throughout the Palaeogene. Compressional tectonics with maximum stress oriented SW–NE resulted in the final uplift of the Dinarides in the Oligocene/Miocene (VLAHOVIĆ et al., 2005). According to BLAŠKOVIĆ (1999), two main geodynamic phases shaped the Kvarner area: Eocene tectonic movements formed faulted and folded structures, whereas Upper Pliocene tectonics caused their reactivation. Due to the intensive tectonics, uplifted carbonates were crushed and karstified under subaerial conditions during the Pleistocene. Karstification progressed to a significant depth during the Last Glacial Maximum (LGM) (SURIĆ et al., 2005) when the sea-level was at least 100 m lower than present (CORREGGIARI et al., 1996). Due to the sea-level rise in the post-LGM period, the karst relief was flooded and the modern rocky eastern Adriatic coast was formed (BENAC & JURAČIĆ, 1998; SURIĆ et al., 2005).

In the investigated area, the data available on the solid rock geology are restricted to outcrops on the islands. As shown in Fig. 2, several stratigraphic members can be distinguished on Prvić, Goli and Grgur: Upper Cretaceous (Cenomanian–Turonian) limestones with breccias dominate on all islands, Palaeogene deposits are composed of carbonate (Eocene foraminiferal limestones) and clastic sediments (Eocene flysh marls with inclusions of sandstone). Eocene foraminiferal limestones, wich transgressively overlie the Upper Cretaceous deposits, are best exposed in the NE and SW parts of Grgur Island, but due to the reverse faulting on Prvić Island, these sediments can only be observed in a narrow strip in its SW part. Eocene flysch (marls and sandstones) were discovered on each of the three islands: on Grgur and Prvić within disturbed synclines and on Goli between two longitudinal faults. The youngest stratigraphic member developed on each of these islands are Eocene breccias and

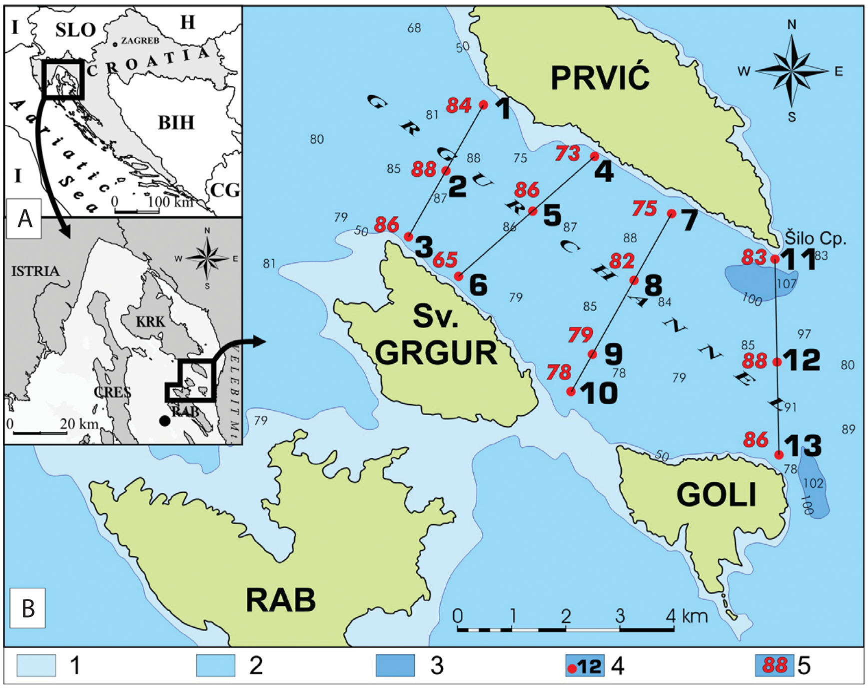

Figure 1: A) Location maps. B) Bathymetric map of the Grgur Channel area.
Legend: 1) water depths 0–50 m; 2) water depths 50–100 m; water depths over 100 m; 4) sediment sampling station; 5) sampling depths; (after HHI, 1997).

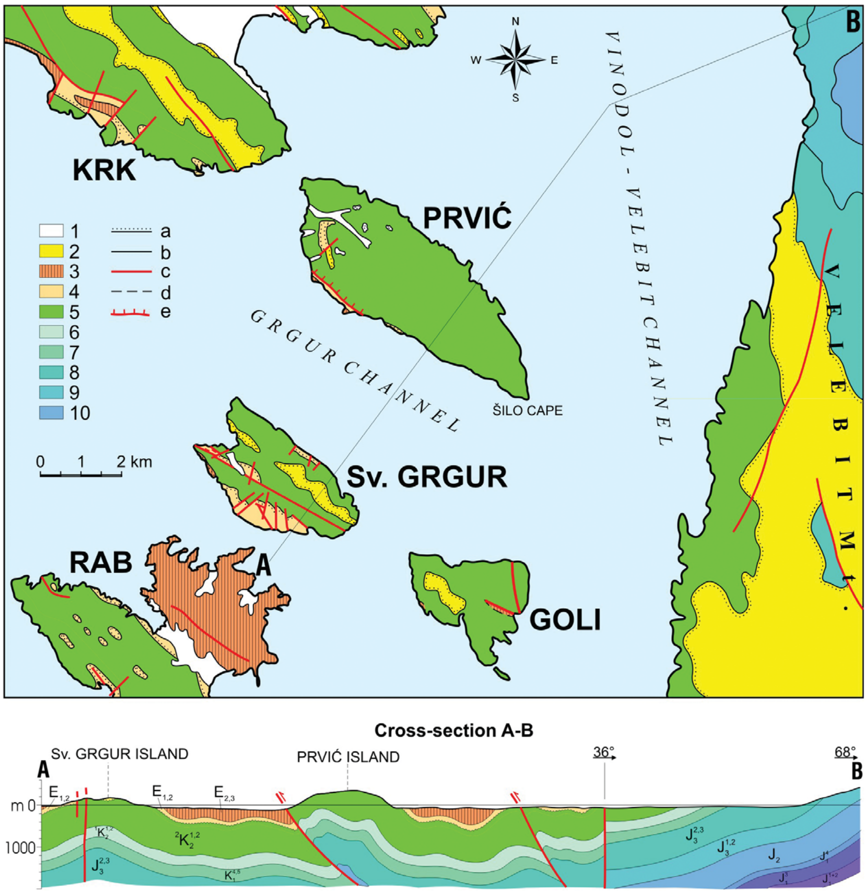

Figure 2: Geological map and cross-section of the Grgur Channel area.
Legend: 1) Quaternary in general; 2) Palaeogene and Neogene carbonate breccias; 3) Eocene flysch marls and sandstones; 4) Eocene foraminiferal limestones; 5) Upper Cretaceous limestones, limestones with dolomite intercalations and limestones with breccias; 6) Upper Cretaceous dolomites and dolomite breccias; 7) Lower Cretaceous limestones and breccias; 8) Upper Jurassic layered limestones with dolomites; 9) Upper Jurassic breccias and limestones with dolomites; 10) Middle Jurassic massive limestones; a) Transgressive contact; b) Normal contact; c) Fault without its character; d) Presumed fault; e) Reverse fault; (simplified after KOROLIJA & BOROVIĆ, 1966; MAMUŽIĆ et al., 1969; MAMUŽIĆ & MILAN, 1973).

conglomerates, deposited as a result of erosion of the older (Cretaceous limestones and Eocene flysch) sediments (KOROLIJA & BOROVIĆ, 1966; MAMUŽIĆ & MILAN, 1973).

From a general structural point of view, the Grgur and Goli Islands form a faulted flank of a syncline, while Prvić is interpreted as a part of an anticline, overturned in the northern-western part of the Island (Fig. 2). According to KOROLIJA & BOROVIĆ (1966) monoclinal layers and reverse faults confirm such a structural setting.

As shown in Fig. 2 and according to the structural features, the Grgur Channel is considered to be a submerged part of a syncline with its core composed of Eocene flysch.

3. MATERIALS AND METHODS

3.1. Sampling and sample preparation

Sea-bottom sediment samples investigated in this paper were collected in 1995 during the cruise of the R/V "Vila Velebita". The samples were taken by a Van Veen grab along four transects (at 13 locations) in water depths between 65 and 88 m (Fig. 1). Samples were air-dried and approximately 100 g of each sample were used for analysis.

3.2. Grain-size analysis

Grain size composition of the sampled sediments has been determined by wet sieving through an ASTM standard sieving set (diameter (d) > 32 μm) on Fritsch Analysette and by a particle coulter Coulter Counter TA II (d < 32 μm). Sediments were then classified according to the internationally accepted classification of sediments (FOLK, 1954).

3.3. Mineralogical analysis

The qualitative mineral composition of bulk sediment samples was determined by the Philips X`Pert Pro X-ray diffractometer. Relative mineral abundances were estimated based on the intensity of major peaks. In addition, randomly chosen gravelly grains from sample 11 were powdered and analyzed on the same diffractometer. The amount of carbonates was determined by gas volumetry (JOBSTRAIBIZER, 1970).

3.4. Grain-shape analysis

Each fraction of the sediment samples was examined with a binocular microscope. Grain morphology analysis was carried out only on the gravelly fraction of sample 11 (see discussion in 4.3). Pebbles were counted and weighed, and short (S), intermediate (I) and long (L) axes of clasts were determined, using a slide caliper. According to I/L and S/I ratio, the shape of each clast was categorized into sphere, rod, disc and blade, using the Zingg classification (ZINGG, 1935). Roundness and sphericity of the grains were determined using a visual comparative graphic chart (GRAHAM, 1988; TUCKER, 2003). Aditionally, the degree of grain flatness (flatness index) was calculated from the L, I and S ratio, using the formula: F= L+I/2S (MÜLLER, 1967).

Table 1: Summary results of the grain size and mineralogical analyses*

Sample	Sampling depth (m)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Mz (µm)	So	Carbonates (%)	Non-carbonate minerals	Sediment type (Folk, 1954)
1	84	0.8	51.3	44.8	3.1	50.7	2.13	55.6	Q, Ms, Chl	slightly gravely muddy sand
2	88	0.0	37.6	58.8	3.6	31.9	1.53	ND**	ND**	sandy mud
3	86	0.9	55.4	42.7	1.0	71.7	1.98	55.6	Q, Ms	slightly gravely muddy sand
4	73	1.0	45.1	44.0	9.9	44.1	2.53	70.5	Q, Chl, Ms	slightly gravelly sandy mud
5	86	0.0	11.4	70.8	17.8	12.1	1.81	54.5	Q, Chl, Ms	sandy mud
6	65	1.1	27.5	62.0	9.4	32.5	3.40	52.3	Q, Ms, Kln, Ill, Pl	slightly gravelly sandy mud
7	75	0.0	38.8	49.5	11.7	27.5	2.37	59.0	Q, Chl, Ms	sandy mud
8	82	0.0	8.7	74.4	16.9	12.1	1.71	54.5	Q, Chl, Ms, Pl	mud
9	79	2.7	11.9	74.2	11.2	15.6	1.71	50.0	Q, Ms, Chl, Ill	slightly gravelly sandy mud
10	78	3.2	31.2	53.9	11.7	20.7	2.33	50.0	Q, Chl, Ms, Ill	slightly gravelly sandy mud
11	83	14.3	22.2	46.6	16.9	44.5	3.99	52.3	Q, Chl, Ms	gravelly mud
12	88	0.0	8.2	80.1	11.7	12.6	1.48	43.2	Q, Chl, Ms, Ill	mud
13	86	0.4	25.8	57.5	16.3	18.4	2.31	56.8	Q, Ms, Ill	slightly gravelly sandy mud

* Mineral abbreviations: Chl – chlorite, Ill – illite, Kln – kaolinite, Ms – muscovite, Pl – plagioclase, Q – quartz.
** ND: not determined

3.5. Micropalaeontological analysis

Pebbles for micropalaeontological analysis of the gravelly fraction in sample 11 were randomly chosen and used for preparation of thin sections in order to define the rock type according to DUNHAM (1962).

4. RESULTS

4.1. Grain-size analysis

Results of grain size analysis of sediments from the Grgur Channel showed a mean grain size between 12 and 70 µm with predominance of the mud fraction (silt + clay) 44–92 % (Table 1). Sediments were classified according to FOLK (1954) into five sediment types: mud (M–8, 12), sandy mud (sM–2, 5, 7), slightly gravelly sandy mud ((g)sM–4, 6, 9, 10, 13), slightly gravely muddy sand ((g)mS–1, 3) and gravelly mud (gM–11) as shown on Fig. 3A. The map (originally at the scale of 1:100000, Fig. 3B) shows an almost symmetrical distribution of sediment types in the Channel regarding its elongate shape.

4.2. Mineralogical analysis

The analyzed sediments have a similar mineralogical composition, which is a mixture of carbonaceous and alumino-silicate components including quartz. The total content of

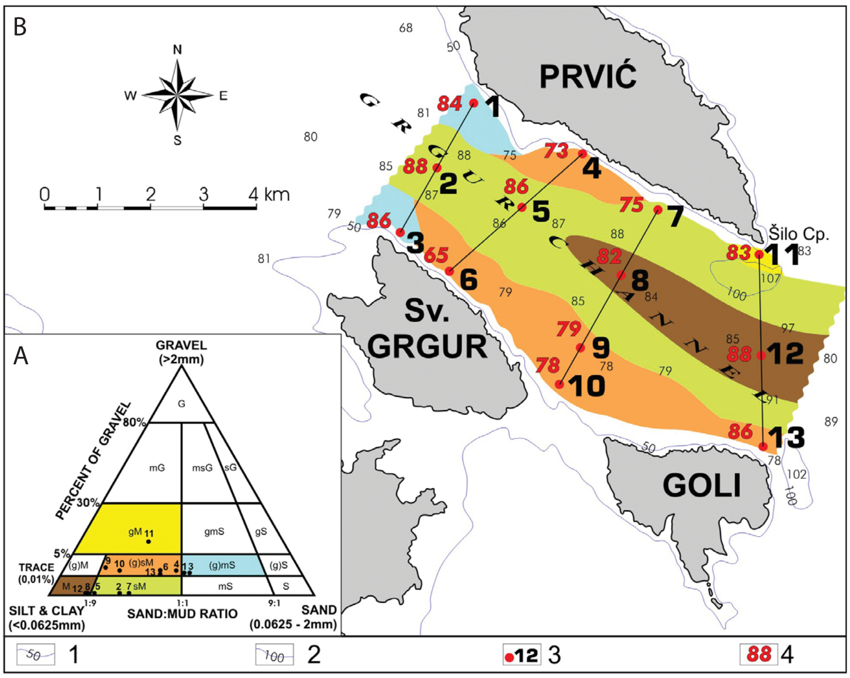

Figure 3: A) Folk (1954) diagram of the percentage of gravel, sand and mud with sediment types present on the seabed of the Grgur Channel (abbreviations explained in the text); B) Surface sediment map of Grgur Channel, bar scale: 1) isobath 50 m; 2) isobath 100 m; 3) sediment sampling station; 4) sampling depths (after HHI, 1997).

carbonate minerals varied between 43.2 % (sample 12) and 70.5 % (sample 4), averaging 54.5 % (Table 1). All samples contained calcite, (as the most abundant mineral), Mg-calcite and aragonite, mostly deriving from shell fragments. The second major mineral was quartz, the amount of which increased in the central part of the Channel (samples 2, 5, 8, and 12). Secondary minerals occurring within the sediments were dolomite, chlorite, muscovite and/or illite, while traces of plagioclase and kaolinite were also found.

Results of the X-ray analysis of the gravel fraction in the sample 11 revealed that all analyzed grains only contained calcite.

4.3. Grain-shape analysis

Sand and gravel in all of the samples consisted of various biogenous remains, except for the two coarsest (2–4 mm, >4 mm) fractions in sample 11, which contained only rock fragments. Because of this unusual finding, grain-shape analysis was only carried out for those fractions. The gravel fraction of sample 11 amounted to 14.3 % by weight and 89 grains were counted. Figure 4 shows a Zingg diagram of grain shapes (ZINGG, 1935). Almost half of the grains fell in the disc field (47.2 %). Spheroids were represented by 20.2 %, rods by 19.1 % and blades by 8.9 %. A small percentage of the grains (4.4 %) had boundary values: 3.3 % between discs and spheres and 1.1 % between discs and blades. Summary results of grain roundness and grain flatness are presented in Table 2.

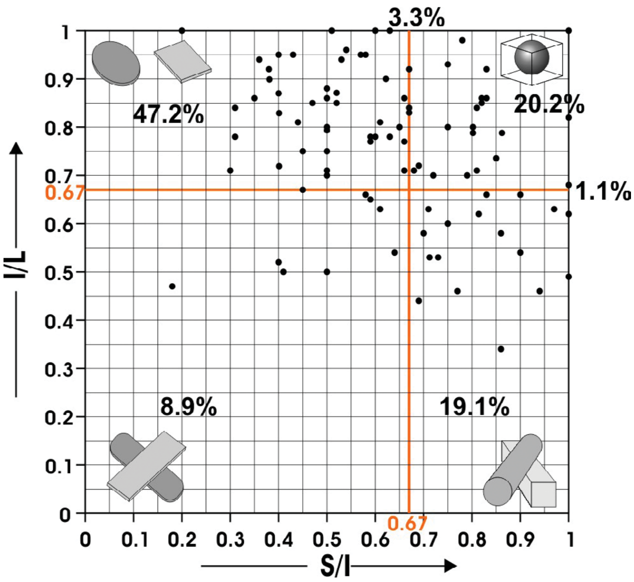

Figure 4: Zingg diagram of grain shape for the gravelly fraction of sample 11, according to intermediate (I)/ long (L) and short (S)/ intermediate (I) axes ratios; (after ZINGG, 1935).

Most of the grains were rounded (32.6 % well-rounded, 24.7 % rounded and 25.8 % sub-rounded). The flatness index (MÜLLER, 1967) ranged between 1.09 and 5. In Table 2 measured flatness indices were divided into three groups: < 1.6, 1.6–2 and > 2 %).

Table 2: Summary results of the grain shape analysis

ROUNDNESS:	%
Very angular	4.5
Angular	3.4
Subangular	9.0
Subrounded	25.8
Rounded	24.7
Well-rounded	32.6
SPHERICITY:	%
High	23.6
Low	76.4
AVERAGE VALUES FOR THE FLATNESS:	%
< 1.6	27.0
1.6–2	29.2
> 2	43.8

4.4. Micropalaeontological analysis

Microfossil assemblages from the examined limestone pebbles indicated an age range from the Lower Cretaceous to Middle Eocene. Fossil remains of *Pseudonummoloculina aurigerica* CALVEZ (Fig. 5A) discoverd in a peloidal-miliolidal grainstone, indicate the Lower Cretaceous (Late Aptian–Early Albian). Fragments of algae *Thaumatoporella parvovesiculifera* RAINIER in several different grains indicate a wider stratigraphic range (Upper Triassic to Palaeogene). However, together with the benthic foraminifera *Pseudolituonella reicheli* MARIE and fragments of *Broeckina (P.) balcanica* CHERCHI et al. in peloidal wackestone (Fig. 5B), this indicates a Middle Cenomanian age. Grains of peletal foraminiferal wackestone containing *Alveolina* sp., *Chrysalidina* sp., *Orbitolites* sp. and *Triloculina* sp. (Fig. 5C) confirmed their Eocene age.

In a few rounded and well-rounded pebbles from the gravelly fraction of sample 11, polychaete and anthozoan remnants were found (Fig. 6A and 6B). Being poorly preserved, determination of the polychaete species was not possible. Remains of the anthozoa, (also deeply weathered), belong to the juvenile form of the solitary coral *Balanophyllia europaea* RISSO (Fig. 6B and 6C) (P. KRUŽIĆ, 2006, personal communication).

5. DISCUSSION

5.1. Seabed sediment distribution

The distribution of sediment types in the Channel is symmetrical along the Channel (Figs. 3 and 7). Sediments from the central part of the Channel contain the largest amount of mud (samples 5, 8 and 12; > 88 %). Peaks of the muddy modes lay in the fine silt fraction (~8 µm, except for sample 3 occuring at 16 µm) (Fig. 7). The proportion of the coarse fractions increases westward and shoreward in the Channel. The sandy fraction content of the samples ranges between 8 and 55 % with the modal peak occurring mostly at 63 µm.

Samples 2, 5, 7 contain more sand than previous ones and were classified as sandy muds, while samples 4, 6, 9, 10, 13 were classified as slightly gravelly-sandy mud, also containing a slightly increased gravel fraction. The highest precentage of sand (> 50%) was found in samples 1 and 3, classified as slightly gravelly muddy sand (Fig. 3). The gravel content of the investigated samples is low (0–3.2 %), except for sample 11 (14.3 %). Visual inspection of this fraction revealed differences between the biogenic origin of this fraction in most of the samples and the terrigenous origin of the gravel fraction in sample 11, as discussed below.

Poor and very poor sorting (Table 1), together with noticeable bimodal and polimodal frequency curves, respectively, (Fig. 7) indicate that all of the analyzed sediment sam-

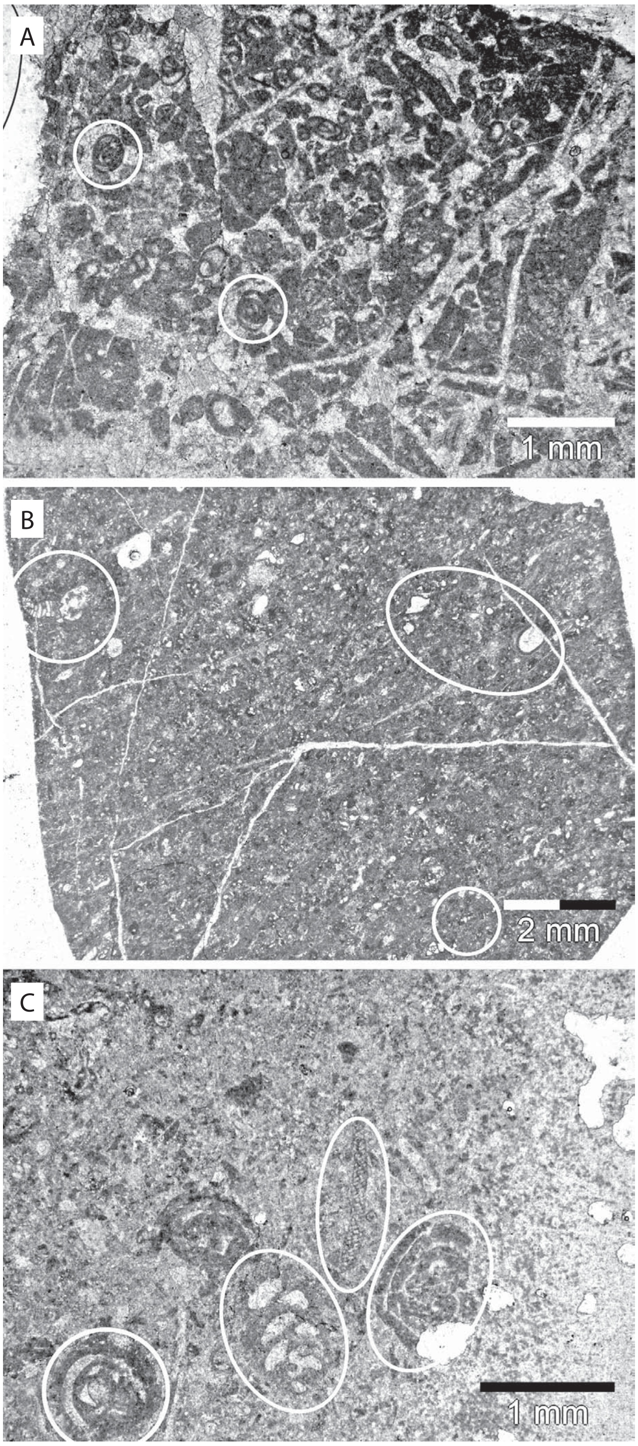

Figure 5: A) Aptian–Albian limestone with *Pseudonummoloculina aurigerica CALVEZ*; B) Cenomanian assemblage of *Pseudolituonella reicheli* MARIE (fragment in oval) and *Broeckina (P.) balcanica* CHERCHI et al. (fragments in circles); C) Eocene foraminiferal limestone with (from left to right) *Triloculina* sp., *Chrysalidina* sp., *Orbitolites* sp. and *Alveolina* sp. (fragments).

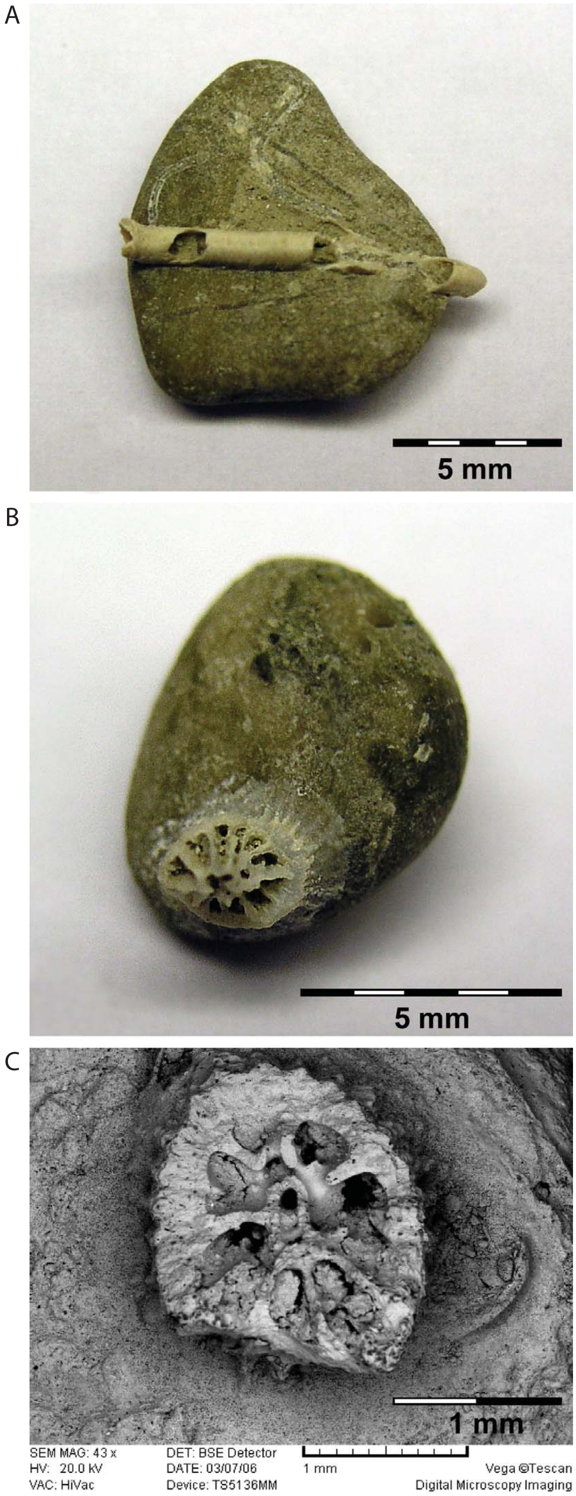

Figure 6: A) Gravel grain with remains of a polychaete; B) Gravel grain with remains of an anthozoan, *Balanophyllia europaea* (Risso); C) *Balanophyllia europaea* (Risso), SEM, BSE.

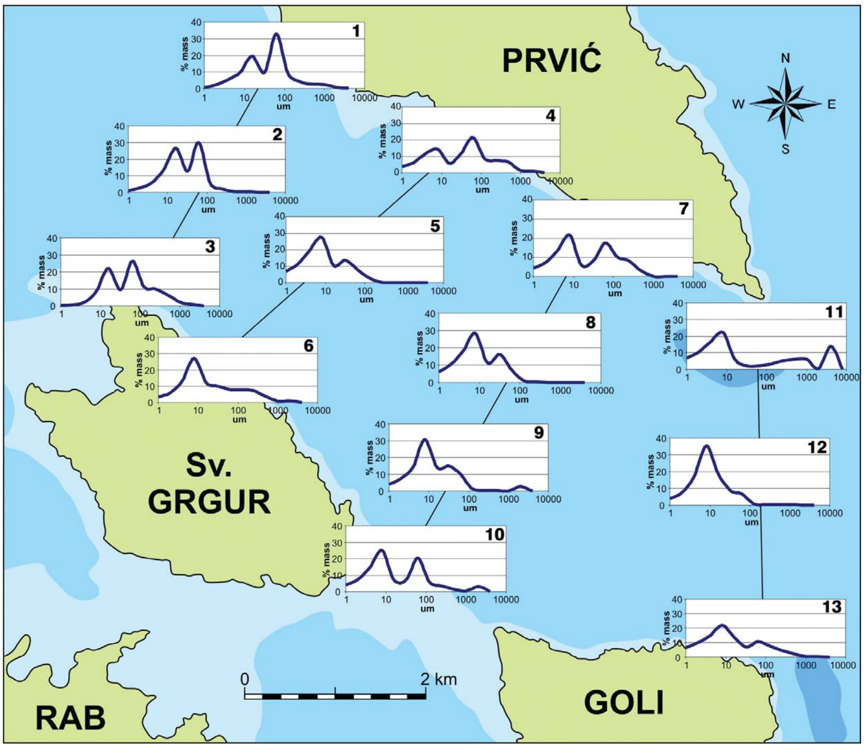

Figure 7: Grain-size frequency distribution of sediment samples in the Grgur Channel.

ples are mixtures of mud with coarser fractions (sand and gravel) in different proportions. These results mainly confirmed the previous characterization of the Grgur Channel bottom sediments as sandy muds (JURAČIĆ et al., 1999). Greater distinction between the sediment types has additionally refined the existing seabed sediment map (Fig. 3).

5.2. Origin of sediments

The pronounced bimodal or polymodal distribution and poor sorting (Table 1, Fig. 7), indicate the various origins of particles found in sediments. Aditionally, nearly equal proportions of carbonate and siliciclastic fractions suggests different sources of particles. The main thesis arising from these results is that the seabed sediment contains particles of biogenic and terrigenous origin, suggesting the possibility of different times of deposition.

The analyzed sediments, with sampling depths between 65 and 88 m, are below the present wave base. An absolute maximum wave height in the Adriatic recorded during the longlasting southeastern wind *Jugo,* (or *Scirocco* in Italian), in the open northern Adriatic was H_{max} = 10.8 m and the average wave length was L_{av} = 112.3 m (HHI, 1999). Thus, the deepest wave base in the open Adriatic is of the order of 50 m. Since the study area is protected by the southern and external islands (Fig. 1A), the wave base here is significantly shallower. Therefore, at the investigated sea depths, only fine-grained terrigenous particles should be expected. However, the results of both granulometric and mineralogical analysis have shown that, as already emphasized, all of analyzed samples have a bimodal/polymodal distribution (Fig. 7) and are mixtures of carbonaceous and siliciclastic material to different extents (Table 1).

5.2.1. Fine-grained fraction

The fine-grained fraction of the analyzed sediments (< 63 μm) contains aluminosilicate minerals. Quartz, as the second major mineral present, together with muscovite and/or illite, plagioclase and kaolinite, indicates a terrigenous source. Such a mineral composition of the fine grained fraction is similar to the composition of flysch deposits of central Istria and the Kvarner Littoral area (with various percentages of carbonates, quartz as the main component and plagioclase, illite, chlorite and montmorilonite as secondary components) (MAGDALENIĆ, 1972). Moreover, some beach sands on Rab Island have been recognised as material supplied by weathering of siliciclastic Eocene sandstones in the nearby hinterland (LUŽAR-OBERITER et al., 2008), while similar mineral assemblages, belonging to the Kvarner Province, can be found in the bottom sediments of the Velebit Channel, Rijeka Bay, northern parts of Kvarner and the Kvarnerić Channel (ŠKRIVANIĆ & MAGDALENIĆ, 1979). Eocene flysch outcrops (marls and sandstones), exposed to present subaerial weathering that could contribute to sediment supply in the Channel occur only on Prvić Island. This flysch might be the source of part of the aluminosilicate minerals present (Fig. 2). These outcrops are both scarce and presumably too small to be the main source of the siliciclastic component of the sea-bed sediments. A possible major source of this component could have been the seabed of the Channel itself. MAMUŽIĆ et al. (1969) interpreted the Channel as the submerged part of a syncline, composed of Eocene flysch sediment. During the lower sea-level, specifically during the last glacial period, most of the presently submerged parts of the Channel were dry land (Fig. 8) (BENAC & JURAČIĆ, 1998). Such exposed flysch bedrock could have been weathered under subaerial conditions. With the onset of the rapid Holocene transgression, this weathered non-lithified flysch debris probably remained on the bottom of the infilled Channel.

5.2.2. Sand and gravel fractions

The coarser-grained fraction (> 63 μm) of the sediment samples contained large amount of skeletons, shells and fragments of different marine organisms. Thereby, the major part of the carbonate fraction (including calcite, Mg-calcite and aragonite) is of biogenic origin. Most of skeletal remains are sand sized (63 μm–2 mm), while a minor part is determined as gravel (> 2 mm). Since these particles are of biogenic origin, their size is a result of the original skeletal size and some degree of fragmentation.

Considering the predominant carbonate lithology of the mainland and the islands in the investigated area, (which is more prone to chemical weathering/karstification), the actual terrigenous input into the investigated area was pressumed to be low (BENAC & JURAČIĆ, 1998). However, dolomite determined as a secondary mineral in the sandy fractions, confirmes the terrigenous origin of part of the carbonate fraction. Grgur Channel coasts (Fig. 2) are exposed to marine erosion (BENAC, 1992), especially due to waves generated by the *Jugo*. Such abrasion could produce small amount of sand-sized particles.

Unlike other samples, sample 11, collected from a depth of 83 m, shows an intriguingly high proportion of gravel (14.3 %). This gravelly fraction is composed only of rock granules and very fine pebbles, whereas bioclastic particles are absent. Referring to the afore-mentioned hydrodynamic setting, the gravelly part of this sediment is obviously not in accordance with the present depositional environment. In order to determine the depositional conditions of this gravel, pebbles were morphologically analyzed. The shape of sedimentary particles is a complex property, depending on many factors (initial mineralogy, weathering degree, transport abrasion degree, transport distance, fluid energy etc). Weathering of rocks of homogenous texture produces spherical, discoidal and isometric grains (TIŠLJAR, 2004). Within the analyzed pebbles, 47.2 % were discs and 20.2 % were spheres (Fig. 4), suggesting high transport energy and/or noticeable transport length. X-ray analysis showed that all of the pebbles are composed of calcite and micropalaeontological analysis showed that the gravel source rocks are limestones having age ranges from the Lower Cretaceous (Aptian–Albian) to Middle Eocene. These source rocks are well stratified (MAMUŽIĆ & MILAN, 1973). If weathered, stratified limestone produces tabular grains, which results in the dominance of discs. Thereby, high flatness indices (> 40 % of the analyzed grains) could be attributed to the structure of a source rock. Therefore, we presume that the high percentage of discs in the gravel fraction is controlled by the structure of the source rocks. Besides the grain shape, grain roundness also confirms a considerable transport distance and/or high transport energy: over 80 % of pebbles are sub rounded, rounded and well rounded (Table 2).

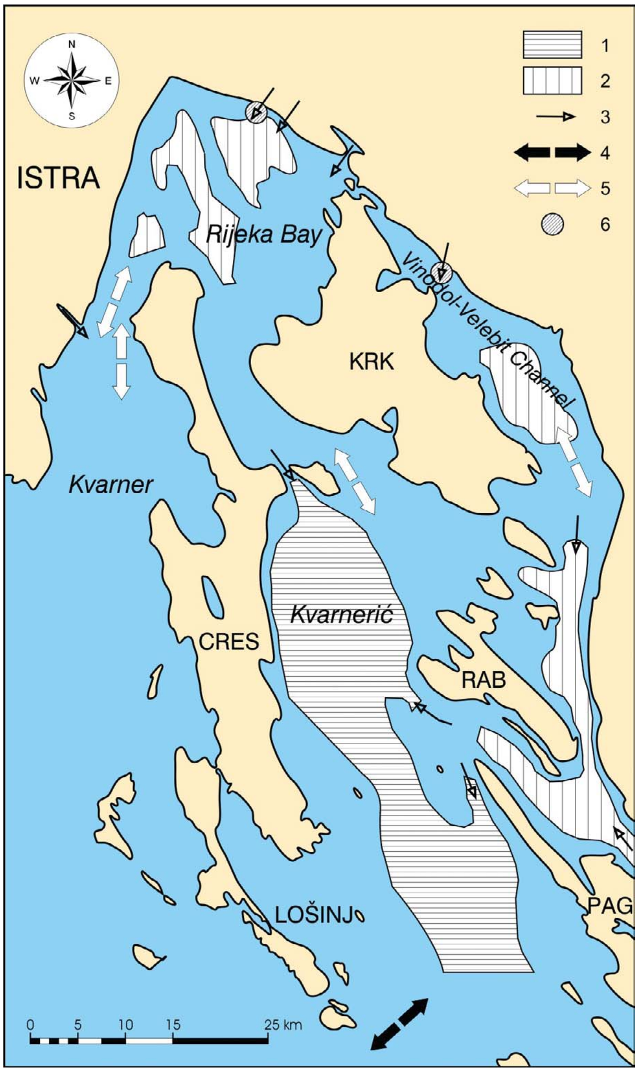

Figure 8: Morphological evolution of the Kvarner area during the last glacial period. Legend: 1) position of the marine basin; 2) position of periodic lakes; 3) position of palaeoflows; 4) continuous connection with the marine basin in the Middle Adriatic; 5) periodically connected with the marine basin; 6) intensive recent sedimentation; (after BENAC & JURAČIĆ, 1998).

Some of the grains, from Upper Cretaceous and Middle Eocene limestones could be transported from adjacent sources. Since Lower Cretaceous sediments do not crop out on the surrounding islands (Fig 2.), part of the gravel was probably transported from more distant sources. One possible transport direction could be from the Velebit Channel toward the Grgur Channel (Fig. 8), since, according to MAMUŽIĆ et al. (1969), Lower Cretaceous deposits oucrop in part of the Velebit Channel seabed (Fig. 2). Erosion of those deposits caused by a palaeostream could produce gravelly material during a low sea-level stand, supplying the studied location with gravelly material.

During the lower sea level, coastlines were shifted away from the recent ones and brackish and/or freshwater lakes could have been formed in deeper and isolated parts of the Kvarner area (Fig. 8). If gravel was brought and deposited by the palaeoflow near the former coastline, it could be further shaped as beach sediment. Therefore, gravelly sediment could be expected to extend along the former palaeoflow and/or coastline. Similar discoveries of gravel (cobbles) at 155 m depth in the Black Sea were also interpreted as an ancient lake shoreline (BALLARD et al., 2000).

The discovery of biological owergrowths on the pebbles indicates sea-level change. *Balanophyllia europea* (RISSO) (*B. italica* MICHELIN), found attached to gravel, is a solitary, ahermatypic zooaxantellate scleractinian coral, about 25 mm high. It lives mostly on a rocky substratum and rarely on a sandy substratum and mollusc shells, and it is well known in the Mediterranean Sea and in some parts of the Atlantic Ocean (ZIBROWIUS, 1980; ZAVODNIK & ŠIMUNOVIĆ, 1997). It has inhabited the wider Mediterranean area since the Miocene (CHAIX & CAHUZAC, 2005). Its depth distribution seems to be restricted due to its symbiosis with zooxantellae; it is found at a maximum depth of 50 m (ZIBROWIUS, 1980). In the Adriatic Sea it inhabits depths between 3 and 50 m (ZAVODNIK & ŠIMUNOVIĆ, 1997). The high degree of roundness (rounded and well-rounded grains, Fig. 6) of the gravel on which the coral was found indicates that transport and/or reshaping processes must have occurred before the coral grew. Therefore, the coral was probably attached while the depth of the seabed was suitable for its colonization (between 3 and 50 m). Due to sea-level rise, grains with coral remains finally ended up below the depth suitable for coral colonisation. Preservation of the attached coral′s theca proves that the pebbles were not further reworked.

5.3. General setting of the depositional environment in the Grgur Channel

The presence of well rounded carbonate gravel, the general composition and bimodality/polimodality of the frequency curves of surface sediments in the Grgur Channel is considered as a good example of the documented change of depositional environment and sediment sources. The Late Pleistocene–Holocene transgression is accepted as a reason for the change in depositional conditions.

The Grgur Channel, as with other channels in the wider area along the Croatian portion of the eastern Adriatic coast, was presumably formed along the bottom of a syncline, as described in section 2 (Fig 2). The investigated area belongs to the Northern Dalmatic Province (NDP) (GIORGETTI & MOSETTI, 1969) – an insular area with water depths in channels up to 125 m, influenced by sea-level changes during the Pleistocene. During the lower sea-level periods, parts of channels in the Kvarner area were probably emergent. At the same time the outer longitudinal island chain kept the inner NDP basins out of Po River dominated continental terrigenous sedimentation, typical for the northern Adriatic shelf during Pleistocene sea-level lowstands (BENAC & JURAČIĆ, 1998). According to these conditions, the Grgur Channel as well as deeper parts of the Kvarner (Kvarnerić Bay, Vinodol Channel, Velebit Channel) probably remained protected from infilling with terrigenous sediments from the west, whilst some other parts of the Grgur Channel could have been dry land (Fig. 8). Exposure of its flysch dominated flanks to subaerial conditions presumably produced substantial amount of debris.

Onset of a global sea level rise caused by rapid ice decay at the end of the MIS 2 (LAMBECK et al., 2002), caused the depositional areas and coastlines to rapidly shift towards the recent ones. The formerly deposited sediment remained on the seabed surface and recent sedimentation has only partially covered it. The sediment is further mixed by bioturbation. Deficient recent sedimentation within the NDP is also noted in palaeontological investigations, after the discovery of fossil elephant skeletal remains on the sea-bottom between Rab and Laganj Islands (approximately 5 km south of Rab Island, black dot in Fig. 1A) (MALEZ & LENARDIĆ-FABIĆ, 1988). Remains of *Mammuthus meridionalis adriaticus* n. ssp. were found at a depth of 80 m below present sea-level, in sediment that authors have called “ancient sands”. The age of this fossil elephant was placed in the Mindel glacial (MIS 12–14?, LOWE & WALKER, 1997), indicating several emersions of this area, caused by sea-level fluctuations during the Pleistocene.

Hence, negligible recent sedimentation in the Channel is evident and resulted in thin recent sediment cover. Biological effects throughout interaction with the substrate (bioturbation processes) probably helped in generating various mixtures of recent and subrecent sediment. Bimodal or polymodal grain size distributions are a result and further proof of this mixing (Fig. 7). For a detailed identification of the thickness of individual sediment layers (if existing) at particular locations, a different sampling procedure (gravity corer, box corer) is required, since the grab sampling could further mix the sediment.

Investigations conducted on the surface sediment cover have revealed complex depositional mechanisms in the Grgur Channel, markedly conditioned by the last sea-level change. Furthermore, it suggests similar depositional patterns in the channel area of the eastern Adriatic coast, where similar geological settings also occur. However, every channel tends to have specific oceanographic characteristics, due to the complicated orography and geometry (ORLIĆ, 2001), which certainly alters the final distribution of sediment types. Nevertheless, these results are in accordance with the distribution of sediment types in other parts of the Kvarner region. Diversity of sediment types in the Grgur Channel certainly contributes to the high biodiversity of the bottom communities indentified by ZAVODNIK et al. (2005), which is an important factor for protecting the Grgur Channel area as a marine park. Moreover, the Channel seabed requires further investigation. In order to gain more precise information on the sediment cover and changes in sedimentation during the subrecent geological past, marine seismic techniques and sub-bottom profiling could be used.

6. CONCLUSIONS

Analyzed sediments of the Grgur Channel were sampled in the quiet depositional environment, below the present wave base. Distribution of sediment types is symmetrical along the Channel. Common characteristics of all analysed sediment samples are bimodality/polymodality of the grain size frequency curves and a combined carbonate-siliciclastic mineral composition, suggesting different sources, transport mechanisms and times of deposition. The Late Pleistocene–Holocene transgression is considered as a main reason for changes in the depositional conditions.

The finest fraction is most abundant in sediment from the central part of the Channel and is mostly in accordance with recent depositional conditions. The other parts of the Channel seabed are covered with a mixture of fine and coarse grained particles that are only partially of recent origin. The most conspicuous characteristic of sediments is the unusual finding of well rounded carbonate gravel at a depth of 83 m, characterized as fluvial and possibly beach sediment. This mixture of recent and subrecent sediment particles is probably due to bioturbation. Thus, the analyzed sediments could be defined as a mixture of recent and subrecent, carbonaceous and siliceous, as well as mixture of biogenic and terrigenous particles.

Results of analyses of seabed sediments from the Grgur Channel are in line with the previous sediment investigation. They also indicate the complex origin of the seabed sediment cover in the channel area of the eastern Adriatic coast.

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