Karstic estuaries along the eastern Adriatic coast

Felja, Igor

University of Zagreb

Faculty of Science

Department of Geology

Igor Felja

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Sveučilište u Zagrebu

Prirodoslovno-matematički fakultet

Geološki odsjek

Igor Felja

Krški estuariji duž istočne jadranske obale: evolucija ušća rijeka Mirne i Neretve u mlađem kvartaru

Doktorski rad

Mentori: Prof. dr. sc. Mladen Juračić

Dr. sc. Alessandro Fontana

Zagreb, 2017.

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BASIC DOCUMENTATION CARD

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Doctoral Thesis

KARSTIC ESTUARIES ALONG THE EASTERN ADRIATIC COAST: LATE-QUATERNARY EVOLUTION OF THE MIRNA AND NERETVA RIVER MOUTHS

IGOR FELJA
Faculty of Science, Department of Geology, Zagreb

Abstract: Sedimentological, macro- and micropaleontological analyses on sediment cores were carried out in the lower section of the Mirna and Neretva River valleys, in order to study depositional facies and environmental evolution during Late Pleistocene and Holocene. The Holocene marine transgression reached river valleys several kilometers upstream from the present-day coast, while in the last 7000 – 6000 years it was followed by progradation of the Mirna and Neretva intra-estuarine deltas. Sediment cores recorded these changes and each depositional environment contains distinctive sedimentary characteristics and fossil assemblages which reflect conditions in which sedimentation and life were occurring. This study highlights the potential role of hand augering in sampling and describing the subsoil for reconstruction of the geomorphological evolution of the area and supporting the study of past relative sea levels, climate changes, and impact of anthropogenic activities.

Key words: karstic estuary, intra-estuarine delta, Holocene, environmental changes, sea-level changes, foraminifera

Thesis contains: 169 pages, 64 figures, 22 tables, 10 appendixes, 2 plates and 233 references.

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KRŠKI ESTUARIJI DUŽ ISTOČNE JADRANSKE OBALE: EVOLUCIJA UŠĆA RIJEKA MIRNE I NERETVE U MLAĐEM KVARTARU

IGOR FELJA
Prirodoslovno-matematički fakultet, Geološki odsjek, Zagreb

Sažetak: Sedimentološke, makro-paleontološke i mikro-paleontološke analize radile su se na sedimentnim jezgrama izvađenim iz deltnih ravnica rijeka Mirne i Neretve, s ciljem da se prouče i rekonstruiraju taložni facijesi i evolucija okoliša tijekom mlađeg pleistocena i holocena. Transgresija u holocenu dosegnula je uzvodno u riječne doline nekoliko kilometara od današnje obalne linije, a u posljednjih 7000-6000 godina uslijedila je progradacija delti u estuarijima rijeka Mirne i Neretve. Sedimentne jezgre sadrže zapis tih promjena, a svaki taložni okoliš sadrži karakteristične sedimentne značajke i fosilne zajednice koje odražavaju uvjete u kojima se odvijala sedimentacija i život. Ovo istraživanje naglašava potencijalnu ulogu ručnog uzorkovanja jezgri u opisivanju sedimenata, u svrhu rekonstrukcije geomorfološke evolucije područja i upotpunjava znanje o promjenama relativne razine mora, klime i utjecaja antropogenih aktivnosti.

Ključne riječi: krški estuarij, estuarijska delta, holocen, promjene okoliša, promjene razine mora, foraminifere

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CONTENT:

The list of used abbreviations and symbols:

~ (*app.*) – approximately

AD – years after Christ

BC – years before Christ

BP – years before present

FOBIMO – FOraminiferal BIo-Monitoring

HST – highstand system tract

LGM – Last Glacial Maximum

LST – lowstand system tract

MIS – marine isotope stage

msl – mean sea-level

rsl – relative sea-level

sp. – species

TST – transgressive system tract

1. INTRODUCTION

1.1. BACKGROUND

The eastern part of the Adriatic coast is built mostly of carbonate rocks, and in prevailing humid climatic conditions, chemical weathering of limestone and dolomites dominates. Along the eastern Adriatic coast, during the Quaternary, the karstic processes have been intensive and the terrigenous (riverborne) load reaching the sea was limited. In such conditons rivers at their mouth in the Adriatic Sea formed a specific type of estuaries that has been described as *karstic estuaries* (Juračić, 1992; Pikelj & Juračić, 2013). Karstic estuaries formed on a karstic bedrock require coastal environment with low energy (sheltered position of the river mouth and low tidal range) and are characterised by the small input of riverborne terrigenous material due to prevalent dissolution of carbonates in the catchment (Juračić, 1992). However, there are some river systems, *e.g.* Neretva, Mirna or Raša rivers, (**Figure 1.1.**), which have somewhat higher terrigenous load, due to the fact that they are allogenic karstic rivers. Therefore, they are the only rivers in Croatia which developed noticeable deltas at their mouths during Holocene.

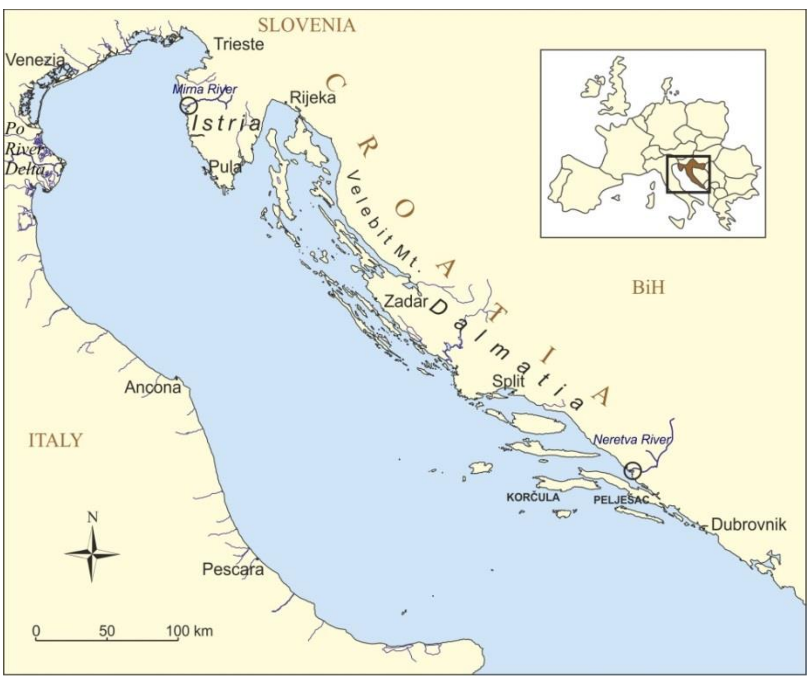

Figure 1.1. The Adriatic Sea and Croatian and Italian coastline, with locations of Mirna and Neretva River delta plains. Rivers are marked in the blue lines.

Slika 1.1. Karta Jadranskog mora s hrvatskom i talijanskom obalom, s označenim lokacijama deltnih ravnica rijeka Mirne i Neretve.

Development of the late Quaternary coastline was related to oscillations in the sea-level caused by alternation of glacial and interglacial periods during Pleistocene and Holocene (Lambeck & Chappell, 2001; Clark et al., 2009). In the Last Glacial Maximum (LGM, 29,000-19,000 years BP, Clark et al., 2009), when sea level was ~120 m lower than today, rivers on the eastern side of Adriatic basin carved their valleys in the carbonate basement. Since the end of the LGM, about 19,000 years ago, large volumes of ice were melted and sea level was rising rapidly, leading to a global transgression, that flooded vast coastal areas, including the Adriatic basin. The Adriatic Sea flooded karstic river valleys along the eastern shores and deep karstic estuaries were formed, including those of Neretva and Mirna River. Sea-level rise slowed down in the last 7000-6000 years (Antonioli et al., 2009; Vacchi et al., 2016) which caused gradual filling of estuaries with terrigenous load and formation of intra-estuarine deltas (Dalrymple, 1992; Stanley & Warne, 1994; Semeniuk et al., 2011).

The paleoecological analyses of the foraminifera and mollusc assemblages, especially benthic foraminifera, that are abundant microorganisms in the shallow and marginal-marine environments (Murray, 2006), were useful in the analysis of Holocene sea-level changes and in paleoenvironmental reconstruction of estuarine systems (e.g. Ruiz et al., 2005, Delgado et al., 2012, Durand et al., 2016). In all marine environments, but especially in these transitional environments, foraminifera distribution is controlled by several environmental parameters such as salinity, sediment grain size, subaerial exposure and organic carbon content (Ruiz et al., 2005).

Transitional environments developed at, or near, mean sea-level (msl), *e.g.* salt marshes, are particulary useful in reconstructing past sea-levels (Scott & Medioli, 1978; Gehrels, 1994; Edwards & Horton, 2000). In order to date sea-level precisely, other factors such as compaction of sediments and subsidence in the area must be taken into account as well.

1.2. RESEARCH AIMS AND OBJECTIVES

This PhD thesis has been planned and developed aiming at the following goals:

1. To describe Late Pleistocene and Holocene succession of depositional facies in karstic river mouths, recorded in the terminal sectors of the Mirna and Neretva River valleys.

2. To reconstruct the geomorphological evolution of these areas.

3. To study past relative sea levels, climate changes and anthropogenic activities that occurred during the “Post-LGM” period.

Sea-level changes occurring during Late Pleistocene and Holocene strongly influenced the evolution and development of different environment in the river mouths. Each environment contains distinctive sedimentary characteristics and fossil assemblages which reflect conditions in which sedimentation and life were occurring. Hence, deposited sediments recorded these changes.

This study should help in the reconstruction of past relative sea levels and climate changes in the area of the eastern Adriatic Sea (which is relatively poorly investigated so far) but also in Mediterranean, during Late Pleistocene and Holocene. Moreover, results of this study could contribute to better understanding of the evolution of intra-estuarine deltas and to their protection and sustainable use.

In this work the use of hand augering in sampling and describing the subsoil down to 13 m depth was tested, suggesting that, due to its cost-effectiveness, it is potentially useful in sampling other low-lying areas along the eastern Adriatic coast that are sometimes remote and not easily accessed with the standard mechanical boring equipment.

2. RESEARCH CONTEXT

2.1. SEA-LEVEL CHANGES: CAUSES AND EFFECTS

Sea-level changes were common during the history of the Earth and had most significant role in the development and shaping of the different coastal environments, which is still very pronounced today. Most researches of the sea-level changes are focused on the Quaternary period (last 2.59 million years), which is characterised by major climatic oscilations (alternations of glacial and interglacial periods). The basic cause for these variations are mainly related to the cyclic changes in orbital parameters of the Earth causing variations in solar radiations on the Earth surface (Fairbanks, 1989) which caused accumulation and melting of the large volumes of ice (Lambeck & Chappell, 2001).

It is important to distuinguish eustatic (global) sea-level changes and relative (local) sea-level changes (Van de Plasche, 1986), which are related to changes of the sea-level position in relation to land. Relative sea-level is sum of eustatic, tectonic, compaction and glacio-isostatic parameters (Van de Plassche, 1986; Lambeck & Chappell, 2001; Lambeck et al., 2004a).

2.2. RELATIVE SEA-LEVEL INDICATORS

Relative sea level (rsl) indicators measure both eustatic sea-level and the sum of all vertical land movements (caused by tectonics, sedimentary compaction and/or isostasy) that affected the indicator since its formation (Hijma et al., 2015; Horton & Shennan, 2009; Rovere et al., 2016, and references therein). Sea-level indicators require stabilization of sea level, for at least a short period, in order for them to form and preserve in the long-term.

Sea-level indicators can be divided into following categories:

1. **Erosional** (*e.g.* abrasion platforms and marine notches).

Important erosional sea-level indicators are marine notches and abrasion platforms (**Figure 2.1.A.**). For example, tidal notches can be very precise sea-level indicators, because they are related to the tidal range of the locality where they were formed and the deepest point of the notch is closely correlated to mean sea level (Antonioli et al., 2015 and references therein). Abrasion platforms are the product of marine erosion on exposed rocky coasts during long periods of stable sea level.

2. **Bioconstructional indicators** (*e.g.* encrustations by marine organsims)

Bioconstructional sea-level indicators include coral reefs (Lighty et al., 1982), vermetid reefs (Laborel, 1986; Sivan et al., 2010), biogenic littoral rims built by the coralline rhodophyta *Lithophyllum byssoides* (Lamarck) Foslie, 1900 (**Figure 2.1.B.**; Faivre et al., 2013), and borings left on rocky carbonate coasts by molluscs (such as *Lithophaga lithophaga* Linnaeus, 1758) or by sponges (Rovere et al., 2015, and references therein).

3. **Depositional indicators** (*e.g.* sediments of estuarine or deltaic environment, salt-marsh, beachrock, *etc.* and their fossil assemblages).

In marginal marine environments, such are those of Mediterranean coastal lagoons and estuarine or deltaic brackish areas, vertical distribution of fossils of foraminifera, ostracoda, diatomea, bivalvia and gastropoda, has proved to be useful for sea level and paleoenvironmental reconstructions during Quaternary (Vacchi et al., 2016).

Benthic foraminifera are very abundant microorganisms in shallow and marginal-marine environments, and they are widely used in ecological studies (Murray, 2006; Schönfeld, 2012). Because of their short life cycles, high biodiversity and narrow environmental tolerances (Murray, 1991, 2006), benthic foraminifera are sensitive to short-term environmental changes and due to high preservation potential and abundance in sedimentary records, foraminifera can provide an excellent temporal archive for long-term ecological data over the past hundreds to thousands of years (Yasuhara et al., 2012).

Foraminifera that inhabit salt-marsh environments are especially useful (**Figure 2.1.C.**), and are one of the most precise depositional indicator (Scott & Medioli, 1978; Gehrels, 1994; Edwards & Horton, 2000). Sediment records in these environments contain specific foraminiferal taxa, which reflects very restricted depth and salinity constraints (*e.g.*, Serandrei Barbero et al., 2006; Shaw et al., 2016).

The sediment deposits in some other marginal marine environments, such are wetlands of the river mouths, coastal lakes and lagoons can also record paleoenvironmental changes related to the sea level changes. Example of these settings are quite common in the Mediterranean shelf which contain multiple depressions and valleys that become flooded during transgressions and highstands, but were isolated from the sea during lowstands (Taviani et al.,2014; Drinia et al., 2014; Felja et al., 2015).

4. **Archeological indicators** (*e.g.* fish tanks, wells, harbors)

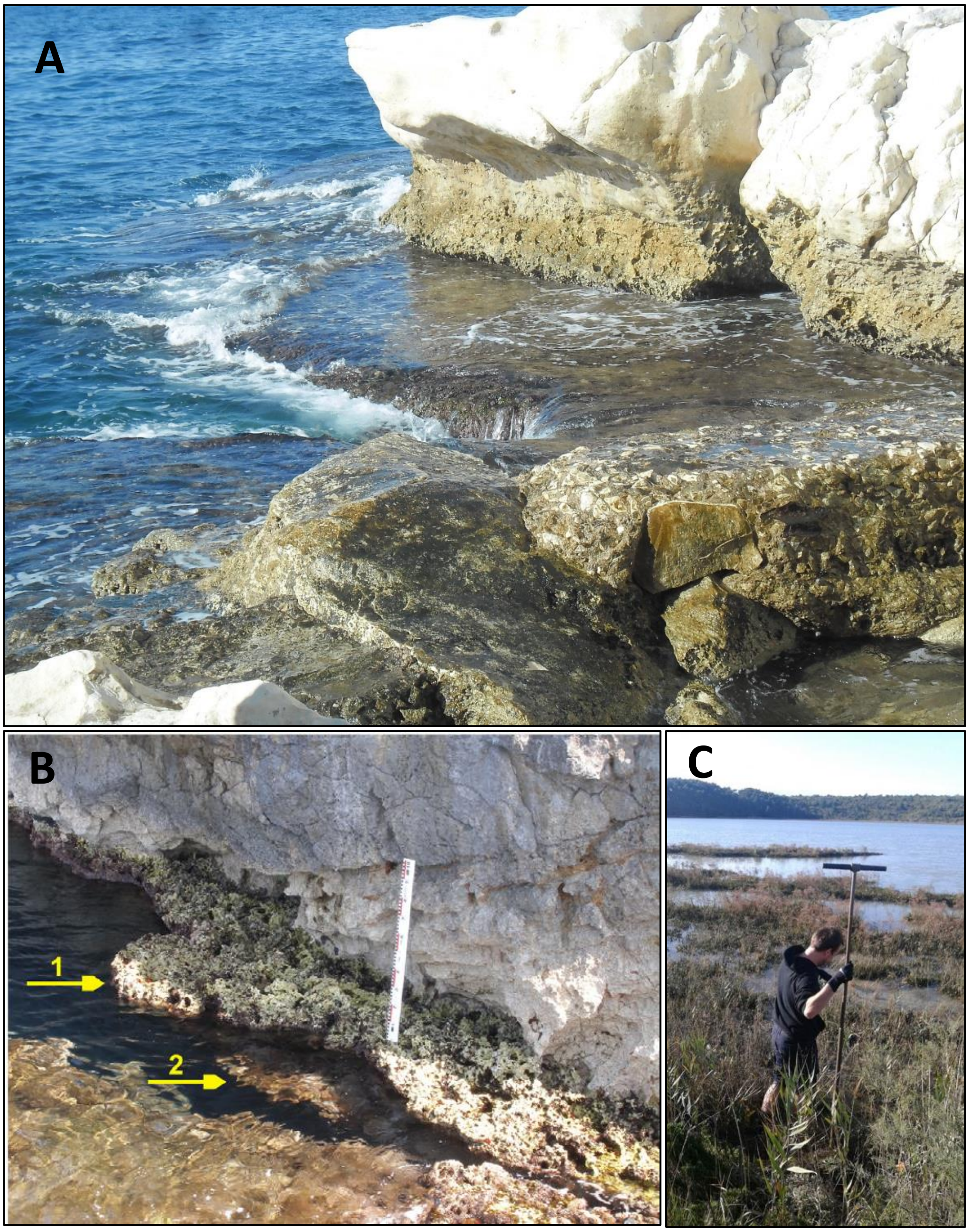

Figure 2.1. Examples of erosional, bio-constructional and depositional sea-level indicators: A. tidal notches and abrasion platforms (Israel); B. biogenic littoral rims built by the coralline rhodophyta *Lithophyllum byssoides* (Lamarck) Foslie, 1900 (Faivre et al., 2013); C. coring operation in salt-marsh near the Mirna River mouth, Croatia.

Slika 2.1. Primjeri erozijskih, bio-konstruktivnih i taložnih indikatora razine mora: A. plimske potkapine i abrazijske platforme (Izrael); B. biogeni litoralni obraštaji algi *Lithophyllum byssoides* (Lamarck) Foslie, 1900 (Faivre i sur., 2013); C. bušenje jezgri u slanoj močvari na ušću rijeke Mirne, Hrvatska.

2.3. LATE-QUATERNARY SEA-LEVEL CHANGES: CAUSES AND EFFECTS ON THE COASTLINE AND HUMANS IN MEDITERRANEAN AND ADRIATIC

The Quaternary period is divided on marine isotope stages (MIS) based on ratio of stabile oxygen isotopes, ^{18}O and ^{16}O, which are measured in the tests of foraminifera which are one of the constitute of the sea bottom sediments (Emiliani, 1955). Figure **2.2.** shows relative sea-level curve and division on the Marine Isotope Stages (MIS) and substages. Generally, glacial or colder periods are marked as even numbers, and interglacial or warmer periods as odd numbers.

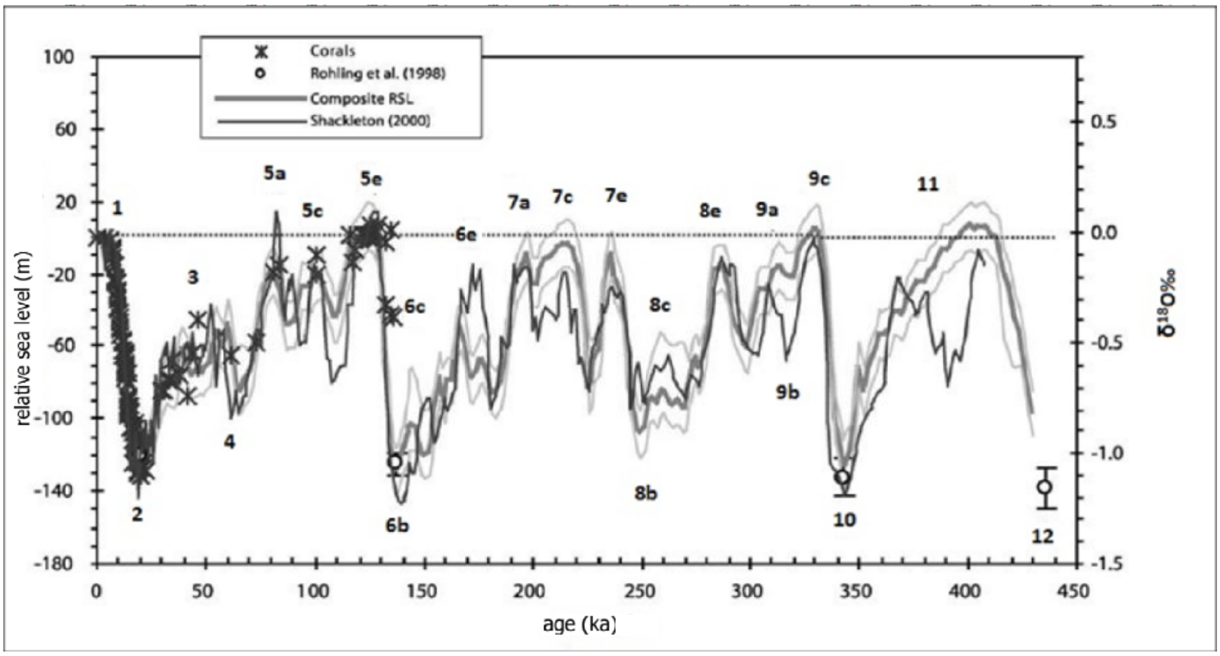

Figure 2.2. Relative sea-level curve during part of Pleistocene and Holocene (Waelbroeck et al., 2002).

Slika 2.2. Krivulja relativne razine mora tijekom dijela pleistocena i holocena (Waelbroeck i sur., 2002).

Global sea levels in the last 2 million years changed positions between 130 m below the present msl during glacial periods, and 6 m (possibly 13-15 m) above msl during interglacial periods (Rohling et al., 1998; Dutton et al., 2015; Grant et al., 2014; Spratt and Lisiecki, 2016). In the next subchapters, 2.3.1., 2.3.2. and 2.3.3., a brief overview of the sea-level changes in the period since the MIS5 to the present days is presented, with focus on Mediterranean area (modified after Benjamin et al., 2017, article submitted).

2.3.1. MIS 5 (130,000-71,000 BP), MIS 4 (71,000-58,000 BP), MIS 3 (58,000-29,000 BP) and MIS 2 (29,000-14,000 BP)

The MIS 5 includes several sub-stages that were characterized by both higher and lower-than-modern sea levels, between 6 m above and 30 m below msl (Waelbroeck et al., 2002; Siddall et al., 2003). For most part of the last glacio-eustatic cycle, the eustatic level was tens of metres lower than its present position (Waelbroeck et al., 2002, Grant et al., 2014). The periods when sea-level was low (MIS 4 and MIS 3) and the period when sea-level reached its maximum lowstand (MIS 2) were crucially important in shaping the present Mediterranean and Adriatic basin. During these periods, large portions of the sea-bottom were exposed to subaerial conditions which caused alteration and/or erosion of the pre-existing deposits and coastlines were further seaward than now. Fluvial and aeolian processes, as well as weathering, soil-forming activity and karstification, all took place over large sectors of the Mediterranean coastal areas. Along the eastern Adriatic coast, more than 140 submarine caves with speleothems were documented, some of which were used for sea-level reconstructions (Surić et al., 2005, 2009, 2010). The deepest speleothems found along the Croatian coast are up to 71 m below msl near the Island of Brač in Southern Dalmatia (Garašić, 2006). In many areas the post-LGM sea-level rise eroded and reworked older deposits.

Because of the incomplete sea-level record in the Mediterranean Sea, data from other regions (e.g. the Red Sea, Tahiti) or a 'global eustatic' curve are commonly used for the period 116,000-20,000 BP (e.g. Imbrie et al., 1984; Bard et al., 1996; Waelbroeck et al., 2002; Siddall et al., 2003; Rohling et al., 2008).

Transition to MIS 2 was characterized by the sea-level fall at a relatively sharp rate to nearly 80 m below msl, with maximum lowstand between 29,000 and 19,000 BP, when sea level is usually estimated to be between 120 and 140 m below msl (Lambeck et al., 2014).

The marine and coastal evolution after MIS 5.5 and before the Holocene transgression was not recorded in the northern Adriatic, due to geometry of the shelf and the shallow sea bottom (< 20 m below msl) which prevented the deposition of sediments in the coastal and marine environments (Antonioli et al., 2009). In the Po River delta plain, between 75 and 25 m below msl, sediment cores contained deposits dated to MIS 4 and MIS 3, which were formed in an alluvial environment (Amorosi et al., 2004). In the central Adriatic, geophysical researches documented sedimentary traces of regressions, which were occurring during the sea-level fall following MIS 5.5 (Ridente et al., 2009; Maselli et al., 2010).

2.3.2. LGM through the early Holocene (18,000-7000 BP)

Since the end of the LGM, significant volumes of meltwater have been released into the global oceans as a consequence of ice sheets melting which has resulted in sea-level rise of about 120 metres (Fairbanks, 1989; Edwards, 2006; Clark et al., 2009). Sea level rose during the period between 19,000-7000 BP by the average rate of 12 mm/yr and was punctuated by periods of higher rates of sea-level rise (particularly between 14,500-14,000 BP, with rates of more than 40 mm/yr, and lesser rates in Younger Dryas, between 12,500-11,500 BP (Lambeck et al., 2014).

The first significant addition of meltwater started ~ 19,000 BP, with sea-level rose ~10-15 m in less than 500 years (Clark et al., 2004). An even more significant phase of accelerated sea-level rise, known as Meltwater Pulse (MWP) 1A, occurred between 14,500-14,000 BP when global sea-level rose ~16 to 24 m (Lambeck et al., 2014). Other studies have suggested sea-level rise during MWP-1A of 20 metres during the period between 14,300-13,800 BP, as a consequence of melting of both Laurentide and Antarctic ice sheets (Bard et al., 1996, Clark et al., 2002; Rohling et al., 2004; Siddall et al., 2010). Deschamps et al., (2012) dated MWP-1A to 14,650-14,310 BP with sea levels rising 14-18 m, coincident with the Bølling warming in the Northern Hemisphere. They suggested that the rate of eustatic sea-level rise exceeded 40 mm/yr in the period of MWP-1A. This is almost certainly a pace which would be noticeable by coastal occupants during a single generation, particularly in low-lying areas where coastal resources were a significant source of dietary proteins, fuel and other aspects of economy (Broodbank, 2013).

This last deglaciation was abruptly interrupted by the Younger Dryas event, which began ~12,800 BP. During this short interval, the rate of sea-level rise slowed, consistent with the overall cooling in the Northern Hemisphere as documented in Tahiti (Bard et al., 1996, 2010), Huon Peninsula, New Guinea (Edwards et al., 1993; Cutler et al., 2003), Vanuatu (Cabioch et al., 2003), and Barbados (Peltier & Fairbanks, 2006). In the Northern Adriatic, the Younger Dryas cooling led to the formation of a well-developed deltaic complex of Po River. This sedimentary body is partly preserved at a depth ~40 m below msl between 40-60 km offshore of the city of Ravenna (Correggiari et al., 1996; Cattaneo & Trincardi, 1999). Slightly north of this area, some younger lagoon-barrier remnants, testify that the marine transgression occurred during early Holocene. In particular, rsl indicators dating to the interval 11,000 – 10,000 BP were found between 38 and 35 m below msl (Moscon et al., 2015). Lagoon facies deposits dating between 10,000-9500 BP were found near the coastline of the present mouth of Po River (Amorosi et al., 2008a) and in other sites along the bathymetric isoline 30 m below msl (Correggiari et al., 1996; Trincardi et al., 2011a,b), while the Adriatic reached the area of Trieste by ~9000 BP (Antonioli et al., 2009; Trincardi et al., 2011a,b).

The average rate of sea-level rise in the period between 11,400-8200 BP was ~15 mm/yr. Meltwater pulse 1B has been reported at ~11,300 BP with slightly higher rise rate of ~16.5 mm/yr for a 500 year period immediately after the Younger Dryas period. This was followed by lower rate of sea-level rise between 8200-6700 BP (Lambeck et al., 2014).

The formation and growth of the Alpine ice sheet during LGM minimally affected the eustatic curve because of its limited volume as compared to polar ice sheets (Lambeck et al., 2004a). The glacial advances in the Alps and partly in the Dinarides and Pyrenees, strongly affected environmental conditions of the northern side of Mediterranean basin. In particular, the fluvial systems of the southern Alps received enhanced sedimentary input supplied by glacial activity, allowing the widespread aggradation and progradation of alluvial fans and megafans, that prograded for tens of kilometres over the exposed shelf in the Adriatic (Fontana et al., 2014).

2.3.3. Middle and late Holocene (7000-2000 BP)

Evidence for middle and late Holocene sea-level changes in the Mediterranean are based on geomorphological evidence (such as tidal notches and beachrocks), fixed biological indicators (such as coralline algae) and archaeological indicators. Holocene sea-level curves have been obtained in Italy (Lambeck et al., 2004a, 2011), Croatia and Slovenia (Antonioli et al., 2007; Faivre et al., 2013), France (Vacchi et al., 2016a); Turkey (Anzidei et al., 2011), Greece (e.g., Pirazzoli, 2005; Vött, 2007). More recently, a comprehensive assessment of Holocene rsl variability along the western Mediterranean coasts was performed by Vacchi et al. (2016b).

Data collected from tectonically stable regions, including negligible isostatic effects (Sivan et al., 2001; 2004; Toker et al., 2012) for the last 4000 years, indicate that sea level was close to present levels between 4000-3600 BP (Galili et al., 2005; Galili & Sharvit 1998; Porat et al., 2008) and has fluctuated below and slightly above the msl since that time (Sivan et al., 2004; Toker et al., 2012). Between 6800 and 4000 BP, the sea level, in what is now the coast of Israel, rose from -7 m msl to the present level at a rate of 2.5 to 3.5 mm/yr. During the Chalcolithic period (6000-5700 BP) sea level was approximately 2.5 to 5 m below msl. By the Middle Bronze Age (~4000 BP) the sea had reached its present level and the coastline reached its present form. Since then sea level has been relatively stable with possible fluctuations of no more than 50 cm vertically (Galili et al., 2005, Sivan et al., 2001, 2004; Anzidei et al., 2011).

In the area of the Adriatic Sea, Holocene submersion was largely completed ~7000 BP and subsequently the sea level rose slowly to the current elevation (Antonioli et al., 2007, 2009). The sea-level change occurring in the Istrian coast since about 5000 BP, has been estimated as a relative rise of about 4 m (Faivre et al., 2011). Some authors, such as Benac et al. (2004; 2008), Antonioli et al. (2007), Faivre et al. (2011) and Furlani et al. (2011) suggested that a sudden Holocene sea-level rise (approximately 0.5–1 m) in the area of the north-eastern Adriatic could have been triggered by an earthquake that submerged the archaeological remains and geomorphological forms (such as marine notches).

2.4. DEVELOPMENT AND EVOLUTION OF RIVER MOUTHS IN RELATION TO SEA-LEVEL CHANGES (DURING LATE QUATERNARY)

2.4.1. Estuaries: definition, classification and importance

River mouths (estuaries and deltas) around the world, are generally well populated evironments of great economic importance (industry, harbors, waste-disposal sites, tourism, fisheries). Additionally, these are sensitive environments of great ecological significance, containing diverse flora and fauna (Dalrymple et al., 1994). From geological point of view, significant quantities of hydrocarbon reserves could be found in older deposits accumulated in such environments (Boyd et al., 2006). Estuaries also have important role in processes such as biogeochemical cycling of elements, transport of nutrients, and filtering of contaminants, which all influence environmental quality of coastal waters.

River mouths are sensitive to both influences from the sea and from the land, and sea-level and climate fluctuations could be used to predict future scenarios of environmental respone to global change (Tessier, 2012). On the other hand, these environments have been investigated as paleoclimate and paleoceanographic sedimentary archives (Tessier, 2012).

Estuary is an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise, generally divided into three parts: a) an upper or fluvial estuary, dominantly under influence of fresh water but subject to daily tidal action; b) a middle/central estuary, subject to strong saltwater and freshwater mixing; c) a marine or lower estuary, which is under dominant influence of the open sea (Fairbridge, 1980).

Classification of the estuaries should be based on physical and geological parameters that are common to all estuaries but are different from one estuary to another. Estuaries are classified based on physiography (Kinsman & Pritchard, 1965), tidal range (Hayes, 1975), morphology (Fairbridge, 1980), evolution (Dalrymple et al., 1992), or morphogenesis (Perillo, 1995). Perillo (1995) suggested that all previous estuarine classifications were too inclusive and proposed a genetic classification of estuaries: primary and secondary estuaries. Primary estuaries are those that have not been changed significantly by marine processes, whereas secondary estuaries have changed into different forms since their genesis. Estuaries can further be classified into a number of categories such as rias, fjords, delta front estuaries, coastal plain estuaries *etc*. *Karstic estuaries* represent special and peculiar form of estuaries, with unique features, which will be described in more detail.

Cooper et al., 2011, proposed classification of estuaries on "*keep up*", "*catch up*" and "*give up*" estuaries.

a) "*Keep up*"estuaries are rare and were developed only when conditions of high sediment supply kept pace with the very high rates of sea-level rise in the early to mid-Holocene.

b) "*Catch up*" estuaries were developed when sedimentation was outstripped initially by sea-level rise, which created a deep water systems; the estuaries were then filled with sediments as sea-level stabilized and fluvial and marine sedimentation progressively filled the basins.

c) "*Give up*" estuaries developed when sedimentation during the Holocene had been so low that the incised valley had simply been drowned and preserved. Examples are the rias in Spain and France (Garcia-Garcia et al., 2005), which margins and drainage areas are usually composed of erosion-resistant bedrock.

2.4.2. Development of recent estuaries and their stratigraphic organization

Estuaries were formed in the narrow zone between the sea and the land and their life is generally short. The shape of estuaries is constantly influenced and altered by erosion, deposition of sediments and sea-level changes. Composition of sediment (lithology and micro- and macrofossils contents) varies depending on the distance of the mouth and the energy of the environment (Kennish, 2016).

As a consequence of glacioeustatic changes during the Quaternary, the estuaries were affected by changes of sea-levels that have ranged over 120 m. During the sea-level lowstands, continental (subaerial) processes dominated and river valleys were incised into older deposits or basement rocks. Sediments underlying present-day estuaries usually accumulate over an incised valley which is laterally related to a subaerial erosional unconformity generated during the LGM lowstand. The subaerial unconformity is considered the sequence boundary (Dalrymple et al., 1992). Overlying sediments are composed by variable amounts of deposits of lowstand system tract (LST), transgressive system tract (TST), and highstand system tract (HST), mainly depending on the interplay between creation of accommodation space led by hydrodynamic factors, relative sea-level rise, and the fluvial supply (Dalrymple et al., 2006). However, in most estuarine systems the bulk of the sediment infilling is considered to be generated during the transgressive and early highstand phases (Dalrymple et al., 1992).

The lowstand unconformity may be covered by fluvial deposits that exhibit very significant variability (Dalrymple et al., 1994). Generally, thick LSTs are favored in narrow incised valleys (Vis & Kasse, 2009). The subsequent transgression would lead to estuarine sedimentation, the composition of which changes along the length of estuary (Zaitlin et al., 1994). Estuarine sediments would be separated from the lower fluvial deposits by an initial flooding (or transgressive) surface (TS) (**Figure 2.3.**). Transgressive deposits may be finally buried by progradational estuarine deposits generated during highstands with an intervening maximum flooding surface (MFS) between transgressive and highstand deposits (**Figure 2.3.**)

(Dalrymple et al., 1992). This change may be induced by a decrease in the rate of sea-level rise and/or by an increase of sediment supply (Emery & Myers,1996), causing MFS to be diachronous in most estuarine settings (Chaumillon et al., 2010).

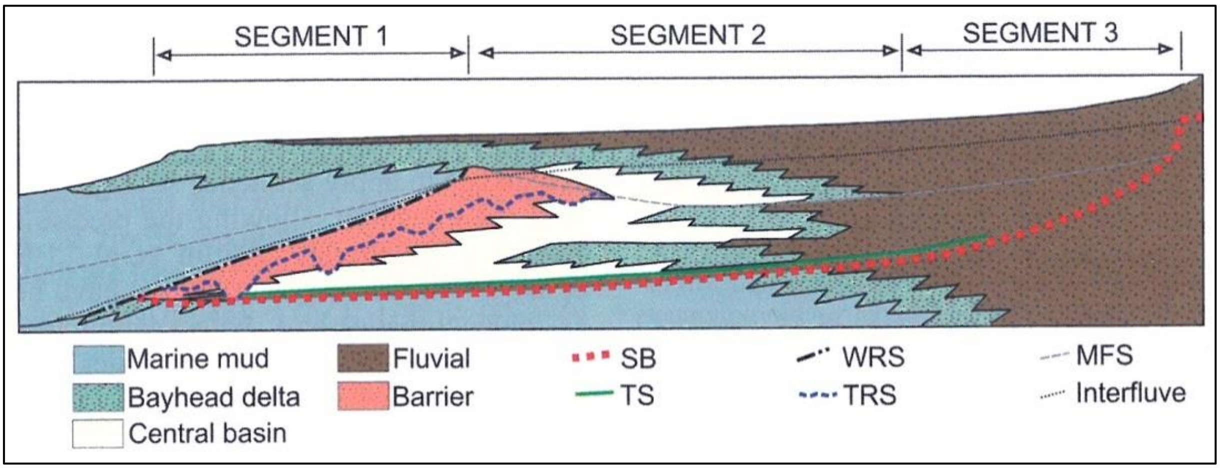

Figure 2.3. Stratigraphic organization of a complete incised-valley succession, divided into three segments. Segment 1 show the seaward portion; segment 2 is the present-day estuarine system; segment 3 remains fluvial during the entire evolution of the system. Legend: SB-sequence boundary; TS-transgressive surface; WRS-wave ravinement surface; TRS-tidal ravinement surface; MFS- maximum flooding surface (Kennish, 2016, modified after Dalrymple et al., 1994).

Slika 2.3. Stratigrafski sklop potpunog taložnog slijeda usječene doline (Kennish, 2016, modificirano prema Dalrymple i sur., 1994).

The sedimentary infill of the present-day estuaries has been mostly generated during the course of the post-LGM sea-level rise (simple infill) although in some cases older sequences may be preserved in deep incised valleys (compound infill). The base of the infill is generally represented by a LGM incised valley, which may be covered by lowstand (to early transgresive) fluvial deposits (Dalrymple et al., 1994; Chaumillon et al., 2010). Compound estuarine infills preserve lower estuarine sequences below the most recent sequence boundary typically related to LGM. These lower sequences tend to be composed of previous relative highstands deposits (e.g. genesis during MIS3 and MIS5). For example, rias and rocky-bound estuaries tend to preserve older sequences in the deep estuarine sections (Dalrymple et al., 1994; Chaumillon et al., 2010).

The development and progradation of the intra-estuarine deltas (Darlypmple et al., 1992) tends to be fostered during highstand conditions (Allen & Posamentier, 1993), particulary under circumstances of enhanced fluvial supply and/or reduced wave activity (by sheltering). Intra-estuarine deltas may coexists with distributary mouth bars, a seaward-migrating channel diastem and distal prodelta deposits that further contribute to the growth of the central basin facies (Nichols et al., 1994; Vis & Kasse, 2009).

2.4.3. Controlling factors on estuarine stratigraphy

The factors that control the development of estuarine stratigraphic features, including different methods of formation and preservation of sediment bodies and stratigraphic surfaces, are the following:

1. Bedrock valley morphology

The shape of the valley may influence its subsequent transformation into an estuarine system and the different development of depositional systems (Dalrymple et al., 1992; Boyd et al., 2006). Additionally, the depth of incision controls the preservation potential of infilling deposits, particulary of the lowermost such as LSTs and/or TSTs (Chaumillon et al., 2010).

2. Hydrodynamic processes

Another major factor in determining the lithology and stratigraphy of estuaries is the coastal hydrodynamic setting of an estuary and intra-estuarine hydrodynamics, i.e. whether the estuary is river-dominated, tide-dominated or wave dominated. Estuarine facies distribution and deposit architecture of the two end-member states (wave versus tide dominance) are variable according to the relative importance of waves and tidal and fluvial currents (Dalrymple et al., 1992).

3. Sea-level fluctuations

The relative sea-level patterns govern the overall stratigraphic change observed in most estuaries from transgressive to regressive conditions, related to a significant decrease of relative sea-level rise (Dalrymple & Zaitlin, 1994).

4. Sediment supply

In general terms, the amount of sediment supply controls sedimentation in estuarine environments. The most extreme case is a “give-up” estuary, where conditions of very reduced sediment supply did not allow an incised-valley fill (Cooper et al., 2011). Low supplied systems are mainly filed with marine sediments, such as the case of French estuarine environments (Chaumillon et al., 2010). In general, those low-suplied estuaries show reduced and absent TSTs. The variability of sediment supply is particulary important during estuarine transgression, as high-sediment supply may account for significant development of estuarine mouth barriers under wave dominance, or high fluvial supply may favor anomalously thick TSTs. In contrast, highstand conditions are generally characterised by increases of sediment supply, as the decrease in the rate of sea-level rise favors the influence of fluvial sedimentation, accounting for the generation of intra-estuarine deltas that may develop seaward into prodeltaic environments and ultimately leading to significant fine-grained sediment delivery to the shelf. In addition, carbonate production may also be enhanced by highstand conditions, thus increasing the volume of HST (Tessier, 2012).

5. Climate change

The impact of recent climatic variability on estuarine sediment infillings has been addressed in several recent studies, e.g. in northwestern Europe (Tessier at al., 2012; Tessier, 2012). Climate can result in a range of lithologic types and stratigraphic types, particulary in tidal and supratidal environments, and it will determine the extent that fluvial sediment will contribute to the filling of an estuarine basin. It will also have a particular effect on the sediments and stratigraphy of facies that have become emergent and inhabited by tidal and supratidal vegetation (mangroves in tropical humid climate/salt marshes in temperate humid climate).

6. Human influences

The exploitation of drainage basins for human activities in the last few centuries is argued to have caused significant modifications of estuarine sedimentation rates. In particular, a recent period (i.e. the last 1000 years) of increased fine-grained deposition documented in several French estuaries has been related to increased soil erosion by deforestation and agricultural practices (Tessier, 2012). The intensifications of agricultural practices as triggering mechanisms for bayhead delta growth has also been documented in some estuaries along the Gulf of Mexico coast (Anderson et al., 2008).

Rapid population growth in this favorable areas and overdevelopment of coastal zones place estuaries among most heavily anthropogenically impacted aquatic environments by humans. Major anthropogenic impacts on estuaries can pose a threat to their ecological integrity and long-term viability, like habitat loss and alteration, eutrophication, sewage pollution, overfishing, chemical contaminants, human-altered hydrological regimes, invasive species, sea level rise, subsidence.

Kennish et al. (2014) identified 12 major anthropogenic stressor on estuarine ecosystems. These include (1) eutrophication; (2) sewage and organic wastes; (3) habitat loss and alteration, shoreline hardening and erosion; (4) chemical contaminants; (5) human-induced sediment/particulate inputs; (6) overfishing; (7) intensive aquaculture; (8) introduced/invasive species; (9) human-altered hydrological regimes; (10) climate change; (11) coastal subsidence; (12) floatables/debris.

2.4.4. Sediment composition in the estuary

Sediment composition in estuaries is strongly influenced by the lithology of the catchment, tidal range, wave hights (near the estuary mouth), sediment availability and sediment transport (Dalrymple, 1992; Bianchi, 2013). Also, estuarine sediment composition is heavily depended on the dominant source of sediment, which is either alluvial or marine.

In estuarine environments, fluvial and marine processes interact, and as a consequence, a tripartite zonation is observed in most estuaries, reflecting specific energy levels and bedload transport patterns (Dalrymple et al., 1992). These incluse:

1. An outer zone dominated by marine processes;

2. A low-energy central basin;

3. An inner, river dominated zone.

The central basin receives sediments both from the fluvial and marine systems and therefore is an area of net convergence.

Sedimentologically, estuary acts as a basin, semi-protected or nearly fully protected from the sea. Therein, fluvial sediment can be delivered and largely trapped. Marine processes deliver sediments at its seaward portion in an open bay setting, or by marine coastal transportation processes through narrow inlets or by washover across a low barrier. Estuarine processes within the estuarine basin itself operate to develop intra-basinal sediment, transport and disperse sediment, and develop sedimentary suites from the materials deliverd from fluvial, marine, and intra-basinal estuarine sources. The magnitude of the tidal range for the region where the estuary resides, and/or the extent that the shape of the estuary magnifies the tidal range, will determine how far upstream tidal effects are experienced and to what degree tidal patterns will influence sedimentation patterns (Dalrymple et al., 1992; Dalrymple et al., 1994).

Independently of the estuarine type, sediment compositon in an estuarine environment varies axially and laterally, as well as vertically (Nichols & Biggs, 1985). Towards the head of the estuary, sediment composition includes silts, clays, plants and roots, grading down to sand, gravel and cobbles. Large clay and silt deposits may be found towards the mixed region of the estuary, together with sandy lenses and laminae. Closer to estuary mouth, the main sediments are marine sands with abundant cross-bedding, and tidally driven sandbanks may be found here. Lateral variations also occur, with shorelines composed of sands, gravel, shells, muds, plant fragments and basal peat; subtidal flats composed of laminated muddy sands and sandy muds; and mid-channel environments dominated by coarse marine sands and massive cross-bedding.

Figure 2.4. shows large diversity of sedimentary sub-environments/facies that may occur in an estuary.

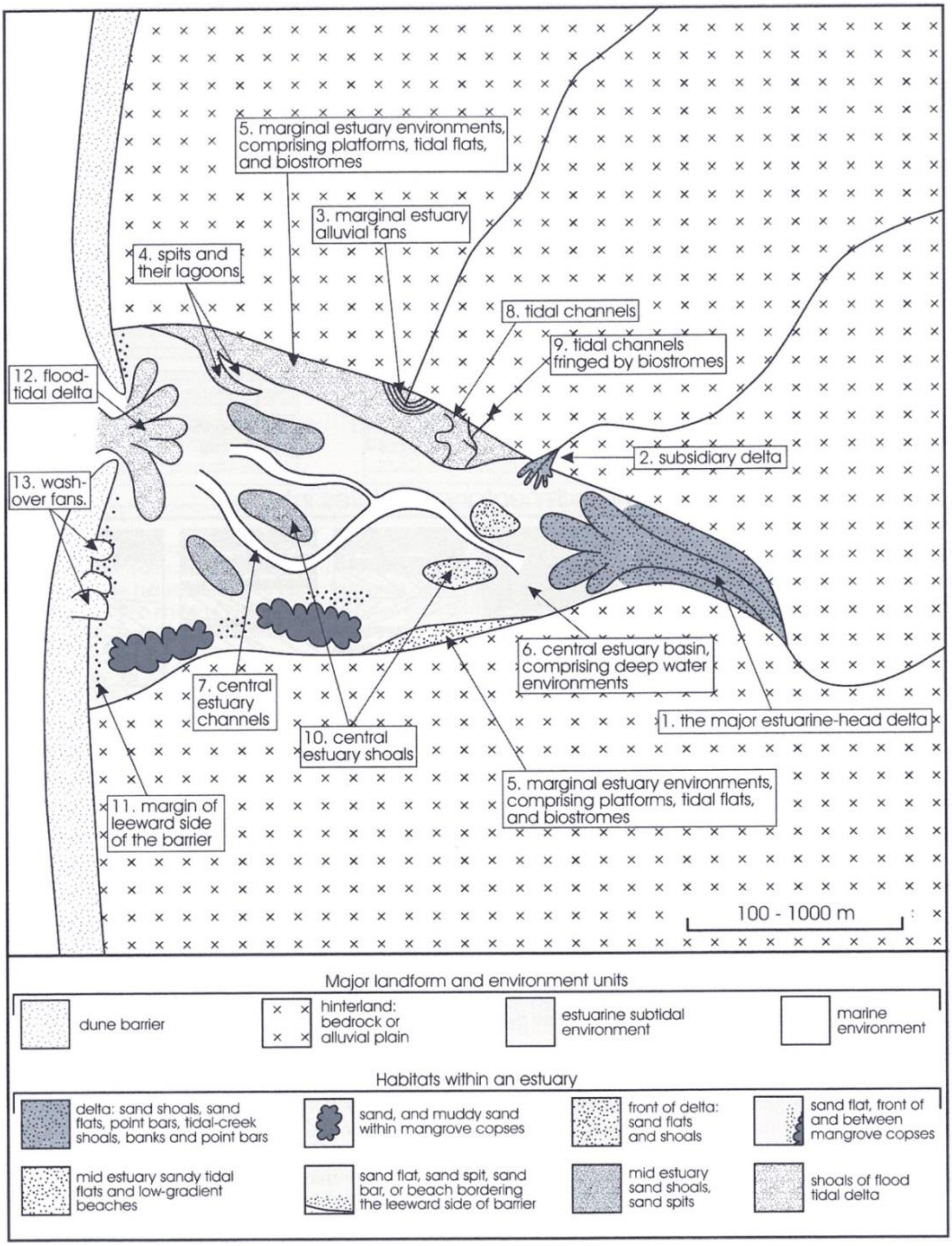

Figure 2.4. The generalized picture of different sub-environments/facies developed in an estuary. Each of sub-environments/facies may have specific sedimentary features and biota (Kennish, 2016).

Slika 2.4. Općeniti prikaz različitih podokoliša/facijesa razvijenih u estuariju (Kennish, 2016).

The sources and types of sediment that build stratigraphic sequences, their transport mechanism to the estuary, and where the sediment finally is emplaced in the estuary are described below in four systems: the riverine system, the central estuary, the marginal estuarine system and the marine system.

The riverine system is usually a shallow water system. By channel flow and floods, it delivers sand (usually quartz sand), terrigenous mud (usually clay minerals and quartz silt), and gravel to the estuary. While these sediments are mainly located in the estuary headwaters, they can be dispersed into the central parts of the estuarine basin, graded in grain size from coarsest sand at the deltas and river mouths to fine and very fine sand away from the deltas. Riverine mud is the sediment type that is most widely dispersed, and since it is carried in suspension, it can be deposited some distance from the river mouth (Dalrymple et al., 1992; Dalrymple et al., 1994).

The central estuary is a shallow water to moderately deepwater system. The central estuary generates gravel (as invertebrate skeletons), sand (as foraminifera, algal fragments, and fragmented invertebrate skeletons), and mud (as shell fragments, disintegrated algal skeletons, diatomea, and sponge fragments). As with fluvial mud, mud-sized particles generated within estuary are the most widely dispersed. The central estuary is also the location where mud delivered by rivers accumulates, because it is generally the deepest part of the estuary and a low-energy sink (Dalrymple et al., 1992; Dalrymple et al., 1994).

The marginal estuarine system is a shallow water to geomorphically emerged system. It recieves exogenic sediment from a number of sources. Sediment may be reworked and delivered from adjoining uplands, other supratidal locations, or alongshore from elsewhere in the estuary (as sand, mud or gravel), or it may consist of peat from plants inhabiting shorelines and marginal shallow water environments, or carbonate mud (in marginal lagoons) generated from algal meadows, or mud brought in by suspension on the high tide by storms. Depending on whether the surroundin uplands are rocky, preexisting older sedimentary deposits, or stranded estuarine deposits, the material reworked by sheetwash, shoreline erosion, or fluvial action may be lithoclast (rock) gravel, sand (usually quartz), and mud (Dalrymple et al., 1992; Dalrymple et al., 1994)..

The marine system is usually shallow water environment. The marine system delivers sand (as quartz and marine skeletal material, foraminifera, algal fragments, and fragmented invertebrate skeletons) and shell gravel to the estuary (Dalrymple et al., 1992; Dalrymple et al., 1994).

2.4.5. Intra-estuarine deltas

A delta is often closely associated in time and space with an estuary (**Figure 2.5.**), but frequently in the literature the two are not adequately separated, particulary for tide-dominated estuaries. For the same riverine outlet, a delta is a geomorphic and sedimentological feature, while an estuary is a hydrochemical one where riverine freshwater flowing into a bay, a lagoon, or semi-enclosed coastal body of water mixes with seawater (Cameron & Pritchard, 1963; Pritchard, 1967; Day, 1981).

Deltas within estuaries generally are relatively small sedimentary accumulations compared to the size of their estuarine setting. They have been variably termed as "bayhead deltas" (*e.g.* Dalrymple et al., 1992), "river deltas" (Hayes, 1975), and "intra-estuarine deltas" (Semeniuk et al., 2011). As not all of them are located in "bayheads", the term "intra-estuarine delta" is used here for those deltas occurring within estuaries.

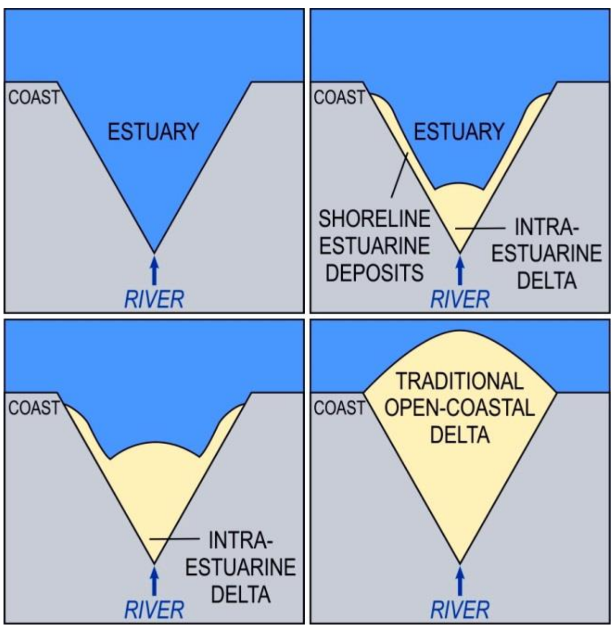

Figure 2.5. Idealized figure showing the evolution from relatively narrow V-shaped open estuary, with minimal or no sediment fill, then development of intra-estuarine delta and stronger sedimentation inside estuary, to a coastal delta where sedimentary accretion has prograded into the marine environment. Intra-estuarine deltas are present and more clearly evident in estuaries where sediments have not fully occluded them (modified after Kennish, 2016).

Slika 2.5. Idealizirani prikaz evolucije estuarija od relativno uskog estuarija s minimalnom sedimentnom ispunom do potpune progradacije delte unutar estuarija (modificirano prema Kennish, 2016).

In a general perspective, all deltas can be estuarine in the sense that some part of them will have a freshwater-to-seawater transition, and large estuarine environments whose basin has not been filled with sediment may contain small-scale deltas along their margins or in their headwaters (**Figure 2.6.** and **2.7.**).

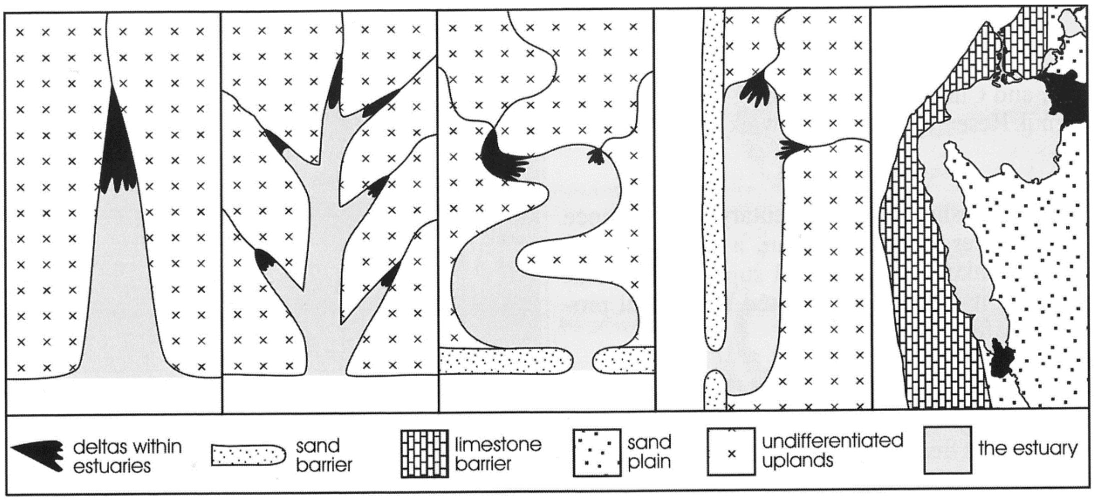

Figure 2.6. Idealized diagram showing a range of estuary types and the occurrence of intra-estuarine deltas (black) inside them (Kennish, 2016).

Slika 2.6. Idealizirani prikaz različitih tipova estuarija i delti unutar estuarija (Kennish, 2016).

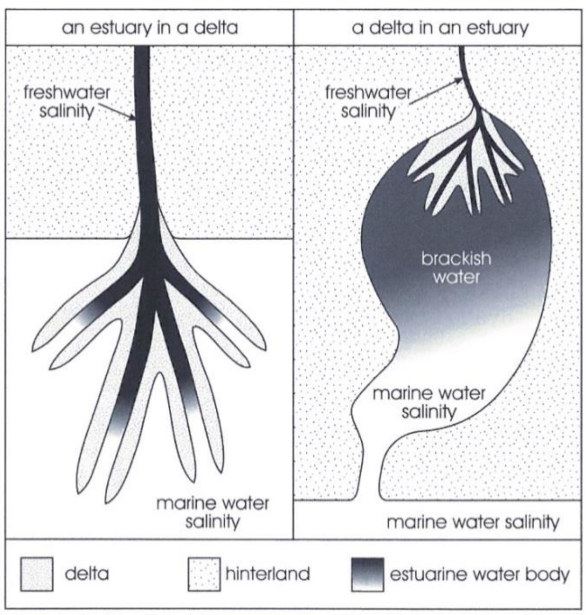

Figure 2.7. Idealised diagram showing the dual concept of an estuary within a large delta and a delta within a large estuary (or an intra-estuarine delta). Legend: freshwater = black; brackish water = gray; marine water = white (Kennish, 2016).

Slika 2.7. Idealizirani prikaz koji pokazuje razliku između estuarija razvijenog unutar delte i delte unutar estuarija (Kennish, 2016).

In contrast, deltas in open coastal settings generally are large sedimentary accumulations but are relevant to smaller deltas that occur within estuaries in that the principles involving hydrodynamics, geometry/morphology, mechanisms of constructions, sedimentology and facies, and stratigraphy are similar. Such deltas have been classified as to their plan geometry in response to their hydrodynamic setting as fluvial-dominated deltas, tide-dominated deltas and wave-dominated deltas (**Figure 2.8.**; Galloway, 1975) or by their depositional architecture and facies (Postma, 1990).

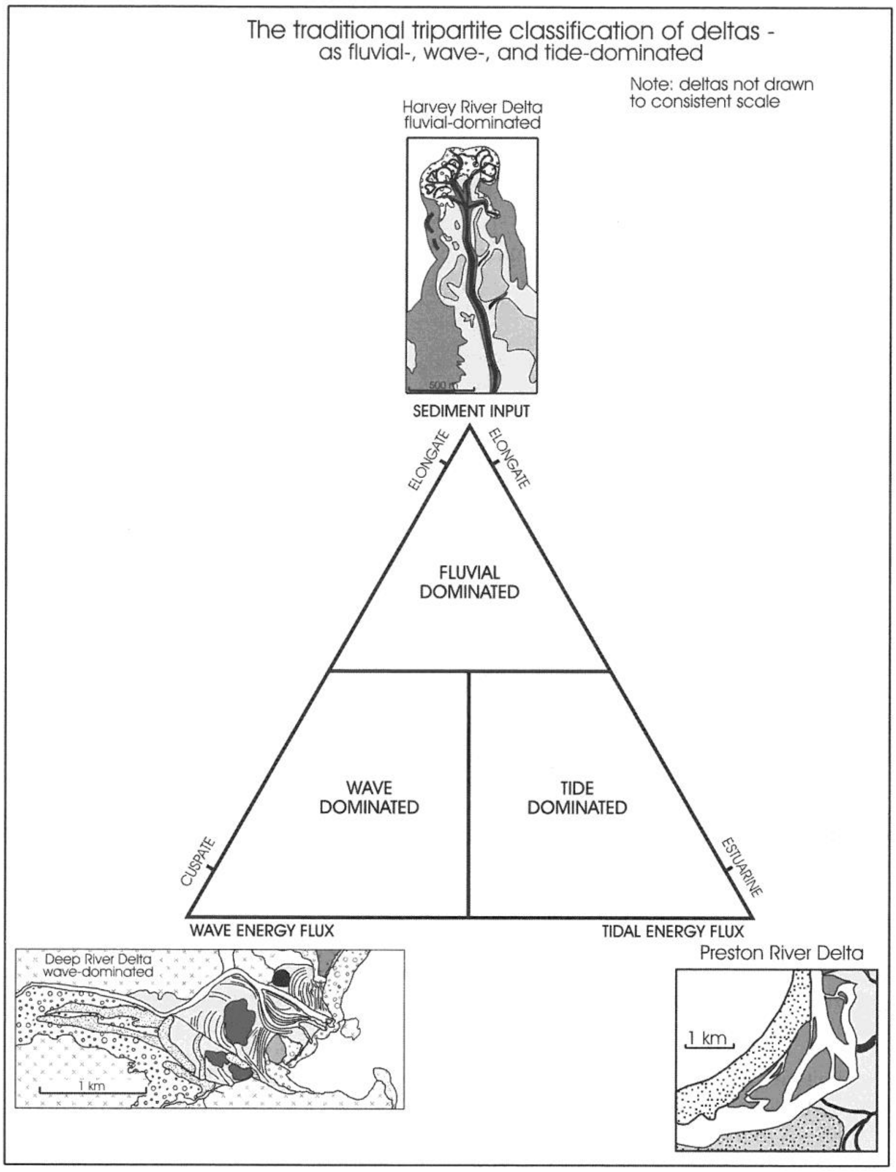

Figure 2.8. The traditional tripartite classification of deltas with some intra-estuarine deltas from southwestern Australia on the ternary diagram (Kennish, 2016, modified after Galloway, 1975).

Slika 2.8. Klasična trodijelna klasifikacija delti (Kennish, 2016, modificirano prema Galloway, 1975).

2.4.6. Recent and future trends

Future research on sediment infill of present-day estuarine systems should be directed at improving the definition of estuarine systems by using different techniques and approaches such as the following (Boyd et al., 2006):

1. Numeric models that can provide a quantitative approach to the major operating processes (sediment flux versus relative sea-level changes) and can be used to predict the future estuarine behavior.
2. 3D seismic data and seabed imagery can enhance visualization of the complexity of estuarine sedimentary environments.
3. Other geological approaches such as brackish ichnology and petrological and chemostratigraphical studies, among others, may be helpful for recognition of estuarine facies and for the subdivision of the estuarine record into different sequences.
4. Improved knowledge of the longitudinal variability of the estuarine infill, because most of the present knowledge involves lateral variability (Tessier, 2012).
5. Better understanding of the influence of anthropic activities in the development of estuarine stratigraphy, which is so far poorly documented (Tessier, 2012).

2.5. EASTERN ADRIATIC RIVER MOUTHS

The eastern coast of the Adriatic Sea is strongly constrained by the structural setting, because the bedrock is composed mostly of Mesozoic carbonate rocks and the tectonic structures are generally elongated in NW-SE direction, leading to the occurrence of a system of valleys that run parallel to the coast. During the Quaternary the karstification was generally dominant in the area and this process led to the development of a limited surface river network and a small production of terrigenous (riverborne) load.

Between Trieste and Albania only several rivers reach the coast and at their mouth they formed a specific type of estuary that has been described as *karstic estuary* (Juračić, 1992; Pikelj & Juračić, 2013). Karstic estuaries are characterized by the karstic bedrock, a coastal environment with low energy (sheltered position of the river mouths and low tidal range) and by the lack of riverborne terrigenous material, due to prevalent chemical weathering (dissolution of carbonates) in the catchment (Juračić, 1992). Moreover, some karstic rivers formed tuffa barriers during Holocene, that trapped material and therefore further limited delivery of the material to the sea. Typical low-sediment input karstic estuaries along eastern Adriatic coast are, for example, those of Krka and Zrmanja River (**Figure 2.9.**).

Figure 2.9. Typical karstic estuaries, along Croatia coast, with limited terrigenous delivery; Zrmanja (left) and Krka (right) estuaries (Google Earth).

Slika 2.9. Tipični krški estuariji duž obale Hrvatske, s ograničenim sedimentnim donosom; Zrmanja (lijevo) i Krka (desno) (Google Earth).

Some karstic estuaries such as those of Dragonja (Ogorelec et al., 1981), Mirna (Felja et al., 2015), Raša (Sondi et al., 1995), Rječina (Benac & Arbanas, 1990) and Neretva River (Vranješ et al., 2007), experienced a intra-estuarine delta progradation during Holocene, due to the larger sedimentary load, supplied by rivers which flow across allogenic formations. This was especially pronounced in the example of Neretva River, characterized by mountain catchment composed of various sedimentary, magmatic, and metamorphic rocks and sediments. Raša River estuary, is an example of a karstic estuary, which formed intra-estuarine delta during Holocene which is prograding towards sea but did not yet fill the estuary (**Figure 2.10.**).

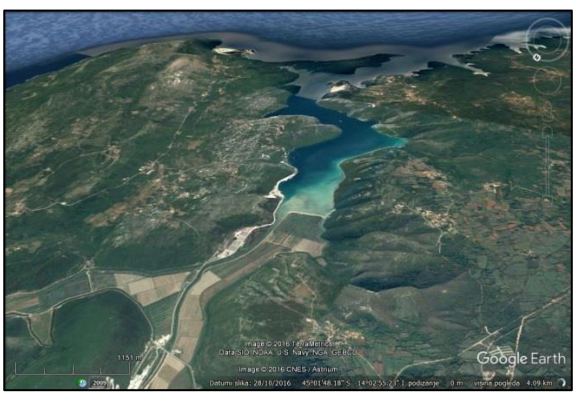

Figure 2.10. Progradation of intra-estuarine delta inside the Raša River estuary (Google Earth).

Slika 2.10. Progradacija delte unutar estuarija rijeke Raše (Google Earth).

3. STUDY AREA

3.1. MIRNA RIVER DELTA

3.1.1. General characteristics

In the eastern part of the Northern Adriatic region, in Istria, one of the largest deltaic plains is the lower part of the Mirna River valley, with particular environmental characteristics that have attracted historians, archaeologists and geographers since the end of the 19th century (Carre et al., 2007; D'Incà, 2007 and references therein), but little attention has been paid to the geomorphological and geological aspects. The stratigraphic setting documented in the Mirna River valley should be comparable with the situation found in the terminal tract of the other Istrian rivers, like in that of Dragonja (Ogorelec et al., 1981), Raša (Sondi et al., 1995) and Rječina (Benac & Arbanas, 1990). At the moment, only a few cores are available in those areas and they do not allow detailed description of the late-Holocene depositional units. Holocene coastal evolution is well documented along the western coast of the northern Adriatic, where deltaic progradation started from about 7500 years ago (e.g. Amorosi et al. 2008b and references therein), but the low-lying landscape and lithology is different from Istria.

The Mirna River is located in the north-western part of the Istrian peninsula, western Croatia. It is the longest river in Istria (53 km), with a hydrographic catchment of approximately 402.9 km^2 (Božićević, 2005). Average discharge of the Mirna River is 16 m^3/s (Wikipedia). Karst processes strongly affected the carbonate formations of Istria and led to the development of complex and well-developed underground water circulation, thus, beside the surficial orographic basin, the Mirna River has a hydrogeological catchment estimated to ~583.5 km^2 (Božičević, 2005). The source of the Mirna River is near the town of Buzet and it discharges into the Adriatic Sea near the town of Novigrad (**Figure 3.1.**). The Mirna River delta plain (from the river mouth to the Ponte Portone) has a surface of ~15 km^2. Drainage area od the Mirna River has relatively warm and humid climate, specifically Cfa and Cfb according to Köppen classification. Mean temperature in January is 4°C, and mean temperature in July is between 22 – 24 °C. Along the western coast of the Istria Peninsula, annual average rainfall is between 800 – 1,100 mm, and slightly increasing landward (Filipčić, 1992; Božičević, 2005).

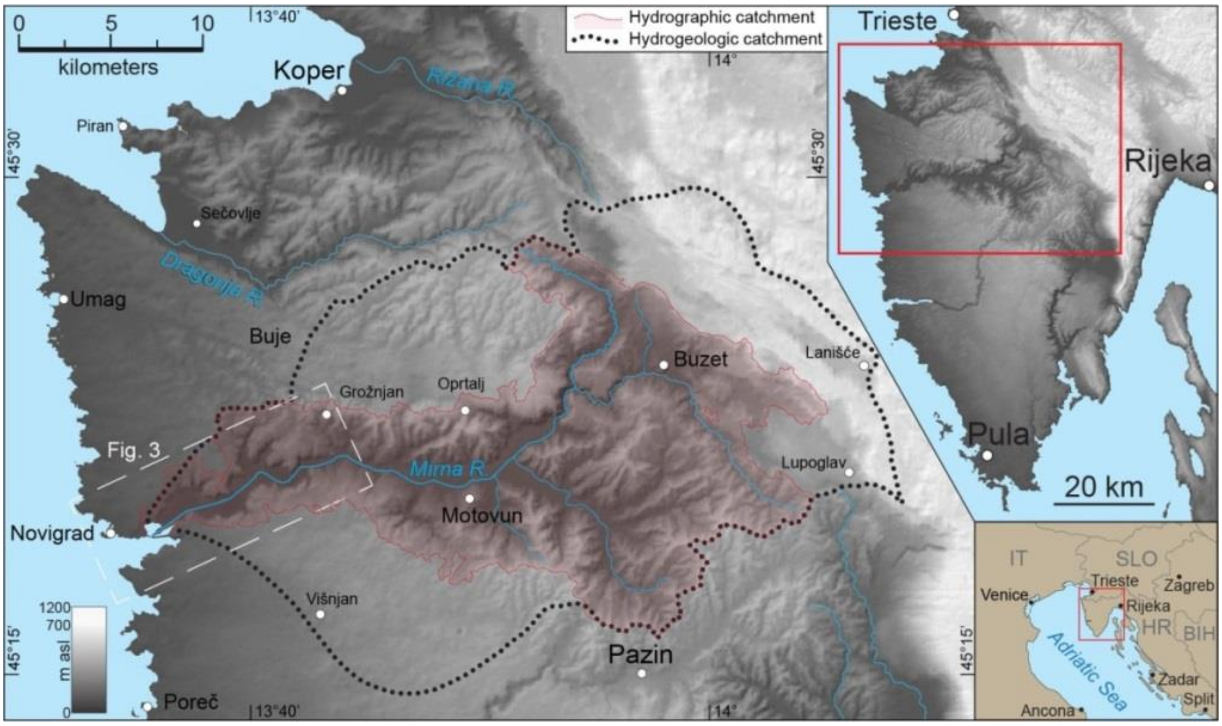

Figure 3.1. Location of the study area (Mirna River and its drainage area). The Digital Elevation Model (DEM) obtained from NASA-SRTM data. The boundary of the hydrogeological catchment is assumed (according to SANTIN, 2013) (Felja et al., 2015).

Slika 3.1. Lokacijska karta područja istraživanja (rijeka Mirna i njeno drenažno područje) (Felja i sur., 2015).

3.1.2. Geological setting

The drainage basin of the Mirna River is composed of carbonates, mostly Cretaceous and Eocene limestone, and clastic Eocene deposits (**Figure 3.2.**; Polšak & Šikić, 1963; Pleničar et al., 1965). These marl and sandstone sediments in alternation (flysch) in the catchment area are morphologically related to a badland landscape (Gulam et al., 2014). Since the beginning of the 20th century, a number of karstic springs were documented on topographic maps of the lower tract of the valley, but they partly disappeared after land reclamation. The Gradole spring is the largest one, with an estimated minimal discharge of 500–600 l s^{-1} (Magdalenić et al., 1995). From a structural point of view, the area is part of the External Dinarides that are dominated by limestone deposited on the Adriatic Carbonate Platform from the Lower Jurassic to the Eocene (Velić et al., 2002). The Dinarides are characterized by compressional tectonics, with maximum stress aligned NE-SW and thrust and reverse faults that strike NW-SE (Castellarin et al., 1992; Vlahović et al, 2005). Seismotectonic activity is not significant in the study area, but there are historical records of a number of very strong earthquakes in the vicinity, such as in the Gulf of Rijeka (Faivre & Fouache, 2003).

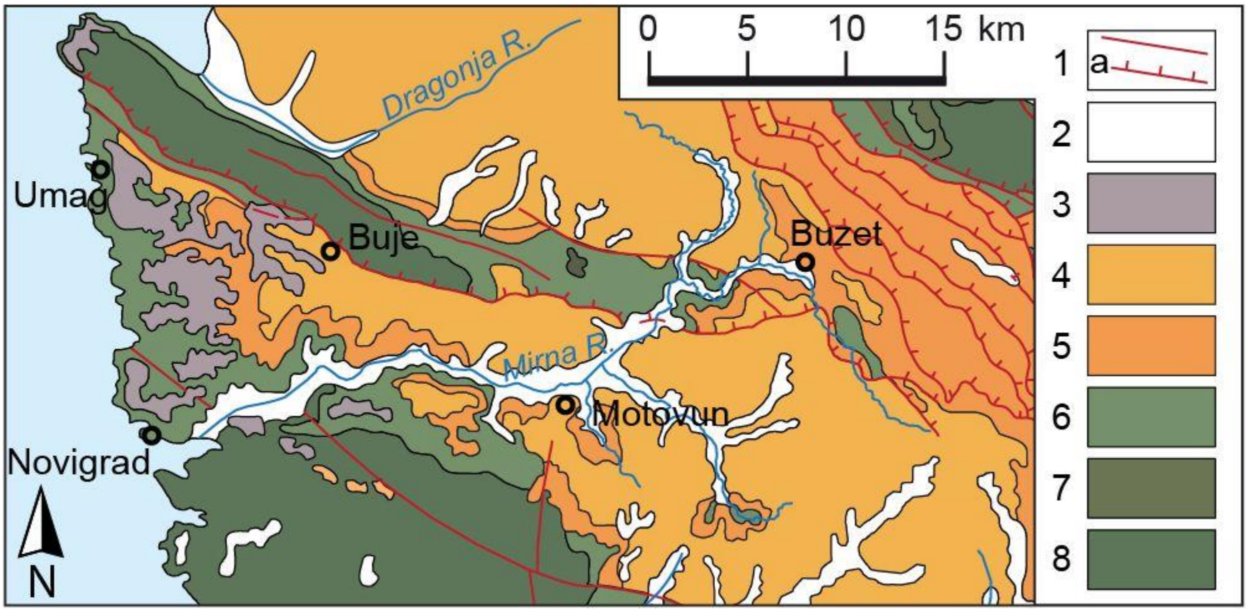

Figure 3.2. A geological map of Istria (modified after the Geological Map of Croatia 1:300000, Croatian Geological Survey, 2009); 1. Fault, 1a. Thrust, 2. Quaternary deposits (mainly Holocene), 3. Terra rossa deposits (Holocene). 4. Flysch deposits (Eocene), 5. Liburnia deposits, Foraminiferal limestone and transitional deposits (Paleocene?, Eocene), 6. Rudist limestone (Cretaceous), 7. Dolomite and breccia (Cretaceous), 8 Limestone and dolomite (Cretaceous) (Felja et al., 2015).

Slika 3.2. Geološka karta drenažnog područja rijeke Mirne (Felja i sur., 2015).

3.1.3. Archaeological setting

Istria was reached by Neolithic people between 5800–5600 BC, when the first farmers settled in the area, especially along the coast (Forenbaher et al., 2013). A major phase of occupation occurred in the ancient and late Bronze Age, characterized by the so-called Castellieri Cultural group. This is related to the construction of fortified villages on hills (*i.e.* the castellieri), defended by sub-rounded drywalls (Sakara Sučević, 2004). The late Bronze Age population mainly concentrated in few large centres that probably later became the major Roman cities. Romans occupied Istria between the 2nd and 1st century BC and they built a complex network of roads and widespread systems of fields (*i.e.* centuriatio). At that time, the Mirna River was probably called the Ningus and some historical sources describe the existence of an important protected harbour, most likely near the present area of Ponte Porton (Parentin, 1974; Carre et al., 2007; D'Incà, 2007). Historical chronicles and maps depict the strong progradation experienced by the river mouth during and after the Medieval Age, up to the present that transformed most of the lower valley into a swampy environment (D'Inca, 2007). Novigrad (Cittanova) became the major city of the area since the Byzantine period and during the Venetian domination the river assumed the name of Quieto, describing its calm flow. A major phase of land degradation occurred between the 12th and 19th centuries, when the Istrian woods supplied the shipyards in Venice (Parentin, 1974; D'Incà, 2007). Historical documents testify to the existence of a harbor near the chapel of S. Maria of the Bastia in 1582 AD and the archaeological evidence documents that at the site of the chapel the valley floor rose about 4.6 m between 1582 and 1857 (Milotić & Prodan, 2014). Since the second half of the 19th century, during the Austrian domination (**Figure 3.3.**), there have been interventions to regulate the river (*e.g.*, some artificial cutting of meanders), but a large reclamation plan was undertaken during the 1920s–1930s (Parentin, 1974; Santin, 2013). The lower valley of the Mirna was transformed into the present farmland through the construction of artificial levees and a dense network of ditches connected to pumping stations. After the 1964 flooding, the regulation and reclamation works were completed (Santin, 2013).

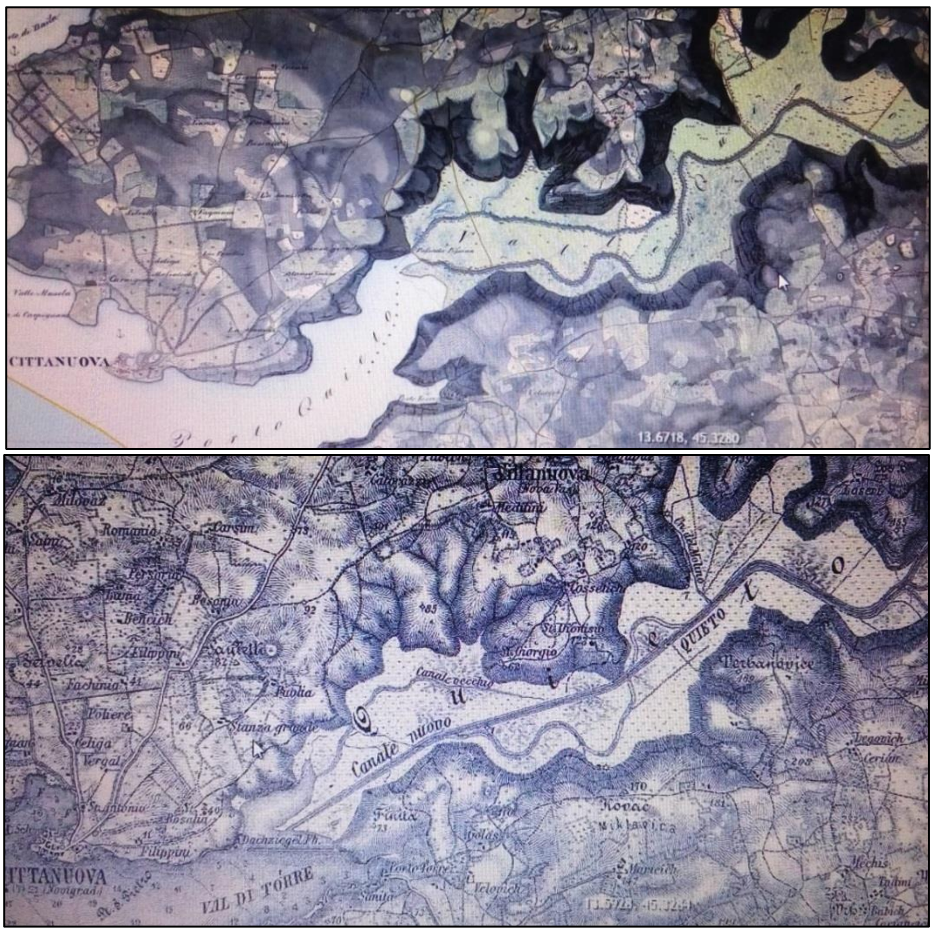

Figure 3.3. Comparision of the historical maps of the Mirna River mouth of the Second (1806-1869) (Timár et al., 2006) and Third (1869-1887) (Molnár & Timár, 2009) military survey of Habsburg Empire (Mapire.eu/en/).

Slika 3.3. Usporedba povijesnih karata područja ušća rijeke Mirne tijekom drugog i trećeg vojnog kartiranja Habsburškog Carstva (Mapire.eu/en/).

3.2. NERETVA RIVER DELTA

3.2.1. General characteristics

Neretva River delta is located in the south-east part of the Adriatic coast (**Figure 3.4.**) and is the largest river along the Croatian part of Adriatic coast, with a hydrogeologic catchment (including Trebišnjica stream) of approximately 13,280 km^2 (3060 km^2 in Croatia). The Neretva River is 215 km long and flows mostly in Bosnia and Herzegovina and only 22 km through Croatia (Slišković, 2014). The Neretva River delta plain covers approximately 170 km^2 and consists of Quaternary alluvial deposits (Juračić, 1998). Several watercourses are flowing through the delta plain. These are the main channel of the Neretva River, the Mala Neretva distributary channels, and local tributary streams draining with strong karstic springs (Jurina et al., 2013).

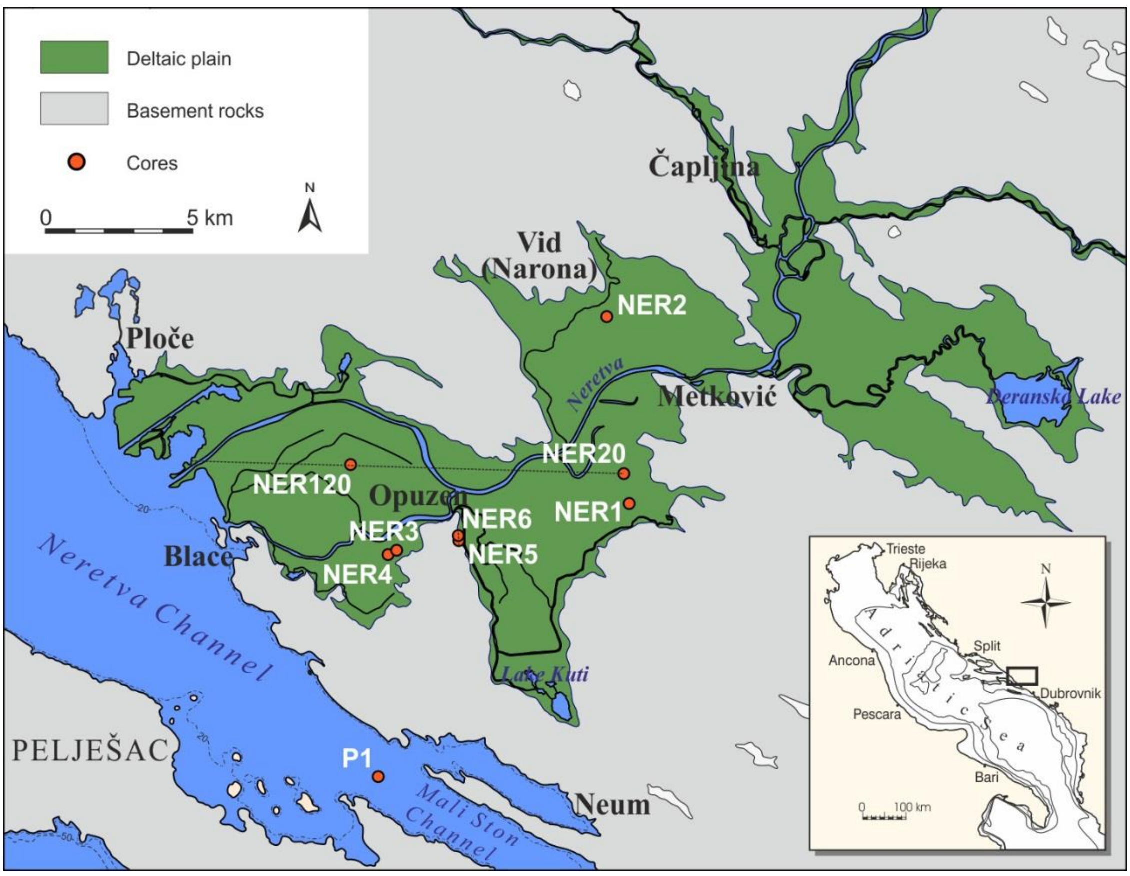

Figure 3.4. Location of the study area (Neretva River delta plain).

Slika 3.4. Lokacijska karta područja istraživanja (deltna ravnica rijeke Neretve).

In this final tract the climate is Mediterranean and it is characterized by an annual average rainfall of 1230 mm and by a mean annual air temperature is 15.7°C, with the highest (25.2°C) in July. The annual average water discharge of Neretva River is 332 m^3/s (Orlić et al., 2006). Artificial dams currently trap most part of the particulate material along the river upstream of Mostar, about 70 km away from the river mouth.

The mean daily tidal range at the mouth of Neretva is 0.23 m, as taken from values from the values measured by the Hydrographic Institute in the tide-gauge of Ploče between 1956 and 2000 (Shaw et al., 2016). Salt-marsh environments are present along the southern external portion of the delta. In particular, a recent investigation analysed the characteristic foraminiferal assemblages of the salt marsh and their relation with sea level near Blace (Shaw et al., 2016).

3.2.2. Geological setting

Since the beginning of the 20th century, geological studies investigated the basin of Neretva River, but little attention has been paid to Quaternary geologic record and especially the evolution of the deltaic area. Daneš (1906) described lower section of Neretva drainage area and development of morphology of the valleys. Group of geologist led by Brunnacker (1969) described quaternary deposits along Neretva River course with special attention to the loess.

Much more detailed description of structural characteristics and geology of the research area can be found in the Basic Geological map of SFRJ 1:100,000 (Mojićević and Laušević, 1973a, 1973b, Raić et al., 1975, Raić et al., 1976, Marinčić et al., 1977, Raić et al., 1980, Sofilj and Živanović, 1980, Mojićević and Tomić, 1982). The Neretva River springs in and flows in upper reaches through mountains of Bosnia and Herzegovina, which are built of magmatic, metamorphic, carbonate and clastic sedimentary rocks. In the lower reaches, it flows through karst region composed of carbonate rocks and clastic flysch, and therefore it is as an allogenic karst river. Geological basement and margins of this area are mostly composed of limestones of Cretaceous and Eocene age (**Figure 3.5.**), which form characteristic residual hills that protrude out from the deltaic sediments and are characterized by karstic landforms (Juračić, 1998).

The investigated area is part of the External Dinarides, strongly tectonized belt, composed of mostly shallow-water carbonates deposited from Middle Permian to the Middle Eocene, mainly on the Adriatic Carbonate Platform (AdCP) (Vlahović et al., 2005). The compression due to the collision processes of the amalgamation of the Adriatic continental micro-plate (bearing the AdCP) and Eurasia continental plate (Battaglia et al., 2004) caused the formation of the Dinaric mountain belt and subsequently adjoining foreland basins. The extension and subsidence happened in the foreland basins during the Neogene and Quaternary.

Sediment input to the sea is nowadays substantially reduced due to the sediment trapping in reservoirs behind large dams, which were built across the Neretva River in the 20th century (Vranješ et al., 2007; Kralj et al., 2015). Jurina et al. (2015) concluded that the Neretva River plume distributes its load over a wide area of the adjacent marine environment in the Neretva Channel, resulting in a relatively uniform mineral composition and similar sedimentation rate, ranging from 4 to 6 mm/y.

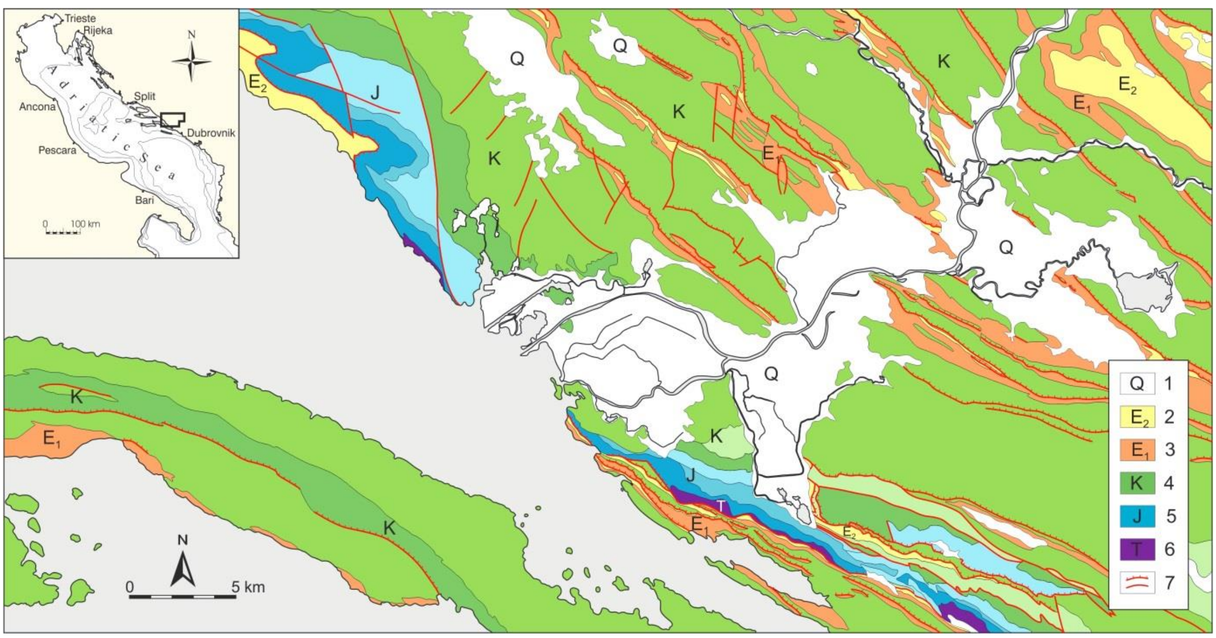

Figure 3.5. Shematic geological map of the Neretva delta plain area. 1 – Quaternary alluvial deposits; 2 – Upper Eocene deposits (flysch); 3 – Lower Eocene limestone; 4 – Cretaceous limestones and dolomites; 5 – Jurassic liestones and dolomites; 6 – Triassic limestones; 7 - Faults (modified after Basic geological map of SFRJ 1:100,000, sheets Metković (Raić et al., 1975), Imotski (Raić et al., 1976), Ploče (Marinčić et al., 1977), Ston (Raić et al., 1980)).

Slika 3.5. Shematska geološka karta šireg područja deltne ravnice rijeke Neretve.

3.2.3. Archeological setting

In the historical maps of the 19th century (**Figure 3.6.**) up to 12 different active branches of the river were depicted, while their number has been reduced only to three after artificial interventions. Presently, besides the main channel of river and the Mala Neretva distribution channel, some other minor local tributary streams are present (Jurina et al., 2013). Since the 19th century the delta plain underwent reclamation that brought to drain large sectors of fresh-water and brackish wetlands. Large freshwater marshes and small lakes (*e.g.* Lake Kuti), still characterize some portion of the delta and represent important ecological zones. West of Metkovic generally the ground elevation is slightly above msl, but large portions are below msl. The highest elevations are reached along the levees of the Neretva branches, that used to form fluvial ridges in the coastal plain.

The pastoral and agricultural practices carried out in the mountain catchment prompted the erosion of the slope deposits, feeding the sedimentary input along Neretva River and leading the historical progradation of the deltaic plain. But the ancient antropogenic activity is testified also in the distal tact of Neretva River and, in particular, near the town of Vid. In this place, located over a small hill almost at the apex of the delta plain, are the ruins of the Roman city of *Narona*. This centre had a strategic location for the communication between Adriatic and the interior areas of Illiricum and was already a Hellenistic emporium in the 4th century BC, when the Greek historian Pseudo-Skilax described the peculiar position of the city. This was about 80 stades (ca. 15 km) from the sea, but was reached by large boats along the *Narenta* River. *Narona* became a Roman colony in the 1st century BC and Plinius the Elder mentioned it in the 1st century AD as the temporary capitol of the Dalmatian province. During late Antiquity *Narona* experienced different phases of crisis and became part of the Byzantine Empire. The city was definitely abandoned in the 7th century because of the Avaric and Slavic invasions. In 1995 the remains of a Roman temple with 17 monumental marble statues have been discovered.

Delta Neretve prije regulacije

Figure 3.6. Neretva River delta of the Second (1806-1869) (Timár et al., 2006) military survey of Habsburg Empire (Mapire.eu/en/).

Slika 3.6. Povijesna karta područja delte rijeke Neretve tijekom drugog vojnog kartiranja Habsburškog Carstva (Mapire.eu/en/).

4. RESEARCH METHODS

4.1. CORE SAMPLING

For the purpose of this research, 14 shallow cores (down to a depth of 13 m) were drilled in the Mirna River (**Figure 4.1.**) and Neretva River delta plains (**Figure 4.2.**). First three shallow cores (M1-M3) were taken in the Mirna River delta plain in the period between 25.-27. 01. 2013., by myself, Dr. Alessandro Fontana, Dr. Stefano Furlani and Prof. Mladen Juračić. Next three cores (M4-M6) were drilled by Dr. Alessandro Fontana and myself, in the period between 11.-13. 05. 2013. Cores M7 and M8 were drilled by Dr. Alessandro Fontana and Dr. Stefano Furlani in the salt marsh or the Mirna River mouth. Cores from the Neretva River delta plain (NER1-NER6) were drilled between 11.-14. 11. 2015. by myself, Dr. Alessandro Fontana, Dr. Sandro Rossato, and students Petra Bakač and Irena Debeljak.

These corings were drilled with an Ejikelkamp hand auger (**Figure 4.3.**) using an Edelman head for sediment above the groundwater table and 1 m long gouge below the groundwater table. Samples collected through the Edelman head have a vertical length of 10 cm and a diameter of 7 cm and each sample could be mixed during coring operation. In contrast, gouge samples are generally almost undisturbed and, especially in silty and clayey deposits, internal depositional features like millimetric laminations could be preserved. The use of the gouge allowed the recovery of samples with a vertical length of 0.5 or 1.0 m and a diameter of 3 cm. The depth reached in the cores was constrained by the limits of the equipment and, in particular, by the stiffness and friction opposed by the sediment or by the collapse of the hole. The depth of the samples were checked in the field and the uncertainty was around ±0.05 m. The coordinates of the sampling sites and their elevation were measured in the WGS84 system using a Leica differential GPS with a vertical precision of ±0.02 m (for the Mirna cores).

The core MIR1 (~120 m) was drilled between 1.-4. 07. 2013. by Geoservizi Inc., with a mechanical probe Atlas Copco mounted on a Magirus truck and equipped with a "simple sampler" that recovers sediment cores of 88 mm of diameter and length between 1.5 and 3.0 m, with Dr. Alessandro Fontana and myself supervising and describing the core on the field. Two cores (NER120 and NER20) were given to us by Prof. Marija Romić from the Faculty of Agriculture. Drilling was performed in the 2014 by company GEOID-BEROŠ d.o.o. Samples from the core P1 was given to us by courtesy of the Institut IGH d.d. and Faculty of Agriculture in 2011.

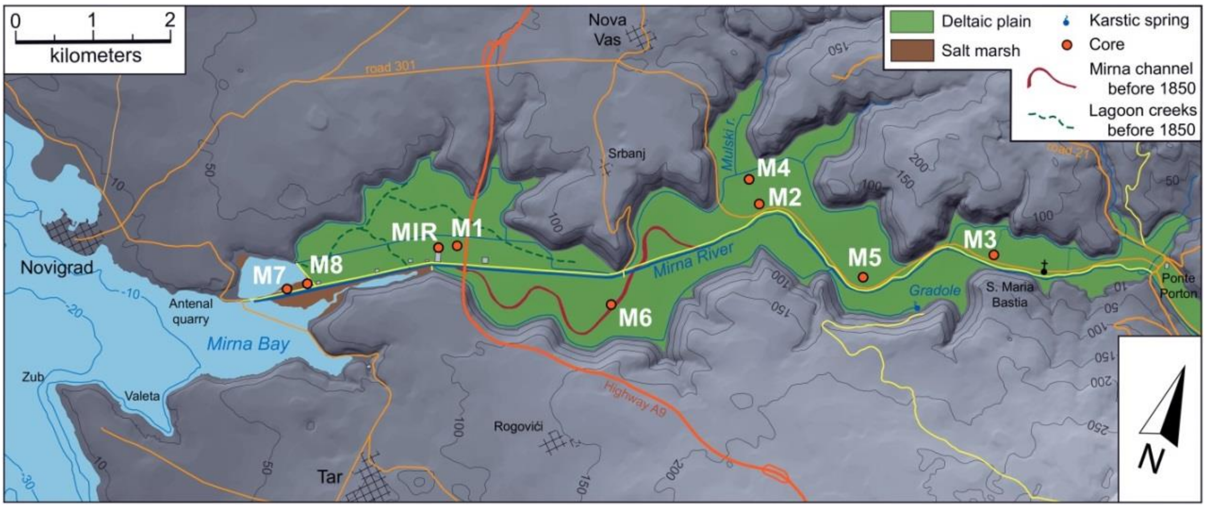

Figure 4.1. Map of the lower valley of the Mirna River with location of the cores. The hillshaded DEM was obtained by digitalization of the isolines represented in the topographic map at scale 1:25,000 (modified after Felja et al., 2015).

Slika 4.1. Lokacijska karta deltne ravnice rijeke Mirne s lokacijama izbušenih jezgri (modificirano prema Felja i sur., 2015).

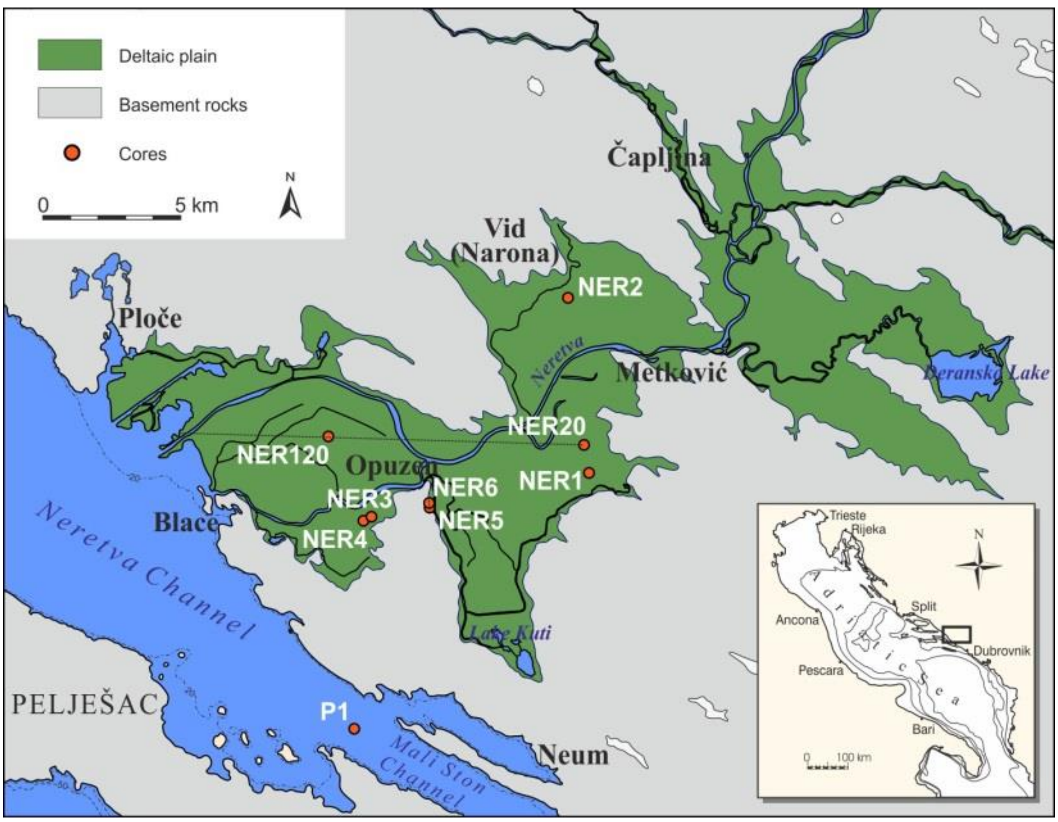

Figure 4.2. Location map of the cores collected in the Neretva River delta plain.

Slika 4.2. Lokacijska karta deltne ravnice rijeke Neretve s lokacijama izbušenih jezgri.

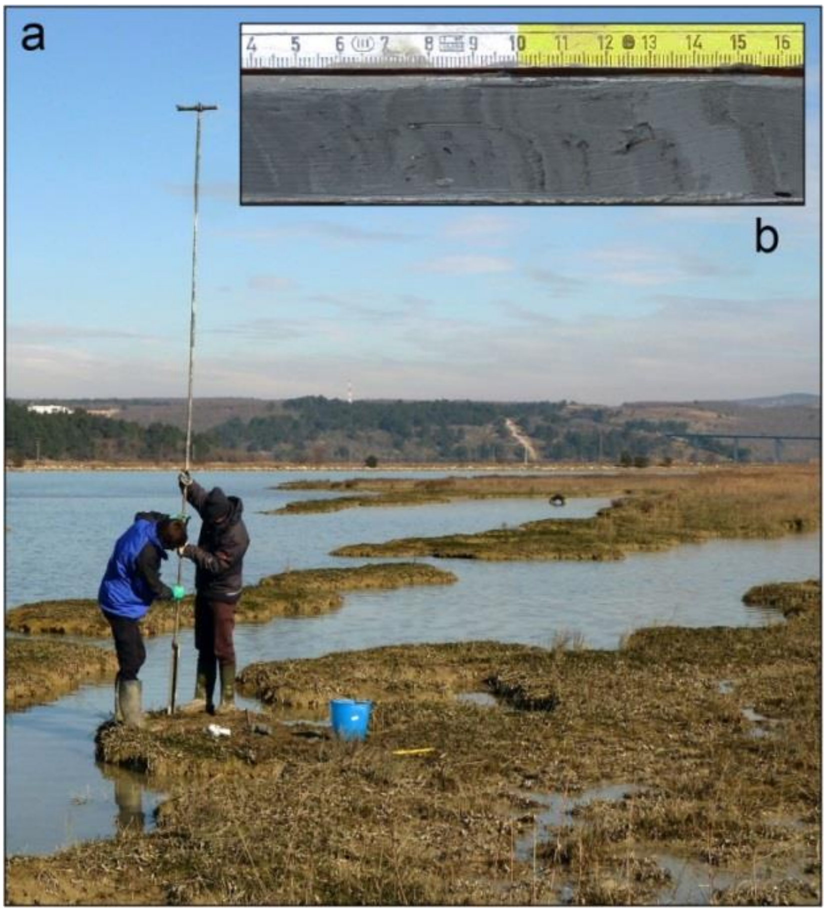

Figure 4.3. a) Coring operations in the salt swamp at the mouth of the Mirna River; in the distance the highway viaduct over the Mirna River valley is visible. **b)** a sample of laminated sediments collected by the gouge head from core M2 between 8.04–8.15 m (Felja et al., 2015).

Slika 4.3. Vađenje jezgri u slanoj močvari na ušću rijeke Mirne (Felja i sur., 2015).

4.2. FIELD DESCRIPTION

The cores were described in the field and soon after they were protected with aluminum foil and sealed in plastic bags to preserve their characteristics for further lab analyses. The sediments were described following the method explained in FAO-ISRIC (2006): sediment color and texture, primary sedimentary structures, and the type and concentration of accessory materials (e.g., roots, plant debris, organic matter, shell macrofossils and soil characteristics) were the main features reported **(Figure 4.4.**). The color of the layers was determined by comparing the moist sediment with the Munsell Soil Color Charts, while the content of calcium carbonate was estimated by observing the reaction with hydrochloric acid (10% of concentration) on a scale from 0 to 4 (FAO-ISRIC, 2006). The shells and their fragments were determined in the field and later in the laboratory with a stereomicroscope.

Figure 4.4. Description of the extracted cores on the field with color chart.

Slika 4.4. Opis izvađene jezgre na terenu i tablica boja sedimenta.

For the MIR1 core, each 1.5 m of the core were first described on the field with same methods as described above, preserved and transported to CNR-ISMAR in Bologna (**Figure 4.5.**), where additional analyses were made and subsamples were taken for micropaleontology and granulometric analyses.

Long Neretva cores (NER120, NER20 and P1) are not described in detail because of bad preservation, but samples were taken for granulometry and calcimetry analyses.

Figure 4.5. Describing and analyzing of the core MIR1 in the CNR-ISMAR, Bologna.

Slika 4.5. Opisivanje i analiziranje jezgre MIR1 u CNR-ISMAR, Bologna.

4.3. LABORATORY ANALYSES

Laboratory analyses, depth of the drilled cores and number of analysed samples, that were performed on 18 cores from Mirna and Neretva River delta areas, are shown in **Appendix 1**.

4.3.1. Granulometric analyses

Samples were sieved through set of 7 standard ASTM sieves (4 - 0.063 mm mesh) with one Φ interval. The fraction that passed 0.063 mm sieve was collected in suspension, from which a subsample has been taken for sedigraph analysis using the standard procedure (MICROMERITICS, 2002). The material retained on sieves was dried and weight and the data obtained by both techniques were merged to obtain the overall grain size range (**Figure 4.6.**). Sediments were classified according to Folk (1954) scheme based on gravel-sand-mud ratio.

Figure 4.6. Wet sieving and sedigraph method for determining grain size in sediment (Division for Geology and Paleontology, Department of Geology, Faculty of Science, Zagreb).

Slika 4.6. Mokro sijanje i sedigraf na Geološko-paleontološkom zavodu PMF-a.

4.3.2. Carbonate content analyses

Carbonate content was determined in replicates in each sample by volumetric measurement of CO_2 evolved after digestion in 1:1 diluted HCl acid, using Scheibler apparatus (**Figure 4.7.**; Önorm, L 1084, 1989). Analytical precision is ±2% and the results represent the average of the two measurements.

Figure 4.7. Calcimeter for determination of carbonate share in samples (Division for Mineralogy and Petrology, Department of Geology, Faculty of Science, Zagreb).

Slika 4.7. Kalcimetar na Mineraloško-petrografskom zavodu PMF-a.

4.3.3. Mineralogical analyses

Qualitative phase analysis, with X-rays diffraction on powdered samples, were performed using Philips vertical X-ray goniometer (X-Pert type), with Cu-tube (40kV, 40mA) (at Division for Mineralogy and Petrology, Department of Geology, Faculty of Science, Zagreb), which radiation is monochromatized with graphitic monochromator. For detection of radiation, proportional counter was used.

Mineralogical analyses were done only for the core P1. Analyses were performed on selected samples from the following core depths: 2 m, 10 m, 28 m, 32 m, 74 m, and 96 m. These samples were chosen because they represent the whole range of the carbonate share.

4.3.4. Foraminiferal analyses

For foraminiferal analyses FOBIMO (FOraminiferal BIo-MOnitoring) standardization protocol (Schönfeld et al., 2012) was applied. Samples from six cores were analysed from the Mirna River valley (M1 – M6) and samples from 2 cores from the Neretva River valley (NER5 and NER6). The core was sliced into 1 cm thick segments (*e.g.* 325-326 cm), but for foraminiferal analysis only those segments that occur close to lithological change were picked up for study. The sub-samples (1 cm thick) were treated in laboratory to remove organic detritus and then washed through the 63 μm sieve. Dried sub-samples were sieved over 125 μm sieve, split into aliquots of at least 300 specimens (except in the subsamples in which fewer individuals were found) and subjected to identification and further bio statistical analysis.

Specimens were classified following Loeblich & Tappan (1987) classification, whereas Cimerman & Langer (1991) criteria was used for generic and species identification. For paleoecological interpretation, biodiversity indices (Species richness, Dominance, Fisher α index, Shannon-Wiener index) were calculated with PAST softwer (Hammer et al., 2001). Selected specimens were photographed by SEM (Scanning electronic microscope) Tescan TS5136 and Stereo Zoom Microscope and EUROMEX ImageFocus 4.0 camera at Division for Geology and Paleontology, Department of Geology, Faculty of Science, Zagreb.

4.3.5. Radiocarbon datings

During field description of the cores, the layers containing suitable material for radiocarbon dating (e.g., organic-rich sediments, peat horizons, wood fragments, and selected shells) were sampled immediately, sealed in plastic bags and afterwards dried. Additional samples were taken later in laboratory. Among these samples, particular attention was devoted to the layers representative of activation or deactivation phases of sedimentation (e.g. top of organic horizons of soil or salt marsh). Samples were selected and radiocarbon dated with the AMS method. In order to avoid calibration problems related to reservoir effect on carbonate material (i.e. shells), only plant or wood fragments were dated. The analyses were carried out by the Ion Beam Laboratory of ETH in Zurich, and the ages were corrected with the OxCal software version 4.2.3 (Bronk Ramsey, 2009), using IntCal13 atmospheric calibration curves (Reimer et al., 2013). In the text, dates are presented with a precision of 2σ.

5. RESULTS

5.1. FIELD AND LABORATORY DESCRIPTIONS AND RESULTS OF THE LABORATORY ANALYSES OF CORES FROM THE MIRNA DELTA PLAIN

Field and laboratory description of 9 sediment cores extracted in the Mirna River delta plain is shown here, along with sedimentological logs. Absolute abundance of foraminifera and biodiversity indices are presented for the cores M1-M6, radiocarbon datings were calculated for the samples in the cores M2, M3 and MIR1, and results of grain size analyses and calcimetry are shown for the core MIR1. Some of foraminifera found on different depth are shown in the **plate1** and gastropoda and bivalvia in the **plate2**.

Core M1

The core M1 was drilled near the viaduct overpassing the Mirna River valley (**Figure 4.1.**) and reached 8 m in depth. The site [45°19'56.6''N – 13°37'30.1''E] was located ~2200 m east of the artificial levee providing a coastal barrier to the sea and is 0.6 m below present mean sea level (msl). Remains of *Cerastoderma* sp. and other lagoon shells (*e.g. Nassarius* sp.) were locally scattered at the surface. The core was generally fine grained (clay, silty clay and clayey silt). The recent plough layer ended at 0.40 m from surface. In the first 1.85 m of the core, carbonate concretions and Fe-Mn nodules were common, as well as mottling (**Table 1; Figure 5.1.**). Shells of *Cerastoderma* sp., *Cyclopes* sp., *Gibbula* sp., *Bittium* sp. and *Loripes* sp. became more abundant with depth down to 4.90, but below that shells again became less frequent. Some layers contained plant remains and seeds. Foraminiferal tests were present in all samples, but more species were present below 5.00 m (**Appendix 2a**). Tests of *Ammonia beccarii* (Linné, 1758) and *Ammonia tepida* (Cushman, 1926) dominated in all the studied assemblages, whereas tests of *Haynesina* sp. were present in greater amounts in the shallower and were less common in the deeper horizons. Tests of genus *Elphidium* and miliolids were more abundant below 7.40 m. At depths of 6.30 m and 7.40 m a few tests of specimens of *Brizalina* sp. were identified (**Appendix 2a; Figure 5.1.**). Biodiversity indices are presented in **appendix 2b** and show relatively low values.

Table 1: Field and laboratory description of the sediment core M1

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures and features	Macrofossils
0.00 – 0.40	Silty clay, clay	Light olive-brown (2.5Y 5/4)	4	Plough layer	-
0,40 – 1,85	Silty clay, clay	Light olive-brown (2.5Y 5/4)	4	Mottling, (10YR 5/6); iron stains (2-4 mm), rare carbonate concretions, manganese nodules, sharp lower erosive boundary	*Scrobicularia plana* (1 valve); rare fragments of shells
1,85 – 2,60	Silty clay, clay	Greenish-grey (G1 5/10Y) Dark greysih-brown (2.5Y 4/2-1)	0-1	Lenses of clay; dispersed organic matter; gradual transition to clayey silt below	Recent roots (mm), shells of *Cearstoderma* sp., *Cyclopes* sp., *Gibbula* sp., *Bittium* sp., *Loripes* sp.
2,60 – 3,00	Silty clay, clayey silt	Grey (2.5Y 6-5/1)	2-3	Groundwater table	Rare shell fragments
3,00 – 4,90	Clay, silty clay	Grey (G1 5/10Y)	2	Partial dissolution of shells	Plant debris (mm); seeds; *Cearstoderma* sp., *Cyclopes* sp., *Gibbula* sp., *Bittium* sp., *Loripes* sp., *Rissoa* sp.
4,90 – 8,00	Clay, silty clay	Grey (G1 5/10Y)	3-4	Soft, laminated on some intervals	*Abra* sp., *Rissoa labiosa;* plant remains

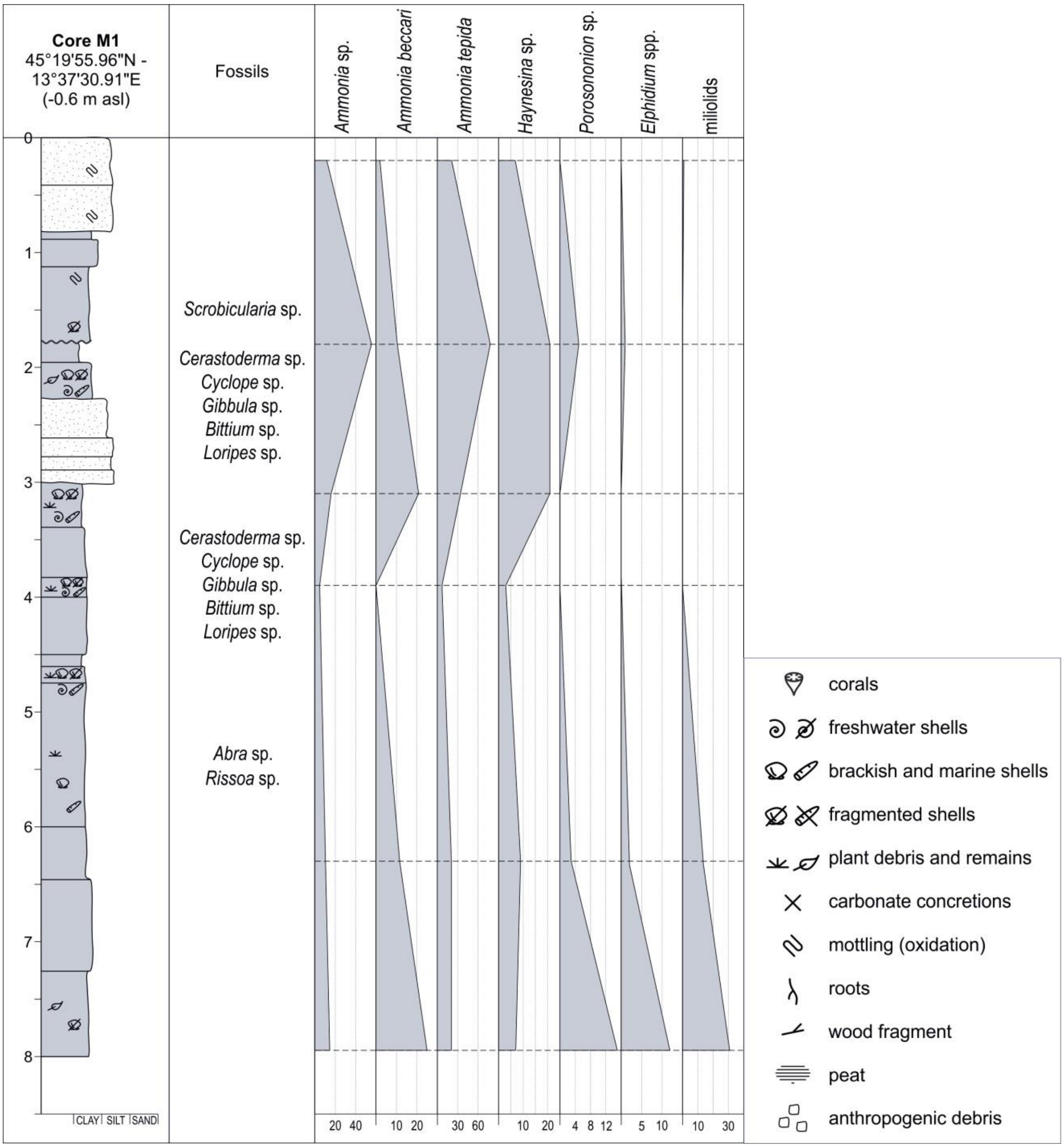

Figure 5.1. Sedimentological log of the core M1 with most common foraminifera and molluscs.

Slika 5.1. Sedimentološki stup jezgre M1 s najčešćim foraminiferama i mekušcima.

Core M2

The core site was about 500 m north of the bridge crossing the Mulski creek and 100 m north of the Mirna River [45°20’53.91”N–13°40’13.87”E] (**Figure 4.1.**). Ground elevation was 2.4 m above msl and the area was a swampy environment until the beginning of the 20th century, when it was reclaimed. The core was 13 m long and composed of fine grained sediments. A plant fragment at -5.27 m from the surface was radiocarbon dated to 1782±25 years uncal BP (138–332 AD, 2σ calibration) (**Table 2; Figure 5.2.**). A fragment of twig found at -12.25 m from the surface was radiocarbon dated to 5774±28 years uncal BP (4702–4547 BC, 2σ calibration) (**Table 2; Figure 5.2.**). The plough layer was stiff and stopped at 0.40 m depth where the lower boundary was sharp and erosive. Down to 5.45 m sediment showed mottling features, carbonate concretions, and fragments of plant remains (**Table 3**, **Figure 5.2.**). No foraminifera were observed above 5.20 m core depth. Below that, shells became more abundant as well as foraminifera tests (dominance of *Ammonia* genera). With the appearance of representatives of *Elphidium* sp. and miliolids at horizons deeper than 8.20 m, the species richness increased (**Appendix 3a, 3b; Figure 5.2.**). *Elphidium* spp. increased in number at 10.50 m and miliolids (*Quinqueloculina seminula* (Linné, 1758)) at 11.10 m. *A. beccarii* was dominant in the deeper horizons (**Appendix 3a; Figure 5.2.**).

Table 2: ^{14}C measurements in the selected core samples

CORE	Conventional ^{14}C age (BP)	Error	Calibrated age	Dated material	Surface elevation (m above msl)	Depth from surface (m)	Corrected elevation (m below msl)
M2	1782	25	138-332AD	Plant	2.00	-5.27	-3.27
M2	5774	28	4702-4547BC	wood twig	2.00	-12.25	-10.25
M3	854	24	1154-1254AD	Plant	4.40	-8.30	-3.90
MIR1	1754	25	225-256AD	Plant	0.55	-2.68	-2.13
MIR1	3666	31	2138-1954BC	Plant	0.55	-5.95	-5.40
MIR1	4530	29	3360-3103BC	Organic	0.55	-19.44	-18.89
MIR1	8316	33	7496-7290BC	Organic	0.55	-30.90	-30.35
MIR1	8745	34	7940-7276BC	Organic	0.55	-31.32	-30.87
MIR1	9159	41	8471-8280BC	Organic	0.55	-33.54	-32.99
NER5	2241	22	385-206 BC	Seed	1.10	-4.75	-3.65
NER6	1914	22	30-132 AD	Peat	0.90	-3.22	-2.32
NER6	2997	23	1370-1126 BC	Plant	0.90	-7.85	-6.95

Table 3: Field and laboratory description of the sediment core M2

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	Macrofossils
0.00 – 0.40	Clayey silt	Light brown and yellow (2.5Y 5/4)	3-4	Plough layer; sharp lower boundary	-
0.40 – 2.60	Clayey silt	Light brown and yellow (2.5Y 5/4)	3-4	Mottling, (2 mm); gradual lower boundary	Fragments of roots; teeth of small carnivore
2.60 – 3.90	Clayes silt passing to silty clay and clay	Greenish-grey (6/5 GY)	4	Carbonate concretions (2-3 mm)	Roots fragments, rare freshwater shells (mm)
3.90 – 5.45	Clay, silty clay	Dark greenish-grey (5/5 GY)	1	Organic rich layers on some places; rae carbonate concretions; sharp lower boundary	Fragments of plants; roots
5.45 – 5.80	Clay, silty clay	Greyish-brown (2.5Y 5/2)	1	Organic matter dispersed in matrix; laminations	Plant remains
5.80 – 10.25	Clay, clayey silt	Grey and greenish-grey (5/N – 6/10 Y)	1	Soft,consistency, intercalations of laminated intervals.	*Abra* sp., *Rissoa* sp., *Loripes* sp., *Gibbula* sp., *Cerastoderma* sp., *Nassarius* sp.; plant remains
10.25 – 13.00	Clay, clayey silt	Grey (6/N – 10Y)	1-2	Soft,consistency, some wood fragments	Rare shells:*Cerithium* sp., *Gastrana fragilis; Limnea* sp., *Rissoa* sp., *Nuculana* sp., *Loripes* sp., *Mytilus* sp.; plant remains

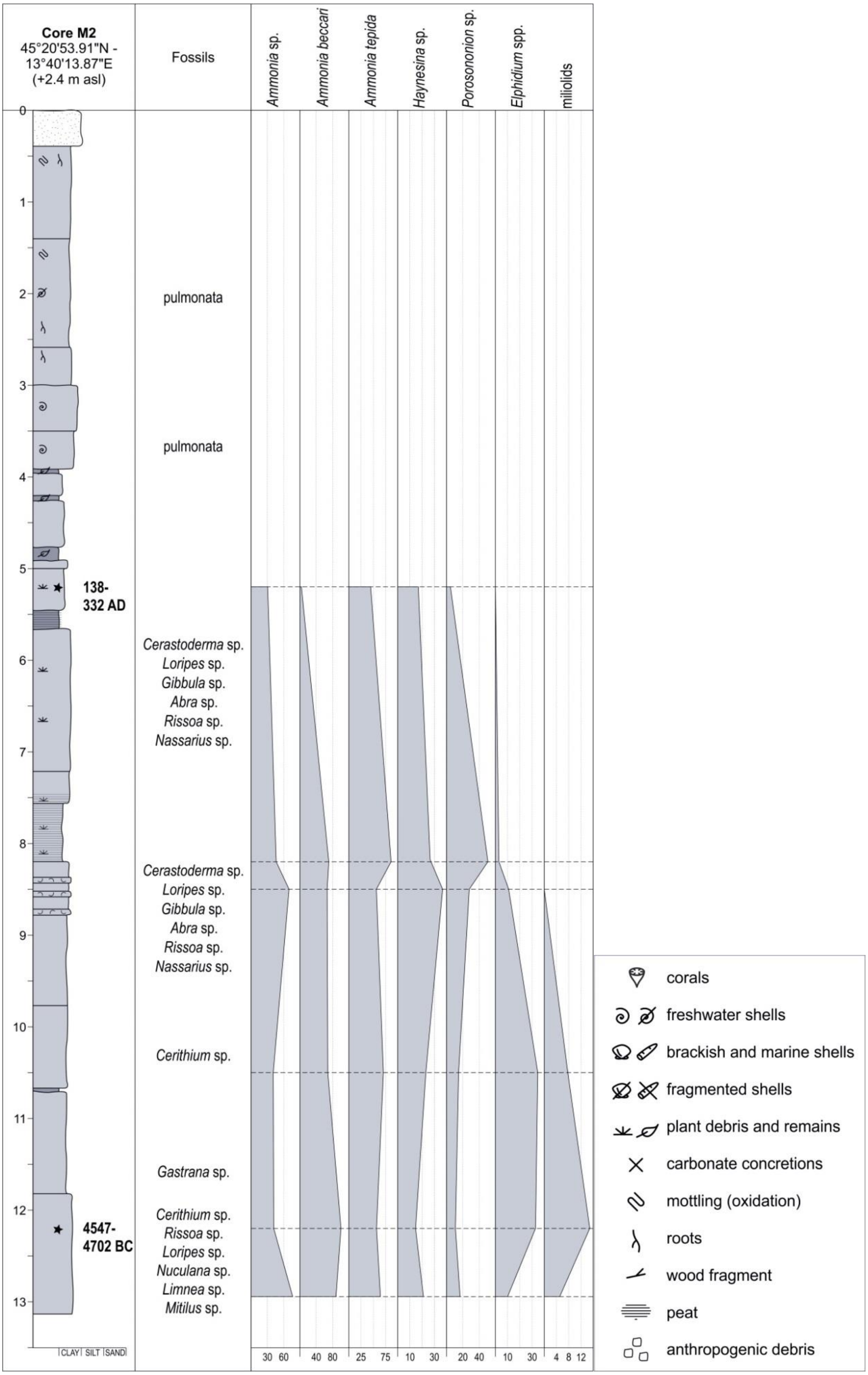

Figure 5.2. Sedimentological log of the core M2 with most common foraminifera and molluscs.

Slika 5.2. Sedimentološki stup jezgre M2 s najčešćim foraminiferama i mekušcima.

Core M3

The core [45°21’8.68’’N – 13°42’41.38’’E] reached 9 m in depth and was collected in the floodplain at ground elevation of 4.5 m above msl, 700 m downstream of the chapel of S. Maria of the Bastia (**Figure 4.1.**). The core was characterized by fine grained sediment, dominantly silty clay and clayey silt, mottling and carbonate concretions along whole depth of the core, and several shells of pulmonata. Plant remains were common along whole core depth (**Table 4**; **Figure 5.3.**).

A millimetre sized fragment of wood at -8.30 m from the surface was dated to the radiocarbon age of 854±24 years BP (1154–1254 AD, 2σ calibration) (**Table 2; Figure 5.3.**). Among the analyzed samples, 3 were completely barren of foraminifera tests and in the other 5 only very few tests were observed (a maximum of 17 specimens at a depth of 5.50 m). *A. beccarii*, *Trochammina inflata* (Montagu, 1808) and *Haynesina* sp. were recognized and biodiversity indices were very low (**Appendix 4a, 4b; Figure 5.3.**).

Table 4: Field and laboratory description of the sediment core M3

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	Macrofossils
0.00 – 2.50	Clayey silt, silty clay	Yellowish-brown (2.5Y 5/4)	3-4	-	Plant remains
2.50 – 5.10	Silty clay, clay	Yellowish-brown (2.5Y 5/4)	4	Mottling; carbonate concretions	Plant remains; fragments of shells of freshwater gastropoda (mm)
5.10 – 7.00	Clay	Greenish-grey (6/N – 10Y)	3-4	Mottling	Plant remains; fragments of shells of freshwater gastropoda (mm)
7.00 – 7.40	Clay	Slightly dark grey (2.5Y 5/1)	2	Organic rich layers on some places; rae carbonate concretions; sharp lower boundary	Fragments of shells of freshwater gastropoda (mm)
7.40 – 8.00	Silty clay, clay, silt	Greenish-grey (6/N)	2	-	-
8.00 – 8.20	Silty clay	Slightly dark grey (2.5Y 5/1)	2	Organic matter in matrix; bioturbation	Fragments of shells of freshwater gastropoda (mm)
8.20 – 9.00	Clay	Grey (6/N – 10Y)	2	Some wood fragments	Some plant remains; fragments of shells of freshwater gastropoda (mm)

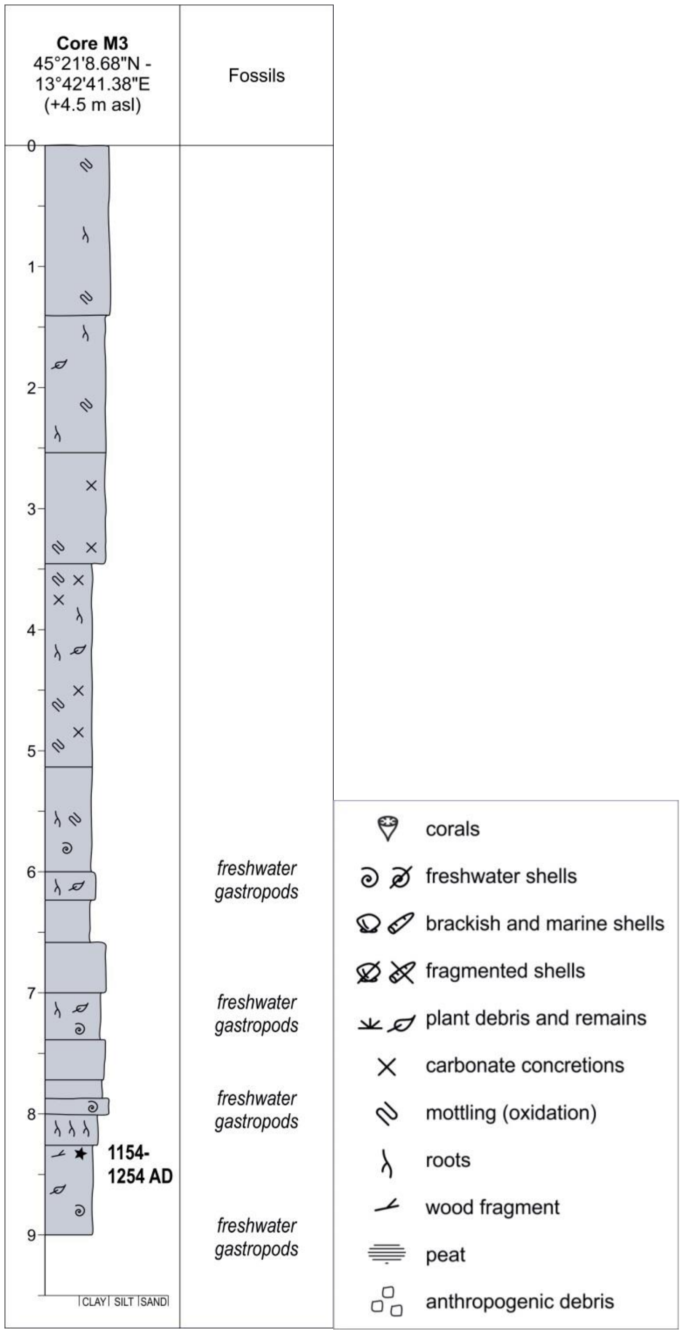

Figure 5.3. Sedimentological log of the core M3.

Slika 5.3. Sedimentološki stup jezgre M3.

Core M4

Core M4 was extracted at coordinates [45°21’07,37’’N - 13°40’1,45’’E] with ground elevation of 1.95 m above msl, near the slope of the hill (**Figure 4.1.**). The depth of the core was 8 meters. This core was composed of silty clay with one layer of silt at around 5 m depth. Mottling and carbonate concretions, as well as abundant plant remains were present down to 2.5 m. Foraminifera tests started to appear at 5.5 m and showed increase in abundance and diversity with depth (**Appendix 5a, 5b; Figure 5.4.**). At the same level, shell of *Loripes* sp. was present. Miliolids were present only in the bottom sample at 7.6 m. Between 6-7 m shells of *Cerastoderma* sp. and *Ostrea* sp. were present (**Table 5**, **Figure 5.4.**).

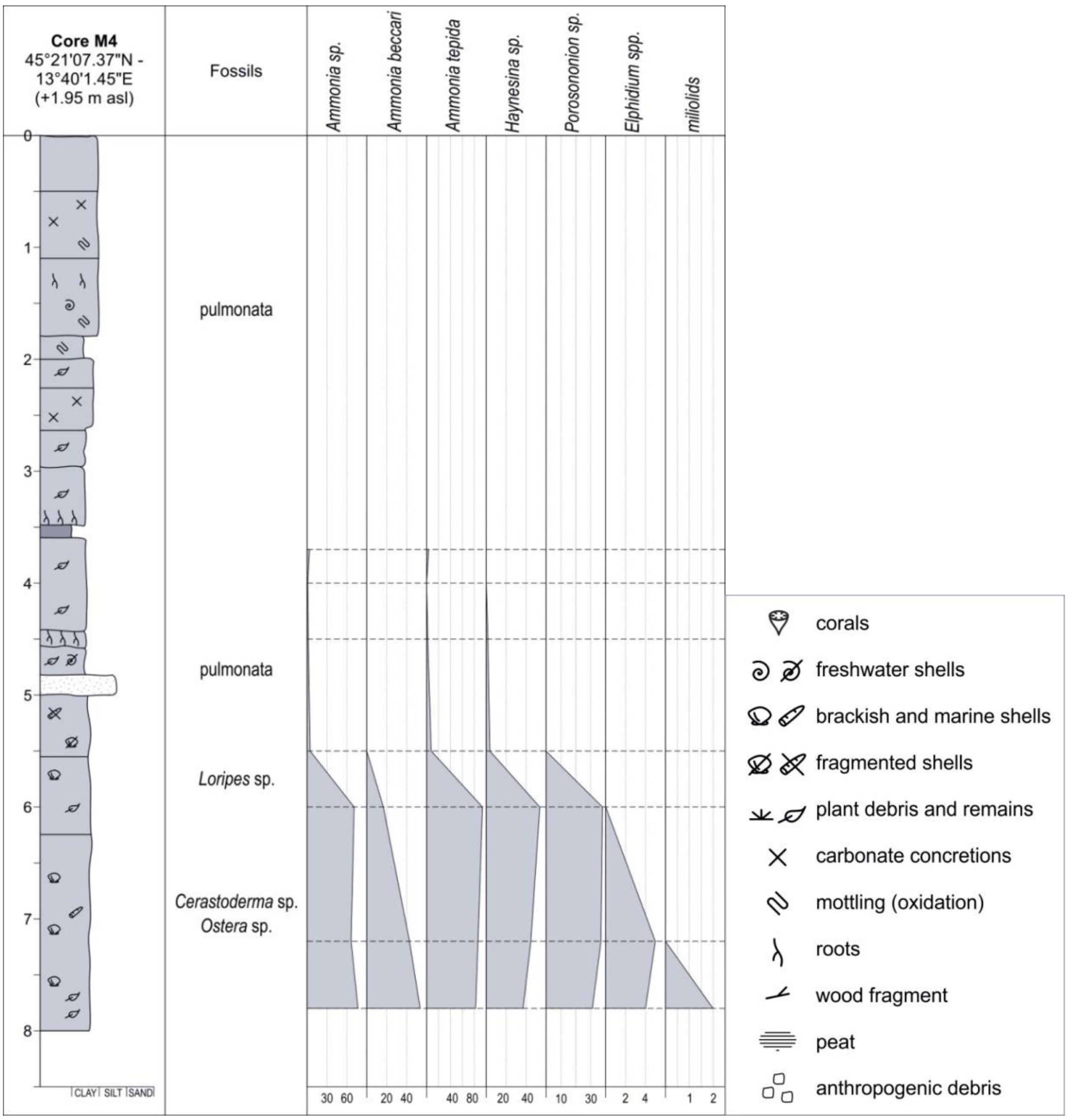

Figure 5.4. Sedimentological log of the core M4 with most common foraminifera and molluscs.

Slika 5.4. Sedimentološki stup jezgre M4 s najčešćim foraminiferama i mekušcima.

Table 5: Field and laboratory description of the sediment core M4

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	macrofossils
0.00 – 1.70	Silty clay	Yellowish-brown (2.5Y 6/4)	4	Diffused mottling; carbonate concretions; gradual lower boundary	Plant remains, roots; shells of pulmonata
1.70 – 2.00	Silty clay	Yellowish-brown (2.5Y 6/4)	4	Large Mottling; carbonate concretions	Plant remains, roots; shells of pulmonata
2.00 – 2.15	Silty clay	Greenish-grey (G1 5/10Y)	3	Mottling ; dispersed organic matter	Plant remains
2.15 – 2.55	Silty clay	Greenish-grey (G1 4/10Y)	4	Soft and rare carbonate concretions; lower boundary bioturbated	-
2.55 – 3.30	Clay	Dark greenish-grey (1G 4/10Y)	3-4	Dispersed organic matter in matrix	Plant remains
3.30 – 3.40	Silty clay	Dark grey, peaty	-	Peaty	-
3.40 – 4.40	Silty clay	Light grey (G1 5/N)	-	-	Plant remains
4.40 – 4.55	Silty clay	Dark grey (2.5Y 4/1)	-	Bioturbated	Plant remains
4.55 – 4.80	Silty clay	Light grey (G1 5/N)	-	-	Plant remains; tinny pulmonata
4.80 – 5.00	Clayey silt, silty clay	Dark grey (2.5Y 5-4/1)	-	Tough layer; laminations	-
5.00 – 5.50	Silty clay	Dark grey (2.5Y 4/1)	-	-	Lots of shell fragments
5.50 – 6.15	Silty clay	Light grey (G1 5/N)	-	-	Plant remains, roots; shells (undetermined)
6.15 – 8.00	Silty clay	Greenish-grey (G1 5/10Y)	-	-	Plant remains; shells of *Cerastoderma* sp; *Ostrea* sp.

Core M5

Core M5 was drilled at coordinates [45°20'44.18"N - 13°41'26.11"E] and was 11 meters deep, with ground elevation of 2.76 m above msl (**Figure 4.1.**). This core is entirely composed of silty clay, with concretions down to 5 m, and mottling down to 2 m. Plant remains and shells (*Cerastoderma* sp., *Rissoa* sp., *Loripes* sp., *Gibbula* sp.) were present at deeper levels, below 7 m (**Table 6, Figure 5.5.**). Foraminifera tests started to be present below 6 m, with abundance and biodiversity indices increasing with depth (**Appendix 6a, 6b; Figure 5.5.**). At 7 m depth, horizon with only several tests of *T. inflata* was present. Tests of miliolids were present around 10 m depth (**Appendix 6a; Figure 5.5.**).

Table 6: Field and laboratory description of the sediment core M5

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	Macrofossils
0.30 – 1.90	Silty clay	Light brown	-	Plough layer (first 30cm); mottling	-
1.90 – 2.80	Silty clay	Greyish brown	-	Mottling	-
2.80 – 4.60	Clay	Bluish grey Grey	-	Carbonate concretions	Roots
4.60 – 5.30	Silty clay	Greyish brown	-	Carbonate concretions	Roots
5.30 – 5.75	Silty clay	Grey	-	Rich in organic content; peaty	Plant remains
5.75 – 6.90	Silty clay	Grey	-	-	Wood fragments, roots
6.90 – 7.10	Silty clay	Grey	-	Organic; concretions; lower boundary sharp	Tinny gastropoda
7.10 – 8.00	Silty clay, clay	Dark grey	-	Laminated; laminae of plant debris	Plant remains; shells, even with closed valves; *Cerastoderma* sp.
8.00 – 9.40	Silty clay	Dark grey	-	Homogenous	*Cerastoderma* sp., *Rissoa* sp., *Loripes* sp.
9.40 – 10.54	Silty clay	Dark grey	-	Laminations, organic debris	-
10.54 – 11.00	Silty clay	Dark grey	-	Peat; laminations	*Gibbula adriatica*

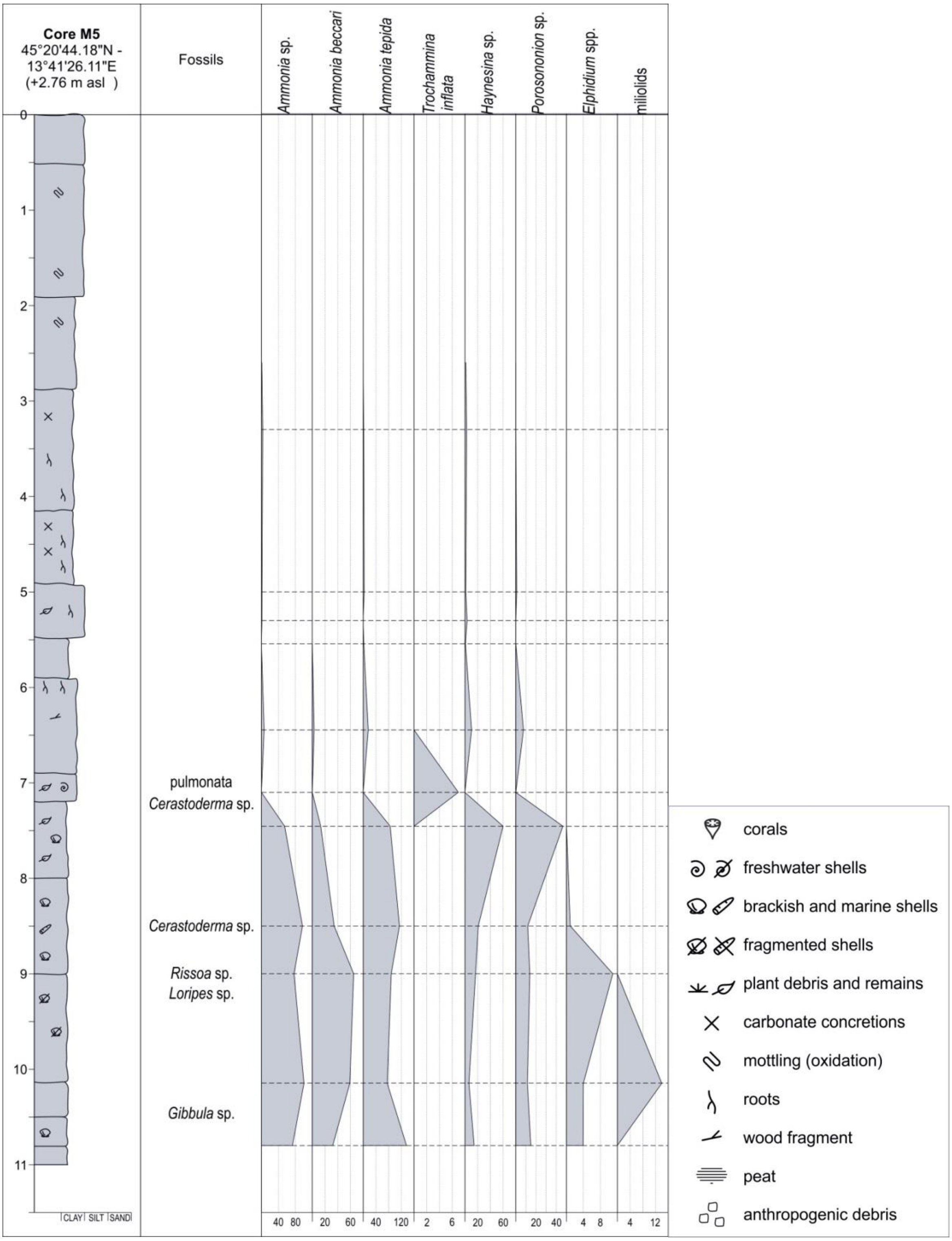

Figure 5.5. Sedimentological log of the core M5 with most common foraminifera and molluscs.

Slika 5.5. Sedimentološki stup jezgre M5 s najčešćim foraminiferama i mekušcima.

Core M6

The core M6 was extracted on the south side of Mirna river valley [45°19'52.97"N - 13°39'6.58"E], in front of the old brick factory. Ground elevation of the core was 1.13 m above msl (**Figure 4.1.**). The core was 7.6 m deep, and consisted of silty clay and clayey silt. Concretions were present down to 3.5 m, and mottling in the first 2 m (**Table 7; Figure 5.6.**). Foraminifera tests occur at 3.6 m of core depth, but biodiversity indices were low along core depth, and tests of miliolids or *Elphidium* spp were not present (**Appendix 7a, 7b; Figure 5.6.**). Shells of *Cerastoderma* sp. and *Cyclope* sp. were present at the depth of 4 m.

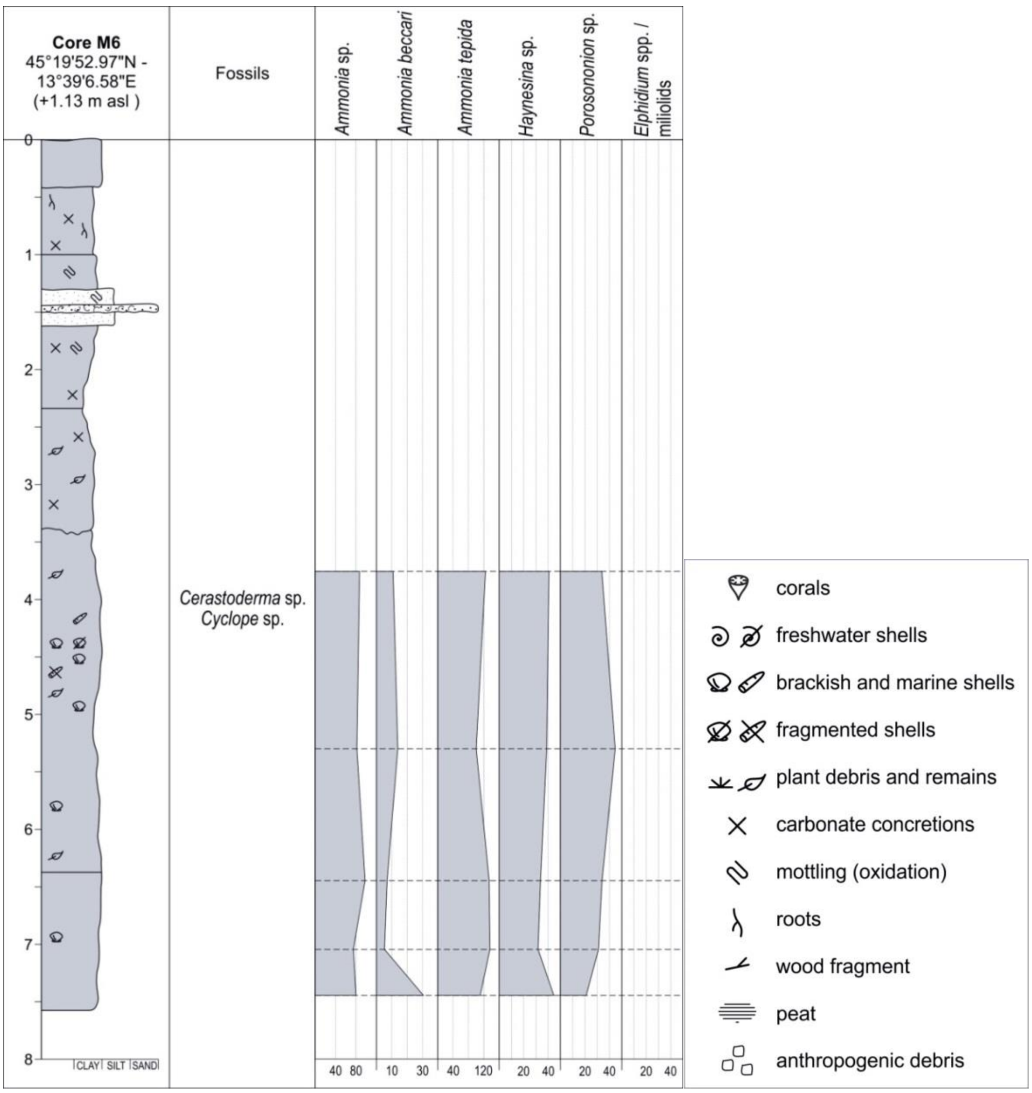

Figure 5.6. Sedimentological log of the core M6 with most common foraminifera and molluscs.

Slika 5.6. Sedimentološki stup jezgre M6 s najčešćim foraminiferama i mekušcima.

Table 7: Field and laboratory description of the sediment core M6

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	Macrofossils
0.00 – 0.40	Silty clay	Light olive brown (2.5Y 5/4)	4	Plough layer	-
0.40 – 1.00	Silty clay , clay	Light olive brown (2.5Y 5/3-4)	4	Mottling (10-20%); Mn-Fe nodules (less than 1mm); carbponate concretions	Recent roots
1.00 – 1.15	Silty clay	Light brownish-grey (2.5Y 6/3-2)	4	Mottling (25%; 2mm)	-
1.15 – 1.50	Coarse silt, fine sand	Light brownish-grey (2.5Y 6/2)	4	Strong mottling; lower boundary gradual	-
1.50 – 2.20	Silty clay, clay	Brownish-grey(2.5Y 6/6-5)	4	Coarsening upward; mottling; soft carbonate concretions (2mm; less than 5%)	-
2.20 – 3.40	Clayey silt	6.5/10Y 4/10Y	4	Soft, sticky sediment; organic remains at the top; rare carbonate concretions; lower boundary gradual	Roots; seeds; shells of mollusc
3.40 – 7.60	Silty clay, clayey silt	5/10Y 4/10Y 5/N	4	Very soft and sticky; unconsolidated; laminations	Shells (*Cerastoderma* sp., *Cyclope* sp.); plant remains

Core M7

This core was extracted in the recent salt marsh very close to the Mirna River mouth to the sea [45°19'8.60"N; 13°35'57.18"E]. The depth of the core was 4 meters and ground elevation ~ 0.20 m above msl (**Figure 4.1.**). The first 0.75 m of the core was composed of recent marsh deposits, dominantly clay and silty, with very soft consistency. Plan remains and roots of the recent marsh were abundant. Next layer, between 0.75 – 1.35 m consisted of homogenous greyish silty clay, with plant remains and shell fragments of millimetric dimensions. (**Table 8**, **Figure 5.7.**). Layer between 2.0 – 4.0 m consisted of silty clay, abundant with plant remains and shell fragments. Few sandy layers were present.

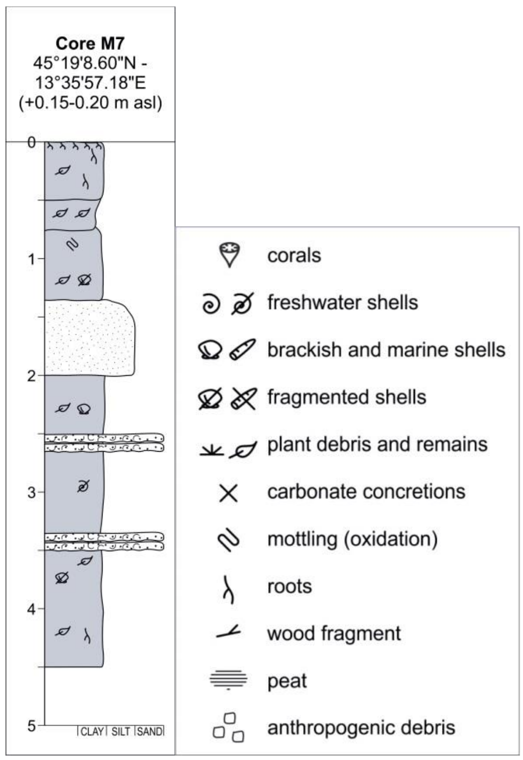

Figure 5.7. Sedimentological log of the core M7.

Slika 5.7. Sedimentološki stup jezgre M7.

Table 8: Field and laboratory description of the sediment core M7

Depth (m)	Grain size	Color	Carbonate share (HCl reaction)	Structures	macrofossils
0.00 – 0.05	Silty clay	Brown	-	Surface layer; unconsolidated, soft, sticky	-
0.05 – 0.50	Silty clay	Greyish-brown	-	-	Recent roots, plant remains
0.50 – 0.75	Clay	Light brownish-grey (2.5Y 6/3-2)	-	Mottling	Plant remains
0.75 – 1.35	Silty clay	Light grey	-	Homogenous	Rare milimetric remains of shells and plants
1.35 – 2.00	Sandy silt	Brownish-grey	-	Homogenous	-
2.00 – 4.00	Silty clay	Brownish-grey	-	Few sandy layers; mars reeds abundant at 3.95 m	Plant remains, shells

Core M8

The core M8 was extracted in the recent salt marsh, in proximity to the Mirna River mouth [45°19'14.61"N; 13°36'11.24"E]. The depth of the core was 2 meters deep with ground elevation of ~ 0.20 m above msl (**Figure 4.1.**). The first 1 m of the core was composed of recent marsh deposits, dominantly clay and clayey silt, with very soft consistency. Plan remains of the recent marsh were abundant. Next layer, between 1 – 2 m consisted of clay with plant remains and shell fragments of millimetric dimensions (**Table 9**, **Figure 5.8.**).

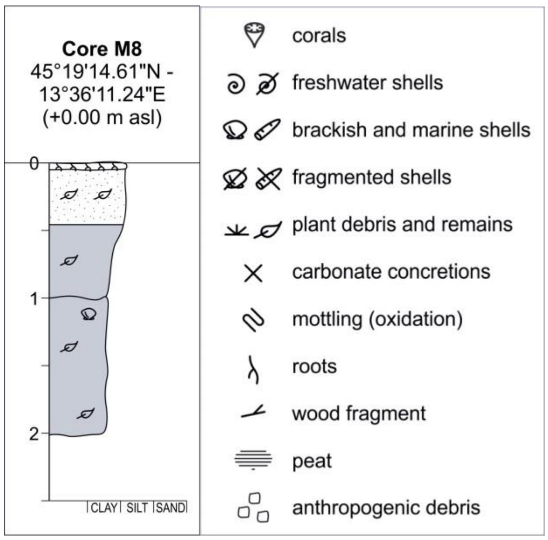

Figure 5.8. Sedimentological log of the core M8.

Slika 5.8. Sedimentološki stup jezgre M8.

Table 9: Field and laboratory description of the sediment core M8

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	macrofossils
0.00 – 0.05	Silty clay	Brown	-	Surface layer; unconsolidated, soft, sticky	-
0.05 – 0.45	Clayey silt	Greyish-brown	-	-	Plant remains
0.45 – 1.00	Clay	Light Grey	-	-	Plant remains
1.00 – 2.00	Clay	Light grey	-	Homogenous	Milimetric remains of shells and plants

Core MIR1

The core MIR1 was extracted in proximity of the core M1 [45°19'53.23"N; 13°37'13.92"E], and was drilled by Geoservizi Inc., with a mechanical probe Atlas Copco mounted on a Magirus truck and equipped with a “simple sampler” that recovers sediment cores of 88 mm of diameter and length between 1.5 and 3.0 m. The core was 120 m deep, however only first 40 m are described here. The core had ground elevation of 0.55 m above msl (**Figure 4.1.**). This core was wider in diameter so additional analyses could be performed (granulometry and calcimetry). Detailed description of the core is described in **table 10**.

The core MIR1 generally was prevalently composed of fine sediments, mostly mud. Three samples (at 2.47 m, 2.97 m and 3.57 m) belonged to the textural group of clay and were moderately well sorted. The share of clay in these samples was between 85.6 to the maximum of 92.8 %. All other samples were poorly or very poorly sorted. Twenty nine samples belonged to the textural group of mud and these were present in the shallower parts of the core down to the depth of 26.17 m. In these samples, share of sand and gravel did not exceed 10 % and 0.5 % respectively and these particles were mostly composed of shells or fragments of molluscs and gastropoda. Slightly higher share of sand and gravel was generally present in the depths between 27.57 m and 34.40 m and were also mostly shells of molluscs and gastropoda (also coarser foraminifera and ostracoda). Fifteen samples fited in the textural group of slightly gravelly mud, 1 sample in gravelly mud (6.1 % of gravel), 5 samples in slightly gravelly sandy mud and 5 in sandy mud textural group. Still, all samples were composed mostly of clay and silt (**Table 11**; **Figure 5.9.**).

Average carbonate share in 58 samples, between 2.07 and 34.40 m, was 23.25 %. The lowest share of carbonate (2.4 %) was present in the sample at the depth of 31.27 m and the highest (45.3 %) at the depth of 29.87 m. It could be observed that shallower part of the core, down to 26.17 m (mostly muds, with low share of sand and gravel) contained lower carbonate share (average ~ 20 %) while deeper part of the core (between 26.17 and 34.40 m) showed somewhat higher share of carbonate content (average 30-40 %). Exceptions were few samples *e.g.* at the depth 31.07 m and 31.27 m with carbonate shares of 4.1 % and 2.4 % respectively. So it could be concluded that coarser fraction (sand and gravel) in the samples was composed mostly of carbonate shells of gastropoda and bivalvia (**Table 11**; **Figure 5.9.**). ^{14}C datings of 6 samples at the various depth of the core are presented in **Table 2**.

Table 10: Field and laboratory description of the sediment core MIR1

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	macrofossils
0.00 – 0.30	Clayey silt	Yellowish grey (2.5Y 5/3)	4	Plough layer, well consolidated, gradual lower boundary	Recent roots (1-2 mm), fragments of shells
0.30 – 0.75	Clayey silt	Dark yellowish grey (2.5Y 3/2)	4	Well consolidated, gradual lower boundary	Recent roots (1-2 mm), fragments of shells (rare)
0.75 – 1.10	Clayey silt	Dark yellowish grey (2.5Y 5/2)	4	Mottling 15% (2-5 mm), well consolidated, gradual lower boundary	Rare roots
1.10 – 1.72	Clayey silt	Dark yellowish grey (2.5Y 5/2)	4	Mottling 10% (2 mm), well consolidated, gradual lower boundary	Fragments of shells (rare)
1.72 – 2.38	Clayey silt	Greenish-grey (5Y 5/2)	3-4	Mottling 50% (2 mm), well consolidated, lower boundary sharp	*Cyclope* sp., *Gibbula* sp., *Bittium* sp. and *Loripes* sp; some plant debris
2.38 – 2.78	Clayey silt	Light grey (5 Y 5/1) Brown grey (5 Y 3/2)	1	Alternations of inorganic and organic clayey silt; gradual lower boundary	Some plant debris; *Cerastoderma* sp., *Gibbula* sp., *Bittium* sp. i *Loripes* sp.
2.78 – 2.98	Clayey silt	Light grey (5 Y 5/1) Brown grey (5 Y 3/2)	1	Lower boundary sharp	Some plant debris
2.98 – 4.08	Clayey silt	Light grey (N5)	4	Gradual lower boundary	Plant debris; *Cerastoderma* sp., *Gibbula* sp., *Bittium* sp. i *Loripes* sp.
4.08 – 5.86	Silty clay	Dark grey (5N5 – 4N4)	3-4	Milimetric laminations Lower boundary clear	Lots of *shells of Cerastoderma* sp., *Rissoa* sp., *Gibbula* sp., *Loripes* sp., *Nassarius* sp., *Gastrana* sp., gastropoda *Pulsatilla* sp.; plant debris
5.86 – 9.60	Silty clay	Dark grey (5N5 – 4N4)	4	Lower boundary gradual	Rare fragments of *Rissoa* sp., *Loripes* sp., *Cerastoderma* sp., *Nucula* sp., *Gastrana* sp (both valves connected)., *Nuculana* sp.
9.60 – 20.60	Silty clay	Dark grey (2.5Y 3/1)	3, 4	Transitional lower boundary	Plant remains; *Nuculana* sp., *Telina* sp., *Nasarius* sp., *Murex* sp., *Cerastoderma* sp., *Dentalium, Donax* sp., *Abra* sp., echinoderma
20.60 – 23.50	Silty clay	Grey (1 4/N)	3, 4	Homogenous; strongly reworked by bioturbation	Rare *Ostrea* sp., *Pecten* sp., *Abra* sp.
23.50 – 29.30	Silty clay	Dark grey (5N5)	4	Homogenous; sttrongly reworked by bioturbation	*Turitella* sp, *Dentalium*, *Pectinide* i *Ostrea* sp.; seeds

29.30 – 30.50	Silty clay	Dark grey (5N5)	4	Homogenous; lower boundary transitional; strongly reworked by bioturbation	*Ostrea* sp., *Dentalium* sp., serpulida, *Mytilus* sp., *Murex* sp.; claws of *Crustacea*
30.50 – 30.83	Silty clay with lenses of organic clay	Dark grey (5N5) (10Y 5/1)	4	Lenses of orgabnic clay; bioturbation; lower boundary erosive with undulations	*Ostrea* sp., *Mytilus* sp., *Cerastoderma* sp., serpulida, *Gastrana* sp.
30.83 – 31.17	Organic silty clay	(2.5Y 4/1) (10Y 2/1)	3-4 peat 0-1	Layered peat and plant fragments; lower boundary transitional.	*Cerastoderma* sp., plant debris
31.17 – 31.73	Organic silty clay	(2.5Y 5/1)	0-1	Transitional lower boundary	Rare shell fragments
31.73 – 32.10	Silty clay and organic silty clay	Lightgrey (2.5Y 4/2) (2.5Y 5/1)	4	Transitional lower boundary	*Turitella* sp,, *Ostrea* sp., Pectinide
32.10 – 32.72	Silty clay and organic silty clay	Light grey (2.5Y 4/2) (2.5Y 5/1)	4	Lenses; gradual lower boundary	Turitella, Ostrea i Pectinide, organska tvar
32.72 – 33.10	Clayey silt	Dark grey (5N5)	4	Sharp lower boundary	Serpulida, *Cerastoderma* sp. i *Dentalium* sp.
33.10 – 33.40	Silty clay	Dark grey (4N4)		Concretions; Bioturbation	-
33.40 – 33.90	Silty clay	(2.5Y 3/1)		Rare carbonate concretions (up to 1cm); gradual lower boundary (bioturbation)	Rare fragments of tinny shells
33.90 – 34.50	Clayey silt	(5Y 5/2 – 6/10 Y)	4	Mottling diffused around carbonate concretions; Layer of fine sand present	-
34.50 – 35.15	-	-	-	Sample missing	-
35.15 – 36.10	Clayey silt	Greenish-grey (6/10 Y)	4	Mottling; carbonate concretions; lower boundary gradual	-
36.10 – 37.10	Silt	Greenish-grey (6/10 Y)	4	Mottling; presence of fine sand and silt layers; lower boundary gradual	-
37.10 – 40.00	Silty clay, clayey silt	Greenish-grey (5Y 5/2)	4	Mottling; lamination; soft carbonate concretions	-

Table 11. Grain size distribution and carbonate share of samples in the core MIR1 (Mirna River delta plain)

Depth (m)	Clay(%)	Silt(%)	Sand(%)	Gravel(%)	Carbonate(%)	Textural group	Sorting
2.07-2.10	54.8	44	1.1	0.1	28.7	mud	poorly
2.37-2.40	57.7	39.1	2.3	0.9	24.1	slightly gravelly mud	poorly
2.47-2.50	85.6	11.2	3	0.2	11.5	clay	moderately sorted
2.97-3.00	87	10.9	2.1	0	11.7	clay	moderately sorted
3.57-3.60	92.8	5.4	1.5	0.3	25.8	clay	moderately well sorted
4.07-4.10	73.3	22.1	3.7	0.9	17.2	slightly gravelly mud	poorly
4.97-5.00	61.8	36.3	1.8	0.1	12.4	mud	poorly
5.47-5.50	59.2	37.8	2.5	0.5	13.1	slightly gravelly mud	poorly
5.97-6.00	47.5	47.9	4.6	0	18.5	mud	very poorly
6.37-6.40	45.6	50.5	3.7	0.2	16	mud	very poorly
6.87-6.90	47.9	49	3.1	0	19.8	mud	very poorly
7.37-7.40	51.5	45.7	2.8	0	15.5	mud	poorly
7.87-7.90	48	45.2	6.8	0	22.3	mud	very poorly
8.27-8.30	41.2	49.9	8.8	0.1	25.1	mud	very poorly
8.97-9.00	39.1	50.1	10.7	0.1	28.2	sandy mud	very poorly
9.37-9.40	41.7	54.5	3.8	0	21.6	mud	very poorly
9.67-9.70	50.4	46.4	3.2	0	21.4	mud	very poorly
10.27-10.30	44	49.5	6.5	0	25.1	mud	very poorly
10.67-10.70	40.7	49.4	9.9	0	22.7	mud	very poorly
11.07-11.10	39.1	52.6	8.3	0	23.6	mud	very poorly
11.37-11.40	38.2	52.5	9.1	0.2	22	mud	very poorly
11.77-11.80	41	53	5.9	0.1	22.5	mud	very poorly
13.27-13.30	43.3	46.5	10.1	0.1	24	sandy mud	very poorly
14.07-14.10	46.2	47.6	6.1	0.1	17.9	mud	very poorly
14.87-14.90	43.1	51.7	5.2	0	16.5	mud	very poorly
15.07-15.10	43	49.5	7.5	0	24.8	mud	very poorly
16.07-16.10	42.3	50.2	7.5	0	22.9	mud	very poorly
17.07-17.10	43.9	50.9	5.2	0	22.2	mud	very poorly
17.87-17.90	50.4	45.4	4.2	0	21.8	mud	very poorly
18.07-18.10	41.8	46.3	11.8	0.1	22.4	sandy mud	very poorly
18.47-18.50	42.4	46.6	11	0	22.7	sandy mud	very poorly
18.97-19.00	47.2	48.9	3.9	0	22.7	mud	very poorly
19.37-19.40	44	46.9	9.1	0	23.2	mud	very poorly
20.07-20.10	47	49.9	3.1	0	25.1	mud	very poorly
21.77-21.80	50.3	48.2	1.5	0	20.3	mud	poorly
22.37-22.40	50.2	48.1	1.7	0	19.2	mud	poorly
23.47-23.50	46.9	51.1	2	0	21.7	mud	poorly
24.07-24.10	49.5	49.2	1.3	0	24.3	mud	poorly
25.47-25.50	53	45.3	1.2	0.5	24.2	slightly gravelly mud	poorly
26.17-26.20	52.5	46.4	1.1	0	21.7	mud	poorly
27.57-27.60	52.5	44.3	1.7	1.5	32.6	slightly gravelly mud	poorly
28.57-28.60	51.3	44.4	1.4	2.9	32.8	slightly gravelly mud	poorly
29.07-29.10	44.8	45.5	3.6	6.1	36.8	gravelly mud	very poorly
29.47-29.50	52	46.2	1.4	0.4	26.9	slightly gravelly mud	poorly
29.87-29.90	42.9	53.3	2.6	1.2	45.3	slightly gravelly mud	poorly
30.77-30.80	73.1	17.6	6.9	2.4	30.1	slightly gravelly mud	very poorly
30.97-31.00	50.8	35.7	12.9	0.6	16.6	slightly gravelly sandy mud	very poorly
31.07-31.10	52.5	30.9	15.9	0.7	4.1	slightly gravelly sandy mud	very poorly
31.27-31.30	70.9	16.8	12	0.3	2.4	slightly gravelly sandy mud	very poorly
31.67-31.70	50.9	42.1	5.5	1.5	37.6	slightly gravelly mud	very poorly
31.87-31.90	52.2	42.1	3.2	2.5	36.8	slightly gravelly mud	very poorly
32.07-32.10	51.7	45	2.3	1	28.9	slightly gravelly mud	poorly
32.77-32.80	49.5	45.8	3.5	1.2	34.5	slightly gravelly mud	very poorly
32.97-33.00	48.4	47.3	2.3	2	38.2	slightly gravelly mud	poorly
33.17-33.20	65.7	25.9	7.3	1.1	8.6	slightly gravelly mud	very poorly
33.77-33.80	35.8	46	16.3	1.9	11.4	slightly gravelly sandy mud	very poorly
34.07-34.10	21.2	50.8	28	0	39.9	sandy mud	very poorly
34.37-34.40	24.4	64.3	10.8	0.5	38.5	slightly gravelly sandy mud	very poorly

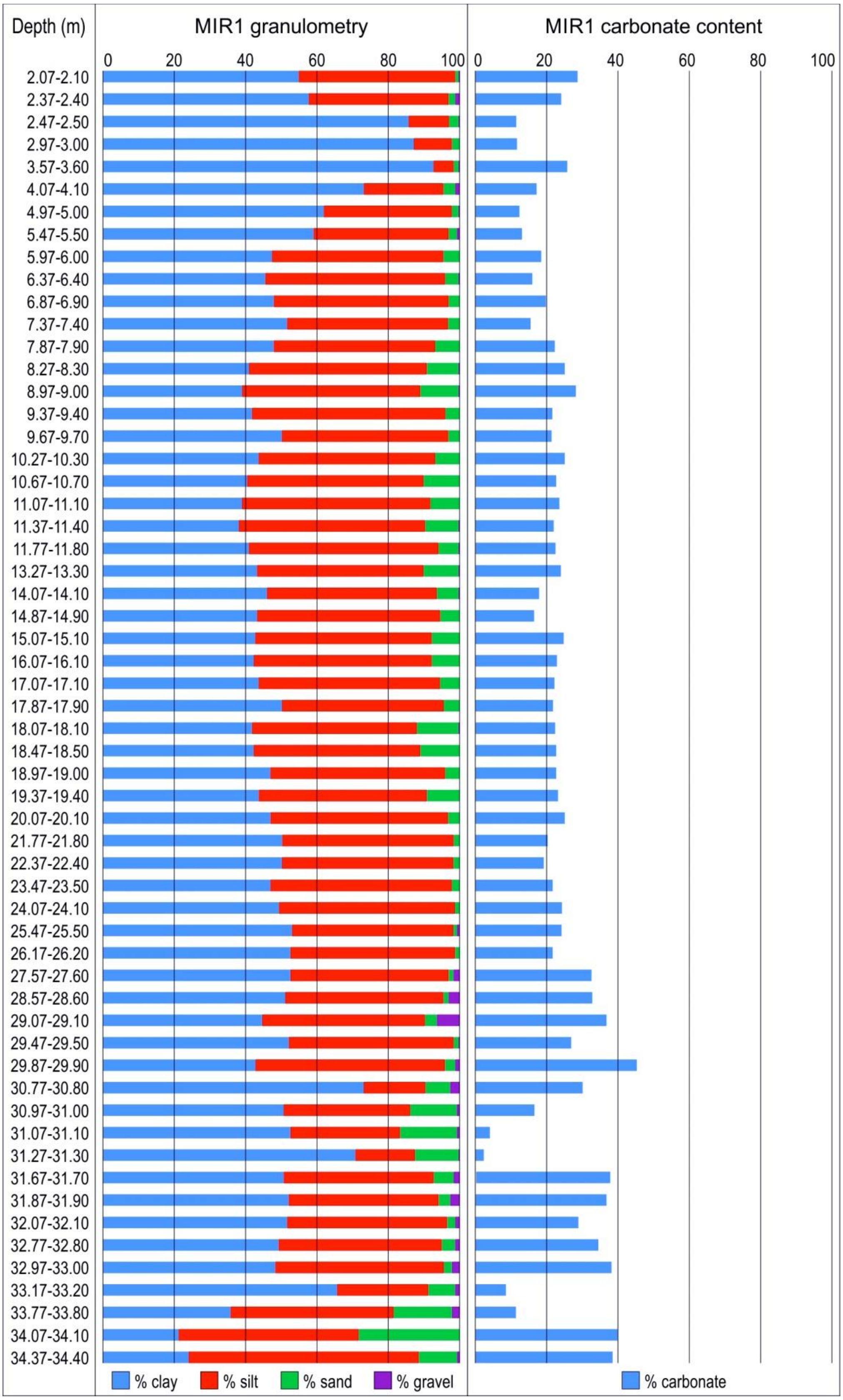

Figure 5.9. Grain size distribution and carbonate share of the core MIR1.

Slika 5.9. Raspodjela veličine zrna i udio karbonata u jezgri MIR1.

5.2. FIELD AND LABORATORY DESCRIPTIONS AND RESULTS OF THE LABORATORY ANALYSES OF CORES FROM THE NERETVA DELTA PLAIN

Field and laboratory description of 8 sediment cores extracted in the Neretva River delta plain and 1 core from the Malostonski Channel are presented here. Results of grain size analyses and calcimetry are shown for the cores NER1, NER3, NER6, NER120, NER20 and P1. Radiocarbon datings are shown in table 2 for the samples in the cores NER5 and NER6. Absoulute abundance and biodiversity indices of foraminifera were calculated for cores NER5 and NER6. The most common foraminifera found on different depth are shown in the plate1 and most common gastropoda and bivalvia in the plate 2.

Core NER1

The core NER1 was located at the coordinates [43°00'50.6"N - 17°38'05.5"E (**Figure 4.2.**)] with the ground elevation of 0 m msl. The depth of the core was 9 m. Core NER1 consist dominantly of silt and sand fractions (**Figure 5.10**). Roots and wood fragment were found down to the depth of ~ 4.00 m. Shells of bivalvia and gastropoda (mostly *Cerastoderma* sp., but also *Mytilus* sp., *Bithium* sp., *Loripess* sp., *Rissoa* sp.) were common on all depth, but much more in the deeper layers, below 6.00 m. One specimen of *Abra* sp. with both valves closed was found at 4.10 m. The coarsest layer was present between 5.13 – 5.95 m, and it ended with erosive boundary. Boundary at 7.60 m was quite abrupt, marked by shell fragments. Between 7.60 – 8.30 m laminations could be observed. At 9.00 m basement rock was reached (**Table 12; Figure 5.11**).

Table 12: Field and laboratorydescription of the sediment core NER1

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	macrofossils
1.60 – 2.55	Silt, clayey silt	Grey	-	Finning upward; poorly visible laminations; lower boundary transitional	Wood fragments, roots; shells fragments
2.55 – 3.79	Silt, sand	Grey (gley)	-	-	Branch; *Cerastoderma* sp., shell fragments; plant remains
3.79 – 4.03	Silty sand	Grey	-	-	Shell fragments; *Cerastoderma* sp., *Mytlius* sp., gastropoda
4.03 – 4.40	Sandy silt	Grey	-	-	Lots of shells, with closed vaves also; *Abra* sp.?
4.40 – 5.05	Silty sand, sandy silt	Grey	-	Organic matter dispersed in matrix; laminations	Rare shell fragments; *Cerastoderma* sp., *Loripes* sp.
5.05 – 5.13	Sandy silt	Light grey	-	-	-
5.13 – 5.95	Sandy silt, silty sand	Grey	-	Coarsening downward; erosive lower boundary; coarsest layer in the core	Rare shell fragments; *Cerastoderma* sp.
5.95 – 7.00	Sandy silt	Grey	-	Thin sandy layers	Fragments of *Mytilus* sp., *Cerastoderma* sp., *Rissoa* sp., *Bithium* sp.
7.00 – 7.60	Silty sand	Grey	-	Sharp lower boundary with accumulation of shell fragments	*Rissoa* sp., *Bithium* sp., Mytilus sp.
7.60 – 8.30	Sandy silt, slightly clayey	Grey	-	Laminations; lower boundary transitional	*Cerastoderma* sp. *Mytilus* sp.
8.30 – 9.00	Silt, very fine sand	Grey	-	At 9.00 m basement rock was reached	Plant remains (mm); *Cerastoderma* sp.

Eleven samples from the core NER1 were analysed for grain size (**Table 13**; **Figure 5.10**). All samples were poorly sorted and belong to the textural groups of sandy muds and muddy sands. Clay fraction ranged between 11.2 % - 35.4 %, with maximum at 0.9 m. Share of silt was between 40.2 % on the surface and 77.4 % at the depth of 8.0 m. Maximum share of sand was at the depth of 1.30 m (42.0 %) and minimum at the depth of 8.0 m (2.6 %). Gravel was not significantly present in samples and did not exceed 2.1 %, except in the sample at the depth of 7.0 m (7.40 %). Carbonate share in samples from the core NER1 ranged between 3.84 % - 55.69 % with minimum at 0.9 m and maximum at 6.0 m. Carbonate share in the uppermost three samples did not exceed 9 %, while between 2.0 m and 9.0 m carbonate share was much higher (39.09 – 55.69 %).

Table 13. Grain size distribution and carbonate share in the core NER1

Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	CaCO3 (%)
0.00-0.10	25.9	40.2	31.8	2.1	9.0
0.90-1.00	35.4	41.9	22.0	0.7	3.8
1.30-1.40	14.7	41.2	42.0	2.1	6.2
2.00-2.10	12.4	75.4	11.6	0.5	43.2
3.00-3.10	16.0	76.3	6.6	1.1	50.6
4.00-4.10	11.2	70.8	17.5	0.5	46.6
5.00-5.10	16.3	72.4	10.8	0.5	39.1
6.00-6.10	15.8	47.1	36.2	0.9	55.7
7.00-7.10	18.9	45.2	28.5	7.4	51.8
8.00-8.10	18.6	77.4	2.6	1.4	45.1
9.00-9.10	17.6	69.8	12.6	0.0	44.0

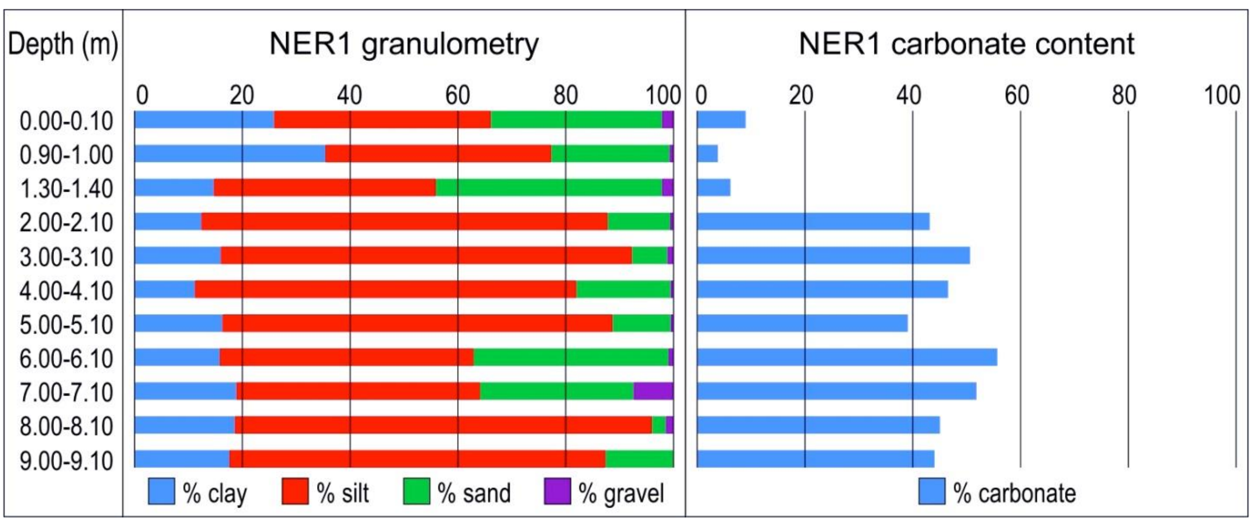

Figure 5.10. Grain size distribution and carbonate share of the core NER1

Slika 5.10. Raspodjela veličine zrna i udio karbonata u jezgri NER1.

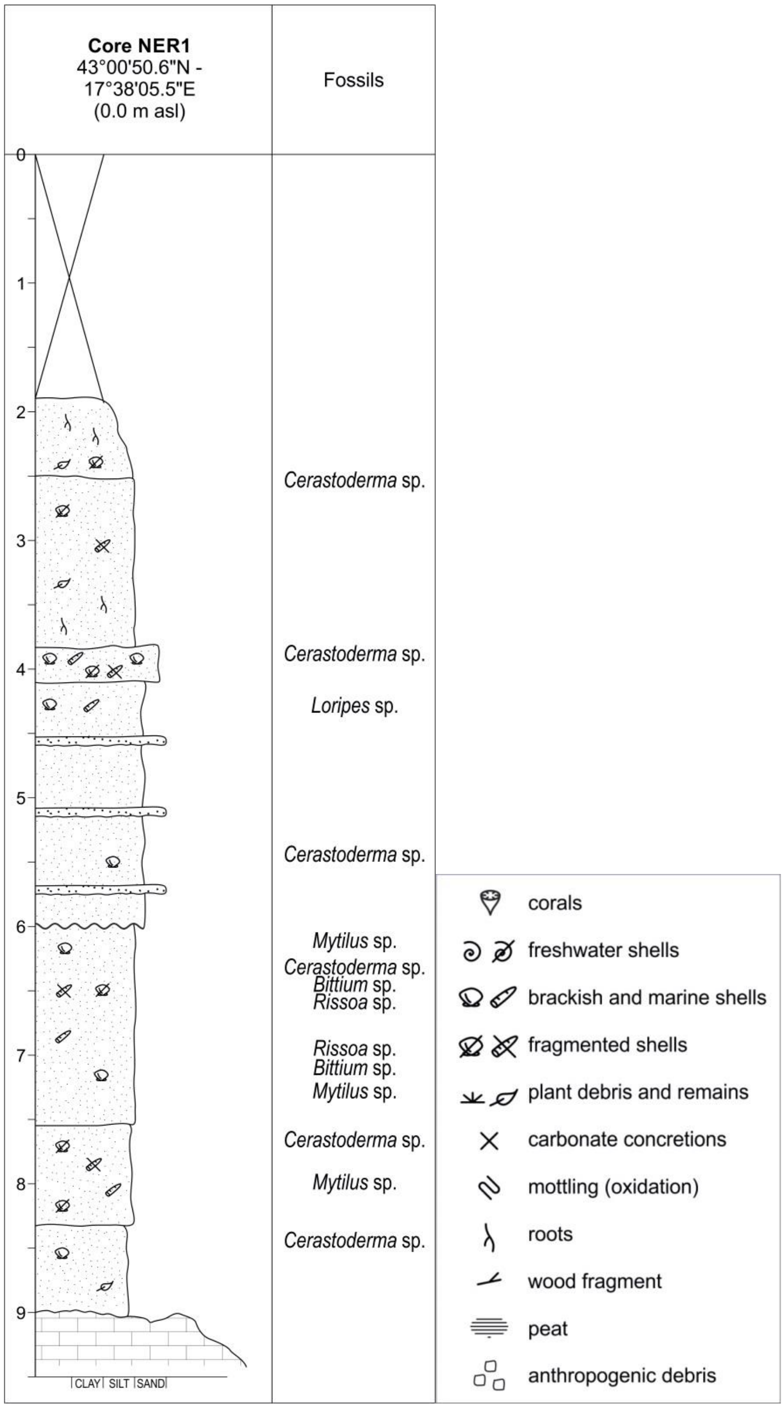

Figure 5.11. Sedimentological log of the core NER1.

Slika 5.11. Sedimentološki stup jezgre NER1.

Core NER2

The core was 6.65 m long and located 25 m north from the path connecting Paleochristan "*Erešove bare"* church to the modern harbor [43°04'36.3"N - 17°37'33.0"E (**Figure 4.2.**); **ground** elevation 1.4 m above msl]. In the first 2.30 m of the core, brick and stone debris were present. Rare shells of freshwater gastropoda were found. Mottling was visible between 3.20 – 4.45 m, as well as lamination. Between 4.45 – 6.38 m, organic rich, peaty layer was present, alternating with thin layers of clay (**Table 14.; Figure 5.12.**).

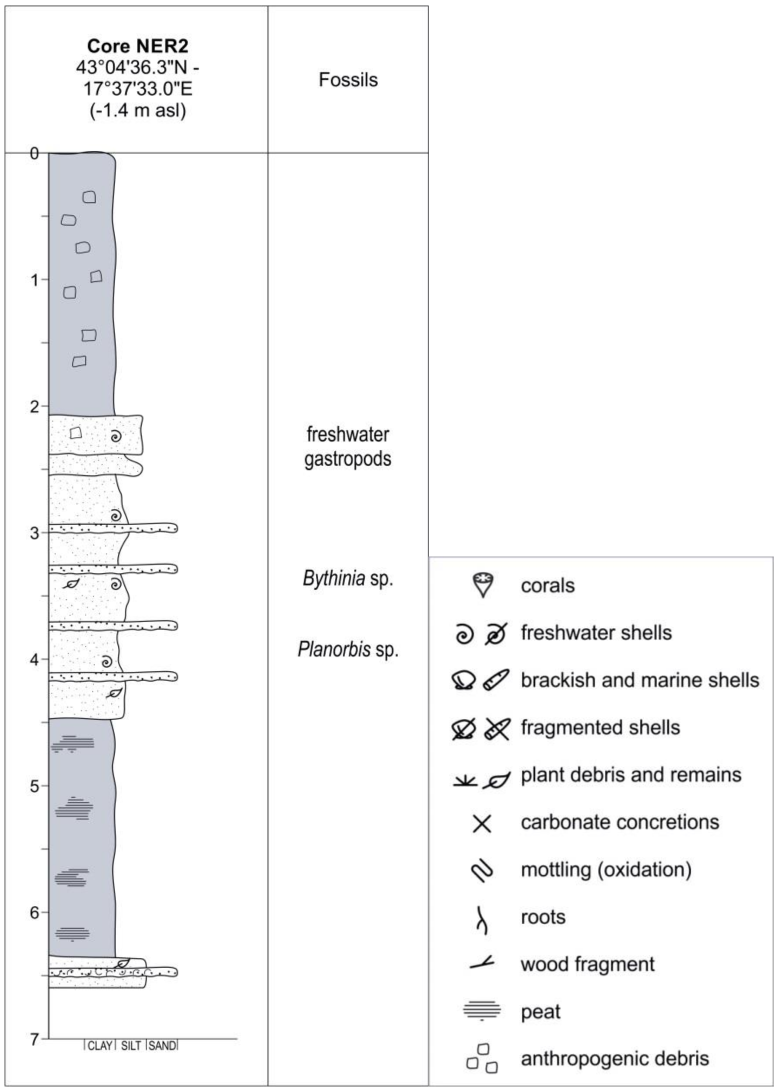

Figure 5.12. Sedimentological log of the core NER2.

Slika 5.12. Sedimentološki stup jezgre NER2.

Table 14: Field and laboratory description of the sediment core NER2

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	macrofossils
0.00 – 2.10	Clayey silt	Brownish-grey	-	Bricks and stone debris	Wood fragments, roots; shells fragments
2.10 – 2.30	Sandy silt	Yellowish-grey	-	Bricks and stone debris	Freshwater gastropod (*Limnea* sp.?)
2.30 – 2.55	Silt, sandy silt	Yellowish-grey	-	Partly laminated; mottling; transitional lower boundary	Shell fragments; *Cerastoderma* sp., *Mytlius* sp., gastropoda
2.55 – 3.20	Clayey sandy silt	Grey	-	Poorly laminated	Gastropod *Bythinia* sp; fragments of freshwater shells
3.20 – 4.45	Clayey sandy silt	Light grey, gley	-	Mottling, tough; lamination at the bottom	Plant fragments; *Planorbis* sp.
4.45 – 6.38	Clay and peat	Light grey	-	Organic and peaty; lamination partly visible	-
6.38 – 6.65	Sandy silt	Grey, slghtly green	-	-	Plant fragments

Field and laboratory description of two adjacent cores (NER3 and NER4), along with sedimentological and macro- and micro- paleontological analyses are presented together. Core NER3 was described and analysed in more detail (e.g. grain size analyses and calcimetry was performed only on the core NER3), considering that it is deeper as well as the fact that the stratigraphy of the core NER4 is similar to the core NER3.

The borehole is not perfectly perpendicular to the surface and some fragments coming from above layers may be present in the stratigraphy, in particular peaty ones. Both cores reached basement rock at the bottom.

Core NER3

The core NER3 was located at coordinates [42°59'52.4"N - 17°32'37.2"E] with ~0 m msl ground elevation (**Figure 4.2.**) and was 7.70 m long. In the first 1 m of the core, lots of plant remains and shell remains (most likely freshwater gastropoda; 2 fragments of *Cerastoderma* sp.) were present. At the depth of 1.33 m, one specimen of *Cerastoderma* sp. with closed valves was found. Generally, in the whole core, shell fragments were rare. At the bottom of this core, in the layer between 7.00 – 7.70 m, abundant fragments of the coral *Cladocora caespitosa* (Linnaeus, 1758) were found. (**Table 15; Figure 5.13., 5.14.**).

Core NER4

This borehole has been drilled 6.8 m southwards of NER3 at the coordinates (42°59'52.2"N - 17°32'37.1"E); with elevation 0.30 m above msl (**Figure 4.2.**) and was 6.80 m long. The core NER4 was located about 15 m from the slope of the hill. The head of the core was on a surface about 30 cm higher than the core NER3. At 2.20 m depth, a sheel of *Scrobicularia plana* (da Costa, 1778) had been found, with closed valves. Towards the bottom, the sandy fraction in NER4 was more abundant and coarser, than the same interval in the core NER3. At the depth between 5.8 m - 6.8 m, the core was characterized by the presence of large fragments of shells and corals.

Table 15: Field and laboratory description of the sediment core NER3

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	macrofossils
0.00 – 0.40	Organic silt, peaty silt	Brownish grey	-	Transitional lower boundary	Plant remains
0.40 – 0.95	Clayey silt	Light grey (gley)	-	-	Plant remains; gastropoda remains (*Hydrobia* sp.?); *Cerastoderma* sp., *Abra* sp.?
0.95 – 2.70	Clayey silt, coarse silt	Light grey (gley)	-	Transitional lower boundary; layering; *Cerastoderma* sp. with closed valves	Shell fragments; *Cerastoderma* sp., *Mytlius* sp., gastropoda
2.70 – 7.40	Coarse silt, fine sand	Grey	-	Alterations of silt and sand; 10% clay	Rare shells fragments; *Cerastoderma* sp.; scapopoda.
7.40 – 7.70	Clayey silt	Grey	-	Somewhere sandy; muscovite	Abundant fragments of *Cladocora coespitosa* Shell fragments

Sediments in the core NER3 were poorly sorted, with dominant silt fraction (50.4 – 71.1 %). Clay fraction ranged between 16.90 – 36.20 %, and sand fraction between 8.8 – 32.7 %. Gravel was represented very scares, between 0.0 and 4.3 % at the depth of 7.40 m. There was no obvious fining or coarsening trend. Carbonate share in the core NER3 ranged between 2.30 % at the depth of 0.3 m and 46.88 % at the depth of 2.0 m. Depths between 2.0 – 7.50 m showed similar share of carbonate content (42.19 – 46.88 %) (**Table 16.; Figure 5.13.**).

Table 16. Grain size distribution and carbonate share in the core NER3

Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	CaCO3 (%)
0.30-0.40	36.2	49.6	12.9	1.3	2.3
2.00-2.10	19.9	71.1	8.8	0.2	46.9
4.00-4.10	23.8	60.2	15.9	0.1	46.8
6.00-6.10	16.9	50.4	32.7	0.0	42.2
7.40-7.50	23.7	52.5	19.5	4.3	42.5

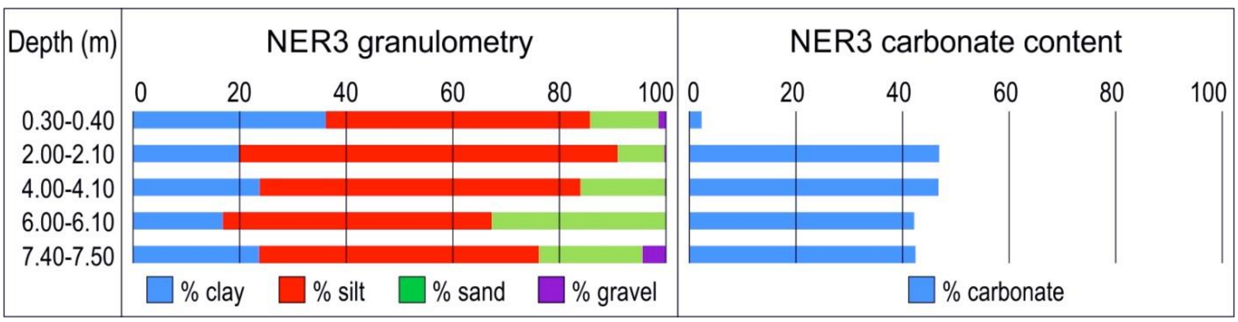

Figure 5.13. Grain size distribution and carbonate share of the core NER3

Slika 5.13. Raspodjela veličine zrna i udio karbonata u jezgri NER3.

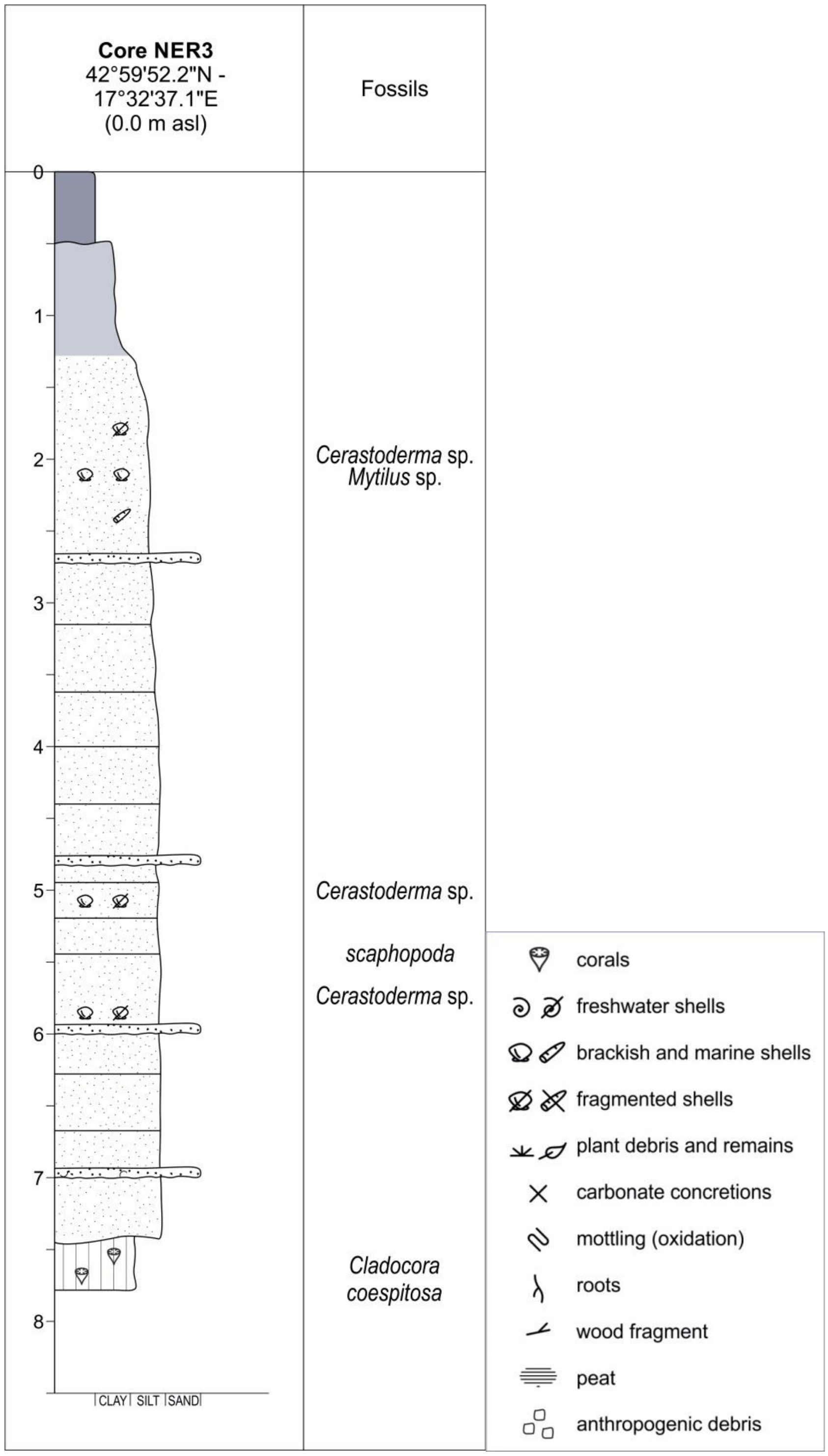

Figure 5.14. Sedimentological log of the core NER3.

Slika 5.14. Sedimentološki stup jezgre NER3.

Field and laboratory description of two adjacent cores (NER5 and NER6), along with sedimentological and macro- and micro- paleontological analyses and radiometric measurements are presented together. Core NER6 was described and analysed in more detail (e.g. grain size analyses and calcimetry was performed only on the core NER6), considering that it is deeper as well as the fact that the stratigraphy of the core NER5 is quite similar to the core NER6.

Core NER5

The core was 4.9 m long and located at coordinates [43°00'04.5"N - 17°34'04.7"E; **Figure 4.2.**; elevation 1.1 m above msl]. Recent anthropogenic landfill was present from surface down to ~ 1.50 m where the boundary was sharp. Between 1.50 m and 2.80 m, layers of organic clay with plant remains, and peat were present. Between 3.20 m and 3.56 m, layer of sandy silt with presence of plant remains and shell fragments was present. At 4.70 m core depth a fragment of *Fluviatilis* sp. was found, whereas a seed from the depth of 4.75 m of core depth was radiocarbon dated to 2241±22 years uncal BP (385-206 BC, 2σ calibration) (**Table 2**). At 4.90 m contact with the bedrock was reached (**Table 17; Figure 5.15.**).

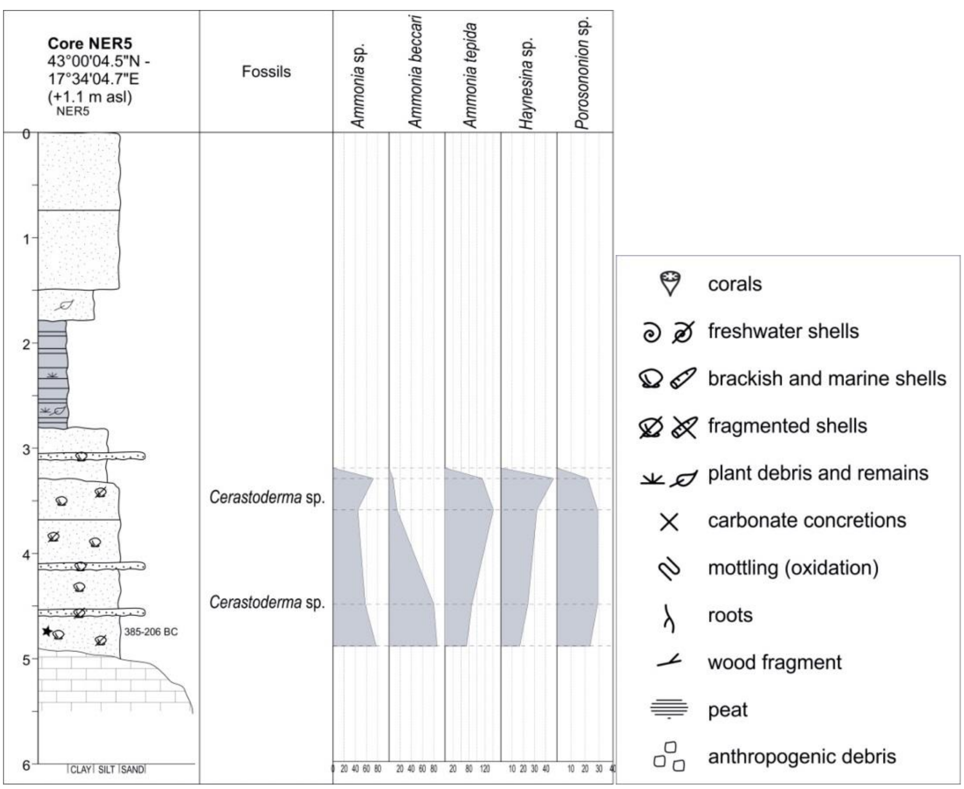

Figure 5.15. Sedimentological log of the core NER5 with most common foraminifera and molluscs.

Slika 5.15. Sedimentološki stup jezgre NER5 s najčešćim foraminiferama i mekušcima.

Table 17: Field and laboratorydescription of the sediment core NER5

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	Macrofossils
0.00 – 0.70	Clayey silt, clay	Brown	-	Recent anthropogenic landfill	-
0.70 – 1.50	Clayey silt	Brown	-	Recent anthropogenic landfill; slightly oxidised; rare Mn and Fe nodules; sharp lower boundary	-
1.50 – 1.80	Silty clay	Brown	-	Organic; peat	Plant remains
1.80 – 2.80	Clay	Brown	-	Alterations of peat and layers of dispersed organic black clay	Plant remains; roots of palustrine reeds
2.80 – 3.20	Clayey silt	Light brown	-	Sligtly organic; few layers of very fine sand;	Plant remains; roots of palustrine reeds
3.20 – 3.56	Sandy silt	Brown	-	Slightly organic	Plant remains; roots of palustrine reeds; shell fragments
3.56 – 4.90	Sandy silt, silty sand, clayey silt	Light grey	-	Cerastoderma with closed valves	Shell fragments; *Cerastoderma* sp. *Fluviatilis* sp.; seed

Core NER6

The core NER6 was 8.2 m long and extracted and coordinates [43°00'04.7"N - 17°34'05.0"E; elevation 0.9 m above msl; **Figure 4.2.**]. The core showed dominantly silty fraction (44.0 – 61.7 %) and sandy fraction (14.7 – 45.9 %). Gravel was significantly present in the shallowest sample at 2.50 m (34.9 %) while in the rest of the core showed low values (0.2 – 2.7 %). Clay share ranged between 6.30 m and 20.0 % **(Table 18; Figure 5.16.**). Carbonate content in the core NER6 ranged between 9.7 % at the depth of 2.5 m and maximum of 50.49 at the depth of 6.50 m. Other samples ranged between 43.80 – 45.86 % (**Table 18; Figure 5.16.**). A sample of peat at the depth of 3.22 m was radiocarbon dated to 1914±22 years uncal BP (30-132 AD). A macro - fragment of plant at 7.85 m of depth was radiocarbon dated to 2997±23 years uncal BP (1370-1126 BC) (**Table 2**). At 8.20 m bedrock was reached (**Table 19; Figure 5.17.**).

Table 18. Grain size distribution and carbonate share in the core NER6

Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	CaCO3 (%)
2.50-2.60	6.4	44.0	14.7	34.9	9.7
3.50-3.60	6.3	50.8	40.2	2.7	45.1
4.50-4.60	12.8	61.7	25.2	0.3	45.9
5.50-5.60	19.1	60.7	20.0	0.2	44.2
6.50-6.60	8.6	44.3	45.9	1.2	50.5
7.50-7.60	20.0	60.1	18.8	1.1	43.8

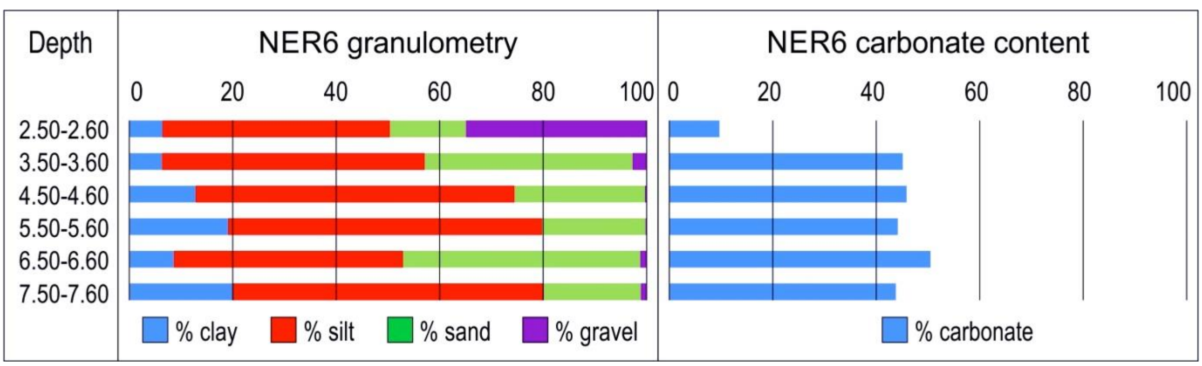

Figure 5.16. Grain size distribution and carbonate share of the core NER6

Slika 5.16. Raspodjela veličine zrna i udio karbonata u jezgri NER6.

Table 19: Field and laboratory description of the sediment core NER6

Depth (m)	Grain size (field assessment)	Color	Carbonate share (HCl reaction)	Structures	Macrofossils
0.00 – 2.00	Clayey silt	Grey	-	Recent anthropogenic landfill; scattered pebbles	-
2.00 – 3.35	Peat	Grey	-	Laminated peat; sharp lower boundary	Plant remains
3.35 – 3.60	Fine sand, silt	Grey	-	Slightly organic	Plant remains, palustrine reeds; shells of *Fluviatilis texturinarius*
3.60 – 3.95	Silt, fine sand	Grey	-	Alterations of peat and layers of dispersed organic black clay	Shell fragments; *Cerastoderma* sp., *Hydrobia* sp.; plant remains, roots
3.95 – 6.65	Clayey coarse silt, fine sand	Grey (2.5Y 4/1; 2.5Y 5/2)	-	Alterations of silt and sand; bioturbation at 4.12m; ;	Shells; *Hydrobia* sp., *Cerastoderma* sp., *Scrobicularia* sp.?; plant remains
6.65 – 8.20	Clayey coarse silt, fine sand	Grey (2.5Y 4/1; 2.5Y 5/2)	-	Abundance of shells; at 8.20m basement rock was reached	Shells; *Ostrea* sp., *Hydrobia* sp., *Cerastoderma* sp., *Scrobicularia* sp., *Abra* sp.; plant remains

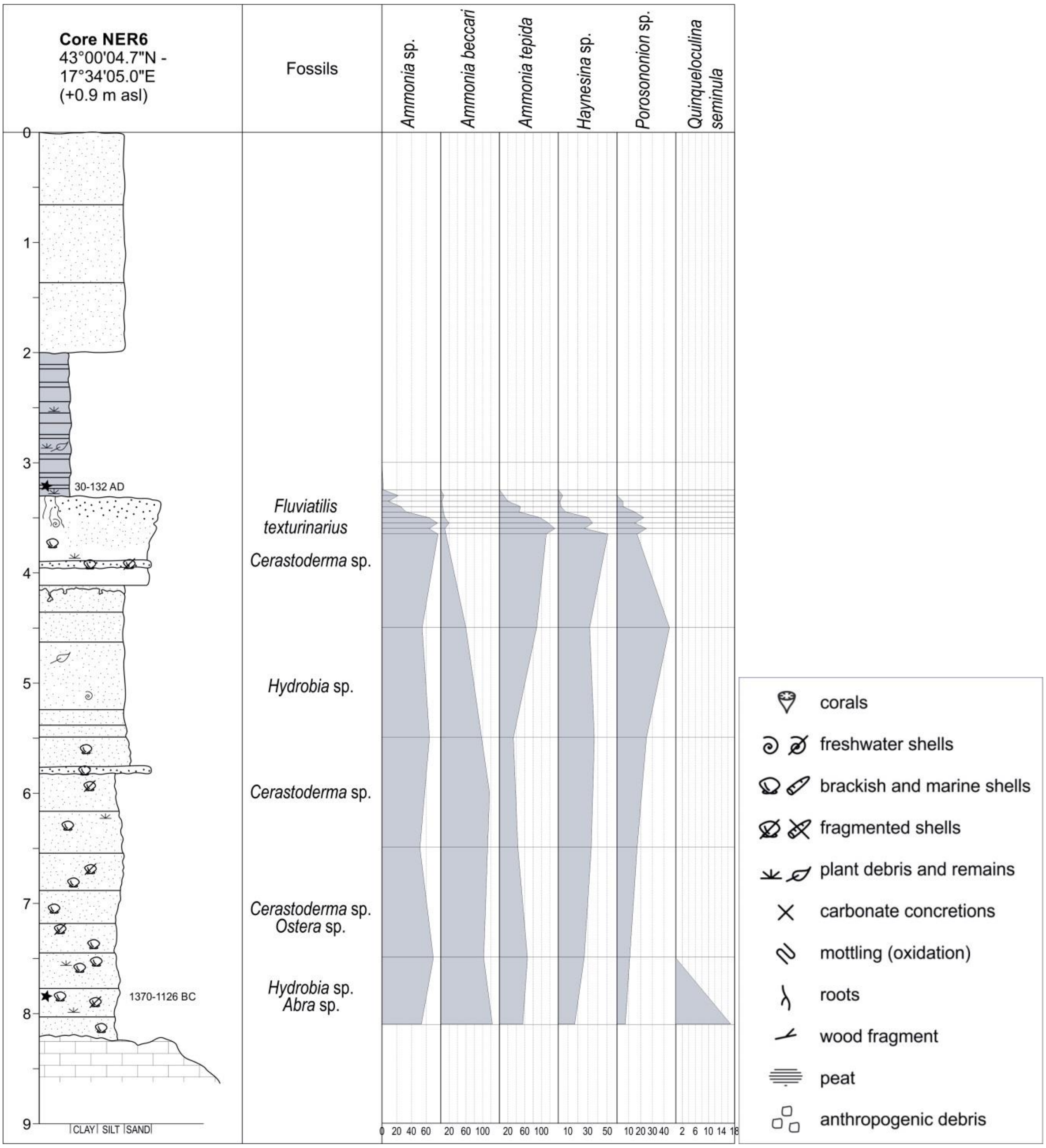

Figure 5.17. Sedimentological log of the core NER6 with most common foraminifera and molluscs.

Slika 5.17. Sedimentološki stup jezgre NER6 s najčešćim foraminiferama i mekušcima.

A total of 13 benthic foraminifera species were identified in the studied sediments of cores (**Appendix 8.a; 9.a**) with species richness varying from 1 - 13. The highest species diversity was found in the core NER6 at 8.10 -8.11 m interval, and in two intervals in the core NER5 at 3.60-3.61 m and 4.90-4.91 m. Among them dominated the representatives of suborder Rotaliina, *A. tepida*, *A. beccarii*, *Ammonia parkinsoniana* (d'Orbigny, 1839), *Ammoni*a sp., *Haynesina sp*. while *Porosononion* sp. showed somewhat greater abundance only in some intervals (**Appendix 8.a; 9.a**). The assamblages containing these foraminifera usually suggest brackish environments (Scott et al., 1991; Hayward & Hollis, 1994; Debenay et al., 2003, 2006; Rodriguez–Lazaro et al., 2013; Graca Camacho et al., 2015; Avnaim-Katav et al., 2016).

In the core NER6, the Shannon-Wiener, H(S) index ranged between 1.47 and 1.87, while Fisher α index ranged between 0.80 and 2.74 (in sample at the depth 8.10 m, **Appendix 9.b**). In the core NER5, altogether 10 species were identified; Shannon-Wiener index (**Appendix 8.b**) has values between 1.71 and 1.82, while Fisher α index ranged between 1.74 and maximum of 1.99. The Shannon-Wiener index showed values typical for estuarine environments (Murray, 2003), with H(S) varying from 1.6 to 1.8 (slightly greater NER6 core in interval 4.50-4.51 cm, and species richness between 1 and 7 (13 in NER6, interval 8.10-8.11 m; **Appendix 8.a,b; 9.a,b**).

Foraminifera predominated in middle and lower parts of the studied cores, in clayey silty sediments. The highest abundance exceeded 374 specimens/cm^3 sediments. Thus, the first major foraminiferal community shift in the two Neretva estuary cores was determined based on the presence/absence of foraminiferal species, as foraminifera were absent from the uppermost parts of both cores, namely in samples NER5_1-NER5_4 and NER6_1-NER6_3 (**Appendix 8.a; 9.a**).

Core NER120

The core NER120 was extracted at the coordinates [43°1'10'', 17°31'20''] and was 120 m long (**Figure 4.2.**). Detailed stratigraphy of the core was not described due to bad preservation of samples, but samples were taken for granulometry and calcimetry analyses.

Granulometry analyses were performed on 38 samples in the core NER120 (**Table 20**). Two samples (at the depth of 37.0 and 42.0 m) were 100 % gravel and were not analysed with wet sieving and sedigraph method. Results showed clearly two different parts of the core: shallower part between 0.0 – 28.0 m with finer sediment and deeper part between 30.0 – 119.20 m with coarser sediment (**Table 20; Figure 5.18.**).

In the shallower part of the core, sediment was mostly mud, sandy mud, and gravelly sandy mud, with higher share of sand in the first 10 m (between 11.9 % – 48.5 %). Silt was most dominant fraction in samples (34.0 % – 74.9 %), while clay share ranged between 9.5 % – 36.9 %. Gravel was significantly present only at the depth of 0.0 m and 1.0 m with 21.8 % and 9.7 % respectively and mostly composed of antropogenic particles (**Table 20; Figure 5.18.**).

In the deeper part of the core, sediment was mostly composed of sand and gravel fraction. Sand fraction ranged between 0 % at the depth of 37.0 and 42.0 m and 69.8 % at the depth of 34 m. Highest share of gravel was 100% at the depth of 37.0 and 42.0 m, and lowest at the depth of 29.5 m (34 %). This coarser fraction was composed entirely of lithogenous particles. Clay and silt fraction in this part of the core did not exceed 4.4 % and 17.3 % respectively (**Table 20; Figure 5.18.**).

Twelve samples belonged to the textural group of sandy gravel, 5 samples to the group of gravel, 4 samples mudy sandy gravel, 8 samples mud, 6 samples sandy mud, 2 samples gravelly mud and 1 sample belonged to the textural group of gravelly sand.

Nineteen samples in the samples from the depth 0.0 – 30.0 m were analysed for carbonate share. Carbonate share ranged between 31.3 % at the depth of 16.0 m and 53.68 % at the depth of 22.0 m. Exception was sample at the depth of 30.0 m with high share of carbonate (85.04 %) (**Table 20; Figure 5.18.**).

Sedimentological log based on grain size distruibution is presented in the figure 5.19.

Table 20. Granulometry of samples in the core NER120 (Neretva River delta plain)

Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	CaCO3 (%)
0.00 - 0.10	9.5	34	34.8	21.8	51.3
0.40 - 0.50	16.1	50.4	33.3	0.2	42.1
0.50 - 0.60	11.9	39.9	48	0.2	44.5
1.00 - 1.10	14.4	38.4	37.5	9.7	49.7
2.00 - 2.10	13.2	43.1	43.4	0.3	41.6
4.00 - 4.10	10.7	39.8	48.5	1	47.6
6.00 - 6.10	15.2	61.9	22.9	0	41.1
8.00 - 8.10	13.7	63.2	22.8	0.3	39.5
10.00 - 10.10	20.2	67.8	11.9	0.1	34.6
12.00 - 12.10	22.9	74.9	2.1	0.1	41.4
14.00 - 14.10	31.3	68	0.7	0	38.4
16.00 - 16.10	32.9	63.8	3.2	0.1	31.3
18.00 - 18.10	36.9	61.8	1.3	0	35.3
20.00 - 20.10	33.4	63.9	1.4	0.3	39.0
22.00 - 22.10	31.6	66.9	1.2	0.3	53.7
24.00 - 24.10	33.1	52.8	9.9	4.3	53.0
26.00 - 26.10	32.1	64.7	2.5	0.7	46.3
28.00 - 28.10	29.1	70	0.6	0.3	47.1
30.00 - 30.10	3.1	11.6	43.2	42.1	85.0
32.00 - 32.20	2.9	7.5	48.3	41.3	-
34.00 - 34.20	0.1	0.6	69.8	29.5	-
37.00 - 37.20	0	0	0	100	-
42.00 - 42.20	0	0	0	100	-
48.00 - 48.20	2.1	3.3	22.6	72	-
56.00 - 56.20	0	0.1	3.8	96.1	-
58.00 - 58.20	0.9	4.4	50	44.7	-
64.00 - 64.20	0.3	1.6	51.6	46.5	-
69.00 - 69.20	0.6	3.3	54.6	41.5	-
74.00 - 74.20	0.6	4	49.9	45.5	-
79.00 - 79.20	0.7	3.6	51.7	44	-
84.00 - 84.20	0.2	0.8	51	48	-
89.00 - 89.20	0.3	1.6	62.1	33.9	-
93.00 - 93.20	0.3	1.7	45.5	52.4	-
99.00 - 99.20	0.4	1.7	33.3	64.6	-
104.00 - 104.20	4.4	17.3	29.6	48.7	-
109.00 - 109.20	0.3	1.4	29.2	69.1	-
114.00 - 114.20	0.6	2.5	45.6	51.3	-
119.00 - 119.20	0.1	1	32.3	66.6	-

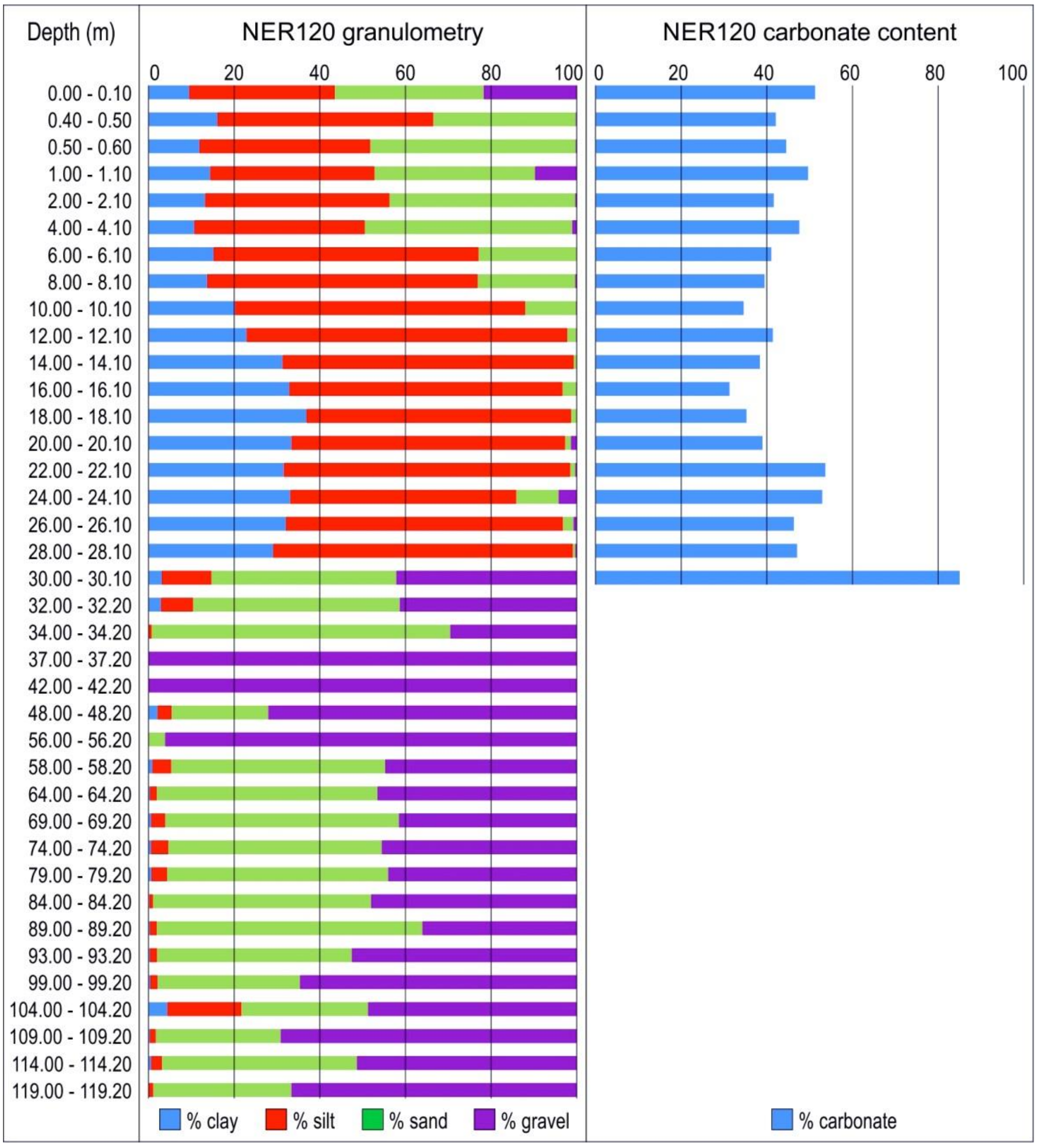

Figure 5.18. Grain size distribution and carbonate share in the core NER120.

Slika 5.18. Raspodjela veličine zrna i udio karbonata u jezgri NER120.

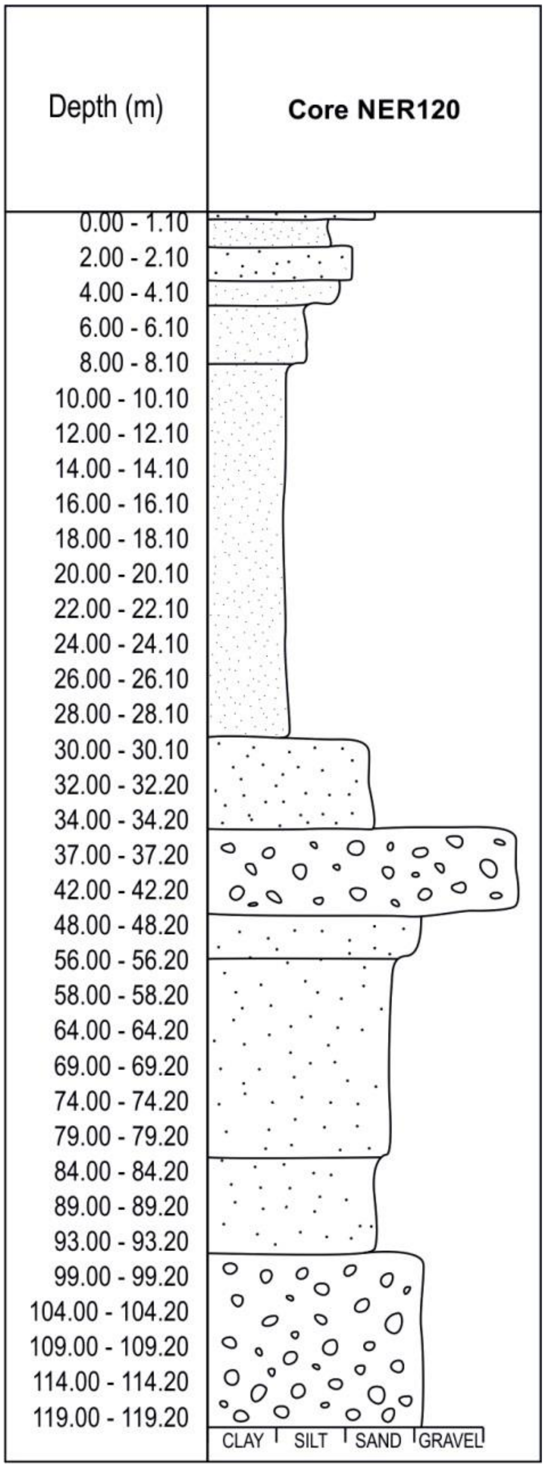

Figure 5.19. Sedimentological log of the core NER120

Slika 5.19. Sedimentološki stup jezgre NER120.

Core NER20

The core NER20 was located at the coordinates [43° 01' 19", 17° 38' 00"] and was 18 m long (**Figure 4.2.**).

The grain size was studied in 14 samples. The last two samples (at the depth 16.0 and 18.0 m) were dominantly gravel fraction (73.4 % and 52.4 % respectively). In shallower samples, gravel was in range between 0.0 % and 3.6 %. Samples between 1.0 m and 14.0 m were mostly silty sand and sandy silt, with highest share of sand at the depth of 14.0 m (86.4 %) and highest share of silt at the depth of 4.0 m (76.8 %). Clay was significantly present in the shallowest three samples, at the depths of 0.0 m, 0.5 m and 1.0 m, with maximum share of 15.8 %. There was an eveident coarsening downward trend (**Table 21; Figure 5.20.**). Sedimetological log based on grain size distribution is presented in the **figure 5.21**.

Table 21. Granulometry of samples in the core NER20 (Neretva River delta plain)

Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)
0.00-0.10	34.6	43.2	21.7	0.6
0.50-0.60	43.1	49.0	7.9	0.0
1.00-1.10	26.3	42.6	29.3	1.8
1.90-2.00	6.3	31.6	61.7	0.3
2.00-2.10	9.1	40.5	50.3	0.1
4.00-4.10	15.8	76.8	6.9	0.5
5.00-5.10	7.4	37.6	54.8	0.2
6.00-6.10	0.5	27.6	67.3	0.0
8.00-8.10	13.2	67.9	18.6	0.2
10.00-10.10	10.7	53.4	35.8	0.2
12.00-12.10	12.3	53.6	33.9	0.2
14.00-14.10	4.4	5.7	86.4	3.6
16.00-16.20	2.0	4.9	19.7	73.4
18.00-18.20	3.6	10.2	33.8	52.4

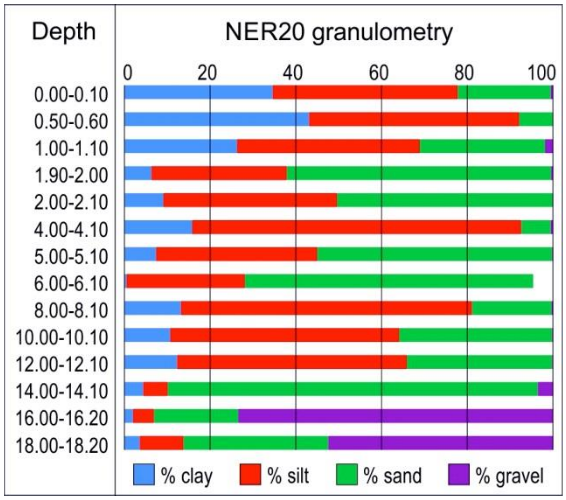

Figure 5.20.. Grain size distribution and carbonate share of the core NER20

Slika 5.20. Raspodjela veličine zrna i udio karbonata u jezgri NER20.

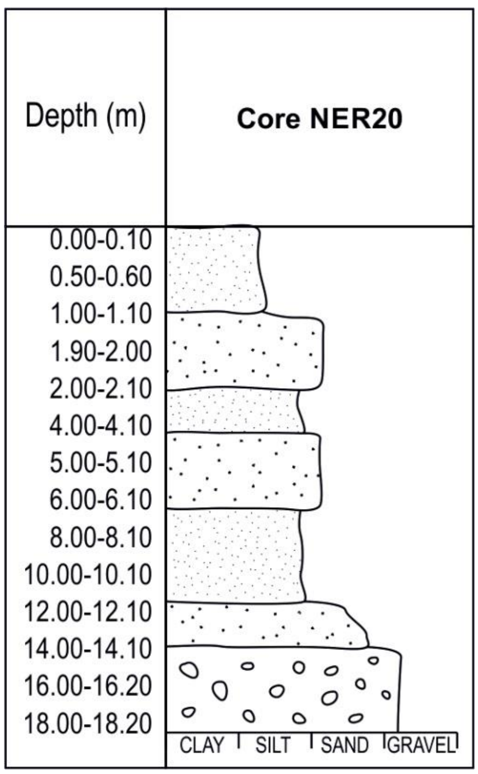

Figure 5.21. Sedimentological log of the core NER20

Slika 5.21. Sedimentološki stup jezgre NER20.

Core P1

The core P1 was located in Malostonski Channel, at the sea bottom of ~ 25 m below msl, and was 96 m long (**Figure 4.2.**). Results of granulometry, calcimetry and mineralogical content from this core were already published in Felja et al. (2016) and are presented below. For the purpose of the Pelješac Bridge construction, several research boreholes were drilled in the Malostonski Channel (Radić et al., 2009). These boreholes revealed sediment thickness varying between 12 and 112 m to the basement rock (Buljan et al., 2012), with flat and muddy seabed, average depth of sea 28 m, and carbonate rock outcrops absent (Leder, 2004).

Grain size distribution, carbonate share, and sorting are shown in Table 22. Based on the Folk (1954) grain-size classification, sediment samples were categorized as muds. Twenty-three samples were classified as slightly gravelly muds, 12 as slightly gravelly sandy muds, 5 samples as muds, and 3 as sandy muds. The average share of gravel was 0.67 %, with the maximum of 4.6 % (mostly composed of various gastropoda and bivalvia shell fragments). Sand fraction showed mean of 8.34 %, with the maximum of 37.0 % at the depth of 96 m. Large portion of sand fraction was composed of ostracod shells. Coarser fractions were more abundant in the lowermost part of the core. Silt and clay fractions varied considerably along the core depth. The average share of silt was 53.1%, with the maximum of 80.9% in the layer at the depth of 16 m and the minimum of 29.6% at the depth of 66 m. There was a considerable difference in clay share along the core (7.0–64.3% of clay, with mean of 37.9%). The layers with the highest share of clay were at the depth of 32 m (61.3%), 64 m (61%), 68 m (60.8%), 70 m (64.3%), and 88 m (61.4%). Generally, the highest shares of clay fraction were present at the depths between 60 and 90 m (46.6–64.3% of clay) (Fig.). All samples were poorly or very poorly sorted (**Table 22; Figure 5.22.**). Carbonate share in samples varied between 1% (at depths 74 m and 76 m) and 95% (10 m), with mean of 40.5% (**Table 22**) and several cycles of increase and sharp decrease in carbonate share could be distinguished. The uppermost 8 m of the core showed carbonate share of approximately 40%, and below it, a sharp increaseup to 95% could be observed in sample at 10 m. Below that, gradual decrease in carbonate share occurred down to 26m(~ 50%) followed by sharp decrease to only 7% of carbonate share at 28 m. This was followed by the sharp increase in share up to 85% in sample at 32 m. Few similar cycle patterns could be observed down to 60 m, below which very low carbonate shares (1–16%) were found. The last three samples (at 90, 94, and 96 m) contained between 27% and 58% of carbonates (**Table 22; Figure 5.22.**). Results of mineralogical content are presented in appendix 9.

Sedimentological log based on grain size distribution is presented in **Figure 5.23** together with fossils of gastropoda that were recognized in the core (*e.g.Viviparus* sp. at depths 8, 12, 14, 18, 32, 34, 40, 42 m; *Turritella* sp. at depths of 2 m; scaphopoda at 4 m).

Table 22. Granulometry and carbonate share in the core P1

Depth	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Carbonate (%)
2.0-2.1	36	59.4	3.7	0.9	36
4.0-4.1	36.5	61.7	1.7	0.1	38
6.0-6.1	42.6	54.8	2.2	0.4	43
8.0-8.1	46.3	50.7	2.7	0.3	44
10.0-10.1	16.2	69.7	13.9	0.2	95
12.0-12.1	13.4	72.3	13.9	0.4	88
14.0-14.1	7	78.5	13.8	0.7	83
16.0-16.1	15.8	80.9	3.2	0.1	83
18.0-18.1	9.9	70	19.8	0.3	72
20.0-20.1	31.6	65.7	2.3	0.4	48
22.0-22.1	24.8	73.6	1.6	0	56
24.0-24.1	30.3	67.6	2.1	0	52
26.0-26.1	44.1	52.4	3.5	0	48
28.0-28.1	61.3	32.5	4.9	1.3	7
32.0-32.1	15.1	72.6	12	0.3	85
34.0-34.1	14.9	69	15.2	0.9	89
36.0-36.1	17	68.6	14.1	0.3	86
38.0-38.1	36.1	59.5	3.2	1.2	44
40.0-40.1	35	56.6	3.8	4.6	50
42.0-42.1	17.7	71.7	11.1	0.1	83
44.0-44.1	28.1	62.4	8.4	1.1	68
46.0-46.1	41.1	56.2	2.2	0.5	51
48.0-48.1	31.1	63.1	5.8	0	49
50.0-50.1	53.4	34	10.3	2.3	15
52.0-52.1	43.2	46.3	10.5	0	16
54.0-54.1	26.4	54.5	17.4	1.7	82
56.0-56.1	20.8	71.7	7.1	0.2	51
58.0-58.1	32	65.1	2.8	0.1	52
60.3-60.4	51.6	39.6	7	1.8	8
62.0-62.1	61	34.7	4.2	0.1	5
64.0-64.1	50.4	47.9	1.7	0	4
66.0-66.1	60.8	29.6	7.7	1.9	13
68.0-68.1	51.4	36.5	10.1	2	16
70.0-70.1	64.3	30.8	4.1	0.8	5
72.0-72.1	47.4	50.7	1.9	0	3
74.0-74.1	48.8	46.2	5	0	1
76.0-76.1	49.1	34.9	16	0	1
78.0-78.1	46.7	30.7	20.4	2.2	11
82.0-82.1	57.4	36.8	5.4	0.4	7
84.0-84.1	54.4	41.2	4	0.4	6
86.0-86.1	54.3	38.6	7	0.1	4
88.0-88.1	61.4	30.8	5.7	2.1	11
90.0-90.1	46.6	49.1	4.3	0	26
94.0-94.1	42.1	37.3	20.6	0	57
96.0-96.1	30.4	32.6	37	0	30

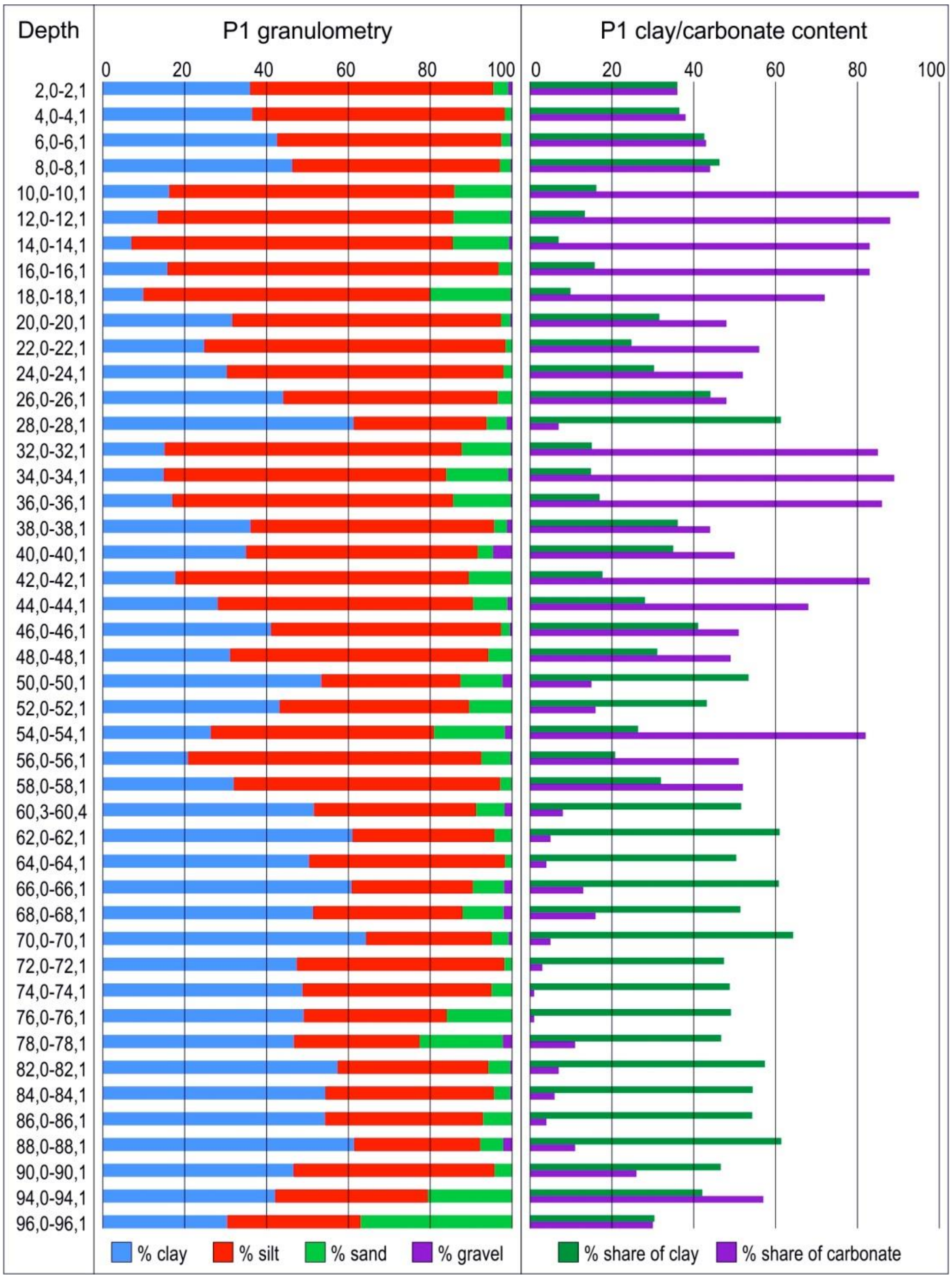

Figure 5.22. Grain size distribution and clay/carbonate share of the core P1 (Malostonski Channel).

Slika 5.22. Raspodjela veličine zrna i udio karbonata u jezgri P1 (Malostonski kanal).

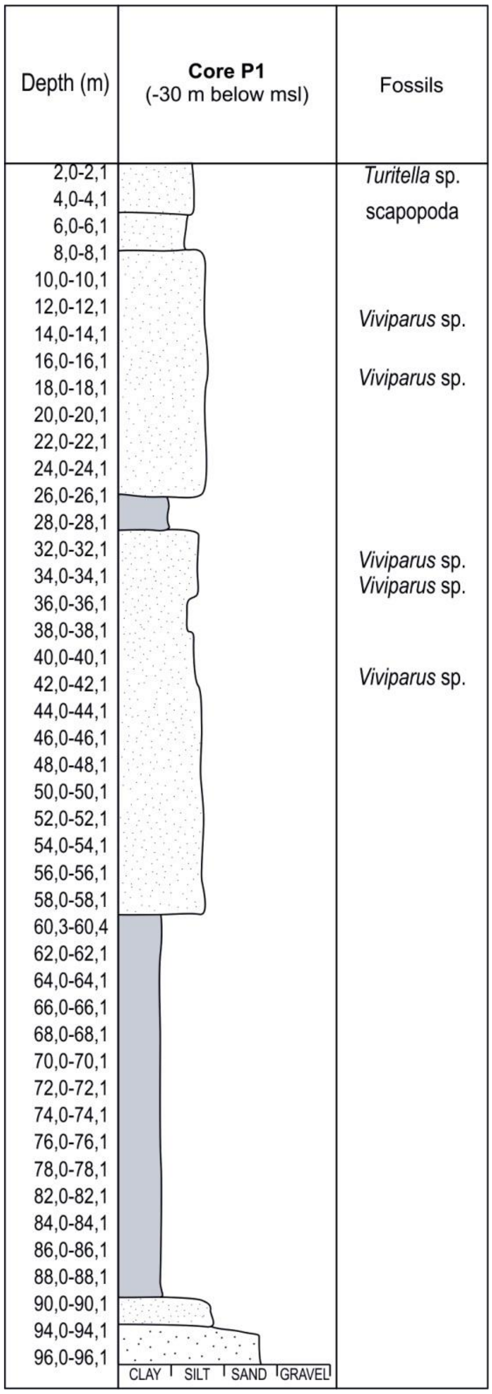

Figure 5.23. Sedimentological log of the core P1.

Slika 5.23. Sedimentološki stup jezgre P1.

6. DISCUSSION

6.1. DEPOSITIONAL ENVIRONMENTS RECORDED IN THE MIRNA RIVER DELTA PLAIN CORES

Recent depositional environment in the in the terminal tract of the Mirna River are mostly deltaic alluvial plain, salt/brackish marsh in the proximity of the river mouth, and small portion under the sea, that can be defined as shallow inner/central estuarine environment.

Common feature of all cores drilled in the Mirna River delta plain was their generally fine grained character. All cores were composed completely of mud, more precisely interchanges of silty clay and clayey silt, with variable share of silt and clay (**Tables 1; 3-11**). Sand particles (very fine sand and fine sand) were rare and biogenous in origin (composed of foraminifera tests and ostracod shells), and gravel particles very rare (shell remains of freshwater and marine bivalvia and gastropoda, carbonate concretions and some plant remains *e.g.* wood fragments).

Based on above mentioned characteristics of deposits and fossil assemblages in the cores, the following environments were described:

A – alluvial/deltaic environments: alluvial plain (Aa); freshwater swamp (Ab);

B – transitional/brackish environments: brackish/salt marsh (Ba), inner estuary (Bb);

E – central/outer estuary (E)

6.1.1. Alluvial/deltaic environments (Alluvial plain (Aa)/freshwater swamp(Ab))

In the lower sector of the Mirna valley, alluvial/deltaic deposits crop out extensively and generally form the present surface and the topmost subsoil (down to several meters). They consist of homogeneous silty and clayey sediments (muds), without visible lamination or other depositional structures, except for planar bedding. Roots were rather common and their diameter ranged from 1 to 10 mm, whereas the macropalaeontological content consisted only of fragments of freshwater snails (*pulmonata*), which were generally not abundant. These deposits were oxidized and partly affected by pedogenesis up to several metres, from the ground surface down to the top of the water table. Mottling (in the depths from the surface down to ~2.5 m) with a brown-yellowish and reddish colour (10YR 6/8, 10YR 5/6, 10YR 5/8, 10YR 5/4, 10YR 4/6,) and, between 2 and 3.5 m, the presence of calcium carbonate concretions, both soft and hard (in the cores M2 and M5 concretions were present even down to ~ 7 m below the surface), suggest much stronger fluvial influence and alluvial deposition in this proximal part of the valley. Concretions were related to the leaching of carbonate from upper horizons and re-deposition in the lower ones. Their width was between 1 - 10 mm and this small dimension was likely to be related to the short time (*i.e.* few centuries) that has elapsed since the deposition of the alluvial parent material or before their burial by younger sediments (Retallack, 1990).

In the investigated area, the deposits interpreted as freshwater facies were mostly without foraminifera, but in the basal portion of core M3, a very small number of specimens of *Ammonia beccarii*, *Trochammina inflata* and *Haynesina sp*. were found (Felja et al., 2015). Their occurrence could be related to some transport processes from nearby brackish transitional environments or from the reworking of slightly older lagoon sediments. Considering the location of core M3 which, according to historical sources, in the last millennium was very close to the Mirna channel, there could be another explanation. Due to the low-lying setting of the lower valley and the slightly pensile position of the Mirna channel, it is possible that floods boosted by extremely high tides (the so-called *acqua alta*) periodically transported brackish or marine microfauna landwards far from the river mouth (Felja et al., 2015). Before the dyke construction in the 20th century, similar episodes were likely occuring along the last few kilometres of the valley (Santin, 2013).

The distinction of different alluvial facies is normally strongly connected to grain-size diversity, in particular to the occurrence of coarser sediments in the fluvial channel or in its proximity (*e.g.* Miall, 1996). However in the lower valley of the Mirna River the late-Holocene deposits consist only of mixtures of clays and silts, while sands are almost completely lacking, even at a few metres distance from the active channel. This particular characteristic is a limit to the possible differentiation of alluvial facies and is mainly related to the strong presence of flysch formation in the catchment that consequently feeds the fluvial system almost exclusively with fine-grained particles. No evidence of channels or natural levee deposits was found in the cores. It is likely that in the investigated area, even the channel facies was composed of silts and clayey silts while, possibly, some slightly coarser elements (*i.e.* sand) were present, but as already explained, only as the basal lag, due to the fact that fine-grained marls dominate in the exposed flysch sequences in the Mirna River catchment (Felja et al., 2015). Thus the Late-Holocene stratigraphy of the cores was characterized by facies of the floodplain and alluvial swamp. The latter was marked by the occurrence of organic-rich and peaty layers where plant macroremains were common or abundant. Seeds and fragments of leaves were also present. The alluvial swamp facies was clearly recorded in core M2 between 3.95–5.20 m, while it was not documented in other cores.

Alluvial facies were not recognized in the cores M7 and M8 (salt marsh environment), and were recognized deepest in the core M5 (down to 7 m) and M3 down to 9 m (possibly deeper, but maximum depth of the core was 9 m).

6.1.2. Transitional environments (Brackish/salt marsh(Ba)/Inner estuary (Bb))

The depositional environments related to brackish waters were generally marked in the core by the presence of shells of molluscs. In particular the occurrence of *Cerastoderma glaucum* and eventually the association with *Loripes* sp., and *Bittium* sp. generally characterized the brackish/hyposaline marsh (Ba) and the inner estuarine facies (Bb) which are dominantly under fluvial influence (and in the case of karstic environment also under influence of freshwater springs), and partly under marine influence. Sediments deposited in these facies were not distinguishable from each other at the macroscopic scale and the lithology in both cases comprised grey and greenish muds, with soft consistency, with a variable degree of bioturbation and the presence of millimetre sized plant debris.

The brackish/hyposaline marshes and marginal environments were strongly dominated by *A. tepida* and *A. beccari,* and secondarily, by *Haynesina* sp. and *Ammonia* sp. (Murray, 1991, 2006; Albani et al., 2007; Amorosi et al., 2004, 2005). In the core M1, such an assemblage was present almost from the surface down to 4.0 m and in M2 between 5.20–7.85 m. These intervals were characterized by low values of the Fisher-α index (**Appendix 2b, 3b**) These data suggest that sedimentation took place in brackish swamp or ponds on tidal flat, with the occasional influx of freshwater during the Mirna River floods.

Dominance of foraminifera species in sediment, such are *Ammonia* spp., *Haynesina* sp. and *Porosononion* sp., first occurrences of *Elphidium* spp. and miliolids (*e.g. Q. seminula*) in the cores (*e.g.* intervals 5.0–6.35 m in M1, 8.20–9.75 m in M2, 7.40 – 8.50 m in the core M5; **Appendix 2-7**) suggest that deposition occurred in the inner estuary environments (Bb). *Elphidium* spp. and miliolids are considered as pioneer species (Vaniček et al., 2000; Debenay et al., 2001) and their presence in sediment suggested environmental changes towards marine conditions (Murray, 2006). Somewhat higher values of Fisher-α indices and a greater number of species (**Appendix 2-7**), but still low values, are in accordance with such a hypothesis.

Although foraminiferal community is similar to those of the northern Adriatic lagoons (Venice, Marano and the Grado lagoons, Albani et al., 2007; Melis & Covelli, 2013), some differences in the composition of foraminifera assemblages were observed in this study. In areas where salinity fluctuates, opportunistic and pioneer species prevail. For example, foraminiferal studies of sediments from the Northern Adriatic, confirm that species *A. beccarii* dominate in very-shallow water marginal environments, where larger nutrient inputs periodically lead to oxygen deficiency (Donnici et al., 2002).

Trochammina inflata and some other agglutinated foraminifera outnumber other foraminiferal species in salt marsh assemblages (Scott & Medioli, 1978; Amorosi et al., 2004; Albani et al., 2007). However, typical salt marsh assamblages were not found in the cores. In the analyses performed in the cores M1 and M2 earlier (Felja et al., 2015), somewhat higher abundance of *T. inflata* in some levels of the cores M1 and M2 was observed in the fraction 63 µm, but other typical salt marsh agglutinated species were absent so these layers could not be recognised as typical salt marsh, but rather brackish marsh.

The core M7 consisted of few sandy layers, which were probably related to the delivery of the sandy sediments from the shallow sea during storm events, considering that sandy layers were not found anywhere in other cores.

Considering that most of the investigated sediments were related to brackish waters, further analysis of ostracoda and diatomea assemblages could probably help in discriminating the brackish environments (hyposaline swamp/inner estuary/lagoon).

6.1.3. Central/Outer estuarine environment (E)

The deep parts of the cores M1 and M2 were characterized by the presence of grey and greenish grey muds with soft to normal consistency and the widespread presence of laminated intervals. The laminae were millimetres thick and could be slightly enriched in organic matter, sometimes evidenced by the concentration of plant and wood debris. Moreover, species like *Cerithium* sp., *Nuculana* sp. and *Mytilus* sp. have been observed, indicating a relatively higher salinity and deposition in the open estuarine environments. Other cores did not reach deposits of this depositional environment (except the core MIR1).

The foraminiferal assemblages found in these samples also suggested deposition in central estuarine environment, where the marine influence is stronger. While the proportion of *Porosononion* sp. and *Haynesina* sp. specimens decreased, miliolids (*Q. seminula* in particular*)* and *Elphidium* spp. increased indicating marine conditions (Murray, 2006). This was evident in intervals 7.40 – 8.00 m in core M1 and 10.50 – 13.00 m in core M2 (**Figures 5.1** and **5.2.; Appendix 2-7**). Somewhat higher values of the Fisher-α indices in these intervals (*e.g.* 4.369 at the depth of 7.95 m in the core M1 and 3.672 at the depth of 12.20 m in the core M2) support this conclusions (**Appendix 2-7**). Assemblages were characterized by greater species richness, greater values of the Shannon-Wiener index (**Appendix 2-7**) and greater abundance of miliolids and rotaliids. The presence of infaunal species, *e.g. Brizalina* sp., despite their low number, indicated that, at least in the near bottom, normal marine conditions prevailed which suggested an central/outer estuary environment. In the deeper parts of the core MIR1 (down to 27 m below surface), shells of *Turitella* sp., *Ostrea* sp. and scaphopoda (**Table 10**) indicate stabile marine conditions and an outer estuarine environments.

All these data suggest a stratified central/outer estuarine environment in the geomorphological setting of the valley protected from sea-storms and waves, offered by the former Mirna bay. These facies were interpreted as subtidal central/outer estuarine environment, influenced by freshwater inputs related to Mirna River influence. The lamination was probably induced by the fluvial floods, which caused sedimentary pulses rich in vegetation and wood remains to the river mouth. A particular and local condition is represented by the additional influx of fresh water along the final tract of the Mirna River by large karstic springs, such as the Gradole spring (**Figure 6.1.**). Due to the large hydrogeological catchment feeding the Gradole spring (113 km^2) it is characterized by a fairly uniform discharge (the ratio of minimum and maximum discharge is only 1:20) not really affected by short meteoric-climatic periods (Magdalenić et al., 1995). In the protected environment of Mirna Bay, the fluvial and karstic freshwater probably induced the occurrence of a highly stratified/estuarine environment even in the area in front of the mouth of the Mirna River, where, in a different geomorphological setting with an open coast, a marine fauna would be generally present. Moreover, as discussed for the continental facies, and for the macrofossil associations of the brackish and marine environments, the lack of sand and coarser sediments could partly limit in the Mirna valley the application of the mollusc associations as they have been generally defined in the Mediterranean (*e.g.* Peres & Picard, 1964).

Despite grain-size uniformity through the cores, the combined use of textural sedimentological, macro- and micropalaeontological characteristics allowed the recognition of different depositional environments and the reconstruction of their longitudinal and vertical distribution, which is schematically shown in the **figures 6.1.** and **6.2.**

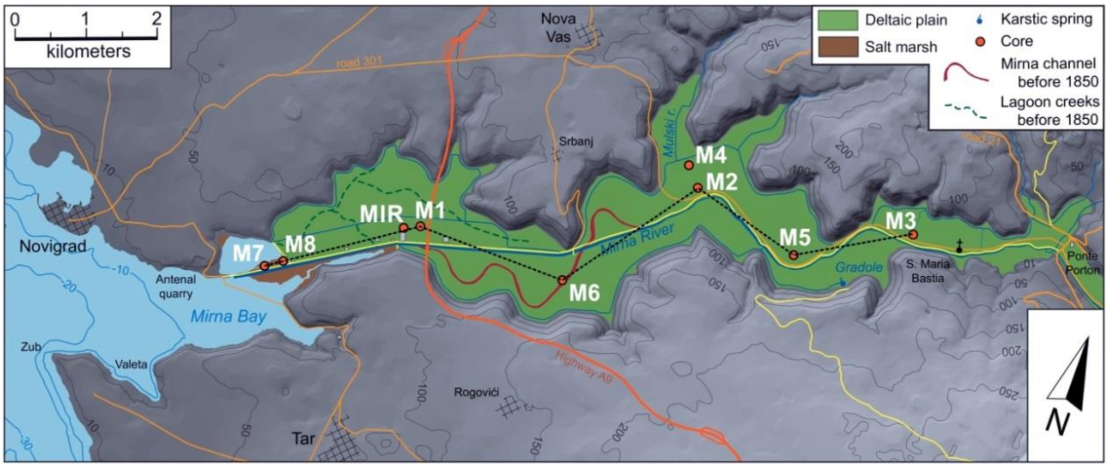

Figure 6.1. Profile lines of the 7 cores in Mirna River delta plain.

Slika 6.1. Linija profila 7 jezgri iz deltne ravnice rijeke Mirne.

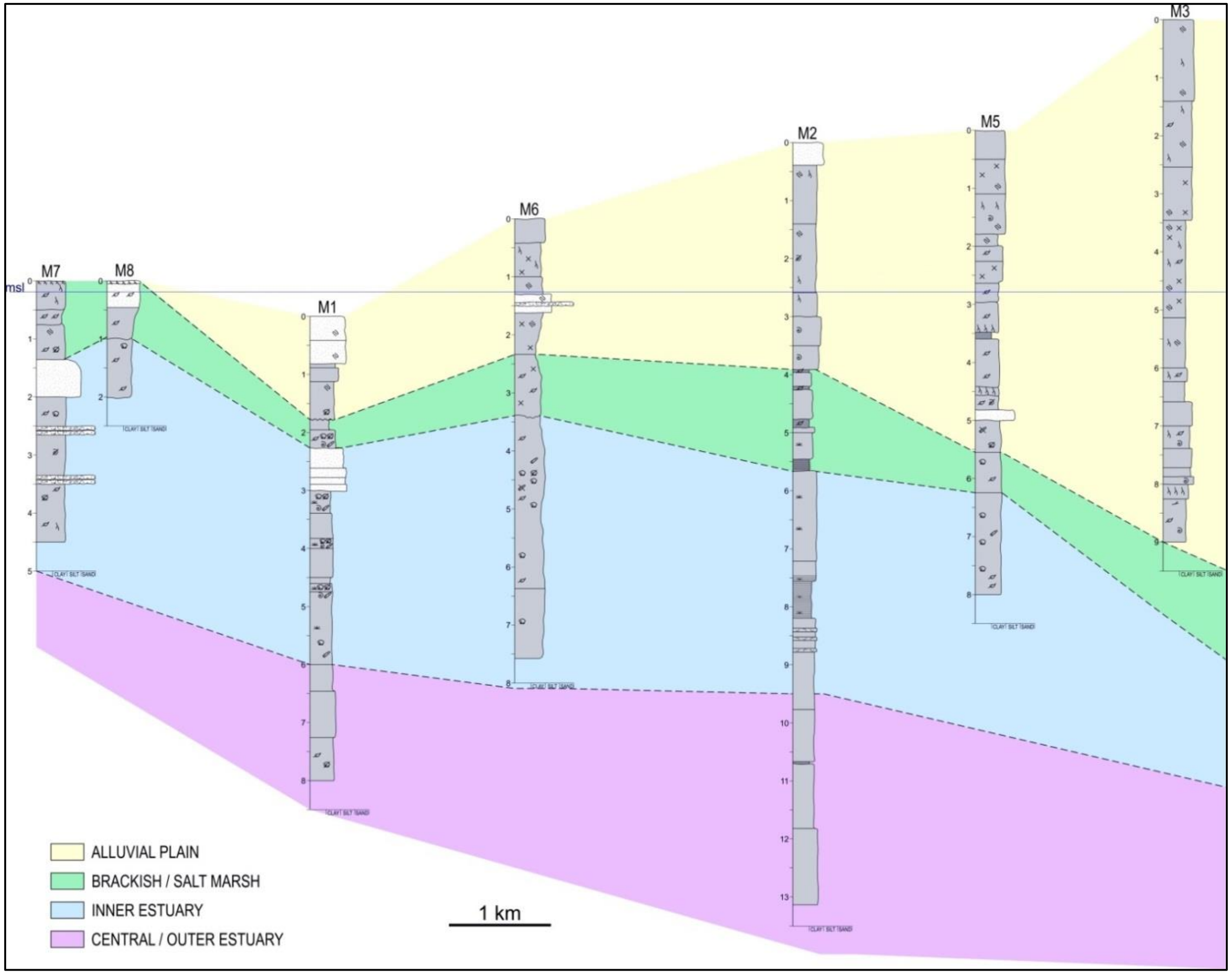

Figure 6.2. Shematic reconstructions of depositional environments along the longitudinal profile in the Mirna River delta plain recorded in the 7 sediment cores (M1, M2, M3, M5, M6, M7, M8).

Slika 6.2. Shematska rekonstrukcija taložnih okoliša kroz longitudinalni profil u deltnoj ravnici rijeke Mirne.

6.2. EVOLUTION OF THE MIRNA RIVER ESTUARY DURING LATE PLEISTOCENE AND HOLOCENE

The evolution of the Mirna River mouth based on the descriptions of the three cores (M1 – M3) was already presented in Felja et al., 2015, therefore below is the overview of that description complemented with results, obtained from the cores M4 – M8 and MIR1.

From the core M3 to M1 there is an elevation difference of approximately 5 m, but the gradient is ~ 1.0‰ between M3 and M2 and even less between cores M2 and M1. The occurrence of areas below the present sea level, downstream of the highway viaduct, is a consequence of the reclamation works carried out in the area in the 19th and 20th centuries. Part of this topography below msl is related to the original morphology of the swampy and lagoon environment, but it could also partly be the result of induced subsidence, prompted by water expulsion, soil ripening and degradation of organic matter since reclamation, as documented in other similar areas (*e.g.* Tosi et al., 2000).

This topographic setting is consistent with the results evidencing that alluvial aggradation in M3 has been significantly higher, with sedimentation of at least 8 m of fluvial deposits, and ~6 m in the core M5. Considering the stratigraphy, it is likely that transitional or estuarine deposits could be present even in the M3 site, but at deeper horizons, because in the adjacent core M5 inner estuary deposits occured below 6 m depth (**Figure 6.2.**). Considering the data documented in the cores M2 and M5, it is evident that marine and transitional environments were present in the early Holocene over 7 km further inland than at present days (probably as much as 11 km all the way to the Ponte Portone). Thus, the studied cores testify that large intra-estuarine delta progradation of 11 km occurred approximately in the last 7000 years, with the seaward migration of transitional and alluvial facies. Considering the geomorphological setting of the valley, prodelta and marine facies related to the early Holocene stages of the transgression should be present in deeper layers and was not reached by the shallow cores. This hypothesis is supported by the geometry of the lower valley, where the boundary between the Quaternary units and the bedrock is more than 100 m below the present surface (up to 160 m, in the location of the Mirna valley viaduct, IGH, 1994), allowing development of large accommodation space which was necessary for deposition of early-Holocene and Late Pleistocene deposits.

Comparing the studied area with the Adriatic basin and the post-LGM sea-level curves, measured or modelled reconstructions for Istria and the surrounding areas (Correggiari et al., 1996; Lambeck et al., 2004a; Antonioli et al., 2007; 2009; Amorosi et al., 2008b), the expected age of the basal Holocene paralic (transitional) facies, in the location of recent river mouth, should be ~10,000-9000 BP, when the sea level in the Adriatic was ~30 m below the present msl.

Description and analyses of the deep core MIR1 (120 m) is still in progress, but upper 40 m of the core (from surface to -40 m) is described in detail (field and laboratory description, grain size analyses, carbonate share, ^{14}C datings) to obtain insights in these older deposits to allow their interpretations. Stratigraphy of the core is described in the **table 10**.

Carbonate share (relatively low) and grain size along core depth does not show much changes with the depth as it is evident from the **figure 5.9.** and **table 11**. Therefore interpretation of depositional environments was based mostly on bivalvia and gastropoda assemblages and sedimentary features.

Between 40.00 m of depth up to 33.90 m, abundance of carbonate concretions and well developed soil at the top, point to deposition of alluvial sediments of the Late Pleistocene age. Organic sample at the depth of 33.54-33.56 m depth from the surface was radiocarbon dated to 9159±41 years uncal BP (8471-8280 BC, 2σ calibration; **Table 2**). First lagoonal input is most likely in the depths from 33.40 m but the first occurrence of lagoonal shells was at 33.10 m. Up to 31.70, on the basis of the fauna shells, deposition environment could be interpreted as an inner estuary. The organic layer between 31.72 – 30.83 m (**Figure 6.3.**) could be salt marsh deposits or deposits of freshwater/brackish swamp that became a salt marsh.

Considering this is good sea-level indicator (also because it lies close to compacted hard soil of the Late Pleistocene so subsidence could not be significant), two samples were radiocarbon dated: sample at the depth 31.32 – 31.34 m was dated to 8745±34 years uncal BP (7940-7276 BC, 2σ calibration) and sample in the layer between 30.90 – 30.92 m was dated to 8,316 years uncal BP (7496 – 7290 BC, 2σ calibration) which is related to period of Early Holocene (**Table 2**). Therefore, it can be concluded that Holocene deposit was ~ 31 m thick in the terminal part of the Mirna River valley (viaduct location).

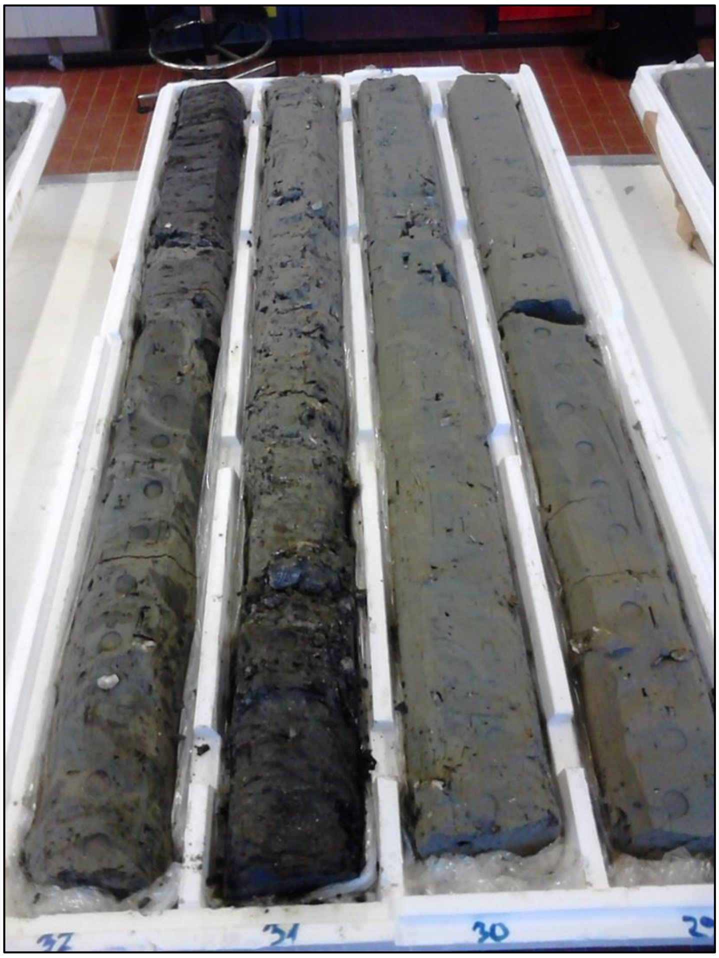

Figure 6.3. Organic layer in the core MIR1

Slika 6.3. Organski sloj u jezgri MIR1.

Probably from 30.30 m toward surface, environment changed to central estuary/open lagoon, progressively grown by sea level rise and passing to a open estuarine environment during TST. Layers between 20.60 m to 29.30 m of the core (**Figure 6.4.**) contained lots of shells of *Turritela* sp. and therefore it was interpreted to represent the maximum flooding, when the maximum Holocene depth was reached (deepest outer estuary, strong marine influence), before the development and progradation of the Mirna intra-estuarine delta. These layers were strongly reworked and bioturbated by activity of *Turitella* sp.

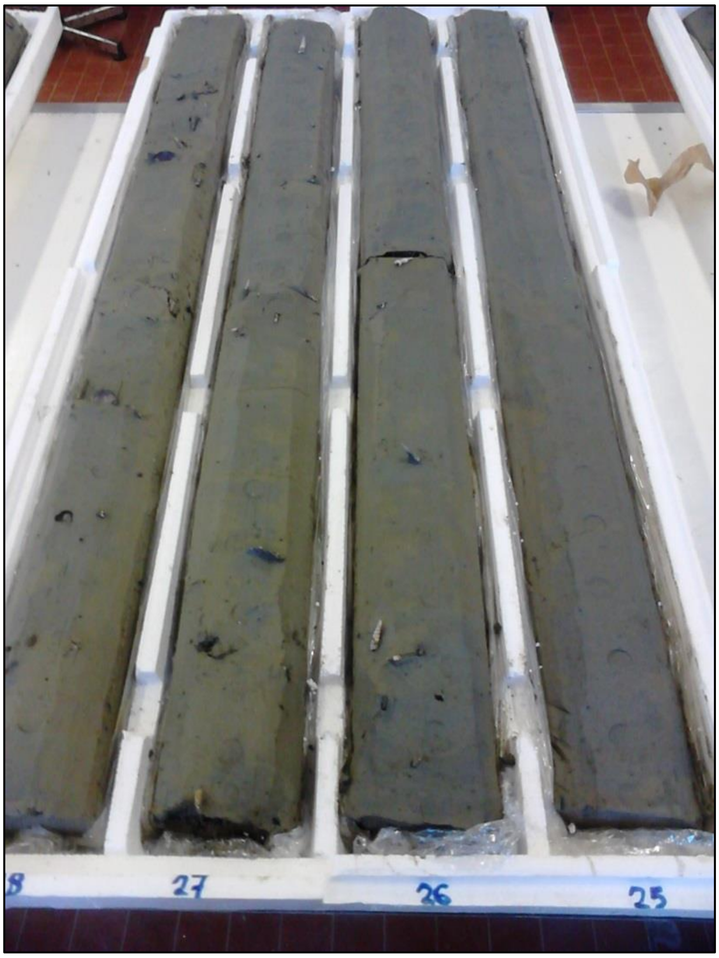

Figure 6.4. Deposits of open estuary environments with shells of *Turittela* sp. in the core MIR1.

Slika 6.4. Sediment otvorenog estuarija, s ostacima *Turittela* sp. u jezgri MIR1.

Changes in the assemblages of bivalvia and gastropoda, in the interval between 20.60 m up to 5.86 m, suggest shallowing of the estuary and intra-estuarine delta progradation towards central/outer estuary environment, during HST. The scarce presence of shells and the abundance of layered millimetric plant debris is probably related to deltaic/estuarine input from Mirna causing fast sedimentary discharge and severe fluctuations in the salinity of the water. Sample at the depth 5.95 – 5.98 m was radiocarbon dated to 3666±31 years uncal BP (2138 – 1954 BC, 2σ calibration) and sample at the depth 19.44 – 19.46 m to 4530±29 years uncal BP (3360 – 3103 BC, 2σ calibration) (**Table 2**). This interval suggests fast deposition of almost 14 m of deposits in ~ 1200 years. The absence of Turitella suggests different conditions compared to the layer below. First 8 m of the core was similar in features and environment interpretation as core M1 considering proximity of these two cores. Between 1.72 m and 2.98 m brackish environment deposits (**Figure 6.5.**) were present and then down to 5.86 the facies were comparable to inner estuary environment with sedimentary input from river which is evident by plant debris. Sample at the depth of 2.68 – 2.70 m was radiocarbon dated to 1754±25 (225 – 256 years AD, 2σ calibration; **Table 2**). From the surface down to 1.72 m alluvial plain deposits were present, with oxidations related to pedogenesis and the groundwater fluctuations (**Figure 6.5.**).

Figure 6.5. Deposits of continental and brackish environments in the first 4 m of the core MIR1.

Slika 6.5. Sediment taložen u kontinentalnim i brakičnim okolišima u gornjih 4 m jezgre MIR1.

Stratigraphic log with macrofossil assemblages and interpretation of depositional environments are presented in the **Figure 6.6.**

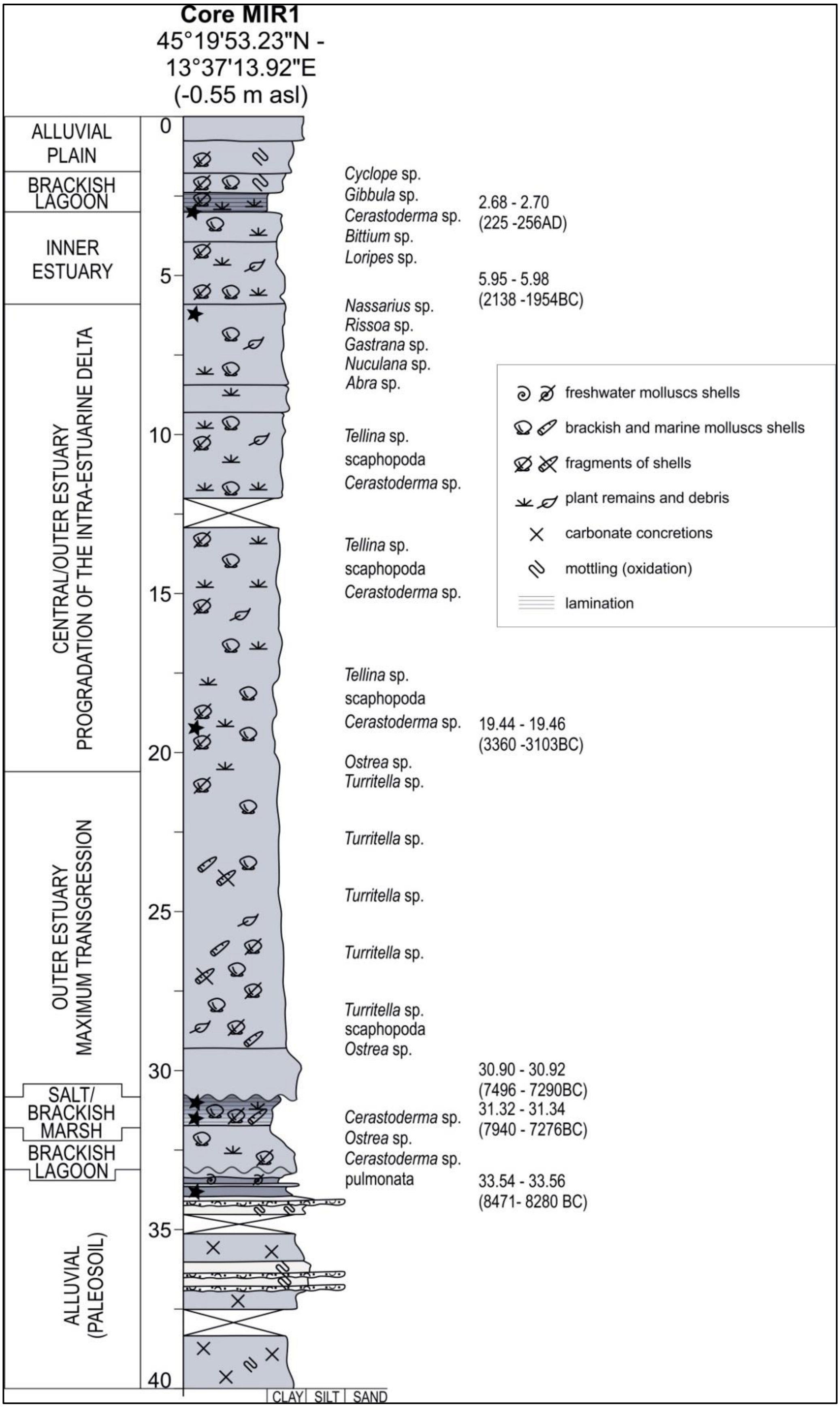

Figure 6.6. Stratigraphic log and interpretations of environment in the core MIR1

Slika 6.6. Stratigrafski stup i interpretacija okoliša iz jezgre MIR1.

Holocene coastal evolution is well documented along the western coast of the northern Adriatic, where deltaic progradation started from about 7500 years ago (*e.g.* Amorosi et al., 2008 and references therein), but the low-lying landscape is different from Istria. Despite the diverse dimensions and geographical setting, a rather good analogue for the lower valley of the Mirna River could be represented by the Tagus River valley, near Lisbon (Vis et al., 2008; Vis & Kasse., 2009). In particular, the brackish-water marshes and tidal flats described in the subsoil of the Tagus mouth present many similarities with facies of brackish marsh and inner estuary documented in this study.

A particular characteristic of the Mirna valley is the lack of coarse deposits in the middle and late Holocene and, thus, even the foreshore and shore-face facies (intra-estuarine delta and prodelta) consist of fine grained material (*i.e.* clays and silts). This singularity partly hampers the possibility for comparison of the facies found in the Mirna lower valley with other river systems, where coarse particles are normally transported up to the bay head delta.

The information collected by this research gave some useful insights in the past relative sea-levels. The dated sample at 5.27 m in M2 (2.87 m below msl) corresponds to the base of a swampy environment that formed over estuarine deposits, and we interpreted it as the shift to freshwater conditions after the Mirna river mouth (intra-estuarine delta) had passed down-stream of the location of M2. The dated layer (–2.9 m below msl, ~280 years AD) is a fairly good marker of the relative past sea level, because it formed in an environment close to sea level during late-Antiquity (*i.e.*, 3rd–4th century AD). For this marker we can assess a vertical error of about ±0.5 m with respect to the sea level existing during its deposition. In other sites in Istria, the observed values of the relative Roman sea level are generally between 1.9 and 1.6 m (Antonioli et al., 2007), demonstrating that, at the site of core M2, quite strong subsidence has occurred since late-Antiquity. As documented in the Po Delta and Venetian Plain (Brambati et al., 2003; Stefani & Vincenzi, 2005), this process is consistent with the sedimentary compaction that in the last millennia most probably could have occurred in the Mirna valley in the lower estuarine and lagoonal deposits, due to the depositional load (over 5 m of silts and clays). Moreover, reclamation activities could have also played a role, especially in the last century, inducing additional anthropogenic subsidence.

The calibrated age obtained at 8.3 m in core M3 (1,154– 1,254 cal AD; **Table 2**) was rather surprising for its young age and deep location, but it matches with the archaeological information available on the nearby Chapel of S. Maria of the Bastia, where the layer of the

16th century is at 4.6 m depth (Milotić & Prodan, 2014). Moreover, these data are comparable with the evolution that occurred in the upstream tract of the Mirna River valley. As reported in Faivre et al. (2011), historical documents recorded that near Motovun, in the 19th century, 0.80 m of alluvial deposits aggraded within 55 years and this huge depositional phase killed thousands of trees (Morteani, 1895). Moreover, in 1994 at the base of the hill of Motovun, a trunk was found 4.5 m below the floor of the Mirna River and its radiocarbon age was 1470–1600 AD (Rubinić et al., 1999; Prodan, 2001; Milotić, 2004).

The new data corroborate the evidence that, since the early Middle Ages, the evolution of the valley has been strongly influenced by human activity and, in particular by the exploitation of woods in the catchment. The operations of forest clearance exposed large areas of flysch, leading to widespread and rapid erosion. A huge quantity of fine sediment was available, overfeeding the Mirna River flux and allowing the dramatic alteration of the valley floor topography and the fast progradation of the intra-estuarine delta. Especially intensive processes of sedimentation were occurring at the Mirna River mouth, at the contact of marine saltwater and fluvial freshwater, by the process of flocculation which creates larger particles and the rapid sedimentation of transported material. These processes were also documented in the Raša estuary where salt-induced flocculation is the dominant process in the sedimentation of fine-grained particles which are preferentially accumulated at the head of the estuary (Sondi et al., 1995). From this perspective, the burial of the lagoon surface located at 2.5 m depth in M1 probably occurred after the Roman period or even in the last centuries, when the Mirna mouth prograded past this point. As documented along the opposite side of the Adriatic, in the Po and Venetian-Friulian plains (Correggiari et al., 2005; Cremonini et al., 2013; Rossato et al., 2015), several flooding phases occurred since late Antiquity with a peak during the early Middle Ages. These events, mainly related to Atlantic atmospheric fronts, should also have partly influenced the Istrian Peninsula and, thus, we can suppose that depositional phases along the Mirna River clustered in some periods as a product of the interplay between anthropogenic activities and peak flooding episodes. It is also worth noting that the occurrence of a phase with possible different environmental conditions from today before about 1000 AD was hypothesized as being responsible for the formation of the NE Adriatic notches (Furlani et al., 2011).

Figure 6.7. shows shematic reconstruction of sea-level and environment changes in the area of the recent Mirna River delta plain based on results of radiocarbon dating . Brackish/salt marsh environment was probably reaching further landward in the period of

early Holocene (7000 - 8000 BC), compared to the recent salt marsh, as evidenced in the core MIR1 at the depth of 31.32 m (**Figure 6.6.**). At that time, sea was ~30 m below recent msl, and flooding of the Mirna River incised valley was occurring (**Figure 6.7.a**), which was previously filled with sediments of river channels and alluvial plain during glacial lowstands. Further drowning of the valley was occurring probably until sea-level rise slowed (~4500 BC), what was evidenced in the core M2 at the depth of 10.25 m below recent msl, where central/outer estuarine environments were recognized, suggesting that sea was reaching further inland, probably as far as Ponte Portone (11 km), where probably shallow transitional environments were present (**Figure 4.1.; 5.2.; 6.7.b**). In the period between 200 - 350 AD, transitional environments (brackish marsh/inner estuary) were recognized in both M2 and MIR1 cores (**Figure 5.2.; 6.6.**) at the depth of 3.27 m and 2.13 m below msl respectively, suggesting already advanced progradation of Mirna intra-estuarine delta (**Figure 6.7c**). Further progradation of Mirna intra-estuarine delta until recent days led to the present distribution of depositional environments, with alluvial plain sediments filling most of the present surface, salt/brackish marsh environment developed at the river mouth, and only in the most seaward portion of the Mirna estuary still existing, corresponding to central estuarine environment (**Figure 6.7.d**).

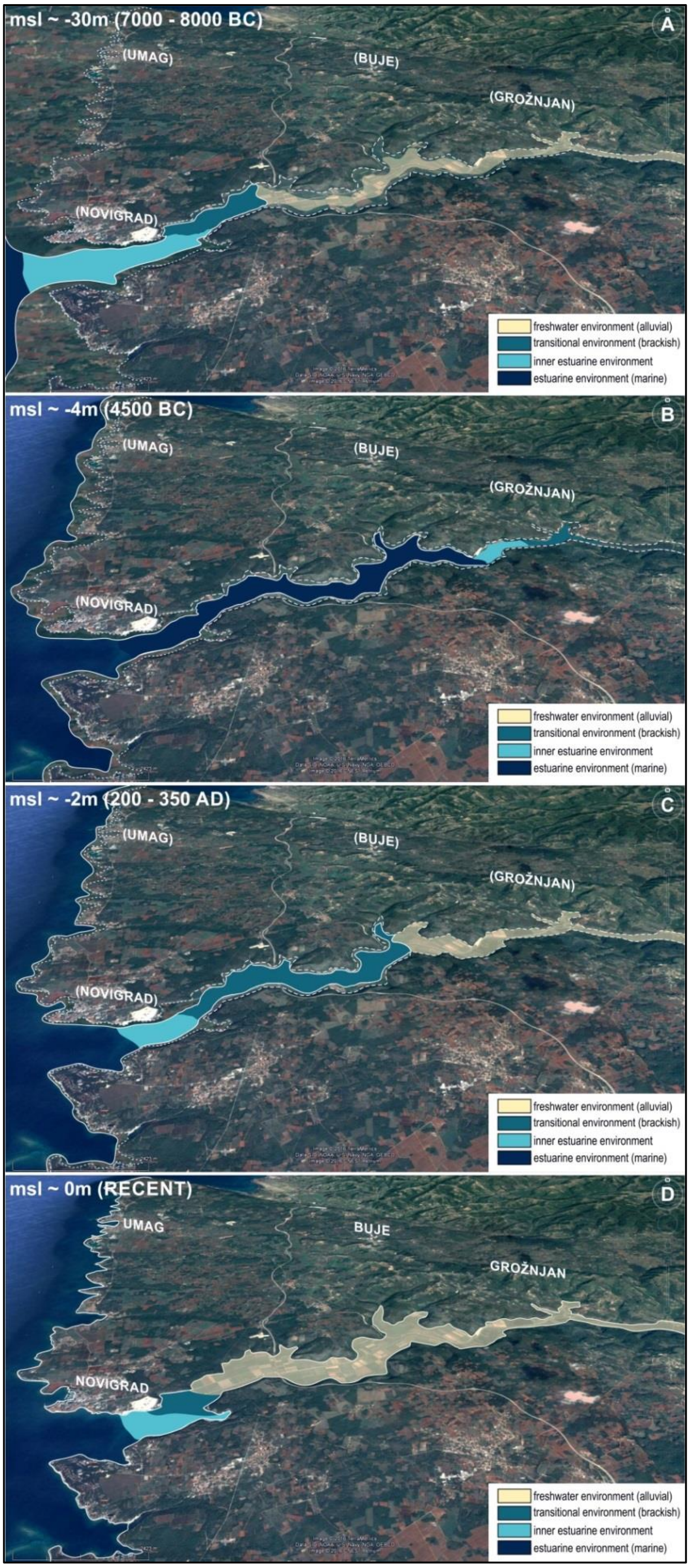

Figure 6.7. Shematic reconstruction of changes of environments in the Mirna River valley/estuary/delta, since early Holocene until recent days.

Slika 6.7. Shematska rekonstrukcija promjena okoliša u estuariju Mirne od ranog holocena do danas.

6.3. DEPOSITIONAL ENVIRONMENTS RECORDED IN THE NERETVA RIVER DELTA PLAIN

Recent depositional environment in the terminal tract of the Neretva River is almost completely cultivated deltaic plain, with many channels, and some lateral portion of alluvial swamps and freshwater/brackish lakes. The sediments in the river mouth are composed of sandy bars and prodelta environment below the sea-level.

Neretva delta plain cores contain sediments with similar sedimentological characteristics and paleontological assemblages, to those described in the Mirna River delta plain. However, several major differences are evident: shape of the Neretva Valley is much more complex, with many protected side-valleys; larger grain sizes of sediments along cores (dominantly sandy mud and muddy sand); Neretva River is much longer, it has ~10x larger drainage area compared to the one of the Mirna River, as well as water discharge, and is composed of magmatic, metamorphic and sedimentary rocks.

The main environments that were recognized based on the results are the same as in the case of the Mirna River:

A – alluvial/deltaic environments: alluvial plain (Aa); freshwater swamp (Ab);

B – transitional/brackish environments: brackish/salt marsh (Ba), inner estuary (Bb);

E – central/outer estuary (E).

6.3.1. Alluvial/deltaic environments (Alluvial plain/alluvial swamp)

In the lower sector of the Neretva valley continental deposits (deposits of alluvial plain and alluvial swamp) generally form the present surface and the topmost subsoil, usually in the first 2-3 m from the surface, except in the core NER2 which is completely composed of deposits of alluvial swamp (down to 6.65 m). This deposits in all cores consist dominantly of muds (clayey silt). The top layers in all the cores were related to anthropogenic landfill, which consisted of mixed material, often with the remains of bricks and pebbles. Roots and plant debris (usually of palustrine reeds) were common and their diameter ranged from 1 to 10 mm, whereas the macropalaeontological content consisted only of fragments of pulmonata shells, which were recognized only in the core NER2 (**Table 14; Figure 5.12.**). Mottling in this core was present down to 4.45 m.

The freshwater swamp (Ab) deposits were distinguishable by the occurrence of laminated organic-rich and peaty layers, with common plant remains, which were recognised in cores NER2, NER5 and NER6 (**Table 14, 17, 19; Figures 5.12., 5.15., 5.17.**). The core NER2 was located in the proximal part of the river course (**Figure 4.2.**) and sea probably did not reach this area, however it is possible that in the deeper, older layers, transitional deposits are present.

6.3.2. Transitional environments (Brackish/salt marsh (Ba)/ inner estuary (Bb))

The depositional environments related to brackish waters (hyposaline/brackish marshes (Ba) and the inner estuarine/lagoon facies (Bb)) were generally marked in the core by the presence of shells of Bivalvia and gastropoda, most dominantly by the occurrence of *Cerastoderma glaucum* (Poiret, 1789), and higher abundance of tests of foraminifera *Ammonia* spp. and *Haynesina* sp. (Murray, 1991, 2006; Albani et al., 2007; Amorosi et al., 2004, 2005). In areas where salinity fluctuated, opportunistic and pioneer species prevailed. Biodiversity indices were generally low in these deposits (**Appendix 8-9**). Sediments deposited in these facies were composed of greyish to brownish clayey silt and sandy silt with variable degree of bioturbation. Presence of millimetre sized plant debris was common (**Tables 12-20; Figures 5.10.-5.17.**). Compared to the Mirna cores, sand fraction was much more abundant and consisted of both biogenous and terrigenous particles (**Tables 13, 16, 18; Figures 5.10., 5.13., 5.16.**).

Salt-marsh foraminifera assemblages were not recognised in the cores collected in the Neretva River delta plain, probably because salt marsh sediments were not preserved in the collected cores. However, further researches should be focused to find such deposits, because, as mentioned earlier, salt marsh represents reliable sea-level marker. For example, this is the case in adjacent area of Blace (Shaw et al., 2016).

These transitional facies were assumed in the cores NER1 (first ~4 m from the surface), NER3 and NER4 (between ~ 0.50-2.00 m of depth) and recognized, more precisely, based on both molluscs and foraminifera assemblages, in the cores NER5 and NER6 (**Figure 5.15., 5.17.; Appendix 8-9**).

6.3.3. Central/outer estuarine environments (E)

The deeper parts of the Neretva cores were composed mostly of sandy silt and silty sand and common presence of mollusk shells *e.g. Ostrea* sp. and *Mytilus* sp. (in the deeper levels of the core NER1), indicating higher salinity compared to the layers above. Plant debris were common in all cores (**Tables 12-20; Figures 5.10.-5.17.**). Cores NER3 and NER4 reached at the bottom layers abundant fragments of coral *C. caespitosa* (**Figure 5.14.**), indicating dominant marine influence (open/central estuary).

The foraminiferal assemblages were analysed in the cores NER5 and NER6 (**Appendix 8-9**). *Ammonia* species were dominant in all samples, whereas proportion of *Porosononion* sp. and *Haynesina* sp. specimens decreased with depth and miliolids (*Q. seminula* in particular*)* were found only in the deepest samples. These results suggest deposition in central estuarine environments, below which cores reached basement rock.

6.3.4. Evolution of depositional environments in the protected side-valley (cores NER5 and NER6)

The combined use of sedimentological and paleontological analyses of two sediment cores (NER5 and NER6) and ^{14}C dating allowed recognizing different depositional environments and their succession in the marginal part of the Neretva delta plain during Holocene highstand. These interpretations were useful in reconstructing sea-level changes and gave insights in the evolution of Neretva delta area in the last 3000 years. The cores consisted of the youngest anthropogenic landfill, transitional palustrine layers and the oldest, estuarine sediments.

The core NER6 was closer to the channel compared to NER5 and more distant from the slope, ~6 m away from the core NER5 (**Figure 6.8.**). The ground surface was about 0.70 m above the water of the channel and between NER5 and NER6 there was difference ~ 0.20 m.

In the studied cores, the foraminiferal groups change downward from almost monogeneric assemblages with *A. tepida* as dominant species to oligogeneric assemblage dominated by *A. beccarii*. Within the studied sediments, *Ammonia spp.*, by species diversity and its tests abundances (making up to 89% of the community) dominate, whereas closely associated are *Haynesina* sp. *Porosononion* sp. occurring as subsidiary species in almost all samples with constant abundances. Foraminiferal genera found in these cores are considered as euryhaline and typical for temperate European estuaries (Cearreta, 1988, Redois & Debenay, 1996; Debenay et al., 2000, 2006; Debenay and Guillou, 2002; Diz et al., 2009; Camacho et al., 2015; Mojtahid et al., 2016). Ammonia species are resistant to unstable conditions (strong variation in oxygen content, fresh water input and changes in quantity and quality of food) that make them common, widespread and distributed over a great variety of habitats (from shallow marine to estuarine, lagoons, hyper- and hypo-saline, including mangroves; Debenay et al., 2000; Murray, 2006; Seuront & Bouchet, 2015 and reference herein). However, studies of Auray River, France, (Debenay 2000; Diz et al., 2009) show that horizontal freshwater to seawater transition is recorded by order of appearances of calcareous foraminifera, from *A. tepida* in the inner/middle parts, to *A. beccarii*, *Haynesina* and *Elphidium* close to the river mouth.

In the core NER5, anthropogenic landfill (A_0) occupied the topmost 1.50 m of the core (**Figure 6.8.**). The clay interval, characterized by abundance of roots of reed, passes down-core into a interval defined by presence of peat fragments and palustrine reeds, all of which indicate a freshwater swamp environment Ab (**Figure 6.8.**). Considering that the rest of the studied deposits are fine grained (clayey silt and silty clay), the sandy layer found between 3.20 – 3.56 m could be explained as Neretva River flooding phase. Below this sediment interval, sediments with foraminifera assemblage and biodiversity indices, characteristic for inner estuary environment (Bb) were found (**Figure 6.8.; Appendix 8.a,b**).

Considering the stratigraphic log of the core NER6, the sedimentary succession from top of the core down to 2 m, was recognized as disturbed anthropogenic deposit. The interval between 2 and 3.25 m lacks foraminifera and contained laminated peat which indicate freshwater swamp environment (Ab) (**Figure 6.8.**). The interval 3.30-3.51m contained foraminifera assemblages characterised by the pronounced dominance of *A. tepida* and only minor abundances of genus *Haynesina* and low biodiversity indices (**Appendix 9.a,b**). These suggest deposition in transitional environments, probably in brackish swamp (Ba) environment (**Figure 6.8.**). Foraminiferal group found in the successive sediment interval 3.55-3.66 m, was characterized by further dominance of *A. tepida* and slightly increase of specimens of genus *Haynesina* (**Appendix 9.a**), representing inner estuary settings, as described in detail in Mojtahid et al., 2016. Further downcore increase of genus *Haynesina* suggested transition from inner toward central and outer estuary setting, as typical longitudinal distribution of genus *Haynesina* shows increase toward the river mouth (Camacho et al., 2015).

The deeper core interval 4.50-7.51 m was composed of silty sediment containing fragments of brackish and marine bivalvia and gastropoda. Foraminiferal assemblages found here are marked by the appearance of the genus *Elphidium* (representatives of this genus favor the more saline water) and distinct change within the *Ammonia* group, *i.e. A. tepida* decreases, while *A. beccarii* becomes the most dominant species (**Appendix 9.a**). Accordingly, observed change of foraminiferal community, together with the fragments of marine bivalvia found in this interval, point to transition to central/outer estuary settings. Increase in abundance of *A. beccarii* and *Elphidium* sp. in other European estuaries was assigned to estuarine environment open to the free circulation of shelf waters (Cearetta, 1988, Delgado et al., 2012; Durand et al., 2016).

Finally, the sample NER6_16, obtained from the 8.10 cm core depth showed first appearance of marine affinity species *Q. seminula* (**Appendix 9.a**). Such community change probably indicates the transition to central/outer estuary with dominant marine influence (Cearetta, 1988, Ruiz et al., 2005).

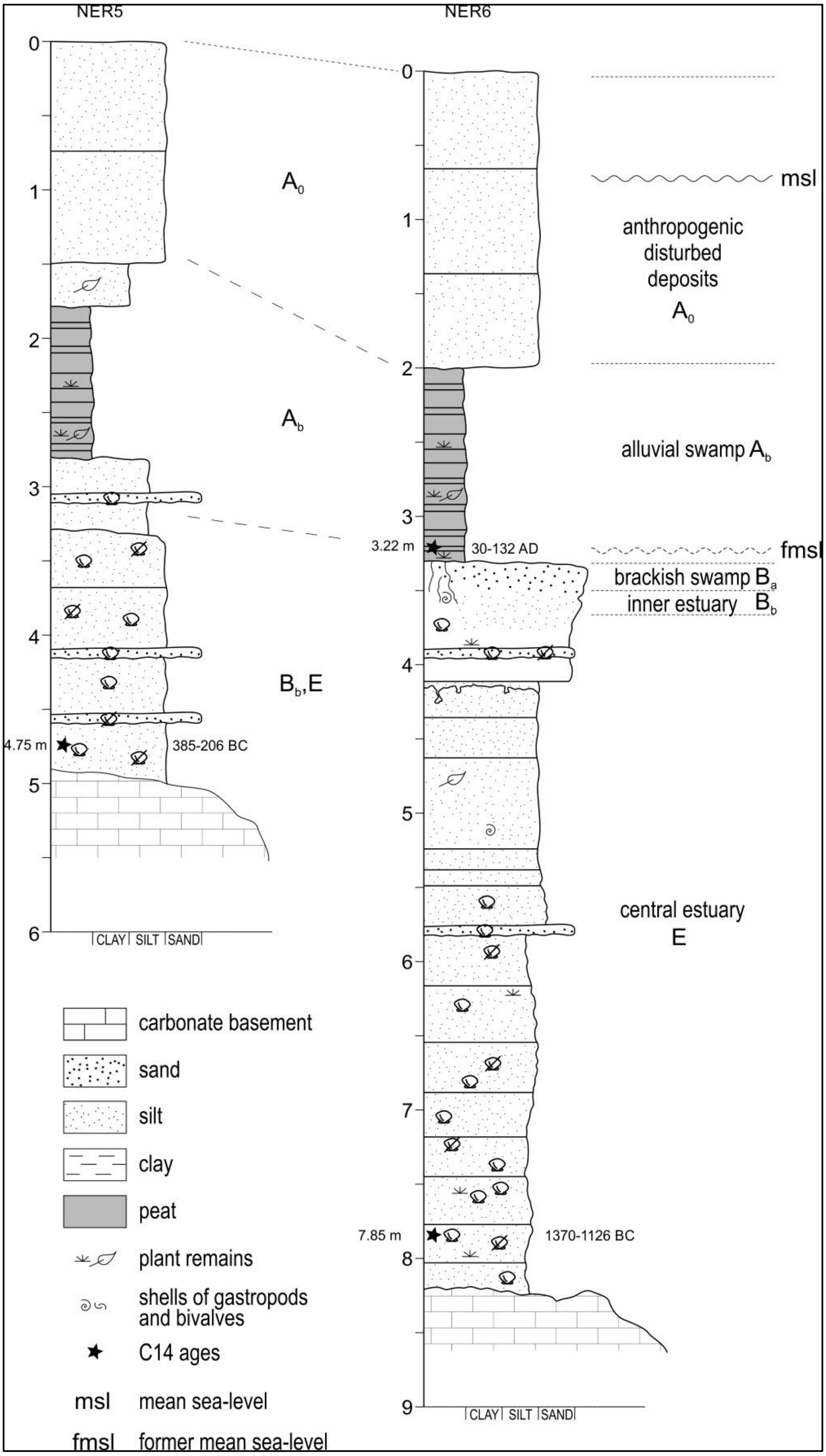

Figure 6.8. Correlation stratigraphic logs of the cores NER5 and NER6 in the Neretva River delta plain.

Slika 6.8. Korelacija stratigrafskih stupova jezgri NER5 i NER6 u deltnoj ravnici rijeke Neretve.

6.4. EVOLUTION OF THE NERETVA RIVER ESTUARY DURING LATE PLEISTOCENE AND HOLOCENE

The area where the Neretva cores were taken was part of Neretva karstic valley which was incised during last glacial period in the karstic basement rocks, and probably during older glacial periods as well. In the period of the LGM when sea-level was about 120 m below recent msl, continental conditions were present across large areas of the present Adriatic Sea and the sea was reaching only the Mid Adriatic Depression (Correggiari et al., 1996; Lambeck et al., 2004a; Amorosi et al., 2015 and references therein).

Paleo-Neretva River was carrying material from its drainage area along Neretva and Korčula Channels to the ancient mouth, which was at that time probably somewhere between Islands of Korčula and Vis, where the present depth of the sea is more than 100 m (Juračić, 1998; Sikora et al., 2014). Sikora et al., 2014. used digital elevation model (DEM) to reconstruct paleochannels and the paleo-coastline during the Last Glacial Maximum (LGM) in the Central Eastern Adriatic area. They presumed that the Neretva River flowed westwards for ~110 km, from the present river mouth (**Figure 6.9., 6.10., 6.11.**). The paleo-river mouth of the Neretva was presumably north of the Island of Sušac, and the total additional length of the Neretva, from the present river mouth to the paleo-river mouth, was 136 km (**Figure 6.9., 6.10., 6.11.**).

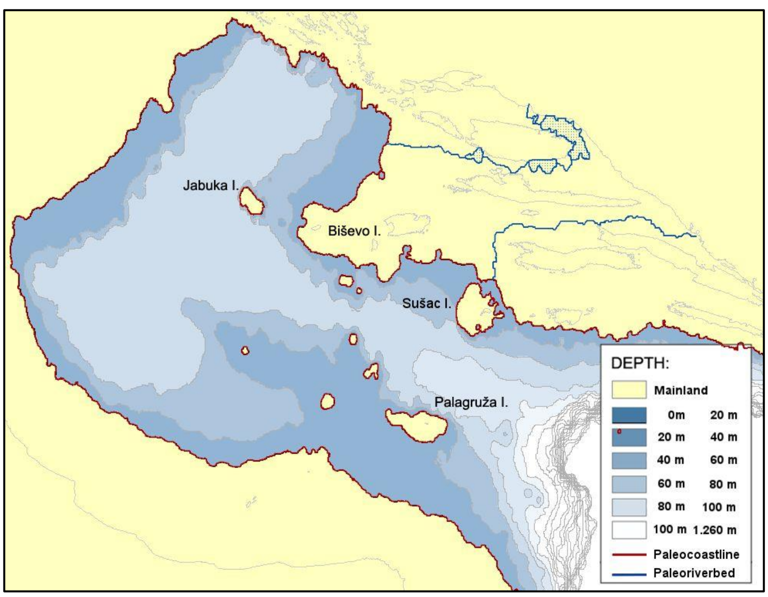

Figure 6.9. Adriatic at the peak of LGM: Paleo-riverbeds of Neretva and Cetina River are shown with thick blue line; paleo shoreline is shown with thin red line (Sikora et al., 2014).

Slika 6.9. Područje Jadrana za vrijeme posljednjeg glacijalnog maksimuma (Sikora i sur., 2014).

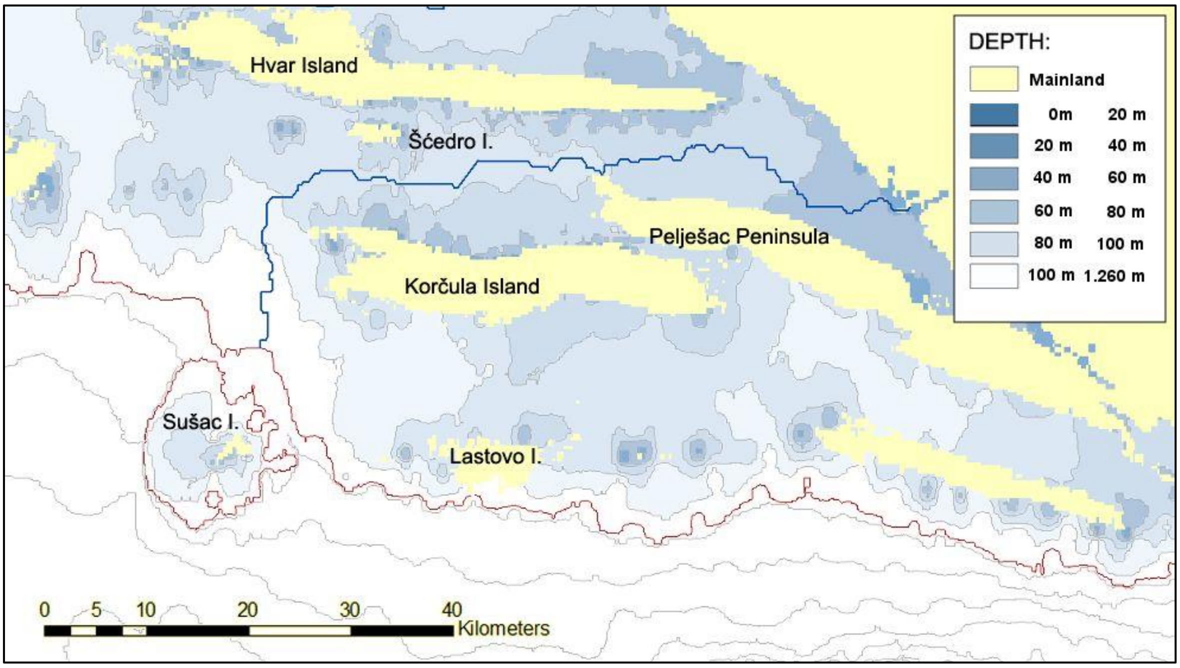

Figure 6.10. The paleo-riverbed of the Neretva River is displayed as line in blue color. Depressions are displayed as polygons with blue outline. The equidistance of contours is 20 m. The paleo-coastline is shown in red color (Sikora et al., 2014).

Slika 6.10. Paleotok rijeke Neretve (Sikora i sur., 2014).

The vertical profile of the Neretva paleochannel (**Figure 6.11.**) showed that in the first part of the profile, near the present river mouth, steep gradient is present, presumably as the consequence of present day delta progardation. In the middle part of the profile a distinct, flat part, stretches from the promontory of Pelješac Peninsula to the eastern promontory of the Šćedro Island. The bottom of this part of the presumed Neretva paleochannel has gradient of only 3 m over 40 km (slope of 0.075‰). The surrounding flat terrain is 40 km long and 5 km wide on average (Sikora et al., 2014) and could probably represent former Neretva delta plain.

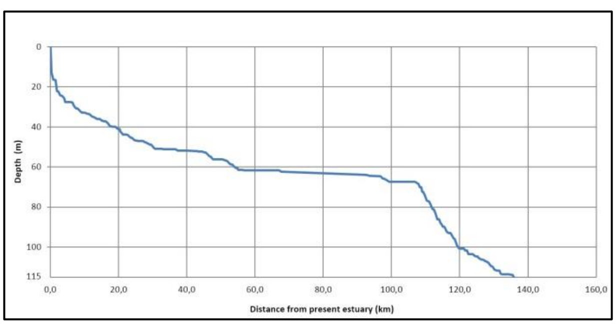

Figure 6.11. The vertical profile of the paleo-riverbed of the Neretva River (Sikora et al., 2014).

Slika 6.11. Vertikalni profil paleotoka rijeke Neretve (Sikora i sur., 2014).

The Neretva used to transport coarse deposits also to the present distal marine sector. In the present coastal plain only few long stratigraphic cores are available and they document the presence of presumably fluvial gravels and conglomerates from a depth of 15-30 m to the carbonate bedrock, while the uppermost part consists only of finegrained and sandy deltaic deposits (*e.g.* Vranješ et al., 2007).

The marine transgression occurred after the LGM flooded the Neretva River valley and formed deep karstic estuary. During the Holocene highstand, high delivery of riverborne material and progradation of Neretva intra-estuarine delta caused rapid filling of the Neretva estuary and adjacent lateral enlargements (lagoons and bays) and led to the preservation of depositional sequence that can be representative of the past rsl in mid and late Holocene. However, sediment input to the sea is nowadays largely reduced due to the sediment trapping in reservoirs behind multiple dams which were built across the Neretva River in the 20th century (Vranješ et al., 2007).

Figure 6.12. shows shematic reconstructions of sea-level and environments changes at the area of the recent Neretva River delta plain based on results of radiocarbon dating in the cores NER5 and NER6. Sample of plant, at the depth of 6.95 m below msl (core NER6), was radiocarbon dated to 2997±23 years uncal BP (1370-1126 BC, 2σ calibration) (**Figure 6.8.; Table 2**) and is presumed to be deposited in central estuary environment (**Figure 6.8.; 6.12.a.**). However, at this period, progradation of intra-estuarine delta was already in progress, so before that, the sea was probably reaching much more inland and transitional environment probably was reaching as far as Čapljina (Deranjsko Lake and Kuti Lake are possibly remnants of these environments). In the core NER5 at the depth of 3.65 m below msl, radiocarbon age of seed was 2241±22 years uncal BP (385-206 BC, 2σ calibration) (**Table 2**). At that time, central estuarine conditions were still present (**Figure 6.8.**) but not as far inland as in the previous period, considering advance progradation of the intra-estuarine delta (**Figure 6.12.b**). The radiocarbon age of peat sample at the depth of 2.32 m below msl in the core NER6 was 1914±22 years uncal BP (30-132 AD, 2σ calibration) **(Figure 6.8.**; **Table 2**). The peat was deposited in freshwater swamp environment so the filling of the estuary ended at this location, and the head of intra-estuarine delta was closer to the present sea (**Figure 6.12.c**), until it prograded completely to the recent Adriatic sea (**Figure 6.12.d**).

It can be assumed that msl was closely related to the water level in swamp, so 1914±22 BP (**Table 2**), sea-level was ~2.5 meters lower than recent sea-level., which means that during Holocene highstand, approximately 4.5 m of sediment was deposited within only 1000 years.

Subsidence due to compaction of sediment was probably negligible considering the fact that carbonate basement was close to the surface, and therefore obtained sea-level estimations are quite reliable, compared to the situation in the Mirna cores, which did not reach basement rocks.

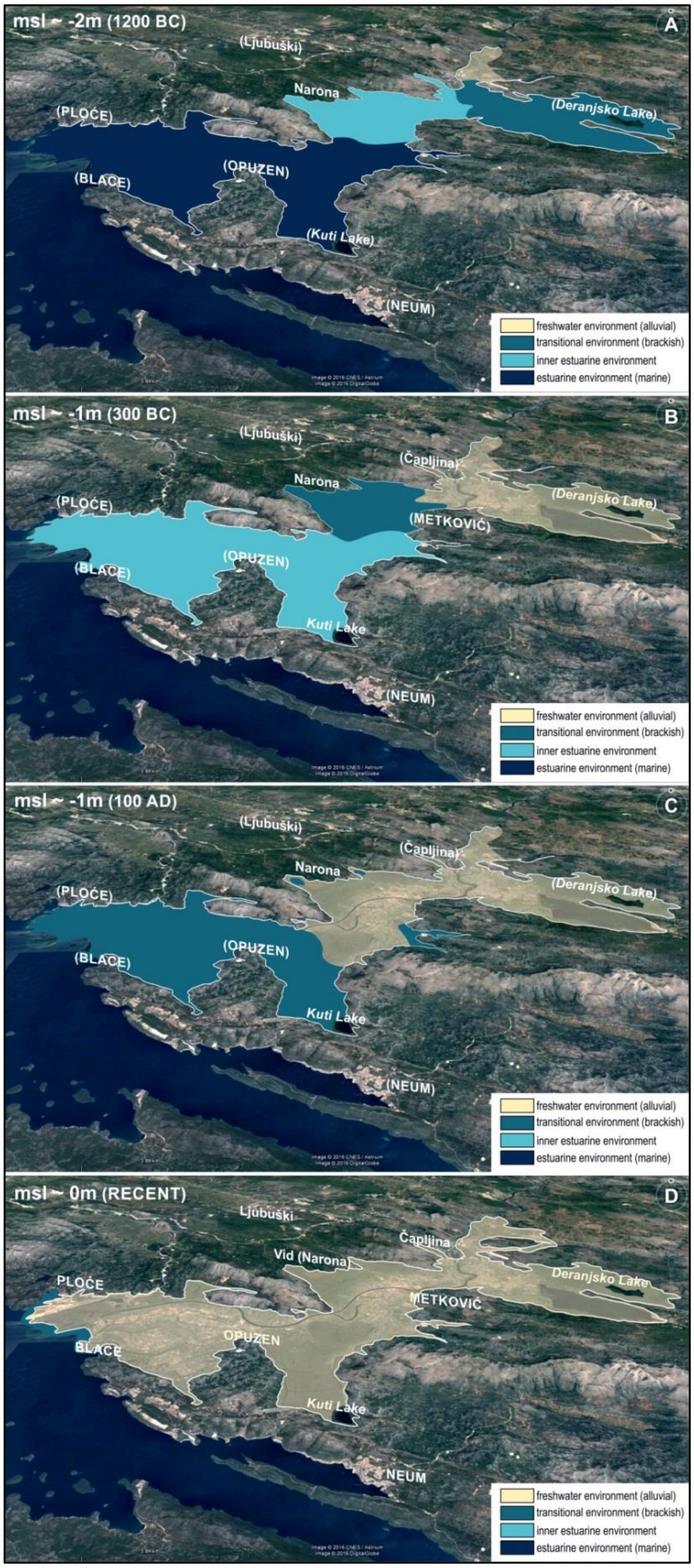

Figure 6.12. Shematic reconstruction of changes of environments in the Neretva River valley/estuary/delta in the last 3000 years.

Slika 6.12. Shematska rekonstrukcija promjena okoliša u estuariju rijeke Neretve u zadnjih 3000 god.

Figure 6.13. and **6.14.** show profile line and shematic interpretation of distribution of deposits of different depositional environment in the two long cores (NER120 and NER20) in the Neretva River delta plain. This interpretation is based on grain size analyses of these two cores, and also shows good correlation with classic progradation scheme of deltas after LGM (Stanley & Warne, 1994). Pleistocene deposits are composed of continental (alluvial) deposits, gravels and sands (**Figure 6.15.**), which were deposited during glacial period (LST), possibly comprising more than one glacial period. Transgression that occurred since the LGM caused flooding of the valley and deposition of transgressive sands and silts, which was followed by Holocene highstand marine/estuarine deposition and progradation of intra-estuarine Neretva delta.

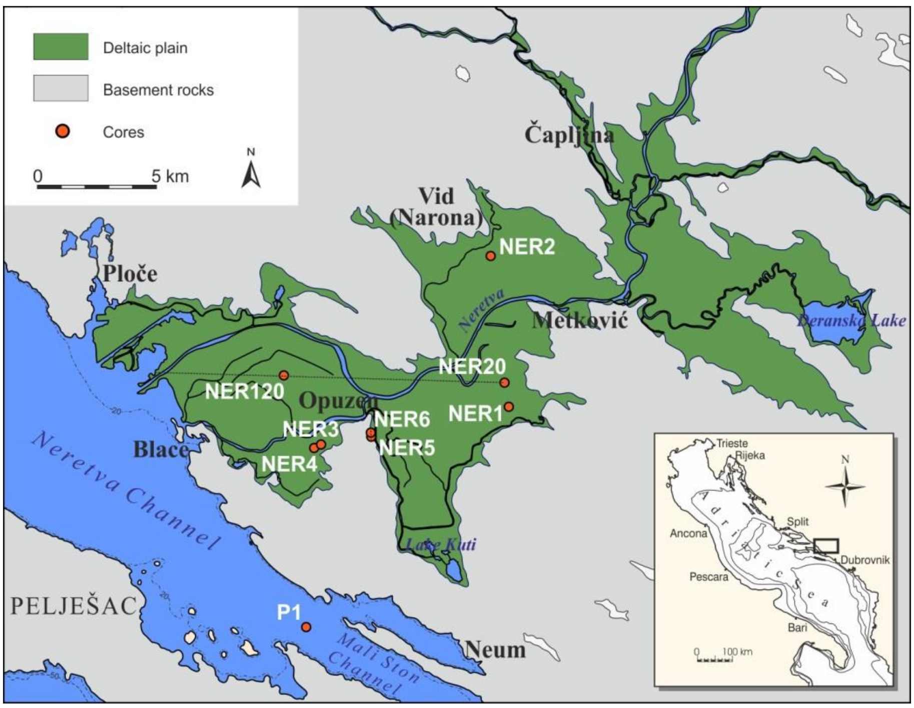

Figure 6.13. Profile line Neretva River mouth – core NER120 – core NER20.

Slika 6.13. Linija profila ušće Neretve – jezgra NER120 – jezgra NER20.

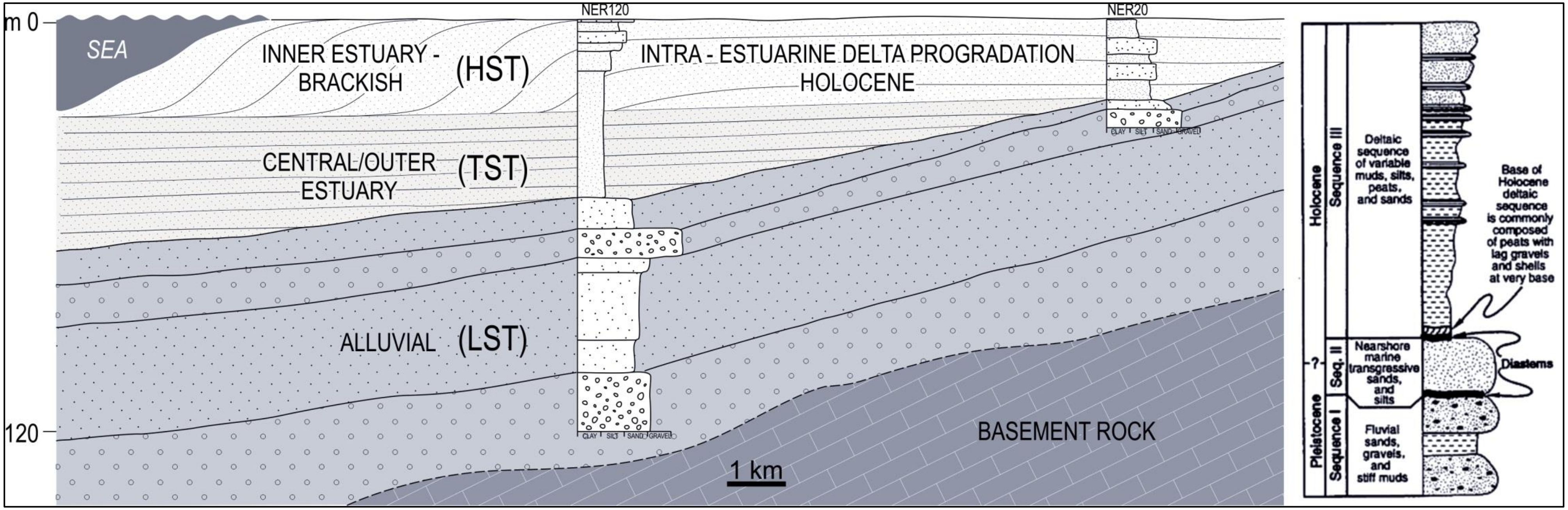

Figure 6.14. Shematic longitudinal profile through Neretva river delta sediments indicating depositional environments during Pleistocene and Holocene. The interpretation is based on differences in grain size distribution in the cores NER120 and NER20.

Slika 6.14. Shematski longitudinalni profil kroz deltnu ravnicu rijeke Neretve i interpretacija taložnih okoliša tijekom pleistocena i holocena.

Figure 6.15. Sandy gravels and gravelly sands from the core NER120 (depth 56-60 m), interpreted as alluvial sands and gravels deposited during last glacial lowstand.

Slika 6.15. Pjeskoviti šljunak i šljunkoviti pijesak iz jezgre NER120 interpretiran kao alluvijalni pijesci i šljunci taloženi tijekom zadnjeg glacijala.

6.4.1. Sedimentation in the Mali Ston Channel and evolution of the Neretva prodelta area

Considering the broader Neretva River delta area, changes in sedimentation during the late Pleistocene and Holocene, are also visible in varying sediment characteristics along the core P1 that was collected in the Mali Ston Channel, which can be considered as the Neretva River prodelta area. Studied sediment core was generally fine grained and mostly composed of muds, while cores drilled in the recent Neretva River mouth (cores NER120 and NER20) showed more coarse-grained sediment and abundant gravel fraction in deeper layers. Low wave impact along with the small tidal range in the Adriatic Sea (HHI, 1999) allowed fine-grained sediments to be deposited in the large prodelta area as revealed by Jurina et al., 2015.

Grain-size analysis of the core P1 (**Table 22; Figure 5.22., 5.23.**) showed the domination of muddy fraction in samples, while sand and gravel fractions referred to remains of shells of ostracoda, gastropoda, and bivalvia. The domination of quartz, kaolinite, and clay minerals (**Appendix 10**), higher clay share, and lower carbonate share in samples at the depths 2 m, 28 m, 74 m, and 96 m suggest strong terrigenous input presumably by the river. On the other hand, samples at depths 10 m and 32 m were dominated by calcite, very high carbonate shares (**Table 22; Appendix 10**), and low clay shares which suggest lacustrine sedimentation of carbonate material.

Such patterns and sediment characteristics were periodically interchanging along the core. This alternation of clay rich horizons and carbonate rich horizons through the whole core suggests periodical input of significant amounts of terrigenous material to the depositional environment in which, under “normal” conditions, carbonate sedimentation prevails. However, based on the mineral composition of the analyzed sediment, the accumulation of carbonate particles indicated two sources. Calcite and dolomite pointed to terrigenous flux, while aragonite and Mg-calcite were from biogenic sources. This is a common feature of the sediments in the eastern Adriatic as reported by Pikelj et al. (2009, 2010). It is assumed that accumulation of lithogenic carbonate is associated with periods of massive terrigenous supply.

The core between 60-96 m is composed of brown and greyish brown sediment which lack fossil remains, indicating that during this period in time (presumably LGM) alluvial material was deposited in this area. This alluvial material is generally fine grained (clay, silt and some sand, with low carbonate share (**Table 22; Figure 5.22., 5.23.**)) so it was probably deposited by flooding of the Paleo-Neretva River and/or delivered by karstic sprigs.

Considering that gravel and sand (paleochannel deposits) are not present in the Mali Ston Channel core, one can presume that paleorivers did not flow through this area.

The sediment in the core P1, between 8-60 m, was composed of white-grey material (dominantly silt) with much higher carbonate share (up to 95%) (**Table 22; Figure 5.22., 5.23.**)), and contained some freshwater gastropoda (*e.g. Viviparus* sp.; **Figure 5.23.**). Results of ^{14}C age dating of organic matter applying AMS method in another core from the Mali Ston Channel showed that the age of sediments at the depth of 35.5 m sediment age was 17,100 years BP (Pavelić, 2005). Taking into consideration the fact that the core P1 was taken in proximity of this core, in the same depositional environment, it could be assumed that sediments in the core P1 are of similar age. These data suggest that deposition of material, after LGM, was occurring in the lacustrine environment. This lacustrine environment/lake could have developed due to higher rivers, streams and karstic springs discharge, as a consequences of warmer climate and melting of the ice after LGM, which flooded underlying LGM alluvial deposits. As already mentioned above, this underlying alluvial deposits consisted dominantly of clays, that is impermeable and it acted as a barrier, so it was possible for lakes to form rather than to be drained into porous karstic basement.

Other result of ^{14}C age dating in same core from the Mali Ston Channel showed that the age of sediments at 5.5 m of the core depth was 8580 years BP (Pavelić, 2005). These results suggested sedimentation rates of 2.08 mm/a in the period between 17,100-8580 years BP, while in the last 8580 years sedimentation rates in the Mali Ston Channel dropped to average 0.64 mm/a (Pavelić, 2005). The sediment in the core P1 between 2-8 m contained marine fossil assemblages (e.g. *Turritella* sp.) (**Figure 5.23.**) which indicated that the sea reached Malostonski Channel in this period and marine sedimentation started. Considering results of ^{14}C datings in the cores NER5 and NER6 and data that progradation of intra-estuarine delta was still occuring between 2997±23 years uncal BP and 1914±22 years uncal BP (**Figure 6.11.**), and did not reach recent coastline, it can be assumed that recent Neretva prodelta deposits could only be present in the topmost layers of the core P1 in the Mali Ston Channel.

6.5. KARSTIC ESTUARIES ALONG THE EASTERN ADRIATIC COAST AND THEIR SIGNIFICANCE IN RECONSTRUCTING SEA-LEVEL CHANGES DURING LATE QUATERNARY

Regarding the fact that eastern part of Adriatic Sea is poorly investigated so far, and data of past rsl are rare, investigations of karstic estuaries and their depositional sequences is quite important.Karstic estuaries along eastern Adriatic coast are peculiar environments in which deposition of material during Holocene is occurring. However, these estuaries are not identical, and karstic estuaries formed along Croatian coast during Holocene, have different sedimentation patterns. A low energy environment (sheltered position of the river mouths and small tidal range) along with water circulation pattern characteristic of a stratified estuary (brackish surface layer seaward current and seawater bottom landward countercurrent bringing back particles that sink from the surface brackish layer), and the enhanced flocculation at the freshwater/sea boundary (Boldrin et al., 1991) lead to the fast sedimentation of most of the riverborne material in the upper part of the estuaries. Compared to the large delta systems (e.g. Po River delta system), deposition of material in karstic estuaries is different, in the way that much smaller amount of material is deposited in the karstic incised valleys considering the lithology of the drainage areas. Furthermore, these valleys are quite shallow (compared to *e.g.* Po River, and compaction and subsidence is much lower as well, which must be taken into consideration when reconstructing past rsl.

Progradation of intra-estuarine deltas in Mirna and Neretva estuaries, during Holocene highstand, caused rapid filling of estuaries and adjacent lagoons and bays. Therefore, depositional sequences could be recognized, allowing reconstructions of evolution of depositional environments and rsl (*e.g.* Felja et al., 2015), at least in the post-LGM period. **Figure 6.16.** show schematic interpretation of canyon-like karstic estuariy evolution and filling since the LGM, on an idealised transversal profile. This interpretation is based on both Mirna and Neretva River delta plain cores discussed in the previous chapters, as well as on available literature.

Regarding the fact that both Mirna and Neretva incised canyon-like valleys are deeper than LGM lowstand rsl (~120 m below msl), it is probable that these valleys were carved in carbonate bedrocks, by Paleo-Mirna and Paleo-Neretva rivers, much earlier than LGM. The deepest sediments probably comprised earlier periods, possible even those of Messinian age.

Other possibility is that during LGM, due to low erosional base, Neretva and Mirna Rivers eroded all older deposits, and were flowing across carbonate bedrock, hence further carving their canyons inside basement rocks. However, since this thesis is dealing mostly with "post-LGM", focus will be put on deposits and evolution of these karstic estuaries since the LGM.

In the period of LGM, Mirna and Neretva rivers were eroding underlying deposits and/or carbonate bedrock (**Figure 6.16.a**). These sediments were composed at that time mostly of alluvial gravels and sands, deposited in the earlier periods. Rapid rise of sea-level since the LGM and until early Holocene caused deposition of alluvial material, which was much thicker in the case of Neretva, considering the fact that Neretva River has much larger drainage area composed of easily erodible material (magmatic, metamorphic and clastic sedimentary rocks) compared to the drainage area of Mirna River, which is composed dominantly of fine-grained flysch deposits and carbonates. When these areas were flooded by the sea in the early Holocene, transitional environments were formed (e.g. salt/brackish marshes, lagoons, inner estuary), in which deposition of transgressive sands and muds was occurring (**Figure 6.16.b**). Some of these transitional environments are very useful in reconstructing sea-level in the early Holocene, as was the case recorded in the core MIR1. In both Mirna (core MIR1, ~ 2 km from the sea) and Neretva (core NER120, ~ 5 km from the sea) examples, deposits of these transitional environments are probably at the depths between 30-35 m, as already discussed in the previous chapters. Maximum flooding occurred ~6000 BP and central/outer estuary environments were formed (**Figure 6.16.c**). Since that time, sea-level rise slowed and Mirna and Neretva rivers formed intra-estuarine deltas and started to fill the estuaries with material. Progradation of deltas led to shallowing of the areas then again formation of transitional environments in the late Holocene, and finally almost complete filling of the estuaries (**Figure 6.16.d**).

According to Cooper et al. 2011 classification, Mirna and Neretva estuaries can be classified as "catch up" estuaries, with the final phase of progradation of intra-estuarine deltas. Neretva intra-estuarine delta quite completely filled former Neretva estuary, whereas remaining of the Mirna estuary is still not completely filled, in the recent Mirna Bay.

Other Croatian river mouths, *e.g.* Krka, Zrmanja, Cetina, Raša and Rječina River estuaries, show some similarities and some differences compared to the Mirna and Neretva estuaries (Prohić & Juračić, 1989; Benac & Arbanas, 1990; Juračić & Prohić, 1991; Benac et al., 1991; Juračić, 1992; Sondi et al., 1995). Due to existence of tufa barriers, *e.g.* in the Krka and Zrmanja River, at the moment most of weathered material is trapped in the river lakes behind natural dams, and therefore small amount of material is delivered to the river mouth (similar effect as with artificial dams and reservoirs built on the Neretva River). As a consequence, Zrmanja and Krka are examples of “give up” estuaries, according to the Cooper et al., 2011 classification. Cetina River has somewhat higher delivery of suspended load to river mouth which is composed dominantly of sands and Rječina River has delta composed of gravels.The quantities of particulates input of the Raša River are much larger due to intensive erosion in the flysch part of the drainage area and the absence of tufa barriers along the Raša River course. The bottom of the lower, canyon-like part of the Raša Bay are filled with Holocene sediments up to 93 m thick (Benac et al., 1991). The location of the actual river mouth shifted southward approximately 4 kilometers within last 240 years as deduced from old maps (Benac et al., 1991).

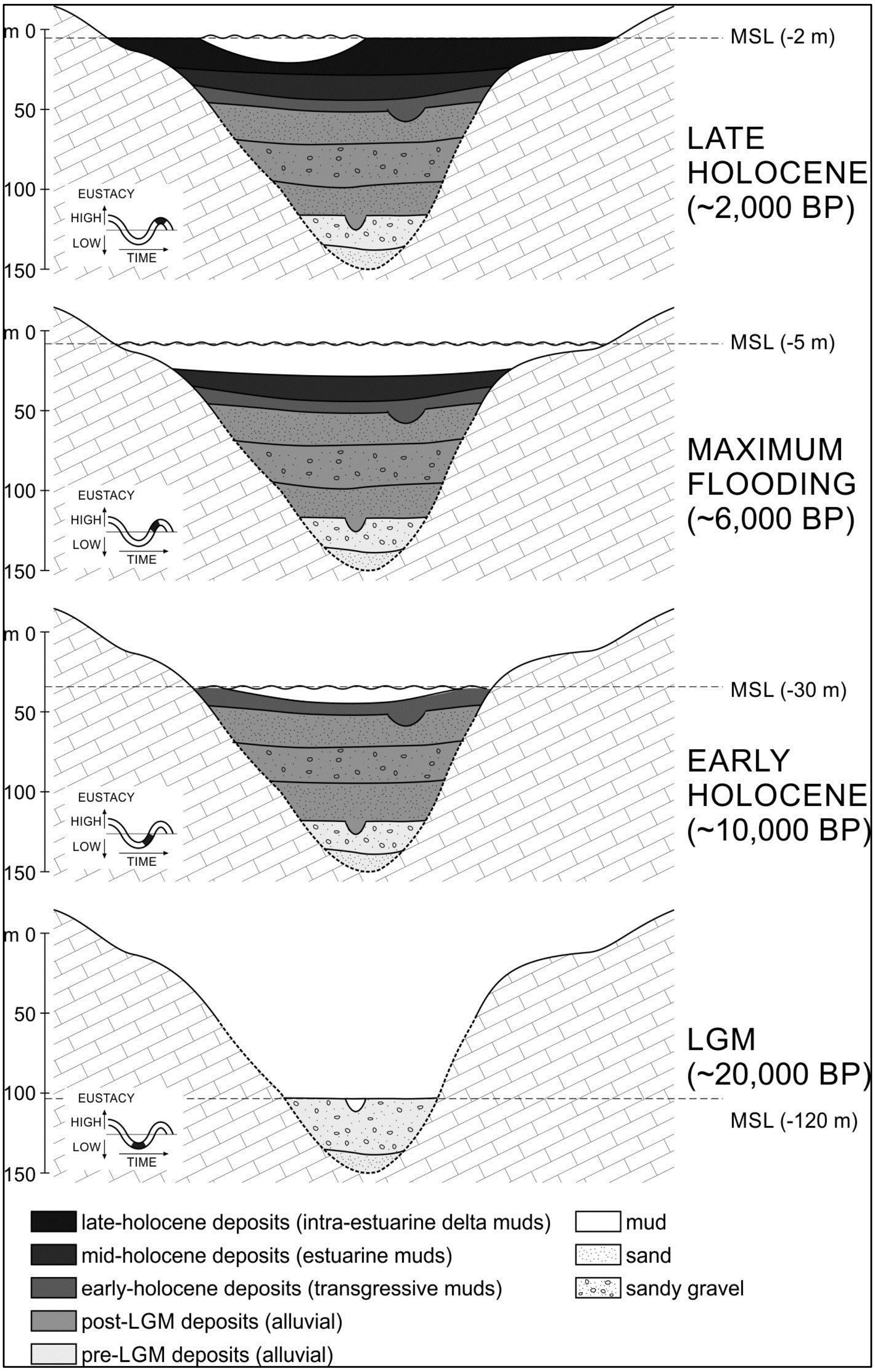

Figure 6.16. Schematic diagram of stages of filling incised karstic valley with sediments since the LGM: a) in the period of LGM, rivers were eroding pre-LGM deposits; b) rapid sea-level rise caused drowning of the valley with the sea and deposition of transgressive deposits atop of alluvial post LGM deposits; c) in the period of maximal flooding, estuarine/marine deposits were deposited; d) intra-estuarine deltas progradation in mid- and early Holocene and filling of the valley.

Slika 6.16. Shematski dijagram koji pokazuje faze ispunjavanja usječene krške doline sedimentom nakon zadnjeg glacijalnog maksimuma.

Radiocarbon ages of the samples from the cores (M2, MIR1, NER5 and NER6) are shown in the Figure 6.17. Radiocarbon ages younger than 6000 BP are much lower than model prediction curves for Trieste and Brijuni, and slightly below curve for Sardinia location (Antonioli et al., 2007). Due to the fact that cores NER5 and NER6 reached carbonate basement rocks quite shallow below surface, compaction should not be significant, and these data are considered to be reliable. Samples with longer vertical range prediciton were deposited in central estuarine environment, and sea-level was surely higher than the deposited sediment. Samples with lower vertical range were deposited in salt/brackish marsh environment and are considered to be reliable sea-level indicators. Three samples from the core MIR1 at the depth of ~30 m (early Holocene age) are quite comparable to the rsl curve from Sardinia and also represent good sea-level indicators considering that they were deposited in salt/brackish marsh near sea-level. However, some compaction of sediment could be expected at these depths, considering the weight of 30 m of sediments above, as well as more than hundred meters of sediments below, which could be prone to compaction if composed of mud.

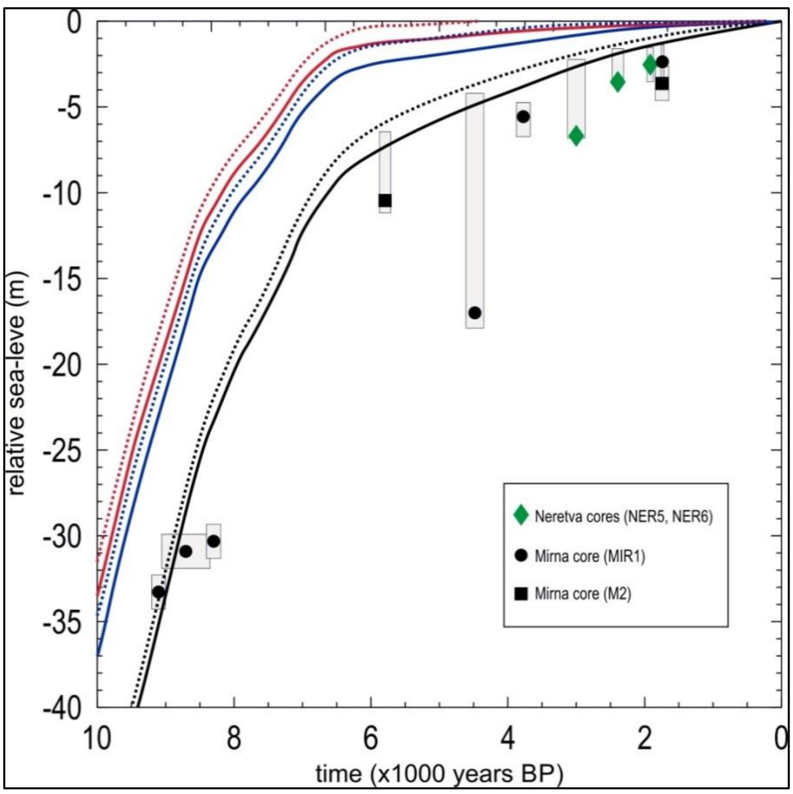

Figure 6.17. Diagram showing ^{14}C results from both Mirna and Neretva cores samples. Curves are model predictions for the mean Sardinia location, for the mean Gulf of Trieste location and for Brijuni. The solid lines are for the model m-3 and the dashed lines are for m-2 (modifeid after Antonioli et al., 2007).

Slika 6.17. ^{14}C dijagram uzoraka iz jezgri iz deltnih ravnica rijeka Mirne i Neretve.

7. CONCLUSIONS

This research of the sediments in the terminal tract of the Mirna and Neretva river valleys was based on a multidisciplinary approach, combining lithological, sedimentological, geochronological and both macro- and microfossil analyses. The Neretva River is the largest river in the eastern Adriatic coast and Mirna River is the largest river of Istria Peninsula. They are one of the major water courses of the eastern side of the Adriatic, and therefore, the reconstruction of the environments which characterized this area (and their Late Pleistocene - Holocene evolution) can be an important reference for other fluvial systems along the eastern Adriatic coast with karstic estuaries (e.g. Raša, Krka, Zrmanja). The conclusions derived from this research are:

1) In the Mirna River delta plain, sediment of Holocene age are dominantly of silt and clay grade particles (muds), whereas in the Neretva River delta plain, sediment is composed of both mud and sand. Older deposits (30-120 m in the core NER120) are composed entirely of sand and gravel fractions. This is due to the fact that Neretva River drainage area is more than 10x larger and composed of easily erodible rocks (clastic sedimentary rocks, metamorphic and magmatic rocks) which allowed Neretva to deliver coarser material compared to the drainage area of the Mirna River which is composed of fine-grained flysch.
2) Depositional sequences preserved in the subsoil of the deltaic plains, displayed distinctive sedimentary characteristics and fossil assemblages (benthic foraminifera, gastropoda and bivalvia) which were related to different environments that were changing in these areas as a consequences of sea-level changes during Quaternary.
3) In the sediment cores from the Mirna and Neretva delta plains (M1-M8; NER1-NER6; maximal depth 13 m), the alluvial facies (alluvial plain (Aa) and alluvial swamp (Ab)) deposits were overlying deposits of transitional environments (brackish swamp/salt marsh (Ba) and inner estuary (Bb)) while below them deposits of central/outer estuary (E) were present.

   The core MIR1 recorded similar sequence compared to cores M1-M6 in the first 10-15 m, but also deposits of maximal transgression (outer estuary) below, and again inner estuary/brackish marsh/lagoon deposits, ending with alluvial deposits and soil at 40 m depth.

The cores NER120 (30-120 m of depth) and NER20 (16-18 m depth) reached deposits of LGM and, possibly, pre-LGM periods (alluvial gravels and sands), atop which are deposits of TST (transgressive sand and silts) and HST (intra-estuarine delta) deposits. The core P1 from the Malostonski Channel recorded fine grained facies (muds) with variable carbonate share (1-95 %). This core is composed of terrigenous alluvial deposits in deeper layers (60-96 m), lacustrine deposits (8-60 m), and topmost (2-8 m) marine deposits (Neretva prodelta deposits).

4) The karstic, canyon-like, valleys of Mirna and Neretva River were probably incised earlier than LGM considering the depth of both valleys are deeper than minimum sea-level during LGM (~120 m below msl). During LGM, Paleo-Mirna and Paleo-Neretva were eroding older deposits, possibly reaching carbonate basement and further incising their valleys. Transgression after LGM caused flooding of the valleys and deposition of transgressive sands and silts, followed by Holocene highstand marine/estuarine deposition and progradation of intra-estuarine Mirna and Neretva deltas and finally complete filling of former valleys with alluvial material and development of recent Mirna and Neretva delta plains.
5) In the Holocene highstand, last 6500 years, an intra – estuarine delta sequence prograded for over 11 km in the lower tract of the Mirna River, filling the pre-existing valley with a sediment thickness of at least 30 m as documented in the core MIR1. Progradation of Neretva intra-estuarine delta possibly prograded even more, considering larger area of Neretva valley, and similar thickness of deposits in the core NER120.
6) Anthropogenic influence have been strong in these areas. Since late Antiquity, alluvial phase started in the Mirna River valley, leading to deposition of several metres of silty clay sediments that are thicker than 9 m in core M3. The sedimentary supply has been partly increased by forest clearance that occurred in the Mirna catchment that was particularly severe during the 15–19th centuries. In the Neretva delta plain, most important anthropogenic influence are dams and reservoirs that were built acroos Neretva River in the 20th century, causing trapping of large quantities of material, which limited delivery of coarse-grained material to the sea.
7) The recent and strong sedimentary load accelerated compaction of the Holocene deposits. This local subsidence also affected the relative sea level position that experienced a downshift of 2.9±0.5 m since the 2nd–3rd centuries AD in the Mirna River delta plain. Therefore, for precise sea-level reconstructions, it is important to

drill cores, that contained transitional environments deposits reliable for ^{14}C dating, at or near the carbonate basement (*e.g.* cores NER5 and NER6).

8) The Mirna and Neretva estuaries could be classified as karstic "catch-up" estuaries, according to Cooper et al., 2011 classification, with the final stage of progradation of intra-estuarine deltas.
9) Further investigetions of karstic estuaries, sedimentological, paleontological (analyses of molluscs, foraminifera, ostracoda, diatomea, and pollen) geochronological and geophysical (seismic), would improve the details and precision in the reconstructions of the depositional facies and environments, as well as relative sea-level in the past. They would allow better predictions of future trends of environmental changes as a consequence of sea-level rise, and protection of these valuable environments.

8. LITERATURE

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9. APPENDIX

Appendix 1: Table showing all laboratory analyses performed on 18 cores from Mirna and Neretva River delta area (mineralogical analyses, macrofossil analyses and field description are not included here).

Core	Depth (m)	Granulometry	Calcimetry	Foraminifera analyses	^{14}C measurements
M1	8	-	-	+ (6 samples)	-
M2	13	-	-	+ (6 samples)	+ (2 samples)
M3	9	-	-	+ (8 samples)	+ (1 sample)
M4	8	-	-	+ (7samples)	-
M5	11	-	-	+ (12 samples)	-
M6	7.60	-	-	+ (5 samples)	-
M7	4	-	-	-	-
M8	2	-	-	-	-
MIR1	40	+ (59 samples)	+ (59 samples)	-	+ (6 samples)
NER1	9	+ (11 samples)	+ (11 samples)	-	-
NER2	6.65	-	-	-	-
NER3	7.70	+ (5 samples)	+ (5 samples)	-	-
NER4	6.80	-	-	-	-
NER5	4.90	-	-	+ (8 samples)	+ (1 sample)
NER6	8.20	+ (6 samples)	+ (6 samples)	+ (16 samples)	+ (2 samples)
NER120	120	+ (38 samples)	+ (19 samples)	-	-
NER20	18	+ (14 samples)	-	-	-
P1	96	+ (45 samples)	+ (45 samples)	-	-
TOTAL (18)	380 (106)	178	145	68 (20,000)	12

Appendix 2a: Absolute abundance of foraminifera in the core M1

CORE/SAMPLE	M1_1	M1_2	M1_3	M1_4	M1_5	M1_6
Depth (m)	**0.20-0.21**	**1.80-1.81**	**3.10-3.11**	**3.90-3.91**	**6.30-6.31**	**7.95-7.96**
Adelosina mediterranesis (Le Calvez, J. and Y., 1958)	1	0	0	0	4	7
Ammonia beccarii (Linné, 1758)	2	11	21	0	12	25
Ammonia parkinsoniana (d´Orbigny, 1839)	0	0	0	0	0	0
***Ammonia* sp.**	12	56	16	5	11	15
Ammonia tepida (Cushman, 1926)	21	78	34	7	21	21
***Brizalina* sp.**	2	0	0	0	0	3
Elphidium aculeatum (d´Orbigny, 1846)	0	0	0	0	0	0
Elphidium crispum (Linnaeus, 1758)	0	0	0	0	0	7
Elphidium macellum (Fichtel and Moll, 1798)	0	0	0	0	0	2
***Elphidium* sp.**	0	1	0	0	2	3
***Eponides* sp.**	0	2	0	0	0	0
***Haynesina* sp.**	7	21	21	3	9	7
***Porosononion* sp.**	0	5	0	0	3	15
Quinqueloculina seminula (Linné, 1758)	0	0	0	0	8	15
***Rosalina* sp.**	0	0	0	0	0	0
Sigmoilinita costata (Schlumberger, 1893)	0	0	0	0	0	2
***Textularia* sp.**	0	0	0	0	0	2
Triloculina marioni Schlumberger, 1893	0	0	0	0	2	4
***Triloculina* sp.**	0	0	0	0	0	1
Trochammina inflata (Montagu, 1808)	2	3	1	0	0	0
Indeterminable	2	3	5	2	8	0
Total	**49**	**180**	**98**	**17**	**80**	**131**

Appendix 2b: Biodiversity indices of foraminifera in the core M1

CORE/SAMPLE	M1_1	M1_2	M1_3	M1_4	M1_5	M1_6
Depth (m)	**0.20-0.21**	**1.80-1.81**	**3.10-3.11**	**3.90-3.91**	**6.30-6.31**	**7.95-7.96**
Taxa_S	8	9	6	4	10	15
Individuals	49	180	98	17	80	131
Dominance_D	0,2711	0,3034	0,2416	0,301	0,1481	0,1146
Shannon_H	1.587	1.462	1.522	1.283	2.072	2.359
Fisher_alpha	2.714	1.994	1,41	1.649	3.017	4.369

Appendix 3a: Absolute abundance of foraminifera in the core M2

CORE/SAMPLE	M2_1	M2_2	M2_3	M2_4	M2_5	M2_6
Depth (m)	**5.20-5.21**	**8.20-8.21**	**8.50-8.51**	**10.50-10.51**	**12.20-12.21**	**12.95-12.96**
Adelosina mediterranesis (Le Calvez, J. and Y., 1958)	0	0	0	0	3	0
Ammonia beccarii (Linné, 1758)	4	71	67	69	101	89
Ammonia parkinsoniana (d´Orbigny, 1839)	0	0	0	0	0	0
***Ammonia* sp.**	31	46	70	41	42	77
Ammonia tepida (Cushman, 1926)	45	87	57	71	57	65
***Brizalina* sp.**	0	0	0	0	1	1
Elphidium aculeatum (d´Orbigny, 1846)	0	1	3	3	5	2
Elphidium crispum (Linnaeus, 1758)	0	0	5	21	21	3
Elphidium macellum (Fichtel and Moll, 1798)	0	0	0	0	0	0
***Elphidium* sp.**	0	2	3	11	7	5
***Eponides* sp.**	2	0	0	2	2	0
***Haynesina* sp.**	17	27	37	23	15	21
***Porosononion* sp.**	5	51	28	15	11	17
Quinqueloculina seminula (Linné, 1758)	0	0	0	4	7	4
***Rosalina* sp.**	0	0	0	0	2	1
Sigmoilinita costata (Schlumberger, 1893)	0	0	0	0	0	0
***Textularia* sp.**	0	0	0	0	2	1
Triloculina marioni Schlumberger, 1893	0	0	0	3	3	0
***Triloculina* sp.**	0	0	0	0	0	0
Trochammina inflata (Montagu, 1808)	0	0	0	0	0	0
Indeterminable	7	4	5	7	2	3
Total	**111**	**289**	**275**	**270**	**283**	**290**

Appendix 3b: Biodiversity indices of foraminifera in the core M2

CORE/SAMPLE	M2_1	M2_2	M2_3	M2_4	M2_5	M2_6
Depth (m)	**5.20-5.21**	**8.20-8.21**	**8.50-8.51**	**10.50-10.51**	**12.20-12.21**	**12.95-12.96**
Taxa_S	7	8	9	12	16	13
Individuals	111	289	275	270	283	290
Dominance_D	0,2734	0,2164	0,1965	0,1768	0,2019	0,2245
Shannon_H	1.516	1,64	1.765	1.979	1.984	1.735
Fisher_alpha	1,66	1.524	1.784	2.574	3.672	2.795

Appendix 4a: Absolute abundance of foraminifera in the core M3

CORE/SAMPLE	M3_1	M3_2	M3_3	M3_4	M3_5	M3_6	M3_7	M3_8
Depth (m)	**1.75-1.76**	**1.85-1.86**	**3.55-3.56**	**4.00-4.01**	**6.95-6.96**	**7.30-7.31**	**8.00-8.01**	**8.99-9.00**
Adelosina mediterranesis (Le Calvez, J. and Y., 1958)	0	0	0	0	0	0	0	0
Ammonia beccarii (Linné, 1758)	0	0	0	0	6	2	0	6
Ammonia parkinsoniana (d´Orbigny, 1839)	0	0	0	0	0	0	0	0
***Ammonia* sp.**	0	0	0	0	3	0	1	2
Ammonia tepida (Cushman, 1926)	0	0	0	0	0	0	0	0
***Brizalina* sp.**	0	0	0	0	0	0	0	0
Elphidium aculeatum (d´Orbigny, 1846)	0	0	0	0	0	0	0	0
Elphidium crispum (Linnaeus, 1758)	0	0	0	0	0	0	0	0
Elphidium macellum (Fichtel and Moll, 1798)	0	0	0	0	0	0	0	0
***Elphidium* sp.**	0	0	0	0	0	0	0	0
***Eponides* sp.**	0	0	0	0	0	0	0	0
***Haynesina* sp.**	0	0	0	0	3	0	0	3
***Porosononion* sp.**	0	0	0	0	0	0	0	0
Quinqueloculina seminula (Linné, 1758)	0	0	0	0	0	0	0	0
***Rosalina* sp.**	0	0	0	0	0	0	0	0
Sigmoilinita costata (Schlumberger, 1893)	0	0	0	0	0	0	0	0
***Textularia* sp.**	0	0	0	0	0	0	0	0
Triloculina marioni Schlumberger, 1893	0	0	0	0	0	0	0	0
***Triloculina* sp.**	0	0	0	0	0	0	0	0
Trochammina inflata (Montagu, 1808)	0	0	0	2	1	0	0	4
Indeterminable	0	0	0	0	4	1	1	1
Total	**0**	**0**	**0**	**2**	**17**	**3**	**2**	**16**

Appendix 4b: Biodiversity indices of foraminifera in the core M3

CORE/SAMPLE	M3_1	M3_2	M3_3	M3_4	M3_5	M3_6	M3_7	M3_8
Depth (m)	**1.75-1.76**	**1.85-1.86**	**3.55-3.56**	**4.00-4.01**	**6.95-6.96**	**7.30-7.31**	**8.00-8.01**	**8.99-9.00**
Taxa_S	0	0	0	1	5	2	2	5
Individuals	0	0	0	2	17	3	2	16
Dominance_D	0	0	0	1	0,2457	0,5556	0,5	0,2578
Shannon_H	0	0	0	0	1.487	0,6365	0,6931	1.461
Fisher_alpha	0	0	0	0,7959	2.387	2.622	0	2.497

Appendix 5a: Absolute abundance of foraminifera in the core M4

CORE/SAMPLE	M4_1	M4_2	M4_3	M4_4	M4_5	M4_6	M4_7
Depth (m)	**3.70-3.71**	**4.00-4.01**	**4.50-4.51**	**5.50-5.51**	**6.00-6.01**	**7.20-7.21**	**7.80-7.81**
Adelosina mediterranesis (Le Calvez, J. and Y., 1958)	0	0	0	0	0	0	0
Ammonia beccarii (Linné, 1758)	0	0	0	0	17	43	54
Ammonia parkinsoniana (d´Orbigny, 1839)	0	0	0	0	0	3	2
***Ammonia* sp.**	4	1	2	5	71	67	77
Ammonia tepida (Cushman, 1926)	4	0	2	8	94	87	82
***Brizalina* sp.**	0	0	0	0	0	0	0
Elphidium aculeatum (d´Orbigny, 1846)	0	0	0	0	0	0	0
Elphidium crispum (Linnaeus, 1758)	0	0	0	0	0	1	1
Elphidium macellum (Fichtel and Moll, 1798)	0	0	0	0	0	0	0
***Elphidium* sp.**	0	0	0	0	0	4	3
***Eponides* sp.**	0	0	0	0	2	3	3
***Haynesina* sp.**	0	0	2	4	54	45	37
***Porosononion* sp.**	0	0	0	0	38	37	31
Quinqueloculina seminula (Linné, 1758)	0	0	0	0	0	0	2
***Rosalina* sp.**	0	0	0	0	0	0	0
Sigmoilinita costata (Schlumberger, 1893)	0	0	0	0	0	0	0
***Textularia* sp.**	0	0	0	0	0	0	0
Triloculina marioni Schlumberger, 1893	0	0	0	0	0	0	0
***Triloculina* sp.**	0	0	0	0	0	0	0
Trochammina inflata (Montagu, 1808)	0	0	0	0	0	0	0
Indeterminable	2	0	4	4	10	8	7
Total	**10**	**1**	**10**	**21**	**286**	**298**	**299**

Appendix 5b: Biodiversity indices of foraminifera in the core M4

CORE/SAMPLE	M4_1	M4_2	M4_3	M4_4	M4_5	M4_6	M4_7
Depth (m)	**3.70-3.71**	**4.00-4.01**	**4.50-4.51**	**5.50-5.51**	**6.00-6.01**	**7.20-7.21**	**7.80-7.81**
Taxa_S	3	1	4	4	7	10	11
Individuals	10	1	10	21	286	298	299
Dominance_D	0,36	1	0,28	0,2744	0,2278	0,1959	0,2011
Shannon_H	1.055	0	1.332	1.341	1.614	1.785	1.773
Fisher_alpha	1.453	0	2.471	1.465	1.296	1.995	2.245

Appendix 6a: Absolute abundance of foraminifera in the core M5

CORE/SAMPLE	M5_1	M5_2	M5_3	M5_4	M5_5	M5_6	M5_7	M5_8	M5_9	M5_10	M5_11	M5_12
Depth (m)	**2.60-2.61**	**3.30-3.31**	**5.00-5.01**	**5.30-5.31**	**5.55-5.56**	**6.45-6.46**	**7.10-7.11**	**7.45-7.46**	**8.50-8.51**	**9.00-9.01**	**10.15-10.16**	**10.80-10.81**
Adelosina mediterranesis (Le Calvez,J. and Y., 1958)	0	0	0	0	0	0	0	0	0	0	2	0
Ammonia beccarii (Linné, 1758)	0	0	0	0	0	3	0	13	35	65	59	32
Ammonia parkinsoniana (d´Orbigny, 1839)	0	0	0	0	0	0	0	0	0	0	0	0
***Ammonia* sp.**	2	4	2	2	1	7	0	58	97	77	101	73
Ammonia tepida (Cushman, 1926)	1	2	3	0	3	17	0	86	115	89	77	138
***Brizalina* sp.**	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium aculeatum (d´Orbigny, 1846)	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium crispum (Linnaeus, 1758)	0	0	0	0	0	0	0	0	0	0	1	0
***Elphidium* sp.**	0	0	0	0	0	0	0	0	1	11	3	4
Elphidium macellum (Fichtel&Moll, 1798)	0	0	0	0	0	0	0	0	0	0	0	0
***Eponides* sp.**	0	0	0	0	0	0	0	2	2	0	2	2
***Haynesina* sp.**	2	3	2	4	1	11	0	61	21	17	7	15
***Porosononion* sp.**	0	0	1	0	0	8	0	47	12	14	12	15
Quinqueloculina seminula (Linné, 1758)	0	0	0	0	0	0	0	0	0	0	12	0
***Rosalina* sp.**	0	0	0	0	0	0	0	0	0	0	0	0
Sigmoilinita costata (Schlumberger, 1893)	0	0	0	0	0	0	0	0	0	0	0	0
***Textularia* sp.**	0	0	0	0	0	0	0	0	0	0	0	0
Triloculina marioni Schlumberger, 1893	0	0	0	0	0	0	0	0	0	0	0	0
***Triloculina* sp.**	0	0	0	0	0	0	0	0	0	0	0	0
Trochammina inflata (Montagu, 1808)	0	0	0	0	0	0	7	0	0	0	0	0
Indeterminable	2	3	2	3	1	2	1	11	6	12	8	11
Total	**7**	**12**	**10**	**9**	**6**	**47**	**8**	**278**	**289**	**285**	**284**	**290**

Appendix 6b: Biodiversity indices of foraminifera in the core M5

CORE/SAMPLE	M5_1	M5_2	M5_3	M5_4	M5_5	M5_6	M5_7	M5_8	M5_9	M5_10	M5_11	M5_12
Depth (m)	**2.60-2.61**	**3.30-3.31**	**5.00-5.01**	**5.30-5.31**	**5.55-5.56**	**6.45-6.46**	**7.10-7.11**	**7.45-7.46**	**8.50-8.51**	**9.00-9.01**	**10.15-10.16**	**10.80-10.81**
Taxa_S	4	4	5	3	4	6	2	7	8	7	11	8
Individuals	7	12	10	9	6	48	8	278	289	285	284	290
Dominance_D	0,2653	0,2639	0,22	0,358	0,3333	0,2326	0,7813	0,2198	0,2932	0,2318	0,2483	0,309
Shannon_H	1.352	1.358	1.557	1.061	1.242	1,59	0,3768	1,63	1.446	1.629	1.645	1.468
Fisher_alpha	3.878	2.101	3,98	1.576	5.245	1,81	0,8559	1.304	1.524	1.297	2.275	1.522

Appendix 7a: Absolute abundance of foraminifera in the core M6

CORE/SAMPLE	M6_1	M6_2	M6_3	M6_4	M6_5
Depth (m)	**3.75-3.76**	**5.30-5.31**	**6.45-6.46**	**7.05-7.06**	**7.45-7.46**
Adelosina mediterranesis (Le Calvez, J. and Y., 1958)	0	0	0	0	0
Ammonia beccarii (Linné, 1758)	11	14	7	5	31
Ammonia parkinsoniana (d´Orbigny, 1839)	0	0	0	0	0
***Ammonia* sp.**	87	82	98	75	80
Ammonia tepida (Cushman, 1926)	125	101	134	136	111
***Brizalina* sp.**	0	0	0	0	0
Elphidium aculeatum (d´Orbigny, 1846)	0	0	0	0	0
Elphidium crispum (Linnaeus, 1758)	0	0	0	0	0
Elphidium macellum (Fichtel and Moll, 1798)	0	0	0	0	0
***Elphidium* sp.**	0	0	0	0	0
***Eponides* sp.**	0	8	3	3	7
***Haynesina* sp.**	41	39	34	32	45
***Porosononion* sp.**	34	45	34	31	21
Quinqueloculina seminula (Linné, 1758)	0	0	0	0	0
***Rosalina* sp.**	0	0	0	0	0
Sigmoilinita costata (Schlumberger, 1893)	0	0	0	0	0
***Textularia* sp.**	0	0	0	0	0
Triloculina marioni Schlumberger, 1893	0	0	0	0	0
***Triloculina* sp.**	0	0	0	0	0
Trochammina inflata (Montagu, 1808)	2	0	0	0	0
Indeterminable	5	7	4	9	2
Total	**305**	**196**	**314**	**291**	**297**

Appendix 7b: Biodiversity indices of foraminifera in the core M6

CORE/SAMPLE	M6_1	M6_2	M6_3	M6_4	M6_5
Depth (m)	**3.75-3.76**	**5.30-5.31**	**6.45-6.46**	**7.05-7.06**	**7.45-7.46**
Taxa_S	7	7	7	7	7
Individuals	305	296	314	291	297
Dominance_D	0,2814	0,2372	0,3037	0,3096	0,2517
Shannon_H	1.458	1.606	1.393	1.411	1.552
Fisher_alpha	1.277	1.286	1.269	1.291	1.285

Appendix 8a: Absolute abundance of foraminifera in the core NER5

CORE/SAMPLE	NER5_1	NER5_2	NER5_3	NER5_4	NER5_5	NER5_6	NER5_7	NER5_8
Depth (m)	**2.10-2.11**	**2.80-2.81**	**3.00-3.01**	**3.20-3.21**	**3.30-3.31**	**3.60-3.61**	**4.50-4.51**	**4.90-4.91**
Ammonia sp.	0	0	0	0	72	44	57	77
Ammonia beccarri (Linné, 1758)	0	0	0	0	7	15	81	86
Ammonia parkinsoniana (d´Orbigny, 1839)	0	0	0	0	42	53	34	31
Ammonia tepida (Cushman, 1926)	0	0	0	0	95	121	67	55
Asterigerinata sp.	0	0	0	0	0	1	0	1
Buccella sp.	0	0	0	0	5	2	6	2
Elphidium sp.	0	0	0	0	0	0	0	0
Elphidium depressulum Cushman, 1933	0	0	0	0	0	0	0	0
Eponides sp.	0	0	0	0	1	2	2	2
Haynesina sp.	0	0	0	0	47	32	24	17
Porosononion sp.	0	0	0	0	22	29	29	24
Quinqueloculina seminula (Linné, 1758)	0	0	0	0	0	0	0	0
Indeterminable	0	0	0	0	9	5	2	6
Total	**0**	**0**	**0**	**0**	**300**	**304**	**302**	**301**

Appendix 8b: Biodiversity indices of foraminifera in the core NER5

CORE/SAMPLE	NER5_1	NER5_2	NER5_3	NER5_4	NER5_5	NER5_6	NER5_7	NER5_8
Depth (m)	**2.10-2.11**	**2.80-2.81**	**3.00-3.02**	**3.20-3.21**	**3.30-3.31**	**3.60-3.61**	**4.50-4.51**	**4.90-4.91**
Taxa_S	0.00	0.00	0.00	0.00	9	10	9	10
Individuals	0.00	0.00	0.00	0.00	300	304	302	301
Dominance_D	0.00	0.00	0.00	0.00	0.21	0.23	0.19	0.20
Shannon_H	0.00	0.00	0.00	0.00	1.74	1.71	1.82	1.78
Fisher_alpha	0.00	0.00	0.00	0.00	1.75	1.99	1.74	1.99

Appendix 9a: Absolute abundance of foraminifera in the core NER6

CORE/SAMPLE	NER6_1	NER6_2	NER6_3	NER6_4	NER6_5	NER6_6	NER6_7	NER6_8	NER6_9	NER6_ 10	NER6_ 11	NER6_ 12	NER6_ 13	NER6_ 14	NER6_ 15	NER6_ 16
Depth	**2.10-2.11**	**3.00-3.01**	**3.25-3.26**	**3.30-3.31**	**3.35-3.36**	**3.40-3.41**	**3.45-3.46**	**3.50-3.51**	**3.55-3.56**	**3.60-3.61**	**3.65-3.66**	**4.50-4.51**	**5.50-5.51**	**6.50-6.51**	**7.50-7.51**	**8.10-8.11**
Ammonia sp.	0	0	2	23	9	27	34	65	76	64	77	55	65	51	71	54
Ammonia beccarri (Linné, 1758)	0	0	0	7	3	5	7	11	21	11	13	57	99	117	103	123
Ammonia parkinsoniana(d´Orbigny, 1839)	0	0	0	15	9	15	21	34	47	32	31	34	27	21	17	21
Ammonia tepida (Cushman, 1926)	0	0	0	12	21	51	47	97	117	132	112	89	34	45	67	56
Asterigerinata sp.	0	0	0	0	0	1	0	0	1	1	0	2	0	2	0	1
Buccella sp.	0	0	0	0	0	0	0	0	4	5	2	1	2	4	2	5
Elphidium sp.	0	0	0	0	0	0	0	0	1	1	0	1	1	0	1	2
Elphidium depressulum Cushman, 1933	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Eponides sp.	0	0	0	0	0	0	1	2	0	0	0	2	2	3	1	3
Haynesina sp.	0	0	0	5	2	3	8	31	35	27	51	32	37	34	27	17
Porosononion sp.	0	0	0	0	5	5	15	23	15	25	17	45	25	17	11	7
Quinqueloculina seminula (Linné, 1758)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
Indeterminable	0	0	0	2	4	2	5	7	4	5	3	5	1	7	2	4
Total	**0**	**0**	**2**	**64**	**53**	**109**	**138**	**270**	**321**	**303**	**306**	**323**	**293**	**301**	**302**	**314**

Appendix 9b: Biodiversity indices of foraminifera in the core NER6

CORE/SAMPLE	NER 6_1	NER 6_2	NER 6_3	NER 6_4	NER 6_5	NER 6_6	NER 6_7	NER 6_8	NER 6_9	NER 6_10	NER 6_11	NER 6_12	NER 6_13	NER 6_14	NER 6_15	NER 6_16
Depth of sample (m)	**2.10 - 2.11**	**3.00 - 3.01**	**3.25 - 3.26**	**3.30 - 3.31**	**3.35 - 3.36**	**3.40 - 3.41**	**3.45 - 3.46**	**3.50 - 3.51**	**3.55 - 3.56**	**3.60 - 3.61**	**3.65 - 3.66**	**4.50 -4.51**	**5.50 - 5.51**	**6.50 - 6.51**	**7.50 - 7.51**	**8.10 - 8.11**
Number of species (S)	0	0	1	6	7	8	8	8	10	10	8	11	10	10	10	13
Number of specimens (N)	0	0	2	64	53	109	138	270	321	303	306	323	293	301	302	314
Dominance (D)	0.00	0.00	1.00	0.24	0.23	0.30	0.22	0.23	0.23	0.26	0.24	0.18	0.21	0.22	0.23	0.23
Shannon-Wiener index (H)	0.00	0.00	0.00	1.57	1.67	1.47	1.71	1.69	1.70	1.64	1.62	1.87	1.75	1.77	1.64	1.83
Fisher α index	0.00	0.00	0.80	1.62	2.16	1.99	1.85	1.55	1.96	1.99	1.50	2.20	2	1.99	1.99	2.74

Appendix 10: Semi-quantitative estimation of mineral abundance based on XRD (Felja et al., 2016).

+++ - dominant minerals; ++ – significant amount of minerals; + - secondary minerals; traces – minerals present only in traces.

Sample	Depth (m)	Quartz	Calcite	Mg-calcite	Aragonite	Chlorite	Dolomite	10Å phyllosilicates	Kaolinite	Plagioclas	K-feldspar
P1	2.0-2.1	+++	+++	+	+	+	+	+	-	-	-
P5	10.0-10.1	traces	+++	-	traces	-	-	-	-	-	-
P14	28.0-28.1	+++	traces	-	-	++	-	++	++	+	traces
P15	32.0-32.1	+	+++	-	+	traces?	traces	traces	traces?	-	-
P36	74.0-74.1	+++	-	-	-	traces	-	-	++	-	-
P45	96.0-96.1	+++	+	-	-	-	+++	traces?	++	-	traces?

Plate 1: A - *Ammonia* sp. ; B - *Ammonia beccarii* (Linné, 1758); C - *Haynesina* sp.; D - *Rosalina* sp.; E - *Elphidium* sp.; F – *Textularia* sp.; G - *Brizalina* sp.; H - *Quinqueloculina sp*; I - *Quinqueloculina seminula* (Linné, 1758) ; J - *Triloculina marioni* Schlumberger, 1893. Pictures taken with SEM Tescan TS5136.

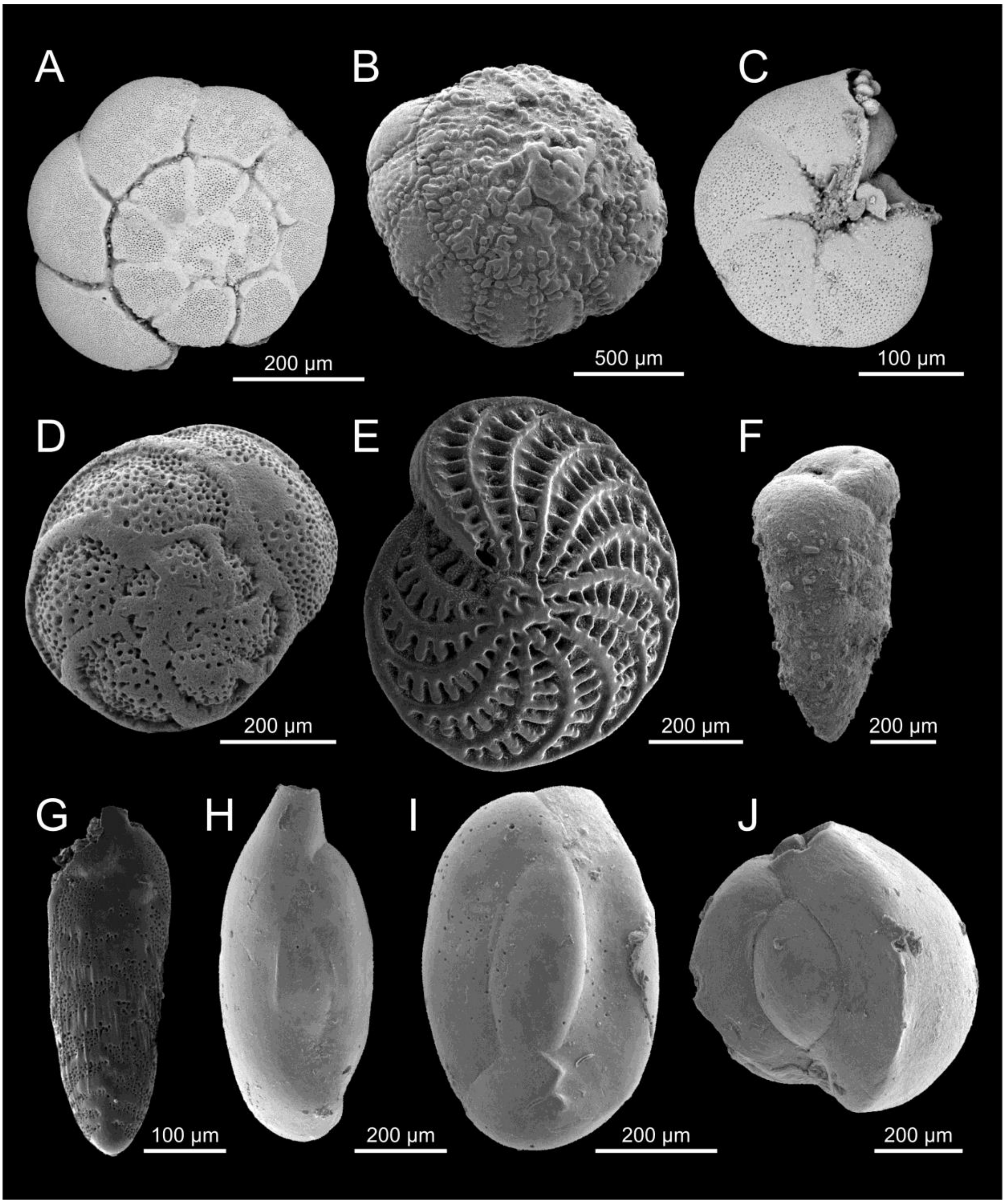
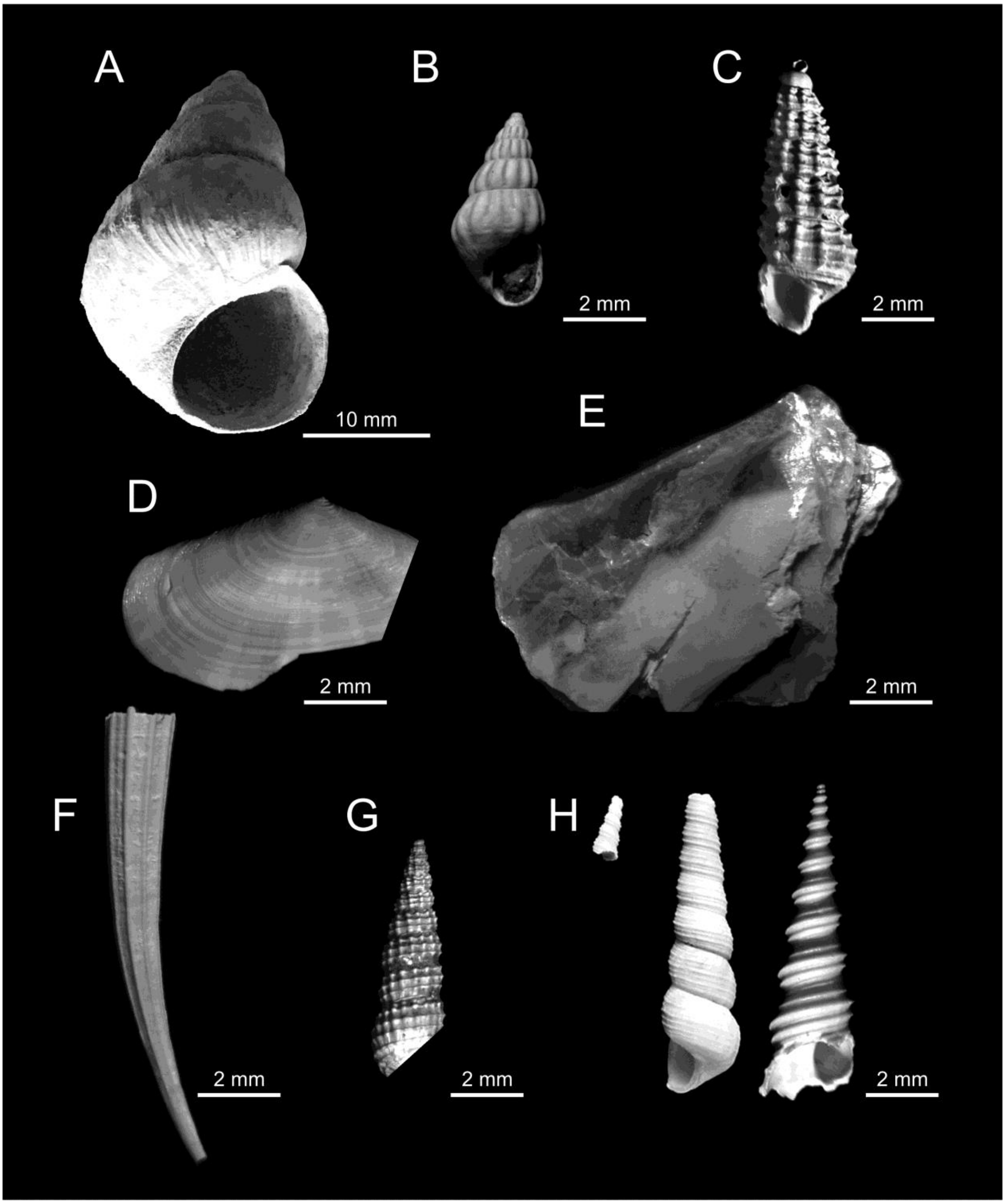


Plate 2: A - *Viviparus* sp. ; B – *Rissoa* sp.; C – *Cerithium* sp.; D – *Tellina* sp.; E – fragment of *Ostrea* sp.; F – scaphopoda; G – Bittium sp.; H – *Turritella* sp. Pictures taken with EUROMEX ImageFocus 4.0 camera.



10. EXPENDED ABSTRACT (CROATIAN)

Istočno obalno područje Jadrana građeno je uglavnom od karbonatnih stijena (vapnenaca i dolomita) kod kojih kemijsko trošenje prevladava nad mehaničkim. U tom području, tijekom kvartara, procesi okršavanja su bili jaki, a riječni, terigeni donos bio je ograničen. U takvim uvjetima, rijeke su na svojim ušćima formirale tzv. krške estuarije. Krški estuariji stvoreni na okršenim karbonatnim stijenama, zahtijevaju obalni okoliš male energije (zaštićena pozicija riječnog ušća i mali raspon visokih i niskih voda) i karakterizirani su malim donosom terigenog (riječnog) materijala, zbog nedostatka donosa klastičnog materijala (otapanje karbonata). Ipak, postoji nekoliko iznimaka, npr. riječna ušća Neretve, Mirne i Raše, kod kojih je donos terigenog materijala nešto veći, jer materijal potječe iz alogenih izvora u drenažnom području, te su jedine rijeke u Hrvatskoj koje su stvorile delte na ušćima tijekom holocena.

Razvoj obale tijekom kvartara povezan je s oscilacijama razine mora, čiji je uzrok izmjena razdoblja glacijala i interglacijala. Tijekom zadnjeg glacijalnog maksimuma (LGM, 29000-19000 godina prije sadašnjosti), kada je razina mora bila ~120 m niža od današnje, rijeke na istočnoj strani jadranskog bazena usijecale su svoje doline u karbonatnu podlogu. Nakon razdoblja glacijalnog maksimuma, velike površine leda su se otapale i razina mora se naglo podizala, što je dovelo do globalne transgresije i poplavljivanja velikih područja, pa tako i područja Jadrana. Jadransko more je poplavilo krške riječne doline i stvoreni su krški estuariji, između ostalih i oni Neretve i Mirne. Porast razine mora se usporio u zadnjih 7000-6000 godina, što je uzrokovalo postepeno ispunjavanje estuarija s terigenim materijalom i stvaranje delti unutar estuarija.

Sedimenti prijelaznih okoliša, koji se razvijaju oko srednje razine mora, npr. slane močvare, posebno su korisni u rekonstrukcijama razina mora u prošlosti. Ipak, u takvim rekonstrukcijama, važno je uzeti u obzir i čimbenike poput slijeganja sedimenata te subsidencije područja.

Ova doktorska disertacija ima sljedeće ciljeve:

1. Opisati kasno pleistocenske i holocenske sljedove taložnih facijesa u krškim riječnim ušćima, koji su zapisani u završnim dijelovima dolina rijeka Mirne i Neretve.

2. Rekonstruirati geomorfološku evoluciju ovih područja.

3. Unaprijediti znanje o razinama mora u prošlosti, klimatskim promjenama i ljudskim aktivnostima, koje su se događale nakon razdoblja zadnjeg glacijalnog maksimuma.

Promjene razine mora koje su se odvijale tijekom kasnog pleistocena i holocena utjecale su značajno na evoluciju i stvaranje različitih okoliša na područjima riječnih ušća. Svaki okoliš sadrži karakteristične sedimentne značajke i zajednice fosila, koji odražavaju uvjete u kojima se odvijao život i sedimentacija. Ovo istraživanje će pomoći u rekonstrukciji razina mora u prošlosti i klimatskih promjena u području istočno-jadranske obale (koja je do sada slabo istražena), ali također i u Sredozemlju, tijekom kasnog pleistocena i holocena. Nadalje, rezultati ovog istraživanja trebali bi doprinijeti boljem razumijevanju evolucije delti unutar estuarija i njihovoj zaštiti i održivom razvoju.

Promjene razine mora su bile česte tijekom prošlosti Zemlje i imale su najznačajniju ulogu u nastanku i oblikovanju različitih obalnih okoliša, što je i danas vrlo izraženo. Razdoblje kvartara (zadnjih 2.59 milijuna godina) karakterizirano je velikim klimatskim promjenama (izmjenama glacijala i interglacijala). Glavni uzroci ovih varijacija su promjene u orbitalnim parametrima Zemlje (Milankovićevi ciklusi), koji uzrokuju varijacije u intenzitetu Sunčevog zračenja na različite dijelove Zemljine površine, što dalje uzrokuje stvaranje ili otapanje velikih površina leda. Relativne promjene razine mora su zbroj eustatskih promjena, tektonskih pokreta, kompakcije sedimenata, i glacio-izostatskih čimbenika.

Globalna razina mora, u zadnjih 2 milijuna godina, mijenjala je poziciju između ~130 m ispod današnje razine mora do ~6 m iznad današnje razine mora. Razdoblja kada su razine mora bile nisko (MIS4 i MIS3) i razdoblje kada je razina mora dosegnula najnižu razinu (MIS2), bila su izuzetno važna u oblikovanju područja današnjeg Jadranskog i Sredozemnog mora. Tijekom ovih razdoblja, velike površine današnjeg morskog dna bila su pod utjecajem atmosferilija, što je uzrokovalo pojačanu eroziju i okršavanje starijih naslaga, a obalna linija bila je znatno dalje prema moru nego danas. Riječni, padinski i eolski procesi, erozija, okršavanje, trošenje, stvaranje tla i okršavanje odvijalo se na velikim područjima sredozemnog obalnog područja, koje je danas ispod morske razine.

Riječna ušća su osjetljiva na utjecaje i s mora i s kopna i izuzetno je važno razumjeti procese koji na njih utječu. Estuariji su proširenja mora u riječne doline, a općenito mogu biti podijeljen na tri dijela: a) gornji ili riječni estuarij, dominantno pod utjecajem rijeke i slatke vode; b) srednji estuarij, koji je podložan jakom miješanju slane i slatke vode; c) marinski ili donji estuarij, pod dominantnim utjecajem mora. Krški estuariji predstavljaju posebni tip estuarija, s jedinstvenim karakteristikama, koje će biti detaljnije opisane.

Estuariji su formirani u uskoj zoni između mora i kopna i njihov vijek je relativno kratak. Na oblik estuarija konstantno utječu erozija, taloženje sedimenta i promjene razine mora. Čimbenici koji utječu na stratigrafski slijed, mehanizam stvaranja i očuvanja sedimentnih tijela u estuariju su morfološke i litološke značajke drenažnog područja, hidrodinamički procesi, fluktuacije razine mora, donos sedimenata, klimatske promjene i ljudski utjecaj

Delte unutar estuarija su relativno mala sedimentne akumulacije u usporedbi s veličinom estuarija. Neki krški estuariji npr. Mirna, Raša i Neretva, stvorile su delte unutar estuarija, koje su progradirale tijekom holocena zahvaljujući povećanom sedimentnom donosu rijekama, koje u gornjim dijelovima porječja teku po područjima građenima od stijena podložnih eroziji, a ne samo po karbonatima.

Rijeka Mirna nalazi se u sjeverozapadnom dijelu Istarskog poluotoka. Najduža je Istarska rijeka (53 km), s hidrografskim slivom od ~402.9 km^2, ali s obzirom na intenzivne krške procese, podzemna cirkulacija vode je dobro razvijena te je hidrogeološki sliv ~583.5 km^2. Prosječni protok rijeke Mirne je 16m^3/s. Drenažno područje rijeke Mirne izgrađeno je od karbonata, uglavnom kredne i eocenske starosti, te eocenskog fliša (lapori i pješčenjaci). Područje deltne ravnice rijeke Mirne, od ušća u more do mosta Ponte Porton iznosi ~14.5 km^2.

Rijeka Neretva nalazi se na južnom dijelu Hrvatske te je najduža rijeka s istočne strane Jadranskog mora, s hidrogeološkim slivom od ~13,280 km^2 (3060 km^2 u Hrvatskoj). Neretva je dugačka 215 km i protječe većim dijelom kroz planine Bosne i Hercegovine (građene od raznolikih sedimentnih, metamorfnih i magmatskih stijena), a u Hrvatskoj teče samo zadnjih 22 km prije ulijevanja u Jadransko more. Prosječni protok rijeke Neretve iznosi 332 m^3/s. Deltno područje rijeke Neretve pokriva ~170 km^2, od toga se 120km^2 nalazi u Hrvatskoj. Stijene podloge dominantno su građene od krednih i eocenskih vapnenaca te eocenskog fliša u deltnom području.

Za potrebe ove disertacije, 8 plitkih jezgri (M1-M8, maks. dubina 13 m) te jedna jezgra 40 m duboka (MIR1), izvađene su u deltnoj ravnici rijeke Mirne. Šest plitkih jezgri (NER1-NER6, do 9 m dubine), te dvije dublje jezgre (NER120 i NER20, dugačke 120 m i 18 m) izvađene su u deltnoj ravnici rijeke Neretve, a jedna jezgra je dobivena iz Malostonskog kanala iz dubine od približno 30 m ispod razine mora (P1, 96 m dugačka). Jezgre su detaljno opisane na terenu i kasnije u laboratoriju (sedimentološki i paleontološki), gdje su dalje analizirane. Ukupna dužina svih izvađenih jezgri je 380 m, a od toga je 106 m jezgri (plitke jezgre) izvađeno ručnim jezgrilom (korerom) marke Ejikelkamp.

Granulometrijske analize napravljene su na ukupno 178 uzoraka, kombiniranom metodom mokrog sijanja i sedigrafa. Kalcimetrija je napravljena volumetrijskim mjerenjem CO2 na Scheiblerovoj aparaturi na ukupno 145 uzoraka. Foraminiferske analize napravljene su na 68 uzoraka iz 8 jezgri pomoću FOBIMO standardizacijskog protokola te su foraminifere određivane na stereoskopskoj lupi Stereo Zoom Microscope i klasificirane na temelju Loeblich i Tappan (1987) te Cimerman i Langer (1991) klasifikaciji. Indeksi bioraznolikosti izračunati su pomoću Past programa. Na ukupno 12 uzoraka određena je starost metodom radioaktivnog ugljika 14C (AMS metoda).

Sedimentne jezgre iz deltne ravnice rijeke Mirne pokazale su relativno jednoličan granulometrijski sastav, dominantno su građene od sitnozrnatih čestica, veličine gline i praha, dok su frakcije pijeska i šljunka prisutne u vrlo malim količinama, i to kao biogena komponenta (ljušturice puževa, školjkaša, foraminifera i ostrakoda). Udio karbonata u jezgri MIR1 ne prelazi 45%. Maksimalni broj vrsta foraminifera primiјećen je u jezgri M2 (17 vrsta), no indeksi bioraznolikosti su u većini uzoraka relativno niski. Najveća starost od 8471-8280 BC, koja je izmjerena u jezgri MIR1 na dubini 33 m ispod srednje razine mora.

Sedimentne jezgre iz deltne ravnice rijeke Neretve su dominantno muljevite frakcije (glina i prah), ali udio pijeska je značajno veći u odnosu na jezgre iz deltne ravnice rijeke Mirne. Jezgra NER120 ispod 30 m dubine građena je od pjeskovitog šljunka i šljunkovitog pijeska. Udio karbonata je također veći i kreće se prosječno između 40-50%. Veći udio krupnozrnate frakcije u jezgrama iz deltne ravnice Neretve je posljedica drenažnog područja rijeke Neretve koje je puno veće i sastoji se od stijena koje su podložne eroziji (klastične sedimentne, metamorfne i magmatske stijene), u odnosu na drenažno područje Mirne koje je izgrađeno isključivo od karbonata i fliša (u kojemu dominiraju lapori nad pješčenjacima).

Najveći broj vrsta foraminifera primijećen je u jezgri NER6 (13 vrsta), no indeksi bioraznolikosti su još niži u odnosu na jezgre iz deltne ravnice rijeke Mirne. Najveća starost izmjerena u jezgri NER6 iznosi 1370-1126 BC na dubini od 7 m ispod srednje razine mora.

Jezgra P1 građena je dominantno od mulja (glina i prah), ali pokazuje izuzetno veliki raspon udjela karbonata (1-95 %).

Taložni slijed sačuvan u sedimentu deltnih ravnica rijeka Mirne i Neretve, pokazuje karakteristične sedimentne značajke i fosilnu zajednicu (bentičke foraminifere, školjkaše i puževe) koji odražavaju različite okoliše u kojima su sedimenti taloženi tijekom kasnog kvartara. U sedimentnim jezgrama iz deltnih ravnica rijeka Mirne i Neretve (jezgre M1-M8; NER1-NER6) određeni su aluvijalni facijesi taloženi na facijesima prijelaznih okoliša (slane/brakične močvare (Ba), unutrašnji estuarij (Bb)), a ispod njih se nalaze sedimenti taloženi u estuarijskom okolišu (E).

U jezgri MIR1 prepoznat je sličan slijed u prvih ~10 m, ali ispod toga se nalaze sedimenti taloženi tijekom maksimuma transgresije u dubokom estuariju (prisutnost *Turitella* sp.), a dublje ponovno okoliši unutrašnjeg estuarija/slane/brakične močvare. Na dubinama 35-40 m izbušene su aluvijalne naslage i paleo-tla taložena tijekom zadnjeg glacijalnog maksimuma.

U jezgrama NER120 (30-120 m dubine) i NER20 (16-18 m dubine) nalaze se aluvijalni šljunci i pijesci, taloženi vjerojatno tijekom zadnjeg glacijalnog maksimuma. Na njih su nataložene naslage transgresivnog trakta, TST, (transgresivni pijesci i prah) i trakta visoke razine mora (HST), odnosno sedimenti nataloženi progradacijom delte unutar estuarija.

U jezgra P1 iz Malostonskog kanala nađeni su terigene aluvijalne naslage u dubljim slojevima (60-96 m dubine), naslage jezerskog sedimenta (8-60 m dubine), te najpliće naslage (2-8 m dubine) morskih sedimenta (sedimenti prodelte Neretve).

Krške doline kanjonskog tipa Mirne i Neretve vjerojatno su usječene za vrijeme zadnjeg glacijalnog maksimuma, ali moguće i ranije, s obzirom da je dolina rijeke Mirne na lokaciji kod vijadukta duboka oko 160 m, što je dublje od najniže razine mora tijekom zadnjeg glacijalnog maksimuma (~120 m niža razina od srednje razine mora). Tijekom zadnjeg glacijalnog maksimuma, Paleo-Mirna i Paleo-Neretva su erodirale starije naslage i vjerojatno dosegnule karbonatnu podlogu, u koju su se zatim još dublje usijecale. Transgresija koja se odvijala nakon zadnjeg glacijalnog maksimuma uzrokovala je potapanje tih fluvio-krških dolina i taloženje transgresivnih naslaga. Tijekom holocena, nakon usporavanja porasta razine mora, taložile su se naslage trakta visoke razine mora uz progradaciju delti unutar estuarija rijeka Mirne i Neretve, što je dovelo do gotovo potpunog ispunjavanja nekadašnjih estuarija i razvoja današnjih deltnih ravnica Mirne i Neretve. Tijekom visoke razine mora u holocenu, u zadnjih 6500-7000 godina, delta unutar estuarija Mirne progradirala je vjerojatno više od 11 km, od mosta Ponte Porton do današnjeg ušća Mirne. Progradacija delte unutar estuarija Neretve vjerojatno je bila još veća (možda čak 25 km od ušća do Čapljine), uzimajući u obzir puno veću površinu današnje deltne ravnice Neretve i veći donos sedimenata u prošlosti. Debljina holocenskih naslaga iznosi između 30-40 m (jezgre MIR1, NER120).

Ljudski utjecaj na obje delte bio je iznimno jak u prošlosti, ali i danas. Od kasne Antike, velike količine aluvijalnog materijala nataložile su se u dolini rijeke Mirne (više od 9 m u jezgri M3). Ova intenzivna sedimentacija djelomično je bila uzrokovana deforestacijom, koja se u dolini Mirne intenzivno odvijala između 15–19 stoljeća. U doline rijeke Neretve, najveći ljudski utjecaj bio je izgradnja brana na Neretvi tijekom 20. stoljeća, koje su uzrokovale zadržavanje znatne količine krupnozrnatog materijala i ograničile njegov donos materijala Neretvom do ušća u more.

Relativno debeo sedimenti nanos ubrzao je subsidenciju i kompakciju holocenskih naslaga što treba uzeti u obzir prilikom rekonstrukcija razine mora u prošlosti. Zbog toga je za precizne rekonstrukcije razine mora važno izbušiti jezgre u sedimentu u bokovima doline, koje će doseći stijene podloge relativno plitko pod površinom, a zahvatiti sedimente taložene u prijelaznim okolišima koji su najpogodni za određivanje razine mora u prošlosti (npr. kao u jezgrama NER5 i NER6).

Estuariji Mirne i Neretve mogli bi se klasificirati kao neravnotežni "catch-up" estuariji, po Cooper et al. (2011) klasifikaciji, u kojima se odvija zadnja faza progradacije delte unutar estuarija.

Uzimajući u obzir činjenicu da je istočna strana Jadrana do sada slabo istražena, istraživanja krških estuarija i njihovih taložnih sljedova je važno. Krški estuariji duž istočne obale Jadranske obale su specifični okoliši u kojima se odvija taloženje materijala tijekom holocena. Ipak, ovi krški estuariji nisu identični i imaju različite obrasce taloženja. Okoliš niske energije (zaštićena pozicija riječnog ušća i mali plimni raspon) te način cirkulacije vode stratificiranog estuarija (brakični površinski sloj prema moru, a slani morski sloj pridneno prema kopnu, što vraća čestice koje su potonule iz brakičnog sloja prema rijeci), i pojačana flokulacija na granici slane/slatke vode, dovode do brze sedimentacije većine riječnog materijala u gornjem dijelu estuarija. U usporedbi s većim deltnim sustavom (npr. onim rijeke Po), taloženje materijala u krškim estuarijima je mnogo manje zbog litoloških karakteristika drenažnog područja. Uz to krške doline su pliće pa je i kompakcija sedimenta i subsidencija područja manja, što treba uzeti u obzir prilikom rekonstrukcije razine mora u prošlosti.

Druga riječna ušća na istočnoj strani Jadranskog mora, npr. ušća rijeka Krke, Zrmanje, Cetine, Raše i Rječine, pokazuju neke sličnost, ali i razlike u usporedbi s estuarijima rijeka Mirne i Neretve. Sedrene barijere koje su se tijekom holocena stvorile na Krki i Zrmanji, zadržavaju većinu materijala koje ove rijeke nose, pa je i donos terigenog (čestičnog) materijala do mora puno manji. Rijeka Cetina ima nešto veći donos suspendiranog materijala do ušća, koje je dominantno građeno od pijeska, iako nije stvorila deltu unutar estuarija. Rijeka Rječina je formirala deltu građenu od šljunka na svom ušću. Količina materijala kojeg rijeka Raša donese do mora je značajno veća, zbog trošenja fliša u njenom drenažnom području te zbog nedostatka sedrenih barijera na njenom toku. Stoga je i progradacija delte unutar estuarija Raše uznapredovala, ali još uvijek nije dosegnula do mora, kao što je slučaj u estuarijima Mirne i Neretve.

Daljnja istraživanja krških estuarija, sedimentološka, paleontološka (analize ljušturica foraminifera, ostrakoda, dijatomea, školjkaša, puževa, te polena), geokronološka te pogotovo geofizička (seizmička) istraživanja, značajno će unaprijediti preciznost i detalje u rekonstrukciji taložnih okoliša, kao i u rekonstrukciji promjena razine mora u prošlosti. Također će omogućiti bolje i sigurnije predviđanje budućih trendova promjena ovih okoliša uslijed promjena razine mora i ljudskog utjecaja i na taj način pomoći u očuvanju ovih ekonomsko i ekološko izuzetno važnih područja.

11. CURRICULUM VITAE

Igor Felja was born on 5th May 1984 in Zagreb, Croatia. He went in VII Gymnasium in Zagreb between 1999-2003. Between 2003-2009 he was a student at University of Zagreb, Faculty of Science, Department of Geology, where he obtained his Master degree in Geology. Since 2011, he is employee of Department of Geology, Faculty of Science, University of Zagreb, as teaching assistant/scientific novice. He held practices for students in several courses in the frame of Bachelor and Master Studies and field course in Geological mapping.

Igor Felja has published 7 scientific papers in journals cited by WOS. Sum of times cited 47 (May 2017) according to Google Scholar and H index 3. He is also co-author on several abstracts. He held several lectures at scientific congresses and held lectures for student projects. He was participant at two Medflood workshops held in Israel and Italy/Croatia/Slovenia. In 2016 he was given award for the best scientific novice (young scientist) at the Faculty of Science in Zagreb and award for the best poster at the phd congress held in Zagreb in 2016.

<u>Research associate at projects:</u>

Jednokratni monitoring hidromorfološkog stanja 19 vodnih tijela prijelaznih voda (2016-2017) (705316) Hrvatske Vode IOR Split MJ

HRZZ 2504 NanoMin (2014-2018, Ivan Sondi)

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