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Environmental changes in the lower Mirna River valley (Istria, Croatia) during the Middle and Late Holocene

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ABSTRACT

Sedimentological, macro- and micropaleontological analyses on 3 cores down to 13 m depth were carried out in the lower section of the Mirna River valley, in order to study the depositional facies and the environmental evolution.

The Holocene marine transgression reached upstream for 7 km from the present-day coast, while in the last 7 ka it was followed by progradation of the Mirna River estuarine delta. The protected coast offered by the lower valley and the strong input of fresh water led to the presence of a brackish microfauna in front of the river mouth.

The oldest sediments in the cores were characterized by the dominance of *Ammonia beccarii* and significant proportions of *Elphidium* spp. and miliolids suggesting a marine/estuarine origin. The foraminiferal assemblage in the overlying sediments became less diverse, as the relative abundance of *Elphidium* spp. and miliolids dropped, implying a shift to a transitional environment (inner estuarine/lagoon facies, Bb). Sediments originating in hyposaline marshes (facies Ba) had the lowest foraminiferal species diversity index (*A. beccarii* predominated over *Trochammina inflata* and *Haynesina* sp.).

Since late-Antiquity a significant input of alluvial matter led to the deposition of several metres of silty clay sediments which reach >9m thick in the M3 core. The sediment supply has been partly increased by deforestation carried out in the Mirna catchment area. This was particularly extensive from the 15th–19th centuries and fed the fluvial system with large amounts of material, causing the increase of sediment input and rapid progradation of the estuarine (bay-head) delta.

This study also 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 anthropogenic activities that occurred during the Holocene.

Keywords: sedimentary facies, karstic estuary, lagoon, bay head delta, foraminifers, radiocarbon age, Adriatic Sea

1. INTRODUCTION

The Northern Adriatic coast is characterized by the dramatic morphological contrast between the low-lying landscape of the northwest coast, with sand ridges and lagoons (CASTIGLIONI, 1997) and the rocky coast of the eastern side, where steep coasts are common and the coastline is often strongly indented (FURLANI et al., 2014). Holocene sediments are extensive along the Italian side, reaching up to 40 m in thickness, and the study of the lagoon and shallow-marine facies allowed detailed description of the marine transgression (*e.g.* BRAMBATI et al., 2003; AMOROSI et al., 2008). In contrast, along the northeast coast between Monfalcone (Italy) and Bar (Montenegro), the Quaternary deposits are rare, often very thin, and generally limited to several places often in protected bays (PIKELJ & JURAČIĆ, 2013; OGRINC et al., 2007; PAVELIĆ et al., 2014). Such a patchy distribution is related to the lithology and geological structure of the coast implying limited sedimentary supply from the karstic rivers. Generally, along the eastern Adriatic coast, the surface hydrographical network is poor and the alluvial inputs reaching the sea are generally scarce. There are a few exceptions for example the Neretva or Raša river systems, having high terrigenous load from allogenic sources in the hinterland.

A few studies, derived from scattered drill cores, document the significant thickness of the Holocene coastal sequence in some of these terminal valleys, as in the Neretva River (VRANJEŠ et al., 2007), Rječina River (BENAC & ARBANAS, 1990) and Raša River (SONDI et al., 1995). In the Dragonja River, near Sečovlje, the base of paralic deposits was discovered 26 m below the surface and was dated to about 10,000 years BP (OGORELEC, 1981). In the eastern part of the Northern Adriatic region, in Istria, one of the largest deltaic plains is the lower valley of the Mirna River, with particular environmental characteristics that have attracted historians, archaeologists and geographers since the end of the 19th century (see CARRE, 2007; D'INCÀ, 2007 and references therein), but little attention has been paid to the geomorphological and geological aspects.

The aim of this research is to describe the Holocene succession of depositional facies recorded in the terminal sector of the Mirna River valley through sedimentological, macro- and micropaleontological analyses of sediment cores. Moreover, this study highlights the potential role of such investigations in reconstructing the geomorphological evolution of the area and supporting the study of past relative sea levels, climate changes and anthropogenic activities that occurred during the Holocene. In this work we tested the use of hand augering in sampling and describing the subsoil for the first 5–15 m, 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. REGIONAL SETTING

2.1. Geological setting

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 400 km^2. 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 basin, the Mirna River has a hydrogeological catchment estimated to about 580 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 (Cittanova) (Fig. 1). The drainage basin of the Mirna River is composed of carbonates, mostly Cretaceous and Eocene limestone, and clastic Eocene deposits (flysch,

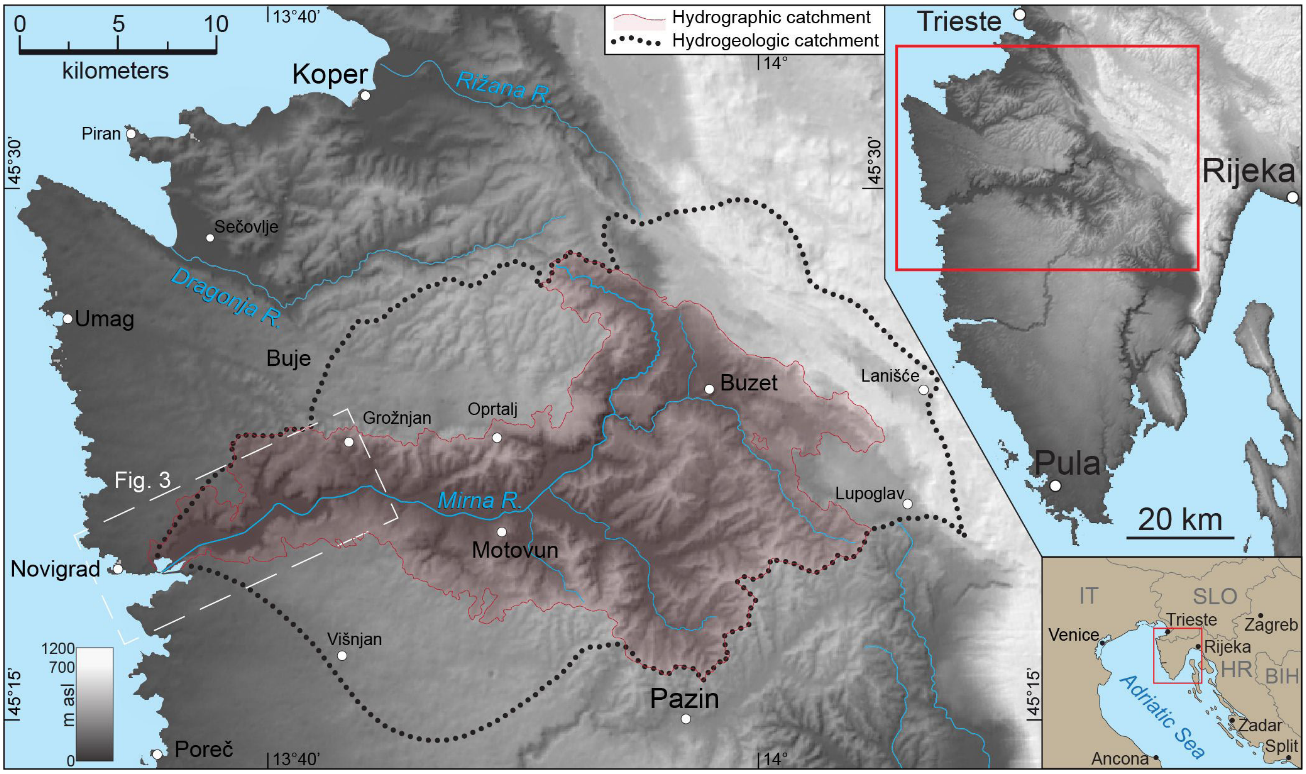

Figure 1: Location of the study area. The Digital Elevation Model (DEM) obtained from NASA-SRTM data. The boundary of the hydrogeological catchment is assumed (according to SANTIN, 2013).

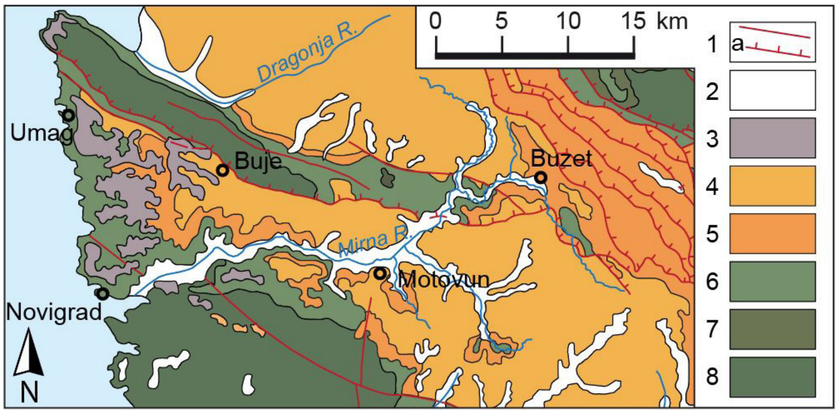

Figure 2. A geological map of Istria (modified after the Geological Map of Croatia, CROATIAN GEOLOGICAL SURVEY, 2009); 1. Fault, 1a. Thrust, 2. Quaternary deposits (mainly Holocene), 3. Terra rossa deposits (Holocene). 4. Flysch deposits (Eocene), 5. Liburnia deposits, Foraminiferal limestone and transitional deposits (Paleocene?, Eocene), 6. Rudist limestone (Cretaceous), 7. Dolomite and breccia (Cretaceous), 8 Limestone and dolomite (Cretaceous), 9. Limestone and dolomite (Jurassic).

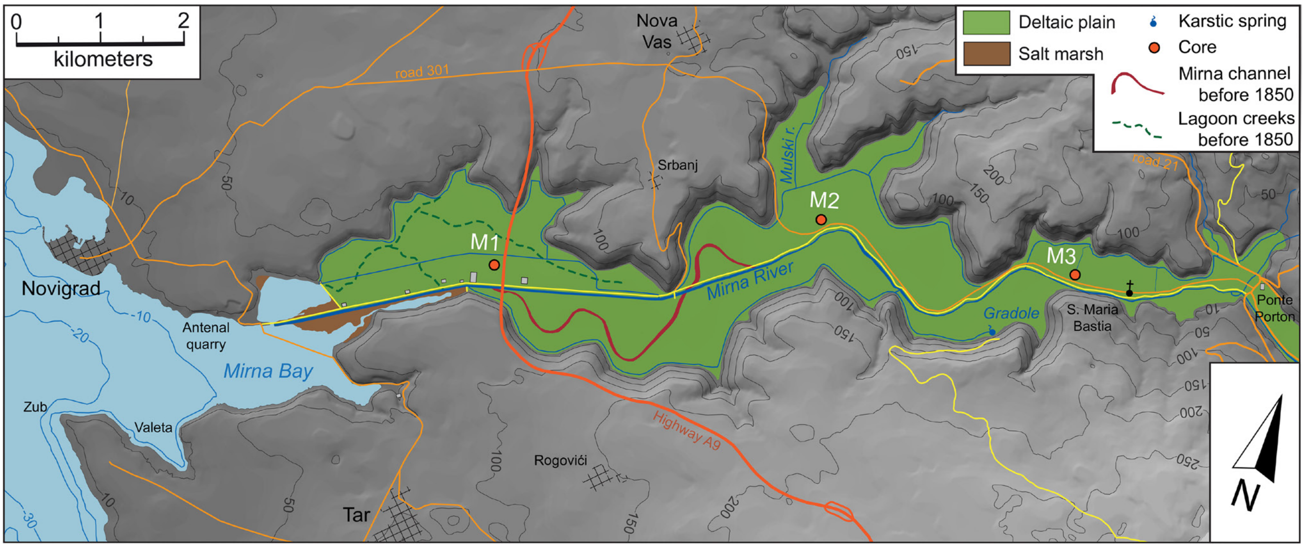

Figure 3: Map of the lower valley of the Mirna River. The hillshaded DEM was obtained by digitalization of the isolines represented in the topographic map at scale 1:25,000.

POLŠAK & ŠIKIĆ, D., 1963; PLENIČAR et al., 1965) (Fig. 2). These marl and sandstone sediments in alternation (flysch) in the catchment area are morphologically related to a badland landscape (GULAM et al., 2014). From 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 (Fig. 3), with an estimated minimal discharge of 500–600 ls^{-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) (Fig. 2). 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). 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 be triggered by an earthquake that submerged the archaeological remains and geomorphological forms (such as marine notches). Several geomorphological, biological and archaeological markers have been used as a source of information from which the relative movements between land and sea have been evaluated. Holocene submersion was largely completed about 7 ka BP and subsequently the sea level rose slowly to the current elevation (ANTONIOLI et al., 2007, 2009). Sea-level markers indicate a vertical tectonic signal at a rate of about –0.75 mm/yr occurring during the last two millennia that produced a significant relative downdrop of the coastline of about 1.5–1.8 m (ANTONIOLI et al., 2009, FAIVRE et al., 2011). The sea level change occurring in the Istrian coast since about 5 ka BP, has been estimated as a relative rise of about 4 m (FAIVRE et al., 2011).

2.2. 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 a 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) (Fig. 3). 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'INCÀ, 2007). Novigrad (Cittanova) became the major city of the area from 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 harbour 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, there have been interventions to regulate the river *e.g.*, some artificial cutting of meanders, but a huge 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 reclamation works were completed (SANTIN, 2013).

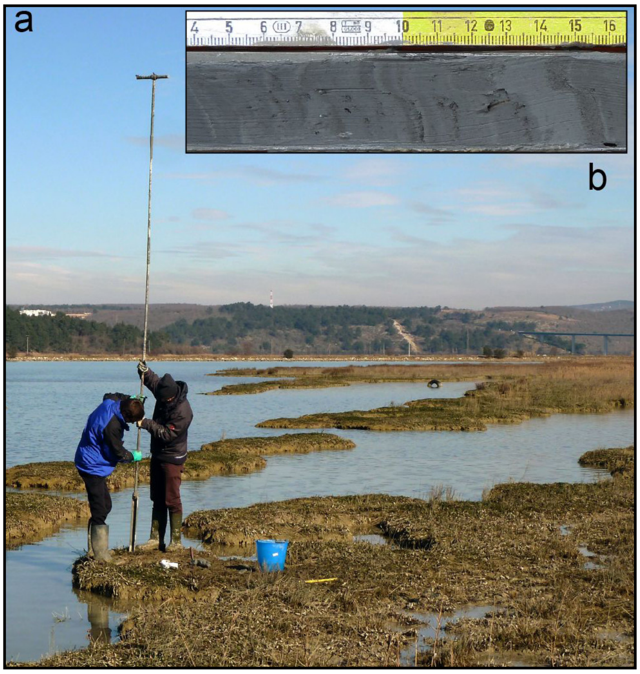

Figure 4: a) Coring operations in the salt swamp at the mouth of the Mirna River; in the distance the highway viaduct over the Mirna River valley is visible. **b)** a sample of laminated sediments collected through the gauge head from core M2 between 8.04–8.15 m.

3. MATERIAL AND METHODS

3.1. Sampling and core description

The corings were done with an Ejikelkamp hand auger (Fig 4a) using an Edelman head for sediment above the groundwater table and 1 m long gauge 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 (Fig. 4b). 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 was checked in the field and the uncertainty was ±0.05 m. Cores M1 and M3 were drilled in January, while core M2 was collected in May 2013. 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. The elevation measures were corrected to the local geoid considering as a reference datum the top of the present salt marshes existing in Mirna Bay (Fig. 3), which is considered to be 0.20 m above mean sea level. The cores were described in the field, but soon after they were protected with aluminium 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 colour 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. The colour of the layers was determined by comparing the moist sediment with the Munsell Soil Colour Charts, while the content of calcium carbonate was estimated 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 some have since been checked in the lab with a stereomicroscope.

3.2. Foraminiferal analyses

The micropalaeontological analyses were carried out on selected sub-samples. Due to the limited width of the cores (3

Table 1: Distribution of foraminifers in the cores M1, M2 and M3.

Depth of the sample (meters)	Number of the sample	*Ammonia* sp.	*Ammonia beccarii*	*Trochammina inflata*	*Haynesina* sp.	*Porosononion* sp.	*Elphidium* sp.	*Elphidium crispum*	*Elphidium aculeatum*	*Elphidium macellum*	*Triloculina* sp.	*Triloculina marioni*	*Quinqueloculina seminula*	*Pyrgo* sp.	*Adelosina mediterranesis*	*Sigmoilinita costata*	*Bulimina* sp.	*Brizalina* sp.	*Lagena* sp.	indeterminable	total
CORE M1																					
0.10 – 0.15	1	23	120	81	58	3														6	291
1.75 – 1.80	2	12	131	97	74	9														3	326
1.95 – 2.00	3	19	170	28	54	25	1													7	304
2.15 – 2.20	4	30	138	47	78	18														3	314
3.15 – 3.20	5	40	168	22	44	7														10	291
3.45 – 3.50	6	38	195	23	21	11														11	299
3.95 – 4.00	7	20	178	28	44	11														17	298
5.00 – 5.05	8	35	170	20	35	19					3		4							12	298
5.75 – 5.80	9	25	175	18	42	17	2	5			2	2	3								291
6.30 – 6.35	10	22	165	44	27	18	2	1				5	6	2				4		8	304
7.40 – 7.45	11	11	98	9	23	27	12	27	23	11	2	14	18	5	2	1	1	3			287
7.95 – 8.00	12	15	76	7	14	15	20	54	8	17	8	25	34	5							298
CORE M2																					
4.50 – 4.55	1																				0
5.00 – 5.05	2																				0
5.20 – 5.25	3	37	205	35																34	311
5.60 – 5.65	4	30	208	23	32															13	306
6.80 – 6.85	5	29	220	27	25															10	311
7.80 – 7.85	6	32	229	31	21															9	322
8.20 – 8.25	7	30	218	7	23	7							2							15	302
8.50 – 8.55	8	14	212	14	39	12	4	3	3			1	1							5	308
9.70 – 9.75	9	26	234		7	13	3	2	3											7	295
10.50 – 10.55	10	20	186	2	23	17	6	11	6			4	5		2			4		16	302
11.10 – 11.15	11	17	157	2	27	10	16	4	7		1		45					1	1	7	295
12.20 – 12.25	12	21	214	2	15	4	12		3		2	6	25	2						4	310
12.65 – 12.70	13	30	173	3	23	5	14	4	3		2	5	31	2						7	302
12.95 – 13.00	14	37	197	2	41	2	5				1	4	7							4	300
CORE M3																					
1.75 - 1.80	1																				0
1.85 – 1.90	2																				0
3.55 – 3.60	3																				0
4.00 – 4.05	4			2																	2
6.95 – 7.00	5	3	6	1	3															4	17
7.30 – 7.35	6		2																	1	3
8.00 – 8.05	7	1																		1	2
8.95 – 9.00	8	2	6	4	3															1	16

cm), every sub-sample was 5 cm thick. Twelve samples were taken from core M1, 14 from core M2, and 8 samples from core M3. Sediment was treated with diluted hydrogen peroxide for one day to remove organic matter, washed on the 63-µm sieve and left to dry. Samples which contained foraminiferal tests were split by a Reich-microsplitter into aliquots with approximately 300 specimens. Species and genera were identified *via* stereomicroscope following the generic classification of LOEBLICH & TAPPAN (1988) and CIMERMAN & LANGER (1991).

Besides the species and generic identification, biodiversity indices were also calculated. Statistical analyses were done using the Past software (HAMMER et al., 2001). In each sample the number of species and individuals was counted. Species diversity was estimated based on the following indices: Species richness (S), Dominance (D), Fisher α index, Shannon-Wiener index (H) (MURRAY, 1991). In Table 1, the total number of counted specimens is presented, but the percentage was not expressed in order to avoid misleading data about M3, where the total number of foraminifers was less than 20, and statistically insignificant.

3.3. Radiocarbon dating

During field description of the cores, the layers containing suitable material for radiocarbon dating (*e.g.*, organic-rich sediments, peaty horizons, wood fragments, and selected shells) were sampled immediately, sealed in plastic bags and afterwards dried. 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). Three 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.

4. RESULTS

4.1. Core M1

The core was drilled near the viaduct overpassing the Mirna River valley (Fig. 3) and reached 8 m in depth (Fig. 5). The site [45°19’56.6”N – 13°37’30.1”E] is located about 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, secondarily, other lagoon shells (*e.g. Nassarius* sp.) were locally scattered at the surface. The core stratigraphy is characterized by the following layers:

0–1.85 m: silty clay and clay with light olive brown colour (2.5Y 5/4) with a high carbonate content. The present plough layer ends at 0.40 m and, below it, mottling features with a yellowish brown colour (10YR 5/6). Iron stains of 2–4 mm diameter are abundant until 1.10 m and common to

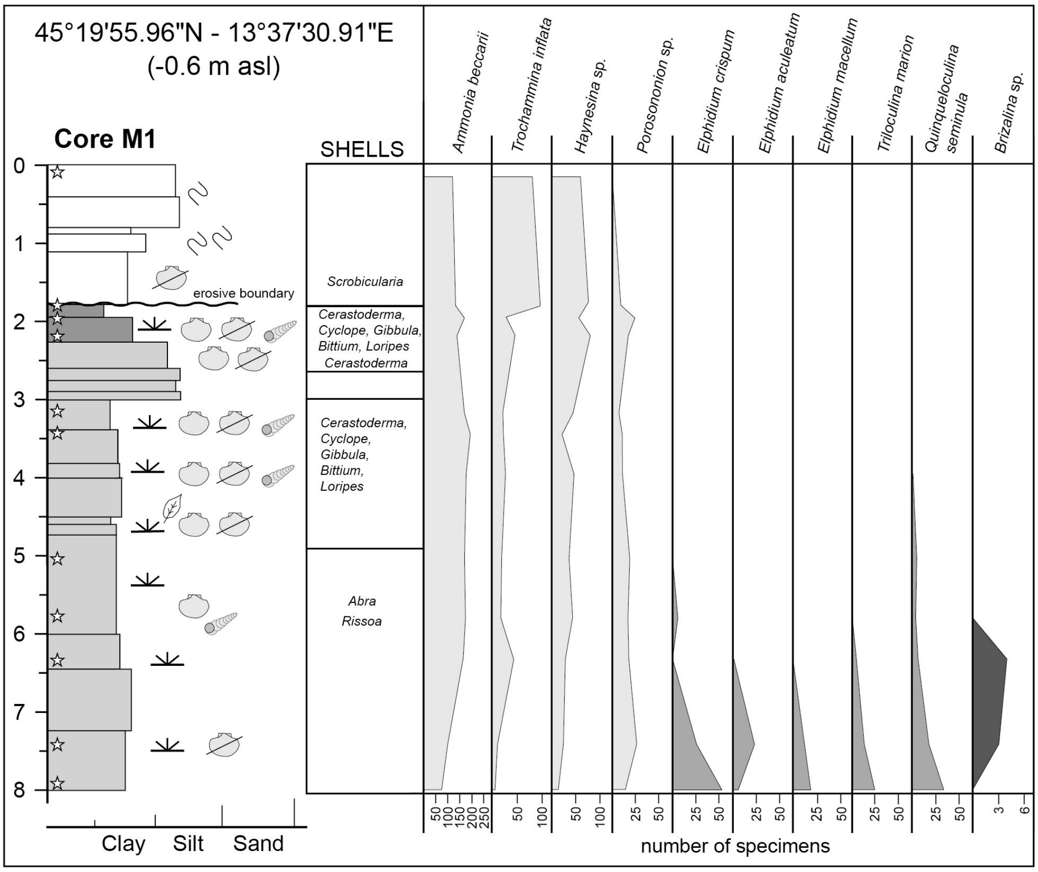

Figure 5: Stratigraphic log of core M1 with diagrams of some selected foraminiferal species. Legend is presented in Fig.6; asl – above mean sea level.

scattered in the lower part. An isolated valve of *Scrobicularia plana* was present at 1.5 m, but shell fragments were generally absent or very rare and of millimetre dimension. Between 0.40–0.80 m rare carbonate concretions (up to 5 mm of diameter) were present along with manganese nodules (1 mm diameter). The lower boundary was sharp and eroded part of the lower layer.

Dominant foraminiferal species were *Ammonia beccarii, Trochammina inflata* and *Haynesina* sp. (Tab. 1).

1.85–2.60 m: down to 2.25 m this layer was formed by greenish grey (G1 5/10Y) silty clay with lenses of dark-greyish brown clay (2.5Y 4/2-1). The sediment was characterized by very poor or no reaction with HCl and dispersed organic matter in the matrix. Lagoon shells, fragmented and complete, were quite abundant (*Cerastoderma* sp., *Cyclopes* sp., *Gibbula* sp., *Bittium* sp. and *Loripes* sp.), along with millimetre plant debris. Similar features and shells were present down to 2.60 m, but around 2.20–2.30 m there was a gradual transition to clayey silt with a lighter greenish grey colour (G1 4/10Y).

Ammonia beccarii and *Trochammina inflata* were dominant foraminiferal species. Compared to previous interval specimens of *A. beccarii* became more abundant, while those of *T. inflata* decreased in number (Tab. 1).

2.60–3.0 m: silty clay and clayey silt, grey in colour (2.5Y 6–5/1), and with medium-strong reaction with HCl (3). Shell fragments were very rare. The layer was partly reworked during coring operations due to the occurrence of the groundwater table.

3.0–4.9 m: alternations of clay and silty clay sediment with a general grey colour (G1 5/10 Y) and a medium reaction to HCl (2). This layer was characterized by the common presence of lagoon shells, both fragmented and well-preserved (*Bitium* sp., *Cerastoderma* sp., *Rissoa* sp., *Gibbula* sp., *Loripes* sp.); some of the fossils showed weathering features including traces of partial dissolution. Millimetre sized plant debris was common and abundant in some decimetre intervals, where the matrix colour was dark-grey brownish (2.5Y 4/2). Some seeds were also present.

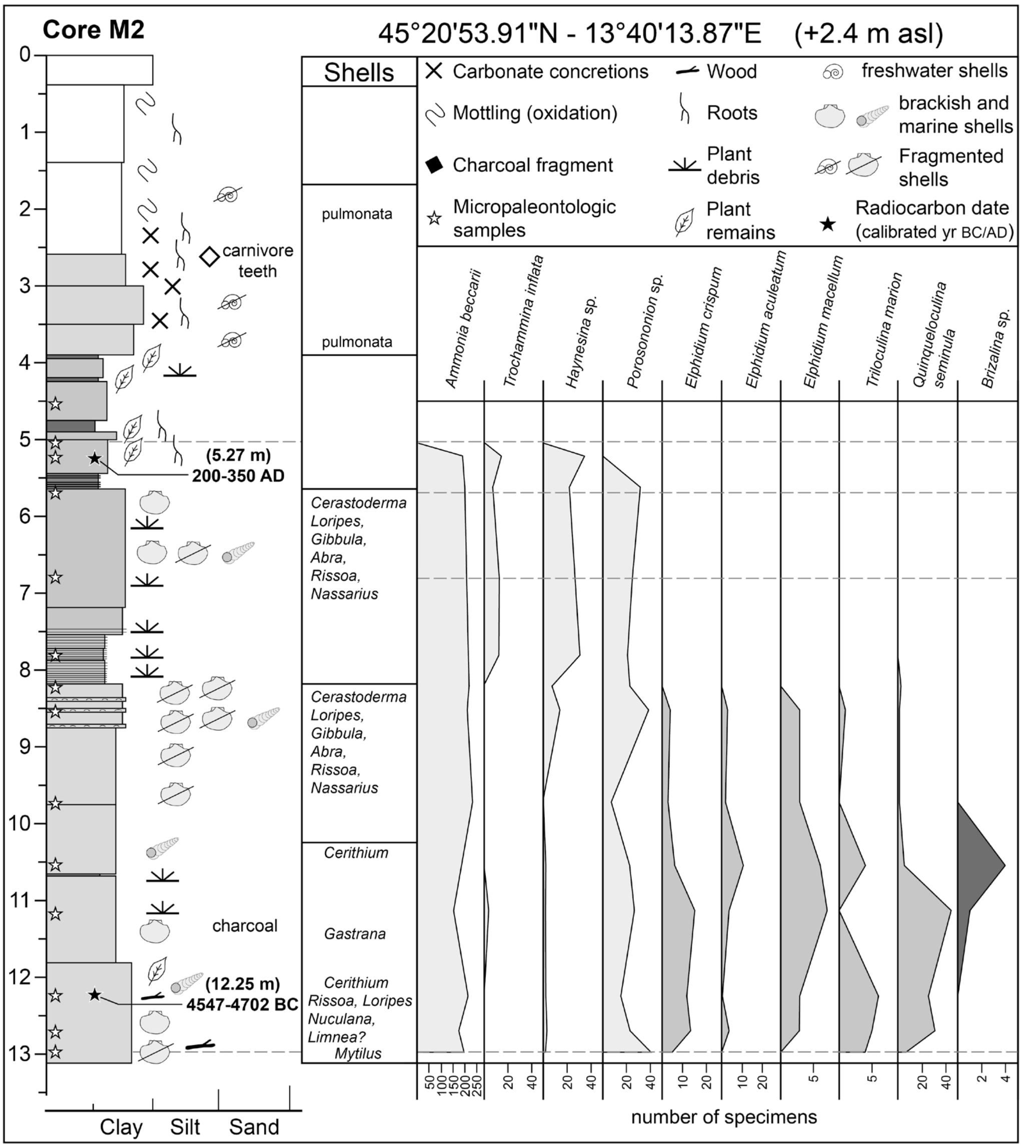

Figure 6: Stratigraphic log of core M2 with diagrams of some selected foraminiferal species; asl – above mean sea level.

The proportion of *A.beccarii* in the foraminiferal assemblage continued to increase, while the proportion of *T. inflata* and *Haynesina* sp. decreased (Tab. 1).

4.90–8.0 m: soft sediment consisting of grey clay and silty clay (G1 5/10 Y) showing a strong reaction with HCl (3–4) that suggests a higher proportion of carbonate compared to the layers above. Shell remains were rare or absent, with a specimen of *Abra* sp. and *Rissoa labiosa* at 5.55 and 5.75 m respectively. Plant remains were common in some laminated decimetre intervals of the core.

From 5.00–5.05 m rare specimens of miliolids occurred (*Triloculina* sp., *Quinqueloculina seminula*). At 5.75 m a few tests of *Elphidium* sp. were observed. Although *Ammonia* sp. dominated in the assemblage from 7.40 - 7.95 m, the trend of decreasing abundance was obvious. At the same time, a greater number of unidentified miliolids and *Elphidium* sp. was recorded (Tab. 1).

In the 12 samples analyzed in this core a total number of 17 benthic foraminiferal species were recognized (Tab. 1). Foraminiferal tests were present in all samples, but more species were present below 5.00 m. *A. beccarii* dominated in all the studied assemblages, while *T. inflata* and *Haynesina* sp. were present in greater amounts in the shallower and were less common in the deeper horizons. Representatives of the genus *Elphidium* and miliolids were more abundant below 7.40 m. At depths of 6.30 m and 7.40 m a few specimens of *Brizalina* sp. and *Bulimina* sp. were identified.

4.2. 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] (Fig. 3). Ground elevation is +2.4 m msl and the area was a swampy environment until the beginning of the 20th century, when it was reclaimed. The core stratigraphy is characterized by the following layers (Fig. 6):

0.0–2.60 m: clayey silt of a light brown and yellowish colour (2.5Y 5/4) and high to medium reaction with HCl (3–4). The plough layer was stiff and stopped at 0.40 m depth where the lower boundary was sharp and erosive. Mottling features 2 mm wide, yellowish brown in colour (10YR 5/6) were common from 0.40 m and abundant between 1.40–2.60 m. Fragments of roots were sometimes present throughout the layer and common at its base, where a gradual transition marked the limit with the lower layer. At 2.5 m the teeth of a small carnivorous mammal were observed.

2.60–3.90 m: greenish-grey (6/5 GY) clayey silt passing to silty clay and clay below 3.2 m. Sediment strongly reacted with HCl (4) and soft carbonate concretions (<3 mm diameter) and also hard concretions (2–3 mm) from 3.0 m to the base was common. Root fragments were common throughout the layer and also some millimetre fragments of freshwater molluscs were observed.

3.90–5.45 m: clay and silty clay with slightly dark greenish grey colour (5/5 GY) with intercalations of organic-rich intervals at 3.90–3.95, 4.20–4.25 and 4.75–4.90 m, where the colour is dark greyish brown (10YR 3/2) and HCl reaction is poor (1). Some isolated carbonate concretions were discovered, up to 2 mm in diameter. Plant macroremains were common through the whole layer, but especially between 4.95 and 5.30 m, where roots and other parts had centimetre dimensions and the sediment was lighter in colour (6/10Y). The lower boundary was sharp. A plant fragment at 5.27 m depth was radiocarbon dated to 1782±25 years uncal BP (138–332 AD, 2σ calibration) (Tab. 2).

No foraminifers were observed above 5.20 m depth.

5.45–5.80 m: greyish brown clay (2.5Y 5/2) with organic matter dispersed in the matrix up to 5.65 m; millimetre and, secondarily, centimetre sized plant remains were common and their distribution highlights a laminated pattern in the sediment; it gradually passes to the lower layer where lagoon shells were present.

A. beccarii dominated the foraminiferal assemblages, while *Ammonia* sp., *T. inflata, Haynesina* sp., and *Porosononion* sp. were subordinate (Tab. 1).

5.80–10.25 m: grey and greenish grey clay and clayey silt (5/N–6/10Y) characterized by a soft consistency and with intercalations of laminated intervals of decimetre thickness. Laminae were of millimetre thickness and were evidenced by the alternation of dark grey (5N, 2.5Y 4/1) and light greenish grey (7/N–10Y) layers. Scattered isolated shells of lagoon molluscs and fragments were present (*Cerastoderma* sp., *Loripes* sp., *Gibbula* sp., *Abra* sp., *Rissoa* sp., *Nassarius* sp.), but some concentrations occurred at 8.34–8.40, 8.51–8.57, 8.71–8.75, 9.10–9.17; 9.30–9.37; 9.45–9.53 m. Millimetre plant remains were dispersed and sometimes common, highlighting the lamination, which was particularly evident between 7.90 and 8.20 m. In some intervals, *e.g.* between 8.75–9.75 m shells were partly dissolved.

In all samples in these intervals *A. beccarii* was the most abundant foraminifer. At 8.20 m representatives of miliolids and *Elphidium* sp. were observed, but only by several specimens.

10.25–13.0 m: grey clay and clayey silt (6/N–10Y) characterized by their soft consistency. This layer was similar to the one above it, but was characterized by the scarce or rare presence of shells; one *Cerithium* sp., at 10.40 m and another at 12.20, one juvenile valve of *Gastrana fragilis* at 11.40 m and an adult at 12.20 m, *Limnea* sp., *Rissoa* sp., *Nuculana* sp. and *Loripes* sp. at 12.25 and one centimetre sized fragment of *Mytilus* sp. at 12.72 m. Millimetre sized plant remains were dispersed in some intervals, with leaf fragments being represented. This plant debris highlighted the horizontal layering but their occurrence was not so frequent as to indicate a laminated pattern. Centimetre sized wood fragments have been documented at 10.55, 11.40 and 12.20 and 12.25 m. At 11.40 m a 3mm sized, rounded fragment of charcoal was found.

A fragment of twig found at 12.25 m of depth was radiocarbon dated to 5774±28 years uncal BP (4702–4547 BC, 2σ calibration) (Tab. 2).

Table 2: Radiocarbon dating.

Sample	Core	Lab. Code	Method	Dated material	Conventional 14C age	Error	Calibrated age 2σ 95.2% prob. (yr cal. BC/AD)	δ13C‰ PDB	Longitudine WGS84	Latitude WGS84	Surface elevation (m msl)	Depth from surface (m)	Corrected Elevation (m msl)
MIR2-690	M3	ETH-57132	AMS	Plant macrofossil	854	24	1154-1254 AD	-25.6	45°21′8.68″	13°42′41.38″	4.40	6.9	-2.5
MIR5-527	M2	ETH-57133	AMS	Plant macrofossil	1782	25	138-332 AD	-27.2	45°20′53.91″	13°40′13.87″	2.00	5.27	-3.27
MIR5-1225	M2	ETH-57134	AMS	Wood twig	5774	28	4702-4547 BC	-27.4	45°20′53.91″	13°40′13.87″	2.00	12.25	-10.25

Table 3: Biodiversity foraminiferal indices of the selected intervals of the core M1.

Depth of sample (m)	0.10–0.15	1.75–1.80	1.95–2.00	2.15–2.20	3.15–3.20	3.45–3.50	3.95–4.00	5.00–5.05	5.75–5.80	6.30–6.35	7.40–7.45	7.95–8.00
Number of species (S)	6	6	7	6	6	6	6	8	10	12	17	13
Number of specimens (N)	291	326	304	314	291	299	298	298	291	304	287	298
Dominance (D)	0.294	0.304	0.364	0.29	0.383	0.455	0.397	0.364	0.398	0.334	0.16	0.135
Shannon-Wiener index (H)	1.371	1.327	1.336	1.424	1.276	1.168	1.279	1.414	1.354	1.567	2.255	2.254
Fisher α index	1.07	1.044	1.278	1.052	1.07	1.063	1.064	1.513	2.006	2.494	3.955	2.774

Table 4: Biodiversity foraminiferal indices of the selected intervals of the core M2.

Depth of sample (m)	5.20–5.25	5.60–5.65	6.80–6.85	7.80–7.85	8.20–8.25	8.50–8.55	9.70–9.75	10.50–10.55	11.10–11.15	12.20–12.25	12.65–12.70	12.95–13.00
Number of species (S)	5	6	6	6	7	12	8	13	14	12	13	10
Number of specimens (N)	311	306	311	322	302	318	295	302	295	310	302	300
Dominance (D)	0.414	0.46	0.469	0.48	0.54	0.46	0.64	0.398	0.313	0.492	0.358	0.466
Shannon-Wiener index (H)	1.188	1.155	1.15	1.121	1.018	1.27	0.84	1.517	1.656	1.245	1.559	1.163
Fisher α index	0.846	1.058	1.054	1.047	1.28	2.465	1.516	2.764	3.057	2.482	2.764	1.991

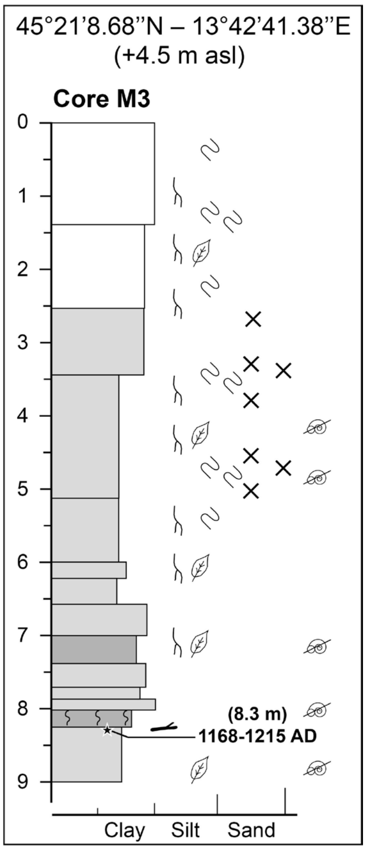

Figure 7: Stratigraphic log of core M3. Legend is presented in Fig.6; asl – above mean sea level.

Elphidium spp. increased in number at 10.50 m and miliolids (*Quinqueloculina seminula*) at 11.10 m. *A. beccarii* was still dominant in the deeper horizons (Tab. 1).

Altogether, in 14 samples from this core, a total number of 16 benthic foraminiferal species were recognized while the two shallowest samples were barren (Tab. 1). With the appearance of *Elphidium* sp. and miliolids at horizons deeper than 8.20 m, the species richness increased significantly. *A. beccarii* made up more than 50% and in some samples more than 75% of the total assemblage and was the dominant species. The proportion of *Trochammina inflata* in the assemblages decreased with depth. In contrast, *Elphidium* sp. and miliolids appeared at 8.20 m below the surface and became more numerous with depth, reaching a maximum proportion at 10.50 m.

4.3. 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 an elevation of +4.5 m msl, 700 m downstream of the chapel of S. Maria of the Bastia (Fig. 3). The core stratigraphy is characterized by the following layers (Fig. 7):

0.0–2.50 m: yellowish brown clayey silt and silty clay (2.5Y 5/4), with strong reaction with HCl (4–3) and with the presence of some centimetre sized plant remains, probably corresponding to roots.

2.50–5.10 m: yellowish brown silty clay and clay (2.5Y 5/4) with dispersed yellowish brown mottling (10YR 5/8) and carbonate concretions (3–8 mm); reaction with HCl was strong (4). Presence of millimetre to centimetre sized plant remains was common and most of them probably correspond to roots. Millimetre fragments of shells of fresh-water gastropods were present below 4.0 m.

5.10–7.0 m: greenish-grey clay (6/N–10Y) with common presence of centimetre sized roots and the occurrence of millimetre fragments of fresh-water gastropods. HCl reaction was high (4–3) and the layer was slightly mottled with yellowish features (10YR 5/4) in the upper part, down to 5.50 m.

7.0–7.4 m: slightly dark grey silty clay (2.5Y 5/1) with medium-low reaction with HCl (2) and a common presence of millimetre fragments of fresh-water gastropods, especially at 7.3–7.4 m.

7.4–8.0 m: greenish-grey (6/N) silty clay, clay and silt.

8.0–8.20 m: slightly dark grey silty clay (2.5Y 5/1) with organic matter present in the matrix and with a medium – low reaction with HCl (2). The presence of bioturbation related to detritivore fauna and some millimetre fragments of fresh-water gastropods was observed.

8.20–9.0 m: grey clay (6/N–10Y) with some plant remains and the presence of millimetre fragments of fresh-water gastropods. A millimetre sized fragment of wood from 8.30 m was dated and gave the radiocarbon age of 854±24 years BP (1154–1254 cal AD) (Tab. 2).

Among the analyzed samples, 3 were completely barren and in the other 5 only very few foraminifera were observed (a maximum of 17 specimens at a depth of 5.50 m). *A. beccarii, T. inflata* and *Haynesina* sp. were recognized (Tab. 1) and, due to their low abundance, no biodiversity indices were calculated for this core.

5. DISCUSSION

The occurrence of fine grained sediments throughout the sedimentary columns generally facilitated hand augering to the significant depth of up to 13 m. This confirmed the possibility of investigating a significant volume of deposits and studying the evolution of the area since 6500 years BP (Fig. 6).

Despite small grain-size differences through the cores, the combined use of sedimentological, macro- and micropalaeontological characteristics allowed the recognition of different depositional environments and the reconstruction of their longitudinal and vertical distribution (Fig. 8).

5.1. Depositional environments

5.1.1. Continental environments (A)

In the lower sector of the Mirna valley continental deposits crop out extensively and generally form the present surface and the topmost subsoil. They consist of homogeneous silty and clayey sediments, 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 fresh-water snails, which are generally

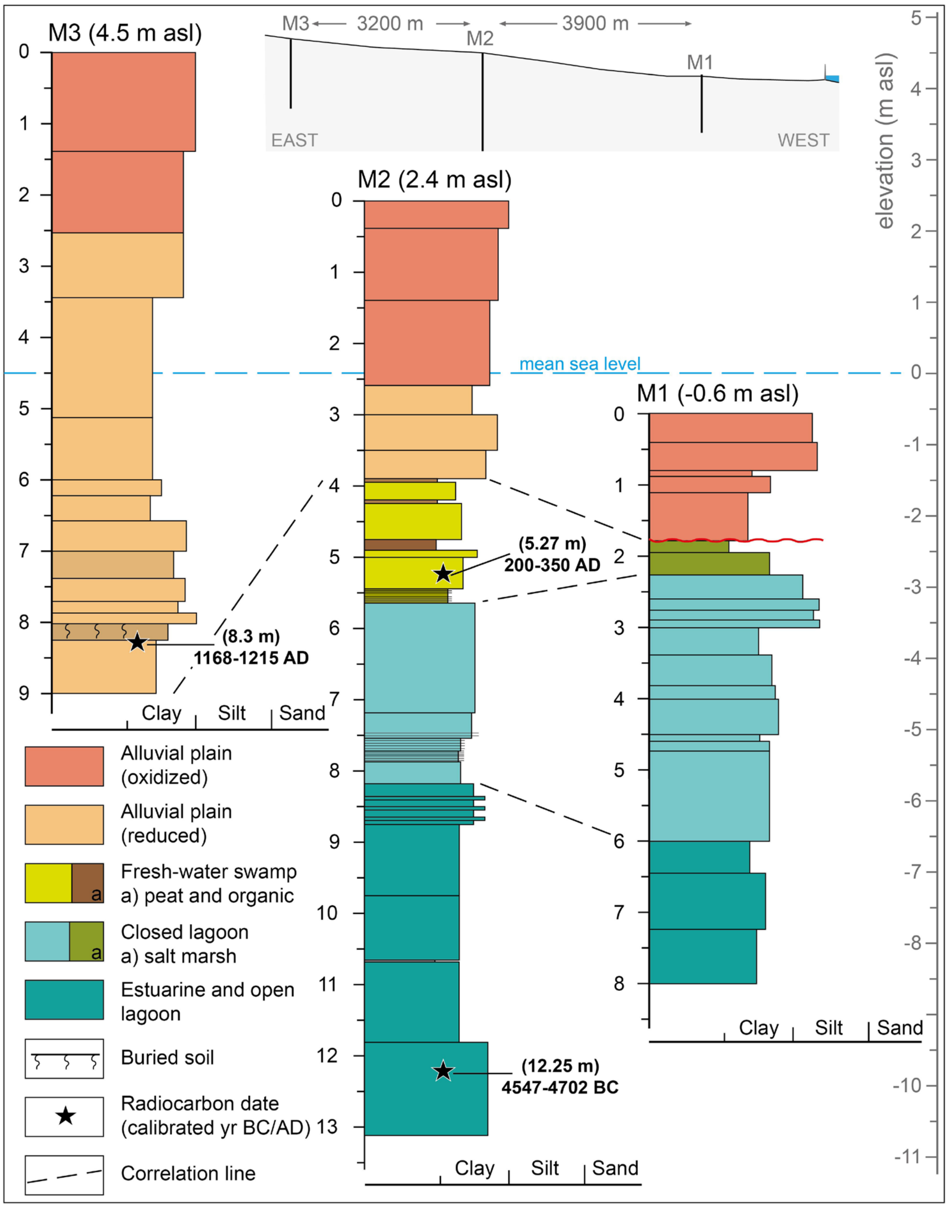

Figure 8: Stratigraphic logs of the studied cores with presumed depositional facies. On the top of the figure the schematic topographic profile of the lower valley is presented. asl – above mean sea level.

not abundant. These deposits were oxidized and partly affected by pedogenesis for several metres, from the ground surface down to the top of the water table. This interpretation is supported in this interval by the occurrence of mottling features with a yellowish and reddish colour (10YR 6/8) and, between 2 and 3.5 m, by the presence of calcium carbonate concretions, both soft and hard. Concretions are related to the leaching of carbonate from upper horizons and re-deposition in the lower ones; their width was <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). Also the shallow depth at which the groundwater table is generally present in the area contrasted with the development of the pedogenic processes (cf. McRAE, 1988). Thus, the pedological profiles of present and buried soils are weak and they could be classified as entisols and rarely as inceptisols according to the USDA pedological descriptive code (SOIL SURVEY STAFF, 2003).

In the investigated area, the deposits interpreted as continental facies are normally barren for foraminifers, but in the basal portion of core M3, a very small number of specimens of *Ammonia beccarii, Trochammina inflata* and *Haynesina* sp. were discovered. Their occurrence could be related to some transport processes from nearby lagoonal 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 that 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 away from the river mouth. Before the dyke construction of the 20th century, similar episodes were likely to occur 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 fed 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 were composed of silts and clayey silts while, possibly, some slightly coarser elements (*i.e.* sand) were present, but only as the basal lag, due to the fact that fine-grained marls dominate exposed flysch sequences in the Mirna River catchment.

Thus the late-Holocene stratigraphy was characterized by facies of the floodplain (Aa) and alluvial swamp (Ab). The latter was marked by the occurrence of organic-rich and peaty layers where plant macroremains could be common or abundant. Seeds and fragments of leaves could be present. The Ab facies was clearly recorded in core M2 between 3.95–5.20 m (Fig. 8), while it was not documented in M1 and M3.

In the core M3, the slightly elevated organic layers observed at 7.0–7.4 and 8.0–8.2 m were interpreted as the A horizons of soils with a very weak degree of development (*i.e.* entisol), with a profile consisting only of horizons A and C. This suggests that they developed during a limited period without sedimentation in the area of core M3, and probably in a poorly-drained environment that hampered pedogenic evolution.

5.1.2. Brackish/transitional environments (B)

The depositional environments related to brackish waters were generally marked in the core by the presence of shells. In particular the occurrence of *Cerastoderma glaucum* and eventually the association with *Loripes* and *Bittium* generally characterizes the hyposaline marshes (Ba) and the inner estuarine/lagoon facies (Bb). 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 a soft consistency, with a variable degree of bioturbation and the presence of millimetre sized plant debris. The recognition of facies Ba was based on benthic foraminiferal assemblages. The hyposaline marshes and marginal environments were strongly dominated by *A. beccarii* and, secondarily, by *T. inflata* and *Haynesina* species (MURRAY, 1991, 2006; ALBANI et al., 2007; AMOROSI et al., 2004, 2005).

In 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 (1.04–1.28 in M1 and 0.85–1.05 in M2; Tabs. 3, 4) All these data, together with a shell–type ratio triangular diagram (modified after MURRAY, 1974; Fig. 9) suggest that sedimentation took place in brackish swamps or ponds on tidal flats with the occasional influx of freshwater from the Mirna floods (Fig. 8).

The inner estuary/lagoon setting (Bb) coincided with the presence of *Elphidium* spp. and miliolids (like *Quinqueloculina seminula*) in the cores (intervals 5.0–6.35 m in M1 and 8.20–9.75 m in M2; Tab. 1). These foraminiferal groups are considered as pioneers (VANIČEK et al., 2000; DEBENAY et al., 2001) and their presence suggested changes in environment towards more stable, marine conditions (MURRAY, 2006). Somewhat higher values of Fisher-α indices (1.51–2.49 in M1 and 1.28–2.47 in M2) and a greater number of species (up to 7–12 species) are in accordance with such a hypothesis (Tabs. 3 and 4). There are some differences in the composition of foraminiferal assemblages observed in this study and from the northern Adriatic lagoons (Venice, Marano and the Grado lagoons, ALBANI et al., 2007; MELIS & COVELLI, 2013). In areas where salinity fluctuates, opportunistic and pioneer species prevail, but the absence of some species (*i.e. A. tepida* in this study) could be related to the laboratory method used (a few studied samples, from a 13m long core, and 14 sub-samples were analyzed), the diameter of the drill (which gave a limited amount of sediment sample), poor preservation of foraminiferal shells that only allowed identification to generic level. However, foraminiferal studies of sediments from the Northern Adriatic, confirm that representatives of *A. beccarii* dominate in very-shallow water marginal environments, where nutrient inputs periodically led to oxygen deficiency (DONNICI et al., 2002). *Trochammina inflata* and *A. beccarii* outnumber other foraminiferal species in marsh assemblages (SCOTT & MEDIOLI, 1978; AMOROSI et al., 2004; ALBANI et al., 2007).

Considering that most of the investigated sediments were related to brackish waters, analysis of ostracod and diatom assemblages would probably help in discriminating the brackish environments, where this kind of ecological indicator could highlight subtle variations in the degree of salinity and water circulation.

5.1.3. Estuarine/outer lagoon 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 are millimetres thick and could be slightly organic, sometimes evidenced by the concentration of plant and wood debris. Shells were not abundant, even rare in some portions and these characteristics contributed to differentiating this facies from Ba and Bb. Moreover, in E the species *Cerithium* sp., *Nuculana* sp. and *Mytilus* sp. have been observed, indicating a relatively higher salinity.

The foraminiferal assemblage was related to estuarine/outer lagoon conditions where the marine influence is stronger (Fig. 8; Fig. 9). While the proportion of *T. inflata* and *Haynesina* sp. specimens decreased, miliolids, (*Q. seminula* in particular) and *Elphidium* spp. increased. This was evident in intervals 7.40–8.00 m in core M1 and 10.5–13.00 m in core M2 (Tab. 1). Values of the Fisher-α index in these intervals ranged between 2.77–3.96 in M1 and 1.99–3.06 in M2. Assemblages were characterized by greater species richness, greater values of the Shannon-Wiener index (Tabs. 3 and 4) and greater abundance of miliolids and rotaliids. The presence of infaunal species, including *Brizalina* sp., despite their low number, indicated that in the near bottom environment normal marine conditions prevailed.

All this information suggested a stratified estuary/outer lagoon environment in the geomorphological setting of the valley with protection offered by Mirna bay from sea-storms and waves. We interpreted this facies as outer lagoon /estuarine conditions, in a subtidal environment influenced by freshwater inputs related to Mirna River activity. The lamination was probably induced by the fluvial floods, which transported 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 important karstic springs, such as the Gradole spring (Fig. 3). 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 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 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).

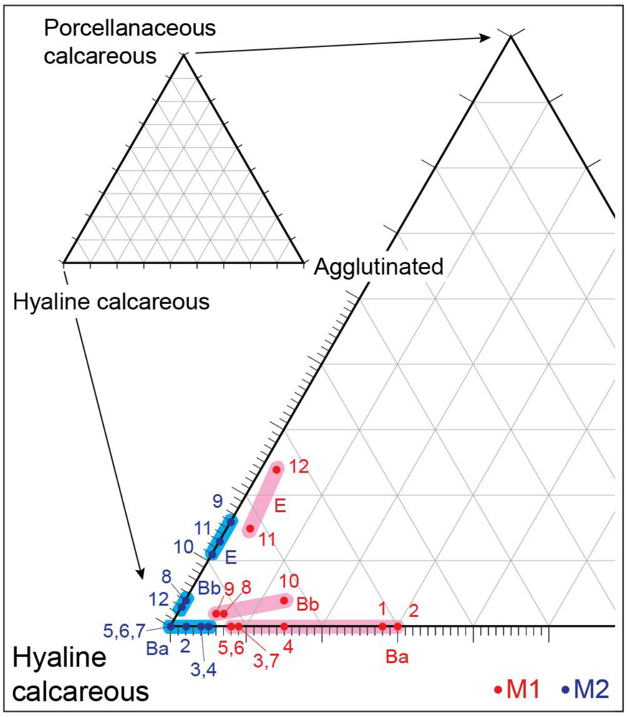

Figure 9: Shell–type ratio triangular diagram (modified after MURRAY, 1974). (Ba) Hyposaline marshes; (Bb) Inner lagoon (hyposaline lagoon); (E). Estuary/outer lagoon.

5.2. Evolution of the Mirna valley

From M3 to M1 there is an elevation difference of approximately 5 m, but the gradient is ~ 1.0‰ between M3 and M2 and it falls to almost 0 between M2 and M1 (Fig. 8). The occurrence of areas below the present sea level, downstream of the highway viaduct (Fig. 3), 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 is also partly 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 at least 8 m of fluvial deposits. Considering the stratigraphy, it is likely that lagoon or transitional deposits could be present even in the M3 site, but at deeper horizons (Fig. 7). Considering only the direct information documented in M2, it is evident that marine and transitional environments were present in the early Holocene over 7 km further inland than at present. Thus, the studied cores testify that the estuarine (bay-head) delta progradation occurred approximately in the last 7000 years, with the seaward migration of continental 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 not reached by the 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, IGH, 1994), allowing the accommodation space necessary for recording early-Holocene and even previous 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., 2004; ANTONIOLI et al., 2007; 2009; AMOROSI et al., 2008), the expected age of the basal Holocene paralic facies should be around 10–9 ka BP, when the sea level in the Adriatic was approximately 30 m below the present msl.

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, as in the bays of Sečovlje, Koper and Raša. 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., 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 can be represented by the Tagus River valley, near Lisbon (VIS & KASSE, 2008; VIS et al., 2009). In particular, the brackish-water marshes and tidal flats described in the subsoil of the Tagus mouth present many similarities with facies Ba and Bb 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 (bay head 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 case of the Mirna could be an example for other deltas developed in karstic environments, such as several examples along the eastern Adriatic coast, where the supply of sands and gravels is poor.

The information collected by this research also supports some considerations about past relative sea levels. The dated sample at 5.27 m in M2 (–2.87 m 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 (bay head delta) had passed downstream of the location of M2. The dated layer (–2.9 m, ~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 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 (1154–1254 cal AD) is rather surprising for its young age and deep location (Fig. 7), but it matches with the archaeological information available in 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 (Montona) (Fig. 1), 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 bay-head delta. Especially intensive processes of sedimentation were occurring in 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).

6. CONCLUSIONS

This research investigated the subsoil of the terminal tract of the Mirna river valley using a multidisciplinary approach, combining lithological, sedimentological, geochronological and both macro- and microfossil analyses. The Mirna is the largest river of Istria and one of the major water courses of the eastern side of the Adriatic, therefore, the reconstruction of the environments which characterized this area (and their Holocene evolution) can be an important reference for other fluvial systems along the eastern Adriatic coast with karstic estuaries (eg. Raša, Krka, Zrmanja, or Neretva rivers). The important results achieved by this research can be briefly described as:

i) In the studied area the late-Holocene deposits consist almost entirely of fine grained sediments (*i.e.* silts and clays), often with a homogeneous appearance and, therefore distinction among the different sedimentary facies needs the use of palaeontological indicators. Foraminiferal investigation was a strong tool, but the combined use with ostracod analysis could probably improve the detail in the results.

ii) In the last 6500 years, a bay-head delta sequence prograded for over 7 km in the lower tract of the Mirna River, filling the pre-existing valley with a sediment thickness of at least 13 m. In the cores the alluvial facies (A) were located above brackish swamps and hyposaline marshes (Ba) while, below them, sediments related to the inner estuary/lagoon (Bb) and outer lagoon/estuary (E) were present.

iii) The large and almost steady input of freshwater supplied by the river and some karstic springs in the lower valley contributed to lowering the salinity due to the protected setting offered by the bay, allowing the presence of an outer-lagoon/estuary (E) assemblage even in front of the river mouth, instead of marine species.

iv) Since late Antiquity an important alluvial phase started, 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. The huge quantity of fine grained alluvial deposits is related to the extensive outcrop of Eocene flysch that is particularly prone to erosion and, thus, facilitated the rapid filling of the karstic valley and progradation of the bay head delta.

v) 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.

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REFERENCES

ALBANI, A.D., SERANDREI–BARBERO, R. & DONNICI, S. (2007): Foraminifera as ecological indicators in the Lagoon of Venice, Italy.– Ecological Indicators, 7, 239–253.

AMOROSI, A., COLALONGO, M.L., FIORINI, F., FUSCO, F., PASINI, G., VAIANI, S.C.& SARTI, G. (2004): Palaeogeographic and palaeoclimatic evolution of the Po Plain from 150–ky core records.– Global Planetary Change, 40, 55–78.

AMOROSI, A., CENTINEO, M.C., COLALONGO, M.L. & FIORINI, F. (2005): Millennial–scale depositional cycles from the Holocene of the Po Plain, Italy.– Marine Geology, 222–223, 7–18.

AMOROSI, A., FONTANA, A., ANTONIOLI, F., PRIMON, S. & BONDESAN, A. (2008): Post–LGM sedimentation and Holocene shoreline evolution in the NW Adriatic coastal area.– GeoActa, 7, 41–67.

ANTONIOLI, F., ANZIDEI, M., AURIEMMA, R., GADDI, D., FURLANI, S., LAMBECK, K., ORRU', P., SOLINAS, E., GASPARI, A., KARINJA, S., KOVAČIĆ, V. & SURACE, L. (2007): Sea level change during Holocene from Sardinia and Northeastern Adriatic from archaeological and geomorphological data.– Quaternary Science Review, 26, 2463–2486.

ANTONIOLI, F., AMOROSI, A., BONDESAN, A, BRAITENBERG, C., DUTTON, A., FERRANTI, L., FONTANA, A., FONTOLAN, G., FURLANI, S., LAMBECK, K., MASTRONUZZI, G., MONACO, C. & ORRU', P. (2009): A review of the Holocene sea–level changes and tectonic movements along the Italian coastline.– Quaternary International, 206, 102–133.

BENAC, Č. & ARBANAS, Ž. (1990): Sedimentacija u području ušća Rječine [The sedimentation in the area of the mouth of Rječina River].– Pomorski zbornik, 28, 593–609.

BENAC, Č., JURAČIĆ, M. & BAKRAN–PETRICIOLI, T. (2004): Submerged tidal notches in the Rijeka Bay NE Adriatic Sea: Indicators of relative sea–level change and of recent tectonic movements.– Marine Geology, 212, 21–33.

BENAC, Č., JURAČIĆ, M. & BLAŠKOVIĆ, I. (2008): Tidal notches in Vinodol Channel and Bakar Bay, NE Adriatic Sea: indicators of recent tectonics.– Marine Geology, 248, 151–160.

BOŽIČEVIĆ, S. (2005): Mirna.– In: BERTOŠA, M. & MATIJAŠIĆ, R. (eds.): Istarska enciklopedija. [Istrian Enciklopedy]. Leksikografski zavod Miroslav Krleža, Zagreb, 493–494.

BRAMBATI, A., CARBOGNIN, L., QUAIA, T., TEATINI, P. & TOSI, L. (2003): The Lagoon of Venice: geological setting, evolution and land subsidence.– Episodes, 26, 263–268.

BRONK RAMSEY, C. (2009): Bayesian analysis of radiocarbon dates.– Radiocarbon, 51/1, 337–360.

CARRE, M.B., KOVAČIĆ, V. & TASSAUX, F. (2007): Quatre ans de recherche sur le littoral parentin.– In: AURIEMMA R., KARINJA S. (eds.): Terre di Mare. L'archeologia dei paesaggi costierei e le variazioni climatiche. Atti del Convegno Internazionale di Studi Trieste, 8–10 novembre 2007, Trieste, 310–315.

CASTELLARIN, A., CANTELLI, L., FESCE, A.M., MERCIER, J.L., PICOTTI, V., PINI, G.A., PROSSER, G. & SELLI, L. (1992): Alpine compressional tectonics in the Southern Alps. Relationship with the N–Apennines.– Annales Tectonicae, 6 (1), 62–94.

CASTIGLIONI, G.B. (Ed.) (1997): Geomorphological Map of Po Plain. MURST–S.El.Ca, 3 sheets, scale 1:250,000, Firenze.

CIMERMAN, F. & LANGER, M. R. (1991): Mediterranean Foraminifera.– SAZU, Ljubljana, 119 p.

CORREGGIARI, A., ROVERI, M. & TRINCARDI, F. (1996): Late Pleistocene and Holocene evolution of the north Adriatic sea II Quaternario – Italian Journal of Quaternary Sciences, 9/2, 697–704.

CORREGGIARI, A., CATTANEO, A., TRINCARDI, F. (2005): The modern Po delta system: lobe switching and asymmetric prodelta growth.– Marine Geology, 222–223, 49–74.

CREMONINI, S., LABATE, D. & CURINA, R. (2013): The late–antiquity environmental crisis in Emilia region (Po river plain, Northern Italy): Geoarchaeological evidence and paleoclimatic considerations.– Quaternary International 316, 162–178.

CROATIAN GEOLOGICAL SURVEY (2009): Geological Map of the Republic of Croatia 1:300000. – Croatian Geological Survey, Zagreb.

DEBENAY, J-P., TSAKIRIDIS, E., SOULARD, R. & GROSSEL, H. (2001): Factors determining the distribution of foraminiferal assemblages in Port Joinville (Ile d'Yeu, France): the influence of pollution.– Marine Micropaleontology, 43, 75–118.

D'INCÀ, C. (2007): Il Porto Quieto e il fiume: un mutare di funzioni e di paesaggi tra l'Istria costiera e l'interno.– In: AURIEMMA, R. & KARINJA, S. (eds.): Terre di Mare. L'archeologia dei paesaggi costierei e le variazioni climatiche. Atti del Convegno Internazionale di Studi Trieste, 8–10 novembre 2007, Trieste, 400–406.

DONNICI, S. & SERANDREI–BARBERO, R. (2002): The benthic foraminiferal communities of the northern Adriatic continental shelf.– Marine Micropaleontology, 44, 93–123.

FAIVRE, S. & FOUACHE, E. (2003): Some tectonic influences on the Croatian shoreline evolution in the last 2000 years.– Zeitschrift für Geomorphologie, 47/4, 521–537.

FAIVRE, S., FOUACHE, E., GHILARDI, M., ANTONIOLI, F., FURLANI, S. & KOVAČIĆ, V. (2011): Relative sea level change in Istria (Croatia) during the last 5 ka.– Quaternary International, 232, 132–143.

FAO–ISRIC (2006): Guidelines for soil description, 4rd edition.– International Soil Reference Information Centre, Rome, 97 p.

FORENBAHER, S., KAISER, T. & MIRACLE, P. (2013): Dating the East Adriatic Neolithic.– European Journal of Archaeology, 16/4, 589–609.

FURLANI, S., CUCCHI, F., BIOLCHI, S. & ODORICO, R. (2011): Notches in the Adriatic Sea: genesis and development.– Quaternary International, 232, 158–168.

FURLANI, S., PAPPALARDO, M., GOMEZ–PUJOL, L. & CHELLI, A. (2014): The rock coast of the Mediterranean and Black Seas.– In: KENNEDY, D.M., STEPHENSON, W.J. & NAYLOR, L.A. (eds.): Rock Coast Geomorphology: A Global Synthesis.– Geological Society, London Memoirs, 40, 89–123.

GULAM, V., POLLAK, D. & PODOLSZKI, L. (2014): The analysis of the flysch badlands inventory in central Istria, Croatia.– Geologia Croatica, 67/1, 1–15.

HAMMER, O., HARPER, D. A. T &, RYAN, P. D. (2001): PAST: Paleontological statistics software package for Education and Data Analysis.– Paleontol. Electron., 4, 1–9.

IGH (1994): Probno ispitivanje pilota za viadukt preko doline rijeke Mirne 2200–1–213255/94 [The preliminary testing of pilots for the viaduct over the Mirna River Valley].– Zavod za geotehniku, Institut građevinarstva Hrvatske, 22 p., Zagreb.

LOEBLICH, JR., A. R. & TAPPAN, H., (1988): Foraminiferal genera and their classification.– Van Nostrand, Reinhold, New York, 970 p. + 847pls.

MAGDALENIĆ, A., VAZDAR, T. & HLEVNJAK, B. (1995): Hydrogeology of the Gradole Spring Draining Area in Central Istria.– Geologia Croatica, 48, 97–106.

McRAE, S. G. (1988): Practical pedology: Studying soils in the field.– Ellis Horwood, Chichester, John Wiley, London, 253 p.

MELIS, R. & COVELLI, S. (2013): Distribution and morphological abnormalities of recent foraminifera in the Marano and Grado Lagoon (North Adriatic Sea, Italy).– Mediterranean Marine Science, 14/1, 432–450.

MIALL, A.D. (1996): The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology.– Springer, Berlin, 582 p.

MILOTIĆ, I. (2004): Dolina Mirne u Antici [The Mirna Valley *in Ancient History*].– Ekološki glasnik, Donja Lomnica, 325 p.

MILOTIĆ, I. & PRODAN, L. (2014): Stoljeće i pol organizirane vodoprivrede u Istri [One and a Half Century of the Organized Water Management in Istria].– Vodoprivreda d.o.o., Buzet, 370 p.

MORTEANI, L. (1895): Storia di Montona [parte VI].– Archeografo Triestino, II serie, vol. XX (XXIV), 410, 5–123.

MURRAY, J.W. (1974): Distribution and Ecology of Living Benthic Foraminiferids.– Heinemann Educational Books, London, 274 p.

MURRAY, J. (1991): Ecology and paleoecology of benthic foraminifera.– Longman Scientific and Technical, London, 397 p.

MURRAY, J.W. (2006): Ecology and Applications of Benthic Foraminifera.– Cambridge University Press, Cambridge, New York, 426 p.

OGRINC, N., FAGANELI, J., OGORELEC, B. & ČERMELJ, B. (2007): The origin of organic matter in Holocene sediments in the Bay of Koper (Gulf of Trieste, northern Adriatic Sea).– Geologija, 50/1, 179–187.

OGORELEC, B., MIŠIĆ, M., ŠERCELJ, A., CIMERMAN, F., FAGANELI, J. & STEGNAR, P. (1981): Sediment sečoveljske soline [Sediment of the salt marsh of Sečovlje].- Geologija 24/2, 179-216.

PARENTIN, L. (1974): Cittanova d'Istria.– Trieste, 303 p.

PAVELIĆ, D., KOVAČIĆ, M., VLAHOVIĆ, I., MANDIC, O., MARKOVIĆ, F. & WACHA, L. (2014): Topography controlling the wind regime on the karstic coast: late Pleistocene coastal calcareous sands of eastern mid–Adriatic, Croatia.– Facies, 60, 843–863.

PÉRES, J.M. & PICARD, J. (1964): Nouveau manuel de bionomiebenthique de la mer Méditerranée.– Rec. Trav. Stat. Mar. Endoume, 31, 137 p.

PLENIČAR, M., POLŠAK, A. & ŠIKIĆ, D. (1965): Osnovna geološka karta SFRJ 1:100000, Tumač za list Trst, L33–88 [Basic Geological Map of SFRY 1:100000, Geology of the Trst sheet, L33–88].– Geološki zavod Ljubljana i Institut za geološka istraživanja Zagreb, 64 p.

POLŠAK, A.& ŠIKIĆ, D. (1963): Osnovna geološka karta SFRJ 1:100000, Tumač za list Rovinj, L33–100 [Basic Geological Map of SFRY 1:100000, Geology of the Rovinj sheet, L33–100].– Institut za geološka istraživanja, Zagreb, 47p.

PIKELJ, K. & JURAČIĆ, M. (2013): Eastern Adriatic Coast (EAC): Geomorphology and Coastal Vulnerability of a Karstic Coast.– Journal of coastal research, 29, 944–957

PRODAN, V. (2001): Hidrografija Sliva Potoka Butoniga [Hydrography of the Butoniga Creek Basin].– Buzetski Zbornik, 155–170.

REIMER, P.J., BARD, E., BAYLISS, A., BECK, J.W., BLACKWELL, P.G., BRONK RAMSEY, C., GROOTES, P.M., GUILDERSON, T.P., HAFLIDASON, H., HAJDAS, I., HATTÉ, C., HEATON, T.J., HOFFMANN, D.L., HOGG, A.G., HUGHEN, K.A., KAISER, K.F., KROMER, B., MANNING, S.W., NIU, M., REIMER, R.W., RICHARDS, D.A., SCOTT, E.M., SOUTHON, J.R., STAFF, R.A., TURNEY, C.S.M. & VAN DER PLICHT, J. (2013): IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP.– Radiocarbon, 55, 1869–1887.

RETALLACK, G.J. (1990): Soils of the Past: An Introduction to Paleopedology. – Unwin Hyman, London, 520 p.

ROSSATO, S., FONTANA, A. & MOZZI, P. (2015): Meta-analysis of the Holocene ^{14}C database of the Venetian-Friulian alluvial plain (NE Italy).– Catena, 130, 34–45.

RUBINIĆ, J., BUŠELIĆ, G., KUKULJAN, I. & KOSOVIĆ, M. (1999): Hidrološka analiza suspendiranog nanosa u istarskim vodama [Hydrological analysis of suspended sediment in the Istrian waters].– Hrvatske Vode, 7/27, 127–137.

SAKARA SUČEVIĆ, M. (2004): Prazgodovinska naselbina pri Novi Vasi, Brtonigla (Istra) [Prehistoric settlement near Nova Vas, Brtonigla (Istria)].– Univerza na Primorskem, Znanstveno-raziskovalno središče, Inštitut za dediščino Sredozemlja, Koper, 205 p.

SANTIN, G.A. (2013): Fiumi e torrenti dell'Istria: caratteristiche e problematiche attuali.– D.i.g. Vodoprivreda d.o.o. Buzet, 12 p.

SCOTT, D.B. & MEDIOLI, F.S. (1978): Vertical zonations of marsh foraminifera as accurate indicators of former sea-levels.– Nature, 272, 528–531.

SOIL SURVEY STAFF (2003): Keys to Soil Taxonomy. 9th Edition.– USDA-NRCS, Washington, 305 p.

SONDI, I., JURAČIĆ, M. & PRAVDIĆ, V. (1995): Sedimentation in a disequilibrium river–dominated estuary. The Raša River Estuary (Adriatic Sea–Croatia).– Sedimentology, 42, 769–78.

STEFANI, M. & VINCENZI, S. (2005): The interplay of eustasy, climate and human activity in the late Quaternary depositional evolution and sedimentary architecture of the Po Delta system.– Marine Geology, 222–223, 19–48.

TOSI, L., CARBOGNIN, L., TEATINI, P., ROSSELLI, R. & GASPARETTO STORI, G. (2000): The ISES project subsidence monitoring of the catchment basin south of the Venice Lagoon, Italy.– In: CARBOGNIN L. et al. (eds.): Land subsidence, vol. 2. La Garangola, Padova (Italy), 113–126.

VANIČEK, V., JURAČIĆ, M., BAJRAKTAREVIĆ, Z. & ĆOSOVIĆ, V. (2000): Benthic Foraminiferal Assemblages in a Restricted Environment – An Example from the Mljet Lakes (Adriatic Sea, Croatia).– Geologia Croatica, 53, 269–279.

VELIĆ, I., VLAHOVIĆ, I. & MATIČEC, D. (2002): Depositional sequences and Palaeography of the Adriatic Carbonate Platform.– Memorie Della Società Geologica Italiana, 57, 141–151.

VRANJEŠ, M., VIDOŠ, D. & GLAVAŠ, B. (2007): Stanje sedimenta u donjoj Neretvi (Status of sediments in the lower Neretva River).– In: GEREŠ, D. (ed.): 4 Hrvatska konferencija o vodama. Hrvatske vode i Europska unija – izazovi i mogućnosti.– Hrvatske vode, Zagreb, 337–344.

VLAHOVIĆ, I., TIŠLJAR, J., VELIĆ, I. & MATIČEC, D. (2005): Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics.– Palaeogeography, Palaeoclimatology, Palaeoecology, 220, 333–360.

VIS, G.J., KASSE, C. & VANDEMBERG, J. (2008): Late Pleistocene and Holocene palaeogeography of the Lower Tagus Valley (Portugal): effects of relative sea level, valley morphology and sediment supply.– Quaternary Science Reviews, 27, 1682–1709.

VIS, G.J. & KASSE, C. (2009): Late Quaternary valley-fill succession of the Lower Tagus Valley, Portugal.– Sedimentary Geology, 221, 19–39.

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