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VERY-HIGH RESOLUTION ANALYSIS OF A TRANSGRESSIVE DEPOSIT IN THE NORTHERN ADRIATIC SEA (ITALY)

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ABSTRACT: The Adriatic Sea is characterized in the northern and central shelf by different generation of isolated transgressive bodies formed and drowned in-place during the last relative sea-level rise. The continental shelf is characterized by a low gradient and, within the transgressive deposits the episodic variations in sea level and sediment supply caused the formation of backstepping parasequences. The transgressive bodies have been studied in detail because they have considerable amount of sorted sand exploitable for beach nourishment. A transgressive deposit, located south of the Po Delta, offshore Ravenna at depth of 34-35 m, has been investigated with a total coverage of very-high resolution (VHR) seismic profiles and high number of cores in order to understand the stratigraphic evolution during the late Quaternary sea-level rise. The transgressive body is composed of four seismic units separated by high-amplitude and high continuity reflectors, corresponding to peat and organic-rich layers indicating different depositional phases. The core analysis confirmed the presence of different units showing sediment variation from clay with peat-layer at the base to fine-grained sand at the top of the deposit. Furthermore, the core analysis gave information about the thickness of the deposit. The thickness of the transgressive body is from 3 to 5 m and each unit varies from 1 to 2 m. In particular, the sand portion reached a maximum thickness of 1.5 meters. The seismic analysis and the digital elevation model constructed for key surfaces highlighted the channel system direction was towards ENE during Last Glacial Maximum and during sedimentation of Unit 1 and 2, while it shifted toward ESE during the formation of Unit 3. Moreover, to constrain the chronology of the sedimentary evolution, some peat and organic-rich samples, have been dated with 14C method. These organic horizons are evident seismic reflectors and correspond to key surfaces. They are characterized by brackish lagoon facies and could be a proxy indicator for the relative paleo-sea level. Along with the previous data, they indicated that the sedimentation of the studied transgressive body occurred around 10,000 cal. a BP.

KEYWORDS: Quaternary, sea-level rise, sequence stratigraphy, beach nourishment, CHIRP-sonar

1. INTRODUCTION

The late glacial and Holocene (Post 18,000 a) sea-level rise is well recorded in the Adriatic Sea due to the peculiar physiographic and sedimentary setting of the basin (Correggiari et al., 1996). During the last sea-level rise the Northern Adriatic Sea was characterized by the formation of different generation of barrier-lagoon systems. These bodies, drowned in-place and partly preserved, crop out in the northern Adriatic seafloor as elongated build-ups parallel to the present coastline. They are interpreted as patches of ancient coastal wedges which have considerable amount of sorted sand and are a significant resource exploitable for beaches nourishment. The sand portion of the transgressive deposits has been studied in detail with grain-size analysis, petrographic analysis, sedimentary architecture and volumes calculation in order to use this resource for coastal nourishment. The detailed characterization of a transgressive deposit located south of the Po Delta, through very-high resolution seismic profiles and facies analysis can shed new lights on the formation and evolution of the transgressive deposits. In particular, as the formation of the transgressive bodies is strongly related to the changes of relative sea level, their multidisciplinary study can produce important data in the reconstruction of the past relative position of the sea level (Antonioli et al., 2009) and detect centennial fluctuations.

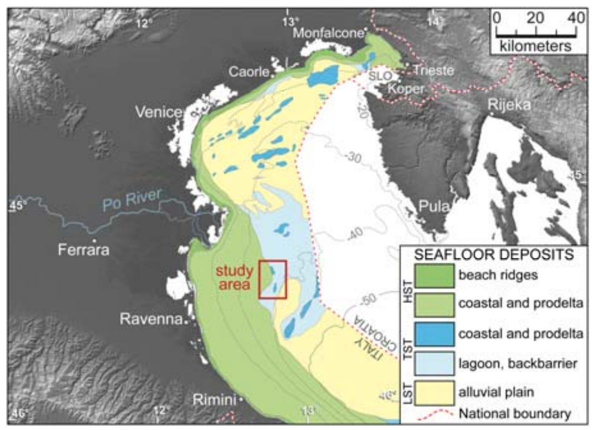


Fig. 1 - Location of the study area in the Adriatic Sea. Bathymetry and superficial geology modified from the Geological Map of Italian seafloor (Fabbri et al., 2001; Trincardi et al., 2011 a, Trincardi et al., 2011 b).

2. GEOLOGICAL SETTING

2.1. The Adriatic Sea

The Adriatic Sea is an epicontinental semi-enclosed basin (Fig. 1) surrounded by three thrust-and-fold-belts: the NE-verging Apennines, the S-verging Southern Alps and the SW-verging Dinarides. The basin records the evolution from a passive margin, during the

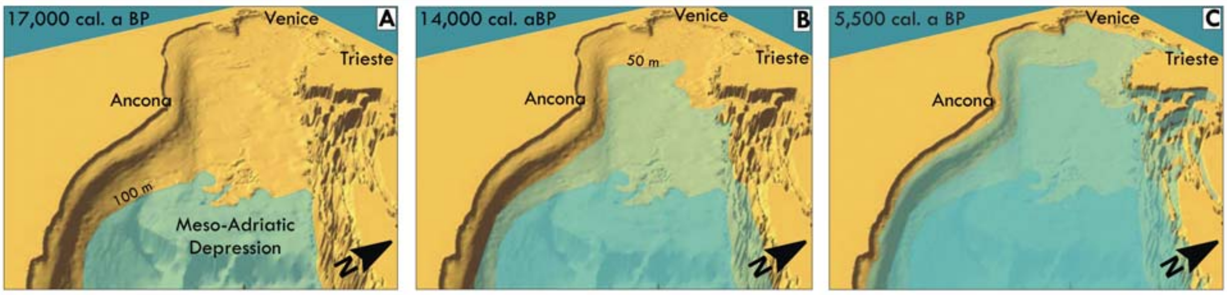


Fig. 2 - Widening of the Adriatic basin during the last transgressive cycle. (A) Sea-level during the Last Glacial Maximum (LGM), an extensive portion of the Adriatic sea was in subaerial condition, while the Meso-Adriatic-Depression (MAD) was a semi-enclosed basin receiving high amount of sediment (Correggiari et al., 1996). (B) Rapid sea-level rising after the LGM. (C) Maximum marine ingression reached 5500 cal. a BP.

Mesozoic, to a foreland basin system, during the Cenozoic (D'Argenio & Horvath, 1984; Ori et al., 1986; Ciabatti et al., 1987; Argnani & Frugoni, 1997). During Quaternary sea-level fluctuations the basin has been shaped by huge change of the oceanographic regime and sedimentary dynamics (Trincardi et al., 1994, 1996). During the Last Glacial Maximum (LGM, 30,000-19,000 14C a BP; Lambeck & Purcel, 2005; Clark et al., 2009) the sea-level was about 120-130 m lower than today and the northern continental shelf was completely in subaerial conditions (Fig. 2A). In this environment several river networks formed, consisting of by a main trunk river (Paleo Po river) and Alpine and Apennines tributaries; the fluvial system terminated in a low-stand delta located at the northern edge of the Meso-Adriatic-Depression, southeast of Ancona (De Marchi, 1922; Correggiari et al., 1996; Ridente & Trincardi, 2005). During the late-glacial to early -Holocene transgression, a glacio-eustatic, non-steady sea-level rise of approximately 120 meters caused substantial basin widening coupled by changes in energy regimes across the basin (Cattaneo & Steel, 2003) (Fig. 2B). The low gradient of the northern Adriatic shelf, together with the sea-level rise (approximately 10-15 mm/a), favoured the deposition and drowning of different generations of transgressive barrier-lagoon system sedimentary bodies. In contrast, the steeper topographic gradient of the southwestern Adriatic shelf has been characterized by the deposition of thick transgressive progradational deposits (Cattaneo & Trincardi, 1999; Maselli et al., 2011). The maximum marine ingression was reached ca. 5500 cal. a BP when the basin occupied much wider area than during the low-stand (Fig. 2C). During highstand the anticlockwise circulation characterizing the Adriatic caused southward transport of sediment along the entire western side of the basin as documented in surficial geology maps of the Adriatic (Fabbri et al., 2001; Trincardi et al., 2011 a; Trincardi et al., 2011 b) (Fig. 1). Our study focused on a transgressive deposit, located 50 km from Ravenna at 34-35 m water

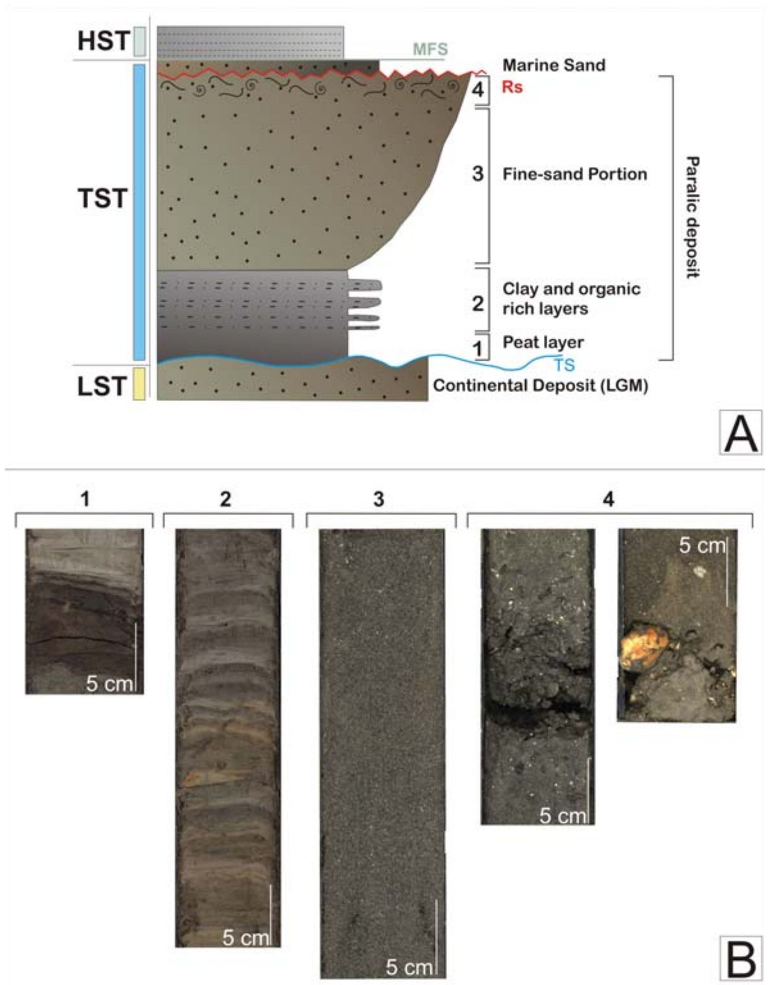


Fig. 3 - Main cores facies description. (**A**) Simplified log of most representative cores. The TST deposits rest on the Transgressive Surface. The paralic deposit is characterized at the base by clay sediment, peat and organic-rich layers and at the top by a sand portion. This deposit ends with ravinement surface. (**B**) Example of cores facies. 1: Peat layer; 2: Interbedded clayey and silty layers; 3: Sand portion; 4: ravinement surface (Rs).

depth (Fig. 1). This transgressive deposit showed a dominant longshore trend parallel to the modern coastline, it extends NS for about 20 km and is 8 km wide. Its thickness varies from 1 m near the boundary areas to 4 meters in the depocenters.

2.2. Transgressive deposits

The late-glacial and Holocene transgressive deposits (Transgressive System Tract, TST) in the Adriatic basin were formed by backstepping barrier-lagoon and incised valley systems in the low gradient northern shelf, while mud sedimentary bodies thicker than 25 m are present in the central Adriatic shelf (Cattaneo & Trincardi, 1999; Maselli et al., 2011, Trincardi et al., 2013) (Fig. 1). The TST rests on an erosive surface of regional extent (transgressive surface, TS) that truncates older low-stand deposits (LST), and is below the maximum flooding surface (MFS) (Fig. 3). Available 14C data show that the time interval encompassed by the TST spans about 11,000 years, between 16,000 and 5500 cal. a BP (Correggiari et al., 1996; Trincardi et al., 1996; Cattaneo & Trincardi, 1999, Correggiari et al., 2001, Maselli et al., 2011).

The transgressive deposits in the northern Adriatic shelf are located at sea bottom between -45 m to -10 m water depth, and they are preserved as elongated undulating elevations almost parallel to the present coastline. The complex geometry and their preservation is probably due to a combination of different factors such as the rate of sea-level rise, the low gradient of the shelf and the coastal dynamics (Belknap & Kraft, 1981, Correggiari et al., 2011). In the northern Adriatic Sea, transgressive deposits are generally associated to a barrier-lagoon system, that is typically characterized by clayey-silty lagoon deposits associated with sandy beach deposits (Fabbri et al., 2001) (Fig. 3).

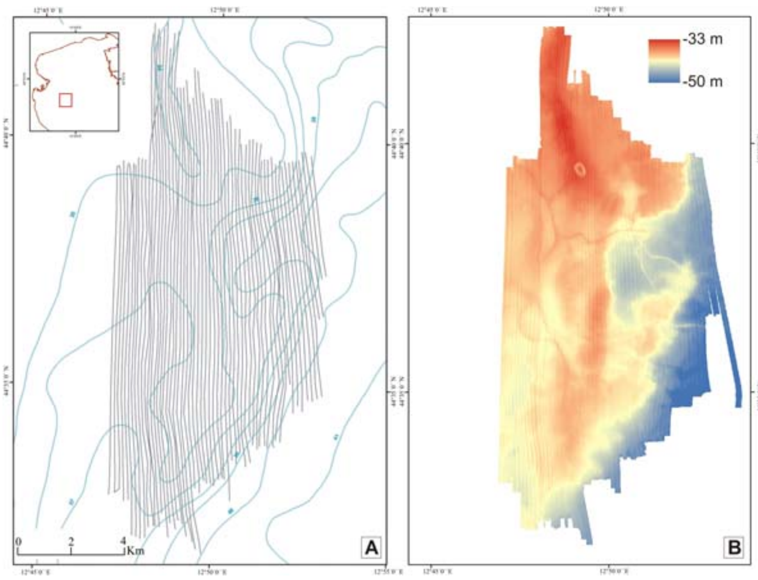


Fig. 4 - Study Area detail. (A) Tracks of VHR seismic profiles, acquired in 2012, covering the study area. (B) Seafloor bathymetry (image resolution of 10 m). Evidence of the ESE channel system trend.

3. METHODS

The transgressive deposit has been examined with a multi-disciplinary approach through very high resolution (VHR) seismic profile analysis and vibrocorer samples, digital elevation model (DEM) of most significant surfaces and 14C dating. All the analysed data have been collected during oceanographic cruises carried out in the last 20 years by CNR-ISMAR onboard Urania R/V. VHR seismic profiles have been acquired with Sub Bottom Profiler CHIRP-Sonar with 16 low-frequency transducers. About 750 km of VHR seismic profiles, oriented NS and spaced 120 meters each other, covered the transgressive deposit (Fig. 4A). The seismic profiles have been processed and interpreted with SeisPrho (Gasperini & Stanghellini, 2009). Cores have been collected by Vibrocorer Rossfelder P5, with a vibrating head and a steel corer 6-m long and 10-cm wide. DEMs of key seismic surfaces, obtained from Conversion Tools ASCII to Raster of ArcMap 10.1 software, have been used to map their areal distribution. Furthermore the top of the transgressive deposit, coinciding with the seafloor, has been analysed with the Digital Elevation Model of the multibeam bathymetry (with image resolution of 10 m) acquired during the NAD12 (in 2012) oceanographic cruise onboard Urania R/V (Fig. 4B). The device used is an EM 710 Multibeam echosounder with 70-100 kHz. The geochronological constrains of the geological evolution have been provided by the 14C dating of 3 samples of organic-rich and peat layers, in the core AR00_22. The AMS analysis has been done at the Ion Beam Laboratory at the ETH Institute in Zurich. Our data have been integrated with those from core CM94_107 (Fabbri et al., 2001). The radiocarbon ages from AR00_22 and CM94_107 cores have been calibrated using CALIB14 Radiocarbon Calibration Program of Stuiver & Reimer (1993). The results have been corrected for isotopic fractionation, but no correction for oceanic reservoir was made because the dated layers are of terrestrial origin.

4. RESULTS

4.1. Seismic analysis

The seismic profiles analysed, were collected during the oceanographic cruises NAD12. The detailed seismic-stratigraphic analysis highlighted three different seismic facies: 1) a semi-transparent unit, due to scarce penetration of the acoustic signal, indicative of sandy sediments, characterized by an irregular, erosive base; 2) an interbedded transparent seismic facies with parallel and subparallel irregular and discontinuous reflectors related to fine-grain deposits with thin fine sand or silty layers; 3) regular and continuous reflectors interpreted as peat and organic-rich layers. In each profile five key surfaces have been identified and traced in order to define the geometry of deposits and to investigate the formation and evolution of the transgressive parase-

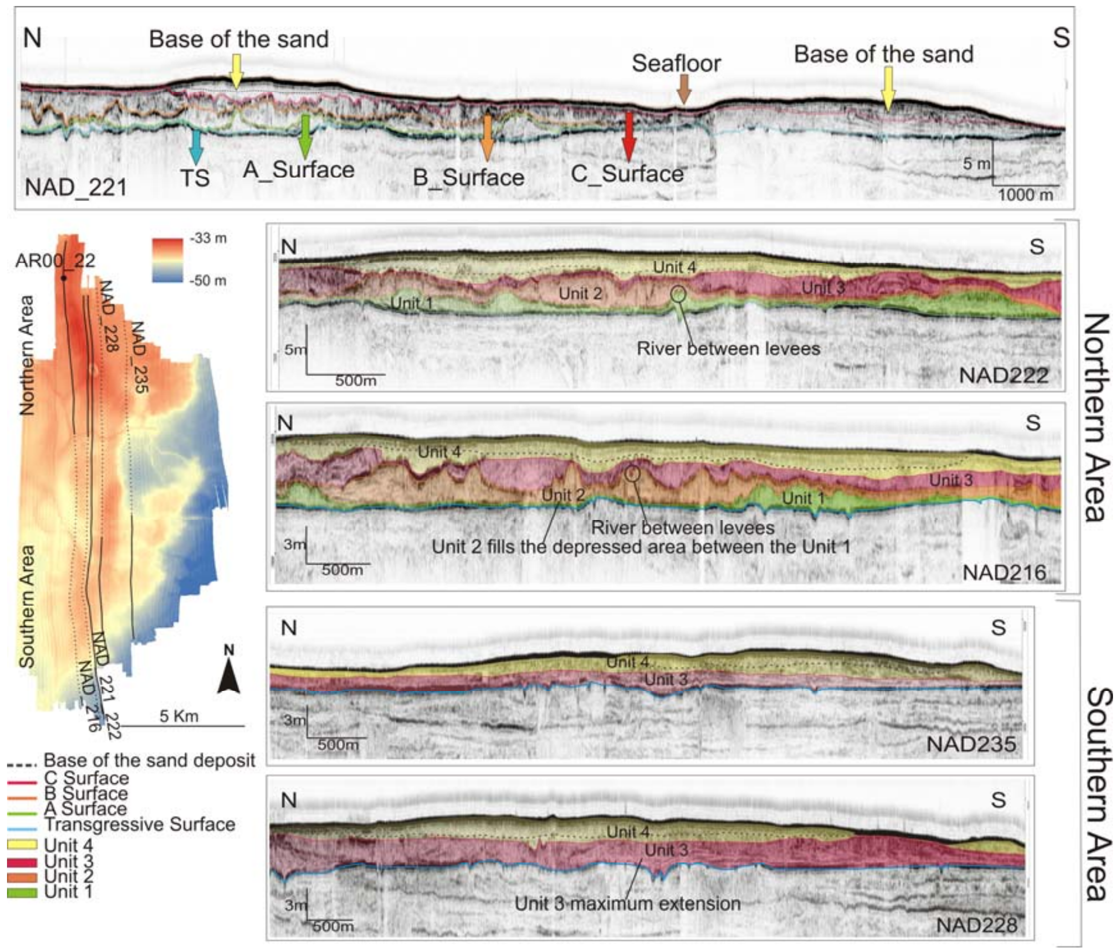


Fig. 5 - Evidence of the key surfaces and units within the sedimentary transgressive body.

quences. The key surfaces, easily visible and traceable along the entire profile, correspond to organic rich and peat layers. The seismic reflector interpreted as transgressive surface marks a different response in the seismic profile and has been traced correlating the dated peat layers from published data (Fabbri et al., 2001; Correggiari et al., 2011). The TS is an erosional surfaces that marks the first major flood of the margin. It rests on the low-stand deposit formed during the LGM where the top was dated at 20,000-21,000 14C a BP by radiocarbon dating of peat samples southern than the investigated deposit by Trincardi et al. (1994); Fabbri et al. (2001); Cattaneo & Steel, (2003). The studied transgressive body rests on the TS. In addition to the TS other three key reflectors have been identified within the transgressive deposit (A surface, B surface, C surface and Seafloor surface at the top, Fig. 5); these surfaces border four different units (from Unit 1 at the base, to Unit 4 at the top) that mark four different depositional environments during the sedimentation of the transgressive deposit (Fig. 5). Moreover within the most recent unit an additional key surface has been identified at the base of the sandy portion. The Unit 1, 2 and 3 were delimited by the digitized key surfaces, corresponding to peat layers, and were characterized by interbedded transparent and discontinuous seismic reflectors, which were more regular within the unit 3. At the top of both the Unit 1 and the Unit 2 seismic profiles revealed the presence of some channels bordered by levees. The Unit 4, was delimitated at the base by the C key surface and at the top by the seafloor. Additional key surface within Unit 4 divided the base with irregular and discontinuous seismic reflectors and at the top a semi-transparent seismic facies indicative of sandy sediments.

4.2. Digital elevation models of key surfaces

The digital elevation models showed the morphology of the surfaces highlighting the occurrence of the channel system network existing when each of them was exposed and active (Fig. 6). Thus, each DEM represents one step in the formation of the transgressive deposit. The TS lies higher to the west and lower towards east, characterized by channels with ENE direction (Fig. 6A). At first, the sedimentation over the TS occurred in the north/northeast and western areas and shows an ENE channel progradation. This situation was highlighted by the DEM of the A surface (top of the Unit 1) and the DEM of the B surface (top of the Unit 2) (Fig. 6B/C), and then the sedimentation of the transgressive

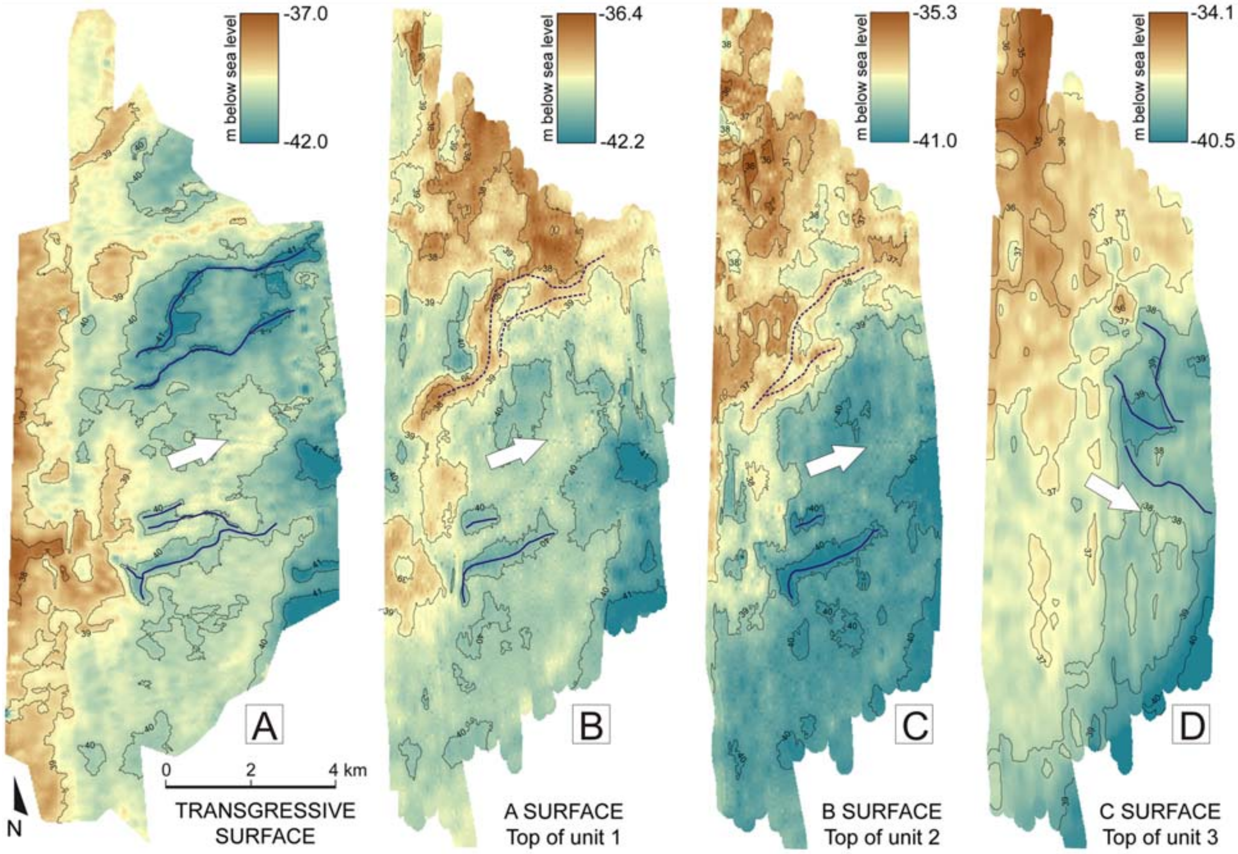


Fig. 6 - DEMs with isopach of the key surfaces obtained from Conversion Tools ASCII to Raster of ArcMap 10.1 program. Comparison of DEM. Variation in channel system trend and preservation of each unit. The channels depicted in each surface have been traced in blue, while the dashed rivers represent the leveed channel systems elevated above the underlying surface.

body shifted to the south/southwest. The DEM of the C surface (top of the Unit 3) highlighted the filling of the southern area together with the variation of the channel direction from ENE to ESE (Fig. 6D). The transgressive body ended at the top with Unit 4, that correspond to the basal clay lagoon layer resting on the C surface, filling and flattening the transgressive body. The seafloor bathymetry (Fig. 4B), that coincides with the top of the Unit 4, maintained the same ESE channel trend as highlighted for Unit 3.

4.3. Cores facies analysis and calibration of seismic units

30 cores collected during the oceanographic cruises CM94 and AR00 (in 1994 and 2000) onboard Urania R/V (CNR-ISMAR) have been described to define the depositional environment corresponding to the sedimentation of the transgressive body. The cores had a length spanning between 1.5-4 m and generally showed coarsening-upward trend with a thin fining-upward layer at the top. The basal portion was formed by clay with some peat layers. This unit was overlain by fine-sand that was capped by an erosional surface. The TST deposit was covered with thin layer (about 15-30 cm) of silty-clay representing a recent distal Po prodelta highstand deposit (Correggiari et al., 2005; Correggiari et al., 2011) (Fig. 3). The Unit 1 rests on the transgressive surface and is capped by the A surface (Fig. 5), it was found only in the northern part of the investigated area and it is organized in elongated river systems that are elevated above the TS and oriented towards ENE. These systems lie on the ancient fluvial system highlighted by the TS, and in the seismic profiles it was possible to recognise some leveed channel systems. The Unit 1 was mainly formed by clay with organic matter and millimetric plant debris interbedded with peat layers (Fig. 7), farther few cores highlighted a fine-sand to silty layer at the top of this unit. The fossil content belonging to this unit was characterized by the mollusc association consisting of Cerastoderma glaucum, Abra segmentum and Lentidium. The Unit 2 was bounded at the base by the A surface and at the top by the B surface (Fig. 5), it was mainly present in the northern and western part of the investigated area and it filled the depressed zones formed between the Unit 1 channel systems. This unit was similar to the Unit 1, characterized by clay with organic matters and carbonaceous frustules, while the top was an easily recognizable layer of peat with a thickness of 10-15 cm (Fig. 7). The fossil content was the same as of the Unit 1. The Unit 3 was bounded at the base by the B surface if present or by the TS surface where it was not present and at the top by the C surface (Fig. 5). Unit

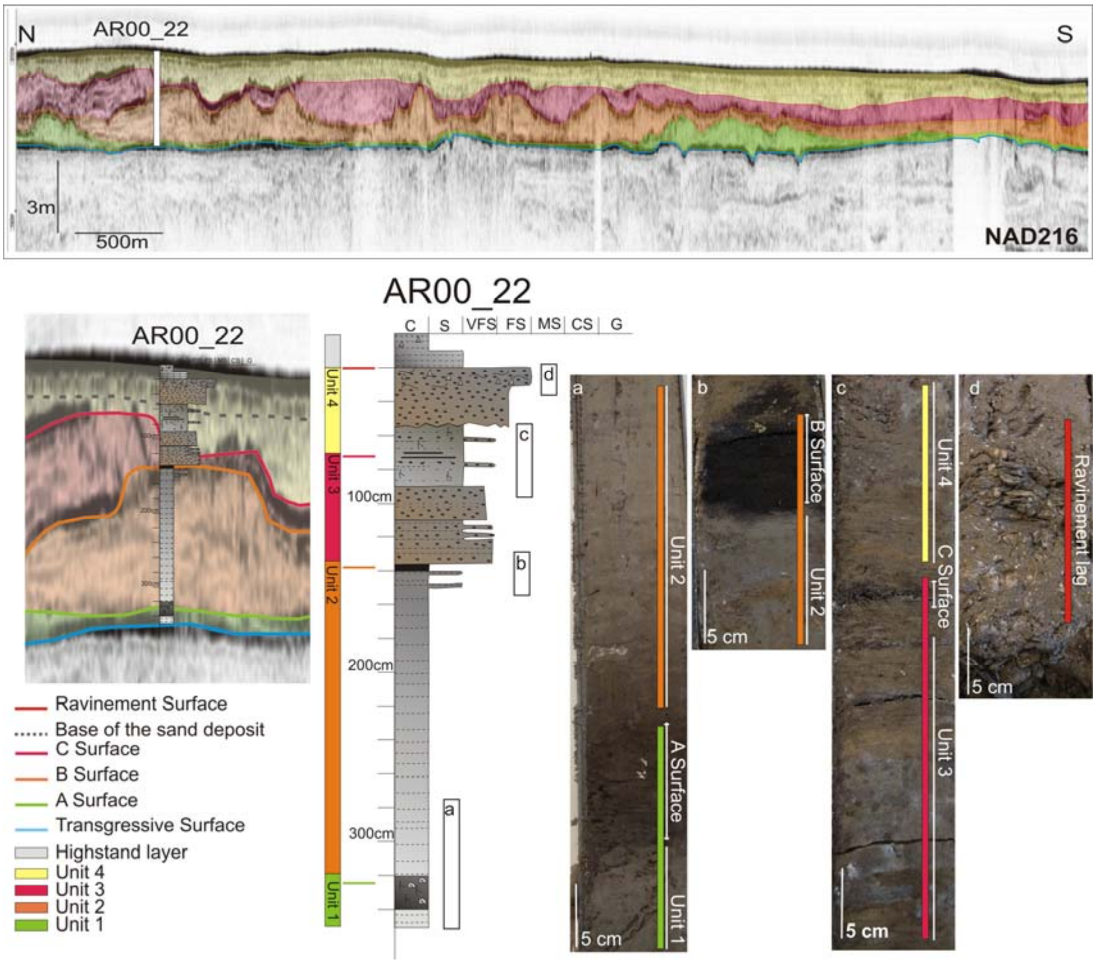


Fig. 7 - AR00_22 core log plotted on NAD216 seismic profile, location in Fig. 5 . On the left, the picture shows the position of AR00_22 in the seismic profile, the seismic units in color bordered by the key surfaces. On the right, the picture shows the description of the AR00_22 core, their core facies, highlighted by the photos, corresponding to the white panels a, b, c, d close to the core log.

3 was mostly developed in the southern part of the area, while in the northern sector was limited to a thin layer below the Unit 4. The southern portion of the Unit 3 was characterized by 2-2.5 meters of clay layers with millimetric plant debris interbedded with parallel-laminated silty layers (Fig. 7). The northern portion of the Unit 3 was formed of a thin layer of clay that filled and smoothed the underlying depressed areas. The paleontological association was characterized by Cerastoderma glaucum, Abra segmentum and Lentidium sp. The Unit 4 was bounded at the base by the C surface and at the top by the seafloor (Fig. 5), its geometry showing two convex landforms with a gentle trough in the middle of the deposit. In this unit a significant amount of sorted sand has been found within the two build ups above a thin clayey layer. The sand portion, that reached up to 1.5 m of thickness, ended with a bioclastic sand layer representing the ravinement surface (Rs) (Fig. 7). The analysis on the sand below the Rs showed a mean diameter between 0.25-0.35 mm and a very scarce content of silt and clay (Correggiari et al., 2011). The top of the deposit is locally characterized by a very thin 15-30 cm layer of clay.

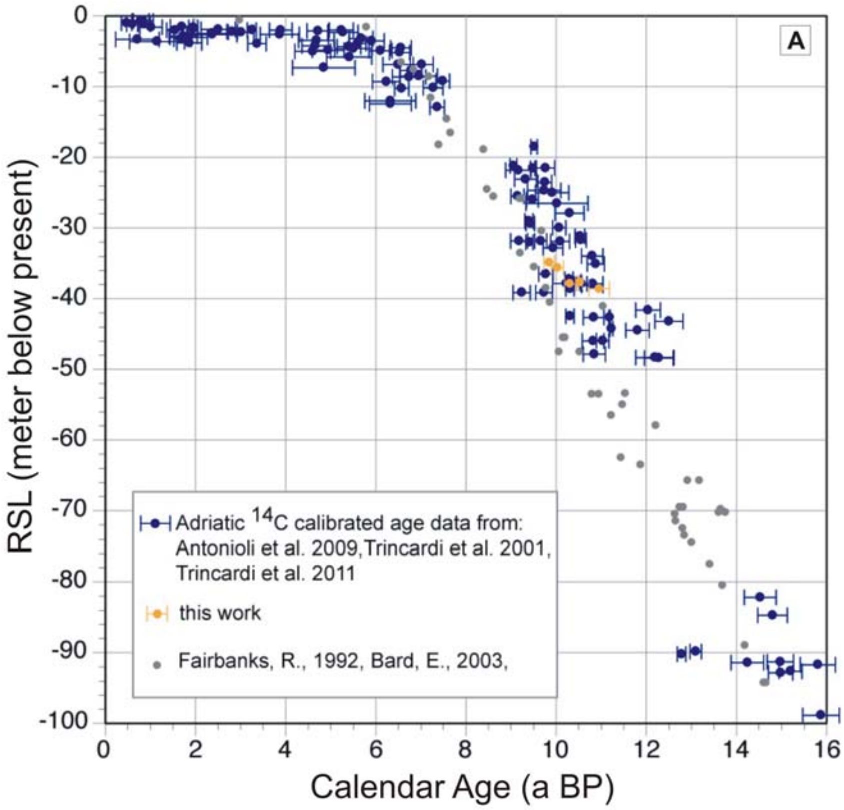
5. DISCUSSION

The combined seismic and core analyses allow us to reconstruct the evolution of the transgressive deposit. The four units, forming the transgressive body, show different environment of sedimentation. The basal units (Unit 1, Unit 2 and Unit 3), consisting of silty-clay sediment with organic matter and interbedded peat layers, are indicative of lower delta plain environments with distributary channels and lagoon. The paleontological content, recognized in clay layers belonging to Unit1, 2 and 3, is indicative of euryhaline association of bivalves peculiar of transitional environment from fresh to brackish water. The more recent unit (Unit 4) consists of basal thin layer of clays formed in a lagoon environment, covered by two plano-convex bodies of basal beach sand. This unit represents a patch of barrier-lagoon system capped by the ravinement surface formed by bioclastic sand. The combined study of seismic profiles and cores emphasizes a marked difference between the basal and the superficial portion of the deposit in terms of sedimentary environment and preservation potential. The buried units, belonging to an inner coastal environment

Sample	Core	Latitude WGS84	Longitudine WGS84	Seafloor bathymetry (m asl)	Depth from seafloor (m)	Corrected Depth (m asl)	Lab. Code	Method	Material	Conventional radiocarbon age	Error (years, ±)	Calibrated age 2σ 95.2% prob. (a cal. BP)	Error	Calibrated medium age 2 sigma (a BP)	δ13C‰ PDB
AR00_22 67-68 cm	AR00_22	44°41.5003	12°48.2207	34.2	0.67	34.9	ETH-57129	AMS	Macrofossils	8828	32	9730-9960 cal. A BP	115	9845	-27.3
AR00_22 135-136 cm	AR00_22	44°41.5003	12°48.2207	34.2	1.35	35.7	ETH-57130	AMS	Macrofossils	8869	23	9895-10160 cal. A BP	132.5	10027.5	-25.9
CM94_107 311-321 cm	CM94_107	44°39,0322	13°42,6896	34.9	3.11	37.9	-	AMS	Peat	9110	60	10180-10430 cal. A BP	125	10305	-
AR00_22 338-339 cm	AR00_22	44°41.5003	12°48.2207	34.2	3.38	37.7	ETH-57131	AMS	Macrofossils	9307	23	10480-10580 cal. A BP	50	10530	-28.3
CM94_107 363-365 cm	CM94_107	44°39.0322	13°42.6896	34.9	3.63	38.6	-	AMS	Peat	9600	70	10730-11180 cal. A BP	225	10955	-

Tab. 1 - Radiocarbon and calibrated dating from CM94_107 (Fabbri et al. 2001) and AR00_22 cores.

compared to the Unit 4, indicate back-barrier environment. The analysis of the seismic profiles highlighted a local aggradation of the Unit 1, 2 and 3 that filled the morphological depressions inherited from of the previous topography. On the contrary, Unit 4, which was strongly affected by marine processes, was characterized by erosion and reworked sediment, as highlighted by the ravinement surface. The comparison among DEMs of the surfaces confirmed limited erosion in Units 1, 2 and 3, while marked reworking occurred at the top of Unit 4. The buried units were characterized by erosion due to the activity of washover fans or fluvial floods, while Unit 4 was subjected to shallow marine processes such as wave activity. Moreover, the seafloor DEM, which shows the present bathymetry, highlights that the path of channels is in relief. This setting suggests differential erosion within Unit 4 with the removal of softer or less stiff sediment.



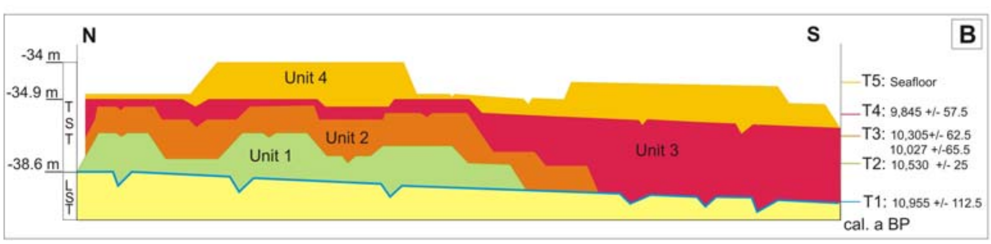


Fig. 8 - A: Depth vs. Age Plot. In blue are represented the Adriatic 14C data from composite table in Antonioli et al. (2009) and from Geological Map of the Italian Sea (Fabbri et al., 2001; Trincardi et al., 2011 a-b). In orange are represented the Radiocarbon dating from this work. In grey are represented Th/U data from Fairbanks (1992) and Bard (2003). B: Simplified scheme of the transgressive deposit with water depth and age of each unit.

The radiocarbon data constrains the time of sedimentation of the transgressive deposit between 11,000 to 9800 cal. a BP, in the time interval following the Melt Waters Pulse 1B (Fairbanks, 1989). This was characterized by both the strong influx of freshwater and the increased sediment loads by rivers, especially the Po (Ariztegui et al., 2000). The dating samples (Tab. 1) gave information about the rate of sedimentation in each unit. The Unit 1 (thickness up to 1 meter) was deposited in about 500 years, the Unit 2 (thickness up to 2 meters) in about 300-500 years, while the Unit 3 (thickness up to 1 meters) was deposited in about 200 years. The obtained data were plotted in a Depth vs. Age plot which groups Adriatic 14C age data from Fabbri et al. (2001), Antonioli et al. (2009) and Trincardi et al. (2011 a-b) (Fig. 8). The new data coincide with the published curves showing in particular 1110 years gap between the base of the Unit 1 and the C Surface. Considering an average thickness of about 4 meters, the estimated, relative sea-level rise was about 0.4 cm/a. Moreover the detailed study of this transgressive deposit showed that the variation of the channel system trend from ENE to ESE, coincides with the incipient sea-level rise.

6. CONCLUSIONS

The VHR seismic profiles, acquired in the northern Adriatic shelf during the NAD12 oceanographic cruise, supported key information to characterize in detail the transgressive deposit located offshore Ravenna at depth of 34-35 m. The combined study of VHR seismic data and cores gave new information about the sedimentation, evolution and age of the deposit.

- The transgressive deposit consists of four units, each one of them representing an evolutionary step. The lower units (Unit 1, Unit 2 and Unit 3) correspond to delta plain setting with some distributary channels and a lagoon, while the upper unit (Unit 4) represents a barrier-lagoon system with patches of ancient beach at the top.
- The sedimentation of the transgressive deposit occurred between 11,000 to 9800 cal. a BP. In particular the radiocarbon data allowed to estimate the rate of relative sea-level rise and sedimentation rate of each unit. Moreover, the dated layers correspond to peat or organic-rich horizons of brackish lagoon facies, thus, they are representative of the paleo-sea level and mark the aggradation steps of each unit.
- The variation of the channel system trend from ENE to ESE occurred during the sea-level rise and it brought to the change of the coastal paleogeography. At the beginning the coast was growing eastward, then the basin flooding (recorded by the Unit 3 at 35 m water depth) caused a preliminary drowning of the investigated area and a consequent variation of the channel system trend. The detailed study of this transgressive body shows not only its evolution but also the paleogeography variation of the surrounding areas due to both sea-level rise and the fluvial pattern.

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