Geological mapping of the Italian seafloors: The Adriatic Project

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ABSTRACT

As part of the "Geological Mapping of the Italian Seas at the scale 1:250,000", sponsored by the Italian Geological Survey (SGI, now part of APAT), we plan to map the whole Adriatic basin east of the 17° Meridian and north of the 41° Parallel. This project follows the guidelines for geological cartography in offshore areas provided by SGI (FABBRI *et alii*, 2002) and builds on the pilot experience made with the preparation of the geological map "NL 33-10 Ravenna" (TRINCARDI, ARGNANI *et alii*, 2001).
Each map ("Foglio") includes three distinct products: 1) a Chart of the seafloor and subsurface, 2) a Chart of the deeper geological structure and 3) the Guidelines to the Charts. The Chart of the seafloor and subsurface represents geological bodies outcropping at the seafloor or lying in the immediate subsurface, and contains information on their stratigraphy, internal geometry, geomorphology, sedimentologic characters and geochronological significance in the context of the late-Quaternary sea-level fluctuation. The Chart of the deeper geological structure focuses, instead, on the geological setting and Meso-Cenozoic evolution of the study area. The Guidelines report in detail all the information on regional geology, major scientific issues, methods of study and relevant applied aspects.

AIMS

In this contribution we illustrate the Chart of the seafloor and subsurface, the main methods used to produce it and the major methodological problems that need to be tackled in the geological mapping of offshore areas. We integrate methods, survey strategies and results including:
- bathymetric surveys from single beam and multibeam echo-sounders;
- morphologic and seafloor backscatter reconstructions from side scan sonars;
- very-high resolution true 3D seismic volume images of a selected shelf sector;
- high-frequency reflection seismic profiles from nested surveys of complementary spatial resolution;
- precisely-positioned sediment coring, using a variety of complementary tools depending on the expected sediment composition or consolidation used to "ground-truth" the seismic data through facies analysis and characterization of sediment physical properties;
- biostratigraphic and geochronological data integrated to reconstruct paleo-environmental scenarios.

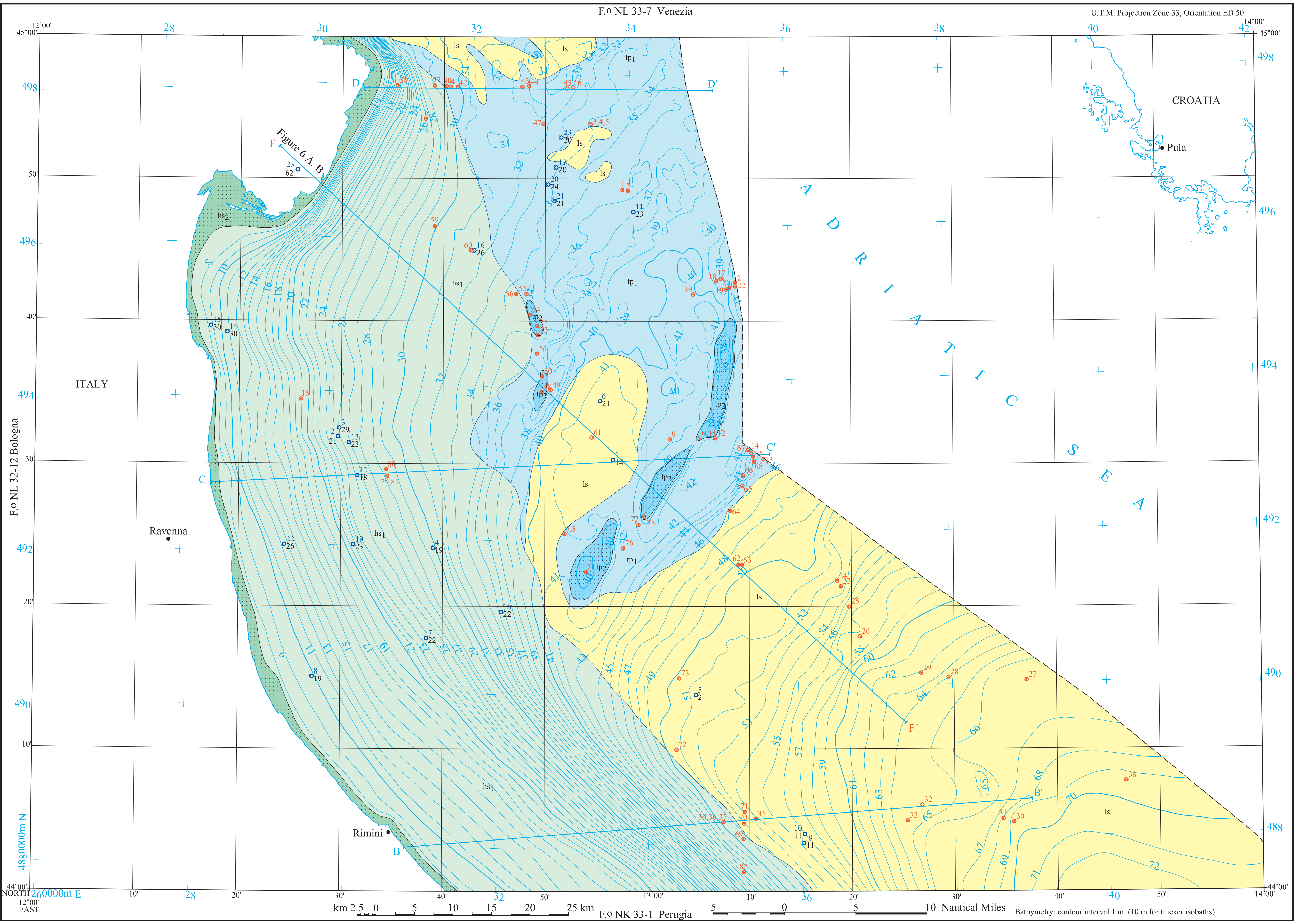
KEY WORDS

Geological mapping, marine geology, seismic stratigraphy, swath bathymetry, sedimentology, late Quaternary, geochronology

RIASSUNTO

Il progetto "Cartografia Geologica dei Mari Italiani a Scala 1:250.000", finanziato dal Servizio Geologico d'Italia (SGI, ora parte di APAT), rappresenta l'estensione all'intera piattaforma Adriatica a est del Meridiano 17° e a nord del Parallelo 41° della carta prototipo realizzata in Adriatico Settentrionale "Carta Geologica dei Mari Italiani in scala 1:250.000, Foglio NL 33-10 Ravenna" (TRINCARDI, ARGNANI et alii*, 2001), e fa riferimento alla normativa del Servizio Geologico d'Italia che illustra le metodologie e i criteri per la cartografia geologica marina a scala 1:250.000 (FABBRI* et alii*, 2002). Ogni Foglio si articola in tre prodotti: 1) Carta Superficiale, 2) Carta del Sottofondo e 3) Note Illustrative. La Carta Superficiale rappresenta i corpi geologici affioranti o subaffioranti sul fondo marino, oltre ai caratteri stratigrafici, di geometria delle unità, geomorfologici, sedimentologici e di significato geocronologico nel contesto delle fluttuazioni tardo quaternarie del livello del mare. La Carta del Sottofondo descrive l'assetto strutturale e stratigrafico dell'area in esame e la sua evoluzione geologica meso-cenozoica. Le Note Illustrative raccolgono informazioni sul contesto geologico dell'area, su problemi scientifici pertinenti, sui metodi di indagine e su alcuni aspetti applicativi di utilizzazione dei dati geologici.*

GEOLOGICAL MAP OF THE NW ADRIATIC SEA



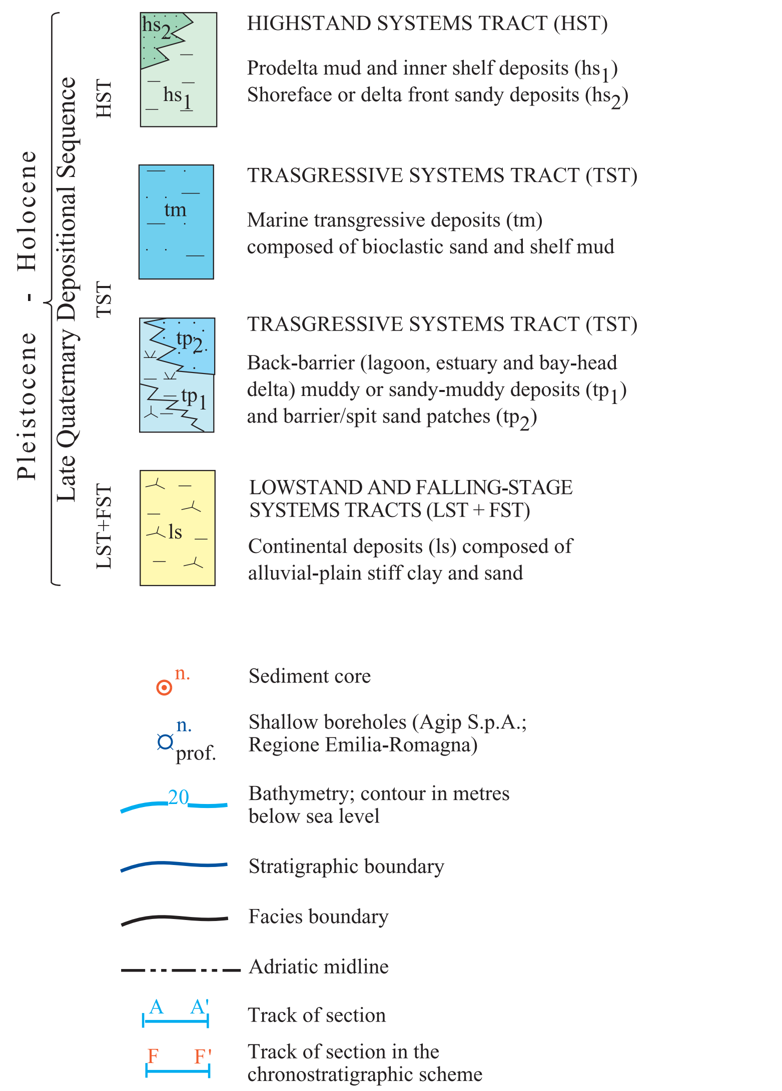
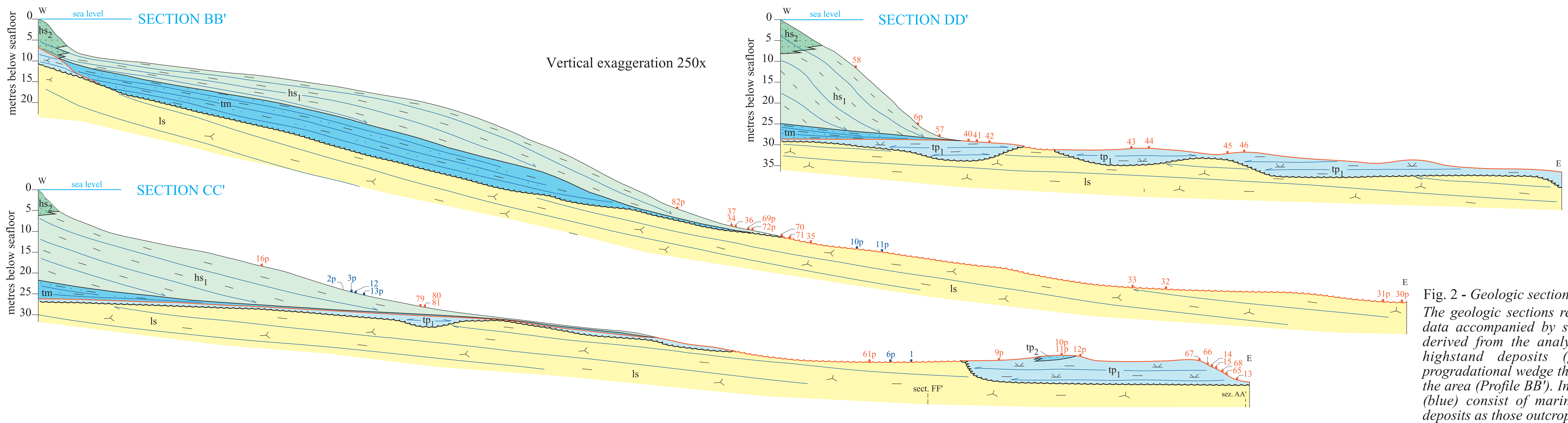


Fig. 1 - *Geologic map of the seafloor and subsurface (NL 33-10 Ravenna, Carta Geologica dei Mari Italiani alla scala 1:250.000). Three distinct stratigraphic units are encountered at the seafloor in the Adriatic sector corresponding to the Ravenna JOG NL 33-10 block. The late-Holocene highstand deposits (in green) are located closer to mainland areas and do not extend deeper than 30 m, in the North, and about 50 m, in the South. Seaward of this deposit, two distinctive units outcrop below a thin drape (typically few cm) of highstand deposits: late-Pleistocene to early-Holocene transgressive deposits (in blue) represent coastal or back-barrier deposits drowned and partially reworked during the post-glacial sea level rise; Pleistocene lowstand deposits (yellow) are typically represented by alluvial-plain deposits that formed when sea level was falling or at peak lowstand.*



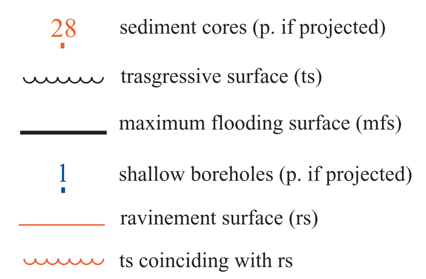


Fig. 2 - *Geologic sections*
The geologic sections report information from seismic-stratigraphic data accompanied by sedimentary facies and geochronology, both derived from the analysis of sediment cores. The late-Holocene highstand deposits (green) are arranged in a low-angle progradational wedge that becomes sigmoidal in the southern part of the area (Profile BB'). In this southern area, the transgressive deposit (blue) consist of marine prodelta mud rather than back barrier deposits as those outcropping on the shelf further north.

INTRODUCTION

Most European Countries have extensive geological mapping programs for their offshore Exclusive Economic Zones. With the JOG-NL33-10 Ravenna map (at the 1:250,000 scale), Italy began a similar project, now extended to the entire Adriatic Sea (Fig. 3).
The Adriatic is a key area as regards geological hazards (earthquakes, tsunamis, landslides, fluid-escape deformation), resources (hydrocarbon, fresh water, and sand for coastal replenishment), human impact and increasing pollution.
Synthetic geological mapping provides the basis for any applied environmental study by making basic information available to a wide range of end-users. In offshore geological mapping, extensive areas can be covered only at much smaller scales than those used for geological mapping on land because of the large costs implied in surveying marine areas. Marine-geology studies rely on complementary geophysical techniques that are all based on sound emission (from hull-mounted or towed sources) and a device recording a signal scattered from the sea floor or the subsurface.
The direct sampling of subsurface units allows the definition of depositional environments from facies, sedimentary structures and palaeontological content. Sampling also provides material (wood, foraminifera tests and mollusc shells) that can be used for dating using several complementary methodologies. Stratigraphic information on stratal geometry and geochronological data can be combined into chronostratigraphic schemes with equally-spaced horizontal timelines defining the amount of stratigraphic time not represented by sedimentary units due to erosion (e.g. subaerial exposure during glacial sea-level lowstands and reworking during sea-level rise) or condensed deposition during rapid sea-level rises and early highstands (Figs. 4, 6A and 6B).

METHODOLOGY

The following main methodological points are reviewed and discussed:
1) Bathymetric data (collection, validation, contouring and 3D rendering);
2) Very-high resolution, true 3D seismic volume images of a selected shelf sector;
3) Acoustic seafloor responses on side scan-sonar records and mosaics.
4) Seismic profiles using broadband sound sources and nested grids of variable resolution;
5) Sampling techniques and relation between seismic reflectors and sediment composition;
6) Biostratigraphic and geochronological data and calibrations of significant seismic reflectors.

1) Bathymetric charts are fundamental to any geological cartography of continental margins just as an accurate representation of land topography is the starting point for any geological mapping. In most cases, however, onshore topographic surveys are provided by dedicated Institutions (the *Istituto Geografico Militare*, in Italy) and are not under the direct responsibility of geological mapping projects. Conversely, offshore, bathymetric data need to be collected as a necessary starting point for

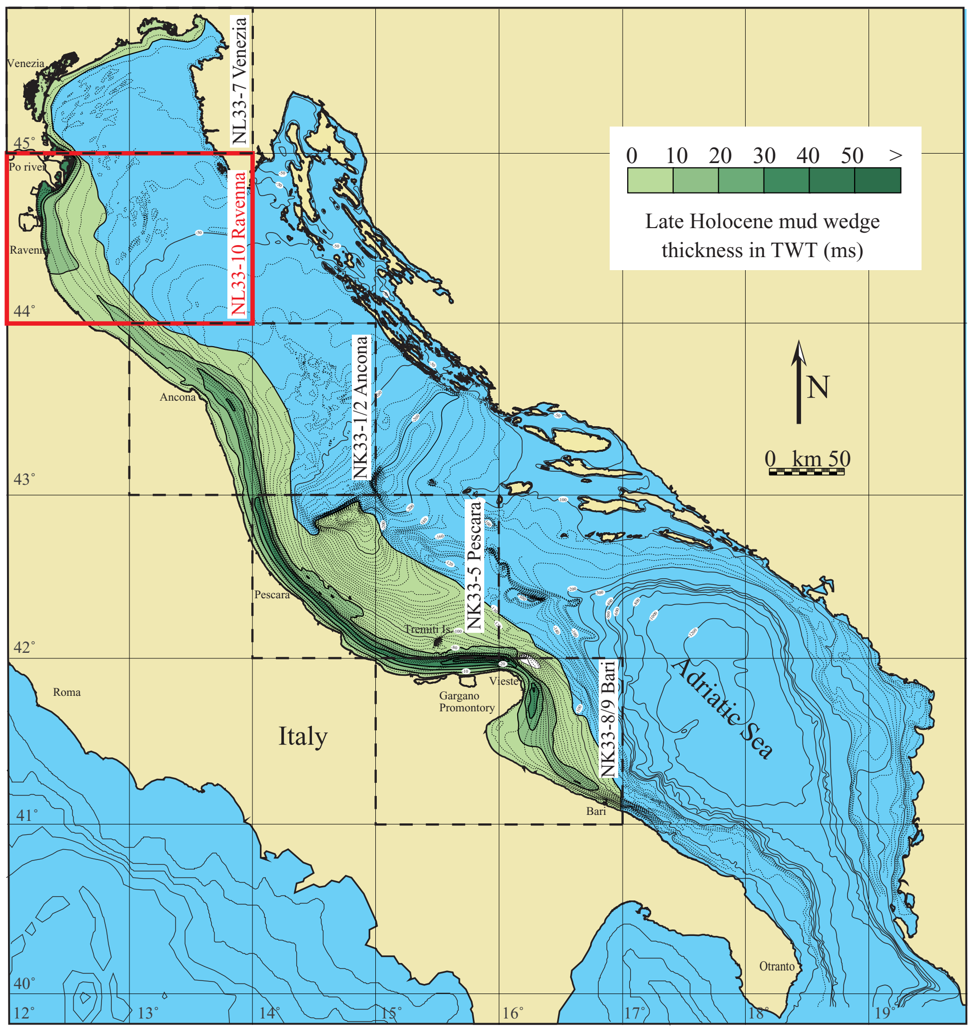


Fig. 3 - *Plan for the geological mapping of the Adriatic Sea following the pilot map completed off Ravenna. The extent of the new geological maps (scale 1:250,000) is reported on the bathymetric map of the Adriatic basin. The thickness distribution of the late-Holocene HST (in TWTT) is shown in green.*

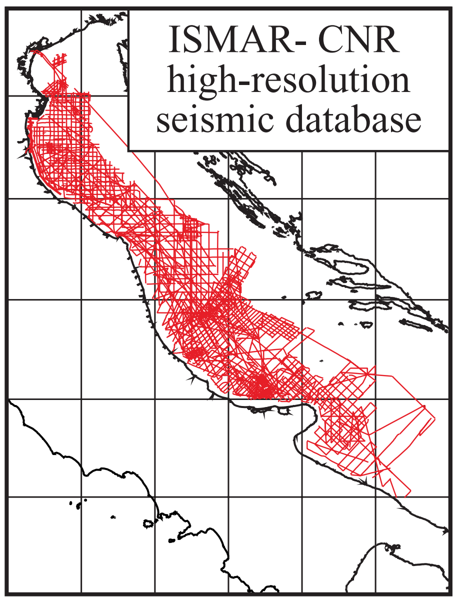
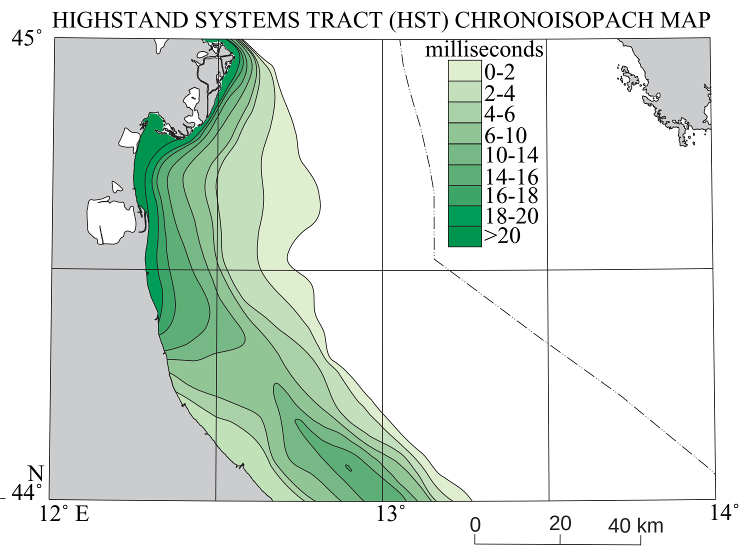


Fig. 4 - *Positioning chart of the ISMAR-CNR high resolution. seismic lines database.*



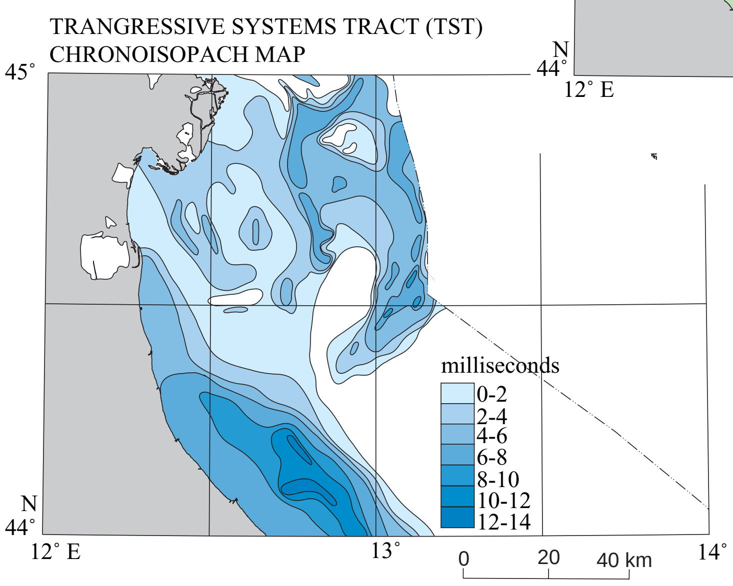


Fig. 5 - *Thematic maps: thickness maps in TWTT and navigation map. The thickness of the highstand and transgressive system tracts are measured by high-resolution seismic profiles and expressed in Two Way Travel Times (TWTT). The transgressive record includes two depocentres; the nearshore depocentre corresponds to prodelta muds similar in facies and geometric arrangement to the overlying highstand deposits. The back-barrier and coastal transgressive deposits have a reduced thickness and a more patchy distribution.*

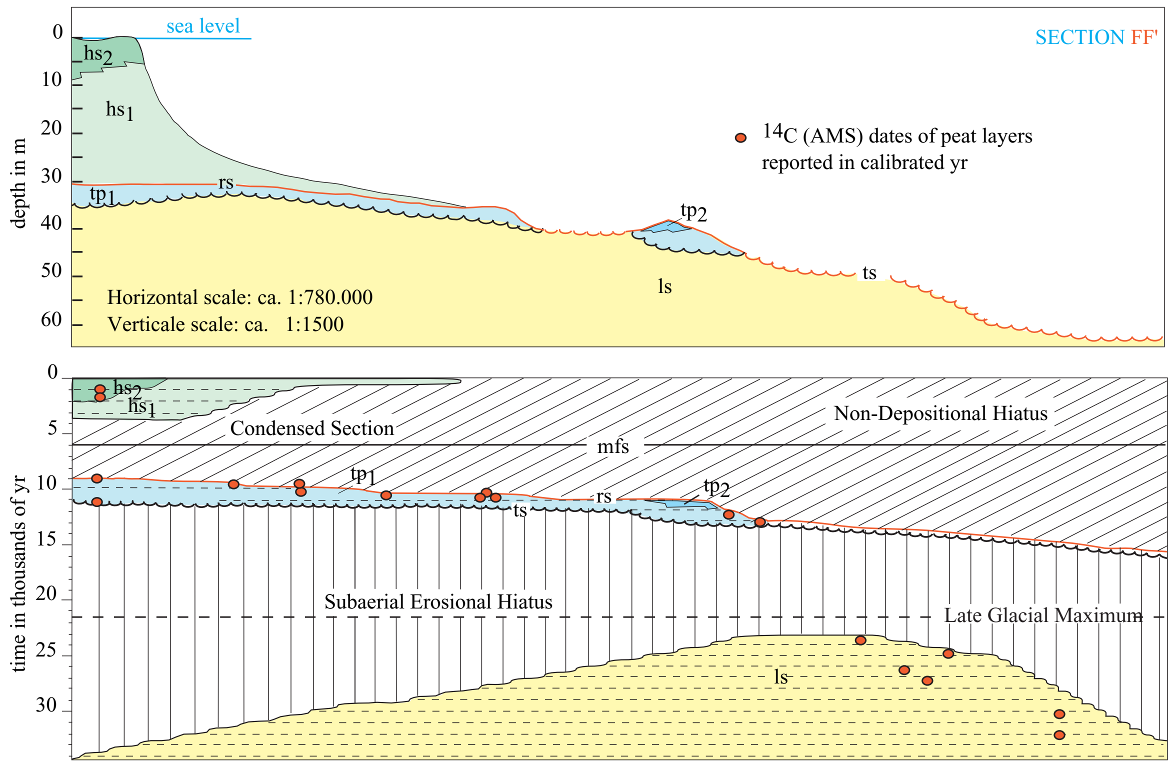


Fig. 6A - *Chronostratigraphic scheme of the late-Quaternary depositional sequence. This kind of representation allows the quantification of the portion of stratigraphic time not recorded by continuous deposition. In particular, the maximum flooding surface records many thousands of years of condensed deposition following the drowning of the North Adriatic shelf and prior to the onset of the highstand progradation.*

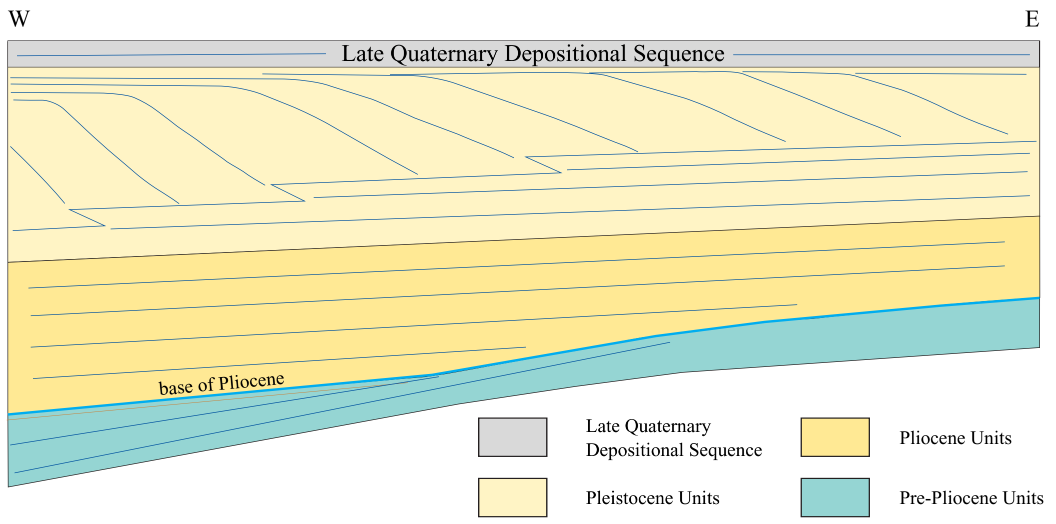


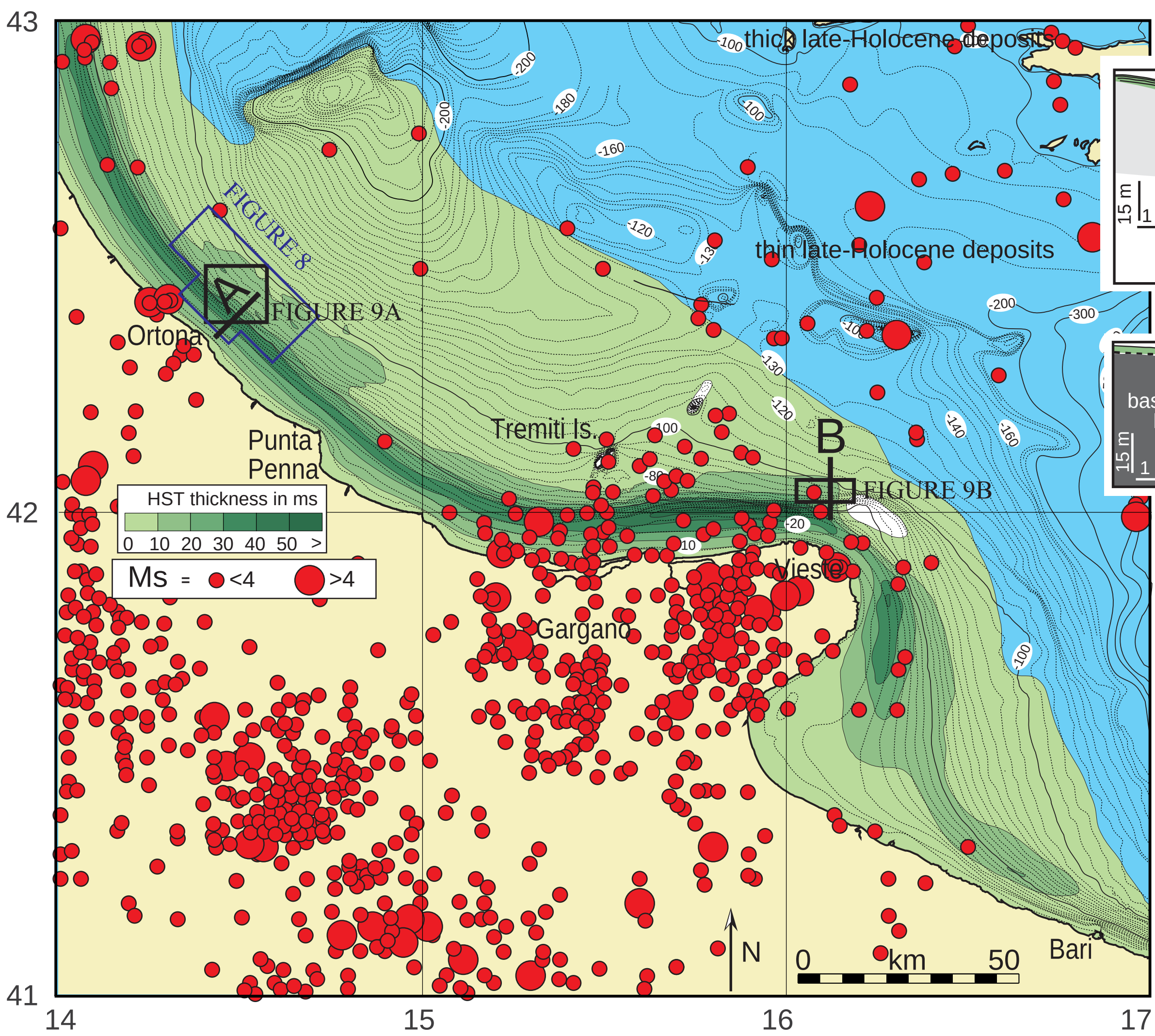
Fig. 6B - *Stratigraphic scheme of the adriatic basin fill (not to scale). The Late Quaternary sequence consists of a thin sediment cover above a thicker and more complex fill of the Adriatic basin. This schematic geological section portrays the unconformity at the base of the Plio-Quaternary fill of the Adriatic foreland basin, and is represented in the Chart of the deeper geological structure that is not discussed here. The Plio-Quaternary basin fill consists of two main sequences: an onlapping marine sequence, below, and a prograding continental to shallow marine sequence, above.*

detailed geomorphologic, stratigraphic and sedimentologic studies.

Bathymetric data are essentially acquired using two kinds of instruments: standard, single-beam sounders or multibeam systems. The latter systems cover a swath of the seafloor on both sides of the ship's nadir (this swath typically corresponds to 3 to 5 times the water depth).

Although originally designed for deep-water studies, multibeam systems have recently been implemented for shallow water investigations. These systems offer a vertical resolution of less than one metre and spatial resolutions of 2-5 m. A regional-scale bathymetric map from conventional single beam soundings (Fig. 7) and a very high resolution swath bathymetry of a particularly complex seafloor stretch in the Central Adriatic are contrasted (offshore Ortona; Fig. 8); contour lines are 5 and 1 m, respectively. Note that the metre-scale complexity of the area is averaged out in the regional contour based on conventional bathymetric soundings. In general the choice between the two types of surveys and representation depends on budgetary constraints and on the scope of the study.

High resolution multibeam bathymetry shows metre-scale shore-parallel undulations and shore-normal mud reliefs (in deeper waters) that remain undetected in conventional, single-beam surveys, where data are collected solely along the ship's tracks and need to be spatially interpolated over several hundred m to a few km. Bathymetric data can be represented in Digital Terrain Models (DTM) with artificial illumination to highlight morphological trends (Fig. 9) or in 3D blocks (Fig. 10: details shown by white squares in Fig. 9). All these representations are of use in the geological interpretation of bathymetric trends. The same bathymetric data can also be reported in illuminated 3D blocks (Fig. 10, location in Fig. 9).



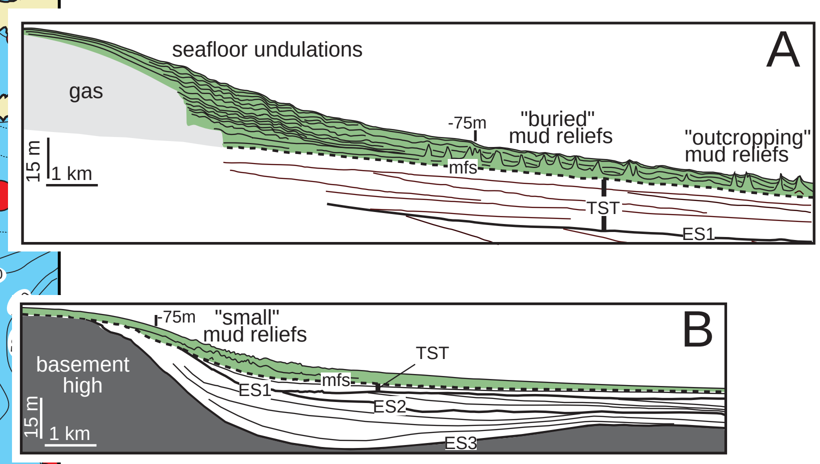


Fig. 7 - *Bathymetry and location of earthquake epicentres in the central Adriatic. An example of bathymetric contour from conventional (single beam) sounders is shown along with the thickness distribution of the modern (late-Holocene) prodelta mud wedge. Areas of detailed investigation with very high frequency multibeam systems (Figs. 8, 9 and 13) were selected for the purposes of studying sediment deformations possibly triggered by earthquake events (red dots show historical epicentres drawn from the literature).*

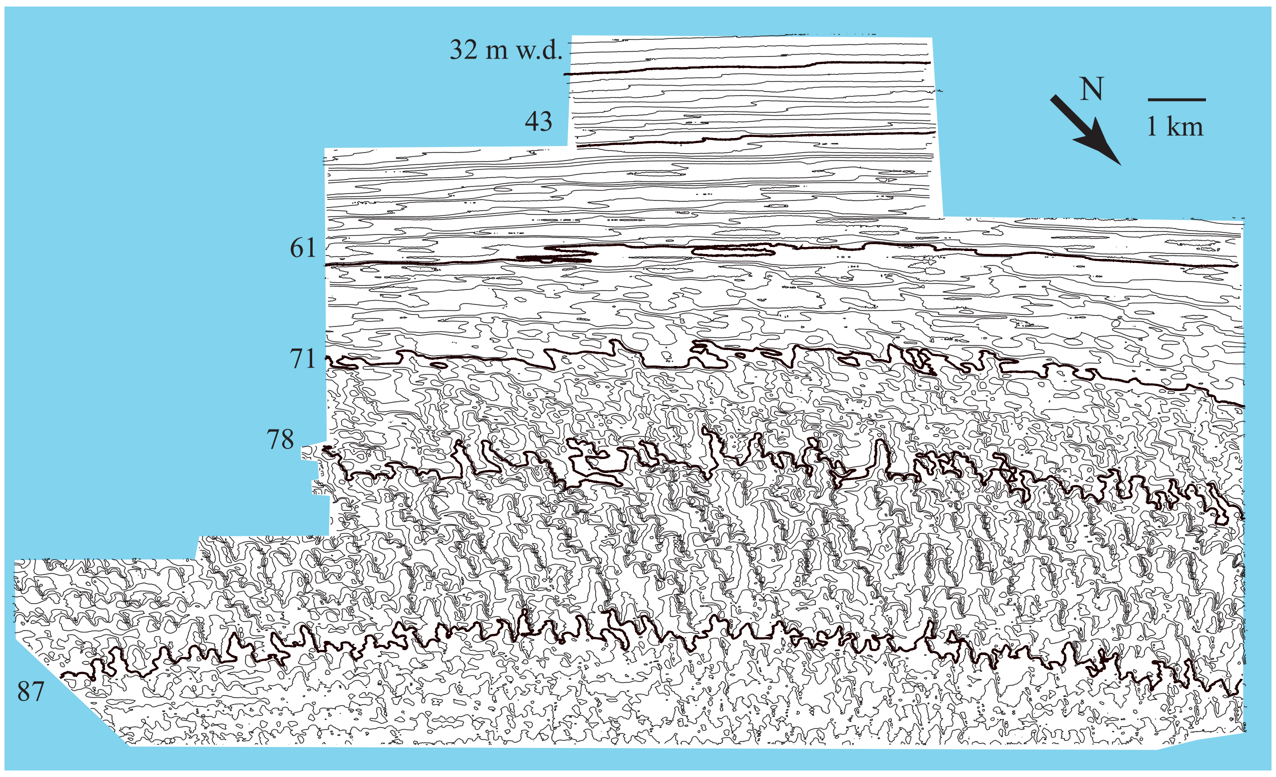


Fig. 8 - *Swath bathymetry offshore Ortona. The high-resolution, multibeam bathymetry shows metre-scale, shore-parallel undulations and shore-normal mud reliefs (in deeper waters) that remain undetected in conventional single-beam surveys, where data are collected solely along the ship's tracks and need to be spatially interpolated over several hundred metres to a few kilometres.*

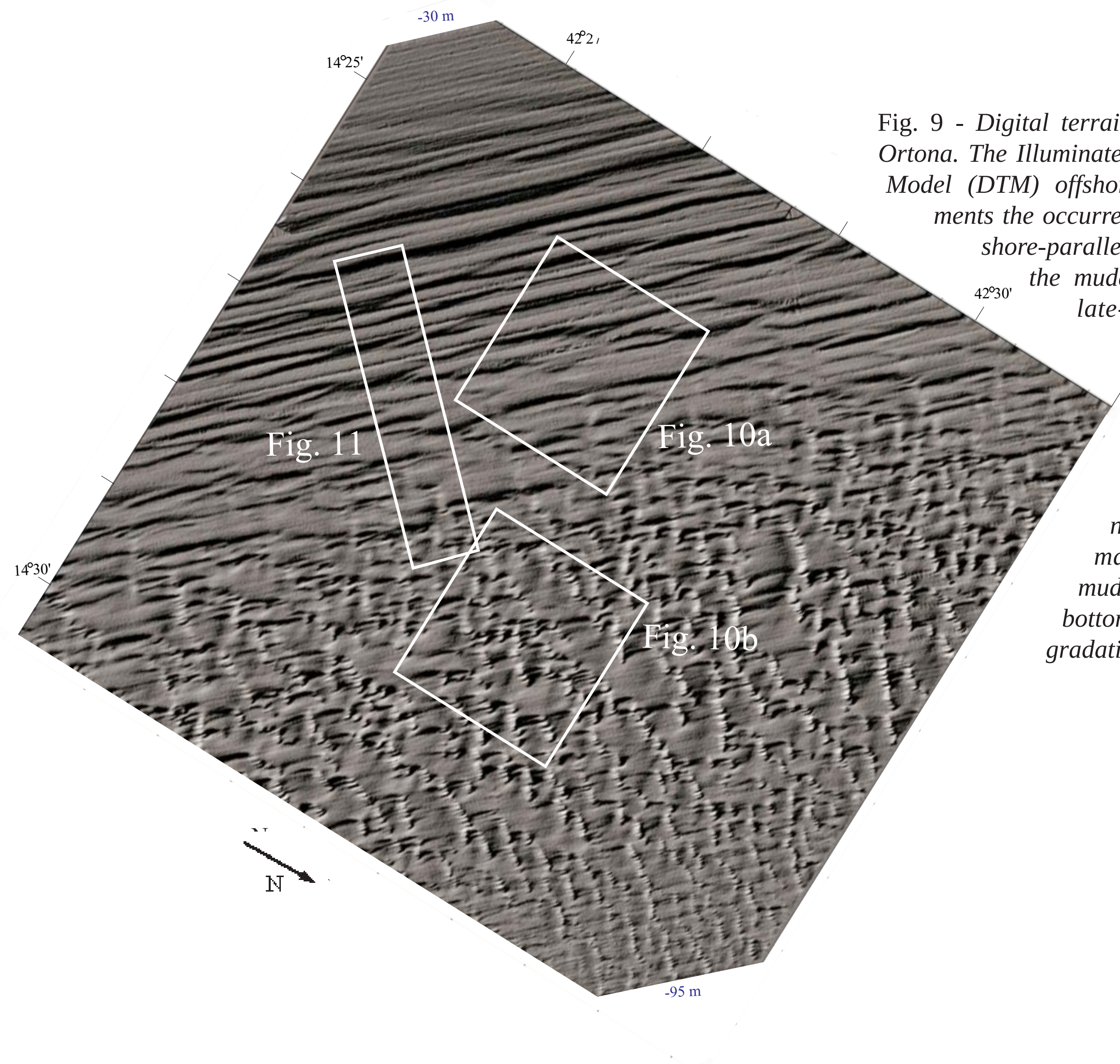


Fig. 9 - *Digital terrain model offshore Ortona. The Illuminated Digital Terrain Model (DTM) offshore Ortona documents the occurrence of elongated, shore-parallel undulations in the muddy foreset of the late-Holocene progradational clinoform. Towards the NE, these features are replaced by discontinuous, shore-normal clusters of muddy reliefs in the bottom set of the progradational clinoform.*

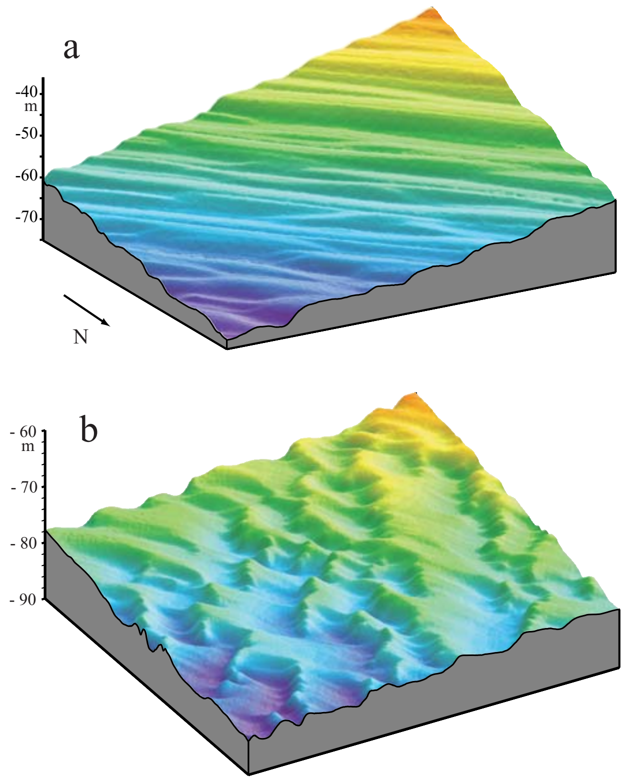


Fig. 10 - *Blocks from DTM. The 3D blocks show that the shore-parallel undulations loose continuity proceeding downslope (a) and that the mud reliefs have a NW-facing gentle side reflecting preferential deposition (b).*

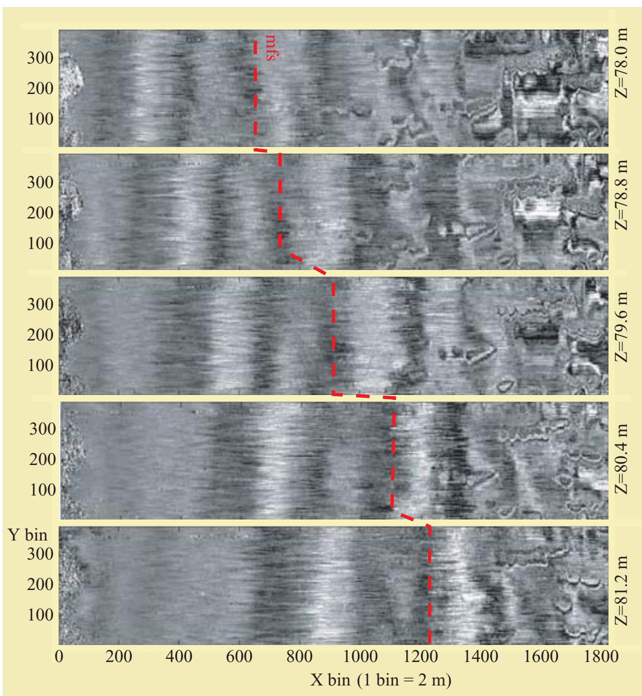


Fig. 11 - *3D seismic survey offshore Ortona. Example of closely spaced horizontal slices from a VHR 3D seismic volume (location in figure 9) showing: a) acoustic masking by gas-charged sediments (very narrow stripe on the left of each time slice); b) gently seaward-dipping reflectors (cut increasingly landward in shallower time slices, bottom-up) under the maximum flooding surface (mfs, dashed red line). The deposits immediately above the mfs show a very complex pattern (on the right) ascribed to soft-sediment deformation at the base of the Late Holocene HST.*

2) 3D-seismic surveys allow the generation of volumes of seismic data and the representation of these data along preferred cuts including horizontal images that approximate time-lines. In the example (derived from a cooperation between IFREMER and ISMAR), a set of closely-spaced horizontal slices (offshore Ortona; Fig. 11) shows evidence of soft-sediment deformation (on the right) on the gently-dipping downlap surface at the base of the Late Holocene HST (location of the 3D survey in Fig. 9).

3) Side-scan-sonar images complement bathymetric data by providing a view of the energy that the sea floor is able to backscatter as a function of its morphology (the steeper the slope of a given feature, the larger the amount of energy backscattered) and lithology (the micro-scale seafloor roughness increases with sediment grain size and/or cementation). Depending on the frequency of the signal emitted, these side-scan sonar systems cover swaths of the sea floor that range from 100 m (at 500 kHz) to several km (at few tens of kHz).

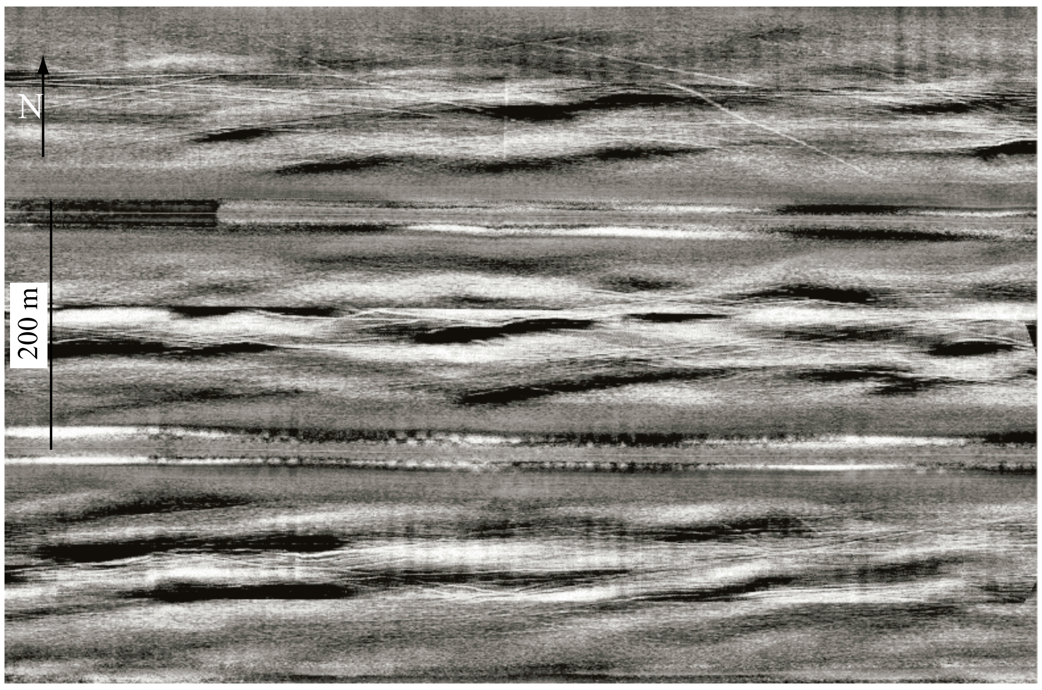


Fig. 12 - *Side scan-sonar mosaic. Example of 100-kHz side-scan mosaic of a portion of the continental shelf off Vieste. The mosaic was acquired and processed by SOC (Southampton) and ISMAR (Bologna) as part of the EU project COSTA (COntinental slope STAbility). The line-spacing is 200 m and pixel resolution is dm-scale (note trawl marks in the upper portion of the mosaic). In this example, the study area is uniformly characterised by mud deposition and the acoustic returns on the side-scan sonar image reflect only the relief on the micromorphology of the seafloor. This interpretation is supported by several sediment cores.*

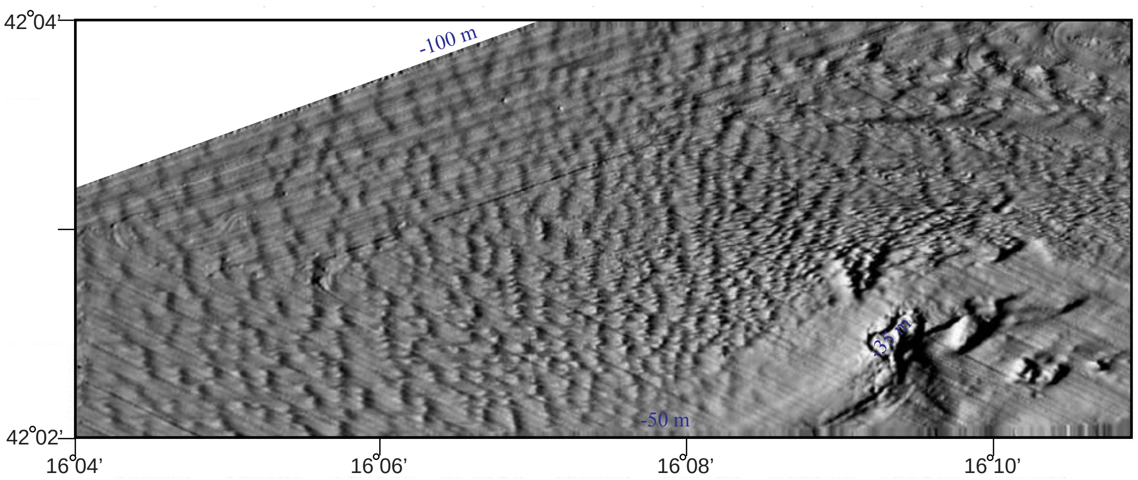


Fig. 13 - *Digital terrain model offshore Vieste. This DTM from multibeam bathymetry shows small scale reliefs with individual crests oriented parallel to structural and morphologic high to the SE (bottom right).*

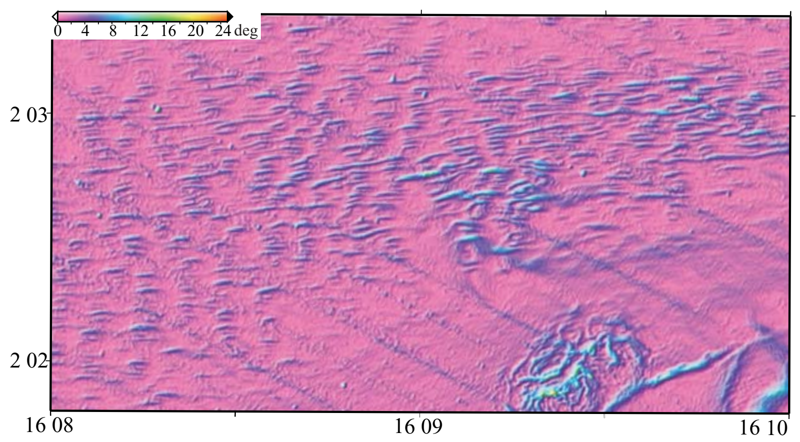


Fig. 14 - *Slope angle map. The map of the seafloor gradients shows the same features observed in Fig. 13 over a wider area. This representation confirms that the elongated strips of increased backscatter are the steeper flanks of mud reliefs, rather than changes in seafloor sediment composition.*

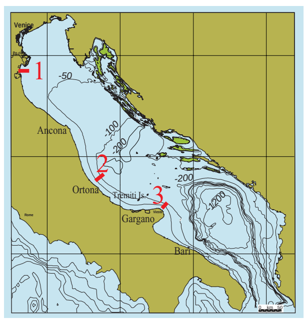


Fig. 15 - *Location of profiles 1-3 (see Figs. 16, 17 and 18).*

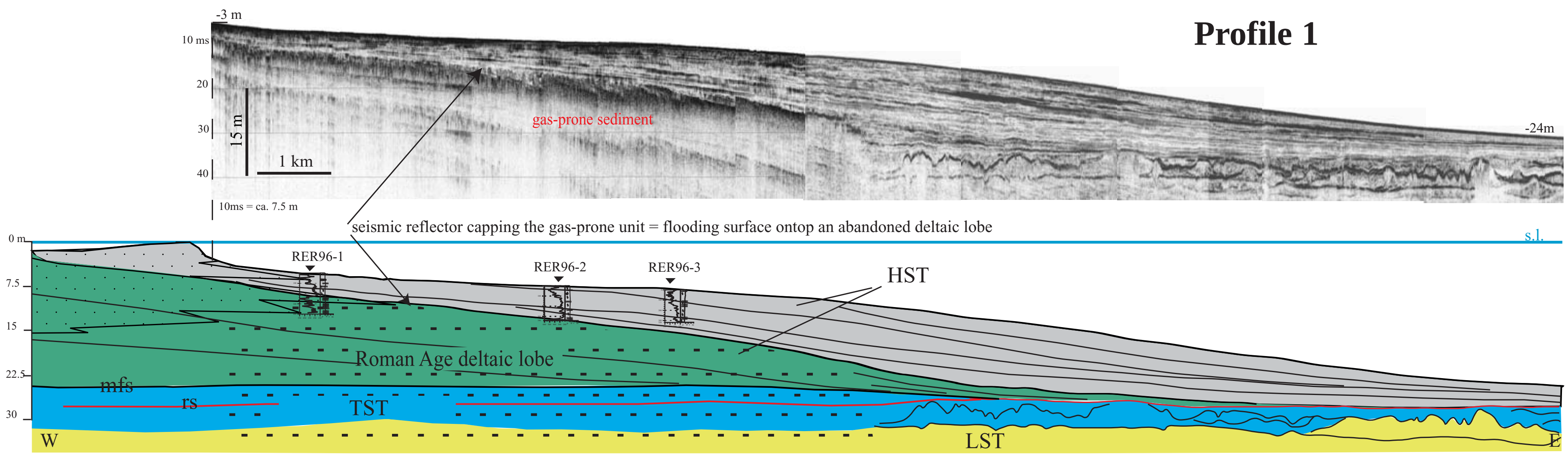


Fig. 16 - *Profile 1 south of modern Po delta showing Roman-age buried lobe. Profile 1 across the southern portion of the Po prodelta shows the downlapping surface at the base of the very recent progradational wedge. Seismic stratigraphic correlation, supported by core data (see next page), indicate that the basal downlap surface coincides with the transgressive erosional surface (ravinement surface) bevelled during the late stages of the Late Quaternary sea-level rise. In the line drawing: LST denotes low-stand alluvial plain deposits; TST denotes transgressive deposits with back-barrier or marine facies respectively below and above the ravinement surface (red line); and HST denotes Late Holocene prodelta deposits originated during the last 5,500 yrs, after the attainment of the modern sea-level high stand. HST deposits in green and grey are sandy (and gas-charged) delta lobe of Roman age and Little-Ice-Age prodelta respectively. Age assignments rely on comparisons with historical cartography on land and direct coring of the topset of the abandoned delta, cores RER96-1 to -3, or through the entire HST in distal areas.*
A particular challenge in geological mapping of coastal areas is posed by the collection of seismic reflection data in very shallow-water environments, where reverberation from sandy sediment and gas impregnation are common. This profile shows meaningful data up to the shoreface zone in water depths of about -3 m. These shallow-water data can be combined, on land, with historical maps, archaeological data, shallow drilling and other kinds of geophysical data, such as those from GPR (Ground Penetrating Radar). This shallow water domain is often included in the marine portion of Geological Maps at the 1:50,000 scale.

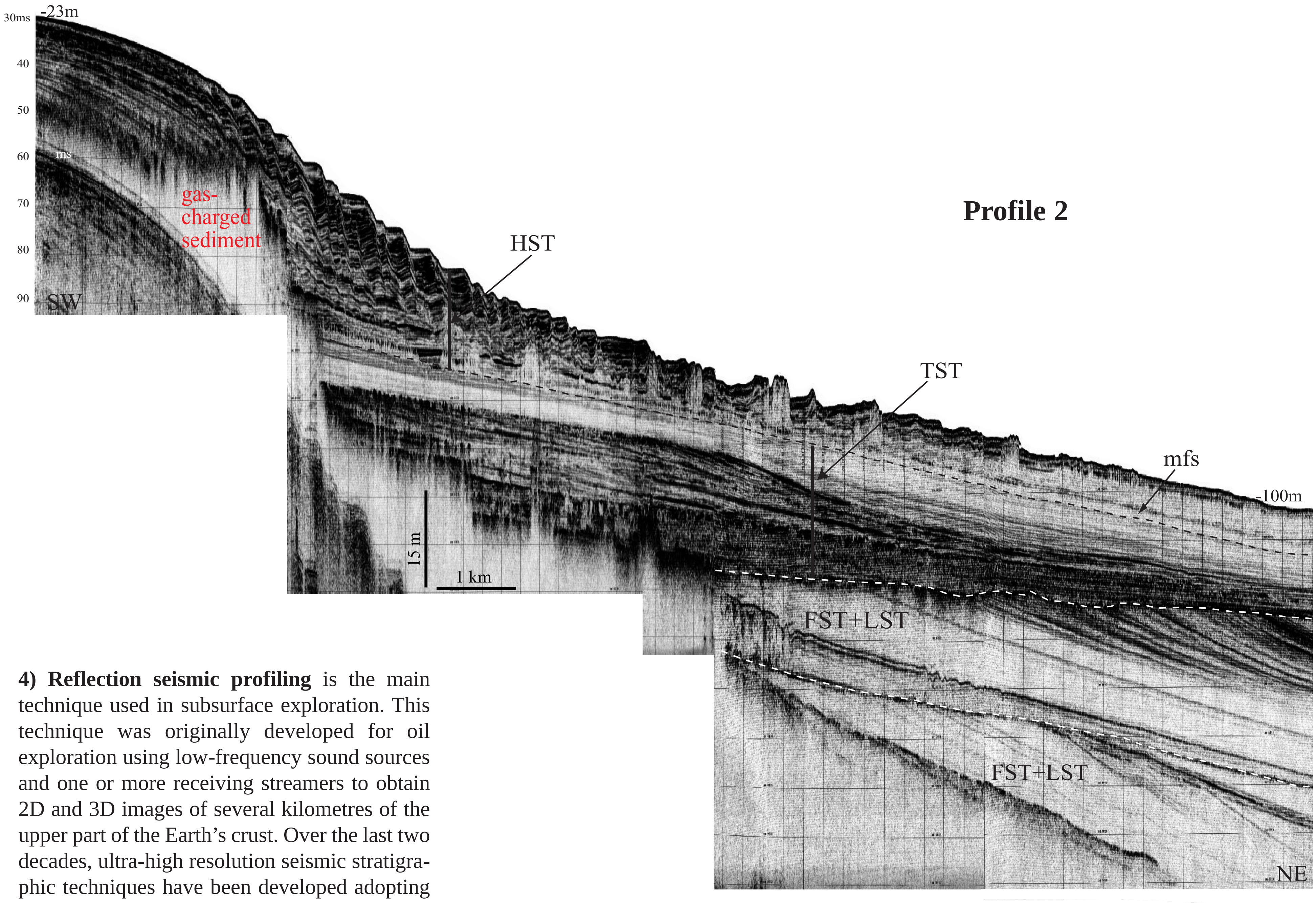


Fig. 17 - *Profile 2 across the central adriatic margin penetrating stacked regressive sequences from Pleistocene glacial-interglacial cycles beneath a composite Late-Quaternary transgressive record. Profile 2 illustrates the HST Apennine mud wedge in an area of high sediment accumulation characterised by soft-sediment deformation and fluid escape (see also 3D images across basal mfs separating the deformed section from the undisturbed TST below). Deformations affect prodelta slope generating undulations and acoustically-transparent mud reliefs. Note that the basal low-angle downlap surface (mfs, dashed line) is above marine mud characterised by low-frequency and high-continuity reflectors. The transgressive record (TST) is tripartite and includes an intermediate progradational wedge recording the Late-Glacial Holocene transition.*
Below this TST, older regressive sequences are separated by regional unconformities (dashed lines) that originated during sea-level lowstands. These regressive sequences (FST+LST) record intervals of prolonged sea-level fall with a 100-kyr cyclicity forced by astronomical cycles and amplified by the dynamic of waxing and waning ice caps.

4) Reflection seismic profiling is the main technique used in subsurface exploration. This technique was originally developed for oil exploration using low-frequency sound sources and one or more receiving streamers to obtain 2D and 3D images of several kilometres of the upper part of the Earth’s crust. Over the last two decades, ultra-high resolution seismic stratigraphic techniques have been developed adopting portable broadband sound sources and single-channel receivers. In the field of ultra-high resolution seismic profiling two main kinds of sound sources used are impulsive sources (to produce a “spike” signal having a very short wavelength) and sweep-modulated sources (filter-matching the return signal with a well-defined, prolonged, outgoing signal). The latter is now very popular for high-resolution seismic stratigraphic surveys and has been adopted as the main tool in the Marine Geological Mapping project of the Adriatic. Three examples of Chirp-sonar profiles along the Adriatic margin are shown, with the same extreme vertical exaggeration (85x) to allow a more direct comparison between the gently dipping reflectors in the north and the steeper and more complex areas in the south.

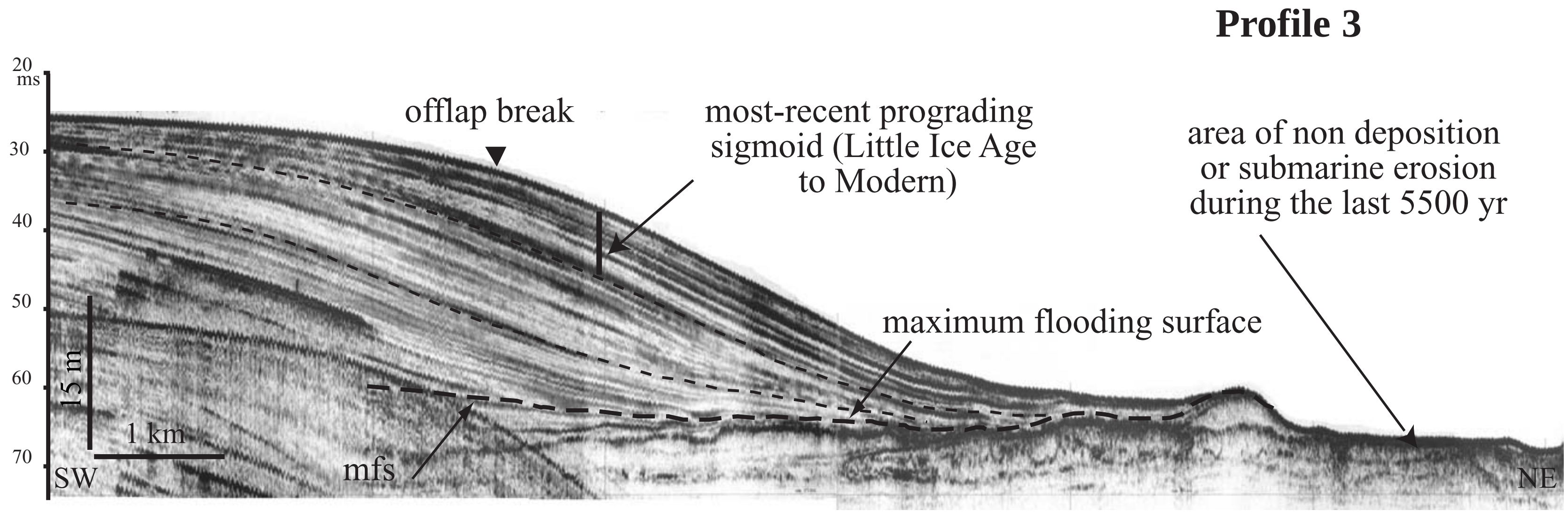


Fig. 18 - *Profile 3 across the Late Holocene Gargano subaqueous delta. Profile 3 is from the Gargano subaqueous delta, a relevant component of the late-Holocene HST, nourished by shore-parallel currents from the north. Here the clinoform geometry is more evident with a subaqueous topset and foresets dipping as much as 1 deg. The most recent sigmoid is ascribed to the interval encompassing the Little Ice Age and the last Century, based on direct dating of the basal surface, multi-proxy reconstructions and interpolations of sediment accumulation rates derived from short-lived radionuclides (^{210}Pb).*

5) Precisely navigated coring provides fundamental information on sedimentary facies, biostratigraphy and geochronological control of the seafloor and subsurface sediment. Conventional coring methodologies, however, are severely limited in their ability to penetrate sediments (reaching typical recoveries in the order of 7-8 m and exceptional recoveries of 12-15 m), and any sampling strategy should take into account these limitations. However, a knowledge of the subsurface geometry of depositional sequences from seismic profiles allows the identification of complementary targets.

The RF 2M seismic profile provides an example of complementary core locations with a thick Late Quaternary progradational wedge (yellow) and its distal pinch-out. The older units underlying the pinch-out on the RF93-77 site, lie about 200 m below the seafloor at site CM92-43, where drilling would be required to reach the same reflectors (dashed red line).

Sampling of surface and subsurface sediment can be achieved using a variety of complementary techniques, depending on the expected lithology. Box and Kasten coring are ideal for facies reconstruction (large sample size), but have limited penetration. Vibracoring also has limited penetration (3-6 m), but recovers samples in sandy deposits (a possible artifact is the liquefaction of sand and consequent loss of primary structures).

Free-fall (gravity) or piston coring (gravity corer helped by a piston inside the barrel to create a depression and enhance penetration) recover up to 5 and 20 m, respectively, but compression or loss of the core top are not infrequent.

The melting of the ice caps after the end of the Last Glacial Maximum caused a rapid eustatic rise of ca. 125 m and the consequent drowning of continental shelves.

The most dramatic palaeogeographic change affected epicontinental shelves, including in the Adriatic, that underwent a substantial broadening.

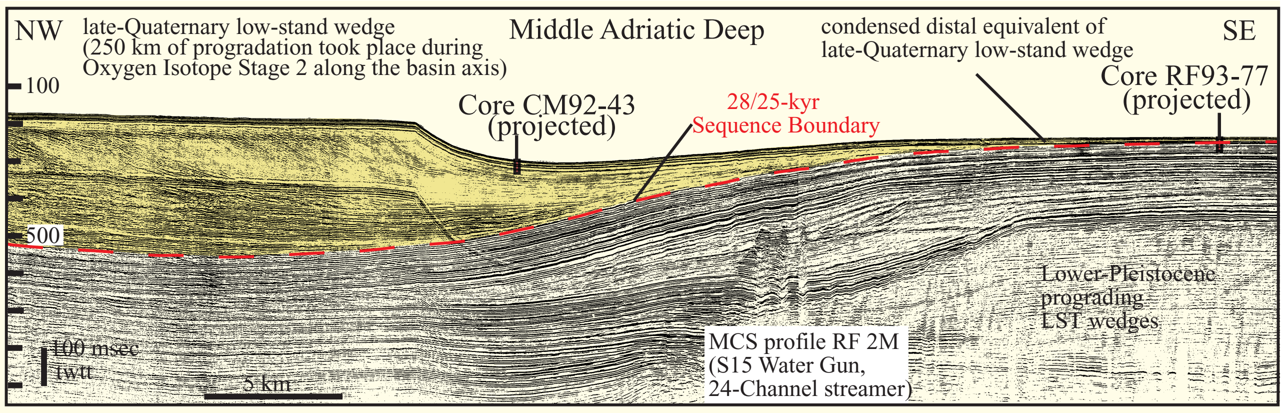


Fig. 19 - *Complementary coring sites from expanded Last-Glacial Maximum wedge (yellow) and its distal pinch-out (core RF93-77) on the right.*

Fig. 20 - *Example of box core in prodelta muds (left) and piston core (right). A box core in prodelta muds (left) is subsampled for X-ray analysis (flat slabs) and geochemistry. In the example on the right, Piston core YD97-10 is compared to the uncompressed trigger core (YD97-11). In this example the piston core (YD97-10) underwent a compression of ca. 400% at the core top; this can be quantified by comparing layers (the dark one is Mediterranean sapropel S1) to the uncompressed trigger core taken at the same site using a light corer (YD97-11). Compression or sediment losses should be taken into account when correlating coring sites and when reporting core information on seismic profiles.*

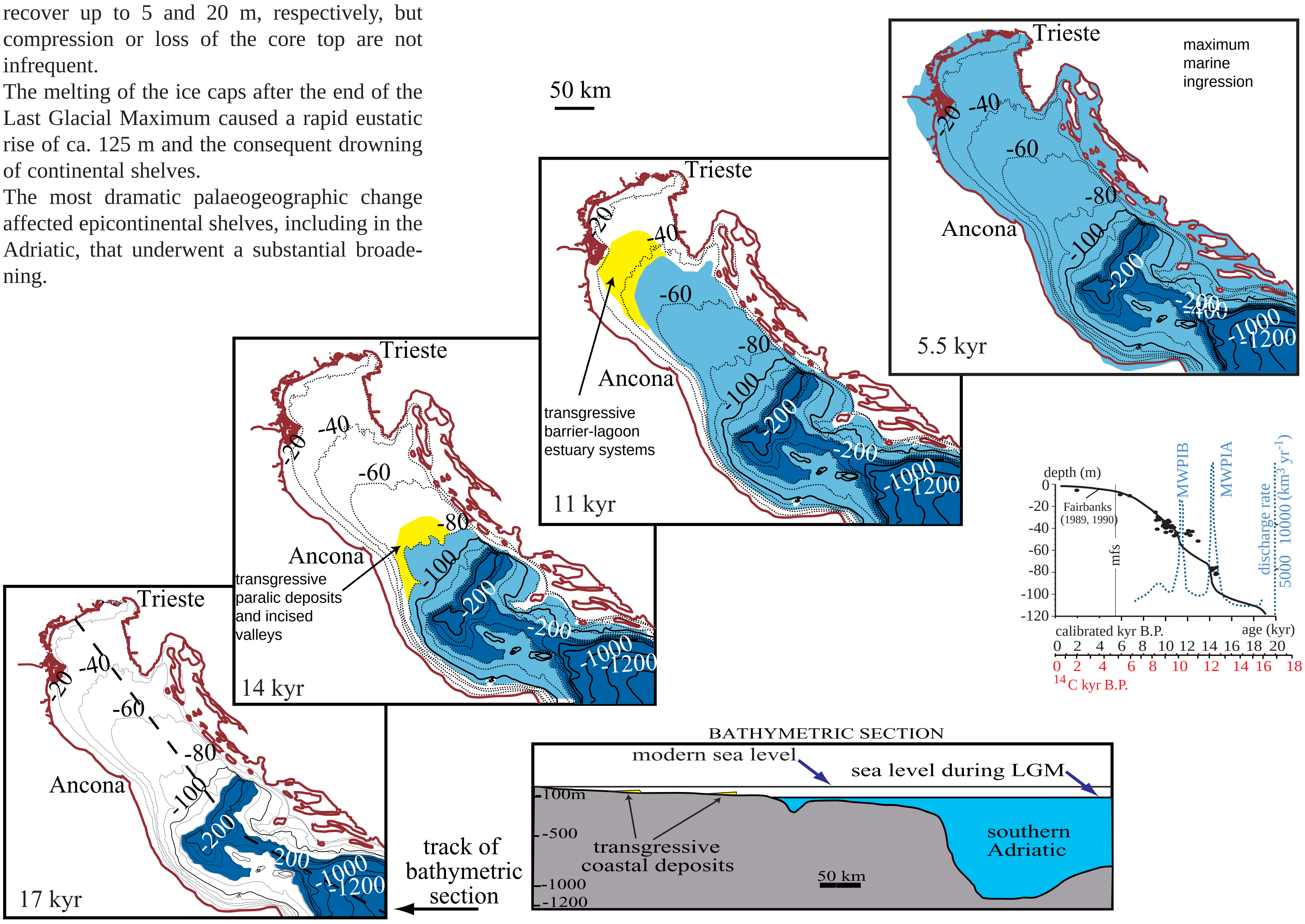


Fig. 21 - *Adriatic palaeogeography during the Late Quaternary sea levl rise. The cartoon above shows the extent of the Adriatic basin at the onset of the sea-level rise (dark blue), the location of drowned coastal lithosomes (yellow) and the extent of the basin culminating at the time of maximum ingression (about 5.5 ka BP). The very low gradient of the north Adriatic shelf allows the monitoring of the phases of the eustatic rise that followed the end of the last glaciation and quantify the magnitude of the main melt water pulses.*

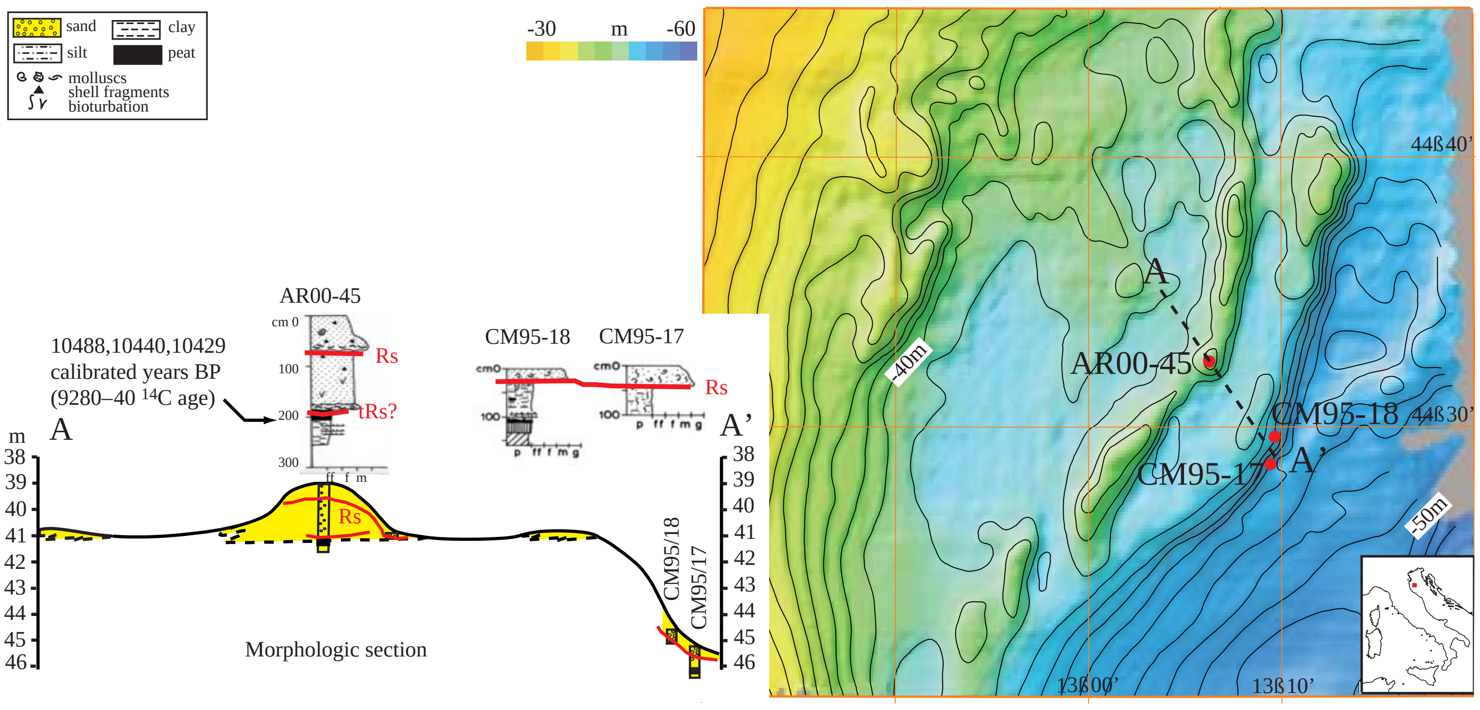


Fig. 22 - *Example of drowned barrier lagoon. Phases of enhanced sea level rise are recorded by the drowning of coastal lagoons and barriers, locally reworked into sand ridges. These deposits can be precisely dated and their present water depth measures the amount of sea-level rise following their transgressive submergence. An improved knowledge of the rates of sea-level rise is important when predicting environmental changes induced by global warming and possible further melting of ice caps. Furthermore, drowned barrier deposits are actively dredged in many areas as they comprise an important resource of sand for beach replenishment, particularly in densely developed or tourist areas affected by coastal erosion.*

6) Biostratigraphic and geochronological data sediment cores from different parts of a basin can be correlated based on the physical properties of layers (magnetic susceptibility, P-waves velocity, density), multiproxy environmental parameters (foraminifera, pollen, stable isotopes) and independent dating. Dating methodologies include radiocarbon, tephrochronology (based on the correlation of volcanogenic layers) and palaeomagnetic saecular variations. Radiocarbon dating is a methodology widely used for dating covering the last 30-40,000 years.

The unstable isotope ^{14}C, generated in the upper atmosphere by cosmic radiation bombarding atmospheric N, becomes fixed in the biosphere through photosynthesis and food web. When any organism (plant or animal) dies, its ratio of ^{14}C to ^{12}C (a stable isotope of C) begins to gradually decrease. The half-life of ^{14}C (5730 yrs) is the time that passes to decrease to 1/2 the quantity at death. By measuring the remaining quantity of ^{14}C, the age of the sample can be calculated.

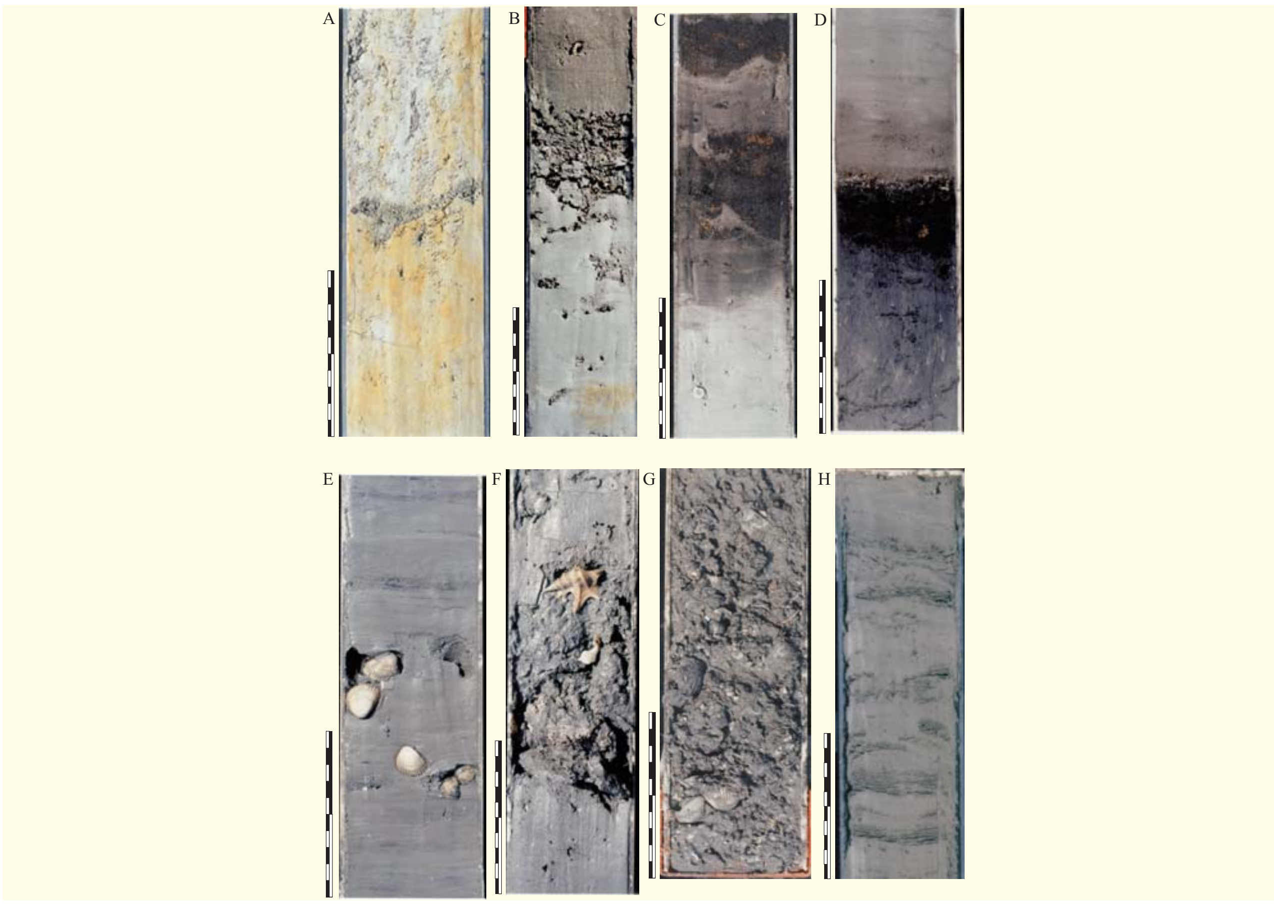
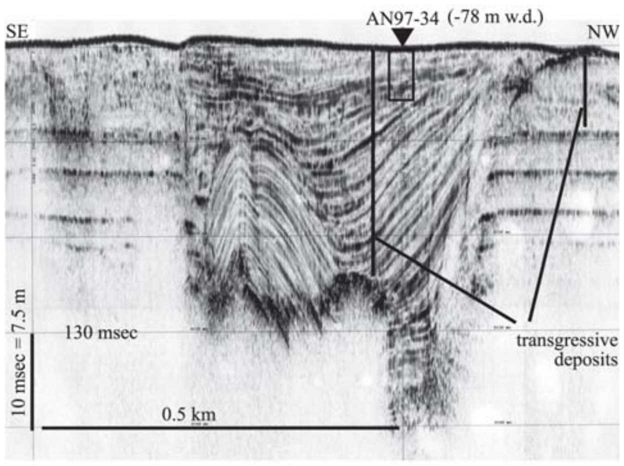


Fig. 23 - *Example of facies from sediment cores from chart NL33-10 Ravenna. Core A shows subaerially-exposed consolidated sandy clays of the Last Glacial Maximum; core B shows the erosion surface above the consolidated clays with a sandy-shelly lag, and a marine deposit fining upward above; cores C and D provide examples of back-barrier deposits with bioturbated peat layers with wood remnants (C), and thin storm beds with Hydrobia molluscs (D); core E is a typical mud-fill of an inlet or estuary with brackish fauna (*Cerastoderma glaucum*); cores F and G show reworked and mixed faunas from back-barrier (*C. glaucum*) coastal (*Glycymeris insubrica*) and offshore (*Aporrhais pespelecani*) deposits on the transgressive erosion surface; core H from modern HST deposits shows silty storm beds encased in marine prodelta muds. The vertical scale bar is 10 cm.*



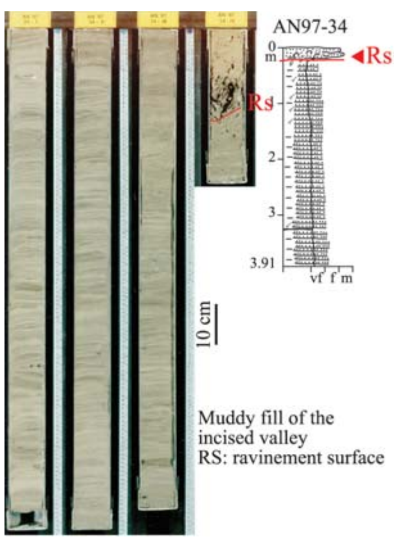


Fig. 24 - *Muddy deposits filling a valley incised into lower-TST deposits.*
Example of core through the transgressive fill of an incised valley on the low-gradient Central Adriatic shelf. Rs is the ravinement surface. Mud deposits in the valley fill are intensely laminated.

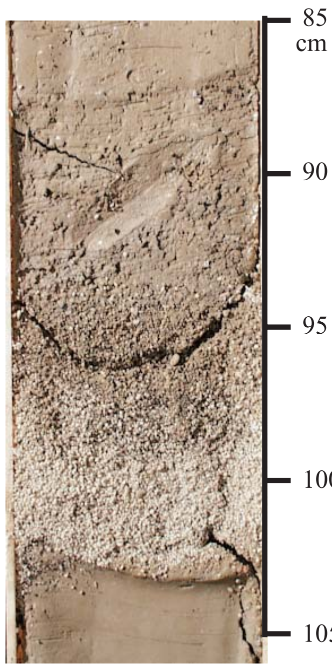


Fig. 25 - *Tephra layer from 79 AD Plinian eruption of Vesuvius. Dating of known tephra layers at sea and on land indicates that the ^{14}C reservoir value has not held constant through time, but varied significantly depending on changes in water-atmosphere exchanges through thermohaline circulation and deep-sea ventilation. The Adriatic is an ideal area for tephrochronology, although these deposits are typically very fine-grained, in contrast to more proximal areas (the example above shows 79 AD pumice from the Tyrrhenian shelf some 150 km south of Vesuvius).*

Fig. 26 - *Diagnostic fossil assemblages from Adriatic sediment cores. Examples of diagnostic fossil assemblages recovered from sediment cores; similar assemblages are recurrent in the geological record of the Mediterranean basin at least since the early Pleistocene. A: pre-transgressive continental facies representing a shallow-lacustrine environment dominated by freshwater gastropods such as* Planorbis *(pl),* Lymnaea *(ly) and* Bythinia *(bt). B: brackish lagoonal assemblage dominated by the euryhaline hidrobiid gastropod* Ventrosia ventrosa*. C: shell lag deposit over the ravinement surface containing a time-averaged assemblage with faunal elements sourced from brackish-protected environments (*Cerastoderma glaucum *(ce),* Gastrana fragilis *(ga),* Loripes lacteus *(lo),* Bittium reticulatum *(bi)) and open-marine shoreface (*Glycymeris insubrica *(gl),* Chamelea gallina *(ch),* Chlamys glaber *etc.).*

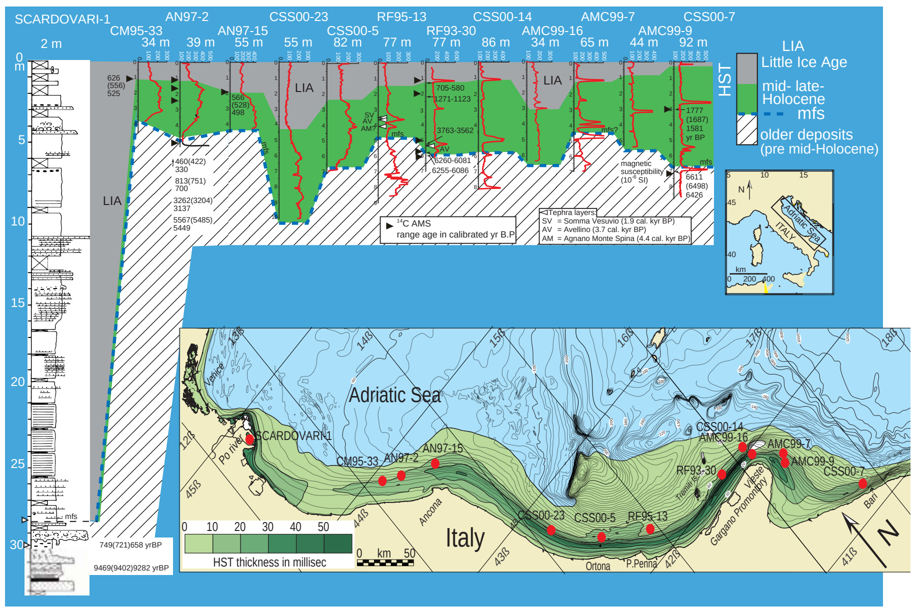


Fig. 27 - *Distribution of late-Holocene prodelta deposits on the Adriatic shelf, based on seismic stratigraphy and core correlation (whole-core magnetic susceptibility, biostratigraphy and tephra analysis). These prodelta deposits are distributed along the western side of the Adriatic basin in response of ocation of main fluvial sources and the dominant geostrophic gyre. The gray pattern above denotes the deposits that record the last few centuries since the onset of the Little Ice Age (LIA, 1450-1880 AD), cold spell. The LIA is the interval when the modern Po delta formed as a supply-dominated system under combined climatic and anthropogenic forcing. The EU-funded EURODELTA project is extending this kind of studies to more recent intervals and other Mediterranean and Black Sea prodelta stratigraphic archives.*

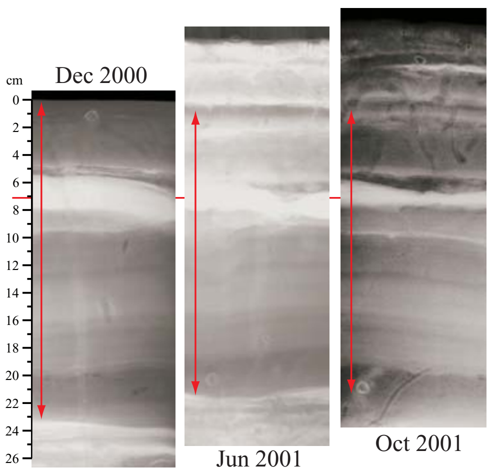


Fig. 28 - *X-ray radiographs of box cores from a repeated site off Po delta. Digitally-recorded radiographs of repeated samples from prodelta mud following Po River flood of Fall 2000 allow to study the preservation of flood layers (identified by the red arrowed bar), against erosion, compaction and bioturbation (EUROSTRATAFORM project funded by the European Union and by the Office of Naval Research).*

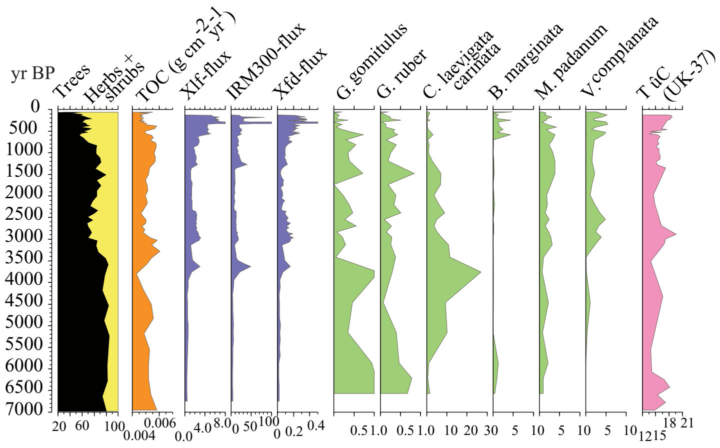


Fig. 29 - *Multiproxy data from the Central Adriatic. A Multiproxy analysis of core data allows the unravelling of environmental change in the geological past (PALICLAS EU project). In this example from a core retrieved in the Adriatic prodelta wedge, human impact can be disentangled from other environmental factors using magnetic stratigraphy, biostratigraphy of foraminifera, and palinology. Independent geochronological techniques (^{14}C dating, palaeomagnetism and tephrochronology) define the timing of climate change and human impact (such as forest clearance, cultivation and accelerated soil erosion) in the central Adriatic area since the Bronze Age (ca 3.7 ka BP).*

REFERENCES

ASIOLI A., TRINCARDI F., LOWE J.J. & OLDFIELD F. (1999)- *Short-term climate changes during the Last Glacial-Holocene transition: comparison between Mediterranean records and the GRIP event stratigraphy*. J. Quat. Sc., **14**: 373-381.

ASIOLI A., TRINCARDI F., LOWE J.J., ARIZTEGUI D., LANGONE L. & OLDFIELD F. (2001) - *Sub-millennial climatic oscillations in the Central Adriatic during the last deglaciation: paleoceanographic implications*. Quat. Sc. Rev., **20**: 33-53.

SERVIZIO GEOLOGICO D'ITALIA & REGIONE EMILIA-ROMAGNA (1999) - *Carta Geologica d'Italia alla scala 1:50.000 Foglio 223-Ravenna*.

SERVIZIO GEOLOGICO D'ITALIA & REGIONE EMILIA-ROMAGNA (in press.) - *Carta Geologica d'Italia alla scala 1:50.000 Foglio 256-Rimini*.

SERVIZIO GEOLOGICO D'ITALIA, ISTITUTO DI GEOLOGIA MARINA & CONSIGLIO NAZIONALE DELLE RICERCHE (2001) - *Carta Geologica dei mari italiani alla scala 1:250.000 Foglio NL33-10-Ravenna*, S.EL.CA. Firenze.

CATTANEO A. & TRINCARDI F. (1999) - *The Late Quaternary transgressive record in the Adriatic epicontinental sea: basin widening and facies partitioning*. In: K.M. BERGMAN & J.W. SNEDDEN (Eds), Isolated shallow marine sand bodies: sequence stratigraphic analysis and sedimentologic interpretation , SEPM Spec. Publ., **64**: 127-146.

CATTANEO A., CORREGGIARI A. & TRINCARDI F. (2002)- *Recognition of turbidite elements in the Late Quaternary Adriatic basin: where are they and what do they tell us?* In: J. MASCLE & F. BRIAND (Eds), Turbidite systems and deep-sea fans in the Mediterranean and Black seas. – CIESM Workshop Series n. 17, Monaco, <www.ciesm.org/publications/Bucharest02.pdf>, 27-32.

CATTANEO A., CORREGGIARI A., LANGONE L. & TRINCARDI F. (2003a) - *The Late Holocene Gargano subaqueous delta, Adriatic shelf: Sediment pathways and supply fluctuations*. Mar. Geol., **193**: 61-91.

CATTANEO A., CORREGGIARI A., PENITENTI D., TRINCARDI F. & MARSSET T. (2003b) - *Morphobathymetry of small-scale mud reliefs on the Adriatic shelf.* In: J. LOCAT & J. MIENERT (Eds) Submarine mass movements and their consequences, 401-408, Kluwer, Amsterdam.

CATTANEO A., CORREGGIARI A., MARSSET T., THOMAS Y., MARSSET B. & TRINCARDI, F. - *Seafloor undulation patterns on the Adriatic shelf and comparison to deep-water sediment waves.* Marine Geology (in press.).

CORREGGIARI A., ROVERI M. & TRINCARDI F. (1996) - *Late-Pleistocene and Holocene evolution of the North Adriatic Sea*. Il Quaternario, **9**: 697-704.

CORREGGIARI A., TRINCARDI F., LANGONE L. & ROVERI M. (2001) - *Styles of failure in heavily-sedimented highstand prodelta wedges on the Adriatic shelf.* J. Sedim. Res., **71**: 218-236.

FABBRI A., ARGNANI A., BORTOLUZZI G., CORREGGIARI A., GAMBERI F., LIGI M., MARANI M., PENITENTI D., ROVERI M. & TRINCARDI F. (2002) - *Carta Geologica dei mari italiani alla scala 1:250.000: guida al rilevamento.* Quaderni Servizio Geologico, Serie III, **8**: 101 pp.

MARSSET T., MARSSET B., THOMAS Y., CATTANEO A., TRINCARDI F. & COCHONAT P. - *Detailed analysis of Late Holocene sedimentary features on the Adriatic shelf from 3D very high resolution seismic data (TRIAD survey).* Marine Geology (in press.).

OLDFIELD F., ASIOLI A., ACCORSI C.A., MERCURI A.M., JUGGINS S., LANGONE L., ROLPH T., TRINCARDI F., WOLFF G., GIBBS Z., VIGLIOTTI L., FRIGNANI M., VAN DER POST K. & BRANCH N. (2003) - *A high resolution Late Holocene palaeo environmental record from the central Adriatic Sea*. Quat. Sc. Rev., **22**: 319-342.

RIDENTE D. & TRINCARDI F. (2002) - *Eustatic and tectonic control on deposition and lateral variability of Quaternary regressive sequences in the Adriatic basin (Italy)*. Marine Geology, **183**: 1-21.

TRINCARDI F., CORREGGIARI A. & ROVERI M. (1994) - *Late Quaternary transgressive erosion and deposition in a modern epicontinental shelf: the Adriatic Semienclosed Basin*. Geo-Mar. Lett., **14**: 41-51.

TRINCARDI F., ASIOLI A., CATTANEO A., CORREGGIARI A. & LANGONE L. (1996) - *Stratigraphy of the Late Quaternary deposits in the Central Adriatic basin and the record of short-term climatic events*. Mem. Ist. Ital. Idrobiol., **55**: 39-70.

TRINCARDI F. & CORREGGIARI A. (2000) - *Muddy forced-regression deposits in the Adriatic basin and the composite nature of Quaternary sea level changes.* In: (D. HUNT & D. GAWTHORPE (Eds), Sedimentary expression of forced regressions. Geological Society Special Publication, **172**: 247-271.

TRINCARDI F. & ARGNANI A. (Eds), with contributions of ASIOLI A., BORTOLUZZI G., CATTANEO A., CORREGGIARI A., FABBRI A., GAMBERI F., LIGI M., PENITENTI D., ROVERI M. & TAVIANI M. (2001) - *Note illustrative della Carta Geologica dei mari italiani alla scala 1:250.000* - FOGLIO NL33-10 RAVENNA. Servizio Geologico d'Italia, Istituto di Geologia Marina, Consiglio Nazionale delle Ricerche, S.EL.CA., 108 pp., Firenze.

TRINCARDI F., CATTANEO A., CORREGGIARI A. & RIDENTE D. - *Evidence of soft-sediment deformation, fluid escape, sediment failure and regional weak layers within the Late Quaternary mud deposits of the Adriatic Sea. Marine Geology* (in press.).