The Po Plain Quaternary deposits between Forlì and Ravenna: Surface and subsurface geology

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ABSTRACT

The geological maps presented in this work are part of the Geological Map of Italy at 1:50,000 scale (Sheets 240 Forlì and 241 Cervia, CARG Project) produced by the Emilia-Romagna Geological Survey with the cooperation of the Institute for Marine Geology of CNR for the Adriatic Sea area. The geological cartography of the Quaternary Po Plain deposits is based upon the identification and representation of stratigraphic units with non conformable limits and their facies associations. These geological maps were produced by integrating the analytical methods typically utilized in both surficial and subsurface geological investigations in order to propose a comprehensive 3D geological model for the territory. Thus, in this work, maps, figures and texts are structured in a general introduction followed by two sections referred to surface and subsurface geology respectively.
The cartographic representations considered most suitable and included in this contribution are:
- a geological map of the surface in which a combination of colour and overlays are used to represent the stratigraphic units and depositional environments which are present in outcrop (up to 1 m in depth from the topographic surface);
- a geological map of the subsurface in which the most significant lithologic bodies from the structural, paleogeographic and application-oriented points of view are shown (with color, overlays and contour lines);
geological cross-sections at varying vertical scales which illustrate the 3D geometry of the mapped units and show the stratigraphic reference setting.

AIMS

The geological cartography presented in this work is based upon an integrated analyses of both surface and subsurface features, with the following objectives:
To understand the origin and distribution of outcrop and buried Quaternary deposits on the Po Plain and describe them in terms of Unconformity Bounded Stratigraphic Units (UBSU; i.e. synthem and subsynthem).
Classification, in terms of UBSUs, of the corresponding dominant lithologies and their associated facies (e.g. floodplain clays and silts, beach-ridge sands, etc.), the distinctive morphological-depositional units that reflect these lithologies and the diversity of depositional systems evident.
The three-dimensional cartographic representation of these units and facies by means of a) a geologic map of the surface, b) a geologic map of the subsurface, and c) several geological cross-sections that depict stratigraphic intervals at varying depths.

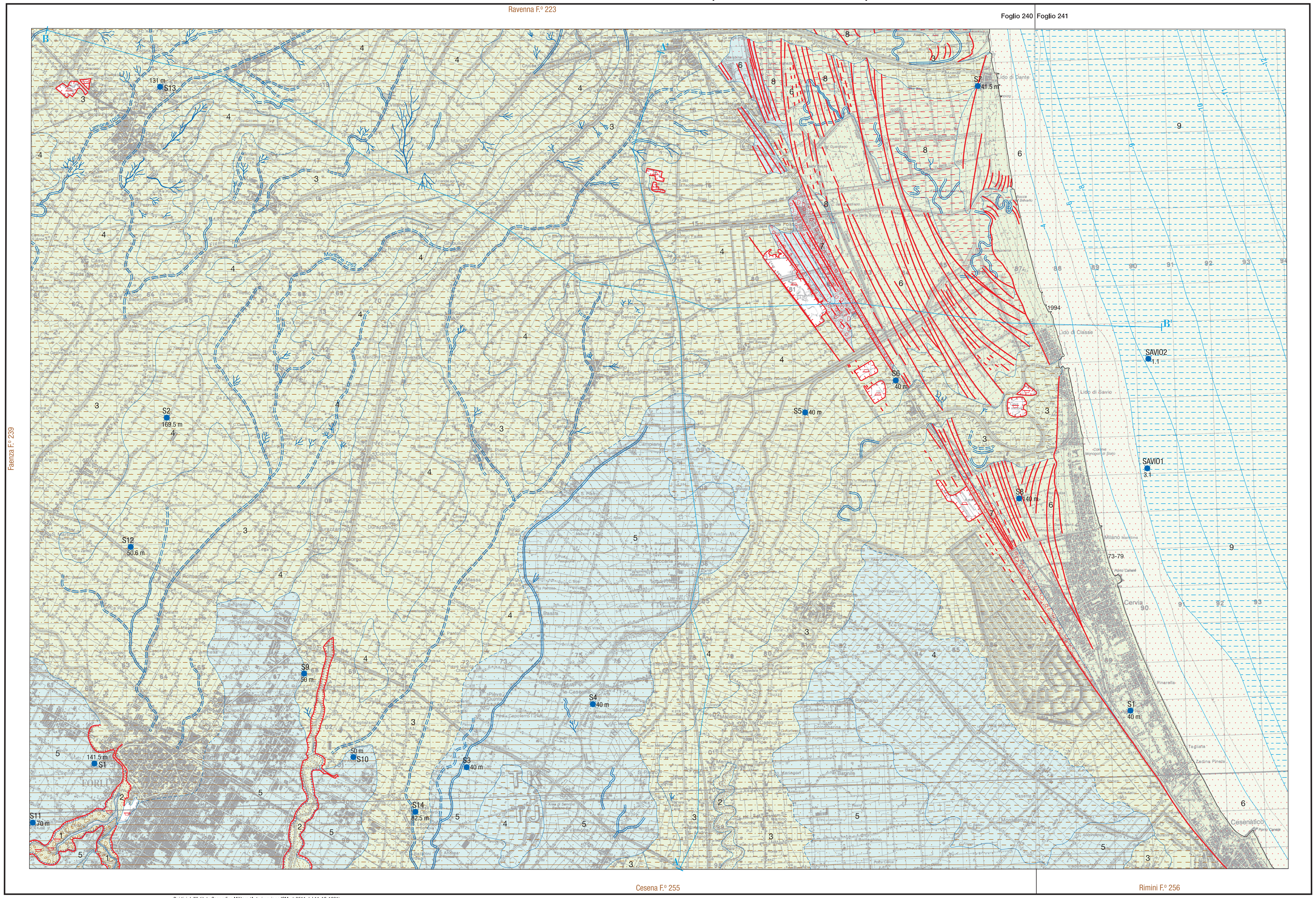
KEY WORDS

Alluvial plain, coastal plain, depositional system,
Unconformity Bounded Stratigraphic Unit

RIASSUNTO

Le carte geologiche riportate in questo lavoro costituiscono un estratto della Carta Geologica d'Italia in scala 1:50.000 (Fogli 240 Forlì e 241 Cervia, Progetto CARG) che il Servizio Geologico della Regione Emilia-Romagna ha elaborato con la collaborazione dell'Istituto per la Geologia Marina del CNR per l'area del Mare Adriatico. La cartografia geologica dei depositi quaternari di pianura si basa sul riconoscimento e sulla rappresentazione di unità stratigrafiche a limiti inconformi e delle facies in esse contenute. Essa viene costruita a partire dall'integrazione di metodi analitici tipici sia della geologia di superficie che di sottosuolo al fine di elaborare un modello geologico complessivo del territorio in 3D. Per questo motivo le carte, le figure ed i testi di questo contributo sono organizzate in una introduzione generale a cui fanno seguito due parti distinte riferite, rispettivamente, alla geologia di superficie e di sottosuolo.
Le rappresentazioni cartografiche ritenute più idonee a questo scopo ed illustrate in questo lavoro sono: la carta geologica di superficie in cui vengono rappresentate tramite la combinazione di colori e retini sia le unità stratigrafiche che gli ambienti deposizionali affioranti; la carta geologica di sottosuolo in cui (tramite colori, retini e linee isobate) sono riportati i corpi litologici più significativi dal punto di vista stratigrafico, paleogeografico ed applicativo; le sezioni geologiche a diverse scale verticali che descrivono la geometria 3D degli oggetti rappresentati nelle singole carte e ne illustrano il quadro stratigrafico Di riferimento.

SURFACE GEOLOGICAL MAP BETWEEN FORLI' AND CERVIA (SE PO PLAIN)



m 1000 0 1 2 3 4 5 km

Fig. 1 - Surfage Geological Map. Geological survey: Working Groups of the Servizio Geologico, Sismico e dei Suoli (Regione Emilia-Romagna) and ISMAR-Istituto di Scienze Marine (CNR, Bologna).

DEPOSITIONAL SYSTEM AND LITHOLOGY

ALLUVIAL DEPOSITS

ALLUVIAL FAN AND PLAIN

1 Fluvial channel-fill gravel
Coarse to fine gravel, with sandy or silty matrix; thickly to very tbickly--bedded, generally amalgamated.

2 Fluvial channel-fill and crevasse sand
Coarse to fine and very fine sand (locally with pebbles) that fines upward to silt and clay Sand layers are thickly to very thickly-bedded, generally amalgamated.

3 Levee, channel and crevasse sand-silt alternations
Alternations of fine and very fine sand with silt, sandy silt and clayey silt. Sand layers are thinly to thickly-bedded; silt layers are very thinly to medium-bedded.

4 Floodplain clay and silt.
Clay and silt in medium to thick layers, rarely very thin to medium layers of sandy silt and silty sand are present. Organic-rich clays may be present at the top of beds.

5 Undifferentiated overbank sand, silt and clay alternation.
Altemations of fine to very fine sand, silt and clay in very thin to thick layers. Include both levee and floodplain deposits that were not differentiated due to erosion, bioturbation and pedogenesis that strongly modified the depositional texture and morphology.

DELTAIC, LITTORAL AND MARINE DEPOSITS

DELTA FRONT AND STRANDPLAIN

6 Beach-ridge sand.
Very fine to coarse well-sorted sand, with abundant mollusc shells, and subordinate sandy silt layers. Sand layers are thinly to medium-bedded and generally amalgamated.

7 Beach-ridge gravel.
Fine and medium gravel and sandy gravel with sandy matrix, occasionally prevailing. Pebbles are flat-shaped and well-sorted. **Matrix** include mollusc shells. Gravel layers are medium to thickly-bedded, occasionally amalgamated or alternating with medium to coarse sand. These deposits are locally included within the beach-ridge sand (gravel beach).

8 Marsh, lagoon and back-barrier organic clay and silt.
Dark organic-rich clay, silty clay, silt and peat layers very thinly to medium-bedded locally alternating with very fine to fine sand. Shells of both brackish anti fresh-water are common.

PRODELTA AND OFFSHORE-TRANSITION

9 Shell-rich clay, clayey silt and silt, with common layers of fine to very fine sand. Sand layers are very thinly to thinly-bedded.

STRATIGRAPHIC UNITS

b1 · Gravel and sand, occasionally silty and clayey matrix is present. They are located within the incised fluvial valleys and comprise the present day fluvial river beds and flooded areas during ordinary flood events.

UPPER EMILIA-ROMAGNA SYNTHEM - AES

Synthem partially composed by subsynthems (AES8, AES7 and AES6, see also the section 2 about subsurface) each one corresponding to a transgressive - regressive cycle at ten to hundred meters scale. Only the Subsynthem AES8 is outcropping and mapped in the surface geological map. Maximum thickness of about 300 m. Age: Medium Pleistocene - Holocene.

RAVENNA SUBSYNTHEM – AES8

Brownish and yellowish clay, silt and silty sand alternations of fluvial floodplain and levee deposits of well-drained alluvial plain with soils at the top. Fluvial channel's gravel and sand can be found in the southern sectors only, always bounded by scarp terraces'. In the eastern sectors are present strandplain deposits made up of beach-ridge sand associated with thin organic-rich clay of back-barrier lagoon.
The upper boundary coincides with the ground surface, with soils varying from non-calcareous to calcareous. Non-calcareous and poorly calcareous soils are dark brownish and dark yellowish brownish, have the thickness of the $CaCO_3$-poor layer varying from 0.5 to 1 m and contain archaeological findings from Bronze to Roman Age. Calcareous soils belong to the AES8a unit and are described in the related section. The lower bounding unconformity is always buried.
Subsynthem containing a hierarchically minor unit (AES8a) that, where present, constitutes its stratigraphic top and is mapped separately.
Thickness range: 20 - 28 m. Age: Late Pleistocene - Holocene (14 Ky BP non calibrated - Present).

Modena unit - AES8a

seaward

In the upper alluvial plain: fluvial channel's gravel and sand, bounded by a single order of scarp terrace. In the middle and lower alluvial plain: alternations of sand, silt and clay of levee and floodplain deposits. In the coast and Adriatic Sea: beach-ridge and delta front sand, grading to prodelta and offshore transition clay and silt; locally, between sand-ridges, are present organic-rich clay of back-barrier lagoon. The upper boundary coincides with the ground surface and is formed by a calcareous soil, olive brownish or yellowish brownish ,without Roman (or older) archaeological findings, characterised by a good preservation of the morphology of depositional features. The lower bounding unconformity is marked by 1) the erosive surface at the base of the main rivers, 2) the contact of the overbank deposits on the non-calcareous soil of Roman Age, and 3) the erosive base of the sandy beach-ridges and delta front truncating the gravel beaches of AES8.
Thickness range: 0-5 m, locally up to 10 m. Age: Post Roman (IV-VI century A.D. - Present).

Artificial banks
Geognostic data (RER data base)
Grain-size profile of continuous borehole
A: clay, L: silt
S: sand, G: gravel
Non- or weakly-calcareous soil
Archeological find,
R: Roman Age B: Bronze Age
1830 ± 65 ^{14}C Age y. B. P.
Boundary of stratigraphic unit
AES_8 Ravenna Subsynthem
AES_{8a} Modena unit
Fluvial channel-fill and crevasse sand
Levee, channel and crevasse sand-silt alternations
Floodplain clay and silt.
Undifferentiated overbank sand, silt and clay alternation
Beach-ridge sand
Beach-ridge gravel
Marsh, lagoon and back-barrier organic clay and silt
Shell-rich with common layers of prodelta and offshore-transition deposits
Boundary of stratigraphic unit and depositional system. Certain, uncertain
Trace of abandoned fluvial channel certain, uncertain (age)
Crevasse splay
Rim of terrace and fluvial escarpment
Beach-ridge crest certain, uncertain
Coast line (age)
Escarpment rim of large quarry
Active quarry
Abandoned quarry
CARG-Project continuous borehole (label and depth in m)
Depth contour of sea floor (m above sea level)
Section trace

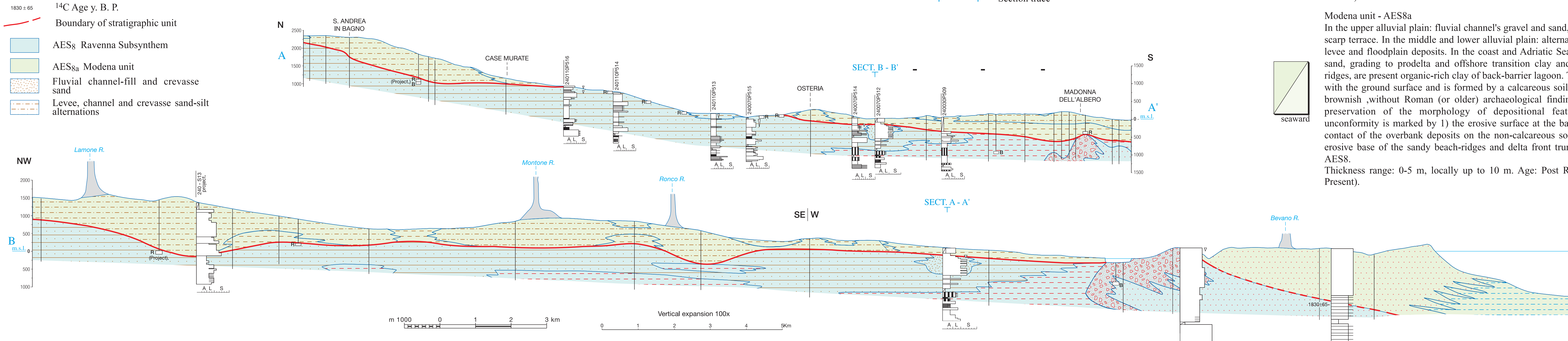


Fig. 2 - Geological cross-sections A-A' and B-B' of the Surface Geological Map (vertical expansion 100x).

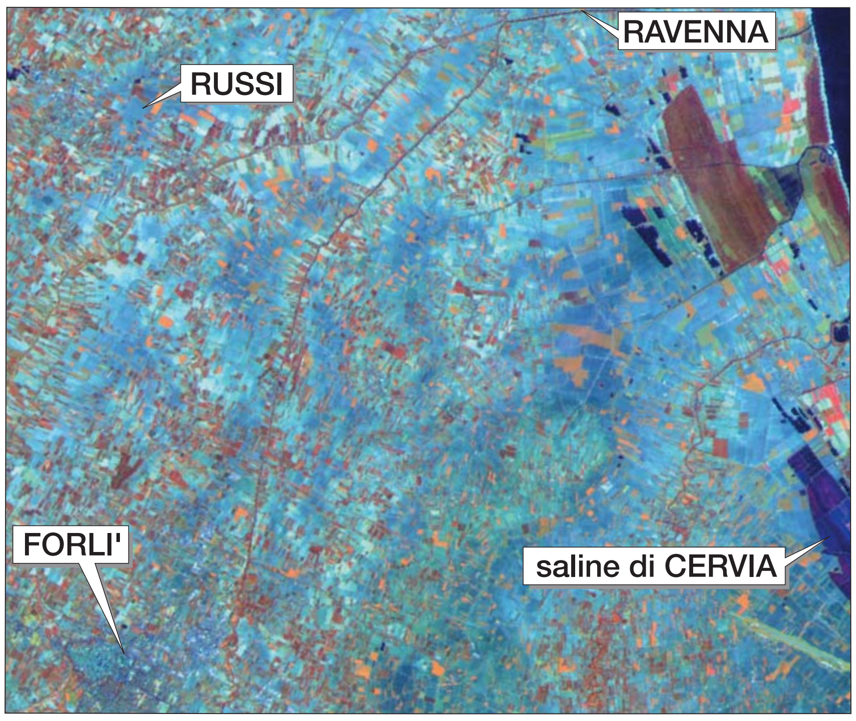


Fig. 3 - *Satellite image of the study area. The picture was taken by the Landsat 5 satellite on October 12, 1986, using a Thematic Mapper (TM) sensor and bandwidths 4, 5, and 3; viewing angle corrections and colour adjustments have been made to the original image. Copyright ESA 1986, distributed by Eurimage, Telespazio for Italy.*

SURFACE GEOLOGY

Surface deposits in the southern portion of the Po Plain reflect the Holocene geological history of the Apennine rivers and, at the eastern margin of the plain, of the Adriatic Sea. In the study area, these deposits are entirely contained within the Ravenna Subsynthem (14 ka BP non-calibrated radiocarbon age to Present), and are the result of the major transformations of the landscape has undergone starting from the beginning of the last deglaciation to date. The Ravenna Subsynthem is the youngest unit of the Upper Emilia-Romagna Synthem (with the base estimated at 400 ka). The cartographic unit with the lowest hierarchical ranking is the Modena informal unit (4th - 6th century AD to the present day), which is a high-frequency depositional cycle that developed as a result of the climatic crisis concomitant with the fall of the Roman Empire. The Modena informal unit constitutes the uppermost level of the Ravenna Subsynthem, and is present over much of the Emilia-Romagna alluvial plain. The overall distribution of the facies association is characterized by a clear bipartition between the western and central sectors, that are dominated by alluvial plain deposits, and the eastern sector up to the Adriatic Sea, dominated by delta front - strandplain and prodelta - offshore transition deposits.

The cartographic representations of surface geological features include, in traditional fashion, a map and several cross-sections. The map (Fig. 1) is projected to show both the stratigraphic units and facies associations of all the geological bodies. Such a representation is realized by combining colour and overlays. In the Adriatic Sea area, the depth contour lines of the sea floor are also shown.

The vertical scales of the cross-sections (Fig. 2) are strongly expanded (100 times the horizontal scale) to emphasize the smoothest morphologic features and geometric relationships between units. They are generated by integrating surface morphology and geognostic data (up to about 10 m below the topographic surface) to describe the inferred geometry of geological bodies in the subsurface.

Fig. 4 - *Excavation wall from the alluvial plain located south-east of the geological map area (highway A14 north of Gambettola). The yellowish, channel-levee sandy deposits of the Modena unit rest on the top of darker greyish, floodplain clay and mud of the Ravenna Subsynthem.*

The study of the surface terrain is based primarily on an analysis of panchromatic air photos and satellite images (Fig. 3). An analysis of the colour tones and patterns, the drainage patterns and soil-usage, as well as morphological analyses inferred from altimetry, have enabled:

a) a preliminary identification of the principal geomorphic units-channels, natural levees, crevasse splays, floodplains, beach-ridge, etc.; b) an approximate evaluation of the sediment lithology; and c) an approximate evaluation of the degree of soil alteration.

The geomorphologic, lithologic and pedologic information deduced from the air photos and satellite images was ground-truthed by means of a geological field survey. The rare outcrops (scarp terraces, quarries, construction excavations, etc., Fig. 4) were mapped and carefully investigated by detailed sedimentological analysis to characterize the surface lithology and depositional ambient and to define the boundaries of the stratigraphic units. These data were implemented by the stratigraphic and sedimentologic analysis of undisturbed cores from boreholes, used extensively for the study of the subsurface geology. With the exception of these few outcrops and boreholes, the surface geological mapping relied mostly on hand-auger drillings pushed to a depth of 1.5 meters on the field plain.

It was possible to greatly improve the geological map thanks to the extensive use of soil data (i.e. sediment grain-size, $CaCO_3$ content, soil features and horizons definition) processed by the Soil Data Bank of the Emilia-Romagna Region

Fig. 6 - *Archaeological site of the Roman country house of Russi (Ravenna). After the II century AD, the house floor mosaics were buried by 10 m of alluvial sediment.*

and combined with data from the Soil Survey Analyses and Consultancy (Fig. 5). Analyses of the soil texture allowed the systematic lithological verification and characterization of the morphologic units recognized and mapped from the air photos and satellite images. The degree of soil alteration was used to estimate the minimum and relative ages of the sediments.

Sediment ages were also determined by consulting bibliographies containing a comprehensive census of archeological finds and their mapping. Most of these date from Roman times and may be relatively abundant in several areas of the map. The excellent archeological site of Russi (Fig. 6) allowed the estimation on the field of the present depth of the Roman topographic plain (base surface of the Modena unit).

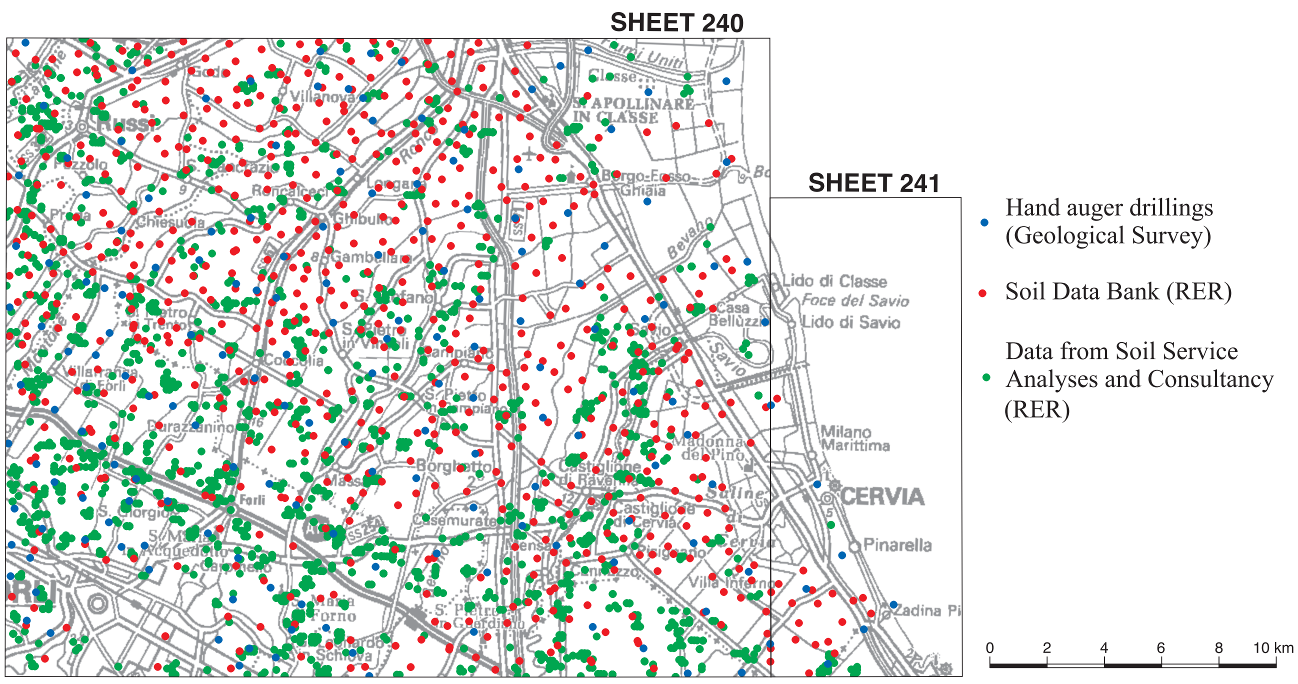


Fig. 5 - *Map distribution of the pedological data used for the geological map.*

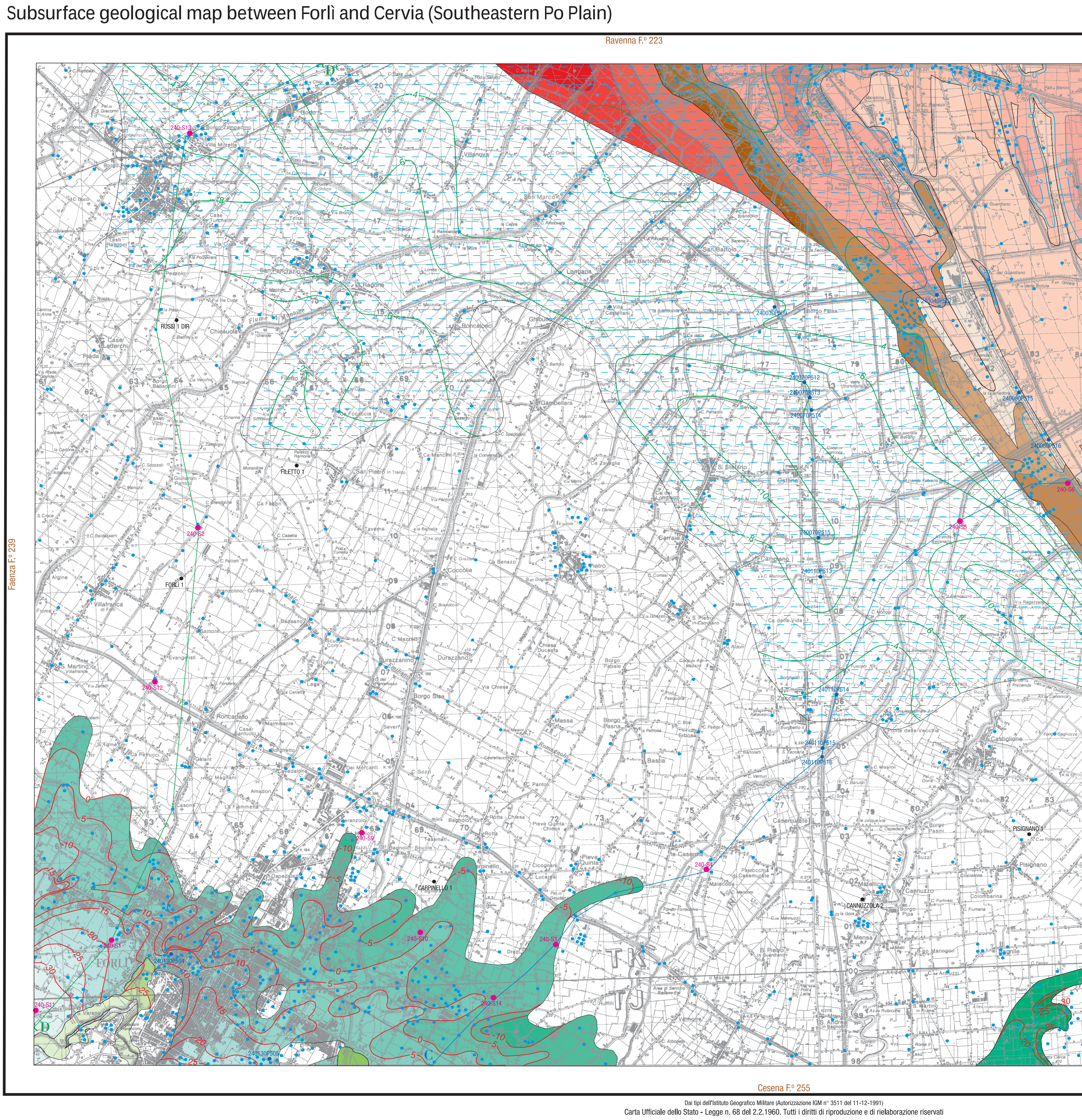


Fig. 7 - *Subsurface Geological Map: top of alluvial gravels and of deltaic and littoral deposits - the Ravenna (AES8) and the Villa Verucchio (AES7) Subsynthems. Geological survey: Working Groups of the Servizio Geologico, Sismico e dei Suoli (Regione Emilia-Romagna) and ISMAR-Istituto di Scienze Marine (CNR, Bologna).*

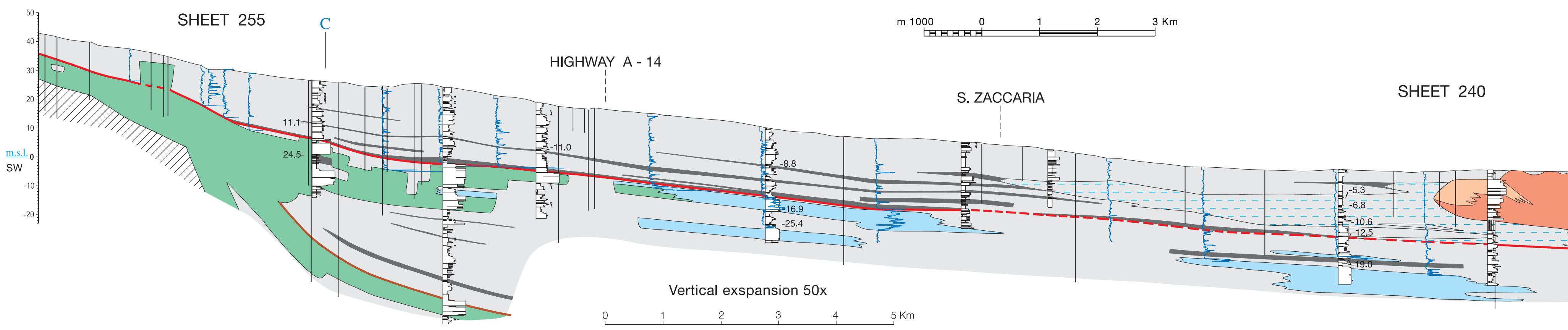
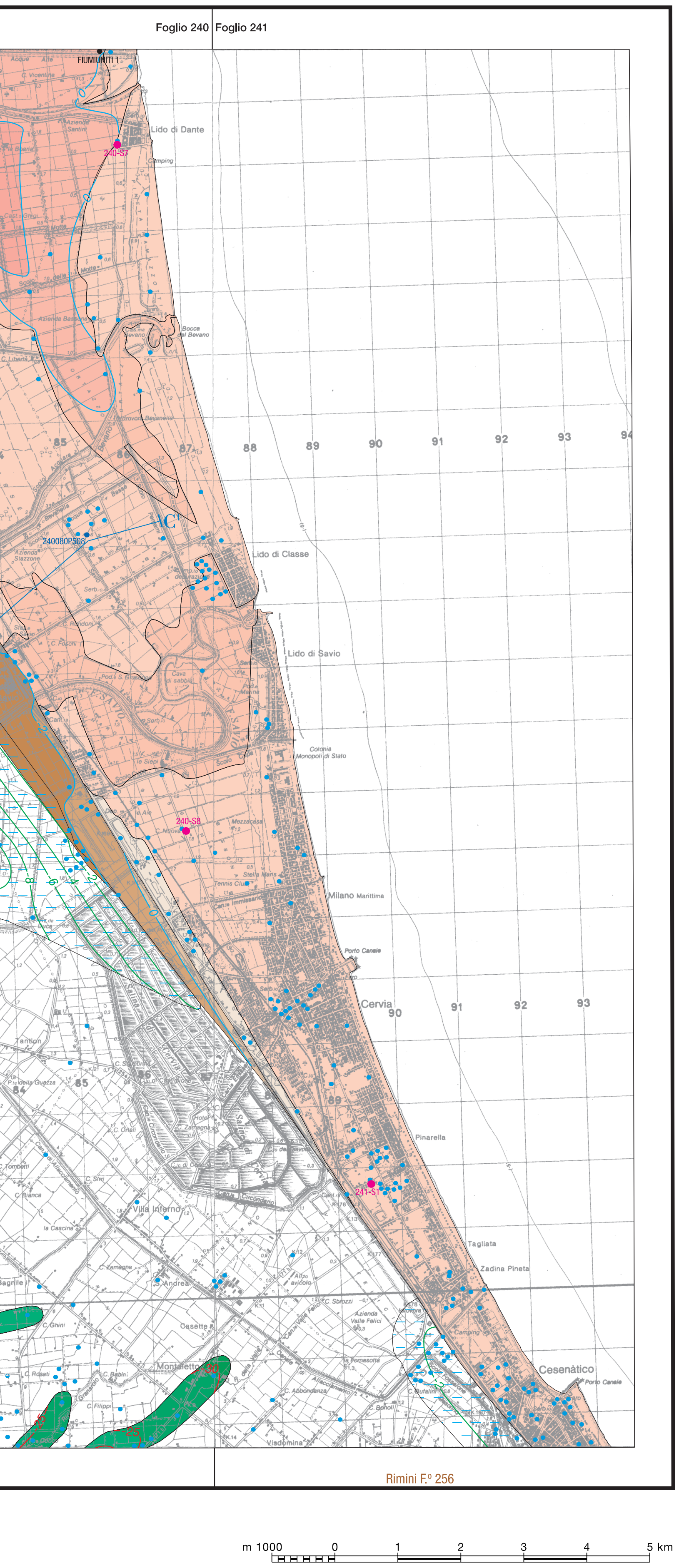


Fig. 8 - *Shallow geological cross-section C-C' of the subsurface geological map (vertical expansion 50x)*.



RAVENNA SUBSYNTHEM - AES8

ALLUVIAL DEPOSITS

Fluvial channel-fill gravel (Outcropping/Buried)
Medium to fine gravel with sandy or silty matrix; thickly to very thickly-bedded, generally amalgamated. Filling deposits of isolated fluvial channels of the alluvial plain. Thickness range: 2-7 m. Age: Late Pleistocene - Holocene (14 ky BP non calibrated - Present).

Depth contour of the top of fluvial channel-fill gravel (m above sea level)

DELTAIC AND LITTORAL DEPOSITS

Beach-ridge sand (Outcropping/Buried)
Very fine to coarse well-sorted sand, with abundant mollusc shells, and subordinate sandy silt layers. Sand layers are thinly to medium-bedded and generally amalgamated. Includes coastal dunes, backshore, foreshore, shoreface and back-barrier transgressive deposits, mostly outcropping (eastern sector) or buried 0 to 15 m below the field surface (northern sector). Locally includes gravel beaches (see following). Thickness range: 5-15 m. Age: Holocene (8 ky BP non calibrated - Present).

Beach-ridge gravel (Outcropping/Buried)
Fine and medium gravel and sandy gravel with sandy matrix, occasionally prevailing. Pebbles are flat-shaped and well-sorted. Matrix include mollusc shells. Gravel layers are medium to thickly-bedded, occasionally amalgamated or alternating with medium to coarse sand. These deposits are locally included within the beach-ridge sand (gravel beach). Thickness range: 2-7 m. Age: Holocene (8 ky non calibrated - Present).

Depth contour of the top of beach-ridge sand and gravel (m above sea level)

Marsh, lagoon and back-barrier organic clay and silt
Dark organic-rich clay, silty clay, silt and peat layers very thinly to medium-bedded locally alternating with very fine to fine sand. Shells of both brackish and fresh-water are common. Deposits of marsh, lagoon and bay located in delta plains or in the landward areas of rapidly transgressing barriers. Thickness range: 1-15 m. Age: Late Pleistocene - Holocene (12 ky BP non calibrated - Present).

Depth contour of the top of marsh, lagoon and back-barrier organic clay and silt (m above sea level)

VILLA VERUCCHIO SUBSYNTHEM - AES7

ALLUVIAL DEPOSITS

Fluvial channel-fill gravel
Very coarse to fine gravel with sandy or silty matrix; thick to very thickly-bedded, generally amalgamated. Filling deposits of laterally and vertically amalgamated fluvial channels (alluvial fan). Towards North gravel separates in thinner and isolated channels (transition to the alluvial plain). Thickness range: 5-18 m. Age: Late Pleistocene (c.a. 40 -17 ky non calibrated).

Depth contour of the top of fluvial channel-fill gravel (m above sea level)

240-S6 — CARG-Project continuous borehole (label and depth in m)

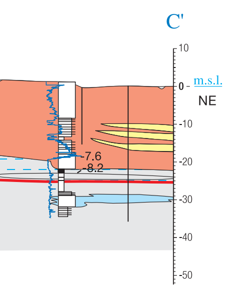
240080P508 — Other continuous borehole (directly examined by the survey team)

Geognostic data (RER data base)

CANNUZZOLA 2 — Hydrocarbon oil-exploration well (AGIP)

C C' — Trace of shallow geological cross section

D D' — Trace of deep geological cross section



ALLUVIAL FAN AND PLAIN DEPOSITS

Fluvial channel-fill gravel

Fluvial channel-fill and crevasse sand

Overbank sand, silt, and clay alternation

Swamp organic clay and silt

DELTAIC, LITTORAL AND MARINE DEPOSITS

Beach-ridge sand

Beach-ridge gravel

Marsh, lagoon and back-barrier organic clay and silt

Prodelta clay with sandy alternation

Plio-Pleistocene marine units

Ravenna Subsynthem (AES8) lower boundary

Villa Verucchio Subsynthem (AES7) lower boundary

Geognostic data (RER data base)

Cone penetration test (CPTE and CPTU)
CARG-Project (cone resistance)

CONTINUOUS BOREHOLE

Grain-size profile of continuous borehole

14,3 — Age 14C Before Present (ky non calibrated)

∇ — Paleosoils (non- or weakly-calcareous)

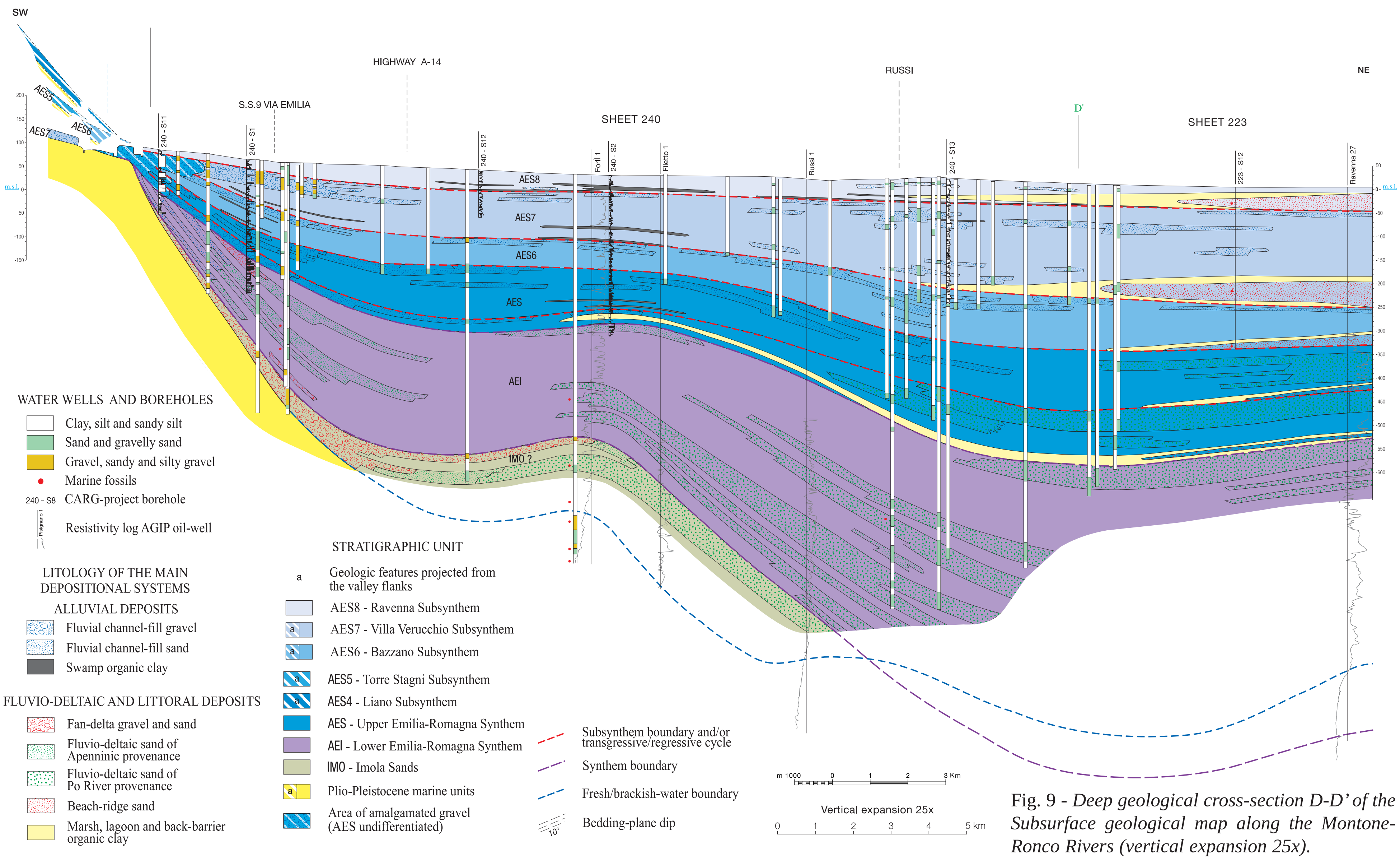


Fig. 9 - *Deep geological cross-section D-D' of the Subsurface geological map along the Montone-Ronco Rivers (vertical expansion 25x).*

SUBSURFACE GEOLOGY

The reconstruction of the Subsurface Geological Map is based on actual data points: the spatial relationships between various sedimentary bodies is based upon a number of interpolation processes (Figs. 7, 8 and 9). A clear delineation of the subsurface's stratigraphical setting is of fundamental importance towards the study of practical problems. Scientific knowledge of the subsurface setting is critical for studies related to subsidence, soil conservation, water resources, etc.

The stratigraphic setting of reference for the area studied is shown in the deep geological cross-section (which also has information that relates to areas adjacent to this map, Fig. 9). This cross-section illustrates the Upper Emilia-Romagna Synthem's (AES) internal characteristics, as well as its relationship with adjacent units. The Emilia-Romagna Synthem is a reference unit for most of the fluvio-deltaic deposits that are either exposed or buried in the upper layers from ten to hundreds of meters in depth of the Emilia-Romagna plain.

In valleys, the Emilia-Romagna Synthem has been subdivided into subsynthems (AES4-8) corresponding to the deposits that outcrop as several different fluvial terraces or sets of terraces. Beneath the plain's surface, the AES subsynthems are correlated to thickening and coarsening upward cycles characterised by their fluctuation between fine-grained sediments (dominated by fluvial overbanks) and coarse-grained sediments (dominated by fluvial channel fillings). At the base of every cycle, overbanks (including organic-rich swamp deposits) transition toward the northeast into deltaic and littoral sediments. Based on their physical correlation to the coast areas, these cycles can be clearly interpreted as being transgressive-regressive in nature, and are considered to be a result of the basic Quaternary climatic-eustatic cycles that have an approximately 100,000-year periodicity.

The shallow geological cross-section (Fig. 8) shows the presence of sediments of the Po Plain up to 50-60 m below the plain's surface. These units belong to the Ravenna (AES8) and the Villa Verucchio (AES7) Subsynthems.

The characteristics that are essential towards depicting stratigraphical relationships and the geometry of the main lithologies of these subsynthems are shown.

In the Subsurface Geological Map (Fig. 7), we have concentrated on mapping those lithologic bodies that may be especially relevant in terms of stratigraphic, paleogeographic, and application-oriented studies, that is:

(1) the principal fluvial gravel deposits of the uppermost sediments (maximum depth of investigation is about 40 m below sea level), which are assigned to AES7 and AES8;

(2) the deposits composed primarily of organic-rich clay and mud within a swamp-lagoon (delta to back-barrier depositional environment), which belong to AES8;

(3) beach-ridge sand and gravel deposits, which belong to AES8;

The study of the subsurface began with the creation of a geognostic data base (Fig. 10) that required:

1) the acquisition of paper copies of the boreholes, cone penetration tests and water-well stratigraphies, retrieved from private and public sources;

2) the location of the geognostic data on the technical regional maps at a 1:10,000 scale, along with their georeferencing, followed by the loading into computer databases of the available stratigraphic and hydrologic information and

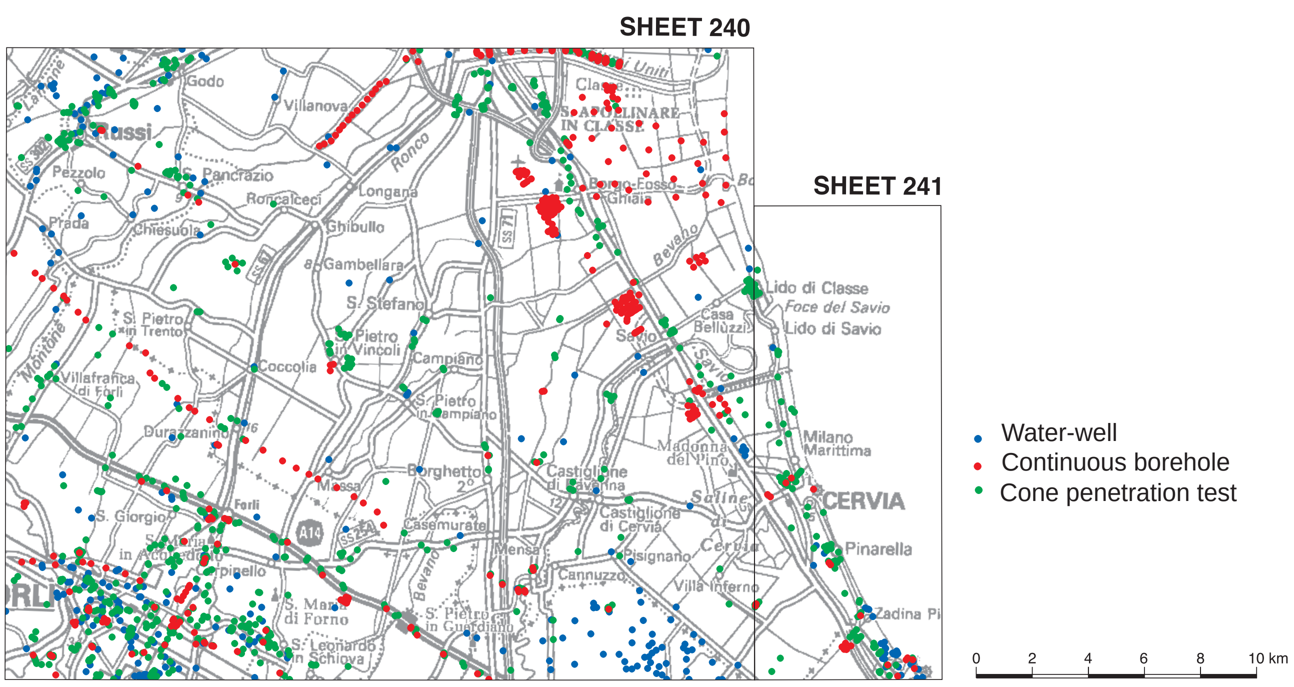


Fig. 10 - *Location of the geognostic investigations contained in the data base of the Geological Survey of the Emilia-Romagna Region and used for the subsurface geologic map.*

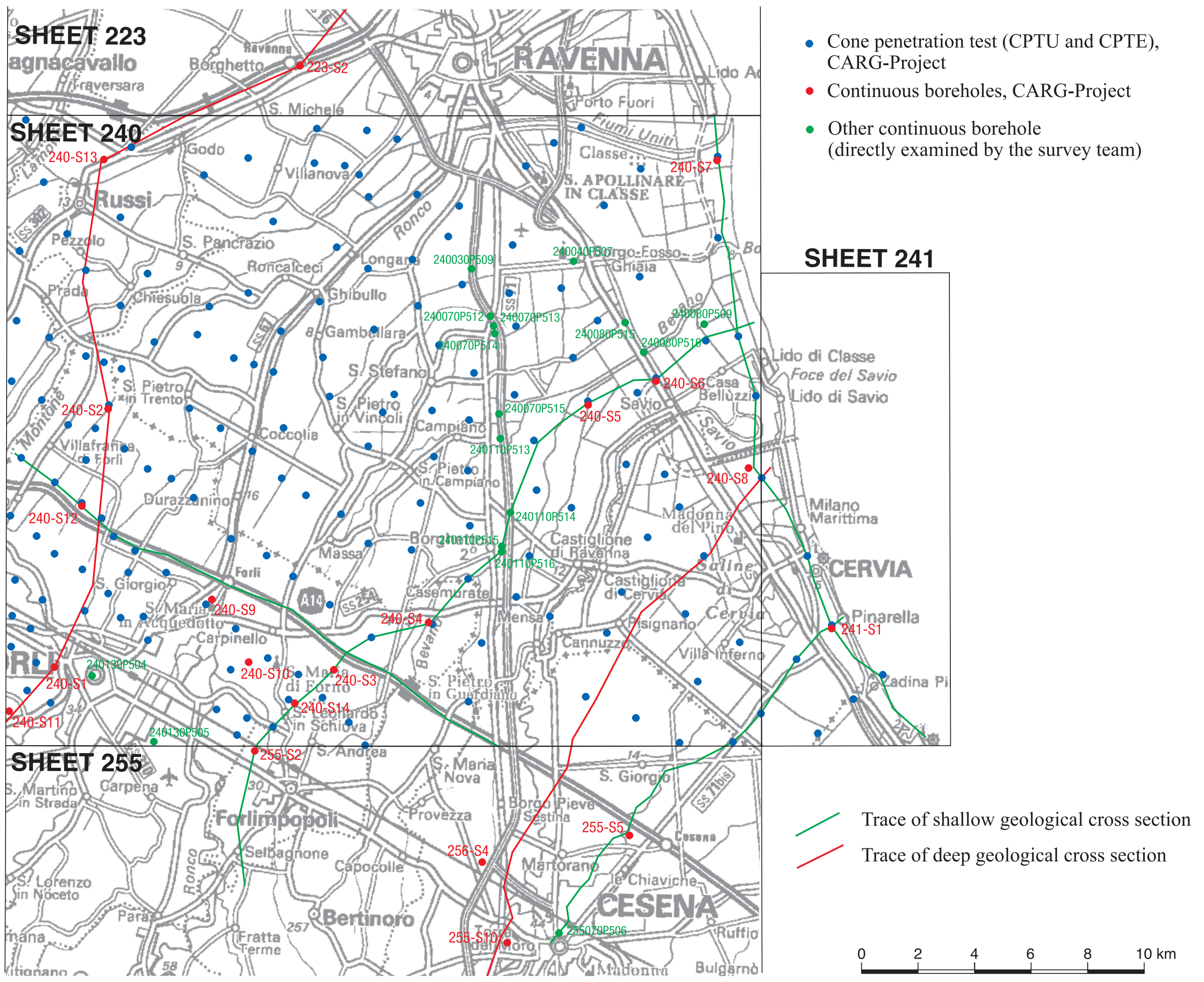


Fig. 11 - *Location of the geognostic investigations conducted by the Emilia-Romagna Geological Survey, as well as of borehole data, which was directly examined by the survey team and collected from public and private sources. Some schematic outlines of subsurface geologic cross-sections and other borehole data from the immediately surrounding map sheets are also shown.*

data checks using automatic self-tests.

3) re-organization of the stored data using data processing software, and development of specific software needed to ease the analysis of key stratigraphic data.

The mean density of the geognostic data available in the study area is 6.3 data points per km², displaying greater density near urban areas and lower density in the surrounding agricultural areas.

Fig. 12 - *The surveying crew of the subsurface geological map conduct high-resolution sedimentary and stratigraphic analyses on core sediments retrieved from borehole 240-S2 (to a depth of 170 m), in order to reconstruct the stratigraphic and paleoenvironmental evolution of the Forlì plain over the last 400-500 thousands of years.*

Studies based upon boreholes continue to comprise a unique means of directly observing subsurface deposits, and are therefore of fundamental importance for their characterization (Fig. 11). The cores that are retrieved from the boreholes are analysed in great detail (at the centimetre scale - Figs. 12 and 13) using established sedimentologic-stratigraphic methods that allow the characterisation of facies, facies associations and their implied depositional environments, and even the definition or recognition of specific stratigraphic units.

The cores may also be sampled for specific analyses (radiocarbon dating, paleontological, palynological, and petrographic analyses, etc.) which provide indispensable information when verifying the proposed stratigraphic correlations.

This is why, for the purposes of this work, it was decided to realize and study fourteen boreholes of depths varying between 40 and 170 meters. Additional observations and analyses were carried out on those cores provided to the project by other public and private sources.

Amongst the new geognostic investigations realized for the project are also 172 cone penetration tests, almost all of which were carried out with pore-pressure measurements (piezocone tests or CPTU), reaching maximum depths of 36 meters. The cost of CPTU tests is significantly lower than that for continuous core boreholes, therefore these penetrometer studies were used extensively to obtain greater amounts of geognostic information, especially in regions for which little data is available.

CPTU data, calibrated in part with the information from nearby continuous boreholes, were used to detect the lithologies in the study area, contributing significantly to the 3D reconstruction of the subsurface deposits.

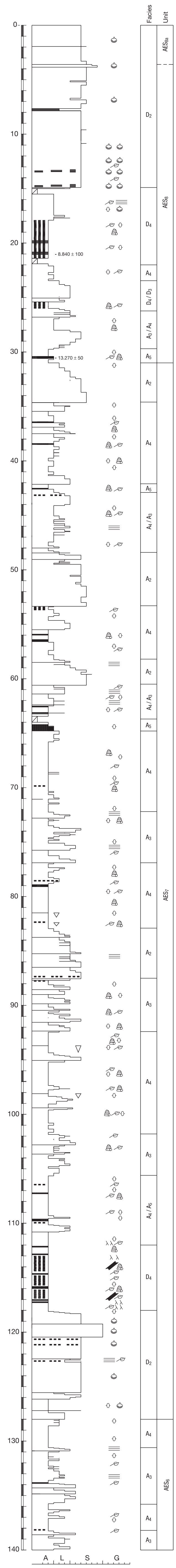


Fig. 13 - *Stratigraphy from borehole 240-S8, including downcore grain-size analyses, sedimentary structures and radiocarbon dates. On the sides the associated facies and stratigraphyc units are shown.*

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