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Sedimentology, stratigraphic architecture and preliminary hydrostratigraphy of the Metaponto coastal-plain subsurface (Southern Italy)

Sedimentologia, architettura stratigrafica e idrostratigrafia preliminare del sottosuolo della piana costiera metapontina (Italia meridionale)

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ABSTRACT - The stratigraphic and hydrostratigraphic architecture of the Metaponto coastal plain subsurface (Southern Italy) was obtained from a data set composed of twenty continuously cored boreholes and over 350 drills, 50-120 m deep. In particular, sedimentological, biostratigraphical and chronostratigraphical analyses were performed on four continuously cored boreholes. Further more,some profiles, parallel and transversal to the present-day shoreline, permitted correlations between the stratigraphic logs obtained from all boreholes. The overall obtained data allowed the distinction of four types of depositional systems of Middle Pleistocene-Holocene age, including eight facies associations in turn subdivided in seventeen lithofacies.

Thanks to the recognition of two discontinuity surfaces of regional extent, the late Quaternary Metaponto buried succession may be subdivided into three units, each made up of different lithofacies. The middle-upper (?) Pleistocene lower unit ("substratum"), at least 60 m thick, is made up of silty and clayey-silty shelf-transition deposits passing upward and landward to sandy and sandy-gravelly deltaic deposits. The upper boundary of this lower unit is represented by a very irregular surface which locally deepens up to 90 m and this can be related to incised valleys formed during time spans of sub-aerial exposition induced by relative fallings and lowstands of the sea level. These "palaeovalleys", mainly filled by estuarine deposits, developed during two time spans comprised between the Marine Isotope Stage 4 (MIS 4) and the Last Glacial Maximum (LGM). The middle unit, called unit MP1 (Metaponto Plain 1), lying on the substratum discontinuously, is late Pleistocene in age and has a thickness of 15 m. However, this thickness reaches 60 m when a palaeovalley is filled. The unit MP1 is composed in the first case of sandy-gravelly fluvial and/or deltaic deposits; in the second case, the paleovalley is filled with silty-sandy estuarine to deltaic deposits. The upper unit, called unit MP2 (Metaponto Plain 2), lying either on the unit MP1 or on the substratum, is late Pleistocene and Holocene in age. The unit MP2 has a thickness of 30 m. However, when palaeovalleys are filled, thickness may reach 90 m. In the first case it is made up of silty-clay offshore-transition deposits passing upward to silty-sandy deltaic deposits and then finally to sandy fluvial deposits; in the second case, the palaeovalley fill, is composed of sandy-gravelly fluvial deposits passing upward to silty and sandy estuarine deposits.

This stratigraphic frame permits us to sketch the hydrostratigraphic picture of the buried Metaponto succession, where units MP1 and MP2, as a whole, correspond to a multilayered aquifer lying on the clayey substratum. Inside each incised valley, this aquifer appears to be laterally confined and vertically partitioned where permeable deposits alternate with low-permeable ones.

KEY WORDS: hydrogeology, Metaponto Plain, Quaternary, Southern Italy, stratigraphy.

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RIASSUNTO – Al fine di proporre una prima interpretazione idrostratigrafica dei depositi sepolti della piana costiera metapontina (Golfo di Taranto - Italia meridionale), un'area che ricade nell'estrema propaggine meridionale della Fossa bradanica, sono stati analizzati venti sondaggi a carotaggio continuo aventi profondità variabili da 50 m fino ad un massimo di 120 m. Lungo quattro carote dei venti sondaggi (quelle per le quali è stata possibile la conservazione presso il Dipartimento di Geologia e Geofisica dell'Università di Bari) sono state condotte analisi di facies di dettaglio ed analisi biostratigrafiche e cronostratigrafiche (datazioni con il metodo del radiocarbonio) di tipo mirato su campioni ritenuti utili. Altre informazioni di carattere esclusivamente litostratigrafico provenienti da oltre 350 sondaggi svolti dall'Ente Irrigazione della Regione Basilicata, di cui non è stato possibile analizzare le carote (ormai perdute) ma solo reinterpretare le stratigrafie di perforazione, ed informazioni indirette di tipo geofisico (*gamma ray logs*) hanno completato il *data set* di partenza. Il riconoscimento di due superfici di discontinuità di significato regionale, ottenuto tramite correlazioni stratigrafiche effettuate lungo profili sia paralleli che trasversali alla linea di costa attuale, ha permesso di suddividere la successione sepolta dell'area metapontina in tre unità sovrapposte, di cui solo la più alta affiorante, ognuna delle quali composta da più litofacies. Il dettagliato studio sui caratteri di facies dei depositi attraversati, sui rapporti latero-verticali delle stesse facies e sull'organizzazione stratigrafica delle loro associazioni ha permesso di distinguere all'interno dei depositi analizzati quattro tipi di sistemi deposizionali: sistema fluviale, sistema deltizio dominato dalle onde, sistema estuarino dominato dalle onde, e sistema di transizione alla piattaforma. Depositi riferibili ad uno o più di tali sistemi costituiscono ognuna delle tre unità, per cui tipi litologici simili, a seconda della loro posizione rispetto alle superfici di discontinutià regionale, possono essere ricondotti ad unità differenti.

L'unità inferiore è stata incontrata a partire da una profondità minima di almeno 40 m sotto il livello del mare; costituisce il substrato della successione attraversata dai sondaggi ed è stata perforata per almeno 60 m senza che la base sia stata raggiunta. Tale unità è costituita da depositi prevalentemente siltosi e siltoso-argillosi di ambienti riferiti a sistemi di transizione alla piattaforma, passanti verso terra e verso l'alto a depositi sabbiosi e sabbioso-ghiaiosi di ambienti riferiti a sistemi deltizi dominati dalle onde. Da considerazioni di carattere geologico regionale, l'unità viene attribuita al Pleistocene medio e, dubitativamente, superiore; inoltre, la parte siltoso-argillosa dell'unità può essere considerata come la porzione più recente della formazione delle argille subappennine, facente parte del ciclo di riempimento della Fossa bradanica. Il tetto dell'unità inferiore è rappresentato da una superficie molto irregolare ed articolata, localmente caratterizzata da bruschi approfondimenti che vengono riferiti ad incisioni vallive prodottesi in intervalli di tempo di esposizione subaerea dell'area e correlati a fasi di caduta e stazionamento basso del livello relativo del mare. Il loro riempimento sarebbe avvenuto prevalentemente ad opera di sistemi deposizionali estuarini dominati dalle onde sviluppatisi durante intervalli di tempo di risommersione dell'area correlati a fasi di risalita del livello relativo del mare. Un primo ciclo di caduta e risalita relativa del livello del mare, riferito ad un intervallo di tempo compreso fra il MIS 4 (*Marine Isotope Stage* 4) e il LGM (*Last Glacial Maximum*) e quindi al Pleistocene superiore, avrebbe permesso prima lo sviluppo e successivamente l'erosione al tetto dell'unità intermedia, definita "unità MP1" (*Metaponto Plain* 1). Questa costituisce un corpo discontinuo e a geometria irregolare il cui tetto può essere riconosciuto ad una profondità di circa 30 m. L'unità MP1 presenta uno spessore di 15 m che aumenta bruscamente fino ad un massimo di 60 m dove riempie una paleovalle; nel primo caso si tratta di depositi sabbioso ghiaiosi di ambienti riferiti a sistemi fluviali e/o deltizi, nel secondo caso di depositi siltoso-sabbiosi di ambienti riferiti a sistemi estuarini passanti verso l'alto a depositi siltoso-sabbiosi di ambienti riferiti a sistemi deltizi. Un secondo ciclo di caduta e risalita relativa del livello del mare avrebbe determinato prima l'incisione di una nuova serie di valli fluviali su entrambe le unità precedenti e successivamente il loro riempimento da parte di depositi di ambienti riferiti a sistemi estuarini; il colmamento delle valli sarebbe stato seguito dall'aggradazione di depositi siltoso-argillosi di ambienti riferiti a sistemi di transizione alla piattaforma che passano verso l'alto a depositi siltoso-sabbiosi di ambienti riferiti a sistemi deltizi ed infine a depositi sabbiosi di ambienti riferiti a sistemi fluviali, questi ultimi costituenti l'attuale piana metapontina. L'insieme di questi depositi costituisce l'unità superiore, definita "unità MP2" (*Metaponto Plain* 2) e riferita ad un intervallo di tempo compreso fra il LGM e l'attuale (parte alta del Pleistocene superiore e Olocene). A causa della base irregolare l'unità MP2 mostra spessori variabili da 30 m fino ad un massimo di 90 m nei riempimenti delle paleovalli.

I caratteri stratigrafici riconosciuti e le caratteristiche di facies riscontrate permettono di considerare i depositi siltosi e siltoso-argillosi dell'unità più bassa, cioè quelli riferiti alla formazione delle argille subappennine, come il substrato dei depositi del sottosuolo della piana metapontina. La superficie di tetto di tale substrato, articolata dalla presenza delle profonde paleoincisioni vallive, corrisponde all'acquitardo di un unico acquifero multistrato ospitato nelle due unità stratigraficamente sovrastanti il substrato. Alla luce dell'architettura stratigrafica riconosciuta nelle due unità sovrastanti il substrato, nei riempimenti delle incisioni vallive l'acquifero si approfondisce ed è confinato lateralmente dai depositi del substrato che costituivano i fianchi delle paleovalli successivamente riempite. Verticalmente l'acquifero risulta partizionato, con falde in pressione presenti nei corpi più porosi ospitati nel riempimento delle paleovalli e falde freatiche, non confinate lateralmente, nei corpi porosi ospitati nella porzione più alta della successione che caratterizza il sottosuolo della piana metapontina.

PAROLE CHIAVE: idrogeologia, Italia Meridionale, Piana di Metaponto, Quaternario, stratigrafia.

1. - INTRODUCTION

To suggest correct land-uses and management of present-day coastal and alluvial plains it is necessary to continuously increase the knowledge regarding the hydrogeologic set-up of sedimentary successions located below the topographic surface of these plains. Therefore, both detailed data regarding subsurface stratigraphy as well as models of spatial distributions of analysed facies are needed. However, these kinds of information cannot be obtained without the knowledge of both sedimentary dynamics of depositional systems and their response to relative sea-level/base-level changes.

Thanks to data interpretation of several cores and following the above outlined approach, this paper represents the first attempt to detail through a sequence-stratigraphy frame the hydrogeologic structure of the buried late Pleistocene to Holocene succession of the Metaponto coastal area (Taranto Gulf, Southern Italy). Interpretation of stratigraphic and sedimentological features allowed us to suggest 2D geometric reconstructions of facies distribution and stratigraphic architectures of late Quaternary buried bodies. This may represent the starting point for a further, more detailed and better constrained picture of the hydrogeologic structure and so for better aquifer-management.

2. - GEOLOGICAL SETTING

The studied succession lies below the Metaponto coastal plain (fig. 1a, b), a wide and flat area facing the Ionian Sea in the Taranto Gulf (Southern Italy). The elevation of this plain reaches no more than 15 m above sea level. In this area, five main rivers (from the south to the north: Sinni, Agri, Cavone, Basento, and Bradano rivers – fig. 1b) run more or less parallel to each other before reaching the shoreline. Regionally, the Metaponto coastal plain represents the most recent exposed sector of the Southern Apenninic foredeep (the Bradanic Trough) (fig. 1a), a foreland basin that, at least since middle Pleistocene times, is in uplift (CIARANFI *et alii*, 1983; DOGLIONI *et alii*, 1994; 1996). Inland, this active uplift allowed us to observe stratigraphic and sedimentological features of the upper part of the infill succession of the Bradanic Trough. The outcropping part of this succession is made up of lower and middle Pleistocene offshore silty clays (Argille subappennine formation) (CIARANFI *et alii*, 1996) followed by coarse-grained coastal and continental deposits known as "regressive coastal deposits of the Bradanic Trough" (PIERI *et alii*, 1996). These regressive deposits diachronously developed onto the Argille subappennine formation (TROPEANO *et alii*, 2002), forming the well-known staircase of marine-terraced deposits of the Metaponto area (*i.e.* CILUMBRIELLO *et alii*, 2008, and references therein), in the southernmost sector of the Bradanic Trough. Studies about the Metaponto coastal plain, starting from COTECCHIA & MAGRI (1967), mostly concerned the geomorphological features or focused on the development of a narrow litoral strip facing the sea (COTECCHIA *et alii*, 1971; COCCO *et alii*, 1975; BONORA *et alii*, 2002; among others). Only recently, as regards the sedimentological characters of the whole plain, lithologies and other facies features of the outcropping deposits were mapped in detail and referred to environments belonging mainly to alluvial or delta/beach systems (PESCATORE *et alii*, 2009).

As regards the buried succession, firstly it was described by VEZZANI (1967) as being made up of post-Tyrrhenian siliciclastic deposits, up to 40 m thick, overlying Calabrian clays (the Argille subap-

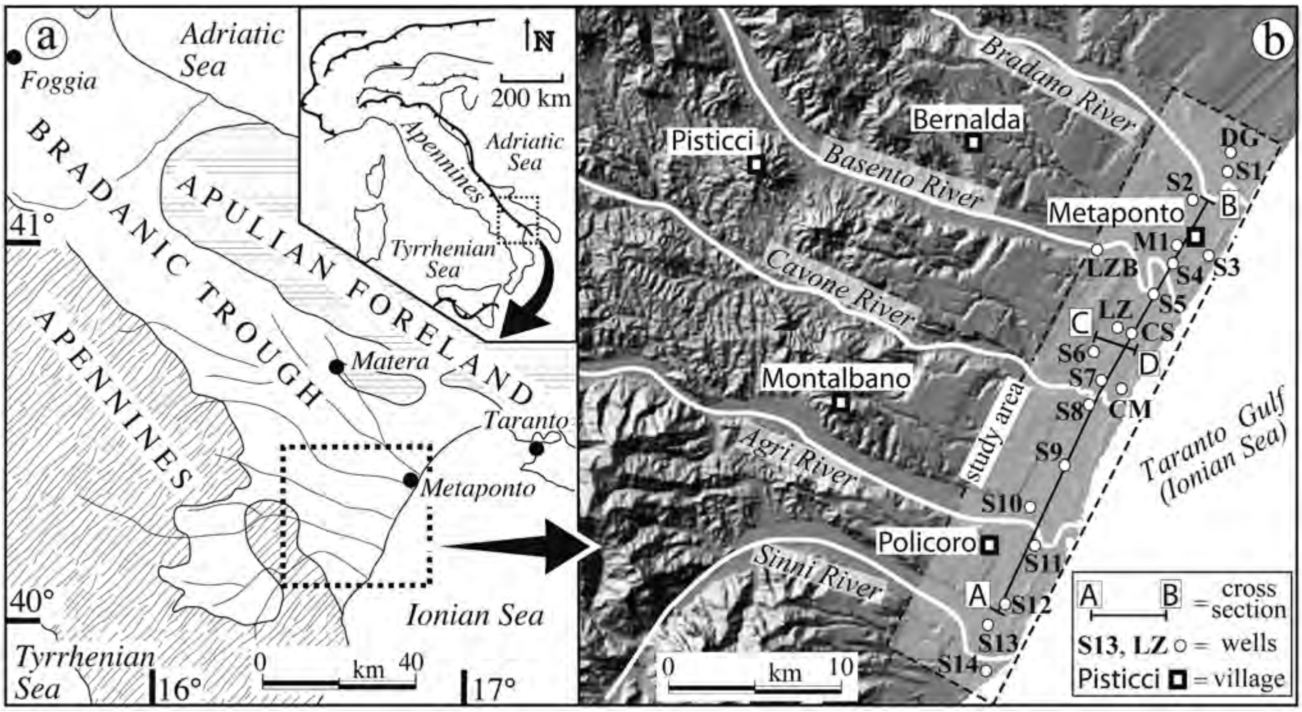

Fig. 1 - a) Schematic geological map of the Southern Italy; b) study area with location of the wells analyzed in this work and trace of cross-sections in figures 4 and 5.
– *a) Carta geologica schematica dell'Italia meridionale; b) area di studio con ubicazione dei sondaggi analizzati in questo lavoro e traccia delle sezioni geologiche nelle figure 4 e 5.*

pennine formation). Later, COTECCHIA *et alii* (1969) obtained a ^{14}C age of 11.700±160 years BP at about 50 m of depth below the Sinni river (fig. 1b), whilst BOENZI *et alii* (1987) suggested the age of the upper part of the buried succession of the Metaponto plain, at about 3 m of depth, thanks to archaeological remains dated between the 7th and the 3rd century BC.

As regards the stratigraphy of the buried succession, thanks to some wells and following a sequence stratigraphic approach, CAPRETTO (2003) recognized the Holocene Transgressive Systems Tracts (TST), below, and the Highstand Systems Tracts (HST), above, in a 50 m thick succession. In the same year, POLEMIO *et alii* (2003a), after a preliminary study of POLEMIO & RICCHETTI (1991) and thanks to a data set of more than one thousand boreholes, proposed a schematic geolithological 2D view of the buried deposits of the Metaponto coastal area. According to POLEMIO *et alii* (2003a), four units, each of them displaying different thicknesses moving either along dip or along strike, characterize the Metaponto subsurface. The upper unit is made up of clays, from a few centimetres up to 10 m thick. The second unit is made up of gravelly sands with thin silty clayey and clayey layers; this unit, whose bottom may reach 45-50 m of depth, is characterized by a variable thickness. The third unit, often only touched by drills, consists of silty clays and clays whose drilled thickness may reach up to over 30 m. The fourth unit, rarely reached by drilling, consists of either fine- or coarse-grained grey sands. From a hydrogeologic point of view the same Authors recognized in the plain two different types of aquifers: one type encloses aquifers constituted by alluvial deposits of present-day rivers; the other type of aquifer is a coastal multilayered one and corresponds to the second unit of the coastal plain. According to POLEMIO *et alii* (2003b), this coastal aquifer is laterally widespread but its transversal continuity is partially reduced by the deep riverbeds of the different rivers flowing into the Ionian Sea.

Later, SPILOTRO (2004), proposing a simplified 2D stratigraphic reconstruction of the buried Metaponto succession, provided a different interpretation of the depth and size of the multilayered aquifer, whose lower boundary corresponds to an erosional profile cutting a "basement" made up of "blue clays". According to this Author, below the present-day shoreline and in correspondence to present-day river mouths, this boundary deepens at about 100 m below the sea level, recording the base level reached by rivers during the Last-Glacial Maximum (LGM) and so the coastal multilayered aquifer of the Metaponto plain comprises the sedimentary fill of these paleovalleys.

A more detailed stratigraphic interpretation of the subsurface of Metaponto coastal plain was recently proposed by PESCATORE *et alii* (2009). The authors drew some geological sections normal to the present-day shoreline and located away from paleovalleys axes; they subdivide the buried succession in three units which, from the bottom to the top, are: a middle and upper Pleistocene first unit, which represents the substratum and corresponds to the Argille subappennine formation passing landward to sandy and gravelly sandy deposits; an upper Pleistocene second unit, bounded by unconformities and which represents an up to 20 m thick buried coarse-grained coastal wedge, and an upper Pleistocene and Holocene third unit, which erosionally overlies both the previous units and is made up of a coarse-grained coastal wedge passing seaward to shelf-transition deposits up to about 50 m thick.

3. - METHODS AND DATA SET

The study of subsurface of alluvial and/or coastal plains needs many integrated data coming from different methodological approaches ranging from core-drilling to seismic analysis and well logs (spontaneous potential logs, gamma ray logs and so on). Moreover, according to AMOROSI (2006), this kind of study requires experience and expertise, since both a good facies reading and the application of sequence stratigraphy may lead to suggest correct 3D interpretations also from either random or apparently ambiguous data.

As regards the buried succession of the Metaponto coastal plain the used data set consists of: i) detailed stratigraphies and sedimentological data derived from four continuously cored boreholes (CS, LZ, CM, LZB) (figs. 1b, 2 and 3) with depths varying from about 50 m up to 120 m. These cores were stored in the "Dipartimento di Geologia e Geofisica" of Bari University (Italy); ii) core stratigraphy of other sixteen continuously cored boreholes reaching a maximum depth of about 120 m (M1, DG, S1-S14) (fig. 1b); samples and some stratigraphic/sedimentological data were collected during drilling even though the cores could not be stored; iii) gamma-logs obtained from several of the studied wells; iv) absolute age on 6 samples represented by valves of marine invertebrates and by organic material (^{14}C radiocarbon uncalibrated dates performed at CEDAD, University of Lecce, Italy); v) palaeoecology and biostratigraphy obtained by macro- and micropaleontological analysis from samples coming both from stored and not stored cores; vi) a simplified stratigraphic description derived from hundreds of wells (num-

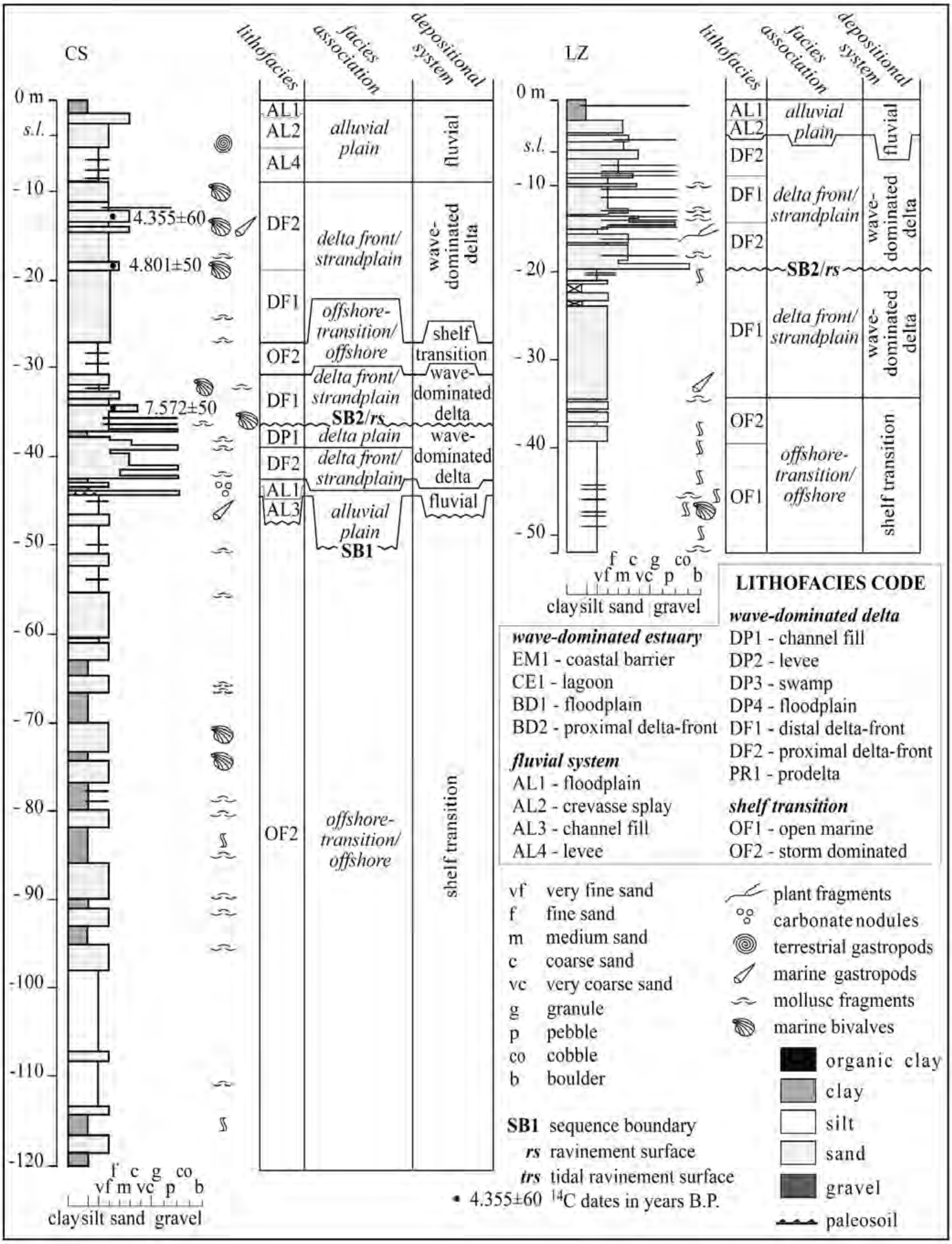

Fig. 2 – Stratigraphy and interpretation of facies associations of cores CS and LZ.
– Stratigrafia delle carote di sondaggio CS e LZ con indicazione dei principali caratteri di facies.

bered from 1010 to 1367) drilled at different times by various regional public bodies.

In order to calibrate the stratigraphic data coming from the complete wells set and to propose facies interpretation of each continuously cored borehole, a detailed facies analysis was performed on the four stored cores; this analysis was subsequently used to interpret data coming from the other wells. 2D correlations along both dip and strike with respect to the present-day shoreline, which may be considered more or less parallel to late Quaternary paleoshorelines, also contributed to provide a stratigraphic interpretation of data. Finally, sequence stratigraphy was used to interpret the stacking pattern of the middle Pleistocene to Holocene buried succession of the Metaponto coastal plain.

4. - DEPOSITIONAL SYSTEMS AND FACIES ASSOCIATIONS

In order to suggest a stratigraphic interpretation of the succession drilled in the Metaponto coastal plain, our study started with a careful description of facies features of the four stored cores from the wells CS, LZ, CM and LZB (figs. 1, 2 and 3). Facies were differentiated according to the following features: thickness, lithology, grain size, texture, sedimentary structures, kind of boundary, fossil content. Facies analysis allowed us to recognize several lithofacies (whose vertical relationships result to be either gradational, sharp or erosional), and were used to refine data coming from other 16 wells (M1, DG, and S1-S14) (figs. 1b and 5). Accordingly, the buried stratigraphic succession of the Metaponto coastal plain results basically made up of siliciclastic lithofacies, whose grain size varies from silty clay to gravel and facies associations may be referred to depositional environments varying from fully marine to continental. Previous similar works performed along Italian coastal plains and some concepts deriving from sequence stratigraphy helped us to better constrain our environmental and stratigraphic interpretations. Present-day Italian coastal plains developed after the sea-level rise which followed the Last-Glacial Maximum (LGM), and, before this rise, continental shelves were exposed and subjected to subaerial and fluvial erosion (TORTORA *et alii*, 2001). Exposed shelves were incised by deep river-valleys in response to up to 100 m of sea level fall linked to the LGM, and this morphology, now buried below a thick sedimentary succession, was recognized below both Tyrrhenian and Adriatic coastal plains (BELLOTTI *et alii*, 1994, 1995; AGUZZI *et alii*, 2005; AMOROSI *et alii*, 2008a; 2008b; MILLI *et alii*, 2008), and also below the Metaponto coastal plain (SPILOTRO, 2004). The post-LGM succession began to develop soon after the onset of the deglaciation phase, when a sea-level rise with a growth rate higher than the rate of sediment supply took place (*i.e.* PIRAZZOLI, 1997). According to sequence-stratigraphy principles and studies, river-valleys deeply cut shelves which become exposed as a consequence of a lowering of the sea level; during transgression due to sea-level rise following this phase of sea-level fall and low-stand, valleys are flooded by the sea (POSAMENTIER & VAIL, 1988) and mainly estuarine systems develop inside previous incisions (DALRYMPLE *et alii*, 1992; ZAITLIN *et alii*, 1994). When, during rise, the sea level reaches margins of flooded valleys, paleointerfluve areas are drowned and shelf environments develop, whereas, when sea level decreases and stops rising, up to a relative still stand, coastal plain progradation takes place on the previous shelf deposits and aggrading to prograding fluvial and wave-dominated delta depositional systems develop (POSAMENTIER & VAIL, 1988). According to these depositional steps, several facies, belonging to different depositional systems, spanning from shelf, delta, estuarine and alluvial systems, should be encountered during drilling of the Metaponto coastal plain. In accordance with this idea, our data demonstrate that the buried stratigraphic succession of the Metaponto coastal plain comprises facies associations belonging to these depositional systems. In order to avoid repetitions and to make the illustration of the buried succession easier, the depositional systems are described first; interpretation of facies and facies associations previously made following the main literature regarding facies analysis and its application to sequence stratigraphy (*i.e.* VAN WAGONER *et alii*, 1990; WALKER & JAMES, 1992; READING, 1996; POSAMENTIER & ALLEN, 1999; CATUNENANU, 2006; POSAMENTIER & WALKER, 2006; among others) is proposed inside the description of each depositional system, whose definition was obtained also in accordance with logs correlations. The different systems are described from continental to fully marine ones.

4.1. - FLUVIAL SYSTEM

As suggested by POSAMENTIER & VAIL (1988), along basin margins recording sea-level changes, fluvial deposition may be described as "widespread" or "incised-valley fill". The first type characterizes deposition during eustatic highstand of the sea level, when progradation rather than aggradation takes place. Deposits of these fluvial systems show a good lateral continuity and often are linked to meandering rivers. On the contrary, the second type of fluvial deposition basically develops during late lowstand and early transgression of eustatic sea-level variations, and characterizes both the lowermost and the landward parts of incised-valley fills (DARLIMPLE *et alii*, 1992; ZAITLIN *et alii*, 1994). Deposits of these fluvial systems are confined within incised-valleys, show an along dip (along incised valley) continuity, and may be linked either to meandering or braided rivers.

Without making differentiations between the two types of fluvial deposition, four lithofacies (AL1, AL2, AL3 and AL4) (fig. 2 and well log LZB in fig. 3), often in relationship to each other and belonging to alluvial plain facies association, were recognized in the drilled deposits.

Lithofacies AL1 is made up of clayey silts and/or massive grey clays rich in organic material (plant fragments). These deposits form up to 10 m thick successions. Yellowish and reddish-brown alteration-colours and pedogenic structures, such as carbonate nodules, often characterize and pervade these deposits. Macropaleontological content is represented by terrestrial gastropods, such as *Helicidae*, while micropaleontological content is formed by ostracods and abundant algae (*Characea* oogonia). This monotonous succession of clays and clayey silts, showing features that testify to phases of subaerial exposure, is interpreted as the result of the deposition from suspension in low-energy subaqueous depositional environments such as ponds or abandoned channels. For these reasons, this lithofacies can be related to floodplain deposits. Lithofacies AL2 consists of sandy silts, which form lenticular bodies up to about 5 m thick, that locally show a coarsening-upward trend, from very fine to medium sands. This lithofacies displays the same macro- and micropaleontological content observed within lithofacies AL1. Based on geometry, macro- and micropaleontological content and coarsening upward tendencies, this lithofacies can be referred to crevasse splay deposits. Lithofacies AL3 is made up of gravels, gravelly sands and sands, which compose erosionally based successions whose thickness varies from 1 m to about 3 m (well log LZB in figure 3, where lithofacies AL3 repeats itself forming an about 10 m thick succession). These deposits form narrow and continuous bodies, mainly elongated perpendicularly to the paleoshoreline. Thicker successions show a fining-upward trend and basically are distinguished in two parts: the lower part is made up of clast-supported and poorly-sorted gravels with angular clasts, composed either of small pebbles and/or pebbles/cobbles; the upper part is mainly made up of poorly sorted and massive sands containing rare and a few decimetres thick gravelly layers. A few decimetres thick dark clays cap the succession. Pedogenic structures, such as carbonate nodules, also characterize this lithofacies. Moreover, terrestrial small gastropods, such as *Helicidae*, were observed. The geometry, texture, fining-upward trend, paleontological content, and erosional base of AL3 lithofacies are characteristics of fluvial channel-fill deposits. The lithofacies AL4 is made up of rhythmical alternation of silty sands and silty clay layers, a few centimetres thick, and commonly shows a brownish colouring. These facies features permit us to refer the lithofacies AL4 to levee deposits.

4.2. - WAVE-DOMINATED DELTA SYSTEM

Along microtidal coasts fed by river sedimentary discharge, where waves energy exceeds river-capacity to build a prominent delta, wave-dominated delta systems develop. These depositional systems consist of a set of laterally continuous beach ridges (delta front/strandplain), landward passing to a delta plain (simulating a widespread fluvial system) and seaward passing to prodelta settings. According to sequence stratigraphy concepts, wave-dominated delta systems mainly develop and aggrade during slow rises of the sea level, for example during eustatic high stands (POSAMENTIER & VAIL, 1988).

Three facies associations belonging to wave-dominated delta systems were recognized within drilled deposits: delta plain, delta front/strandplain and prodelta facies associations.

The delta plain facies association is composed of four lithofacies: DP1, DP2, DP3 and DP4 (well log CS in fig. 2 and fig. 3). Lithofacies DP1 is characterized by up to 4 m thick sandy-silty deposits, showing an erosional basal surface coupled with a basal channel lag and a fining-upward trend. These deposits generally form isolated bodies and this involves a scanty correlation with the adjacent cores. Based on geometry, grain size tendencies and erosional base, this lithofacies can be attributed to channel-fill deposits. Lithofacies DP2 is made up of a few centimetres thick silty sands and silty clay layers, showing a rhythmical alternation, up to 4 m thick. Some layers show a yellow shading caused by subaerial alteration. Locally these deposits present a fining-upward trend. On the basis of facies features, this lithofacies can be referred to levee deposits. Lithofacies DP3 is basically made up of up to 50 cm thick intensively bioturbated dark clays with abundant plant fragments. These deposits are the result of sedimentation in stagnant environments and so are interpreted as swamp deposits. Lithofacies DP3 generally alternates with lithofacies DP4. The latter is made up of grey clays and silty clays which display characteristic yellow and brown colours, due to the presence of iron and manganese oxides, and form up to 6-7 m thick successions. These kinds of features can indicate floodplain deposits.

The delta front/strandplain facies association forms up to 25 m thick and laterally continuous bodies and consists of two major lithofacies: DF1 and DF2 (fig. 2 and well log CM in figure 3). Lithofacies DF1 is made up of about 15 m thick successions of well-sorted and thin laminated fine sands and silts with intercalations of very-fine sand layers, up to 1 m thick. Indeterminable shell fragments are abundant throughout this lithofacies. Based on these facies features, lithofacies DF1 is interpreted as the lower part of delta front/strandplain facies association and represents the distal delta front/lower shoreface deposits. Lithofacies DF2 is made up of up to about 10 m thick successions of fine sands with thin pebbly layers, passing upward to fine- to coarse-sands and pebbly sands. This lithofacies contains assemblages of marine molluscs, such as *Tellina* sp., *Spisula subtruncata*, *Chamelea gallina*, *Cerithium* sp. and *Fissidentalium rectum*, in addition to abundant indeterminable shell fragments (LA PERNA, 2010, *pers. comm.*). On the basis of sedimentary features and fossil content, the lithofacies DF2 can be referred to proximal delta front/upper shoreface deposits.

The micropaleontological content of samples coming from both distal delta front/lower shoreface (lithofacies DF1) and proximal delta-front/upper shoreface deposits (lithofacies DF2) is scanty: benthic foraminifers are mainly represented by relatively deep species (*Euuvigerina peregrina, E. mediterranea, Lenticulina* sp.) often included in Low-Oxygen Foraminiferal Assemblages (LOFA *sensu* BERNHARD & GUPTA, 1999); planktonic foraminifers are very scarce and reworked.

The prodelta facies association forms up to about 10 m thick successions whose thickness decreases moving landward. Within this facies association, one lithofacies (PR1) (well log CM in figure 3) was recognized and it is made up of rhythmic alternation of silts and very fine-grained sands.
Abundant marine molluscs, such as *Tellina* sp. and *Fissidentalium rectum*, besides indeterminate fragments of bivalves, scaphopods, serpulids, and gastropods, were found. The micropaleontological content includes foraminifera assemblages represented by *Ammonia beccarii, Elphidium macellum, Lachlanella sp., Pseudotriloculina oblonga, Textularia sp., Nonion sp., Sigmoilina schlumbergeri*. The described facies features, and macro-and micropaleontological content are typical of relatively deep, oxygen-poor and high-organic matter environments such as those of prodelta.

4.3. - WAVE-DOMINATED ESTUARY SYSTEM

This depositional system typifies flooded incised-valleys (BOYD *et alii*, 2006, and references therein) and related successions aggrade in these valleys during transgressions induced by eustatic sea-level rises following a main phase of relative sea-level fall and lowstand. Within this system three facies associations were recognized: bayhead delta, central estuary and estuary-mouth complex facies associations (according to settings standardized by DARLYMPLE *et alii*, 1992, and to terminology recently introduced by CATUNEANU, 2006). Also in the studied logs, sediments related to awave-dominated estuary system characterize incised-valley fill successions that can reach up to 65 m of thickness.

The bayhead-delta facies association forms up to about 10 m thick successions, and is represented by two lithofacies: BD1 and BD2 (well log LZB in fig. 3). Lithofacies BD1 is basically represented by up to about 9 m thick grey silty-clayey deposits, showing yellow and brown mottles, due to iron and manganese oxides and pedogenic phenomena. Moreover, these deposits contain abundant plant debris. These facies features allowed us to refer BD1 lithofacies to floodplain deposits. Lithofacies BD2 is made up of very fine and medium sandy deposits showing occasionally a coarsening upward trend. Remains of plants are present. These deposits form sandy bodies interpreted as delta front deposits.

The central estuary facies association is composed of up to about 20 m thick monotonous successions, within which only one lithofacies was recognized: CE1 (fig. 3). This lithofacies is made up of silts and organic clays with intercalations of thin (from a few centimetres to some decimetres) parallel-laminated sand layers. Paleontological analyses, performed on these deposits, show a highly bioclastic content which includes, besides foraminifers, ostreids, gastropods, echinoids, and *Ditrupa* sp., also fragments of bivalves, rare fragments of bryozoans and echinoids, and very rare fish teeth. Foraminiferal assemblage is dominated by *Ammonia beccarii*, *Elphidium crispum* and, less abundant, *Valvulineria bradyana*. The latter has been documented in LOFA and tolerates dysoxic conditions (MURRAY, 2006). *Ammonia beccarii* also belongs to the LOFA, and tolerates a wide range of salinity and temperature. Other *taxa*, such as Bolivinids and Buliminids, along with Textulariids and Nonionids, also indicate low-oxygen contents (BERNHARD & GUPTA, 1999); other observed species correspond to low-oxygen tolerant taxa, along with other forms typically from *Posidonia oceanica* meadows (*i.e. Pseudotriloculina/Triloculina* spp., *Quinqueloculina vulgaris, Lobatula lobatula, Textu-*

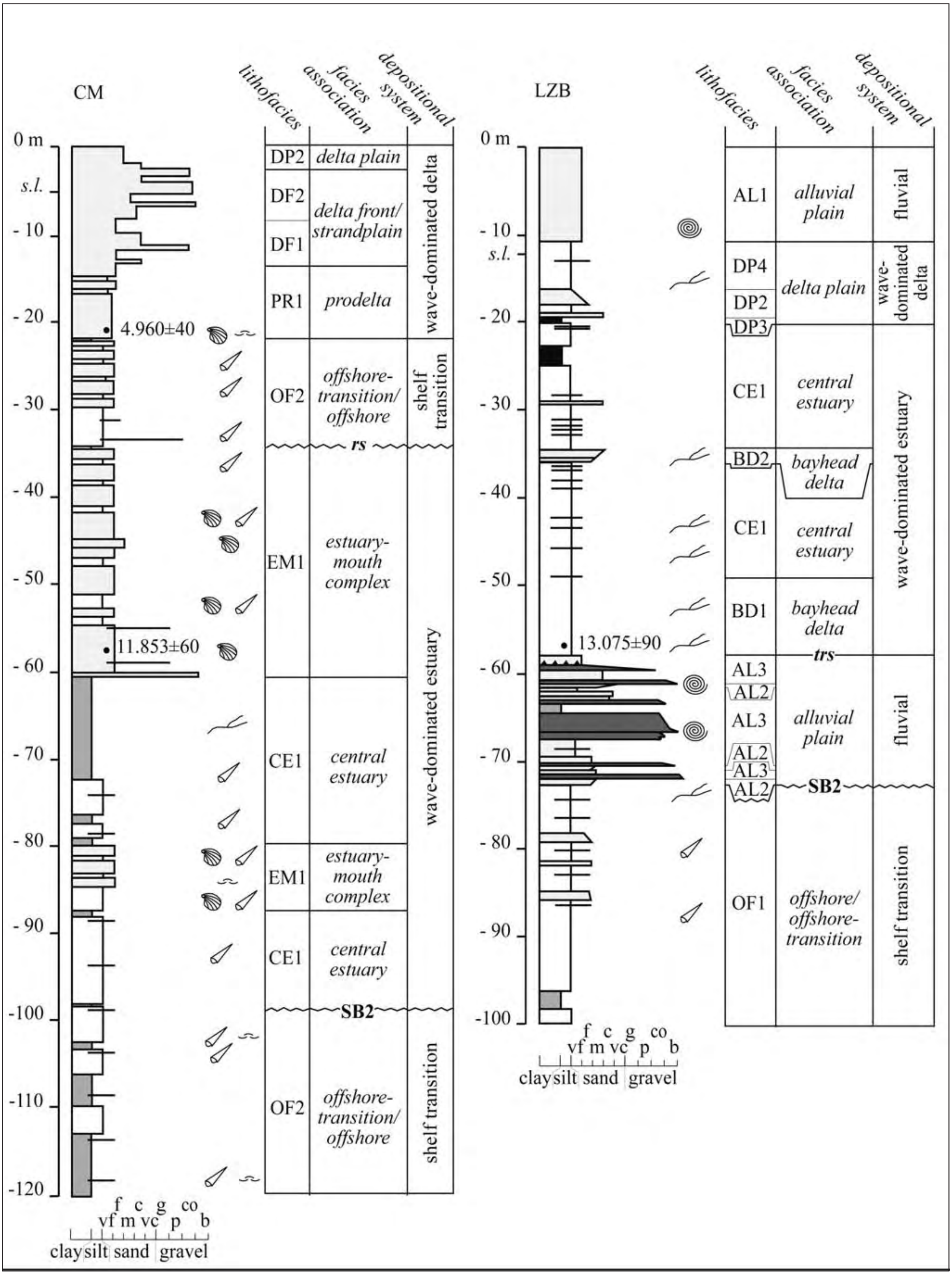

Fig. 3 - Stratigraphy and interpretation of facies associations of cores CM and LZB. Key as in figure 2.
– Stratigrafia delle carote di sondaggio CM e LZB con indicazione dei principali caratteri di facies. Per la legenda vedi figura 2.

laria gramen). Also *Elphidium crispum, Elphidium macellum* and Miliolids (*Pseudotriloculina trigonula*) and Textularids (*Textularia communis, Textularia gramen*) can be related to *Posidonia oceanica* meadows. Reworked planktonics are also present (genera *Globigerinoides* sp. and *Globigerina* sp.). Fine sediments, sedimentary structures, presence of organic matter and micropaleontological content are relative to low energy environments, such as lagoon deposits in estuarine context.

The estuary-mouth complex facies association forms up to over 25 m thick successions and is composed of one lithofacies: EM1 (fig. 3). This lithofacies is made up of silty sands to well-sorted and thinly laminated fine sands, with intercalation of silty layers. Locally, thinner pebbly layers can be observed. Many fragments of molluscs are present and among these, it is possible to recognize *Turritella communis*. These facies features and their location in the studied successions allowed us to refer EM1 lithofacies to a sandy barrier (coastal-barrier deposits) aggrading during short still-stands of the relative sea-level characterizing a major relative sea-level rise.

4.4. - SHELF-TRANSITION SYSTEM

Shelf-transition system corresponds to widespread settings located both seaward of clastic shorelines and below main wave-base level. According to sequence stratigraphy concepts, shelf deposits may be cyclically exposed and cut by rivers (incised valleys) during main eustatic sea-level falls and lowstands. In the studied successions, shelf-transition system deposits were diffusely drilled below suites of deposits belonging to the previously described depositional systems, but they also represent facies of shallow-marine settings located seaward of either wave-dominated delta systems or wave-dominated estuary systems.

The shelf-transition system forms laterally extensive and up to 75 m thick sedimentary bodies. One facies association was recognized (offshore transition/offshore facies association) and two lithofacies were distinguished (OF1 and OF2) (figs. 2 and 3). Lithofacies OF1 is made up of silty and clayey deposits, commonly constituted by massive strata, locally homogenized by an intense bioturbation. This lithofacies shows facies characteristics typical of open-marine deposits. Lithofacies OF2 is made up of an alternation of either beds or bedsets made up of silts, clays and very fine-grained sands. Silts and clays are massive or thinning laminated; the sands are very sorted and laminated, and are organized in layers forming up to 5 m thick bedsets bounded both at the base and top by erosional/sharp surfaces. Sands may contain very thin intercalations of grey silty clays. Marine macrofossils are abundant and commonly constitute assemblages of *Ditrupa aretina*, *Turritella communis*, and *Corbula gibba*. The characteristics of lithofacies OF2 are representative of deposits developing below the mean fairweather wave base when storm events cause the accumulation of sandy deposits inside silty and clay deposits which form, on the contrary, during fairweather conditions (storm-dominated deposits).

5 - STRATIGRAPHY OF CORES CS, LZ, CM AND LZB

5.1. - CORE CS

Core CS (fig. 2) was drilled about 2.5 km inland from the present-day shoreline (fig. 1b), starting from 4 m a.s.l., and reaching 120 m in length. According to the presence of two main erosional surfaces, the drilled stratigraphic succession shows a 75 m thick lower portion, made up of shelf-transition deposits, an 8 m thick middle portion made up of fluvial and wave-dominated delta deposits, and finally a 37 m thick upper portion, mainly composed of either wave-dominated delta or fluvial deposits (fig. 2).

The lower portion is characterized by very-fine sand, clay and silt offshore-transition/offshore deposits (storm-dominated lithofacies OF2). As regards the middle and upper portions, they form a vertical stack of two transgressive-regressive cycles. The first cycle, about 8 m thick, lies on an erosional surface and starts with clay, sand and gravel alluvial plain deposits (channel-fill lithofacies AL3 passing upward to floodplain lithofacies AL1). Sand and gravel deposits of delta front/strandplain (proximal delta front/upper shoreface lithofacies DF2) overlay with a sharp contact the alluvial plain unit; these lithofacies pass upwards to clay, sand and gravel deposits of the delta plain (channel-fill lithofacies DP1). The second cycle, about 37 m thick, opens with silt, sand and gravel delta front/strandplain deposits (distal delta front/lower shoreface lithofacies DF1) passing upward to silt and sand offshore-transition/offshore deposits (storm-dominated lithofacies OF2). The succession continues again with mainly sandy delta front/strandplain deposits (distal delta front/lower shoreface lithofacies DF1 passing upward to proximal delta front/upper shoreface lithofacies DF2) passing upward to clay, silt and sand alluvial plain deposits (levee, crevasse splay and floodplain respectively lithofacies AL4, AL2 and AL1).

Each cycle is bounded by important disconformity surfaces. The base of the first cycle (about 45 m of depth) is represented by a subaerial erosional surface, since fluvial deposits with paleosoils lie onto marine clays. Stratigraphic correlations with others cores (fig. 4) allowed us to interpret it as a sequence boundary (SB1 in figs. 2 and 4). The boundary between the first and the second cycle, located at about 37 m of depth, is represented by an erosional surface along which delta plain deposits below and delta front/strandplain deposits above come in contact (fig. 2). This contact records a ravinement process which occurred in the studied area, and, thanks to stratigraphic correlations with others cores, it is interpreted as being part of a sequence boundary locally reworked during a transgression (SB2/*rs* in figs 2 and 4).

Moreover, radiocarbon analyses were performed on mollusc samples coming from deposits of the second cycle. In particular, the samples yielded these results: a ^{14}C uncalibrated age of 7.572±50 years B.P. at 35 m core depth (sample C6), a ^{14}C uncalibrated age of 4.801±50 years B.P. at 19 m core depth (sample C3), and a ^{14}C uncalibrated age of 4.355±60 years B.P. at 13 m core depth (sample C2).

5.2. - Core LZ

Core LZ, 52 m long, was recovered about 3.5 km inland from the present-day shoreline (fig. 1b), starting from 6 m a.s.l. According to the presence of a main erosional surface the core LZ has been subdivided into two portions (fig. 2). The lower portion is 33 m thick and is made up of shelf-transition deposits passing upward to wave-dominated ones; the upper portion, 19 m thick, is composed of wave-dominated deposits passing upward to fluvial ones.

In particular, the lower portion is characterized by silt and very fine sand offshore-transition/offshore deposits (open-marine lithofacies OF1 and

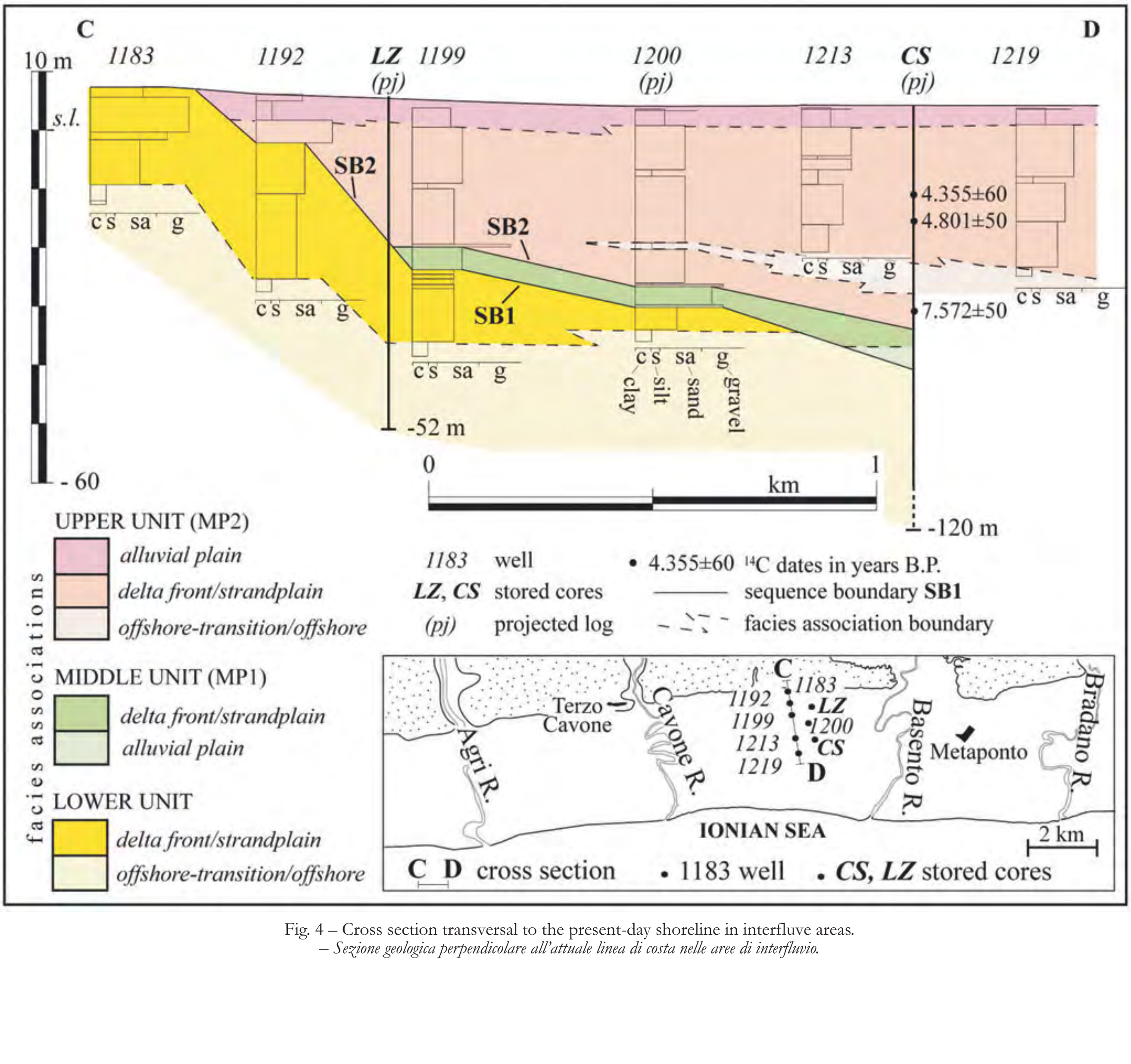

Fig. 4 – Cross section transversal to the present-day shoreline in interfluve areas.
– *Sezione geologica perpendicolare all'attuale linea di costa nelle aree di interfluvio.*

storm-dominated lithofacies OF2) passing to very fine sand delta front/strandplain deposits (distal delta front/lower shoreface lithofacies DF1). On these deposits lies the upper portion, consisting of a transgressive-regressive cycle. This cycle is formed mostly by very fine to medium sand and thin gravel delta front/strandplain deposits (proximal delta front/upper shoreface lithofacies DF2, distal delta front/lower shoreface lithofacies DF1, and finally lithofacies DF2 again) passing upward to fine sand and clay alluvial plain deposits (crevasse splay lithofacies AL2 and floodplain lithofacies AL1). The base of this cycle is characterized by an erosional surface overlain by a lag deposit, that can be interpreted as a ravinement surface (*rs*). Stratigraphic correlation with other cores (fig. 4) allowed us to interpret this surface as a part of a sequence boundary which was later and locally reworked by a transgression (SB2/*rs* in figures 2 and 4).

5.3. - Core CM

Core CM (fig. 3) was recovered about 920 m inland from the present-day shoreline (fig. 1b), starting from 5 m a.s.l and reaching 120 m in length. Thanks to the presence of a main erosional surface, the drilled succession may be subdivided into a lower part made up of shelf-transition deposits, and an upper part mainly made up of wave-dominated estuary passing upward to wave-dominated delta deposits (fig. 3).

The lower part of the core, about 21 m thick, is represented by clay, silt and very thin sand offshore-transition/offshore deposits (storm-dominated lithofacies OF2). The upper part of the drilled succession is instead characterized below by a vertical stack of transgressive-regressive cycles formed by alternating clay/silt central estuary deposits and silt/ very fine sand estuary-mouth complex deposits (respectively lagoon lithofacies CE1 and coastal barrier lithofacies EM1), about 64 m thick. Above these cycles develops a 35 m thick succession made up of: i) silt and very fine sand offshore-transition/offshore deposits (storm-dominated lithofacies OF2), ii) very fine sand prodelta deposits (lithofacies PR1), iii) sand to gravel delta front/strandplain deposits (distal delta front/lower shoreface lithofacies DF1 and proximal delta front/upper shoreface lithofacies DF2) and iv) fine sand delta plain deposits (levee lithofacies DP2).

Two important surfaces characterize the entire stratigraphic succession. The first surface, located at about 99 m of depth (fig. 3), represents a sharp and erosional contact, also recognized thanks to gamma log analyses. Along this surface offshore-transition/offshore deposits and central estuary deposits come into contact. Thanks to stratigraphic correlations with other cores, this surface is interpreted as a sequence boundary (SB2 in figures 3 and 5a). Moreover, two radiocarbon data were obtained from this core, since molluscs fragments sampled at 58 m (sample CM2 in figure 3) and at 21 m (sample CM1 in figure 3) of depth indicated respectively a ^{14}C uncalibrated age of 11.853±60 years B.P. and of 4.960±40 years BP. These ages allowed us to interpret the sequence boundary SB2 as related to the sea-level fall linked to the Last Glacial Maximum (LGM). Another significant surface is observed at about 35 m of depth (fig. 3). Along this surface estuary-mouth complex deposits and offshore-transition/offshore deposits come into contact. This surface is also underlined by the occurrence of scattered pebbles and is interpreted as a ravinement surface (*rs* in fig. 3).

5.4. - Core LZB

Core LZB, drilled about 6.8 km inland from the present-day shoreline (fig. 1b), starts at 12 m a.s.l. and reaches 100 m of length. The stratigraphic succession is composed of two portions, separated by a disconformity surface, located at about 72 m below the core head (fig. 3). The lower portion consists of about 26 m thick shelf-transition deposits, while the upper 74 m thick portion is made up of fluvial to wave-dominated estuary deposits, passing upwerd to wave-dominated delta, and finally to fluvial deposits again.

In particular, the lower portion displays silt, fine sand and clay offshore-transition/offshore deposits (open-marine lithofacies OF1). The upper portion forms a transgressive-regressive cycle lying on the previous deposits through an erosional surface. At the base, this cycle includes about 16 m thick alluvial plain deposits (gravel with sand and clay) represented by an alternation of crevasse splay deposits (lithofacies AL2) and fluvial-channel deposits (lithofacies AL3). These fluvial deposits are capped by a palaeosoil on which the upper part of the cycle, about 58 m thick, lies. The first 38 m are mainly comprised of a series of high-frequency transgressive-regressive cycles. These cycles are formed by alternation of silt and sand bayhead delta deposits (delta front lithofacies BD1 and floodplain lithofacies BD2) and silt and organic clay central estuary deposits (lagoon lithofacies CE1). The last 20 m are made up of silt and sand delta plain deposits (levee lithofacies DP2, swamp lithofacies DP3 and floodplain lithofacies DP4) passing upward to very fine sand alluvial plain deposits (floodplain lithofacies AL1).

Two important surfaces are recognizable along the succession LZB. A first surface is located at about 74 m of depth (fig. 3) and can be assigned to a subaerial erosional surface, since fluvial deposits lie onto marine clays. This surface is interpreted as a sequence boundary (SB2 in figure 3). At about 58 m of depth a second surface is observed; it represents a sharp surface along which alluvial plain deposit below and bayhead delta deposits above come into contact. This surface can be referred to a flooding surface (a tidal ravinement surface *sensu* ZAITLIN *et alii*, 1994) (*trs* in fig. 3).

Finally, an important radiocarbon age determination was obtained from this core, since plant fragments sampled at 58 m of depth (sample LZ5 in fig. 3) yielded a ^{14}C uncalibrated age of 13.075±90 years B.P.

6. - STRATIGRAPHY AND HYDROSTRATIGRAPHY OF BURIED METAPONTO COASTAL PLAIN DEPOSITS

The detailed stratigraphy and facies analysis of the four stored cores were used to calibrate stratigraphic and lithological data coming from the other wells. All these data allowed us to make bi-dimensional correlations and to propose a preliminary "sequential" interpretation of the stratigraphic organization of the buried deposits of the Metaponto coastal plain. Correlations were made along two geological profiles which cross each other: one runs for about 2 km perpendicularly to the coast (fig. 4), the second runs for about 24.5 km parallel to the coast (about 2.5 km inland) (fig. 5a). A preliminary hydrostratigraphic interpretation was also obtained thanks to these profiles (fig. 5b).

6.1. - LITHOSTRATIGRAPHICAL SUBDIVISION

Both the geological profiles show that the buried succession can be vertically divided into three units (figs. 4 and 5a), which will be described from bottom to top.

6.1.1. - *The lower unit*

The lower unit, whose bottom was not reached by the studied wells, is bounded at the top by a very irregular surface. This surface (SB1 in figures 4 and 5a), in the section running parallel to the coast, is mainly located at 40-45 m of depth but, locally it sharply deepens up to about 90 m (logs S4 and CM; fig. 5a) or at least up to about 60 m in those wells where the top of the lower unit was not reached by drillings (logs S3, S9 and S11; fig. 5a).

Along the same geological section, this unit results to be basically made up of clayey-silty shelf-transition deposits, while, along the geological profiles drawn perpendicularly to the coast, the clayey-silty deposits pass landward to sandy-gravelly delta front/strandplain deposits (fig. 4). Micropaleontological analyses performed on samples of this unit (coming from S1, S8, S12, CS and LZ cores) indicate that calcareous nannofossil assemblages are often poorly preserved and characterized by several reworked *taxa*. The most significant *taxa* are represented by: *Gephyrocapsa oceanica* (> 4 micron), rare to common *Pseudoemiliania lacunosa*, and very rare and possibly reworked specimens of *Gephyrocapsa omega*. This content suggests an age not older than the Middle Pleistocene, between the upper part of *Pseudoemiliania lacunosa* zone and *Gephyrocapsa oceanica* zone of RIO *et alii* (1990). The Last Occurrences of *Gephyrocapsa omega* and *Pseudoemiliania lacunosa*, which represent valuable Middle Pleistocene bioevents in the Mediterranean record according to the scheme of RIO *et alii* (1990), cannot be identified with certainty due to reworking. In accordance with the interpretation proposed in the geological sheet 508 "Policoro" (SABATO *et alii*, in prep.) of the New Geological Map of Italy (CARG Project), this unit represents the "substratum" ("basement" in SPILOTRO, 2004) of the buried succession of the Metaponto coastal plain.

Clayey-silty deposits observed along the section parallel to the shoreline may be interpreted as the youngest part (middle and, dubitatively, upper Pleistocene) of the Argille subappennine formation. When the top of this unit deepens, it indicates the presence of paleoincisions, which, thanks to interpretation of natural gamma radioactivity profiles, were for the first time regionally recognized by SPILOTRO (2004).

6.1.2. - *The middle unit*

The middle unit, here called MP1 (Metaponto Plain 1), is a discontinuous body lying on the substratum; in the section parallel to the coastline, the MP1 unit shows a thickness of about 15 m (logs CS, S5, and S12; fig. 5a), with boundaries (unconformities locally represented by erosional surfaces due to ravinement processes) located between 30 m (top) and 45 m (bottom) below the Metaponto coastal plain. Locally, the lower boundary deepens to 90 m of depth and the unit reaches a thickness of about 60 m (log S4; fig. 5a). According to sequence stratigraphy interpretations, this deepening is interpreted as related to a valley incision which occurred during a phase of falling and early lowstand of the relative sea-level; differently where the lower boundary is found at about 45 m of depth, it represents the exposed surface (palaeotopography) in the interfluve areas during the same time span. Accordingly, the lower boundary of the MP1 unit represents a sequence boundary (SB1). Above the SB1, estuarine deposits (log S4 in fig. 5a) developed in the paleovalley during rise of the relative sea-level; when the relative sea-level reached interfluve areas, alluvial plain deposits (fluvial-channel, levee, and crevasse splay lithofacies) followed by wave-dominated delta deposits (delta front/strandplain facies associations) developed both above the SB1 in the interfluve areas, and above the incised-valley fill deposits incorrespondence of the paleovalley. According to sequence stratigraphy concepts and to environmental interpretation and superimposition of drilled deposits, estuarine deposits filling the paleoincision are interpreted to be part of the Transgressive System Tract (TST) of a sequence (whose age and hierarchy will be defined below); also fluvial deposits and, partly, the wave-dominated delta deposits (both extending beyond the margins of the incised valley and above it) belong to this TST. The upper part of the wave-dominated delta and the overlying fluvial deposits represent the Highstand Systems Tract (HST) of the same sequence. The upper boundary of the MP1 unit corresponds to the base (lower boundary) of the uppermost unit (see the following paragraph).

6.1.3. - *The upper unit*

The upper unit, here called MP2 (Metaponto Plain 2), develops from about 30 m of depth up to the topographic surface (logs CS, S4, S5, and S12; fig. 5a) but locally the lower boundary sharply deepens to 90 m in depth (log CM; fig.5a) (paleoincisions). The deepening of this boundary may be observed in four wells and corresponds to the occurrence of four different incised valleys (logs S11, S9, CM and S3; fig. 5a). Again, according to sequence stratigraphy concepts, where the boundary is found at about 30 m of depth, it is interpreted as the exposed surface in the interfluve areas during a fall and early lowstand of relative sea-level, which led to the deep incision of the four paleovalleys. These paleovalleys roughly correspond to the present-day river courses. Accordingly, also the lower boundary of the MP2 unit represents a sequence boundary (SB2). In the incised valleys, above the SB2 (in the geological section running parallel to the coastline), bayhead delta, central estuary and estuary-mouth complex deposits were drilled. Landward, in the same incised valleys, fluvial deposits (alluvial plain facies associations) lie on the SB2 below estuary-system deposits (well log LZB; fig 3). Both fluvial and estuarine deposits developed during the relative sea-level rise. When the relative sea-level reached interfluve areas, wave-dominated delta (delta front/strandplain facies associations), passing upward to shelf-transition systems, developed (offshore-transition/offshore facies association) above both the SB2 in the interfluve areas and the incised-valley fill deposits in correspondence of paleovalleys (fig. 5a). At the end of the transgression, a depositional regression took place since, on previous deposits, progradational wave-dominated delta deposits developed (figs. 4 and 5). The oldest buried sediments linked to this depositional regression were found at least about 7 km landward from the present-day shoreline (well log LZB; fig. 3).

According to sequence stratigraphy concepts, environmental interpretation and superimposition of drilled deposits, fluvial and estuarine deposits that fill palaeoincisions together with overlying wave-dominated delta deposits passing to shelf-transition deposits are to be interpreted as the TST of a sequence. Wave-dominated delta deposits passing upward to fluvial-system deposits (the present-day Metaponto alluvial plain), which developed due to a depositional regression, represent part of the HST (the present-day systems-tract in progress) of the same sequence.

Radiocarbon dating allowed us to assign the MP2 unit to late Pleistocene and Holocene time. In particular, six ^{14}C uncalibrated dates were obtained from fragments of shells collected in the upper 60 m of cores CM, LZB and CS (see position of samples and ages obtained in figures 2 and 3). As regards biostratigraphical data, calcareous nannofossil content was generally very poor and represented by *Coccolithus pelagicus, Reticulofenestra* spp., small *Gephyrocapsa* and scattered specimens of *Gephyrocapsa oceanica* (> 4 micron) and *Emiliania huxleyi*. The occurrence of the latter *taxa*, found in samples coming from the uppermost 10 m of the upper unit in the S3 core, may be considered in good agreement with the age obtained by radiometric data.

6.2. - Age and sequential hierarchy of MP1 and MP2 units

As suggested on first approximation, the two units above the substratum correspond to systems tracts of two sequences (or to parts of them).

The MP2 unit is the uppermost unit of the buried Metaponto coastal deposits and its upper part corresponds to the outcropping coastal plain deposits. It is bounded below by an unconformity surface (sequence boundary SB2) which sharply deepens from about 30 m up to 90 m in depth (fig. 5a). According to radiocarbon age obtained for deposits belonging to the MP2 unit and to quoted li-

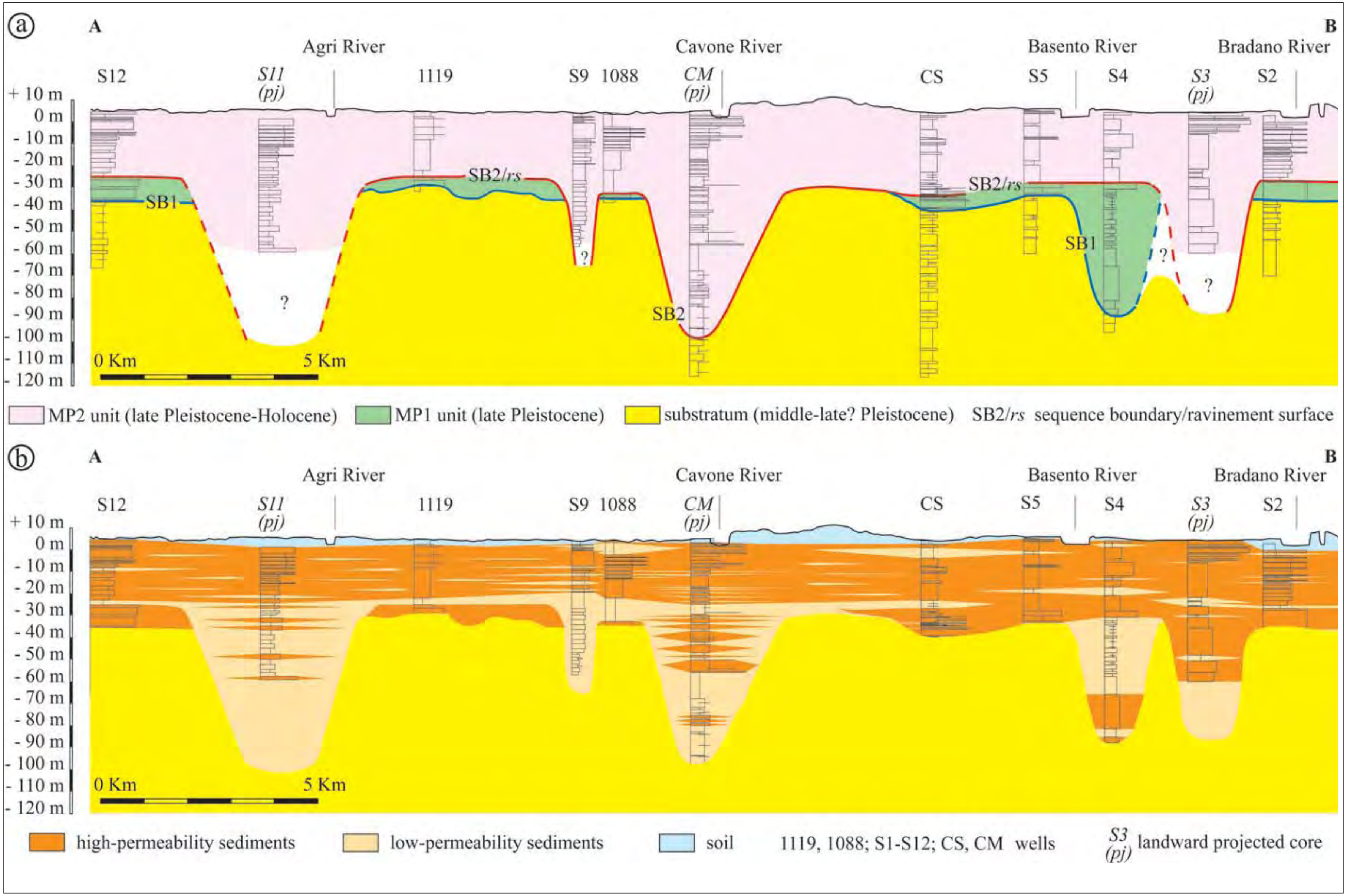

Fig. 5 – a) Cross section parallel to the present-day shoreline showing the stratigraphic architecture of buried Metaponto coastal plain succession (see fig. 1 for location); b) Lithostratigraphical cross-section parallel to the present-day shoreline showing the major acquifer systems identified within the buried Metaponto coastal plain (see fig. 1 for location).

– *a) Sezione geologica parallela all'attuale linea di costa che mostra l'architettura stratigrafica della successione sepolta della piana costiera metapontina (vedi fig. 1 per l'ubicazione della sezione); b) Sezione litostratigrafica parallela all'attuale linea di costa che mostra i maggiori sistemi di acquiferi identificati nell'ambito della successione sepolta della piana costiera metapontina (vedi fig. 1 per l'ubicazione della sezione).*

terature on development of other coastal plains in Italy, these paleovalleys were incised during the last falling and early low stand of the relative sea-level, namely during the LGM. Therefore, the MP2 unit developed after the LGM, and its age is late Pleistocene and Holocene. Palaeovalleys filling was mainly due to backstepping of depositional systems whose deposits, characterized by a deepening-upward trend, record a “long term” late Pleistocene to early Holocene transgression. At the end of the transgression, a depositional regression took place since, on previous deposits, progradational wave-dominated delta deposits developed (figs. 4 and 5). According to sequence stratigraphy concepts, the whole transgressive phase, recorded in the MP2 unit before the depositional regression, corresponds to the last Quaternary TST (the post-LGM TST), the age of which spans from no more than about 18ky B.P. (according to the interpretation of the origin of the sequence boundary below the MP2 unit) up to about 5.5ky B.P. (according both to literature data and to collected radiocarbon ones). The regressive phase of the MP2 unit, according to sequential interpretations, corresponds to the last Quaternary HST (late Holocene in age and post 5.5ky B.P., following radiocarbon data) and is the still-active phase in the Metaponto coastal area. Both thickness and age span of the MP2 unit suggest to ascribe it to a high-frequency sequence (a 5th order sequence); according to late Quaternary cyclicity (*i.e.* WAELBROECK *et alii*, 2002) and in accordance with interpretations made by BELLOTTI *et alii* (1995) for coeval and similar deposits, the MP2 unit may be considered also the initial part of the 4th order sequence that developed since the LGM. Therefore the SB2, i.e. the lower boundary of the MP2 unit, represents contemporaneously both a 5th and a 4th order sequence-boundary.

Unit MP1 discontinuously lays between the substratum and the MP2 sequence. Also the MP1 unit is characterized by the filling of a paleovalley. This paleoincision developed during a phase of fall and early lowstand of the relative sea-level. Since the sequence boundary below the MP2 unit cut the MP1 unit, this phase of fall and early lowstand was older than that which led to the incision at the base of the MP2 sequence. According to sequence stratigraphy concepts, age of the MP1 unit could be indirectly obtained, since this unit developed between a relative sea-level fall and a subsequent one; therefore, since MP2 unit formed after the LGM, corresponding to the Marine Isotope Stage (MIS) 2, the sea-level fall preceding the LGM corresponds to MIS 4, and, accordingly, the top of the MP1 unit most likely developed around the MIS 3 (late Pleistocene in age).

Thickness and age of MP1 suggest to ascribe it to a high-frequency sequence (a 5th order sequence); following the cyclicity and sea-level changes proposed for the Late Pleistocene (*i.e.* WAELBROECK *et alii*, 2002), the MP1 unit should represent a 5th order sequence punctuating a Falling Stage System Tract (FSST) of a 4th order sequence, namely the FSST of the 4th order sequence that followed the MIS5 (post Tyrrhenian in age) and that preceded the LGM. Accordingly, the SB1, namely the lower boundary of the MP1 unit, corresponds to a 5th order sequence boundary, while, in accordance with the FSST definition proposed by PLINT & NUMMENDAL (2000), the SB2, bounding on top the same unit, corresponds to a 4th order sequence boundary (as suggested before), locally coinciding with a 5th order sequence boundary.

6.3. - HYDROSTRATIGRAPHY

Thanks to the complete wells database, to decades of piezometric measurements, and to the stratigraphic interpretation of the buried Metaponto coastal plain succession (fig. 5a), it is possible to make a preliminary hydrostratigraphic interpretation of this succession, even though, considering the alternance between less and more permeable sedimentary bodies, the hydrostratigraphic architecture appears to be very complex (fig. 5b). As a whole, on a first approximation, the MP1 and MP2 units correspond to a multilayered aquifer, in accordance with the definition of POLEMIO *et alii* (2003a; 2003b) and with the size (considering paleovalleys infills) suggested by SPILOTRO (2004). The aquifer lies on clays and silty clays of the Argille subappennine formation (the lower unit of the lithostratigraphic subdivision of drilled deposits), and almost the whole thickness of the aquifer lies below the sea level and is confined by fine-grained sediments toward the coast.

Close to the coast, in an along-strike section, the lower part of the aquifer system is laterally partitioned; each partition corresponds to a paleovalley infill and is laterally confined by clays and silty clays deposits, belonging to the argille subappennine formation, which were cut during sea-level falls and exposed along flanks of paleoincisions. Each of these partitions of the aquifer system is, in turn, vertically partitioned, given that water permeates sandy silty and sandy gravelly layers which alternate with mainly silty layers (fig. 5b). Moving landward, inside paleovalleys, sandy-silty and sandy-gravelly layers are elongated along dip and become thicker and thicker, gradually passing to a more vertically continuous porous body made up mainly of sands (deposits of the inner part of estuary systems) and sandy gravels (deposits of fluvial systems feeding marine-transitional systems). On the contrary, moving seaward and according to both facies and depositional systems interpretation, the same sandy-silty and sandy-gravelly layers should become thinner and thinner up to the termination within shelf-transition clays and silty clays. Accordingly, inside paleovalleys and close to the coast, the multilayered aquifer shows artesian features, since inland it is fed by flows running along buried fluvial deposits and seaward it is characterized by thinning confined layers enclosed in low-permeable sediments.

Above paleovalleys fills and below the present-day Metaponto coastal plain, up to about 30-40 m of depth, the multilayered aquifer becomes a phreatic one; fresh water splits into several horizons with a low inclination, the shallowest of which is characterized by free piezometric oscillations. Also in this case, water flowing along coarse-grained deposits inside valleys (note that, inland, paleovalleys coincide with present-day valleys) feeds the coastal multilayered aquifer, but, according to POLEMIO *et alii* (2003a; 2003b), also water coming from coarse-grained deposits cropping out inland in the interfluves areas (terraced marine-deposits) may feed this part of the multilayered aquifer system.

7. - CONCLUSIONS

A new view of the subsurface stratigraphy/hydrostratigraphy of the Metaponto coastal plain is proposed. This view was obtained combining lithological criteria in the interpretation of a large number of wells drilled in the last few decades with the contribution that both a modern sedimentological/stratigraphic approach and the wide literature on late Quaternary development of coastal plains may offer to the topic. The new stratigraphic picture of the Metaponto coastal-plain subsurface shows a complex architecture governed either by lateral and vertical variations of facies within a depositional system or by the overlap of different depositional systems through time, in accordance with changes of the relative sea-level. Thanks to the distinction of two main boundaries (two erosional surfaces of regional extent), three units were recognized in the drilled Quaternary deposits of the plain (up to about 120 m in depth): a lower unit, mainly formed by clays and silty clays, that represents the substratum of the middle and upper units formed by a complex alternation between coarse- and fine-grained facies. Both the middle and upper units host a multilayered aquifer basically located below the present-day sea-level. The aquifer locally reaches about 100 m in depth, given that the buried deposits of either the middle or the upper unit may fill paleovalleys cut in the clayey and silty-clayey substratum. Paleovalleys developed at least twice, during phases of relative sea-level fall and lowstand linked to the MIS 4 and the LGM; fluvial and mainly estuarine deposits filled paleovalleys, while shallow-marine deposits followed by coastal-plain deposits developed after filling of incised valleys.

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