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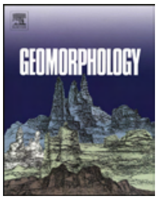

Surface and subsurface of the Metaponto Coastal Plain (Gulf of Taranto—southern Italy): Present-day- vs LGM-landscape

Marcello Tropeano [a,*], Antonietta Cilumbriello [a], Luisa Sabato [a], Salvatore Gallicchio [a], Antonio Grippa [a], Sergio Giuseppe Longhitano [b], Marcello Bianca [c,d], Maria Rosaria Gallipoli [d], Marco Mucciarelli [c,1], Giuseppe Spilotro [e]

[a] *Dipartimento di Scienze della Terra e GeoAmbientali, Università degli Studi di Bari "Aldo Moro", Bari, Italy*
[b] *Dipartimento di Scienze, Università degli Studi della Basilicata, Potenza, Italy*
[c] *Dipartimento di Strutture, Geotecnica, Geologia Applicata all'Ingegneria, Università degli Studi della Basilicata, Potenza, Italy*
[d] *Istituto di Metodologie per l'Analisi Ambientale—CNR, Tito Scalo, Potenza, Italy*
[e] *Dipartimento delle Culture Europee e del Mediterraneo, Università degli Studi della Basilicata, Matera, Italy*

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ABSTRACT

The Metaponto Coastal Plain (MCP), in southern Italy, stretches 60 km-long and 5 km-wide along the Gulf of Taranto in the Ionian Sea, and is presently subject to strong anthropogenic pressure. A multidisciplinary study reviewed the geomorphology, lithostratigraphy and sedimentology of the MCP and its subsurface. Incorporating both borehole and radiocarbon-dating information in the review, this paper focuses on comparisons and differences between present-day and buried Late Pleistocene landscapes (LGM and MIS 3).

The modern coastal plain is the top of a late Holocene coastal wedge prograding on a very narrow-shelf, that is connected to a deep basin (the Ionian Sea) by a steep slope. This scenery likely resembles those produced during earlier late Quaternary relative highstands and is in marked contrast with that produced during the last sea-level fall and lowstand, and buried in the MCP subsurface. The last scenery corresponds to the LGM landscape, where river-valleys deeply dissected a previous highstand coastal wedge (MIS 3) whose remnants represented interfluve areas. Thanks to resonance properties of the subsurface, this buried landscape was obtained in a 3D visualization, highlighting location and shape of incised valleys and interfluve areas during the LGM.

1. Introduction

It is well known that during the Last Glacial Maximum (LGM) the sea level was globally about 130 m lower than today (e.g. Yokoyama and Esat, 2011, and references therein). Therefore, regions that host coastal plains and shelf seas today, during the LGM were exposed land, dissected by river valleys. These ancient continental landscapes are now submerged and buried by post-LGM sediments (e.g. Boyd et al., 2006; Suter, 2006; among many others). The availability of dense grids of high-quality, high-resolution seismic lines has allowed the detection of offshore spatial features of buried past landscapes, for example in the Gulf of Mexico (e.g., Anderson and Fillon, 2004) and the Gulf of Lions in the western Mediterranean (e.g., Jouet et al., 2006; Rabineau et al., 2006). Onshore, below coastal plains, instead only patchy information on the position of the base of the post-LGM succession is typically obtained. In Italy, thicknesses and sedimentary features of the Late Pleistocene to Holocene follow from boreholes drilled along fluvial and coastal urbanized plains hosting big towns and crossed by the Po, the Tiber, and the Arno rivers (Bellotti et al., 1994, 1995; Amorosi et al., 1999, 2004; Aguzzi et al., 2005, 2007; Amorosi et al., 2008a, 2008b; Milli et al., 2008; Zecchin et al., 2009; Rossi et al., 2011; among many others).

The Metaponto Coastal Plain (MCP) in southern Italy is one of the wider coastal plains of the peninsula, recently subjected to increased anthropogenic pressure and investigated through several drills. The MCP is the SSW–NNE striking shore of the northwestern sector of the Ionian Sea (Gulf of Taranto; Fig. 1). Five small and short rivers traverse the coastal plain, running perpendicular to the shoreline. In the subsurface, filled paleovalleys that can be referred to these rivers, are recorded (Fig. 2). Their incision depths relate to the base level reached during the LGM (Cotecchia et al., 1969; Spilotro, 2004; Cilumbriello et al., 2010; Grippa et al., 2011; Tropeano et al., 2011).

Recently acquired seismic and borehole data make it possible to update the geomorphological and stratigraphic interpretation of the MCP subsurface. Reviewing these data with those regarding physical and sedimentary features of the modern coastal plain and offshore led us to highlight similarities and differences between present-day and past landscapes. In this regard, a non-invasive and low-cost geophysical

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* Corresponding author.
E-mail address: marcello.tropeano@uniba.it (M. Tropeano).
[1] Present Address: Centro di Ricerche Sismologiche—Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS), Udine, Italy.

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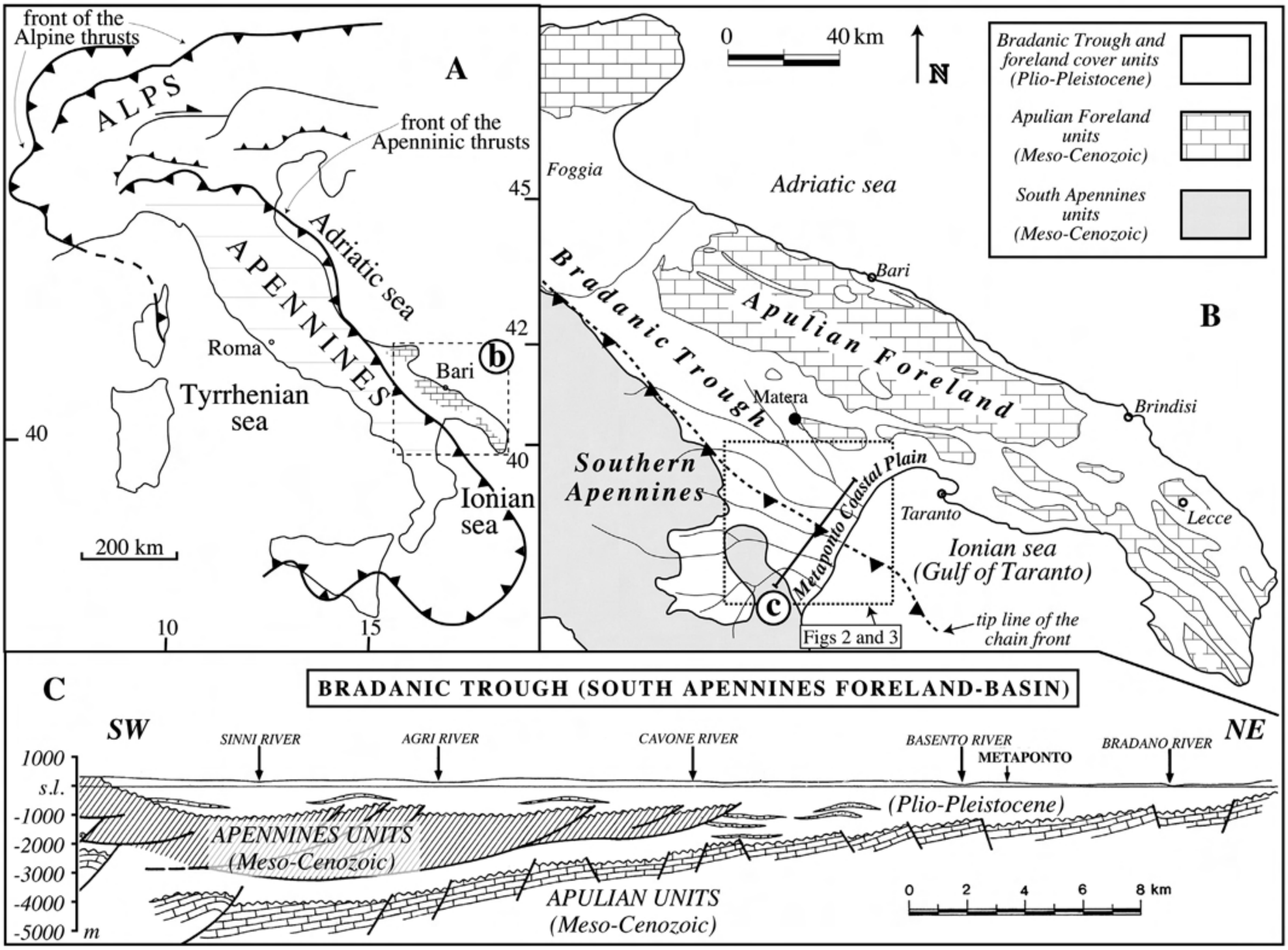

Fig. 1. Geographic and tectonic setting of the study area: A) Schematic structural map of Italy; B) schematic structural map of southern Italy, with location of the Metaponto Coastal Plain (MCP); C) geological cross-section of the Bradanic Trough showing the deep tectonic structures characterizing the basement of the MCP (modified from Sella et al., 1988).

method allowed us to generate a 3D visualization of the LGM landscape buried below the MCP.

2. Geological setting

In southern Italy, a NW–SE striking foreland basin (the Bradanic Trough) is confined between the Apennines Chain to the West and the exposed Apulian foreland to the East (Fig. 1). This foreland basin has been uplifting at least from the Middle Pleistocene (Doglioni et al., 1994, 1996; Pieri et al., 1996; Patacca and Scandone, 2001). The MCP stretches roughly perpendicular to the axis of the foreland basin, running from the chain toward the foreland, and bounds the present-day exposed sector of the basin (the Bradanic Trough) from its submerged counterpart (the Gulf of Taranto) (Figs. 2 and 3).

Along strike (from NW to SE), the Bradanic Trough progressively became emerged land facing the Gulf of Taranto in the Ionian Sea (Tropeano et al., 2002) (Fig. 1). A flight of marine terraces cut by wide valley incisions partly filled by aggrading river plains has recorded both the regional uplift and its interference with the middle-late Pleistocene eustatic sea-level changes (Cotecchia and Magri, 1967; Vezzani, 1967; Brückner, 1980; Amato, 2000; Westaway and Bridgland, 2007; Caputo et al., 2010; Sauber et al., 2010) (Fig. 2). These marine terraces represent tops of uplifted coastal wedges with an internal complex stratigraphy (Cilumbriello et al., 2008). The MCP thus represents the top of the last coastal wedge produced by the most recent interferences between uplift and sea-level changes (Cilumbriello et al., 2010).

The MCP succession was initally described by Vezzani (1967) as being made up of siliciclastic deposits, of post-Tyrrhenian age, up to 40 m-thick, overlying Calabrian clays (the “argille subappennine” formation). A C-14 date of 11,700 ± 160 yr BP was obtained from a sample collected at about 50 m depth in a paleovalley sediment infilling (Cotecchia et al., 1969). More recently, the base of the buried MCP succession has been surveyed with the help of gamma-ray borehole logs (Spilotro, 2004). This base shows an irregular erosional profile cutting the “basement” of “blue clays” at about −40 m below the present-day sea level; the erosional profile deepens to about −100 m below the present-day sea level in correspondence to the present-day rivers. The deepest parts of the profile were interpreted as paleovalleys reflecting the base levels experienced by rivers during the LGM (cross section in Fig. 2) (Spilotro, 2004). Several stratigraphic subdivision schemes have been proposed to describe the MCP subsurface, based on different interpretations of successive drilling investigations. The most recent stratigraphic interpretation, proposed by Pescatore et al. (2009) and revised by Cilumbriello et al. (2010), shows that the MCP subsurface succession is stratigraphically subdivided in three units bounded by two main erosional surfaces. These units are distinguished in: i) a lower unit, middle to upper Pleistocene in age, drilled for about 80 m without reaching the base; ii) an intermediate unit, upper Pleistocene in age and up to about 10 m-thick; and iii) an upper unit, upper Pleistocene to Holocene in age

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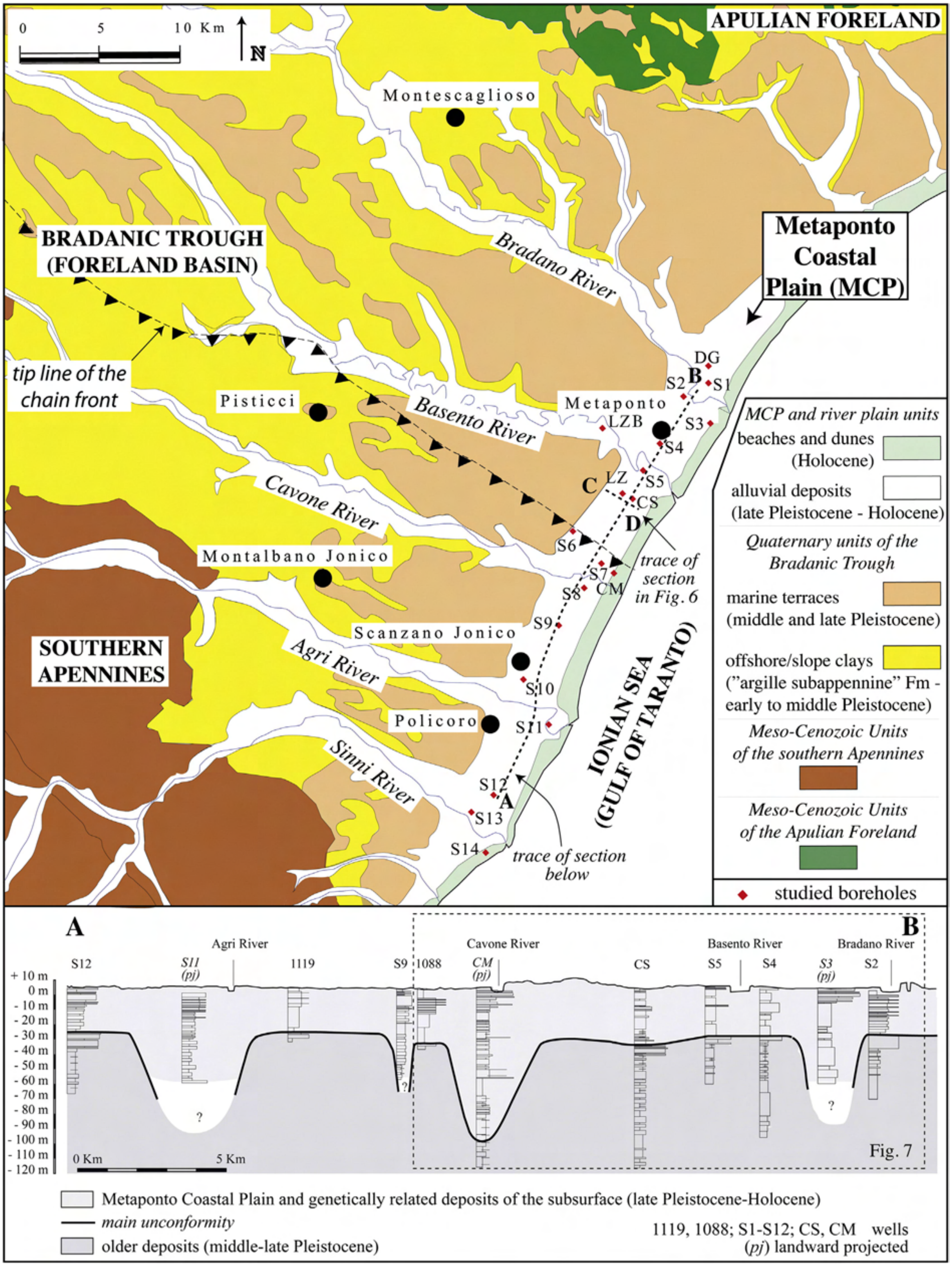

Fig. 2. Geology of the study area (see Fig. 1 for location). Above: schematic geological map of the MCP and its hinterland (modified from: Gallicchio et al., 2009; Sabato et al., in press), with location of cross-sections based on studied boreholes (Figs. 4–7). Below: cross-section showing the occurrence of buried incised-valley fills and interfluve areas in the subsurface of the MCP (modified from Cilumbriello et al., 2010; further detailed in Fig. 7).

and up to about 50 m-thick. According to Cilumbriello et al. (2010), this stratigraphy is representative of the successions drilled away from LGM paleovalleys (i.e. in correspondence to the LGM paleointerfluve areas). In fact, boreholes intercepting paleovalleys and their filling show that the intermediate unit is missing and that the lower unit is deeply incised and covered only by sediments of the upper unit.

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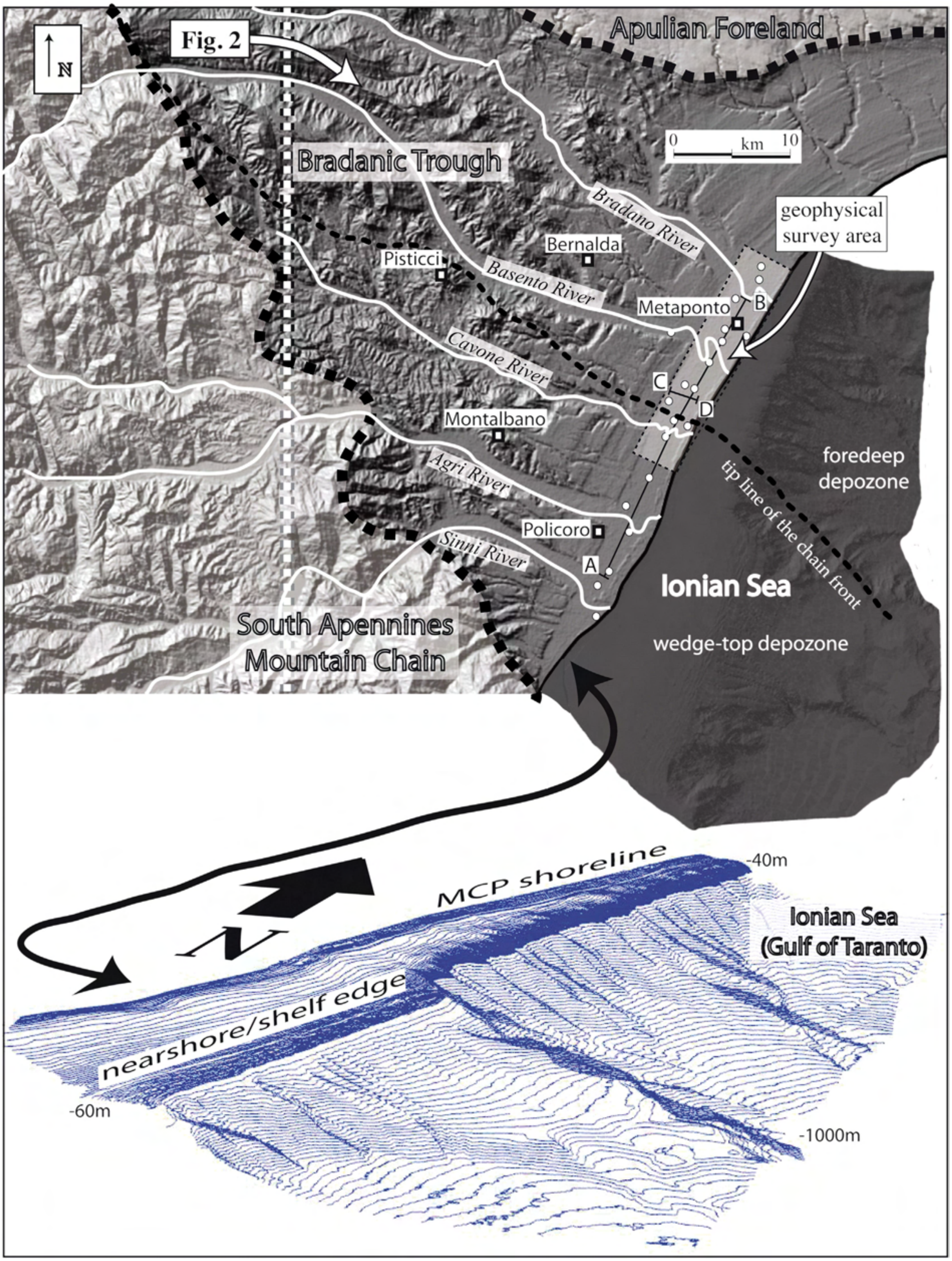

Fig. 3. Topographic and bathymetric setting of the study area. Above: DEM of the hinterland and the offshore of the MCP. See Fig. 2 for geology of the same area. Below: 3D view of the sea floor off the MCP, based on the bathymetric map of Regione Basilicata (2005). Note: (i) the shallow position of the nearshore/shelf edge, (ii) the scars characterizing the shelf edge, (iii) the steep slope connecting the narrow shore to the deepest sector of the Gulf of Taranto.

3. Methods and dataset

In order to interpret the sedimentology and stratigraphy of the MCP and its subsurface succession, and to highlight similarities and differences between present-day and past landscape, a review of a wide dataset and literature was performed. The dataset includes: i) a geological survey at 1:50,000 scale of a wide area comprising the MCP between the Bradano and Sinni rivers (Sabato et al., in press); ii) a

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detailed geological survey of the MCP at 1:25,000 scale in an area located between the Bradano and Cavone rivers (Pescatore et al., 2009); iii) historical analysis of aerial photos of the southern MCP coastline concerning the last 100 years (Sabato et al., 2011a); iv) grain size and morpho-bathymetric features of the MCP submerged environments obtained by a bathymetric survey performed reaching 13 m water depth (Sabato et al., 2012); v) a bathymetric survey performed by the Regione Basilicata (2005) regarding the Ionian Sea and including the MCP offshore; vi) detailed facies analysis on four continuously cored (and stored) boreholes (CS, LZ, CM, LZB) having depths ranging from about 50 m to 120 m (Figs. 4 and 5) (Cilumbriello et al., 2010); vii) stratigraphic descriptions of about twenty continuously cored (but not stored) boreholes, reaching a maximum depth of about 120 m (Grippa, 2010); viii) the palaeoecology and biostratigraphy obtained by macro- and micropaleontological analysis on samples from the stored boreholes (personal communications by: La Perna; Mateu Vicent; Maiorano; see also: Cilumbriello et al., 2010); ix) simplified stratigraphic descriptions of hundreds of wells (Spilotro et al., 2002); x) six radiocarbon dates obtained from organic material and valves of marine invertebrates (Figs. 4 and 5).

Furthermore, since the network of boreholes alone is not dense enough to obtain a 3D view of the stratigraphic architecture, a non-invasive and low-cost geophysical method was applied to survey the MCP subsurface. The survey was carried out in the 20 km-long and 5 km-wide coastal plain sector between the mouths of the Cavone and Bradano rivers (Fig. 3 inset). The method is based on the practical estimation of subsurface resonance properties, using the single station HVSR (Horizontal-to-Vertical Spectral Ratio) by microtremors as seismic input (Nakamura, 1989; Ibs-Von Seth and Wohlenberg, 1999; Delgado et al., 2000; Oliveto et al., 2004; Grippa et al., 2011), at 126 seismic ambient noise measurements. Some measurements were carried out close to those boreholes whose down-hole tests were available, and this led us to make a direct comparison between the stratigraphic and geophysical data. The 126 HVSR curves were inverted using the Model HVSR software described by Herak (2008).

4. The Metaponto Coastal Plain (MCP) and its offshore

4.1. Geomorphology and sedimentary environments of the MCP

The MCP is an about 60 km-long and 5 km-wide sedimentary strip facing the Gulf of Taranto (Ionian Sea). Five rivers cross it to reach the shoreline, running roughly parallel to each other (from the South to the North: Sinni, Agri, Cavone, Basento, and Bradano rivers—Figs. 2 and 3). Inland, the coastal plain onlaps older deposits, and does not reach higher than 10 m above sea level (Pescatore et al., 2009; Sabato et al., in press). Upstream of the coastal plain, the feeding rivers occupy relatively wide and flat aggradational plains encased in older deposits. These are partly backfilled reaches of valleys that dissected older marine terraces and their marine-clay substratum (Fig. 2). In the present-day riverbed at the upstream side of the coastal plain, the oldest outcropping alluvial sediments are dated to about 7 ka BP (Boenzi et al., 2008; Piccarreta et al., 2011). In contrast, near the present-day shoreline (1 km inland), a similar age is obtained for shallow-marine sediments encountered in a borehole at about 35 m depth below the topographic surface (about −30 m below sea level) (Pescatore et al., 2009; Cilumbriello et al., 2010). Archaeological and historical data collected in the vicinity of the same borehole indicate that the shoreline reached this place between the 4th and the 3rd century BC (Boenzi et al., 1987, 2002); these ages suggest that aggradation and progradation of the whole coastal plain occurred mainly during the late Holocene.

The lithological and sedimentological features of the uppermost coastal plain deposits (a few meters thick, late Holocene in age) are indicative of depositional environments that are quite similar to those characterizing present-day depositional systems of the plain. These systems are distinguished by Pescatore et al. (2009) into: i) continental, with fine- to coarse-grained sediments attributed to eluvial, fluvial, lacustrine and palustrine environments, and ii) transitional, with sands and silts attributed to beach and delta environments. Until the first half of the last century, in backshore positions, wide palustrine and shallow lacustrine environments characterized the plain, but these areas are today totally reclaimed. The plain is now characterized by sandy and silty meandering fluvial systems, with some artificial and often channelized reaches, forming, at the mouth, wave-dominated deltas (deflected deltas, sensu Bhattacharya and Giosan, 2003) in a microtidal regime (Sabato et al., 2012). Reclaimed areas, flanking rivers along the plain, are still subject to occasional flooding during major rainfall events. Landward, the fluvial systems are characterized by gravelly and sandy braided channels. The southernmost rivers of the MCP (rivers Sinni and Agri) show these braided features all the way to the shoreline. The more northerly rivers (Cavone, Basento and Bradano) have a meandering lowest reach, developed in the relatively wide valleys encased in Pleistocene marine terraces.

The present-day beach is characterized by low-gradient sandy coasts, limited landward by several meters thick sand dune ridges running parallel to the beach and marking the seaward beach migration from historical earlier stages of the MCP development. Fine marshy deposits accumulated in between these different generations of dunes. Towards the south, coastal deposits are more enriched in gravels, forming gravelly-sandy and, locally, gravelly beaches. The seaward migration of the MCP shoreline ended several tens of years ago, when dam construction on rivers and sediment exploitation from river beds caused severe coastal erosion, resulting in the retreat of the shoreline (Cocco et al., 1975; Sabato et al., 2012).

4.2. Geomorphology and sedimentary environments off the MCP

The shelf-to-slope features of the Gulf of Taranto in front of the MCP are described here, based on a marine survey provided by the local government (Regione Basilicata, 2005) and reinterpretation of data from several previous studies. The Gulf of Taranto may be subdivided in two main sectors: (i) the NE sector, seaward of the coast between the Bradano and Cavone rivers, and (ii) the SW sector, seaward of the coast between the Cavone and Sinni rivers (Fig. 3). A main buried tectonic structure, represented by the tip line of the active chain front, separates these two sectors: using the foreland-basin definition proposed by DeCelles and Giles (1996), the NE sector is located on the foredeep depozone, and the SW sector is located on the wedge-top depozone (Fig. 3). Bathymetric data show that the main break in the cross-shore profile is found at about 40 m water depth in the NE sector and at about 60 m in the SW sector (Fig. 3). Therefore, the shelf area corresponds to the shallow nearshore that is very narrow and steep, being about 2.5 km-wide and 1° dip in the NE sector and about 7.5 km-wide and 0.5° dip in the SW sector. The seafloor becomes steeper seawards from the shelf break (from 5°, to the NE, to 2.5°, to the SW), passing, through an uneven edge, to a very long slope (Fig. 3) whose connection with the toe is not depicted in the Regione Basilicata (2005) bathymetric map.

The NE sector is characterized by a main structurally-controlled canyon (the Taranto Valley, i.e. the foredeep depocenter) (Pescatore and Senatore, 1986; Pescatore et al., 1987). The shelf break of the NE sector is also characterized by a series of closely-spaced and side-by-side scars (Fig. 3), that appear as heads of gullies sloping toward the Taranto Valley.

Very recent studies were carried out on a sector of the submerged coast facing the MCP focusing on nearshore/shelf sedimentary features (Sabato et al., 2011a, 2011b, 2012). These studies confirm that the main direction of sediment dispersal (littoral drift) is towards the NE (Brondi et al., 1974; Benassai et al., 1976; Belfiore, 1984), with dominant SE quadrant winds and average values of wind speeds equal to 8.69 m/s. Along the same sector, the fair weather wave base is at about 5 m water

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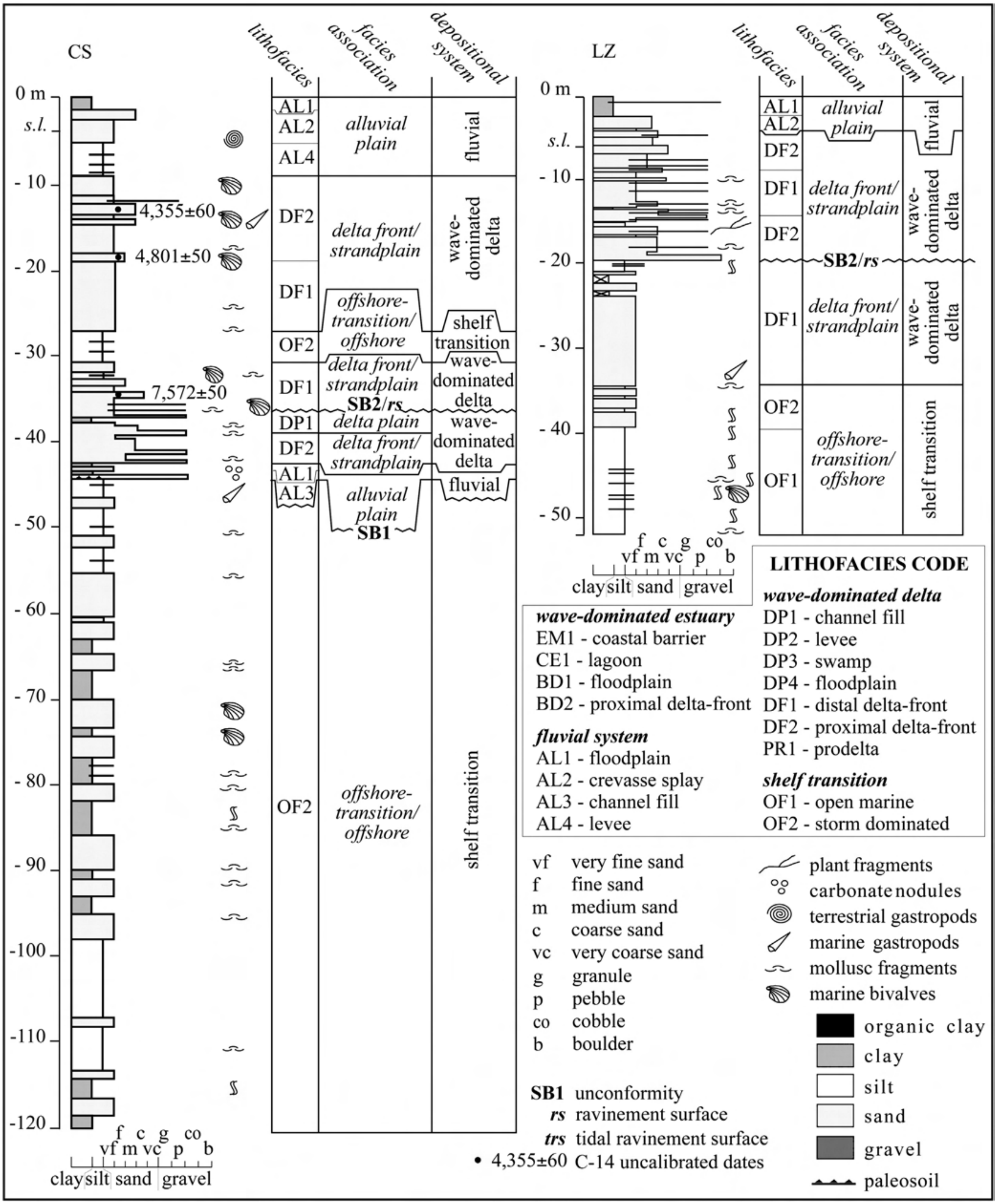

Fig. 4. Sedimentary logs for cores CS and LZ (modified from Cilumbriello et al., 2010). See Fig. 2 for borehole locations.

depth (Cocco et al., 1975; Parea et al., 1980; Sabato et al., 2011a). From the shoreline down to 5 m water depth bedforms are characterized by a complex system of submerged, mostly elongated, nearly parallel-to-shoreline bars and troughs, with the bar toe at about 5 m water depth and the bar crest at about 2 m water depth. Such bedforms occur up to 400–500 m from the shoreline; seawards of this distance and up to 1.5 km from the shoreline no remarkable morpho-bathymetric feature was detected (Sabato et al., 2011a, 2012).

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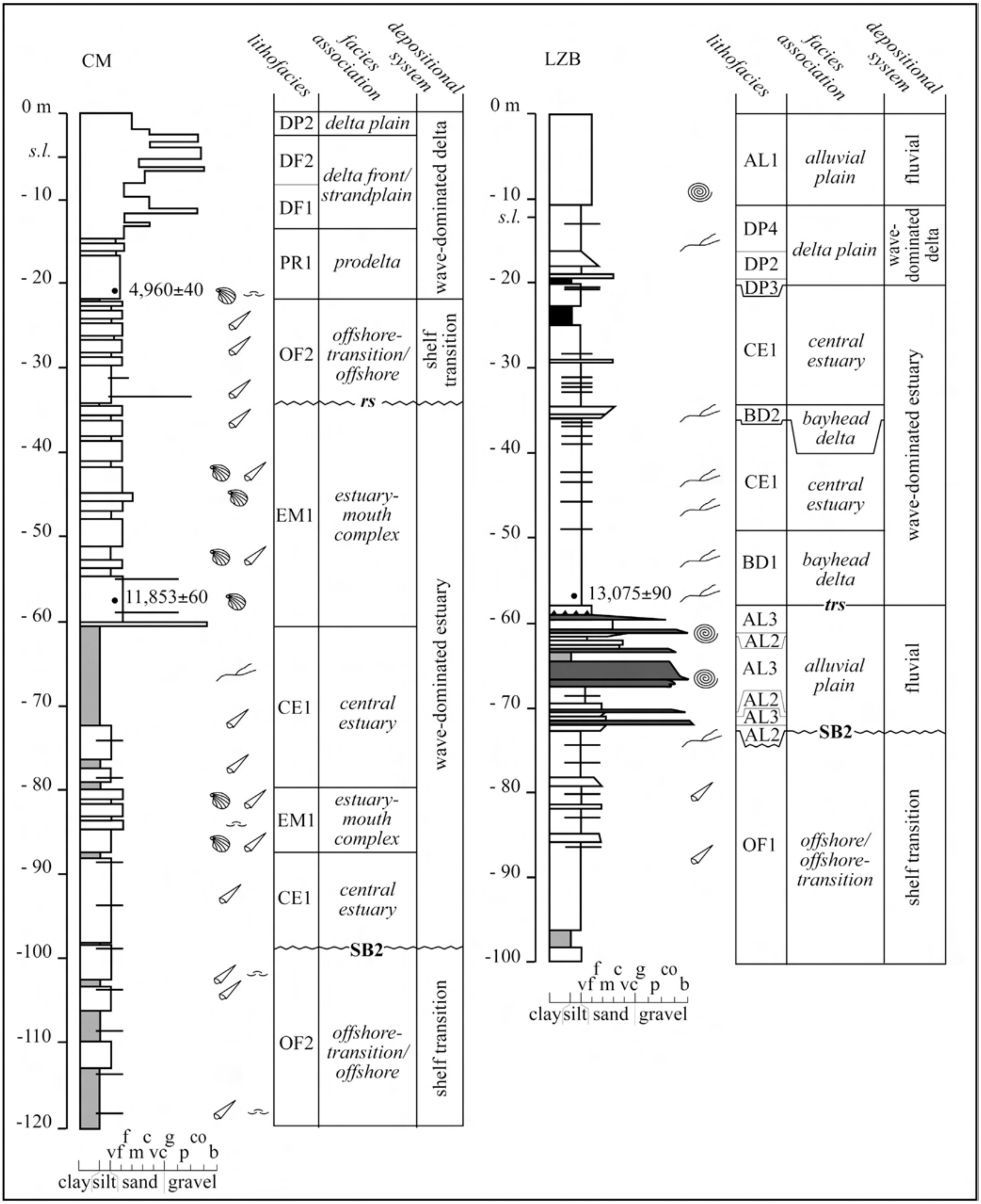

Fig. 5. Sedimentary logs for cores CM and LZB (modified from Cilumbriello et al., 2010). See Fig. 2 for borehole locations.

Sediments along the submerged area of the beach show a regular decrease in the average diameter of the particles from the beachface-upper shoreface to the offshore transition, according to parallel-to shoreline belts of variable extent. The coarser sediments, mostly sands (very coarse to coarse) and rarely gravels, are distributed between the shoreline and 6 m water depth. Finer sediments (medium to fine sands) occur between the bathymetrics of 6 and 10 m; seaward, they are substituted by very fine sands (Sabato et al., 2011a, 2012).

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According to the sedimentological observations on the terraced marine deposits of the Gulf of Taranto, coarse-grained delta/beach deposits developed about 20 m-thick successions prograding onto offshore silty-clay facies (Cilumbriello, 2008; Cilumbriello et al., 2008), suggesting also the bathymetry of the offshore silty-clay facies during deposition. This is in agreement with data from samples collected in the present-day nearshore bottom, showing that the local occurrence of silts begins at least from about 15 m water depth and the local occurrence of clays begins at least at about 35 m water depth (Regione Basilicata, 2005).

5. The Metaponto Coastal Plain (MCP) subsurface

The stratigraphic scheme proposed by Cilumbriello et al. (2010) represents the starting point for describing the MCP subsurface succession. As mentioned in Section 2, along boreholes intercepting LGM interfluve areas the succession is subdivided in three units; along boreholes intercepting LGM incisions, the succession lacks the intermediate unit, and here the upper unit comprises palaeovalley fills (Fig. 6).

5.1. Lithostratigraphy and sedimentology of drilled units

Along boreholes intercepting LGM interfluve areas, the lower unit is typically encountered below 40–50 m depth and is drilled for tens of meters without reaching the base (Fig. 7). It is mainly represented by shelf-to-slope marine fine-grained facies, correlating with silty clay successions in outcrops on land referred to as the “argille subappennine” formation (e.g. Ciaranfi et al., 1996, 2010). The uppermost fine-grained deposits of this unit pass landward to sandy and gravelly sandy beach/deltaic deposits (partly cropping out). These deposits are indicative of the progradation of a coastal body over nearshore facies and in turn upper-slope deposits (Fig. 6). This interpretation is supported by the comparison of these sedimentary successions with present-day depositional systems.

The intermediate unit, whose top represents LGM interfluve areas, is typically encountered at 35–40 m depth, and is of variable thickness (Fig. 7). It represents sandy and gravelly coastal deposits: a palaeocoastal wedge preserved as a buried marine terrace. The progradation of this coarse-grained coastal body is not genetically linked with the facies that it overlies (unlike the lower unit), since a clear unconformity separates it from the lower unit (Figs. 4 and 6).

The upper unit above paleointerfluve regions records shallow-water facies at its base. These are represented by silty clays and silts referred to nearshore/shelf environments unconformably developed onto the flat top (a ravinement surface) of the intermediate unit. Higher up in the sequence of the upper unit, aggrading and prograding coarse-grained delta and beach facies conformably cover

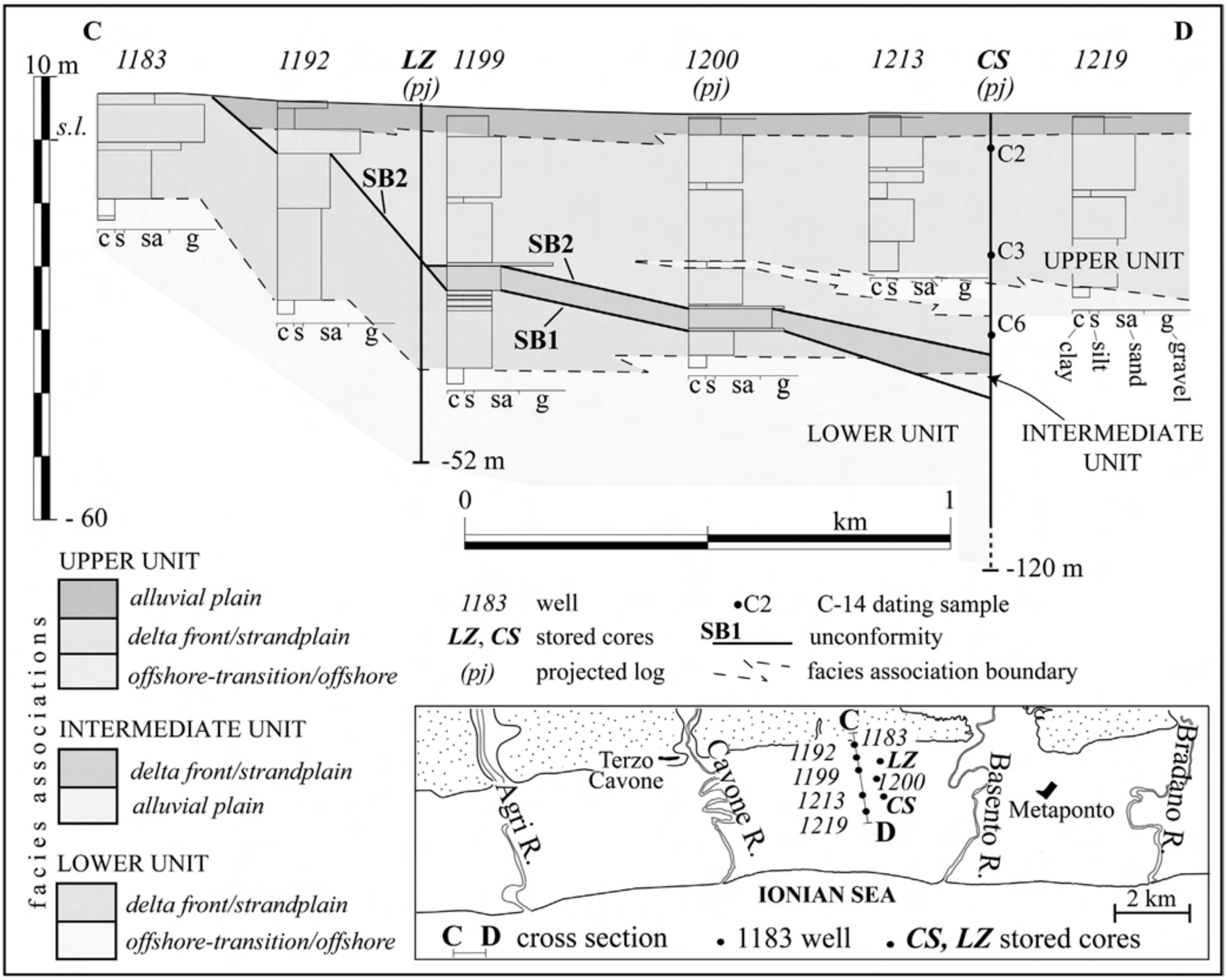

Fig. 6. Cross-section perpendicular to the present-day shoreline (modified from Gallicchio et al., 2009). Note the coastal wedge (intermediate unit) sandwiched between the lower and the upper units.

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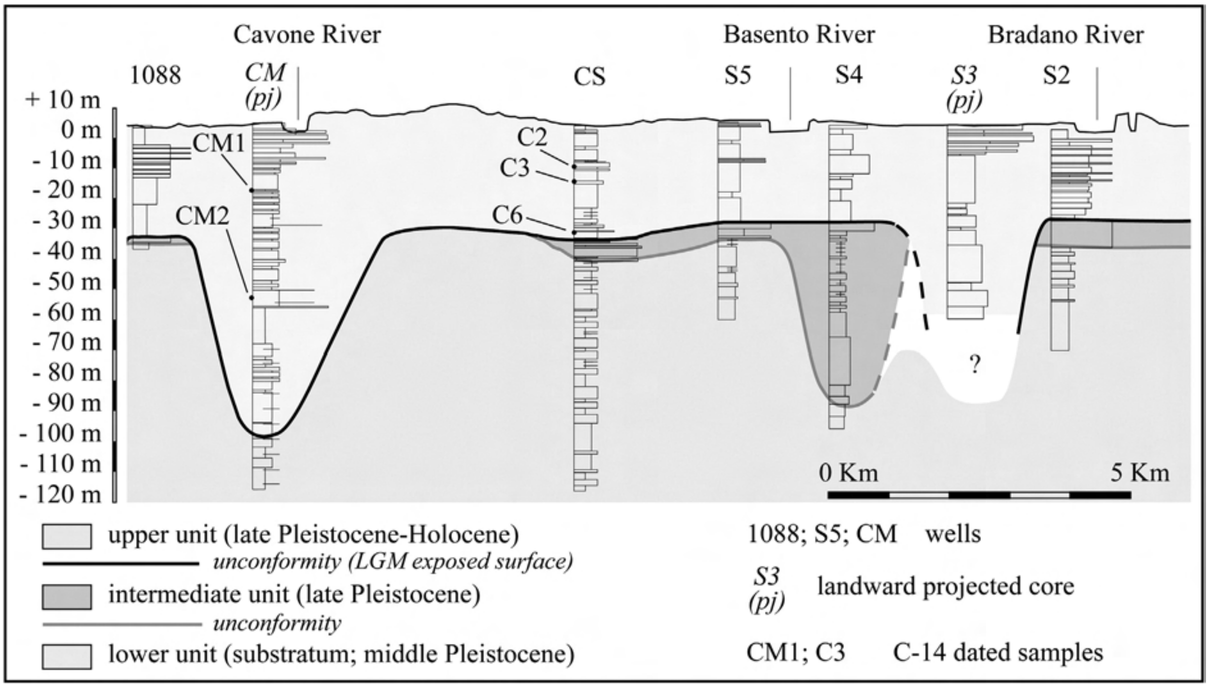

Fig. 7. Detail of the section in Fig. 2 that highlights the discontinuous occurrence of the intermediate unit in the MCP subsurface (modified from: Cilumbriello et al., 2010; Grippa et al., 2011).

the previous shallow-marine facies. The top of the unit is still developing today (Section 4).

The described stratigraphy must be integrated with that obtained along boreholes intercepting the LGM incised-valleys, where the intermediate unit and the top of the lower unit are eroded, and the valley fill is mainly represented by estuarine deposits (Cilumbriello et al., 2010). Upwards these pass to outer delta/shelf deposits, the same ones that laterally drown remnants of the intermediate unit through a ravinement surface (Figs. 5 and 7).

5.2. Age of the upper unit

The CS cored borehole (Figs. 4, 6 and 7) penetrates the upper unit at an interfluve location (overlying the intermediate unit) and yielded three radiocarbon datings from molluscs fragments: 7572 ± 50 yr BP at 35 m (sample C6), 4801 ± 50 yr BP at 19 m (sample C3), and 4355 ± 60 yr BP at 13 m core depth (sample C2). All reported ages are uncalibrated and uncorrected for marine reservoir age. This indicates middle and (mainly) late Holocene aggradation and progradation of the MCP.

The CM and LZB boreholes (Figs. 5 and 7) penetrate the upper unit at incised valley fill locations. Two radiocarbon dates on mollusc fragments were obtained from the CM core, yielding 11,853 ± 60 yr BP at 58 m (sample CM2) and 4960 ± 40 yr BP at 21 m core depth (sample CM1). Plant fragments were radiocarbon dated at 58 m of depth (sample LZB5) along the LZB core, yielding 13,075 ± 90 yr BP.

In sequence stratigraphy models, river valleys cut previously deposited successions when experiencing sea-level falls (e.g. Posamentier and Vail, 1988), and such incised valleys are filled with estuarine deposits during rise of sea level (e.g. Dalrymple et al., 1992; Zaitlin et al., 1994). Applying such models to the studied case, the estuarine filling developed between the end of the LGM and the drowning of paleointerfluve areas. That interpretation is consistent with the radiocarbon dating results and the facies features of the upper unit, as drilled in the valley fills and on the interfluves. Consequently, the intermediate unit in the interfluve regions must be considered older than the LGM (an inferred age for it is reported in the Section 6.1).

5.3. Seismic stratigraphy of drilled units

The three main units of the MCP subsurface potentially have different seismic impedances. To start with, the propagation of the *Vs* (shear wave velocity) indicated that the values of seismic impedance sharply increase in the lower part of the investigated succession. This allowed assessing the depth of the contact between sediments marked by an impedance contrast, i.e. a seismic discontinuity (Fig. 8). Our down-hole tests indicated the lower and intermediate units ("bedrock") to have very similar *Vs* values (450–500 m/s), considerably higher than for the "post-LGM" upper unit (200–300 m/s). Because the *Vs* of the "bedrock" is higher than the overlying sediments, it is possible to recognize the contact. The depth of contrasting seismic impedance was obtained at each measurement station, and was used to create a 3D isobaths map showing the geometry of the discontinuity surface, approximately corresponding to the base of the upper unit, namely to the boundary between pre- and post-LGM deposits (Fig. 8). Therefore, the obtained surface visualizes the LGM landscape. It is characterized by the occurrence of three NW–SE trending elongate and narrow depressions, which are roughly parallel to the present-day Cavone, Basento and Bradano riverbeds, and connect to their hinterland valleys. Their geophysically estimated depth increases downstream from about 50 m (inland) to about 90 m below the present-day sea level at the present-day shoreline.

6. Discussion

6.1. The inferred MIS-3 age of the intermediate unit

The upper unit is directly radiocarbon dated (post-LGM), the older units are not; however, using other constraints, their age may be inferred.

The intermediate unit is of coastal-marine origin, is bounded by unconformities, is sandwiched between offshore deposits, and is dissected by younger valleys. This should allow it to be correlated with known past history of sea-level variations, following sequence stratigraphy principles also considering vertical land movement and sediment

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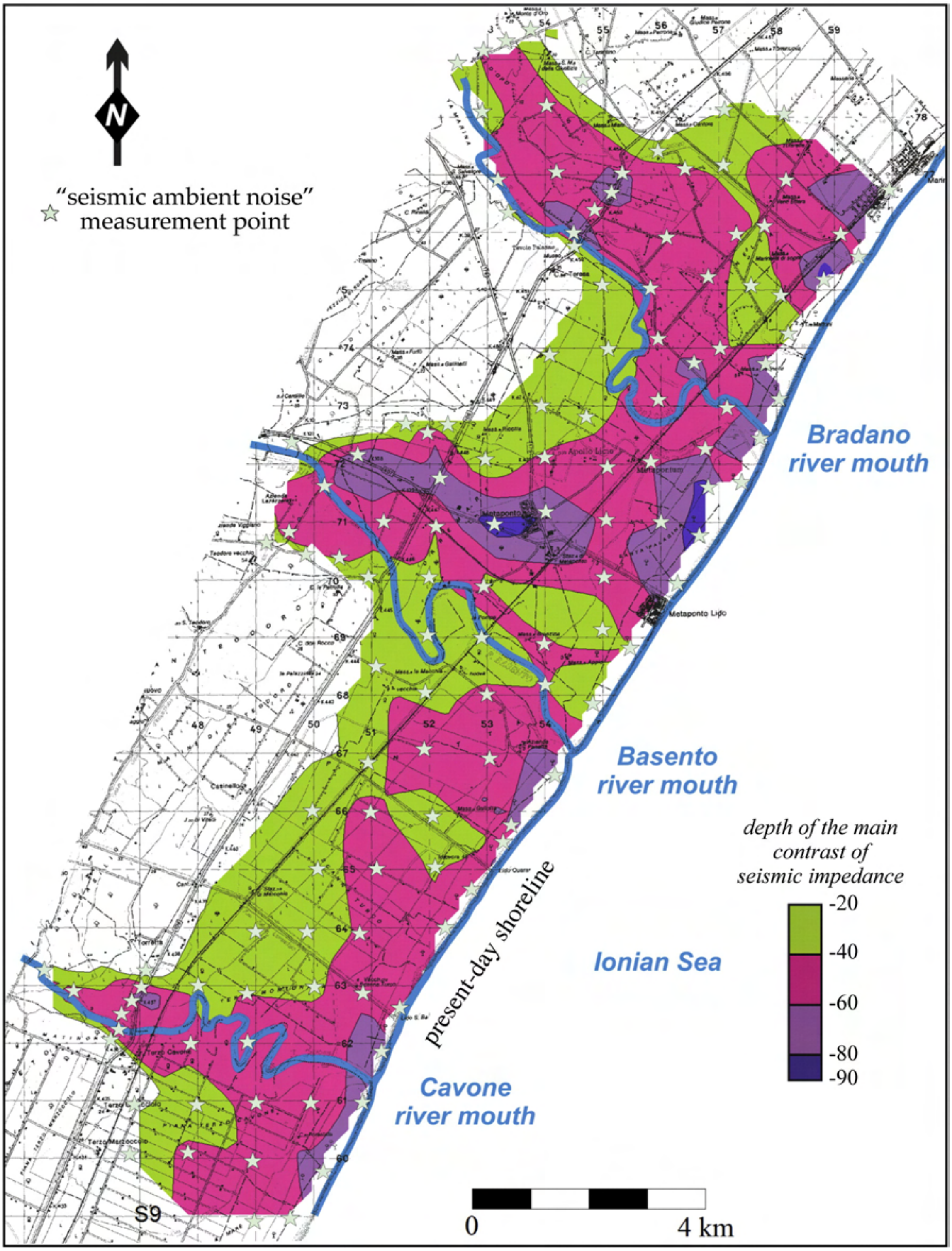

Fig. 8. Isobaths map of the main *Vs* discontinuity surface (modified from Grippa et al., 2011). Map and contour lines based on Natural Neighbour gridding of original XYZ data file. See Fig. 3 for survey area location.

input. In particular, studies on dated Pleistocene marine terraces in uplifting settings suggest that they form during relative sea-level highstands (Lajoie, 1986). In the Middle and Late Pleistocene, the main sea-level controlling factor was glacio-eustasy, with sea-level variations exceeding magnitudes of 100 m and with a dominant 100-kyr cyclicity (fourth order) (Hays et al., 1976; Pillans et al., 1998; Schwarzacher, 2000), reflected in a variety of records, including O^{18}/O^{16} ratio in deep ocean foraminifera, which allows direct linkage to Marine Isotope Stages (MIS) and global sea levels (Fig. 9). Various competing reconstructions of glacio-eustatic sea-level variation are available (e.g. Waelbroeck et al., 2002; Caputo, 2007) and continue to improve in accuracy and resolution. Unfortunately, curves obtained by various authors for diverse localities and record types are affected by discrepancies higher than ±20 m in the last few 100 kyr.

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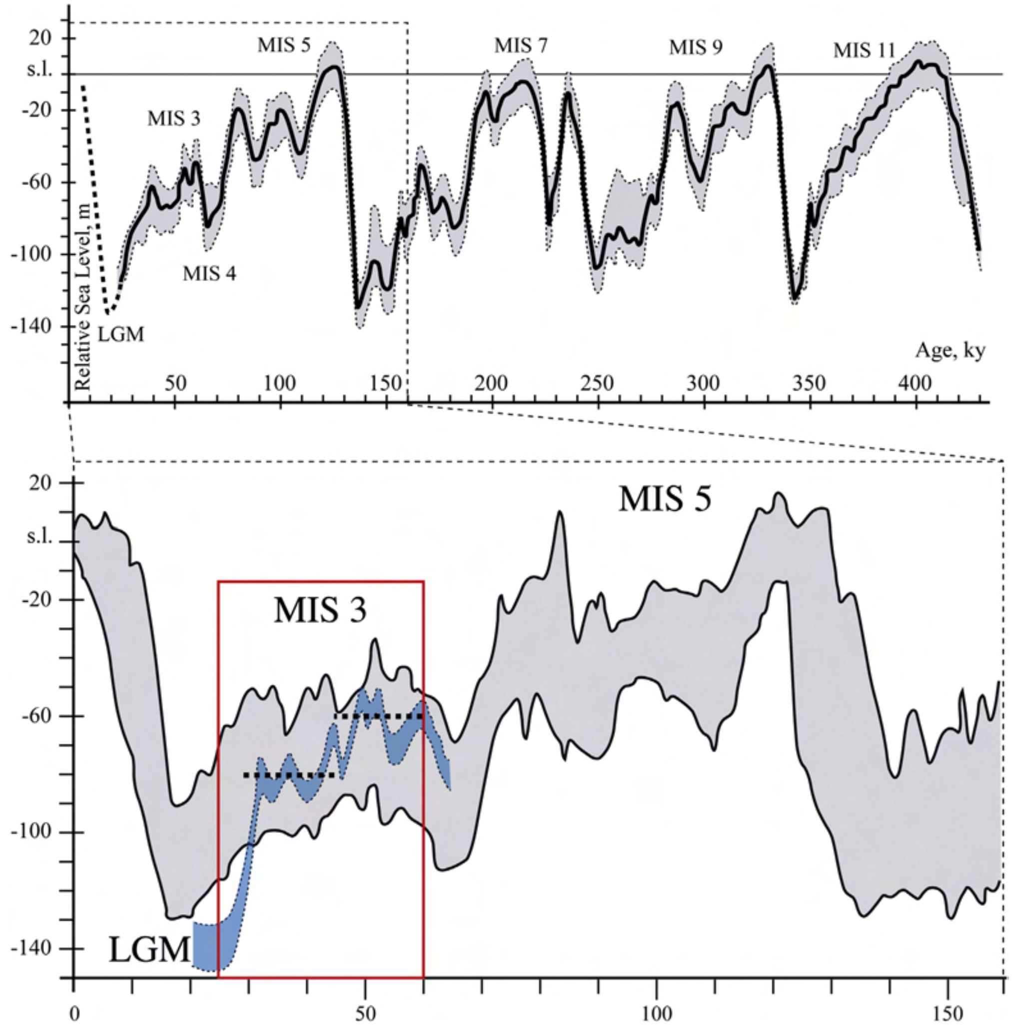

Fig. 9. Relative curves of sea-level variations induced by glacio-eustacy. Above: Ocean water δ^{18}O-based reconstruction for the last 430 ka, with confidence interval (modified from Waelbroek et al., 2002). Below: Envelope of the maximum and minimum positions of the sea level of the last 150 ka ('summing' curves reviewed by Caputo, 2007). The inset for MIS 3 shows curves proposed by Lambeck et al. (2002a, 2002b). According to Siddall et al. (2008) dotted lines at −60 m and −80 m are the "typical" sea-levels positions for the earlier and later parts of MIS 3.

In spite of these discrepancies, the evolution of each recognized unit was linked to a sea-level position. As shown, the buried top of the lower unit drilled in the MCP subsurface is made up of shelf deposits, interpreted to be the distal part of a coastal wedge cropping out landwards of the present-day MCP, and against which the upper unit laps out (Fig. 6). This ancient coastal wedge is correlated with the youngest marine terrace stranded landward as a consequence of the regional uplift, and it is interpreted to be part of the MIS 5 suite of deposits (MIS 5.1 by Cilumbriello et al., 2008), or a MIS 3 terrace (Caputo et al., 2010).

The MIS 5.1 attribution, combined with the sea-level curves for MIS 5 of Fig. 9, implies an uplift rate ranging between 0.3 and 0.6 mm/yr in the MCP area located between the Cavone and Basento rivers (Cilumbriello et al., 2008). Uplift rates are considered to decrease from south to north landward of the MCP from about 0.9 to 0.4 mm/yr, on the basis of a wide age dataset referred to markers of the last interglacial (i.e., MIS 5.5) (Hearty and Dai Pra, 1992; Bordoni and Valensise, 1998; Ferranti et al., 2006), even considering longer time spans (Schiattarella et al., 2006). These uplift rates have been confirmed by several recent studies around the Gulf of Taranto (e.g. Santoro et al., 2013).

Other authors have proposed higher tectonic uplift rates decreasing from 1.8 to 0.7 mm/yr from south to north along marine terraces located landward of the MCP (Caputo et al., 2010). These authors assigned a MIS 3 age to the lowermost suite of outcropping terraced marine deposits that the slower-uplift interpretation assigns to MIS 5.1. Shallow-marine deposits cropping out to the northwest of the MCP in a more tectonically stable area have been assigned to the MIS 3 by Belluomini et al. (2002). By contrast with the faster-uplift interpretation, these authors invoked the eventuality that some very-high peaks of the sea-level position could have characterized the MIS 3 stage.

It is important to underline that MIS 3 corresponds to a period between 60 and 25 ka, whereas MIS 5.1 corresponds to a period between 90 and 80 ka (Fig. 9). At the beginning of MIS 3, sea level rose from the MIS 4 lowstand position, reaching "typical" sea-level positions at 60 and 80 m below present-day sea-level respectively during the earlier and later parts of the stage (Siddall et al., 2008) (Fig. 9). Additional short-term (millennial) climatic fluctuations could have led to very high-frequency and relative large-amplitude sea-level changes, superimposed on lower-frequency sea-level changes (Lambeck and Chappell, 2001; Lambeck et al., 2002a, 2002b; Anderson et al., 2004; Peltier and Fairbanks, 2006; Rohling et al., 2008; Siddall et al., 2008; Frigola et al., 2012).

For the study area, attributing an MIS 3 age to the lowermost marine terraces cropping out along the inland edge of the MCP, implies attributing a similar age to the shelf deposits located below the intermediate

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unit (i.e., the buried coastal wedge), and would force the intermediate unit to be slotted in MIS 2. This is in disagreement with our findings regarding the dissection of the intermediate unit (mechanism and age, with the fill being just post-MIS 2) and with our environmental interpretation of its coarse deposit as a coastal deposit. Our data suggest that at the time of MIS 2, the study area experienced the lowest base level and was in a considerably lower position than where the intermediate unit is found. In an unlikely scenery, both the lowermost cropping out terraced marine deposits and the buried coastal wedge formed within MIS 3. In that case the shelf deposits below the buried coastal wedge should not be correlated with the terraced outcrops inland of the MCP, and two alternative hypotheses could be evaluated. In the first one, the inland outcrops developed early in MIS 3 (global sea level at −60 m) and the buried intermediate unit developed in the later part (global sea level at −80 m, Fig. 9). Since 50 m in elevation separate the inland from the buried deposits, this is not consistent with the global sea-level variation (20 m). The second hypothesis considers that the millennial climate variations within the MIS 3 could have caused high frequency and high amplitude sea-level changes, and, consequently, the development of many simple sequences. In that case, the outcropping deposits could represent the compound result of several Highstand Systems Tracts (HSTs), whereas the buried wedge could represent the compound result of several Lowstand Systems Tracts (LSTs), perched on the shelf. If so, however, one would expect to have recognized more unconformities in the HST and LST deposits, than has been the case. Anyway, these interpretations disagree with the facies analysis and well-log correlation shown in Fig. 6, and are disfavored as explanations.

In contrast, accepting a MIS 5 age for the lowermost outcropping terraced marine deposits (in accordance with the majority of quoted works), and for their distal counterpart located below the intermediate unit, the correlation of the buried coastal wedge with the MIS 3 would be straightforward. This interpretation would explain the variety of facies associations (from fluvial to deltaic) drilled in this relatively thin unit as the result of MIS 3 climatic and sea-level fluctuations. The recognition of an incised-valley fill below the buried coastal wedge (Cilumbriello et al., 2008; Fig. 7: core S4; depicted as part of the intermediate unit) could be seen as a disectional imprint of the MIS 4 sea-level fall. This stage was followed by the filling of the valley and by the depositional regression of a coastal wedge above the interfluve areas during the subsequent relative sea-level highstand (MIS 3) (Fig. 10). This interpretation seems to be consistent with recent sea-level curves for the Late Pleistocene, including the data from the Mediterranean Sea (e.g. Lambeck et al., 2002b; Siddall et al., 2003; Arz et al., 2007; Rohling et al., 2008; Siddall et al., 2008; Rovere et al., 2011; Yokoyama and Esat, 2011; Antonioli, 2012; Frigola et al., 2012).

6.2. The inferred LGM landscape

The irregular surface imaged in the MCP geophysical survey and corresponding to the main seismic unconformity depicts the buried paleogeography of the main LGM valleys. Since deposits below the unconformity developed before the sea-level fall linked to the LGM, and deposits above the unconformity (the upper unit) began to develop soon after the valleys incision related to the same sea-level fall, the irregular surface of the seismic unconformity (Fig. 8) corresponds to the exposure surface produced on the older units during the sea-level fall recorded between the MIS 3 and MIS 2 (Fig. 11). Therefore, this surface represents the inland landscape of the Gulf of Taranto during the relative lowstand of the sea level related to the LGM. The main features in this landscape are the incised valleys produced at that time by the same rivers running through the MCP today. The paleogeography of main incised valleys suggests the possible confluence of two paleorivers (Bradano and Cavone) at a position below the modern coastal plain. The dendritic aspect of the suggested lower-order drainage network was probably linked to the development of minor tributaries induced by the retrogradation of scar features (Fig. 11). Considering the present-day offshore bathymetry (Fig. 3) representative of the seafloor equilibrium-surface in earlier high-stand times, one can assume LGM lowstand rivers to have been forced to cut the previous equilibrium-surface including the shelf edge. The present-day shelf edge is located between 40 and 60 m below the sea level, considerably higher than the lowest position of the sea level during the LGM. This means that at the LGM, the river mouths delivered sediment directly to the slope, with much less potential to construct a coastal plain than during highstand conditions. This justifies also the depths reached by the rivers during last relative sea-level lowstand, and means that inferred incised valleys were very close to the LGM coastline. It may be that the distal reach of these incised valleys was the head of gullies running towards the main submarine canyon. In fact, if sea level would lower in the future to depths comparable to those of the LGM, present rivers would be forced to run in these widespread gullies (Fig. 3).

A threshold is observed in the inferred LGM surface along the paleovalley corresponding to the Basento paleoriver (the central paleovalley in Figs. 8 and 11). This physiographic "anomaly" may indicate the occurrence of coarse-grained sediments belonging to the base

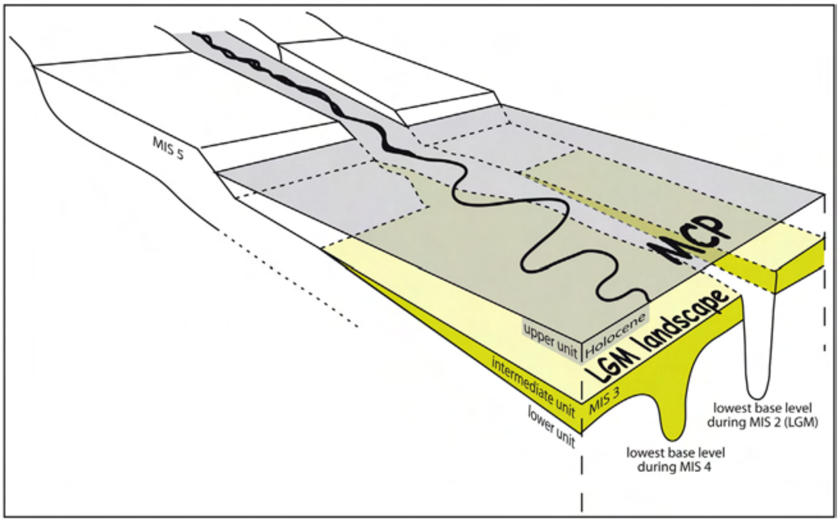

Fig. 10. Block diagram showing the stratigraphic architecture of the MCP subsurface.

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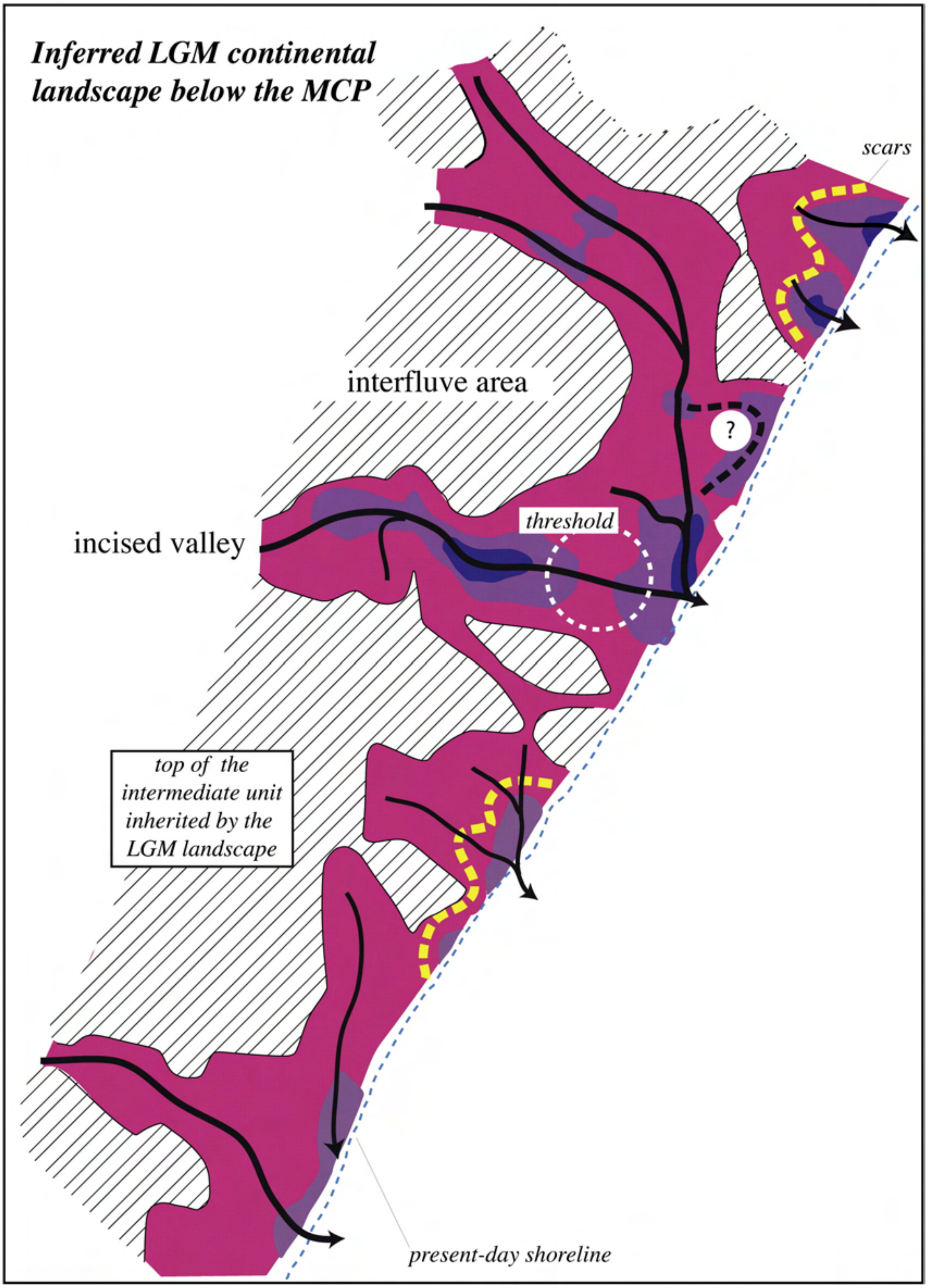

Fig. 11. Map derived from the interpretation of the isobaths map of Fig. 8. Main features of the LGM landscape are shown, including possible course of main rivers and tributaries. Interfluve areas were the remnants of the top of the MIS 3 terrace (the intermediate unit in the MCP subsurface). According to the late Pleistocene relative sea-level curve, during the LGM these flat areas were located at least at 90 m of elevation with respect to the sea level. Riverbeds inside incised valleys were located at least 60 m below these interfluve areas.

of the upper unit, whose shear wave velocities are similar to those of the deposits of the underlying unit. The threshold is localized where the paleovalley opens seaward; such an area could have hosted a coarse-grained beach/shoreface barrier since a wave-dominated estuarine system (sensu Darlymple et al., 1992) could have developed in the microtidal setting of the Gulf of Taranto. This coarse-grained body, having the same seismic impedance of the underlying clays and a lower seismic impedance with respect to the overlying sediments, could produce a local elevation of the surface obtained by mapping the main impedance contrast in the subsurface (an apparent geological threshold along the river course). In contrast, it could represent a morphological threshold (a sedimentary body) developed during the transgression in the estuarine system and not a morphological feature of the LGM landscape (Fig. 12).

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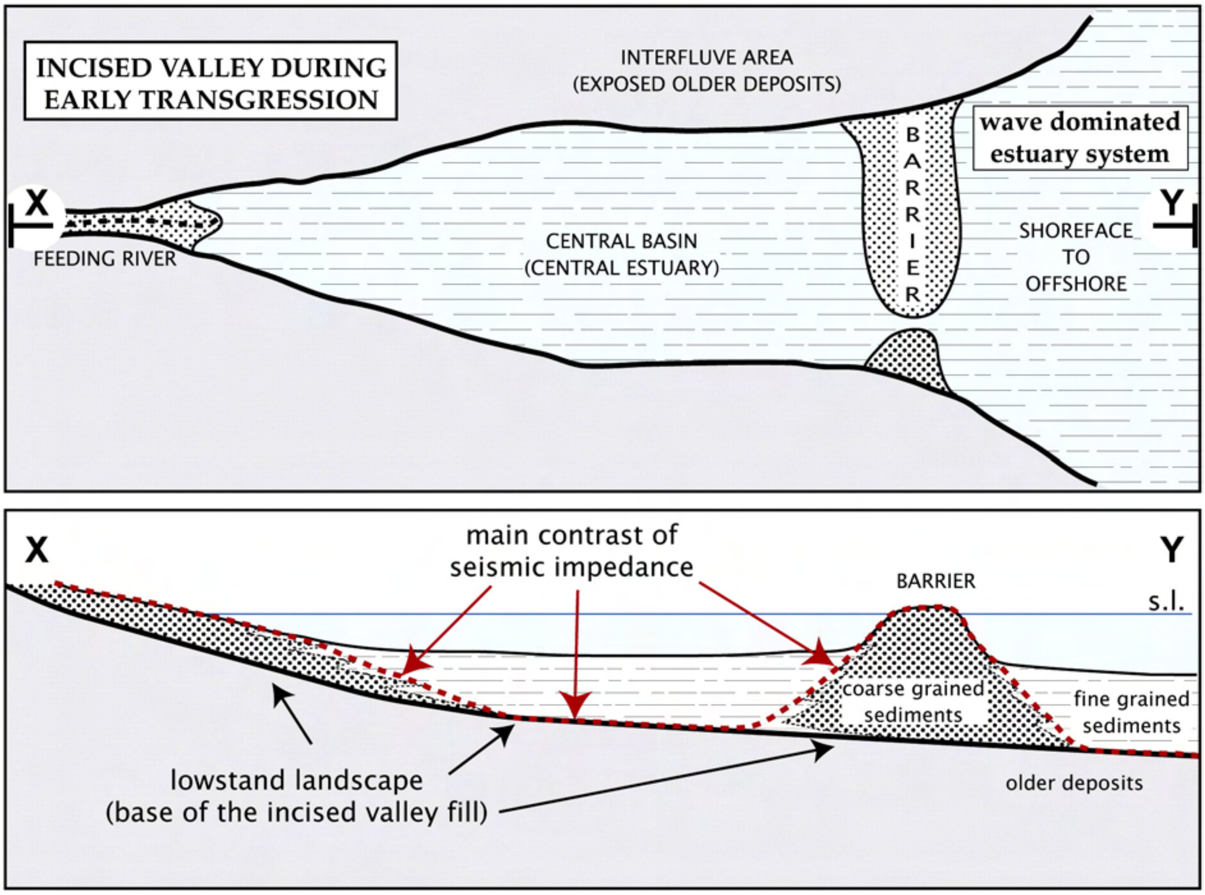

Fig. 12. Plan view and section of a wave-dominated estuary system occupying a previous incised valley during early transgression (after Dalrymple et al., 1992). Sediments of both feeding river and beach barrier are coarser than those ones of both central basin and offshore. Coarser sediments are characterized by higher *Vs* values (similar to those ones of the encased older deposits) than finer sediments. After burial of the estuary system, the use of a geophysical method based on seismic impedance to detect the lowstand landscape can induce a wrong lecture of this ancient surface. This can explain the occurrence of a threshold in the inferred LGM landscape shown in Fig. 11.

6.3. Timing of drowning and burying of the LGM landscape

As is recognized below other coastal plains of Italy too (e.g. Tortora et al., 2001), the post-LGM succession below the MCP began to develop soon after the onset of the deglaciation phase. Since the sea level rose at a rate that exceeded the sedimentation rate, incised valleys were progressively flooded and their sedimentary fills were produced by backstepping estuarine systems (in accordance with sequence stratigraphy models; Posamentier and Vail, 1988; Darlymple et al., 1992, 1994; Zaitlin et al., 1994; Darlymple et al., 2006). When the sea level reached the margins of the valleys, paleointerfluve areas were drowned, and "suddenly" shelf environments developed on previously exposed lands. Estuarine deposits (filling paleovalleys) and the underlying shelf deposits (aggrading onto both previously exposed lands and top of successions filling incised valleys) are characterized by a deepening-upward trend, recording a "long term" late Pleistocene to early Holocene transgression; at the end of the transgression, a depositional regression took place, since on previous shelf deposits progradational wave-dominated delta developed (Figs. 4 to 6).

According to sequence stratigraphy concepts, the whole transgressive phase recorded in the upper unit of the MCP before the depositional regression corresponds to the last Quaternary Transgressive Systems Tract (i.e. the post-LGM TST), the age of which spans from about 18 ka to about 5.5 ka (e.g. Cattaneo and Trincardi, 1999). The regressive phase recorded in the topmost part of the upper unit, which is the still active phase in the MCP, corresponds to the last Quaternary HST (late Holocene in age and post 5.5 ka).

In terms of sequence stratigraphy, the upper unit covers the last fourth order sequence-boundary produced in response to the 100 kyr eustatic sea-level cyclicity, globally dominating until the transition from the Early to the Middle Pleistocene.

7. Conclusions

The dataset concerning the MCP and its offshore equivalent allowed us to obtain a background about depositional profiles and systems accompanying relative highstands of the sea level in the area during the Late Quaternary. The present-day coastal plain represents the top of a coastal wedge prograding on a very narrow-shelf; the nearshore/shelf edge is located a few tens of meters below the sea level and the coastal wedge is destined to be perched on the steep slope (up to 5° dip) that connects the nearshore/shelf to a deep basin (the Ionian Sea). Likely, this was the same scenery during previous relative highstands of the sea level.

A lowstand scenery is represented by the LGM landscape, marked by the local occurrence of incised-valleys whose base deepens to about 90 m below present day sea level. Flat interfluve areas located between LGM incised valleys represent inheritance of the top of a past highstand coastal body, likely developed during the MIS 3. This coastal wedge was perched in the vicinity of the shelf edge, and so, during the relative sea-level fall and lowstand, the same wedge was deeply incised by rivers. This landscape was the same during almost the whole post-LGM sea-level rise when the valleys were progressively flooded. LGM interfluves were drowned only when the sea level reached the margin of incised

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valleys, and, according to radiocarbon data, this drowning occurred not before 8 ka.

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