

Use of the HVSr method to detect buried paleomorphologies (filled incised-valleys) below a coastal plain: the case of the Metaponto plain (Basilicata, southern Italy)

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ABSTRACT A non-invasive and low-cost geophysical method for the H/V spectral ratio (HVSr) of microtremors was employed for the first time in the Metaponto coastal plain (Basilicata region, southern Italy) in order to draw 3D unconformities within the subsurface. Through the stratigraphical analysis of several boreholes, the occurrence of two irregular erosional surfaces, bounding three main sedimentary units, was inferred. The upper unit fills and covers some paleovalleys that were incised during the Last Glacial Maximum (LGM). Filling was induced by a sea level rise and a high stand that followed the LGM. According to the stratigraphy of some boreholes, a 4-layer model of the Metaponto coastal plain subsurface was used in the geophysical investigation. The inversion of the HVSr data has been performed using the velocities of the shear waves calculated by some down-hole tests, and the main geophysical unconformity was recorded below the uppermost unit, corresponding to the topmost two layers of the 4-layer model. A 3D view of this main geophysical unconformity shows a surface with the occurrence of some deeper, narrow, and sinuous zones running roughly perpendicular to the present-day coastline and at depths of up to 90 m below the present-day sea level. These narrows likely correspond to the paleovalleys that developed in the region during the LGM and are buried below the Metaponto coastal plain. The satisfactory fit obtained by the comparison of geophysical sections with geological ones highlights the reliability of the HVSr method for reconstructing the geometry of buried paleomorphologies characterized by an appreciable contrast of seismic impedance between “bedrock” and “cover”.

Key words: Metaponto plain, HVSr of microtremors, buried morphology, incised valley fill, Quaternary.

1. Introduction

It is accepted worldwide that present-day depositional coastal plains developed after the sea-level rise that followed the Last Glacial Maximum (LGM), and that, before this rise, the continental shelves of Italy were also exposed and subjected to subaerial and fluvial erosion (Tortora *et al.*, 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 in Italy below the Tyrrhenian, Adriatic, and Ionian coastal plains (Bellotti *et al.*, 1994, 1995; Spilotro, 2004; Aguzzi *et al.*, 2005; Amorosi *et al.*, 2008a, 2008b; Milli *et al.*, 2008; Cilumbriello *et al.*, 2010). In the last two decades, both paleogeographic distribution of this kind of buried incised valleys and features of their sedimentary fill represent some of the main goals for hydrocarbon research (i.e., Darlymple *et al.*, 1994) but recently, in Italy, their study has become important also for aquifer management (i.e., Valloni, 2007; Bersezio and Amanti, 2010). This kind of knowledge about coastal-plain subsurface characterized by buried incised valleys increased thanks to both detailed sedimentary analyses and application of sequence-stratigraphy principles, but a multidisciplinary approach needs to better define these features and to constrain interpretations of data.

In the present work, litho-stratigraphical and geophysical data coming from two different research-projects are synthesized, and a preliminary 3D configuration of the Metaponto coastal-plain subsurface is proposed. The Metaponto coastal plain (Fig. 1a) belongs to two regions of southern Italy: the south-western part of the plain belongs to the Basilicata region, while the north-eastern part of the same plain belongs to the Puglia region. In particular, this work focuses on the area which is crosscut by some rivers of the Basilicata region (see inset in Fig. 1b). In this area, Cilumbriello *et al.* (2010), collecting and studying litho-stratigraphical data coming from tens of wells, reconstructed a 2D architecture of drilled sedimentary bodies along some geological sections, recognizing a series of incised paleovalleys covered by an up to about 100 m thick upper Pleistocene-Holocene sedimentary succession. At the same time and in the same area, independently from the lithostatigraphic study, Grippa *et al.* (2009) and Grippa (2010) applied a geophysical approach to the investigation of subsurface features, based on a survey of HVSR (Horizontal-to-Vertical Spectra Ratio) measurements of the ambient noise. Findings emerging from such an approach are now described in detail with the aim of proposing a virtual 3D view of the Metaponto coastal-plain subsurface, exalting the paleogeographic (areal) distribution of the paleovalleys.

2. Geological setting of the Metaponto coastal plain and the litho-stratigraphical approach

The Metaponto coastal plain (Fig. 1a) strikes SW-NE for about 70 km and extends between the exposed front of the south-Apenninic chain and the exposed part of the Apulian Foreland. This coastal plain represents the narrow, exposed part of the present-day depositional coastal wedge bordering the Taranto Gulf in the Ionian Sea. It corresponds also to the southernmost and most recent outcropping part of the Bradanic Trough, which represents the filled foredeep-basin of the Apenninic orogenic-system in southern Italy (Fig. 1a).

The sedimentary infill succession of the Bradanic Trough, up to 2 km thick, is mainly buried. Because the basin has undergone uplift at least since middle Pleistocene, the upper part of the infill succession crops out, and it is basically made up of coarse-grained deposits of coastal environments (Tropeano *et al.*, 2002). When approaching the Ionian coast of the Taranto Gulf, these deposits form a staircase of marine terraces corresponding to discrete depositional coastal-wedges; the top of the youngest and lowermost coastal wedge is the present-day Metaponto coastal plain (Vezzani, 1967; Brückner, 1980; Caputo *et al.*, 2010).

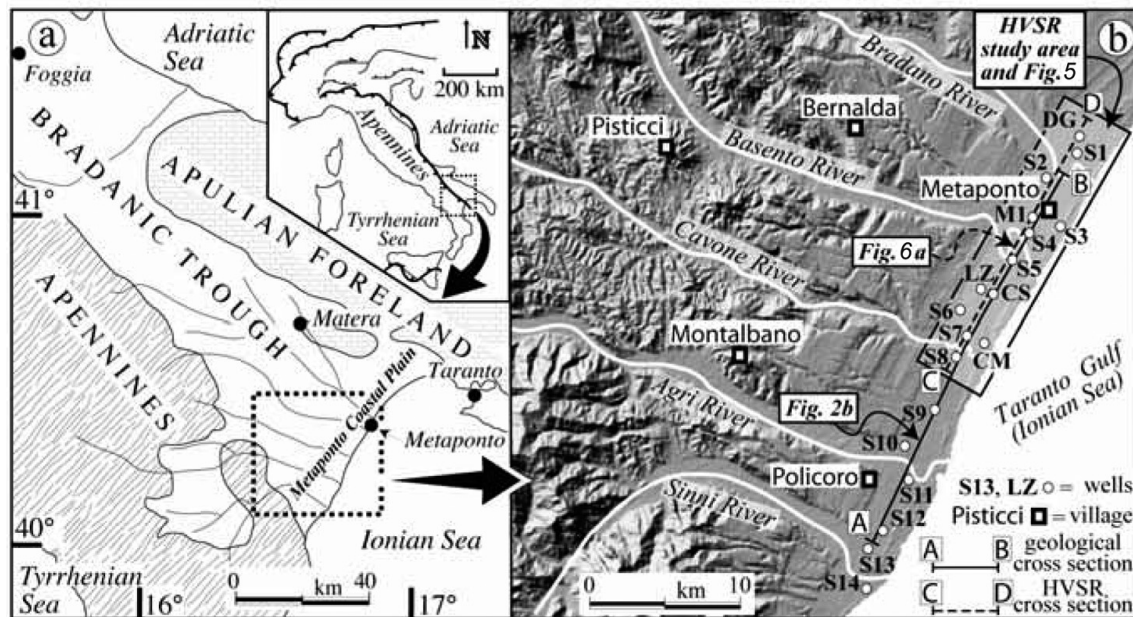


Fig. 1 - Main structural domains of southern Italy (a); study area (b) with location of wells used to realize the geological cross-section of Fig. 2b. The shaded inset area refers to HVSR measurement sites as shown in Fig. 5. Traces of sections in Figs. 2b and 6 are also shown.

2.1. Surface features

Recently, a detailed geological map of the Metaponto coastal plain located north of the Cavone River was proposed by Pescatore *et al.* (2009). The coastal area studied by these authors is characterized by the presence of three rivers (Cavone, Basento and Bradano) with their interfluvial and intermouth zones. Considerations regarding the geomorphological and sedimentological features made for this area by Pescatore *et al.* (2009) may be extended to the whole coastal plain. The outcropping deposits of the plain developed after the last eustatic rise of sea level; in particular, they basically aggraded up to about the present-day topographical surface up to the late Holocene, since archaeological remains dated between the VII and the III century B.C. were found at a depth of 3 m (Boenzi *et al.*, 1987; and references therein). Landwards, the plain leans against the younger (late Pleistocene in age), outcropping marine terrace of the Metaponto area [the 7th order terrace, *sensu* Vezzani (1967); the 1st order, *sensu* Brückner (1980)], reaching a maximum elevation of about 14 m above sea level; seaward, the same plain corresponds to the present-day retreating beach. According to Pescatore *et al.* (2009), the outcropping deposits of the Metaponto coastal plain may be subdivided into continental deposits and transitional (marine-continental) ones. Continental deposits belong to alluvial environments, either located along main river channels or on wide flood plains, where small marshes “survive” after heavy land reclamation suffered by the Metaponto coastal plain some decades ago. Transitional deposits belong to delta and beach environments, whose depositional systems, during the late Holocene, prograded up to the present-day shoreline.

2.2. Subsurface features

Different kinds of subdivisions of the subsurface deposits of the Metaponto coastal plain were proposed in the last years.

Polemio *et al.* (2003) opted for a lithological subdivision of the subsurface leading their interpretations to no more than 40-50 m of depth. According to these authors, the buried succession is characterized, from the bottom to the top, by four units, each displaying different thicknesses moving either along dip or along strike. The lowermost, fourth unit consists of grey, fine-to-coarse-grained sands; the third unit consists of grey silty clays and clays whose drilled thickness may reach over 30 m; the overlying, second unit is made up of gravelly sands, with thin layers of silty clays and clays, and is characterized by a variable thickness, up to 45-50 m moving seawards; finally, the uppermost, first unit is made up of grey and/or yellow clays, showing a thickness variable from a few centimetres to 10 m, moving landwards.

Spilotro (2004) first recognized the presence of filled paleovalleys in a more than 100 m thick succession (Fig. 2a); these paleovalleys were interpreted as induced by a base-level fall linked to the LGM. Accordingly, a very irregular erosional surface bounds two main units, schematically represented below by “blue clays” (the “basement” of the local aquifer system) and above by alluvial sediments (filling paleovalleys and aggrading in the paleo-interfluvial areas) (Fig. 2a).

More recently, Pescatore *et al.* (2009), thanks to facies analysis and stratigraphical correlations obtained by some cores, subdivided the buried succession of the Metaponto coastal plain, drilled down to an approximate depth of 120 m, in three units, the uppermost of which comprises the outcropping deposits of the plain. The three units were identified thanks to the presence of two main discontinuity surfaces, successively interpreted by Cilumbriello *et al.* (2010) as sequence boundaries (SB1 and SB2 in Fig. 2b). According to these last authors, the upper Holocene evolution of the Metaponto coastal plain is linked to the last relative high stand of the sea level, but buried deposits record other environments and depositional systems linked to other positions of the relative sea level.

The stratigraphical subdivision proposed by Cilumbriello *et al.* (2010) can be synthesized as follows (Fig. 2b).

- The lower unit, of middle-late (?) Pleistocene and drilled down to a maximum thickness of 75 m without reaching the base, is considered the substratum of the Metaponto coastal plain deposits and is made up of shelf-transition silts, clays and sands. The upper boundary of this substratum is represented by an irregular surface that is generally found at a depth of about 20-40 m but it can deepen locally to a depth of about 100 m, in correspondence to the paleovalleys.

- The middle unit (MP1, Metaponto Plain 1) lies on the substratum discontinuously, is late Pleistocene in age and generally shows a thickness of 15 m, but locally, in correspondence with a paleovalley, can reach a thickness of 60 m. The paleovalley fill is made up of estuarine silty-sandy deposits. Above the paleovalley fill, estuarine deposits pass upwards to fluvial and/or deltaic sandy-gravelly deposits with very thin clayey intercalations. These fluvial and/or deltaic deposits characterize the whole unit except for the paleovalley fill.

- The upper unit (MP2, Metaponto Plain 2) erosionally overlies either unit MP1 or the substratum, and is late Pleistocene and Holocene in age. Unit MP2, whose upper boundary corresponds to the topographic surface, has a thickness of 30 m and locally deepens to a depth of 90 m, where paleoincisions are located. Paleovalley fills are composed of fluvial sandy-gravelly

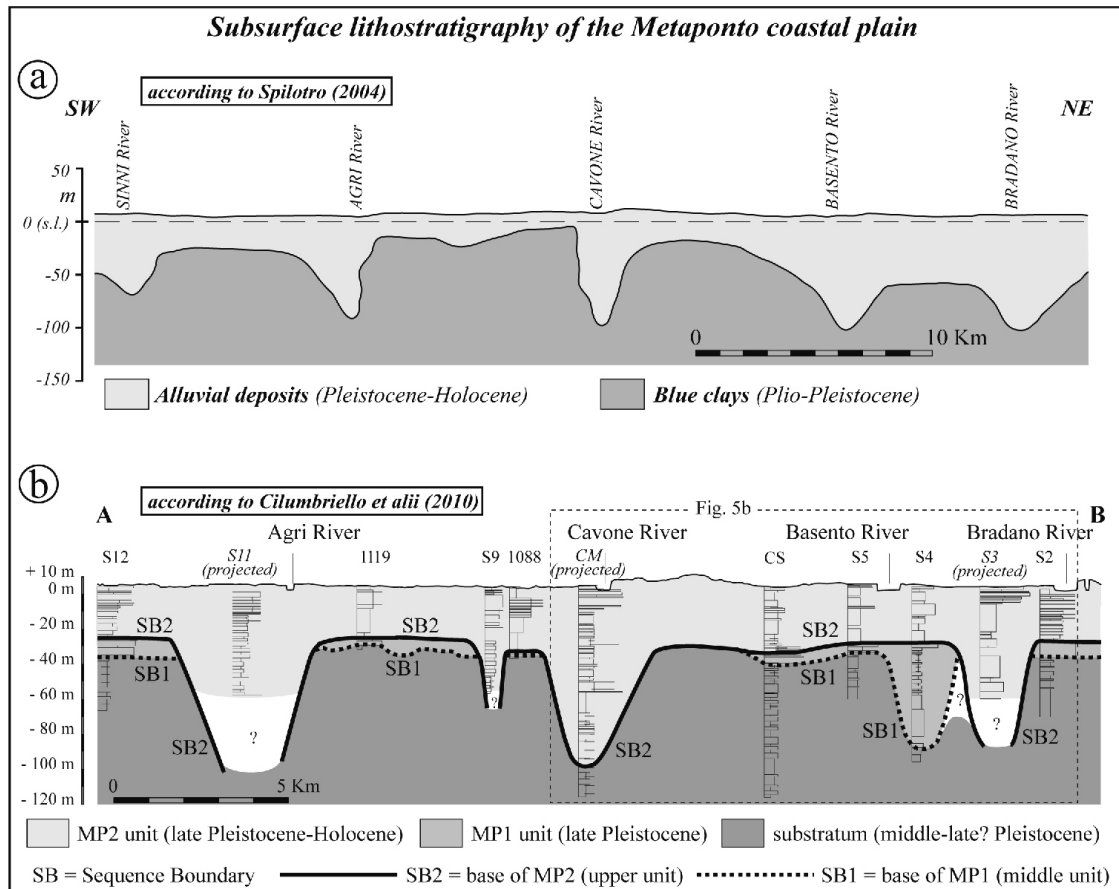


Fig. 2 - Subsurface stratigraphy of the Metaponto coastal plain: a) schematic section proposed by Spilotro (2004) highlighting the presence of several paleovalleys incised in the clay of the “substratum”; b) cross section parallel to the present-day shoreline (see Fig. 1b for location) showing the stratigraphic architecture of buried Metaponto coastal plain succession as proposed by Cilumbriello *et al.* (2010); note the presence of two sequences above the “substratum”.

deposits passing upwards to estuarine silty and sandy deposits; upwards, above the valley fills, these deposits pass to offshore-transition silty-clay, then to deltaic silty-sands, and finally to fluvial sands. These offshore-transition-to-fluvial deposits characterize the whole unit where it is only up to 30 m thick. The MP2 unit was also dated by radiocarbon analyses that supplied ^{14}C uncalibrated ages variable from $4,355\pm 60$ years B.P. at a depth of 13 m to $13,075\pm 90$ years B.P. at a depth of 58 m (Cilumbriello *et al.*, 2010); these data are in accordance with a ^{14}C age of $11,700\pm 160$ years BP provided by Cotecchia *et al.* (1969) for deposits located at a depth of 50 m below the same coastal plain.

3. The geophysical approach

Since direct analyses on drilled sediments could be performed only for some of the most recent boreholes while only the drawn stratigraphical logs were randomly available from the old

boreholes, a geophysical approach was performed to characterize the subsurface of the Metaponto coastal plain. The geophysical survey was performed before the publication of the stratigraphical and sedimentological study of Cilumbriello *et al.* (2010); consequently, the geophysical survey was based on the stratigraphical model proposed by Spilotro (2004) who was the first to suggest the occurrence of deep valleys incised in the “bedrock” (marine “blue clays”) filled and covered by alluvial deposits (Fig. 2a). According to Spilotro (2004), a main stratigraphical discontinuity between clays (below) and covering deposits should have been detected everywhere at different depths. Since direct information about stratigraphy coming from some recent boreholes suggested the presence of silts and sand above gravels before finding the “bedrock”, several HVSR measurements have been carried out close to those boreholes whose down-hole tests were available, in order to make a comparison between stratigraphical and geophysical data. The goal was to elaborate a 3D model of the main seismic unconformity within the subsurface, based on the fact that the V_S of the “bedrock” should be rather higher than the V_S of the overlying sediments. To obtain this result, a detailed geophysical survey based on the HVSR method applied to ambient noise (Nakamura, 1989) was performed on a selected sector of the Metaponto coastal plain (see inset in Fig. 1b).

3.1. The HVSR technique

Since Nakamura (1989) published his famous paper on the practical estimation of the amplification properties of soil layers using HVSR of ambient noise, or microtremor, this method has attracted the attention of numerous investigators who have applied it all over the world. Indeed, the use of the microtremor as seismic input makes this technique non-invasive, rapid and of low cost.

The main goal of the HVSR method is to underline the resonance frequency or fundamental mode of the soil.

The spectrum of the seismic waves which travel through the Earth’s crust, including the low-amplitude waves of the microtremor, can be considerably altered by the heterogeneity of the rheological and physical parameters of the shallow geological layers. Each geological layer, whose physical parameters are considered almost constant, is characterized by its own seismic impedance (Z), i.e., the resistance of the geological layer to the motion of its particles. The impedance is given by the product of the density (ρ) of the layer and by the velocity of the S waves (V_S) in the same layer.

If we consider the simplest stratigraphical example represented by an H-thick, soft sedimentary layer with density ρ_2 , velocity of S waves V_{S2} and seismic impedance Z_2 overlying a stiff bedrock with density ρ_1 , velocity of S waves V_{S1} and seismic impedance Z_1 , and given that $Z_2 < Z_1$, a contrast of seismic impedance occurs. The seismic waves travelling upwards undergo a process of multiple reflection inside the soft layer and consequently interfere with the incident waves, reaching the maximum amplitudes, i.e., the resonance conditions, when the incident wavelength is 4 times (or its odd multiples) the thickness of the overlying layer. This phenomenon is known as local seismic amplification and it is the basis of the microzoning studies.

The fundamental resonance frequency f_r of the upper layer whose thickness is H , relative to the S waves is equal to:

$$f_r = V_S / 4H. \quad (1)$$

The validity of the HVSR method applied to ambient noise is based on the following three hypotheses:

- 1) ambient noise is generated by local surface sources and the contribution of deep sources is negligible;
- 2) amplification is due to the wave propagation inside a soft layer overlying a stiff bedrock characterized by a higher value of seismic impedance;
- 3) the vertical component of motion is not subject to amplification.

The amplification of the horizontal components of vibration relative to the vertical one is explained either as a direct consequence of the soil-induced modification of the Rayleigh waves ellipticity, or by considering a response of local soil to the excitation of the incoming body waves' field.

The measurements of ambient noise were carried out by using the digital tromograph TROMINO which is instrumented by three electrodynamic velocimeters oriented N-S, E-W and Up-Down. The lightness and handiness of this instrument allowed us to perform measurements on every kind of terrain, even in sites that are not easily accessible to vehicles.

The recorded signal is finally processed by the software Grilla, whose main product is the HVSR diagram showing the frequency range (x-axis) versus the values of the spectral ratio H/V (y-axis). In this diagram, a peak indicates the amplification value of the horizontal components of the soil motion with respect to the vertical component (y-axis) relative to the resonance frequency (x-axis).

Based on Eq. (1), the value of the resonance frequency is inversely proportional to the depth of the interface between two layers characterized by a contrast of seismic impedance. The higher the contrast of impedance, the higher the expected amplitude of the H/V peak, although the correlation between the amplitude of the peak and the seismic amplification is not linear (Mucciarelli and Gallipoli, 2001). Therefore, Eq. (1) allows us to assess the depth of a stratigraphical contact marked by an impedance contrast if the V_S of the upper layer is available or, viceversa, to calculate the V_S of the upper layer if we have a stratigraphical log from a borehole (Ibs-Von Seth and Wohlenberg, 1999; Delgado *et al.*, 2000; Oliveto *et al.*, 2004).

As regards the maximum depth of investigation, since this kind of tromograph can measure a resonance frequency down to 0.1 Hz, if the upper layer has a V_S velocity of 400 m/s, for example, we can detect an about 1-km deep stratigraphical interface (Castellaro *et al.*, 2005).

It is worth noting that, even if we do not consider the lateral heterogeneities of the geological bodies, in any case, the real stratigraphical successions are generally more complex than the example described above, since in most cases (and the Metaponto coastal plain is one) we deal with sedimentary sequences that are characterized by different layers with different seismic impedances. However, when a multilayer stratigraphical succession is investigated by this geophysical technique, the final HVSR diagram shows as many peaks as the horizons of seismic impedance, thus giving information also about the thickness of the geological layers (Oliveto *et al.*, 2004).

An overview of controversies, history and various applications of the method can be found in Mucciarelli and Gallipoli (2001).

Table 1 - Stratigraphical features and V_S values of the model of the soil used for the inversion of the HVSR data.

LAYER	LITHOLOGY	THICKNESS (approx.)	DEPTH (approx.)	V_S (approx.)
Layer 1	Silt and sand	5 m	0-5 m	200 m/s
Layer 2	Silt and sand	25-35 m	5-30/40 m	300 m/s
Layer 3	Gravel	0-10 m	30/40-40/50 m	450-500 m/s
Layer 4 (BEDROCK)	Clay	hundreds m	30/40-? m	450-500 m/s

3.2. Geophysical survey and inversion of data

The geophysical survey consisted of 126 HVSR measurements along the 20-km long, 90-km² wide sector of the Ionian coast which includes the mouths of the Cavone, Basento and Bradano rivers (see inset in Fig. 1b). Each measurement was characterized by an acquisition time of 16 minutes with a sampling frequency of 128 Hz.

In order to define the depths of the main seismic unconformity underneath the Metaponto plain, the 126 HVSR curves were inverted using the program Model HVSR described by Herak (2008), which consists of a number of modules (Matlabs mat- and m-files, compiled dynamic link libraries, and sets of empirical constants), each dedicated to a particular topic.

The program Model HVSR requires an initial 1D stratigraphical model of the soil integrated with the average velocities of S-waves for each stratigraphical layer. Then, a forward modelling is repeated N times with a Montecarlo procedure. A typical, two-stage session of $N = 10,000$ perturbations of parameters of a 6-layered model lasts only a few minutes on a standard high-end PC. This inversion program can assess the depth of the surfaces of seismic impedance with an accuracy of about 10% (Guéguen *et al.*, 2007). The program turned out to be a useful and robust tool to interpret observed HVSR of ambient noise at various sites in Croatia, Slovenia and Macedonia (Gosar and Lenart, 2010; Herak *et al.*, 2010). In the wide majority of cases a reasonable fit between the observed and the theoretical HVSR is obtained.

In the study case of the Metaponto Plain, an initial 1D, 4-layer model of the subsoil was carried out and was integrated by the available down-hole data indicating the average V_S velocities for each geological layer of the models. The stratigraphical features and the V_S of the soil model are schematized in Table 1.

The available down-hole tests have been carried out in some recent boreholes down to a maximum depth of -30 m below ground level; the average V_S for the gravel layer and clays (which are generally deeper than 30 m and therefore have not been reached by the 30-m deep boreholes) have been deduced from down-hole tests relative to similar lithotypes which have been drilled in the first 30 m of depth and, therefore, at shallower stratigraphical levels. The first two layers do not have a precise stratigraphical meaning, but are differentiated in order to grasp the real behaviour observed in the available down-hole: the first meters show a much higher increase of velocity with respect to deeper strata. Since the program Model HVSR cannot use gradient within strata, we add this extra degree of freedom to facilitate convergence of the model.

The average V_S of Layer 3 and the clayey bedrock (both of about 450-500 m/s) have been

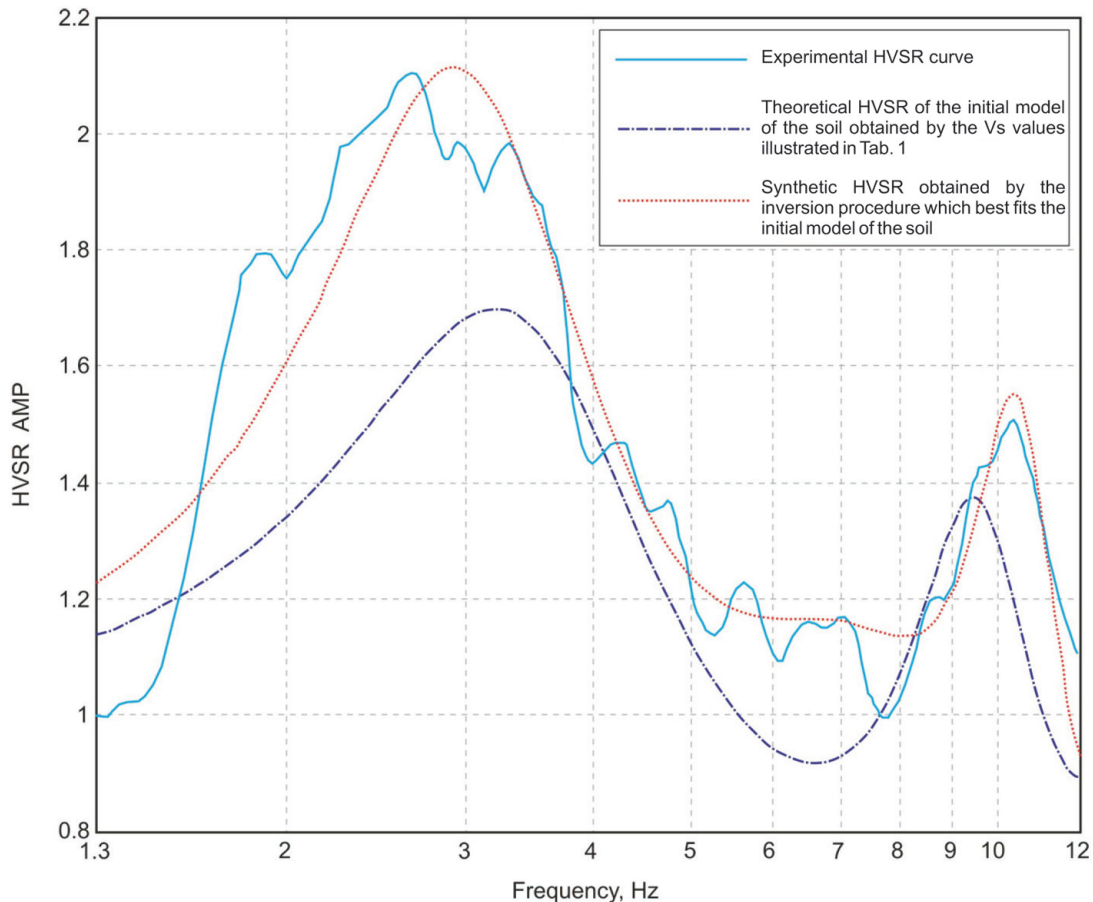


Fig. 3 - Comparison between the experimental HVSR curve of the soil (continuous blue line), the theoretical HVSR of the initial model of the soil, obtained by the V_S values illustrated in Table 1 (dotted-dashed black line) and the synthetic HVSR curve carried out by the inversion procedure which represents the best-fit with respect to the experimental data (dotted red line).

measured in two boreholes drilled in Scanzano Jonico and Policoro villages which intercepted both a gravel layer, analogous to Layer 3 at a depth ranging between -3 and -7 m, and the top of the clays, here located at a depth of about -20 m.

Since the stratigraphical position of gravel and clays used for assessing the V_S is about 20-25 m shallower than Layers 3 and 4, respectively, it is likely that the drilled sediments are less compacted and/or cemented than the deeper (analogous) sediments: therefore, we can expect that the effective V_S of Layers 3 and 4 should be even higher than the calculated V_S .

Table 1 shows that the thickness of Layer 3 ranges from 0 to 10 m, i.e., the gravel layer usually located at a depth of 30-40 m is not always present in the succession. Indeed, several of the available boreholes clearly indicate the absence of Layer 3, with the sandy-silty deposits of Layer 2 overlying directly onto the clays of the bedrock (Layer 4).

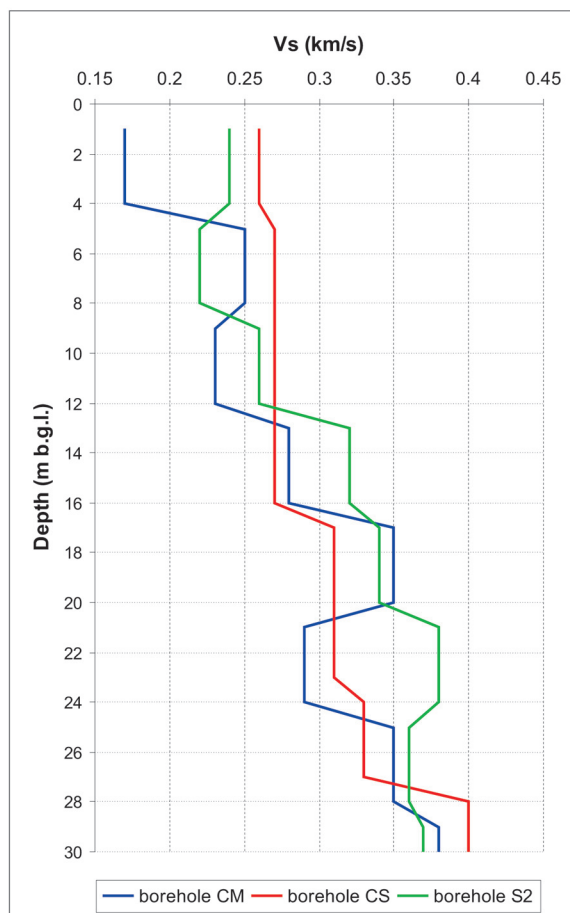


Fig. 4 - V_s obtained by down-hole tests carried out in boreholes CM, CS and S2 (see Figs. 1b and 5 for location). See text for the comments.

Therefore, in summary,

- i) the main geophysical goal was to detect the deepest surface of seismic impedance inside the stratigraphical succession of the plain;
- ii) the most evident contrast of seismic impedance is between Layer 2 and Layer 3 (if present) or Layer 4 (if Layer 3 is absent); and
- iii) the maximum thickness of Layer 3 is about 10 m, i.e., it is comparable to the accuracy of the inversion method used by the program Model HVSR (10%, inside an about 100-m deep stratigraphical succession).

Then, the program Model HVSR has inverted the 1D model of the soil by means of a forward modelling characterized by 3×5000 perturbations of the initial model with a Montecarlo procedure.

Fig. 3 shows three HVSR curves relative to one of the sites which has been considered as more representative for the stratigraphy of the study area, namely: i) the experimental HVSR curve obtained by the tomograph (continuous line), ii) the theoretical HVSR of the initial model of the

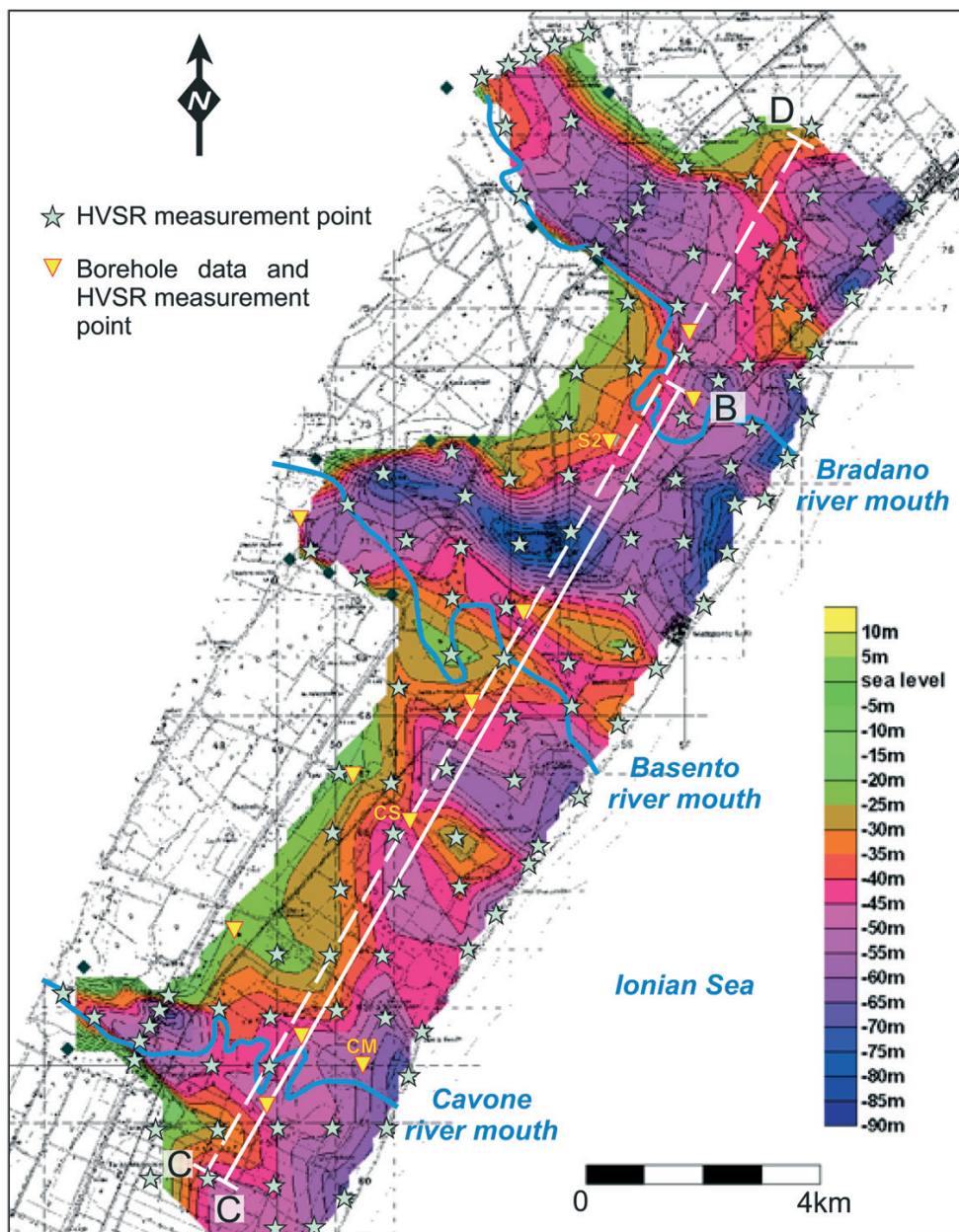


Fig. 5 - Map of the isobaths of the main discontinuity surface detectable through the HVSR inversion procedure. Traces C-D and C-B are relative to the geophysical and geological cross-sections (respectively) illustrated in Fig. 6. Trace C-D is the same as that shown in Fig. 1b.

soil obtained by the V_S values illustrated in Table 1 (dotted-dashed line), and iii) the synthetic HVSR curve carried out by the inversion procedure which represents the best-fit with respect to the experimental data (dotted red line).

The good agreement between the experimental HVSR curve and the HVSR curve obtained

from the final model of the soil provides valid evidence that the final model of the soil (Fig. 3) is the best geophysical representation of the subsurface of the Metaponto plain, taking into account that Layer 3 is not laterally continuous. The geophysical approach is reinforced by the comparison of three of the recent 30-m deep, down-hole tests carried out in the Metaponto plain, namely those performed in the boreholes CM, CS and S2 (Fig. 4; see Figs. 1b and 5 for location). Indeed, although these boreholes are rather far from one other, their down-hole tests show analogous V_S vs. Depth curves (Fig. 4), thus supporting the reliability of the geophysical model of the soil obtained and its validity for the entire study area, at least down to a depth of 30 m.

Finally, all the maximum depths of the base of Layer 2, obtained through the inversion program Model HVSR, were used to carry out a 3D map of the isobaths showing the geometry of the main discontinuity surface detectable through this geophysical approach (Fig. 5). The irregular surface represented by this map is characterized by the occurrence of several NW-SE-trending narrow depressions which are roughly parallel to the present valleys of the Cavone, Basento and Bradano rivers and whose depth generally increases towards the present coastline from about -50 m down to about -90 m below sea level.

4. Litho- vs. geophysical stratigraphy

A preliminary correlation between HVSR 3D data and litho-stratigraphy of the subsurface of the Metaponto coastal plain suggests that the deepest surface of seismic impedance (which is represented by the lowest value of resonance frequency in each of the 126 HVSR curves obtained during the geophysical survey) could represent the base of the uppermost unit recognized in the area. According to Cilumbriello *et al.* (2010), this unit (MP2 in Fig. 2b) developed after the LGM filling paleovalleys incised in the clays of bedrock and successively covering gravels representing remnants of older sediments (an older unit) “survived” in the paleointerfluvial areas. According to Cilumbriello *et al.* (2010), the gravel layer drilled in some boreholes at more than a depth of 30 m corresponds to the top of the middle unit (MP1 in Fig. 2b) and represents the “geophysical” substratum of the Metaponto plain deposits. In the model proposed by Spilotro (2004), middle and upper units of Cilumbriello *et al.* (2010) form the only unit lying on the geological “substratum”, whose top cannot be correctly detected with the HVSR method because the velocity of gravels of the middle unit is similar to that of clays of the geological substratum (see Table 1). Since the HVSR method led to the recognition of the base of the uppermost unit of the Metaponto coastal plain subsurface in a 3D view (Fig. 5), the same method highlights the areal distribution of paleovalleys that developed during the LGM and that were buried mainly by silts and sands during the subsequent sea level rise.

Some contrasts may be observed comparing an HVSR section with a geological section crossing the same area (Fig. 6), but some of these discrepancies could be explained by comparing the data. The first contrast regards the presence of two paleovalleys between the Basento and Bradano rivers in the geological section (Fig. 6b) while the geophysical section (Fig. 6a) shows only one paleovalley (see Fig. 1b for the location of these sections).

According to Cilumbriello *et al.* (2010) only the paleovalley on the right developed during the LGM, while the paleovalley on the left was incised during an older sea level fall, and was sealed on top by the gravel layer later. As explained above, in this case, the HVSR method may detect

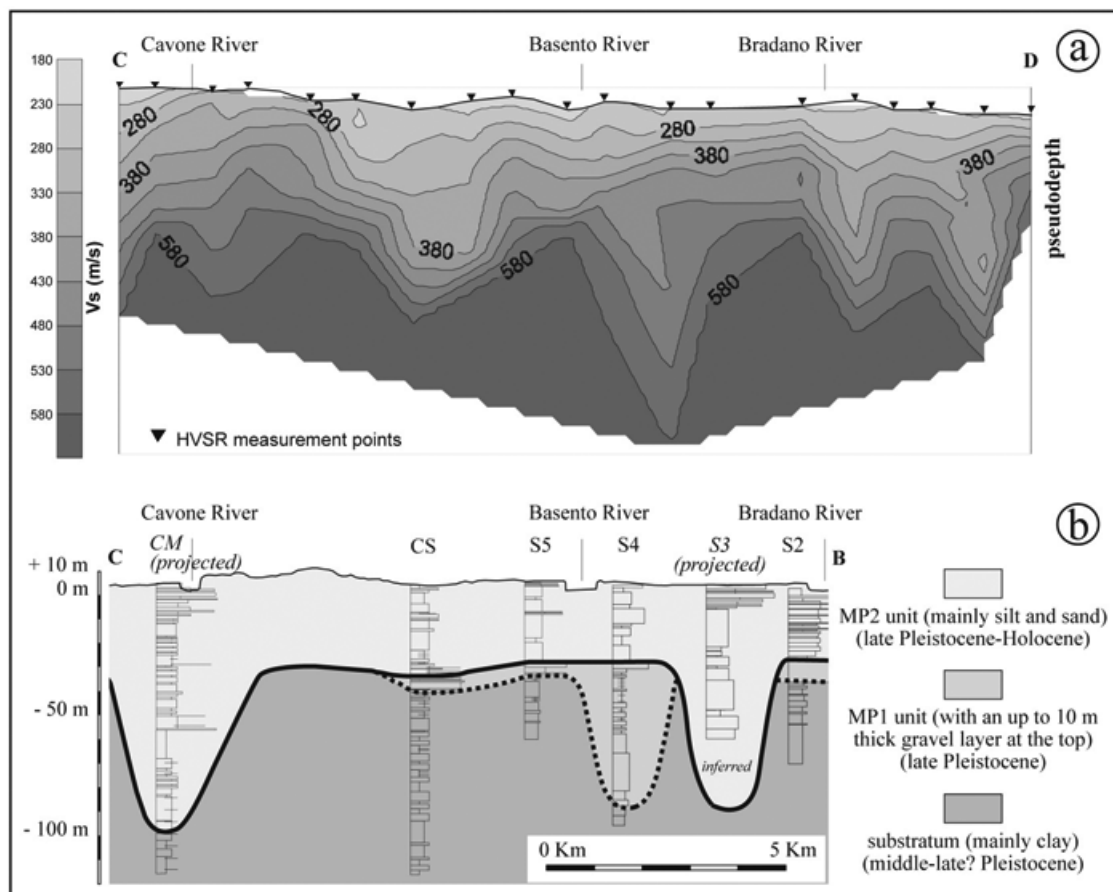


Fig. 6 - Comparison of geophysical with geological data along the same cross-section (see Figs. 1b, 2b, and 5 for location). See text for the comment.

only the discontinuity at the base of the younger incised valley fill, since the older one has the gravel layer on top. The most reliable position of the valley depocenter is that suggested by the HVSR method, since the position proposed in the geological section is inferred through the perpendicular projection of a core, drilled in the vicinity of the coast (seawards respect to the section) (see Fig. 1b for the location of this projected core). Sinuosity of paleovalleys, well shown in Fig. 5, may justify errors in the position of these old depocenters, whose presence is inferred only from a few 1D lithostratigraphical data. The same justification may explain the different position of the paleovalley located below the Cavone River (Figs. 6a and 6b, on the left). The different depth of the same paleovalley shown in the two sections of Fig. 6 may be explained considering the landward projection of the litho-stratigraphic 1D datum, because the base level of rivers goes up landwards, and probably the geophysical section best approximates the right depth of the paleovalley in that site.

The few discrepancies between the geophysical and the geological sections (Fig. 6) might also be explained by a local lack of resolution of the geophysical data, probably due to a low-density

of HVSR measurements. A further geophysical survey could clarify the question.

5. Conclusions

As shown, the HVSR method applied to the Metaponto coastal plain represents a low-cost possibility to obtain a detailed 3D view of a main subsurface horizon which could be directly detected only by 1D sedimentological analysis of single boreholes. It is easy to believe that this horizon roughly corresponds to the base of the uppermost sequence developed in this area; this sequence is linked to the last sea level rise which followed the LGM. The non-casual distribution of the depths of the seismic reflectors obtained by the inversion process of the HVSR curves, makes the HVSR survey, based on the ambient noise, a reliable tool for the geological-geophysical characterization of the subsoil down to a depth of several hundreds of meters. The HVSR map view shows narrow zones where the detected horizon is deeper compared to other subhorizontal areas and this distribution and sinuosity of narrow zones could be easily correlated to the presence of filled paleovalleys, whose existence was suggested by previous works.

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