# Geophysical and geochemical multi-method investigations for reconstructing subsurfaces, alluvial sedimentology, and structural geology (Tiber valley, Rome)

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**Abstract**

Geophysical and geochemical methods were applied to detect the subsurface setting of an Upper Pleistocene-Holocene fluvial incised-valley where a travertine body intercalates between alluvial deposits of the Tiber river (central Italy), at Prima Porta (close to Rome). This study allowed us to provide more information regarding the local stratigraphic architecture and structural features, as a reference analogue to similar settings: i.e., hard (stiff) lithic travertines buried below fine and loose alluvial plain covers.

Two Electrical Resistivity Tomography (ERT) profiles, interpreted and calibrated using previously collected litho-stratigraphic data from a borehole, identified a massive body, with a relatively high resistivity that correlates with the travertine deposit of Prima Porta. In addition to ERT, ambient noise measurements, processed with the HVSR technique and 2D array, and seismic refraction tomography were carried out; HVSR data were highly consistent with ERT results and allowed to discriminate between the travertine body and the silty-sand channels and overbank deposits, which were attributed to the Tiber river's evolution during Upper Pleistocene-Holocene. Finally, the presence of cracks/fractures could be inferred, as suggested by slight polarisation effects recorded in the HVSR results and soil-gas anomalies.

**Keywords:** buried travertine deposit, Electrical Resistivity Tomography, ambient noise measurement, soil-gas survey, Tiber valley, Upper Pleistocene, Holocene.

## 1. INTRODUCTION

Geophysical methods, such as seismic methods, ground penetrating radar, and electrical resistivity tomography, are widely used to detect the subsoil structures of recent alluvial plains, where the lack of adequate outcrops prevents a detailed reconstruction of buried stratigraphic and morpho-structural elements (Bridge, 2003; Miall, 2014). Similarly, in these settings (i.e., alluvial plains), geochemical investigations have been used to infer the presence of morpho-structural discontinuities buried below the sediment cover (Klusman, 1993; Ciotoli et al., 2007).

Here, we propose an integrated geophysical-geochemical approach aimed at defining the main features of the shallow subsoil of a portion of alluvial plain in the Tiber valley, central Italy, just north of Rome; this portion is considered as a case study and possible methodological reference for similar settings.

The Tiber valley corresponds to a NNW–SSE trending extensional basin that has been developing since the early Pliocene along the western flank of central Apennines (Funiciello and Parotto, 1978; Malinverno and Ryan, 1986; Barberi et al., 1994). Most of the basin-fill consists of fluvial and deltaic deposits; the most recent deposits, which pertain to the valley's actual alluvial depocenter, consist of gravels and sands or silty sands alternating with floodplain muds. As a morpho-tectonic depression of extensional origin, the valley is bounded by dominant NNW-SSE trending normal faults and subordinate transversal fault systems, which may represent important routes for ascending, mineralised hot waters whose manifestations are visible in some places, especially along the borders (such as those which emerge in our case study) but also towards the centre (Giustini et al., 2018); in general, the deposition of continental carbonate bodies associated with these manifestations is always evident. In fact, especially along its western boundary, several deposits of continental carbonates crop out and/or are locally buried under the prevailing siliciclastic alluvial deposits of the Tiber river (Tentori et al., 2016; Giustini et al., 2018). The reconstruction of the sedimentary sequence within the central portion of the valley is impossible unless drilled cores are investigated.

Recently, an Upper Pleistocene travertine body of about 4 m in thickness, intercalated between Holocene and upper Pleistocene alluvial deposits, was identified in an 18 m deep borehole at Prima Porta, north west of Rome, and at a distance of 400 m from the right bank of the Tiber river, (Giustini et al., 2020). The borehole, drilled for agricultural water supply, revealed $CO_2$-dominated free gas emissions and the presence of mineralised, hypothermal waters that were recorded a few metres below the field level.

To comprehend the alluvial sedimentary sequence and the travertine body in relation to the gas emissions, the groundwater, and the local structural geology, a knowledge of the subterranean sedimentary setting is needed. Geophysical methods may conveniently be used for this type of investigation. In the present paper, we investigated the subterranean sediment sequence of Prima Porta using the Electrical Resistivity Tomography (ERT) which allows remarkable penetration depths even if the presence of fluids can mask the geoelectrical contrasts between geological

formations (Loke and Barker, 1996; Loke and Dahlin, 2002). The ERT technique has been successfully applied in several studies in which travertines were embedded within different sediments (Qarqori et al., 2012; De Filippis et al., 2013; Pola et al., 2014; Huerta et al., 2016; Török et al., 2019). In the present paper, ERT was coupled with spectral measurements of seismic ambient noise (Horizontal to Vertical Spectral Ratio - HVSR technique) (Nakamura, 1989; Lunedei and Malischewsky, 2015; Sánchez-Sesma, 2017, and references therein). This technique was used to study subsoil settings by means of determining the seismic velocity contrasts that locate interfaces between sedimentary bodies with different mechanical characteristics. As an area characterised by rising mineralised waters and natural gases, geochemical soil-gas prospection was also used to investigate the most likely routes of fluid flowing through the strata up to the atmosphere in subterranean settings (Klusman, 1993; Ciotoli et al., 2007).

The aim of this study is to test a multimethod approach for reconstructing buried stratigraphic and structural features and demonstrate their complementarity and ability to compensate the limits of each one.

## 2. GEOLOGICAL FRAMEWORK

The study area is located in the lower valley of the Tiber river, north of Rome and west of the central Apennines (Fig. 1a). The investigated Prima Porta site is located in the Tiber alluvial plain which crosses, along the NNE-SSW direction, a hilly belt consisting of Pliocene-Quaternary sedimentary and pyroclastic deposits. In particular, the study area lies in the inner convex bank of an eastward-directed meander of the Tiber (Fig. 1b).

Structurally, the valley corresponds to a morpho-tectonic depression of extensional origin, the Rome Basin, bounded by dominant NNW-SSE trending normal faults and subordinate SW-NE directed transfer faults; short N-S trending dextral strike slip faults are also found within the basin (Faccenna and Funiciello, 1993).

Since the Early Pliocene, the extensional regime related to the opening of the Tyrrhenian Sea back arc basin has controlled the growth and development of the Rome basin (Funiciello and Parotto, 1978; Malinverno and Ryan, 1986; Barberi et al., 1994). The pre-rift succession comprises Trias to Miocene calcareous, cherty, and siliciclastic pelagic sequences, which were stacked to form the Apennine Chain fold-thrust belt during the Tortonian-Messinian (Patacca et al., 1990; Cosentino et al., 2010). The Pliocene-Quaternary syn-rift successions consist of marine, transitional, and continental sediments (up to 1 km in thickness) covering the pre-rift limestones and turbidites with an angular unconformity.

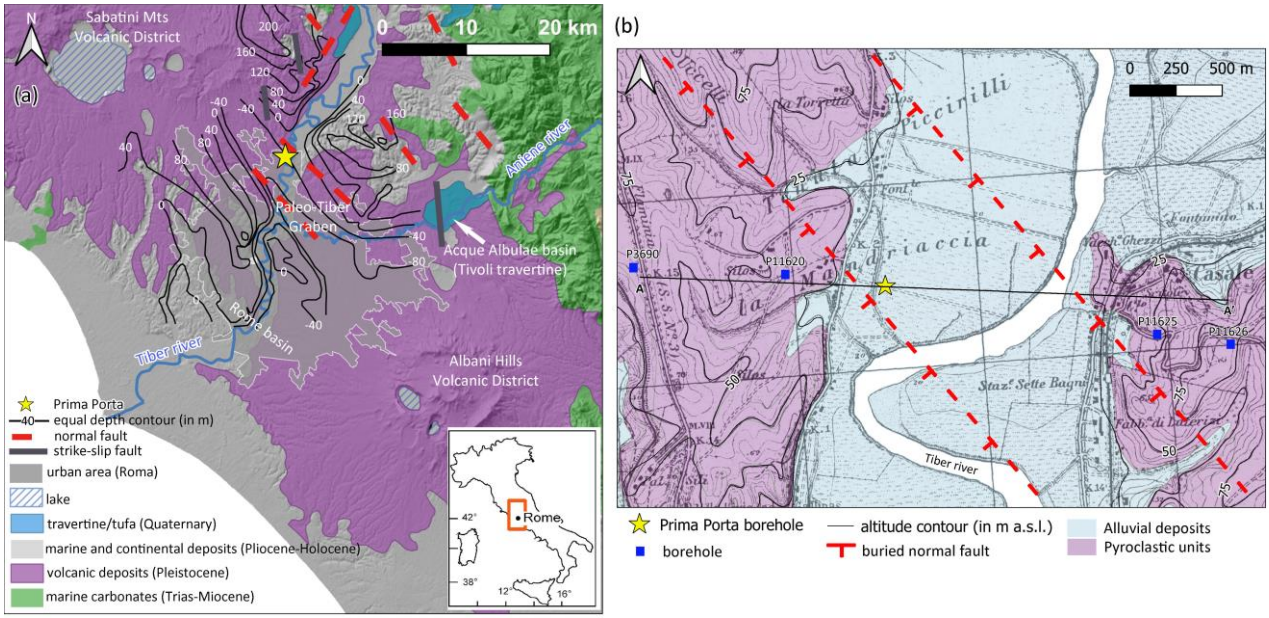


**Fig. 1.** a) Geological map of the Tiber valley showing the location of the Prima Porta site: geology from SGI-ISPRA, faults from Faccenna (1994), equal depth contour from Funiciello et al. (1992); b) Sketch map of the Prima Porta area: geology from the Geological Map of the Lazio Region, scale 1:25,000 and topography from 1:25,000 topographic maps of Italy from the Istituto Geografico Militare. The trace of the cross section A-A′ (Fig. 2a), location of the boreholes (from Ventriglia, 2002; Di Bella et al., 2002), and buried inferred normal faults (from Funiciello et al., 1992) are also drafted. Modified from Giustini et al. (2020).

Since the late Early Pleistocene (~1.3 Ma), active uplift has affected the whole area, which has led to the emergence of the former sea floor. This phase was dominated by the fluvial sedimentation of the juvenile Tiber river ("Paleotiber" in Funiciello et al., 1994; Mancini and Cavinato, 2005; Mancini et al., 2007) and by the deposition of eruptive products from the Sabatini Mts and Albani Hill volcanic districts (De Rita et al., 1993; Sottili et al., 2004; Funiciello and Giordano, 2010). The ancient Tiber river incised the Pliocene-Early Pleistocene marine clay and silt defining a NNW-SSE trending deep paleo-valley, filled with gravels, sands, and minor mud. These deposits rarely crop out since they are buried below younger pyroclastic successions (ignimbrites, phreato-magmatic ashes, pumice, and ash falls), dated at approximately 600-280 ka (Barberi et al., 1994), and locally by Upper Pleistocene-Holocene fluvial deposits.

The Prima Porta site is, in fact, located on the west side of the recent Tiber's alluvial plain that, in this area, is ~2 km wide and has elevations ranging from 19 to 22 m above sea level (Fig. 1b). NNW-SSE trending normal faults, inferred from Funiciello et al. (1992), bound the ancient paleo-valley to the north-east and are those and are related to the development of the Paleotiber graben, buried by younger pyroclastic successions and fluvial deposits.

The alluvial plain corresponds to the top of the fluvial incised-valley fill of the Upper Pleistocene-Holocene Tiber Depositional Sequence or TDS (Milli et al., 2016) (Fig. 2a). The last cycle of sea level changes (from MIS5d to MIS1; 116-0 ka) controlled the valley fill, which comprises the complex stack of deposits belonging to the lowstand to transgressive and highstand systems tracts, totalling a thickness of 60 m.

The oldest TDS deposits are attributed to the early lowstand phase (116-26 ka) and define rare depositional terraces perched on the incised-valley slopes and buried below more recent transgressive sediments. These terraces record short-lived phases of sedimentation which occurred during the long phase of the lowering of base level.

Younger basal gravels, organised into amalgamated channel bodies in the deepest portion of the incised valley, and overlaying channel sand and floodplain muds, are respectively ascribed to the late lowstand-early transgressive (26-14 ka) and late transgressive-highstand (14-0 ka) phases (Milli et al., 2016). In particular, the sands define channel-fill bodies with different stacking patterns for the transgressive and the highstand systems tracts of TDS (Milli et al., 2016), also related to the laterally confining floodplain fines: from relatively narrow and vertically accreted channel bodies of the transgressive systems tract, with high rates of accommodation, to wider and laterally amalgamated channel bodies of the highstand systems tract, with decreasing rates of accommodation and increasing channel clustering (see also Schumm, 1993).

The stratigraphy of the 18 m-long core recovered at Prima Porta (Fig. 2b) corresponds to one of the detached depositional terraces and overlying transgressive sediments (Giustini et al., 2020): above the basal layer, which consists of 1.5 m thick yellow-beige massive silty sands, attributed to the Paleotiber unit (i.e., Fosso della Crescenza and Santa Cecilia Formations, in Funiciello and Giordano, 2008), a 11 m thick body represents the buried terrace; this is part of the *Fiume Tevere* Synthem or TDS (according to Funiciello and Giordano, 2008, or Milli et al., 2016, respectively), and consists of a 5.5 m thick succession of grey, massive pebby-silty sand and clay with sparse carbonate encrustations (unit a), ~4 m of travertine at Prima Porta (unit b), and ~1 m of massive dark brown/red clayey paleosols (Fig. 2b). The travertine was dated between 53.5 ± 10 ka to 24.2 ± 4.7 ka by U/Th method (Giustini et al., 2020) and can be correlated to the MIS 3. The remaining upper sequence consists of beige massive silt and clay that record the recent phases (age ≤6.0 ka, middle-late Holocene) of river flooding (unit c).

### 2.1. The travertine of Prima Porta

The travertine of Prima Porta macroscopically consists of a hard and quite dense crystalline material, which appears to be structureless or with horizontally bedded and inclined layers which are a few centimetres to decimetres thick. These features, as well as their microfacies associations (i.e., micrite crusts and rafts, both intercalated within and between the shrubs), suggest that the deposition of this travertine was associated with low-to-moderate energy environments, such as gently-dipping, shallow pools of low-angle terraced slopes (Giustini et al., 2020). Currently, the travertine of Prima Porta is associated with hypothermal, saline water and deeply derived $CO_2$ gas emissions, whose ascent through the rock units is probably connected with a crustal structural lineament (Giustini et al., 2018). Diagenetic alteration appears to be limited, as inferred from macroscopic and petrographic observations (Giustini et al., 2020). The travertine was

dated between 53.5 ± 10 ka to 24.2 ± 4.7 ka by U/Th method (Giustini et al., 2020), its deposition started approximately coevally with the wettest climatic conditions occurring during MIS3 (Fig. 2c), whereas the end of the deposition period coincides with the cold and arid phase of the last glacial maximum (Giustini et al., 2020).

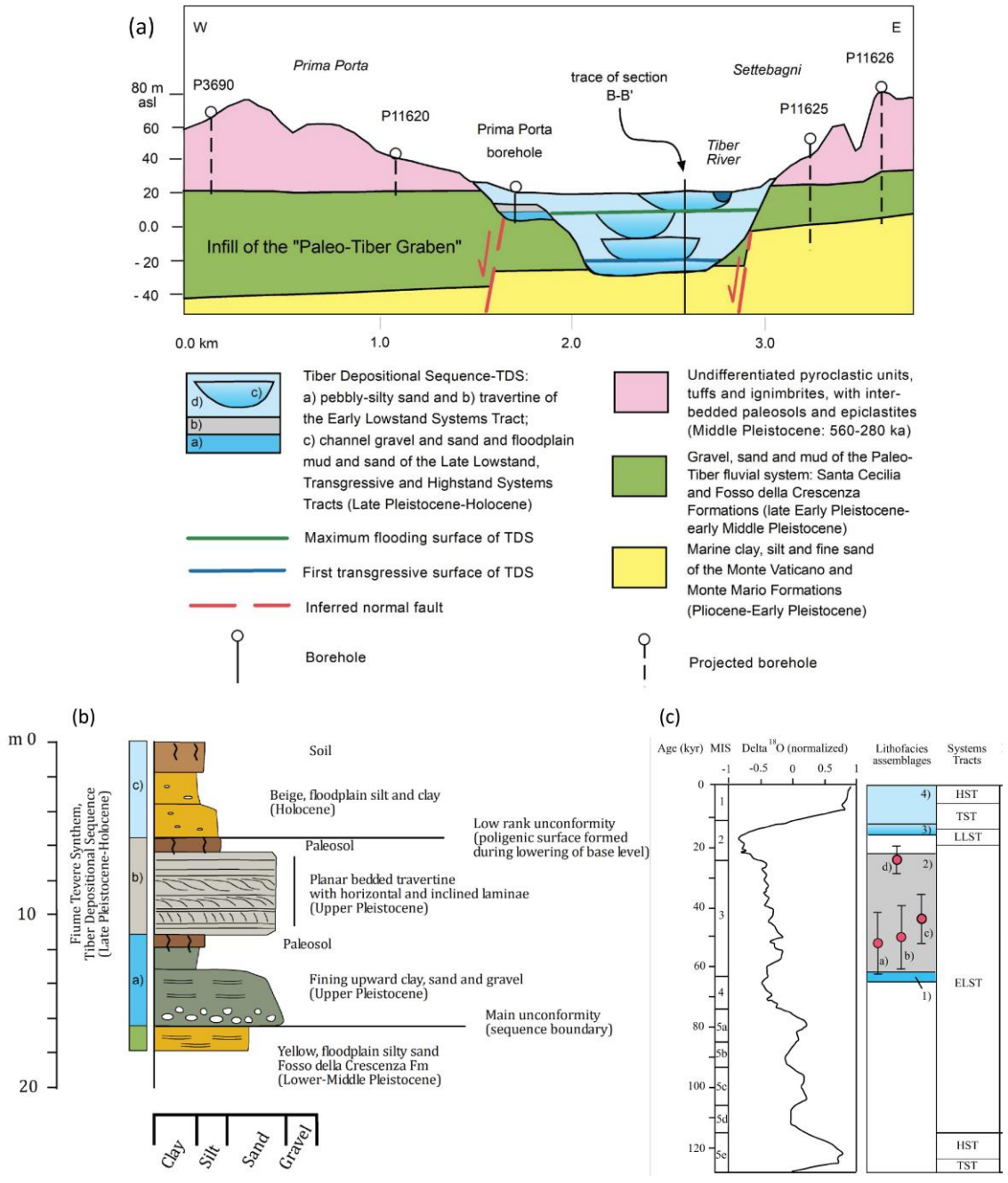


**Fig. 2.** a) Geological cross sections showing the stratigraphic architecture of the middle Tiber valley, based on the geological map of Funiciello and Giordano (2008) and borehole data from Di Bella et al. (2002) and Ventriglia (2002); b) Schematic section of the drilled core; the travertine deposit is embedded within alluvial sediments of the Tiber river. Reproduced from Giustini et al. (2020); c) Chronostratigraphic scheme of the Prima Porta deposit; Prima Porta travertine ages (red circles) are from Giustini et al. (2020), lithofacies assemblages correspond to the schematic section in b), oxygen isotope curve is from Martinson et al. (1987), Systems Tracts of the Tiber depositional sequence are based on Milli et al. (2016) (HST: Highstand Systems Tract; TST: Transgressive Systems Tract; LLST: Late Lowstand Systems Tract; ELST: Early Lowstand Systems Tract).

## 3. METHODS

Different methods were applied to study the subsurface setting of the study area, including: electrical (ERT), surface waves based (HVSR and 2D arrays), shallow seismic refraction, and geochemical ($CO_2$ and $^{222}Rn$ soil-gas survey) methods. Each method was processed separately and then a joint interpretation was performed. The location of the measurements is shown in Figure 3.

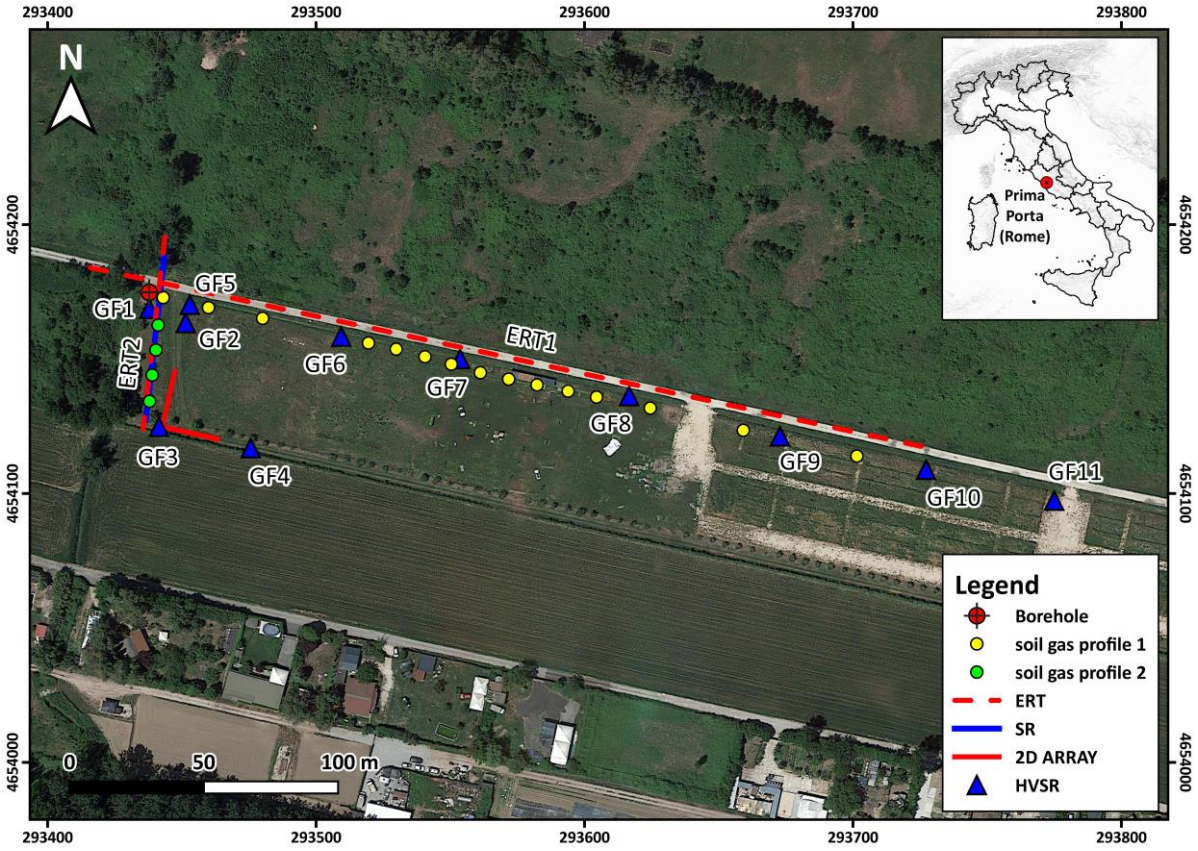


**Fig. 3.** Aerial view of the study area with the location of the Prima Porta borehole, HVSR, 2D array, Electrical Resistivity Tomography (ERT), Seismic Refraction (SR) surveys, and soil-gas measurements.

### 3.1. Electrical Resistivity Tomography (ERT) surveys

ERT surveys were carried out to determine the specific electrical resistivity ρ of the ground and to obtain 2D images of its distribution in vertical ground sections.

ERT consists of the application of a direct electrical current into the ground using a quadrupolar dispositive, the acquisition of A/D converted data of voltages through a computer-controlled acquisition system, and the computation of resistivity using Ohm laws. The quadrupole consists of two current electrodes, through which direct current is fed into the ground, and two measuring electrodes, through which the voltage is measured. There are many different electrode array configurations available, but all configurations are aimed at gathering data that can be used to estimate lateral and

vertical variations in ground resistivity values with different resolutions (Loke and Barker, 1996; Loke and Dahlin, 2002).

Two ERT measurements were performed using a georesistivimeter 16SG model (Pasi, S.r.l.), equipped with 64 electrodes with variable spacing using the Wenner-Schlumberger configuration. As conventionally reported in the literature, the depth of investigation is up to 1/5 or 1/6 of the total length of the electrical profile. Data were processed using the Res2dinv software from Geotomo Software. The 2D inversion is based on the robust constrained least-squares inversion implemented with a Gauss-Newton method.

The first measurement (ERT-1) was carried out in the W-E direction, using 64-electrodes with a 5 m electrode distance, which allows the 2D reconstruction of the resistivity trend in the subsoil up to a depth of about 50 m along a 315 m long profile. The ERT-1 profile crosses the Prima Porta borehole – whose stratigraphy is known (Fig. 2b) and which was used to calibrate the resistivity measurement – down to electrode n. 40. The second measurement (ERT-2) was performed with a N-S orientation; in this case, 48 electrodes were used with an electrode distance of 1.5 m and a total length of 70.5 m, reaching a depth of about 12 m. The two arrays intersect between the electrodes n. 40 of the W-E array and n. 7 of the N-S one, as shown in Figure 4.

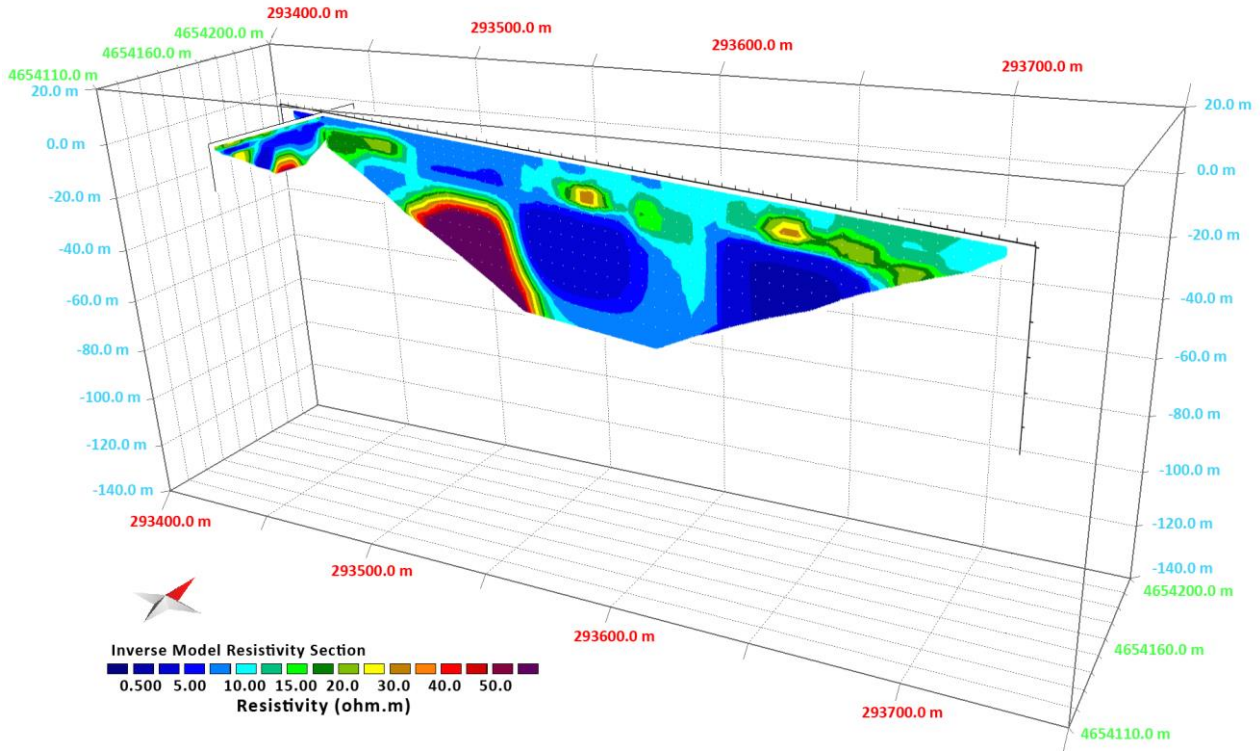


**Fig. 4.** Inverted 2D resistivity models for the two perpendicular electrical resistivity tomographs. ERT-1 is oriented W-E; ERT-2 is oriented N-S. The models are displayed in perspective to visualise the 3D subsoil structure starting from the 2D cross-sectional images.

197 **3.2. Ambient noise survey**

198 A series of eleven ambient noise measurements, labelled from GF1 to GF11, was conducted along the two cross-
199 sections (Fig. 3). The equipment consisted of SS02 SARA velocimetric sensors with a cut-off frequency of 0.2 Hz,
200 connected to six-channel SL06 SARA data loggers. Data were recorded with a sample rate of 200 samples per second.
201 During installation, particular care was adopted to deploy sensors in order to guarantee an adequate coupling with the
202 ground and to avoid the positioning of the sensors directly over sources of disturbance. Shallow holes were realized to
203 emplace sensors and remove the possible disturbance of the grass.
204 Recordings of about one hour of noise were collected and the Horizontal to Vertical Spectral Ratio (HVSR) technique
205 was applied (Nakamura, 1989). This is a well-established approach: inferences for the subsurface seismic velocity
206 contrasts may be extrapolated from the retrieved peaks in the HVSR curves, considering for instance that shallower
207 interfaces produce higher peak frequencies. Each ambient vibration recording was divided into 50 s-long time windows
208 in the open-source software Geopsy (http://www.geopsy.org/) (Wathelet et al., 2020). We computed the amplitude
209 spectra for the vertical and horizontal components (north and east components). Spectra were smoothed using the
210 Konno and Omachi (1998) window with a *b* value of 40, while the horizontal spectra were computed from the north and
211 east components as: $\sqrt{(north2 + east2)}$ before computing the HVSR for each time window. Then, we computed the
212 average HVSR for each station.
213 In addition to the HVSR noise measurements at single stations, surface-wave methods were also applied, allowing the
214 acquisition of 2D array ambient vibrations data and one S-waves velocity profile. The latter was retrieved from a joint
215 inversion of Rayleigh dispersion curves with ellipticity. In more detail, 2D arrays are based on the acquisition of
216 ambient vibrations and the interpretation of the recordings obtained at synchronised seismic stations, or geophones
217 (seismic antenna) with the ground, according to different geometries. The geophones were arranged in a two-
218 dimensional L-shaped geometry with regular spacing (3 m on each side; see also Fig. S4b in Supplementary Materials).
219 Even if more regular and symmetrical shapes (circular or triangular shapes) are recommended in general, T or L shapes
220 are also possible (Foti et al., 2018). Thus, a L-shaped geometry can be a compromise among the number of sensors, the
221 operating time available and a desired highest resolution of the uppermost layer description. In this case, the choice of
222 limited inter-geophonic distance (3 m) and the consequentially maximum dimension of each branch lower than 36m
223 agreed with the necessity of exploring the presence of lateral heterogeneities and the first uppermost layers. The basic
224 scheme of the application of all surface-wave methods consists of three steps: i) measuring the wave trains of surface
225 waves by means of the arrays of seismic stations or geophones, suitably deployed on the surface; ii) estimating the
226 apparent dispersion curve of surface waves; and iii) solving the inverse problem to estimate the soil structure looking
227 for the best-fit between the experimental and theoretical dispersion curves. Joint inversions with the HVSR technique

related to Rayleigh wave ellipticity are generally performed to obtain more robust representative S-waves velocity profiles. In this case, the dispersion curve was derived by applying two different methods: MSPAC (Modified SPatial Auto-Correlation, Bettig et al., 2005) and the conventional beamforming f-k (Lacoss et al., 1969). The registrations of the noise wave-field were performed for a minimum duration of 40 minutes with 24 vertical geophones (cut-off frequency equal to 4.5 Hz). Geophones are equipped with spikes which serves as a screw to secure the coupling with the ground. Also in this case, before emplacing geophones, the grass around each 1-component sensor was removed to avoid any possible disturbance. Different codes were used: the Geopsy software (www.geopsy.org) (Wathelet et al., 2020) was used to retrieve the dispersion curves for applying f-k and MSPAC analyses, while HV-inv (García-Jerez et al., 2013, 2016; Piña-Flores et al., 2016; Sánchez-Sesma et al., 2011) was used for solving the inverse problem. Hv-inv is based on the diffuse field assumption, therefore the resulting modelled ellipticity curve is comprehensive of both Rayleigh and Love waves. Rayleigh wave ellipticity used for the joint inversion was defined directly from the HVSR curve.

### 3.3. Seismic refraction tomography survey

Seismic refraction (SR) is generally applied to determine impedance contrast for engineering applications, to investigate the depth to bedrock, as well as for groundwater exploration, crustal structure, and tectonics (Kilner et al., 2005; Asokhai et al., 2008; Varughese et al., 2011; Chiemeke and Aboh, 2012). The seismic refraction method is based on the measurement of the travel time of seismic waves refracted at the interfaces between subsurface layers of different velocity (Ayolabi et al., 2009). The seismic signal is introduced into the subsurface via a shot point using an elastic wave generator. The energy generated either travels directly through the upper layer (direct arrivals) or down through the various layers before returning to the surface (refracted arrivals). It is then detected at the surface by a series of geophones (10 Hz), spaced at regular intervals. Both compressional waves (P-waves), which provide depth information about the interfaces, and shear waves (S-waves), which provide additional data about the engineering properties of the subsurface media, can be used in the seismic refraction method (Igboekwe and Ohaegbuchu, 2011; Gabr et al., 2012). SR surveys use the process of critical refraction to infer interface depths and layer velocities. Based on the analysis and inversion of the field data, seismic profiles are constructed to evaluate the thickness and type of materials of the subsurface (Okiongbo et al., 2011). In this case study, the technique was usefully joined with the 2D array results: the P-waves profile obtained was applied as a constraint for the dispersion curve inversion. In particular, the Vp model obtained from the seismic refraction tomography survey was used as Vp profile max and min in the dispersion curve joint inversion. The resulting Poisson's ratio is about 0.5 and is comparable with the value assumed of the uppermost saturated deposits. The data are presented as cross-sectional plots representing the path, velocities, and depths of P-

waves to various interfaces. SR was performed along the aforementioned ERT-2, using a geophone inter-distance of 2.5 m for a total length of 57.5 m.

### 3.4. Soil-gas survey

Soil-gas measurements were performed along two profiles parallel to the ERT profiles, according to a sampling distance ranging from 20 to 40 m. Nineteen soil-gas samples were collected using a well consolidated technique (Beaubien et al., 2013; Ciotoli et al., 2007) consisting of pounding a 6.4 mm, thick-walled, stainless-steel probe into the soil at a depth of about 0.6-0.8 m using a co-axial hammer; such a depth ensures the negligible influence of atmospheric air (Hinkle, 1994). A portable multi gas analyser (Draeger X-am 7000) directly connected to the probe was used to measure carbon dioxide ($CO_2$) concentrations directly in the field. Soil-gas radon ($^{222}Rn$) concentrations were measured with a portable RAD7 alpha detector (Durridge Company Inc.), performing three/four measurements of radon and thoron activity each, with a 5-minute integration time, and using a drying tube (filled with $CaSO_4$) to maintain the relative humidity below 10%.

## 4. RESULTS

### 4.1. ERT profiles

Two ERT profiles were performed along perpendicular directions. The first tomograph (ERT-1) was made in the W-E direction, across the valley, and the second (ERT-2) in N-S direction, down the valley and located in the innermost portion of the meander (Fig. 3). Resistivity values varied from 0.5 to 60 ohm×m; three zones could be distinguished on the basis of these values (Fig. 4).

Zone 1, characterised by low resistivity (<15 ohm×m) is coloured in blue in Figure 4. In ERT-1, this zone appears quite surficial between the metric coordinates of 80 and 150 m, and deeper than 20 m in the central-eastern part of the profile. In ERT-2, the zone of low resistivity is located below 1.5 m and appears as a sub-horizontal layer (about 3 m thick) that becomes increasingly deep between 40-50 m toward the south.

Zone 2 represents resistivities between 15 and 30 ohm×m, and is shown in green to yellow colours. In ERT-1, two levels with resistivities between 15 and 30 ohm×m are recognised in the eastern and western parts of the tomograph, disconnected by a low resistivity area in the centre. In ERT-2, Zone 2 is located just below surface and is about 1.5 m thick. In addition, a level with resistivities between 15 and 30 ohm×m displays a concave-upward section wedging out toward the central part of the profile, where the resistivity tends to increase up to 50 ohm×m. Finally, a lens of Zone 2 is located in the eastern part of the profile, embedded within a low resistivity area.

289 Zone 3 is characterised by the highest resistivities (>30 ohm×m), shown in orange to purple colours. Zone 3 is well
290 represented in ERT-1 by a resistant block with a sharp lateral variation of resistivity in the central-western part of the
291 profile, whose top is at a depth of about 20 m.
292
293 **4.2. Ambient noise survey**
294 Results from noise measurements in terms of HVSR and single spectra are reported in Figures 5 and 6, respectively.
295 HVSR amplitude never overcomes the value of 2.5; therefore, a smooth change in impedance properties is expected.
296 Moreover, as seen in Figure 5, the mean HVSR at the GF1 to GF7 sites has amplitude values lower than 1, between
297 about 2 and 4 Hz; this may be associated with an inversion of S-wave velocity in the soil profile, i.e., the upper
298 sediments have a higher S-wave velocity than the underlying layers. Single spectra in Figure 6 would show a behaviour
299 traceable to stratigraphies with similar characteristics. In this case, the amplitude of the vertical component at the same
300 range of frequencies increases from the GF1 to GF5 and GF1 to GF7 sites and the vertical component has higher values
301 than those of the horizontal components. In these cases, as suggested from Castellaro and Mulargia (2009), local
302 minima of the vertical component associated with flat or local maxima in the horizontal ones have to be carefully
303 considered, since they may hide important HVSR peaks such as the one at 2.5 Hz.
304 Otherwise, both HVSR and single spectra at the GF8, GF9, GF10, and GF11 sites show the expected behaviour in the
305 case of a soil profile with S-wave velocities increasing with depth.
306 From the analyses of the single spectra, despite the high variability of the measured HVSR curves, it arises that the
307 predominant frequency f of the study area is 1.5 Hz in the range 1-10 Hz. A further peak occurs at frequencies lower
308 than 0.8 Hz. This is relative to the Tiber river valley resonance referring to the deepest bedrock interface (see Carlucci,
309 2017; Marcucci et al., 2019 and reference therein), and it was not considered because our study only focuses on the
310 characterisation of the first layers (up to 30-40 metres in depth). Another peculiar shape is recognisable at frequencies
311 greater than 5.
312

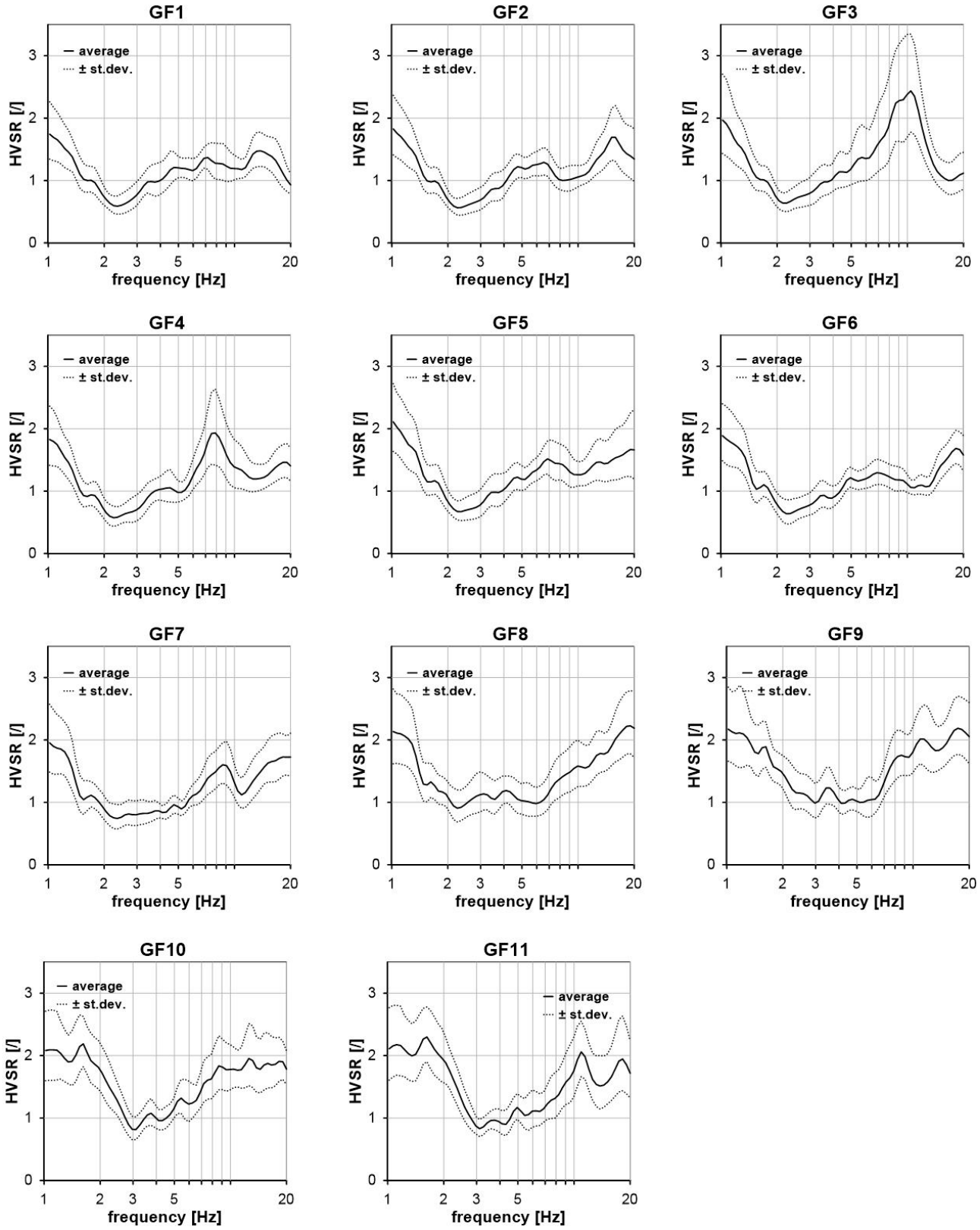


**Fig. 5.** Measured HVSR curves. Single plots refer to the band 1-20 Hz for the clarity. Curves plotted in the range 0.2-20 Hz may be found in the Supplementary Materials.

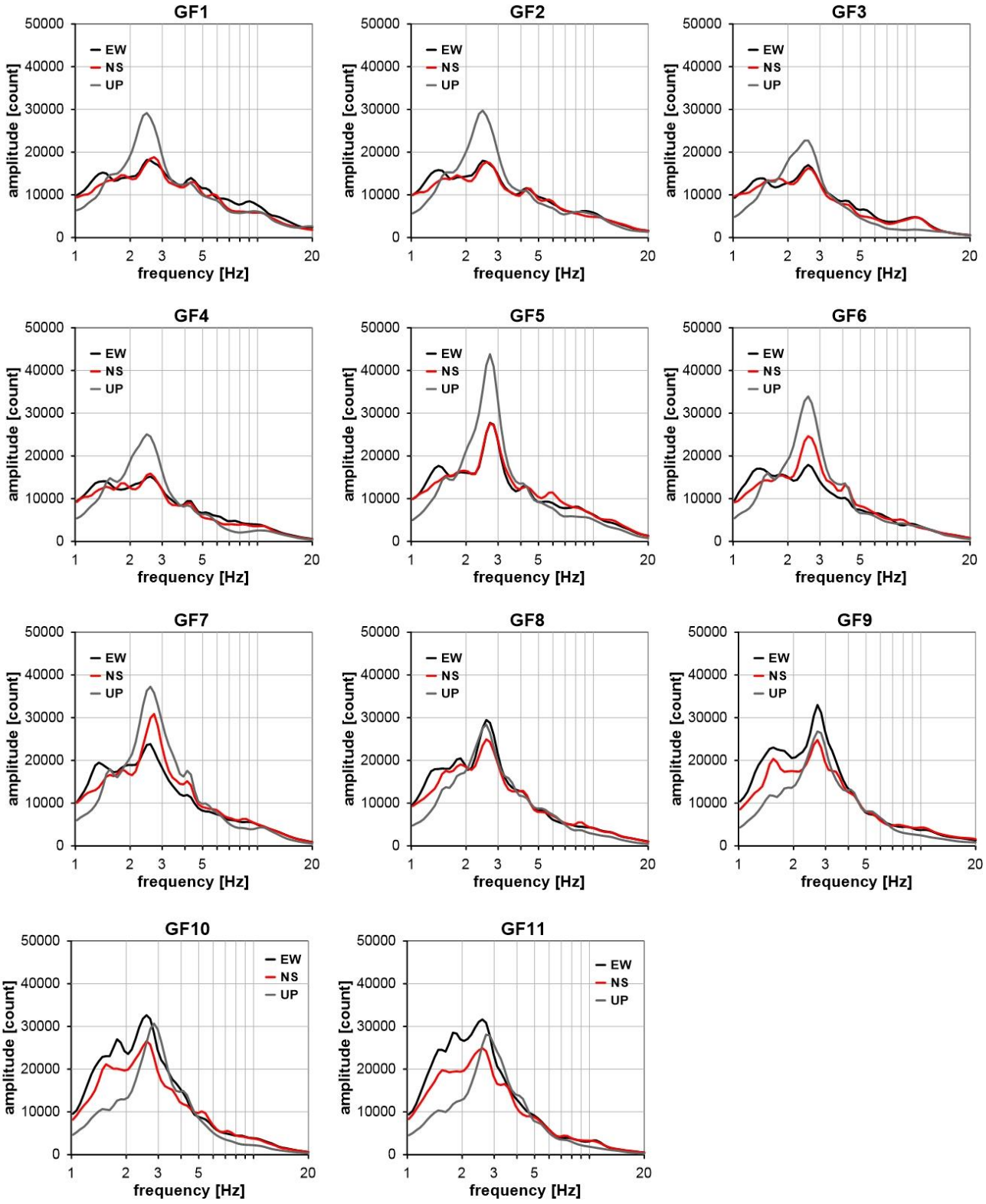


**Fig. 6.** Measured single spectra curves. Single plots refer to the band 1-20 Hz for the clarity. Curves plotted in the range 0.2-20 Hz may be found in the Supplementary Materials.

All these considerations led us to group the HVSR into three different clusters. The first cluster exhibits a bi-modal shape (in blue in Fig. 7); the second cluster shows a very broad band peak at a higher frequency which may be related to a 2D/3D subsoil model; and the third cluster shows a peak with very high amplitude values and one with HVSR

characterised by the clearest peaks (grouping GF3 and GF11). Both of them are quite different from those retrieved at stations in their immediate vicinity, but further data would be necessary to retrieve insights about this behaviour.

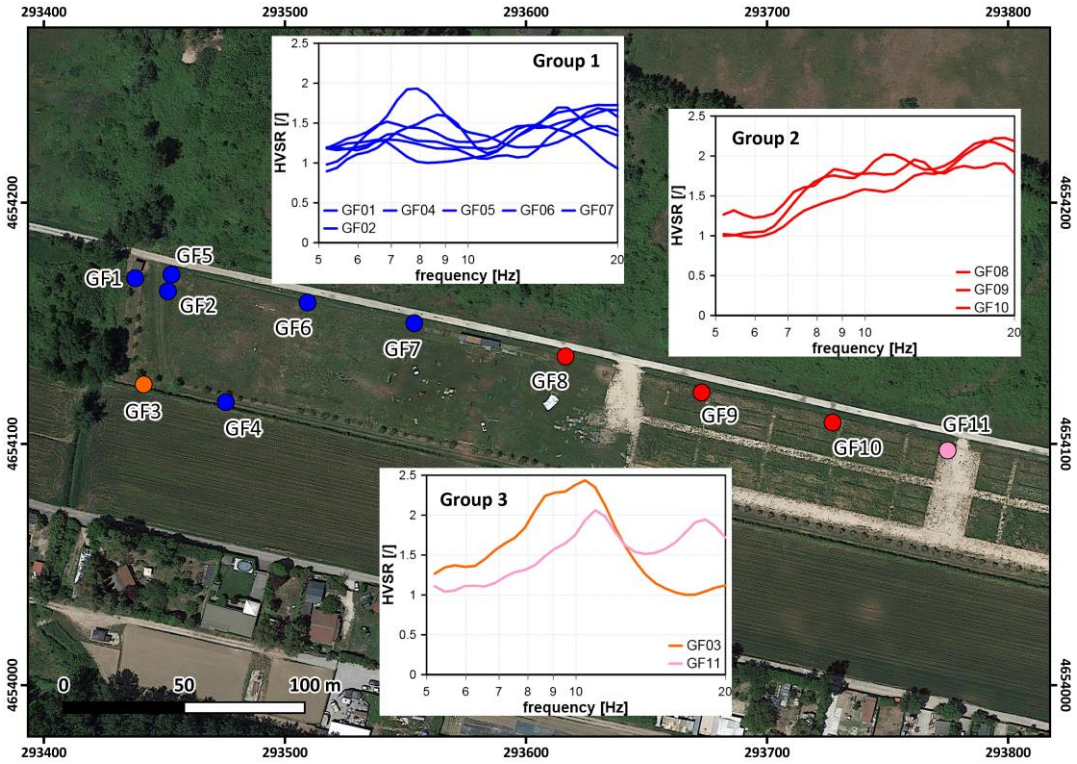


**Fig. 7.** Groups of HVSR curves.

Wavefield polarisation analysis was also applied to the ambient noise measurements (Fig. 8). The GF1, GF3, and GF4 stations show a slight polarisation with an azimuth of N80-100° for frequencies >6 Hz; the GF7 and GF8 records have a similar characteristic, but with a slightly lower azimuth (N0-20°). The GF5 and GF6 stations seem to show a transitional behaviour. The peaks in the range 0.2-1 Hz show a N120° polarisation in almost all the measurements (see Supplementary Figure 1). This analysis may reveal the possible presence of high angle to sub-vertical structural or paleo-morphological discontinuities within the sedimentary complex as they may tend to align the waves' oscillation plane perpendicular to or at a high angle to the direction of the lineaments themselves.

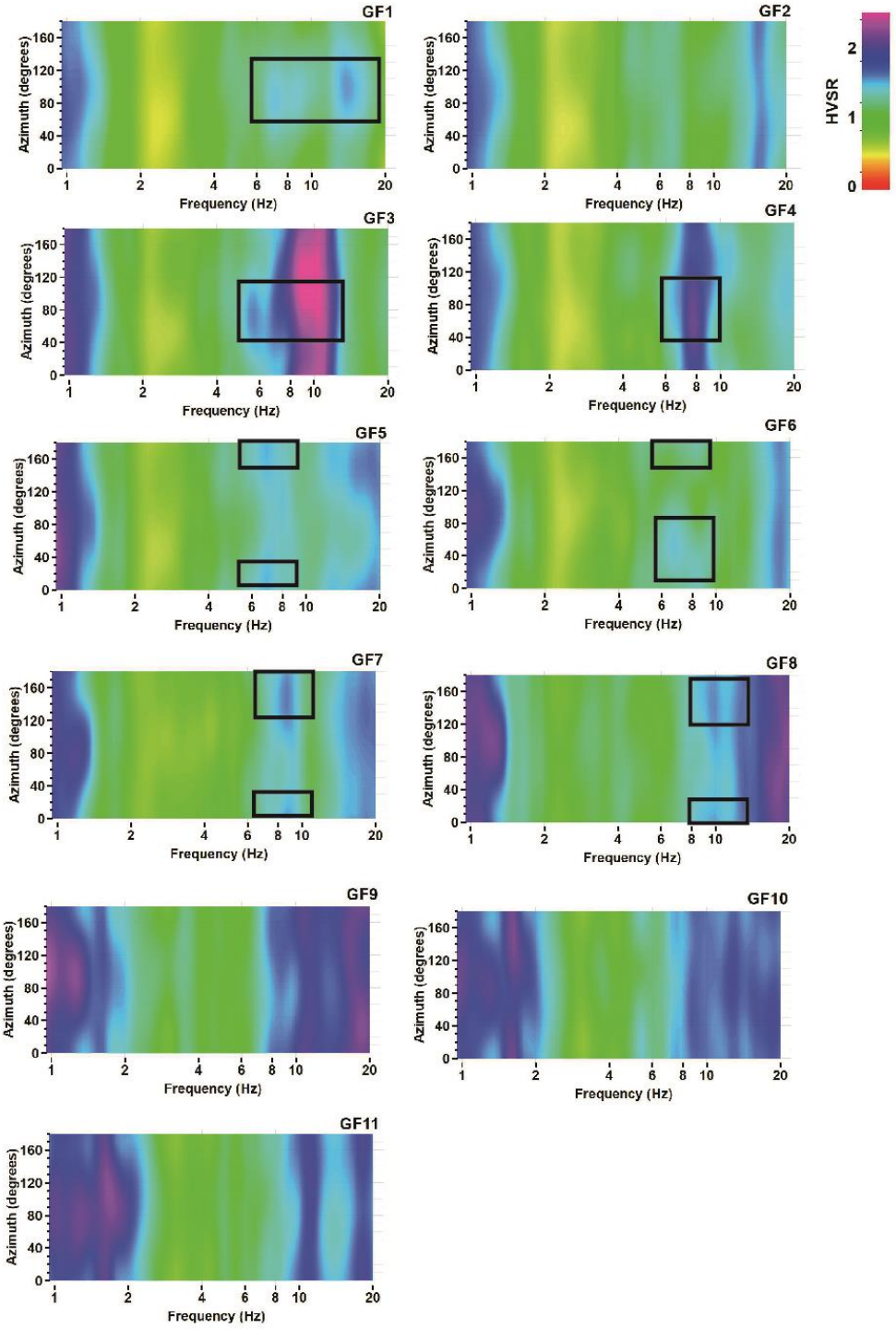


**Fig. 8.** Rotational HVSR results for each station, referring to the band 1-20 Hz for the clarity: HVSR curves plotted in the range 0.2-20 Hz may be found in the Supplementary Materials. Black boxes indicate the main polarisations: measurement at GF1 and GF3 sites show a slightly polarisation with an azimuth of N80-100° for frequencies >6 Hz, measurements at GF5 and GF6 sites show amplification in the band N0-20° and about N160-180°; measurement at GF7 and GF8 sites show amplification in the band N0-20° and in a wider azimuthal range (about N120-180°).

Regarding the 2D array measurement, since one of the hypotheses at the base of this method is the assumption of an infinite semi-space with parallel layers, before computing the dispersion curve, a control was made on the single spectra of the vertical component acquired at each geophone. This analysis led to the exclusion of eight geophones (four at each

extreme of the L-shaped array). The variability of the vertical components on all the geophones of the array is shown in the Supplementary Figure 2.

The results from the 2D array are shown in Figure 9. These latter, as well as the frequencies highlighted by the HVSR curves, are useful for making inferences about the site's characterisation. Regarding the agreement shown in Fig. 9b, we have overlapped the peaked f-k and MSPAC dispersion curves. Results showed that the combination of different methods (f-k and MSPAC techniques) give complementary results. Average dispersion curves are comparable in the range 9-13 Hz for both the techniques, and this increases the confidence about the results, while peaking the f-k dispersion curve out of the bounds of the results obtained from MSPAC, remaining into the kmax and kmin limits, allows extending the imaging towards highest frequencies. The general trend of the MSPAC curve seems similar to the best-fit, while this latter is within the average and ± standard deviation f-k dispersion curves.

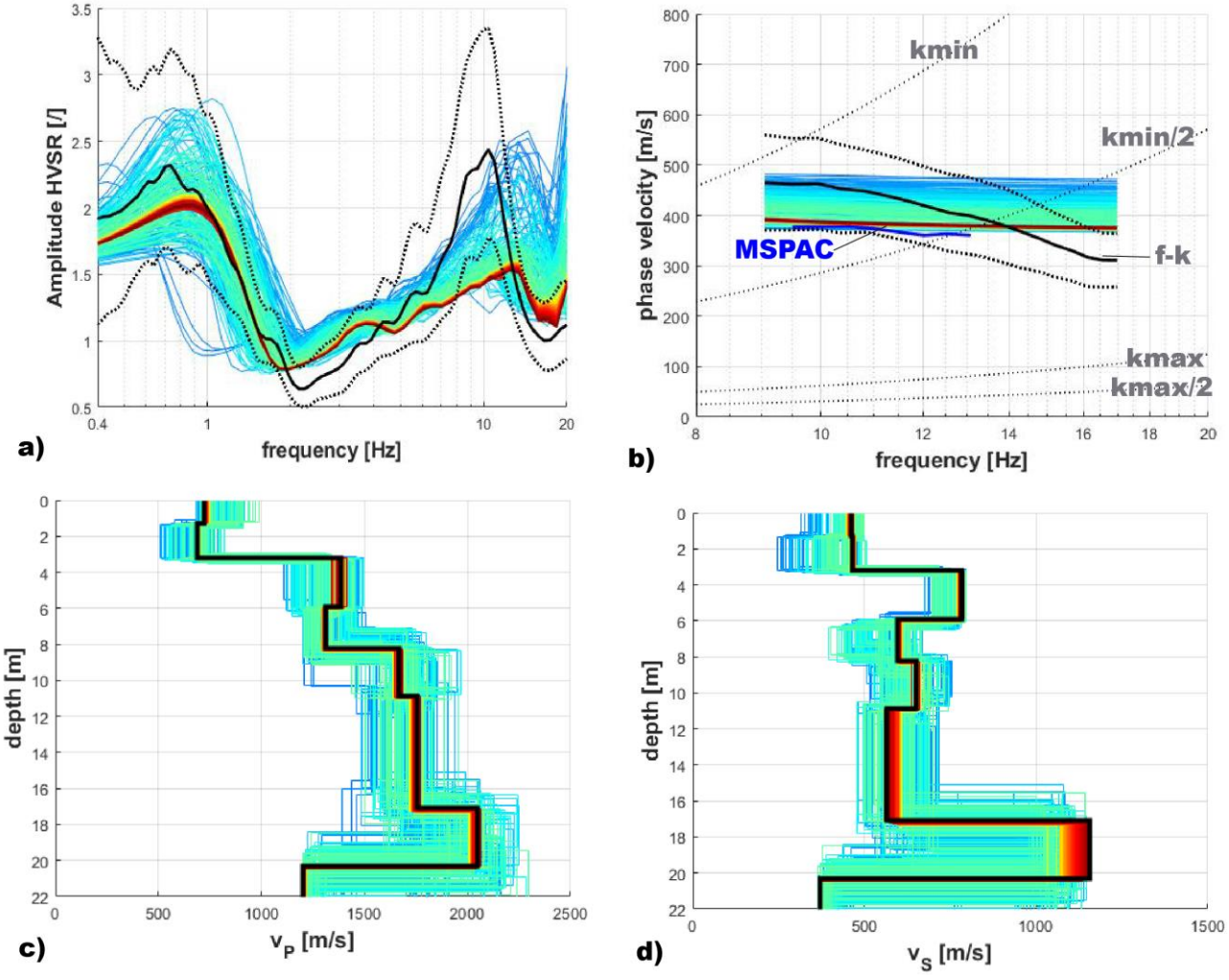


**Fig. 9.** Results from 2D array measurement. The theoretical models of the fundamental mode Rayleigh-wave, in terms of ellipticity curves and dispersion, are shown in (a) and (b), respectively. The colour scale is proportional to the misfit resulting from the inversion, and the black curves are the measured dispersion and HVSR curves. The phase velocities in panel b are retrieved by the application of two methods (f-k and MSPAC) used for the processing of the 2D array recording. $V_P$ and $V_S$ models are shown in (c) and (d), respectively.

366 **4.3. Soil-gas profiles**

367 Soil-gas concentrations ($CO_2$ and $^{222}Rn$) were measured along two profiles parallel to the ERT acquisitions, to verify the
368 presence of possible structural or buried morphological discontinuities (faults, fractures, buried scarps) which provide
369 routes for deep-gas leakages in correspondence to the low resistivity areas recognised in the ERT profiles. The data are
370 reported in Table 1; the soil-gas samples exhibited concentrations of up to 10.6% for $CO_2$ and up to 7.98 kBq/m$^3$ for
371 $^{222}Rn$.

372 Along profile 1 (Fig. 10a), the spatial distribution of $CO_2$ and $^{222}Rn$ values shows two peaks that occur between 100 and
373 150 m, in correspondence with the low resistivity zone observed along ERT-1

374 Along profile 2 (Fig. 11a), the highest $^{222}Rn$ activity (7.98 kBq/m$^3$) was measured at the southern end of the profile, in
375 correspondence with the high resistivity zone observed in the ERT-2 profile; $CO_2$ concentrations follow a trend similar
376 to radon isotopes, but their values are relatively lower (up to 3.6%) than those measured along profile 1.

377

| **Distance from borehole m** | **$CO_2$ %. v/v** | **$^{222}Rn$ kBq/m$^3$** |
|---|---|---|
| | ***Profile 1*** | |
| 2 | 3.6 | 5.79 |
| 20 | 3.2 | 4.40 |
| 40 | 2.2 | 5.24 |
| 80 | 1.4 | 5.36 |
| 90 | 1.0 | 3.61 |
| 100 | 0.8 | 1.04 |
| 110 | 4.0 | 6.97 |
| 120 | 1.0 | 2.46 |
| 130 | 3.2 | 3.28 |
| 140 | 10.6 | 6.84 |
| 150 | 1.6 | 4.67 |
| 160 | 3.6 | 5.54 |
| 180 | 1.6 | 5.55 |
| 220 | 0.6 | 1.47 |
| 260 | 0.6 | 1.53 |
| | ***Profile 2*** | |
| 9 | 3.6 | 5.79 |
| 18 | 1.0 | 3.14 |
| 27 | 2.8 | 6.68 |
| 36 | 3.0 | 7.98 |

378 **Table 1.** Soil-gas data collected along two profiles (location in Fig. 3).

379

380 **5. INTERPRETATION OF DATA AND DISCUSSION**

381 The correlation between borehole stratigraphy, geomorphological observations, geophysical, and geochemical data
382 provides clues about the surface and subsurface geometry of the Prima Porta travertine body and the embedding

sediments which are useful for better defining the stratigraphic and morpho-structural architecture of this sector of the Tiber valley.

In plan-view, the Prima Porta meander is featured by the lateral stack of several, east-directed, and convex-shaped scroll bars (Fig. 12), which suggests a generalised eastward expansion of the entire meander point-bar and river-channel system. Indeed, scroll bars typically record the incremental growth of a point-bar (Russell et al., 2018, with references); in this case, they have been identified on map and on Google Earth images by small topographic irregularities (i.e., ridges and swales), by alignments of localised creeks, and by alternating belts of different soil moisture and vegetation cover densities.

Regarding the subsoil structure, since the ERT-1 survey was performed in correspondence with the Prima Porta borehole, it was possible to calibrate the ERT results and to directly correlate resistivity values with the litho-stratigraphic characteristics. From top to bottom, the borehole, whose stratigraphy is shown in Figure 2b, intercepts alluvial sediments (silt and clay of floodplain environment) attributed to the most recent phase of deposition of overbank floods from the Tiber (middle-late Holocene, ~6 ka), which display a low resistivity (below 15 ohm×m); the travertine layer, at depths between 9 and 12 m, and with an intermediate resistivity (Zone 2, green to yellow in Figs. 4 and 10c) between 15 and 30 ohm×m; beneath the travertine unit, the resistivity decreases again below 15 ohm×m, and this zone matches the alluvial sediments (silt and silty sands) attributed to the lower portion of the buried terrace (Upper Pleistocene) and to the underlying Paleotiber unit (Middle Pleistocene) in the core stratigraphy. These measures were fundamental for attributing characteristic resistivities to the local deposits, which, in comparison with values from the literature for the same sediments are generally low, especially those of the travertine (Pola et al., 2014; Huerta et al., 2016; Török et al., 2019). This behaviour can be attributed to the quantity and quality of groundwater that almost reaches the field level and is particularly mineralised (the electrical conductivity of water is 3080 μS/cm; Giustini et al., 2018), generally reducing the resistivity (Loke and Barker, 1996; Loke and Dahlin, 2002; Oudeika et al., 2020).

At depths greater than 20 m, at a distance between 70 and 130 m from the origin of the profile, a zone with resistivity values higher than 30 ohm×m (Zone 3), showing a sharp lateral variation of resistivity, is observed. There are no borehole data that could aid in directly constraining the interpretation of this zone; however, considering the stratigraphic architecture of the Tiber valley, this zone could be related both to gravels and sands from the basal channel of the Paleotiber unit and/or to an even lower-occurring travertine body. The HVSR curves agree with both interpretations. In fact, the GF1 to GF7 sites (Fig. 10b) show an inversion of S-wave velocities in the soil profile (i.e., with the presence of layers with a lower velocity with respect to the upper ones) which is consistent with lithoid materials such as travertine and/or well-cemented gravels.

In the middle part of ERT-1, a wide zone of low resistivity values (<15 ohm×m) may be ascribed to saturated deposits (probably silty and sandy alluvial sediments, based on the stratigraphic correlation; Giustini et al., 2020), characterised by a remarkable presence of mineralised waters. Corresponding to this part of the section, the soil-gas profile shows two peaks of $CO_2$ and $^{222}Rn$ concentrations (Fig. 10a). Overall, low resistivity values and soil-gas anomalies suggest the presence of a zone of intense water-fluid circulation, possibly associated with the presence of a structural or buried morphological discontinuity (perhaps represented by the sharp lateral variation between Zones 2 and 3 of the ERT) which allows the ascent of thermal waters and/or gas emissions. A $CO_2$-rich gas phase of deep origin (metamorphic and partly mantle/magma degassing) is associated with the Prima Porta borehole, and several gas vents, locally connected with crustal structural lineaments, have been documented along the Tiber valley (Vaselli et al., 1997; Minissale et al., 2002; Giustini et al., 2018). Generally, deep-gas leakage is facilitated by faults and fractures because they are deep, weakened zones consisting of highly fractured materials that increase permeability at the surface. The migration of $CO_2$ and $^{222}Rn$ by diffusion and/or advection along buried active faults can generate shallow anomalies with concentrations significantly higher than background levels. Radon, a radioactive inert gas with a half-life of 3.82 days, is particularly sensitive to buried discontinuities because of its ability to migrate along relatively long distances from host rocks, using $CO_2$ as a carrier gas (King et al., 1996; Ciotoli et al., 2007, 2014, 2016).

A fractures system in this part of the section could be also supported by the wavefield polarisation analysis. At frequencies >6 Hz, the GF5, GF6, GF7, and GF8 sites show a slight polarisation, with an azimuth of N0-20°; a slight polarisation is observed for sites GF1, GF3, and GF4 with an azimuth of N80-100° (Fig. 8). Moreover, a further preferential direction is enhanced from the rotational HVSR at GF5, Gf6, GF7 and GF8: the measurements at GF5 and GF6 sites show amplification in the band about N160-180°, while the measurements at GF7 and GF8 sites show amplification in a wider azimuthal range (about N120-180°). To discuss the rationale behind this evidence, it should be underlined that buried fault zones may be very challenging to investigate due to the complex geological structures (i.e., S-wave velocity inversion with depth) in which the combination of several phenomena of wave propagation (reflection, resonance, Love wave trapping) modifies components with different weights and may render the interpretation difficult. Nevertheless, many authors have demonstrated that, in fault zones, horizontal polarisation is often strong and tends to be perpendicular to the fracture field or has a high-angle relative to the fault strike (Pischiutta et al. 2010, 2012, 2013, 2017; Napolitano et al., 2018 and reference therein; Panzera et al., 2016, 2017). The polarisation of the particle motion of seismic noise is also known to be modified by heterogeneities in local structure such as cleavages or fractures (Ben Zion, 1998; Pischiutta et al., 2012). Famiani et al. (2015) also identified peaks which were broader and with lower amplitude and an important difference in terms of the signal polarisation across a seismogenic fault in central Italy (i.e., Pizzoli fault). Therefore, the observed polarisation in our data, further joined with the geochemical observations

444 discussed above, and the local fracture trends (N90-110°) traced in Figure 1, let us hypothesize a role of the fracture
445 systems (i.e., cracks) in the amplification at the study site.
446 In the eastern part of ERT-1, the resistivity Zone 2 overlies the high conductivity zone; it is located approximately at the
447 same level as the travertine deposit intercepted by the borehole. According to the resistivity values, this zone might be
448 interpreted on a first approximation as a large travertine body, extending between 150 m and the eastern end of the
449 ERT, slightly dipping towards the present-day Tiber river's course. However, the HVSR curves and soil-gas
450 concentrations do not bolster this interpretation. The HVSR curves, measured at the GF8, GF9 sites, show a very broad
451 band peak at higher frequencies (Figs. 5 and 7). Otherwise, the HVSR amplitude values in Fig. 10b at about 50 m from
452 the start of the W-E measurements alignment are lower than those measured in correspondence with the borehole; this
453 configuration is coherent with a relatively surficial horizon of materials with poor mechanical properties such as
454 relatively loose sands. This interpretation is confirmed by the low soil-gas concentrations measured with respect to the
455 other parts of the profile (Fig. 10a), typical of a very ventilated soil. Therefore, this resistivity zone can be interpreted as
456 being due to the lateral stack of sandy channel-fill bodies, consisting of eastward-migrating bars and featuring the
457 multilateral stacking pattern of channel bodies (Rajchl and Uličný, 2005; Gibling, 2006), which is a typical expression
458 of the channel clustering in the TDS' late transgressive and highstand systems tracts (Milli et al., 2016). The laterally
459 migrating bars in cross-sectional view correspond to the scroll bars on a plane shown in Figure 12. Relatively high
460 resistivity sand-dominated channel-fill bodies, which are embedded into more conductive floodplain fines, have
461 commonly been revealed by ERT investigations (Baines et al., 2002; Bersezio et al., 2007; Nimnate et al., 2017; Guinea
462 et al., 2018).
463 The two ERT arrays have a point of intersection between electrodes n. 7 (of the ERT-2) and n. 40 (of the ERT-1), and
464 ERT-2 also intercepts the travertine body, at a depth of about 4 m. In this tomography (Fig. 11c), travertine displays a
465 concave-upward section wedging out toward the central part of the profile; here, the resistivity tends to increase up to
466 50 ohm×m. A seismic refraction (SR) survey was performed above this high resistivity block; this measure allows one
467 to constrain the S-wave profile obtained throughout the 2D array measurement (Fig.11b) and to further confirm the
468 interpretation of this block as a unique travertine body. In fact, S-wave velocity increases up to 800 m/s in
469 correspondence with the high resistivity block, values that are compatible with compact and massive materials (Forte et
470 al., 2019). In contrast, the Zones 2 of resistivity, which are about 1.5 m thick and located just below surface in the
471 northern and southern parts of the profile, are not attributed to travertine, but to anthropogenic deposits – possibly a
472 buried basement of an old edifice whose perimeter is still recognisable in old satellite images. The other zones of lower
473 resistivity (<15 ohm×m) were interpreted as alluvial deposits covering the travertine.

Considering as a whole the high-strength structures of the two profiles, the upper surface of the travertine deposit appears to have a curved shape, which is gently dipping towards the east (i.e., towards the present-day Tiber river), and forms a concave-upward section wedging out toward the south; the maximum thickness could be 20 m. This curved shape is consistent with the morphology inferred from macroscopic and microfacies observations (Giustini et al., 2020), a pool in a terraced slope dam which is gently dipping towards the south and east. The real extension of the buried travertine body is unknown, but we speculate that it is roughly extended along a N-S direction, along the western border of the plain (Fig. 12), between the normal faults with roughly a NW-SE direction inferred from Funiciello et al. (1992). Ancient springs were probably connected to these structural features and related to the rising hydrothermal fluids precipitating travertine.

The combined application of these ERT, seismic refraction, ambient noise measurements, and soil-gas survey methodologies may be successfully used in similar geological contexts for identifying buried travertine bodies and other complex 2D/3D structures. The alluvial valleys are often located in tectonically active areas, similarly to the Tiber valley; travertine deposits can be quite common along their boundaries because they are associated with rising hydrothermal fluids, whose ascent is favoured by the presence of structural discontinuities. In these contexts, travertine deposits can potentially represent valuable archives of paleo-sources of $CO_2$ in places where gas emanations are no longer visible, evidencing active tectonics and low-enthalpy geothermal areas.

## 1. CONCLUSIONS

The alluvial deposits of the Tiber river, at the Prima Porta site, were investigated using non-invasive geophysical and geochemical methods. The results were calibrated and interpreted using previously collected litho-stratigraphic data of a borehole drilled in the study area. The applied geophysical and geochemical techniques (ERT, seismic refraction, ambient noise measurements, and $CO_2$ and $^{222}Rn$ concentrations in soil-gas surveys) complement each other and their combination allowed us to delineate the subsoil structure of this sector of the Tiber valley. In particular, the geometry of the buried travertine body of Prima Porta was defined; its upper surface appears to have a curved shape, gently dipping towards the east to the present-day Tiber river, and forming a concave-upward section wedging out toward the south. Due to its hydrothermal origin, this travertine unit is a poorly porous, hard and crystalline material, and consequently its specific electrical resistivity values were relatively high with respect to those measured in the embedding alluvial sediments (silt and silty sands). This shape is consistent with the morphology inferred from macroscopic and microfacies observations, i.e., a pool in a terraced slope dam (Giustini et al., 2020). Other stratigraphic and structural features of this sector of the Tiber valley were inferred, such as the presence of silty-sand channels, deposited by the Tiber river after the last glacial maximum. Finally, a weakness zone, permeable to the ascent of $CO_2$ and $^{222}Rn$, was

inferred in correspondence with low resistivity zone, a soil-gas anomaly, and slight polarisation effects recorded in the HVSR.

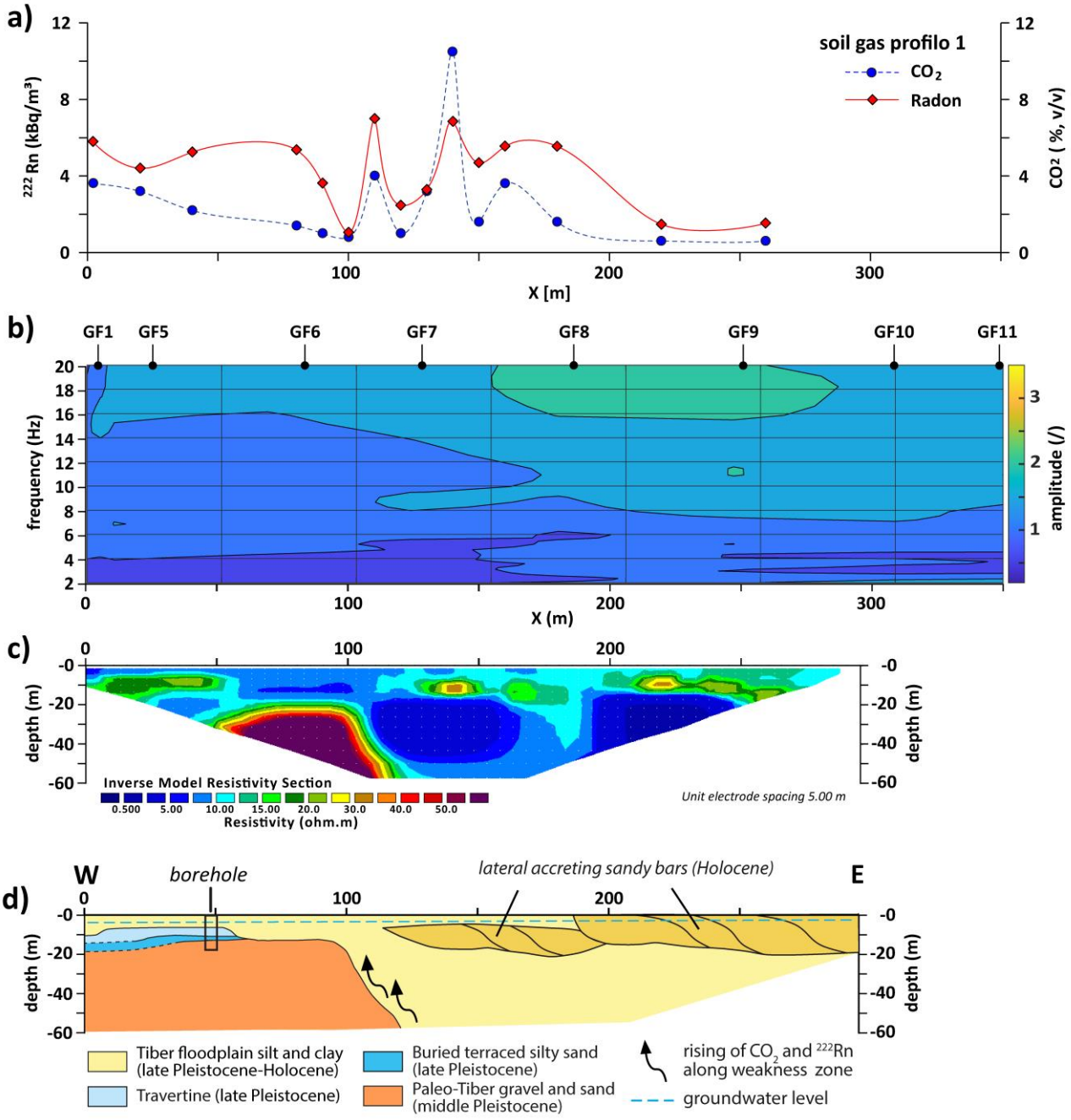


**Fig. 10**. a) Soil-gas ($CO_2$ and radon) profiles; b) HVSR cross-section; c) ERT-1; d) geological interpretation of the ERT-1 profile.

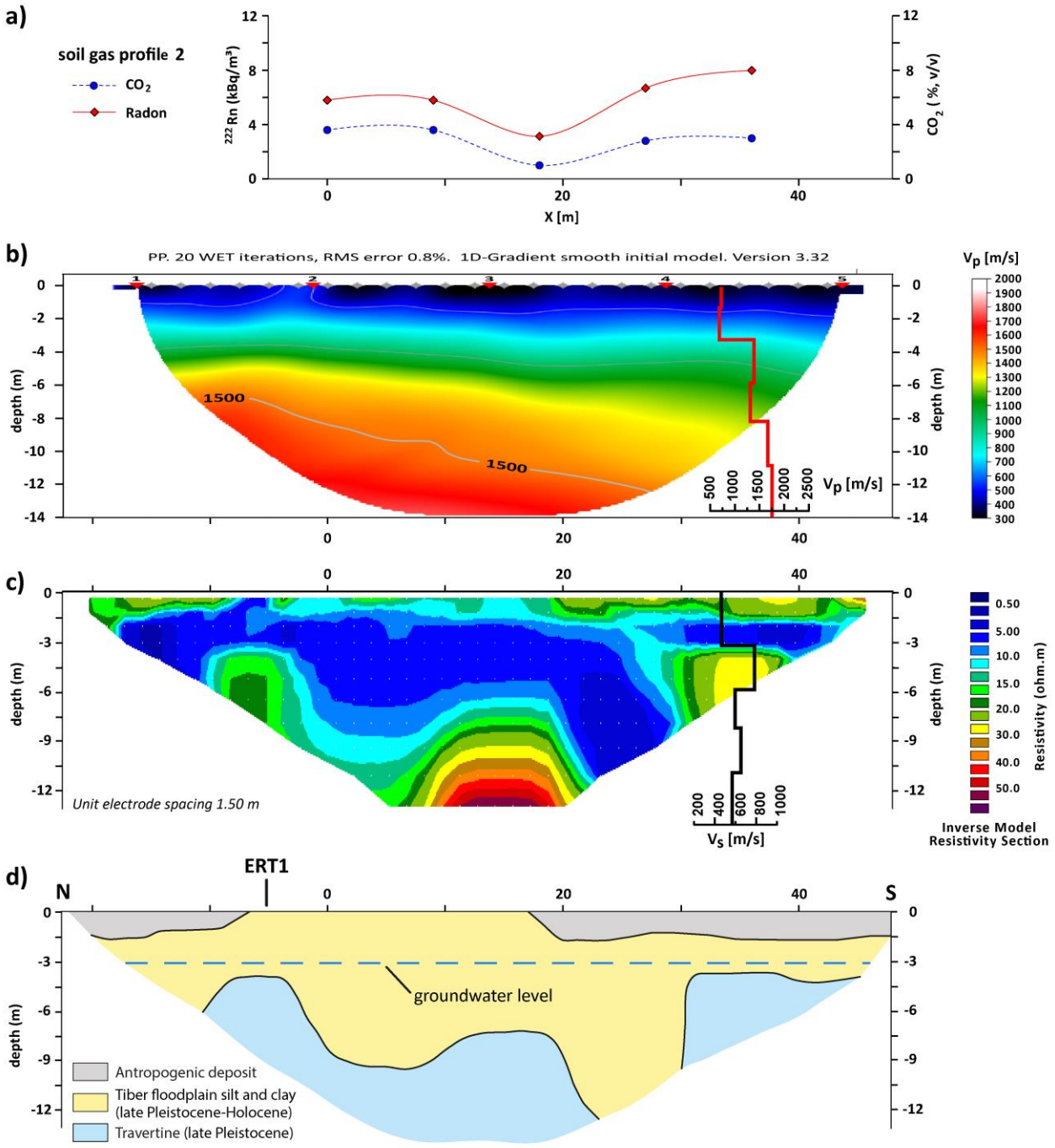


**Fig. 11.** a) Soil-gas ($CO_2$ and radon) profiles; b) $V_P$ profile from the 2D array superimposed on SR section; c) $V_S$ profile from the 2D array superimposed on ERT-2; d) geological interpretation of the ERT-2 profile.

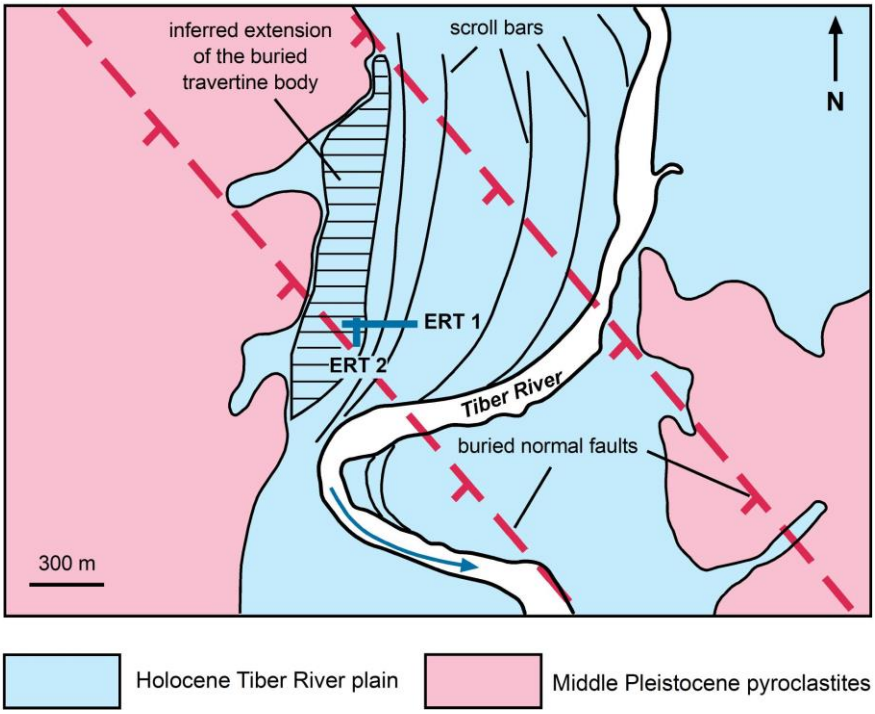


**Fig. 12.** Sketch map showing the eastward-directed and convex-shaped scroll bars and the supposed extension of the buried travertine body. The buried inferred normal faults are from Funiciello et al. (1992).


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## CONFLICT OF INTEREST

None of the material reported in the work has been published or is under consideration for publication elsewhere. Authors have no conflict of interest with any of the material presented.

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