



**Università
degli Studi
di Palermo**

AREA RICERCA E TRASFERIMENTO TECNOLOGICO
SETTORE DOTTORATI E CONTRATTI PER LA RICERCA
U. O. DOTTORATI DI RICERCA

PhD in Earth and Marine Sciences
Department of Earth and Marine Sciences (DiSTeM)
Scientific Sector GEOS 04/B

3D GEOLOGICAL AND GEOPHYSICAL MODELS OF THE SUBSOIL

PhD STUDENT
Alessandro Canzoneri

TUTOR
Prof. Raffaele Martorana

COORDINATOR
Prof. Christian Conoscenti

CO TUTOR
Prof. Mauro Agate

XXXVII CICLO
A.A. 2023/2024

ABSTRACT (pg.1)

INTRODUCTION (pg.2)

CHAPTER I - GEOPHYSICAL METHODOLOGIES (pg.6)

1.1 Seismic Refraction Tomography (SRT) (pg.6)

1.2 Multichannel Analysis of Surfaces waves (MASW) (pg.8)

1.3 Horizontal to Vertical Spectral Ratio method (HVSr) (pg.11)

1.4 Vertical electrical sounding (VES) (pg.15)

1.5 Electrical Resistivity Tomography (ERT) and Induced polarization tomography (IPT) (pg.17)

1.6 Transient Electromagnetic (TEM) (pg.19)

*CHAPTER II – MULTIDISCIPLINARY STUDY TO RECONSTRUCT 3D SUBSOIL MODEL
IN URBAN AREAS (pg.20)*

*2.1 Description of the Case Study of the Palermo Plain: Objectives, Studied Areas, Data Used, Results
Obtained (pg.20)*

2.2 Previous geological and geophysical data (pg.22)

2.3 Geological and geomorphological setting (pg.23)

2.4 Geological data collected (pg.26)

2.4.1 City GIS database (pg.26)

2.4.2 Stratigraphic reconstructions derived from boreholes analysis (pg.29)

*2.4.3 Stratigraphic reconstructions derived from well cutting, trenches and outcrops
analysis (pg.31)*

2.5 Geophysical data collected (pg.40)

2.5.1 SRT and MASW surveys (pg.40)

2.5.2 HVSr surveys (pg.52)

2.6 Reconstruction of the 3D model of the Palermo, close to the Oreto River (pg.59)

2.7 Discussion on the model produced and conclusion about the case study (pg.64)

*CHAPTER III – MULTIDISCIPLINARY STUDY TO CHARACTERIZE THE SURFACE
WATER BODIES THROUGH THE CONSTRUCTION OF GEOPHYSICAL
AND GEOLOGICAL 2D AND 3D MODELS (pg.66)*

*3.1 Description of the cases study of the Caronia (CGWB), Sant'Agata -Capo d'Orlando
(SCGWB) and Barcellona P.G. -Milazzo (BMGWB) Groundwater bodies; Objectives, Studied
Areas, Data Used, Results Obtained (pg.66)*

*3.2 "Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater
Body in Caronia (Sicily)" (pg.67)*

*3.3 "Coastal Groundwater Bodies Modelling Using Geophysical Surveys: The Reconstruction of the
Geometry of Alluvial Plains in the North-Eastern Sicily (Italy)" (pg.89)*

*CHAPTER IV - MULTIDISCIPLINARY STUDY TO PRODUCE A SUBSOIL MODEL
USEFULL FOR THE SEISMIC CHARACTERIZATION OF AN AREA (pg.111)*

*4.1 Description of the case study of the plains of San Vito Lo Capo, Macari and
Castelluzzo; Objectives, Studied Areas, Data Used, Results Obtained (pg.111)*

*4.2 "Near Surface Geophysics Contribution for First Level Seismic Microzonation Studies
For The Municipality Of san Vito Lo Capo, Western Sicily, Italy." (pg.112)*

CHAPTER V – CONCLUSIONS (pg.122)

REFERENCES (pg.123)

ACKNOWLEDGMENTS (pg.130)

ABSTRACT

This work has been developed to highlight the importance of an integrated approach between geological and geophysical data in the construction of 2D and 3D subsoil models. This approach allows the best of the information available from both datasets for different research areas and in the new field of engineering applications. In this work several case studies will be presented, in which the implementation of pre-existing datasets through geophysical methodologies has been aimed at a more detailed definition of the subsoil in areas of alluvial and coastal plain of Sicily. First is presented the case study of the plain of Palermo in which a 3D model of the area near the Oreto river is reconstructed. This first case is presented to show how the integrated geological and geophysical approach can be used in urban contexts by better describing paleo morphologies masked by the urban network. A second part of the work is focused on the construction of water bodies in the province of Messina; also, in this case the geological data were coupled with geophysical data. In the specific case of soil 3D-models of soil resistance, after integration with other geological and geophysical data, it was possible to define the thicknesses of alluvial coverings. A third part of the work is devoted to the case study of the coastal plains of the peninsula of San Vito Lo Capo, in the province of Trapani. In this field, geological and geophysical data were interpreted and processed together to define a preliminary study for the computing of the local seismic response.

INTRODUCTION

The project entitled "3D Geological and Geophysical Models of the Subsoil" aims at constructing accurate geological and geophysical models of the subsoil. Within the project underground modelling of several urban and rural areas of Sicily, represented in figure 1, was carried out. These models were mainly constructed by a joint interpretation of data derived from different geophysical methods and stratigraphic data.

The main goal of this work is to highlight the importance of multidisciplinary geophysics and stratigraphic approach to define bidimensional and tridimensional models of the subsoil. Within the profession of a geologist this kind of approach is translated into a multidisciplinary study of an area and its physical environment to produce correct and accurate geological modelling that serves to monitor, plan, secure and protect human and productive activities.

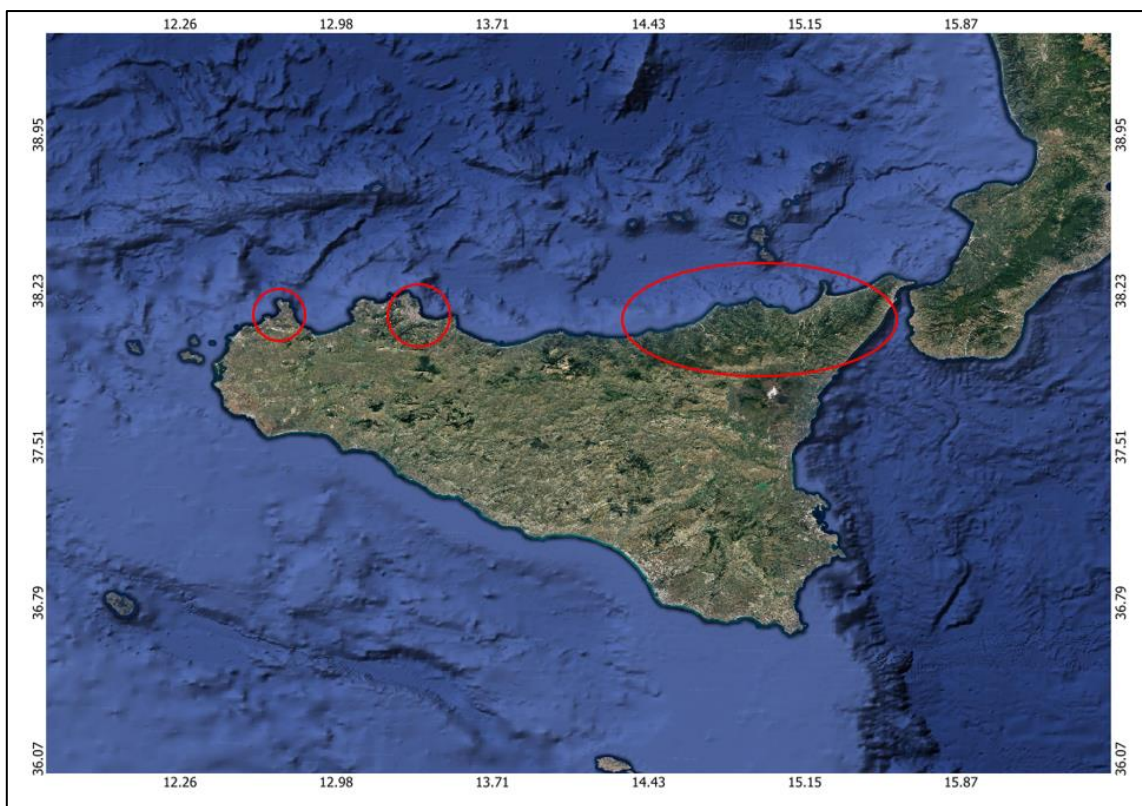


Figure 1: Study areas circled in red; proceeding from west to east: area of the municipality of San Vito, province of Trapani; area of the plain of Palermo; exanimated areas of the province of Messina (Caronia, Sant 'Agata, Capo D'Orlando, Barcelona Pozzo di Gotto, Milazzo).

For this reason, the several case studies presented in this work are indeed mainly focused on the importance of the joint interpretation of data acquired by geophysical surveys and geologic data to better define the subsoil features. The geophysical data acquired had been constrained by the information derived from direct investigation to provide a fundamental tool for the integration and definition of subsurface models and to emphasize the main risks that could affect a studied area. This practice is well known to be widely used and is useful to increase the robustness, precision and accuracy of subsurface models. The kind of work carried out in this study is summarized in a workflow model shown in figure 2.

The multidisciplinary and integrated building of these models proves extremely useful in urban and touristic and industrialized areas. In these highly populated areas, it is not always possible to carry

out direct surveys that provide information on the subsoil. Therefore, it appears extremely helpful to reconstruct the geological model of the subsoil based on data derived from previous direct investigation, integrating them by geophysical surveys. This is one of the main topics for urban area 2D and 3D subsoil reconstruction considering the actual cost of geophysical instrumentation; the relationship between the amount of data acquired and the economic evaluation of a geophysical survey makes geophysical methodologies quite economical compared to direct investigations to produce accurate subsoil models.

The multidisciplinary approach, presented in this work, had often been used in several application fields like geological surveys (Smallwood & Maresh, 2002, Martelet et al. 2004, Zhang et al. 2022), archaeological research (Cardarelli & Di Filippo, 2009, De Beer et al., 2012, Moscatelli et al., 2014), studies about local seismic site effects and engineering works (Shaffner et al. 2009, Panzera et al., 2022). During the past these kinds of models, realized integrating geological and geophysical data have also been used for hydrogeological research for various purposes, from the protection of aquifers to the definition of groundwater volumes (Martorana et al. 2014, Panagopoulos et al. 2021, Tarallo et al. 2023). Moreover, this workflow had also been helpful to reconstruct the geological model of the subsoil in urban areas (Andersen 2020, Gutierrez et al. 2023).

The geological and geophysical models described in this work, both two-dimensional and three-dimensional, have been realized for the subsoil of the Northern Sicily coast (figure 1). The activity of acquisition of geophysical and stratigraphic data has concerned coastal and alluvial plains and river valleys located in the provinces of Trapani (San Vito Lo Capo, Macari, Custonaci), Messina (Caronia, Sant'Agata-Capo D'Orlando, Barcellona-Milazzo) and Palermo. For the latter sector in particular, many mechanical surveys were considered useful to calibrate geophysical surveys.

The choice of study areas stems from the fact that Sicily is a geologically complex area. Increasing knowledge of the geological and geophysical model is a very problematic subject. In this sector, in fact, to the geological complexity resulting from the overlapping of different geological environments and tectonic phases of various kinds is added an important seismic activity.

In particular, the sectors studied are alluvial and coastal plains that are areas often critically important for different reasons. They are usually densely populated and, considering their proximity to the sea, host strategic harbors; seaside tourism causes a clear increase in the population during the warm months. Moreover, the gentle morphology favors the development of numerous road and railway communication routes and, consequently, of industrialized areas adjacent to the main towns. Unfortunately, coastal alluvial plains are often subjected to various risks, both natural, such as floods and paroxysmal events linked to wave motion, and those linked to the development of anthropic activities. Furthermore, the human impact on these areas causes excessive exploitation and contamination of aquifers.

Moreover, in these areas' new direct surveys, which are very expensive, are hampered by the presence of a dense urban network that also masks the original morphologies.

For these reasons, geological and structural characterization, through geophysical methodologies and already collected geological data, could lead to an increase in knowledge useful to model and manage water resources, anthropic activities and natural hazards in urbanized coastal plain.

Firstly, this workflow can be used for the reconstruction of the geological model of the subsoil in urban areas. Defining the geometry and extension of the lithotypes is indeed useful for the definition and implementation of urbanistic plans but as often happens in highly populated areas, it is not always possible to carry out direct surveys that provide information on the subsoil. Therefore, it appears extremely helpful, in an urban context, constructing geological models defined based on geophysical surveys integrate with available subsoil information derived from previous direct surveys. For the urban area these reconstructions allows us to identify the original natural constraints, such as the presence of watercourses, which influenced the primary anthropized landscape evolution and to understand which urban areas are nowadays subjected to geological hazards.

In addition, describing the lithology and geometry of the sedimentary bodies could be useful to circumscribe and quantify water bodies, allowing their hydrogeological study, monitoring and assessment of possible exploitation.

Finally, this study is extremely handy to implement information on the areas under consideration, thus providing indications on peculiar elements (sediment thickness, presence of faults, uplift estimation) caused by seismic activity and that are involved in the development of the latter.

To summarize, the 2D and 3D modelling of the subsoil, based on the integration of geological and geophysical data, can be considered a fundamental instrument to investigate and detail the characteristics of the subsoil. This approach can be used for different study sectors like urban subsoil reconstruction, the quantification of water bodies extent and the seismic risk analysis, to obtain a clearer understanding of the features of a studied area.

The research activity described in the work is essentially based on the processing of active and passive seismic, geoelectric and electromagnetic data the interpretation of the data previously collected geophysical data, correlating them with geological and geotechnical data obtained from mechanical surveys, field surveys or bibliographical studies or previous work. The geophysical data acquired in this work are derived from the following geophysical techniques: Seismic Refraction Tomography (SRT) (Rawlinson et al., 2010); Multichannel Analysis of the Surface Waves (MASW) (Park et al. 2000); analysis of seismic noise with the Horizontal to Vertical Spectral Ratio (HVSr) (Nakamura 1989, 1996, 2000) Vertical Electrical Sounding (VES) (Kosinski & Kelly, 1981); Electrical Resistivity Tomography (ERT) (Loke et al. 2015); Induced Polarization Tomography (IPT) (Seigel, 1959); Transient Electromagnetic (TEM) (Mejy 2005, Goldman et al., 1994).

The inversions of geophysical data and their interpretation were constrained by geological and geotechnical data obtained from wells stratigraphy. Moreover, the combined and integrated use of different geophysical methods has long been considered extremely useful for the definition of subsurface characteristics (Carollo et al. 2020, Cafiso et al. 2023) and for the subsequent elaboration of 2D and 3D models. Following this approach, the inversions of several acquired data had been limited by data obtained with other geophysical techniques. For example, some subsurface models V_s have been obtained by forcing the inversion of HVSr curves from velocity V_s derived from MASW surveys carried out (Castellaro & Mulargia 2009, Dal Moro 2024, Castellaro 2016).

The geophysical data analyzed mainly describe the seismic waves velocity pattern and electrical resistivity with depth. These had been used to estimate the depth of the seismic bedrock and the thickness and seismic velocity features of the overlying deposits.

The project is part of the PON (Programma Operativo Nazionale) "Research and Innovation" 2014-2020 Asse IV "Education and research for recovery" Action IV.4 "Doctoral degrees and research contracts on innovation themes". In particular, the project is part of the thematic area "Digital Agenda, Smart Communities, intelligent mobility systems: technological development paths to national priority" of the SNSI (Strategia Nazionale di Specializzazione Intelligente), particularly in the trajectory "Systems for the safety of the urban environment, environmental monitoring and prevention of critical events or risks" and in the large PNR (Programma Nazionale per la Ricerca) area "Security for social systems", under "Security natural systems".

For this reason, a six-month long stage was performed at SERING S.r.l. The company is responsible for several projects related to various infrastructures in the areas of Palermo; this allowed continuous and indispensable access to the site that facilitated data acquisition operations and analysis. The firm also provided access to its archives, from which further data were extracted to deepen knowledge of the areas studied.

In this work, the first chapter will briefly present the geophysical methodologies used to collect data on the models produced.

The following chapters present the different case studies in the areas of northern Sicily highlighting the importance of a multidisciplinary approach to 2D and 3D underground modelling for specific research topics.

In this way the second chapter shows the workflow applied for the reconstruction of a 3D model of the subsoil in urban areas representing the case study of the Palermo plain. The sector of the plain closer to the Oreto River has been analyzed, collecting geophysical and geological data, in an effort to reconstruct the features of the pre-anthropic landscape (Canzoneri et al 2024).

In the third chapter the importance of the integration of geological and geophysical surveys to define 2D and 3D models of the subsoil within alluvial plains is shown. In this chapter the case studies regarding several water bodies of the north coast of Sicily are reported: the Caronia Water Body (CGWB), the Sant 'Agata di Militello – Capo D'Orlando water body (SCGWB) and the Barcellona Pozzo di Gotto – Milazzo water body (BMGWB). These studies have been conducted to characterize the thickness of the deposits consisting the three groundwater bodies and to identify the depth of the bedrock by the integration of geological and several geophysical surveys. These studies were published in two papers submitted to the journal *Water* in September 2023 and April 2024 (Canzoneri et al 2023 b, Capizzi et al 2024).

The fourth chapter regards the case study about the San Vito, Macari, Castelluzzo plains. This shows the work made, integrating geophysical and geological data, to realize subsoil models useful to define the seismic risk that could affect an area. These studies were conducted to define the first level seismic microzonation of the Municipality of San Vito lo Capo. This work is presented in a long abstract submitted to the *41st National Conference of the GNGTS (National Group of Solid Earth Geophysics)*. The conference took place in Bologna from 7 to 9 February 2023 and an oral presentation about the work was provided. (Canzoneri et al.2023 a).

The final chapter will be a short and conclusive evaluation and review of results obtained in each study area.

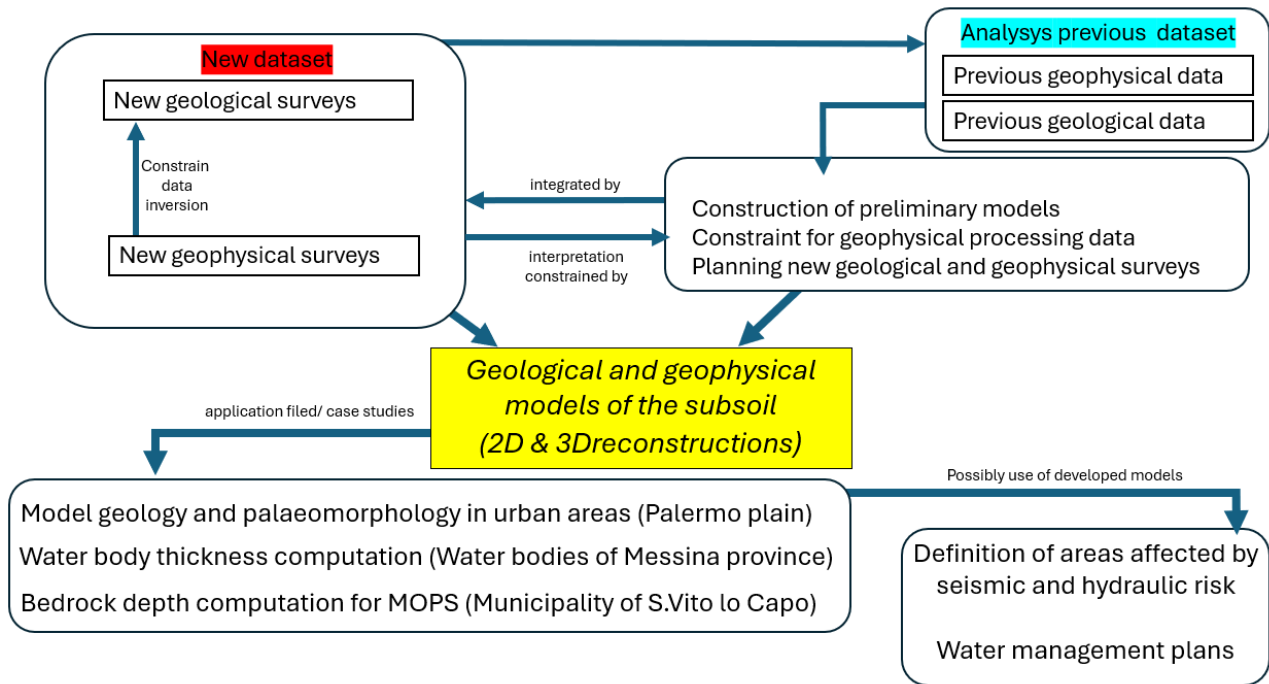


Figure 2: workflow followed for the cases study analyzed in the different application fields

CHAPTER I

GEOPHYSICAL METHODOLOGIES

This chapter will briefly list the geophysical methodologies used in the field or related to data acquired from previous work. The principles of each technique and their main characteristics will be described. The methodologies presented are: Seismic Refraction Tomography (SRT); Multichannel Analysis of the Surface Waves (MASW); Horizontal to Vertical Spectral Ratio (HVSr); Vertical electrical sounding (VES); Electrical Resistivity Tomography (ERT); Transient electromagnetics (TEM).

1.1 Seismic Refraction Tomography (SRT).

Seismic Refraction Tomography (SRT) allows the reconstruction of an image of the subsoil distribution of seismic wave velocity and its anomalies with high resolving power. This technique is an indirect, active seismic survey that uses refracted waves generated by contrasts of waves velocity to reconstruct subsurface characteristics.

The SRT technique allows the acquisition of two-dimensional sections of the seismic velocity of P and S waves. This seismic survey technique is based on the analysis of the propagation times of seismic waves. The direction of propagation of the waves in depth follows Snell's law and at each interface there are phenomena of refraction, reflection and diffraction. In refraction surveys, as the name implies, only refracted waves will be considered.

By observing the propagation of elastic waves, this technique allows us to study the behavior of rocks by detecting their routes and the velocities at which they propagate. By analyzing wave propagation, information is obtained on the nature and geometry of the subsoil, and the presence of elastic discontinuities which make the wave propagation paths vary. The velocity of seismic waves depends on the density and elastic properties of the material crosses. These properties are attributable to the lithological characteristics of the substrate investigated.

The main objective of the SRT technique is to detect the path of the seismic beam and the shortest travel time, usually referred to as the first arrival of the seismic waves, between the source and the receivers (figure 3). Data acquisition is conducted in the field according to a precise configuration of source and receivers. The source is usually a swinging mass, usually a hammer, of various sizes. This strikes a plate located at a known distance from the receivers and generates a seismic signal that is detected by a group of receivers called geophones, which are arranged according to an appropriate configuration called array. Geophones detect the generated signal and transform it into electrical pulses. These travel within a multichannel cable that transfers the data to the capture and storage system named seismograph.

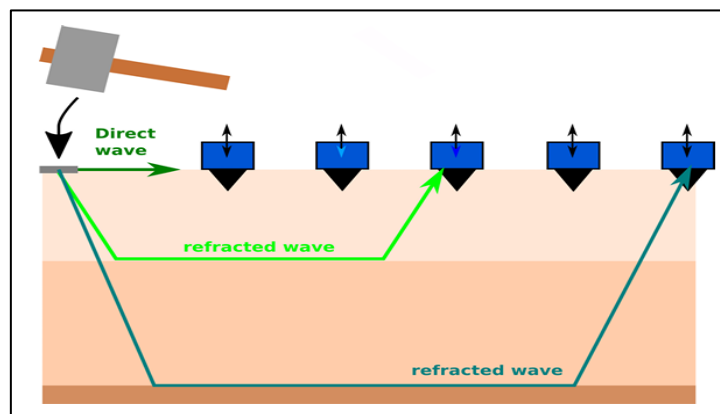


Figure 3: Schematic representation of a seismic refractive survey (from Dangeard et al., 2018)

The acquisition system is based on the connection of the plate and the hammer respectively to the opposite poles of the multichannel cable. When the hammer strikes the plate the circuit closes. This generates the trigger signal corresponding to the signal that triggers the recording. In this way, the initial instant of recording at the geophones coincides with the energization by the battery, called the shot, which generates the elastic waves at an instant t_0 . To reconstruct the velocity variation of the generated waves in the subsurface, it is necessary to perform several energizations in different positions along the array.

The data are recorded and shown on a seismogram for each shot taken. The experimental data analyzed are the times of first arrival of wave trains at different recording points where the geophones are located. This operation is carried out by picking the first arrival times. The trace picking allows us to identify the exact position of first arrival of a P or S wave relative to each individual geophone within the seismogram produced by any single shot (figure 4).

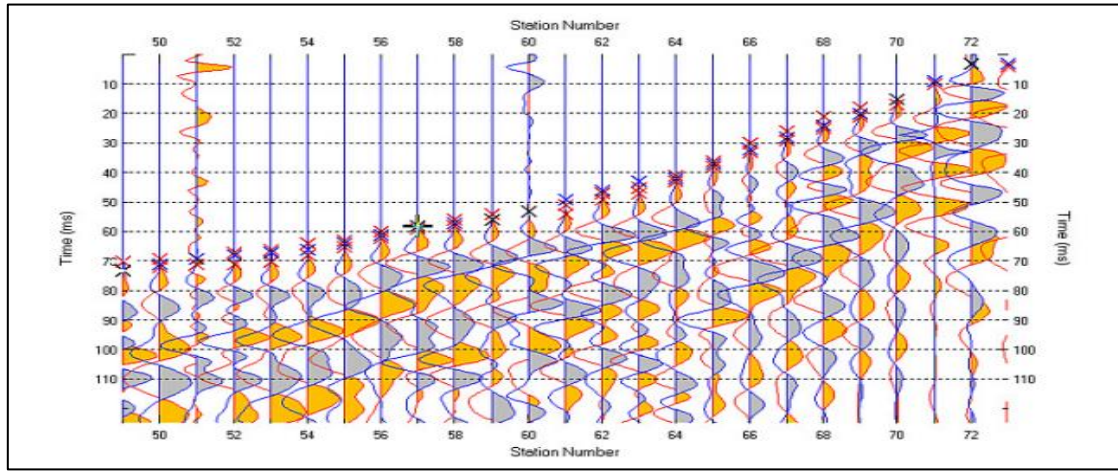


Figure 4: An example of picking a seismic trace from Rayfract (™) Userguide Manual)

After picking each trace of a seismograph, the so-called dromochrone are obtained. The dromochrone, also known as travel-time curves, represents the arrival times of seismic waves as a function of distance from the source. The dromochrone graph (figure 5) is a diagram in which one axis reports the position of the receivers (or the distance from the source) while the other axis indicates the time taken to reach the receivers by a given type of seismic wave. In a model with two uniform layers in which the underlying layer has a velocity $V_2 > V_1$ the dromochrone graph is represented by two straight segments.

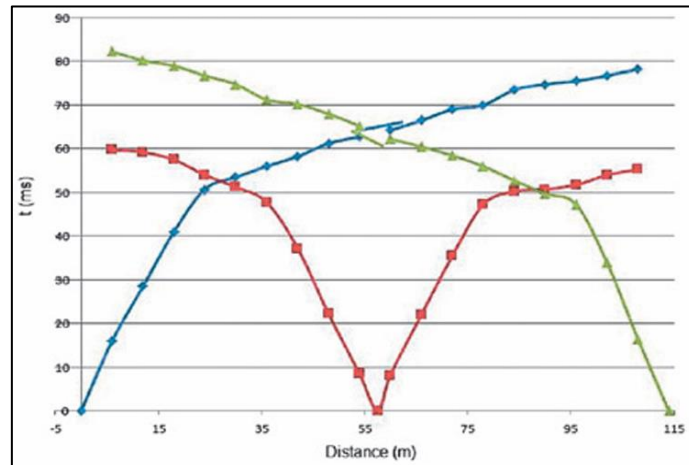


Figure 5: An example of dromochrones acquired by a seismic refraction survey from Belmonte-Jimenez et. al.2012.

Starting from dromochrones, refraction seismic tomography allows us to obtain a picture of the velocity distribution in the subsurface highlighting the continuous changes in velocity rather than a layered model, which is typical of the other refraction survey methodologies like intercept time (Willmore & Bancroft, 1960), delay-time (Barry, 1967), plus-minus (Hagedoorn, 1959) and generalized reciprocal (Palmer, 1980) methodologies.

The tomographic technique involves the creation of an initial synthetic model of the subsurface. This initial model is the basis for several inversions realized in search of the minimum deviation between the data acquired on the ground and the measurement recorded on the synthetic model. This analysis, , performed through interactive procedure described by Kirsch (2006), can be summarized as the solution of a large inverse problem to obtain a heterogeneous seismic model (figure 6) that is consistent with observations (Rawlinson et al., 2010, Cafiso et al., 2023).

In this work, field-acquired refractive seismic data were analyzed with the Rayfract™ software”. This software allows data inversion to be carried out by following different steps and inversion algorithms: specifically, the Delta-tV method was first used (Gibson et al., 1979) to generate an initial one-dimensional model (Gebrande & Miller, 1985; Rohdewald, 2011). Subsequently, based on the initial models obtained from Delta-tV, further iterations were made using the eikonal travel time method (WET) (Schuster & Quintus-Bosz, 1993) which also models the multiple paths of signal propagation and wave diffraction. Working with this algorithm, numerous iterations were made to produce models that present a root mean square error equal to or lower than 5 % or a good correlation with the available geological data.

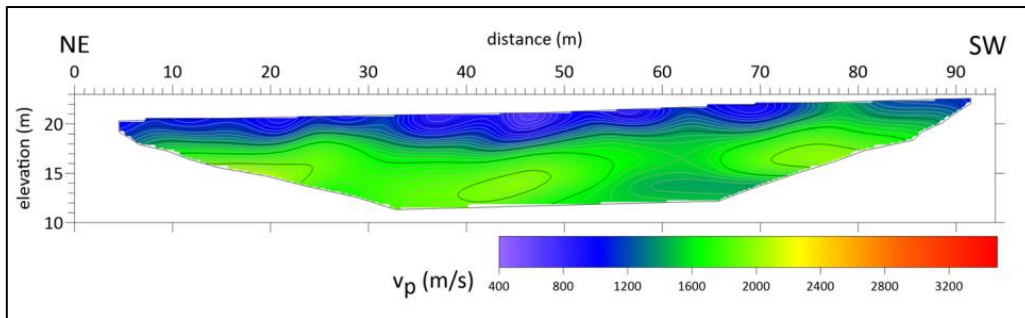


Figure 6: An example of seismic refraction tomography from Cafiso et. al.2023.

1.2 Multichannel Analysis of Surfaces waves (MASW)

The Multichannel Analysis of Surface Waves (MASW) method (Park et al. 2000) has represented an important advancement in surface wave analysis due to the integration of spectral analysis and multichannel recording systems. The MASW method provides the evaluation of important mechanical characteristics of the soil through the analysis of the geometric dispersion of surface waves.

The dispersion phenomenon is observed in a subsoil composed by some heterogeneous strata or geological units (figure 7). In these conditions, where layers with different mechanical properties are present, the behavior of surface waves becomes dispersive: different frequencies correspond to different phases of velocities. Therefore, in the case of heterogeneous strata or geological units, surface waves exhibit multiple phase velocities at different frequencies: this phenomenon depends on the spatial distribution of the seismic properties of the subsoil.

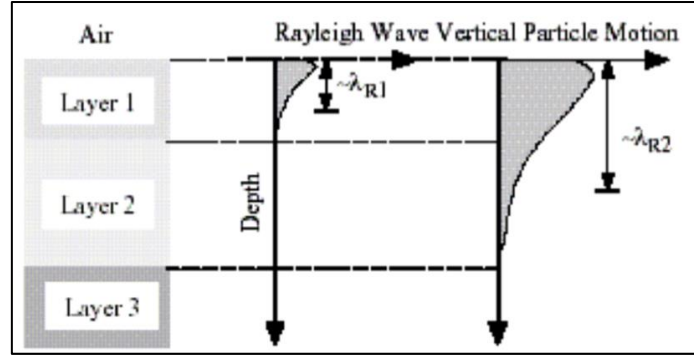


Figure 7: The dispersive behavior of Rayleigh waves in a stratified subsoil.

The MASW method is an active survey technique. The acquisition phase involves recording surface waves generated by a source with vertical or horizontal impact using a striking mass. The signal produced is recorded using a set of geophones with either vertical or horizontal components, placed on the ground surface. The signal acquired from the geophones is transmitted via a multichannel cable and recorded by a datalogger, known as a seismograph. The configuration normally used for MASW measurements as shown in figure 8 (Jafri et al., 2018).

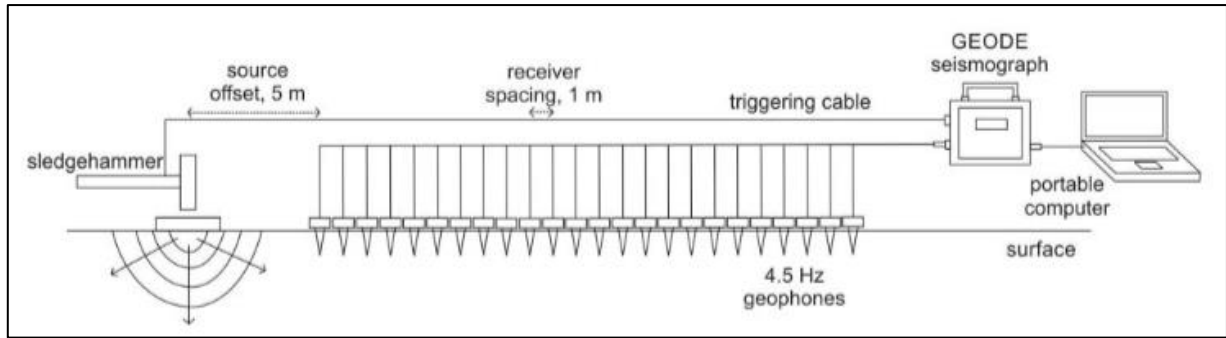


Figure 8: Schematic representation of a MASW survey from Jafri et al., 2018.

The main objective in the MASW data processing phase is to extract information on different velocities (phase velocities) that characterize the dispersion cone from the seismic section recorded. The analysis of the recorded signal dispersion is usually realized in the frequency - phase velocity domain that allows to easily detect the properties of the recorded signal.

In the processing phase indeed, firstly is realized the transition of the recorded signal from the time-distance domain to the frequency- number of waves domain by applying the Fourier transform. The acquired data is then translated into the frequency- phase velocity domain using the following equation:

$$V = 2\pi f/k \quad (1)$$

In this equation V is the phase velocity, f the frequency and k the wave number.

In the frequency-velocity phase domain, the values of the oscillation amplitude are represented with a color scale. They are proportional to the amount of energy propagating, for a given frequency, with different wave numbers, as shown in figure 9. By sampling the maximum amplitude values for each frequency, curves are obtained which relate to each vibratory mode the frequency, wave number and phase velocity. By means of this operation, called picking (figure 9a), an experimental dispersion curve is defined.

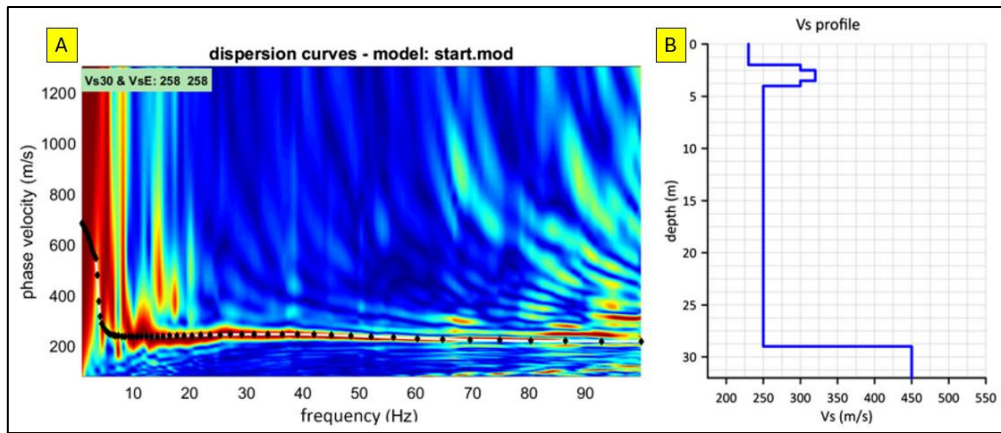


Figure 9: Dispersion curve picking in the frequency-phase velocity domain (A) and V_s vertical profile (B) obtained from the analysis of a MASW survey from Cafiso et. al.2023.

The inversion step allows a vertical profile of the S-wave velocity to be defined from the dispersion curve obtained from picking the velocity spectrum (figure 9b). The software used for the analysis and inversion of the MASW data is winMASW™; This software allows the inversion process develops into three main phases.

The first involves the definition of an initial model of the subsoil characterized by several layers in which the underground could be hypothetically subdivided based on previous knowledge; to each layer is attributed a value of thickness, V_s , ρ (density) and ν (Poisson ratio) that reconstruct a synthetic dispersion curve.

In the second stage, the initial synthetic model produced is modified by a Genetic algorithm (Eliosoft 2010) which is used to minimize the distance between the experimental computed dispersion curve and the theoretical dispersion curves produced by the synthetic model reconstructed; The result of inversion is a vertical profile consisting in several seismic strata with thickness and values of V_s , ρ (density) and ν (Poisson ratio) that varying for each layer. A root mean square error value, due to the discrepancy between experimental and synthetic curve, is attributed to the inversion.

The third phase involves an assessment of the mathematical and geological reliability of the inversion process. This assessment is carried out by analyzing both the geological knowledge acquired, as an example from a borehole carried out near the MASW surveys, and by evaluating the misfit between the experimental dispersion curve obtained from picking and the synthetic curve produced by the velocity model defined by the inversion. Following this approach, the inversion algorithm is once again applied to the synthetic curve produced by the previous inversion to reduce the root mean square values that quantify the misfit range; this iterative process, in which the initial synthetic model is constantly modified to reach a good compromise between experimental and synthetic data, is repeated several times.

Usually when the root mean square value is equal or close to 0 the inversion phase can stop; the final model produced, derived from the data inversion, should be the most reliable consider both the geophysical and geological characteristics of the studied area.

The MASW method has many advantages over other survey techniques in that it allows the V_s profile to be detected even when there are inversions of velocities in the underground. The MASW method, on the other hand, gives information only on the most superficial part of the soil (30m-50m), depending on the nature of the source. Other disadvantages are the limitations imposed by the theoretical foundations of the MASW method. In fact, the basic hypothesis refers to a stratified half-space with parallel and horizontal layers, so a limitation of its applicability could be represented by the presence of significant slopes. In practice it has been observed that if the test is carried out on a steep slope, it involves a translation of the experimental dispersion curve. This problem can be solved by measuring in a direction perpendicular to the maximum slope.

1.3 Horizontal to Vertical Spectral Ratio method (HVSr)

The Horizontal to Vertical Spectral Ratio method (Nakamura 1989, 1996, 2000) is a key tool for site amplification estimation using seismic noise recordings.

Seismic noise is made up of ubiquitous ground oscillations ranging in amplitude from a few microns to several tens of microns. These imperceptible movements of the ground are generated both by natural vibrations, such as wind and rain, and by anthropic sources; these oscillations are formed by the overlapping of waves of surface and volume.

The HVSr method allows the estimation of the site resonance frequency through the ratio of the average of the two horizontal components (H) of the spectrum and the vertical component (V) of the spectrum of the background noise recorded at a site. The H/V functions can be inverted, if appropriately constrained, to derive a model of velocity distribution of S-waves in sedimentary cover. For the definition of the HVSr methodology, Nakamura based his research on several assumptions and evaluated studies and reports produced from previous research on ambient noise and the relationships between this one and seismic amplifications. Moreover, Nakamura exposed also several considerations about the subsoil transfer function; the function describing how the subsoil transforms a seismic oscillation that travel through it. A detailed explanation of Nakamura's assumptions and the application of the HVSr technique and its developments is described by Xu, R., & Wang, L. (2021) that also provided the useful scheme represented in figure 10; basing on this scheme the principles of this methodology are briefly illustrated.

According to Nakamura, movements recorded by a sensor installed on a free surface can be analysed in the form of HVSr spectral ratio between the horizontal (H_s) and the vertical (V_s) components of motions; In this way HVSr value can be expressed as follows:

$$HVSr_s = \frac{H_s}{V_s}$$

A first assumption of this methodology requires that an $HVSr_B$ values computed for a seismic sensor hypothetically installed in the underground on a bedrock is equal to 1 considering that both horizontal and vertical waves travel equally on bedrock:

$$HVSr_B = \frac{H_B}{V_B} = 1$$

The method moreover assumes that when a seismic wave travels from the bedrock to the surface, the vertical transfer function TF_V computed by a sensor positioned on the surface deposits should be equal to 1 due to the vertical component of that should not increase its oscillation like show in the following relation where V_B and V_s represent the amplitude spectra of the vertical component at bedrock and free surface respectively:

$$TF_V = \frac{V_s}{V_B} = 1$$

Considering the same model, the relation reported below show the transfer function that describe the transverse component of the oscillation:

$$TF_H = \frac{H_s}{H_B}$$

This latest formula can also rewrite as follow considering the assumptions and the relations before presented:

$$TF_H = \frac{H_s}{H_B} = \frac{H_s}{V_B} * \frac{V_s}{V_B} * \frac{V_B}{H_B} = \frac{H_s}{V_s}$$

According to Nakamura, the relationship between $HVSr_s$ and TF_H , illustrated in the following formula, allow to understand how local seismic features of an investigated sector can be detected by the spectral ratio between horizontal and vertical components of a recorded ambient noise.

$$HVSr_s = TF_H$$

To summarize the Nakamura assumptions, base of the exposed formulations, can be listed as follows: Ambient noise is mainly made up of volume waves and a little account can be taken of the

contribution of surface waves ; the vertical component of the amplification of volume waves is minimal when this wave moving from bedrock to upper deposits characterized by low velocities; the ratio between horizontal and vertical components of an oscillation recorded in the top of a bedrock surface is about 1. Thus, the TF transfer function is mainly influenced by horizontal wave amplifications at the transition from bedrock to sedimentary cover. The ratio between horizontal and vertical component of a recorded signal provides some peaks that are related to the passage of an oscillation from layers characterized by high velocities to layers presenting lower velocities during its travel to the surface; within this passage an amplification of the horizontal components of the oscillation happened that produce an increasing of the values of the horizontal spectral components of a recorded signal and the presence of a peak in the spectral ratio curve (figure 11). Nakamura's multiple assumptions and the principles of HVSR theory were often contested and discussed and were the subject of numerous works and reviews on this methodology (Mucciarelli & Gallipoli., 2001, Molnar et al., 2018); these studies are relevant considering that this methodology is often used in public work and in the base of several studies focused on the seismic characterization of a region.

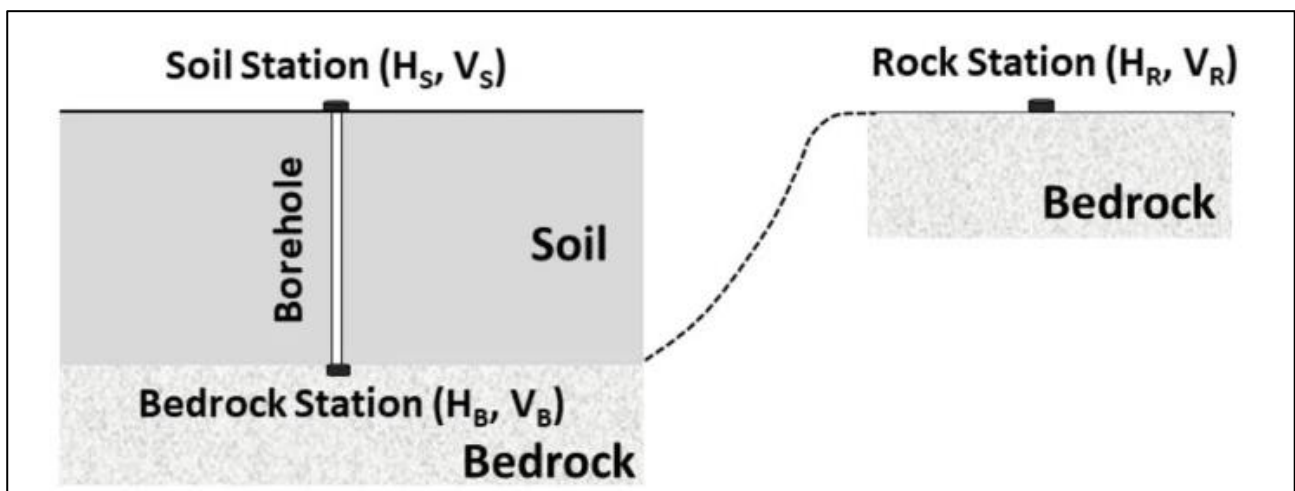


Figure 10: A schematic representation provided by Xu, R., & Wang, L. (2021) to explain the HVSR methodology principles.

The HVSR methodology requires the acquisition of environmental seismic noise measurements through a tri-directional acquisition system with sufficient sensitivity. Due to the stochastic nature of ambient noise and the need for an average spectral ratio, the measurement must be carried out over a sufficiently long interval to ensure statistically adequate sampling (Piccozzi et al. 2005).

The spectral curves (figure 11) are obtained by calculating the H/V ratio by dividing the acquired signal into windows of equal duration. For each window, the signal amplitude spectrum in the three components is estimated and the final curve produced is the results of the H/V ratio computed by the average of all values computed in each window for each frequency. Recording a given ambient noise for a long time and the analysis of this signal subdividing the data acquired into windows increases the statistical value of the curve and allows individualize and eliminate portions of seismograms containing environmental disturbances. Ambient noise recorded during a not sufficiently long-time acquisition, less than 10 minutes, may be affected by abnormal amplifications that would not be present if we repeated the measurement even after a short time in the same position. These outliers are often related to anthropic environmental disturbances (vehicles, machinery oscillations) that alter the average of values recorded during an acquisition, especially if short-lived. A longer acquisition would allow us to identify and eliminate these possible disturbances, easily recognizable as they are present in some time windows and not equally throughout the entire duration of the recording.

This type of acquisition and subdivision, then, has many advantages: it is reduced or cancelled the elements of disturbance that can affect the quality of the measurement, also increasing the stability, representativeness and veracity of the signal.

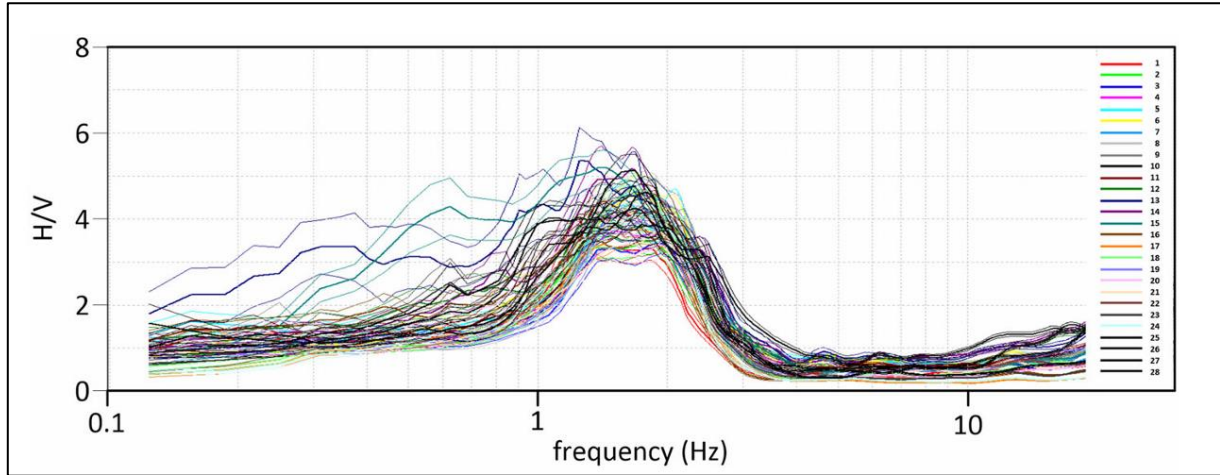


Figure 11: Representation of the horizontal-to-vertical spectral ratio (HVSr) curves obtained from several microtremor acquisitions from Cafiso et al., 2023.

The basic hypothesis of this technique refers to a strictly one-dimensional model with homogeneous and parallel horizontal layers with strong impedance contrast compared to the rigid base. This means that only a mechanically remarkable contrast between different lithotypes generates a net peak in the HVSr function. In contrast, when there are regular velocity gradients without significant impedance contrasts, the HVSr methodology generally fails to show a clear amplification peak.

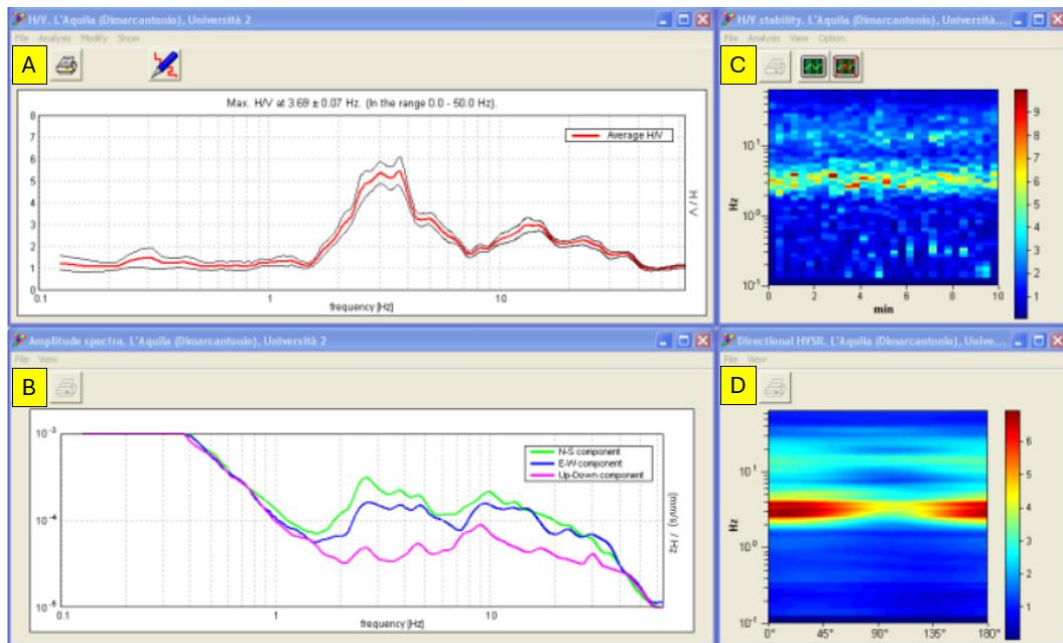


Figure 12: Working screen of the software Grilla TM

To fully evaluate the response of the site the acquired microtremors data were processed using Grilla TM, by Micromed S.P.A., which enables spectral analysis of the H/V ratio from ambient noise recordings. This software allows a full analysis of processed traces and the resulting H/V ratio.

Firstly, the spectral ratio calculated as a function of frequency can be observed as shown in figure 12a; from this representation the resonance frequency for the site under consideration can be identified.

Secondly, the amplitude spectra of the three components NS, EW, UD can be displayed (figure 12b). This graph can distinguish whether the peak in the HVSR function is of natural or anthropogenic origin: for a natural peak, the vertical component will show a minimum amplitude and the horizontal components a maximum, or vice versa in cases of velocity inversion in the subsoil. In the case of an anthropogenic peak there will be a maximum amplitude in all components at a given frequency instead.

Grilla also allows us to make considerations on the H/V Stability, and therefore on the natural or anthropogenic origin of the signal, observing the spectrogram of the HVSR function (figure 12c). If this shows, for a given frequency, a spectral ratio that is kept constant over time, the source of the acquired signal can be defined as natural. If a frequency shows an isolated peak over time, it is likely anthropogenic and time windows with isolated frequency peaks not consistent over time should be removed.

Finally, Grilla allows a directional analysis of the HVSR signal. Considering the orientation of the instrument set at 0° North, the prevailing direction of ambient noise recorded for the different frequencies is analyzed. Based on the shape of this graph (Figure 12d), it is possible to interpret polarization of horizontal components, indicating unnatural transients or complex structures inconsistent with a one-dimensional model. The HVSR signal directionality analysis can also be used to determine certain natural phenomena, such as strong atmospheric disturbances or even the presence of linear or planar elements such as faults (Panzera et al. 2020) and landslide triggering surfaces (Panzera et al. 2013, Maresca et al. 2022). In these cases, the presence of these elements amplifies the signal along a certain angle with respect to the point of acquisition.

The Grilla software allows the inversion of HVSR curves to obtain a one-dimensional model of the subsoil based mainly, but not exclusively, on the distribution of the Vs in depth (figure 13b). The Vs subsoil model inversion generates a synthetic model (blue curve in Figure 13a) aligned more closely with the experimental curve model (red curve in Figure 13a). The characteristic parameters of each layer described in the model are thickness, Vs, Vp and Poisson ratio. The modeling process is constrained by data from previous surveys, such as borehole stratigraphy, penetrometric tests, or MASW near the HVSR recording point. Without this kind of constraint there would be infinite sets of parameters that can fit to the same curve.

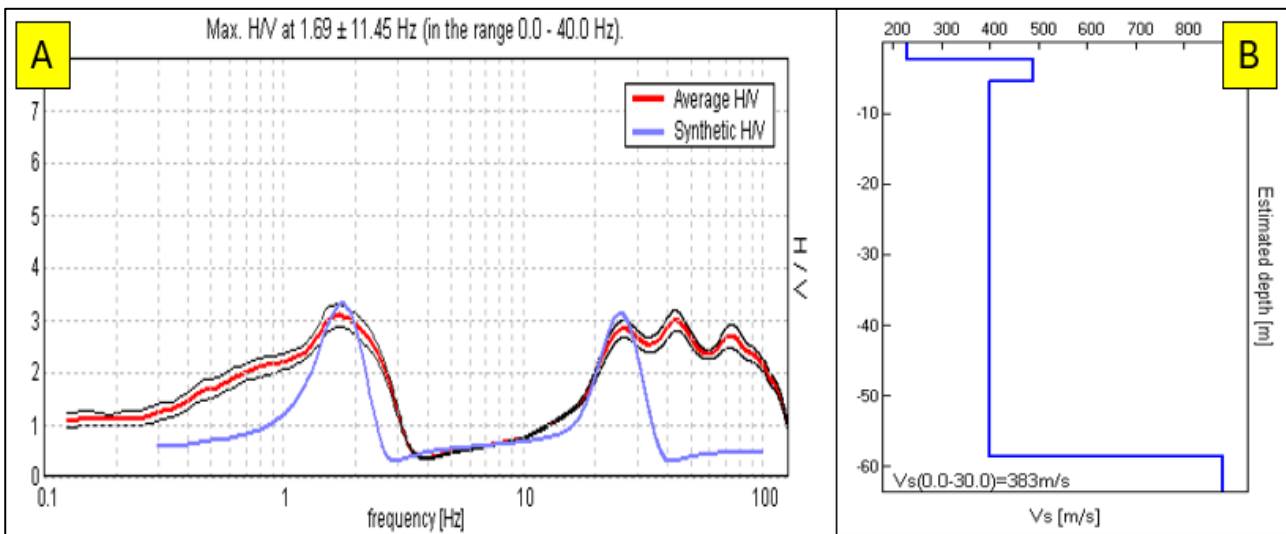


Figure 13: A) An example of a theoretical curve (blue) superimposed on the experimental HVSR curve function (red). B) Vs velocity model of the subsoil provided by the HVSR inversion.

1.4 Vertical electrical sounding (VES)

Vertical Electrical Sounding is part of the geoelectric methods. This method studies the distribution of electrical resistivity in the subsoil. Electrical resistivity is inversely proportional to conductivity. The law of Archie, refined by later studies, explains the dependence of conductivity on other natural factors:

$$\sigma_a = \sigma_w \varphi^m + \sigma_{clays} \quad (2)$$

According to this, the conductivity of a water-saturated rock (σ_a) depends on both the conductivity of the liquid filling the rock (σ_w) and the porosity of the rock (φ). In addition, the soil conductivity is also influenced by parameters like soil temperature and clay content (σ_{clays}), which is often considered as an addition to the electrical conductivity, depending on the cations present and their exchange capacity (Keller and Frischknecht, 1970). In formula "m" is a factor between 1.2 and 1.9. Electrical resistivity is the inverse of conductivity and represents the property of a material to resist the flow of electric current. It is a specific physical quantity and therefore cannot be directly investigated and apparent resistivity (ρ_a) measurements are carried out. The apparent resistivity can be considered as a "mean" of the resistivity of the elementary volumes of the subsoil, whose contribution is "weighed" in relation to their position with respect to the measuring electrodes and the current passing through them.

Geoelectric methods are based on the relationships between electrical resistivity, current and potential, described by the Ohm laws. According to these the electrical potential due to a point current source located in x_s is given by:

$$\nabla \left[\frac{1}{\rho(x,y,z)} \nabla \phi(x,y,z) \right] = - \frac{\partial j_c}{\partial t} \delta(x_s) \quad (3)$$

in this formulation ρ is the resistivity, ϕ is the potential and j_c is the charge density. The solution of this equation solves the direct problem, that allows us to calculate the potential at any point on the surface or inside the medium if the resistivity distribution is known.

Apparent resistivity measurements can be made with various types of electrodes configuration: four electrodes are sufficient for all the configuration: two to input current (a current dipole in which the electrodes are generally called A and B) and two to measure the potential difference (a potential dipole in which electrodes are generally called M and N).

An apparent resistivity measurement is then carried out by measuring the current input (I) between the current electrodes, A and B, and the potential difference ΔV generated by the above-mentioned current between the electrodes of potential, M and N. To calculate the apparent resistivity (ρ_a) the "measured resistance" R, that is the ratio of potential difference to input current, is multiplied by the geometrical coefficient K.

$$\rho_a = K R = K \Delta V_{MN} / I_{AB} \quad (4)$$

The K factor depends on the geometry of the body in which the apparent resistivity measure is performed and is also related to the electrode distribution used for the measurement. The K factor serves to return an apparent resistivity value, which corresponds to the real resistivity of the subsoil only in the simplifying hypothesis that it is homogeneous and isotropic.

Vertical Electrical Surveys (VES) are one-dimensional (1D) electrical surveys that reconstruct the trend of resistivity along a vertical. They consist of a series of apparent resistivity measurements aimed at an interpretation with horizontal flat layer models characterized by the same electrical resistivity values for each identified layer. VES surveys consist of successive measurements of apparent resistivity, these are performed extending progressively the distance AB between the current electrodes keeping the potential electrodes MN fixed or spacing ranging those latter in such a way as to leave the projection to the surface of the center of the array inside the center of gravity of the presumed volume investigated. For small interelectrode distances only small and shallower portions of the soil will be affected and as the electrodes A and B move further apart, deeper subsoil layers will be investigated.

The Schlumberger configuration is the most well-known and widely used array. In a Schlumberger alignment the current electrodes are external while the potential electrodes are positioned in the

internal sector of the array; these latter are located at the center of the array and the distance between them is very small relative to the total length of the alignment, practically less than 1/5 of AB. The measurement is carried out by progressively increasing the distance between A and B (figure 14a).

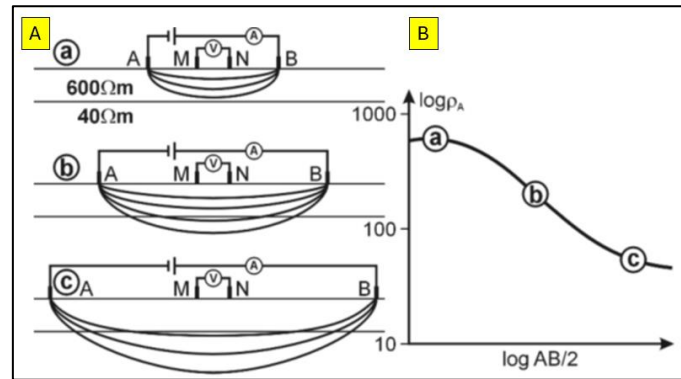


Figure 14: A) Schematic diagram of a Schlumberger survey experienced on flat horizontal soil. B) The representation of the apparent resistivity data acquired by the survey.

The experimental data are given on a bi-logarithmic graph, where the half-electrode spacing $AB/2$ is represented on the x-axis and the apparent resistivity in the y-axis (Figure, 14b).

After data acquisition and processing, the compatibility with one dimensional modeling is checked. If compatibility with the parallel stratification model is confirmed, interpretation can begin. This process consists in searching for a theoretical model of distribution of electrical resistivity that represents a theoretical curve (figure 15a) that shows the best fit with experimental data curves. The interpretative process enables identification of a one-dimensional electro-stratigraphic model representing resistivity values as a function of depth. (figure 15b); this model is referred to the center of the alignment realized. For this reason, the SEV technique has obvious limitations in describing lateral variations of the subsoil of an investigated area, especially if a single acquisition is made. For this reason, dense SEV networks are often realized (CASMEZ 1978) to derive a series of point values which can be interpolated successively with each other to obtain 2D sections or 3D models. The limit in depth of survey varies in connection with the length of the array from 1/3 in the most favorable cases to about 1/10 in the most unfavorable cases; on average it is between 1/5 and 1/6. To better interpretate the model, it is necessary to associate a compatible lithostratigraphic model. This model is chosen based on the resistivity values of the rocks, obtained from calibration surveys and/or detailed geological knowledge of the area investigated (Rusdy et al. 2020).

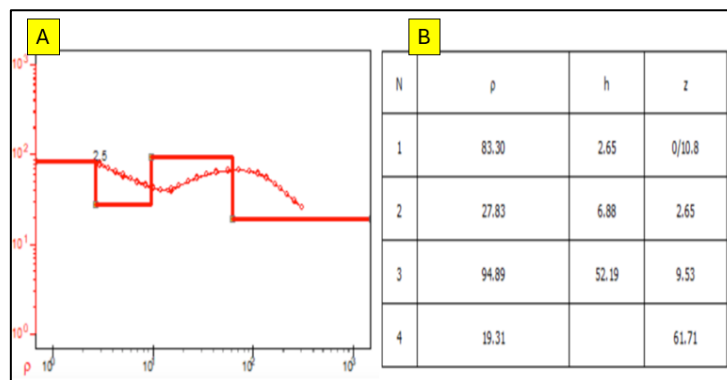


Figure 15: Example of an interpretative model of a VES elaborated by the ZOND 1D software A) The experimental data (dots) and the theoretical apparent resistivity curve are shown in the graph, as is the electro stratigraphic model. B) table showing parameters of the interpretative model.

The software has produced some preliminary resistivity sections which have proved useful for the construction of geological sections of river basins (figure 16). In addition, the inverted electrical resistivity models have been interpolated using Voxler software, provided by Goldens Software, to obtain three-dimensional representations of electrical resistivity.

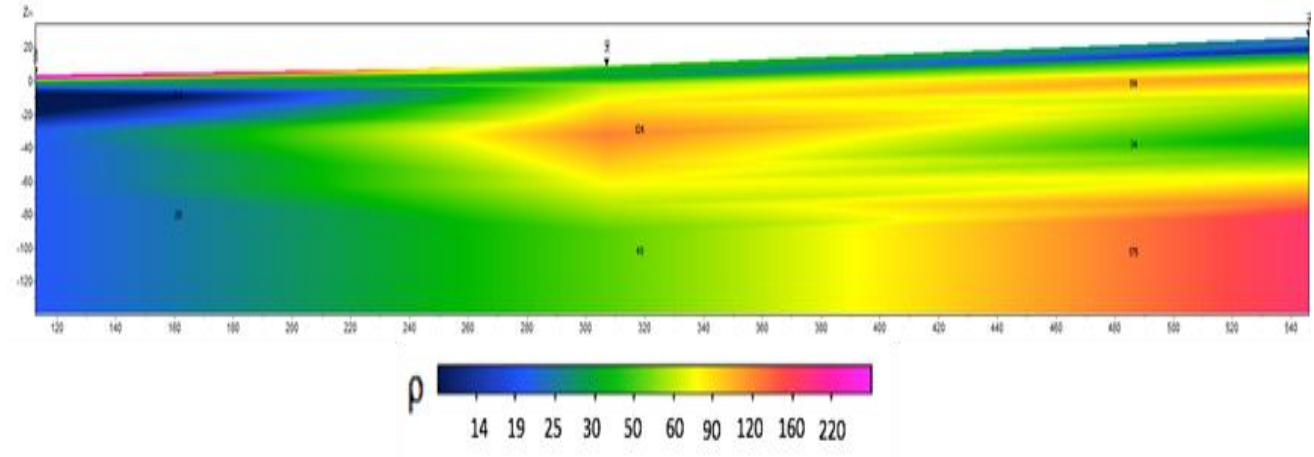


Figure 16: Example of electrostratigraphic cross-section obtained by laterally interpolating inverse models relative to several SEV aligned along a profile.

1.5 Electrical Resistivity Tomography (ERT) and Induced Polarization tomography (IPT)

The Electrical Resistivity Tomography (ERT) and Induced Polarization tomography (IPT), Seigel (1959), are geo-electrical techniques to analyze subsoil features by the passage of electric current in the subsoil and the resistance of the ground in the release of the residual charge remaining in the soil after the interruption of the current flow.

ERT surveys give the trend of electrical resistivity, related to porosity, water saturation and clay content, similar to other geoelectrical method, while IPT investigates the capacitive properties of the subsoil.

IPT provides distributions of chargeability, related to clay content or fluids with metal salts. Induced polarization exploits the capacitive properties of some geological materials which function as capacitors, charging during the introduction of electric current into the soil and discharging when this is interrupted. Energy storage mainly occurs as chemical energy, due to ion mobility changes within the porous structure (membrane polarization) and changes in the current conduction mechanism (electrode polarization).

ERT and IPT methodologies allow us to obtain detailed 2D sections of electrical resistivity and chargeability using several aligned and equally spaced electrodes. For this kind of survey, multielectrode instrumentation is usually used (figure 17). This permits the simultaneous acquisition of all voltage measurements relating to a determined current dipole, so allowing, with an appropriate array sequence, a high surveying speed.

Recent advances in instrumentation and inversion algorithms have improved geoelectrical methods, enabling subsoil discretization into a grid of cells to represent resistivity and chargeability trends (Loke et al. 2003). The inverse problem is non-linear and must be addressed by iteratively solving the forward problem and trying to minimize the misfit between the observed and predicted data. The inversion and interpretation of resistivity and induced polarization data, within this work were performed using the RES2DINVx64© software from Geotomo Software. This software implements finite element calculation methods for direct modelling and iterative least squares nonlinear algorithms for solving the inverse problem. In both topographies, the inversion process stopped after several iterations, reducing misfit to acceptable levels despite high contact resistance noise and large data volume (Cafiso et al., 2023).

The results of electrical resistivity tomography and induced polarization tomography are two-dimensional sections showing models derived from field data inversion. In these, the depth and lateral variation of electrical resistivity (figure 18a) and chargeability (figure 18b) can be observed.

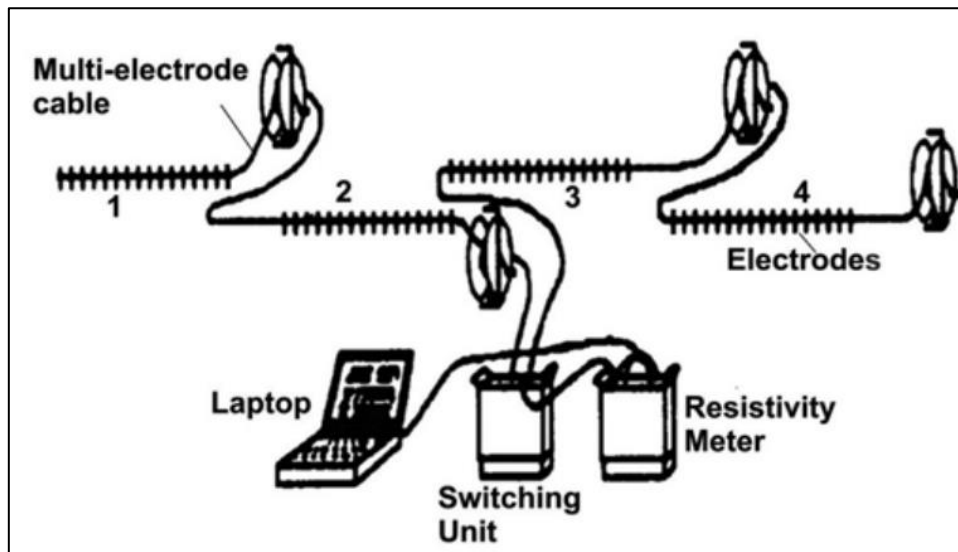


Figure 17: Basic representation of an ERT survey with four multi-core cables each fitted with 16 electrodes from Rai et al.2013.

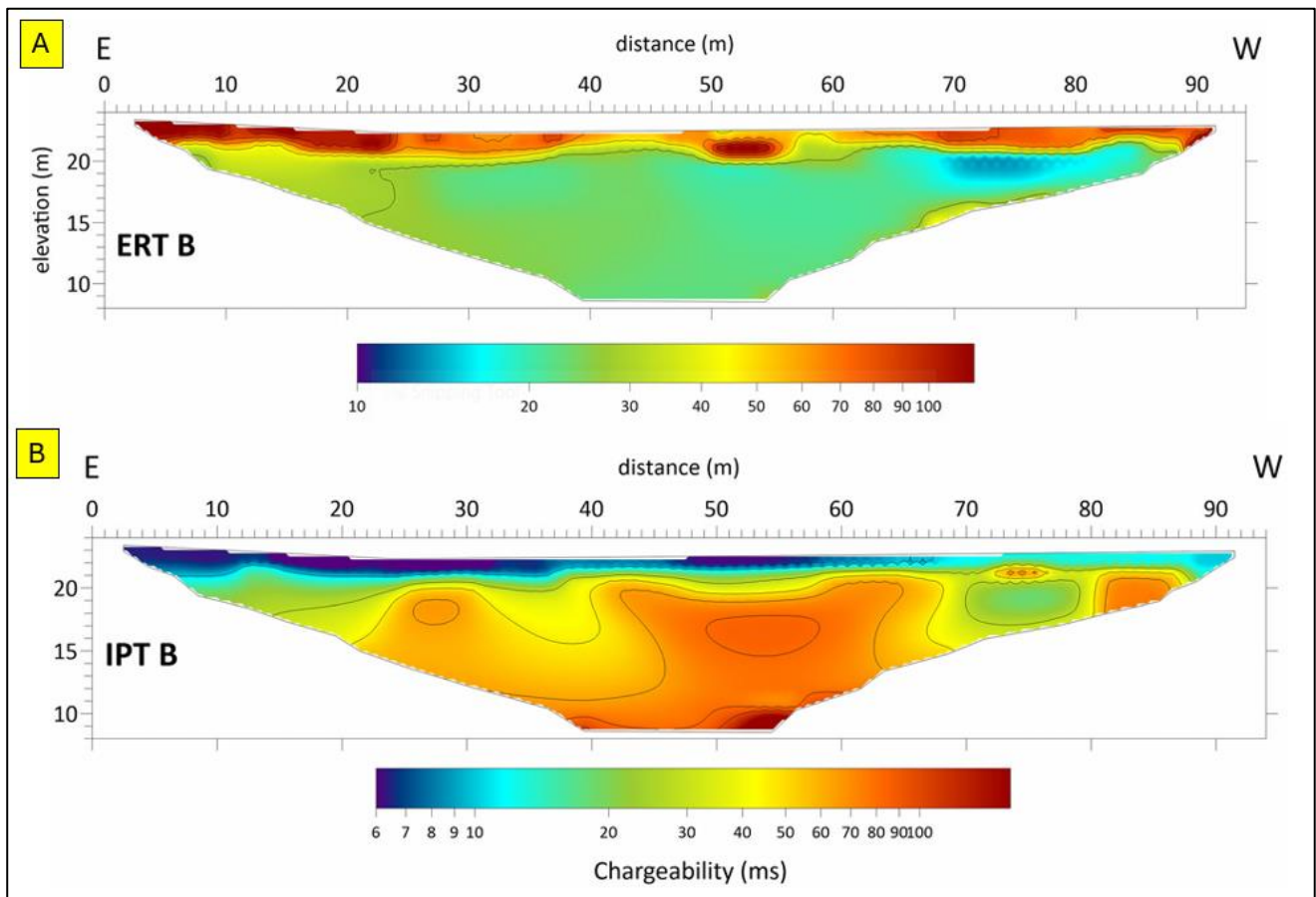


Figure 18: Example of electrical resistivity tomography (A) and an Induced polarization tomography (B) from Cafiso et al.2023.

1.6 Transient Electromagnetic (TEM)

The TEM method is an electromagnetic induction technique (Meju 2005, Goldman et al., 1994) which measures the earth's response to an electromagnetic impulse in the time domain to reconstruct the conductivity of affected volumes (Jorgensen et al., 2003). This method infers underground rocks and ore bodies based on differences in conductivity and polarizability.

During TEM surveys an electromagnetic field, defined as primary, is generated in the field and propagates into the ground via alternating current in the subsoil. Usually, the pulse is generated by a transmitter that imparts current in a coil placed on the ground with respect to a given geometry and extension of its sides. The geological bodies in the subsoil are hit by the electromagnetic field generated by the electromagnetic pulse and produce a secondary field in the form of eddy currents. When current input stops, eddy currents gradually fade instead of disappearing immediately. The secondary electromagnetic magnetic field gradually generated by the eddy currents propagates to the earth's surface where it is recorded by an antenna or other coil linked to a receiver (figure 19). The electric data recorded by the receiver is used to determine the electrical distribution of the underground bodies. The standard configuration is usually composed of a single-turn transmitter loop with the receiver antenna or coil positioned in the center of the loop (Xue et al., 2020). The configuration represents a compromise between resolution and field efficiency (Jorgensen et al., 2003). The estimated penetration depth of investigation for this kind of survey is usually not greater than about 100 m. It generally depends on the size of the transmitting coil and from environmental parameters like the average resistivity of the ground and on the natural background noise (Spies, 1989).

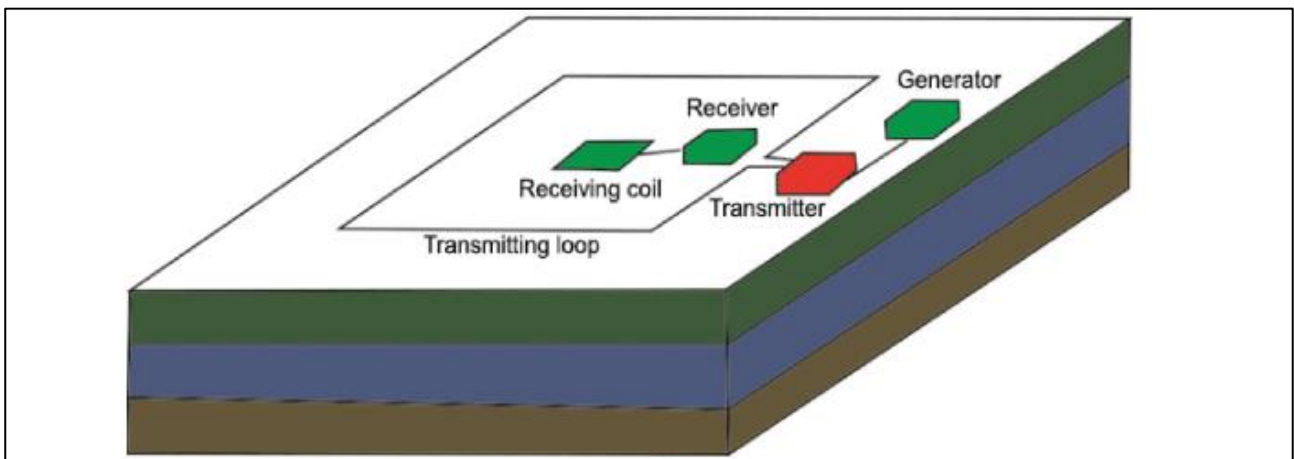


Figure 19: Example of TEM array configuration provided by Jorgensen et al. 2003

To invert TEM data, a synthetic resistivity-depth model of the subsoil is used. This is usually a simple model to approximate the real geological structure. This model, proceeding with the inversion, is modified by changing its parameters looking for the best fitness between forward synthetic modeling and recorded data. Responses for synthetic models can be computed numerically using finite difference, finite element, or finite volume methods (Joung et al., 2022). The TEM technique had been used in several fields of application like hydrogeological research investigations (Meju et al., 1999), the detection of sedimentary and structural elements (Jorgensen et al., 2003, Sørensen et al., 2005).

CHAPTER II

MULTIDISCIPLINARY STUDY TO RECONSTRUCT 3D SUBSOIL MODEL IN URBAN AREAS.

2.1 Description of the Case Study of the Palermo Plain: Objectives, Studied Areas, Data Used, Results Obtained.

The case study of Palermo plain is shown below to highlight the contribution of various kinds of data, both geological and geophysical, to create a 3D subsoil model in urban areas. This kind of approach is useful for modeling areas covered by an anthropic layer, which almost completely masks their geomorphological and geological features (Figure 20). In that area, the management of previous geological data and the application of geophysical techniques are becoming increasingly important considering that new direct investigations are strongly invasive due to possible interference with the subservices of the urban networks. Moreover, carrying out a direct investigation, such as drilling or trenching, requires several permits and complex and costly management of the yard.

The plain of Palermo, located along the coastal belt of North-West Sicily, hosts one of the largest and most populous Italian cities (figure 21). The city experienced continuous expansion from the 8th century BC, increasing, over time, its population and extent under the control of different dominations; the expansion took place firstly within the historic walls, subsequently outside them affecting different parts of the plain over time. The succession of different dominations has produced a clear mutation of the original urban landscape. Numerous streams that once dominated the plain have undergone changes in path, reduced flow, or have been partially embedded or drained. In addition, after the Second World War, many ruins were accumulated in areas close to the sea causing a deep morphological variation of the coast. Considering that it was only in 1962 that the city had a master plan, the urban expansion continued to develop uncontrollably for several decades, even during the 20th century (Canzoneri et al., 2024).

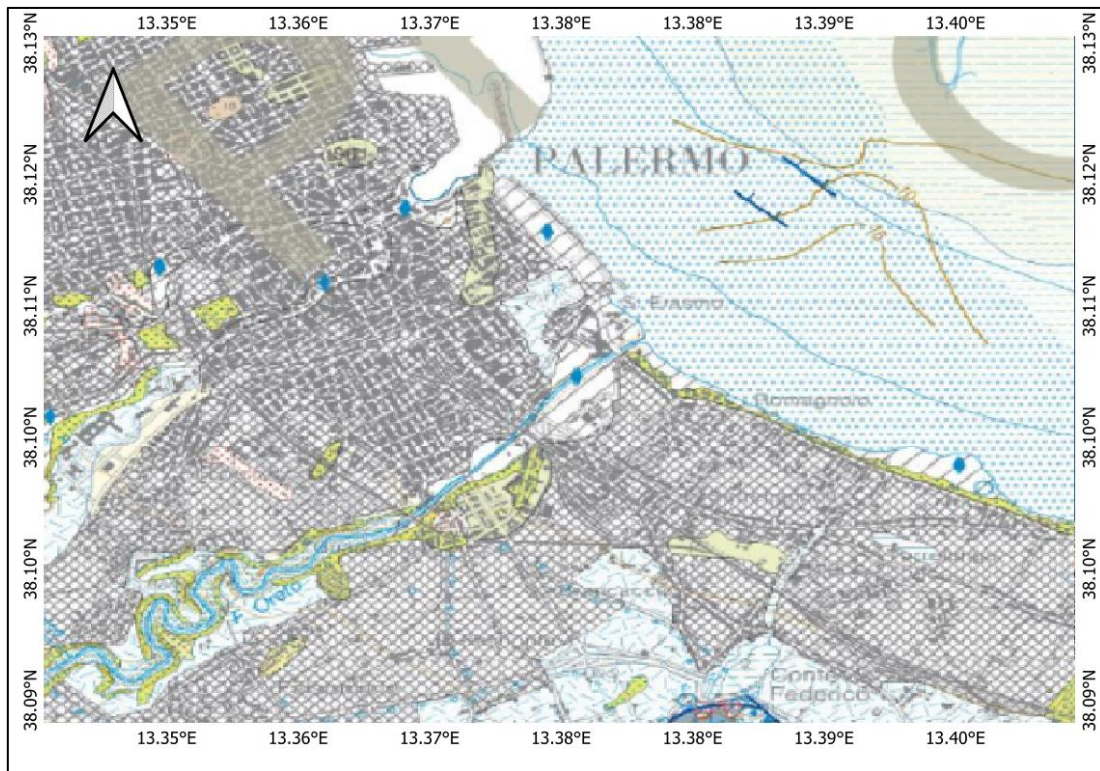


Figure 20: Extract from the national geological sheet 595 describing the area of Palermo; the geology of the outcrops is completely masked by the cover of the urban network.

Both because of this uncontrolled urbanization and the geomorphological and geological features of the plain, characterized by important lateral variations of facies, many residential buildings and infrastructure are in areas subject to several natural hazards.

Considering all these items, the plain of Palermo is a natural laboratory and can be taken as a reference for the construction of 3D subsoil model reconstruction of urban undergrounds according to the great amount of stratigraphic data, more than 2000 cores, collected by the Department of Earth and Sea Sciences of the University of Palermo (Gimmarinaro et al., 2002).

A model had been created for the area of the plain near the Oreto river, by integrating the numerous borehole data collected and having been integrated using non-invasive geophysical methodologies: recordings of seismic microtremors analyzed according to the Horizontal to Vertical Spectral Ratio technique (HVSr) and Multichannel Analysis of Surface Waves (MASW). These techniques allow us to estimate important physical parameters of the subsoil detailing the model without necessarily having to use new drilling and excavations. Indeed, the HVSr data have been inverted in seismographic columns constraining the inversion by means of the stratigraphic data, provided by the closest boreholes, and by Vs parameters obtained by MASW carried out for the main lithologies outcropping in the plain. The integration of stratigraphic and geophysical data has provided a 3D useful geological model that allows the reconstruction of geomorphology and shoreline, the geometry of the geological bodies of the subsoil and the definition of ancient, pre-anthropogenic, morphology and shore line. The model highlighting areas possibly subject to geological risk.



Figure 21: Area studied within the Palermo plain in the red circle.

2.2 Previous geological and geophysical studies.

Considering the importance and centrality that the city of Palermo has always had in various aspects (historical, civil, strategic, economic and tourism-related), this sector of northwestern Sicily has been the subject of numerous studies, both geological and geophysical, aimed at describing and characterizing both the subsoil and the morphology of the urban area. These works have highlighted the importance of representing the hidden features of the territory to highlight areas more exposed to natural risks and define the natural landscapes that characterized the area before urban development. The studies carried out in the purely geological – stratigraphic (Catalano et al., 2013a, Incarbona et al., 2016, Agate et al., 2017) and geomorphological field (Agnesi 2021, Parrino et. Al., 2023) defined the rocky sequences that only partially emerge in the plain, in the surrounding mountains and in the marine areas of the Gulf of Palermo (Lo Iacono 2013). Gimmarinaro et al. (1999) created a detailed collection of lithostratigraphic data, subsequently inserted into GIS database (Gimmarinaro et al., 2002). Some research related to these topics has partly focused on the possible paleo-environmental reconstructions of the area of the plain. These studies have often placed emphasis on the presence of paleo-morphologies hidden by the urban network: Columba (1910) created a simplified geological map that highlights the connection between the historic city center and the rivers, as shown in figure 22. Subsequently, Cappadonia et al. (2020) produced a map of the original landforms present within the plain.

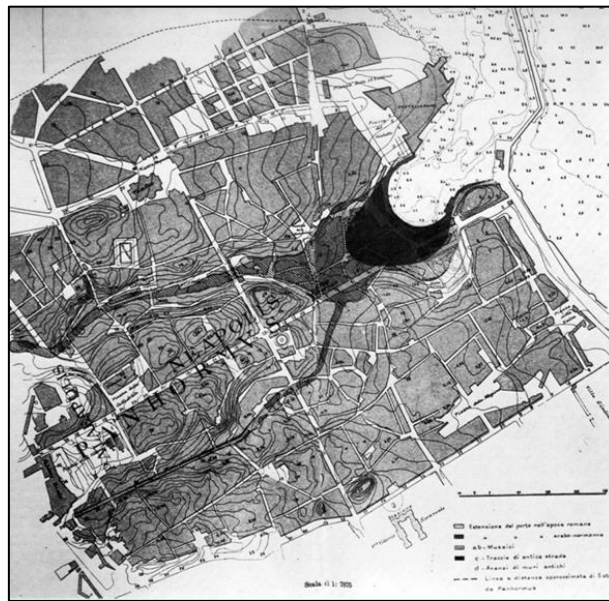


Figure 22: Historical Map of Palermo (from Columba, 1910).

Moreover, several other studies had focused on modifications that occurred in ancient times on outcropping and underground morphologies resulting from human activities: Todaro (2000) collected a great amount of studies about human exploitation and uses of the city subsoil; Lofrano et al. (2013) described the historical morphological aspects of the plain water collection and distribution system in the Middle Ages; Brandolini et al. (2020) analyzed how the coastal sector of the plain was affected by atrophic activities; Todaro (2019) and Agnesi (2021) report on the reclamation of ancient wetlands; Cafiso et al. (2023) illustrate the characteristics of the geological substrate in an artificial lake created during the Arab domination of the city.; a study on the urban subsidence, induced by natural and human factors was provided by Famiglietti et al. (2023).

Other research has been carried out on the geophysical characterization of the territory defining Vs values (Bosco 1996, Martorana et al., 2018) derived by active seismic surveys. Several studies focused on areas more susceptible to seismic shaking (Todaro 2006), analyzing the damaging effects

which some historical earthquakes have produced on buildings in the city: Contino et al. (2006), Gimmarinaro et al. (2001), Giammarinaro et al. (2003), Giammarinaro et al. (2006), provided an initial model of geological surfaces and a characterization of physical-mechanical properties that controlled the seismic response.

A large amount of information from these studies has been the basis for the subsoil modelling of the plain area, close to the Oreto river, described in this chapter.

2.3 Geological and geomorphological setting.

The Palermo plain displays a maximum extension of about 6 km and an altitude between 0 m and 150 m. s.l.m. This area is located between the Tyrrhenian Sea and the Meso-Cenozoic carbonate reliefs. These mountains develop their structure mainly along a N-S alignment, in the western sector, and along a NW-SE trend in the eastern corner of the plain.

From a structural point of view, the Palermo plain is set on a composite half graben structure (figure 23b; from Di Maggio et al., 2017) situated within the northern margin of Western Sicily sector that belongs to the SE-verging Alpine orogenic belt. The already mentioned mountains surrounding the Palermo plain are the topographical expression of this belt, named Sicilia Apennines (Catalano et al., 2013 b). Inside the examine area, particularly the tectonic belt units forming the structural building of the Palermo - Belmonte Mezzagno -Trabia mountainous reliefs (see figure 23a). These are made up of both Upper Triassic–Oligocene mainly carbonate successions and Oligocene Lower Miocene terrigenous successions (Numidian flysch). Among the Mesozoic deposits, shallow water limestones of the ancient Panormide carbonate platform crop out in the northern and central areas of the Palermo Mountains and deep water calcilutites, dolomites, and siliceous rocks of the ancient the Imerese basin crop out in the southernmost areas of the Palermo Mountains and in the Belmonte Mezzagno-Trabia Mountains. The flyschoid deposits consist of fore-deep clayey, marly-clayey, and sandy-clayey and are partly located above the Mesozoic units due to the present of thrusts. (figure 23b). The meso-Cenozoic carbonate rocks and Cenozoic flyschoid deposits composing the mountains surrounding Palermo town have been intercepted and recognized by some boreholes at depths over a hundred meters beneath the Palermo plain (Cappadonia et al., 2020). A continuous strip of flood fans is the link between the mountains and the plain

Within the plain, older lithologies are covered by 1.5-0.8 Ma aged, mostly carbonates arenitic and sandy, deposits from a few to tens of meters thick that outcrop in a large area of the plain (Incarbona et al., 2016). This stratigraphic setting is the results of a marine transgression that affected the area starting from the Pleistocene. These covering deposits, describable as a shallowing upward succession, are assembled in the Marsala synthem, and lie on the older Meso–Cenozoic units with strong angular unconformities. (Agate et al., 2017; Basilone & Di Maggio, 2016; Di Maggio et al., 2009; ISPA 2013b). These rocks are composed by conglomerates, sands, blue clays (“Ficarazzi clays”; Ruggieri et al., 1975) and variously cemented sandy and bioconstructed deposits of the “Palermo Calcarenites”. The rocks of the Marsala system form an extended sedimentary prism whose thickness reaches a hundred meters along the coast. Proceeding inward, they reduce in thickness and are all tapered at the foot of the mountains where they have a thickness close to 0 m. This prism is stratified, with layers inclined on average by 5° towards the sea and overlaps directly on the Mesozoic and Cenozoic rocks (Agnesi 2021). Above these marine rocks, the coastal conglomerates and sands of “Sintema of Buonfornello- Campofelice” (middle Pleistocene) and of the “Sintema of Barcarello” (upper Pleistocene) may also outcrop. These latter consist of conglomerates and variously cemented sandstones and colluvial deposits of coastal environment (Cappadonia et al., 2020). The Holocene deposits, along the coast and within the current hydrographic network completes the deposits succession. These latter are inscribed into recent synthem reported in figure 24 (Agate et al., 2017) where a schematic and synthetic representation of a common stratigraphic deposit present in the Palermo plain is shown.

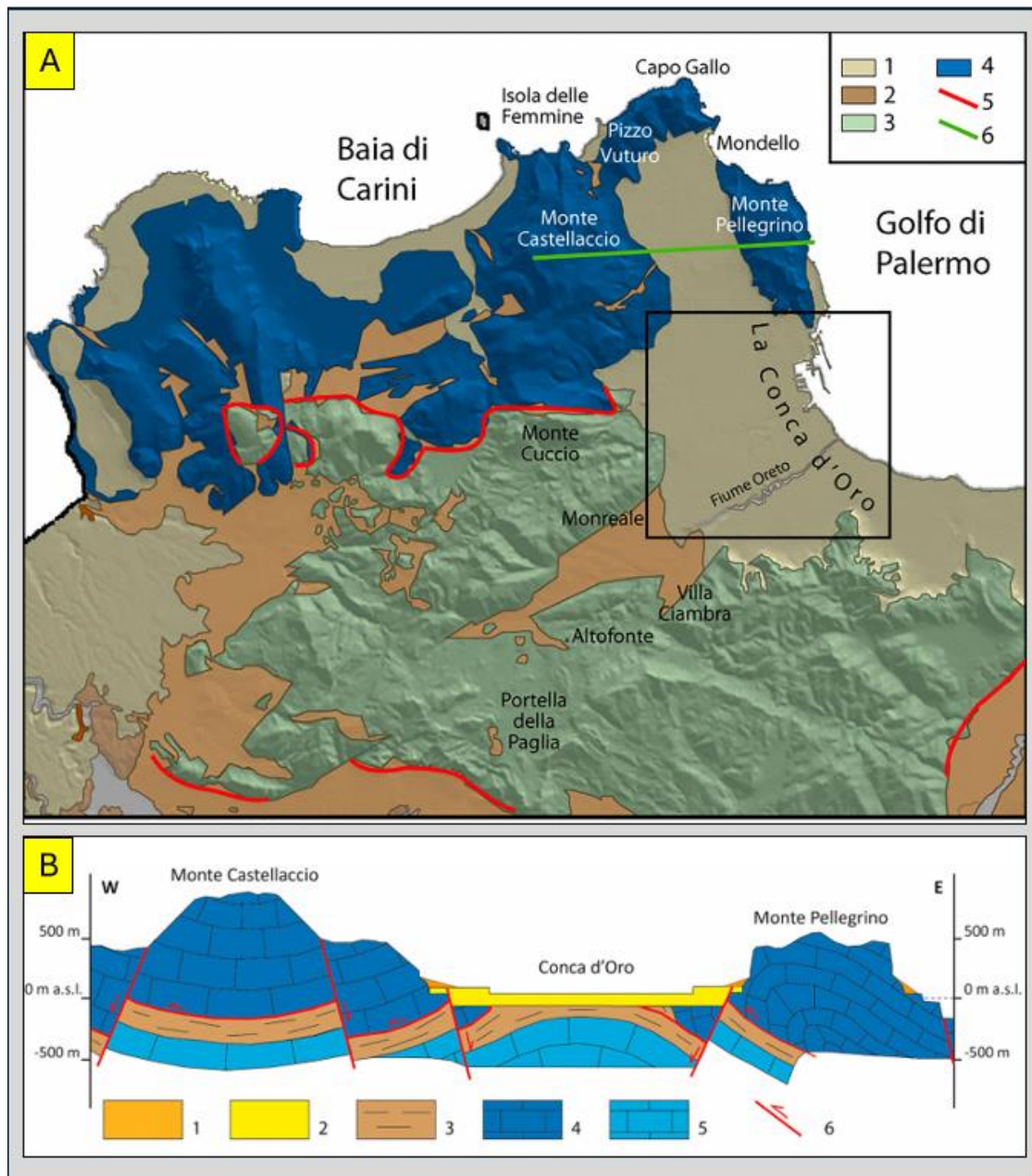


Figure 23; A) Geological sketch of Palermo-Belmonte Mezzagno-Trabia Mountains from ISPRA 2013 b.: 1 - Marine conglomerate and arenite; continental breccia, arenite, and silt (Quaternary); 2 - Clay and quartz sandstone– Numidian flysh (Oligocene Lower Miocene); 3 - Limestone, marl, dolostone, and cherty limestone– Imerese basin successions (Upper Triassic– Oligocene); 4 - Limestone and dolostone– Panormide platform successions (Upper Triassic– Oligocene); 5 - Main thrust; 6. Track of the geological section shown in b. B) In the section (Di Maggio et al., 2017) : 1- Slope deposit (Middle Pleistocene– Holo cene); 2 - Coastal/marine deposit– Marsala synthem (Calabrian-Ionian); 3 - Clay and quartz sandstone– Numidian flysh (Oligocene Lower Miocene); 4 - Limestone– Panormide succession of the upper tectonic units (Upper Triassic– Oligocene); 5 - Limestone Panormide succession of the lower tectonic units (Upper Triassic– Oligocene); 6 - Fault or thrust.

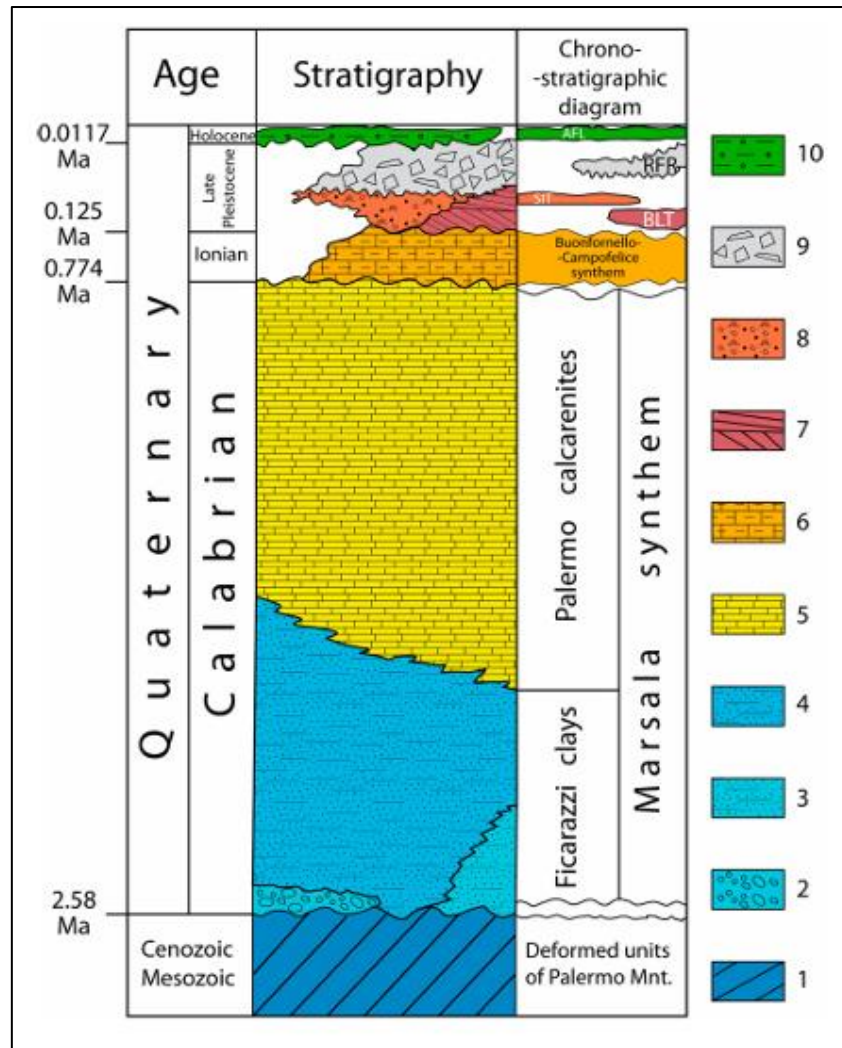


Figure 24: Stratigraphy of the Quaternary deposits in the Palermo area (Agate et al., 2017). BLT - Polisano synthem; SIT - Barcarello synthem; RFR - Raffo Rosso synthem; AFL - Capo Plaia synthem; 1 - carbon ate and terrigenous rocks; 2 - conglomerates; 3 - marine sands; 4 - grayish clayey silts; 5 - bioclastic calcarenites and sands; 6 - coastal conglomerates; 7 - aeolian arenites (BLT); 8 - coastal conglomerates, arenites and colluvial cemented deposits (SIT); 9 - cemented clast-supported breccias (RFR); 10 - colluvial, river, littoral and land slide deposit (AFL).

The main course of the Oreto River is about 20 km long and originates approximately from the above-describe zone of Palermo Mounts, up to its outflow located in the Gulf of Palermo. In the Palermo plain the river path is confined within a valley carved in the Oligo-Miocene deposits of the Numidian Flysch.

In the stretch of the river flowing in the urban area, watercourse has a meandering trend with recessed forms and several meters high banks consisting of Pleistocene deposits. The final stretch of the watercourse, modified by hydraulic structures built in the early 1900s, was originally characterized by a meandering morphology and divided into several free branches before its mouth (Agnesi, 2021). In a stretch of the geomorphological map provided by Cappadonia et al. (2020), reported in figure 25, a reconstruction of the original landforms due to natural processes of the Palermo area is described. The presence of many ancient rivers is noticeable; over time, these watercourse shaped valleys within the plain (pale green areas) that are characterized by different degrees of the slope. Moreover, alluvial plain areas close to the coastline are reconstructed (dark green).

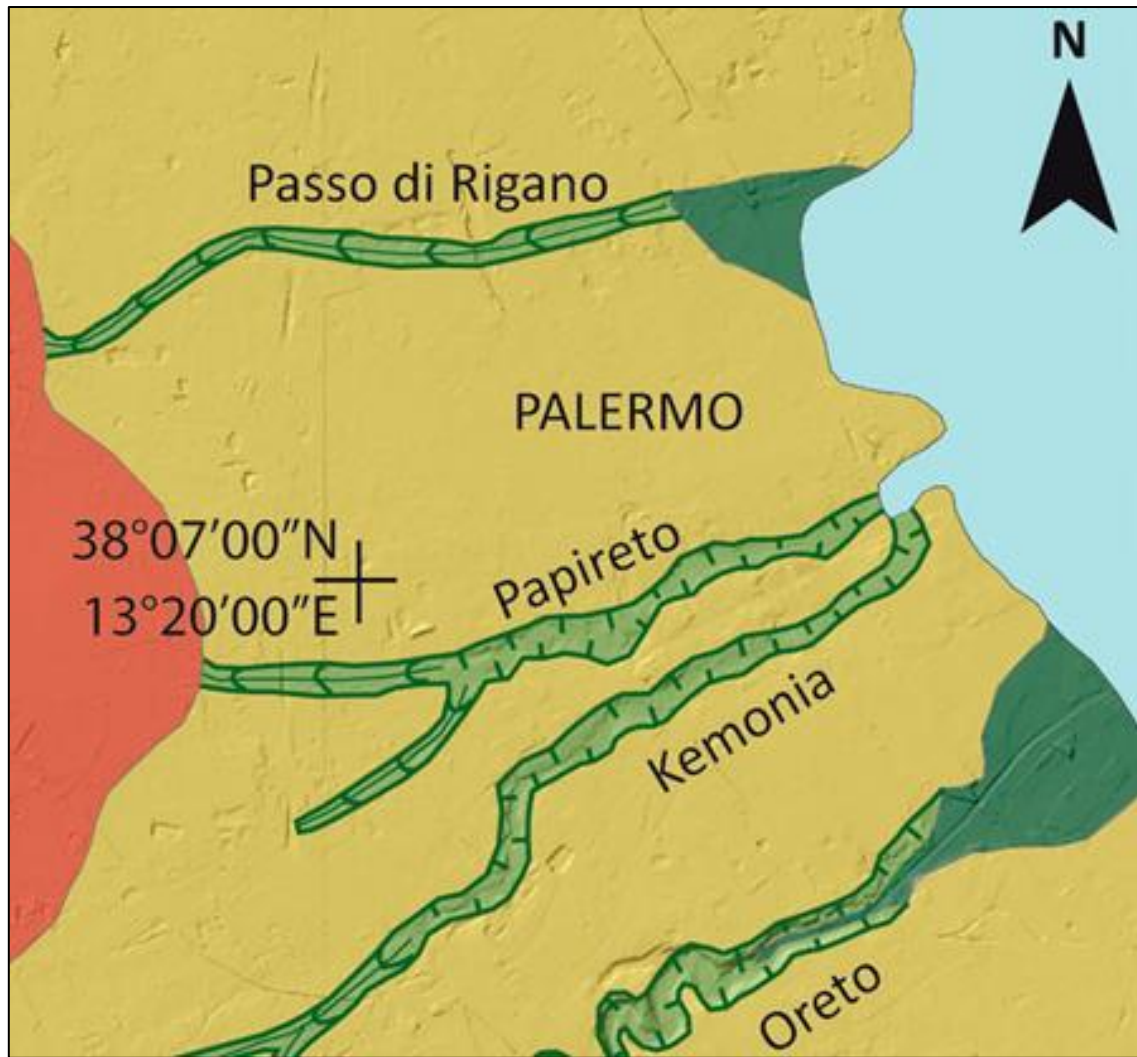


Figure 25: Geomorphological chart provided by Cappadonia et al., 2022: in red alluvial fan; in yellow coastal terrace surface; in pale green presenting integer lines degraded fluvial erosion scarp with inclination of the scarp $< 35^\circ$ inclined; in pale green presenting interrupted lines fluvial erosion scarp $> 45^\circ$ inclined; in dark green alluvial plain areas.

2.4 Geological data collected.

2.4.1 City GIS database.

The City -GIS is a database that collects different types of data, including a vast collection of survey stratigraphies. The database, developed in a GIS environment, is the property of the Department of Earth and Sea Sciences of the University of Palermo (DISTEM). It has been designed to be continuously growing, dynamic and easily accessible through software with an easy-to-consult multimedia interface (Giammarinaro et al., 2001). This software allows the execution of numerous operations and in particular the processing and export of data contained in the database. The City-GIS has promoted and supported the execution of numerous researches, some focused on studying and understanding the Palermo area (Giammarinaro et al., 2003; Giammarinaro et al., 2006) and has been used by different territorial Administrations that in the project phases related to important public works. The City-GIS module called «Surveys», dedicated to stratigraphic and geotechnical themes, was used in this study. This section of the database collects more than 2500 boreholes stratigraphies provided by public bodies, research institutes and private companies. The position of the boreholes present within the database is shown in figure 26b.

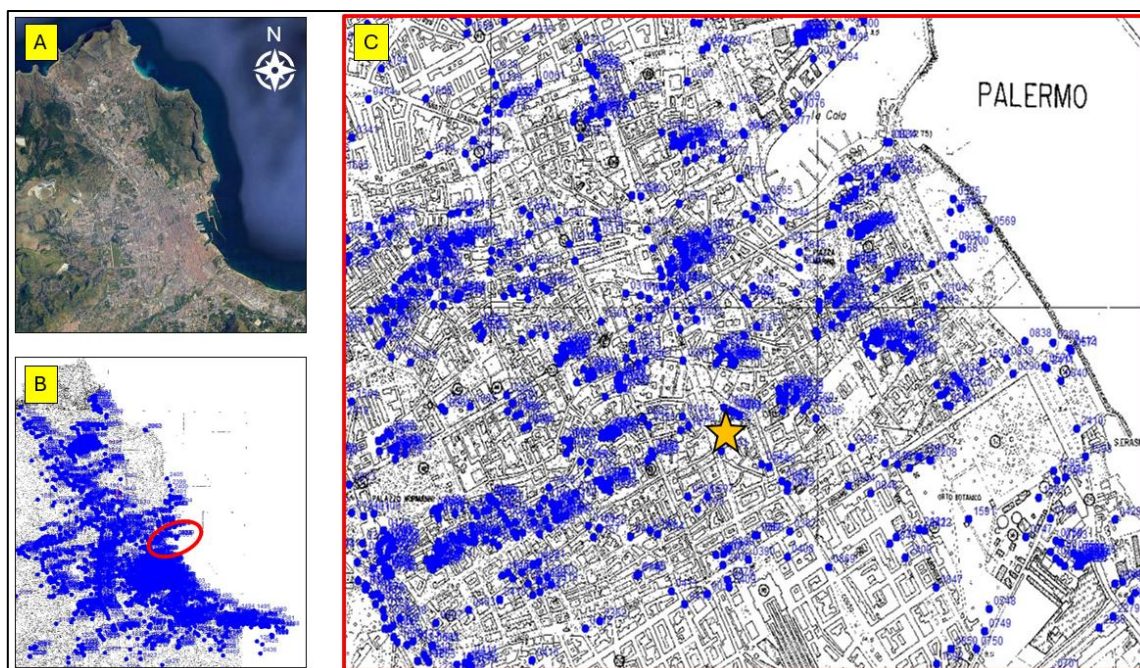


Figure 26: A) Satellite view of the area of the plain of Palermo affected by the presence of data from the City GIS; B) Location of surveys within the City GIS (blue points); C) An enlargement of the interface of the City GIS related to a sector of the historic center of Palermo (red circle in B). The yellow star represents the position of the survey shown in figure 27.

Each borehole collected presents the following data: location, lithologies, depth, lithotypes thickness, depth of the aquifer; an example of one borehole, related to position indicated by the yellow star in figure 26c, is presented in figure 27.

Ubicazione: Oratorio di S. Anna					
Sondaggio: - Identificativo N°: 0551					
quota (m)	profondità(m)	spessore (m)	stratigrafia	sigla	falda
9.5					
2.3	7.2	7.2		R	5.5
-1.7	11.2	4.0		AL	
		11.3		DM	
-13.0	22.5	7.5		CC	
-20.5	30.0				

Figure 27: An example of the data for a borehole survey contained within the City GIS. The example is related to a survey carried out around Sant'Anna Square, in the historic center of Palermo. The position is represented by the yellow star in figure 26c.

As observed in figure 27, the descriptions of the lithology of deposits in the surveys are given as abbreviations. Within the City GIS, 87 abbreviations have been defined for the different lithological facies covered in the surveys, including the presence of the abbreviation “*Sea*” for offshore surveys and the presence of the “*Ipo*” and “*Cav*” categories where anthropic or natural cavities are described in surveys. To show the remarkable variety of facies, the example concerning facies classified as “*yellow calcarenite of the south*” in the City GIS is reported in figure 28; A total of 15 different types of facies have been described for this type of deposit alone.

CG	<i>Quaternary marine detrital organogen complex, with silt to gravel grain size</i>
CGt	<i>Altered surface area with pockets of erosion filled with red soils</i>
CGr	<i>Calcirudites in decimetric leyers, places are very cemented. In the highest part of the succession</i>
CGc	<i>Calcarenites in banks and centimetric and decimetric layers with present fine sandy levels</i>
CGfc	<i>Calcarenites with low cementation alternating with more cemented</i>
CGf	<i>Calcarenites with low cementation</i>
Cgi	<i>Sand with rare interlayer cemented layers</i>
Cga	<i>Alternation of calcarenites and calcareous sands</i>
CGn	<i>Calcarenites and pseudonodal calcilutites</i>
Cgo	<i>Alternation of calcarenites pseudonodulars and fine calcareous sands</i>
CGp	<i>Fine calcareous sands with scattered nodules of calcarenites and calcilutites</i>
CGs	<i>Calcareous sands</i>
CGg	<i>Coarse sands and calcareous gravel</i>
CGl	<i>Fine sand and silt with rare calcareous elements</i>
CGv	<i>Fine calcareous sands and silt of greenish or brown colour</i>

Figure 28: List of facies reported in the City GIS database concerning deposits defined as “*Yellow calcarenite of the south*”.

The deposits described within the database can be grouped into the following 23 macro-categories of soils and materials according to their age, composition and genesis. A schematic chart of this subdivision is represented in figure 29.

AAZ	<i>Ficarazzi Clays</i>	LA	<i>Lake deposits</i>
ALL	<i>Alluvial soils</i>	PAL	<i>Paleosols</i>
DC	<i>Dolomitic limestone</i>	R	<i>Deposits of anthropic genesis</i>
CC	<i>Palermo Calcarenites</i>	RRL	<i>Radiolarites</i>
CO	<i>Eluvial and Colluvial soils</i>	SCLL	<i>Scillato Fm.</i>
CG	<i>Conglomerates</i>	SEA	<i>Sea</i>
DOL	<i>Dolostone</i>	SMA	<i>Holocenec marine deposits</i>
DM	<i>Upper Pleistocene marine deposits</i>	TO	<i>Peat</i>
DT	<i>Rock Debris</i>	TRS	<i>Red beds</i>
EL	<i>Aeolian deposits</i>	TV	<i>Topsoils</i>
FN	<i>Nunidic Flysch</i>	TVR	<i>Travertine</i>
IPO	<i>Cavities (natural and antropic)</i>		

Figure 29: List of 23 macro-categories of soils and materials defined analyzing City GIS database descriptions.

From the City GIS database, a total of 1404 stratigraphy surveys (figure 30), presenting a varying depth between 2 and 170 m, and falling in the exanimated sector of this case study, the area closest

to the urban stretch of the Oreto river, were extracted. This area corresponds to the land between the eastern coastline and a western sector, enclosed between the Altofonte and Monreale towns, where the major road SS624 intersects the Oreto river that is crossed by a bridge. The northern border of the studied area is represented by the axis defined from the connection “Via Amari -Corso Finocchiaro Aprile - Via degli Emiri” while the southern border is the "Acqua dei Corsari” sector”.

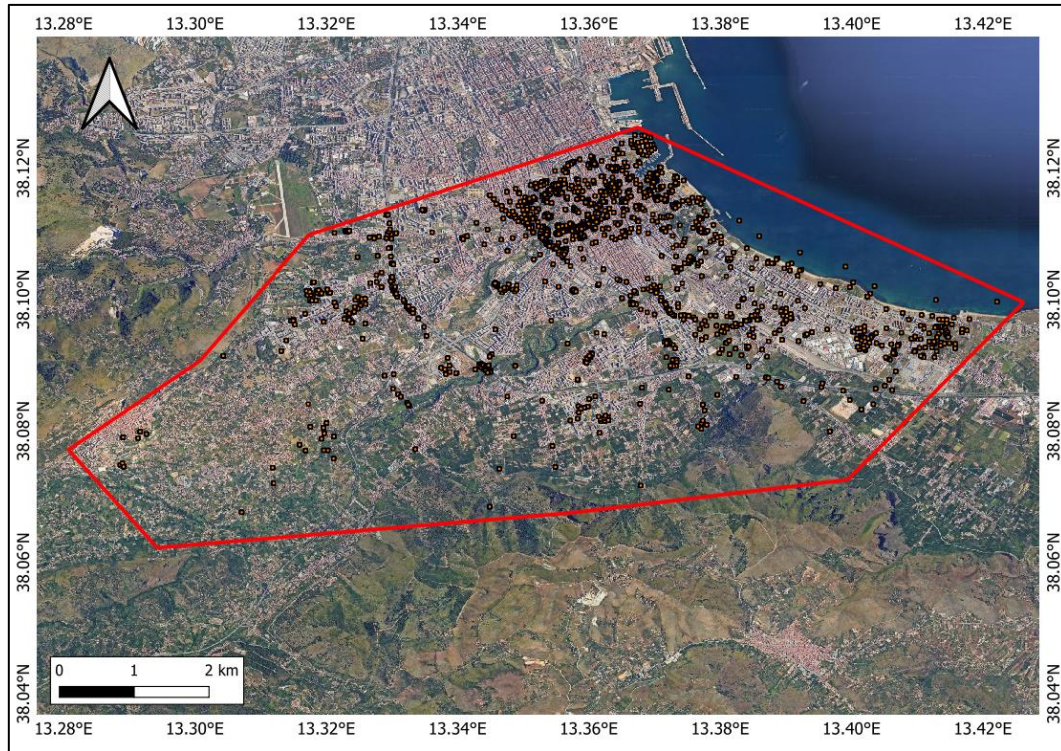


Figure 30: Location of the surveys extracted from the City Gis catalogue (orange rectangles) within the study area (red line).

2.4.2 Stratigraphic reconstructions derived from boreholes analysis.

Another 126 boreholes (Figura 31) were collected to obtain more information on the area under consideration. These surveys, not present in the City GIS database, have different origins: some of them were carried out in the last ten years during project phases for the construction of a tram line, others were conducted to characterize the harbor area for modernization as a tourist destination. Other data come from previous studies carried out in areas of the sector examined where there was a lack of documentation within the City GIS such as the areas near and within the Civico and Policlinico hospitals. Finally, several have been collected by direct analysis of samples from drillings related to the current construction of an urban. Almost all these surveys were carried out by the continuous core-drilling method, which provided detailed information, even on individual sites, on the successions in the subsoil.

The depth reached by these wells varies between 5 m and 50 m. The identified sediments mostly belong to the Marsala Synthem (Palermo Calcarenes and Ficarazzi Clays), but other types of deposits were also found, including late Pleistocene and Holocene marine and coastal deposits, red beds, travertines and alluvial deposits. Only for the deeper boreholes the oligogenic deposits of Numidic Flysch had been found and described. Due to the varied and heterogeneous origins of these data (figure 32), a standardization and homogenization process was applied in the description of the deposits. For this reason, all the sediments described in the stratigraphies have been defined and classified following the lithological subdivision in macro categories exposed in figure 29. This kind of process allows us to realize a better interpretation of all the data available from boreholes.



Figure 31: Position of the 126 boreholes data points not included in the City Gis database.

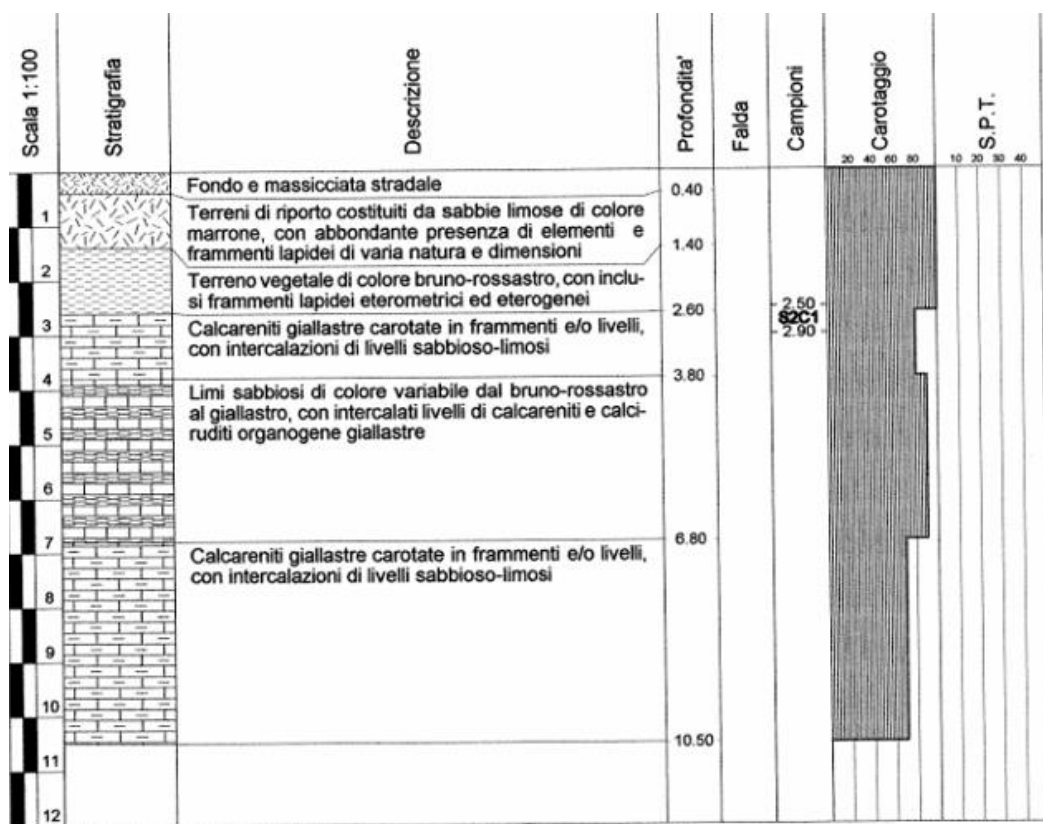


Figure 32: One of the boreholes analyzed and not already collected in the City GIS database.

2.4.3 Stratigraphic reconstructions derived from well cutting, trenches and outcrops analysis.

The excavation of wells for the subsequent installation of series of poles within the works related to the construction of the sewer collector has allowed to acquire more data in 6 sites within the area under consideration. In each site, about 30 wells per sector were dug, each about 20 meters deep. This allowed us to observe the sediments extracted with bucket (figure 35) or core-destroying drilling (figure 34). The analysis of the cuts of the excavations carried out for the wells and the successive trenches, as well as the existing outcrops, made it possible to figure out the subsoil model of the 8 sectors under study, based on information applicable to a broader area rather than isolated boreholes.



Figure 33: Location of the areas where geological field surveys have been carried out.

For each site, visible in figure 33, a typical geological sequence has been described. These are listed below. For some of the 8 sites multiple stratigraphic patterns were identified and documented.

Site 1 - Brasa

- 0 m - 0.3 m: Soil and vegetation.
- 0.3 - 1 m: Red beds (figure 37a).
- 1 m - 3 m: Red altered calcarenites, weakly cemented. (figure 37b).
- 2m - 6 m: Calcarenites without fossil content from average to well cemented. There are stratifications of different colors, whitish and yellowish. This stratified material is extracted as prismatic benches with a thickness of between 4 and 10 cm and a maximum length of 50 cm. (figure 37c and 37d).

- 6 m - 13 m: Nodular calcarenites extracted as silty sandy gravel with calcareous elements of size even greater to 5 cm; these elements have sub-angular edges and a generally elongated shape. The aquifer was found in these deposits at a depth of about 12 m. (figure 37f).
- 13 m - 20 m: Blue clay in silty sand facies with presence of grey nodular structures and fossils. From 14.50 m to 15 m, the samples are more plastic. In some sections, there were centimetric thickness smelling levels of blackish (peat). The blue-colored clays were extracted from the bucket as cylinders of even one meter length seen at the Wn near the Wp (Figure 37e).



Figure 34: core-destroying drilling.

Site 2 - Tukory:

- 0 m - 1.2 m. Anthropic cover with presence of bricks. (figure 38a).
- 1.2 m -2.2 m: Conglomerates composed of polygenic centimetric elements rounded strongly cemented by a whitish carbonate matrix with. (figure 38b).
- 2.2 m - 3.5 m: Fossiliferous reddish altered calcarenite from weakly to well cemented. (figure 38c).
- 3.5m - 13 m Yellowish white fine-grained calcareous sands (figure 38d) These materials are extracted from the bucket as centimeter-sized calcareous blocks with edges from angular to sub-rounded. In different sections there are well cemented calcarenite levels of more than 10 cm thickness showing color from yellow to reddish and laminated structure.
- 13 m - 17m: Nodular Calcarenites extracted as silty sandy gravel with calcareous elements of size even greater than 5 cm; these elements have sub-angular edges and a generally elongated shape. (figure 38e).
- 17 m – 20 m: Black clays. (figure 38f)

Site 3 -Indipendenza

- 0 m – 2 m Anthropic over

- 2 m to 8 m: Calcarenites strongly cemented in several levels; Around 6.5 meters change from grey to yellowish how seen both between the cuttings and inside cavities (figure 39a,b).
- 8 m to 14 m: Fossiliferous calcarenites, weakly cemented; centimetric calcareous nodules in yellowish sandy matrix (figure 39c). At a depth of about 13 meters, the interdigitation with the blue-colored clay below is observed (figure 39d).
- 14 m – 20 m: Blue clay with nodules from 16 m; more clayey levels from 16 m fFigure 39e,f).

Site 4 - Criscione – Section 1

- 0 m -1.5 m: Brown anthropic cover with stone elements of various nature and fragments of pottery and bricks (figure 40a)
- 1.5 m - 2.5m Reddish altered calcarenites (figure 40b)
- 2.5 m - 9 m: Fossiliferous calcarenites strongly cemented in several sections of maximum thickness 50 cm (figure 40c). Inside, at a depth of 7 m, there are sandy mudflats of reddish-brown color that have Wn greater than Wp. These deposits are between 1 and 2 m thick (figure 40d).
- 9 m - 13.50 m: Nodular calcarenites. (figure 40e,f)
- 13.50 m -20 m: Blue-colored clay, with nodules from 16 m; more clayey levels are present at 16 m.

Site 4 - Criscione – Section 2

- 0 m - 2m: Anthropic coverage (figure 41a).
- 2m - 20 m: Travertine deposits with greyish and reddish color. These are porous, with print of plant remains. These materials had been extracted like blocks of 60 cm diameter up to 1.5 m height (figure 41b,c,d,e,f).



Figure 35: Bucket used to extract soft materials.

Site 5 – Sacro cuore -Section 2

- 0 m -0.8 m: Anthropogenic carry-over

- 0.8 m - 6 m: Low-cemented vacuolar calcarenites in yellowish sandy matrix and hard-cemented calcarenite.
- 6 m - 14.15 m: Calcarenites sand with decimetric levels of silty sands.
- 24.50 m - 15.20 m: Polygenic conglomerate.
- 15.20 m - 20 m: Numidc flysch, altered in the first 2.5 meters.
-

Site 5 – Sacro cuore -Section 2

- 0 m -0.5 m: Anthropogenic carry-over.
- 0.5 m - 6.50 m: Alternance of low-cemented vacuolar calcarenite in yellowish sandy matrix and calcarenites, strongly cemented.
- 6.50 m -7.50 m: Calcareous sand and weak.
- 7.50 m -16 m: Nodular calcarenite.
- 16- 17.20 m: Basic conglomerates.
- 17.20 - 20 m: Numidian Flysch altered in the first 0,8 meter.

Site 6 - Ascoli

- 0 m – 5 m: brown clay with polygenic elements.
- 5 m – 20 m: Calcarenites and sandy limes.

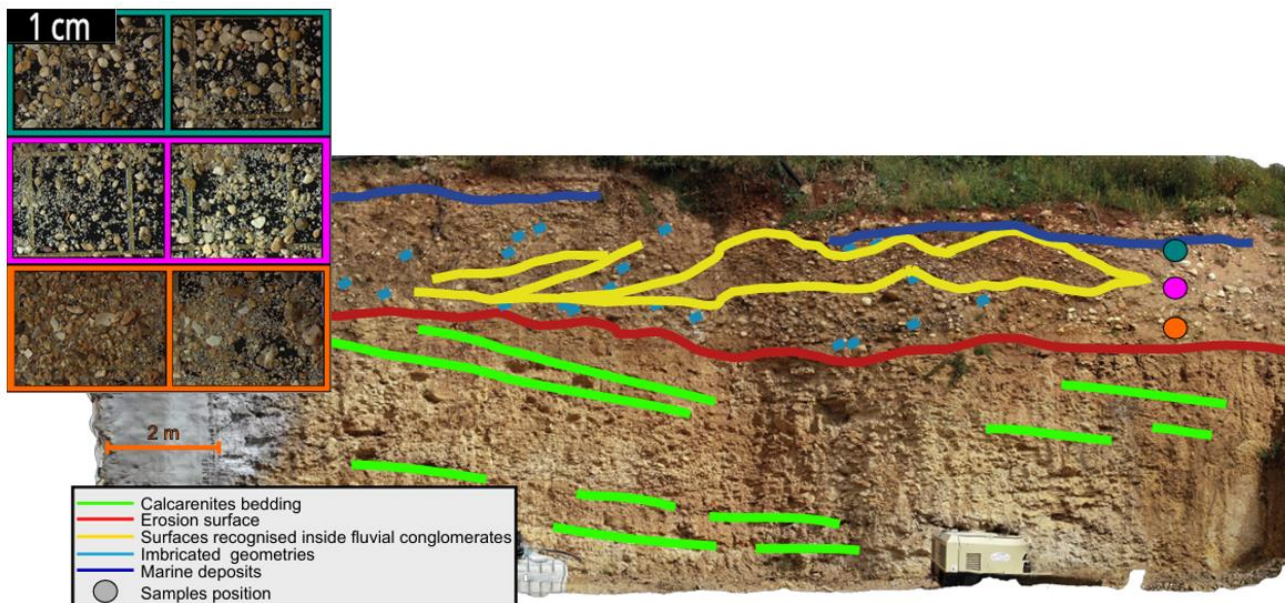


Figure 36: Reconstruction of the vertical outcrop detected with drone in the site Ascoli. The recognized sedimentary structures and the location of the samples are represented on the outcrops surface. The microscope images of the samples examined are shown on the table on the left.

At the Ascoli site, moreover a collection of images was also made by drones (figure 36) to describe the compositional characteristics and sedimentary geometries characterizing an outcrop that had been successively covered with benthic spritz coverage. The photos were combined, and they were to highlight the presence of two levels related to calcarenites, in the lower part, and possible fluvial deposits in the middle section of the outcrop and marine in the upper part. To support this thesis, samples were collected and observed under a microscope for a sedimentary characterization. The analysis confirms the hypothesis of a river system in view of the absence of organisms for the central area of the outcrop.

For all the site analyzed the same workflow focused on homogenizing and standardizing lithologies had been done; this operation has further increased the geological database available.

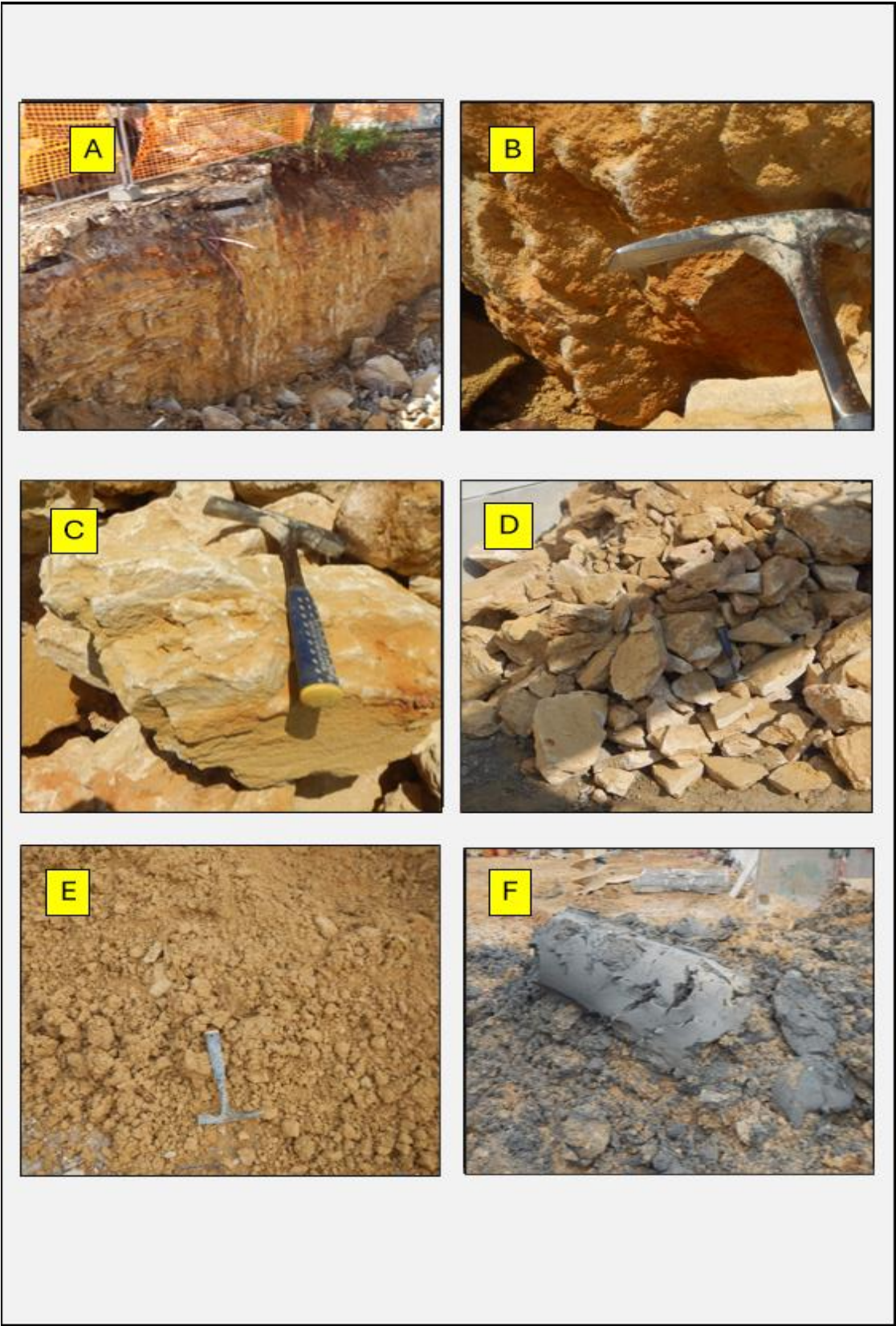


Figure 37: Characteristics of the deposits analyzed at Brasa site.

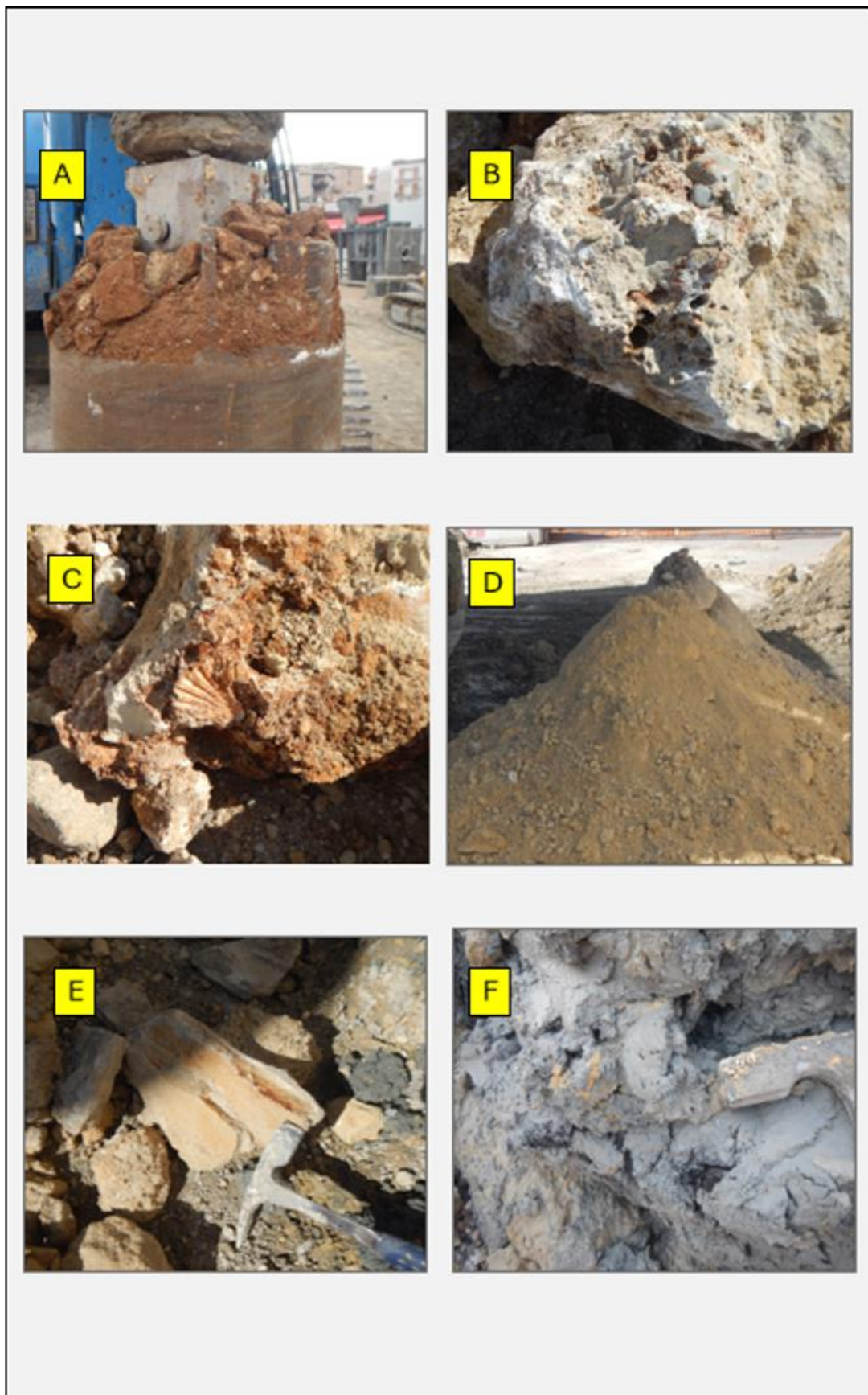


Figure 38: Characteristics of the deposits analyzed at Tukory site



Figure 39: Characteristics of the deposits analyzed at Indipendenza site.

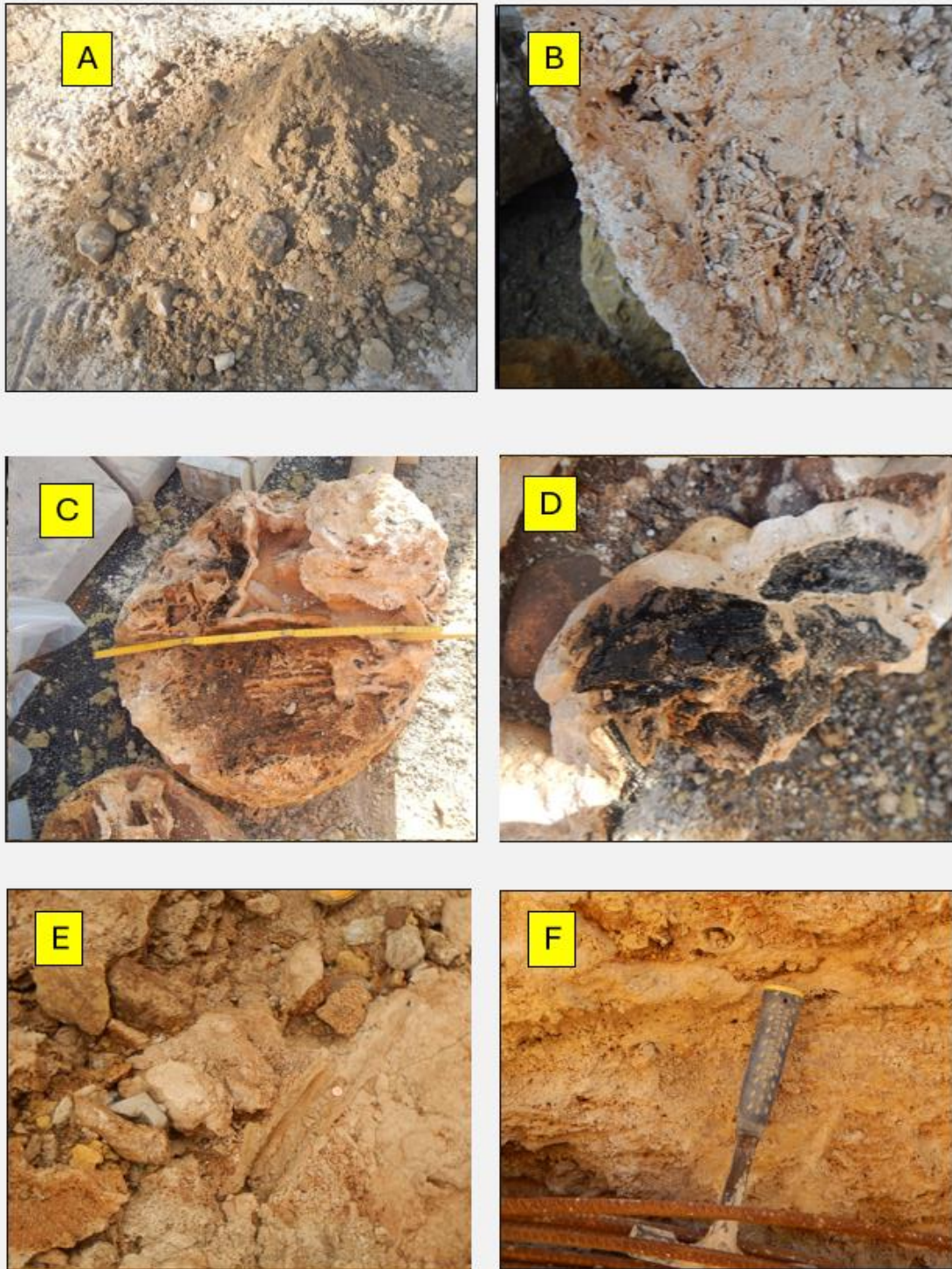


Figure 40: Characteristics of the deposits analyzed at Criscione site., section I

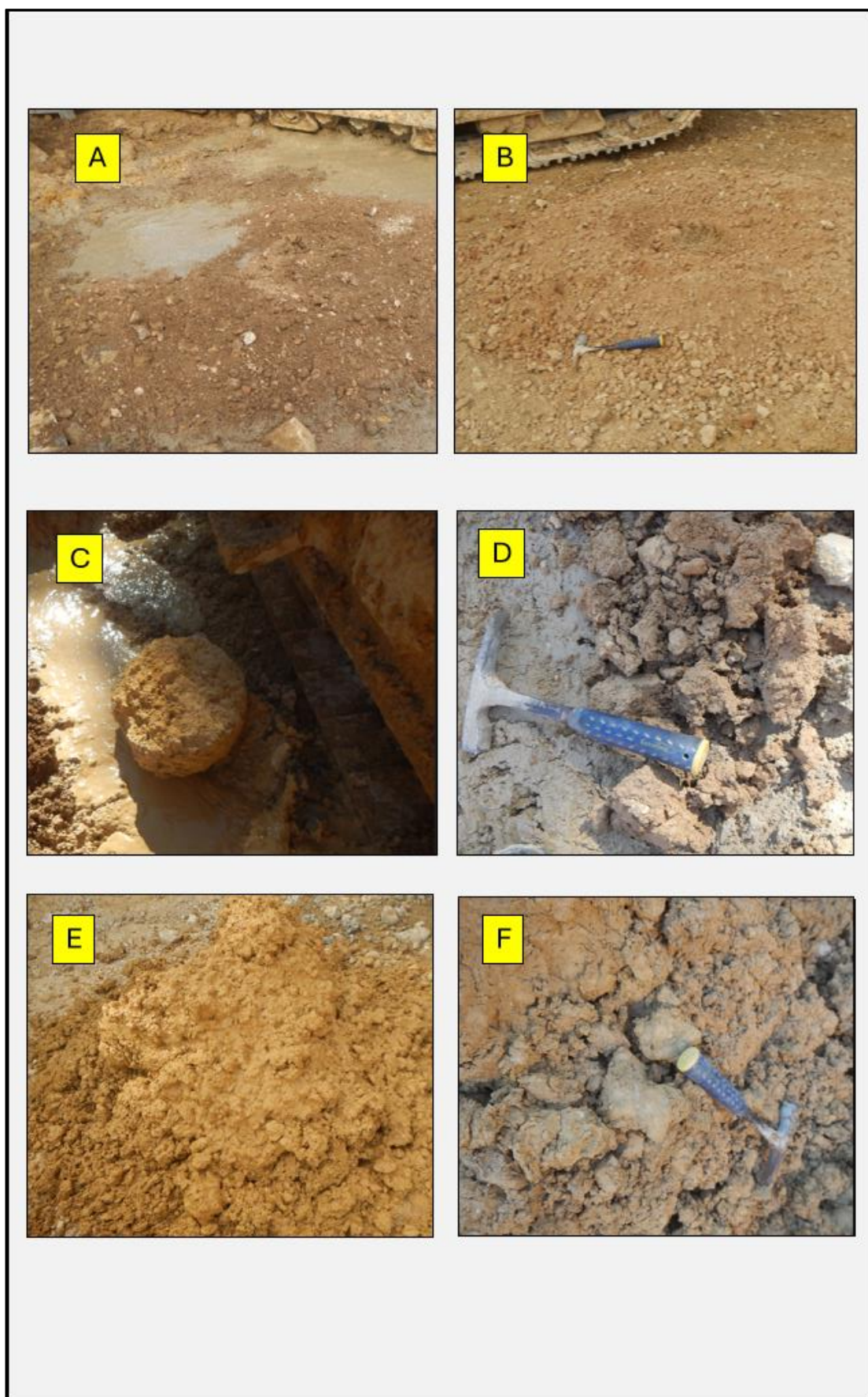


Figure 41: Characteristics of the deposits analyzed at Criscione site, section 2.

2.5 Geophysical data collected.

To expand the available dataset many geophysical data were considered. Data include active (SRT and MASW) and passive (HVSr) seismic measurements. These have been acquired in the field at different sites in the city, within the study area or in neighboring sectors. Much of these data was acquired specifically for this work; other acquisitions were carried out within an agreement between DISTEM, CURSA (University Consortium for Socio-economic Research and the Environment) and the Department TERIN (Energy Technologies and Renewable Sources Department) of ENEA (National Agency for New Energy Technologies and Renewable Sources) on the project "*MOD-Energy*" "Application and dissemination of application models in the field of smart lighting/street/building for the containment of energy consumption in Metropolitan Cities". Other data have been reworked: several HVSr acquired by the Municipality of Palermo for the implementation of the city's master plan were provided to DISTEM as raw data, given the collaboration of the Department in the planning phase of these surveys.

2.5.1 SRT and MASW surveys.

Five active seismic surveys (SRT) had been realized according to the seismic refraction tomography methodology. These were carried out in areas adjacent to the Oreto river (figure 44). The seismic arrays were made using 24 geophones according to the following two configurations: intergeophonic distance was 2 meters for the acquisitions "Oreto mouth West" and "Buonriposo"; for these sites 8 shots had been realized, two of which were made externally with at 5 m offset. In the sites "Bennici" and "Ponte Rotto West" inter-geophone distance was set to 3 meters and 9 shots were performed. In this case too, two external shots were carried out at the ends of the spread with an offset of 5 m.

In the same sites, MASW were conducted using the same array configuration changing the acquisition parameters.

In addition, only MASW surveys were carried out in other 4 sites according to the following configurations:

- "Ascoli" surveys: 12 geophones spaced 2 m with an offset of 5 m.
- "Oreto mouth East", "Oreto bridge" surveys: 24 geophones spaced 2 m, offset equal to 5 m.
- "Stend Florio" survey: 16 geophones spaced 2 meters, offset equal to 5 m.

In other 8 sites, (Agostino, Alagna, Di Vittorio, Kolbe, Natoli, Sacco -Vanzetti, San Ciro, Salgari) MASW surveys were carried out for the above-mentioned MOD-Energy project: for all these the array configuration used as follows: 12 geophones spaced 2 m, offset equal to 5 m.

The data inversion process was carried out considering data of V_p and V_s derived from previous works and was constrained, when possible, by the stratigraphic data collected within the City Gis and in the extra boreholes database mentioned in paragraphs 2.4.3 and 2.4.4. A map collecting all the studied sites is shown in figure 42.

Oreto mouth West surveys.

The position of Oreto mouth West surveys is represented in figure 45a; V_p values computed by STR performed (figure 45b) show a low velocity layer in which the velocity does not exceed 900 m/s. This layer extends to a maximum depth of about 10 m and is followed by a continuous increase in V_p values reaching a maximum value slightly above 2000 m/s between 15 m and 20 m on the left side of the section. The V_s model provided by MASW (figure 45c) shows several layers from 0 to of about 15 m with V_s characterized by velocity ranging from 300 to 350 m/s. Considering boreholes 429 and 854 of the City GIS database as shown in figure 43, the low velocities recognized in both surveys should be attributed to the presence of cover anthropic material (MR) for the first 5 – 8 meters. Going deeper, the increase in velocities could be related to the presence of alluvial (AL) deposits ($V_p \approx 1500$ and $V_s \approx 350$). The highest velocities could be linked with a calcarenites substratum.

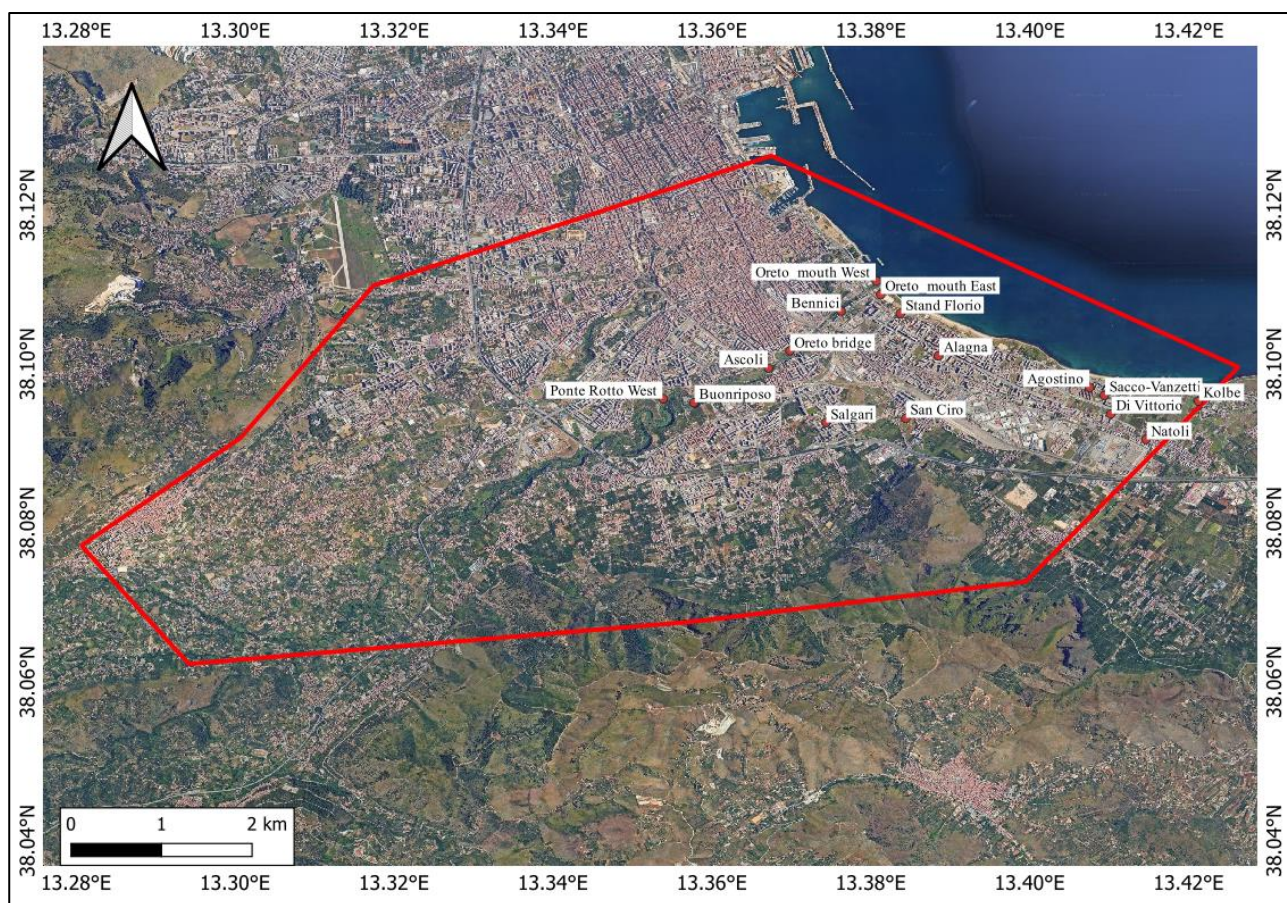


Figure 42: Map of sites where active seismic surveys had been realized.

Ubicazione: Via Scaricatore (S. Erasmo)						Ubicazione: Via Messina Marine (Foce F. Oreto)					
Sondaggio: - Identificativo N°: 0429						Sondaggio: - Identificativo N°: 0854					
quota (m)	profondità(m)	spessore (m)	stratigrafia	sigla	falda	quota (m)	profondità(m)	spessore (m)	stratigrafia	sigla	falda
1,5	4,5	4,5		MRf	3,2	-4,3	8,3	8,3		MRg	2,5
-4,0	10,0	5,5		ALg		-9,6	13,6	5,3		ALT	
-14,0	20,0	10,0		ALi		-16,0	20,0	6,4		ALf	

Figure 43: lithological log of boreholes 429 and 854 of City Gis database.

Buonriposo site surveys.

The position of Buonriposo surveys is represented in (figure 46b); Vp values showed are equal to a value not higher than 900 m/s until a depth of 6 m. A second Vp pattern is present until the down bottom of the section where values reach 2200 m/s around 15 m. Equally low Vs velocities, from 250 to 400 m/s are described for the first 10 meters of the MASW model (figure 46c) and increase until 600 m/s proceeding down stare. Considering the position of the survey (figure 46 a) carried out within a river bend, the low Vp and Vs superficial velocities of the two models are attributed to alluvial deposits that should range a thickness of approximately 8 m. Calcarene should represent the higher Vp and Vs values of the lower parts of the two models.

Bennici site surveys.

The position of Bennici site is shown in figure 47a; the area examined is situated on the right side of the Oreto river, close to the watercourse. The borehole (figure 47b) is characterized by a huge succession of alluvial deposits positioned above 5 meters of anthropic coverage. Considering these geological features, the velocities, present in SRT model carried out (figure 47c), are lower or equal to 500 m/s and describe the upper coverage while the higher values of Vp should be referred to alluvial. In the same way the Vs computed by the MASW (figure 47d) shows Vs around 250 m/s for the upper 5-meter-thick layer, that is considered as a human filling; the Vs that are characterized by medium values of 400 m/s are attributed to the alluvial deposits.

Ponte Rotto West site surveys

The SRT carried out in Ponte Rotto West (figure 48a) has maximum Vp values ranging from 300 and about 1200 m/s for a surface layer extending up to 5 m in the underground (Figure 48c). Below these layers the values increase considerably to more than 2000 m/s, like at 15 m depth. A similar trend has been calculated for model Vs (Figure 48d) in which a sharp increase in velocity from 400 to 600 m/s is recorded at about 10 m of depth. The highest velocities, recognized from 10 meters of depth, are related to the calcarenites (CC) described by survey 1722 (figure 48 b); the slowest ones are probably associated with old watercourse deposits due to their proximity to the Oreto River.

Ascoli site survey

The active seismic acquisition for the definition of the Vs was carried out at the Ascoli site very close to the Oreto river (figure 49a); the data relating to the Vs was obtained by linking the values of the shear waves to the stratigraphic sedimentary that is described by survey S2 (figure 49c). The seismic - stratigraphic model (figure 49b) shows values below 200 m/s for the first 2.5 meters; later the values reach 350 m/s up to 15 m. These surface conditions are related to alluvial material described in S2. The further increase of values Vs, which deeper show a velocity equal to 550 m/s is due to the presence of calcarenites.

Stand Florio site survey.

The model Vs (figure 50c) defined for the site Stand Florio (figure 50a) was realized by linking the inversion of the MASW data with the survey 1601 of the City GIS database (figure 50b); the first meters have Vs equal to about 200 m/s and should describe either the anthropic filling material materials (MR) or the sands of recent beach (SM), given the proximity to the coast. The increase in velocities is to be related to the presence of older marine deposits (DM). At a depth where Vs reaches 550 m/s, the values are likely due to calcarenites.

Oreto mouth East site survey.

The model V_s (figure 51c) for the site under study (figure 51a) can be essentially divided into three layers: the first one has low values (200 m/s) and is linked to the presence of anthropogenic cover; as described in the City GIS borehole number 855 (figure 51b); follows a seismic layer of about 10 m thickness, which can be attested to alluvial at a velocity of 250 m/s. The highest values, more than 400 m/s, are to be linked to calcarenites described in survey 855.

Oreto bridge site survey.

The low velocities described by the V_s model (figure 52d) had been computed by means of the Masw survey and are to be attributed, on this site, to the presence of river deposits due to the survey's location near the river Oreto (figure 52a). These alluvial deposits are described in surveys 1471 and 1472 (figure 52 b,c) and reach a depth of at least 15 m. The increase in velocity should be attributable to the presence of deep calcarenites but there is no stratigraphic data that give indications about this.



Figure 44: Active seismic data acquisition phase: at the top, the instrumentation used, at the bottom, the preparation phases of an array.

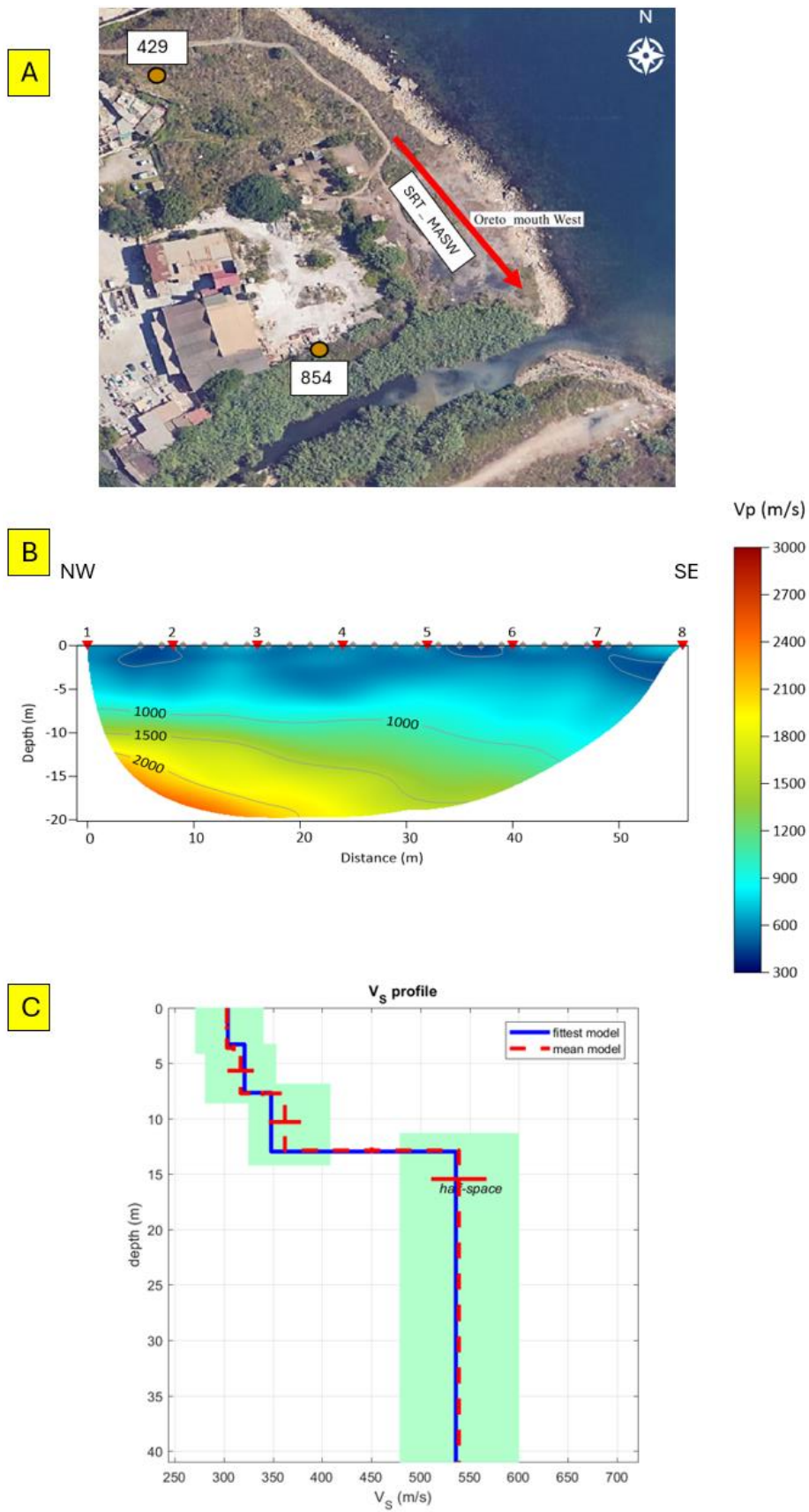
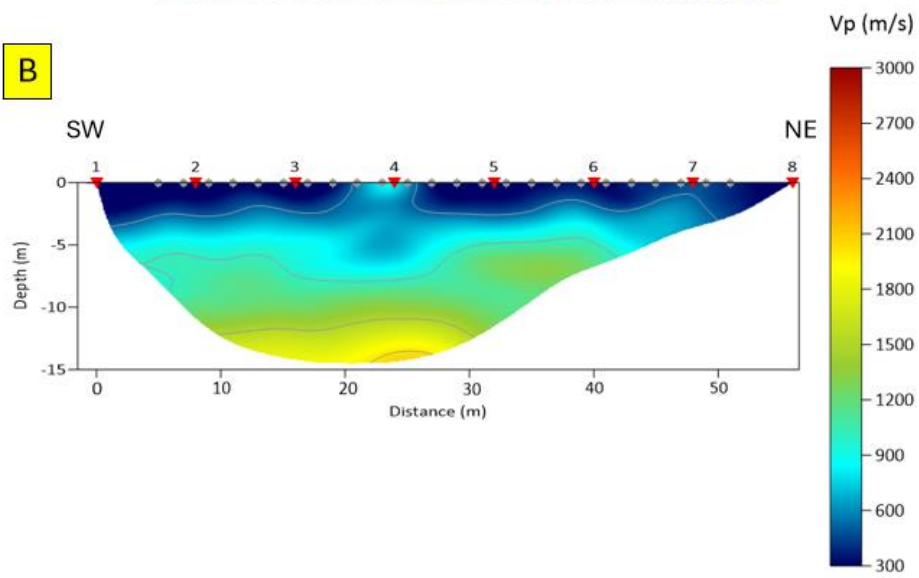


Figure 45: Surveys carried out at the Oreto mouth West site

A



B



C

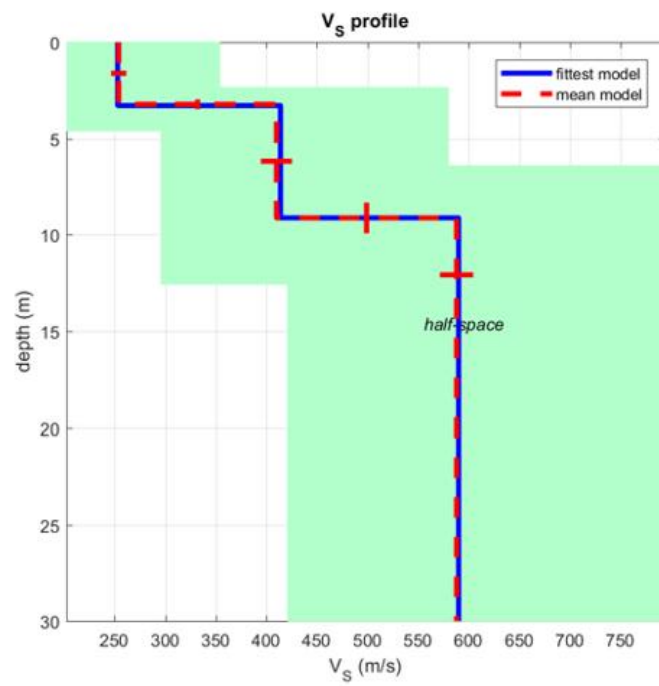


Figure 46: Surveys carried out at the Buonriposo site.

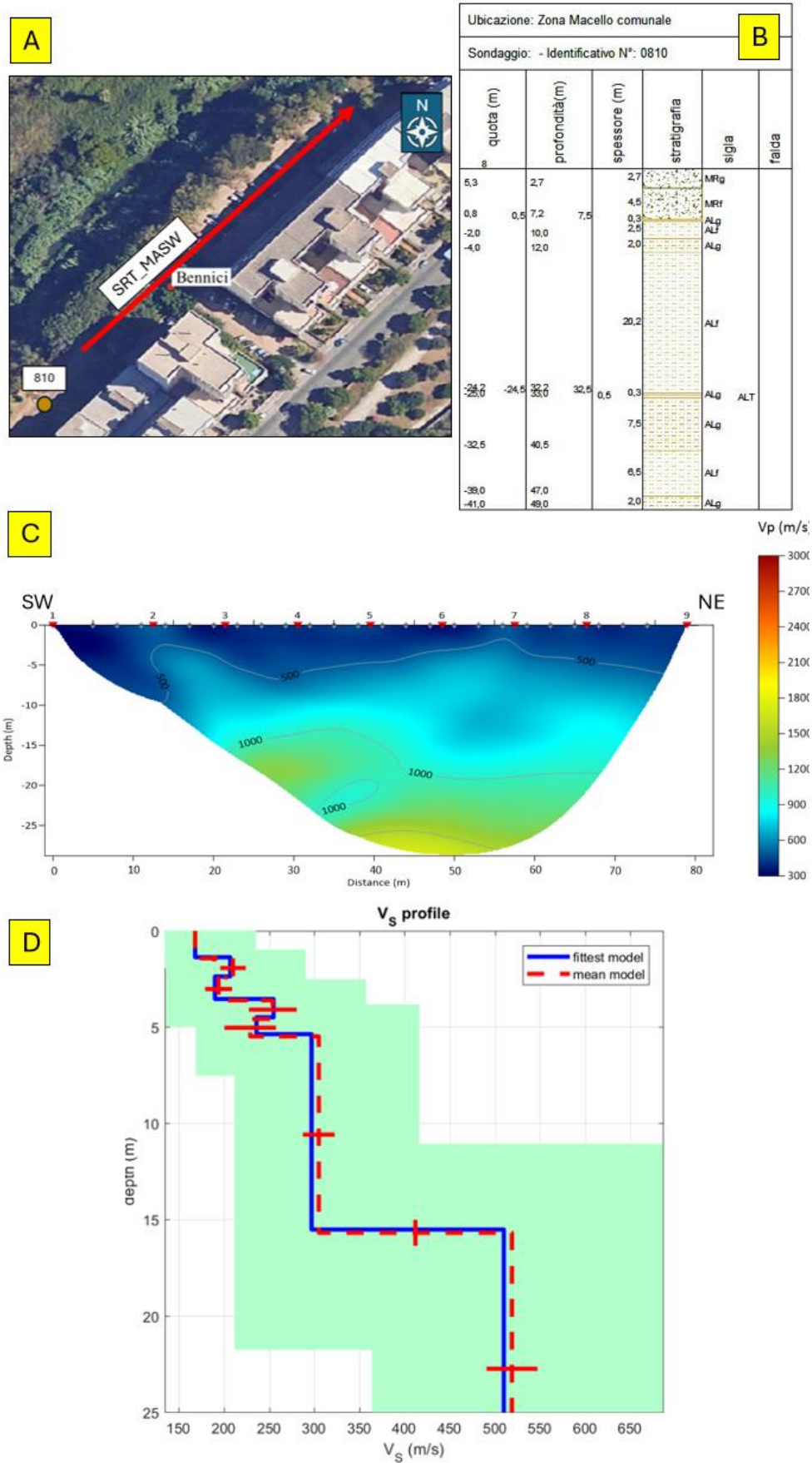


Figure 47: Surveys carried out at the Bennici site.

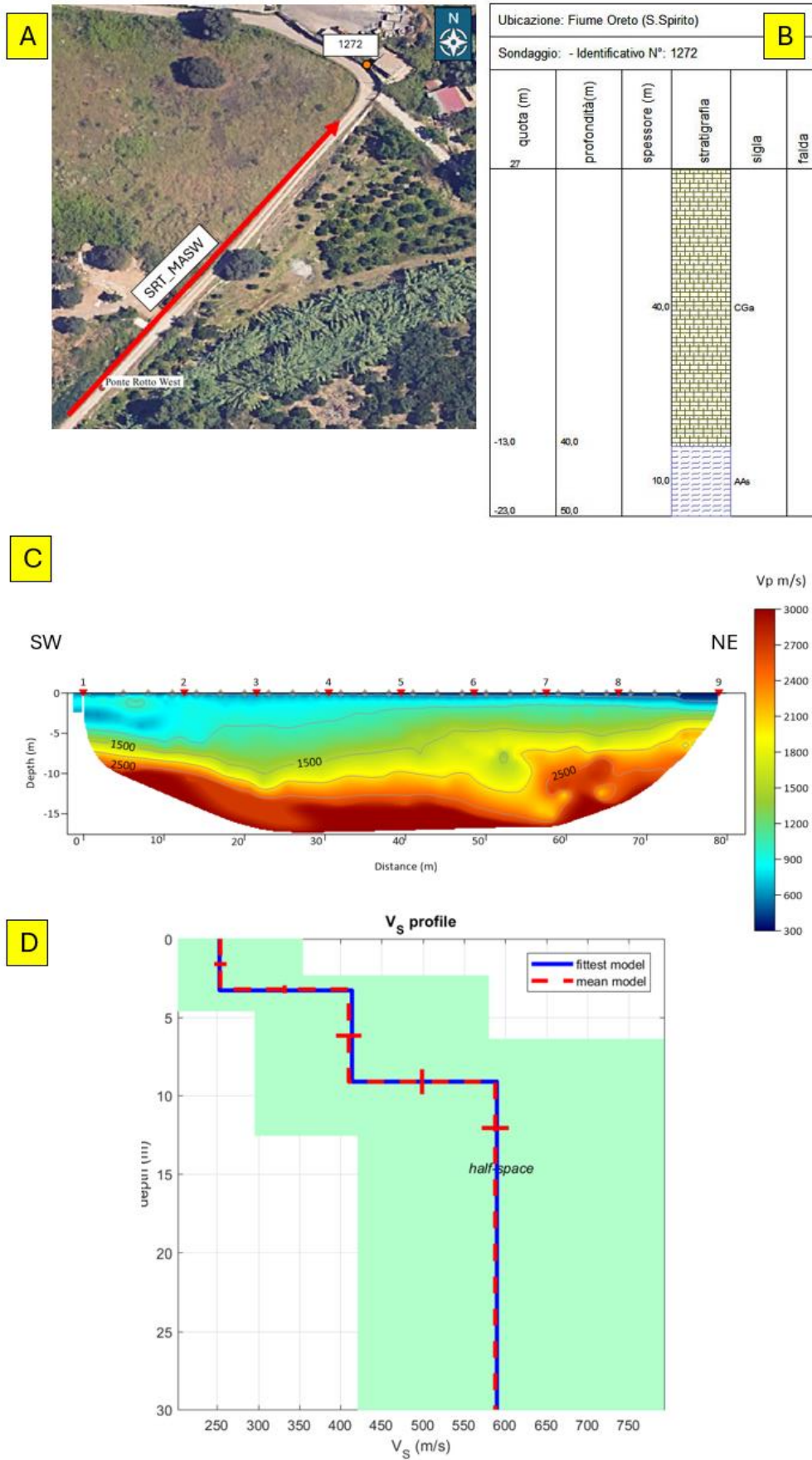
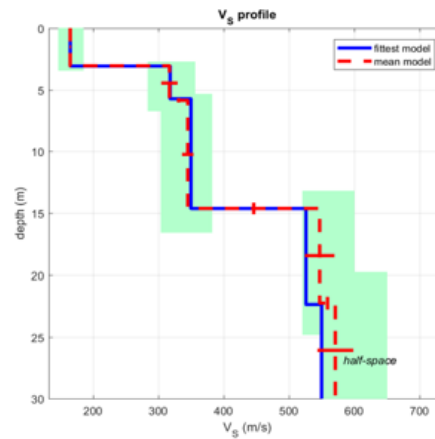


Figure 48: Surveys carried out at the Ponte Rotto West site.

A



B



C

(Rotazione a c.c.)						
mt. 15			Località:	Cantiere Via M. Ascoli-Palermo		
Trivella: CMV600			Oggetto:	Stratigrafie sondaggi Opera di scarico		
			Committente:	Palermo Sud-Est Scarl		
			D.L.	Ing Sergio Di Maio		
Prof. (m)	Spess. (m)	Litologia	Descrizione	Campioni (m)	Presenza d'acqua	Note
1						
2						
3						
4	9		Alternanza di argilla limosa con intercalazione di calcarenite nodulare alterata			
5						
6						
7						
8						
9						
10	4,5					
11			Calcarenite nodulare e sabbie di colore giallastro			

Figure 49: Masw survey carried out at the Ascoli site.

A



B

Ubicazione: Romagnolo					
Sondaggio: - Identificativo N°: 1601					
quota (m)	profondità(m)	spessore (m)	stratigrafia	sigla	falda
1,5					
-3,5	5,0	5,0	MR		
-5,0	6,5	1,5	SM		
-6,3	7,8	1,3	DMc		
		12,2	CGa		
-18,5	20,0				

C

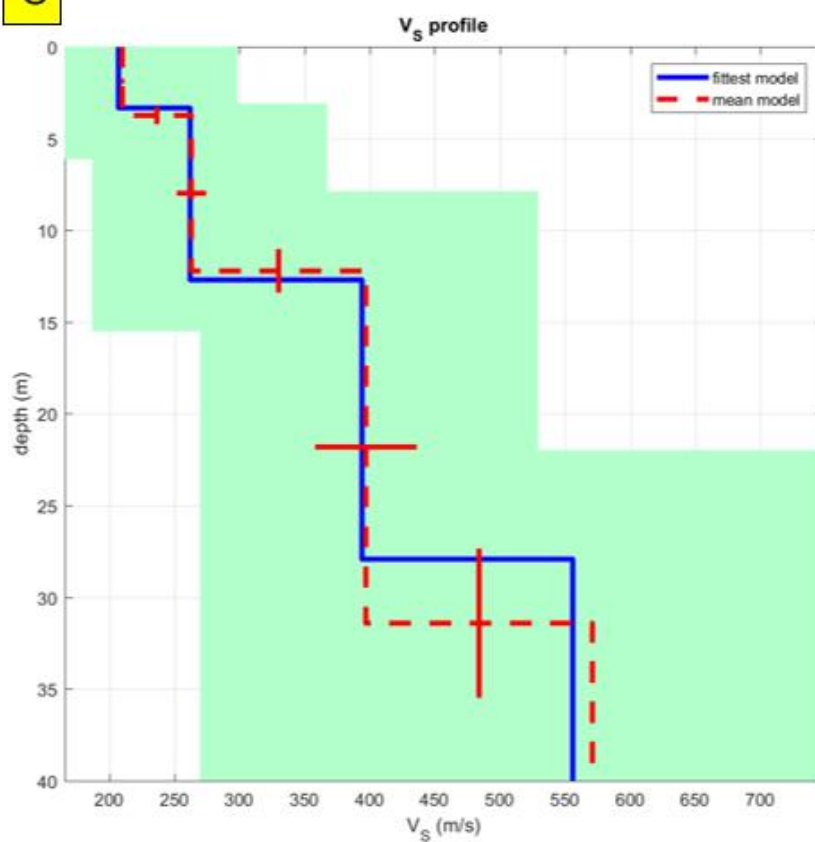


Figure 50: Masw survey carried out at the Stand Florio site.

A



B

Ubicazione: Via Messina Marine (Foce F. Oreto)					
Sondaggio: - Identificativo N°: 0855					
quota (m)	profondità(m)	spessore (m)	stratigrafia	sigla	falda
4,4					
0,6	3,8	3,8		MRg	
-3,0	7,4	3,6		ALc	5,2
		12,6		CGn	
-15,6	20,0				

C

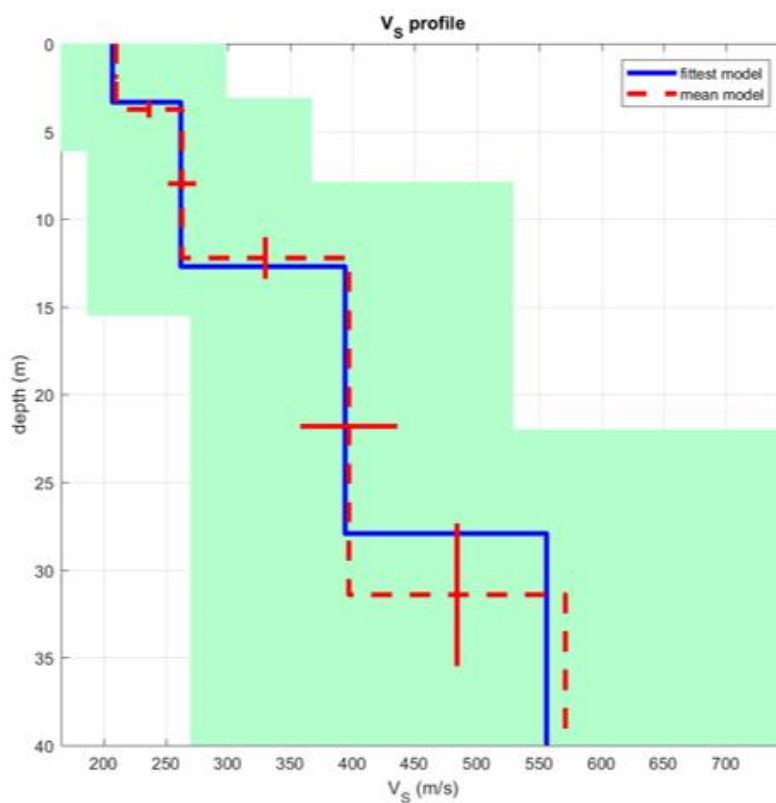
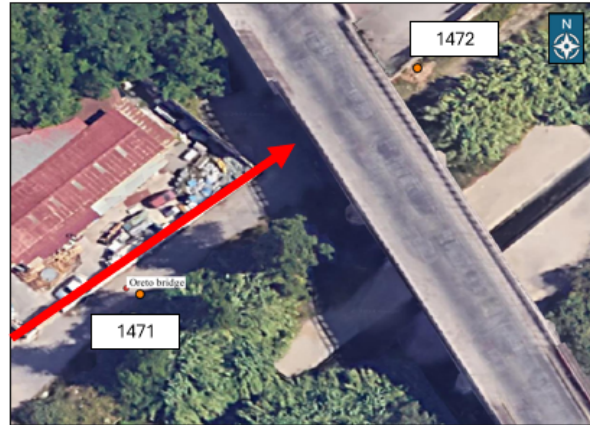


Figure 51: Masw survey carried out at the Oreto mouth East site.

A



B

Ubicazione: Ponte Via Oreto					
Sondaggio: - Identificativo N°: 1471					
quota (m)	profondità(m)	spessore (m)	stratigrafia	sigla	falda
8,95					
7,8	1,2	1,2		MR	
6,5	2,5	1,3		ALg	
		12,5		ALf	
-8,1	15,0				

C

Ubicazione: Ponte Via Oreto					
Sondaggio: - Identificativo N°: 1472					
quota (m)	profondità(m)	spessore (m)	stratigrafia	sigla	falda
8,85					
5,9	3,0	3,0		ALg	
		8,0		ALf	
-2,2	11,0				

D

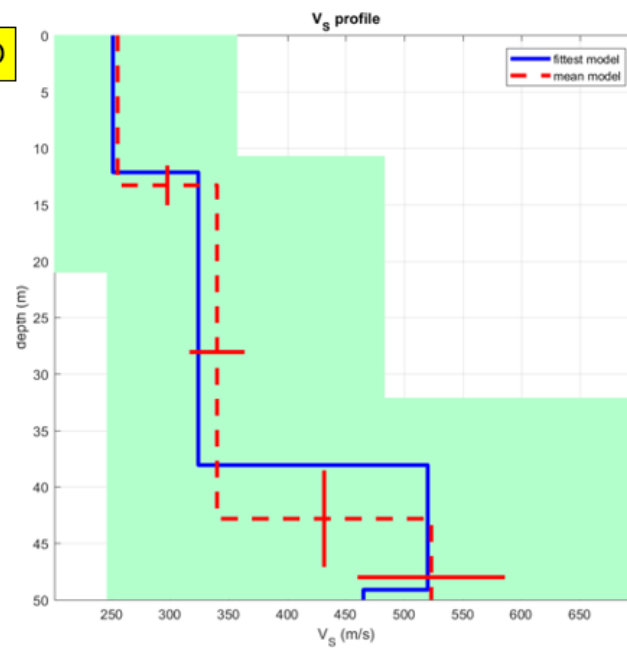


Figure 52: Masw survey carried out at the Oreto bridge site.

The data derived from Masw surveys carried out for the MOD Energy project provided Vs ranges that were associated with the lithologies described in the City GIS boreholes situated closer to the examined areas. Analyzing these acquired datasets, the superficial covers should present values ranging from 180 and 250 m/s while red beds show values varying between 200 and 300 m/s. Deposits linked to the numerous facies of calcarenites have been linked to Vs ranging between 300 and 750 m/s. Finally, data computed within this project for the Ficarazzi clays vary from 370 to 650 m/s.

The data collected from the survey campaigns carried out in this study have been combined with previous data from works already mentioned in paragraph 2.2. This work had been realized to assign to each lithological unit present in the subsoil of the plain, listed in figure 29 of paragraph 2.4.1, a range of values Vp and Vs. Obviously, the data on "Sea" and "Ipo" layers has been excluded in this correlation between velocities and soils. Figure 53 shows the defined ranges for Vp and Vs. These values, integrated with the geological information derived by boreholes, have been used to constrain the inversion of HVSR data as described in the following paragraph.

Lithologies	Vs (m/s)
Deposits of anthropic genesis (R) ; Topsoils (TV)	90 -300
Recent deposits and soils: Alluvial soils (ALL); Eluvial and Colluvial soils (CO); Upper Pleistocene marine deposits (DM); Rock Debris (DT); Aeolian deposits (EL); Lake deposits (LA); Paleosols (PAL); Holcenic marine deposits (SMA); Peat (TO); Red beds (TRS); Travertine (TVR).	250 -800
Calcarenites: Palermo Calcarenites (CC)	450 - 1200
Ficarazzi Calys (AZZ) and Conglomerates (CG)	200 -750
Numidic Flysch (DN)	450 -1900
Mesozoic deposits: Dolomitic limestone (DC); Dolostone (DOL) Radiolarites (RRL); Scillato Fm. (SCLL)	>750 -2500

Figure 53: Different ranges of Vs for each of the 21 lithological units, where the nomenclature of the deposits present in the subsoil of Palermo has been simplified, standardized and homogenized. The ranges are defined from past data and from data processed as a results of field activities during this in this study.

2.5.2 HVSR surveys

To further detail the subsoil model of the Palermo plain, 55 HVSR surveys (green triangle in figure 54) were considered. This data set, commissioned by the Municipality of Palermo in 2016, was created for the entire plain of Palermo for the preparation of the "General Town Plan - Palermo 2025 (PRG 2.0. The original set includes 250 environmental noise recordings. Of these, only a portion has

been selected for the work presented here. The data were acquired using the seismometer named Tromino, produced by MoHo s.r.l. As shown in figure 54, the passive seismic data examined are those that fall within the urban section of the Oreto river and surrounding areas; to better identify the HVSR selected area, which corresponds to the zone enclosed between the coastline at east and a western sector where the town ring road intersects the river path. Northern and southern limits of the area are represented by two of the main road axes of Palermo; respectively the northern axis of “Via Lincoln-Corso Tukory-Via Ernesto Basile” and the southern axis of Via Giafar.

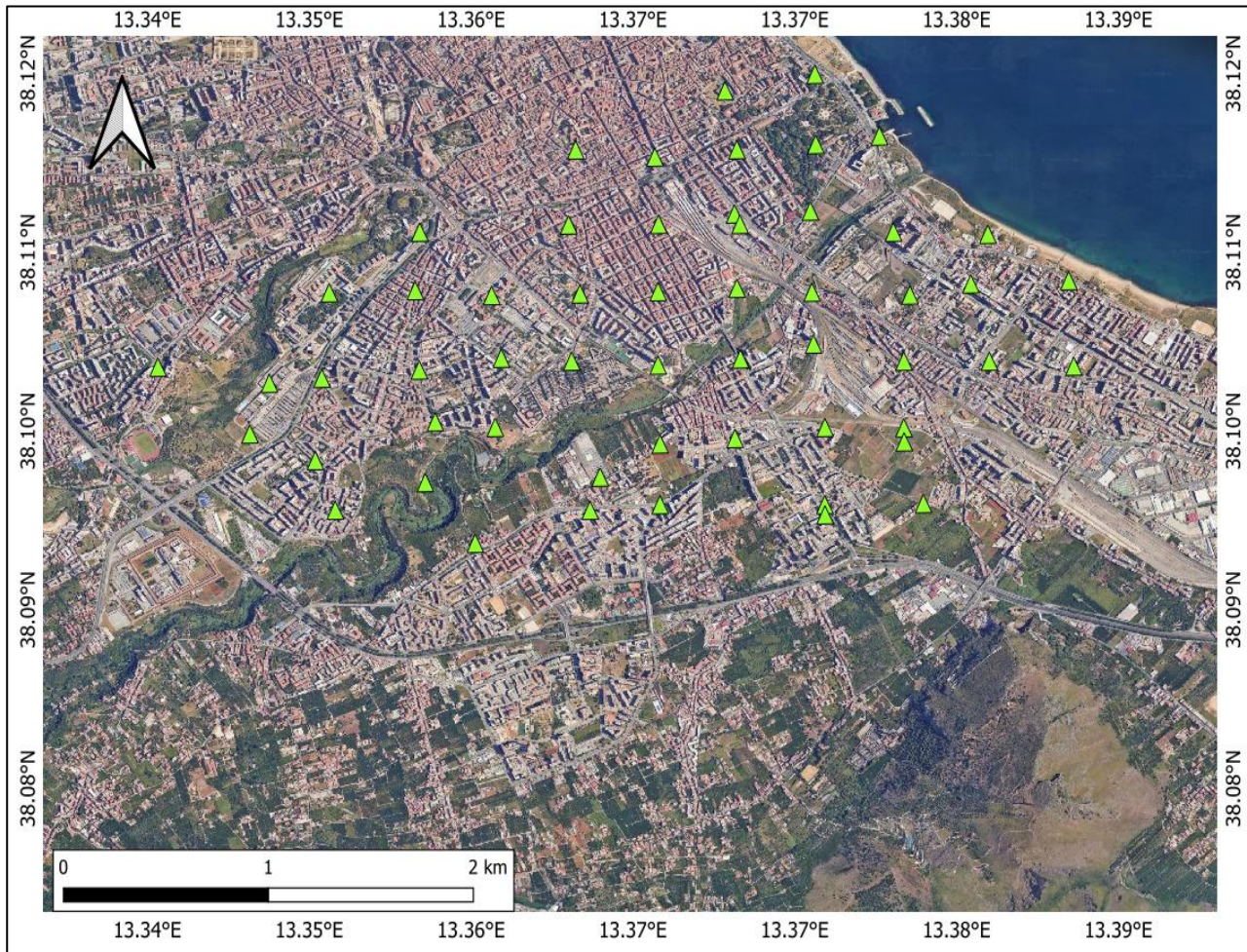


Figure 54: Location of HVSR surveys, green triangles.

The data were analyzed using Grilla software, which allows for the definition of the H/V curve. The raw data of each measurement, relating to a 30-minute acquisition, has been processed to detect any external disturbances which might compromise the validity of the H/V curve. Before processing, these data were filtered to exclude time windows likely affected by transient anthropogenic noise (figure 55).

The analysis of the whole set of HVSR curves (figure 56a) allowed us to recognize a general trend characterized by the presence of a main peak between about 0.8 Hz and 2.5 Hz and by other secondary peaks at higher frequencies, generally between 15 Hz and 35 Hz. Furthermore, a sharp velocity inversion, defined by the H/V ratio lower than 1, has been recognized for a frequency range between 2.5-3 Hz and 15-20 Hz.

A preliminary joint qualitative analysis of the available boreholes and microtremor was conducted. The analysis has been indeed implemented by the geological data provided during this study and collected from the already mentioned studies on the plain. (Giammarinaro et al., 1999; Contino et al., 2005, Martorana et al., 2018; Cappadonia et al., 2020; Agnesi, 2021). Based on the analysis of the

HVSR curves trend (figure 56a), several correlations between the peaks in the H/V curve and the main stratigraphic boundaries within the Palermo plain subsoil (Agate et al., 2017) (figure 56b), had been found.

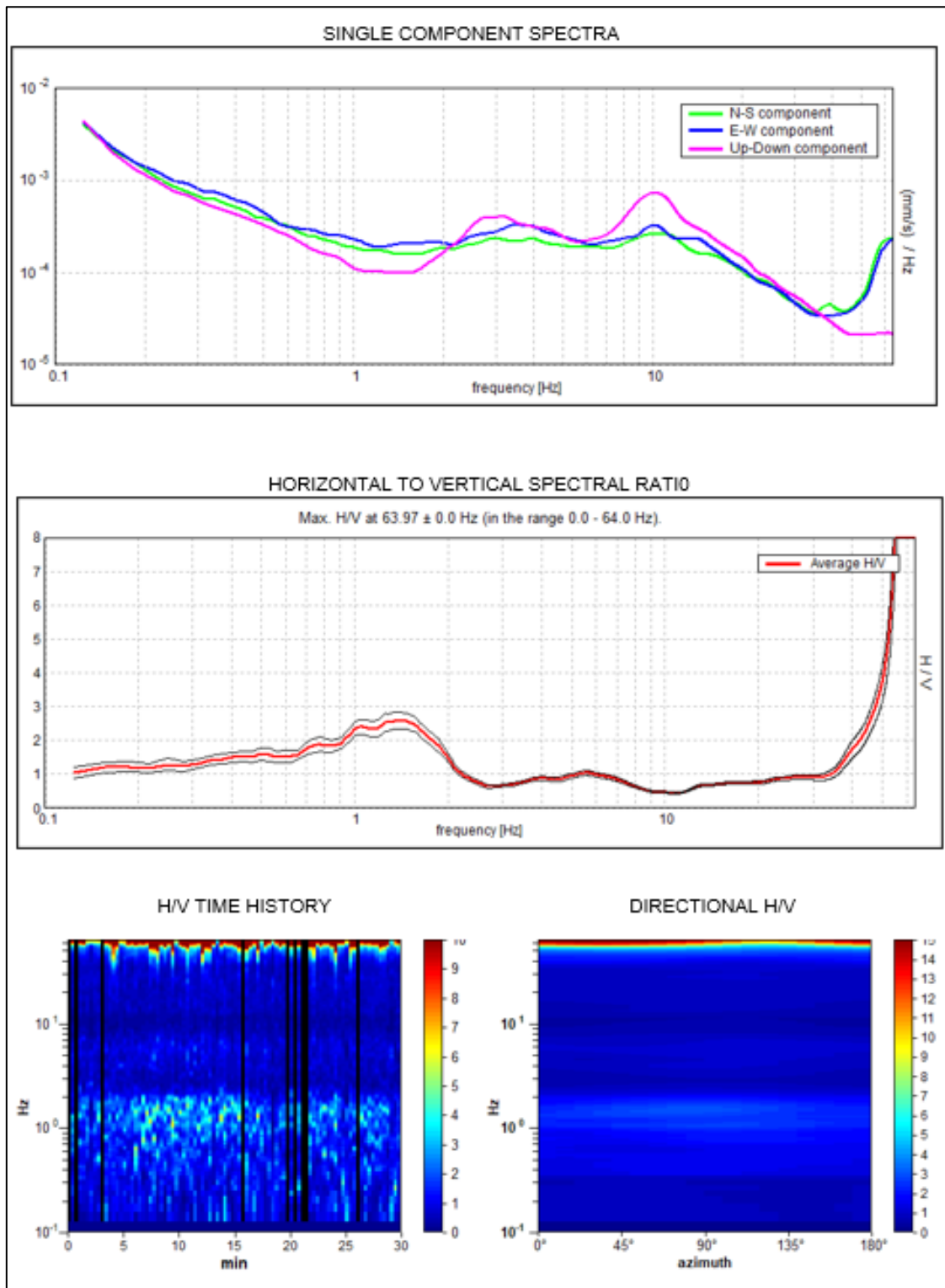


Figure 55: An example of data processing environment noise recording. During the processing phase, some recording windows have been removed to improve the definition of the Horizontal to vertical spectral ratio curve.

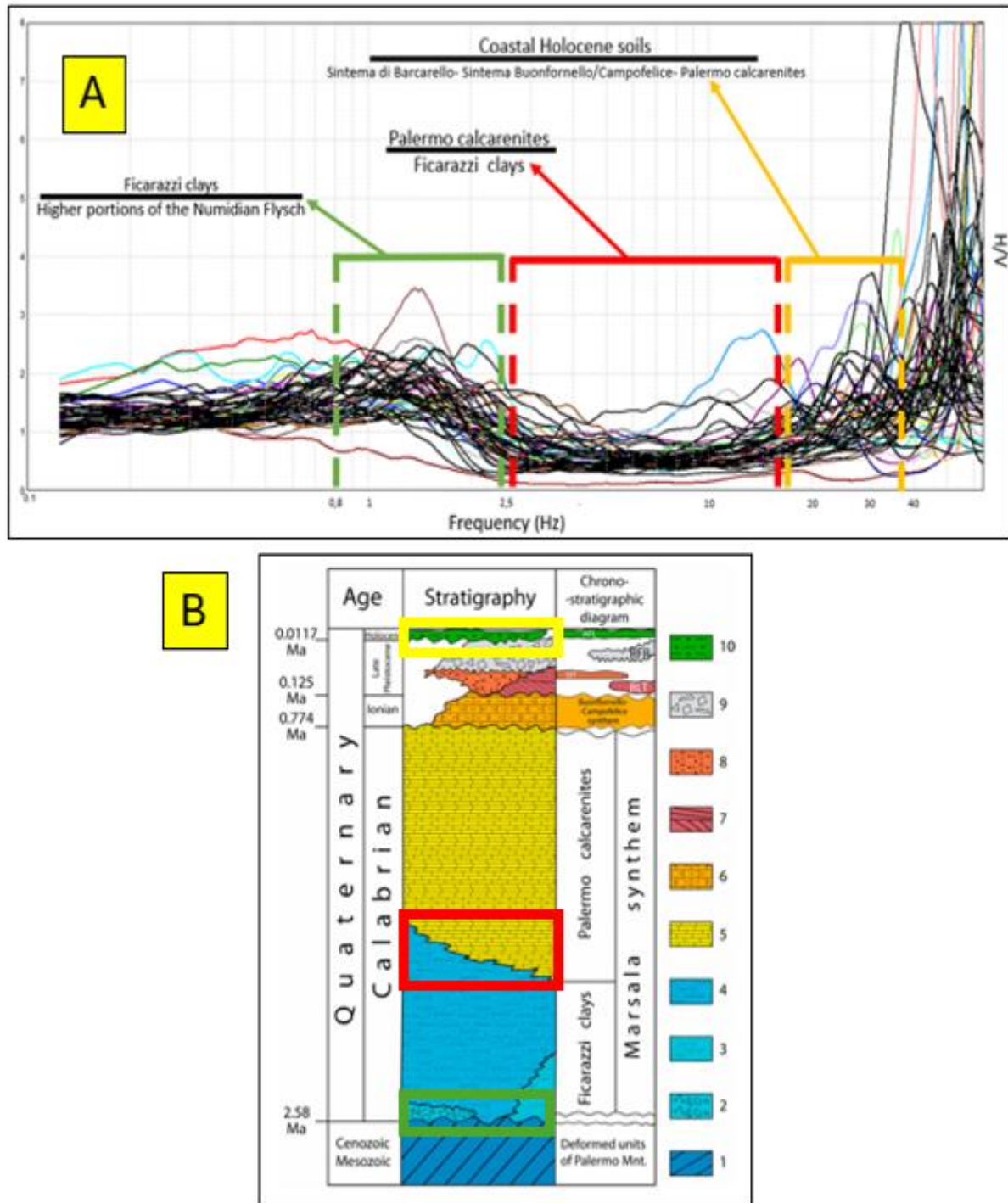


Figure 56: Comparison of HV curve peaks and stratigraphy of the Palermo plain. A) representation of the whole HVSr curves dataset; the green, red and yellow boxes represent the different cluster of peaks recognized and attributed to the presence of lithological boundaries that characterize the Palermo plain subsoil (B).

According to this analysis, low frequency main peaks (0,8 -2.5 Hz) are probably generated by the contact between the Pleistocene clays and the higher portions of the Numidian Flysch. The blunt shape of the peaks also suggests that these are probably caused by the contact between the Oligo-Miocene Flysch deposits and the underlying Meso-Cenozoic carbonate basement (Martorana et al 2018). The reversal of velocity, that is evident at higher frequencies in almost all the H/V curves, could be attributed to the contact between calcarenite deposits and the underlying Pleistocene clays.

the area closer to the Oreto River, a correlation was found between the reconstruction of maps of the Numidian Flysch depth (figura57b), that represents the bedrock for the Palermo plain (Grassi 1996, Martona et al., 2018), defined by boreholes data (Gimmarinaro et al., 2003) and the distribution of peaks belonging to the lower frequency range (0.8 -2.5 Hz) recognized in HVSR curves. In figure57a are also represents the iso-frequency line defined by the interpolation of these peaks. This correlation indicates that high peaks correspond to shallower Flysch portions, while lower peaks correspond to areas with deeper Flysch.

The HVSR curves were subsequently inverted to produce Vs - depth models. Considering the possibility of inverting an HVSR curve with infinite equivalent models (Castellaro & Mulargia 2009, Dal Moro 2024, Castellaro 2016) the inversions were constrained by the closest stratigraphic data and the described velocities Vs defined in figure 53 for lithologies present in the study area. An example of inversion with the corresponding Vs-depth models is shown in figure 58. One of the lithological denominations chosen to subdivide the subsoil of the plain was assigned to each seismic-stratigraphic layer of these models, or alternatively to several layers with similar characteristics such that they can be included in one of the 23 macro groups described in figure 29

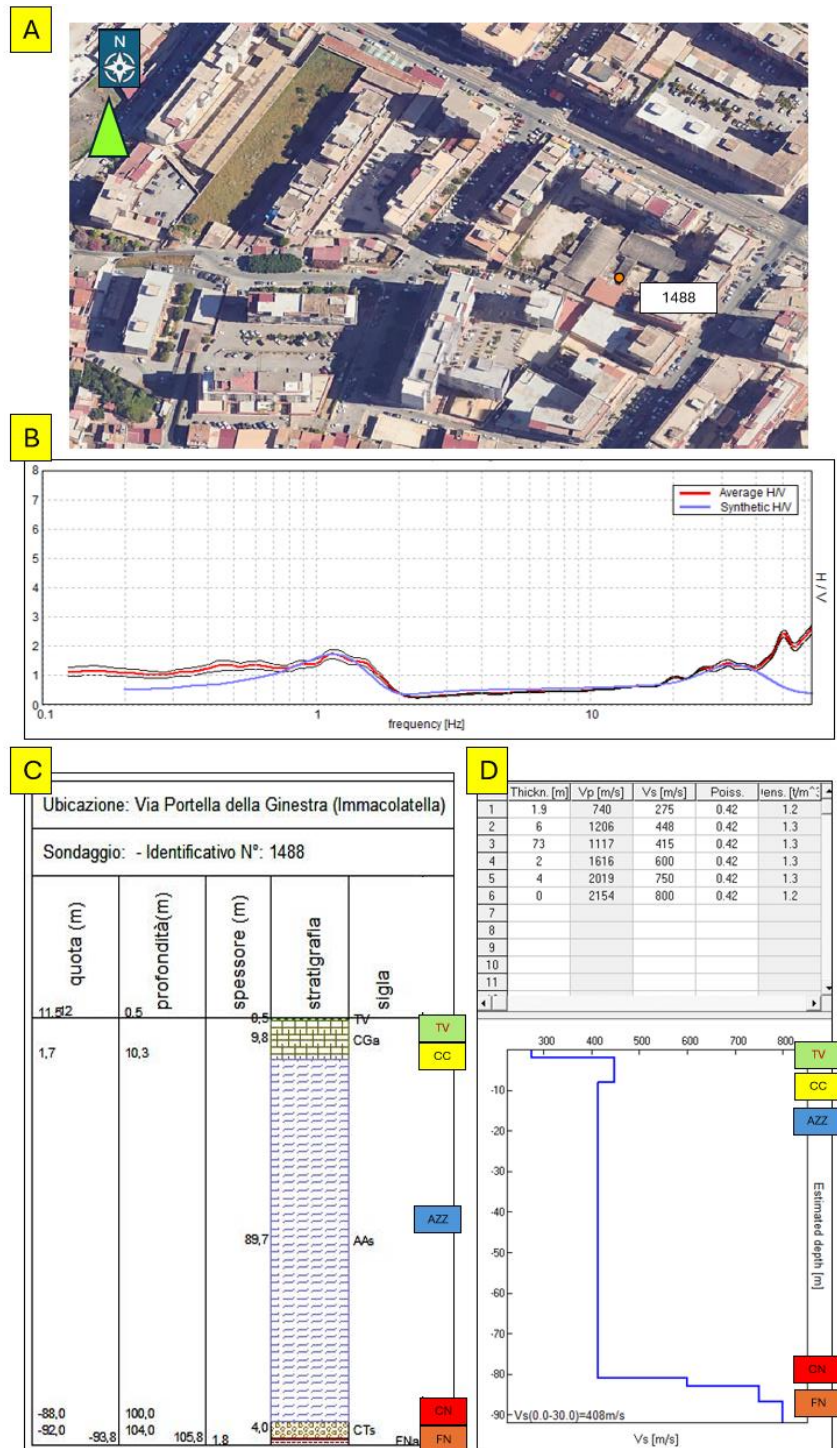


Figure 58: A) Position of the HVSR measurement and a survey used to constrain data inversion. B) experimental HVSR curve (in red) and synthetic model (in blue) related to the V_s model described in figure D. In C, the stratigraphy of the site and the nomenclature chosen to simplify and homogenize all stratigraphic data is reported; This designation, with reference to figure 29, has also been attributed to the seismic layers described in D.

2.6 Reconstruction of the 3D model of the Palermo, near the Oreto River.

All the data collected, with the primary objective of the study being to describe the original geological structure and ancient paleo-morphology beneath the anthropogenic covers, has been homogenized and standardized as defined in figure 29 as already described. A qualitative and quantitative analysis was carried out on the available dataset.

All available stratigraphic columns, derived from both geological surveys and the inversion of HVSR data into geological features, have been rearranged as follows: For each data point, the transitions between the described lithologies were considered, using the top level for each layer as a reference. According to this approach, a total database was created in which every data point present in the study area is represented as shown in figure 59: for each point, in addition to latitude and longitude, data about the lithologies present along the vertical and the elevations of top of each lithology has also been inserted. At this stage, it was also decided to eliminate the layers of anthropic cover and topsoil, considering the study's aim.

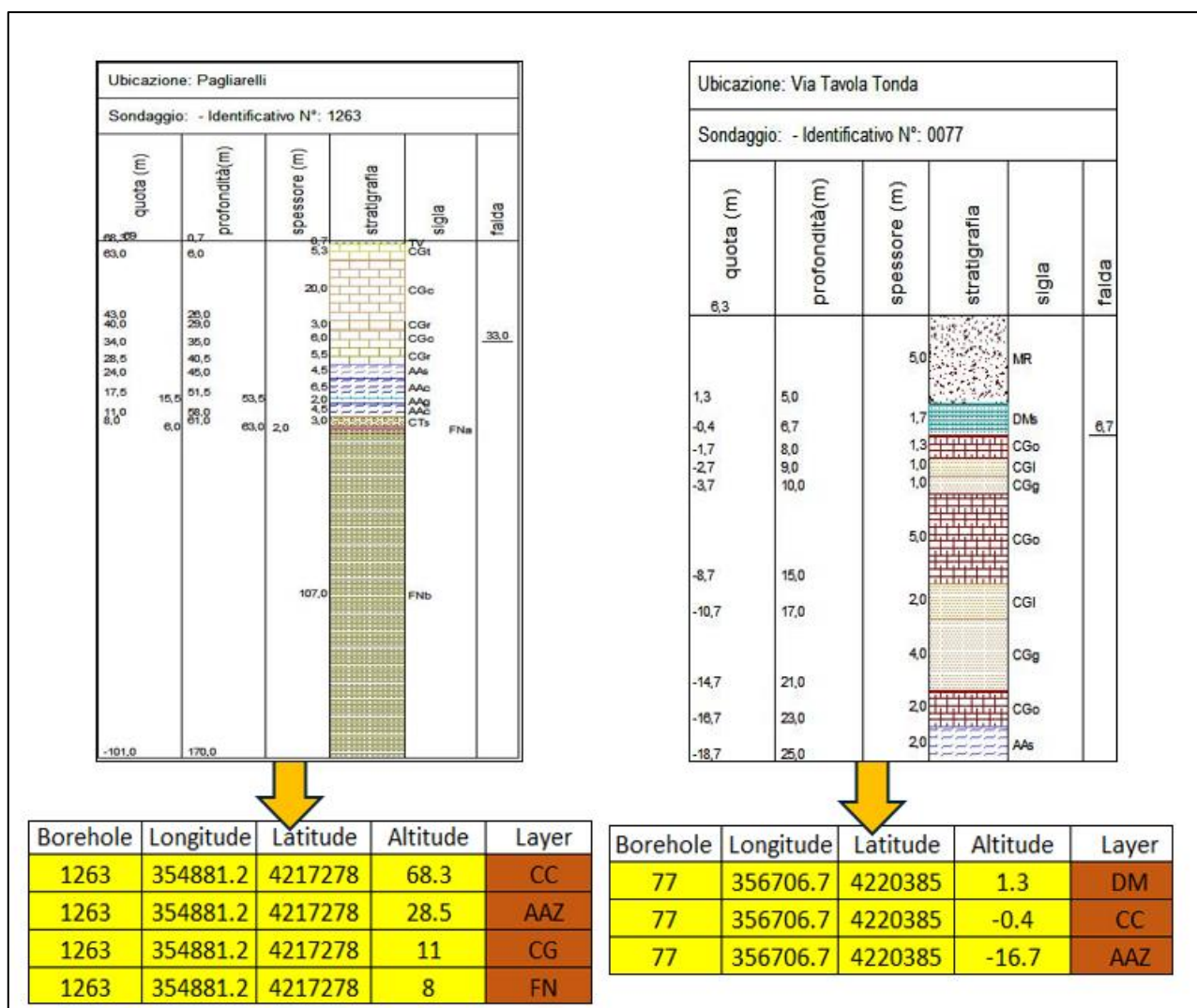


Figure 59: Two examples of the operation of synthesis of geological data collected: for each point, starting from a heterogeneous geological dataset, the data on the present lithologies has been standardized and digitized with latitude, longitude, lithology type and the altitude of the top of each lithologic layer indicated.

Using this data subdivision, an analysis was subsequently carried out on the number of available points for each lithology in the dataset; This analysis was conducted to assess the quality of data available for 3D modeling of lithology top surfaces. Following this review, it was decided not to exclude from the modeling any lithologies with few data points in the database: Aeolian deposits (EL); Lake deposits (LA) Peat (TO); Travertine (TVR); Dolomitic limestone (DC).

The data selected after this screening was entered and processed into Move software to produce initial interpolation surfaces of the data. The data were inserted as in figure 60. This allowed the software to display each top relative to individual stratigraphic data.

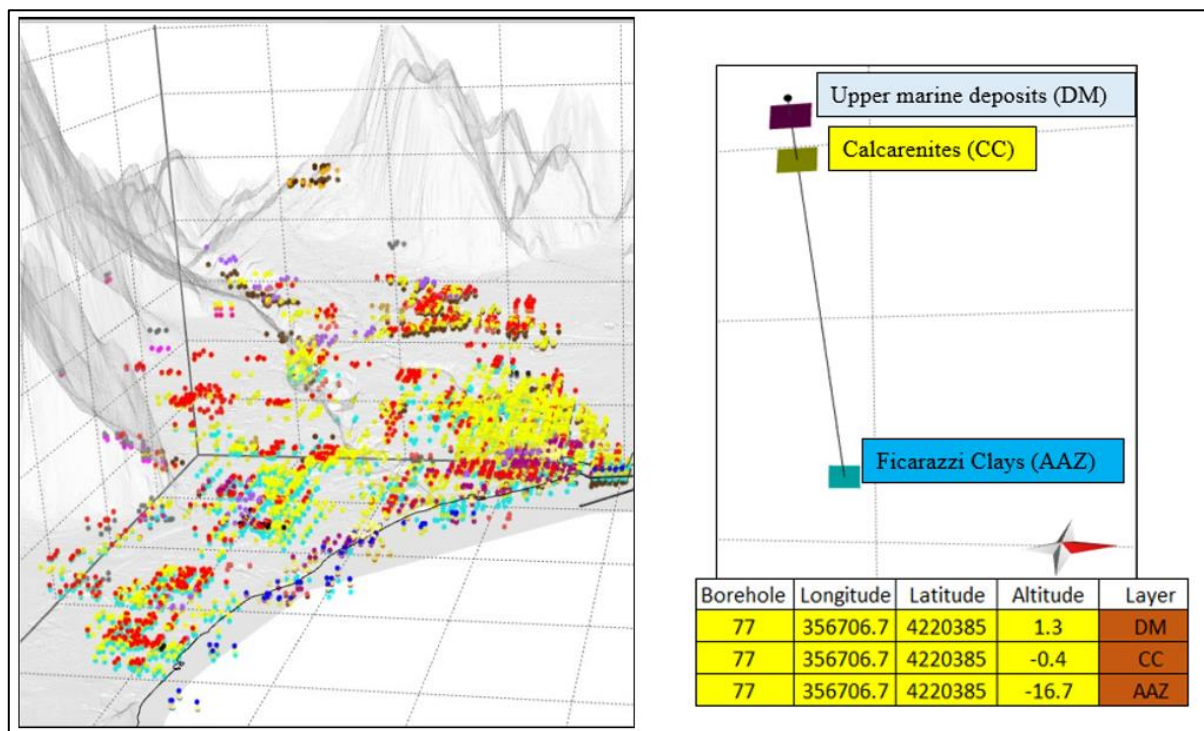


Figure 60: Import of the data into Move software. On the left, view of the top layers projected on the DEM of the study area; each color indicates a different lithology present in the dataset. On the right the relative three-dimensional representation from a single set point: each square represents the top of a layer described by the table (visible at the bottom) inserted in the software.

Data relative to the top points of each lithology were interpolated to draw the upper surfaces of the geologic layers. The interpolation method was different for each surface produced; the choice was made by carrying out numerous tests, with respect to the number of points available, the reciprocal distance between the points and the nature and genesis of the deposit to be modelled. To summarize, the interpolation algorithms have been chosen following the Delaunay triangulation or Inverse distance weight method, modifying time by time the parameters of the two methods of interpolation. The Delaunay interpolation method was chosen in cases of high point density over large areas; for example, this was applied to surfaces related to the Palermo Calcarenes, Ficarazzi Clays (Figure 61a) and Numidian Flysch. The interpolation algorithm based on inverse distance weight method was used when surfaces were modelled according to a network of points not equally spaced but distributed in more restricted areas, where they nevertheless have a good density of data (figure 61 b).

Following this approach, the 14 surfaces within the 3D model were modelled in a preliminary way. This preliminary model had several errors and inaccuracies regarding the failure to respect topography and the regular succession of deposits extensively described in the literature about the plain of Palermo.

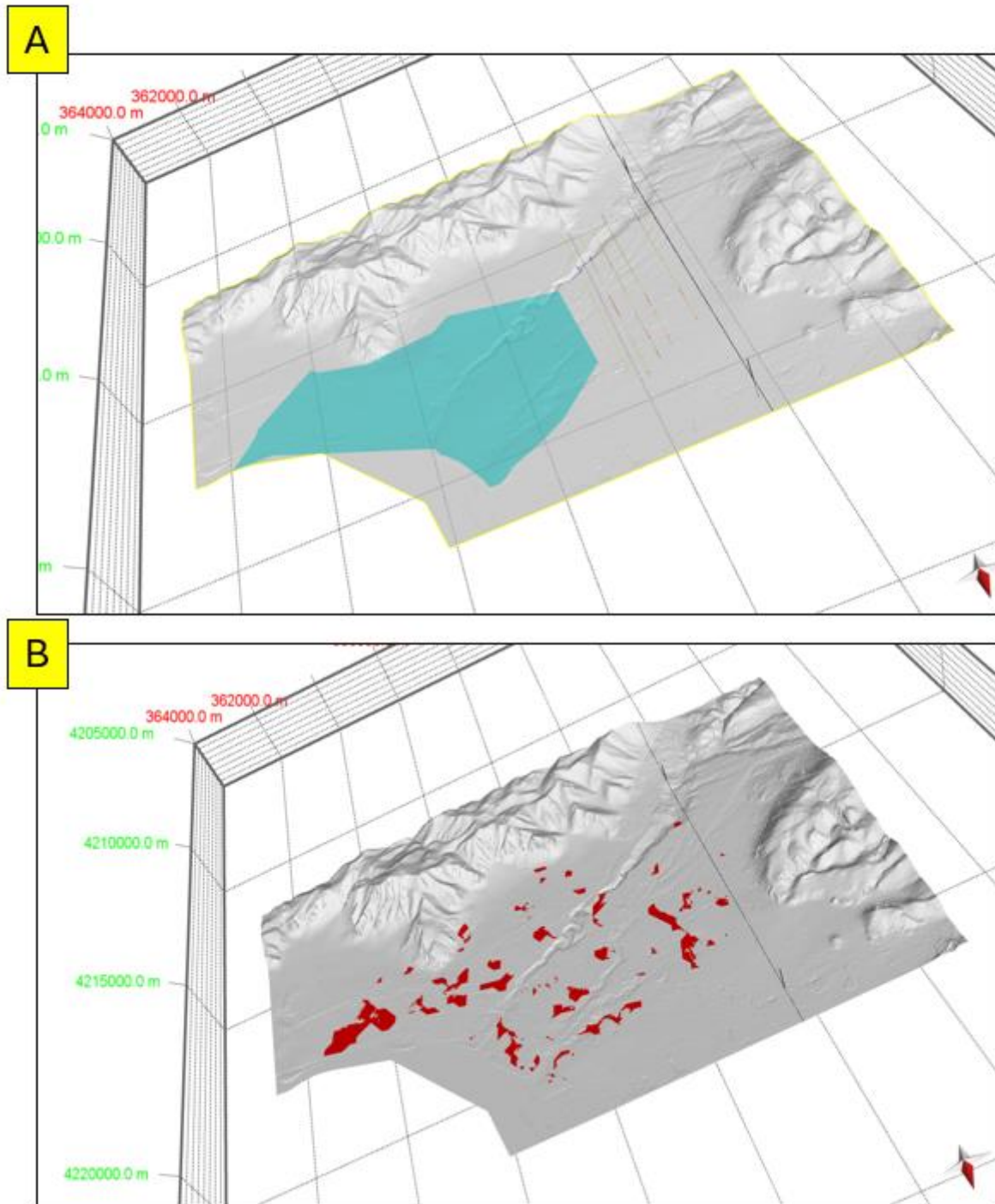


Figure 61: A) Example of a surface created by interpolation of data following the Delauney triangulation method for Ficarazzi Clays; b) Surface created for the red beds by interpolation data according to the inverse distance weighting method.

These errors, visible in Figure 62, are attributed to the lack of surface morphology constraining to bind and confine data interpolation. Moreover, these are also due to the interaction of surfaces modelled according to a very heterogeneous set of data in number.

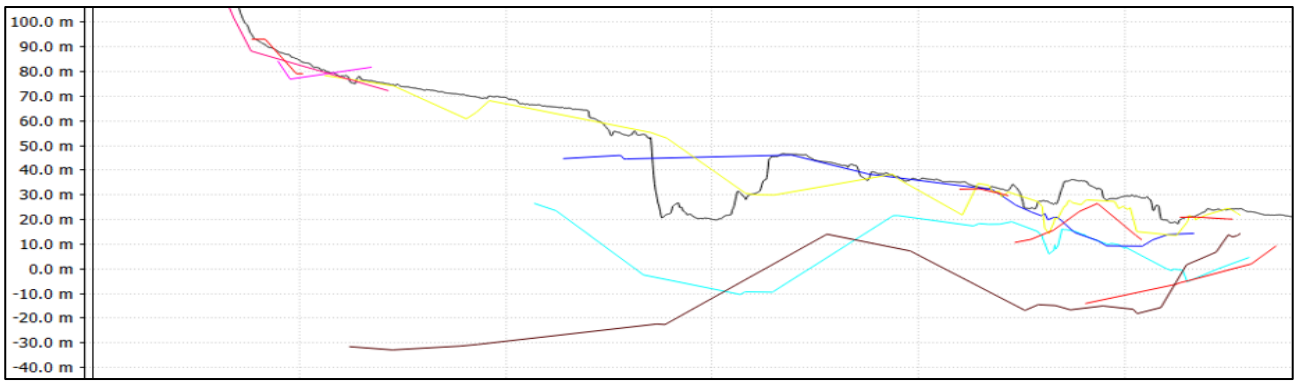


Figure 62: Two-dimensional section showing some preliminary surfaces produced. Modelling errors from the preliminary processing can be observed: several surfaces intersect and extend beyond the DEM-projected surface.

To correct the inaccuracies in the preliminary model, it was decided to adjust point data and surfaces using sections through the model. A regular grid of 70 sections (figure 63a), with 40 oriented West - East and 30 North - South, was inserted into the model. All the data relating to the previously produced surfaces and the points of the stratigraphic data, present within a buffer of 200 m distance from the line section, were projected on each 2D representation (figure 63b).

Within these sections, the surfaces were modified to better align with the projected wells and avoid exceeding the topography (figure 63c).

After this operation, the surfaces were re-projected, generating the final 3d model shown in figure 64.

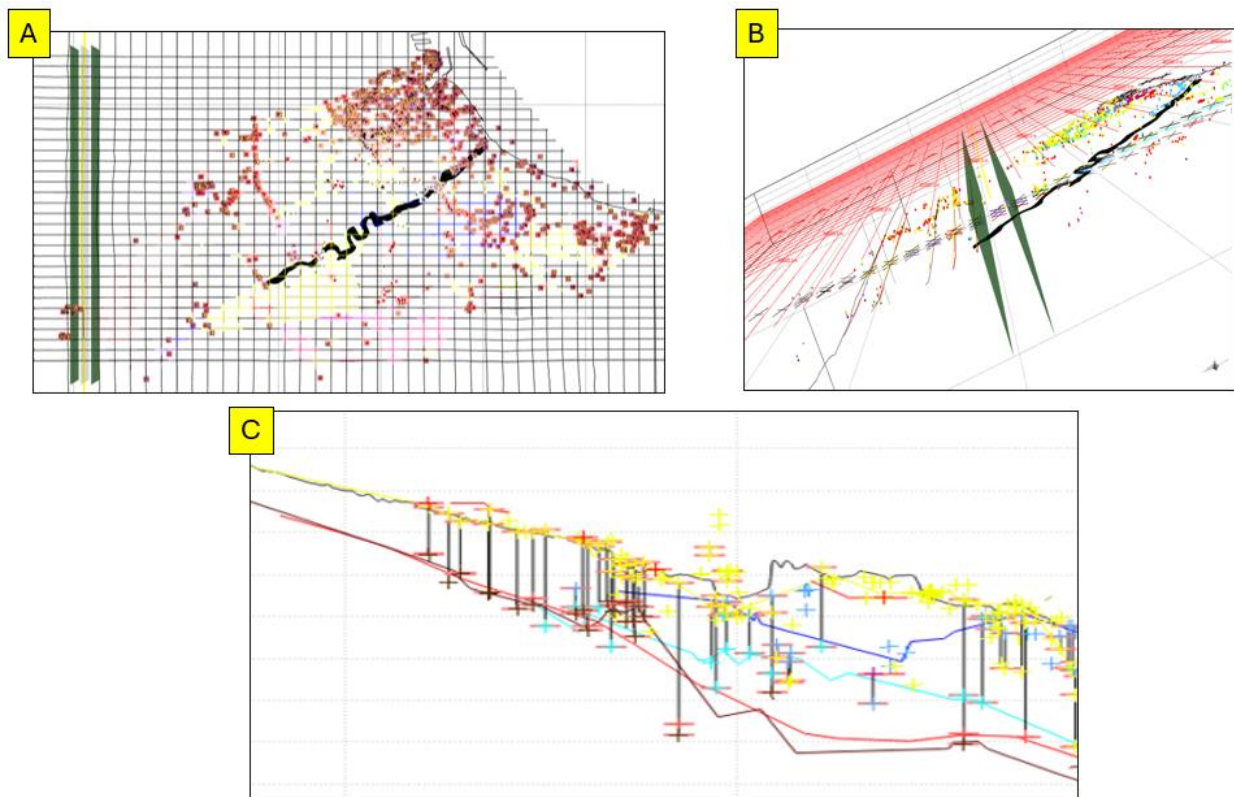


Figure 63: A) Grid of section B) Buffer (green walls) showing the projection area of data points onto a section C) Example of a section with modified surfaces to achieve a more accurate representation of the subsoil of the plain.

The model shows the 14 types of deposits present in the Palermo plain, with tops modeled to represent the pre-anthropogenic structure of the area under consideration (figure 64).

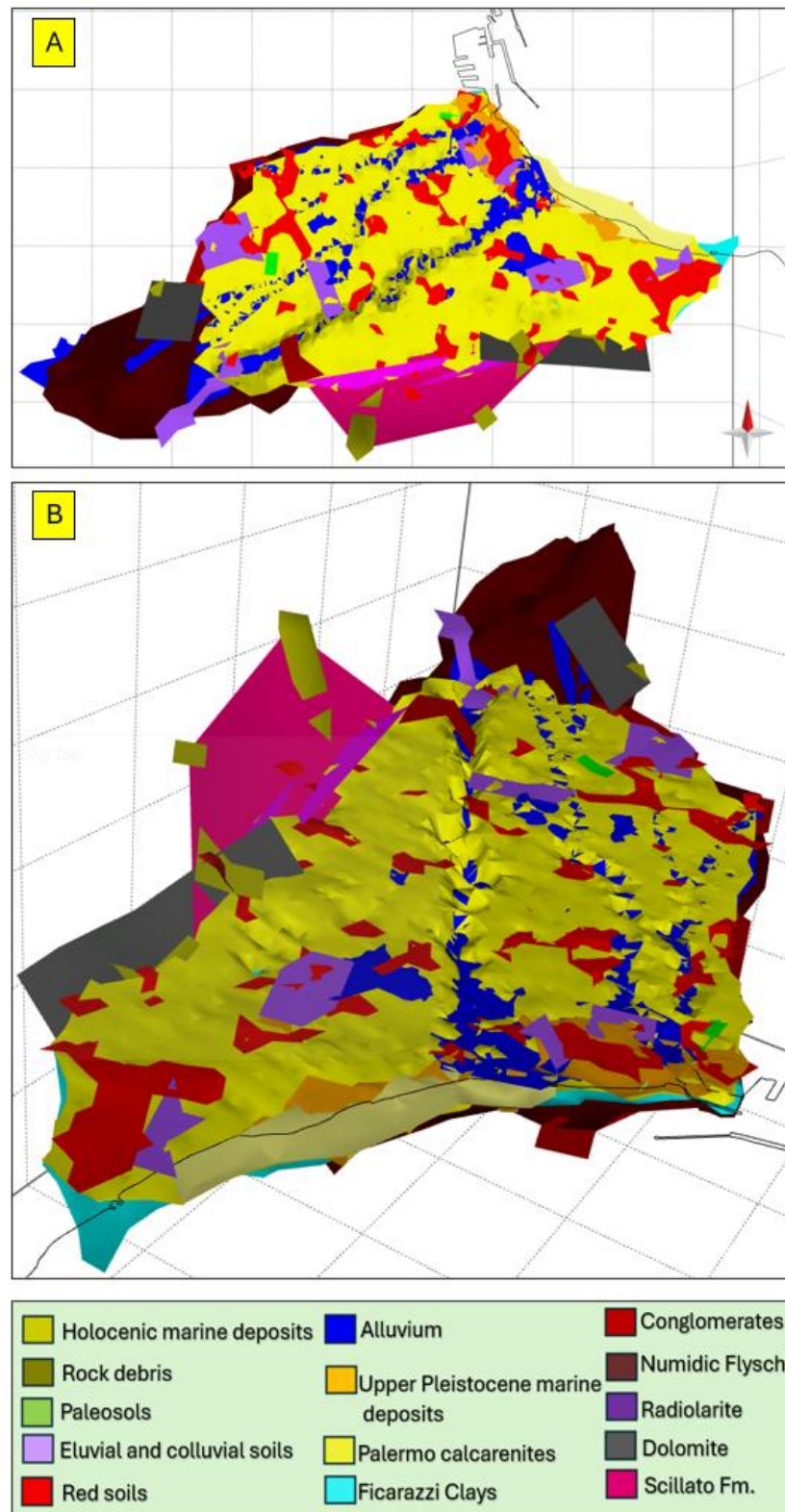


Figure 64: Two views of the 3D model produced for the Palermo plain; A) model representation seen from above B) model seen from a North-East perspective.

2.7 Discussion on the model produced and conclusion about the case study.

The analysis of the 3D model allows us to make some important observations regarding the outcrops within the study area. This can also highlight areas potentially subject to geological risks or that have experienced such risk in the past. Firstly, from the reconstruction, it can be observed that calcarenite is the main lithology present in the plain, forming a plateau crossed by; most of them are no longer visible and have been identified in the model by the presence of numerous areas where alluvial deposits are present. This is the case of the rivers "Papireto" and "Kemonia" currently covered by the urban network; in the area within these two ancient watercourses the first Phoenician urban settlements initially developed (figure 65).

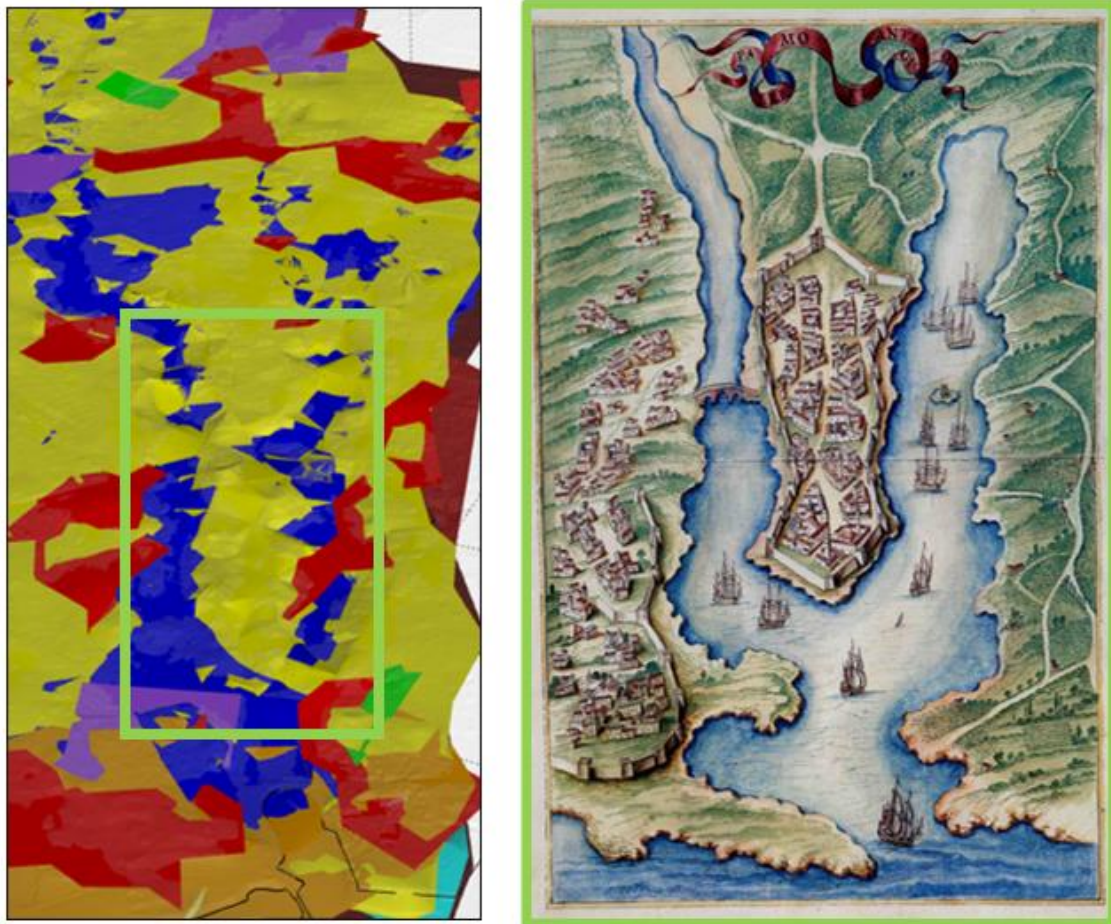


Figure 65: Representation of the area of the plain former between the two rivers Kemonia and Papireto; the presence of the two, nowadays invisibles, rivers is indicated by the alluvial in blue. On the right a reconstruction of the Phoenician Palermo (VIII th century BC).

Other areas not currently affected by rivers are also described in the model as being covered by alluvial deposits. This is the case of the "Ponte dell' Ammiraglio" sector (figure 66a) which was in the past affected by the presence of a river bend of the Oreto. Currently, however, the area is densely populated since it was deprived of water flow following the rectification of the last section of the river performed at the beginning of the twentieth century. Defining areas with alluvial deposits is also useful to identifying possible hydraulic hazards scenarios, due to the potential for floods development that, as often happened, several times affected the plain (Cusimano 1989).

Another important consideration can be made in advance of the line to coast. Following the massive discharge of anthropogenic material, mainly after the Second World War, the coastline has advanced by almost 100 meters compared to its original configuration. Figure 66c shows the morphology of

the present coastline, and the paleo-coastline reconstructed by modelling coastal sediments, represented in orange in figure 66b.

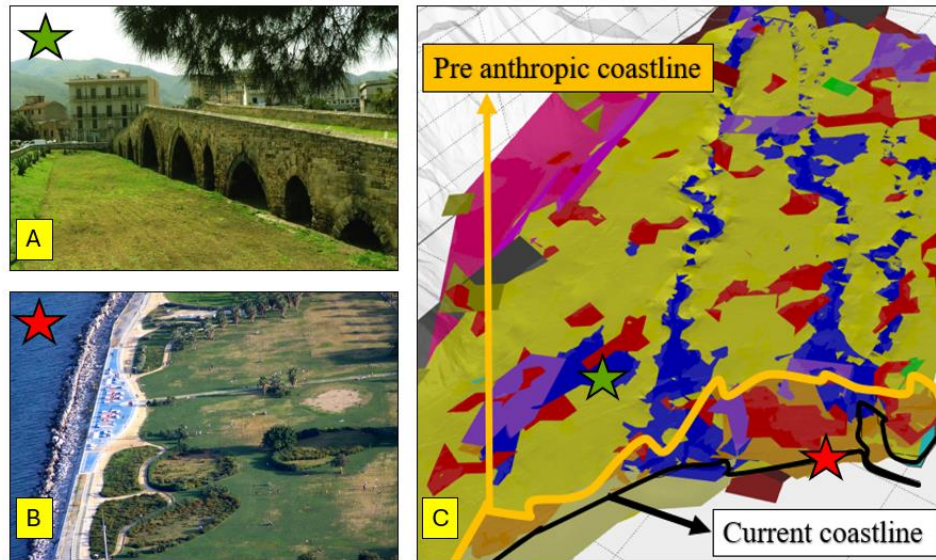


Figure 66: A) Area of the "Ponte dell'Ammiraglio" in C marked by a green star; B) Nowadays coastal area whose genesis is linked to the discharge cover; the location of the site is represented by a red star within the 3D model. C) Representation of the current (black line) and original (orange line) coastlines.

Aside from historical observations, the model is important as it provides general knowledge of the subsoil and the deposits that would likely be encountered during excavation work, for example. In this view, the model can be useful for urban planning and for planning of survey plans related to works of relevance to the city. This assistance can be provided, for example, by defining volumes, as shown in the case of Ficarazzi clay; Figure 67 shows the volume of blue clay (green prisms) in contact with the top layer of the Numidian Flysch, represented in brown. Defining the thickness of lithologies is also a very effective tool for assessing potential seismic amplification effects that could occur, as they have in the Palermo plain (Giammarinaro et al., 2006)

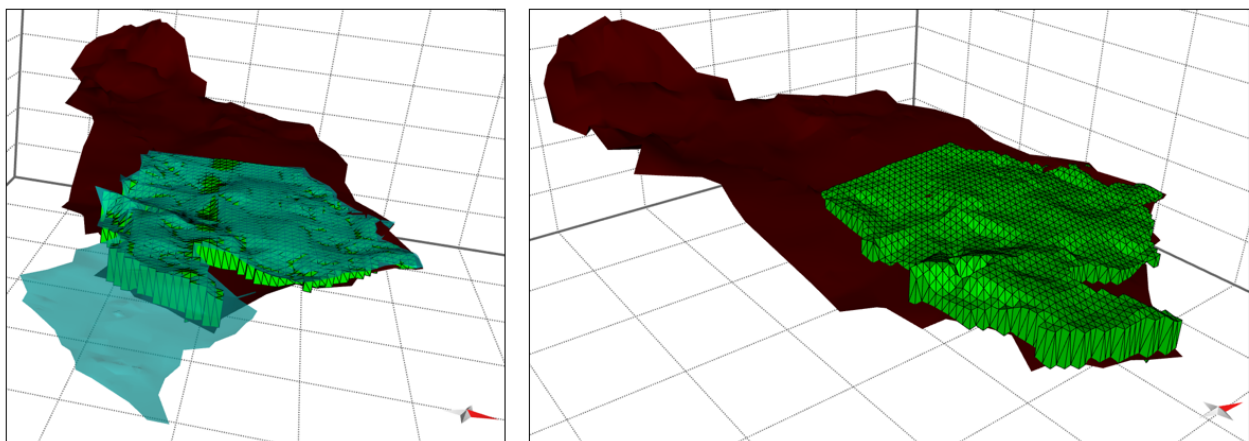


Figure 67: In both figures the volume of deposits of Ficarazzi Clays, present above the Numidic Flysch is represented in green

CHAPTER III

MULTIDISCIPLINARY STUDY TO CHARACTERIZE THE SURFACE WATER BODIES THROUGH THE CONSTRUCTION OF GEOPHYSICAL AND GEOLOGICAL 2D AND 3D MODELS.

3.1 Description of the cases study of the Caronia (CGWB), Sant 'Agata -Capo d' Orlando (SCGWB) and Barcellona P.G. -Milazzo (BMGWB) Groundwater bodies: Objectives, Studied Areas, Data Used, Results Obtained.

The case studies concerning the alluvial plains of Caronia, Sant 'Agata di Militello - Capo d' Orlando and Barcellona Pozzo di Gotto - Milazzo can be considered a remarkable example of integrating diverse data types to define surface aquifer areas and volumes in flood plains adjacent to the coast.

This approach is fundamental for defining the potential to safeguard coastal aquifers, providing a useful tool to implement good management and conservation plans for the aquifers. The study areas are located on the north-east coast of Sicily (figure 68) and are within the province of Messina. Specifically, an area within the municipality of Caronia was analyzed in the first study; in the second study, the territories between the municipalities of Sant 'Agata di Militello and Capo d' Orlando on one side and Barcelona Pozzo di Gotto and Milazzo on the other, were characterized. Three groundwater bodies were identified for the three areas examined through joint interpretation of geophysical and geological data: The Caronia Groundwater Body (CGWB) (Canzoneri et. al 2024), the Sant 'Agata -Capo D'Orlando Groundwater Body (SCGWB) and the Barcellona P.G. -Milazzo Groundwater body (BMGWB).

The data used were partially provided by a 1970 CASMEZ (Cassa del Mezzogiorno) (CASMEZ 1978) project and were supplemented by several surveys conducted within an INGV-DAR project (Granata et al.) focused on the characterizations of groundwater bodies. Seismic refraction (SRT), Vertical Electrical Sounding (VES) data acquired from the CASMEZ project were qualitatively analyzed and partially re-interpreted to build 3D resistivity models describing each superficial groundwater. Subsequently the data collected during the acquisition campaigns of DAR-INGV (boreholes, SRT, HVSR, ERT and TEM) were analyzed jointly in detail, starting from the evidence derived from the 3D resistivity model to understand the subsurface extent of the examined areas.

For the three water bodies, models describing the thickness of deposits within the flood plains were developed following the above-mentioned approach. In the case of CGWB, a preliminary flow model was also developed.



Figure 68: Location of the three water bodies examined along the north-east coast of Sicily: In red is the CGWB area, in light blue the SCGWB, in green the BMGW.

3.2 “Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater Body in Caronia (Sicily)”

In this paragraph, the paper published in international journal *Water* in 2023 (Canzoneri et al. 2023 b) is annexed.

Article

Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater Body in Caronia (Sicily)

Alessandro Canzoneri ¹, Patrizia Capizzi ^{1,*}, Raffaele Martorana ¹, Ludovico Albano ²,
Alessandro Bonfardecì ¹, Nunzio Costa ² and Rocco Favara ²

¹ Department of Earth and Marine Sciences (DISTEM), Università degli Studi di Palermo, 90123 Palermo, Italy; alessandro.canzoneri@unipa.it (A.C.); raffaele.martorana@unipa.it (R.M.); alessandro.bonfardecì@unipa.it (A.B.)

² Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, 90146 Palermo, Italy; ludovicoalbano80@gmail.com (L.A.); n.costa@hotmail.it (N.C.); rocco.favara@ingv.it (R.F.)

* Correspondence: patrizia.capizzi@unipa.it

Abstract: The characterization of a groundwater body involves the construction of a conceptual model that constitutes the base knowledge for monitoring programs, hydrogeological risk assessment, and correct management of water resources. In particular, a detailed geological and geophysical approach was applied to define the alluvial Caronia Groundwater Body (CGWB) and to reconstruct a hydrogeological flow model. The analysis of the CGWB, located in north-eastern Sicily, was initially approached through a reanalysis of previous stratigraphic (boreholes) and geophysical (vertical electrical soundings and seismic refraction profiles) data, subsequently integrated by new seismic acquisitions, such as Multichannel Analysis of Surface Waves (MASW) and horizontal-to-vertical seismic ratio (HVSr). The analysis and reinterpretation of geoelectrical data allowed the construction of a preliminary 3D resistivity model. This initial modeling was subsequently integrated by a geophysical data campaign in order to define the depth of the bottom of the shallow CGWB and the thickness of alluvial deposits. Finally, a preliminary mathematical model flow was generated in order to reconstruct the dynamics of underground water. The results show that integration of multidisciplinary data represent an indispensable tool for the characterization of complex physical systems.

Keywords: groundwater body; VES; HVSr; MASW; 3D model; hydrogeological flow model



Citation: Canzoneri, A.; Capizzi, P.; Martorana, R.; Albano, L.; Bonfardecì, A.; Costa, N.; Favara, R. Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater Body in Caronia (Sicily). *Water* **2023**, *15*, 3206. <https://doi.org/10.3390/w15183206>

Academic Editor: Craig Allan

Received: 31 July 2023

Revised: 24 August 2023

Accepted: 4 September 2023

Published: 8 September 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The definition of the hydrogeological features of a specific territory represents an important topic because the protection and management of water resources are matters of public interest, and there is growing concern about underground water resources quality and quantity [1–3]. Until a few decades ago, the study of hydrogeological structures was carried out mainly using stratigraphic data derived from field geology, drilling, and logging [4,5] as well as from aquifer test methods [6,7]. Many authors instead used geochemical information, obtained from sampling of wells or springs, indicating the origin and the path followed by the groundwaters, to study the hydrogeological features of a natural system [8–10].

Moreover, the integration of stratigraphic logs and geophysical surveys allows characterization and description of heterogeneity of surface and subsurface sediments, over large areas [11,12], especially in alluvial environments where deposits can be characterized by strong lateral and vertical variations, linked to fluvial dynamics [13,14]. The non-invasive geophysical techniques, initially limited to vertical electric sounding [15–20] and seismic refraction methods [21–23], have always represented an important tool in hydrogeological

research. In the past few decades, geophysical investigation applied to hydrology and hydrogeology added quantitative analysis to a simple qualitative approach, aimed at defining the general architecture and geometry of underground aquifers [24,25].

Furthermore, with the development of new methods of investigation and with the improvement in the pre-existing techniques and instrumentation, geophysical investigations have acquired a crucial role for the knowledge and characterization of underground coastal aquifers [26–33], especially regarding water pollution detection [34,35] and seawater intrusion [15,28,36–40]. Different seismic methodologies have been used to improve the definition of geometric features of the underground aquifers, also resolving some ambiguities about the subsurface geological structures deduced from geoelectrical investigation in particular environments, such as coastal areas [41,42]. In particular, the Multichannel Analysis of Surface Waves (MASW) method [43] helps to recognize some properties of subsurface materials and the depth of important buried interfaces, analyzing seismic shear-wave velocity (Vs) variations [40,44].

An alternative approach to estimate the depth of the seismic bedrock and thickness of surface deposits involves the use of the horizontal-to-vertical spectral ratio (HVSr) methodology [45–47], which is also applied to the groundwater exploration and aquifer geometry characterization [12,41,48]. Many authors demonstrated that reliable S-wave-velocity models can be obtained by inverting HVSr data with other stratigraphic and geophysical constraints [47,49–52]. In particular, the uncertainty about the HVSr stratigraphic interpretation [53] can be addressed or at least limited using S-wave velocity models obtained by MASW as constraints [46,47,54].

The correct definition of the advanced and refined flow model, which helps in the management of water resources, also represents a powerful tool for governments and public administrations. Different guidelines have been developed in order to control, protect, and manage water resources following a quantitative and qualitative approach [8,55]. In particular, for the study of groundwater bodies and monitoring of their quantitative status, the definition of a conceptual model is required [56]. This approach also requires the definition of a surface map of the aquifer, together with an evaluation of hydraulic connectivity between adjacent groundwater bodies and the underground waters' flow rate and direction [57]. Moreover, all these elements are extremely useful for realizing a synthetic scheme of hydrogeological basin balance.

In this view, in 2018/2019 the INGV (National Institute of Geophysics and Volcanology—Palermo Section) in collaboration with the Sicilian Regional Water and Waste Department (DAR) carried out a study (hereafter INGV-DAR 2019), with the aim of analyzing the groundwater bodies of Eastern Sicily [58]. Part of this study was focused on the characterization of coastal alluvial aquifers and relative groundwater bodies of this Sicilian sector, such as that related to the Caronia area [59].

The aim of this work is to analyze the Caronia Groundwater Body (CGWB), integrating stratigraphic, geophysical, and hydrogeological data, in order to quantitatively reconstruct the pattern of this underground structure and obtain a numerical flow model. Furthermore, the multidisciplinary approach adopted can allow the correct definition and future management of the water resources in the study area.

2. Geology and Hydrogeology

2.1. Geomorphological and Geological Setting

The Caronia Groundwater Body (CGWB) is located on the northern Sicilian coast, near the Caronia village. The CGWB falls in the north-eastern sector of the Nebrodi Mounts, representing a morphologically and geologically important area, adjacent to the orographic boundary between the Nebrodi and Peloritani Mounts.

Sicily is located in the central-western Mediterranean region, at the boundary between the African and European plates, and represents the connecting element between the African Maghrebian and the Southern Apennine Chains [60–63]. As part of the Apennine-Tyrrhenian System, the geological setting of Sicily (Figure 1a) is characterized by very

articulate “collisional” complex (Figure 1a), which presents the typical configuration of a foreland–foredeep–chain system [63–66]. The growth of this complex, led by the convergence between African and European plates and the coeval roll-back of the subduction hinge of the Ionian Slab (Figure 1a), started in the late Oligocene–early Miocene and persisted through different tectonic phases (compressional, extensional, and transcurrent) until the late Quaternary [60,62,67,68].

The upstream sector of the CGWB area is characterized by smoothed outline hills, formed in the flyschoid sedimentary sequences and dissected by a narrow streambed, which gradually widens towards the mouth area. The river presents a characteristic delta shape, on which a wide coastal and alluvial plain rises.

The Nebrodi Mountains, together with the Peloritani Mountains, occupy the central-eastern sector of the Sicilian Maghrebian Chain (SMC), which represents the orogenic domain of the so-called “collisional” complex of Sicily [60,62,67–74]. In particular, the Sicilian orogen presents the maximum axial depression in the north-eastern sector [68], through a first-order thrust surface. This important structure, known as “Taormina Line” [75,76], outcrops along the San Fratello–Alcantara alignment, where the overlap of the Peloritani Tectonic Units on the Nebrodi ones occurs [61].

Furthermore, the SMC is also displaced and fragmented by a complex strike- and dip-slip “Neotectonic” fault grid (Plio-Quaternary), expressed by right-lateral, synthetic, NW–SE and W–E oriented, and left-lateral, antithetic, NE–SW and N–S oriented structures [68,77–80]. This complicated structural setting is well observable in the Caronia area (Figure 1b) [72], where recent high-angle normal and transcurrent faults are present, often reactivating and re-orienting older fault surfaces [61,68,72,76].

The tectono-stratigraphic sequence outcropping in the area adjacent to the CGWB (Nebrodi Mts.) consists of units derived from the deformation of the so-called Sicilide [81] and Numidian domains [82–84], generally detached from their original substrate and dismembered in first-order tectonic units, unconformably covered by early-middle Miocene thrust-top basin deposits and by Plio-Quaternary marine, transitional, and continental successions, as shown in Figure 1b [61,72,76,85,86].

2.2. Hydrogeological Setting

Starting from the analysis of the Potential Infiltration Coefficients [8,41,87], it is observed that the lithotypes with higher permeability are concentrated along the coastal plain and the Caronia stream. These sectors are entirely characterized by recent alluvial deposits and middle-late Quaternary deposits, mainly consisting of gravels, sands, and silts (Figure 1b) [61,76]. These lithotypes are characterized by a high permeability due to primary porosity and generally host unconfined aquifers, with transmissivity increasing in the direction of the outlet of the rivers and on the coastal plains, proportionally with the increase in the thickness of the aquifer [15,88]. These types of aquifers are generically in hydraulic connection with the recharging areas to the coastal plains [3,15,89,90]. Despite having a low capacitive role, due to its limited extension, the CGWB has been considered to be able to satisfy the local water needs (INGV-DAR 2019).

The CGWB is hydrogeologically superimposed on flyschoid lithotypes with lower permeability [91]. Laterally, with the exception of the northern margin represented by the sea, the CGWB is delimited by boundaries with no or very low flow, represented by the flyschoid lithotypes of the Reitano-Monte Castellaci and Pizzo Michele-Monte Castelli [41,59]. Regarding the hydrogeological characteristics of the lithotypes outcropping in the CGWB [92–94], the following hydrogeological complexes have been distinguished [41,91,95,96]:

- Present and recent alluvial hydrogeological complex (Holocene): deposits with high permeability (10^{-2} m/s $>$ $k >$ 10^{-4} m/s) which form the main part of the CGWB, extending in length for about 6 km and just under a kilometer wide.
- Hydrogeological complex constituted by river and marine terrace deposits (middle-late Pleistocene) and “Ghiaie e sabbie di Messina” (middle Pleistocene): it does not

- outcrop as it is covered by recent alluvial deposits. These deposits have high permeability ($10^{-2} \text{ m/s} > k > 10^{-4} \text{ m/s}$) due to primary porosity, even if very heterogeneous.
- Hydrogeological complex of the Reitano Flysch (early-middle Miocene): it presents localized and variable permeability, mainly due to fracturing. It is composed of micaceous sandstone and lithic arkoses with medium-large grain, lightly cemented, with decimetric intercalations of silty-clays. In the upper part of this complex, decametric conglomeratic bodies relative to the so-called “Conglomerati di Caronia”, intercalated with the arenaceous deposits of Reitano Flysch, are often present. These lithotypes vary from moderately permeable ($10^{-4} \text{ m/s} > k > 10^{-5} \text{ m/s}$) to semi-permeable ($10^{-6} \text{ m/s} > k > 10^{-7} \text{ m/s}$) and constitute the main substrate of the CGWB.
 - Hydrogeological complex of the Numidian Flysch belonging to the Monte Maragone Unit (Late Oligocene-early Miocene): it consists of argillites alternated with silty-clays, followed upwards by quartzarenites and quartzosiltites in large banks. These lithotypes have low and very low permeability ($10^{-7} \text{ m/s} > k > 10^{-9} \text{ m/s}$). For these characteristics, the Numidian Flysch deposits constitute the impermeable substrate of the southernmost part of CGWB.

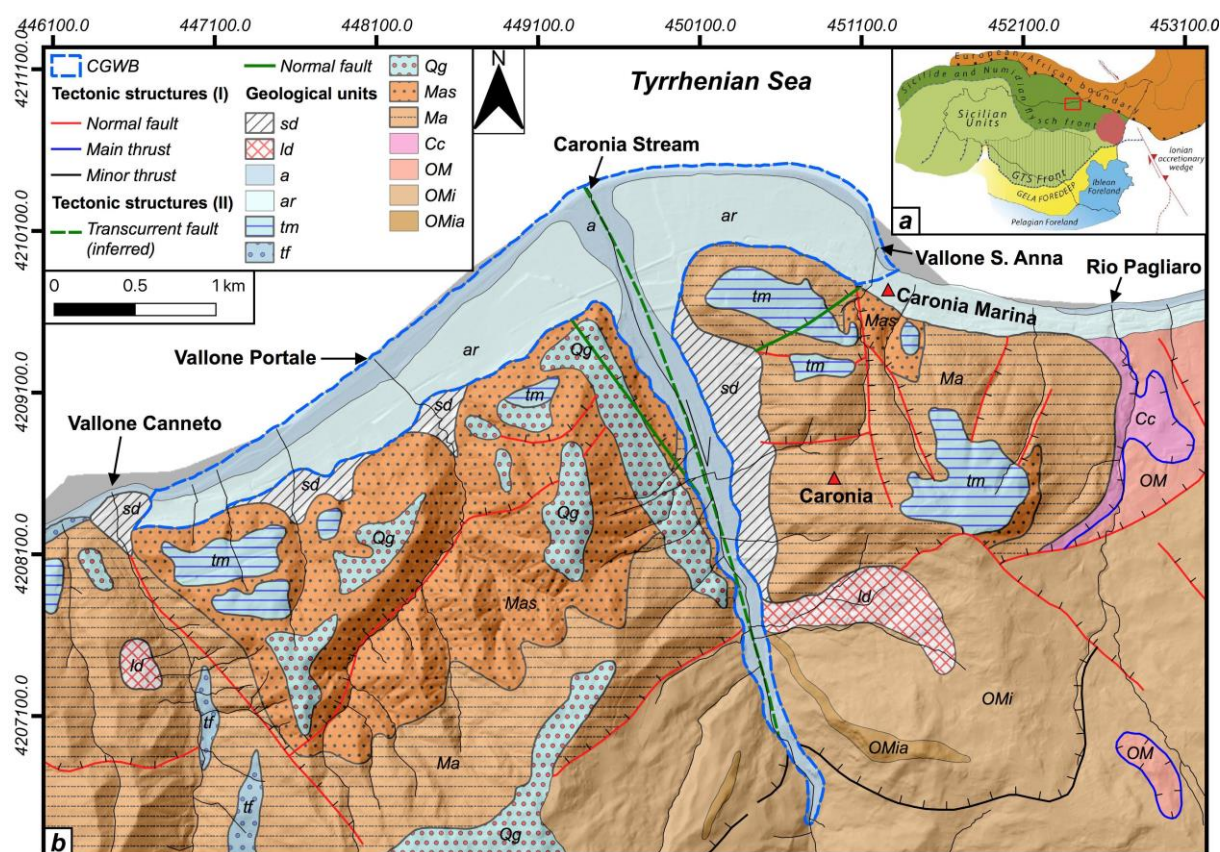


Figure 1. Geological sketch map of the area adjacent to the CGWB (blue dashed line). Inside (a), the tectonic map illustrating the main elements of the “collisional” complex of Sicily. The geological sketch map (b) was elaborated with GIS software (QGIS 3.16), using a DEM image as topographic support. The stratigraphic and tectonic information for this map are derived from previous work [85] and from the official geological map [86], as well as from the accompanying explanatory notes [61,76]. Moreover, the tectonic structures described by previous authors [76,85] are reported as I in this map, while those derived from the official geological chart [86] are indicated as II. OMi-OMia = Numidian Flysch-Monte Maragone Tectonic Unit; OM = Numidian Flysch-Monte Salici-Monte Castelli Tectonic Unit; Cc = “Argille Scagliose Superiori” Tectonic Unit; Ma = Reitano Flysch; Mas = Reitano Flysch “Conglomerati di Caronia” Member; Qg = “Ghiaie e sabbie di Messina”; tf = stream terrace deposits;

tm = marine terrace deposits; ar = recent alluvial deposits; a = present alluvial deposits; ld = landslide deposits; sd = slope deposits.

3. Materials and Methods

3.1. Previous Geognostic and Geophysical Investigation

Six boreholes, falling within the studied area, were analyzed in order to better characterize the alluvial deposits and geological substrate features and thickness (Figure 2). Four of these boreholes (BH1, BH2, BH3, and BH6) were drilled using the core destruction method, in relation to the geological and hydrogeological surveys for the construction of an aqueduct between the villages of Santo Stefano di Camastra and Caronia. The remaining two boreholes (BH4 and BH5) were instead drilled using the continuous coring method, during the geological surveys for the construction of the A20 highway (Palermo-Messina). Similar stratigraphic succession was found in the analyzed boreholes, except for the BH2 entirely drilled in the alluvial deposits of the Caronia River (up to 25 m depth). In the other boreholes, the cumulative thickness of the alluvial deposits ranges from a minimum of 9 m up to a maximum of 15 m (Figure 2). Below the alluvial deposits, arkoses interbedded with silty clays are present. These latter deposits, ascribed to the Reitano Flysch, often present a surface-deteriorated and -fractured cap, the thickness of which varies between 4 and 5 m. In general, the maximum thickness of the Reitano Flysch deposits, observed in the analyzed boreholes, ranges between 8 and 29 m (Figure 2).

Geoelectric surveys and seismic refraction surveys (Figure 3) were realized within the Caronia water body in the 1970s in order to describe the aquifer present in the Caronia area. These acquisitions were made as part of a project sponsored by [97] CASMEZ (1978). This project produced maps concerning the geophysical (geoelectric and seismic) characterization of the area. In particular, 17 vertical electrical sounding (VES) and three refraction seismic lines were carried out inside the CGWB. Each line consists of several segments of measurements arranged in continuity.

The seismic lines were positioned, distancing them from each other by about 200 m, along a direction almost perpendicular to the axis of the Caronia stream so as to intercept increasing volumes of alluvial deposits proceeding from upstream to downstream. The seismic refraction data show a two-layer model, with the thickness of the first layer varying from a few meters up to a maximum of 30 m in the northernmost area. However, original data were not available and only interpretive models could be evaluated.

3.2. New Processing and Interpretation of Vertical Electrical Soundings

Although the vertical electrical sounding (VES) technique allows, in theory, the solution of the inverse problem for electrical resistivity one-dimensional models, in many cases this method is applied to reconstruct 3D resistivity models in the subsoil, through the interpolation of 1D models which are mutually constrained, each with the adjacent models, compatibly with the tectonic structures present in the studied area. Practically, during the interpolation phase, optimization criteria must be followed to guarantee the acceptability of the model from a geological point of view. In fact, especially for large-scale geoelectric investigations, the application of 2D and 3D techniques is often impractical, for economic or logistical reasons, as the data acquisition would be impracticable or at least considerably difficult to carry out.

The use of this method of reconstruction is advisable only when the resistivity gradient is small along the directions parallel to the ground surface. In these cases, therefore, 2D or 3D resistivity models can be made by performing VES surveys on more or less regular meshes or along profiles, possibly reserving the application of 2D and 3D acquisition techniques to sectors of limited extension within the investigation area, when the resistivity varies with high horizontal gradients.

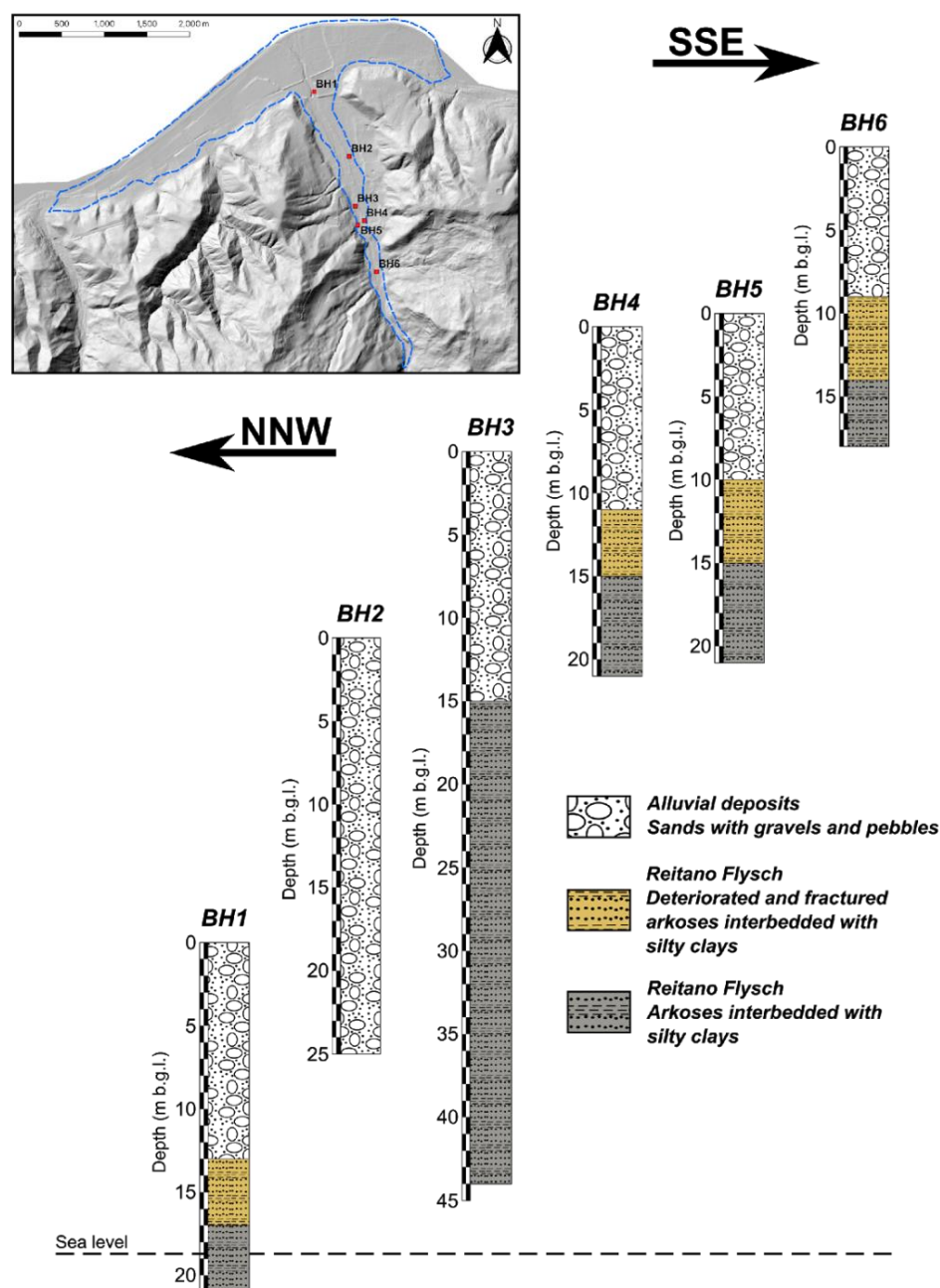


Figure 2. Stratigraphic successions of the six boreholes analyzed for this study. In the map on the top of the figure, the location of each borehole within the CGWB area is shown. Stratigraphic logs in this scheme are positioned with respect to their altitude above sea level, even if the horizontal distance among them is not to scale.

All the VESs collected were available only in paper format, given only by the graph of the apparent resistivity curves as a function of the half-distance $AB/2$ between the current electrodes. For each VES, an ASCII file was created containing the geographic coordinates and the altitude of the center of the survey, the array type, the number of measurements considered for each curve (corresponding to the number of points picked on the graph), and, for each measurement, the value of $AB/2$ and apparent resistivity.

Subsequently, using a MATLAB script, data were imported into the ZondIP1D software (v. 5.2) and converted into the proprietary format. By grouping them into a single database, all the VESs were carried out within the water body of the Caronia torrent.

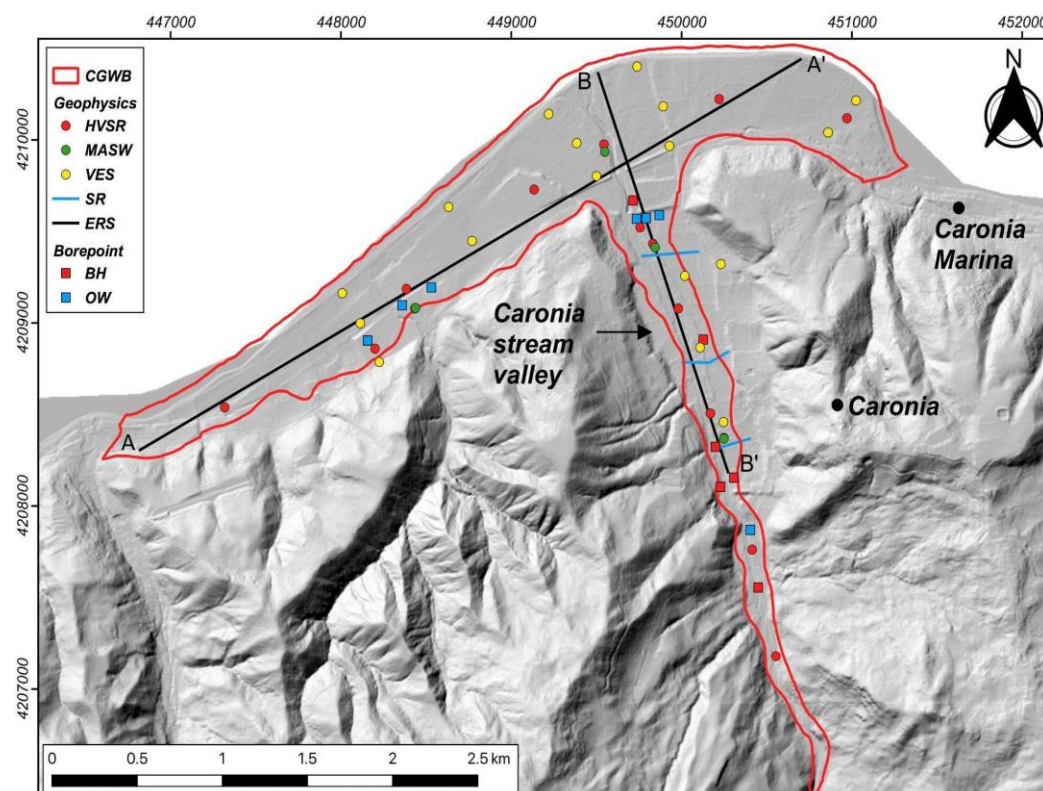


Figure 3. DEM image of the area adjacent to the CGWB (solid red line), illustrating the location of the geophysical surveys, boreholes, and wells analyzed for this study. In particular, the positions of horizontal-to-vertical spectral ratio (HVSr), Multichannel Analysis of Surface Waves (MASW), vertical electrical sounding (VES), seismic refraction (SR), electrical resistivity sections (ERS), boreholes (BH), and observation wells (OW) are shown.

ZondIP1D software allowed inversions with the least squares method. The inversions were carried out taking care to limit the lateral heterogeneities and constraining the inversions, where possible, with coring stratigraphic data. In the areas characterized by quite regular geological structures, a 1.5D inversion algorithm was used, in which the deeper layer of the resistivity section is considered almost horizontal, while the most superficial layers of the section can have sharper lateral variations. In consideration of this, a window comprising three or more adjacent VESs is inverted simultaneously, giving greater weight to the points of the central curve for the poorly fitting calculation.

The 1D inverse models obtained were therefore interpolated with each other to derive the electrical resistivity sections (Figure 4). The choice of the section traces was made considering the VES areal distribution and, at the same time, the shape of the geological structures.

The preliminary resistivity sections were useful for the making of the geological sections of the river basin. In fact, from the analysis of these resistivity sections, a first description of the characteristics of the subsoil was obtained within the Caronia water body. A preliminary geological interpretation was given to each “resistivity pattern” recognized in the sections, based on the mapped lithology and the geometry of the sedimentary bodies expected, given the structural and geomorphological asset of the area.

3.3. New Geophysical Surveys

Previous geophysical studies were improved with new geophysical measurements to define with greater precision the depth of the substrate of the groundwater body and the thicknesses of the lithologies present in the subsoil. The new geophysical data were acquired with active seismic techniques using the Multichannel Analysis of the Surface

Waves (MASW) technique and microtremor recordings elaborated with the horizontal-to-vertical spectral ratio (HVSr) technique. The location of seismic investigations was based on the position of previous investigations, with the aim of integrating the available data mesh (Figure 3). The HVSr (horizontal-to-vertical spectral ratio) methodology [45,98] is a useful technique for the analysis of seismic noise. This methodology consists of calculating the ratio between the horizontal components with respect to the vertical component of the spectrum of seismic ambient noise. A 3D velocimeter records microtremor signals along the three directions and the H/V spectral ratio is calculated. The inversion of this curve returns an S-wave velocity profile and can be used to recover stratigraphical information if the inversion process is constrained by some other variable and soil features.

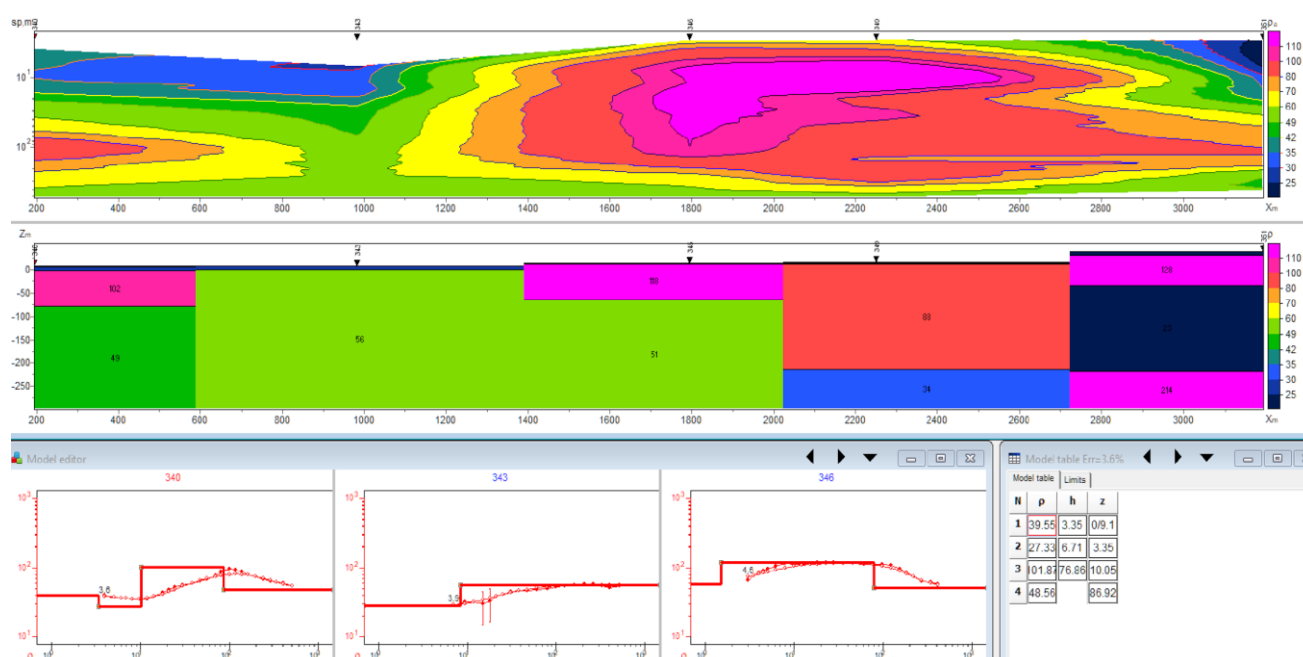


Figure 4. Example of the inversion of a series of aligned VESs and construction of the electrical resistivity section, using the ZondIP1D software: (**top**) pseudo-section of apparent resistivity, (**middle**) preliminary section obtained by aligning the inverse models relating to each VES, (**bottom**) apparent resistivity curves and related inverse models.

An total of 15 seismic microtremor acquisitions were made using a 3D velocimeter specially designed for ambient noise studies. This instrument provides good accuracy in the frequency range from 0.1 to about 30 Hz. The location of the seismic microtremor measures concerned not only the main arm of the water body but also the area of the flood plain, where other acquisitions were realized both on the left hydrographic and on the right hydrographic of the Caronia torrent. The duration of each ambient noise recording was 18 min.

MASW methodology [43] is based on the analysis of the surface waves dispersion curve. This is derived by picking the maximum oscillation on the phase velocity vs. frequency graph, derived by applying a Fourier transform to seismic signals registered at the geophones. The seismic source is generated by a heavy sledgehammer, which hits the ground at a determined offset from the geophone spread. The dispersion curve obtained is inverted by starting from an initial conceivable S-wave velocity model and solving the inverse problem via the Gauss–Newton least squares inversion algorithm.

Four MASW surveys were carried out to obtain more detailed information on the trend of Vs near surface and to constrain the inversion of the HVSr curves [53]. Indeed, constraining the HVSr inversion with independent parameters, such as shear wave velocity or the thickness of upper layers derived from MASW inversion, is useful for reducing the

number of equivalent inverse HVSR models. In this way, four active seismic measurements were selected in correspondence with the same number of HVSR measurements chosen in different positions of the Caronia water body, and their inverse models served to constrain the most superficial part of the corresponding inverse HVSR models.

MASW surveys were carried out along the road of the Caronia stream and in the coastal plain, at four points distant from each other in an attempt to better describe the changes in S-wave velocity and in flood thickness along the river path (Figure 5).

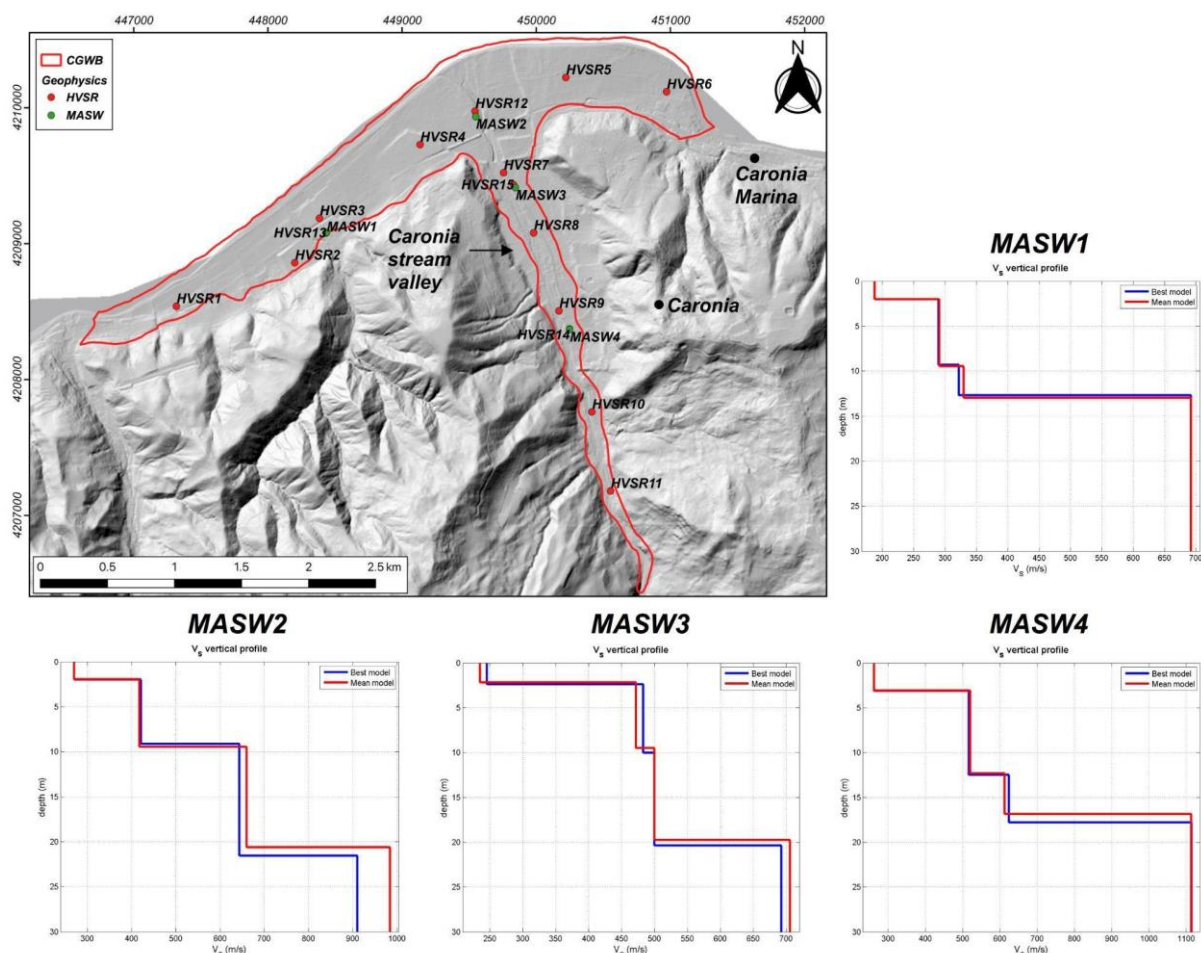


Figure 5. Inverse models resulting from the four MASW surveys performed to study the CWGB. Top left, location of the MASW surveys (green dot) and of the HVSR recordings (red dot).

All acquisitions were realized using a high-resolution multichannel seismograph. The MASW array generally consisted of twelve 4.5 Hz vertical geophones, 2 m spaced and at an offset of 5 m. A single measurement (MASW 3) was carried out using 24 vertical geophones spaced 2 m and at an offset of 8 m. HVSR surveys carried out in the water body were divided into clusters on the basis of their geographical proximity and lithological similarity to the nearest MASW survey, whose inverse model was used as a constraint.

4. Results and Discussion

4.1. MASW and HVSR Results

MASW results show the velocity of the S-wave compatible with the outcropping succession present in the investigated sites (Figure 5). MASW 2, 3, and 4, carried out along the main axis of the Caronia torrent from the southern sector towards the north, show an average velocity value equal to 259 m/s, attributed to the current alluvial deposits.

Results of 15 seismic passive measurements (HVSr), constrained by four MASW acquisitions, allowed reconstruction of seismostratigraphic patterns. Figure 6 shows the HVSr curves related to those measures carried out near the four MASW surveys, whereas their inverse 1D models, constrained by the corresponding MASW models, are presented in Figure 7.

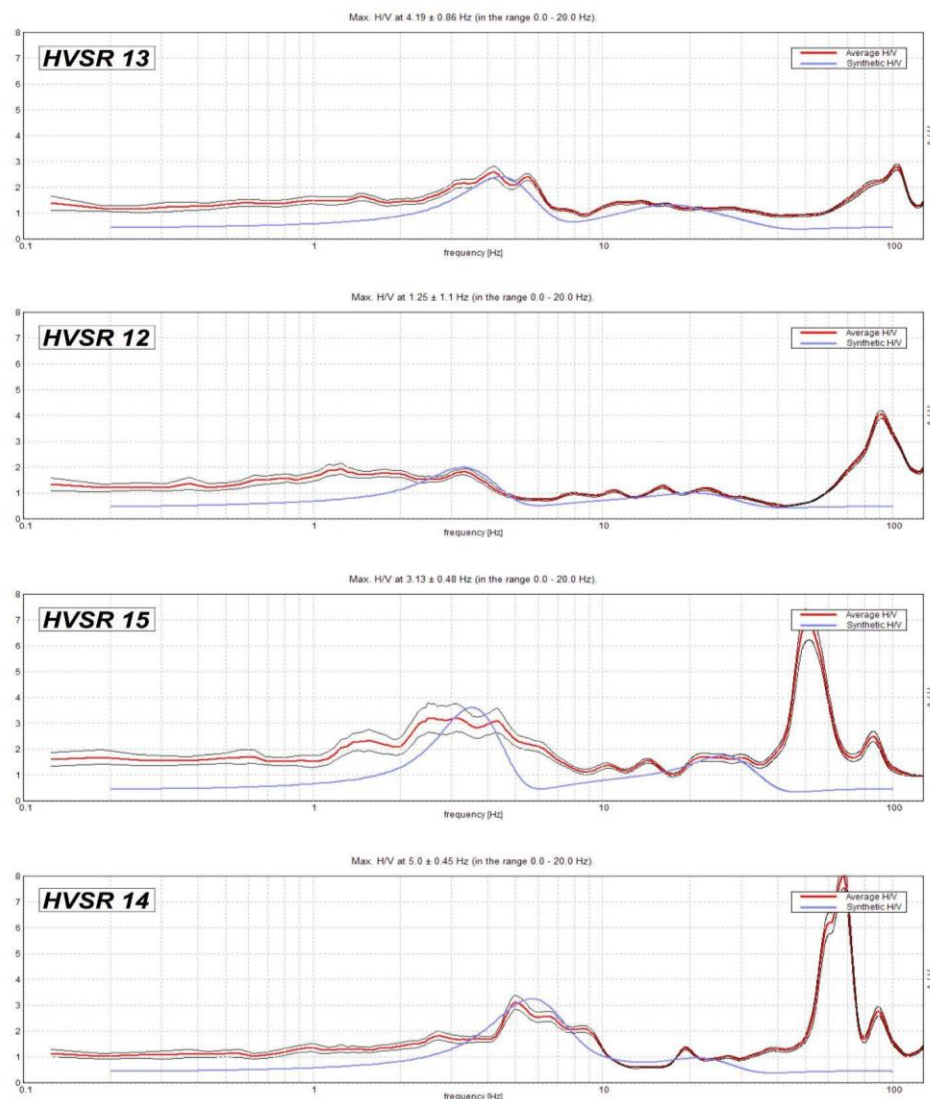


Figure 6. Comparison between the observed (red) and predicted (blue) HVSr curves, relating to the four microtremor recordings performed in proximity to the MASW surveys. The gray lines indicate the standard deviation of the observed curve.

Referring to these models, a seismostratigraphic level is shown with an average value of 272 m/s for the top of the sedimentary deposits. The thickness of this upper layer varies from 1.5 m to 4 m. Based on the geological survey, these Vs characteristics can be associated with the alluvial deposits located near the current river for HVSr 12, HVSr 14, and HVSr 15. Very similar Vs features have been described in previous works: similar values, slightly higher and confirmed to 300 m/s, have been reported for conglomerates, gravels, and sands from alluvial deposits [99]. The lowest shear wave velocity calculated for this upper layer corresponds to values close to 180 m/s, as shown for HVSr 13. This latter value is attributable to the recent alluvial plain deposits present in the wide plain next to the sea. A second deeper seismostratigraphic level is recognized for each of the four HVSr models shown in Figure 7. For this layer, Vs varies from 300 to 500 m/s. Its thickness varies from 10 m in HVSr 15 to 25 m in HVSr 12. This layer could be associated

with permeable non-surfacing alluvial deposits. These would constitute the largest volume of the CWB.

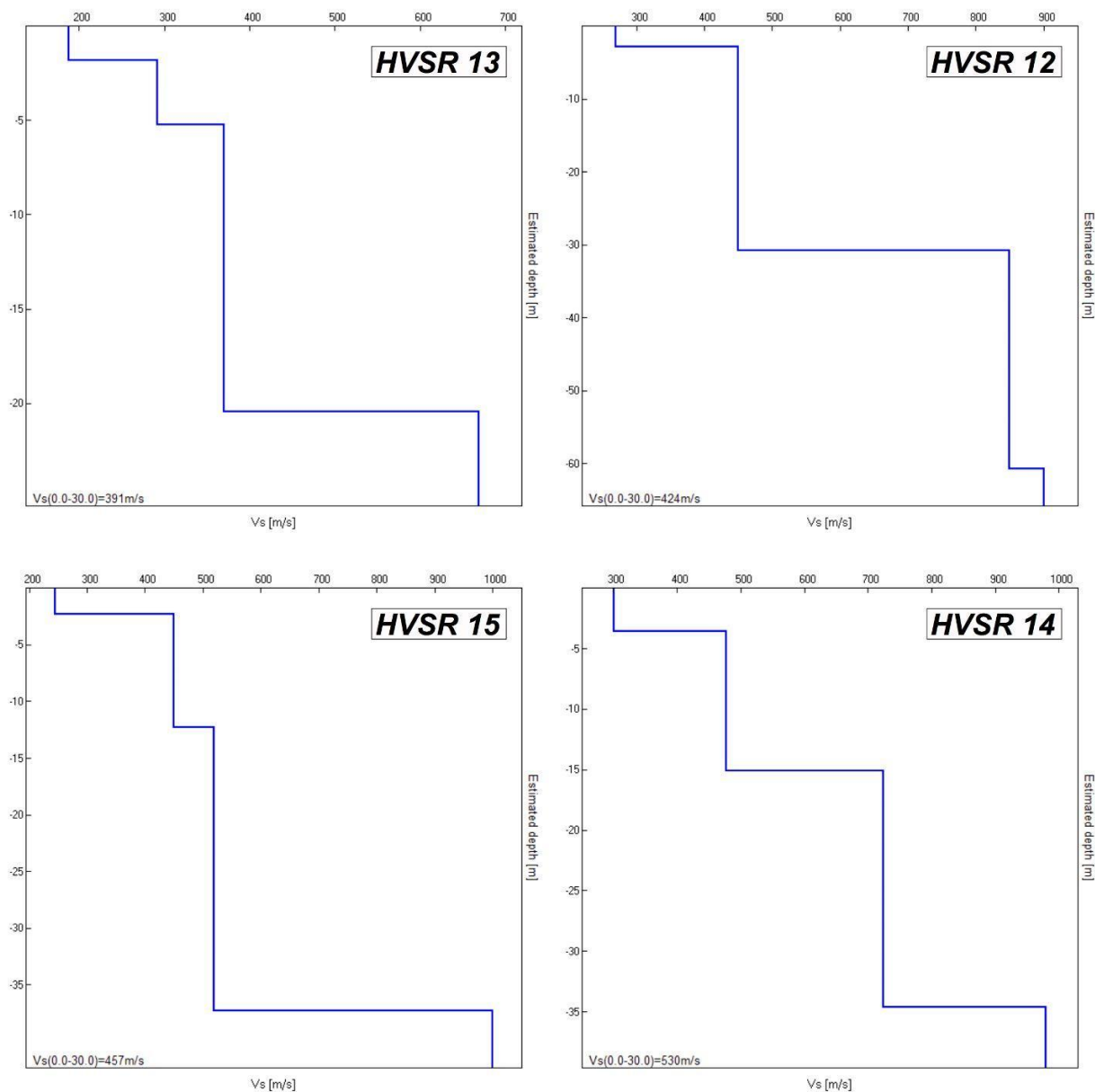


Figure 7. Inverse models related to the HVSR curves shown in Figure 6.

A third layer is characterized by a higher S-wave velocity, ranging from 400 m/s to 800 m/s. The thickness of this layer is greater in HVSR 13, where it is equal to 30 m. The V_s values are attributable to the Reitano Flysch. The wide range of velocities of this layer is due to the heterogeneous nature of these deposits, which are more altered in the upper part and more compact in depth.

A last seismic stratigraphic layer is present in all velocity models except HVSR 13. Resulting velocities between 900 and 1000 m/s could be associated with clayey deposits of varicolored clays.

4.2. A Tridimensional Model of the Electrical Resistivity

The inverse models of electrical resistivity, obtained by the above-discussed re-inversion of the available VES in the area, were interpolated using Voxler software (Golden Software, v. 4.0), to obtain a 3D graphic representation of the trend of electrical resistivity. This is

limited at the top by the Digital Elevation Model of the area, at the sides by the boundaries of the water body, and at the base by the depths of the investigation reached by each VES (Figure 8). To take into account the high contrasts of the geophysical parameter, the logarithm of electrical resistivity was preferred.

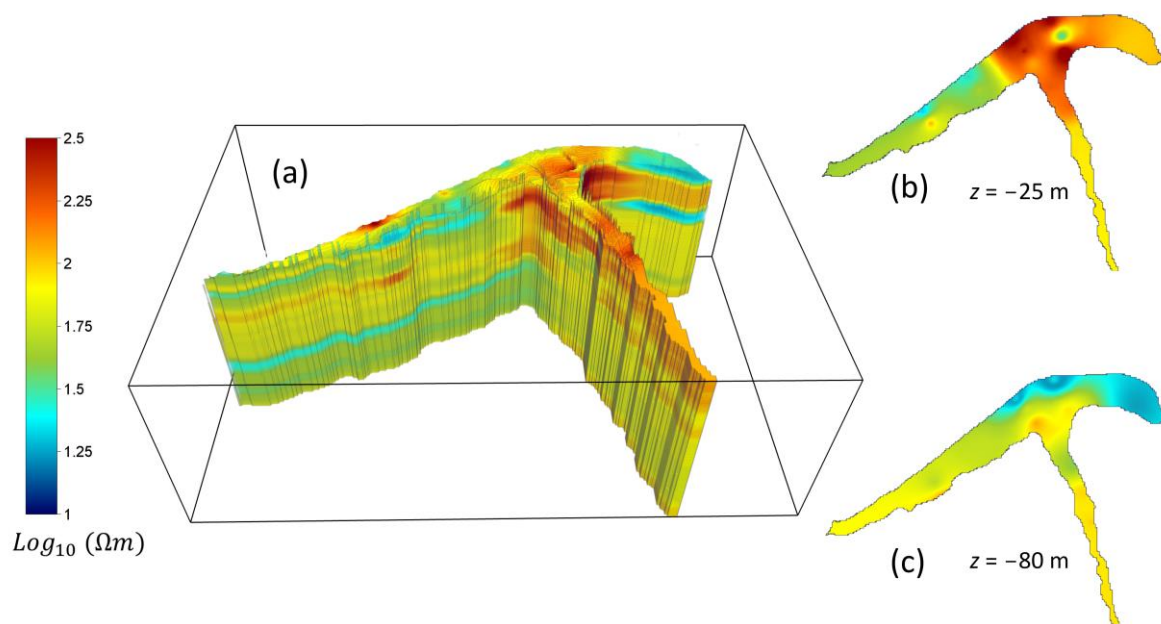


Figure 8. (a) Three-dimensional resistivity model obtained by the interpolation of the 1D inverse models related to the VES surveys in the Caronia water body and horizontal slides of the model at altitude of (b) 25 m b.s.l. and (c) 80 m b.s.l.

The tridimensional model describes the presence of a resistive overburden (60–80 Ωm), interpreted as alluvial materials, above a conductive substrate (7–20 Ωm), corresponding to the clayey-marly matrix soils of the Reitano Flysch surfacing near the river. In order to have a clearer view of the electrical resistivity trend within the model, horizontal slices were extracted at predefined levels below sea level. Two of them are presented and discussed here as examples. The first horizontal slice at 25 m b.s.l. (Figure 8b) shows high values of resistivity at the possible marine intrusion (therefore located in the most superficial portion) and a strong contrast of resistivity located at a transcurrent fault in evidence in the mountain zone. The second slice at 80 m b.s.l. (Figure 8c) instead shows very low resistivity values in the north-eastern part. This could be indicative of a marine intrusion phenomenon, probably located in the most porous portion of the alluvial material of the plain.

Starting from the 3D model, two vertical sections are also presented, useful for geological interpretation. The first section (A-A') extends for 4400 m along the coastal strip, in a direction subparallel to the coastline. The second section (B-B') extends along the axis of the stream for a length of 2300 m (Figure 9). The location of the two sections is shown in Figure 3.

The electrical resistivity features of the sedimentary deposits observable in sections A-A' and B-B' show horizontal and vertical variations, ranging from 20 to 500 Ωm (Figure 9). In particular, these electrical resistivity variations allowed different horizons and layers to be distinguished (Figure 9). These latter features, characterized by precise resistivity values, were attributed to the geological deposits outcropping around the Caronia area (Figure 1) and used to reconstruct the stratigraphic and structural setting.

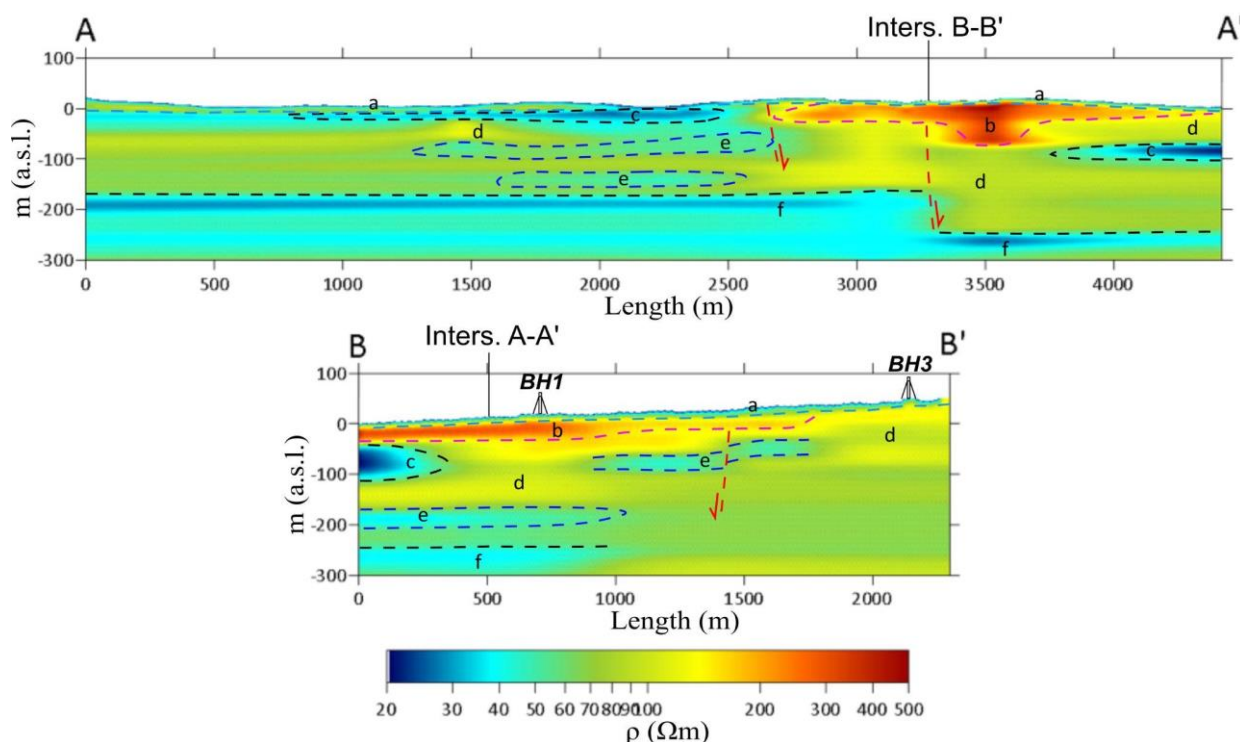


Figure 9. Vertical sections of electrical resistivity obtained from the 3D model: **(top)** section A-A' subparallel to the coastline; **(bottom)** section B-B' along the axis of the Caronia stream. Letters a to f indicate the different layers, bounded above and below by relative dashed lines, identified on the basis of the electrical resistivity variations. Red dashed lines indicate the presence of normal and transtensional faults. BH1 and BH3 are relative to the boreholes located along the B-B' section (for further details see Figures 2 and 3).

From the bottom to the top of the two sections, layer f, with resistivity values of about 40 Ωm , could refer to the clays and marls of the “Argille Scagliose Superiori” unit, outcropping to the east of the Caronia area. This layer has been continuously recognized in section A-A' and only in the northernmost part of section B-B'. Above these deposits, the increasing resistivity values, here identified by the layer d (60–100 Ωm), can be associated with the arenaceous facies with intercalations of silty-clays belonging to the Reitano Flysch formation. In this view, layers labeled e (50–60 Ωm) could represent thicker clayey portions of the Miocene lithological unit. The highest resistivity value portions (200–500 Ωm) observed in both sections, named layer b, can be related to the “Conglomerati di Caronia” member deposits and/or to conglomeratic channeled structures in correspondence with the central sector of the streambed. From another point of view, these high resistivity values, coinciding with the mouth sector of the Caronia stream, could also indicate the presence of freshwaters flowing below the streambed. The low resistivity lenticular and cuneiform bodies (20–40 Ωm) observed in both sections, named layer c, probably describe the seawater intrusion in the Caronia sedimentary succession, in correspondence with sectors with high porosity and/or minor freshwater hydraulic load. Finally, observing the BH1 and BH3 stratigraphic logs and the resistivity values (40–70 Ωm), the uppermost layer a was ascribed to the alluvial deposits, filling the Caronia streambed and the relative coastal plain.

The three stepped forms recognized in the sections (Figure 6), indicated by red dashed lines, could represent normal tectonic structures. These faults are compatible in terms of location, shape, and type of dislocation with those recognized and already mapped [86] (APAT, 2013) in the hills immediately west and east to the terminal part of the Caronia stream valley, and with the inferred transtensional structure where the streambed develops

(Figure 1). Moreover, this latter structure could also be responsible for the thickening of the succession, especially as regard to layers a and b, in correspondence with the central sector of the Caronia stream mouth (Figure 9). In this view, space created by the net-slip movement linked to this fault may have been gradually filled by Reitano Flysch conglomeratic bodies (i.e., “Conglomerati di Caronia” member and/or channeled structures) and by Quaternary deposits.

4.3. Estimate of the Bottom of the CGWB

All the geophysical surveys performed (VES, SR, HVSr, and MASW) were geologically interpreted using the stratigraphic logs (from BH1 to BH6) as calibration. This made it possible to transform the information of the geophysical parameters in terms of the thickness of the water body in the investigated points. These values were interpolated by applying a kriging-type algorithm using the Surfer software (v. 18). In correspondence with the water body superficial limit, the thickness of the groundwater body was set equal to zero. The resulting thickness map (Figure 10a) shows two areas with significant thicknesses: the smallest is located in the extreme eastern portion, where 30 m thicknesses are reached; the largest is located west of the current delta, where thicknesses reach about 40 m. This part coincides with the area already identified as a transcurrent fault in the 3D resistivity model. The thicknesses of the CGWB are larger in the eastern part of this probable fault area.

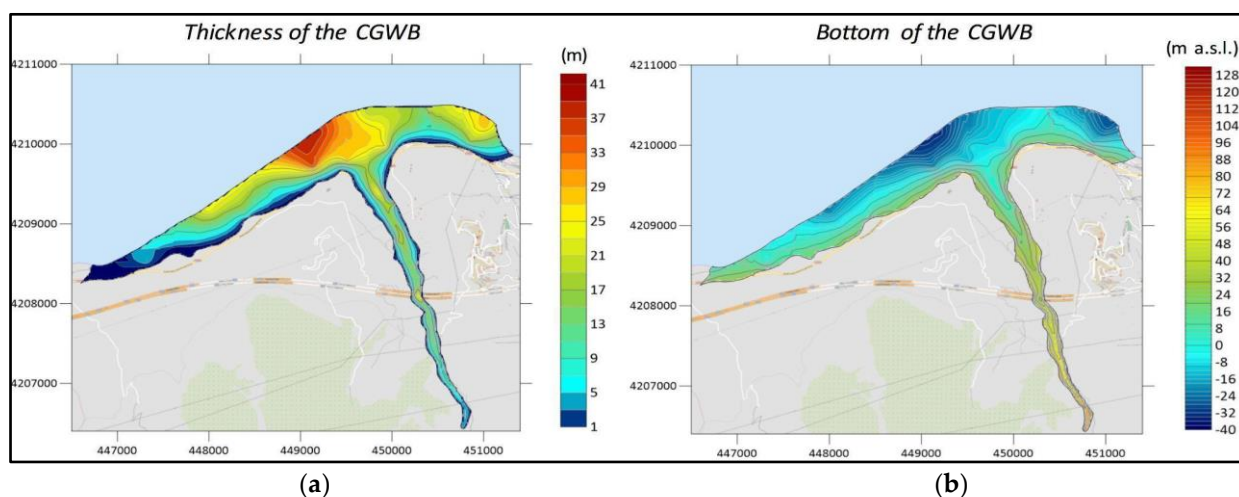


Figure 10. (a) Thickness of the Caronia Groundwater Body; (b) altitude of the bottom of the Caronia Groundwater Body (m a.s.l.).

Furthermore, the bottom of the water body was rebuilt (Figure 10b) because it is needed as an input for the construction of a mathematical flow model.

4.4. Numerical Flow Model for the CGWB

The reconstruction of the lower boundary of the water body plays a key role in the construction of the mathematical model of static flow. This was carried out to implement the hydrogeological model of the CGWB. The finite difference calculation code MODFLOW [100] in steady state was used to create the flow model. This kind of analysis solves the groundwater flow differential equation using the finite difference approach within the groundwater systems through a gridded spatial discretization [101]. In order to create a numerical model, which describes the hypothetical trend of flow within a groundwater body, it is necessary to define the model in the spatial domain. This must be divided into cells, to each of which is assigned both the initial and boundary conditions and the physical and hydrogeological properties. These conditions and properties are considered homogeneous within the cell itself, and attributed to the center of the cell [102].

The sectors considered by the numerical flow model correspond to the coastal plain and the Caronia stream mouth. In the first phase, the top and bottom levels were defined. For the top, corresponding to the topographic surface, altitudes derived from the DEM of Sicily were assumed. The hydrogeological substrate, defined in the digital model of the CGWB, was adopted as the bottom of the flow model. For the horizontal discretization, the modeled area (coastal plain) was subdivided using a mesh of 50×50 m cells, while 12 layers were identified for the vertical subdivision (Figure 11). Subsequently, the hydrogeological properties were defined to be assigned to the various sectors of the model. Hydraulic conductivity values along the three spatial directions ($K_x = 3.5 \times 10^{-5}$ m/s, $K_y = 3.5 \times 10^{-5}$ m/s, and $K_z = 3.5 \times 10^{-6}$ m/s) were attributed to layers 1 to 11, describing the part of the succession in which the groundwater flows. Finally, layer 12, corresponding to the bottom, was defined as null flow. A further step for the realization of a flow model is related to the definition of the boundary conditions [103].

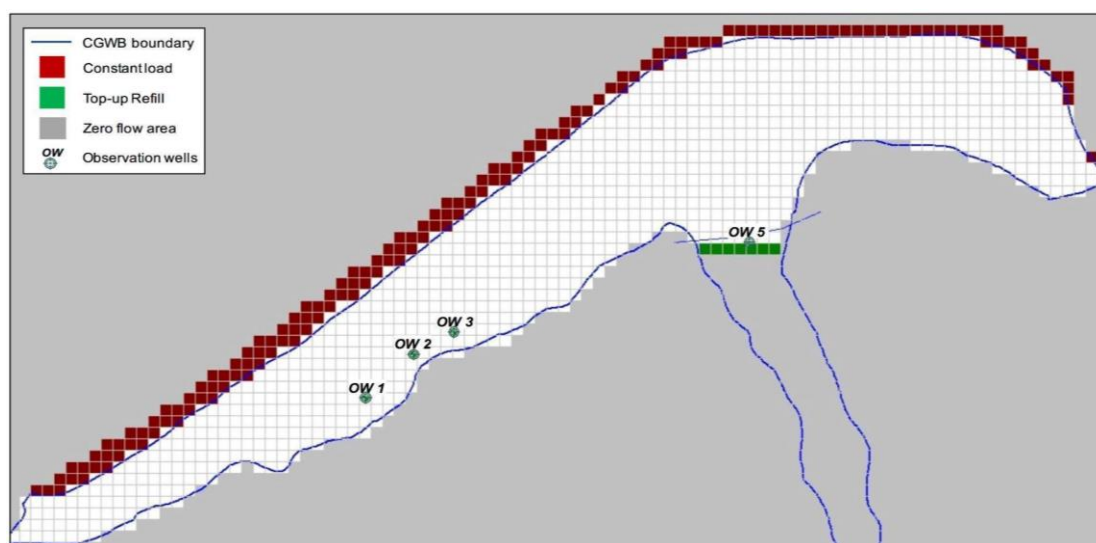


Figure 11. Horizontal discretization of the modeled area subdivided using a mesh of 50×50 m cells and boundary conditions used for the numerical flow model.

These features define the physical constraints in the perimeter cells that are imposed on the flow model (Figure 11). As boundary conditions, the following parameters were adopted:

- (A) Refill value: 161 mm/year for 365 days. This refill was applied only to layer 1, which defines the portion of the model identifiable with the topographic surface.
- (B) Constant load: An area representing the portion of the model (red cells in Figure 11) where the flow stops being considered as having a constant hydraulic load. It was defined by assigning the value 0 to the coastline downstream of the domain.
- (C) Top-up refill: This parameter represents the sub-alveal contributions. This feature describes the direct contributions provided by the upstream hydrological basin. These values were assigned, as saturated cells (green cells in Figure 11), corresponding to the groundwater depth measured in the observation well n.5.
- (D) The area outside the modeled area was considered to be zero flow (gray sectors in Figure 11).

The mathematical model obtained was finally calibrated and validated thanks to the piezometric values detected during the field activities performed in the area under study. Four wells were considered, one of which (OW 5) was inside the Caronia streambed. These wells have an undisturbed piezometric level and are sufficiently far from other wells in use. The simulation results are shown in Figure 12. The trend of the simulated piezometry shows how the aquifer is fed by the inputs coming from the mountain. Furthermore, the

stream portion considered in this model provides an important contribution to feed the coastal plain aquifer.

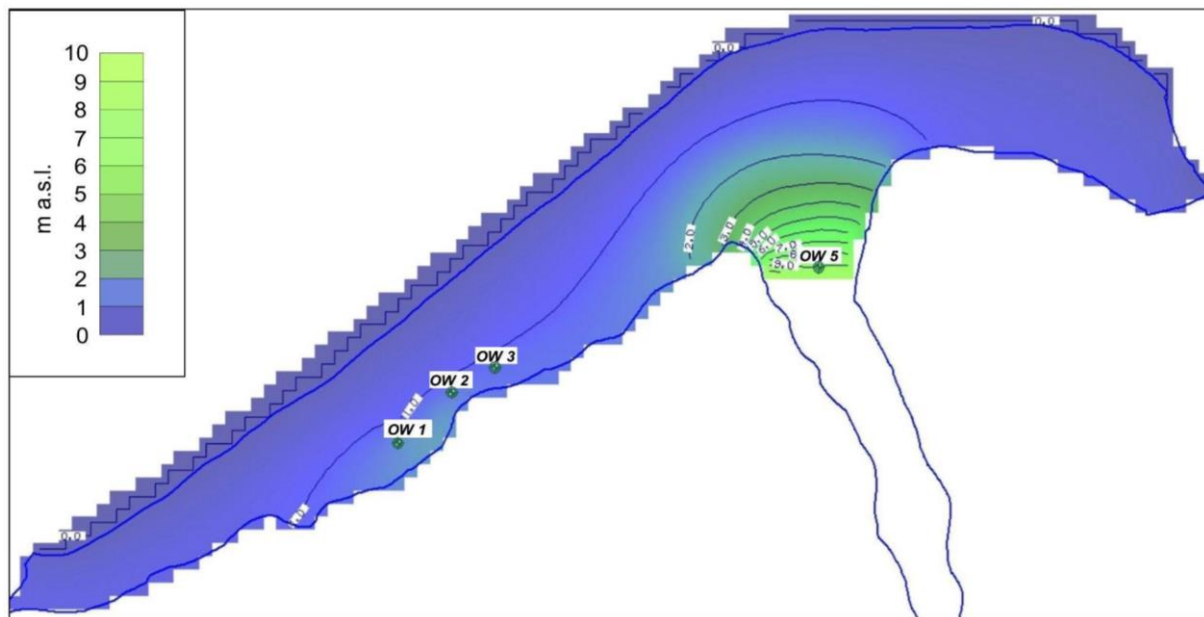


Figure 12. Results of the mathematical flow model with relative values of simulated piezometry.

Finally, the calculated vs. observed piezometric values are shown in Figure 13. A normalized RMS of 7.49% is obtained, with an average square deviation of 0.63 m. This is considered to be an acceptable value considering the width of the simulated area.

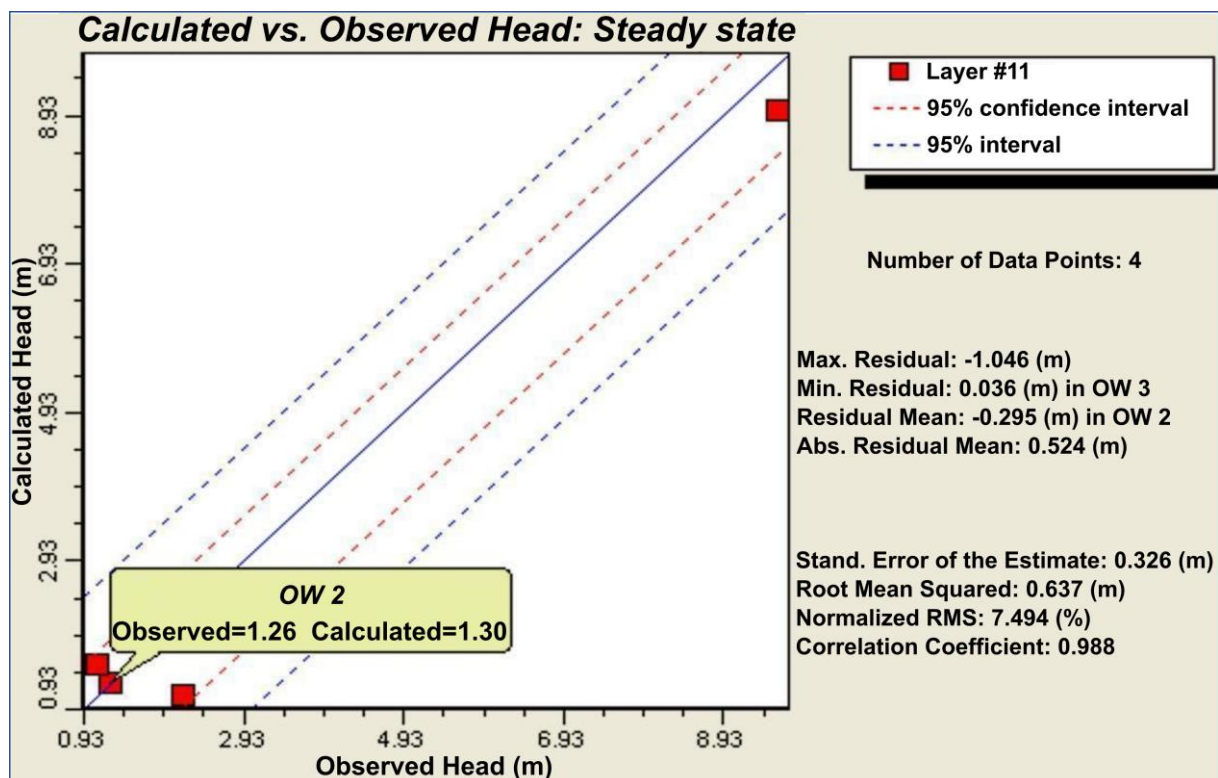


Figure 13. Calculated vs. observed piezometric values.

5. Conclusions

The characterization of the Caronia Groundwater Body (CGWB), in north-eastern Sicily, was realized thanks to the construction of a conceptual physical model and the related hydrogeological flow model, which is fundamental for the definition of monitoring programs, hydrogeological risk assessment, and correct water resources management.

A series of previous geophysical data (vertical electrical sounding surveys and refraction seismic profiles) were re-inverted using constraints obtained from stratigraphic data. The new geophysical models obtained, together with the information obtained from new surveys with surface wave and microtremor techniques (MASW and HVSR), made it possible to obtain three-dimensional models of physical parameters of the subsoil (electrical resistivity, seismic velocity of pressure, and shear waves). These models were used to define the depth of the bottom of the CGWB and the thickness of the alluvial deposits that characterize the streambed. This allowed shape, volume, and physical characteristics of the CGWB to be defined in sufficient detail. This numerical information served as a basis to generate a mathematical model of groundwater flow in order to simulate the spatial and temporal variability of the flow and, consequently, to make forecast estimates of the water supplies to the coastal plain. The underground flow model was preliminarily tested by comparing the theoretical results with some piezometric measurements performed. The main result of the calibration of the model was the refinement and validation of the assignment of the average hydrodynamic parameters of the modeled aquifer. In this way, it was possible to carry out realistic and reliable simulations of the underground flow in the CGWB. The results showed a good correspondence between predicted and observed data, confirming the reliability of the model obtained for the description of the aquifer dynamics.

Author Contributions: Conceptualization, P.C., R.M. and R.F.; Methodology, A.C., P.C., R.M. and A.B.; Software, R.M.; Validation, P.C. and R.M.; Formal analysis, A.C., P.C., R.M., A.B. and N.C.; Investigation, A.C., L.A. and A.B.; Data curation, P.C., R.M. and N.C.; Writing—original draft, A.C., P.C., R.M., L.A., A.B. and N.C.; Writing—review & editing, A.C., P.C., R.M. and A.B.; Visualization, A.C. and R.M.; Supervision, P.C. and R.F.; Project administration, R.F.; Funding acquisition, R.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Regione Siciliana, Commissario Delegato per l’Emergenza Bonifiche e la tutela delle Acque in Sicilia.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Chenini, I.; Zghibi, A.; Kouzana, L. Hydrogeological investigations and groundwater vulnerability assessment and mapping for groundwater resource protection and management: State of the art and a case study. *J. Afr. Earth Sci.* **2015**, *109*, 11–26. [\[CrossRef\]](#)
2. Erdoğan, M.; Karagüzel, R. A new hydrogeologically based approach to determining protected areas in drinking water supply reservoirs: A case study in the Ağlasun sub-basin (Burdur, Turkey). *Environ. Earth Sci.* **2016**, *75*, 126. [\[CrossRef\]](#)
3. Käser, D.; Hunkeler, D. Contribution of alluvial groundwater to the outflow of mountainous catchments. *Water Resour. Res.* **2016**, *52*, 680–697. [\[CrossRef\]](#)
4. Paillet, F.L.; Reese, R.S. Integrating Borehole Logs and Aquifer Tests in Aquifer Characterization. *Groundwater* **2000**, *38*, 713–725. [\[CrossRef\]](#)
5. Zuffetti, C.; Comunian, A.; Bersezio, R.; Renard, P. A new perspective to model subsurface stratigraphy in alluvial hydrogeological basins, introducing geological hierarchy and relative chronology. *Comput. Geosci.* **2020**, *140*, 104506. [\[CrossRef\]](#)
6. Straface, S.; Yeh, T.-C.J.; Zhu, J.; Troisi, S.; Lee, C.H. Sequential aquifer tests at a well field, Montalto Uffugo Scalo, Italy. *Water Resour. Res.* **2007**, *43*. [\[CrossRef\]](#)
7. Alexander, M.; Berg, S.J.; Illman, W.A. Field Study of Hydrogeologic Characterization Methods in a Heterogeneous Aquifer. *Groundwater* **2011**, *49*, 365–382. [\[CrossRef\]](#)
8. Fontana, M.; Grassa, F.; Cusimano, G.; Favara, R.; Hauser, S.; Scaletta, C. Geochemistry and potential use of groundwater in the Rocca Busambra area (Sicily, Italy). *Environ. Geol.* **2008**, *57*, 885–898. [\[CrossRef\]](#)
9. Cangemi, M.; Madonia, P.; Albano, L.; Bonfardecì, A.; Di Figlia, M.G.; Di Martino, R.M.R.; Nicolosi, M.; Favara, R. Heavy Metal Concentrations in the Groundwater of the Barcellona-Milazzo Plain (Italy): Contributions from Geogenic and Anthropogenic Sources. *Int. J. Environ. Res. Public Health* **2019**, *16*, 285. [\[CrossRef\]](#)

10. Chen, Q.; Jia, C.; Wei, J.; Dong, F.; Yang, W.; Hao, D.; Jia, Z.; Ji, Y. Geochemical process of groundwater fluoride evolution along global coastal plains: Evidence from the comparison in seawater intrusion area and soil salinization area. *Chem. Geol.* **2020**, *552*, 119779. [\[CrossRef\]](#)
11. Massey, A.C.; Taylor, G.K. Coastal evolution in south-west England, United Kingdom: An enhanced reconstruction using geophysical surveys. *Mar. Geol.* **2007**, *245*, 123–140. [\[CrossRef\]](#)
12. Sauret, E.S.G.; Beaujean, J.; Nguyen, F.; Wildemeersch, S.; Brouyere, S. Characterization of superficial deposits using electrical resistivity tomography (ERT) and horizontal-to-vertical spectral ratio (HVSr) geophysical methods: A case study. *J. Appl. Geophys.* **2015**, *121*, 140–148. [\[CrossRef\]](#)
13. Larkin, R.G.; Sharp, J.M., Jr. On the relationship between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvial aquifers. *Geol. Soc. Am. Bull.* **1992**, *104*, 1608–1620. [\[CrossRef\]](#)
14. Gregory, K.; Benito, G.; Downs, P. Applying fluvial geomorphology to river channel management: Background for progress towards a palaeohydrology protocol. *Geomorphology* **2008**, *98*, 153–172. [\[CrossRef\]](#)
15. Cimino, A.; Cosentino, C.; Oieni, A.; Tranchina, L. A geophysical and geochemical approach for seawater intrusion assessment in the Acquadolci coastal aquifer (Northern Sicily). *Environ. Geol.* **2007**, *55*, 1473–1482. [\[CrossRef\]](#)
16. Hamzah, U.; Samsudin, A.R.; Malim, E.P. Groundwater investigation in Kuala Selangor using vertical electrical sounding (VES) surveys. *Environ. Geol.* **2006**, *51*, 1349–1359. [\[CrossRef\]](#)
17. Alile, O.M.; Ujuanbi, O.; Evbuomwan, I.A. Geoelectric investigation of groundwater in Obaretin Iyanomon locality, Edo state, Nigeria. *J. Geol. Min. Res.* **2011**, *3*, 13–20. [\[CrossRef\]](#)
18. Coker, J.O. Vertical electrical sounding (VES) methods to delineate potential groundwater aquifers in Akobo area, Ibadan, South-western, Nigeria. *J. Geol. Min. Res.* **2012**, *4*, 35–42. [\[CrossRef\]](#)
19. Fadele, S.I.; Sule, P.O.; Dewu, B.B.M. The use of vertical electrical sounding (VES) for groundwater exploration around Nigerian College of Aviation Technology (NCAT), Zaria, Kaduna State, Nigeria. *Pac. J. Sci. Technol.* **2013**, *14*, 549–555.
20. Abdullahi, M.G.; Toriman, M.E.; Gasim, M.B. The Application of Vertical Electrical Sounding (VES) for Groundwater Exploration in Tudun Wada Kano State, Nigeria. *J. Geol. Geosci.* **2015**, *4*, 1–3. [\[CrossRef\]](#)
21. van Overmeeren, R.A. A combination of electrical resistivity, seismic refraction, and gravity measurements for groundwater exploration in Sudan. *Geophysics* **1981**, *46*, 1304–1313. [\[CrossRef\]](#)
22. Haeni, F.P. Application of seismic refraction methods in groundwater modeling studies in New England. *Geophysics* **1986**, *51*, 236–249. [\[CrossRef\]](#)
23. Grelle, G.; Guadagno, F.M. Seismic refraction methodology for groundwater level determination: “Water seismic index”. *J. Appl. Geophys.* **2009**, *68*, 301–320. [\[CrossRef\]](#)
24. Dafflon, B.; Irving, J.; Holliger, K. Use of high-resolution geophysical data to characterize heterogeneous aquifers: Influence of data integration method on hydrological predictions. *Water Resour. Res.* **2009**, *45*. [\[CrossRef\]](#)
25. Khan, U.; Faheem, H.; Jiang, Z.; Wajid, M.; Younas, M.; Zhang, B. Integrating a GIS-Based Multi-Influence Factors Model with Hydro-Geophysical Exploration for Groundwater Potential and Hydrogeological Assessment: A Case Study in the Karak Watershed, Northern Pakistan. *Water* **2021**, *13*, 1255. [\[CrossRef\]](#)
26. Bowling, J.C.; Rodriguez, A.B.; Harry, D.L.; Zheng, C. Delineating Alluvial Aquifer Heterogeneity Using Resistivity and GPR Data. *Groundwater* **2005**, *43*, 890–903. [\[CrossRef\]](#)
27. Kim, J.-W.; Choi, H.; Lee, J.-Y. Characterization of hydrogeologic properties for a multi-layered alluvial aquifer using hydraulic and tracer tests and electrical resistivity survey. *Environ. Geol.* **2005**, *48*, 991–1001. [\[CrossRef\]](#)
28. Goldman, M.; Kafri, U. Hydrogeophysical Applications in Coastal Aquifers. In *Applied Hydrogeophysics*; Springer: Dordrecht, The Netherlands, 2007; pp. 233–254. [\[CrossRef\]](#)
29. Wattanasen, K.; Elming, S. Direct and indirect methods for groundwater investigations: A case-study of MRS and VES in the southern part of Sweden. *J. Appl. Geophys.* **2008**, *66*, 104–117. [\[CrossRef\]](#)
30. Doro, K.O.; Leven, C.; Cirpka, O.A. Delineating subsurface heterogeneity at a loop of River Steinlach using geophysical and hydrogeological methods. *Environ. Earth Sci.* **2013**, *69*, 335–348. [\[CrossRef\]](#)
31. Dickson, N.E.M.; Comte, J.-C.; McKinley, J.; Ofterdinger, U. Coupling ground and airborne geophysical data with upscaling techniques for regional groundwater modeling of heterogeneous aquifers: Case study of a sedimentary aquifer intruded by volcanic dykes in Northern Ireland. *Water Resour. Res.* **2014**, *50*, 7984–8001. [\[CrossRef\]](#)
32. Vilhelmsen, T.N.; Behroozmand, A.A.; Christensen, S.; Nielsen, T.H. Joint inversion of aquifer test, MRS, and TEM data. *Water Resour. Res.* **2014**, *50*, 3956–3975. [\[CrossRef\]](#)
33. Michael, H.A.; Post, V.E.A.; Wilson, A.M.; Werner, A.D. Science, society, and the coastal groundwater squeeze. *Water Resour. Res.* **2017**, *53*, 2610–2617. [\[CrossRef\]](#)
34. Daniels, J.J.; Roberts, R.; Vendl, M. Ground penetrating radar for the detection of liquid contaminants. *J. Appl. Geophys.* **1995**, *33*, 195–207. [\[CrossRef\]](#)
35. Benson, A.K.; Payne, K.L.; Stubben, M.A. Mapping groundwater contamination using dc resistivity and VLF geophysical methods—A case study. *Geophysics* **1997**, *62*, 80–86. [\[CrossRef\]](#)
36. Frohlich, R.K.; Urish, D.W.; Fuller, J.; O'Reilly, M. Use of geoelectrical methods in groundwater pollution surveys in a coastal environment. *J. Appl. Geophys.* **1994**, *32*, 139–154. [\[CrossRef\]](#)

37. Cosentino, P.; Capizzi, P.; Fiandaca, G.; Martorana, R.; Messina, P.; Pellerito, S. Study and Monitoring of Salt Water Intrusion in The Coastal Area Between Mazara Del Vallo And Marsala (South-Western Sicily). In *Methods and Tools for Drought Analysis and Management*; Springer: Berlin/Heidelberg, Germany, 2007; pp. 303–321. [\[CrossRef\]](#)
38. Capizzi, P.; Cellura, D.; Cosentino, P.; Fiandaca, G.; Martorana, R.; Messina, P.; Schiavone, S.; Valenza, M. Integrated hydrogeochemical and geophysical surveys for a study of sea-water intrusion. *Boll. Geofis. Teor. Appl.* **2010**, *51*, 285–300.
39. Di Napoli, R.; Martorana, R.; Orsi, G.; Aiuppa, A.; Camarda, M.; De Gregorio, S.; Candela, E.G.; Luzio, D.; Messina, N.; Pecoraino, G.; et al. The structure of a hydrothermal system from an integrated geochemical, geophysical, and geological approach: The Ischia Island case study. *Geochem. Geophys. Geosyst.* **2011**, *12*. [\[CrossRef\]](#)
40. Martorana, R.; Lombardo, L.; Messina, N.; Luzio, D. Integrated geophysical survey for 3D modelling of a coastal aquifer polluted by seawater. *Near Surf. Geophys.* **2013**, *12*, 45–59. [\[CrossRef\]](#)
41. Capizzi, P.; Martorana, R.; Favara, R.; Albano, L.; Bonfardeci, A.; Catania, M.; Costa, N.; Gagliano, A. Geophysical Contribution to the Reconstruction of the Hydrological Model of “Barcellona-Milazzo Plain” Groundwater Body, Northern Sicily. In *25th European Meeting of Environmental and Engineering Geophysics*; European Association of Geoscientists & Engineers: Moscow, Russia, 2019; pp. 1–5. [\[CrossRef\]](#)
42. Paz, M.C.; Alcalá, F.J.; Medeiros, A.; Martínez-Pagán, P.; Pérez-Cuevas, J.; Ribeiro, L. Integrated MASW and ERT Imaging for Geological Definition of an Unconfined Alluvial Aquifer Sustaining a Coastal Groundwater-Dependent Ecosystem in Southwest Portugal. *Appl. Sci.* **2020**, *10*, 5905. [\[CrossRef\]](#)
43. Park, C.B.; Miller, R.D.; Xia, J. Multimodal Analysis of High Frequency Surface Waves. In *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, Oakland, CA, USA, 14–18 June 1999.
44. Alcalá, F.J.; Martínez-Pagán, P.; Paz, M.C.; Navarro, M.; Pérez-Cuevas, J.; Domingo, F. Combining of MASW and GPR Imaging and Hydrogeological Surveys for the Groundwater Resource Evaluation in a Coastal Urban Area in Southern Spain. *Appl. Sci.* **2021**, *11*, 3154. [\[CrossRef\]](#)
45. Nakamura, Y. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quat. Rep. Railw.* **1989**, *30*, 25–33.
46. Martorana, R.; Capizzi, P.; Avellone, G.; D’alessandro, A.; Siragusa, R.; Luzio, D. Assessment of a geological model by surface wave analyses. *J. Geophys. Eng.* **2016**, *14*, 159–172. [\[CrossRef\]](#)
47. Martorana, R.; Agate, M.; Capizzi, P.; Cavera, F.; D’Alessandr, A. Seismo-stratigraphic model of “La Bandita” area in the Palermo Plain (Sicily, Italy) through HVSR inversion constrained by stratigraphic data. *Ital. J. Geosci.* **2018**, *137*, 73–86. [\[CrossRef\]](#)
48. Sorensen, C.; Asten, M. Microtremor methods applied to groundwater studies. *Explor. Geophys.* **2007**, *38*, 125–131. [\[CrossRef\]](#)
49. Delgado, J.; Casado, C.L.; Estévez, A.; Giner, J.; Cuenca, A.; Molina, S. Mapping soft soils in the Segura river valley (SE Spain): A case study of microtremors as an exploration tool. *J. Appl. Geophys.* **2000**, *45*, 19–32. [\[CrossRef\]](#)
50. Martorana, R.; Capizzi, P.; D’Alessandro, A.; Luzio, D.; Di Stefano, P.; Renda, P.; Zarccone, G. Contribution of HVSR measures for seismic microzonation studies. *Ann. Geophys.* **2018**, *61*, 225. [\[CrossRef\]](#)
51. Pino, P.; D’Amico, S.; Orecchio, B.; Presti, D.; Scolaro, S.; Torre, A.; Totaro, C.; Farrugia, D.; Neri, G. Integration of geological and geophysical data for revaluation of local seismic hazard and geological structure: The case study of Rometta, Sicily (Italy). *Ann. Geophys.* **2018**, *61*, SE227. [\[CrossRef\]](#)
52. Scolaro, S.; Pino, P.; D’Amico, S.; Orecchio, B.; Presti, D.; Torre, A.; Totaro, C.; Farrugia, D.; Neri, G. Ambient noise measurements for preliminary microzoning studies in the city of Messina, Sicily. *Ann. Geophys.* **2018**, *61*, 228. [\[CrossRef\]](#)
53. Dal Moro, G. *Surface Wave Analysis for Near Surface Applications*; Elsevier: Amsterdam, The Netherlands, 2014.
54. Cafiso, F.; Canzoneri, A.; Capizzi, P.; Carollo, A.; Martorana, R.; Romano, F. Joint interpretation of electrical and seismic data aimed at modelling the foundation soils of the Maredolce monumental complex in Palermo (Italy). *Archaeol. Prospect.* **2020**, *30*, 69–85. [\[CrossRef\]](#)
55. Gisser, M.; Sánchez, D.A. Competition versus optimal control in groundwater pumping. *Water Resour. Res.* **1980**, *16*, 638–642. [\[CrossRef\]](#)
56. Percopo, C.; Brandolin, D.; Canepa, M.; Capodaglio, P.; Cipriano, G.; Gafà, R.; Iervolino, D.; Marcaccio, M.; Mazzola, M.; Mottola, A.; et al. Criteri tecnici per l’analisi dello stato quantitativo e il monitoraggio dei corpi idrici sotterranei. *ISPRA Man. E Linee Guid.* **2017**, *157*, 1–108.
57. Heilweil, V.M.; Brooks, L.E. *Conceptual Model of the Great Basin Carbonate and Alluvial Aquifer System: US Geological Survey Scientific Investigations Report*; U.S. Geological Survey: Reston, VA, USA, 2011.
58. Granata, A.; Castrianni, G.; Pasotti, L.; Gagliano Candela, E.; Scaletta, C.; Madonia, P.; Morici, S.; Bellomo, S.; La Pica, L.; Gagliano, A.L.; et al. Studio per la definizione dei modelli concettuali dei corpi idrici sotterranei di Peloritani, Nebrodi e ragusano e indagini geofisiche correlate. *Atti del 37° Convegno del Gruppo Nazionale di Geofisica della Terra Solida-GNGTS. OGS* **2018**, *37*, 104–108.
59. Canzoneri, A.; Capizzi, P.; Martorana, R.; Albano, L.; Bonfardeci, A.; Costa, N.; Gagliano, A.L.; Favara, R. Modello idrogeologico del corpo idrico “Fiumara di Caronia” (Sicilia Settentrionale). *Atti del 38° Convegno del Gruppo Nazionale di Geofisica della Terra Solida-GNGTS. OGS* **2019**, *38*, 636–640. Available online: <https://gngts.ogs.it/atti-del-38-convegno-nazionale-2/> (accessed on 1 July 2023).
60. Catalano, R.; Di Stefano, P.; Sulli, A.; Vitale, F. Paleogeography and structure of the central Mediterranean: Sicily and its offshore area. *Tectonophysics* **1996**, *260*, 291–323. [\[CrossRef\]](#)

61. Giunta, G.; Giorgianni, A. *Note Illustrative del F.598 “S. Agata di Militello” Della Carta Geologica d’Italia Alla scala 1:50.000*. SystemCart; ISPRA—Università degli Studi di Palermo: Rome, Italy, 2013.
62. Catalano, R.; Valenti, V.; Albanese, C.; Accaino, F.; Sulli, A.; Tinivella, U.; Gasparo Morticelli, M.; Zanolle, C.; Giustiniani, M. Sicily’s fold/thrust belt and slab rollback: The SLRI.PRO. seismic crustal transect. *J. Geol. Soc.* **2013**, *170*, 451–464. [\[CrossRef\]](#)
63. Basilone, L. *Lithostratigraphy of Sicily: UNIPA Springer Series*; Springer International Publishing: Berlin/Heidelberg, Germany, 2018; pp. 1–349.
64. Amodio-Morelli, L.; Bonardi, G.; Colonna, V.; Dietrich, D.; Giunta, G.; Ippolito, F.; Liguori, V.; Lorenzoni, F.; Paglionico, A.; Perrone, V.; et al. L’Arco Calabro-Peloritano nell’orogene Appenninico-Maghrebide. *Mem. Soc. Geol. Ital.* **1976**, *17*, 1–60.
65. Bigi, G.; Cosentino, D.; Parotto, M.; Sartori, R.; Scandone, P. Structural Model of Italy (scale 1:500.000): Geodynamic Project: Consiglio Nazionale delle Ricerche, S.EL.CA: Rome, Italy, 1990. Available online: <https://www.socgeol.it/438/structural-model-of-italy-scale-1-500-000.html/> (accessed on 1 July 2023).
66. Giunta, G.; Nigro, F. Tectono-sedimentary constraints to the Oligocene-to-Miocene evolution of the Peloritani thrust belt (NE Sicily). *Tectonophysics* **1999**, *315*, 287–299. [\[CrossRef\]](#)
67. Nigro, F.; Renda, P. Evoluzione geologica ed assetto strutturale della Sicilia centro- settentrionale. *Boll. Soc. Geol. Ital.* **1999**, *118*, 375–388.
68. Giunta, G.; Luzio, D.; Agosta, F.; Calò, M.; Di Trapani, F.; Giorgianni, A.; Oliveri, E.; Orioli, S.; Perniciaro, M.; Vitale, M.; et al. An integrated approach to investigate the seismotectonics of northern Sicily and southern Tyrrhenian. *Tectonophysics* **2009**, *476*, 13–21. [\[CrossRef\]](#)
69. Bianchi, F.; Carbone, S.; Grasso, M.; Invernizzi, G.; Lentini, F.; Longaretti, G.; Merlini, S.; Mostardini, F. Sicilia orientale: Profilo geologico Nebrodi-Iblei. *Mem. Soc. Geol. Ital.* **1987**, *38*, 429–458.
70. Catalano, R.; Franchino, A.; Merlini, S.; Sulli, A. Central western Sicily structural setting interpreted from seismic reflection profiles. *Mem. Soc. Geol. Ital.* **2000**, *55*, 5–16.
71. Catalano, R.; Gatti, V.; Avellone, G.; Basilone, L.; Frixa, A.; Ruspi, R.; Sulli, A. Subsurface Geometries in Central Sicily FTB as a Premise for Hydrocarbon Exploration. In Proceedings of the 70th EAGE Conference and Exhibition Incorporating SPE EUROPEC, Nuova Fiera Di Roma, Italy, 9–12 June 2008. [\[CrossRef\]](#)
72. Lentini, F.; Carbone, S. Geologia della Sicilia (Geology of Sicily). *Mem. Descr. Carta Geol. d’It.* **2014**, *XCV*, 7–414.
73. Morticelli, M.G.; Valenti, V.; Catalano, R.; Sulli, A.; Agate, M.; Avellone, G.; Albanese, C.; Basilone, L.; Gugliotta, C. Deep controls on foreland basin system evolution along the Sicilian fold and thrust belt. *BSG-Earth Sci. Bull.* **2015**, *186*, 273–290. [\[CrossRef\]](#)
74. Basilone, L.; Bonfardeci, A.; Romano, P.; Sulli, A. Natural Laboratories for Field Observation About Genesis and Landscape Effects of Palaeo-Earthquakes: A Proposal for the Rocca Busambra and Monte Barracù Geosites (West Sicily). *Geoheritage* **2018**, *11*, 821–837. [\[CrossRef\]](#)
75. Giunta, G.; Bellomo, D.; Carnemolla, S.; Pisano, A.; Profeta, R.; Runfola, P. La “Linea di Taormina”: Residuo epidermico di una paleostruttura crostale del fronte cinematico maghrebide? *Acts 8° GNGTS Congr.* **1989**, *8*, 1197–2013.
76. Lentini, F.; Catalano, S.; Carbone, S. Note Illustrative Della Carta Geologica Della Provincia di Messina, Scala 1:50.000: S.EL.CA, Firenze. 2000; pp. 1–70. Available online: https://www.isprambiente.gov.it/Media/carg/note_illustrative/601_Messina_Reggio_Calabria.pdf (accessed on 1 July 2023).
77. Giunta, G.; Nigro, F.; Renda, P. Extensional tectonics during Maghrebides chain building since Late Miocene: Examples from Northern Sicily. *Ann. Soc. Geol. Polon.* **2000**, *70*, 81–89.
78. Giunta, G.; Nigro, F.; Renda, P.; Giorgianni, A. The Sicilian–Maghrebides Tyrrhenian Margin: A neotectonic evolutionary model. *Mem. Soc. Geol. Ital.* **2000**, *119*, 553–565.
79. Renda, P.; Tavarnelli, E.; Tramutoli, M.; Gueguen, E. Neogene deformations of Northern Sicily, and their implications for the geodynamics of the Southern Tyrrhenian Sea margin. *Mem. Soc. Geol. Ital.* **2000**, *55*, 53–59.
80. Nigro, F.; Renda, P. Plio-Pleistocene strike-slip deformation in NE Sicily: The example of the area between Capo Calavà and Capo Tindari. *Boll. Soc. Geol. Ital.* **2005**, *124*, 377–394.
81. Ogniben, L. Nota illustrativa dello schema geologico della Sicilia Nord-Orientale. *Riv. Min. Sic.* **1960**, *2*, 183–212.
82. Wezel, F.C. Geologia del flysch numidico della Sicilia nord-orientale. *Mem. Soc. Geol. Ital.* **1970**, *9*, 225–280.
83. Wezel, F.C. Flysch succession and the tectonic evolution of Sicily during the Oligocene and early Miocene. In *Geology of Italy*; Squires, C.H., Ed.; Earth Sciences Soc. Libyan Arabian Republic: Tripoli, Libya, 1974; pp. 105–127.
84. Giunta, G. Problematiche ed ipotesi sul bacino numidico nelle Maghrebidi siciliane. *Boll. Soc. Geol. Ital.* **1985**, *104*, 239–256.
85. Lentini, F. Carta Geologica della Provincia di Messina, Scala 1:50.000: S.EL.CA, Firenze. 2000. Available online: https://www2.regione.sicilia.it/beniculturali/dirbenicult/bca/ptpr/documentazione%20tecnica%20messina/CARTOGRAFIA/ANALISI/03_Geologia.pdf (accessed on 1 July 2023).
86. APAT. Carta Geologica d’Italia in scala 1:50.000—Foglio 598, S. Agata di Militello: ISPRA-Regione Siciliana-D.S.G.-uni., Palermo, SystemCart, Roma. 2013. Available online: https://www.isprambiente.gov.it/Media/carg/598_SANTAGATA_MILITELLO/Foglio.html (accessed on 1 July 2023).
87. Celico, P. *Prospezioni Idrogeologiche, Vol. I e Vol. II*; Liguori Editore Napoli: Naples, Italy, 1988.
88. Pantaleone, D.V.; Vincenzo, A.; Fulvio, C.; Silvia, F.; Cesaria, M.; Giuseppina, M.; Ilaria, M.; Vincenzo, P.; Rosa, S.A.; Gianpietro, S.; et al. Hydrogeology of continental southern Italy. *J. Maps* **2018**, *14*, 230–241. [\[CrossRef\]](#)

89. Ferrara, V.; Amantia, A.; Pennisi, A. Lineamenti idrogeologici e vulnerabilità all'inquinamento degli acquiferi della fascia costiera tirrenica del messinese (versante settentrionale dei M. Peloritani—Sicilia NE). In *Proceedings of the Congresso Biennale*, Palermo Torre Normanna, Palermo, Italy, 21–23 September 1993.
90. Ferrara, V. Vulnerabilità all'inquinamento degli Acquiferi dell'area Peloritana (Sicilia Nord-Orientale), Studi Sulla Vulnerabilità Degli Acquiferi 14. In *Quaderni di Tecniche di Protezione Ambientale: Edizione Pitagora*; Pitagora Editrice Srl.: Bologna, Italy, 1999.
91. Civita, M. *Idrogeologia Applicata e Ambientale*; CEA Editore: Rozzano, Italy, 2005; p. 800. ISBN 8808087417.
92. Castany, G. *Idrogeologia*. In *Principi e Metodi: Edizione Flaccovio Dario*, Palermo; Pitagora Editrice Srl.: Bologna, Italy, 1985.
93. Hiscock, K.M.; Bense, V.F. *Hydrogeology: Principles and Practice*, 2nd ed.; Wiley-Blackwell: Oxford, UK, 2014.
94. Gorla, M. Pozzi per acqua. In *Manuale Tecnico di Progettazione: Edizione Flaccovio Dario*; Pitagora Editrice Srl.: Bologna, Italy, 2010.
95. Civita, M. *Geologia Tecnica*; ISCED: Ottawa, ON, Canada, 1975.
96. Mouton, J.; Mangano, F.; Fried, J.J. *Studio Delle Risorse in Acque Sotterranee Dell'Italia*; Schafer Druckerei: Hannover, Germany, 1982; p. 515.
97. CASMEZ (CASsa per il MEZZogiorno)—Direzione Generale Progetti Speciali. Progetto Speciale n. 30: Utilizzazione delle acque degli schemi idrici intersettoriali della Sicilia. In *Indagini Idrogeologiche e Geofisiche per il Reperimento di Acque Sotterranee per L'approvvigionamento Idrico del Sistema IV Zona Nord Orientale Della Sicilia (Messinese)*; CASMEZ: Palermo, Italy, 1978.
98. Nogoshi, M.; Iragashi, T. On the propagation characteristic of the microtremors. *J. Seismol. Soc. Jpn.* **1970**, *24*, 24–40.
99. Forte, G.; Chioccarelli, E.; De Falco, M.; Cito, P.; Santo, A.; Iervolino, I. Seismic soil classification of Italy based on surface geology and shear-wave velocity measurements. *Soil Dyn. Earthq. Eng.* **2019**, *122*, 79–93. [[CrossRef](#)]
100. Harbaugh, A.W.; Banta, E.R.; Hill, M.C.; McDonald, M.G. MODFLOW2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the Ground-Water Flow Process. *U.S. Geol. Surv. Open-File Rep.* **2000**, *92*, 121.
101. Guzman, J.A.; Moriasi, D.N.; Gowda, P.H.; Steiner, J.L.; Starks, P.J.; Arnold, J.G.; Srinivasan, R. A model integration framework for linking SWAT and MODFLOW. *Environ. Model. Softw.* **2015**, *73*, 103–116. [[CrossRef](#)]
102. McDonald, M.; Harbaugh, A. *A Three Dimensional Finite Difference Ground Water Flow Model*; U.S. Geological Survey: Reston, VA, USA, 1988.
103. Batu, V. Numerical Flow and Solute Transport Modeling in Aquifers. In *Applied Flow and Solute Transport Modeling in Aquifers: Fundamental Principles and Analytical and Numerical Methods*; CRC Press, Taylor & Francis Group: Boca Raton, FL, USA, 2006; pp. 215–344. ISBN 9780849335747.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

3.3 “Coastal Groundwater Bodies Modelling Using Geophysical Surveys: The Reconstruction of the Geometry of Alluvial Plains in the North-Eastern Sicily (Italy)”

In this paragraph, the paper published in international journal *Water* in the 2024 (Capizzi et al.2024) is annexed.

Article

Coastal Groundwater Bodies Modelling Using Geophysical Surveys: The Reconstruction of the Geometry of Alluvial Plains in the North-Eastern Sicily (Italy)

Patrizia Capizzi ^{1,*} , Raffaele Martorana ¹ , Alessandro Canzoneri ¹ , Alessandro Bonfardeci ¹ 
and Rocco Favara ²

¹ Department of Earth and Marine Sciences (DISTEM), Università degli Studi di Palermo, 90123 Palermo, Italy; raffaele.martorana@unipa.it (R.M.); alessandro.canzoneri@unipa.it (A.C.); alessandro.bonfardeci@unipa.it (A.B.)

² Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, 90146 Palermo, Italy; rocco.favara@ingv.it

* Correspondence: patrizia.capizzi@unipa.it

Abstract: The integration of various geophysical methodologies is considered a fundamental tool for accurately reconstructing the extent and shape of a groundwater body and for estimating the physical parameters that characterize it. This is often essential for the management of water resources in areas affected by geological and environmental hazards. This work aims to reconstruct the pattern and extent of two groundwater bodies, located in the coastal sectors of the North-Eastern Sicily, through the integrated analysis and interpretation of several geoelectrical, seismic and geological data. These are the Sant'Agata-Capo D'Orlando (SCGWB) and the Barcelona-Milazzo (BMGWB) Groundwater Bodies, located at the two ends of the northern sector of the Peloritani geological complex. These two studied coastal plains represent densely populated and industrialized areas, in which the quantity and quality of the groundwater bodies are under constant threat. At first, the resistivity models of the two groundwater bodies were realized through the inversion of a dataset of Vertical Electrical Soundings (VES), constrained by stratigraphic well logs data and other geophysical data. The 3D resistivity models obtained by spatially interpolating 1D inverse VES models have allowed for an initial recognition of the distribution of groundwater, as well as a rough geological framework of the subsoil. Subsequently, these models were implemented by integrating results from active and passive seismic data to determine the seismic P and S wave velocities of the main lithotypes. Simultaneous acquisition and interpretation of seismic and electrical tomographies along identical profiles allowed to determine the specific values of seismic velocity, electrical resistivity and chargeability of the alluvial sediments, and to use these values to constrain the HVSR inversion. All this allowed us to recognize the areal extension and thickness of the various lithotypes in the two investigated areas and, finally, to define the depth and the morphology of the base of the groundwater bodies and the thickness of the filling deposits.

Keywords: Vertical Electrical Soundings; active and passive seismics; well log; groundwater body; coastal alluvial plain; 3D resistivity model



Citation: Capizzi, P.; Martorana, R.; Canzoneri, A.; Bonfardeci, A.; Favara, R. Coastal Groundwater Bodies Modelling Using Geophysical Surveys: The Reconstruction of the Geometry of Alluvial Plains in the North-Eastern Sicily (Italy). *Water* **2024**, *16*, 1048. <https://doi.org/10.3390/w16071048>

Academic Editor: Adriana Bruggeman

Received: 24 February 2024

Revised: 26 March 2024

Accepted: 2 April 2024

Published: 5 April 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The integration of geological and geophysical data for the reconstruction of subsurface models is a widespread practice nowadays. In numerous research fields, direct investigations, such as trenches and boreholes, are associated with data obtained by geophysical acquisitions to expand the available dataset and improve the subsurface characterization. Furthermore, the net of the actual cost of geophysical instrumentation, the relationship between the amount of data acquired and the economic evaluation of a geophysical survey make geophysical methodologies quite economical when compared to direct investigations.

This approach had been often used in many studies regarding stratigraphic [1–3] and structural geology [4–7], the analysis of depositional sequences [8–10], archaeological [11–13] and civil engineering research [14–16]. In these studies, acquired geophysical data constrained by the information derived from direct investigation provide a fundamental tool for the integration and definition of subsurface models. Even hydrogeology research exploits this workflow for numerous purposes: the description of groundwater depth and thickness [17–19], definition of the physical–chemical characteristics of an aquifer [20–22], assessment of marine ingression in coastal areas [23–25] and evaluation of water quality and degree of pollution [26–28].

In recent years, several studies based on integrated approaches of geological and geophysical datasets have focused on coastal areas that host floodplains [29–31]. These flat areas are often critically important for different reasons. They are usually densely populated and, considering their proximity to the sea, host strategic harbors; seaside tourism causes a clear increase in the population during the warm months. Moreover, the gentle morphology favors the development of numerous road and railway communication routes and, consequently, of industrialized areas adjacent to the main towns.

Unfortunately, coastal alluvial plains are often subjected to various risks, both natural, such as floods and paroxysmal events linked to wave motion, and those linked to the development of anthropic activities. Furthermore, the human impact on these areas causes excessive exploitation and contamination of aquifers. All this can lead to serious damage to infrastructure, negatively affecting industrial, tourism, fishing, and agricultural activities. Knowledge of the subsoil is, therefore, fundamental to effectively addressing all these problems.

This work presents the 2D modelling of two coastal alluvial plains, present in North-Eastern Sicily, hosting groundwater bodies: the Barcellona–Milazzo (BMGWB) and the S. Agata–Capo D’Orlando plain (SCGWB). The characterization of the alluvial geometries present in these two sectors have been defined by combining the boreholes data and several data collected by geophysical acquisition campaigns carried out at different times. Firstly, Vertical Electrical Soundings (VES) and Seismic Refraction (SR) profiles were realized in the 1970s by a project sponsored by a public entity named “Cassa per il Mezzogiorno” (CASMEZ), created by the Italian government to finance industrial initiatives aimed at the economic development of Southern Italy [32]. Subsequently, in 2019, these data were partly reinterpreted and integrated by other both active and passive seismic methods as part of a project conducted by the INGV (National Institute of Geophysics and Volcanology—Palermo Section) and DAR (Regional Water and Waste Department) [33]. Through the integration of all the data, the thickness of the alluvial deposit and the depth of the bottom were defined.

The subsoil models produced are a basic tool for evaluating the water resources of the area and the possibilities of exploiting them. Moreover, these study results should be a useful tool to define the geological hazards of the two sectors analyzed and to identify any areas that may be subject to environmental pollution. In conclusion, for all these reasons, the models created can also be considered fundamental to follow for basic studies in defining the city’s master plans.

2. Geology and Hydrogeology

2.1. Geomorphological and Geological Setting

The Sant’Agata–Capo D’Orlando and Barcellona–Milazzo plains are in the Tyrrhenian coastal sector of the Peloritani Mountains (North-Eastern Sicily). In particular, the two areas studied are spread over an area of about 40.70 km² for the Sant’Agata–Capo D’Orlando plain and of about 1319 km² for the Barcellona–Milazzo one.

Several towns and villages lie in these two coastal plains, among which Sant’Agata di Militello, Capo D’Orlando, Barcellona Pozzo di Gotto and Milazzo are the main municipalities. Strategical infrastructures like harbors, highways, and railway lines, as well as industrial plants and several farms, are present in these sectors. Noteworthy is the site

of national interest (SIN) represented by the petroleum refinery and chemical industries located east of Milazzo, at the mouth of the Corriolo Stream.

From a geo-structural point of view, the North-Eastern Sicily lies in a crucial sector of the central Mediterranean region in correspondence of the African and European plates boundary, characterizing the Sicilian foreland–foredeep–chain system (Figure 1c) [34–36]. The Peloritani Mountains' geological complex (hereafter, Peloritani Complex; PC) constitutes the innermost and structurally highest sector of the Sicilian Fold and Thrust Belt (SFTB) [36–38], (Figure 1b). In particular, the PC represents the southern termination of the Calabrian–Peloritani Arc (CPA), as well as the linking element between the Southern Apennines and the Sicilian Maghreb Chain [39]. The PC is formed by different south-verging tectonic units (nappes), mainly composed by high-to-low-grade metamorphites, deriving from the deformation of an ancient Hercynian basement (Kabalo-Calabride Units) and related carbonate–clastic Meso-Cenozoic sedimentary covers [35,40–44]. The piling up of the tectonic units belonging to the PC and its incorporation into the SFTB began in the upper Oligocene and continued up to the Upper Miocene [45]. During the Plio-Pleistocene, extensional and transcurrent tectonic regimes affected the PC, producing an articulate dip-slip and strike-slip faults pattern, with NW-SE/W-E and NE-SW/N-S orientation [35,46–50]. Lastly, one of the most important tectonic structures of North-Eastern Sicily is represented by the fault zone known as “Taormina line”, constituting the outer front of the PC [35,51]. Furthermore, through this latter tectonic structure, the PC overlaps on the Apennine–Maghrebidi Units (Figure 1c); more precisely, on those deriving from the deformation of the Sicilide complex, widely outcropping in the Nebrodi Mountains [40–44].

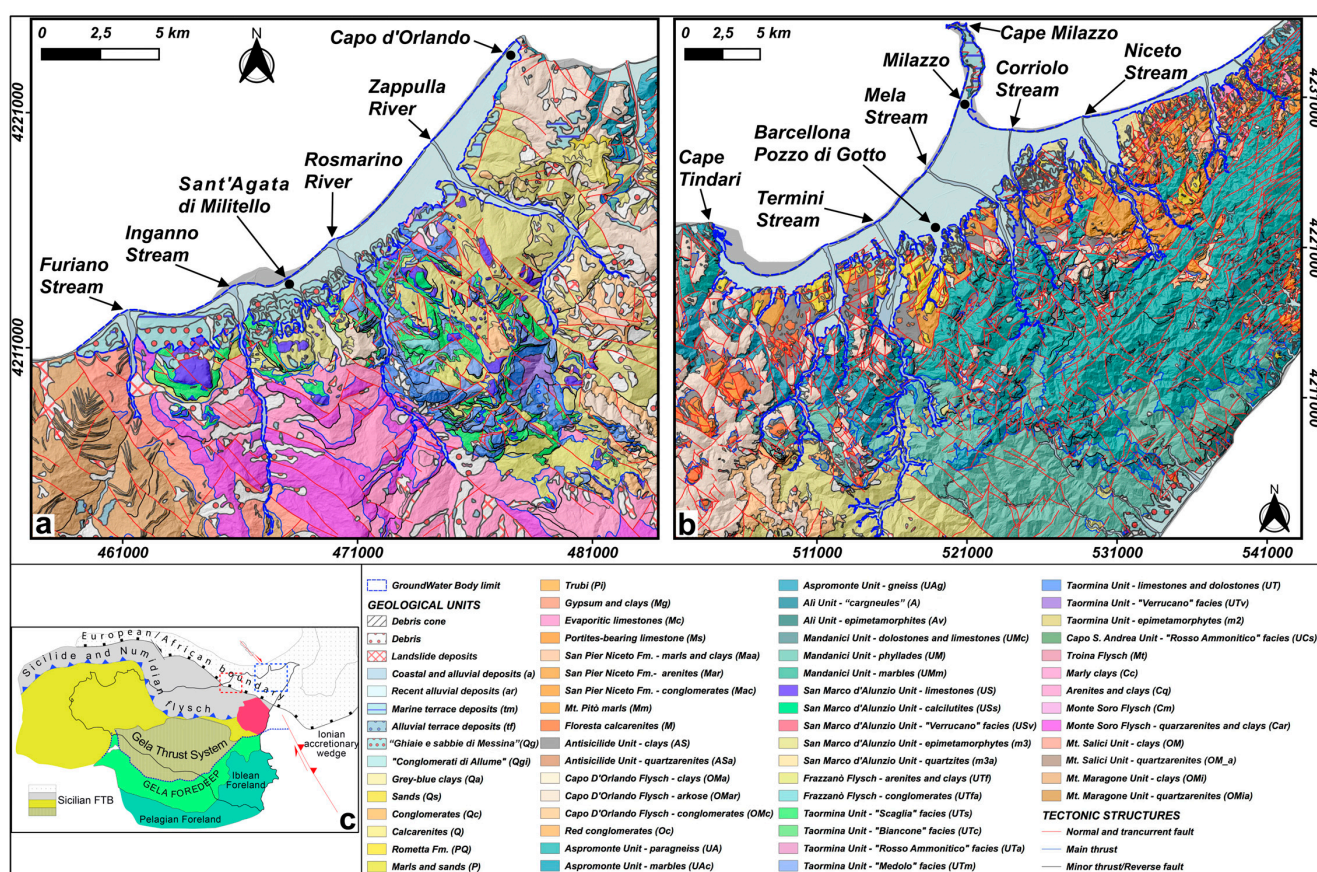


Figure 1. Geological sketch maps of the two investigated areas: the SCGWB on the left (a) and the BMGWB on the right (b). In the bottom left, (c) the structural map of Sicily, illustrating the main

elements of the foreland–foredeep–chain system, is shown (modified from [52]). The location of the study areas of SCGWB (red dashed line) and BMGWB (blue dashed line) is highlighted in this latter map. The geological sketch maps (a,b) were drawn with the QuantumGIS 3.16 software, provided by Open Source Geospatial Foundation (OSGeo), adopting a DEM image as a topographic base. Polygons and lines present in these two maps are referred to the outcropping geological units and tectonic structures, based on geological chart [53] and explanatory notes [40]. The description of the geological units and tectonic structures of the two geological sketch maps is shown in the bottom-right panel.

The tectono-stratigraphic sequence outcropping in the investigated sectors is composed, from the bottom to the top, by the Numidian Flysch, Sicilide and Kabilo–Calabride Units, unconformably covered by syn- and post-orogenic sedimentary sequences [40,44].

In particular, the Numidian Flysch and Sicilide (Figure 1a) complexes are composed of the following:

- the Upper Oligocene–Lower Miocene clays and quartzarenites of the Mt. Maragone and Mt. Salici Units;
- the clays and quartzarenites of the Monte Soro and the marly clays unit, Lower Cretaceous in age.

Tectonically superimposed to the Numidian Flysch and Sicilide Units, the Kabilo–Calabride Units and related Meso-Cenozoic sedimentary covers (Figure 1b) are present [40,44]. This latter sequence is composed of the following, from the bottom to the top:

- Capo Sant’Andrea, Longi-Taormina and San Marco d’Alunzio Units, comprising epimetamorphites deriving from an ancient Hercynian basement and Meso-Cenozoic carbonate covers;
- low- to high-grade metamorphic rocks belonging to the Mandanici and Aspromonte Units, derived from the deformation of the innermost sectors of the Kabilo–Calabride domain (Paleozoic);
- the Upper Oligocene–Lower Miocene syntectonic terrigenous deposit of the Capo d’Orlando Flysch;
- the Upper Cretaceous clays and quartzarenites of the Antisicilide Unit, overthrusting the Capo d’Orlando Flysch;
- the Lower-Middle Miocene Floresta calcarenites and the Mt. Pitò marls, unconformably lying on the deposits of the Antisicilide Unit;
- the Middle-Upper Miocene post-orogenic deposits belonging to the San Pier Niceto Fm. and to the evaporitic series upward.

The tectono-stratigraphic units described are unconformably covered by the Plio-Quaternary marine, fluvio-deltaic and alluvial sequences. These marine deposits, mainly outcropping toward the Tyrrhenian and Ionian coastal sectors, are composed of the Trubi unit (Lower Pliocene), the Upper Pliocene marls and sands, and the Rometta Fm. deposits (Upper Pliocene–Lower Pleistocene), passing laterally and upward to the conglomerates, sands and marly clays of Lower–Middle Pleistocene age. This sedimentary sequence ends with late Quaternary fluvio-deltaic (“Conglomerati di Allume” and “Ghiaie e sabbie di Messina”), marine and alluvial terrace, and alluvial and coastal plain deposits.

The Sant’Agata-Capo d’Orlando and Barcellona-Milazzo plains arise in two wide coastal sectors with peculiar NE-SW orientation. Several rivers and streams, arising further south in the central mountain areas of the PC, are characterized by articulated hydrographic patterns with predominant NW-SE and N-S direction of the river courses [41–43]. Furthermore, the orientation and development of the drainage direction of these streams appears orthogonal to the strike of the belts from which they arise [54]. Their northward flowing into the Sant’Agata-Capo d’Orlando and Barcellona-Milazzo coastal plains guarantees a considerable contribution in terms of freshwater recharge and sediments supply to these sectors.

Therefore, both the rivers and stream drainage patterns and the geometry and orientation of the two coastal plains appear directly controlled by the tectonic setting of these sectors of the PC. Normal and transtensional faults with predominant NW-SE and NE-SW trends characterize the geometry of the Sant'Agata-Capo d'Orlando and Barcellona-Milazzo coastal plains and the thickness of the sedimentary infill. The coastal plains infill is composed by the Middle-Late Pleistocene to Holocene fluvio-deltaic, marine and alluvial terrace deposits, recent alluvial and coastal deposits, reaching the thickness of even more than 100 m, as in the case of the central portion of the Barcellona-Milazzo plain [41,55–57].

2.2. Hydrogeological Setting

The lithology and stratigraphic setting of the sedimentary infill directly influence the groundwater circulation and its storage in the SCGWB and BMGWB. The Potential Infiltration Coefficient (CIP [19,58,59]) can be considered as the parameter through which the permeability of rocks and sedimentary deposits is quantified. As regards the Groundwater Bodies characterising the Sant'Agata-Capo d'Orlando and Barcellona-Milazzo coastal plains and related rivers and all tributaries, the CIP reaches the highest values (0.8–0.9%) estimated in the PC [33]. In these coastal sectors the groundwater bodies are composed by different Middle-Late Quaternary geological units mainly consisting of alternations of gravels, sands and clayey-silts, which are characterized by high permeability for primary porosity [60,61]. Therefore, due to the high porosity and thickness, generally increasing in correspondence of the river and stream mouths, and to the shoreline, SCGWB and BMGWB host significant unconfined aquifers [55,62,63]. The freshwater input on the SCGWB and BMGWB occurs with direct charging or, locally, through exchanges with the adjacent groundwater bodies and aquifers.

In particular, the SCGWB consists of the “Ghiaie e sabbie di Messina”, marine and alluvial terrace deposits, alluvial and coastal plain [40,42,43], characterized by high-to-very high permeability for porosity. The SCGWB lower boundary is characterized by the presence of the flyschoid deposits of the Numidian Flysch and Monte Soro Flysch Units in the westernmost portion, the epimetamorphites and limestones of the San Marco d'Alunzio and Longi-Taormina Units in the central sector, and the Aspromonte Unit and Capo d'Orlando Flysch deposits in the north-easternmost portion. All these lithologies are characterized by medium-low-to-low fracture permeability [61].

The BMGWB is formed by the “Ghiaie e sabbie di Messina”, marine and alluvial terrace deposits, alluvial and coastal plain [40,41,56,57], characterized by high-to-very high permeability for porosity. The BMGWB is superimposed on the Upper Pliocene–Pleistocene marly sandy sequences, the post- and syn-orogenic deposits in the western and central portion and the metamorphites of the Aspromonte Unit in the north-easternmost part of it. All the described units are characterized by medium-low-to-low permeability for porosity and fracturing [61].

3. Materials and Methods

3.1. Previous Geognostic and Geophysical Investigation

Litho-stratigraphic logs of several boreholes, lying in the two study areas, have been collected and analyzed to obtain information about the main sedimentological and stratigraphic features of the deposits. In total, 151 boreholes, lying in the two investigated sectors, were collected. In particular, as shown in Figure 2, 11 of these boreholes were located in the area of the SCGWB and 140 in the BMGWB one.

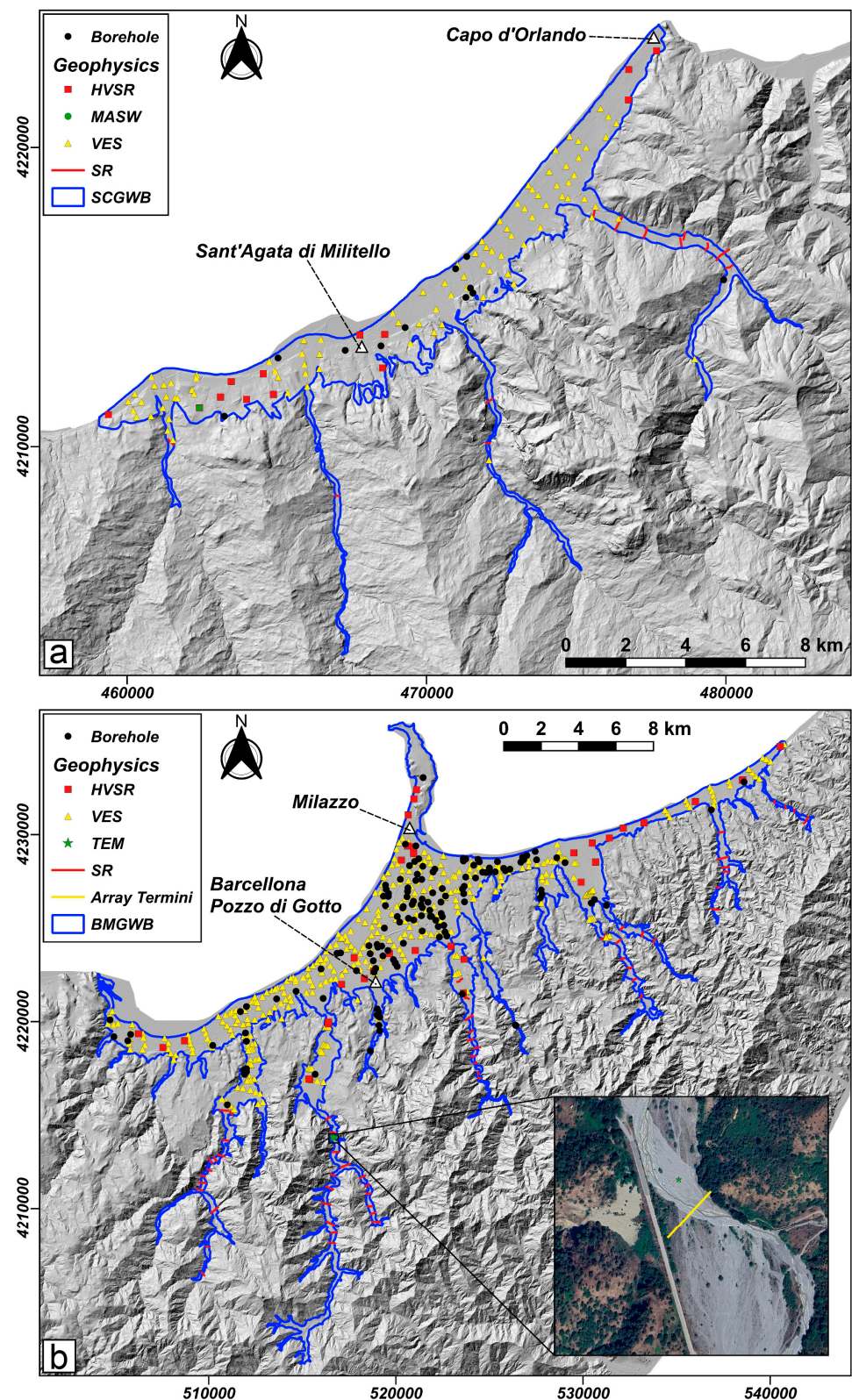


Figure 2. Charts illustrating the location of the boreholes and geophysical surveys analyzed for the study areas. DEM images were used as a topographic base. On the map at the top (a), the data available for the SCGWB are shown, while on the map at the bottom (b), the dataset for the BMGWB is described. As regards the (b) map, in the bottom-right satellite image, the location of the array (yellow line) carried out in the Termini Stream is shown. This array is referred to as the ERT and the SRT realized in this portion of the stream valley.

Most of the analyzed boreholes were drilled using the non-coring drilling method, mainly for groundwater research, while the remaining were drilled using the continuous coring method. The data obtained through the analysis of the boreholes have been reinterpreted and validated, homogenizing the lithologies described with those related to the litho-stratigraphic units present in the geological cartography [53] and the related explanatory notes [40] used for this work. The litho-stratigraphic information provided by these surveys has been used to constrain the inversion of the available geophysical data.

Both the previous SR and VES surveys, as shown in Figure 2, were carried out in the seventies in the two coastal plains for water research activities foreseen by a CASMEZ project [32]. In total, 90 VES and 12 SR profiles were selected within SCGWB, while BMGWB hosted 376 VES and 69 SR. The latter were carried out perpendicular to the axes of rivers present within the two alluvial plains.

3.2. New Processing and Interpretation of Vertical Electrical Soundings

Vertical Electrical Soundings (VES) are a geophysical methodology that usually provides a one-dimensional electrical resistivity model [64]. VES have often been used with good results for studying the physical properties of aquifers and their geometric characterization [65,66]. Despite all this, these surveys can also be useful to describe three-dimensional resistivity models. Indeed, within a studied area, several 1D resistivity data close to each other can be used to constrain the values of each VES. This approach, suitable when the studied area is characterized by a not-too-high resistivity gradient, is useful when large sectors need to be investigated, considering that electrical resistivity tomography appears impractical and expensive.

All vertical electrical soundings considered were performed using the Schlumberger array, with AB current dipole lengths increasing exponentially, so as to obtain roughly equally spaced values in a graph with logarithmic axes. Generally, 10 measurements were performed per logarithmic decade, with maximum AB/2 lengths ranging from 300 m for the shortest soundings up to 500 m for the longest ones, allowing maximum depths of investigation of about 250 m. Among all the VES carried out in the two groundwater bodies, we chose only those whose apparent resistivity vs. AB/2 curves presented a trend compatible with a one-dimensional layered modeling so as to be able to obtain from them 1D layered inverse models with a misfit not exceeding 5%.

For each VES, starting from analog data, the plot of the measured apparent resistivity ρ_a as a function of the half-distance AB/2 between the current electrodes has been digitalized and saved in ASCII files also containing topographic information and the array type.

The digitalized VES were inverted by ZondIP1D (v. 5.2), provided by Zond Software Ltd., Republic of Cyprus (EU) using the least squares method to constrain the inverse models with boreholes data where available. Considering that the studied areas present a fairly regular stratigraphy, a 1.5D inversion algorithm was used, according to which the deepest layer of the resistivity section is considered almost horizontal, while the more superficial layers may be affected by lateral variations in resistivity, albeit slight [67]. Therefore, given these assumptions, inverse models from contiguous VES are mutually constrained (Figure 3a). Consequently, the data were inverted by considering some VES alignments within the study areas, based on the mutual distance between VES points and the alleged geometric features of the geological bodies present in the substrate. The mutually constrained inverse models were laterally interpolated in order to construct two-dimensional electrical resistivity sections along the chosen alignments (Figure 3b). These vertical sections proved useful for providing an initial geological characterization of the two water bodies and as starting data for the subsequent creation of 3D electrical resistivity models.

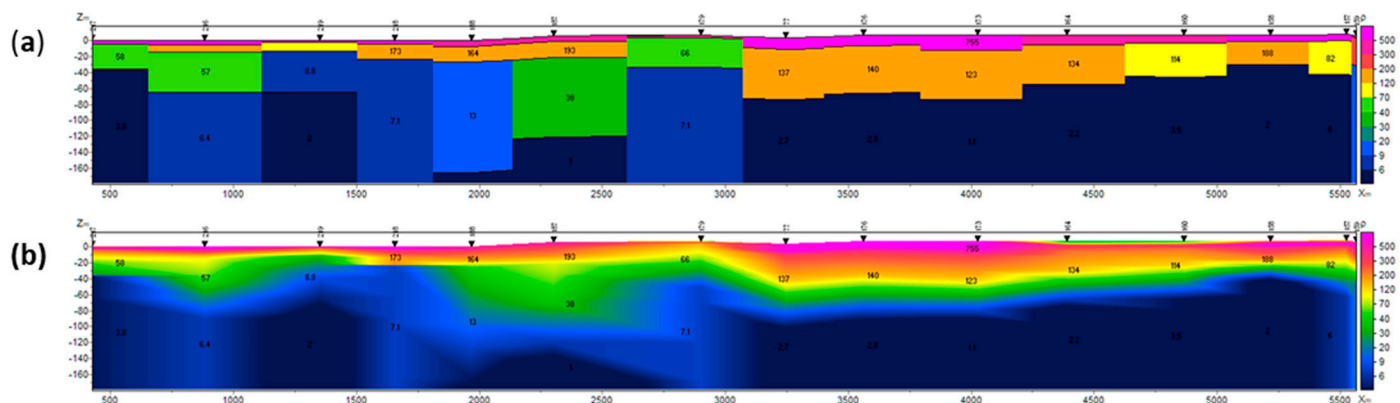


Figure 3. (a) Example of aligned 1D inverse electrical resistivity models obtained from the VES soundings; (b) corresponding 2D resistivity section by lateral interpolation.

3.3. New Geophysical Surveys

A new geophysical acquisition campaign was realized during the DAR project to better describe the geometrical features of SCGWB and BMGWB. For these reasons, both passive and active seismic surveys were performed with the aim of describing the volumes of deposits that could host groundwater.

In detail, 13 recordings of microtremor were acquired for the SCGWB and 50 for the BMGWB, as shown in Figure 2. The environmental noise records were acquired by a 3D velocimeter along the two plains and analyzed according to the HVSr (Horizontal-to-Vertical Spectral Ratio) methodology [68,69].

The inversion of an HVSr curve is subject to significant equivalence limitations and, thus, must be constrained by other geophysical data, mainly for shallower layers, to be considered reliable [70,71]. To this end, it was beneficial to consider the obtained 3D electrical resistivity models and the results of refraction seismic profiles. However, for a more detailed characterization of the v_p and v_s values of lithotypes and the correlation with other observed geophysical parameters, a joint survey Seismic Refraction Tomography (SRT), Electrical Resistivity Tomography (ERT), and Induced Polarization Tomography (IPT) were carried out in coincident position [13]. Furthermore, a Transient Electromagnetic (TEM) survey was performed nearby. Finally, a Multichannel Analysis of Survey Waves (MASW) survey [72] was performed in SCGWB, close to the Acquadolci Town. These surveys were situated in areas where geological knowledge allowed for their joint and detailed interpretation. The geophysical models derived from such surveys, along with other available geophysical models, were used to better constrain HVSr curve inversions, thereby obtaining layered models of seismic velocities. The latter, together with electrical resistivity models and seismic refraction sections, were crucial for determining the thickness of the affected alluvial sediments and the aquifer base.

The ERT, IPT and SRT surveys were carried out in coincident position within the Termini Stream (see Array Termini in Figure 2b). The SRT technique uses a series of aligned and equidistant geophones and a high number of shot records in order to obtain detailed sections of the trend of P-wave velocity in the subsurface [73]. Analogously, ERT and IPT methodologies allow us to obtain detailed 2D sections of electrical resistivity and chargeability using several aligned and equally spaced electrodes, and are often utilized in hydrogeological applications [74–76]. The aim of performing seismic and electrical tomographies along the same alignment in a noticeably area is to characterize the main lithologies in detail from a geophysical point of view, through the joint interpretation of the tomographic sections.

TEM is based on the study of a transient electromagnetic field artificially induced underground in order to reconstruct the trend of electrical conductivity in the investigated volumes. In addition to the mapping of aquifers, this methodology had been used for several applications and studies, such as the characterization of the thickness of volcanic

covers [77], the identification of hydrocarbon reservoirs [78] and the identification of geothermal areas [79].

The MASW survey was performed close to the Acquedolci Town. A multichannel seismograph was used to acquire the data, using 48 vertical geophones (central frequency of 16 Hz) for the SRT and 24 vertical geophones (4.5 Hz frequency) for MASW.

4. Results and Discussion

4.1. Litho-Stratigraphic Interpretation of the Boreholes

The analysis of all the boreholes data for the SCGWB has allowed us to distinguish different kinds of geological substrates, characterized by different lithofacies and units, covered by the recent alluvial deposits. In the western part of the SCGWB, the alluvial deposits cover predominantly clayey–marly layers belonging to the Monte Maragone (OMi) and Monte Soro Flysch (Car) or the limestones and marly limestones of the San Marco (US) and Longi-Taormina Units (UTs). In the eastern part of the SCGWB, however, the geological substrate consists of the metamorphic lithofacies of the San Marco (m^3), Longi-Taormina (m^2) and Aspromonte Units (UA). Finally, in the North-Eastern sector of the SCGWB, under the coastal plain and alluvial deposits, the arkoses (OMar) and clays (OMa) of the Capo D’Orlando Flysch unit are present.

As regards the boreholes falling in the BMGWB, below the coastal plain and alluvial deposits, gray-blue clays (Qa), the calcarenites of the Rometta Fm. (PQ) and the clays (Maa), arenites (Mar) and conglomerates (Mac) belonging to the San Pier Niceto Fm. are present.

4.2. Results from SR Profiles and New Geophysical Surveys

As regards the SR profiles carried out during the CASMEZ project [32], although the original dataset is no longer available, several interpretative models have been evaluated. According to these models, the P-wave velocities in the SCGWB show values of about 2200–3000 m/s for the substrate; beneath the alluvial materials and altered portions of the substrate, the velocities are characterized by values of about 500 and 1300 m/s. The seismic velocity model concerning BMGWB describes a lower substrate and alluvial covers above characterized by 2200–3000 and 1000–1300 m/s, respectively.

The results of the joint-acquired SRT, ERT and IPT (Array Termini) carried out within the BMGWB are shown in Figures 4 and 5. SRT (Figure 4) shows a constant increase in velocities from the top to the bottom of the tomography. Values that characterize the upper 15–18 m vary from 400 to 1000 m/s. Velocities increasing from 1000 m/s to 3000 m/s are described from 20 to 40 m of depth. The deepest part of the section shows the highest P-wave velocity values by a maximum of 4500 m/s found at 60 m depth. Considering the data from the geologic map and from the boreholes located near the SRT, the lower velocities were attributed to recent alluvial sediments; the increase in the velocities of the intermediate layers could be related to the saturated part of these deposits. The highest values have been attributed to the metamorphic rocks of the Aspromonte Unit (UA) that constitute the substrate of this portion of the stream course, also outcropping at the banks.

Results of ERT and IPT are shown in Figure 5. The highest values of resistivity and chargeability have been identified mainly in the lower sections of the profile and are associated with the metamorphic basement. Low values in chargeability are, instead, present in the subsurface. These values, associated with medium-low resistivity values, should indicate the presence of alluvial deposits. These superficial deposits present lower values of resistivity where they are affected by the fluid presence.

The 1D resistivity model obtained by inverting the TEM survey provided a vertical model of resistivity values comparable with those derived from ERT near-realized. The TEM model shows resistivity values ranging from about 100 Ωm to 500 Ωm , according to the layers described in ERT as water-saturated.

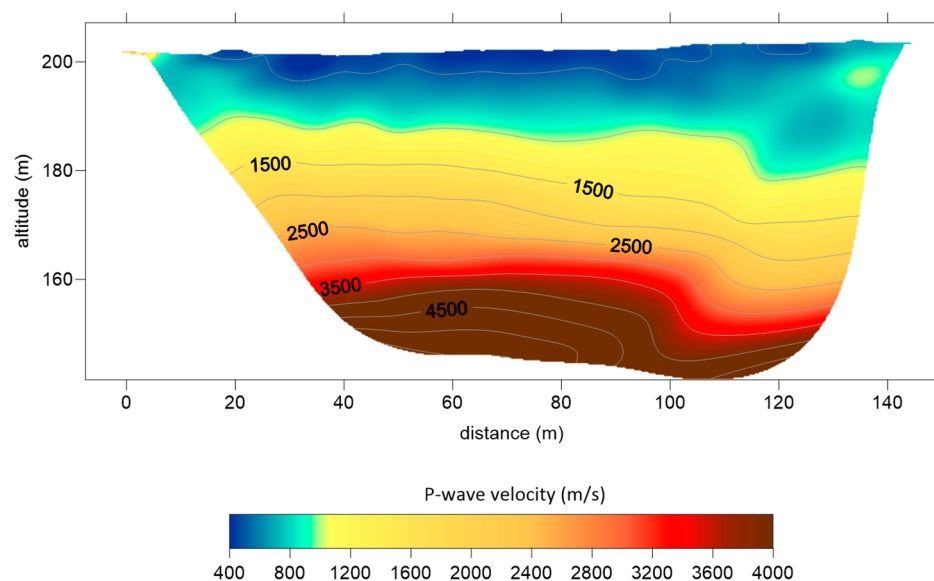


Figure 4. Results of seismic refraction tomography carried out inside the Barcelona–Milazzo Plain, within Termini Stream.

The simultaneous acquisition and interpretation of SRT, ERT and IPT allowed for characterizing the alluvial deposits for their typical values of P-wave velocity, electrical resistivity and chargeability. These values were used for lithotype recognition and the identification of their thickness in both 3D resistivity models and HVSR inverse models.

The MASW realized close to Acquadolci Town, within the SCGWB, provides a seismic-stratigraphic model (Figure 6) composed of a 250 m/s upper superficial cover followed by a 6 m thick layer characterized by a shear waves velocity of 480 m/s. Based on the outcropping rock and information taken from lithologic logs, these values are correlated to the alluvial deposits overlying the “Ghiaie e sabbie di Messina” (Qg) unit.

All the HVSR curves have been inverted, providing inverse shear wave velocity models constrained by all the geophysical and geological data discussed above [80]. Some example results are shown in Figures 7 and 8.

The HVSR inverse models regarding the SCGWB (Figure 7) are generally subdivided into layers varying from two to four. The shallower layers, characterized by an average value of 350 m/s and thickness varying from 5 to 30 m, should represent the alluvial and coastal deposits that predominantly outcrop along the plain. Several previous studies [19,81,82] attributed these velocities to sediments from coarse- to fine-size that usually fill the alluvial plains. The layers, with an average value of 600 m/s, correspond to the intermediate portions of the Vs-profiles. These show a maximum thickness of about 60 m and are associated with “Ghiaie e sabbie di Messina” (Qg). The deeper sections of the models represent high velocities, ranging from 800 to 1100 m/s. These values should describe the presence of different units that do not outcrop in the plain. In the west area of the SCGWB, the flyschoid deposits of Mt. Salici Unit (OM) and the limestones of San Marco d’Aluzio Unit (US) should cause these velocities. High values are, instead, attributed to the Frazzanò Flysch unit (UTf) and to the epimetamorphic rocks of the Longi-Taormina Unit (m2) for the easter sector. Finally, in the subsoil present between the Inganno and Rosmarino Streams, the overlapping of layers of the Marly clays (Cc) and the Flsych of Monte Soro Unit (Cm and Car) could be responsible for these elevated velocities computed.

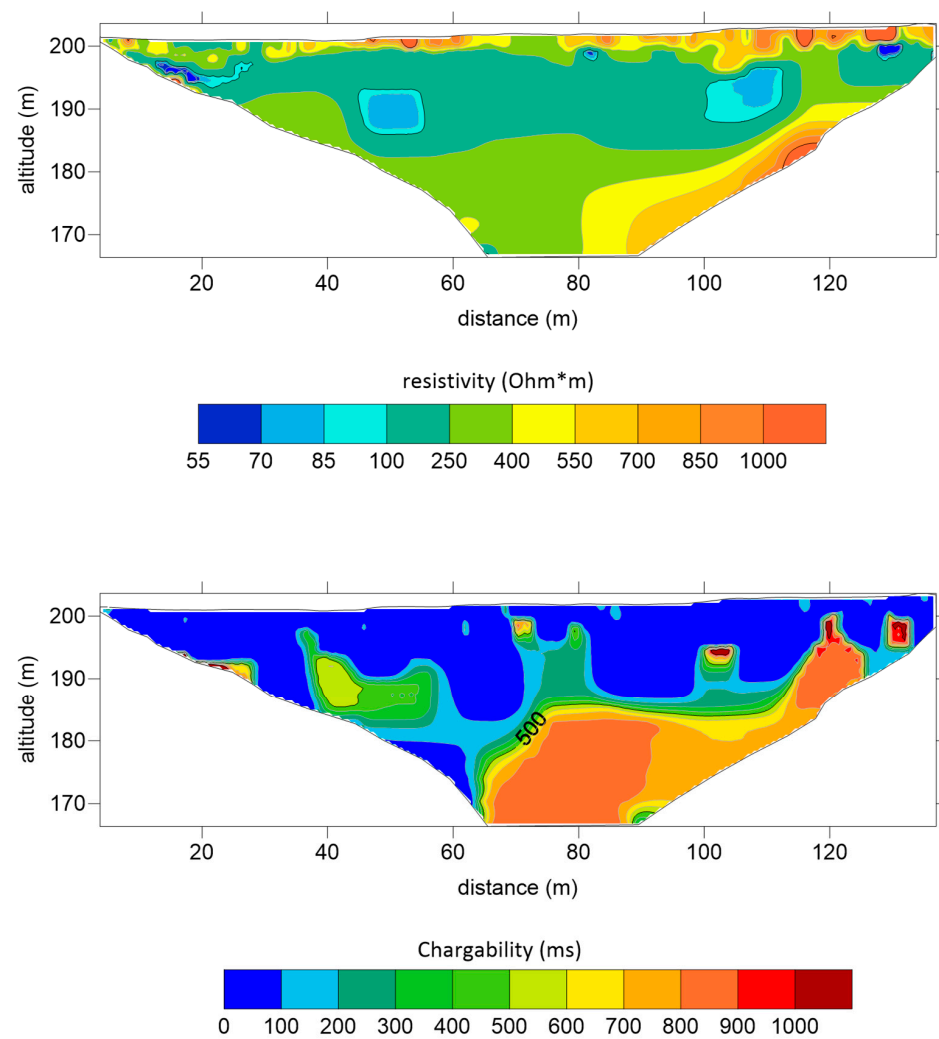


Figure 5. 2D models of resistivity (**above**) and chargeability (**below**) derived from the ERT and IPT carried out in the Plain of Barcelona–Milazzo, within Termini Stream (Array Termini).

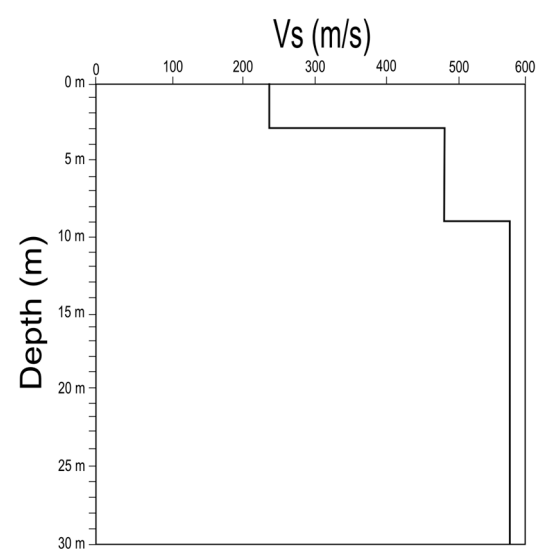


Figure 6. Inverse model resulting from the MASW survey performed in the S. Agata–Capo D’Orlando plain.

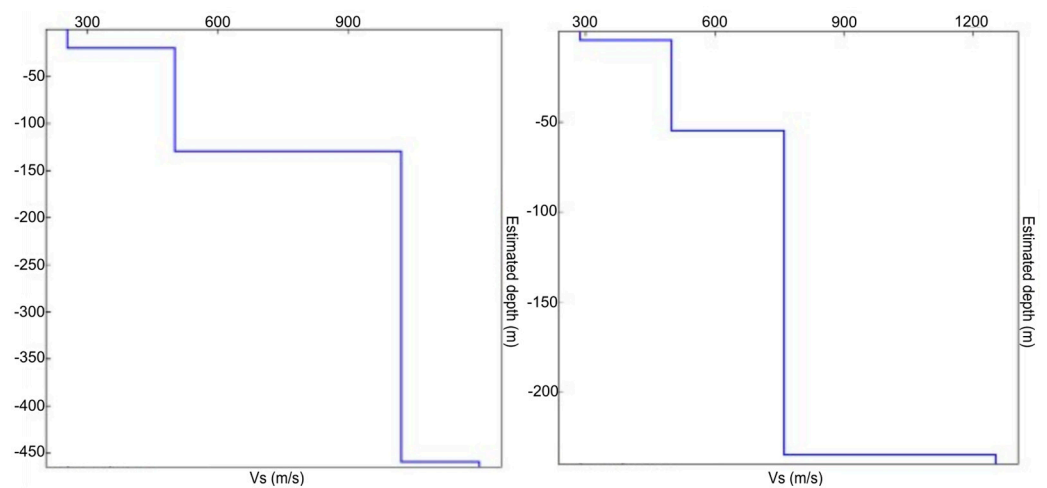


Figure 7. Examples of inverse models related to the HVSR carried out within the Sant’Agata–Capo D’Orlando Plain.

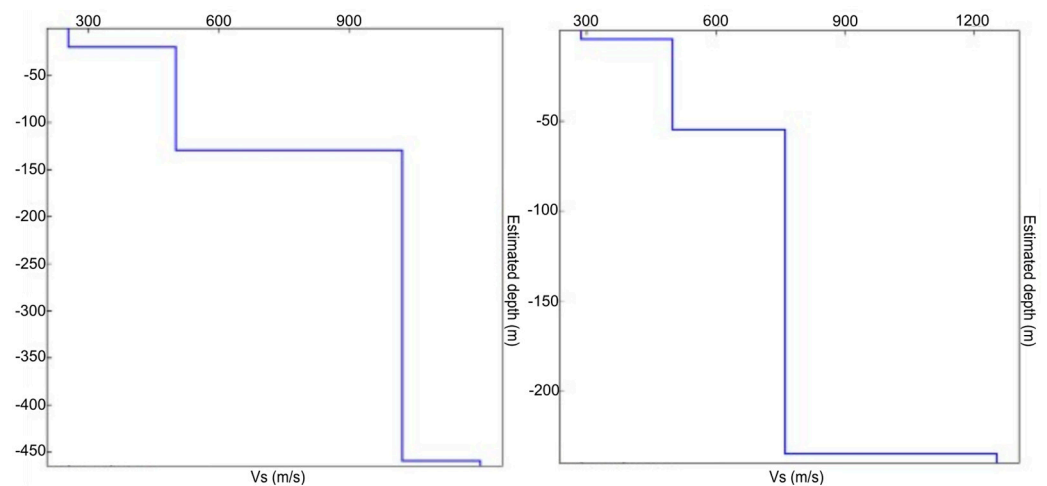


Figure 8. Examples of inverse models related to the HVSR carried out in the BMGWB.

The HVSR surveys realized in the BMGWB, shown in Figure 8, provide similar results about the near surface layers; inside also this waterbody, the superficial alluvial cover shows average V_s values of 300 m/s. Analyzing several single models, the increase of V_s within these first layers is noted, reaching values of 450 m/s, where alluvial deposits present the maximum thickness. This occurs, for example, south of the Milazzo Cape where 80 m of the alluvial deposits are described. Going deeper in the models, a V_s value from 500 to 700 m/s is often present; these values could both be referred to the following formation: “Ghiaie e sabbie di Messina” (Qg), Grey-blue clays (Qa), Rometta (PQ), Trubi (Pi), San Pier Niceto (Maa; Mar; Mac) and Capo d’Orlando Flysch (OMar; OMc). The highest values are found, also for BMGWB, at the base of the HVSR models. The Antisicilide Unit (AS) clays and the metamorphic rocks of the Peloritani Mountains, such as those from the Aspromonte units (UA), have been linked to velocities that exceed 800 m/s.

4.3. Tridimensional Models of the Electrical Resistivity

Three-dimensional models related to the variation of electrical resistivity were realized for SCGWB and BMGWB. These models were produced through the Voxler software v.4, provided by Golden Software (Golden Software, LLC, Golden, CO, USA), LLC, that allowed to laterally interpolate the inverse models of electrical resistivity, obtained from the new reanalyzes of the VES. The lower boundary of the models is given by the depth of investigation of VES while the lateral confinement is provided by the perimeters of the

two groundwater bodies examined. The logarithm of electrical resistivity was chosen to be represented due to the high parameter contrasts found in the two areas.

The model realized for SCGWB, represented in Figure 9, shows areas characterized by different resistivity patterns. In the eastern side of the plain, higher values (200–500 Ω m) have been observed. Within the Furiano water stream, these values should be attributed to the presence of Monte Soro Flysch (Car) and Mt. Maragone Unit (OMia) at shallow depth, below the deposits of SCGWB. The alluvial deposits are, indeed, thin in this area and cover the aforementioned units, mainly composed of the alternations of quartzarenites and clays. Eastwards, in the mouth sector of the Rosmarino River, the resistivity values are high, probably due to the amount of fresh water flowing within alluvial deposits. Furthermore, in this sector of the Rosmarino River, these deposits reach the highest thickness. Lastly, around the Zappula River, the high values of resistivity can be linked to the presence of phyllades and metamorphosed arenites, rich in quartz. These deposits belong to the Longi-Taormina Unit (m²) and are covered by thin alluvial bodies.

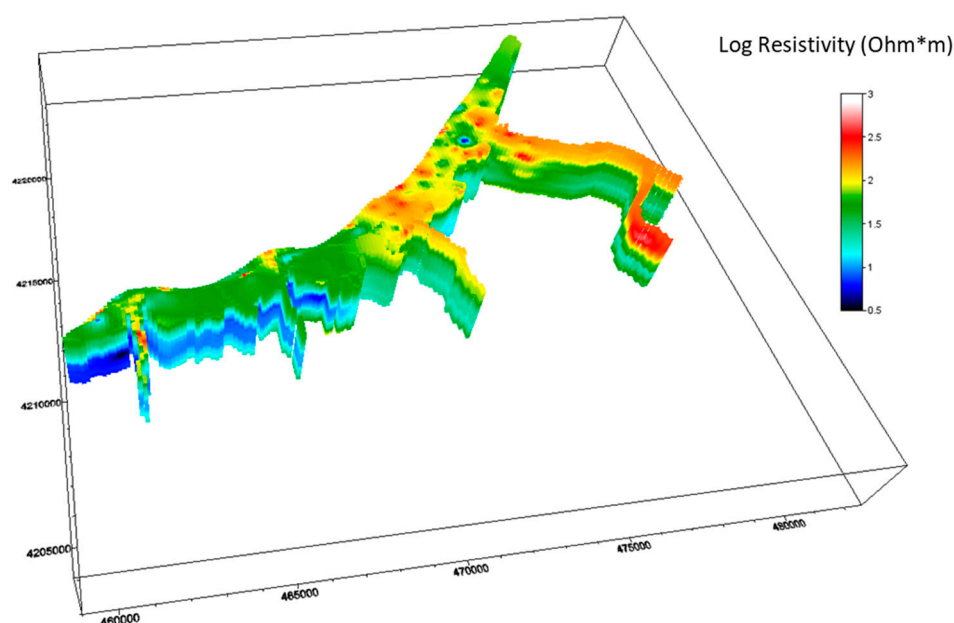


Figure 9. 3D model of the distribution of the logarithm of the electrical resistivity of the water body of the Sant'Agata–Capo D'Orlando Plain (SCGWB).

Medium resistivity values, comprising between 35 and 70 Ω m, are present in several areas of the SCGWB floodplain. In the area between the Furiano and Inganno streams, the abovementioned resistivity values are related to sands, silt and sandy matrix conglomerates, largely outcropping in this sector and also found in the borelogs. These latter sediments are ascribed to the “Ghiaie e sabbie di Messina” (Qg) unit and to the marine terrace deposits (tm). Moreover, the presence of gravels, pebbles and sands in a clayey matrix, identifying recent alluvial (ar), coastal, and stream deposits (a), may be the cause of the not elevated resistivity recognized along the coastline.

Low resistivity values (5–20 Ω m) are observable in the eastern sector of the SCGWB 3D model. The sea water intrusion could be considered one of the causes that produce this decrease in resistivity. Alluvial (ar) and coastal sediments (a) are partly composed of coarser deposits such as polygenic blocks, gravel, and coarse sands. An increase in grain size is often present in the lower portions of these deposits. Due to the sedimentological features, these deposits can be affected by strong sea water intrusion and the formation of a salt wedge below the plain. Moreover, not outcropping conductive rocks, such as those of the Marly clays (Cc) unit and the fractured limestones of the San Marco d'Alunzio Unit

(US), should be responsible for the decrease in the resistivity values, as observed in the deeper part of the model.

The 3D resistivity model of the BMGWB, shown in Figure 10, describes different resistivity trends. Resistivity values from $80 \Omega \text{ m}$ to $1000 \Omega \text{ m}$ are represented in different sectors of the BMGWB; most of the river arms, the central sector of the plain and the area of the Cape Milazzo promontory are characterized by these high values. The highest values, represented in white in Figure 10, are generally located in some sectors of the river arms in which the presence of fresh water causes an increase in resistivity, such as along the Termini and Niceto Streams. Resistivity values of about $80 \Omega \text{ m}$ are widely present in all river courses, both along the plain and in the areas located to the south, closer to the reliefs. In several areas around the mouths of the watercourses, these values are probably linked to the presence of thick alluvial deposits, such as in the coastal sectors of the Termini, Mela, Corriolo and Niceto Streams. Lastly, in the Cape Milazzo promontory, the outcropping metamorphic rocks of the Aspromonte Unit (UA; UAg) induce these medium-high values of resistivity.

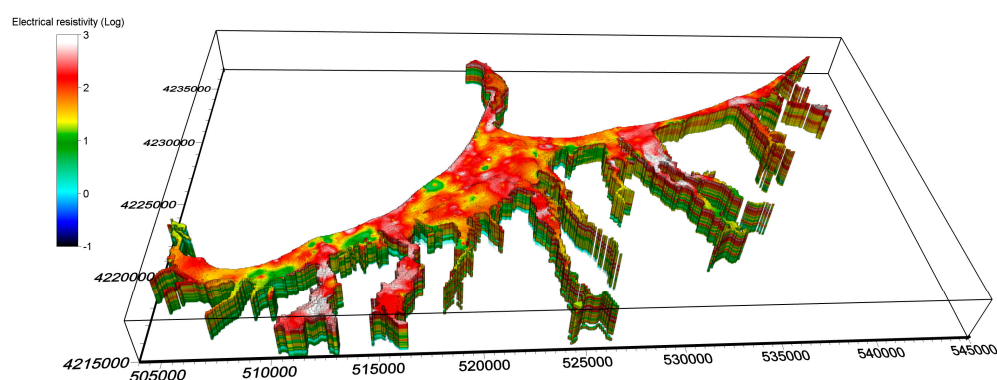


Figure 10. 3D model of the distribution of the logarithm of the electrical resistivity of the BMGWB.

Other areas of the BMGWB are affected by mean resistivity values of about $10\text{--}30 \Omega \text{ m}$; these resistivities characterize the westernmost sector of the coastal plain, along some stream courses and in some areas between them. These values could be linked to portions of the BMGWB hosting alluvial sediments with less thickness. The lowest values described by the model are visible in the deepest parts of the plain, at depths between 40 and 120 m. As an example, the area between the towns of Barcelona P.G. and Milazzo, where the plain presents its greatest extension in N-S direction, is characterized by values less than $10 \Omega \text{ m}$. This feature should be attributed to the presence of clays in the subsurface, as described by other studies performed in this area [57]. Moreover, for the lower values that appear quite shallow and close to the coast, marine ingression phenomena should not be excluded.

By analyzing the two resistivity models, we can notice the different contributions made by the floods and deposits that make up the water body. In the coastal plain areas, the resistivity model is, in fact, more influenced by the deposits of the SCGWB and BMGWB. In these areas, these deposits reach higher volumes. Within the mountain sector, represented in the models by the several arms of the rivers, the variation of resistivity is more linked to the characteristics of the rocks of the substrate, considering the thin thickness of the alluvial cover.

4.4. Estimate of the Bottom of the SCGWB and BMGWB

The thickness of the deposits that constituted SCGWB and BMGWB has been computed by a two-step workflow. Firstly, the deposits' thickness and depth were estimated at several points of the groundwater bodies, considering the results of HVSr inverse models. These were compared with 3D electrical resistivity models and other available geophysical data; additionally, this information was integrated, compiled and interpreted using data from several available boreholes in order to identify the main lithotypes and their thick-

nesses, as appropriate. Subsequently, all punctual thickness and depth data were spatially interpolated using a kriging algorithm available in the Surfer software v.16, provided by Golden Software, LCC (Golden Software, LLC, Golden, CO, USA). In this way, maps of both the bottom of the two water bodies and the thicknesses of the deposits were created (Figures 11 and 12).

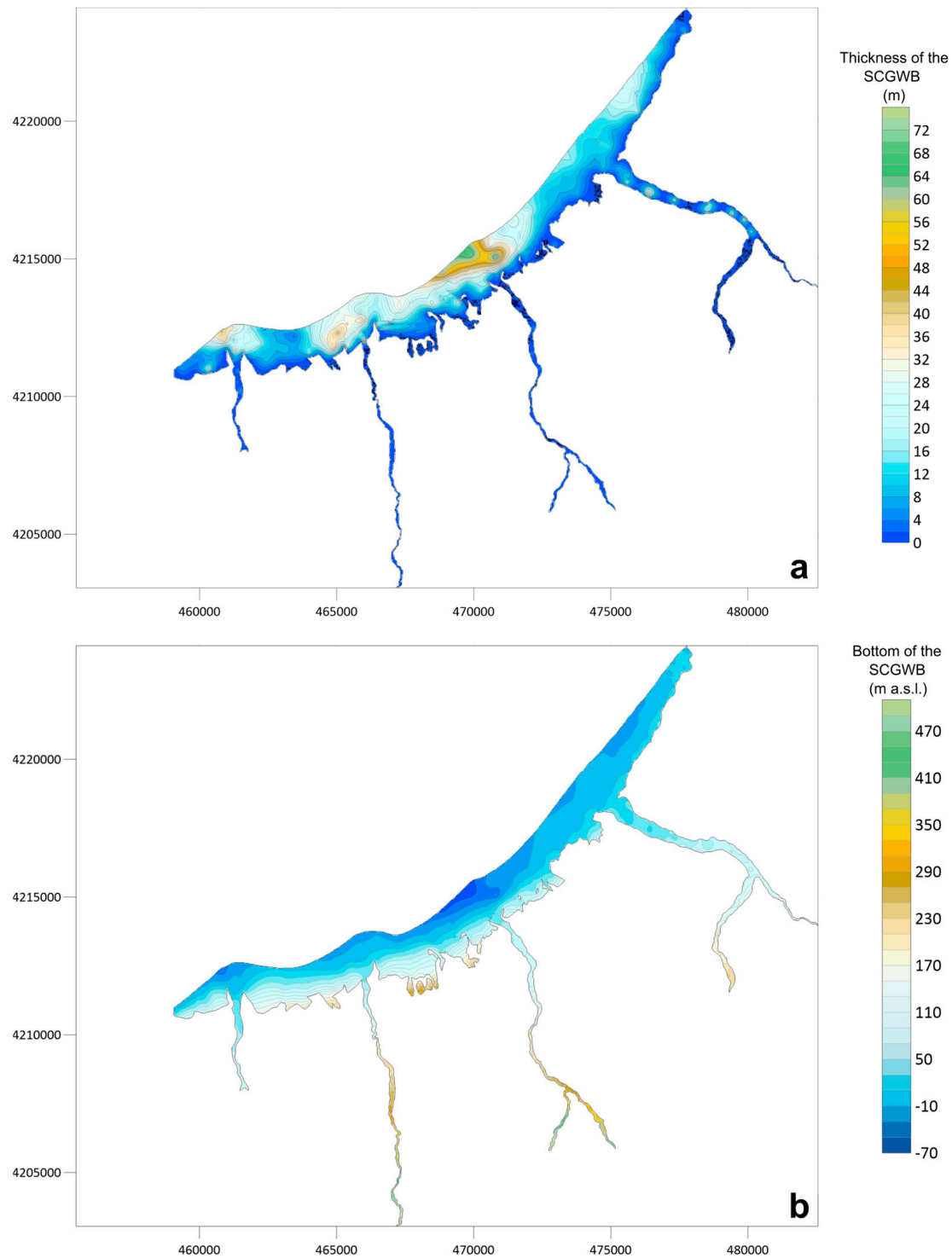


Figure 11. Maps of the thickness of the floods (a) and the depth of the flood bed (b) reconstructed through the integration of geophysical and geological data available within the water body of Sant'Agata-Capo D'Orlando (SCGWB).

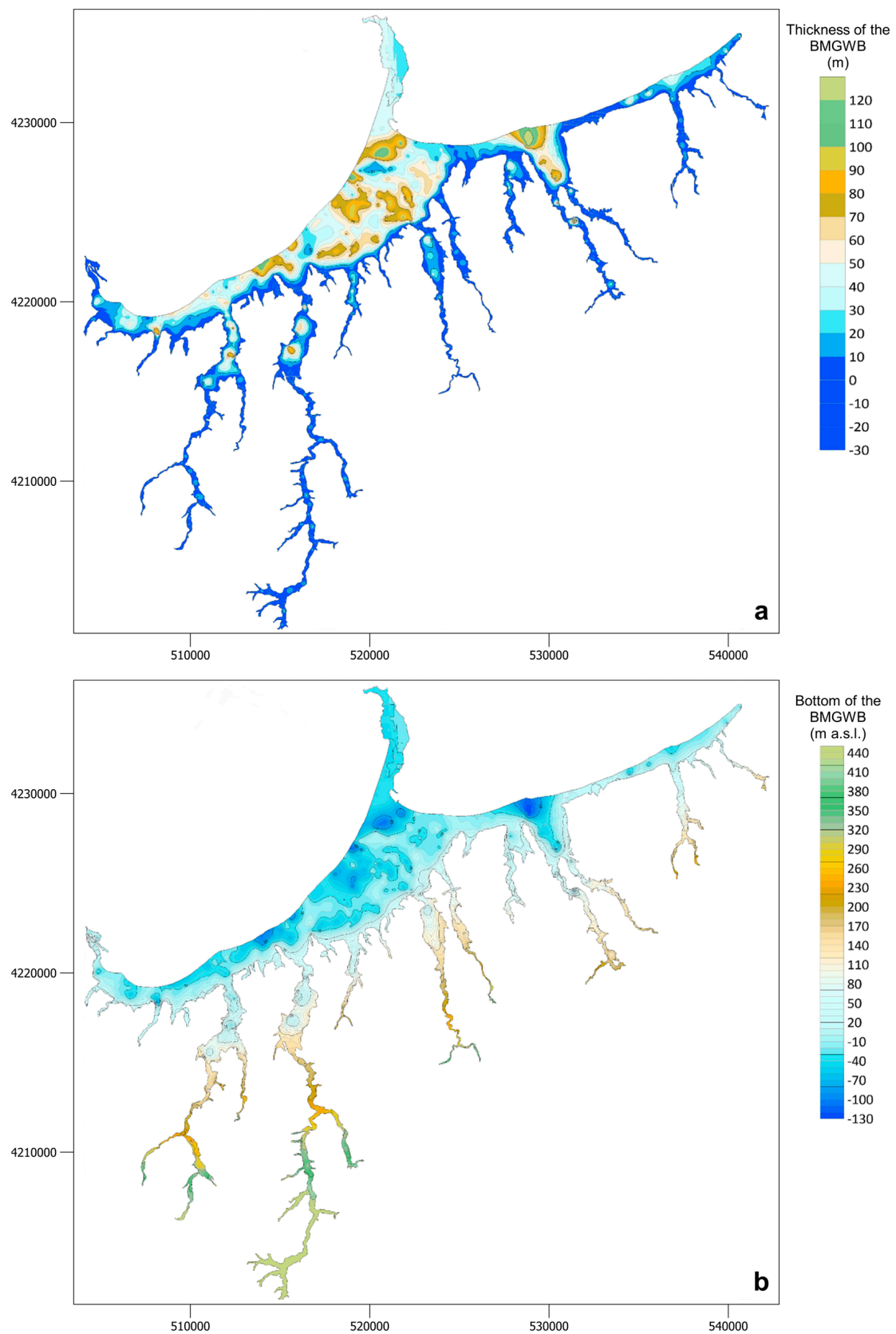


Figure 12. Maps of the thickness of the floods (a) and the depth of the flood bed (b) reconstructed through the integration of geophysical and geological data available within the water body of Barcellona P.G.–Milazzo (BMGWB).

Significant deposit volume variation in the different sectors of SCGWB and BMGWB can be noticed by analyzing the two thickness maps.

With regard to SCGWB (Figure 11a), the largest thicknesses are found in the coastal sector. A maximum depth of about 70 m b.s.l. is noted at the mouth of the Rosmarino river. Other large thicknesses are defined at the mouth of the Furiano Stream. About 30–40 m of floods are, instead, described on the left of the Inganno Stream, in a position slightly decentralized from the current estuary. In the eastern part of the SCGWB, the thicknesses are not large, as seen on the sides of the Zappula Stream. Along the mountain river paths of the SCGWB streams, the floods have been described with thicknesses that generally do not exceed 4–8 m. The same values are present in the plain areas close to the hilly and mountainous areas.

The area described within the BMGWB, shown in Figure 12a, shows the highest flood thicknesses in the northern parts of the plain. In particular, proceeding from West to East, a thickness of the surface coulters of more than 100 m and maximum values of about 120–130 m were obtained for these areas: near the mouth of the Termini Stream, in a coastal area close to the Mela Stream, inside the sector situated in the south of Milazzo Cape, in the area of the mouth of the Niceto stream. Moreover, 70–80 m of deposits were found within the central section of the plain, between Barcelona P.G. and Milazzo towns and in some small areas along the mountain river rods. This occurs, for example, along the Termini stream and along other river courses situated in the east sector of the coastal plain. Thicknesses of 30–50 m are widely present in the coastal areas of the plain, as well as in some small parts of the mountain arms of the rivers. These higher sectors of the BMGWB are mainly characterized by minimum thicknesses, which do not exceed 10 m.

5. Conclusions

The integrated analysis of geological and geophysical data allowed us to reconstruct the thickness of the alluvial deposits present in the two water bodies of the North-Eastern sector of Sicily, exploiting all the stratigraphic and geophysical data available for the two coastal floodplains. In particular, VES data were re-interpreted using a laterally constrained joint inversion algorithm and a 3D interpolation of the inverse models to provide 3D models of the electrical resistivity for the studied areas. Further active and passive seismic surveys, distributed in the study areas, allowed us to characterize the water bodies also with regard to the seismic P- and S-wave velocity of the different lithotypes and alluvial sediments.

The joint performing and interpretation of seismic and electrical tomographies along the same alignment helped to identify, in detail, the seismic velocity, electrical resistivity and chargeability values for the most common lithotypes.

Using all stratigraphic data collected and the geophysical models achieved, maps of the bottom and of the thickness of the deposits filling SCGWB and BMGWB were reconstructed.

These maps are tools that can be used to quantify the water flow rates possibly present in the subsoil. With an appropriate monitoring network, the hydrogeological flow model for these coastal plains could be indeed defined. The latter is a useful elaboration to indicate the opportunity for aquifer exploitation and to individuate the possible causes that could deplete the wealth of the aquifer by forced emulation or pollution.

Furthermore, the geophysical models obtained can be used for stratigraphic studies since the geometric characteristics of deposits can be better defined. Moreover, the variation of the thickness of the alluvial sediments can be correlated with the recent tectonic activity and the rates of uplift experienced by the northern coast of Sicily.

Finally, using such detailed subsurface models is of great interest for studies addressing the characterization of the geological hazards of the two areas that were often affected, in the past, by floods and earthquakes. Furthermore, the models and maps obtained can be a valid aid for identifying and analyzing areas subject to flooding or liquefaction phenomena, and can constitute the starting models for local seismic response studies.

The illustrated research approach, conducted on the North-Eastern coast of Sicily, can be used in similar hydrogeological contexts with a shallow groundwater body, mainly constituted by alluvial deposits. The study shows that the integration of the results of multiple geophysical surveys, supported by the constraint of boreholes, is a useful instrument to define more detailed and accurate subsoil models. Therefore, the different geophysical techniques adopted allow us to reduce the uncertainties related to the results and models derived from the use of geophysical individual surveys.

Author Contributions: Conceptualization, P.C., R.M. and R.F.; methodology, P.C. and R.M.; software, P.C., R.M., A.C. and A.B.; validation, P.C. and R.M.; formal analysis, P.C., R.M. and R.F.; investigation, P.C., A.C. and A.B.; resources, P.C., R.M. and R.F.; data curation, P.C. and R.M.; writing—original draft preparation, A.C. and A.B.; writing—review and editing, R.M.; visualization, P.C. and R.M.; supervision, P.C.; project administration, R.F.; funding acquisition, R.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Regione Siciliana, Commissario Delegato per l’Emergenza Bonifiche e la tutela delle Acque in Sicilia.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to funder restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Cacas, M.C.; Laigle, J.M.; Albouy, E.; Sulzer, C. Integrating stratigraphic modelling and seismic interpretation: Two practical examples. *Pet. Geosci.* **2008**, *14*, 253–261. [\[CrossRef\]](#)
2. Villa, V.; Vermoux, C.; Chaussé, C.; Degeai, J.P.; Robert, V.; Kuzucuoglu, C.; Boschian, G.; Agostini, S.; Aureli, D.; Pagli, M.; et al. The long sedimentary succession of the Valle Giumentina basin (Abruzzo, Central Italy): New evidence from stratigraphic studies and Electrical Resistivity Tomography (ERT). *Alp. Mediterr. Quat.* **2016**, *29*, 193–199.
3. Martorana, R.; Agate, M.; Capizzi, P.; Cavera, F.; D’Alessandro, A. Seismo-stratigraphic model of “La Bandita” area in the Palermo Plain (Sicily, Italy) through HVSR inversion constrained by stratigraphic data. *Ital. J. Geosci.* **2018**, *137*, 73–86. [\[CrossRef\]](#)
4. Caputo, R.; Salviulo, L.; Piscitelli, S.; Loperte, A. Late Quaternary activity along the Scorciabuoi Fault (Southern Italy) as inferred from electrical resistivity tomographies. *Ann. Geophys.* **2007**, *50*, 213–224. [\[CrossRef\]](#)
5. Imposa, S.; Mele, G.; Corrao, M.; Coco, G. Borehole seismic surveys for the mechanical characterization of a calcarenite cliff in the area of Ispica (southern Sicily). *Bull. Eng. Geol. Environ.* **2015**, *74*, 971–980. [\[CrossRef\]](#)
6. Drahor, M.G.; Berge, M.A. Integrated geophysical investigations in a fault zone located on southwestern part of İzmir city, Western Anatolia, Turkey. *J. Appl. Geophys.* **2017**, *136*, 114–133. [\[CrossRef\]](#)
7. Wang, Z.; Cai, X.; Yan, J.; Wang, J.; Liu, Y.; Zhang, L. Using the integrated geophysical methods detecting active faults: A case study in Beijing, China. *J. Appl. Geophys.* **2018**, *156*, 82–91. [\[CrossRef\]](#)
8. Abbas, A.; Zhu, H.; Zeng, Z.; Zhou, X. Sedimentary facies analysis using sequence stratigraphy and seismic sedimentology in the paleogene Pinghu Formation, Xihu depression, east China sea shelf basin. *Mar. Pet. Geol.* **2018**, *93*, 287–297. [\[CrossRef\]](#)
9. Ni, J.; Zhao, D.; Liao, X.; Li, X.; Fu, L.; Chen, R.; Xia, Z.; Liu, Y. Sedimentary Architecture Analysis of Deltaic Sand Bodies Using Sequence Stratigraphy and Seismic Sedimentology: A Case Study of Jurassic Deposits in Zhetybay Oilfield, Mangeshrak Basin, Kazakhstan. *Energies* **2022**, *15*, 5306. [\[CrossRef\]](#)
10. Todaro, S.; Sulli, A.; Spatola, D.; Basilone, G.; Aronica, S. Seismic stratigraphy of the north-westernmost area of the Malta Plateau (Sicily Channel): The Middle Pleistocene-Holocene sedimentation in a tidally influenced shelf. *Mar. Geol.* **2022**, *445*, 106740. [\[CrossRef\]](#)
11. Abu Zeid, N.; Corradini, E.; Bignardi, S.; Nizzo, V.; Santarato, G. The Passive Seismic Technique ‘HVSR’ as a Reconnaissance Tool for Mapping Paleo-soils: The Case of the Pilastr Archaeological Site, Northern Italy. *Archaeol. Prospect.* **2017**, *24*, 245–258. [\[CrossRef\]](#)
12. Bottari, C.; Martorana, R.; Scudero, S.; Capizzi, P.; Cavallaro, D.; Pisciotta, A.; D’Alessandro, A.; Coltelli, M.; Lodato, L. Coseismic damage at an archaeological site in sicily, italy: Evidence of roman age earthquake surface faulting. *Surv. Geophys.* **2018**, *39*, 1263–1284. [\[CrossRef\]](#)
13. Cafiso, F.; Canzoneri, A.; Capizzi, P.; Carollo, A.; Martorana, R.; Romano, F. Joint interpretation of electrical and seismic data aimed at modelling the foundation soils of the Maredolce monumental complex in Palermo (Italy). *Archaeol. Prospect.* **2023**, *30*, 69–85. [\[CrossRef\]](#)
14. Butchibabu, B.; Khan, P.K.; Jha, P.C. Foundation evaluation of underground metro rail station using geophysical and geotechnical investigations. *Eng. Geol.* **2019**, *248*, 140–154. [\[CrossRef\]](#)
15. Liu, B.; Wang, C.; Liu, Z.; Xu, Z.; Nie, L.; Pang, Y.; Wang, N.; Feng, S. Cascade surface and borehole geophysical investigation for water leakage: A case study of the Dehou reservoir, China. *Eng. Geol.* **2021**, *294*, 106364. [\[CrossRef\]](#)

16. Polonia, A.; Albertazzi, S.; Bellucci, L.G.; Bonetti, C.; Bonetti, J.; Giorgetti, G.; Giuliani, S.; López Correa, M.; Mayr, C.; Peruzza, L.; et al. Decoding a complex record of anthropogenic and natural impacts in the Lake of Cavazzo sediments, NE Italy. *Sci. Total Environ.* **2021**, *787*, 147659. [CrossRef]
17. Chaudhuri, A.; Sekhar, M.; Descloitres, M.; Godderis, Y.; Ruiz, L.; Braun, J.J. Constraining complex aquifer geometry with geophysics (2-D ERT and MRS measurements) for stochastic modelling of groundwater flow. *J. Appl. Geophys.* **2013**, *98*, 288–297. [CrossRef]
18. Kumar, D.; Rao, V.A.; Sarma, V.S. Hydrogeological and geophysical study for deeper groundwater resource in quartzitic hard rock ridge region from 2D resistivity data. *J. Earth Syst. Sci.* **2014**, *123*, 531–543. [CrossRef]
19. Canzoneri, A.; Capizzi, P.; Martorana, R.; Albano, L.; Bonfardeci, A.; Costa, N.; Favara, R. Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater Body in Caronia (Sicily). *Water* **2023**, *15*, 3206. [CrossRef]
20. Gondwe, B.R.; Lerer, S.; Stisen, S.; Marín, L.; Rebolledo-Vieyra, M.; Merediz-Alonso, G.; Bauer-Gottwein, P. Hydrogeology of the south-eastern Yucatan Peninsula: New insights from water level measurements, geochemistry, geophysics and remote sensing. *J. Hydrol.* **2010**, *389*, 1–17. [CrossRef]
21. Zouhri, L.; Lutz, P. Hydrogeophysical characterization of the porous and fractured media (chalk aquifer in the Beauvais, France). *Environ. Earth. Sci.* **2016**, *75*, 343. [CrossRef]
22. Muhammad, S.; Ehsan, M.I.; Khalid, P.; Sheikh, A. Hydrogeophysical modeling and physio-chemical analysis of quaternary aquifer in central part of Bari Doab, Punjab, Pakistan. *Model. Earth Syst. Environ.* **2023**, *9*, 1427–1443. [CrossRef]
23. Hasan, M.; Shang, Y.; Jin, W.; Shao, P.; Yi, X.; Akhter, G. Geophysical Assessment of Seawater Intrusion into Coastal Aquifers of Bela Plain, Pakistan. *Water* **2020**, *12*, 3408. [CrossRef]
24. Sendrós, A.; Urruela, A.; Himi, M.; Alonso, C.; Lovera, R.; Tapias, J.C.; Rivero, L.; Garcia-Artigas, R.; Casas, A. Characterization of a shallow coastal aquifer in the framework of a subsurface storage and soil aquifer treatment project using electrical resistivity tomography (Port de la Selva, Spain). *Appl. Sci.* **2021**, *11*, 2448. [CrossRef]
25. Tarallo, D.; Alberico, I.; Cavuoto, G.; Pelosi, N.; Punzo, M.; Di Fiore, V. Geophysical assessment of seawater intrusion: The Volturno Coastal Plain case study. *Appl. Water. Sci.* **2023**, *13*, 234. [CrossRef]
26. Matias, M.S.; Da Silva, M.M.; Ferreira, P.; Ramalho, E. A geophysical and hydrogeological study of aquifers contamination by a landfill. *J. Appl. Geophys.* **1994**, *32*, 155–162. [CrossRef]
27. Ciampi, P.; Esposito, C.; Cassiani, G.; Deidda, G.P.; Flores-Orozco, A.; Rizzetto, P.; Chiappa, A.; Bernaberi, M.; Gardon, A.; Papini, M.P. Contamination presence and dynamics at a polluted site: Spatial analysis of integrated data and joint conceptual modeling approach. *J. Contam. Hydrol.* **2022**, *248*, 104026. [CrossRef] [PubMed]
28. Mohammed, M.A.; Szabó, N.P.; Szűcs, P. Exploring hydrogeological parameters by integration of geophysical and hydrogeological methods in northern Khartoum state, Sudan. *Ground. Sustain. Dev.* **2023**, *20*, 100891. [CrossRef]
29. Dochartaigh, B.E.O.; Archer, N.A.L.; Peskett, L.; MacDonald, A.M.; Black, A.R.; Auton, C.A.; Merritt, J.E.; Goaddy, D.C.; Bonell, M. Geological structure as a control on floodplain groundwater dynamics. *Hydrogeol. J.* **2019**, *27*, 703–716. Available online: <https://nora.nerc.ac.uk/id/eprint/521927> (accessed on 23 February 2024). [CrossRef]
30. Cianflone, G.; Vespasiano, G.; De Rosa, R.; Dominici, R.; Apollaro, C.; Vaselli, O.; Pizzino, L.; Tolomei, C.; Capecchiacci, F.; Polemio, M. Hydrostratigraphic framework and physicochemical status of groundwater in the Gioia Tauro Coastal Plain (Calabria—Southern Italy). *Water* **2021**, *13*, 3279. [CrossRef]
31. von Suchodoletz, H.; Pohle, M.; Khosravichenar, A.; Ulrich, M.; Hein, M.; Tinapp, C.; Shultz, J.; Ballasus, E.; Veit, U.; Ettel, P.; et al. The fluvial architecture of buried floodplain sediments of the Weiße Elster River (Germany) revealed by a novel method combination of drill cores with two-dimensional and spatially resolved geophysical measurements. *Earth Surf. Process. Landf.* **2022**, *47*, 955–976. [CrossRef]
32. CASMEZ (CASsa per il MEZzogiorno)—Direzione Generale Progetti Speciali. Progetto Speciale n. 30: Utilizzazione delle acque degli schemi idrici intersettoriali della Sicilia. In *Indagini Idrogeologiche e Geofisiche per il Reperimento di Acque Sotterranee per L'approvvigionamento Idrico del Sistema IV Zona Nord Orientale Della Sicilia (Messinese)*; CASMEZ: Palermo, Italy, 1978.
33. Granata, A.; Castrianni, G.; Pasotti, L.; Favara, R.; Gagliano Candela, E.; Scaletta, C.; Madonia, P.; Morici, S.; Bellomo, S.; La Pica, L.; et al. Studio per la definizione dei modelli concettuali dei corpi idrici sotterranei di Peloritani, Nebrodi e ragusano e indagini geofisiche correlate. In *Proceedings of the 37 Convegno del Gruppo Nazionale di Geofisica della Terra Solida-GNGTS*, Roma, Italy, 19–21 November 2018; Volume 37, pp. 104–108. Available online: <https://hdl.handle.net/10447/316230> (accessed on 10 January 2024).
34. Catalano, R.; Di Stefano, P.; Sulli, A.; Vitale, F. Paleogeography and structure of the central Mediterranean: Sicily and its offshore area. *Tectonophysics* **1996**, *260*, 291–323. [CrossRef]
35. Giunta, G.; Luzio, D.; Agosta, F.; Calò, M.; Di Trapani, F.; Giorgianni, A.; Oliveri, E.; Orioli, S.; Perniciaro, M.; Vitale, M.; et al. An integrated approach to investigate the seismotectonics of northern Sicily and southern Tyrrhenian. *Tectonophysics* **2009**, *476*, 13–21. [CrossRef]
36. Catalano, R.; Valenti, V.; Albanese, C.; Accaino, F.; Sulli, A.; Tinivella, U.; Gasparo Morticelli, M.; Zanolle, C.; Giustiniani, M. Sicily's fold/thrust belt and slab rollback: The S.I.R.I.PRO. seismic crustal transect. *J. Geol. Soc.* **2013**, *170*, 451–464. [CrossRef]
37. Morticelli, M.G.; Valenti, V.; Catalano, R.; Sulli, A.; Agate, M.; Avellone, G.; Albanese, C.; Basilone, L.; Gugliotta, C. Deep controls on foreland basin system evolution along the Sicilian fold and thrust belt. *BSG-Earth Sci. Bull.* **2015**, *186*, 273–290. [CrossRef]

38. Basilone, L.; Bonfardecì, A.; Romano, P.; Sulli, A. Natural Laboratories for Field Observation About Genesis and Landscape Effects of Palaeo-Earthquakes: A Proposal for the Rocca Busambra and Monte Barracù Geosites (West Sicily). *Geoheritage* **2018**, *11*, 821–837. [CrossRef]
39. Amodio-Morelli, L.; Bonardi, G.; Colonna, V.; Dietrich, D.; Giunta, G.; Ippolito, F.; Liguori, V.; Lorenzoni, F.; Paglionico, A.; Perrone, V.; et al. L'Arco Calabro-Peloritano nell'orogene Appenninico-Maghrebide. *Mem. Soc. Geol. Ital.* **1976**, *17*, 1. Available online: <https://arpi.unipi.it/handle/11568/1278> (accessed on 10 January 2024).
40. Lentini, F.; Catalano, S.; Carbone, S. Note Illustrative Della Carta Geologica Della Provincia di Messina, Scala 1:50.000: S.EL.CA, Firenze. 2000; pp. 1–70. Available online: https://www.isprambiente.gov.it/Media/carg/note_illustrative/601_Messina_Reggio_Calabria.pdf (accessed on 1 February 2024).
41. Carbone, S.; Messina, A.; Lentini, F. *Note Illustrative dei F. 587–600 “Milazzo–Barcellona Pozzo di Gotto” della Carta Geologica d'Italia Alla Scala 1:50.000*; S.EL.CA., 2011; 262, pp. 146 ff., 5 tavv., 4 tabb. ISPRA—Regione Siciliana—Università di Catania; Servizio Geologico d'Italia: Rome, Italy.
42. Servizio Geologico d'Italia. *Carta Geologica d'Italia Alla Scala 1:50.000, F. 599 Patti*; Servizio Geologico d'Italia: Rome, Italy, 2023. [CrossRef]
43. Giunta, G.; Giorgianni, A. *Note Illustrative del F.598 “S. Agata di Militello” Della Carta Geologica d'Italia Alla Scala 1:50.000*; SystemCart; ISPRA—Università degli Studi di Palermo: Rome, Italy, 2013. Available online: https://www.isprambiente.gov.it/Media/carg/note_illustrative/598_S_Agata_di_Militello.pdf (accessed on 1 February 2024).
44. Lentini, F.; Carbone, S. Geologia della Sicilia (Geology of Sicily). *Mem. Descr. Carta Geol. d'It.* **2014**, *XCV*, 7–414.
45. Giunta, G.; Nigro, F. Tectono-sedimentary constraints to the Oligocene-to-Miocene evolution of the Peloritani thrust belt (NE Sicily). *Tectonophysics* **1999**, *315*, 287–299. [CrossRef]
46. Nigro, F.; Sulli, A. Plio-Pleistocene extensional tectonics in the Western Peloritani area and its offshore (northeastern Sicily). *Tectonophysics* **1995**, *252*, 295–305. [CrossRef]
47. Giunta, G.; Nigro, F.; Renda, P. Extensional tectonics during Maghrebides chain building since Late Miocene: Examples from Northern Sicily. *Ann. Soc. Geol.* **2000**, *70*, 81–89.
48. Giunta, G.; Nigro, F.; Renda, P.; Giorgianni, A. The Sicilian–Maghrebides Tyrrhenian Margin: A neotectonic evolutionary model. *Mem. Soc. Geol.* **2000**, *119*, 553–565.
49. Renda, P.; Tavarnelli, E.; Tramutoli, M.; Gueguen, E. Neogene deformations of Northern Sicily, and their implications for the geodynamics of the Southern Tyrrhenian Sea margin. *Mem. Soc. Geol.* **2000**, *55*, 53–59.
50. Nigro, F.; Renda, P. Plio-Pleistocene strike-slip deformation in NE Sicily: The example of the area between Capo Calavà and Capo Tindari. *Boll. Soc. Geol.* **2005**, *124*, 377–394.
51. Giunta, G.; Bellomo, D.; Carnemolla, S.; Pisano, A.; Profeta, R.; Runfola, P. La “Linea di Taormina”: Residuo epidermico di una paleostruttura crostale del fronte cinematico maghrebide? *Atti 8^o GNGTS Congr.* **1989**, *8*, 1197–1203.
52. Gasparo Morticelli, M.; Avellone, G.; Sulli, A.; Agate, M.; Basilone, L.; Catalano, R.; Pierini, S. Mountain building in NW Sicily from the superimposition of subsequent thrusting and folding events during Neogene: Structural setting and tectonic evolution of the Kumeta and Pizzuta ridges. *J. Maps* **2017**, *13*, 276–290. [CrossRef]
53. Lentini, F. Carta Geologica della Provincia di Messina, Scala 1:50.000: S.EL.CA, Firenze. 2000. Available online: https://www2.regione.sicilia.it/beniculturali/dirbenicult/bca/ptpr/documentazione%20tecnica%20messina/CARTOGRAFIA/ANALISI/03_Geologia.pdf (accessed on 1 February 2024).
54. Arisco, G.; Arnone, G.; Favara, R.; Nigro, F.; Perricone, M.; Renda, P.; Mondello, C. Integrated neotectonic and morphometric analysis of northern Sicily. *Boll. Soc. Geol.* **2006**, *125*, 221–244. Available online: <http://hdl.handle.net/2122/2497> (accessed on 10 January 2024).
55. Ferrara, V. Vulnerabilità all'inquinamento degli Acquiferi dell'area Peloritana (Sicilia Nord-Orientale), Studi Sulla Vulnerabilità Degli Acquiferi 14. In *Quaderni di Tecniche di Protezione Ambientale: Edizione Pitagora*; Pitagora Editrice Srl.: Bologna, Italy, 1999.
56. Cangemi, M.; Madonia, P.; Albano, L.; Bonfardecì, A.; Di Figlia, M.G.; Di Martino, R.M.R.; Nicolosi, M.; Favara, R. Heavy Metal Concentrations in the Groundwater of the Barcellona-Milazzo Plain (Italy): Contributions from Geogenic and Anthropogenic Sources. *Int. J. Environ. Res. Public Health* **2019**, *16*, 285. [CrossRef] [PubMed]
57. Capizzi, P.; Martorana, R.; Favara, R.; Albano, L.; Bonfardecì, A.; Catania, M.; Costa, N.; Gagliano, A. Geophysical Contribution to the Reconstruction of the Hydrological Model of “Barcellona-Milazzo Plain” Groundwater Body, Northern Sicily. In Proceedings of the 25th European Meeting of Environmental and Engineering Geophysics; European Association of Geoscientists & Engineers, Moscow, Russia, 8–12 September 2019; pp. 1–5. [CrossRef]
58. Celico, P. *Prospezioni Idrogeologiche, Vol. I e Vol. II*; Liguori Editore Napoli: Naples, Italy, 1988.
59. Allocca, V.; De Vita, P.; Manna, F. La variabilità climatica in Italia meridionale e gli effetti sulla ricarica degli acquiferi carbonatici. *EHE Geol.* **2012**, *14*, 9–10. Available online: <https://hdl.handle.net/11588/425079> (accessed on 23 February 2024).
60. Castany, G. Idrogeologia. In *Principi e Metodi: Edizione Flaccovio Dario, Palermo*; Pitagora Editrice Srl.: Bologna, Italy, 1985.
61. Civita, M. *Idrogeologia Applicata e Ambientale*; CEA Editore: Rozzano, Italy, 2005; p. 800. ISBN 8808087417.
62. Cimino, A.; Cosentino, C.; Oieni, A.; Tranchina, L. A geophysical and geochemical approach for seawater intrusion assessment in the Acquadolci coastal aquifer (Northern Sicily). *Environ. Geol.* **2007**, *55*, 1473–1482. [CrossRef]
63. Pantaleone, D.V.; Vincenzo, A.; Fulvio, C.; Silvia, F.; Cesaria, M.; Giuseppina, M.; Ilaria, M.; Vincenzo, P.; Rosa, S.A.; Gianpietro, S.; et al. Hydrogeology of continental southern Italy. *J. Maps* **2018**, *14*, 230–241. [CrossRef]

64. Kosinski, W.K.; Kelly, W.E. Geoelectric Soundings for Predicting Aquifer Properties. *Groundwater* **1981**, *19*, 163–171. [\[CrossRef\]](#)
65. Heigold, P.C.; Gilkeson, R.H.; Cartwright, K.; Reed, P.C. Aquifer Transmissivity from Surficial Electrical Methods. *Groundwater* **1979**, *17*, 338–345. [\[CrossRef\]](#)
66. Van Overmeeren, R.A. Aquifer boundaries explored by geoelectrical measurements in the coastal plain of Yemen: A case of equivalence. *Geophysics* **1989**, *54*, 38–48. [\[CrossRef\]](#)
67. Auken, E.; Christiansen, A.V. Layered and laterally constrained 2D inversion of resistivity data. *Geophysics* **2004**, *69*, 752–761. [\[CrossRef\]](#)
68. Nogoshi, M.; Iragashi, T. On the propagation characteristic of the microtremors. *J. Seismol. Soc. Jpn.* **1970**, *24*, 24–40.
69. Nakamura, Y. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quat. Rep. Railw.* **1989**, *30*, 25–33. Available online: <https://worldcat.org/oclc/3127232> (accessed on 23 February 2024).
70. Castellaro, S.; Mulargia, F. VS30 estimates using constrained H/V measurements. *Bull. Seismol. Soc. Am.* **2009**, *99*, 761–773. [\[CrossRef\]](#)
71. Castellaro, S. The complementarity of H/V and dispersion curves. *Geophysics* **2016**, *81*, T323–T338. [\[CrossRef\]](#)
72. Park, C.B.; Miller, R.D.; Xia, J. Multichannel analysis of surface waves. *Geophysics* **1999**, *64*, 800–808. [\[CrossRef\]](#)
73. White, D.J. Two-Dimensional Seismic Refraction Tomography. *Geophys. J. Int.* **1989**, *97*, 223–245. [\[CrossRef\]](#)
74. Koch, K.; Wenninger, J.; Uhlenbrook, S.; Bonell, M. Joint interpretation of hydrological and geophysical data: Electrical resistivity tomography results from a process hydrological research site in the Black Forest Mountains, Germany. *Hydrol. Process. Int. J.* **2009**, *23*, 1501–1513. [\[CrossRef\]](#)
75. Robert, T.; Dassargues, A.; Brouyère, S.; Kaufmann, O.; Hallet, V.; Nguyen, F. Assessing the contribution of electrical resistivity tomography (ERT) and self-potential (SP) methods for a water well drilling program in fractured/karstified limestones. *J. Appl. Geophys.* **2011**, *75*, 42–53. [\[CrossRef\]](#)
76. Martorana, R.; Lombardo, L.; Messina, N.; Luzio, D. Integrated geophysical survey for 3D modelling of a coastal aquifer polluted by seawater. *Near Surf. Geophys.* **2014**, *12*, 45–59. [\[CrossRef\]](#)
77. Frischknecht, F.C.; Raab, P.V. Time-domain electromagnetic soundings at the Nevada Test Site, Nevada. *Geophysics* **1984**, *49*, 981–992. [\[CrossRef\]](#)
78. Wightman, W.E.; Kaufman, A.A.; Hoekstra, P. Mapping gas-water contacts in shallow producing formations with transient EM. In SEG Technical Program Expanded Abstracts. *Soc. Explor. Geophys.* **1983**, *0059*, 59–60. [\[CrossRef\]](#)
79. Fitterman, D.V.; Stanley, W.D.; Bisdorf, R.J. Electrical structure of Newberry volcano, Oregon. *J. Geophys. Res. Solid Earth* **1988**, *93*, 10119–10134. [\[CrossRef\]](#)
80. Martorana, R.; Capizzi, P.; Avellone, G.; D'Alessandro, A.; Siragusa, R.; Luzio, D. Assessment of a geological model by surface wave analyses. *J. Geophys. Eng.* **2017**, *14*, 159–172. [\[CrossRef\]](#)
81. Di Capua, G.; Peppoloni, S.; Amanti, M.; Cipolloni, C.; Conte, G. Site classification map of Italy based on surface geology. *Geol. Soc. Lond. Eng. Geol. Spec. Publ.* **2016**, *27*, 147–158. [\[CrossRef\]](#)
82. Forte, G.; Chioccarelli, E.; De Falco, M.; Cito, P.; Santo, A.; Iervolino, I. Seismic soil classification of Italy based on surface geology and shear-wave velocity measurements. *Soil Dyn. Earthq. Eng.* **2019**, *122*, 79–93. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

CHAPTER IV

MULTIDISCIPLINARY STUDY TO PRODUCE A SUBSOIL MODEL USEFULL FOR THE SEISMIC CHARACTERIZATION OF AN AREA.

4.1 Description of the case study of the plains of San Vito Lo Capo, Macari and Castelluzzo; : Objectives, Studied Areas, Data Used, Results Obtained.

The case study of the municipality of San Vito Lo Capo, which includes the three coastal plains studied, is presented to highlight the importance of a multidisciplinary approach, geological and geophysical, to develop usable subsurface models by defining the geomorphological and subsurface characteristics that may cause site effects. In the study, in particular, the surveys carried out and the models developed to deliver a first-level seismic micro-zonation study for the Municipality of San Vito lo Capo are shown. This analysis is fundamental to the editing of future General Town Plan of the Municipality of San Vito Lo Capo

The study area lies in northwestern Sicily and is part of the province of Trapani (figure 69). In particular, the work is divided into the analysis of each individual plain within the municipality of San Vito Lo Capo where urban agglomeration are present; San Vito Lo Capo, Macari and Castelluzzo.

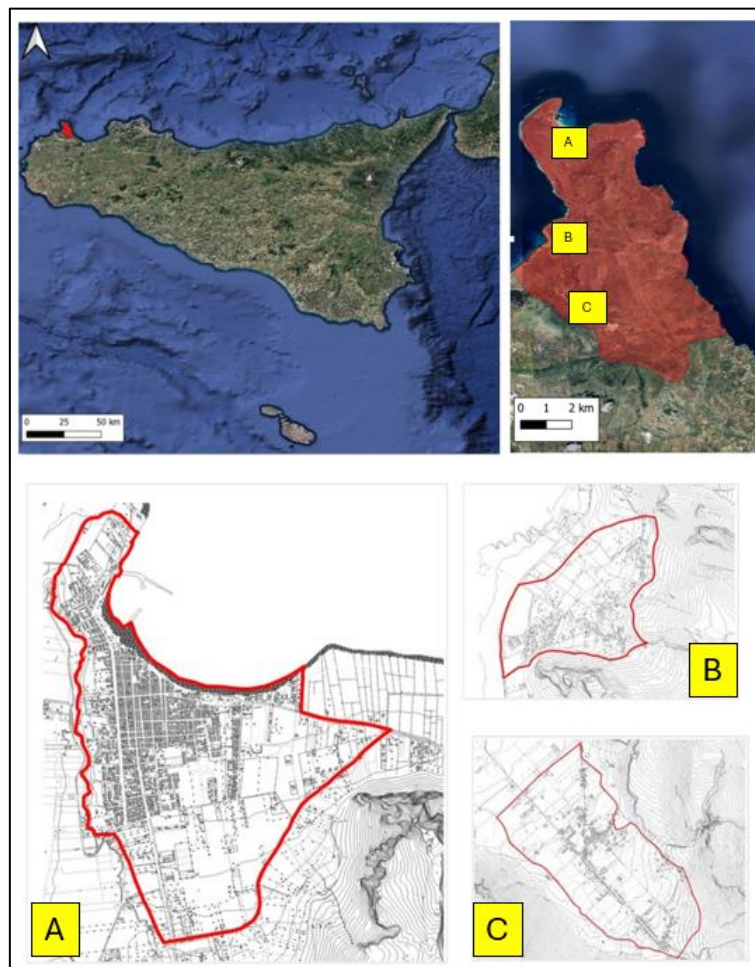


Figure 69: Localization of the municipal territory of San Vito within Sicily (above). Map of the three areas studied within the sector considered: A) San Vito Lo Capo B) Macari C) Castelluzzo(down).

The data used were provided by the municipality of San Vito Lo Capo and include several geophysical surveys and borehole: Seismic refraction (SRT), Vertical Electrical Sounding (VES), Electrical Resistivity Tomography (ERT). These data, for which the San Vito Lo Capo Municipality has provided only the results of previous acquisitions, were qualitatively interpreted to provide a preliminary characterization of the local stratigraphy. The municipality also provided many raw data concerning noise seismic data elaborated using the Horizontal to Vertical Spectral Ratio (HVSr) method. The H/V curves had been analyzed and inverted in 1D seismic-stratigraphic models constraining the inversion of the data to information derived from previous geological and geophysical data (figure 70).

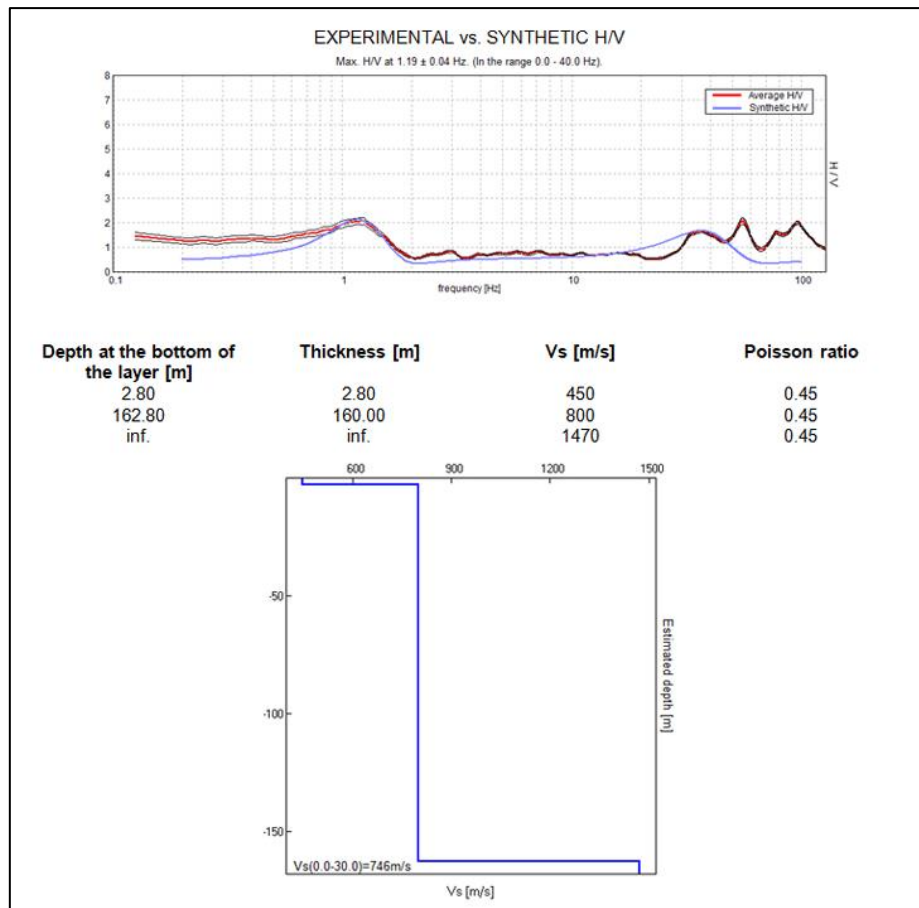


Figure 70: Example of a one-dimensional layered model of the shear wave velocity (bottom) obtained from the inversion of the data provided by an HVSr survey (upper).

By means of a joint interpretation of all the available data, the results obtained were the definition of a bedrock depth map for each area under investigation. Moreover, basing on the available geological, geomorphological and geophysical observations a Map of Homogeneous Microzones in Seismic perspective (MOPS) was created.

2.2 “Near Surface Geophysics Contribution for First Level Seismic Microzonation Studies for The Municipality Of san Vito Lo Capo, Western Sicily, Italy.”

This paragraph includes the work presented at the 41st National Conference of the GNGTS (National Group of Solid Earth Geophysics). The conference took place in Bologna from 7 to 9 February 2023, during which an oral presentation of the work was given (Canzoneri et al.2023 a).

Near Surface Geophysics Contribution For First Level Seismic Microzonation Studies For The Municipality Of san Vito Lo Capo, Western Sicily, Italy

A. Canzoneri, A. Bonfardecì, P. Capizzi, R. Martorana

Università di Palermo, Dipartimento di Scienze della Terra e del Mare, Palermo, Italy

Introduction

Recent studies, carried out by the University of Palermo, allowed to define different seismic aspects of the area of San Vito Lo Capo, located in the north-western Sicily, Italy.

These investigations were helpful to recognize and highlight, on a sufficiently detailed scale, the lithostratigraphic and morphological characteristics of the study area. Moreover, this approach has a particular importance in understanding which features could induce seismic shaking amplification episodes, instability phenomena and earthquake-triggered permanent deformation.

These analyses underlie the Seismic microzonation (SM) of an area, which represents a useful tool for seismic prevention and risk assessment. The first level SM studies, applied to the Municipality of San Vito Lo Capo, has been based on the collection and analysis of pre-existing data and integrated by new *in situ* investigations. Finally, the interpretation and correlation of these data allowed to identify seismic bedrock depth and the homogeneous microzones from a seismic perspective (MOPS).

Geological and geomorphological setting

The area belonging to the Municipality of San Vito Lo Capo is located on the north-western coast of Sicily and extends from the promontory of Capo San Vito, to the north, to the village of Castelluzzo and the Zingaro natural reserve to the west and east respectively. The geological lithotypes that characterize the area are limestone and recent clastic-terrigenous terrains. Morphologically the area is characterized by a main contrast between mountains (Monte Monaco - Pizzo di Sella ridge) and flat and tabular areas hosting San Vito town and Macari and Castelluzzo villages. The mountain reliefs are characterized by several slope breaks, steep slopes and

detachment niches, while the flat sectors present extensive terraced surfaces and debris deposits.

The perimeter of the area subjected to first-level SM corresponds to the main urban center of San Vito Lo Capo and the areas of Macari and Castelluzzo fractions.

Definition of the basic hazard for seismic classification

Through the reconstruction of the seismic history of an area it is possible to evaluate the danger of the site and consider the possible impacts of an earthquake on the territory in time. The seismic events that characterized the area were chosen by consulting the Italian Macroseismic Database (DBMI15, Locati et al., 2022), the Italian Earthquake Parametric Catalogue (CPTI15 v3.0) (Rovida et al., 2021), the Italian Macroseismic Historical Archive (ASMI; Rovida et al., 2017) and the Catalogue of Strong Earthquakes in Italy (461 BC-1997) and in the Mediterranean area (760 BC-1500) (CFTI5Med; Guidoboni et al., 2018).

The main historical earthquakes that from the 4th century BC had significant macroseismic effects in Western Sicily and those that, starting from the 1900 have recorded significant effects in the municipality of San Vito Lo Capo include the Mw 6.41 earthquake in the Belice Valley, dated 1968, and the Mw 4.79 earthquake of 29.05.1988 with epicenter near the Egadi islands.

To reduce the effects of the seismic shaking expected on the national territory, with a view to safeguarding human life, Italian legislation has made a reclassification of the seismic hazard of the entire country. This classification is based both on the intensity and frequency of past earthquakes and on the application of technical standards for constructions in seismic classified areas.

According to the latest seismic classification of the Region, dated 24.02.2022, the municipality of San Vito Lo Capo falls in an area characterized by a medium basic seismic hazard since it has maximum acceleration values to the ground (a_g) between 0.15 g and 0.25 g.

For the evaluation of the basic seismic hazard of an area an important element is the seismogenic zonation of the Italian territory. The recent seismogenic zonation ZS9 (Meletti and Valensise, 2004) divides the entire Italian territory into 36 zones. According to this the study areas do not fall into any seismogenic zone.

As regards the definition of the seismic hazard of the area, reference was made to the data published on the web database of the National Institute of Geophysics and Volcanology (INGV) (<http://esse1.mi.ingv.it>) described by Meletti et al. (2006). In this dataset was researched the values of maximum horizontal acceleration to the ground, named a_g , with probability of excess of 10% in 50 years. The examined area presents a_g values between $0.050 < a_g < 0.075$ g.

Finally, a fundamental element for the classification of the seismicity of an area is the recognition of active and capable faults. For this purpose we consulted the ISPRA online database which is

based on the development of the project ITHACA (2019). In particular this project was realized to research and describe the capable faults, defined as faults that potentially can create permanent coseismic deformation on the surface. According to this catalogue the area does not present active and capable faults. Moreover, by analyzing the DISS (Database of Individual Seismogenic Sources) catalog, published by INGV (2021), the territory of the Municipality of San Vito Lo Capo does not result affected by any seismogenic element and the presence of active and capable faults is not reported.

Nevertheless, a fault located in the western part of San Vito Lo Capo and indicated in pre-existing geological cartography, results poorly investigated and for this reason it was not possible to clearly identify deformation or morphostructural evidence of recent movements. Therefore, on the basis of the available data it was not possible to reconstruct the extent of the fault displacement and the age of the movement.

Data collection

As required by the SM guidelines for the study of first level, a collection of pre-existing geognostic and geophysical data has been used. These were appropriately selected basing on the reliability of the results that is linked to the methodology data acquisition and processing.

As regards geognostic surveys, ten pre-existing continuous core drilling were used to improve the information about the subsoil and to calibrate the depth of the seismic bedrock since five of them reach the geological substrate.

Geophysical data analyzed included Seismic Refraction surveys (SR), Vertical Electrical Soundings (VES), Electrical Resistivity Tomography (ERT) and noise seismic data elaborated using the Horizontal to Vertical Spectral Ratio (HVSr) method.

52 SR investigations were carried out during public or private professional studies for the determination of the compression waves velocity useful to define the bedrock depth. These surveys were realized both in San Vito Lo Capo, Macari and Castelluzzo. The depth of investigation of almost all surveys did not exceed ten meters due to the detection of the seismic bedrock within this depth in all investigated areas.

In a large area upstream of the village of Castelluzzo seven VES were performed, whose interpretation allowed to reconstruct the local stratigraphy up to depths of about 100 m below ground level. The results of these surveys cannot be fully validated because due to the lack of fundamental information concerning the acquisition parameters and the resistivity curves obtained from the measured values.

In addition, other information was provided by five ERT carried out in the town of San Vito Lo Capo.

The 47 HVSR surveys considered include 32 measures carried out in the 2012 and 15 measures carried out in February 2022. These latter were realized for the geological study preparatory to the editing of the General Town Plan of the Municipality of San Vito Lo Capo. In particular 21 surveys were located within San Vito Lo Capo, 12 in Macari and 14 in Castelluzzo. The HVSR surveys were located in an almost homogeneous distribution on the most urbanized territory. All HVSR measurements, acquired with 3D seismic velocimetric sensors, were reworked and reinterpreted in the light of the available data.

Data analysis and definition of the subsoil model

The HVSR surveys were interpreted trying to identify the mean frequency peak within the frequency window of 0,1-20 Hz, as well as secondary peaks that may be present. In almost all HVSR measurements low frequency peaks were recognized, generally between 1 Hz and 3 Hz and other peaks at higher frequencies, around 20 Hz.

The recognized peak frequencies were used to realize the frequency maps for each area, in which the spatial distribution of the HVSR surveys is reported together with peak values recognized. HVSR curves that presented stratigraphic peaks were interpreted with seismic velocity models, constraining the inversion and interpretation with the available geological and geophysical data to compute the depth of the seismic bedrock.

Based on the results of the seismic tomography, which show seismic velocities greater than 800 m/s already in layers a few meters deep, the low-frequency peaks (1-3 Hz) of the HVSR curves have been considered as caused by very deep stratigraphic interfaces. Conversely the cover/bedrock interface could be responsible for the higher frequency peaks (around 20 Hz). The bedrock depth model, represented in Fig. 1, shows that investigated areas are characterized by limestone rocks that constitute the shallow seismic bedrock. Above these rocks a coverage of a few meters is present. In particular, the area of the town of San Vito Lo Capo shows very shallow seismic bedrock, excluding a restricted area characterized by the presence of an ancient quarry filled by heterogeneous material. Even the area of Castelluzzo shows few meters of coverage above the seismic bedrock. Finally, the Macari area shows greater depth variations of the seismic bedrock, reaching maximum value of 12 m b.g.l..

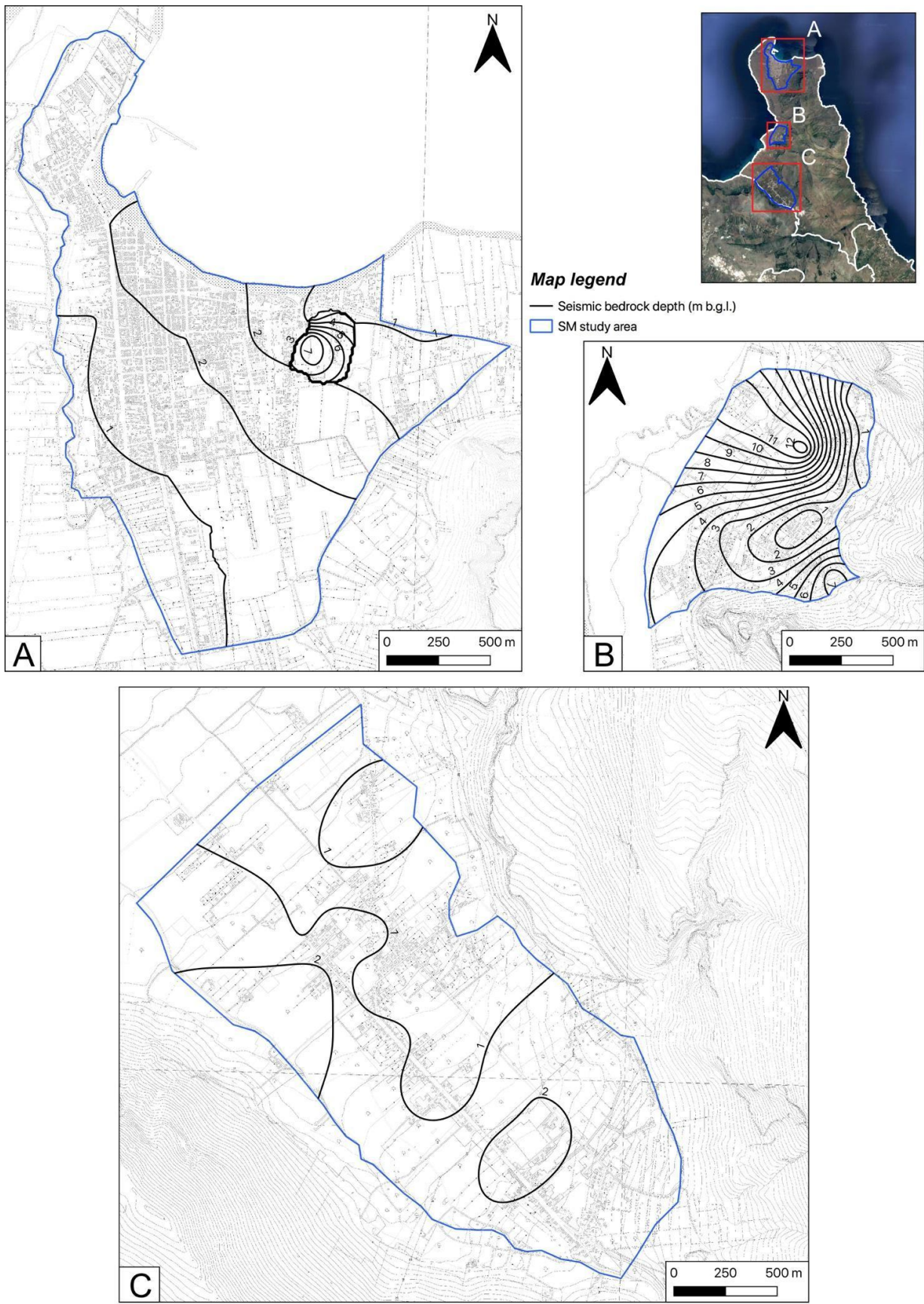


Fig. 1: Maps of the bedrock depth ($V_s > 800$ m/s) for San Vito Lo Capo (A), Macari (B), Castelluzzo (C) areas.

Map of homogeneous microzones in seismic perspective based on first level studies

The processing of the map of homogeneous microzones in seismic perspective (MOPS) is based on the criteria defined by “Gruppo di lavoro MS” (2008). Basing on the available geological, geomorphological and geophysical observations three different categories were identified:

A first category is that of *stable zones*, where no local effects of amplification of the seismic shaking are hypothesized. These zones present an outcropping geological and seismic substrate ($V_s > 800$ m/s), characterized by flat morphology or inclined less than 15° ; stable areas can present a thickness of cover deposits less than 3 m. According to these features two stable zone, 1012 and 1022, were defined.

A second category is constituted by *stable zones susceptible of local seismic amplification*. In these areas the amplification of the seismic input is connected to the presence of a rigid ground ($V_s < 800$ m/s) outcropping or covered by non-cohesive soils with thickness less than 3 m. Belong furthermore to this category outcrops anthropogenic, eluvial, colluvial and debris deposits characterized by thickness greater than 3 m and V_s less than 800 m/s.

In particular, the 2099 zone presents heavily weathered and fractured limestone on the top and silico-clastic deposits up to a maximum of about 12 m. A debris cover characterizes the 2001 zone, while the 2002 and 2003 zones are characterized by alluvial soils and beach deposits respectively. A cover of anthropogenic origin, characterized by the presence of heterogeneous and heterometric material, defines the 2004 zone.

Finally, two *zones of attention for instability* were defined, on the basis of the type of movement and the state of activity (landslides): the 30112001 zone that presents active rockfall and rock topple and the 30152099 zone characterized by widespread erosion processes. All the described MOPS for the three examined areas are shown in Fig. 2. As regards the poorly investigated fault located in the western sector of the San Vito town, reported in the pre-existing cartography, a buffer zone was mapped.

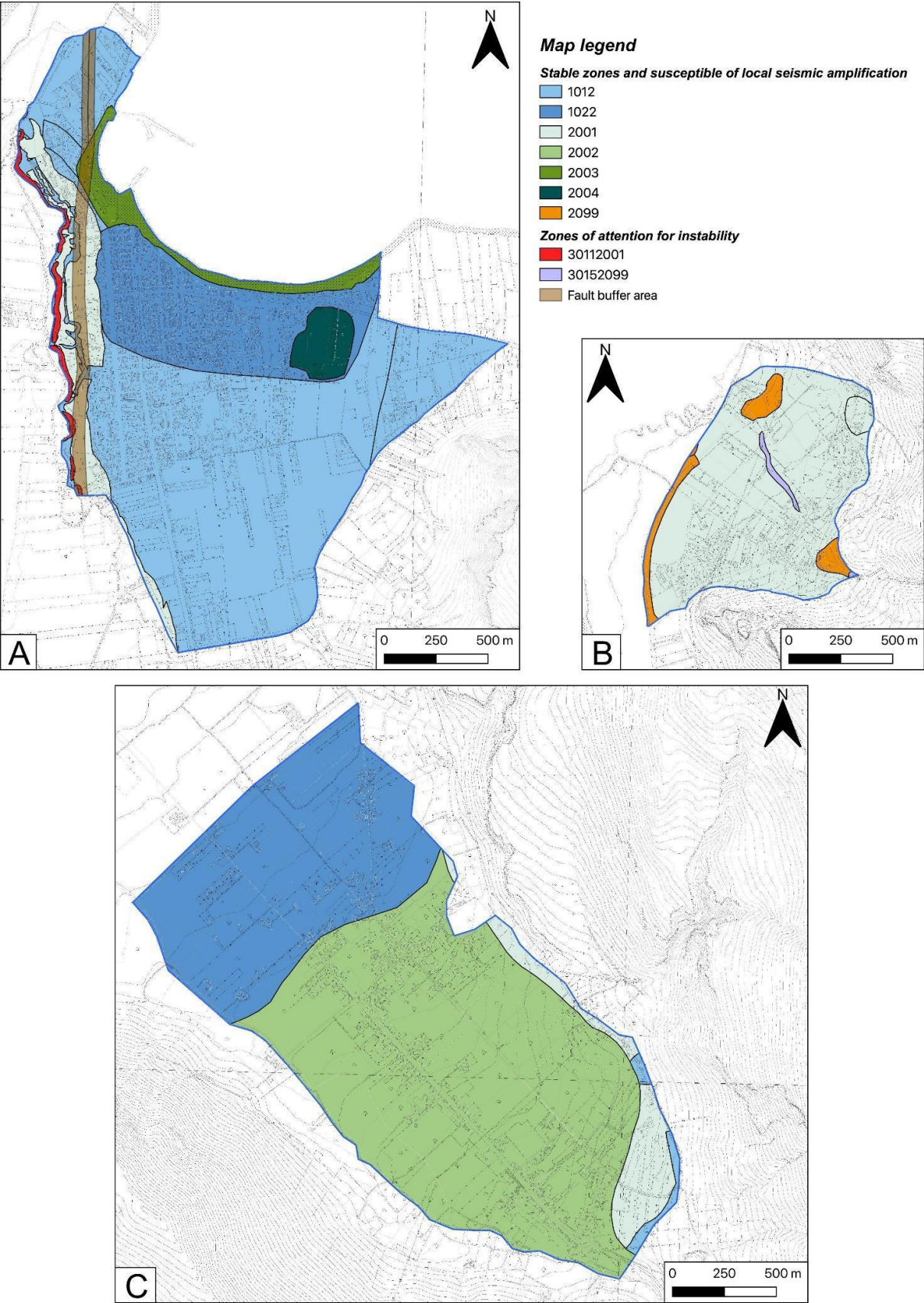


Fig. 2: Maps of the mops for San Vito Lo Capo (A), Macari (B), Castelluzzo (C) areas.

References

DISS Working Group; 2021: Database of Individual Seismogenic Sources (DISS), Version 3.3.0: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas. Istituto Nazionale di Geofisica e Vulcanologia (INGV). doi: <https://doi.org/10.13127/diss3.3.0>.

Gruppo di Lavoro ITHACA; 2019: ITHACA (ITaly HAZards from Capable faults) – Catalogo delle faglie capaci in Italia, Istituto Superiore per la Protezione e la Ricerca Ambientale. doi: <http://sgi2.isprambiente.it/ithacaweb/viewer>.

Gruppo di Lavoro MS; 2008: Indirizzi e criteri per la microzonazione sismica. Conferenza delle Regioni e delle Province autonome - Dipartimento della protezione civile, Roma, 3 vol.

Guidoboni E., Ferrari G., Mariotti D., Comastri A., Tarabusi G., Sgattoni G. and Valsenise G.; 2018: CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 a.C.-1997) e nell'area Mediterranea (760 a.C.-1500). Istituto Nazionale di Geofisica e Vulcanologia (INGV). doi: <https://doi.org/10.6092/ingv.it-cfti5>.

Meletti C. and Valensise G. (2004): Zonazione sismogenetica ZS9 – App. 2 al rapporto conclusivo. Gruppo di Lavoro MPS (2004). Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM, 3274.

Meletti C., Montaldo V., Stucchi M. and Martinelli F.; 2006: Database della pericolosità sismica MPS04. Istituto Nazionale di Geofisica e Vulcanologia (INGV).

Locati M., Camassi R., Rovida A., Ercolani E., Bernardini F., Castellini V., Caracciolo C.H., Tertulliani A., Rossi A., Azzaro R., D' Amico S. and Antonucci A.; 2022: Database Macrosismico Italiano (DBMI15), versione 4.0. Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.13127/DBMI/DBMI15.4>.

Regione Sicilia; 2022: Aggiornamento della classificazione sismica del territorio regionale della Sicilia. Applicazione dei criteri dell'Ordinanza del Presidente del Consiglio dei Ministri 28 aprile 2006, n. 3519 - Deliberazione n. 81 del 24 febbraio 2022 con i relativi allegati e le elencazioni dei Comuni con la rispettiva classificazione.

Rovida A., Locati M., Camassi R., Antonucci A., Bernardini F. M. A., Caracciolo C. H. and Maffezzoni L.; 2017: L'Archivio Storico Macrosismico Italiano (ASMI). 36° Convegno del Gruppo Nazionale di Geofisica della Terra Solida (GNGTS).

Rovida A., Locati M., Camassi, R., Lolli B., Gasperini P. and Antonucci A.; 2021: Parametric Catalogue of Italian Earthquakes CPTI15, Version 3.0.

Alessandro Canzoneri
alessandrocanzoneri88@gmail.com

CHAPTER V - CONCLUSIONS

5.1: Synthesis of results and models obtained from the multi-disciplinary approach

The case studies presented in this work demonstrate the potential to produce two-dimensional and three-dimensional subsoil models through an integrated approach combining geological and geophysical data and methodologies.

The workflow presented in the three experiments consistently emphasized how geological data can constrain geophysical data and models. This makes the geophysical models more robust by maximizing the advantages of this type of acquisition, particularly its speed and cost-effectiveness compared to geological surveys (e.g., wells, trenches). Similarly, geophysical data can effectively guide the often-indispensable geological surveys. The models built by combining these two methodologies are certainly very effective in different areas of research and design of engineering works as shown in the various cases presented.

In addition, the three case studies highlighted the importance of the constraint in the inversion of geophysical data according to physical parameters acquired by other non-direct surveys as demonstrated in the case of the inversion of HVSR data constrained by Vs values derived from MASW.

The case study of the Palermo plain showed how a 3D model can be developed by integrating extensive preexisting geological data and using it as a foundation to appropriately enhance the information available through geophysical methodologies, linking physical parameters to a comprehensive geological dataset. The 3D model produced for Palermo can be used as a reference model for subsoil construction in urban environments. This analysis identifies the ancient characteristics of the territory, often obscured by urban infrastructure and highlights areas highly susceptible to geological hazards, such as local seismic effects and floods.

The third case study provided similar findings. In this work several previous geophysical surveys were qualitatively analyzed and integrated into a relatively simple geological model to develop a preliminary evaluation of the local seismic response. The subsoil model was produced while minimizing the costs of geological surveys.

The case study of the alluvial plains in the province of Messina has shown how 3D models can guide the development of effective subsurface models in hydrogeology. The integration of geological and geophysical data in this case produced models of water bodies that can be utilized for safeguarding and monitoring coastal aquifers.

In this case, the underground model was also used to describe subsurface water flow, as illustrated by the CGWB. This approach can serve as a valuable guideline for similar studies.

REFERENCES

- Agate, M., Basilone, L., Di Maggio, C., Contino, A., Pierini, S., & Catalano, R. (2017). Quaternary marine and continental unconformity-bounded stratigraphic units of the NW Sicily coastal belt. *Journal of Maps*, 13(2), 425-437.
- Agnesi, V. (Ed.). (2021). *La geomorfologia di Palermo* (Vol. 24). Sapienza Università Editrice.
- Andersen, T. R., Poulsen, S. E., Pagola, M. A., & Medhus, A. B. (2020). Geophysical mapping and 3D geological modelling to support urban planning: A case study from Vejle, Denmark. *Journal of Applied Geophysics*, 180, 104130.
- Barry, K. M. (1967). Delay time and its application to refraction profile interpretation.
- Basilone, L., & Di Maggio, C. (2016). Geology of Monte Gallo (Palermo Mts, NW Sicily). *Journal of Maps*, 12(5), 1072-1083.
- Bosco, G. (1996). Analisi preliminare della risposta dinamica locale del sottosuolo di Palermo.
- Belmonte-Jiménez, S. I., Jiménez-Castañeda, M. E., Pérez-Flores, M. A., Campos-Enríquez, J. O., Reyes-López, J. A., & Salazar-Peña, L. (2012). Characterization of a leachate contaminated site integrating geophysical and hydrogeological information. *Geofísica internacional*, 51(4), 309-321.
- Brandolini, P., Cappadonia, C., Luberti, G. M., Donadio, C., Stamatopoulos, L., Di Maggio, C., Faccini, F., Stanislao, C., Vergari, F., Paliaga, G., Agnesi, V., Alevizos, G., ... & Del Monte, M. (2020). Geomorphology of the Anthropocene in Mediterranean urban areas. *Progress in Physical Geography: Earth and Environment*, 44(4), 461-494.
- Cafiso, F., Canzoneri, A., Capizzi, P., Carollo, A., Martorana, R., & Romano, F. (2023). Joint interpretation of electrical and seismic data aimed at modelling the foundation soils of the Maredolce monumental complex in Palermo (Italy). *Archaeological Prospection*, 30(1), 69-85.
- Cardarelli, E., & Di Filippo, G. (2009). Integrated geophysical methods for the characterisation of an archaeological site (Massenzio Castellaro, S.; Mulargia, F. VS30 estimates using constrained H/V measurements. *Bull. Seismol. Soc. Am.* 2009, 99, 761–773.
- Canzoneri, A., Bonfardecì, A., Capizzi, P., & Martorana, R. (2023a). Near Surface Geophysics Contribution For First Level Seismic Microzonation Studies For The Municipality Of San Vito Lo Capo, Western Sicily, Italy. In *Book of Abstracts 41st National Conference* (pp. 974-982).
- Canzoneri, A., Capizzi, P., Martorana, R., Albano, L., Bonfardecì, A., Costa, N., & Favara, R. (2023b). Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater Body in Caronia (Sicily). *Water*, 15(18), 3206.
- Canzoneri, A., Martorana, R., Agate, M., Capizzi, P., Gasparo Morticelli, M., & Alessandra, C. (2024, April). Geophysical surveys to reconstruct the geological model of the urban area of Palermo, Italy. In *EGU General Assembly Conference Abstracts* (p. 13156).
- Carollo, A., Capizzi, P., & Martorana, R. (2020). Joint interpretation of seismic refraction tomography and electrical resistivity tomography by cluster analysis to detect buried cavities. *Journal of Applied Geophysics*, 178, 104069.
- Cappadonia, C., Di Maggio, C., Agate, M., & Agnesi, V. (2020). Geomorphology of the urban area of Palermo (Italy). *Journal of Maps*, 16(2), 274-284.

- Capizzi, P., Martorana, R., Canzoneri, A., Bonfardeci, A., & Favara, R. (2024). Coastal Groundwater Bodies Modelling Using Geophysical Surveys: The Reconstruction of the Geometry of Alluvial Plains in the North-Eastern Sicily (Italy). *Water*, 16(7), 1048.
- CASMEZ(CASSaperilMEZzogiorno)—Direzione Generale Progetti Speciali. Progetto Speciale n. 30: Utilizzazione delle acque degli schemi idrici intersettoriali della Sicilia. In Indagini Idrogeologiche e Geofisiche per il Reperimento di Acque Sotterranee per L’approvvigionamento Idrico del Sistema IV Zona Nord Orientale Della Sicilia (Messinese); CASMEZ: Palermo, Italy, 1978.
- Castellaro, S., & Mulargia, F. (2009). VS 30 estimates using constrained H/V measurements. *Bulletin of the Seismological Society of America*, 99(2A), 761-773.
- Castellaro, S. (2016). The complementarity of H/V and dispersion curves. *Geophysics*, 81(6), T323-T338.
- Catalano, R., Avellone, G., Basilone, L., Contino, A., Agate, M., Di Maggio, C., Lo Iacono, C., Sulli, A., Gugliotta, C., & Gasparo Morticelli, M. (2013a). Carta geologica d’Italia alla scala 1: 50.000, Foglio 595 Palermo. ISPRA, Servizio Geologico d’Italia, Regione Siciliana, Assessorato Territorio ed Ambiente.
- Catalano, R., Valenti, V., Albanese, C., Accaino, F., Sulli, A., Tinivella, U., Gasparo Morticelli M., Zannola C., & Giustiniani, M. (2013b). Sicily’s fold–thrust belt and slab roll-back: the SI. RI. PRO. seismic crustal transect. *Journal of the Geological Society*, 170(3), 451-464.
- Contino, A., Giammarinaro, M. S., Vallone, P., Varsalona, S., & Zuccarello, A. (2006). Analisi stratigrafico geotecnica del settore meridionale della città di Palermo finalizzata alla caratterizzazione di fattori di pericolosità sismica in esso presenti. *BOLLETTINO-SOCIETA GEOLOGICA ITALIANA*, 125(3), 329.
- Columba, G. M. (1910). *Per la topografia antica di Palermo*. Stabilimento Tipografico
- Cusimano, G. (1989). *Le alluvioni Palermitane: cronologia e cause, dal 934 al 1988*. [Univ.], Dipartimento di Geologia e Geodesia.
- Dangeard, M., Bodet, L., Pasquet, S., Thiesson, J., Guérin, R., Jougnot, D., & Longuevergne, L. (2018). Estimating picking errors in near-surface seismic data to enable their time-lapse interpretation of hydrosystems. *Near Surface Geophysics*, 16(6), 613-625.
- Dal Moro, G. (2014). *Surface wave analysis for near surface applications*. Elsevier.
- De Beer, J., Price, S. J., & Ford, J. R. (2012). 3D modelling of geological and anthropogenic deposits at the World Heritage Site of Bryggen in Bergen, Norway. *Quaternary International*, 251, 107-116.
- Di Maggio, C., Agate, M., Contino, A., Basilone, L., & Catalano, R. (2009). Unità a limiti inconformi utilizzate per la cartografia dei depositi quaternari nei Fogli Carg della Sicilia nord-occidentale. *Alpine and Mediterranean Quaternary*, 22(2), 345-364.
- Di Maggio, C., Madonia, G., Vattano, M., Agnesi, V., & Monteleone, S. (2017). Geomorphological evolution of western Sicily, Italy. *Geologica Carpathica*, 68(1), 80.
- Eliosoft (2010). winMASW user manual. Eliosoft, Portogruaro, Italy. www.winmasw.com
- Famiglietti, N. A., Miele, P., Petti, L., Guida, D., Guadagno, F. M., Moschillo, R., & Vicari, A. (2023). What Have We Learned from the Past? An Analysis of Ground Deformations in Urban Areas of

Palermo (Sicily, Italy) by Means of Multi-Temporal Synthetic Aperture Radar Interferometry Techniques. *Geosciences*, 13(10), 298.

Giammarinaro, M. S., Spotorno, R., Sulli, A., & Catalano, R. (1999). Analisi litostratigrafica del sottosuolo del centro storico della città di Palermo finalizzata alla stima della pericolosità sismica dell'area. *Naturalista Siciliano*, 23(3/4), 335-357.

Giammarinaro, M. S., Guidoboni, E., Maiorana, S., Mariotti, D., & Rovelli, A. (2001). A GIS system as a tool for the integrated analysis of geological data and seismic effects: historic centre of Palermo. In *IEEE/ISPRS Joint Workshop on Remote Sensing and Data Fusion over Urban Areas (Cat. No. 01EX482)* (pp. 288-292). IEEE.

Giammarinaro, M. S., Canzoneri, V., Maiorana, S., & Vallone, P. (2002). La tecnologia GIS nella microzonazione sismica delle aree urbane. *Proc. XXI Congr GNGTS*, 179-181.

Giammarinaro, M. S., Canzoneri, V., Vallone, P., & Zuccarello, A. (2003). Effects of the 6th September 2002 earthquake: damage amplification in the south-eastern sector of Palermo explained by GIS technology. *Annals of Geophysics*, 46(6).

Giammarinaro, M., Barba, D., Cionco, D., Contino, A., & Vallone, P. (2006). Site effects assessment through historical and instrumental data integration. In *Quaderni del Museo Geologico "GG Gemmellaro"* (Vol. 9, pp. 170-177). Dipartimento di Geologia e Geodesia-Università di Palermo.

Gibson, B. S., Odegard, M. E., & Sutton, G. H. (1979). Nonlinear least-squares inversion of traveltime data for a linear velocity-depth relationship. *Geophysics*, 44(2), 185-194.

Gutierrez, I., Weibull, W., Watson, L., Olsen, T. M., & Escalona, A. (2023). Holistic 3D model of an urban area in Norway: an integration of geophysical, geotechnical, remote sensing, and geological methods. *Remote Sensing*, 15(11), 2872.

Goldman, M., Du Plooy, A., & Eckard, M. (1994). On reducing ambiguity in the interpretation of transient electromagnetic sounding data1. *Geophysical prospecting*, 42(1), 3-25.

Granata, A., Castrianni, G., Pasotti, L., Gagliano Candela, E., Scaletta, C., Madonia, P., ... & Martorana, R. (2018). Studio per la definizione dei modelli concettuali dei corpi idrici sotterranei di Peloritani, Nebrodi e ragu-sano e indagini geofisiche correlate. In *GNGTS-Atti del 37° Convegno Nazionale. Riassunti Estesi delle Comunicazioni*. (Vol. 37, pp. 104-108). OGS.

Gebrande, H., & Miller, H. (1985). Refraktionsseismik. *Angewandte Geowissenschaften II*, 226-260.

Hagedoorn, J. G. (1959). The plus-minus method of interpreting seismic refraction sections. *Geophysical prospecting*, 7(2), 158-182.

Incarbona, A., Contino, A., Agate, M., Bonomo, S., Calvi, F., Di Stefano, E., Giammarinaro M.S., Priulla, A., & Sprovieri, R. (2016). Biostratigraphy, chronostratigraphy and paleoenvironmental reconstruction of the Palermo historical centre Quaternary succession. *Italian Journal of Geosciences*, 135(3), 512-525.

ISPRA. (2013b). Foglio 595 Palermo. Carta Geologica d'Italia alla scala 1:50.000. Servizio Geologico d'Italia, Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA). Assessorato Territorio e Ambiente, Regione Siciliana.

- Jafri, N. J. S., Ab Rahim, M. A., Zahid, M. Z. A. M., Bawadi, N. F., Ahmad, M. M., Mansor, A. F., & Omar, W. M. S. W. (2018). Assessment of soil compaction properties based on surface wave techniques. In *E3S Web of conferences* (Vol. 34, p. 01002). EDP Sciences.
- Joung, I. S., Cho, S. O., Kim, B., Jeong, J., Jeong, S., Jang, H., Reninger P.A., & Nam, M. J. (2022). A Review of the Time-Domain Electromagnetic Method: Research Trends and Applications. *Journal of the Korean Society of Mineral and Energy Resources Engineers*, 59(4), 364-378.
- Jørgensen, F., Sandersen, P. B., & Auken, E. (2003). Imaging buried Quaternary valleys using the transient electromagnetic method. *Journal of Applied Geophysics*, 53(4), 199-213.
- Keller G.V., & Frischknecht F.C. (1966) Electrical methods in geophysical prospecting. Pergamon Press, New York, pp 1–517
- Kirsch, R. (Ed.). (2006). *Groundwater geophysics: a tool for hydrogeology*. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Kosinski, W. K., & Kelly, W. E. (1981). Geoelectric soundings for predicting aquifer properties. *Groundwater*, 19(2), 163-171.
- Martelet, G., Calcagno, P., Gumiaux, C., Truffert, C., Bitri, A., Gapais, D., & Brun, J. P. (2004). Integrated 3D geophysical and geological modelling of the Hercynian Suture Zone in the Champtoceaux area (south Brittany, France). *Tectonophysics*, 382(1-2), 117-128.
- Maresca, R., Guerriero, L., Ruzza, G., Mascellaro, N., Guadagno, F. M., & Revellino, P. (2022). Monitoring ambient vibrations in an active landslide: Insights into seasonal material consolidation and resonance directivity. *Journal of Applied Geophysics*, 203, 104705.
- Martorana, R., Lombardo, L., Messina, N., & Luzio, D. (2014). Integrated geophysical survey for 3D modelling of a coastal aquifer polluted by seawater. *Near Surface Geophysics*, 12(1), 45-59.
- Martorana, R., Agate, M., Patrizia, C., Cavera, F., & D'Alessandro, A. (2018). Seismo-stratigraphic model of “La Bandita” area in the Palermo Plain (Sicily, Italy) through HVSR inversion constrained by stratigraphic data. *Italian Journal of Geosciences*, 137(1), 73-86.
- Meju, M. A., Fontes, S. L., Oliveira, M. F. B., Lima, J. P. R., Ulugergerli, E. U., & Carrasquilla, A. A. (1999). Regional aquifer mapping using combined VES-TEM-AMT/EMAP methods in the semiarid eastern margin of Parnaiba Basin, Brazil. *Geophysics*, 64(2), 337-356.
- Meju, M. A. (2005). Simple relative space–time scaling of electrical and electromagnetic depth sounding arrays: implications for electrical static shift removal and joint DC-TEM data inversion with the most-squares criterion. *Geophysical prospecting*, 53(4), 463-479.
- Molnar, S., Cassidy, J. F., Castellaro, S., Cornou, C., Crow, H., Hunter, J., Matsushima, S., Sanchez-Sesma F.J., & Yong, A. (2018). Application of microtremor horizontal-to-vertical spectral ratio (MHVSR) analysis for site characterization: State of the art. *Surveys in Geophysics*, 39, 613-631.
- Moscattelli, M., Piscitelli, S., Piro, S., Stigliano, F., Giocoli, A., Zamuner, D., & Marconi, F. (2014). Integrated geological and geophysical investigations to characterize the anthropic layer of the Palatine hill and Roman Forum (Rome, Italy). *Bulletin of Earthquake Engineering*, 12(3), 1319-1338.
- Mucciarelli, M., & Gallipoli, M. R. (2001). A critical review of 10 years of microtremor HVSR technique. *Boll. Geof. Teor. Appl.*, 42(3-4), 255-266.

- Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Railway Technical Research Institute, Quarterly Reports*, 30(1).
- Nakamura, Y. U. T. A. K. A. (1996). Real-time information systems for hazards mitigation. In *Proc. 11th World Conf. Earthquake Eng., Pergamon, Oxford, 1996*.
- Nakamura, Y. (2000, January). Clear identification of fundamental idea of Nakamura's technique and its applications. In *Proceedings of the 12th world conference on earthquake engineering* (Vol. 2656, pp. 1-8).
- Lofrano, G., Carotenuto, M., Maffettone, R., Todaro, P., Sammataro, S., & Kalavrouziotis, I. K. (2013). Water collection and distribution systems in the Palermo Plain during the Middle Ages. *Water*, 5(4), 1662-1676.
- Lo Iacono, C., Sulli, A., Agate, M., Lo Presti, V., Pepe, F., & Catalano, R. (2011). Submarine canyon morphologies in the Gulf of Palermo (Southern Tyrrhenian Sea) and possible implications for geo-hazard. *Marine Geophysical Research*, 32, 127-138.
- Loke, M. H., Acworth, I., & Dahlin, T. (2003). A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. *Exploration geophysics*, 34(3), 182-187.
- Loke, M. H., Wilkinson, P. B., Chambers, J. E., Uhlemann, S. S., & Sorensen, J. P. R. (2015). Optimized arrays for 2-D resistivity survey lines with a large number of electrodes. *Journal of Applied Geophysics*, 112, 136-146.
- Palmer, D. (1980). The generalized reciprocal method of seismic refraction interpretation: Soc. *Expl. Geophys.*
- Panagopoulos, G., Souplos, P., Vafidis, A., & Manoutsoglou, E. (2021). Integrated use of well and geophysical data for constructing 3D geological models in shallow aquifers: a case study at the Tymbakion basin, Crete, Greece. *Environmental Earth Sciences*, 80, 1-17.
- Panzer, F., D'Amico, S., Galea, P., Lombardo, G., Gallipoli, M. R., & Pace, S. (2013). Geophysical measurements for site response investigation: preliminary results on the island of Malta.
- Panzer, F., Tortorici, G., Romagnoli, G., Marletta, G., & Catalano, S. (2020). Empirical evidence of orthogonal relationship between directional site effects and fracture azimuths in an active fault zone: The case of the Mt. Etna lower eastern flank. *Engineering Geology*, 279, 105900.
- Panzer, F., Alber, J., Imperatori, W., Bergamo, P., & Fäh, D. (2022). Reconstructing a 3D model from geophysical data for local amplification modelling: The study case of the upper Rhone valley, Switzerland. *Soil Dynamics and Earthquake Engineering*, 155, 107163.
- Park, C. B., Miller, R. D., Xia, J., Ivanov, J., Hunter, J. A., Good, R. L., & Burns, R. A. (2000, August). Multichannel analysis of underwater surface waves near Vancouver, BC, Canada. In *SEG International Exposition and Annual Meeting* (pp. SEG-2000). SEG.
- Picozzi, M., Parolai, S., & Albarello, D. (2005). Statistical analysis of noise horizontal-to-vertical spectral ratios (HVSR). *Bulletin of the Seismological Society of America*, 95(5), 1779-1786.
- Rai, S. N., Thiagarajan, S., Kumar, D., Dubey, K. M., Rai, P. K., Ramachandran, A., & Nithya, B. (2013). Electrical resistivity tomography for groundwater exploration in a granitic terrain in NGRI campus. *Current Science*, 1410-1418.

- Rawlinson, N., Pozgay, S., & Fishwick, S. (2010). Seismic tomography: a window into deep Earth. *Physics of the Earth and Planetary Interiors*, 178(3-4), 101-135.
- Rayfract (™) Userguide Manual from <https://rayfract.com/help/manual.pdf>
- Rohdewald, S. R. (2011). Interpretation of first-arrival travel times with wavepath eikonal traveltime inversion and wavefront refraction method. In *Symposium on the Application of Geophysics to Engineering and Environmental Problems 2011*, Society of Exploration Geophysicists, 31-38.
- Rusydy, I., Setiawan, B., Zainal, M., Idris, S., Basyar, K., & Putra, Y. A. (2020). Integration of borehole and vertical electrical sounding data to characterise the sedimentation process and groundwater in Krueng Aceh basin, Indonesia. *Groundwater for sustainable development*, 10, 100372.
- Ruggieri, G., & Sprovieri, R. (1975). RICERCHE SUL SICILIANO DI PALERMO: LE ARGILLE DEL FIUME ORETO.
- Schuster, G. T., & Quintus-Bosz, A. (1993). Wavepath eikonal traveltime inversion: Theory. *Geophysics*, 58(9), 1314-1323.
- Seigel, H. O. (1959). Mathematical formulation and type curves for induced polarization. *Geophysics*, 24(3), 547-565.
- Shaffner, P., Heisler, R., Krosley, L., Kottenstette, J., & Wright, J. (2009). Characterization of dam foundation blocks using digital photogrammetric mapping and borehole geophysical logging to create comprehensive 3D foundation models. In *Proc. of the 29th Annual USSD Conf.*
- Smallwood, J. R., & Maresh, J. (2002). The properties, morphology and distribution of igneous sills: modelling, borehole data and 3D seismic from the Faroe- area.
- Sørensen, K. I., Auken, E., Christensen, N. B., & Pellerin, L. (2005). An integrated approach for hydrogeophysical investigations: new technologies and a case history. *Near-surface geophysics*, 2, 585-603.
- Spies, B. R. (1989). Depth of investigation in electromagnetic sounding methods. *Geophysics*, 54(7), 872-888.
- Tarallo, D., Alberico, I., Cavuoto, G., Pelosi, N., Punzo, M., & Di Fiore, V. (2023). Geophysical assessment of seawater intrusion: the Volturno Coastal Plain case study. *Applied Water Science*, 13(12), 234.
- Todaro, P. (2000). Palermo sotterranea. *Storia di Palermo II*, 238-255.
- Todaro, P. (2006). Il rischio sismico nel centro storico di Palermo: Rigidità sismica e modelli geologici semplificati per terreni di sedime di fondazioni datate. *Archeometria del Costruito. l'Edificato Storico: Materiali, Strutture e Rischio Sismico*, 239-255.
- Todaro, P. (2019). Le paludi del Papireto e la bonifica idraulica del XVI secolo. *Notiz. archeol. Sez. Archeol. Soprintendenza BB. CC. AA. Palermo*, 47, 14.
- Willmore, P. L., & Bancroft, A. M. (1960). The time term approach to refraction seismology. *Geophysical Journal International*, 3(4), 419-432.
- Xue, G., Li, H., He, Y., Xue, J., & Wu, X. (2020). Development of the inversion method for transient electromagnetic data. *IEEE Access*, 8, 146172-146181

Xu, R., & Wang, L. (2021). The horizontal-to-vertical spectral ratio and its applications. *EURASIP Journal on Advances in Signal Processing*, 2021, 1-10.

Zhang, B., Tong, Y., Du, J., Hussain, S., Jiang, Z., Ali, S., & Khan, U. (2022). Three-dimensional structural modeling (3D SM) and joint geophysical characterization (JGC) of hydrocarbon reservoir. *Minerals*, 12(3), 363.

ACKNOLEDGMENTS

Il lavoro presentato è frutto di più di tre anni di studio realizzato in sinergia e grazie al fondamentale aiuto di docenti, ricercatori e liberi professionisti che hanno contribuito alla realizzazione di questa tesi.

Un ringraziamento va' ai miei tutor, il Prof. Martorana ed il Prof. Agate, che mi hanno seguito in questi tre anni di lavoro fornendomi supporto e confronto nelle diverse fasi della mia attività di ricerca. Ringrazio inoltre la Prof.ssa Capizzi ed il Professore Gasparo Morticelli per avermi fornito numerosi dati e spunti di riflessione fondamentali per gli studi condotti. Un sentito ringraziamento va' ai Dottori Bonfardeci, Carollo, Lo Presti, Mercurio e Bongiovanni come anche al Prof. Calabrese, per avermi aiutato nella realizzazione delle campagne di indagine effettuate; ringrazio anche l' ONT , il Prof. D'Alessandro, la sezione INGV di Palermo ed il Dottore Rocco Favara per il supporto tecnico fornito ed i dati condivisi in questi anni di ricerca ed il Prof. D'Amico e la Dott.ssa Pirrotta per le revisioni effettuate utili a rifinire e migliorare il lavoro esposto.

Un particolare ringraziamento agli Ingegneri Canzoneri, Di Maio, Speciale, Sammataro, Nigrelli e alla Sering Ingegneria in toto per avermi dato continuo supporto nella mia attività di studio: numerose acquisizioni di dati pregressi, campagne di acquisizione sul campo ed informazioni sulle aree di studio non sarebbero stati possibili senza l'aiuto dell'Azienda. A questo proposito ringrazio anche la Manelli Group che con la sua collaborazione e disponibilità mi ha fornito supporto nel reperimento dei dati sul campo nell'area della piana di Palermo.

Alessandro Canzoneri