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GPR survey for the reconstruction of the canalization system beneath the *orchestra* level of the Ancient Theatre of Catania (Italy)

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Abstract

Geophysical prospecting was carried out with GPR (Ground Penetrating Radar) at the *orchestra* floor of the Ancient Theatre in Catania (Italy) to reconstruct the lithological pattern of the substrate and to identify cavities and/or channels used in the past for the drainage of rainwater or groundwater. On the basis of the data acquired, the existence of pre-existing north-south oriented drainage channels below the *orchestra* floor can be confirmed, now partly blocked by sediments that have accumulated over the centuries. In particular, interpretation of radar sections indicated the occurrence, in the center of the *orchestra*, of a masonry vault one meter deep, supported laterally by jambs. It has been interpreted as a channel that should have been used to drain groundwater, since it appears connected towards the south with another channel, still visible below the stage, almost completely filled with debris. Another channel probably occurs at the same depth in the eastern sector of the *orchestra*.

Keywords: Geoarcheology; Ground Penetrating Radar; Drainage systems

1. Introduction

Ground Penetrating Radar (GPR) is a non-invasive geophysical technique used in archaeological prospection (Conyers, 2015; Manataki et al., 2015) to detect subsurface targets which is exploited in many investigation fields like the mapping of the bedrock depth (Davis and Annan, 1989), the determination of the thickness of layers and the aquifer depth (Doolittle et al., 2006), the location of burials (Kwan et al., 2024) and natural/artificial cavities in the subsurface (Benson, 1995) and detecting fracture zones (Theune et al., 2006; Imposa et al., 2015). GPR has also been successfully used in the mapping of ancient Roman structures like cisterns, theatres, living quarters and villas (e.g. Goodman et al., 2004; Papadopoulos et al., 2009).

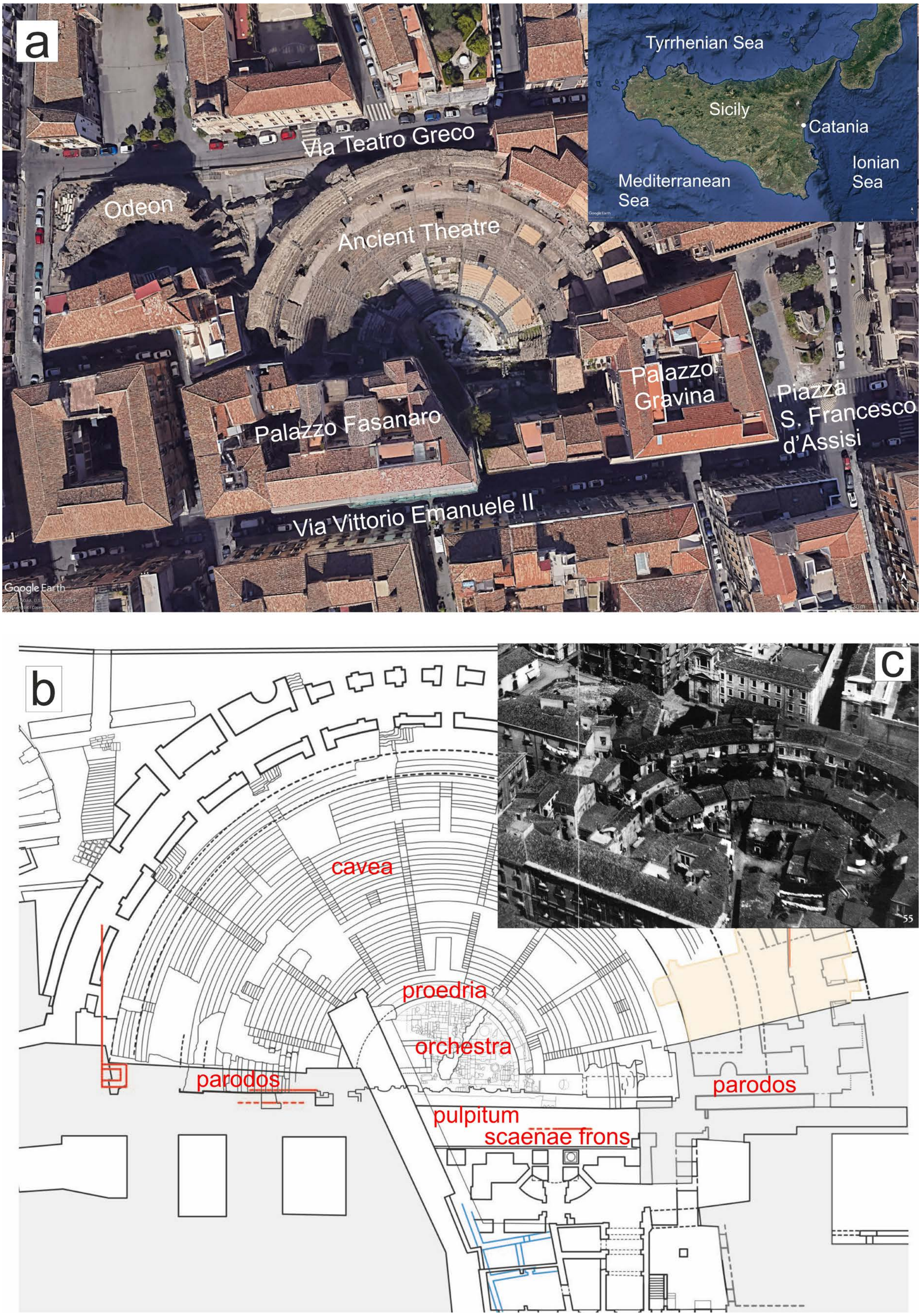

Figure 1. (a) Satellite view of the Ancient Theatre (Google Earth, 2024). The names of the main streets, squares and buildings are indicated. The inset shows the location of the city of Catania in the Central Mediterranean. (b) Plan of the theatre with Latin nomenclature of the architectural parts (from Branciforti and Pagnano, 2008, modified). (c) Aerial photo dated 1930 (Archive of Parco Archeologico e Paesaggistico di Catania).

The Ancient Theatre of Catania (Sicily, southern Italy, Fig. 1a), built by Romans in the 1st century AD (Falco et al., 2024; Branciforti and Pagnano, 2008; Branciforti, 2010; Taormina, 2010, 2015; Tortorici, 2010 and references therein), shows a collapse of the paving in the south-eastern sector of the *orchestra*. This latter is seasonally invaded by the positive fluctuations of the water table present in the subsoil, which covers a large part of the stone paving of the *orchestra* itself and the lower part of the monument (Fig. 2a). The runoff of water, which flows out particularly from the western *parodos* and between the gaps in the paving of the western sector of the *orchestra*, deposits abundant detrital material, while prolonged stagnation favors the growth of biodeteriorating patinas and weeds, damaging the monument (Fig. 2b). To better understand the causes of paving collapse and the impact of the rising water table on the exposed surfaces, a collaboration has been established between the *Parco archeologico e paesaggistico di Catania e della Valle dell'Aci* and the Department of Biological, Geological and Environmental Sciences of the University of Catania (Earth Sciences section) with the final aim of identifying strategies to counteract the deterioration of the theatre. In particular, a non-destructive geophysical investigation with GPR (Ground Penetrating Radar) was carried out at the *orchestra* level with the dual purpose of reconstructing the lithological units of the substrate and identifying cavities and/or underground collection channels used in the past for the drainage of rainwater or groundwater (see also Falco et al., 2024).

2. The Theatre-Odéon complex of Catania

The Theatre-Odéon complex of Catania stands on the southern slopes of the Montevergine hill, the acropolis of the ancient city, the heart of the urban center in antiquity, as it is still today (Fig. 1a). The Theatre was built by Romans in the 1st century AD on pre-existing structures from the Greek period (Branciforti and Pagnano, 2008; Branciforti, 2010; Taormina, 2015; Tortorici, 2010, 2016). Similar to the other ancient Roman theatres, the building is composed of a semicircular *orchestra*, a *cavea*, and the *scaena* building (Fig. 1b). The *orchestra*, the flat area used in the Greek period for actors and stage, in the Roman period was partly dedicated to the seats of honour (*proedria*). The *cavea*, a seating area 98 m-wide, is located in front of the *orchestra* bounding its perimeter and leaning against the natural slope of the hill. The scene building was 46 m long. In the 2nd-3rd centuries AD, the Theatre was enlarged and the *scaenae frons* was enriched with multiple stories, articulated by freestanding columns and lavishly ornamented with statues of gods and heroes and portraits of the imperial family and local luminaries. In the same period, the *Odéon* (Fig. 1a) was added to the west (Branciforti and Pagnano, 2008; Branciforti, 2010; Tortorici, 2016). Later on (4th-5th century AD), the building undergone important structural changes also related to its adaptation for aquatics exhibitions, like other theatres in Sicily and in the Italian peninsula (Branciforti and Pagnano, 2008; Buda, 2015; Gottardo, 2025). In the 6th-7th centuries AD, Theatre and *Odéon* were abandoned and progressively covered by noble palaces (Palazzo Fasanaro, Palazzo Gravina, see Fig. 1a) and by the modest dwellings of the Grotte popular neighborhood (Fig. 1c). These latter were demolished during the 20th century to restore the monumental complex for public use (Tortorici, 2010, 2016; Pagnano, 2010). Nowadays, the area of the Theatre's *orchestra* is subject to the rise of the superficial aquifer, which periodically floods it for several months in the rainiest years (Fig. 2a).

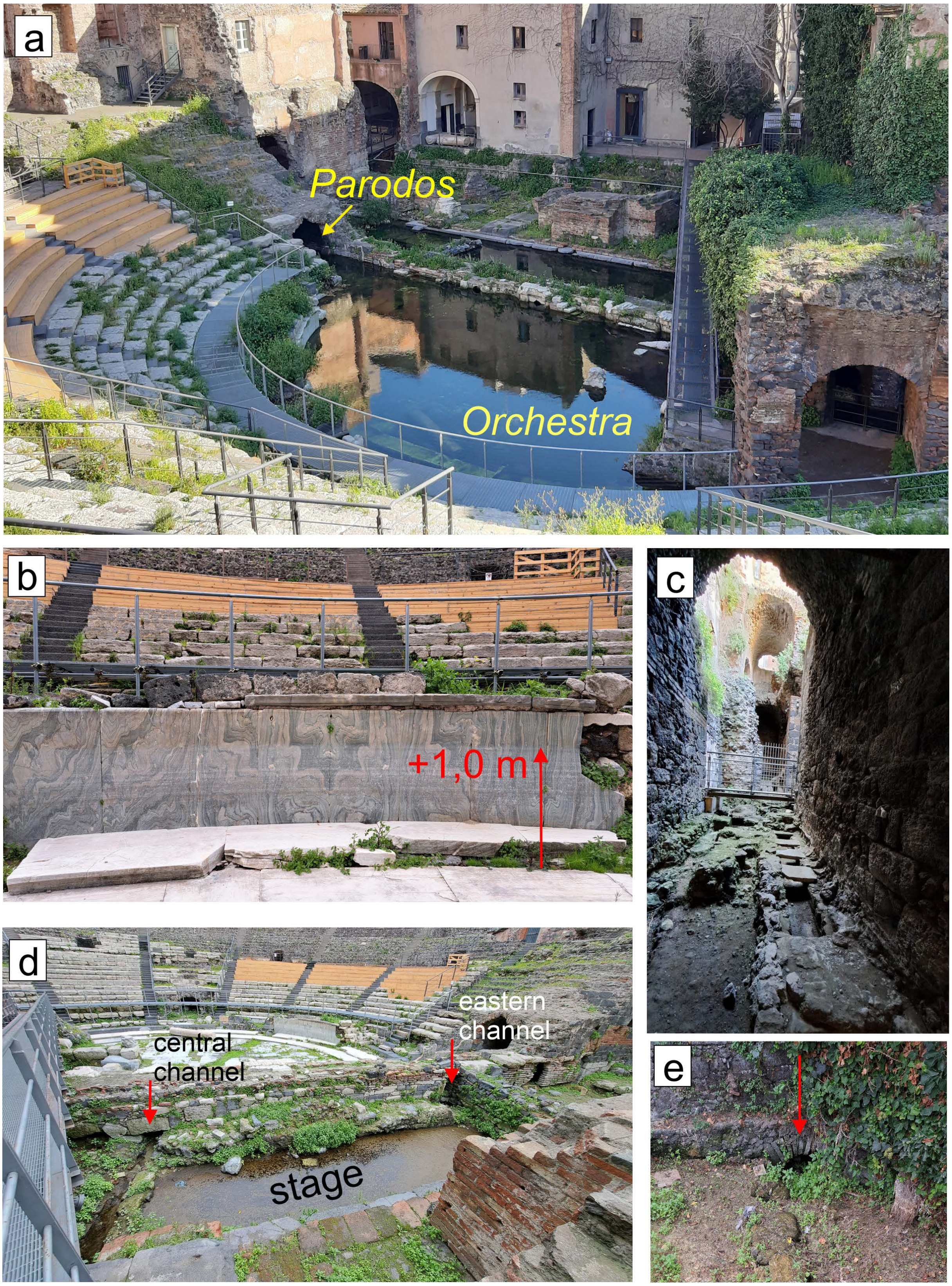

Figure 2. (a) View from the northwest of the *orchestra* level of the Ancient Theatre of Catania, flooded by groundwater (February 24, 2022). (b) Corrosion stains on the marble slabs of the podium show the level reached by groundwater in the past. (c) channel located along the western *parodos* of the theatre, probably built for the drainage of the groundwater; (d) Outlets towards the stage of the drainage channels located beneath the *orchestra*. (e) Southward outlet of the central drainage channel highlighted in Fig. 2d.

3. Geological and hydrogeological framework of the Ancient Theatre area and surrounding sectors

Based on the reconstruction by Castagnino Berlinghieri and Monaco (2008, 2010), the Ancient Theatre was built on the southern slope of the Montevergine hill (Fig. 3), from an elevation of approximately 24 m a.s.l. to the north (Via Teatro Greco level, see Fig. 1a) to 10.40 m a.s.l. (*orchestra* level). The hill is a flat-topped sedimentary rise that dominated, before the 1669 lava flow, the Catania plain and the coastal strip of the Plaia to the south (Fig. 3). To the east, at the base of the hill, extended the large prehistoric lava flow of Larmisi (Fig. 4a); from the west, another prehistoric lava flow, the so-called Barriera del Bosco lava, had partially invaded the hilly area. The elevation of the road called Via Vittorio Emanuele, slightly south of the *orchestra* level (Fig. 1a), is approximately 13 m a.s.l. Thanks to the analysis of stratigraphic logs of boreholes provided by various municipal and regional agencies (see Geological Map of the urban area of Catania, Scale 1:10,000, Monaco et al., 2000), updated with other boreholes commissioned by the Public Works Department of the Municipality of Catania for the study of the aquifer (year 2001) and for the renovation of the sewer connection of Via Vittorio Emanuele (year 2014), it has been possible to reconstruct the geological setting of the subsoil in the investigated area (see also Lombardo et al., 2006; Bottari et al., 2015).

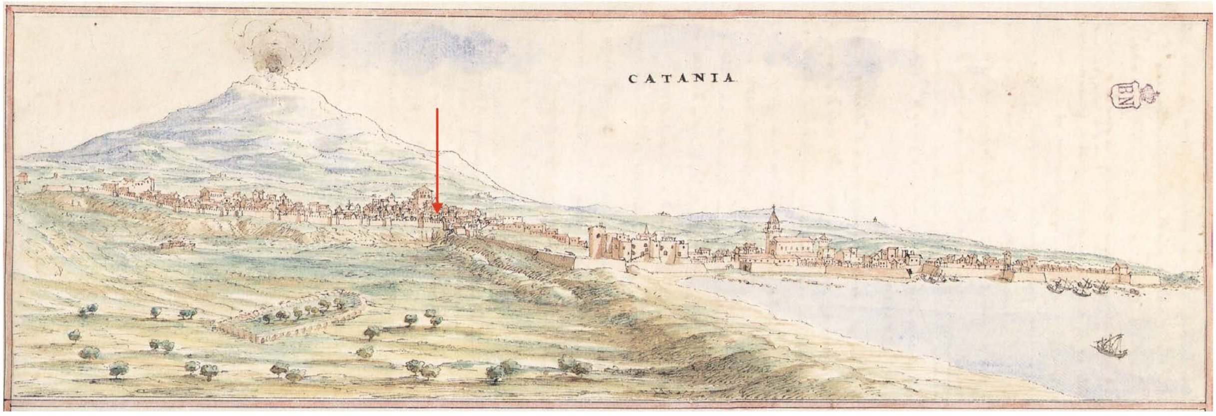

Figure 3. Panoramic view from the south of the city of Catania before the 1669 eruption with Etna in the background in the drawing by T. Spannocchi dated 1578 (from Giuffrè, 1980). Note the morphological terrace of Montevergine on which the ancient city was built, on whose edges the sixteenth-century fortifications were adapted. The red arrow indicates the location of the Ancient Theatre, built on the southern slope of the Montevergine hill. In the foreground, dominating the harbor area, is visible the XII century Swabian Castle (Castello Ursino). The lava flow of 1669 surrounded the city, resting on the edges of the terraces and on the western and southern walls, upsetting the morphology of the area (see Fig. 4a).

A borehole (Fig. 4b) carried out a few meters southeast of the *orchestra* level (at an elevation of 10.40 m a.s.l.) revealed the presence of a basaltic lava flow (Barriera del Bosco Lavas? see Magli et al., 2022) at a depth of 24.50 m from the same level, above which lie 18 m of brownish-red silts of probable marshy and/or lagoon origin, covered by considerable thicknesses (6 m) of fill material and wall structures. Other boreholes drilled downstream eastwards, along Via Vittorio Emanuele – Piazza San Francesco d’Assisi (Fig. 1a), show a similar stratigraphic configuration, while those upstream reveal the presence of the lava flow directly below the fill material.

On the basis of geological data, we infer that the *cavea* of the Theatre rests on the Barriera del Bosco lavas, while the *orchestra* level lies on marshy and/or lagoon sediments which, together with the underlying lavas, must have filled a deep valley incision located at the current Via Vittorio Emanuele (see Fig. 4c). This valley incision was probably carved by a branch of a paleo-river at the beginning of the Holocene, when the sea level was about 50 m below the current level. It is also hypothesized that the hydrographic network still maintained this configuration upon the arrival of the ancient Greek colonizers and perhaps even in Roman times, and that the altimetric position of the axis of the current Via Vittorio Emanuele allowed in antiquity the outflow of water from the Theatre area towards the sea (the current harbor area, see Fig. 4a). The fillings performed in the following centuries, also due to numerous earthquakes, the occurrence of the 1669 lava flow, and the road leveling carried out in the 19th century, have definitively altered the original morphology of the area.

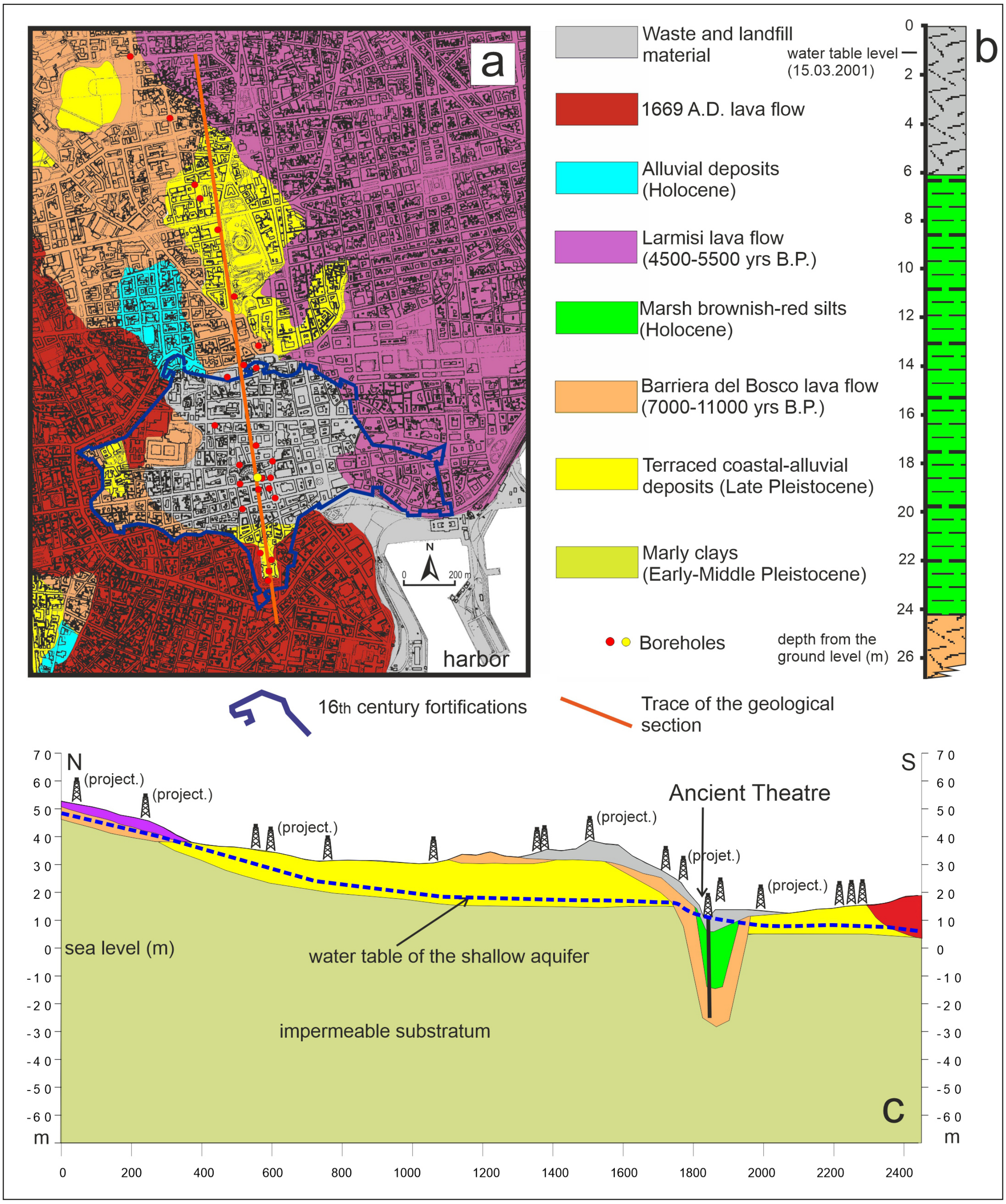

Figure 4. (a) Geological map (from Monaco et al., 2000, modified). (b) Stratigraphic log of the survey carried out in 2001 on behalf of the Public Works Department of the Municipality of Catania for the study of the aquifer in the area of the Ancient Theatre (location in Fig. 4a, yellow filled circle). (c) Geological section (reconstructed from borehole data, from Monaco et al., 2000; Lombardo et al., 2006) of the historical center area of Catania (trace and legend in Fig. 4a). Dating of the Barriera del Bosco and Larmìsi lavas from Magli et al. (2022). The blue dotted line shows the water table of the surface aquifer (reconstructed using borehole data), hosted by permeable soils (lava, sands and filling material). Vertical scale in the profile is exaggerated. The yellow dot in (a) indicates the location of the stratigraphic log shown in (b).

The waters that periodically invade the *orchestra* level belong to the superficial aquifer present in the subsoil, the top of which has been reconstructed thanks to borehole data (Fig. 4c). The aquifer is hosted by the permeable superficial soils (lavas, sands, and fill material) and is supported by the impermeable marly-clayey substratum. The top of the aquifer is normally found at a depth of about 15 m at the Montevergine hill, down to a few meters at the base of the hill (2.5 m below Via Vittorio Emanuele-Piazza San Francesco d'Assisi, see Fig. 1a), reaching the base level (sea level) at the coast. It should be noted that in the southern sector, the aquifer has probably undergone a significant rise in the piezometric level over the centuries due to the invasion of the 1669 lava flow (Fig. 4a) and subsequent fillings due to road leveling.

As mentioned above, the water table periodically submerges the *orchestra* floor and most of the coverings and lateral structures of the Theatre. In this regard, the corrosion stains on the marble slabs of the so-called *podium* (Fig. 2b) show that the water level has also reached a height of one meter above the *orchestra* level in the past, although in the summer seasons and during periods of low rainfall, the level may have dropped to the total disappearance of water, as observed at present. The aquifer still periodically emerges in the form of a spring and, according to a hypothesis currently under study and further investigation, probably in late Roman period it was captured and channeled (Fig. 2c) along the western *parodos* of the Theatre to be used, with the support of the cistern located along the median axis of the *cavea*, to create a *colimbetra* in the *orchestra* area during aquatic exhibitions (Buda, 2015). Based on observations made in situ and on georadar surveys (see below), it is assumed that the Theatre was equipped with a system of drainage channels (Fig. 2d) that allowed, when necessary, to regulate the flow of water. This system of underground channels must have passed under the stage to be connected toward the south, through an outlet (Fig. 2e), to a watercourse or an artificial channel located along the current Via Vittorio Emanuele, which, in turn, must have conveyed the water towards the sea.

4. GPR Survey

4.1 Methods

Ground-penetrating radar or GPR is an electronic system with which it is possible to investigate soils and materials with a considerable degree of detail, using the propagation and reflection of electromagnetic waves produced by the system itself (Annan, 2009 and references therein). The GPR survey consists of sending into the subsoil pulses of electromagnetic energy of very short duration and with a well-defined spectral content (commonly 35-1000 MHz). By measuring the time required for the electromagnetic wave to be reflected by the object and received by the radar, it is possible to evaluate the depth of the targets found. By appropriately processing and visualizing the signals, vertical sections (radargrams) of the subsoil can be reconstructed, in which the trends of discontinuities and inhomogeneities are recognized. The GPR system used is the PROCEQ GS8000 from Screening Eagle (Fig. 5), a stepped-frequency continuous-wave (SFCW) ultrawideband radar (~40-3400 MHz) whose operating

Figure 5. Ground-penetrating radar equipment used and survey phase.

principles combine advanced radar physics, precise geolocation, and real-time data processing. The radar device can investigate large areas with a 3D view of the subsoil with high resolution and penetration depth. The data are acquired in real time on a tablet dedicated to the control and saving of electromagnetic signals. The PROCEQ GS8000 is equipped with a GPS receiver for the geographical positioning of the scans and the targets identified on the ground. The instrumental error, from calibration and from indication of the CEI 306-8 standard, is equal to 10% of the indicated planimetric-altimetric data. An initial dielectric constant of 9.7 was assumed during acquisition, while time-to-depth conversion was operated using different dielectric constants for each identified electromagnetic layer (see Section 4.2).

4.2 Data Acquisition and processing

A nearly regular grid of 24 GPR sections, for a total length of 192 meters, was acquired to homogenously cover the *orchestra* area (Fig. 6b). To ensure the correct planimetric and altimetric positioning of the identified electromagnetic anomalies, GPR profiles were georeferenced directly in the field using a DGPS RTK system. The radar profiles were processed by using GPR Insights 3 software and adopting common GPR processing techniques. To improve their SNR (signal to noise ratio) the following mathematical operators (filtering) were applied on the raw data:

- Vertical bandpass filter – a time-domain filter operating along the depth direction to filter the noise located beyond the useful signal band; cut-off frequencies at <200 MHz (low) and >600 MHz (high) were used.
- Move start time – in order to define the correct origin of the scansion along the time-axis (e.g., the air-ground interface). This algorithm must always be applied to align the radar signal with the surface position.
- Background Removal – with this tool the Clear-X filtering algorithm is applied, used to remove continuous components along the X-axis (horizontal direction). The adopted delay value is 20 ns and the propagation speed 12 cm/ns. The adopted propagation velocity is a purely numerical parameter required by the Clear-X filtering processing algorithm and does not represents an assumed physical propagation velocity in the subsurface.
- Smoothed gain – a signal trace equalization to improve the visibility of deep targets.

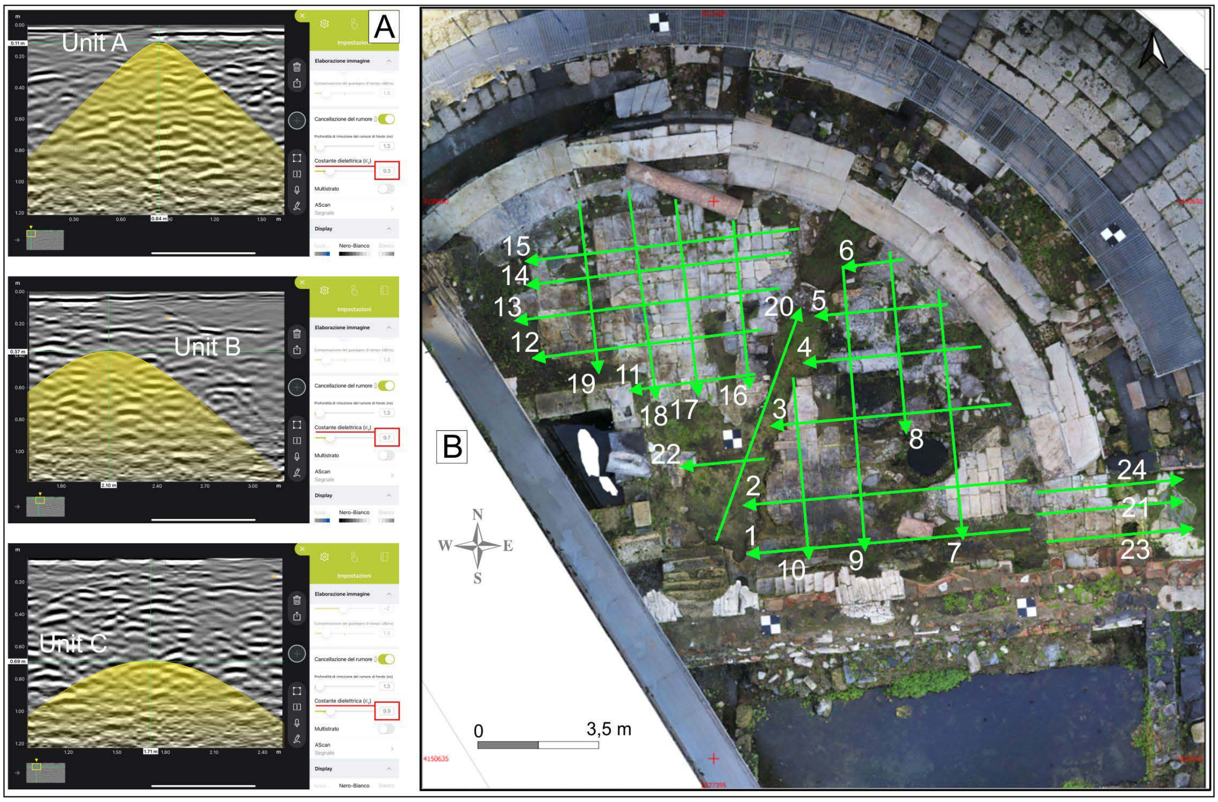

Figure 6. (a) Hyperbola fitting procedure adopted to retrieve dielectric constants for the identified electromagnetic units A, B, and C. (b) Grid of profiles acquired through georadar survey.

Using hyperbola fitting technique, which relies on the characteristic hyperbolic shape that target produces, different dielectric constants were obtained for each identified electromagnetic facies. In detail, $\varepsilon_r = 9.3$, 9.7, and 9.9 were assigned to Units A, B, and C, respectively considering materials above the diffractor (see Fig. 6a and Section 4.3). The maximum penetration depth was found to exceed 1.80 m at a dominant frequency of 600 MHz. The limited penetration is probably due to the presence of the aquifer at depth (October 2023). Given the shallow domain of investigation and the inferred limited extent of the buried relics, high-resolution and low penetration provided by the dominant frequency band used for interpretation after filtering (600 MHz) was adopted also considering the high signal-to-noise ratio (30-40 dB) obtained at this frequency. Accordingly, the most representative 600 MHz radar sections are then interpreted also considering field observation and available borehole data.

4.3 GPR Data Interpretation

Five representative radar sections were selected to interpret the subsurface setting of the investigated sector. An electromagnetic facies analysis approach was followed for interpreting layering with depth, whereas diffraction hyperbolas were exploited to detect buried man-made targets. The ~8 m-long section n. 9 in the eastern sector of the *orchestra* provides elements for interpreting the subsurface setting. Strong electromagnetic reflections are found at various depths along the section interpreted as continuous to semi-continuous, high and low amplitude parallel reflections resembling bedded electromagnetic facies. The uppermost is found at 0.05 m-depth and exhibit a flat geometry and separates the stone paving from the underlying *Unit A*. *Unit A* exhibit low-reflectivity facies with medium amplitude discontinuous electromagnetic reflectors about 0.2 m-thick. The *Unit B* is characterized by a top-reflector with medium-high amplitude and a slightly undulated geometry. The 0.5 m-thick *Unit B* electromagnetic facies is mostly semi-transparent with local high-amplitude and discontinuous reflector in the upper portion. The *Unit C* is characterized by high-frequency and high-amplitude electromagnetic reflectors and it is separated from the *Unit B* by an undulated low-medium amplitude discontinuity. A strong electromagnetic attenuation is found in the western sector of the radar section.

According to the electromagnetic facies analysis and to the stratigraphic log provided by the borehole S1 (see Fig. 4b), the detected electromagnetic Units are interpreted as follows (Fig. 7):

Unit A: heterogeneous layer of poorly compacted material with coarse elements (blocks and/or stones) – *orchestra* flooring foundation soil material.

Unit B: heterogeneous layer of loose, moderately compacted material with less coarse elements – waste and landfill material.

Unit C: homogenous layer of finely stratified material – lagoonal silts brownish-red in color (see Fig. 4).

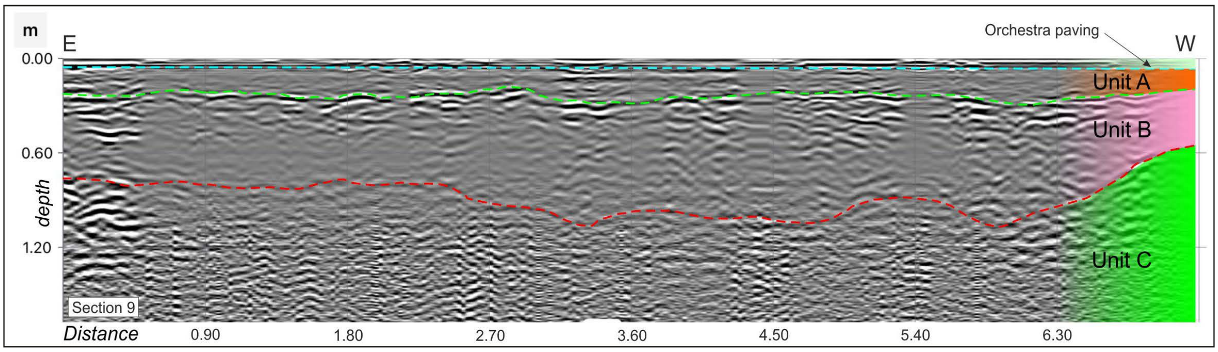

Figure 7. 600 MHz georadar section n. 9 with the stratigraphic succession interpreted below the *orchestra* (location in Fig. 6b).

Diffraction hyperbole and amplitude slice-maps were instead used to detect possible buried man-made targets. With this aim, four representative radar sections were selected. The about 7 m-long, 600 MHz section n. 21 (Fig. 8a) cross the eastern side of the *orchestra* in a W-E direction. In the middle sector of the section, a hyperbola is found at a depth of approximately 0.5-0.6 m, and it is interpreted as generated by the occurrence of a buried cavity. On the basis of field observation, the hyperbola signal is associated with the 0.25-0.30 m-wide and approximately 0.6 m-high rectangular-shaped drainage channel (i.e., the eastern channel in Fig. 2d). The N-S orientation of the channel is retrieved by amplitude slice-map of Fig. 8b.

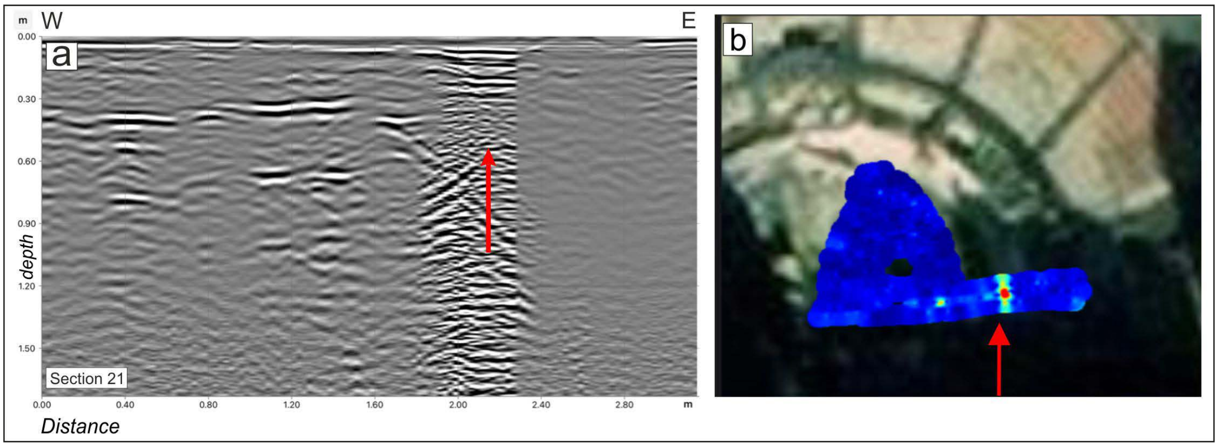

Figure 8. (a) West-east oriented 600 MHz ground-penetrating radar section (n. 21, see location in Fig. 6b) showing the occurrence, in the eastern sector of the *orchestra*, of a probable underground channel. (b) Amplitude-slice-map at 0.6 meters showing the orientation of the channel.

In the center of the *orchestra*, another anomaly compatible with channel-like features has been identified at depth along three parallel E-W trending radar sections (Fig. 9), namely the n. 12, 13, and 15 (see Fig. 6b for location). The hyperbola signal associated with this possible buried channel is found at a depth of 0.60-0.70 m (apex), with a width of 0.30-0.40 m and a height of approximately 0.60 m. Along section n. 12, a masonry vault resting on lateral abutments may be interpreted by the electromagnetic contrasts (Fig. 9a). The masonry channel position and orientation (about N-S) is geometrically consistent with the Theatre plan since it occurs in the middle of the *orchestra*. Field observation reveals that the detected underground channel may be the prolongation of the one still visible below the central-northern sector of the stage (the central channel, see Fig. 2d), which is still today the site of the groundwater outflow (when emerging). Visual inspection suggests that the aforementioned channel should have continued southwards, as demonstrated by the presence of a vaulted conduit on the southern wall of the stage cavity, currently partially obstructed by sediments and debris, interpreted as a water outlet (Fig. 2e). Using the first-Fresnel-zone approximation, the expected lateral footprint at 0.60 m depth is approximately 0.30 m for the 600 MHz antenna and about 0.50-0.55 m when lower effective frequencies (e.g., 200 MHz) dominate the processed signal. Although the footprint increases at lower frequencies, the identified targets are spaced at distances well above these values, ensuring that the adopted frequency filtering does not compromise the reliability of the interpretation. However, other factors such as attenuation contrasts, scattering effects, and antenna radiation pattern may influence the apparent geometry of electromagnetic anomalies.

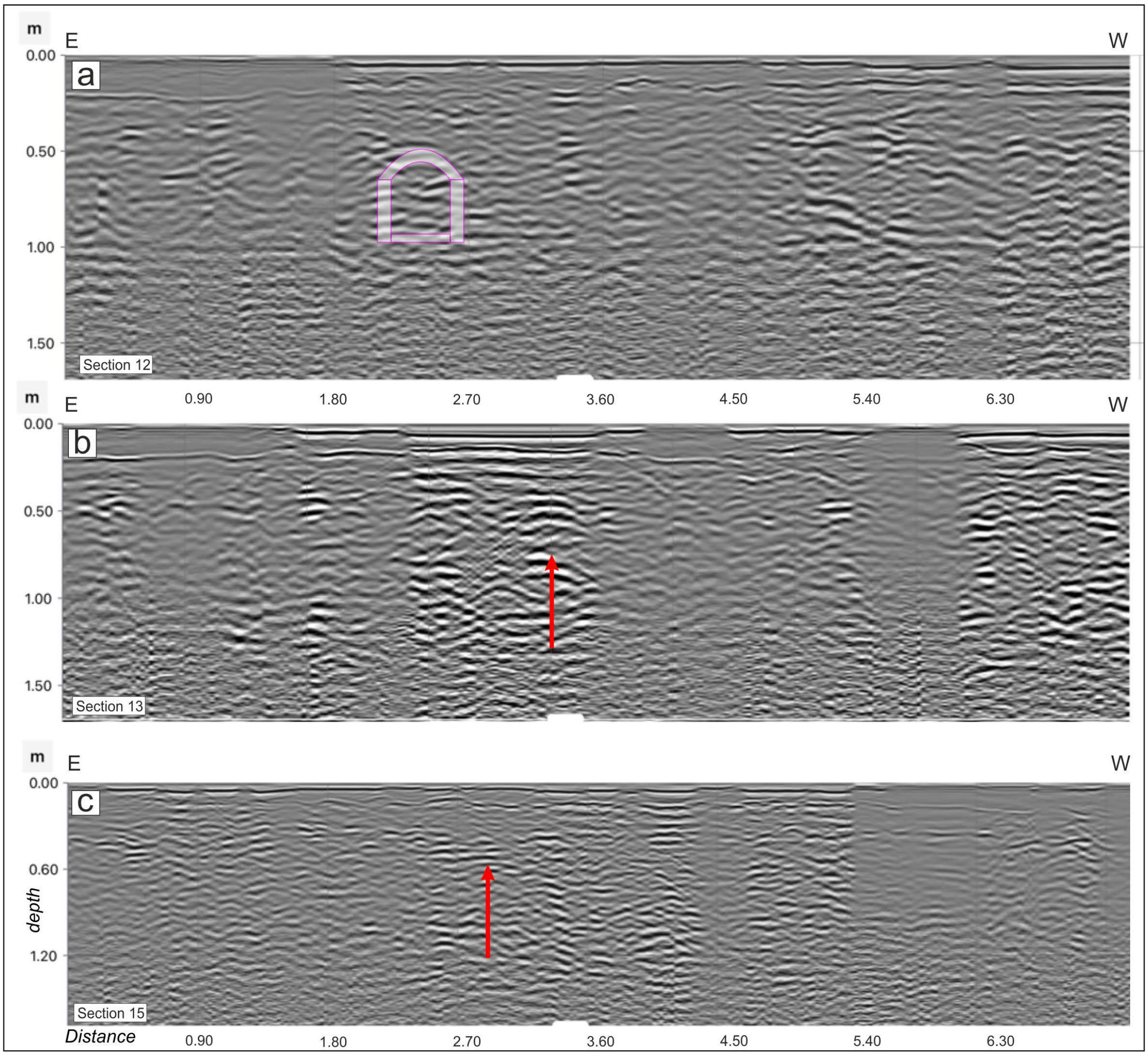

Figure 9. Representative 600 MHz georadar sections n. 12, 13 and 15 (location in Fig. 6b) showing the presence, at the center of the *orchestra*, of a probable underground drainage channel.

5. Concluding Remarks

The geological analysis and GPR survey carried out on the *orchestra* of the Theatre have allowed us to characterize the behavior of the aquifer, as well as the location of underground electromagnetic anomalies compatible with channel-like features present below the walking surface of the *orchestra*. Depending on rainfall, the water-table elevation undergoes significant variations both seasonally and over the years (ranging from −180 cm to +100 cm relative to the *orchestra* level), periodically flooding the *orchestra* area and contributing to the deterioration of the stone pavements. Based on previous studies (Monaco et al., 2000) and on the analysis of numerous boreholes stratigraphic logs, the aquifer is preliminarily interpreted as an unconfined system. Nevertheless, further investigations such as additional boreholes and well permeability tests together with continuous monitoring of groundwater levels, are required to confirm this interpretation.

Based on the data acquired with the GPR and field observations, it can be stated that there are two underground channels oriented approximately north-south below the *orchestra* level (Fig. 10), at a depth of about 60 cm, the outlets of which are still visible inside the stage cavity (Fig. 2d, e). Both channels must have been connected upstream to the so-called *euripus*, the drainage conduit to channel drainage water running along the northern perimeter of the *orchestra* (Branciforti and Pagnano, 2008). The trace of the channel located at the eastern end of

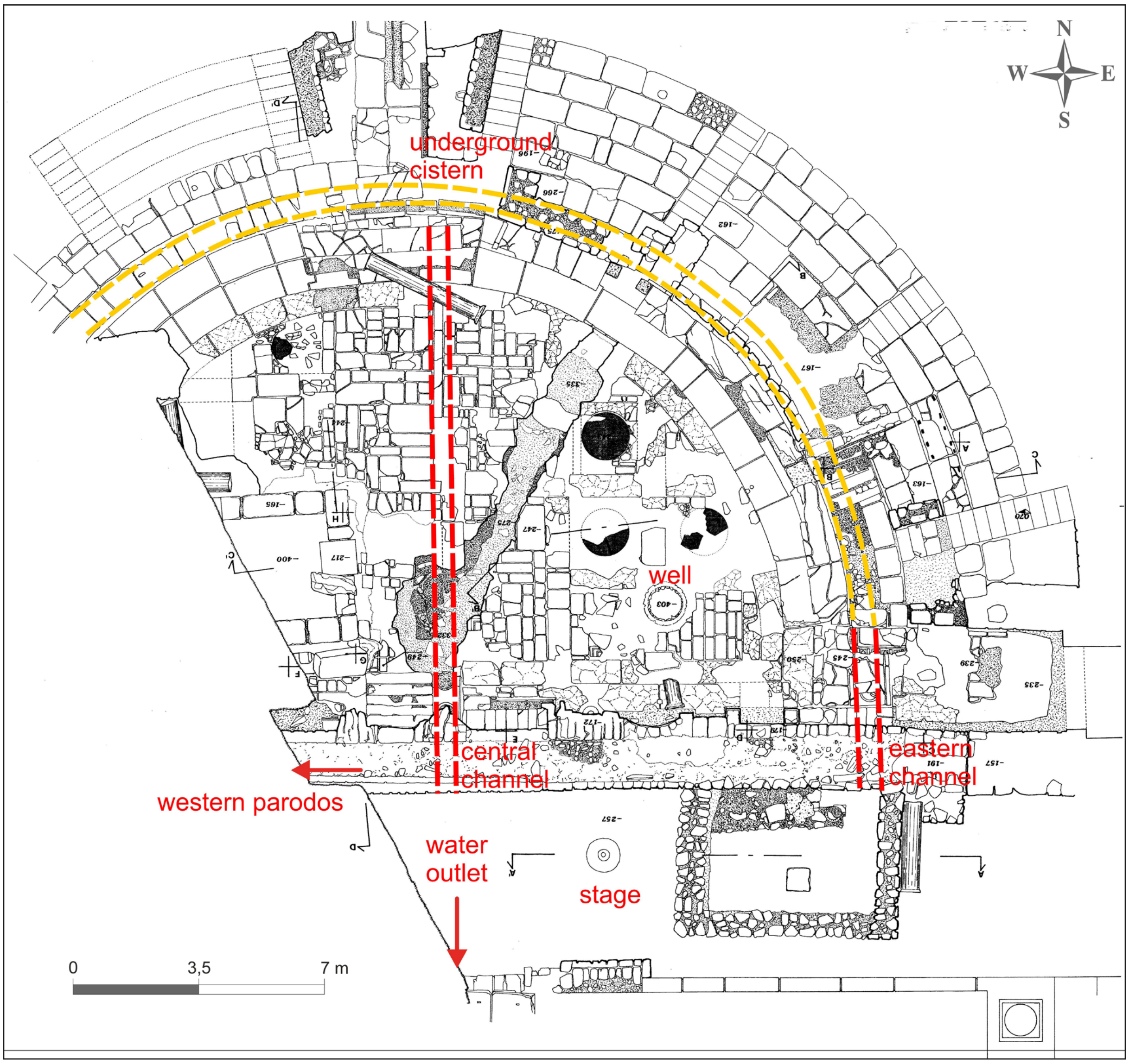

Figure 10. Planimetric reconstruction of the possible layout of the drainage channels beneath the *orchestra* level of the Ancient Theatre of Catania (survey with laser scanner technology from “Project for the enhancement and increase of the use of the Roman Theatre and the Rotonda Baths of Catania”, Sicilian Region – Department of Cultural Heritage and Sicilian Identity, 30 May 2015). Subsurface sections identified through ground-penetrating radar are shown with red dashed lines, while the trace of the *euripus* is indicated by a yellow dashed line.

the *cavea* coincides with the area affected by the paving collapse of the *orchestra*. Further N-S oriented underground channel may occur in the western sector of the *orchestra* level, although it cannot be detected due to the overlying 19th-century building (Palazzo Fasanaro, see Fig. 1a). Overall, these features likely constitute a canalization system, now partly blind and/or obstructed by sediments accumulated over the centuries, which must have served to convey both rainwater and groundwater flowing from upslope. The drainage system may have discharged southeastward through an outlet channel leading toward the sea. It seems plausible, in fact, that despite the current elevation of Via Vittorio Emanuele south of the Theatre being about 13 m, while the elevation of the *orchestra* level is 10.40 m, natural phenomena and human interventions have altered the original morphology of the area, as also shown by the considerable thicknesses (6-7 m) of fill material and wall structures found in the numerous boreholes carried out in the area. Therefore, the presence of an outflow channel of natural origin (a branch of an ancient river?), located at the current Via Vittorio Emanuele, is hypothesized, towards which water was drained in antiquity when necessary.

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