Medium- to High-Resolution Integrated Geophysical Surveys to Reconstruct an Archaeological Settlement: New Perspectives from the Ancient Town of Nora, Southwestern Sardinia (Italy).Preliminary Results

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Abstract. Non-invasive and wide-area geophysical prospections are an important scientific tool for investigating ancient settlements. Through the integration with historical reconstruction studies, they allow a "highly probable" visualization of signs left under the ground by ancient civilizations. This is demonstrated once again by the application of integrated geophysical methods to the wide archaeological area of Nora: the preliminary results of electrical resistivity tomography (ERT), multichannel ground penetrating radar(GPR)-in customized or standard towed configuration-, and electromagnetic (EM) applications to the site are presented and interpreted here as a tool for the reconstruction of ancient settlements urban structures, even if a detailed analysis of the correspondences between archaeological and geophysical findings is left to a more mature work. The geophysical discovery of new neighborhoods, expected from the site location and archaeological expeditious surveys, opens new frontiers in the archaeological study of the area. The non-trivial data-based geophysical results suggest the opportunity for fruitful further analyses and development indicated at the end of the present manuscript.

Keywords: Applied Geophysics · Preventive Archaeology · Multichannel GPR · ERT · EM · Roman settlements · Nora

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1 Introduction

The archaeological site of Nora is localized on the southern coast of the Gulf of Cagliari, Italy, in the proximity of the city of Pula (southwestern Sardinia, Fig. 1(a)). The ancient town was built on a little peninsula, the isthmus of Capo Pula, and occupied a central strategic position as a fundamental maritime crossroads in the ancient Mediterranean Sea (Fig. 1(b)).

The geological features of the area comprise different lithologies derived from past volcanic manifestations, including volcanic breccias, conglomerates, and massive effusive lavas. Quaternary deposits, composed of beach sands (Olocene-Present) and locally sandstones and conglomerates of Thyrrenian, are present in the northern area of the ancient town. The sedimentary deposits overlay the substrate with a variable thickness. These materials are characterized by abundant content of fossils and organogenic components [1]. The stone materials utilized for the construction of numerous archaeological structures are volcanic rocks outcropping in the Sarroch-Pula district [2].

"The first settlements date back to the Nuragic period, as evidenced by the discovery of ceramics. The presence of the Phoenicians (VIII to VI century B.C.) is well documented with important findings of epigraphic documents and features related to the late Phoenician age [3]. The ancient town of Nora was the center of important trade routes, as demonstrated by its three ports, now mostly submerged. The town, already flourishing in the fifth century, underwent further development in the fourth century thanks to the contact with the Italian world and especially Rome. The Roman domination began in 238 B.C. and lasted until 456 A.D., when pirate raids and Vandals invasions resulted in the rapid decay of Nora. The "coup de grace" was the Arab raids on the southern coast of Sardinia in the early VIII century. The area was then abandoned, but sporadic traces of life have been found in higher levels of the collapsed Roman buildings" [4]. Furthermore, many ruins of ancient buildings are visible in the waters around the peninsula and various findings were discovered in the sea and lagoon waters [5].

The archaeological excavations started in 1889 when the Punic tophet appears after an intense coastal storm. The archaeological surveys carried out in the 1952 by the superintendent Gennaro Pesce allowed to dig part of the ancient city consisting of structures pre-existing the Roman city [6]. After sporadic interventions during the 1970s and 1980s, since 1990, searches on the site have continued steadily up until today.

Previous geophysical investigations carried out in the northern area of the open archaeological digs have highlighted the traces of the buried perimetral constructions of the ancient Roman amphitheater of the town. The buried sub-elliptical structures were identified through a GPR survey performed in the narrowest part of the isthmus, in an area devoted to parking for visitors of the archaeological site [4]. The presence of the buried monumental structures is confirmed by subsequent recent direct excavations [4] and by archive research on historical pictures of other historical excavations [7, 8].

In the months of June and July 2013 a joint campaign of study started in the area formerly devoted to military uses on the small hill just northern to the archaeological park (Fig. 1b and c), [9, 10]. Since then, the archaeological excavations have gone on, revealing many important elements of the ancient city stratification, and an integrated cross-disciplinary prospection is planned for the next future in the remaining free area.

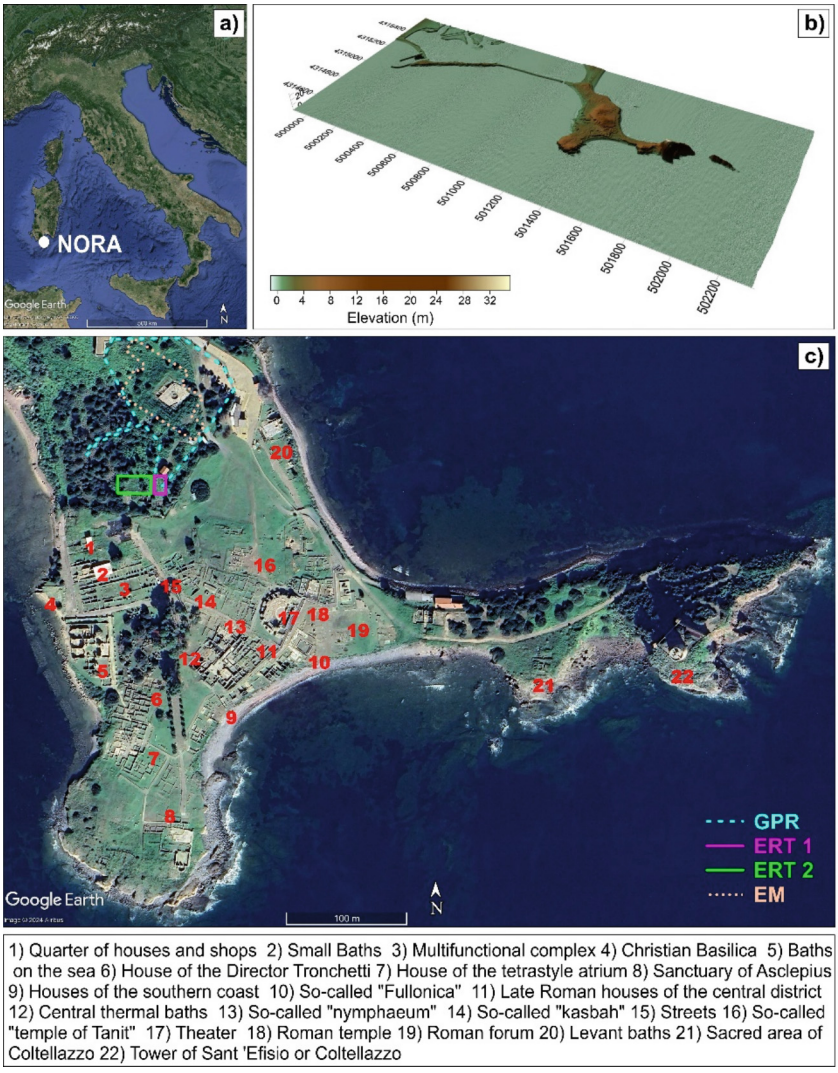

Fig. 1. Geographic location of the archaeological site of Nora in Southwestern Sardinia, Italy(up-left pane), Digital Terrain Model (DTM) of the Peninsula of Nora (up-right), andaerial view of the investigated area and the archaeological park with theindication of ground penetrating radar (GPR), electric resistivity tomography(ERT), and induction electromagnetic (EM) surveys with respect the archaeological remains (bottom).

The preliminary experimental results of the geophysical surveys are presented here, even in the light of the first results from the archaeological findings.

Integrated geophysical surveys have been widely and successfully utilized to study different archaeological settings worldwide, such as buried prehistoric structures [11–14], temples [15, 16], theatres [17], amphitheaters [18], basilicas [19–21], complex

ancient towns [22–24], water systems and underground aqueducts [25, 26], necropolis [27–29]. More recently, traditional geophysical techniques have been integrated with remote and proximal sensing ones to perform non-destructive inspections of historical and monumental structures [30–35] and to study static and dynamic behavior of ancient valuable buildings and archaeological remains [36–38].

2 Geophysical Datasets

The methodological approach for the acquisition of the geophysical datasets was based on the complementary use of fixed arrays and mobile measurement systems for a fully non-invasive inspection of areas with different irregular macro- and micro-topography of the ground surface (Fig. 2). The multichannel GPR survey was performed using a mobile radar system towed by an off-road vehicle; for uneven and small areas the system was customized to be pushed by a walking operator. This instrumental equipment is suitable to explore wide areas with the main advantage of collecting big datasets through a relatively high speed of acquisition. The EM was implemented to integrate GPR survey and cap no-data sectors. The 2D-ERT surveys were focused on two southern zones of the site of study and were designed to highlight shallow-to-mid-depth geophysical anomalies. In order to improve the archaeological interpretation of the experimental outcomes, underground models of ERT, GPR, and EM anomalies have been derived from the measurements.



Fig. 2. The Stream-X array system towed by the off-road vehicle (top, left), the half-battery Stream-X arraycustomized for small subsets (top, right); example of FDEM acquisition (middle-left) and view of the archaeological park from the investigated area (middle-right); ERT profile (bottom, left) acquired using the Syscal Pro–10 channel multi-electrode resistivity imaging equipment (bottom, right).

2.1 GPR

Ground Penetrating Radar is considered a very effective geophysical method to identify shallow archaeological structures with high spatial resolution. GPR methods comprise numerous techniques of measure which mainly differ for the use of reflected or transmitted electromagnetic signals to study inaccessible domains of the medium. GPR surveys could be performed to find buried objects [39–42] and to evaluate the status of integrity of materials at different working scales [43, 44]. The great interest in archaeological geophysical prospection has encouraged the development and improvement of several high-resolution geophysical methods. These techniques utilize both new instrumental configurations and unconventional layouts of acquisition to reliably collect high-density datasets and are suitable to detect underground structures and buried remains with centimetric precision. At the same time, the large extension of many archaeological sites suggests the use of mobile acquisition systems, permitting exploration of wide areas within a few hours [45].

In the case study investigated, a multichannel high-resolution radar system, just acquired to the laboratory assets, was tested on the most accessible (but still rough) surfaces of the site to address the specific challenge of an extensive investigation in a fast and precise way over quite irregular surfaces and areas. The GPR survey was carried out by the Subsurface Tomographic Radar Equipment for Assets Mapping (STREAM X by IDS Ingegneria Dei Sistemi, Italy) (Fig. 2). This system, initially designed to map buried pipes and to inspect subgrades and roads pavements, has quickly found application for archaeological surveys [45, 46]. The acquisition instrument was equipped by sixteen parallel dipoles, oriented along the forward direction of the profile (vertical polarization) and arranged inside two boxes. The electromagnetic signals are emitted by the transmitter unit and are characterized by a central frequency band of 200 MHz. The electromagnetic antennas are positioned inside two boxes with a reciprocal distance of 12 cm. The spacing between two adjacent radar profiles corresponds to the distance between the radar dipoles, and the measurement conventionally positioned in the middle of each couple, working as a transmitter and a receiver. The measurement equipment was trained by means of a vehicle moving on the ground surface with a velocity mainly depending on the topographic features of the area and the related local roughness. The GPR data were geo-referenced in real-time by means of a differential GPS system directly connected to the acquisition unit. A Radar Doppler system allowed to real-time measurement of the covered distance during the acquisition of the radar profiles. A customized acquisition system was specifically arranged for the most challenging sub-areas of the site by using only one of the two boxes containing the antennas; assembled with the same positioning technologies of the towed full-system, the customized apparatus was controlled and pushed by a walking operator.

The raw GPR data are collected into acquisition missions, inside which they are available as swaths, the 15 parallel channels of each acquisition profile (for the full-system). After georeferencing calibration and data normalization, raw data have been processed with standard 2D steps as it follows: De-wow; Soil sample; Background removal; Band-pass filtering; Gain amplifying.

The resulting GPR data were then processed using the 2.5-D Kirchhoff migration procedure [47, 48]. Considering the typical EM velocity on materials similar to Nora

shallowest subsoil layers, and after evaluating its compatibility with the radar events recorded on the radargrams, a homogeneous velocity of 0.10 m/ns was chosen for the 2.5D migration and for the time-to-depth conversion. Finally, depth-slices by means of the planar interpolation of signal parameters were extracted from thickness-defined slices of the migrated radargrams. Figure 3 reports some results from the GPR survey: A-to-D letters indicate some subsets characterized by a certain coherence of the recorded and processed signals.

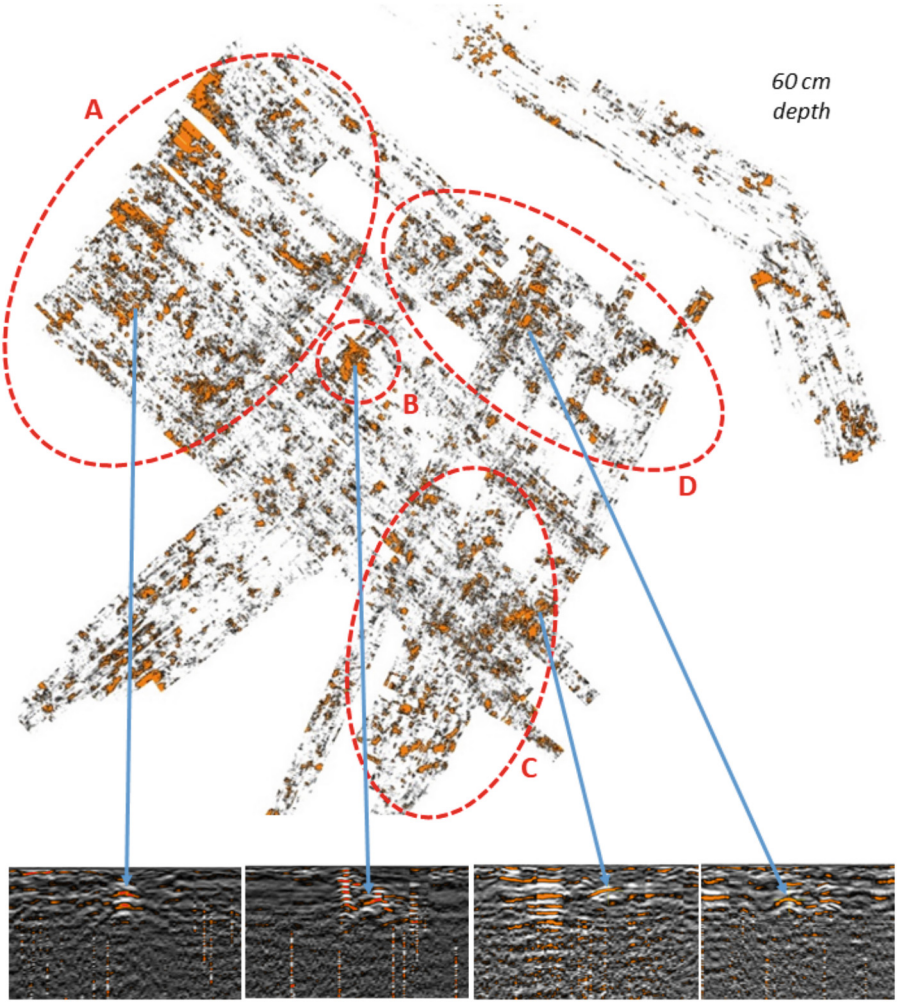

Fig. 3. Georadar multichannel survey on the flattest slope of the hill just outside the archaeological park: depth-slice at 60 cm (top section of the image), with identification of most interesting areas depending on density and coherence of reflected signals, and samples of the radargrams crossing most intense radar events.

2.2 EM

Frequency-domain electromagnetic (FDEM) is a method based on the induction of low-frequency alternating currents through a transmitting coil underground by a primary electromagnetic field. It spreads in the ground and therefore also through target bodies, inducing eddy currents which generate a secondary electromagnetic field perceived by a receiving coil. The secondary field can be decomposed into the in-phase (real) component, sensitive to metallic objects, and the quadrature (imaginary) component, related to conductive materials, expressed in parts per million (ppm), [49, 50].

In this site, data acquisition was carried out using the CMD-1 antenna by GF instruments (10 kHz, 0.98 m coils offset, sampled at 10 Hz), which automatically converts the quadrature component of the recorded signal into apparent electrical conductivity at a specific depth for each instrumental configuration (Fig. 4). The preliminary analysis of the EM results leads to the recognizance of two very conductive linear patterns most probably attributable to a modern net of technological services of the military area but anyway to be verified in terms of exclusion from possible clay- and water-rich pipes eventually datable back to the ancient settlements of the area. Some further interesting EM pieces of evidence, to be jointly investigated with the other geophysical and archaeological information, are constituted by soft dynamics of spatial variability of the apparent conductivity (in combination with variations of the in-phase values), possibly related to the variation of the fine-to-coarse composition of the filling sediments or presence of sparse archaeological remains. Finally, some saturating events were detected that are possibly linked to archaeological values like for example tombs, voids, or tanks. Processing and interpretation of the EM data is very preliminary and needs to be

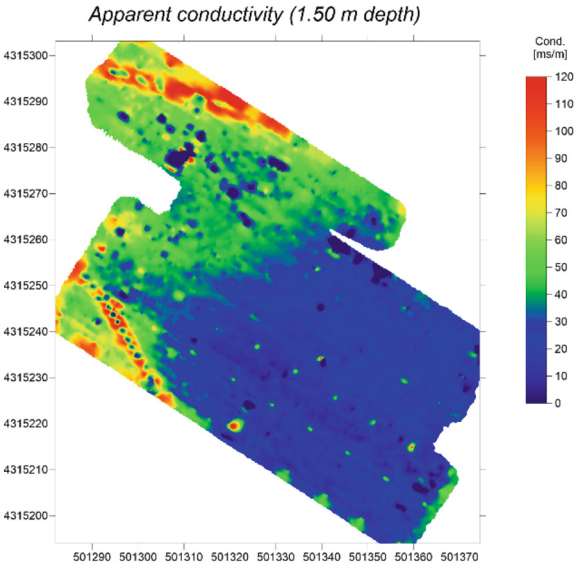

Fig. 4. Apparent conductivity map at a nominal depth of 150 cm.

further investigated against GPR, subsequent geophysical surveys, and archaeological contextualization based on the literature and the diggings within the project.

2.3 ERT

Electrical Resistivity Tomography allows the identification of main anomalous bodies perpendicular to the direction of the profile and is an effective method to highlight both vertical and lateral electrical resistivity heterogeneities of the underground layers. The method is widely utilized for archaeological investigations but is also considered more expensive and time-consuming than other ground-based geophysical techniques [51].

The electrical Resistivity Tomography method allows to derive the apparent electrical resistivity of the underground materials by using a set of fixed-surface steel electrodes. The electrical current flows in the ground through a transmitter dipole (current dipole) and the electrical potential is measured by a second dipole (potential dipole). Two-dimensional electrical resistivity tomographies usually use linear equally-spaced electrode profiles with different quadrupolar configurations of acquisition. The use of the electrode array is suggested based on the purpose of the survey (e.g. depth of investigation, signal decay, special resolution, etc.). The sensitivity function of the array allows the evaluation of the reliability of the experimental measurements [52]. The electrical model of the subsurface is derived from the inversion of the experimental data of apparent resistivity [53].

Two sets of Electrical Resistivity Tomographies were acquired at the site of study (see Fig. 1). The first group of ERT profiles was localized in the southern sector of the surveyed area, in the zone indicated with *ERT2*(green rectangle) in Fig. 1, and included thirteen parallel profiles forming a grid with 2-m of profile spacing, oriented in easting direction. The ERT profiles were designed (done) using forty-eight steel surface electrodes with 1-m electrode spacing. The second group of measurements was acquired in the higher part of the hill and covered a rectangular surface, indicated with *ERT1*(magenta rectangle) in Fig. 1. Twenty-three parallel ERT tomographies were oriented in northing direction. In order to collect a high-density dataset of apparent resistivity measurements, the second group of tomographies was designed to improve the effectiveness and the resolution of the method with the purpose of detecting also small archaeological structures and little resistivity anomalies. The electrode spacing and the distance between adjacent ERT profiles were set equal to 0.5 m. A Syscal Pro–10 channel multi-electrode resistivity imaging equipment (by Iris Instruments, France) was utilized to record the apparent resistivity data with an accuracy of 0.1 Ω·m. The measurements were performed by using Wenner (W) electrode array. The minimum dipole spacing was set equal to the electrode spacing of the ERT profiles. The second configuration provided to obtain high-resolution measurements up to 2 m of depth.

Raw data of apparent resistivity were filtered to remove outliers and data points affected by high contact resistance. The filtered data were processed through a two-dimensional inversion algorithm (Res2DInv, [54]). The inversion procedures allowed the definition of 2D and 3D electrical resistivity models of the underground structures. The package used for the processing of ERT data, implements the smoothness-constrained least-squares inversion, based on the Gauss-Newton optimization technique [55], and is based on finite-element discretization to take into account the topographic profile. In

most cases, the acceptable inverse models were obtained after five or six iterations with a final percentage Root Mean Square (RMS) error lower than 5%.

The following Figs. 5 and 6 show 3D axonometric views and location of the two ERT datasets and their tomographic reconstruction, evidencing the main alignments potentially related to architectonic/urbanistic elements like buried walls, roads, tanks, or pipes, to name some.

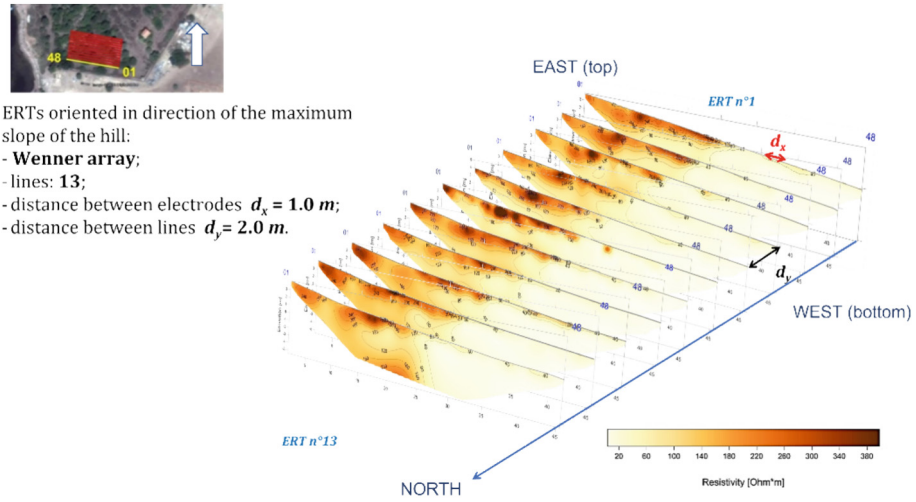

Fig. 5. 3D view of ERTs oriented in direction of the maximum slope of the hill (E1).

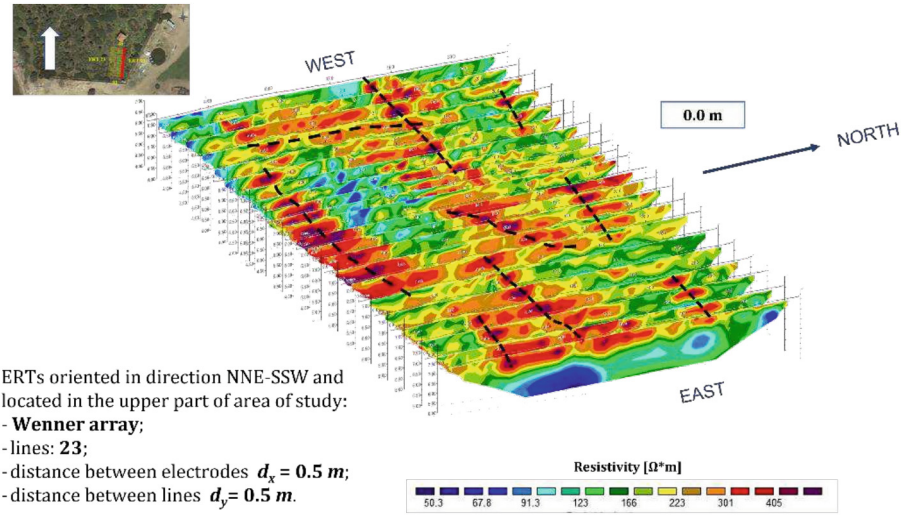

Fig. 6. 3D view of ERTs oriented in direction NNE-SSW and located in the upper part of the study area (E2).

3 Archaeological Results

The excavations carried out by the University of Cagliari at Nora, which began in 2013, are concentrated in an area of approximately 15,000 square meters, located in the north-eastern sector of the promontory and part of an area for a long time occupied by an Italian Navy base [10, 56, 57]. The area is set in a sector that, starting from the north-western slopes of the so-called Colle di Tanit, extends to the limits of the archaeological area, in the direction of the modern access road to the site. The analysis of the urban spaces of the southern sector has made it possible to highlight the presence of a series of buildings and finds that, through a topographical analysis of the area and of the elements of material culture, make it possible to advance hypotheses on the use of this area. We find ourselves, in fact, in the sector facing the so-called Cala di Libeccio, in an area gravitating around the western harbor berth and which has yielded numerous features that make it possible to highlight aspects strongly connected with the sea and related activities.

The northernmost sector of the investigated parcel has instead returned to a context of considerable importance for the definition of the urban spaces of the city of Nora and their distribution in the imperial age, with phases of abandonment of the area marked by ceramic materials with a chronological span that reaches the 5th-6th century AD. In particular, an open area paved with local purple andesite stones [58] has been brought to light, created using the same technique as the arterial roads that run through the whole settlement, probably a public space of a city that seems to denote its polycentric nature. This sector is notable for the presence of buildings on the eastern side, still under excavation. The structures present masonry built by laying large irregular blocks and reused elements, with rooms characterized inside by the presence of materials and artifacts related to wheat processing and bread baking.

The open space presents a circular basin with a diameter of approximately 6 m and an exedra structure, located in correspondence to the GPR anomaly indicated with B in Fig. 3, built with deliberate decorative intent, seeming to depict a situation relative to a monumentalized square certainly connected to important civil and religious functions [58–60]. In the center of this sector, a portion of a circular facility on the level of the pavement has come to light, and a trench relating to a pipeline with a slight slope towards the semicircular structure. The channel carved out below the level of the paving, filled with compacted earth and whose trajectory joins the exedra and the southern sector of the excavation area, ends in a circular open space (diameter hypothesized to be between 5.50 and 6 m.), characterized by the presence of hydraulic mortar elements and negative traces of metal structures pertaining to the channeling of water. The internal profile of the basin, where the presence of hydraulic mortar is evident, is marked by a row of large rectangular blocks with visible face dimensions of 40x40 cm.

In fact, the exedra is unique in the panorama of Roman-age cities in Sardinia. The monument (approximately 2.8 x 1.9 m, preserved in height from the floor level at 1.7 m) is set on a space partly spared of the paved surface and located to the east of a large building with a quadrangular plan and separated from it by a kerbstone made of elongated monolithic quadrangular blocks, of the same local andesite and entirely similar to those found in the other sectors of the city served by the arterial roads. The exedra structure consists of a core of rubble and mortar, reshaped by bessales bricks cut in half diagonally and inserted in such a way as to leave the longest side exposed, with several layers of

mortar also covering patches of the surrounding paving (Fig. 7). The residual mortar is mainly concentrated near the paving level, with a clear waterproofing intent, so as to form a kerbstone that ran along the entire lower external side of the structure, adhering to the andesite paving stones on which the structure is set, in order to create invitations for the outflow of water towards the sides of the road.

On the eastern side of the exedra, there is a monolithic quadrangular basin, heavily damaged in the central part and characterized by sharp corners on the outside and rounded corners on the inside. The basin rests on a plinth consisting of three blocks of local biocalcarenite that rest directly on the paved road surface, a fact that would lead one to hypothesize the construction of this forepart in a second phase.

This wide public area, marked by elements related to water supply in the city in the imperial age, seems to be part of an impressive single project connected with the construction of a portion of Nora's main road network.



Fig. 7. The monumental exedra excavated (Archivio UniCa).

4 Discussion and Concluding Remarks

Although the joint analysis of the geophysical datasets and archaeological findings is very preliminary and a specific and deeper cross-interpretation is planned to be performed on both these datasets and new ones we expect to collect over specific regions, some brief considerations are already possible. The three geophysical methods adopted in different sectors of the area of study were mainly chosen to take into account the surface roughness, the presence of trees, the soil acclivity, and the presence of possible external noise and interferences.

ERTs in two different configurations were implemented over the less accessible sectors, allowing for the recognition of some alignments in the 3D electrical resistivity patterns, probably related to some primary (like possible roads, large pipes, and bordering walls of urban blocks, in the case of the lowest spatial resolution setup) and secondary urban elements (like walls differentiation inside buildings, small dry or humid sediment filled cavities, in the case of the highest spatial resolution setup). The low-resolution ERTs, collected over the slope of the hill, allowed to detection of a ramp of the electrical resistivity potentially linked to the underground intrusion of seawater in the lowest layers of the subsoil.

FDEM data were acquired with the two orthogonal positions of the transmitting and receiving coils. The investigated area was smaller than the GPR one and was chosen by keeping in mind the necessity to walk far from the metallic wire mesh on the border of the area of study and small piles of rubbish, known sources of heavy noise on induction EM measurements. Nevertheless, the investigated area was sampled continuously (differently from what happened with the GPR, limited by the off-road car practicability), and some important features were recognized and preliminarily interpreted as possible archaeological values.

Automated and customized GPR acquisition covered the widest areas with the highest 3D spatial resolution in a relatively short collection time. Some features have been recognized with exceptional detail, like in the case of the exedra monumental fountain reported in Fig. 7 (picture) and anomaly B in Fig. 3. The site is known to be challenging for GPR investigations [61], and this is confirmed by our preliminary results that evidenced different diagnostic performances over archaeological features even very close to each other: this aspect will be further investigated in the context of the planned deepening of the cross-check of the archaeological-geophysical results and new multimethod acquisitions (and integrated excavations) over sample areas.

Finally, the preliminary results of the integrated geophysical-archaeological investigation of the ex-military areas in the promontory of Nora are very promising in terms of both specific and general remarks related to the archaeological site and the effects that background elements (e.g. filling soil stratifications, sea proximity) introduce on the recognizability of archaeological and non-archaeological features. Further investigation is planned in the next months to perform a more detailed critical comparison of the geophysical results against the archaeological findings and documented stratigraphies. This will be done in parallel to the development of additional processing and positioning strategies aiming at the extraction of the most diagnostic information possible from the experimental dataset. New acquisitions are also planned to better constrain the geophysical study.

Disclosure of Interests. The authors have no competing interests.

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