Geology and geophysics at the archeological park of Vulci (central Italy)

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Article history
Received May 29, 2013; accepted Jannuary 20, 2014.
Subject classification:
Vulci Archeological park, Geological survey, Electrical resistivity tomography, Magnetic susceptibility.

ABSTRACT

The Vulci archeological site was object of interest by the Soprintendenza ai beni culturali dell'Etruria meridionale (Italian government department responsible for southern Etruria's cultural heritage) since the beginning of the 20th century. In 2001, the Ministero dei Beni Culturali (Italian ministry of cultural heritage) along with the local authorities, opened a natural-archeological park. In this area, it lies most of the ancient Etruscan city of Velch (today known by its Latin name, Vulci) including the Osteria Necropolis that is the object of this study. Recently, new archaeological excavations were made and the local authorities needed major geological information about the volcanic lithotypes where the Etruscans used to build their necropolis. The aim of this study is to define the geological and geophysical characteristics of the rock lithotypes present in the Vulci park. For this purpose, a geological map of the area (1:10000) has been realized. Moreover, two different geophysical methods were applied: measurements of magnetic susceptibility and electrical resistivity tomography. Magnetic susceptibility analyses clearly identify magnetic contrasts between different lithotypes; the characteristics of the pyroclastic flow that originated the Sorano unit 2 and its vertical facies variations are well recorded by this parameter that along with lithostratigraphic observations provides information about the depositional conditions. Two electrical resistivity tomographies were performed, which show the Sorano unit 2 thickness to be of c. 7 m with resistivity values ranging from 200 to 400 $\Omega \cdot m$. This kind of multidisciplinary approach resulted to be suitable to study this type of archaeological sites, revealing that areas characterized by a relevant thickness and wide areal extension of volcanic lithotypes can be a potential site where Etruscans might have excavated their necropolis.

1. Introduction

Geophysical methods are often employed to investigate archeological sites and in a few cases buried necropolis. As reported by many authors [e.g. Brizzolari et al 1992, Cardarelli et al. 2008, Quesnel et al. 2011], these techniques are non-destructive, fast and quite inexpensive. Cammarano et al. [1998] used a multi-methodological approach (Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), self potential and magnetometric methods) in the *Sabine Necropolis* in Rome, Italy, to evidence structures through the study of different parameters. Some years later Cardarelli et al. [2008] investigated a new area in the same necropolis using ERT, Fluxgate and GPR methods. Furthermore, Quesnel et al. [2011] used ERT and magnetic measurements to evidence a roman - early medieval necropolis in Provence.

In the recent years local authorities focused their interests in valorizing the necropolis of Vulci (Figure 1). Four necropolis areas dating from the 8th century B.C. have been found around the city of Vulci, with the *Osteria Necropolis* towards the north. This was the main necropolis of Vulci, with tombs dating from the Villanovan Period [Eutizi et al. 2010]. Tombs from the 6th and 5th centuries B.C. are generally of the hypogeal type. The habit of placing statues of mythical creatures to guard the tombs is characteristic of Vulci. Immensely valuable grave goods have been found in these tombs, in particular a large number of ceramics of Greek production, and bronze objects of local production [Moretti Sgubini 1997].

The most important tomb located at the necropolis of Ponte Rotto is the François tomb, famous for its paintings (now at Villa Albani in Rome) portraying, as well as the deceased, episodes from Greek mythology together with characters from Etruscan myths and history [Tamburini 1987].

The tombs of the *Osteria Necropolis* are mostly

Figure 1. Area Location.

chamber tomb type with an open air vestibule. The sloping corridor led to an antechamber open to the sky. Several side chambers completely hewn out of the rock with a ceiling opened on to this antechamber [Banti 1973].

Considering that the geological formations and structures present in the Vulci park have never being studied so far, we retained necessary as first step to elaborate a geological map of the study area with a high resolution scale of 1:10000. The geology of Vulci area was then interpreted in the context of Vulsini Volcanic District (VVD) which is well described in literature [Washington 1907, Nappi et al. 1986, Nappi et al. 1998] and provides crucial information in order to understand the genesis and characteristics of the geological deposits in the Vulci site.

The geophysical prospections were used to define the electrical and magnetic characteristics of the volcanic lithologies outcropping in the necropolis of Vulci. These analyses were conducted to find out if it might be possible, through the use of these methods, to identify other locations where Etruscans excavated their tombs. Therefore, magnetic susceptibility has been measured in situ and in a laboratory to evaluate magnetic contrasts between different lithostratigraphic units. ERT were also performed along two profiles and made it possible to define the areal extension and thickness of the lithotype on which the *Osteria Necropolis* was excavated.

2. Methods and results

2.1. Geology and geological map

The area of Vulci park is part of the coastal plain of Maremma which is characterized by the presence of clastic sedimentary rocks, deposited on Pleistocene marine terraces. Along the coastal area, the bedrock is mainly constituted by Pliocene clays and silts, whereas in the hinterland it consists of Cretaceous-Oligocenic Tuscan and Liguride facies sediments [Capelli et al. 1994]. In the hinterland, after the building of the Apennine chain, extensional tectonics produced intense volcanism in the Roman Comagmatic Province [Washington 1907] of which the VVD is part [Nappi et al. 1998]. The geological structure of Vulci developed in this framework.

The Fiora river, characterized by huge flow in a N-S direction separates the area into two main plateaus. In the past the river flowed along a more easterly course; later deviated by the emplacement of the Latera pyroclastic deposits [Fabbri and Villa 1987]. The two main plateaus are laterally interested by river drainage with up to 30 meter high slopes, exposing outcrops of different lithotypes. Rock falls occur along the slopes, mainly comprising tephrite-lava clasts and the bed of the Fiora River is occupied by a huge volume of debris. The valley bedrock is a 35 m thick dark-grey colored lava deposit, with a compact fine-grained structure, named *Tefrite del Castellaccio dei Vulci* [Alberti et al. 1970], and characterized by a porphyric isotropic structure. The lava has a teprithic-phonolitic composition with plagioclase, pyroxene, and few sanidine phenocrysts (Figure 2). In the Fiora gorge this lithotype exhibits a well-developed columnar jointing, possibly due to the fast cooling of the lava in contact with the river water. The limited extension of the lava flow into the present Fiora valley led the assumption [Sposato et al. 1993] that the lava flow filled a proto Fiora valley. The lava flow was probably erupted by local regional fractures now buried under the travertine plateau, on the eastern side of Fiora River. The fractures were probably connected to the regional fault systems controlling the evolution of the

Figure 2. Tephritic lava - travertines contact.

Figure 3. Pseudo-stratified *Sorano unit I*.

Siena-Radicofani Graben [Vezzoli et al. 1987]. The age of this lava flow was investigated by Fabbri and Villa [1987] and it is dated to the medium Pleistocene.

In the Vulci park area, the prevalent lithology is the *Sorano Formation* [Palladino et al. 2010] erupted by the Latera volcano between 194 ± 5 ka and 187 ± 8 ka ago [Turbeville 1992]. This formation is subdivided in two units, characterized by different matrix colors, abundance of clasts and lithification rates. In this study, the units are named *Sorano unit 1* (the lower unit) and *Sorano unit 2* (the upper unit). The *Sorano unit 1* outcrops only near the Fiora river, or in minor valleys excavated by secondary streams. The unit is a medium-fine grey-colored ash deposit, about 5 m thick, enriched with light-colored lapillus-sized pumices. The clasts/matrix ratio is about 30 %, this means that about 30% of the lithology is represented by clasts. This unit is poorly lithified and exhibits a pseudo-stratified base due to the presence of clay levels enriched with floating pumices (Figure 3), as in *Sorano unit 2*. The pseudo-stratification evidenced in the lower part of both the Sorano units suggests that the volcanic flow entered locally in the water of a low-energy aqueous depositional environment characterized by the presence of several pools, like a shallow marsh. By this reconstruction it is plausible that both the Sorano units entered the water of the marshy environment, following different paths. In fact, in distal areas pyroclastic flows might form finger-like lobes [Jessop et al. 2012].

The *Sorano unit 2* is a fine-ash red-colored deposit, 8 m thick. The clasts/matrix ratio is lower than the

Figure 4. Tephra lithics scattered in *Sorano unit 2*.

Figure 5. *Sorano unit 2*.

Figure 6. Carved ceilings Tombs, excavated in *Sorano unit 2*.

basal unit (15 %). Inside the deposit there are many cm-sized lithics (Figure 4), ripped up from the underlying tephritic lava. Lithics show imbrication, with a NE-SW direction. A process of zeolitization of the glassy matrix could have caused the lithification of this lithology. The lithification and the extent of the *Sorano unit 2* explain the major number of tombs excavated in this unit. (Figure 5). It is our opinion that the progressive cooling of the pyroclastic flow, facilitated by the interaction with the water of the marshy environment present in the area during the unit's emplacement, have caused the lithification of this lithology. In fact this process in pyroclastic units increases the lithification of the tuffs without compromising their malleability [Cerri et al. 2013] and it likely results in higher electrical resistivity values. These characteristics were known by Etruscans that chose these lithotypes to excavate their necropolis.

Thin sections of the Sorano units show the same characteristics (clasts/matrix ratios, matrix color) observed in the field. Both of them include sanidine and monocline amphibole minerals. Public access to Tombs with carved ceilings enabled the observation of a few meters of *Sorano unit 2* (Figure 6). The upper part of this unit (Figure 7) mostly comprises a homogeneous medium-fine ashy matrix while the lower part is pseudo-stratified and includes a lava-conglomerate bank and three clay levels. Above the *Sorano Formation* there are few exposures of the *Grotte di Castro Formation* [Palladino et al. 2010] near the Vulci ruins. It has been hypothesized that this formation originally had greater extension than now, and that it has been progressively eroded. In the 1.5 m thick deposit, a 30 cm interval is recognizable, characterized by a succession of levels of dark and light pumices with sedimentary ripple structures (Figure 8).

The *Sorano Formation* in the western sector of the study area (Figure 9) is based on sand sediments by an unconformity limit. These sediments have been ascribed to the Pleistocene and correlated with the circumlittoral *Pleistocene Sand formation* known in literature [Alberti et al. 1970]. In correspondence with the sands, the morphology of the area exhibits steeper slopes, a dendritic drainage network (Figure 9), and a yellow-colored soil enriched with quartz clasts, unlike the brown-colored soil formed by the oxidation of the ferric minerals of the volcanic deposits.

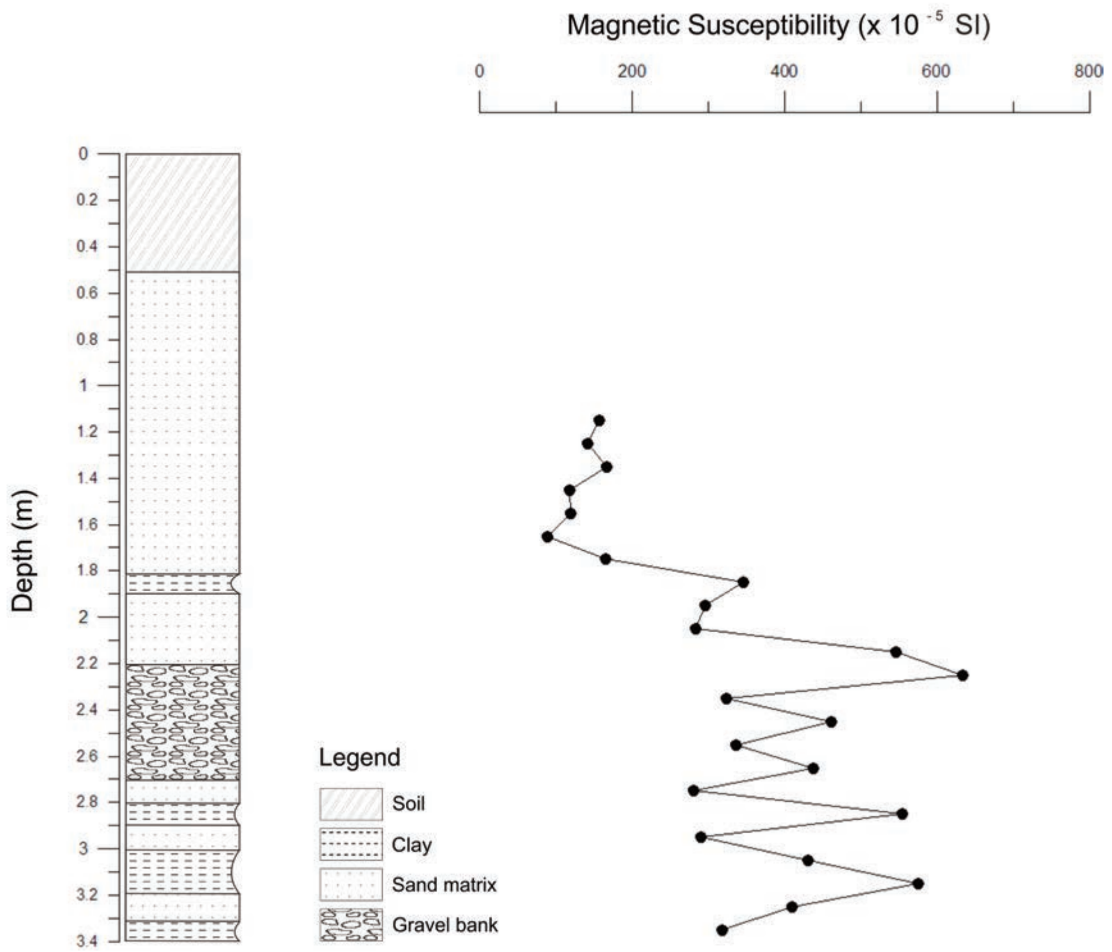

Figure 7. Lithostratigraphic column and magnetic susceptibility log of a section of the *Sorano unit 2*.

Figure 8. *Sorano unit 2 (*lower unit) and *Grotte di Castro Formation* (upper unit) contact.

In the eastern part of the area, lying above the units already described, there is a 8 m thick travertine bank originated by hydro-thermalism (Figure 2). Travertine shows horizontal pseudo-stratification and contain volcanic clasts. The values of the isotope ratio U^{234}/U^{238} indicate mixing of deep and shallow groundwater. Th^{230} data suggest the *travertine formation* is 8.2 ± 1.6 ky old [Taddeucci and Voltaggio 1987].

2.2. Magnetic susceptibility

Magnetic susceptibility measurements are often used in archeological prospection in addition to other geophysical surveys both for investigating buried features and their characteristics and for mapping human habitations [Schmidt 2007, 2009]. Low-field magnetic susceptibility per unit volume (κ) of the Vulci deposits was measured using a Bartington MS2 susceptibility meter equipped with a D loop sensor [Lecoanet et al. 1999]. In particular, measurements performed on a surficial trench revealed that brown-colored soils, derived from the alteration of the volcanic units, exhibit an average susceptibility of 500 x 10^{-5} SI, with the exception of soil derived from alteration of the upper part of the *Sorano unit 2* which exhibits an average susceptibility of 200-300 x 10^{-5} SI. This finding evidence a contrast between the two kind of soils derived by different parent material. Thus, the measure of the magnetic susceptibility of the soil in this area could help in identifying buried tombs in the cases in which the upper part of the *Sorano unit 2* is near to the surface enough to significantly contribute to the formation of the overlaying top-soil. Developing maps of magnetic susceptibility could be taken into account for future prospections. In this case the measurements were carried out on a trench but the effectiveness of the method could be tested also before the beginning of excavations.

Lava blocks, scattered within the *Sorano unit 2*, present variable grain size and have an average susceptibility of 500 x 10^{-5} SI (a punctual F sensor was employed in this case). A few lava blocks were measured at the laboratory of paleomagnetism of the Istituto Nazionale di Geofisica e Vulcanologia using a Kappabridge system AGICO (KLY-2 model) and they exhibited a mass specific susceptibility of 850 x 10^{-8} m^3/kg.

Near the Tombs with carved ceilings, a 3.4 m deep stratigraphic section of the *Sorano unit 2* was selected for detailed geophysical investigation. In this section, the *Sorano unit 2* has vertical facies variations as the basal part of the pyroclastic flow likely emplaced underwater. The section is therefore ideal for investigating variations in susceptibility derived from different lithological characteristics of the unit. Susceptibility

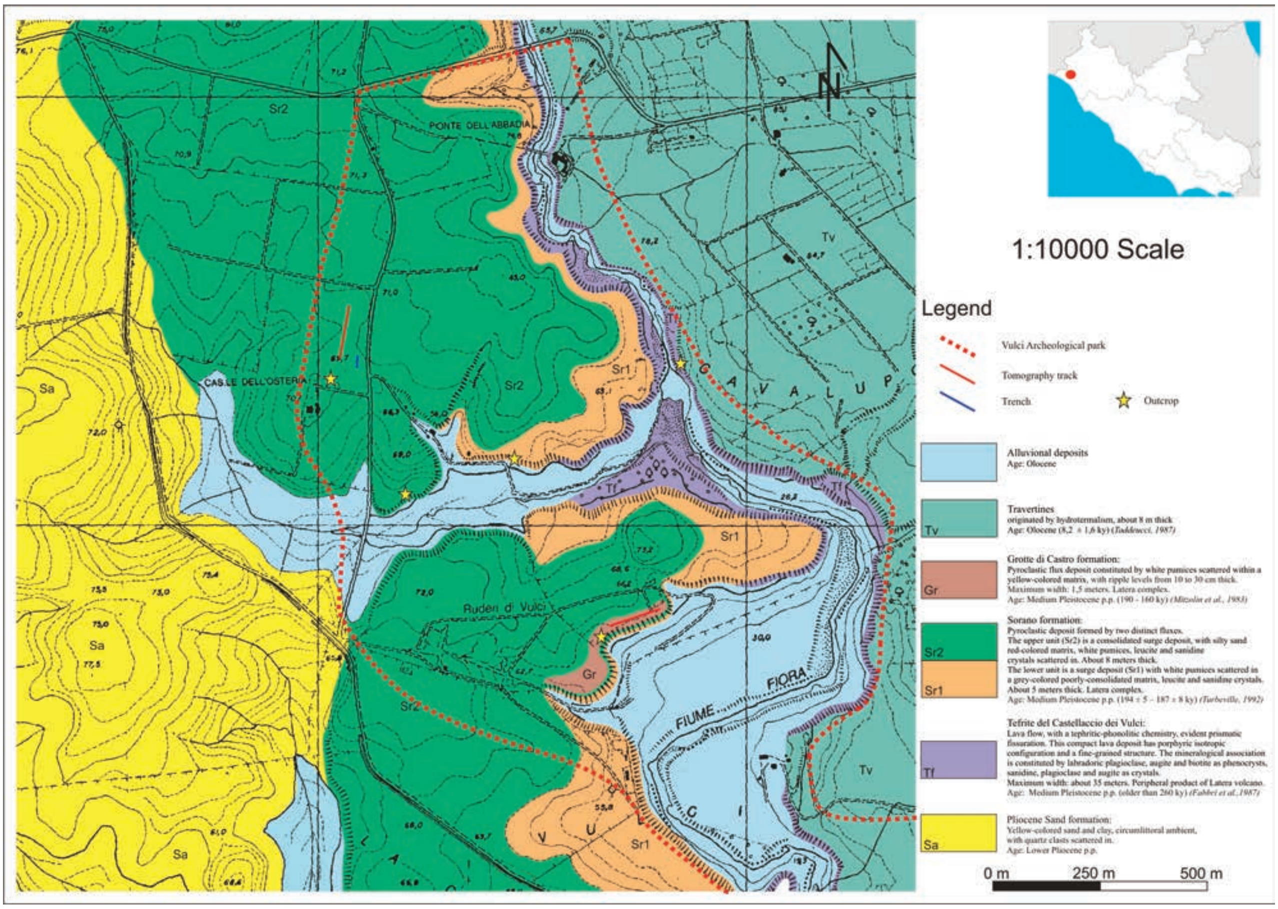

Figure 9. Geological map (1:10000 scale) of the Archeological park of Vulci.

was measured using an F sensor with sampling resolution of 10 cm. Figure 7 shows the relative lithological and susceptibility log. From the bottom up to 1.8 m, the average susceptibility is 393 x 10^{-5} SI and it is characterized by a peak that reaches the highest value of 600 x 10^{-5} SI matching with a gravel bank made of volcanic clasts, and by two peaks corresponding to clay intervals. Toward the top of the section, susceptibility decreases and becomes quite constant (average value of 132 x 10^{-5} SI) while the lithology change by pseudo-stratified to a homogeneous medium-fine ashy matrix.

The clasts occurring in the gravel bank have a major grain size compared to those contained in the ashy matrix and may contribute to increase the average susceptibility value. Magnetic susceptibility is a concentration parameter and depends on the content of magnetic minerals in rocks and sediments [Thompson and Oldfield 1986]. Therefore, peaks observed for the clay intervals are not surprising and indicate increases in concentration of magnetic minerals. Moreover, a major concentration of magnetic minerals in the lower part of the unit (below 1.8 m) could be related to both different depositional conditions of the pyroclastic flow and energy of the system. A low energy system may have favored the deposition of high density magnetic minerals. Similarly, in the Albano maar in Italy, it was recorded a major concentration of magnetic grains in the valley pond facies respect to the overlying ignimbrite veneer facies and it was explained with a lower density and higher turbulence of the flow during the deposition of the upper more diluted deposits [Porreca et al. 2003]. In this framework it is likely that a lacustrine-marshy environment was present in the study area at the time of the pyroclastic flow emplacement as suggested by stratigraphic observations.

2.3. Electrical resistivity tomography

ERT is a geophysical technique employed for imaging the sub-surface in many geological [Zhou et al. 2000, Chambers et al. 2006, Rucker et al. 2011, Omosanya et al. 2012] and archaeological applications [Urbini et al. 2007, Tsokas et al. 2007, Bermejo et al. 2010, Berge et al. 2011, Alashloo et al. 2011]. The ERT method consists of a multiple electrode string placed on the surface; by mean a computer controlled data acquisition, each electrode can serve both as a source and as a receiver, so at the same time a large amount of electrical data can be collected quickly.

Electrical resistivity data were collected using a georesistivimeter Syscal R2 (Iris Instruments) equipped with 64 electrodes. It was used the Wenner electrode array to investigate the resistivity contrasts of the subsoil up to a depth of 20 m. The profile length has been established based on the known geological layers depth informations. Since the depth of investigation is roughly 1/5 and or 1/6 of the total length of the electrical profile [Loke 1999], we collected electrical data by means of 64 electrodes, 2 m spaced, that fitted the requested depth of investigation.

Raw data have been manually pre-processed using Prosys II from Geotomo software. The processing consisted to remove outliers from the measured data before the inversion is run. In our specific case, the collected data were not affected by high resistance contact at the electrode, and therefore no datum has been culled from our dataset. We used the algorithm proposed by Loke and Barker [1996] for the automatic 2D inversion of apparent resistivity data. The inversion routine is based on the smoothness-constrained least-squares inversion [Sasaki et al. 1992] implemented by a quasi-Newton optimization technique. The optimization adjusts the 2D resistivity model trying to iteratively reduce the difference between the calculated and the measured apparent resistivity values (RMS). The Root Mean Squared (RMS) error measures directly this difference, which in our case is lower than 2 %.

The first profile tomography was realized over an outcrop consisting in the *Sorano Formation* and *Grotte di Castro Formation*, in order to verify if the units could be distinguished by their electrical resistivity values. The outcrop, from the top to the bottom, consists of a 2 m thick *Grotte di Castro Formation*, followed 7 m thick *Sorano unit 2*, which in turn overlay the *Sorano unit 1*, already known to be 5 m thick [Conticelli et al. 1987]. The resulting tomography regards the first 20 m, including all the units recognizable in the outcrop. At the limit of the geophysical method resolution, electrostrata and lithological units show an excellent correspondence (Figure 10). The upper electrostratum, visible in the first 2 m of the tomography, is characterized by resistivity values from 80 to 130 $\Omega \cdot m$. It was associated to the *Grotte di Castro Formation* and it records changing lateral resistivity. Beneath the *Grotte di Castro Formation*, the electrostratum recognized as the *Sorano unit 2* is defined by high resistivity values (200 – 400 $\Omega \cdot m$). The resistive electrostratum thickness matches this unit, 6-8 m thick, and it decreases on the left of the tomography, because of a paleomorphology hidden on field by alluvial sediments and soil.

We interpreted the underlying electrostratum to be the response of the *Sorano unit 1*. This unit shows lower resistivity values (60-100 $\Omega \cdot m$) compared to *Sorano unit 2*, likely due to a higher water content or changes in physical characteristics.

The resulting tomography shows an excellent match between lithological units and electrostrata produced by the inversion process, so a range of electrical resistivity can be assigned to each volcanic litho-

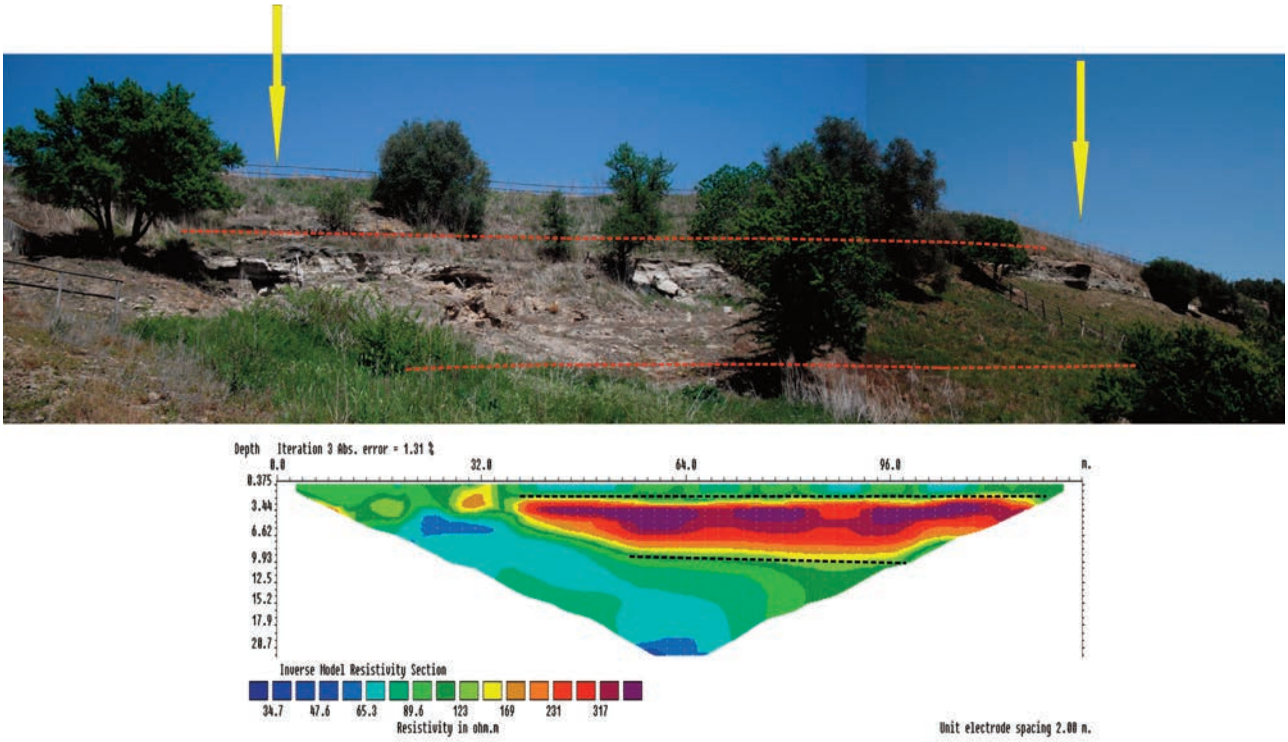

Figure 10. Eletric Resistivity Tomography performed on a outcrop.

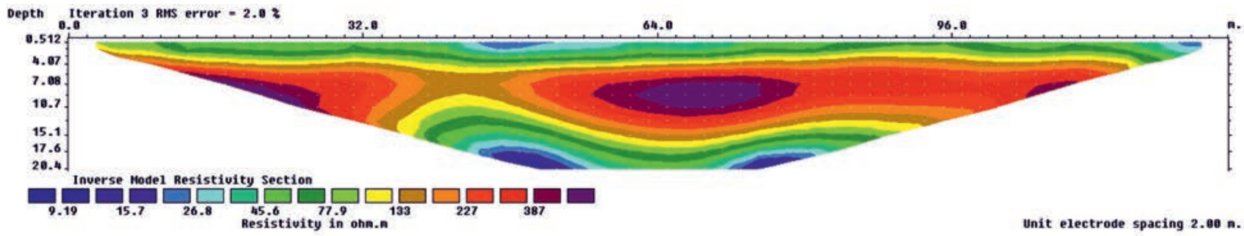

Figure 11. Eletric Resistivity Tomography performed on *Osteria Necropolis*.

type (*Grotte di Castro Formation*: 80-130 $\Omega \cdot$m, *Sorano unit 2*: 200-400 $\Omega \cdot$m, *Sorano unit 1*: 60-100 $\Omega \cdot$m). The *Sorano unit 2* is geophysically recognizable because of its higher resistivity values compared to those of the underlying and overlying units. This peculiarity consents to identify in an easy way the *Sorano unit 2* by resistivity tomography.

The second tomography was performed in the central part of the Osteria Necropolis, using 64 electrodes with 2 m spacing, in order to investigate the contact between the two Sorano units (Figure 11). The upper resistive layer (8 m thick) has resistivity values of 200-400 $\Omega \cdot$m and is separated from a lower conductive layer (ca. 80 $\Omega \cdot$m) by a limit 10 m deep. Referring these resistivity values to those measured on the outcrop described above, the limit can be recognized as the stratigraphic contact between the two *Sorano units*. Considering the thickness of the *Sorano unit 2* (8 m) the presence of other tombs disposed on more levels could be possible in other sectors of the *Osteria Necropolis*.

3. Conclusions

In this work, the lithostratigraphical units present in the Vulci park has been identified and interpreted within the context of the VVD. A geological map at 1:10000 scale has been developed, which shows the areal extension and thickness of the volcanic deposits outcropping in the area.

Magnetic susceptibility and electrical resistivity of the volcanic deposits record variations related to changes in the lithology. The basal part of both the Sorano units were likely emplaced in a marshy environment as suggested by lithological observations and supported by magnetic susceptibility data. ERT clearly indicates an average thickness of the *Sorano unit 2* of 7 m corroborated by high resistivity values (200-400 $\Omega \cdot$m) and reveals a close match between the geophysical electrostrata and the existing geological units.

These results are useful for defining the areal extension and thickness of the lithotype where Etruscan necropolis were excavated and furnish new elements to archeologists for better planning new field surveys in the future.

Acknowledgements. The authors are extremely grateful to Dr. Anna Maria Moretti, Superintendent for Archaeological Heritage of Rome and Southern Etruria and Dr. Laura Ricciardi for giving us the opportunity to carry out these studies in the park of Vulci. The authors would also like to thank the Mastarna Company for allowing them to operate within the park, the Director, Dr. Carlo Casi and Dr. Emanuele Eutizi for information and useful advice.

References

Alberti, A., M. Bertini, G..L. Del Bono, G. Nappi and L. Salvati (1970). Note illustrative della carta Geologica d'Italia, foglio n. 136 Tuscania e n.142 Civitavecchia, Servizio Geologico d'Italia.

Alashloo, S. Y. M., R. Saad, M. N. M. Nawawi, M. Saidin and M. M. Alashloo (2011). Magnetic and 2D electrical imaging methods to investigate an archaeological site at Sungai Batu, Kedah, Malaysia, 3rd International Conference on Chemical, Biological and Environmental Engineering, IPCBEE, 20, IACSIT Press, Singapore.

Banti, L. (1973). The Etruscan cities and their culture, University of Californian press.

Bermejo, L., R. Guérin and A. Canals (2010). Subsoil characterization by electrical Resistivity Tomography around Rosières-la-Terre des-sablons site (Lunery, Region Centre, France), Annali dell'Università di Ferrara, Museologia Scientifica e Naturalistica, 6.

Berge, M.A. and M.G. Drahor (2011). Electrical Resistivity Tomography Investigation of MultiLayered Archaeological Settlemets: part I Modelling, Archaeological Prospection, 18 (3), 159-171.

Brizzolari E., E. Cardarelli, M. Feroci, S. Piro and L. Versino (1992). Magnetic survey in the Selinunte Archaeological Park, Bollettino di Geofisica Teorica ed Applicata 34, 157-168.

Cammarano F., P. Mauriello, D. Patella, S. Piro, F. Rosso and L. Versino (1998). Integration of high resolution geophysical methods. Detection of shallow depth bodies of archaeological interest. Annali di Geofisica 41, 359-368.

Capelli, G. and R. Mazza (1994). Lineamenti idrogeologici dei terrazzi marini pleistocenici del Lazio settentrionale, Risultati della campagna ri rilevamento "1991 - 1992", Geologica Romana, 30, 589-600.

Cardarelli E., F. Fischanger and S. Piro (2008). Integrated geophysical survey to detect buried structures for archaeological prospecting. A case-history at Sabine Necropolis (Rome, Italy), Near Surface Geophysics, 2008, 6, 15-20.

Cerri, G., A. Brundu, P. Mameli, P. Cappelletti, A. Langella, P. Petrosino, G. Rapisardo, R. De Gennaro, A. Colella, M. D'Amore, M. De Gennaro (2013). Zeolitizazion of the "Ignimbrite Orvieto Bagnoregio" Central Italy, XV International Clay Conference, Rio de Janeiro, 2013

Chambers, J.E., O. Kuras, P.I. Meldrum, R. Ogilvy and J. Hollands (2006). Electrical resistivity tomography applied to geologic, hydrogeologic and engineering investigations at a former waste-disposal site, Geophysics, 71 (6), 231-239.

Conticelli, S, L. Francalanci, P. Manetti and A. Peccerillo (1987). Evolution of Latera Volcano, Vulsinian district (Central Italy): stratigraphical and petrological data, Periodico di Mineralogia, 56, 175-199.

Eutizi, E., T. Belardinelli, T. Del Papa, M. Paganelli and D. Petrino (2010). Tesori, storie e leggende d'Italia: Vulci, 34, Edizioni Historia, Viterbo.

Fabbri, M. and I.M. Villa (1987). Problemi cronologici del vulcano di Monte Calvo (Lazio), Rendiconti della Soc. It. di Min. e Petr., 42, 182-183.

Jessop, D.E., K. Kelfoun, P. Labazuy, A. Mangeney, O. Roche, J.L. Tillier, M. Trouillet and G. Thibault (2012). LiDAR derived morphology of the 1993 Lascar pyroclastic flow deposits, and implication for flow dynamics and rheology; Journal of Volcanology and Geothermal Research, 245-246, 81-97

Lecoanet, H., F. Lévêque and S. Segura (1999). Magnetic susceptibility in environmental applications: comparison of field probes, Physics of the Earth And Planetary Interiors, 115, 191-204.

Loke, M.H. and R.D. Barker (1996). Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method, Geophysical Prospecting, 44, 131-152.

Loke, M.H. (1999). Electrical imaging surveys for environmental and engineering studies, technical notes, http://www.heritagegeophysics.com/images/lokenote.pdf.

Moretti Sgubini, A.M. (1997). Il carro di Vulci dalla Necropoli dell'Osteria, Carri da Guerra e Principi Etruschi, 139-145.

Nappi, G. and A. Marini (1986). I cicli eruttivi dei Vulsini orientali nell'ambito della vulcanotettonica del complesso, Mem. Soc. Geol. It; 35, 679-687.

Nappi, G., F. Antonelli, M. Coltorti, L. Milani, A. Renzulli and F. Siena (1998). Volcanological and petrological evolution of the Eastern Vulsini District, Central Italy, J. of Volcanologic and Geothermal Research, 87,. 211-232.

Omosanya, K.O., G.O. Mosuro and L. Azeez (2012). Combination of geological mapping and geophysical surveys for surface-subsurface structures imaging in Mini-Campus and Methodist Ago-Iwoye NE Areas, Southwestern Nigeria, Journal of Geology and Mining Research, 4 (5), 105-117.

Palladino, D.M., S. Simei, G. Sottili and R. Trigila (2010). Integrated approach for the reconstruction of stratigraphy and geology of Quaternary volcanic terrains: an application to the Vulsini Volcanoes(central Italy), In G.Groppelli e L. Viereck (Eds.) "Stratigraphy and geology in volcanic areas", Geol. Soc. Am., Spec. Pap., 464, 66-84.

Porreca, M., M. Mattei, G. Giordano, D. De Rita and R. Funiciello (2003). Magnetic fabric and implications for pyroclastic flow and lahar emplacement, Albano maar, Italy, Journal of Geophysical Research, 108, B5, 1-14.

Quesnel, Y., A. Jrad, F. Mocci, J. Gattacceca, , P.E. Mathé, J.C. Parisot, D. Hermitte, V. Dumas, P. Dussouillez, K. Walsh, C. Miramont, S. Bonnet and M. Uehara (2011). Geophysical Signatures of a Roman and Early Medieval Necropolis, Archaeological Prospection, 18, 105–115. doi:10.1002/arp.411.

Rucker, D., G.E. Noonan and W.J. Greenwood (2011). Electrical resistivity in support of geological mapping along the Panama Canal, Engineering Geology, 117, 121-133.

Sasaki, Y., Y. Yoneda and K. Matsuo (1992). Resistivity imaging of controlled-source audiofrequency magnetotelluric data, Geophysics, 57, 952-955.

Schmidt, A. (2007). Archaeology, magnetic methods, in D. Gubbins and E. Herrero-Bervera (eds) Encyclopedia of Geomagnetism and Paleomagnetism, Encyclopedia of Earth Sciences Series Heidelberg, New York, Springer.

Schmidt A. (2009). Electrical and magnetic methods in archaeological prospection, in S. Campana, S. Piro (Eds.), Seeing the Unseen, Geophysics and Landscape Archaeology, 67-81, Taylor and Francis, London.

Sposato, A., D. De Rita, A. Bertagnini, P. Landi and F. Salvini (1993). Guide geologiche regionali: Lazio, BE-MA Editrice.

Taddeucci, A. and M. Voltaggio (1987). Th230 dating of the travertines connected to the Vulsini Mts. Volcanism (Northern Latium, Italy): neotectonics and hydrogeology, Periodico di Mineralogia, 56, 295-302.

Tamburini, E. (1987). I titoli funerari della tomba François e il sepolcreto di Vel Saties, La Tomba di Vulci, Catalogo della Mostra (Musei Vaticani, 20 Marzo-7 Maggio 1987).

Thompson, R. and F. Oldfield (1986). Environmental Magnetism, Allen and Unwin, London.

Tsokas, G.N., P.I. Tsourlos, G. Vargemezis and M. Novack (2007). Non-destructive electrical resistivity tomography for indoor investigation: the case of Kapnikarea Church in Athens, Archaeological Prospection, 15 (1), 47-61.

Turbeville, B.N. (1992). Ar40/Ar39 ages and stratigraphy of the Latera Caldera, Italy, Bullettin of Volcanology, 55, 110-118.

Urbini, S., L. Cafarella, M. Marchetti, P. Chiarucci and D. Bonini (2007). Fast geophysical prospecting applied to archaeology: results at «Villa ai Cavallacci» (Albano Laziale, Rome) site, Annals of Geophysics, 50 (3), 291-299.

Washington, H.S. (1907). The Roman Comagmatic Region, Nabu Press.

Zhou, W., B.F. Beck and J.B. Stephenson (2000). Reliability of dipolo-dipole electrical resistivity tomography for defining depth to bedrock in covered karst terranes, Environmental geology 39 (7).

Vezzoli, L., S. Conticelli, F. Innocenti, P. Landi, P. Manetti, D.M. Palladino and R. Trigila (1987). Stratigraphy of the Latera Volcanic Complex: proposals for a new nomenclature, Periodico di Mineralogia, 56, 89-110.

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