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Resilient and sustainable cities of tomorrow: the role of applied geophysics

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ABSTRACT The main goal of this review is to emphasize the emerging role of the scientific community of applied geophysics in supporting actions for urban planning. We analyse the new scenario related to the global urbanization process and its impact on environmental sustainability and resilience to natural disasters of urban areas. A selected list of case-studies concerning the application of geophysical methods for the subsurface exploration in historical cities of Italy and megacities located in Asia and south America are described and discussed. The analysis clearly demonstrates that the geophysical surveys are assuming a great relevance to manage the underground urban environment and to adopt new strategies for the mitigation of geological risks. The sensor synergy strategy, the novel algorithms for the tomographic imaging and the capability to explore the subsoil with a multi-resolution approach are the key of success of the urban geophysics. Finally, the innovative aspects of the CLARA project funded by MIUR for promoting the integration of the remote and ground-based technologies for surface and subsurface imaging in urban areas are presented and discussed.

Key words: cities, resilience, sustainability, subsurface, geophysical tomography.

1. Introduction

To-date, more than one half of the world population lives in urban areas and the global urbanization trend is changing completely the landscape of human settlements. In 2050 the number of megacities with over 10 million inhabitants will strongly increase (Fig. 1) and about the 66% of the world's population will reside in urban areas (UNDESA, 2014). This relentless process of urbanization strongly requires the adoption of new strategies and programs for urban planning to make the cities resilient to natural disasters and to increase their energy and environmental sustainability (UNFCCC, 2015; UNISDR, 2015; Mysiak *et al.*, 2016).

One of the key actions to tackling this social and economic challenge is to better explore and manage the subsurface geological structures in urban areas, for this reason there is a growing demand of innovative products and services to obtain high-resolution images of subsoil (Li, 2012; Bobylev, 2016; Bobylev and Sterling, 2016). The mitigation of the effects of natural disasters (e.g., earthquakes, landslides), the implementation of new strategic infrastructures (energy pipelines, transport networks) and the enhancement of natural and cultural resources of the subsoil (e.g., groundwater, geothermal fluids, cultural heritage) are strategic priorities for urban planning and

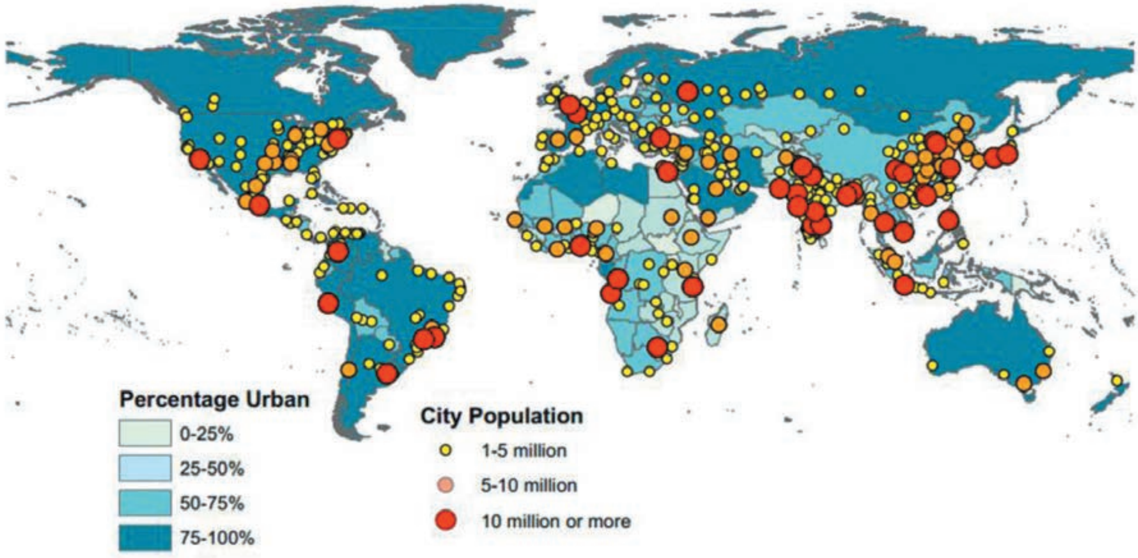

Fig. 1 - The scenario for the growing urbanization process at global scale. The world is expected to have 41 megacities with more than 10 million inhabitants in 2030 (*source*: UNDESA, 2014).

require a complete geological-geophysical characterization of the subsurface (Wycisk *et al*., 2009; Miller, 2013; Gabas *et al*., 2014). A better knowledge of the shallowest layer (from few metres to 1-2 km depth) of the subsurface is fundamental for any program for the geological risk mitigation in urban areas. In addition, the urban subsurface can be considered as a reservoir of economic and cultural resources (aquifers, geothermal fluids, archaeological sites, etc.), and as a physical space where strategic infrastructures (energy grids, networks for urban mobility, etc.) can be realized (Fig. 2). Then, it is mandatory to make "visible" the underground part of the cities.

At present, there is a strong need to develop innovative approaches for obtaining 3D geological models in urban areas. This aspect was emphasized in recent international initiatives (Showstack, 2014), such as the "Urban Geoscience Program" promoted by British Geological Survey with the aim to reconstruct the 3D high-resolution geological models in metropolitan areas (e.g., Glasgow, London) and the "Urban Geology" program carried out in Germany (Van der Meulen, 2016; Mielby *et al*., 2017). Applied geophysics fully responds to this kind of technological demand with the integration of robust methodologies (active and passive, direct and indirect, multi-source and multi-resolution) for the exploration of the subsoil in an urban environment, in which there is generally an intrinsic difficulty to perform direct surveys and invasive drilling.

In this paper we analyze the current state of the art and the main research perspectives of applied geophysics in the study and characterization of the urban underground environments. We analyze two different typologies of urban areas: i) historical centres located in zones characterized by a high geological hazard; ii) megacities interested by extreme natural events and/or scarse availability of groundwater.

Finally, the main objectives and the expected results of the CLARA project "*Cloud Platform and smart underground imaging for natural risk assessment*" are shortly described and discussed. This project is funded by the Italian Ministry for Research and University (MIUR) in the frame of a national competitive call on the "Smart Cities & Communities" theme and it is actually ongoing.

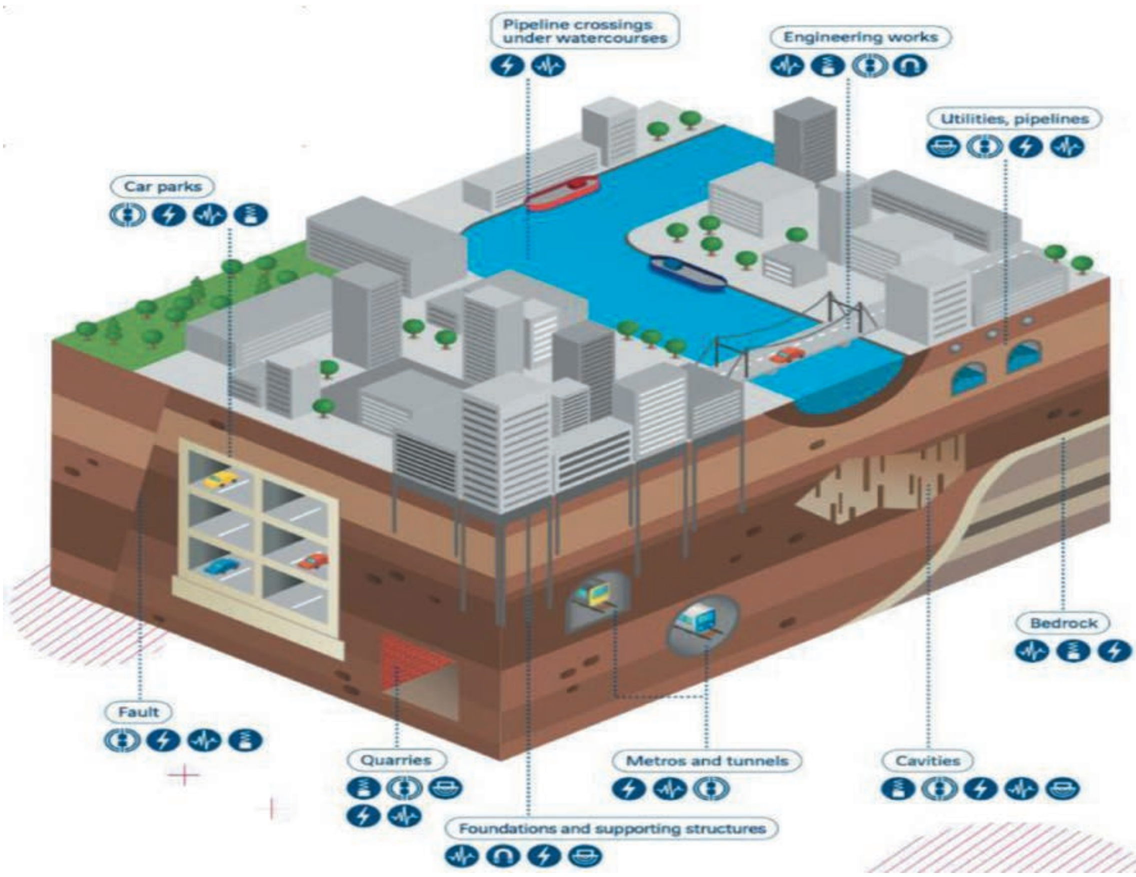

Fig. 2 - Underground city and urban planning (source: Sixsense geophysics www.soldata_geophysic.com).

2. The role of applied geophysics: state of the art and future perspectives

The scenario of the growing urbanization represents an opportunity for the applied geophysics. To manage a wide-class of underground activities in urban areas it is necessary the technological support of robust methodologies for subsurface imaging. The geophysical methods are prove to be able in reconstructing the geometry of faults, detecting the presence of groundwater or depicting a sliding surface in geological environments characterized by a low-level of anthropic noise (e.g., energy pipelines, railways, roads, etc.) and generally located out from the urban centres. The application of the geophysical methods in urban areas, where there are both geological and logistic complexity, is a new scientific and technological challenge for the geophysicists.

Recently, the geophysical methods have been successfully applied in many studies of urban subsurface giving effective contributes to plan new strategies for the georesources management and the geological risk mitigation (Giocoli *et al.*, 2011; Mucciarelli *et al.*, 2011; Gallipoli *et al.*, 2012; Krawczyk *et al.*, 2012; Carbonel *et al.*, 2015; Leucci *et al.*, 2017; Mehta *et al.*, 2017). In this paper, we present and discuss some novel applications in the study of two classes of urban areas: i) small cities and historical centres; ii) megacities located in emerging and/or developing countries.

2.1. Small cities and historical centres

The first example concerns the study of the Montemurro city, a small urban centre located in the heart of the Apennine chain: the south-eastern sector of the northen Agri Valley (southern Italy). This area was completely destroyed by a landslide triggered by one of the largest seismic events occurred in Italy, the *M* 7.0 1857 great Neapolitan earthquake. A multidisciplinary geophysical study based on the integration of remote sensing (Satellite SAR Interferometry, aero-photogrammetry) and in-situ (Ground-based SAR interferometry, ERT, HVSR) methodologies was planned for detecting and characterizing areas affected by surface deformation phenomena and/or site seismic amplification effects (Giocoli *et al*., 2012; Perrone *et al*., 2012). A cascade modality was adopted for the monitoring activities. The first step was devoted to the analysis of radar satellite time series (TerraSAR-X, ENVISAT) with the SBAS algorithms (Lanari *et al*., 2004; Bonano *et al*., 2013). A zone located close to the Montemurro town with anomalous surface deformation patterns was clearly identified. In a second step, this zone was monitored and controlled by using a ground-based SAR system for studying, with spatial and temporal resolution, the surface deformation process. In the last step, in situ geophysical surveys, aerial photo interpretation, morphotectonic investigation, geological field survey and borehole data allowed to detect the geometry of the different lithological units and their mechanical and dynamical properties and to characterize the geometry of an active landslide that is still causing damage to civil infrastructures (Fig. 3). This case-study represents a best-practice of multidisciplinary, multi-sensor and multi-resolution geophysical approach for monitoring high seismogenic and hydrogeological hazard areas.

The evaluation of in-situ seismic effects in the historical centres is mandatory for improving the safeguarding of cultural heritage, even small earthquakes can produce amplifications that can damage buildings or architectural structures of remarkable value. The presence of anthropic layers in the subsurface of historical centres could be responsible of local seismic effects, then the study of the geometry and mechanical properties of these layers is fundamental to better estimate the amplitude and the frequency range of the seismic amplifications. The geophysical methodologies respond to this need by guaranteeing very high-resolution images of the urban subsoil. Recently, an interesting case-study is represented by the integrated geological and geophysical surveys (Moscatelli *et al*., 2013) carried out for mapping the anthropic layer of the Palatino hill and Roman Forum (Roma, Italy). The joint interpretation of the boreholes and ERT images made it possible to well define the geometry of the anthropic cover of the Palatino hill and surrounding areas (Fig. 4). The integration of the ERT results with the GPR investigations discloses the way to discriminate anthropic backfill units of the recent suburban area, mainly used to smooth the topography, from the anthropic backfill units of the historical centre that also contain archaeological elements. These results were used as input for assessing the local seismic hazard.

Applied geophysics can give a contribution to the urban geomorphology: the study of man-made and natural geomorphologic changes in urban environments. To better understand the historical transformations in the anthropogenic subsoil it is necessary to apply cost-effective, not-invasive and high-resolution geophysical methods. A recent study, based on the application of electrical and electromagnetic methods, was carried out for the subsurface investigation of an anthropogenic mound in the urban environment of Florence (Italy). In particular, ERT and VLF-EM profiles were planned for investigating subsurface of the English cemetery, where historical documents testify impressive sequences of morphological changes (Pazzi *et al*., 2016). The 2D electrical images highlighted the presence of remnants of the ancient wall that are still buried along

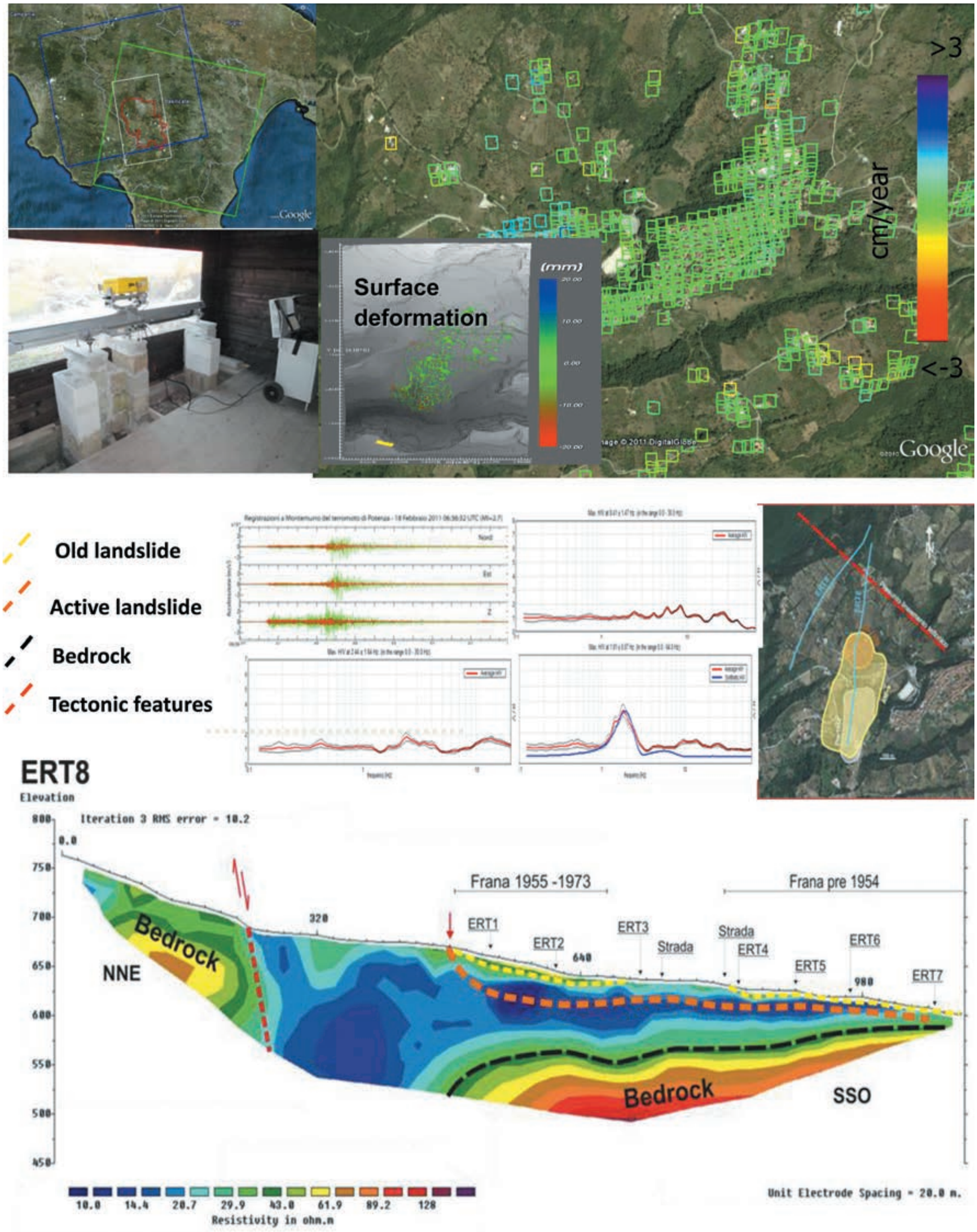

Fig. 3 - Integrated geophysical survey of Montemurro landslide (southern Italy). The surface deformation pattern identified by means of satellite and ground-based SAR technologies is plotted on the top of the figure. The results of Electrical Resistivity Tomography and the spectral analysis of the seismic ambient noise are reported on the bottom of the figure (modified from Giocoli *et al.*, 2012).

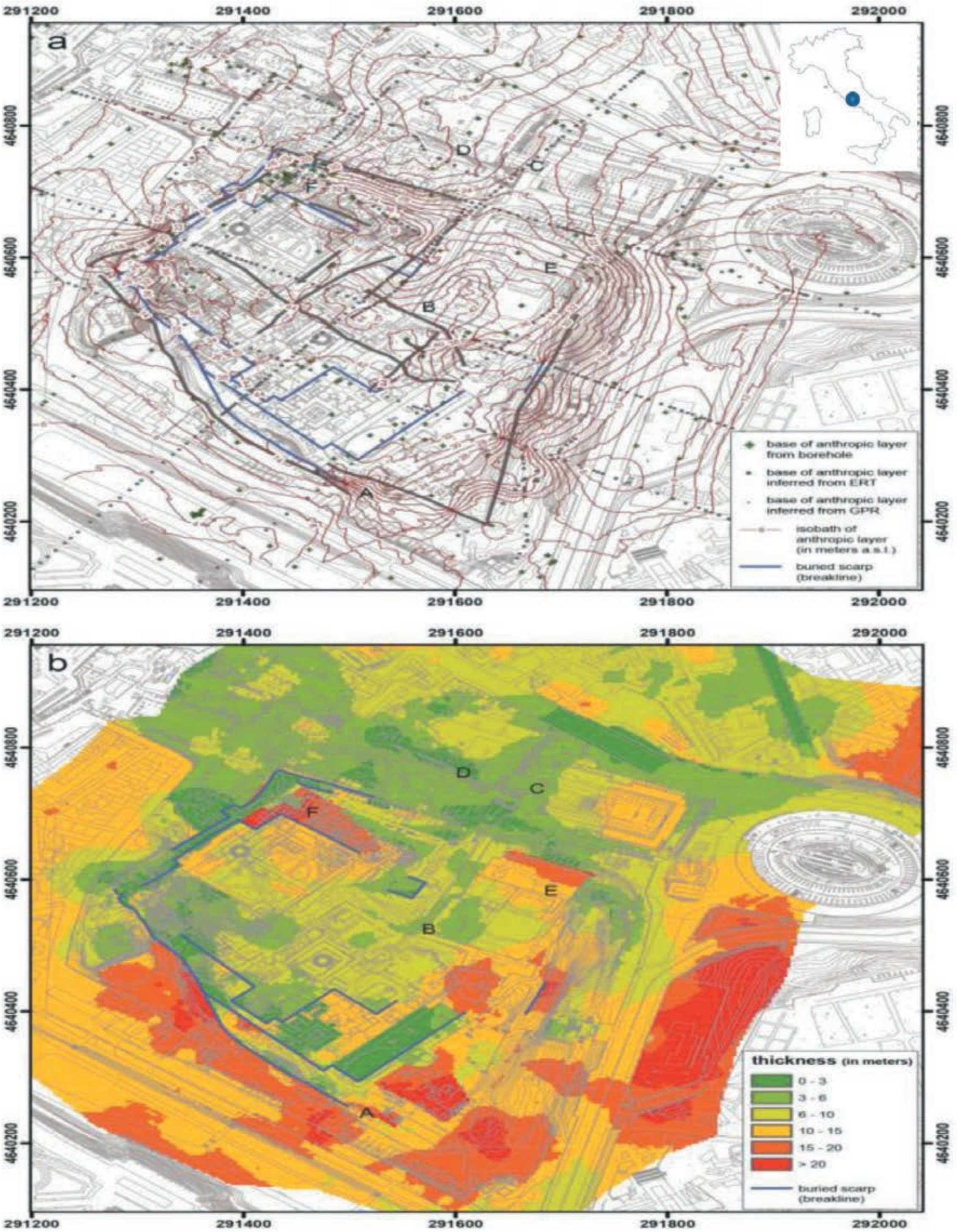

Fig. 4 - Geophysical survey of the Palatino hill (Rome, Italy). The isobaths (a) and the thickness (b) of the anthropic layer are reported on the figure (modified from Moscatelli *et al*., 2013).

the southern side of the mound. Furthermore, the integration of ERT and VLF-EM results were used for mapping tombs and to have information to better design the maintenance and restoration measures in the areas affected by ground instability (Fig. 5). This aspect is of great relevance if we consider that the mound has historic and cultural value and is used for civilian purposes.

2.2. Megacities

To complete the short panorama on urban geophysics, we briefly analyze and discuss some case-studies concerning the exploration of georesources and the geohazard monitoring in megacities. In the next future, the monitoring of groundwater resources in urban areas will become a strategic action to guarantee the quality of life and security of citizens. A recent geophysical survey carried out in the São Paulo city (Brazil) clearly demonstrated the great potentiality of the applied geophysics to support hydrogeological studies in complex urban environment (Porsani *et al*., 2012). The Time Domain Electromagnetic (TDEM) method was used for investigating the resistivity pattern of subsurface in a zone located close to the campus of the University of São Paulo (Fig. 6). The results allowed to obtain information about the sedimentary aquifer that has the greatest potential for groundwater exploration and is of crucial importance for São Paulo city, due to river and lake pollution. Furthermore, the integration of geological and geophysical information was used for better estimating the depth of the basement of São Paulo basin and for characterizing the crystalline aquifer with fractured zones filled with water inside of granitic rocks of São Paulo basin basement. Finally, the results of this work open new perspectives in using TDEM method in urban environment where there are operative difficulties due the presence of a high level of electromagnetic noise.

In recent years the geophysical methods were largely applied for mapping active faults and to characterize the geological structures responsible of seismic amplification effects (i.e., sedimentary basin). These studies are of great relevance for improving the earthquake hazard assessment in megacities, located in seismic active zones of the globe. In a recent study, a geophysical survey based on the joint application of geoelectrical (ERT) and seismic refraction methods in the urban area of Dhaka (Bangladesh) megacity was planned for better evaluating the earthquake hazard (Khan, 2016). The impact of these activities is of strategic relevance, Dhaka is ranked one of the 20 most vulnerable cities in the world mainly due to inherent vulnerable building infrastructure, high population density, poor emergency response and poor recovery capability (Fig. 7). The results of the ERT survey were used for improving the geological knowledge of active faults and to better estimate local seismic amplification effects.

The civil infrastructures of urban areas (i.e., tunnels, bridges, pipeline) could be used as platforms for geophysical measurements. The presence of tunnels could open the possibility to locate sensors in deep geological environment with low level of environmental noise. An interesting example is represented by a recent study carried out in Japan. A novel approach (Tanaka, 2015) for obtaining a muographic mapping of the subsurface density structures was applied in Miura, Boso and Izu peninsulas (Japan). Detectors located in underground tunnels were used to monitor the vertical muon flux arriving on the Earth surface and partially attenuated by the presence of geological structures. The attenuation of the muon flux is related to the density of rocks. Then, the muography was used for mapping the presence of faults that are generally characterized by geological material with low-density (Fig. 8).

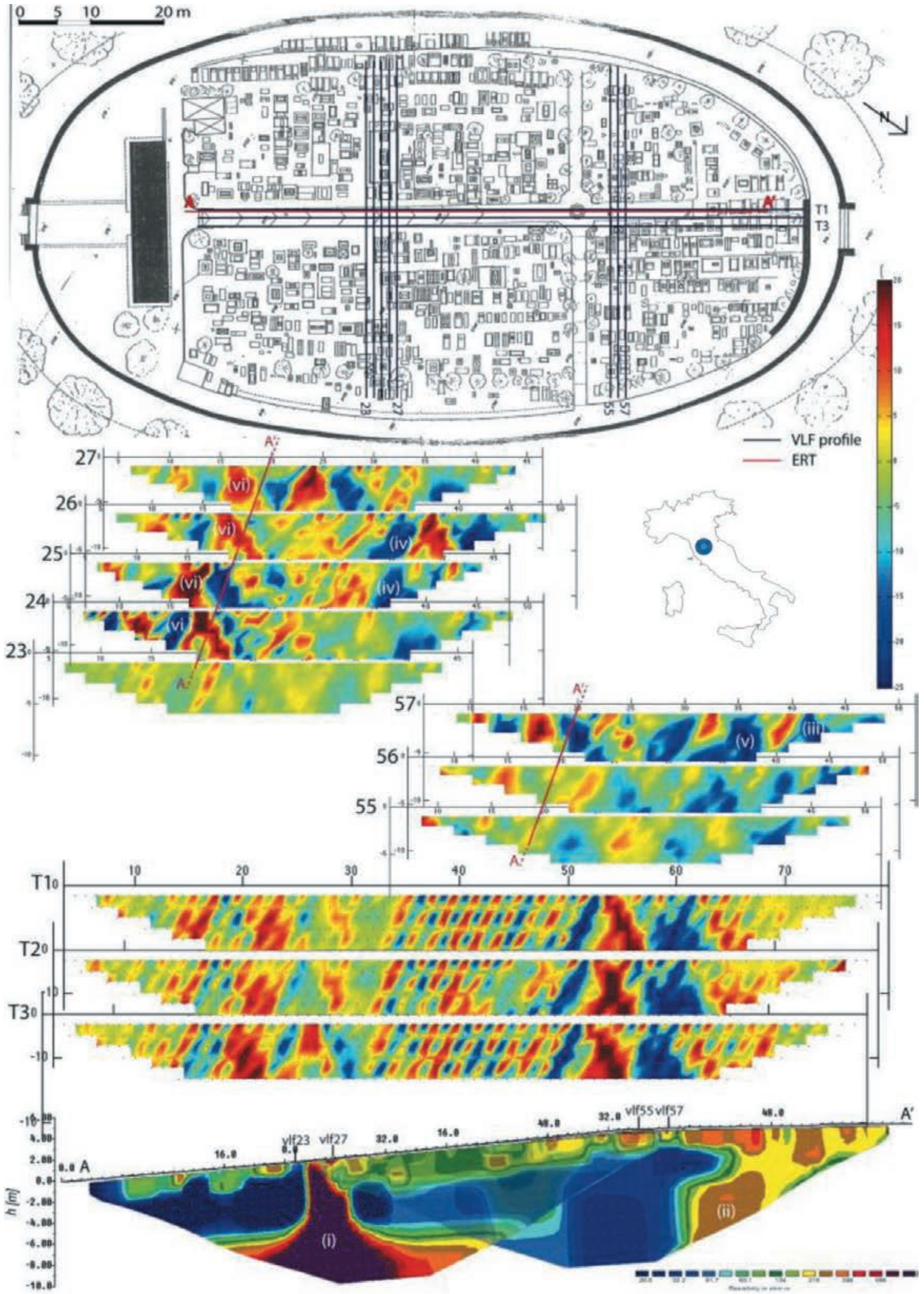

Fig. 5 - Integration of the ERT and VLF-EM profiles for the subsurface investigation of an anthropogenic mound located in an urban environment (the English cemetery, Florence) (modified from Pazzi *et al*., 2016).

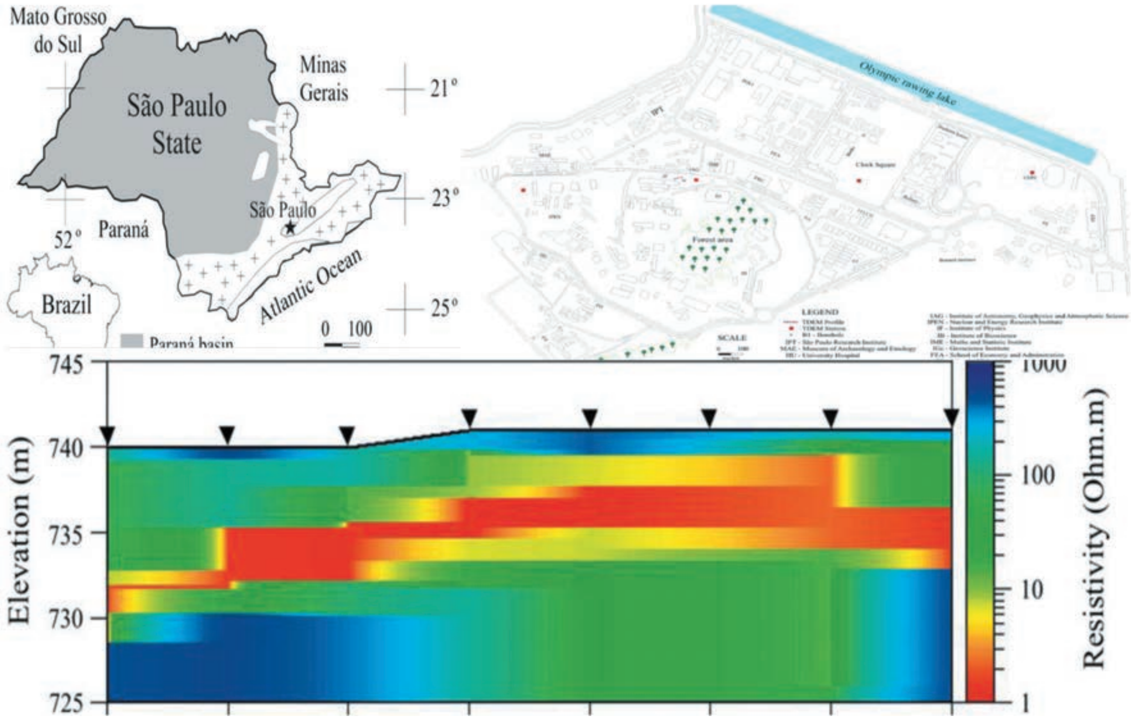

Fig. 6 - Electromagnetic exploration (TEM) of groundwater in the urban area of São Paulo (Brasil). The resistivity section highlights the presence of a conductive layer associated with the presence of water (modified from Porsani *et al.*, 2012).

3. The CLARA project

The CLARA project is promoted by a large public-private partnership with the participation of three institutes of the Consiglio Nazionale delle Ricerche of Italy (IMAA, IREA, ISTC), the Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS) public research centre, the University of Ferrara, the University of Roma - La Sapienza, the University of Enna and the University of Catania, leading international private companies, technological clusters and consortia of small and medium enterprises.

In this project, great attention has been devoted to the multi-disciplinary approaches based on the integration of geophysical exploration technologies with different spatial and temporal resolution in line with the guidelines of the Global Earth Observation System of Systems (GEOSS) and Global Monitoring for Environment and Security (Copernicus) international programs.

The case-studies of the project are the cities of Ferrara and Matera and some urban areas, located in the province of Enna (Fig. 9). The Ferrara municipality is interested in the management of geothermal resources and in the mitigation of seismic risk; the city of Matera, recently appointed as capital of European Culture in 2019, is characterized by the presence of the Sassi historical centre affected by a diffuse hydrogeological risk; while the third test site is an urban area of Sicily with a high level of hydrogeological and seismic risk.

The CLARA project proposes a novel systemic approach for the characterization of the physical and geometrical properties of the surface and near-surface in urban areas located in seismic

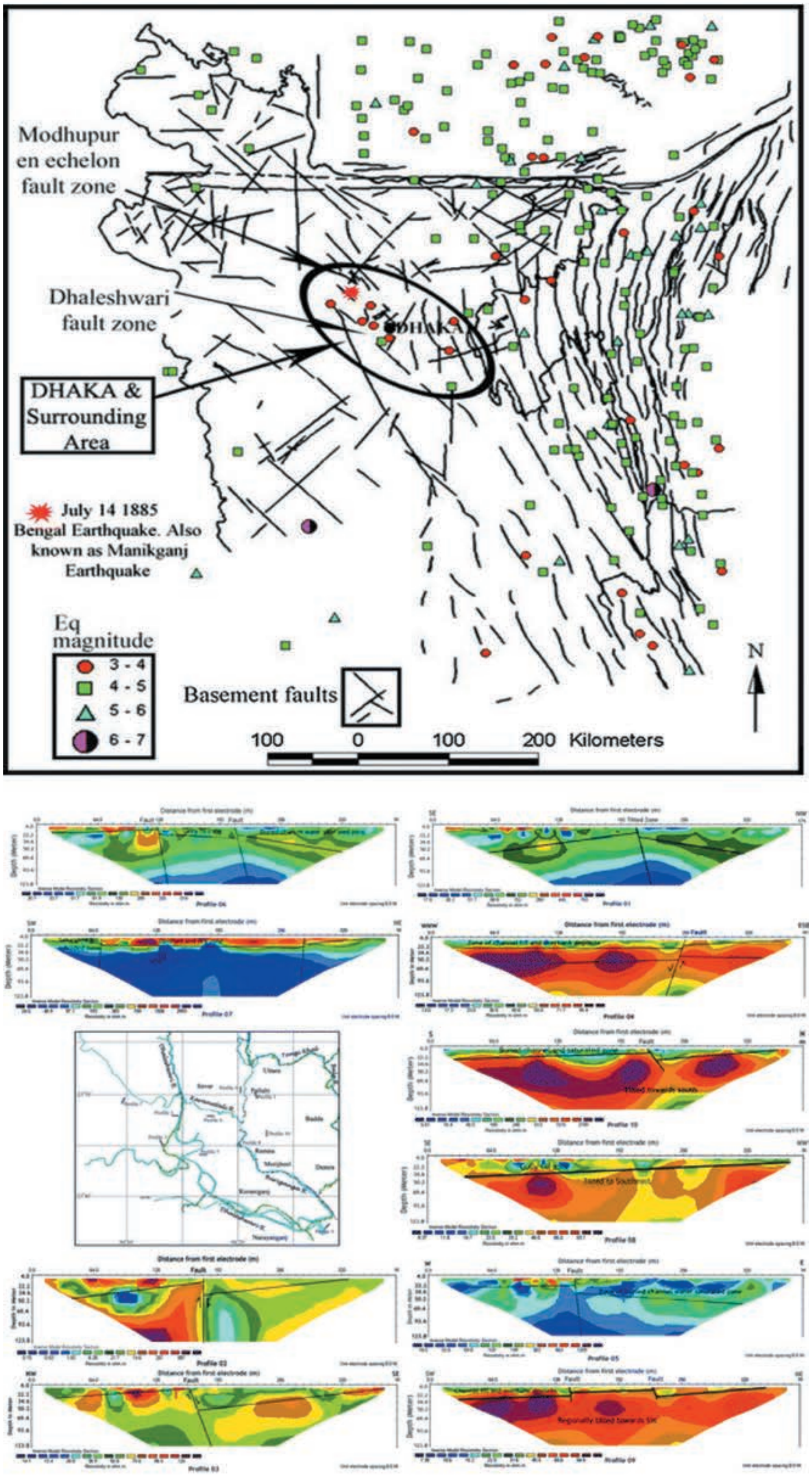

Fig. 7 - Seismotectonic setting of the study area (top of the figure). Electrical Resistivity Tomographies (bottom of the figure) carried in the urban area of Dhaka for investigating seismic structures and to give a contribute to evaluate the seismic amplification phenomena (modified from Khan *et al.*, 2016).

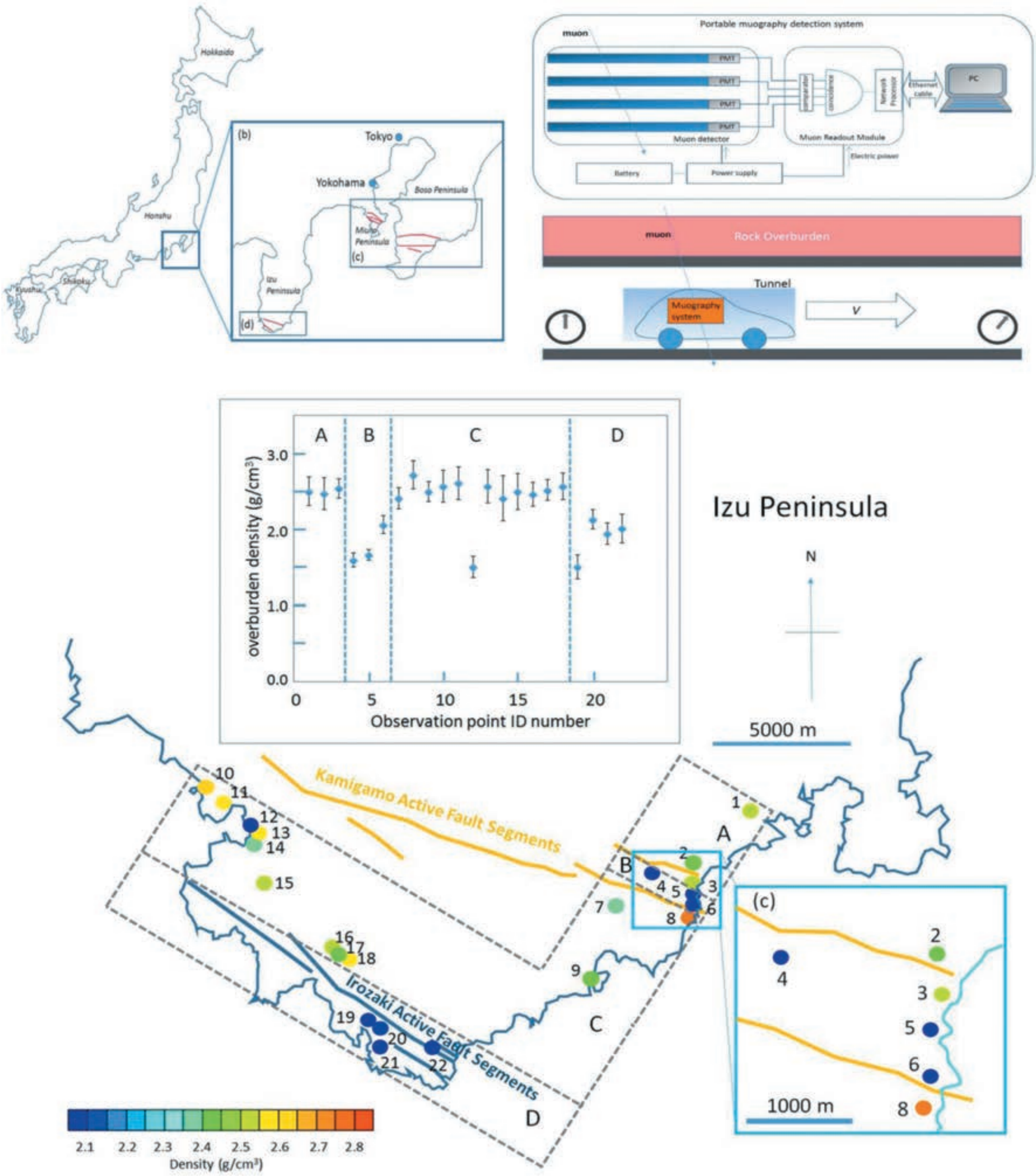

Fig. 8 - The simplified scheme for the measurements of muon flux in underground tunnels in Boso peninsula (Japan) is displayed on the top of the figure. The study of muon flux allowed to estimate the rock density (see the bottom of the figure) and to identify fractures zones with low-density associated with the presence of faults (modified from Tanaka, 2015).

active zones and/or interested by hydrogeological instability phenomena. The approach is based on the full integration of satellite remote sensing (optical and radar technologies), geophysical exploration technologies (seismic tomography, electromagnetic tomography, resistivity and self-potential tomography, etc.), advanced sensors (fiber-optic sensors, low-cost accelerometers, MEMS, etc.) and ICT architecture (web-services, web-sensors, google-like services etc.) for the

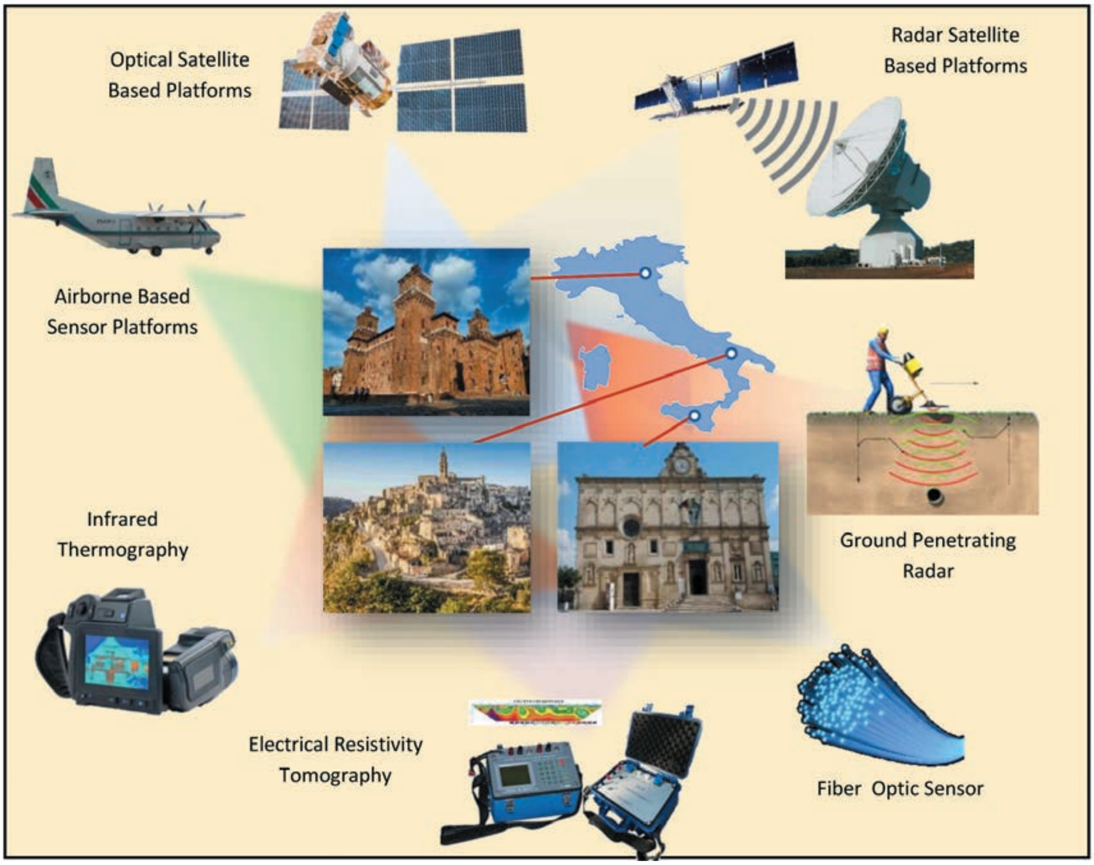

Fig. 9 - Map of the test-sites and simplified diagram illustrating the geophysical monitoring strategy approach adopted by the CLARA project. The approach combines satellite and ground-based observations, geophysical tomographic methods, new sensors with multi-resolution in space and time domains.

development of an open, scalable and interoperable cloud platform for the sharing, visualization and management of geospatial data in urban areas (Fig. 9).

This project responds to the scientific changes of urban geophysics by integrating the latest enabling technologies (remote sensing and ground-based, active and passive; direct and indirect; multi-sources and multi-resolution) for the geophysical exploration of the surface, the near-surface and the dynamic characterization of soil structure/infrastructures interactions. The proposed system is based on the integration of satellite remote sensing and non-invasive technologies suitable for 2D and 3D geophysical imaging of the subsurface in an urban environment, in which there is generally an intrinsic difficulty to work with direct surveys and invasive drilling. A first preliminary result concerning the use of the ERT method for studying the subsurface environment in the surrounding area of the Tramontano castle, located in the urban area of Matera, is briefly described. The investigated area is interested by a landslide, the ERT was carried out along a profile with direction parallel to the main axis of the movement. The 2D electrical image is characterized by resistive material associated with sand material just under the castle and conductive layers along the slope associated with the presence of clay material involved in the movement (Fig. 10).

The three test areas represent extraordinary "living labs" to transform historic centres into geophysical urban laboratories that see the active participation of researchers, technicians of

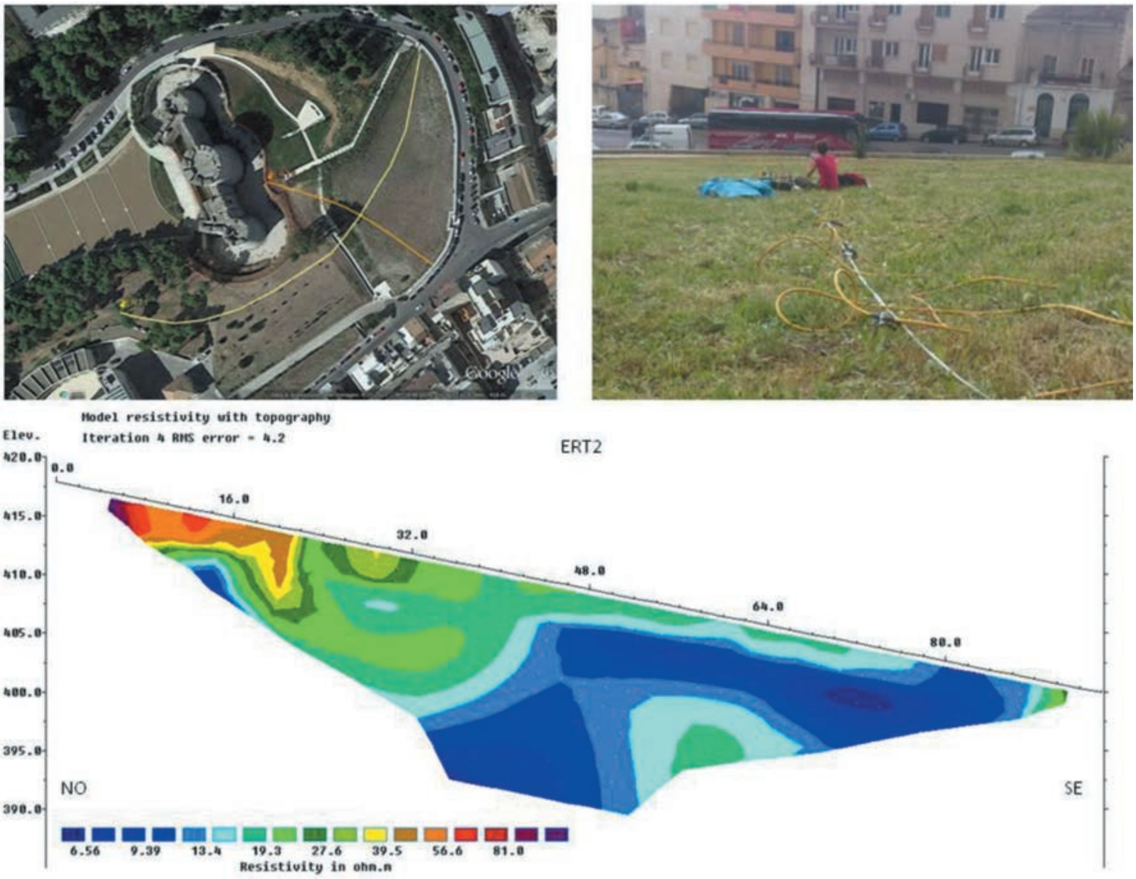

Fig. 10 - ERT carried out close to the Tramontano castle in the urban area of Matera. A Wenner array with an electrode spacing of 2 m was used during the geophysical survey. The length of the profile is 94 m with an exploration depth of about 15 m. The distance and the elevation reported in the figure are expressed in metres. The Root Mean Squares associated to the inversion procedure is lower that 5%. The good contrast between the conductive zone (clay material) and the resistive zone (sand material) is clearly evident.

innovative companies, technicians of public institutions and citizen associations (quadruple-helix model of innovation). The project involves the implementation of a participatory governance model that will allow widespread involvement in the process of addressing the project and broad sharing of objectives among the various stakeholders (citizens, local administrators, businesses). This strategy aims to promote significant structural and behavioral changes in the smart cities and communities to make cities more resilient to natural disasters and extreme climatic events.

4. Conclusions

At present, there is a growing demand of innovative products and services for the management of activities to be implemented in urban subsurface environments. The mitigation of the effects of natural and man-made geohazards (earthquakes, landslides, collapses and sinkholes, etc.), the realization and monitoring of strategic infrastructures (energy pipelines, road and railway network, etc.) and the exploitation of the natural resources (groundwater, geothermal fluids, etc.) are strategic priorities in any approach of urban planning and strongly require a complete geological/geophysical characterization of subsurface. Then, applied geophysics could play a more relevant role in the urban planning and give a contribute to build new models of resilient and sustainable cities.

In this paper, a selected list of case-studies of urban geophysics concerning historical centres and megacities are described. Our analysis clearly demonstrated that the geophysical methods (passive and active, in-situ and remote sensing) represent an optimal toolbox for the subsurface exploration in urban areas. They are cost-effective and completely no-invasive methods for giving a contribution to realize 3D geological models in urban areas. In the next future, the scientific community of applied geophysics has to orient all its efforts to develop novel approaches for the integration of a wide spectra of geophysical methods with the aim of obtaining high-resolution imaging of urban subsurface. A more effective collaboration between geophysicists and urban decision makers must be encouraged.

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