NON-INVASIVE METHODOLOGIES FOR THE CHARACTERIZATION OF THE EARTH'S CRITICAL ZONE

Ph.D. candidate: LAURA BUSATO, I course
Tutor: Prof. GIORGIO CASSIANI, Co-Tutor: Dott. JACOPO BOAGA
Cycle: XXIX

Abstract

The Earth's Critical Zone is the near-surface domain where the interactions between rock, soil, water, air, and living organisms take place. In this heterogeneous boundary layer, processes operate on second-to-eon timescales and atomic-to-global space-scales, and, above all, determine the availability of life-sustaining resources (e.g., nutrients, food production, and water quality). Although ECZ is strongly interconnected with human activity, its characterization is still in an early stage because of the complex and interacting phenomena occurring. We investigated two examples of ECZ subdomains employing non-invasive techniques provided by applied geophysics: the areas surrounding an alpine river (using electrical resistivity tomography and distributed temperature sensing) and the root zone of orange trees (using 3D micro-electrical tomography). Albeit our preliminary data well highlighted both structures and processes in these regions, a more detailed time-lapse monitoring, paired with flow and transport models, is still necessary to deeper understand this complex domain.

Introduction

The Earth's Critical Zone (ECZ) is the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources (National Research Council, 2001). These interacting phenomena occur at small-to-large scale in terms of both time and space and have a strong interconnection with human activity. Therefore, several disciplines are currently studying this shallow boundary layer (e.g., geology, biology, hydrology, etc.) but, despite that, we are still far from a deep understanding of this complex domain. A major step forward in the characterization of the ECZ can be provided by the application of non-invasive geophysical techniques combined with flow and transport models. These cost-effective and relatively fast methodologies allow the monitoring of the domain of interest at different scales both in terms of time and space and, moreover, the data thus obtained can be linked to the information supplied by other disciplines through an appropriate modelling process, so as to apply a more complete holistic approach.

In order to characterize the ECZ, one of the most commonly employed techniques is the electrical resistivity tomography (ERT), both from surface (Nyquist et al., 2008) and in (micro-)boreholes (Crook et al., 2008; Boaga et al. 2013; Cassiani et. al 2014), since it allows the measurement of resistivity (ρ), a parameter strongly related to the water content. Conversely, a promising methodology is the distributed temperature sensing (DTS). Its usage for these applications has been developing since the last two decades, revealing a wide adaptability to the typical issues of this field of study. DTS is based on Raman scattering spectroscopy (Gardiner, 1989) and employs heat as tracer (Anderson, 2005) using fiber-optic cables to acquire temperature (T) values (Westhoff et al, 2001). During this first year we investigated three case studies representing two examples of ERC subdomains particularly interconnected with human activity: the areas surrounding a stream (i.e., hyporheic and riparian zones) and the root zone of two orange trees. In the first case study we combined ERT and DTS measurements employing an innovative instrumentation deployment, while the surveys on the second and the third case studies were carried out using the 3D micro-electrical tomography (3D micro-ERT).

Case studies and methodologies

Vermigliana creek

The Vermigliana creek is the main watercourse of the Upper Val di Sole (northern Italy), originates from the Presena Glacier and has a nivo-glacial regime. Moreover, discharge variation can be identified also on a daily basis. The whole Upper Val di Sole bottom is filled with heterogeneous glacial till and quaternary slope deposits, whose granulometry ranges from clays to boulders. Our site is located near the small village of Vermiglio (TN). Here, we combined two different methodologies, electrical resistivity tomography (ERT) and distributed temperature sensing (DTS), taking advantage of two horizontal oriented boreholes drilled below the river itself. More in detail, the first technique is carried out using a waterproof multicore cable with 48 brass electrodes, spaced 1 m, placed inside the upstream borehole. To ensure a higher data reliability, we deployed also a superficial survey line of 24 stainless steel electrodes (12 on each river levee) spaced 1 m, in vertical correspondence to the horizontal borehole. Furthermore, 4 take-outs allowed the connection of the 4 electrodes nearest to the watercourse to the cable itself, which was partly located over the bridge upstream. Each ERT survey is performed with an IRIS Syscal Pro resistivimeter using all 72 electrodes, with a "skip 0" dipole-dipole scheme. The final dataset of each acquisition is made up of 4885 values of both direct and reciprocal measurements, obtained exchanging the current electrodes with the potential ones. The 200 m long fiber-optic for the DTS measurements is located in the downstream horizontal borehole, parallel to the ERT perforation. Since the DTS perforation is 70 m long, the fiber-optic has been folded, creating a "double-ended" configuration (i.e., both ends are connected to the DTS instrument). For every DTS survey we used the AP Sensing N4386A Distributed Sensing system setting both the sampling interval and the spatial resolution equal to 1 m. In each survey, we acquired three single traces with update time and measurement time both equal to 30 s (i.e., every 30 seconds a new trace acquisition begins and lasts 30 seconds) and then averaged the three temperature values thus obtained for every sampling point.

<u>First orange tree (Bulgherano site)</u>
The first plant consists of the trunk and the root system of a dead orange tree located in an orange orchard in Bulgherano (Lentini, SR). In 2013, the characterization of the same, but alive, orange tree was carried out by Cassiani et. al (2014). During this last year, in order to gain new and complementary information about this site after the death of the tree, we carried out a new irrigation test monitored through time-lapse 3D micro-ERT. This methodology calls for a three-dimensional electrodes arrangement, which implies the usage of both superficial and buried electrodes. In particular, we employed 24 superficial electrodes, each one located at a node of a grid of about 1.3 m side, with the orange tree trunk as its center . Thus, each one of these electrodes is 0.22 m far from the surrounding ones. Then, we added 48 metal electrodes placed in four micro-boreholes (i.e., 12 electrodes in each one) located at the external vertex of the superficial grid. Here, the buried electrodes are spaced 0.1 m, thus letting the deepest ones reach a depth of 1.2 m below the surface. In order to perform our irrigation test, we divided the superficial grid into four quarters and irrigated each one of them in sequence with 15 l of water. After each irrigation we carried out a 3D micro-ERT survey on the whole root zone: Thus, we obtained a time-lapse monitoring of the whole seepage process made up of five time steps (i.e., one background survey before the irrigation test and four surveys during the irrigation). Also for this case study we performed our 3D micro-ERT surveys with an IRIS Syscal Pro resistivimeter using all 72 electrodes, a "skip 0" dipole-dipole scheme (i.e., the irrigation test lasted about 3.5 hours). The dataset of each time step acquisition is made up of 4885 values of both direct and reciprocal measurements.

<u>Second orange tree (Palazzelli site)</u>
The second orange tree is a relatively younger plant (10 year-old) located in an experimental farm of the CRA-ACM (Centro di Ricerca in Agrumicoltura e Colture Mediterranee) in Palazzelli (Lentini, SR). Given the constant water scarcity affecting Sicily and the need of improving water use efficiency, in this orchard different deficit irrigation techniques are currently employed, i.e., PRD (partial root zone drying) and RDI (regulated deficit irrigation). Therefore, we performed our time-lapse monitoring on the base of the irrigation schedule established by the experimental farm. In particular, the first survey took place before the beginning of the irrigation, while the second and the third surveys were carried out 15 minutes and 65 minutes after the end of the irrigation, respectively. For this case study we employed the same technique and the same set-up described for the irrigation test in Bulgherano, so also here we obtained a time-lapse 3D micro-ERT monitoring with 3 time steps (i.e., one background survey before the scheduled irrigation and two after its end). Moreover, we used the IRIS Syscal Pro resistivity meter, 72 electrodes, a "skip 0" dipole-dipole scheme and each survey lasted 25 minutes. The dataset of each time step acquisition is made up of 4885 values of both direct and reciprocal measurements.

Data processing, preliminary results and discussions

Vermigliana creek

The ERT data at our disposal call for two different types of inversion. The first one leads to the representation of the absolute resistivity cross-section, which allows the description of the state of the domain of interest at the survey time. After removing all the measurements pairs (direct and reciprocal) with an error higher than the fixed threshold, we performed the ERT data inversion thanks to the R2 code (Lancaster University, UK). An example of the result of such a processing is the resistivity cross-section depicted in Fig.1.1 (the resistivity distribution here illustrated is largely comparable to those of the other ERT surveys). In this ρ cross-section, a very low resistivity domain (50 Ωm) characterizes the area beneath the Vermigliana creek till a depth of 4 m below ground level. At first glance, the presence of this domain may be justified by the seepage process, which modifies the resistivity as described, e.g., by Archie's law. An average resistivity of 50 Ωm is however incompatible with the values characterizing both deposits and waters of the Vermigliana creek (ρ orders of magnitude are equal to 1000 Ωm and 100 Ωm, respectively). In order to explain this incongruity, we hypothesize the presence of a high clay fraction coming from the glacial moraines and transported by the creek itself. Then, if we focus on the riparian zones, it is possible to highlight a difference between the left and the right bank (Fig. 1.1), since the former has an average electrical conductivity slightly lower than the latter.

The second inversion technique aims at highlighting how resistivity varies over time. As described by, e.g., Boaga et. al (2013), this approach allows to express these variations in percentage term, with respect to the background survey (100% indicates no changes, higher values imply an increase in resistivity, and lower values are related to a decrease). In the sub-riverbed, between May and July 2014 an increase in resistivity variation takes place (up to 150%), followed by a rapid decrease to 100%. Such behaviour may be due to a glacial water pulse, usually characterized by a high resistivity. On the other hand, the left bank is characterized by a constant decrease in resistivity variation, from values higher than 120% to values around 60% (on average). This is probably related to the presence of an effluent of two small lakes upstream, whose waters are presumably more conductive. Finally, the right bank shows a slight increase in resistivity variation over time (values are always, on average, higher than 100%) that may be caused by a constant flux of new glacial water poor in ions.

Together with the ERT technique, we also applied the DTS methodology, with the resulting temperature profiles represented in Fig. 1.2. According to the partitioning in this picture, Part 1 is characterized by the highest temperature values, since here the fiber-optic cable is rather shallow; in Part 2 the trend of each T profile is fairly linear and the temperature values are relatively high, since here there may be an influence from the effluent of the lakes upstream; Part 3 represents the segments corresponding to the sub-riverbed: Here the trend is more variable and sharpens over time, given the complexity of the processes taking place; Part 4 shows the traces relative to the right bank, which are clearly characterized by the lowest temperature values (probably because of a flux of glacial water); finally, Part 5 represents the part of the fiber-optic cable in excess, rolled and located at a depth of 0.5 m below ground level. From the first to the last survey, the average T increases of 2.09 °C. This variation is not constant along the whole fiber, so we can hypothesize that the left and right riverbanks behave in two different ways, or, more likely, that are subject to different phenomena (i.e., flux of lacustrine and glacial water, respectively). Nevertheless, a quantitative analysis is still necessary.

Orange trees (Bulgherano and Palazzelli sites)

The preliminary analysis of the time-lapse 3D micro-ERT data is based on the same approach described for the Vermigliana case study, since it is independent from the site geometry. An example of resistivity ratio with respect to the background survey in represented in Fig. 1.3. In detail, this picture shows the isosurface representing the main injection plume after the irrigation of the first quarter of the superficial grid in the Bulgherano site (this isosurface is identified in terms of resistivity ratio percentages). The same data processing is applied to the Palazzelli orange tree and, for both case studies, a quantitative interpretation of the data is currently underway.

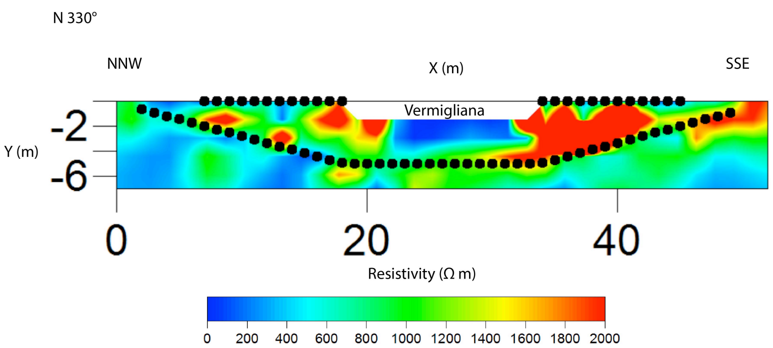

Fig. 1.1 Example of resistivity cross-section resulting from the ERT survey conducted in Vermiglio on 20th June 2014. The cross-section is facing downstream. A low resistivity domain is located under the Vermigliana creek, while the riparian zones show, on average, higher resistivity values. The black dots represent the electrodes position both on the levee surface (24 stainless steel electrodes) and inside the perforation drilled under the Vermigliana creek (48 brass electrodes)

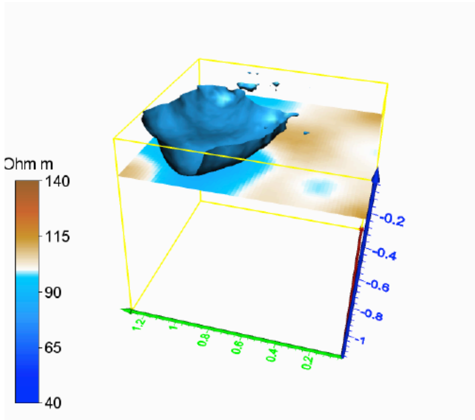

Fig. 1.3 Isosurface representing the injection plume in the irrigation test in Bulgherano, at the first time step of the time-lapse 3D micro-ERT monitoring. The values are expressed as resistivity ratio percentages with respect to the background survey.

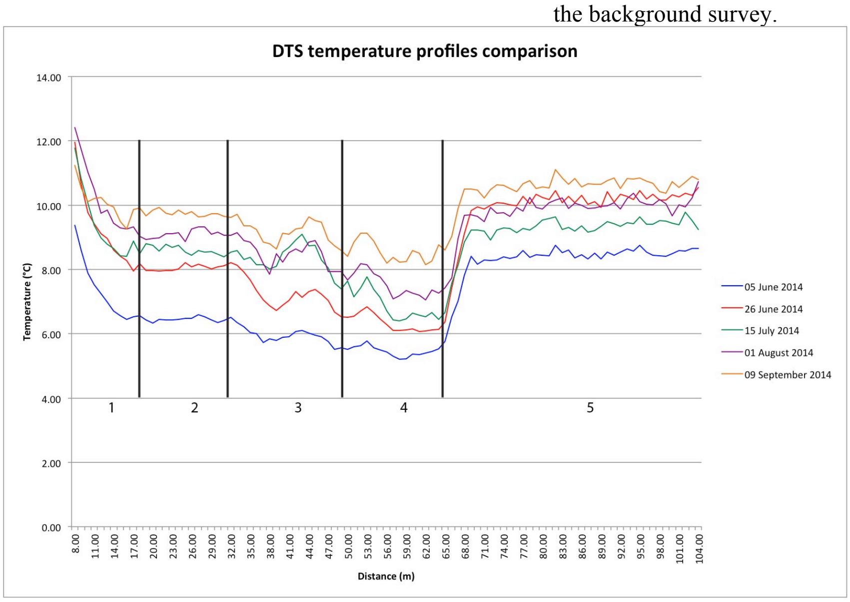

Fig. 1.2 Comparison between DTS temperature profiles acquired in the Vermigliana site. In each profile five segments can be identified: 1, initial part; 2, left bank of the Vermigliana creek (comparable with the left bank of the ERT cross section); 3, Vermigliana creek; 4, right bank of the Vermigliana creek (comparable with the right bank of the ERT cross section); 5, fiber-optic cable rolled at 0.5 m below ground level. All the temperature profiles show the same trend, with higher temperatures in the left bank and lower values in the right one, while the hyporheic zone is characterized by a variable trend that sharpens over time.

Conclusions and future work

One of the main problems in the ECZ characterization is the obvious need of investigating a complex domain constantly interconnected with human activity, where several phenomena are occurring simultaneously and at different scales. Applied geophysics provides several non-invasive techniques (e.g., ERT, 3D micro-ERT, and DTS), whose application can lead to a good imaging of both structures and processes in this domain. The preliminary results here described already show their high potential, which, however, will be fully expressed only through a more detailed time-lapse monitoring and an appropriate hydrological modelling. To achieve this second future goal, we will use the CATHY (CATchment HYdrology) model combined with data assimilation methods, thanks to whom it is possible to assimilate both ERT and DTS data inside the numerical model itself.

References

ANDERSON, M.P. 2005. Heat as a ground water tracer. *Groundwater*, **43**(6), pp. 951-968.

BOAGA, J., ROSSI, M. and CASSIANI, G. 2013. Monitoring soil-plant interactions in an apple orchard using 3D electrical resistivity tomography. Procedia Environmental Sciences, **19**, pp. 394-402

BOANO, F., HARVEY, J.W., MARION, A., PACKMAN, A.I., REVELLI, R., RIDOLFI, L. and WÖRMAN, A. 2014. Hyporheic flow and transport processes: Mechanism, models, and biogeochemical implications. *Reviews of Geophysics*, **52**.

CASSIANI, G., BOAGA, J., VANELLA, D., PERRI, M.T. and CONSOLI, S. 2014. Monitoring and modelling of soil-plant interactions: the joint use of ERT, sap flow and Eddy Covariance data to characterize the volume of an orange tree root zone. Submitted to *HESS*.

CROOK, N., BINLEY, A., KNIGHT, R., ROBINSON, D.A., ZARNETSKE, J. and HAGGERTY, R. 2008. Electrical resistivity imaging of the architecture of substream sediments. *Water Resources Research*, **44**(4).

GARDINER, D.J. and GRAVES, P.r. 1989. Pratical Raman Spectroscopy, Springer-Verlag

NATIONAL RESEARCH COUNCIL 2001. Basic Research Opportunities in Earth Science. Washington, DC, The National Academies Press.

NYQUIST, J.E., FREYER, P.A. and TORAN, L. 2008. Stream bottom resistivity tomography to map ground water discharge. *Groundwater*, **46**(4), pp. 561-569.

WESTOFF, M.C., GOOSEFF, M.N., BOGAARD, T.A. and SAVENIJE, H.H.G. 2011. Quantifying hyporheic exchange at high spatial resolution using natural temperature variations along a first-order stream. *Water Resources Research*, **47**(10).

SUMMARY OF ACTIVITY IN THIS YEAR

***Courses*:**

ROSS J. ANGEL: “Scientific Communication”, Dipartimento di Geoscienze, Università degli Studi di Padova
MONICA BORG: “Consolidating skills in English: A Multimedial Approach”, Dipartimento di Geoscienze, Università degli Studi di Padova
LYDIA GULICK: “Corso avanzato di Inglese Scientifico”, Dipartimento di Geoscienze, Università degli Studi di Padova
LANG WU and LUIGI SALMASO: “Statistics for Engineers 2014”, Dipartimento di Ingegneria Industriale, Università degli Studi di Padova
LUCA BERGAMASCHI, MASSIMILIANO FERRONATO, and MARIO PUTTI: “Numerical Methods”, Dipartimento di Ingegneria Civile, Edile ed Ambientale, Università degli Studi di Padova

---

***Communications*:**

BOAGA, J., **BUSATO, L.**, PERRI, M.T., STRAPAZZON, G., BELLIN, A. and CASSIANI, G. 2014. Time lapse Electrical Resistivity Tomography and Distributed Temperature Measurements in the hyporheic zone of an alpine river. *GSA Annual Meeting*, Vancouver, 19-22 October 2014.

BUSATO, L., BOAGA, J., PERRI, M.T. and CASSIANI, G. 2014. Time-lapse monitoring of the hyporheic zone of an alpine river using non-invasive methodologies. *GNGTS, 33° Convegno*, Bologna, 25-27 November 2014.

BUSATO, L., BOAGA, J., PERRI, M.T. and CASSIANI, G. 2014. Metodologie non invasive per la caratterizzazione della zona iporeica di un corso d'acqua alpino. *XI Workshop in Geofisica e II Giornata di formazione*, Rovereto (TN), 4-5 December 2014.

BOAGA, J., **BUSATO, L.**, PERRI, M.T., STRAPAZZON, G., PASETTO, D., PUTTI, M., CANO PAOLI, K., MAJONE, B., BELLIN, A. and CASSIANI, G. 2014. Time lapse Electrical Resistivity Tomography and Distributed Temperature measurements and modeling in the hyporheic zone of an alpine river. *AGU Fall Meeting*, San Francisco, December 2014.

***Other*:**

Field activities:

- Vermiglio (TN): Electrical resistivity tomography and distributed temperature sensing measurements in order to characterize the hyporheic and the riparian zones of the Vermigliana creek;
- Bulgherano (SR): 3D electrical resistivity tomography measurements for the monitoring of soil-plant interactions of an orange tree;
- Palazzelli (SR): 3D electrical resistivity tomography measurements for the monitoring of soil-plant interactions of an orange tree;
- Saletto (PD): Electrical resistivity tomography and multichannel analysis of surface waves for the characterization of the right embankment of the Frassine river after its rupture and reconstruction in 2010.