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# 2D STOCHASTIC INVERSE MODELING AND 3D INVERSION OF MAGNETOTELLURIC DATA FROM THE LARDERELLO-TRAVALE GEOTHERMAL FIELD

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## Introduction

The Magnetotelluric (MT) method is one of the most effective geophysical techniques for investigating deep geothermal systems because it can image the electrical-resistivity distribution of the Earth from a few meters to hundreds of kilometers of depth (Chave and Jones, 2012). The MT inverse problem is ill-posed in nature with nonlinear and equivalent solutions. The standard approach to solve the inverse problem is the iterated and linearized inversion. It is also possible to perform stochastic inverse modeling by adopting Monte-Carlo or metaheuristic methods. Global search methods have become of major interest in geophysics because they are theoretically able to find the global minimum of a function as the final solution without being trapped in one of the several local minima. The potential advantages of metaheuristics are also to ensure a complete sampling of the search space of solutions and the independence from the starting model. Stochastic inverse modeling of MT data from geothermal areas has considerable potential, mainly in those cases where the geological complexity and the difficulty in retrieving reliable external constraints can negatively affect the solution of the inverse problem. One of the most extraordinary geothermal resources globally is located in the Larderello-Travale geothermal area (LTGA), Italy. The site has been the object of extensive industrial and scientific research over the past century. Nonetheless, some geological, physical and chemical aspects are still a matter of investigation.

This work presents recent advances in the interpretation of MT data from the LTGA. The data sets acquired during the last decades were re-examined following the most recent techniques of MT data analysis of the impedance and tipper tensors. The geoelectrical dimensionality, directionality and phase tensor properties were determined. Then, two MT profiles from LTGA were interpreted by using 2D stochastic inverse modeling, namely, the Particle Swarm Optimization (PSO) algorithm. Finally, we focused on the Travale geothermal field to apply the state of the art of MT inversion techniques, that is, 3D derivative-based inversion. It is nowadays of pivotal importance to characterize the geoelectrical structures from geothermal areas for the simple and obvious reason that we need 3D inversion methods to model a 3D Earth.

## Stochastic inverse modeling of MT data by employing Computational Swarm intelligence

Computational Swarm Intelligence is a sub-branch of Artificial Intelligence and encompasses several nature-inspired population-based metaheuristic methods. One of these algorithms is PSO, which has been widely applied to geophysical data (for a review, see Pace et al., 2021). The application of PSO to solve the 2D MT inverse problem has been investigated in Pace et al. (2019a), where the algorithm was accurately calibrated to enhance the stability and convergence of the solution and was parallelized to speed up the computation. The method was validated on synthetic data and then applied to field data. PSO provided a resistivity model of the Earth in line with results from previous interpretations and demonstrated that there is no need for a priori initialization to obtain robust 2D models. The stochastic nature of PSO and the combination of exploration and exploitation behaviors played a crucial role in finding the global minimum of the search space as the final solution.

## The MT data set from the Larderello-Travale geothermal area

Since the 90s, several MT surveys have been carried out in the Travale geothermal field to aim for industrial exploration or scientific research (Manzella et al., 2006; Santilano, 2017). The collection of the "vintage" MT data is composed of three data sets. Fig. 1 shows the data sets acquired in 1992 (black-labeled squares covering both the Larderello and Travale areas), in 2004 (55 sites in blue-labeled circles) and in 2006-07 (19 sites in red-labeled triangles). These data were studied following the latest techniques of MT data analysis to determine the geoelectrical dimensionality, directionality and phase tensor properties by means of the WALDIM software and *MTpy* python toolbox (Martí et al., 2009; Kirkby et al., 2019). This thorough analysis of the observed MT tensors provided an overview of the underlying resistivity distribution. It revealed a 3D behavior of the deep structures and a primary direction of N130°E for the geoelectrical strike (Pace, 2020). 3D inversion was proved to be the best approach to interpret this MT data set, while the 2D strike direction can be considered a "first-order approximation". So far, the MT data acquired in Travale have been interpreted using both 1D PSO and 2D inversion (Santilano, 2017; Manzella et al., 2006). Therefore, both 2D PSO and 3D inversion represent new valid tools to provide novel resistivity models and further knowledge of the LTGA.

## PSO of MT data from the Larderello-Travale geothermal field

The PSO algorithm was applied to two MT profiles located in the LTGA (Pace et al., 2019b, c). Even though the dimensionality analysis suggests 3D interpretation as the most appropriate for this data set, there are some conditions for the validity of 2D interpretation: inadequate spatial coverage (isolated MT profile), a clear strike direction (as suggested from directionality of the tensors) and the high computational and numerical complexity of 3D modeling (Ledo, 2005). The final models succeeded in imaging very complex resistivity structures and confirmed those presented in the past (Manzella et al., 2006; Santilano, 2017). PSO models offered the following advantages (Pace et al., 2019b, c): (i) the final models have not been initially biased by an external starting model derived from geology and (ii) the RMSEs associated with the final PSO models were lower than those associated to the models published in the past by using different inversion techniques.

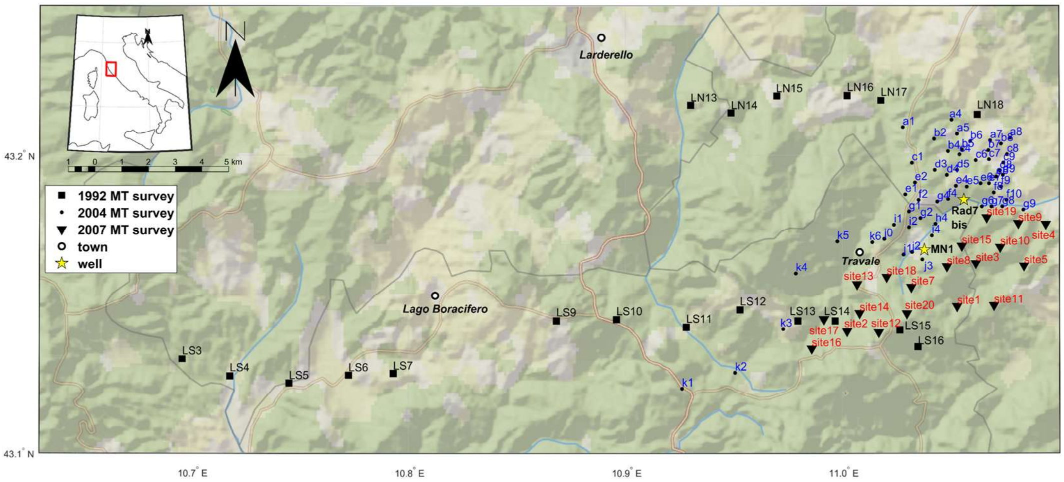

Fig. 1 - The collection of MT data sets in the Larderello-Travale area. The data set acquired in 1992 is marked with black-labeled squares. The data set acquired in 2004 (55 sites) is marked with blue-labeled circles. The data set acquired in 2006-07 (19 sites) is marked with red-labeled triangles.

## 3D inversion of MT data from the Travale geothermal field

Derivative-based 3D MT inversion is currently a field of very intensive research because it exploits all the information stored in the full MT impedance tensor and the vertical magnetic transfer function (i.e., tipper). 3D inversion of MT data from the Travale geothermal field represents a novelty (Pace et al., *under revision*). 51 of the MT sites shown in Fig.1 were chosen for 3D inversion, which was computed using the ModEM software (Kelbert et al., 2014). Several 3D MT inversion tests were performed by changing the components of the tensor to be inverted, the rotation of the mesh, the error floor of the data and the starting model, in order to assess the resistivity distribution of this complex and largely-investigated geothermal system. The outcome of the 2D PSO of the Travale MT profile was used to build the a priori starting model for some of the 3D inversion tests.

The final 3D resistivity models of the different tests generally imaged similar structures. Fig. 2 shows a vertical section drawn from the 3D model of the test with the best data fitting and

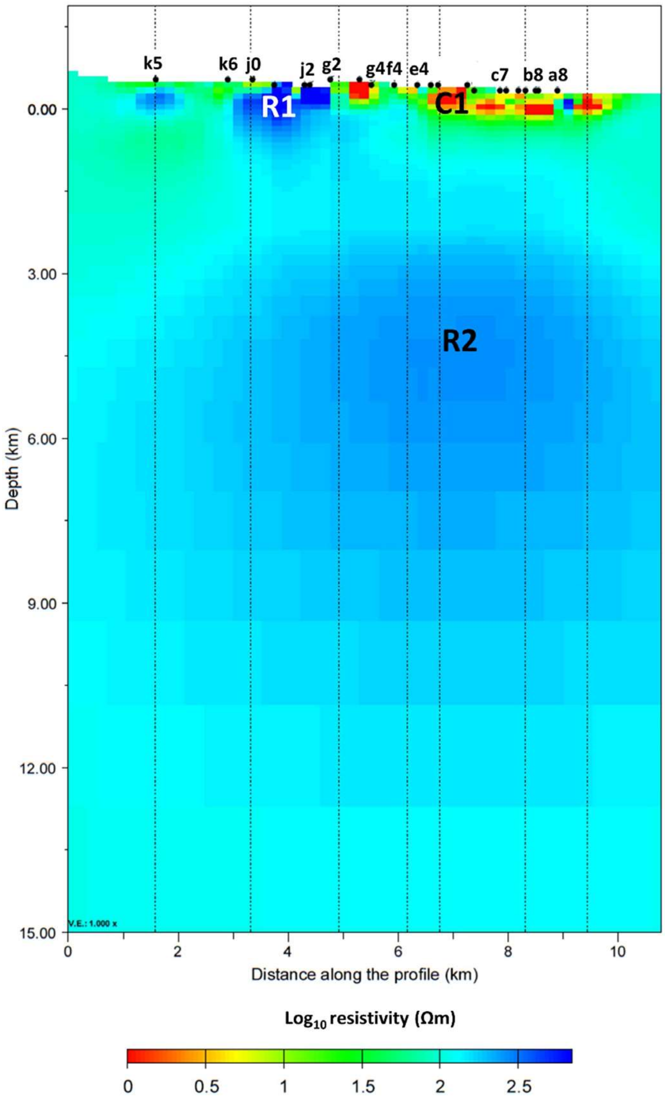

Fig. 2 – Vertical cross-section of the 3D resistivity model. The SW-NE profile is orthogonal to the geoelectrical strike direction and crosses sites from k5 to a8.

coherence with the known geology of the area (Pace, 2020). A deep resistive body (*R2* in Fig. 2) was imaged in agreement with previous 2D models, but new insight emerged about its spatial extension and orientation. At a depth of 3-7 km, the resistivity was higher than 200 Ωm, and the orientation was around N40-50°E. This orientation is quite similar to that observed for the deep 3D structures imaged below the "Lago Boracifero" area in the adjacent Larderello geothermal field (Santilano, 2017). Given the same spatial orientation, the deep structures differ in that the one in the Larderello field is less resistive (< 100 Ωm), while the one imaged in the Travale geothermal field is more resistive than the background (> 200 Ωm). The resistive nature of the deep body was actually not unexpected because it is hosted in a vapor-dominated system in correspondence to the granite units. The final 3D resistivity model was also compared with other subsurface data and models. The outcome of this study provides new insight into the interpretation of the complex geothermal system of Travale.

## Conclusion

This work presented the recent advances in the interpretation of the MT data from the Travale geothermal field. Two different methods were applied for the first time to the Travale data set: 2D stochastic inverse modeling and 3D derivative-based inversion. The former overcame any prior bias on the final resistivity model; the latter revealed the complete spatial extension of the imaged subsurface structures, thus extending previous knowledge. 3D MT inversion was challenging due to computational reasons: it usually requires 100 unknowns more than 2D inversion and the forward modelling calculation is much heavier. Future work should broaden the MT characterization of the LTGA by means of new acquisition campaigns that would enlarge the investigated zone, ideally with a regular space-covering of the sites. The existing data set need to be enriched for all the sites with the acquisition of the geomagnetic transfer function, which is fundamental for 3D inversion. The integration of multiple geophysical data sets would also be beneficial for a comprehensive study and better exploration of the geothermal system.

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