Deep and Shallow Electrical Resistivity Tomographies on the Budoia-Aviano Thrust (NE Italy)

Enzo Rizzo[1,2,3,*], Maria Eliana Poli[3,4], Giulia Patricelli[1,3,4], Valeria Giampaolo[2], Gregory De Martino[2], Fabrizio Mucchi[1], Alessandro Marchesini[4], Paola Boldrin[1], Davide Russo[1,3], Fabio Luca Bonali[5], and Riccardo Caputo[1,3]

[1]Università di Ferrara, Dipartimento di Fisica e Scienze della Terra, Ferrara, Italy
[2]Consiglio Nazionale delle Ricerche, Istituto di Metodologie per l'Analisi Ambientale, Tito, Italy
[3]Centro Interuniversitario per la Sismotettonica 3D con Applicazioni Territoriali (CRUST), Chieti, Italy
[4]Università di Udine, Dipartimento di Scienze AgroAlimentari, Ambientali e Animali, Udine, Italy
[5]Università di Milano Bicocca, Dipartimento di Scienze dell'Ambiente e della Terra, Milan, Italy

**Corresponding author: enzo.rizzo@unife.it*

Introduction

The research group was involved in the NASA4SHA PRIN2020 Project (*Fault segmentation and seismotectonics of active thrust systems: the Northern Apennines and Southern Alps laboratories for new Seismic Hazard Assessments in northern Italy*), which aims to explore the complexity of faults in active thrust systems in the Northern Apennines and Southern Alps of Italy. The study area, located within the external Pliocene-Quaternary front of the Eastern Southalpine Chain (Friuli, NE Italy), is characterized by distinct WSW-ENE trending and S-verging reverse fault planes, arranged in thrust systems that affect the Quaternary succession. The Deep and Shallow Electrical Resistivity Tomography were integrated to define a multiscale geophysical approach on the Budoia-Aviano thrust system, which is part of the Polcenigo–Montereale fault system. Adopting a multilayer approach, the integration of geological and morphotectonic field surveys with geophysical investigations and paleoseismological analyses enabled the detection of the Budoia-Aviano backthrust, revealing the first evidence of its activation during the Late Pleistocene to Holocene.

Geological setting

The study area is located in the pre-Alpine Carnic belt, where the first hilly terrains overlook the Friulian plain. The geophysical investigations were carried out in the territory of the Budoia village, where Galadini et al. [2005] and Poli et al. [2015], based on previous morphotectonic surveys, identify the presence of the Budoia-Aviano blind thrust (BA), which belongs to the Polcenigo-Montereale (PM) reverse fault system (Figure 1). The identified Polcenigo-Montereale reverse fault system is considered the source of the 1873 earthquake (Mw 6.3) in the Belluno area [Galadini et al., 2005; Burrato et al., 2008] and extends across the pre-Alpine Carnic belt from Polcenigo to Montereale Valcellina. It consists of a main fault (Polcenigo-Montereale) and several smaller S-verging splays, including the Budoia-Aviano fault, which are buried in the Late Pleistocene foreland plain. The Polcenigo-Montereale thrust (PM) overlaps the Calcare del Cellina Cretaceous carbonates on the upper Miocene-Pliocene Molasse and the Budoia-Aviano (BA) thrust causes the outcrop of upper Miocene-Pliocene Molasse and pre-Last Glacial Maximum (LGM) units on the Pliocene-Quaternary deposits of the alluvial piedmont plain [Patricelli et al., 2024].
The study area is located within a large Late Pleistocene alluvial fan built by the Artugna River.

The alluvial fan exhibits significant morphological anomalies linked to the presence of active faults belonging to the Polcenigo-Montereale system [Galadini et al., 2005; Burrato et al., 2008; Poli et al., 2015]. Specifically, the Budoia-Aviano thrust is believed to be responsible for the deformation of the Late Pleistocene alluvial fan of the Artugna stream and the drainage anomalies observed within the fan itself.

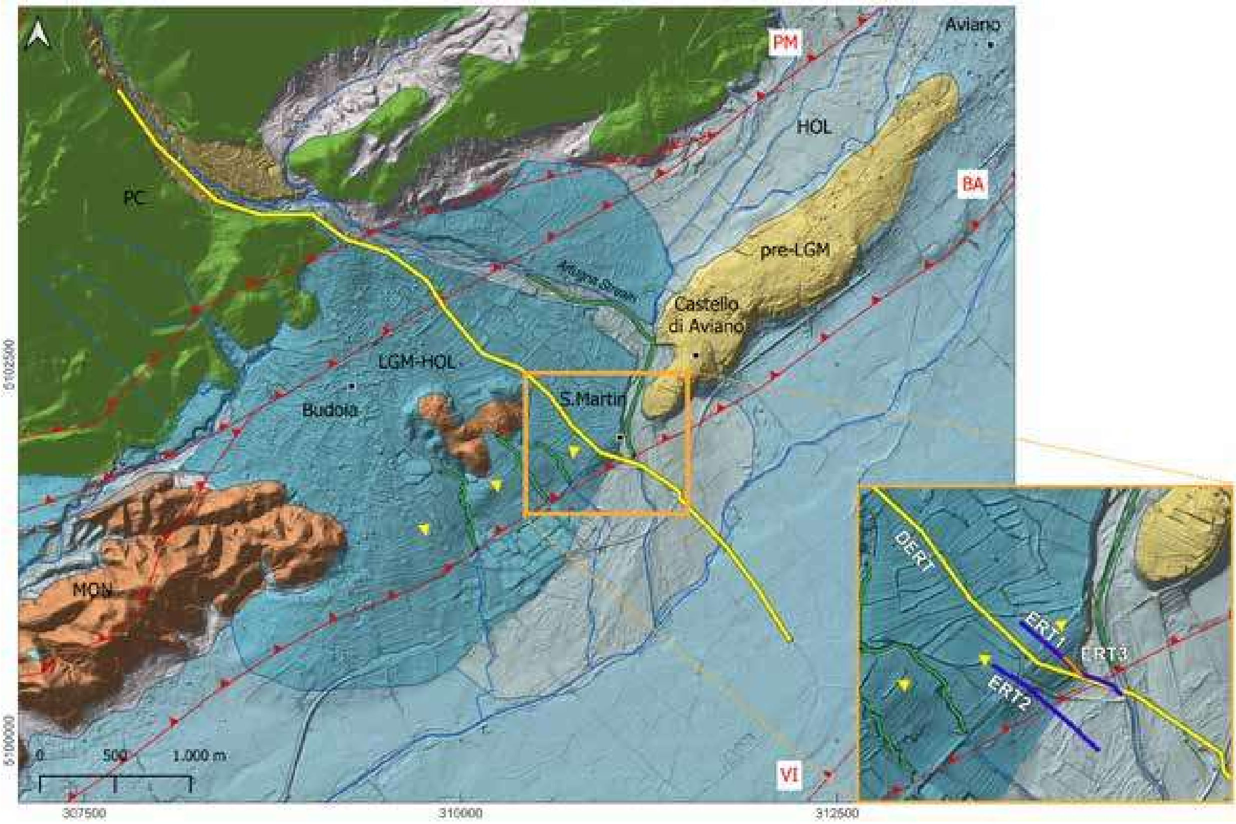

Figure 1 Geological map of the investigated area. PC: Jurassic-Cretaceous Carbonate Platform; LGM-HOL: Upper Pleistocene-Holocene *p.p.* alluvial fan of the Artugna river; pre-LGM: Pliocene-Upper Pleistocene conglomerates; MON: upper Miocene-Pliocene Molasse; PM: Polcenigo-Montereale thrust; BA: Budoia-Aviano thrust; VI: Vigonovo thrust. The long yellow line represents the DERT profile, while the shortest blue lines the ERT1 and ERT2 and the orange one is the ERT3 (modified from Poli et al. [2015]).

Geophysical methods

The ERT method is a cost-effective, user-friendly, and reliable geophysical tool widely used across various geological fields. It is arguably the most popular geophysical technique for near-surface exploration, but there is great attention to improving the efficiency and the capability of the ERT method in deep geological investigations. Therefore, a Deep ERT method was introduced increasing the spacing between the electrodes used for injecting currents into the ground (A and B) and for receiving the voltage signals (M and N). In order, to use large distance between the two couples of electrodes in the DERT method the emitting and receiving systems are generally decoupled and the dipole-dipole array configuration is generally adopted. The current injecting system is physically separated from the receiving one and the distance between the two dipoles (r) is gradually increased along a selected profile on the surface to obtain the 2D resistivity patterns of deep geological sections [Balasco et al., 2023].

The DERT instrumentation is a multichannel system designed and implemented by CNR-IMAA [Rizzo et al., 2004]. It is characterized by a high power transmitter (10 kVA up to 1000V, 20 Amp) to inject the current and several receivers (Campbell datalogger at 1Hz) for the drop of potential acquisitions. Each data logger station consists of four electrodes placed to have av MN distance approximately between 300 and 900 m. This configuration allowed to extend the DERT investigation over approximately 6000 m and it provided a subsurface investigation depth of around 1000 m. The dataloggers were also connected to a GPS receiver so that the clock were used for data processing.

After acquisition, the acquired data were processed using few principal steps [Rizzo and Giampaolo, 2019]: i) alignment of the injected current and drop of potential acquisition data, ii) data filtering, iii) FFT analysis, and iv) apparent resistivity calculation. Finally, the electrical resistivity 2D model along the defined profile of the investigated area is thus obtained by applying an inversion algorithm approach of the elaborated apparent electrical resistivity data. This DERT approach was carried out across the Polcenigo-Montereale thrust system (Figure 1) to define the origin of the morphological features observed in the investigated area and to reconstruct the tectonic architecture at depth.

While the DERT survey primarily targeted the relatively deep subsurface geological features, a series of high-resolution shallow geophysical surveys were also conducted near the major morphotectonic scarps along the Budoia-Aviano thrust fault. Two shallow Electrical Resistivity Tomographies (ERT) with an electrode spacing of approximately 5 m and one very shallow ERT with an electrode spacing of approximately 1 m were carried out to constrain the best location(s) for digging the palaeoseismological trench.

Results

Figure 2 shows the 2D tomography model obtained from processing the data acquired along the DERT profile. The 2D electrical resistivity image was processing using ERTlab software [Morelli and LaBrecque, 1996], which employs a regularized least-squares inversion algorithm with smoothness constraints minimizing the objective function that combines data misfit and model roughness, applying regularization to stabilize the solution in the presence of noise.

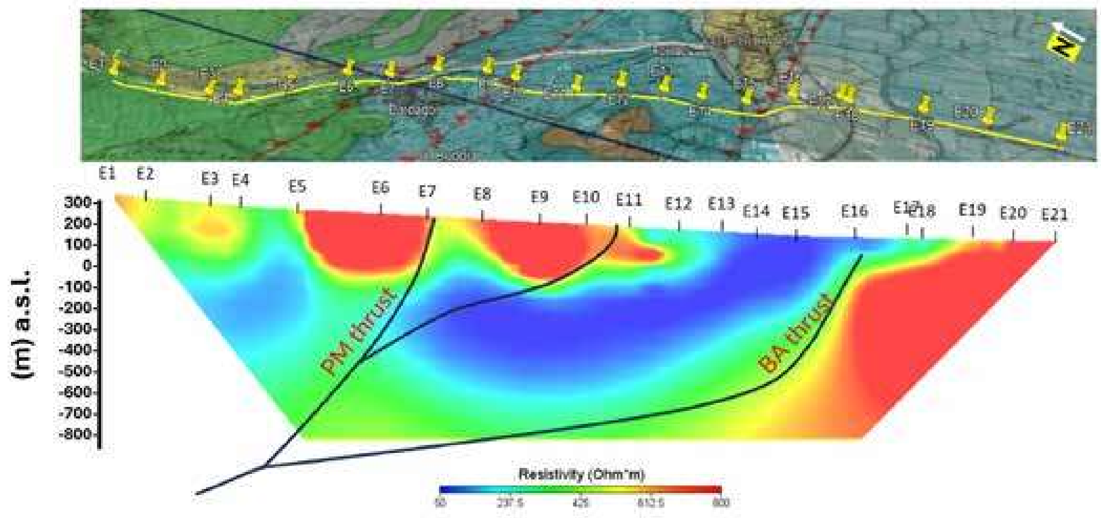

Figure 2 DERT model with the interpretation of the two main thrust systems: Polcenigo-Montereale (PM) and the Budoia-Aviano (BA) thrusts.

The model highlights a resistivity range from 50 to 1000 Ω·m, and it can be divided in three electro-layers: EL1: electrical resistivity values <100 Ω·m; EL2: electrical resistivity values between 100 and 500 Ω·m; EL3: electrical resistivity values >500 Ω·m.

The DERT image can be interpreted taking into account the geological setting of the investigated area. The two main thrust systems, Policenigo-Montereale (PM) and the Budoia-Aviano (BA), are well identified in the depth with the lateral contrast of the electro-layers. The first fault branch of the PM thrust is located between the electrodes E7 and E8, where a relative good lateral resistivity contrast is well identified. The second branch of the PM thrust is well identified between the electrode E10 and E11, where the lateral resistivity contrast between the two electro-layers EL3 and EL1 could be associated with the overlaps of the Jurassic-Cretaceous Carbonate Platform (PC) on the upper Miocene-Pliocene Molasse (MPM). Therefore, the MPM formation should be associated with the electrolayer EL1, where relative low resistivity values are highlighted in the DERT model and these values also extend deep underground. Continuing eastwards, there is a new well lateral contrast in electrical resistivity below the electrodes E16, which can be associated with the BA thrust. This resistivity contrast between the EL 1 and EL3 could be associated with the geological contact between the upper MPM units with the LGM gravelly and pre-LGM (Last Glacial Maximum) conglomeratic units. Moreover, this resistivity contrast is clearly visible deep down and does not appear to reach the surface, because the pre-LGM conglomeratic units are covered by LGM gravels of the Cellina river alluvial fan (Vivaro syntem, Late Pleistocene in age).

Shallow tomographies were performed at electrode 16 of DERT, to better analyze the most superficial portion of the BA thrust. The Figure 3 shows the shallow ERTs acquired at the San Martino locality, where two parallel palaeoseismological trenches were excavated after the geophysical acquisitions [Patricelli et al., 2024; Poli et al., 2024].

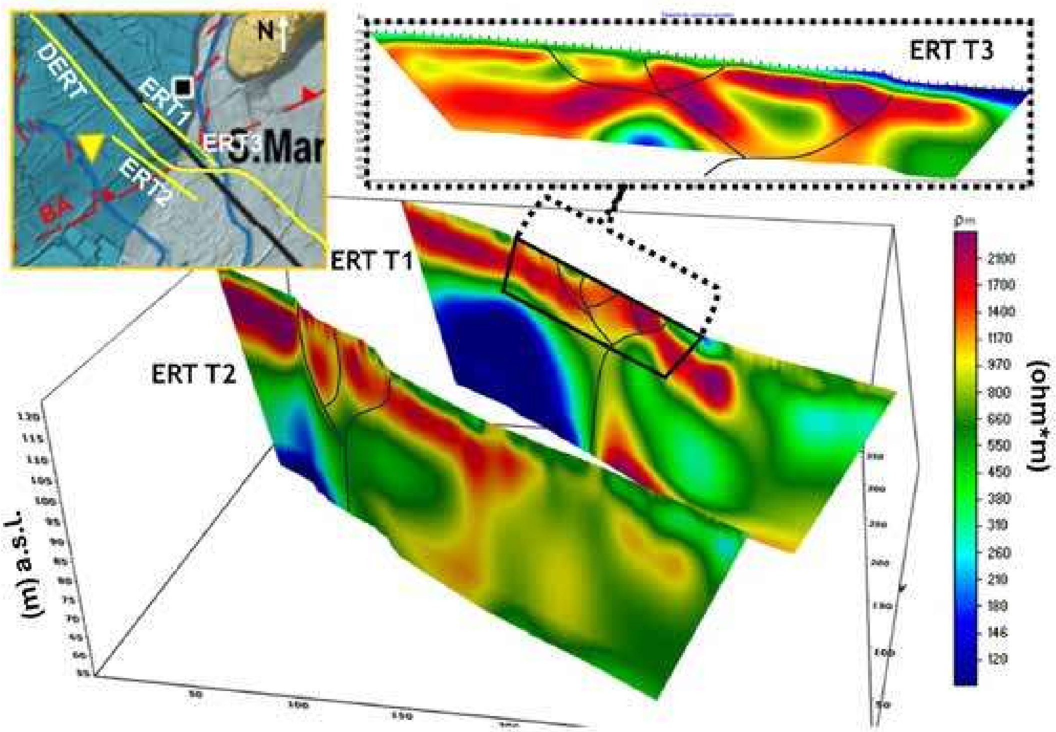

Figure 3 Shallow ERTs across the Budoia-Aviano (BA) thrust. ERT 1 and ERT3 were carried out where two parallel palaeoseismological trenches were excavated at the San Martino locality. The ERT2 was acquired across the same morphological scarp associated to the BA thrust. In black the interpreted faults.

The ERT1 and ERT2 highlight the resistivity models up to 50 m with a resistivity range between 100 to 2500 Ω·m. In general, three electro-layers could be clearly recognized: EL1 with resistivity values <250 Ω·m; EL2 with resistivity values between 250 and 800 Ω·m; EL3 with resistivity values > 800 Ω·m. The 5 m electrode spacing ERT highlighting the high-angle discontinuity separating at depth the low resistivity body (EL 1) to the North, interpreted as the fractured upper Miocene-Pliocene Molasse, from EL2 to the South associated to the Last Glacial Maximum (LGM) gravels of the Cellina River alluvial fan (Vivaro syntem, Late Pleistocene in age). The deep discontinuity propagates upwards affecting the high-resistivity electro-layer (EL3) interpreted as the late Pleistocene-Holocene Artugna alluvial fan.
The ERT3 depicts the resistivity model up to 10 m characterizing the EL3 resistivity layer described before. The high resolution resistivity ERT highlights the shallow alluvial fan of the Artugna River, where most of the resistivity values are > 800 Ω·m. Only two electro-layer EL1 (< 250 Ω·m) are well depicted, the deeper one could be associated with the upper Miocene-Pliocene Molasse and the shallow one with the humid soil of the alluvial fan. Moreover, the ERT3 resistivity model shows many discontinuities within the high resistivity electro-layer, highlighting a set of dipping surfaces displacing the geological layers of the late Pleistocene-Holocene alluvial deposits of the Artugna River.

Concluding remarks

This research activity highlighted a geophysical survey where several electrical resistivity tomographies were carried out for the purpose of a multiscale application to characterize the Budoia-Aviano thrust system. In order to carry out multiscale geophysical investigations, the ERT survey was first conducted using a Deep approach (Deep Electrical Resistivity Tomography-DERT) for obtaining a general overview of the study area and identify large-scale tectonic structures (up to 1000 m). Indeed, the DERT was able to identify the deep characteristics of the BA thrust system. Subsequently, detailed ERTs were carried out to better characterize the shallower subsurface deformation associated to the BA thrust system. Therefore, two ERTs with an electrode distance of 5 m allowed to characterize the shallow deformed areas up to 50 m-depth. An additional shallow ERT was carried out with an electrode spacing of 1 m which provided even higher resolution up to 10 m-depth. The latter was performed at the same site where ERT1 was carried out. This showed a clear discontinuity, particularly in the most resistive electro-layer, and this discontinuity is likely associated to reactivation(s) along the Budoia-Aviano thrust system. Finally, two parallel palaeoseismological trenches were excavated at the San Martino locality, exposing late LGM-to-Holocene alluvian fan deposits of the Artugna River. The trenches highlight several geological information depicting a back-verging reverse planes of the Budoia-Aviano thrust system, testifying the occurrence of intense deformation since the post-Last Glacial Maximum and represent the first evidence of latest Pleistocene-Holocene activation within the Carnic prealpine area between Polcenigo and Montereale [Patricelli et al., 2024].

References

Balasco, M., Lapenna, V., Rizzo, E., and Telesca, L., (2022). *Deep Electrical Resistivity Tomography for geophysical investigations: the state of the art and future directions*. Geosciences, 12, 438. https://doi.org/10.3390/geosciences12120438

Burrato, P., Poli, M.E., Vannoli, P., Zanferrari, A., Basili, R., and Galadini, F., (2008). *Sources of Mw 5+ earthquakes in northeastern Italy and western Slovenia: an updated view based on* *geological and seismological evidence*. Tectonophysics, 453(1-4), 157-176.

Galadini, F., Poli, M.E., and Zanferrari, A., (2005). *Seismogenic sources potentially responsible for earthquakes with M≥ 6 in the eastern Southern Alps (Thiene-Udine sector, NE Italy)*. Geophysical Journal International, 161(3), 739-762.

Morelli, G., and LaBrecque, D.J., (1996). *Advances in ERT modeling*. European Journal of Environmental and Engineering Geophysics, 1, 171–186.

Patricelli, G., Poli, M.E., Falcucci,E., Gori, S., Paiero, G., Rizzo, E., Marchesini, A., and Caputo, R., (2024). *First evidence of Holocene activity and surface diplacement of the Budoia-Aviano Thrust System in north-eastern Italy, unravelled through the integration of geological, geophysic and paleoseismological analyses*. EGU General Assembly 2024, Vienna, Austria, 14-19 Apr 2024, EGU24-16527 https://doi.org/10.5194/egusphere-egu24-16527, 2024.

Poli, M.E., Monegato, G., Zanferrari, A., Falcucci, E., Marchesini, A., Grimaz, S., Malisan, P. and Del Pin, E. (2015). *Seismotectonic characterization of the western Carnic pre-alpine area between Caneva and Meduno (Ne Italy, Friuli)*. DPC-INGV-S1 Project "Base-knowledge improvement for assessing the seismogenic potential of Italy" (D6/a2.1).

Poli M.E., Patricelli G., Falcucci E., Gori S., Rizzo E., Marchesini A. and Caputo R. (2024). *New palaeoseismological evidence of coseismic surface rupture across the Carnic Prealpine front (NE-Italy): the Budoia-Aviano Thrust System*. GNGTS 2024.

Rizzo, E., Colella, A., Lapenna, V., and Piscitelli, S., (2004). *High-resolution images of the fault controlled High Agri Valley basin (Southern Italy) with deep and shallow Electrical Resistivity Tomographies*. Physics and Chemistry of the Earth, 29, 321-327.

Rizzo, E., and Giampaolo, V., (2019). *New deep electrical resistivity tomography in the High Agri Valley basin (Basilicata, Southern Italy)*. Geomatics, Natural Hazards and Risk, 10:1, 197-218. https://doi.org/10.1080/19475705.2018.1520150