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MULTIVARIATE MODELLING OF GEOPHYSICAL TOMOGRAPHIC DATA TO IDENTIFY A TECTONIZED AREA

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Introduction. An integrated analysis approach, based on geological investigations and 2D high-resolution shallow geophysical data, was proposed along a slope in the Bellolampo landfill area (Palermo, Italy) where the presence of a fault zone was hypothesized.

Geophysical surveys included electrical resistivity tomography (ERT), induced polarization tomography (IPT) and seismic refraction tomography (SRT) techniques. The inversion of single geophysical parameter often does not allow to justify the complexity of the subsoil structures. The most appropriate solution should be to add additional physical or geological information so to get a constrained geological model. However, it is not at all easy to work with multivariate datasets due to the lack of well-defined relationships between different parameters.

A solution can be a joint inversion procedure with mathematical constraints that favoured final models providing similar spatial distribution of the discontinuities (Gallardo and Meju 2007; 2011).

In addition, the use of post-inversion techniques of independent univariate models can help to understand the relationships between different observable parameters (Bedrosian *et al.*, 2007; Dell'Aversana 2001; Di Giuseppe *et al.*, 2014). In particular, these techniques have shown excellent results when applied to seismic and electrical tomography data (Bohm *et al.*, 2017; Capizzi *et al.*, 2017; Gallardo and Meju 2003; 2004).

Geological model. The study area is located in the northern sector of the Palermo Mountains where the Mesozoic carbonate platform succession pertaining to the Panormide paleogeographic

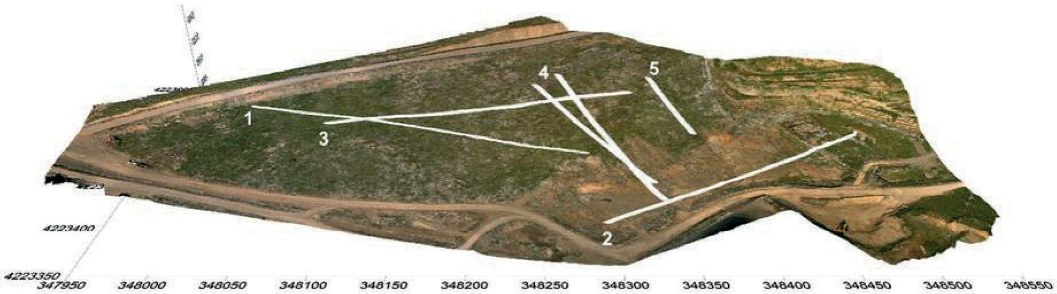

Fig. 1 - 3D representation of the Bellolampo landfill project area. White lines are the traces of the geophysical surveys.

domain extensively crops-out (Catalano *et al.*, 1996). The outcropping succession represent a portion of a tectonic unit belonging to the Sicilian Fold and Thrust Belt, which in this sector shows SW-ward tectonic transport. These tectonic units are affected by more recent transpressive high-angle faults with N-ward tectonic transport. Geological investigations, aimed at defining the morphological, geomorphological, stratigraphic and structural characteristics of the outcropping units, were carried out in correspondence of over 60 measurement stations, which provided hundreds of stratigraphic and sedimentological data and the kinematics of the tectonic elements. We carried out two trenches across the study area (perpendicular to the direction of the fault being studied and parallel to it) to analyse the fracturing pattern and the stratigraphic and lithological features along the excavation walls.

Based on the collected and processed data, the geological model of the site was defined. The integrated geological and geophysical analysis and the k-means cluster analysis allowed to reconstruct the lateral variations of the deformed carbonate breccias and better define the stress-field-orientations. The fracturing and kinematic analysis on fault planes observed along the trenches, highlighted systems of left and right-lateral transtensional faults NW-SE, NNW-SSE and NE-SW trending, respectively, which antedate the extensional tectonic event.

Geophysical survey. In order to obtain detailed information on the geological structure of the investigated area, integrated geophysical surveys (Fig. 1) have been performed using electrical resistivity tomography (ERT), induced polarization tomography (IPT) and seismic refraction tomography (SRT) techniques. In particular, five seismic tomographies were performed for a total of about 928 m in length. Coincident topographic traces were used for the electrical tomographies, in order to facilitate the joint interpretation of the different geophysical methods. The sequences of about 5000 resistivity and 1000 chargeability measurements have provided for the use of the multiple gradient (Dahlin and Zhou, 2006) in the modified multi-coverage version (Martorana *et al.* 2016; 2017). The surveys were supported by a detailed photogrammetric survey.

The tomographies generally show high values of P-wave velocities (1000-3000 m/s) and electrical resistivity values from medium to very high (10^3-10^4ohm.m) according to the carbonate lithologies outcropping in the area. In the shallow part, a layer of fractured limestone shows thicknesses varying from 2 to 5 meters, characterized by lower P-wave velocity and resistivity values.

The lateral variations of the seismic velocity and resistivity values are well correlated with the geological and tectonic discontinuities from the detailed geological-structural survey. Relatively lower seismic velocity and resistivity values have been correlated with tectonized Upper Jurassic carbonate breccias, whereas the presence of clayey intercalations is evidenced by chargeability values greater than 0 ms, which never exceed 20 ms, however compatible with the absence of leachate (Mondelli *et al.*, 2007).

The interpretation model related to the resistivity tomography (ERT3), chargeability tomography (IPT3) and refraction seismic tomography (SRT3) are shown in Fig 2.

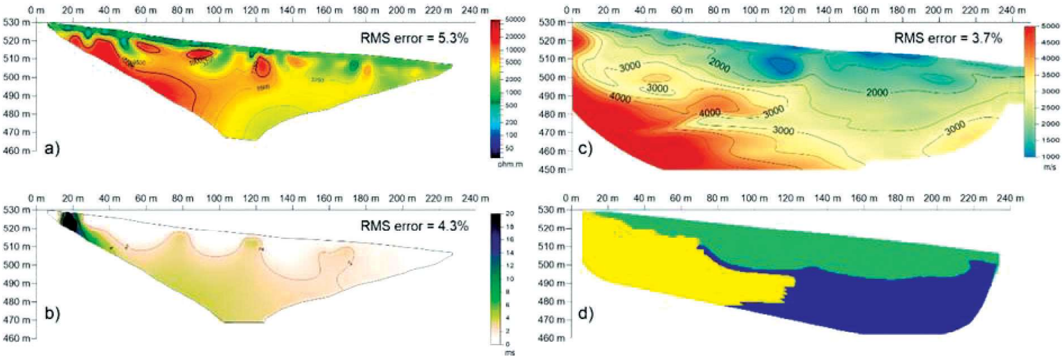

Fig. 2 - a) ERT3 electrical resistivity tomography; b) IPT3-induced polarization tomography; c) SRT3 Refraction seismic tomography; d) Results of the cluster analysis of SRT3 refraction seismic tomography and ERT3 resistivity tomography data.

Cluster analysis. Where seismic and electrical surveys were acquired with coincident profiles, cluster analysis techniques were used to facilitate the data interpretation.

Cluster analysis is a multivariate technique that makes it possible to group statistical units, characterized by different parameters (in this case, electrical resistivity, seismic velocity, seismic ray density and position in space *xz*), which show similar characteristics to each other and dissimilar from those of other groups or clusters. At the end of the procedure, the final clusters should exhibit a high internal consistency (intra-cluster) and high external heterogeneity (inter-cluster). So, if the partition is successful, the objects within the clusters are close to each other, while objects belonging to different clusters are more distant from each other (Barbarito 1999). Generally, in the analysis for grouping it is not necessary to have in mind any interpretative model (Fabbris 1983). Although various studies (Rand 1971; Ohsumi 1980) indicate that different grouping strategies often lead to dissimilar results, however, the criteria for choosing algorithm have not yet been sufficiently explored.

We choose a centroid-based algorithm that generally requires the number of clusters, k, and the initial centroid coordinates to be specified in advance. This aspect is considered to be one of the biggest drawbacks of these algorithms. An inappropriate choice of k may yield poor results. The proposed algorithm (Capizzi *et al.* 2017) does not fix the number of k clusters and choose automatically for each k value the initial centroids from data set.

The used algorithm starts the first iteration by choosing the coordinates of the first centroids autonomously, splitting the interval between the minimum and maximum values of the used parameters in a number of intervals equal to number of partitions. The distance of each element from the initial nuclei and from the nuclei obtained after each iteration was calculated as the weighted sum of the Euclidean distances of all the considered variables:

D=,

where a, b, c and d are the weights and dx, dy, dC, $d\varrho$ and dv are respectively the differences between the parametric *xz* coordinates, density of the seismic rays, electrical resistivity and P-wave velocity.

The results related to the cluster analysis, for k=3, of SRT3 refraction seismic tomography and ERT3 resistivity tomography data are shown in Figure 2(d). In particular, the green cluster represents a layer of fractured limestone formations, whereas the yellow and the blue ones represent the carbonate and the tectonized Upper Jurassic breccias, respectively.

Conclusions. The integrated analysis of 2D high-resolution shallow seismic refraction tomographies (SRT) and electrical resistivity tomographies (ERT& IPT) allowed to better define the lateral geometry of the NE-SW trending band composed of intensely tectonized carbonate breccias. Furthermore, the k-means cluster analysis allowed to reconstruct the lateral variations of these tectonized carbonate breccias, with respect to their electrical and seismic characteristics and better define the stress-field-orientations.

Finally, the fracturing and kinematic analysis on fault planes observed along trenches, highlighted systems of left and right-lateral transtensional faults, NW-SE, NNW-SSE and NE-SW trending respectively, which antedate the extensional tectonic event. The reconstructed stress-field-orientation related to the last tectonic system does not comply with the active stress field for this sector of the Sicilian chain. Moreover all the tectonic structures are sealed by Upper Pleistocene – Holocene continental deposits.

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