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Integrated Approach for a Successful Geothermal Wells Location in the Mt. Amiata Area (Southern Tuscany)

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ABSTRACT

Sorgenia Geothermal has been recently awarded some exploration licenses in Southern Tuscany, near the geothermal fields of Bagnore and Piancastagnaio, around the Mt. Amiata volcano complex.

In order to successfully locate the first deep wells, an integrated exploration program has been developed, firstly based on a complete collection and analysis of existing critical data, which include mining data, previously drilled geothermal wells data and some geophysical data (gradient wells data, gravimetric data, geoelectrical data, CROP 18B and SIF 12–15/87 seismic reflection raw data).

The available seismic data have been reprocessed in order to better focus on the geothermal target and at the same time a new planned 2D seismic reflection survey (approx. 50 km) will be carried out in 2014 to achieve the best coverage in the areas under exploration.

An MT survey has been carefully designed and performed (250 stations) considering the severe increase of EM noise in the areas.

Geological and hydrogeological surveys, as well as the soil CO_2 degassing measurements, a useful tool in confirming the existence of a deep-seated active geothermal system, have been also carried out.

The whole dataset has been uploaded and analyzed in a dedicated geodatabase and 2D gravimetric modeling has been performed. Subsequently, the 3D structural model of the area, mainly based on the 3D resistivity and gravity models properly calibrated with wells data, has been shaped and utilized as the basis of the 3D thermofluid-dynamic model of the existing reservoir. Hydrothermal circulation has been modelled using the TOUGH2 code (simulation of multi-dimensional, multiphase and multi component flow and heat transport in porous and fractured media), a useful tool for the assessment of the geothermal potential and for the prediction of the evolution of the system.

This integrated approach contributes to substantially reducing the mining risk in deep geothermal exploration, leading to the building of a better-defined conceptual model of the geothermal reservoir and a more precise resource detection and assessment for the most appropriate and sustainable exploitation of the field.

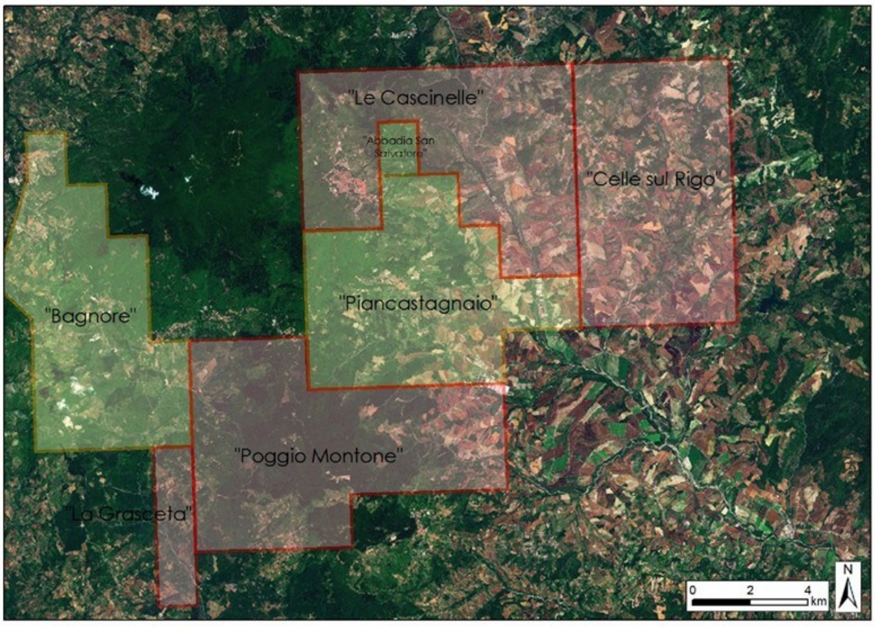

Figure 1: Sorgenia exploration licences in Mt Amiata region (red areas).

1. INTRODUCTION

In the last couple of years, as a consequence of the liberalization of the Italian geothermal market, new exploration projects have been developed and implemented near the well-known geothermal fields of Tuscany.

Sorgenia, the leading private operator in the power and natural gas market in Italy, has been recently awarded some exploration licences in Southern Tuscany, near the geothermal fields of Bagnore and Piancastagnaio (Fig.1).

2. GEOTHERMAL SETTING

Southern Tuscany is the cradle of geothermal energy, with significant geothermal potential. Mount Amiata geothermal area is characterized by a very high heat flow (50 - 400 mW/m^2, Baldi et al., 1994) probably due to the presence of a granitic pluton at a depth of approximately 6 km (Gianelli et al., 1988). The geothermal exploration in this area started in the '60s and led to the discovery of three geothermal fields: Bagnore, Piancastagnaio and Poggio Nibbio (Fig. 2). This area has been also subjected to an intense mining exploration and cinnabar exploitation since the Etruscan period. In addition, Mount Amiata has two water-dominated geothermal reservoirs: the shallower, hosted in the carbonatic-evaporitic successions belonging to the Tuscan Nappe, and the deeper, hosted in fractures in the Tuscan Metamorphic Complex, with temperatures up to 300°C (Bertini el al., 1995 and Bertani, 2010).

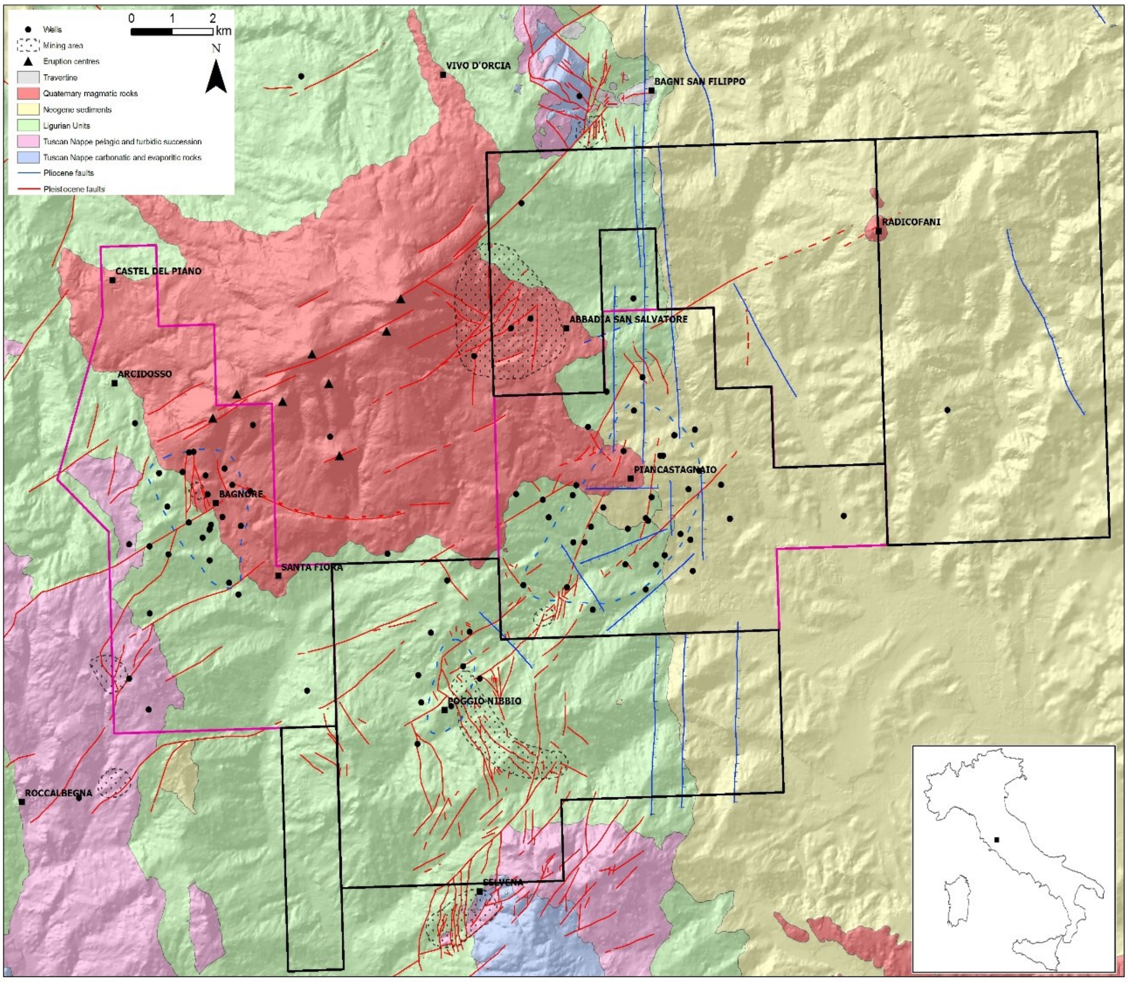

Figure 2: Geological sketch map of the Mt. Amiata and its surroundings

3. EXPLORATION

A geological survey allowed the reconstruction of an updated geological and structural framework of the area. Geothermal manifestations and cinnabar mineralization are a clear expression of hydrothermal circulation from Pleistocene to nowadays, linked to the brittle deformation. Main recent structures are represented by strike-slip faults and associated tensional basin (Brogi and Fabbrini, 2009). The former, which previously drove the rise of magma in the Mt. Amiata volcano, currently act as preferential path for the rise of hydrothermal fluids (water and gases).

Cold and thermal springs were sampled and analyzed for major and minor elements and for stable isotopes (δ^{18}O and δD). The data suggests that there is no evidence of a possible rise of deep hydrothermal waters from the high temperature geothermal reservoirs in the whole area. This is indicative of the good efficiency of the impermeable cover of geothermal reservoirs, although the area shows strong gas emissions.

A further exploration method, based on the measurement of soil CO_2 degassing, has been applied in Sorgenia's licences. CO_2 is the most common gas in geothermal fluids. In recent years some attention has also been paid to measuring the diffuse flow of CO_2 through soil in geothermal fields for the purposes of geothermal exploration (Fridriksson, 2009 and references therein). This survey is in fact included among the most powerful tools that geochemists may apply for the geothermal exploration of high and medium enthalpy resources. Soil CO_2 flux has been measured through the closed-chamber method, using a LI-COR 8100 instrument. The CO_2 flux measurements show a wide range of geochemically anomalous values with respect to regional background, the latter being relatively high in this area (CO_2 flux >3 μmol m^{-2} s^{-1}). The whole dataset has been statistically processed showing a polimodal distribution that allowed the identification of different populations of CO_2 flux data. Their distribution can be represented on a flux map as showed in Fig. 3. This kind of map highlights the zones where the CO_2 flux is significantly higher (up to 5-10 times) than its background values. The distribution of CO_2 flux anomalies can be related to the geological setting such as: a) the expected depth of the geothermal reservoir; b) active faults and tectonic structures, which may represent preferential paths for the rise of CO_2 from the geothermal reservoirs to the surface; c) the thickness of impermeable successions that cover the geothermal system.

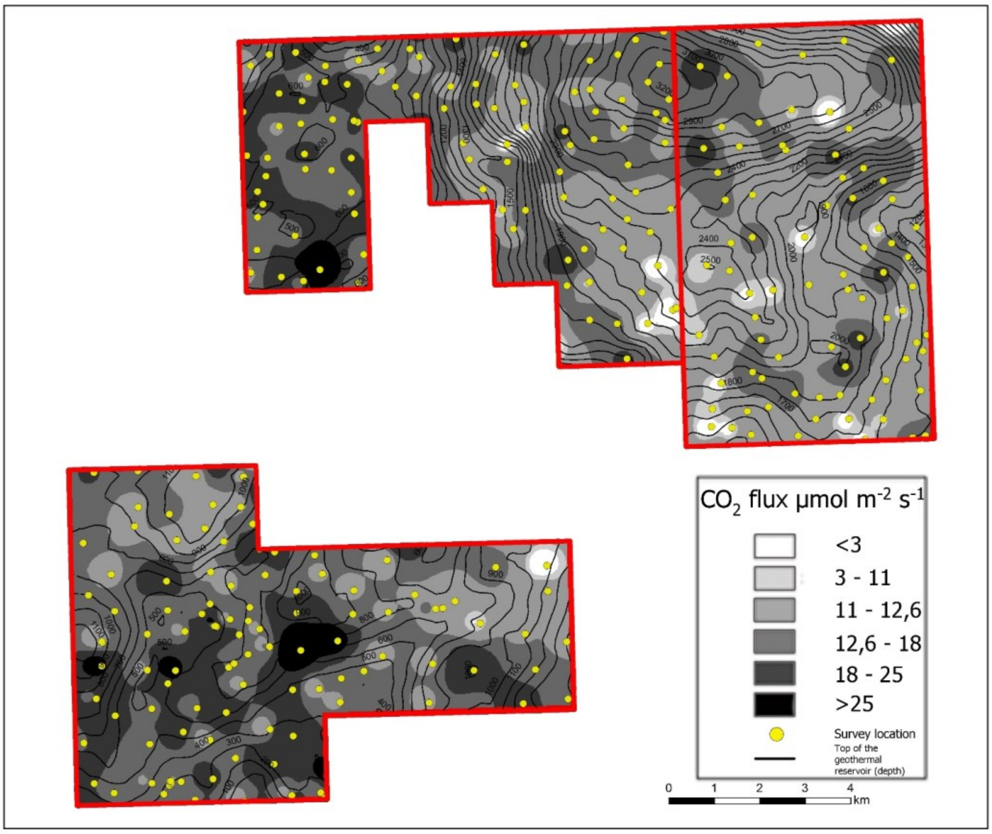

Figure 3: CO_2 flux map of Sorgenia exploration licenses in the Mt Amiata area. Gray scale is proportional to CO_2 flux (darker colours correspond to higher flux).

This data allowed for a rough evaluation of the natural total CO_2 flux coming from each exploration license, which varies between 1100 CO_2 ton/day and 2800 CO_2 tons/day, significantly higher (up to 4 times) than the carbon dioxide emissions released by the geothermal power plants currently under operation in the Mt Amiata area. The anomalously high CO_2 flux discovered, generated by both geothermal and magmatic-hydrothermal environment, has been a useful tool in confirming the existence of a deep-seated active geothermal system and for the localization of potentially interest geothermal areas.

From a geophysics point of view, a MT survey (250 stations) has been carefully designed and performed (Fig.4) in order to detect the resistivity distribution in the area under investigation and consequently define the most significant structures of the geothermal system. In fact, reservoir carbonate formations are characterized by resistivity values much higher than the ones related to the covering formations.

The study area is affected by severe electromagnetic noise mainly originated by many electric power lines and railways. The latter cause the so called "train effect" that strongly disturbs the middle-low frequencies and hence reduces the reliability of the results at higher depths.

For this reason a robust remote reference processing has been performed (Larsen et al. 1996) by using two remote stations properly located at hundreds of kilometers from the survey area. This generally produced quite an improvement in the signal/noise ratio extending the reliability of the resistivity and phase curves from 1-2 s up to about 10 s (see Figure 5).

Starting from a 100 ohm*m homogeneous resistivity a-priori model, the MT processed data have been inverted by means of 2D (Rodi and Mackie 2000) and 3D (Mackie and Madden 1993) inversion procedures. The final 3D model was compared with the available well data (Fig. 6) so that the resistivity distribution matched the available geological features. This allowed mapping the top of the resistive substratum to be referred to the carbonate reservoir formations.

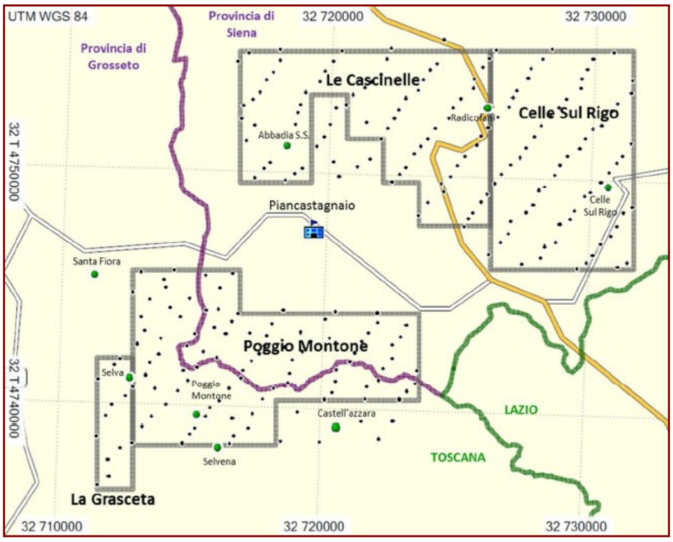

Figure 4: MT site location and permit boundaries

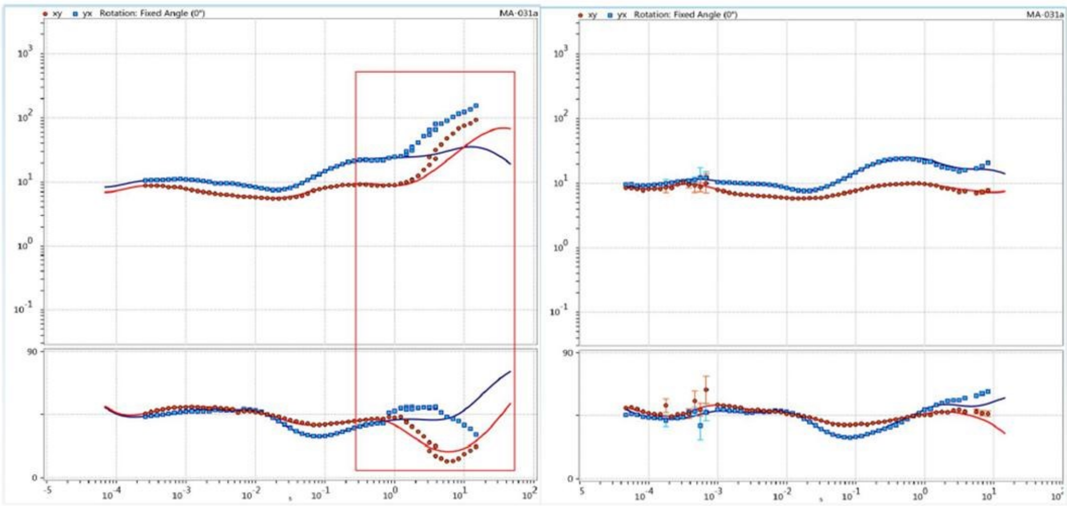

Figure 5: Improvement of the original MT curve (left) for periods higher than 1s by using a robust remote reference processing (right)

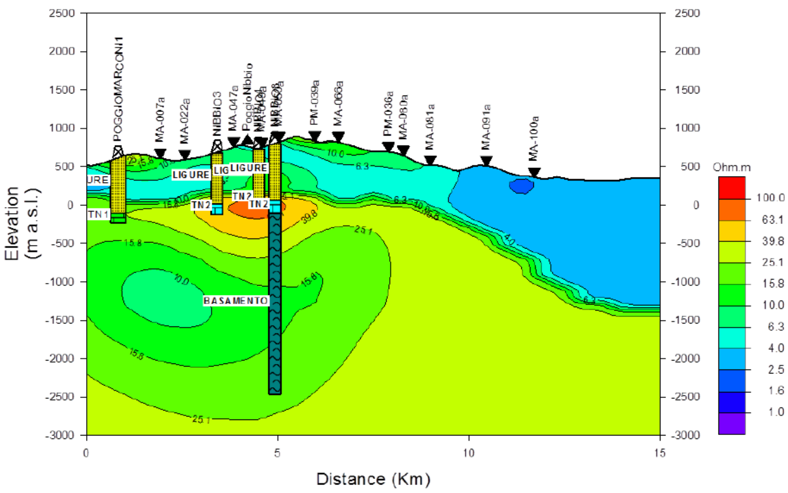

Figure 6: Example of resistivity cross-section from 3D model checked with well data

Also the available gravity data (Bouguer anomaly with d=2.67 g/cm3 extracted from the Gravity Map of Italy) was modeled in 3D, but the 3D density model does not fit very well with the resistivity one (Fig.7), mainly in correspondence of sharp structural changes.

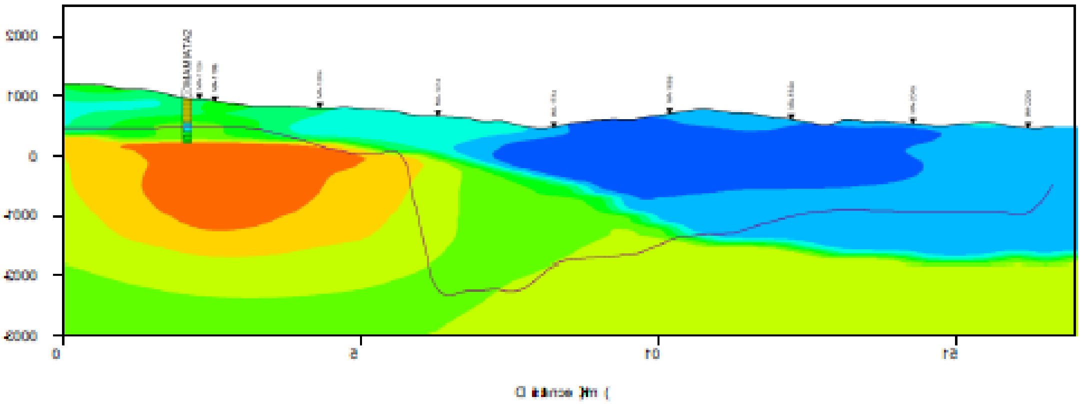

Figure 7: Section of the top of the denser carbonate formation (black line) from 3D gravity model superimposed to the same section from 3D resistivity model

For this reason the whole set of the available gravity data has been uploaded and analyzed in a dedicated geodatabase and 2D gravimetric modeling has been performed and compared with well data and available 2D seismic lines (Fig.8).

The CROP18b line (Fig.9), acquired during the seismic survey named "CROP - Profili Sismici a riflessione della Crosta Italiana" carried out by ENEL, ENI-AGIP and CNR in 1995, has been the first one to be re-processed. Since the acquisition parameter had been optimized for very deep targets at the time, the re-processing was aimed to better focus on the seismic markers associable to the geothermal target (top of the carbonate reservoir). Although the results showed important limits in terms of identification of these main reflectors, a preliminary interpretation has been carried out (Fig.10).

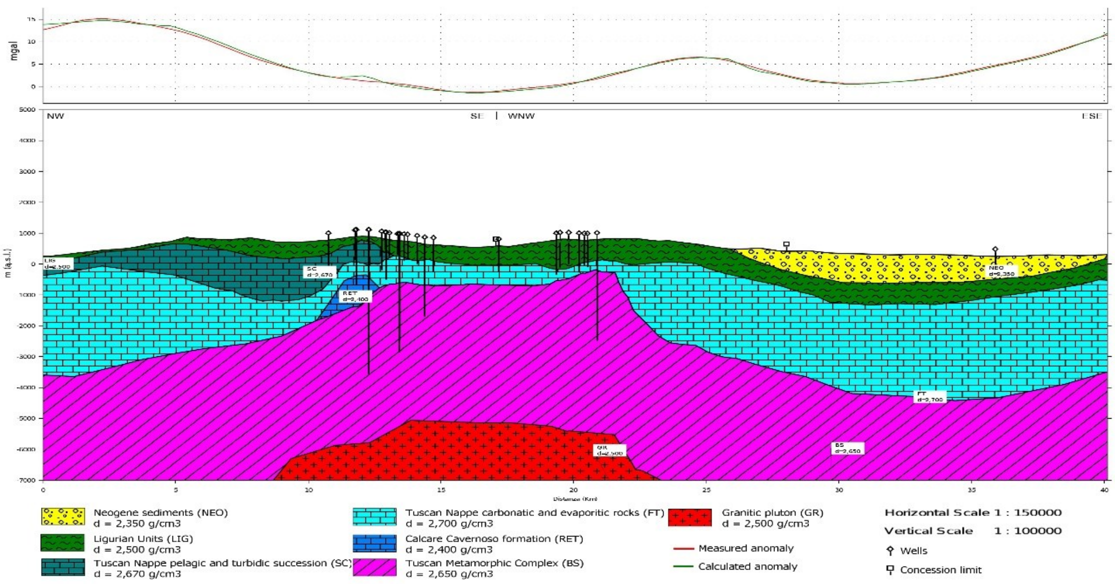

Figure 8: Example of a gravimetric 2D model performed along a section within the area under exploration

Later on, Sorgenia re-processed a set of 2D seismic raw data (lines named SIF12 ÷ 15/87), part of a Vibroseis seismic survey carried out in 1987 by an ENI/TOTAL JV for hydrocarbons exploration (see Figure 9). The re-processing of these lines, which extend across the Mount Amiata and the Radicofani Neogene Basin areas, was performed both to enhance the CROP18b seismic imaging and to validate and refine the structural model of the area. The interpretation of these lines is still on course.

Furthermore, a new planned 2D seismic reflection survey (approximately 50 kilometers) is planned to be carried out within the end of 2014 to achieve the best coverage in the areas under exploration.

Subsequently, the 3D structural model of the areas, based on the geological surveys, deep well data, available cross sections, 3D resistivity and gravity models, has been shaped and utilized as the basis of the 3D thermofluid-dynamic model of the areas. Hydrothermal circulation has been modelled using the TOUGH2 code (simulation of multi-dimensional, multiphase and multi component flow and heat transport in porous and fractured media), a useful tool for the assessment of the geothermal potential and for the prediction of the evolution of the system (Pruess et al., 1999).

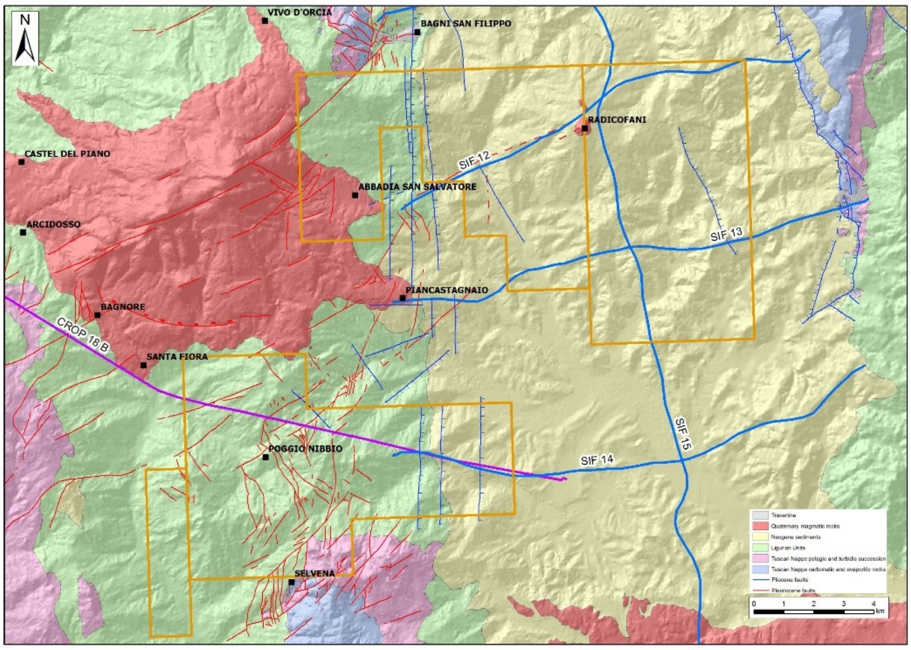

Figure 9: Seismic surveys carried out in the '80s and '90s in the area under investigation- CROP18b (dark blue) and SIF 12 - 15/87 (light blue)

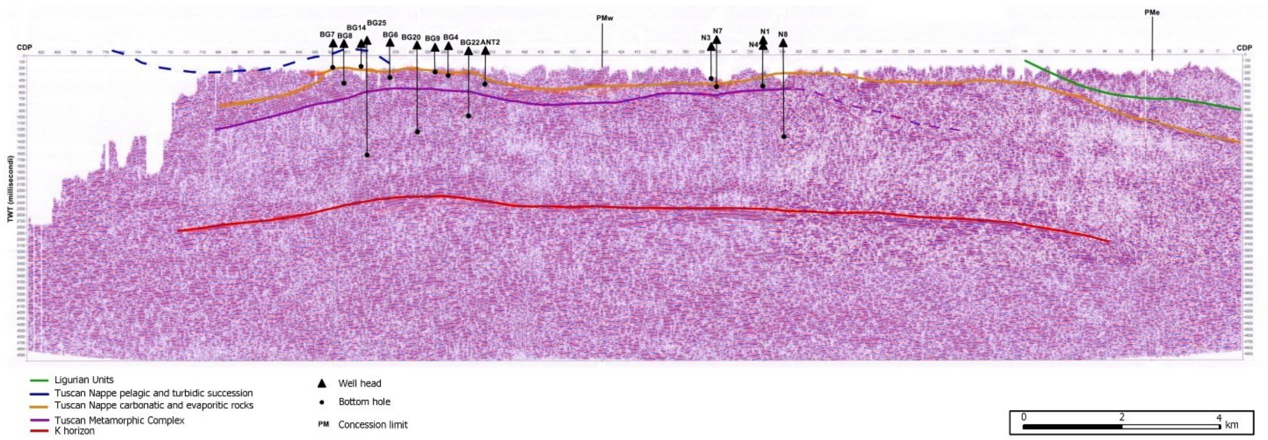

Figure 10: Reprocessed CROP18B seismic line and preliminary interpretation

The simulation of the natural state (steady state) covers a period of 200000 years in order to match the temperature distribution at depth, based on the available temperature measurements in existing wells, some simulation parameters (mainly permeability and temperatures at the bottom layer) were appropriately tuned. Simulated well temperature profiles were compared with the measured ones, verifying the reliability of simulation. A good match between simulated and measured temperature in deep wells was obtained (Fig.11), suggesting that a satisfactory preliminary simulation was achieved.

The main results of the preliminary numerical modeling simulations are shown in Figure 12 for the exploration license named "Poggio Montone". As can be seen, in the western part of the permit, at the level of the top of the first geothermal reservoir (approximately 0 m above sea level, see Figure 12 (a)), the simulation shows that relatively high temperatures (> 140°C) would occur in a wide area of the license. It is also important to point out that temperature distributions shown in Figure 12 are mainly due to the geological structures rather than wells available data, as one might assume observing the results.

3. CONCLUSION

The integrated approach followed represents an adequate answer to the geothermal exploration needs and peculiarities. A 3D modeling software easily allowed integrating both the existing data, some of them requiring an adequate re-processing, and the ones collected from new exploration surveys. As a result, it has been possible to generate a structural model of the area and represent the top of the first (shallower) geothermal reservoir, as shown in Figure 13 below. Finally, the thermofluid-dynamic modeling, based on the above-mentioned 3D structural model, allowed reconstructing the temperature profile at depth as well as the temperature at the top of the first geothermal reservoir (Fig.14).

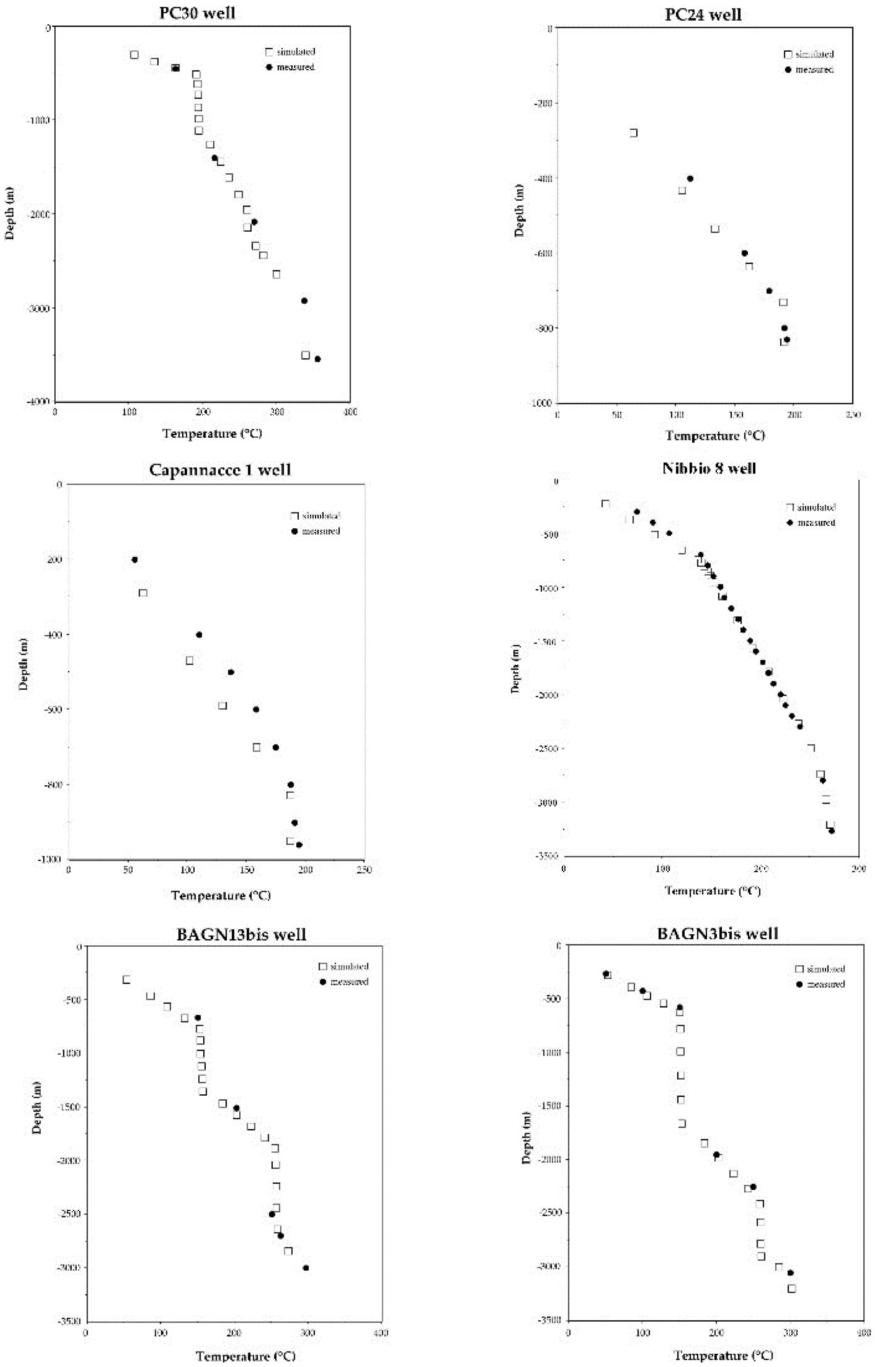

Figure 11: Simulated (squares) and observed temperature (dots) vertical profiles for selected deep geothermal wells of Mt. Amiata area (UNMIG data)

As said before, the interpretation of SIF seismic lines as well as the new seismic survey will allow a refinement of the 3D structural model used until now in order to improve the coherence between the numerical thermofluid-dynamic simulation and the measured data.

At the end of this enhancement process, it will be possible to select the best location for the first exploration wells from the geothermal point of view. At the same time, this numerical tool will be used to predict the behavior of the geothermal field under the future exploitation.

This integrated approach contributes to substantially reduce the mining risk in deep geothermal exploration, leading to the building of a better-defined conceptual model of the geothermal reservoir towards a more precise resource detection and assessment for the most appropriate and sustainable exploitation of the field.

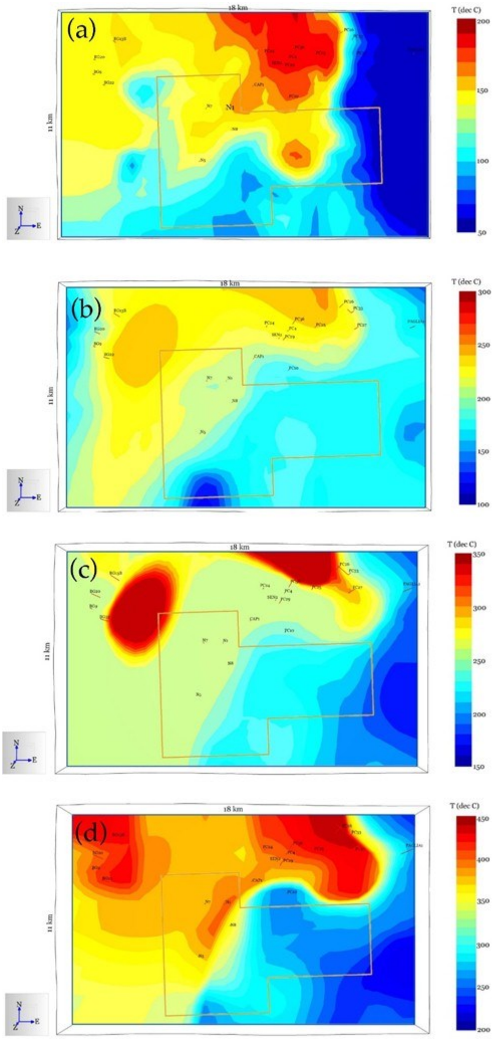

Figure 12: Temperature distribution of "Poggio Montone" exploration permit at 0 m.s.l. (a), -1000 m.s.l. (b), -2000 m.s.l. (c), -3000 m.s.l. (d) respectively, as deduced from numerical modeling experiments. Please note the average ground level is approximately 700 m.a.s.l. and each figure has its own coloured scale.

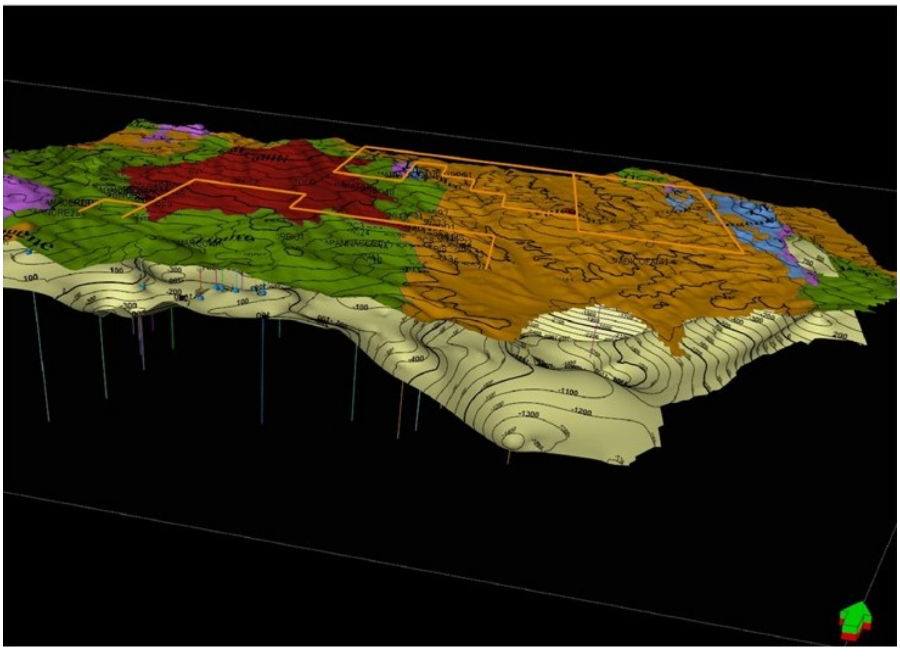

Figure 13: 3D geological model of the Eastern sector of Mt Amiata area with the visualization of the top of the first (shallower) geothermal reservoir in the license exploration areas

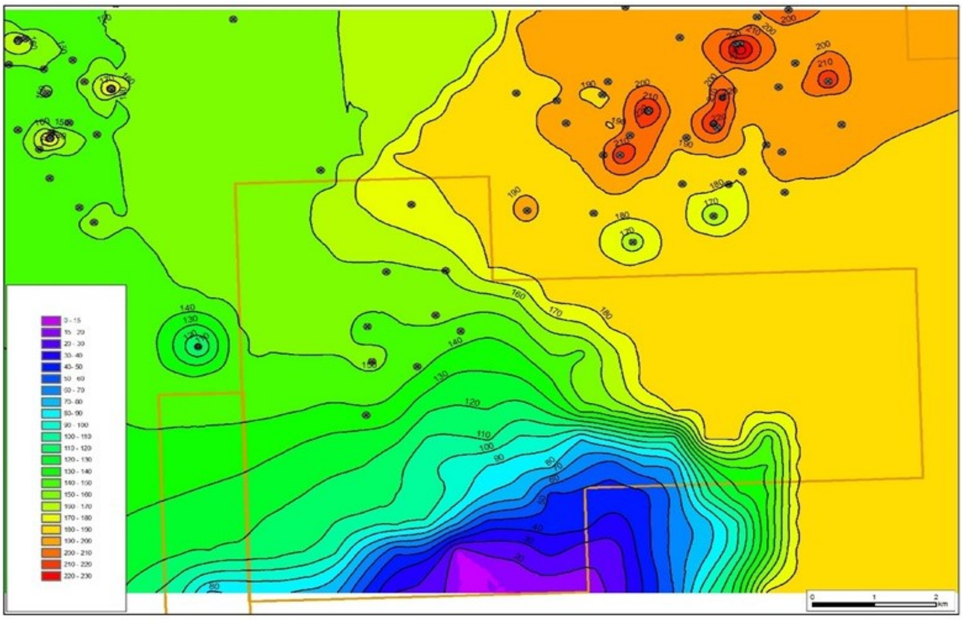

Figure 14: Map of the isotherms at the top of the first geothermal reservoir in the "Poggio Montone" exploration permit as elaborated by the integration of 3D geological and numerical modeling.

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