Unconventional, super-hot geothermal resources are attracting the world geoscientific community and electric power industries as a promising renewable energy source. Particularly, supercritical fluids play an important role in establishing a new green energy strategy. By exploiting a fluid above its supercritical point, which for pure water is at 374°C and 22 MPa, the energy output per production well increases by an order of magnitude in comparison with a conventional geothermal well. However, the abundance, location and size of such resources are still undefined.

As the thermal structure is the main critical parameter, we investigated the underground temperature distribution in Southern Italy by integrating a large set of geological, geochemical and geophysical information. To study the regional-scale steady-state thermal structure resulting from the coupled heat transfer and fluid flow equations, we set-up several numerical models, each of theme characterized by a computational domain of about 100x100x20 km³. The solution is approximated through the finite element method within a numerical mesh of tetrahedral elements. As reliable subsurface temperatures are essential in geothermal studies, we analysed several hundred boreholes included in the Italian National Geothermal Database (BDNG, Trumpy and Manzella 2017). Geothermal boreholes provided static bottom-hole temperatures or high-resolution thermal profiles measured after large shut-in times (SBHT). The highest temperatures in geothermal areas are 420°C in the San Vito 1 well and 450°C in
the Latera 10 well both measured around 3 km depth and located in the Phlegreaean and Vulsini volcanic districts, respectively. Hydrocarbon exploratory wells provided essentially raw bottom-hole temperatures (BHT) and drill-stem test (DST) temperatures. To correct the raw BHTs, we applied two different techniques depending on the available data and their characteristic. For the time-temperature series, with two up to six measurements during successive logging runs, the well-known Horner procedure is applied (Horner 1951, Dowdle and Cobb 1975). Instead, when only one BHT is available, we calibrated a less precise but overall accurate empirical correction method based on the correlation between the Horner slope and the depth (Pasquale et al., 2008). Thermal petrophysics is investigated for porosity, thermal conductivity, radiogenic heat production and hydraulic permeability. In order to establish reliable porosity-depth and permeability-depth relationships and to infer accurate thermal conductivity and radiogenic heat production values by lithothermal unit, we integrated a large set of laboratory data, wire-line logs and DST data. This approach allowed the definition of the main input parameters for the numerical models.

The subsurface geometrical model is defined by three main geological surfaces, from the top to the bottom: i) the topography and/or bathymetry, ii) the top of the carbonate units hosting the regional hydrothermal reservoir (Montanari et al., 2014, Vezzani et al., 2010) and iii) the top of the crystalline/metamorphic basement, as defined from geomagnetic data in Cassano et al. (1986). Since the rocks above the carbonate reservoir (i.e. the cap-rock units) and the crystalline/metamorphic basement are mostly impervious rocks, we evaluated the thermal effects of the interplay of the free convection and topographically driven groundwater flow in the permeable carbonate units. Accounting for the recharge zones, we applied a stress boundary condition where the carbonate rocks crop out in the Apennine chain. The regional reservoir is assumed fully saturated and the pressure on those boundaries is set equal to the freshwater head calculated with a reference water density of 1000 kg/m$^3$ and the sea level as datum. Locally, we accounted for the thermal effects of crustal magmatic bodies of variable sizes, emplacement depths and temperatures by solving a set of possible scenarios constrained by volcanological and geophysical evidences. The available SBHT data are used to check the accuracy of the numerical results by the root-mean-square error (RMSE). The calibration procedure enabled us to select suitable boundary conditions that minimized the RMSE.

Fig. 1 shows the simulated temperature distribution of the Northern Latium sector (the areal extension of the numerical domain is in Fig. 1A). The top of the permeable carbonate units and the comparison between the computed and measured temperatures in selected deep boreholes are reported in Fig. 1B. The numerical results fit the measured temperatures and mimic the pronounced lateral variability of the regional thermal anomalies (Mongelli et al., 1991, Cataldi et al., 1995, Della Vedova et al., 2000). Conductive heat transfer dominates in the continental crust under middle to lower conditions where the low permeability values of the crystalline rocks ($K \ll 10^{-16}$ m$^2$) limit an efficient convective heat transport (Manning and Ingebritsen 1999, Ingebritsen and Manning 2003). Instead, the permeability of the shallow crustal levels, largely dominated by the carbonate platform units, exceeds the threshold value for a well-organized hydrothermal convection ($\sim 10^{-15}$ m$^2$). In the well-known geothermal areas, where the favourable geological conditions lead to the development of deep-seated hydrothermal systems, the magnitude of the convective heat flow is greater than the conductive one by many times. In the young volcanic districts, in order to reproduce numerically the observed anomalies, a reservoir permeability of $\sim 10^{-14} - 10^{-13}$ m$^2$ and localised heat sources with temperature variable from 400°C up to 800°C are required.

From the optimized 3D thermal structure, we extracted the modulation in depth of the 400°C isotherm being this value more representative of the critical temperature for a geothermal brine (Fig. 1C). The volcanic districts in the peri-Tyrrhenian zone are the best candidate environments where supercritical conditions could occur at drillable depths. These zones display an enhanced thermal anomaly, a shallow cut-off depth of seismicity, a $^3$He/$^4$He ratio higher than
and locate in a thinned/transitional crustal domain. Finally, the favourability map for the supercritical geothermal resources has been evaluated in the Southern Italy regions considering thermal structure, depth of the brittle-ductile transition, geodynamic setting and isotopic signature of deep crustal magmatic processes. The data were organized in form of raster maps and the Matlab environment provided the tools for processing the selected parameters. Scoring from 1 (less favourable) up to 5 (most favourable) the elements of the four maps and weighting from 0 to 1 each thematic map by the Analytic Hierarchy Process, the favourability index was calculated using the Index Overlay method. Such results can be seen as a useful planning tool for any geothermal supercritical project, and related exploration to be carried out in the Southern Italy in the future.

Fig. 1 - 3D thermal model of the Northern Latium sector. The areal extension of the numerical domain is shown in Fig. 1A. The modulation in depth of the top of the carbonate units hosting the regional hydrothermal reservoir and the comparison between the simulated (black line) and measured (red circles) temperatures in selected deep boreholes are reported in Fig. 1B. The modulation in depth of the 400°C isotherm is shown in Fig. 1C.

2.5 and locate in a thinned/transitional crustal domain. Finally, the favourability map for the supercritical geothermal resources has been evaluated in the Southern Italy regions considering thermal structure, depth of the brittle-ductile transition, geodynamic setting and isotopic signature of deep crustal magmatic processes. The data were organized in form of raster maps and the Matlab environment provided the tools for processing the selected parameters. Scoring from 1 (less favourable) up to 5 (most favourable) the elements of the four maps and weighting from 0 to 1 each thematic map by the Analytic Hierarchy Process, the favourability index was calculated using the Index Overlay method. Such results can be seen as a useful planning tool for any geothermal supercritical project, and related exploration to be carried out in the Southern Italy in the future.

Acknowledgements. This work was carried out within the framework of the GEOTHERMAL ATLAS OF SOUTHERN ITALY Project, one of six Projects constituting the Program “CNR per il Mezzogiorno” of the Italian National Research Council, aimed at improving know how in the fields of advanced technology for energy efficiency, environmental protection, agro-food innovative methodologies for the Made in Italy and biotech medicine production.
References