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Assessment and Simulation of Various Utilization Scenarios of a Medium-Enthalpy Reservoir in Southern Italy (Guardia Lombardi)

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ABSTRACT

The energy potential of geothermal reservoirs mainly depends on thermal regime, geological structure, and petrophysical properties. However, practical issues have a main importance in the planning, such as the kind of energy utilization, the design of the geothermal doublet, or the vicinity of energy end users. The evaluation approach here described tackles and integrates the different aspects.

The approach is tested in the medium-enthalpy geothermal reservoir of Guardia Lombardi (Campania, Italy). The surface area of the entire study region is about 42 km by 28 km. It is characterized by specific surface heat flow of up to 90 mW m^{-2} and geothermal gradients of about 58 K km^{-1}. The geothermal target is the shallow water Apulian Platform, a fractured and possibly locally karstified carbonate layer, dissected by a number of steep faults. The complex geological structure has been interpreted from several seismic profiles and hydrocarbon exploration wells. A numerical model was set up describing the relevant regional advective and conductive heat transport processes in the reservoir. A set of borehole-temperature data was used for its calibration. As simulator we used the code SHEMAT-Suite.

First, we investigate the natural flow and temperature conditions in the entire reservoir. Second, we choose several sub-models, based on temperature and flow rates as well as on social decision parameters such as vicinity to villages or natural reserve restrictions. For these sub-models we assess the rates of energy production and sustainability for various utilization scenarios. Relevant aspects, beside infrastructure and natural reserve restrictions, are: (a) borehole locations and distance between injector and producer; (b) drilling depth vs. estimated temperature; (c) influence of preexisting fracture and fault systems; (d) stimulation.

1. INTRODUCTION

Guardia Lombardi is located in Campania, central Italy (see Figure 1, top) It is one of the study areas of the VIGOR Project (VIGOR "Geothermal Potential of the Convergence Regions" is part of the activities of the European Commission European Regional Development Fund "Renewable Energies and Energy Savings" FESR 2007-2013 –Activity line 1.4 "Experimental Actions in Geothermal Energy"). This area was chosen due to locally enhanced specific heat flow with maximum values of about 90 mW m^{-2} at the surface (Della Vedova et al., 2001). The evaluation of the geothermal potential of this area based on numerical simulation and prognosis is the aim of the cooperation of the VIGOR and the MeProRisk research consortium consisting of academic and commercial partners in Aachen, Berlin, Freiberg and Kiel (MeProRisk "Methods for Prediction and Risk minimization in geothermal reservoir development" is supported by the German Federal Ministry of the Environment).

Earlier, this area was the target for hydrocarbon explorations by ENI S.P.A. From this exploration phase, a number of reflection seismic profiles and information from some shallow and five deep boreholes (Bonito 1 Dir, Monte Forcuso 1, Monte Forcuso 2, Serroni 1, and Taurasi 1(see Figure 1) exist in or adjacent to the study area. Two of the boreholes have a depth of about 3 km and the other three have depths ranging between 1 km and 2 km. They all show temperatures above 100 °C at a depth of less than 1.7 km, therefore depicting a medium enthalpy reservoir.

Evaluation of the geothermal potential of this area requires an accurate reservoir characterization with a comprehensive assessment of the geology and the hydrothermal properties of the subsurface rocks. Here we present firstly, the results of a reservoir characterization and the transfer of the information into a gridded model for hydrothermal simulation. Secondly, we evaluate the geothermal potential of the entire area based on the simulation model. In a third step, we identify locations in the area which are of primary interest for geothermal use based on the results of both our hydrothermal model and social conditions. In a last step, we simulate a geothermal doublet installation at these sites and study the possible energy production rate and its sustainability.

2. RESERVOIR CHARACTERIZATION

A three-dimensional geological model of the Guardia Lombardi region was developed by the VIGOR research group based on a number of seismic profiles and shallow wells, as well as five wells deeper than 1 km (Inversi et al., 2013). All the seismic profiles and the wells stem from hydrocarbon exploration. Gamma ray and resistivity logs from the deep wells were used to determine porosity and thermal conductivity of the various rock types intersected. This information was supplemented by data from lab measurements of density, thermal conductivity and porosity on a number of samples obtained from surface outcrops of characteristic rocks. Finally, surface temperature (Galgaro, et al., 2012) and several measurements from wells at depths ranging from 300 m to 3500 m were used for calibration of the numerical flow and heat transport model.

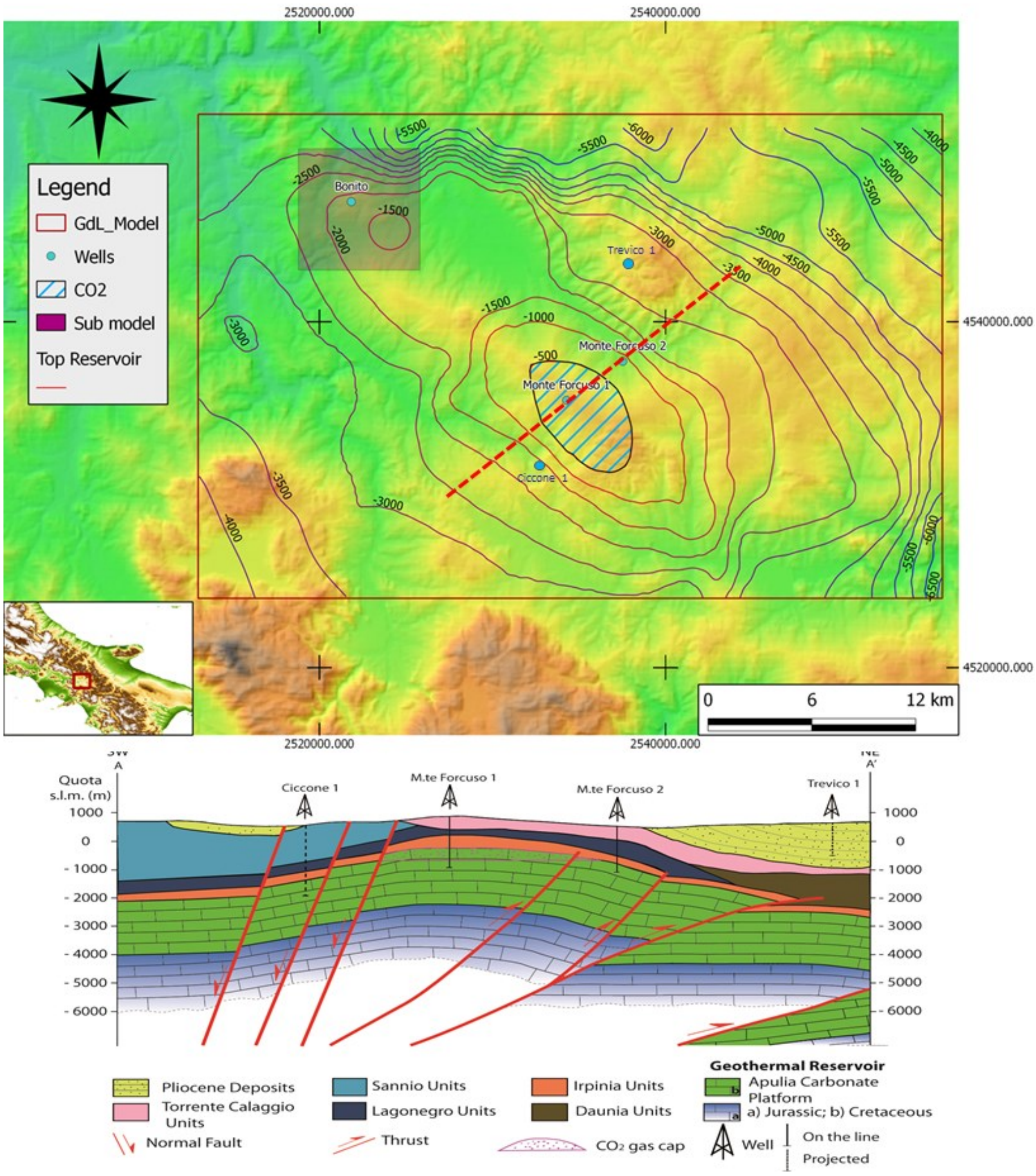

Figure 1: Top: Location and topography of the study area (red box). Contour lines show the top of the Apulia carbonate platform, considered as the target for geothermal exploration. The carbon dioxide accumulation under an anticline of the platform in the center of the area is shown as a shaded area. The dashed red line indicates the profile for the cross-section shown below. The black shaded square defines the area for a geothermal doublet installation. Bottom: Cross-section of the central anticline of the Apulia platform. Red lines indicate two consecutive tectonic phases of thrusting and normal faulting (movement directions according to the red arrows) (modified from Inversi et al. (2013))

2.1 Geological model

The geothermal target formation in Guardia Lombardi is a fractured carbonate reservoir which originated from Cretaceous to Eocene shallow-water sediments. It is part of the large Apulia carbonate platform (Upper Triassic to Miocene) which was folded and thrust-faulted during the Pliocene Apennine orogeny and later affected by extension associated with normal faulting in the Pleistocene.

A geological model of the Guardia Lombardi area (Inversi, et al., 2013) was derived from interpretation of an integrated dataset, comprising boreholes, seismic profiles, geochemical, and hydrogeological information and a geodynamic model by Scrocca (2010). This interpretation also revealed low-angle thrust-faults in and below the Apulia Platform and steep normal faults involving also younger cover layers. In addition, a CO_2 accumulation in an anticline structure of the Apulia platform in the center of the area was detected and is connected to a surface emanation of CO_2 (“Mefite d'Ansanto”). This indicates at least a locally increased permeability (Chiodini, et al., 2010). The geological model incorporates the fractured carbonate reservoir rocks as well as the CO_2

cap and the overlying sedimentary cover. One of the steep normal faults in the model can be related to Mefite d'Ansanto. The main geological successions of the cover layers are the Lagonegro and Sannio units and the Torrente Calaggio complex.

The Lagonegro and Sannio units mainly consist of little permeable calcareous pelagic successions (Patacca & Scandone, 2007). A cross-section of the geological model is shown in Figure 1 (bottom) and the full 3D model with topography, the Apulia platform, and the fault system in Figure 2.

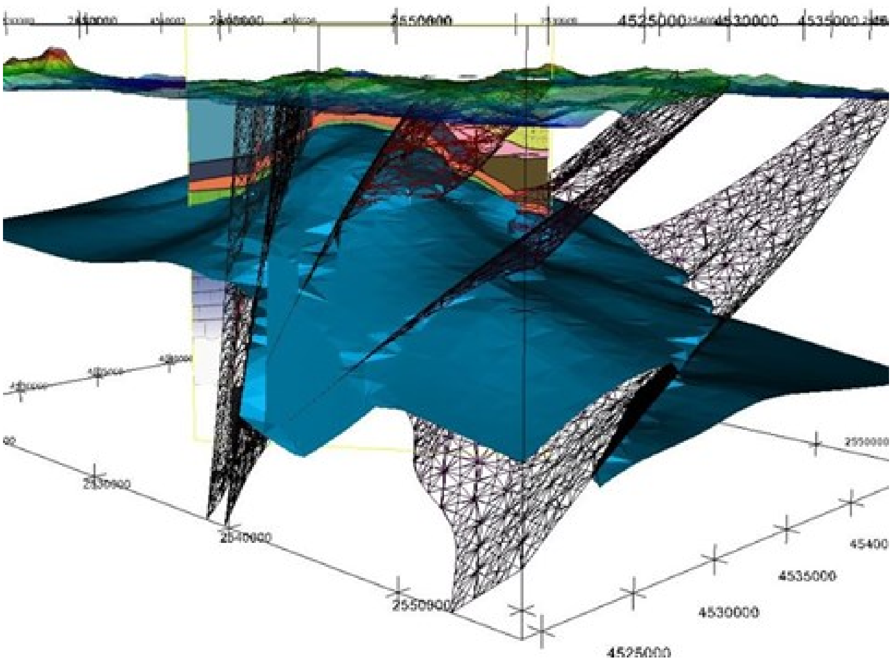

Figure 2: Geological model showing topography, Apulia platform, and the various faults detected from reflection seismic data alongside the cross-section from Figure 1 (bottom) . (vertical exaggeration 3:1.)

2.2 Petrophysical properties

Petrophysical properties of the lithological units were derived from logging data, a series of laboratory measurements on nine core samples from surface outcrops, and from ENI reports on lab measurements on eight core sample (mainly from the Apulia platform) from three deep bore holes and hydraulic tests in these bore holes.

The nine cores which we studied in our lab were taken from sites representative of the Cretaceous-Eocene stratigraphy of the Apulian carbonate platform. Main lithologies are dense limestones and dolostones, which show layering and micro-joints. As laboratory measurements were performed under ambient temperature/pressure a systematic error in some of the measured values (porosity, thermal conductivity, density, p-wave velocity) is possible.

2.2.1 Thermal conductivity and porosity

The majority of the measured core samples have low porosity between 1 % and 3 %; dolomitized samples have higher porosities of up to 6 %. This agrees well with the ENI report on porosity, except for one single core from the Apulia platform with up to 9 % porosity. The information on porosity from core measurements was supplemented by porosities calculated from resistivity logs based on information on formation water salinity; this analysis confirm the low porosity also for the deeper Apulia platform.

Thermal conductivity was measured in our lab in both dry and saturated condition, but the data were quite similar in both cases (min: 2.14 W m^{-1} K^{-1} to max: 2.66 W m^{-1} K^{-1}), due to the low porosity and similar lithology. Using the geometric mean, matrix thermal conductivities were calculated for dry and saturated condition, yielding realistic mean values of 2.58 W m^{-1} K^{-1} (dry) and 2.48 W m^{-1} K^{-1} (saturated). In general, measurements in dry condition are more reliable, as complete re-saturation of low-porosity rocks is difficult to achieve.

2.2.2 Permeability

In a partially dolomitized, highly fractured carbonate reservoir, permeability is less related to porosity but more to the fracture networks. Fracture series were repeatedly reported from several wells, particularly at the transition of the overburden to the Apulian carbonates. In some cases, significant losses of drilling fluid were recorded near the transition from cap rocks to reservoir rocks.

Permeabilities measured by ENI on their core samples are very low between 10^{-16} m^2 and 10^{-15} m^2, even for the core with the highest porosity. However, it should be taken into account that these low values represent only matrix permeabilities. Evaluation of the hydraulic test data provided by ENI yielded permeabilities between 0.5×10^{-13} m^2 and 2×10^{-13} m^2 for various depth ranges between 1500 m and 3100 m. This depth range refers to limestones and dolomitic limestones of the Apulian carbonate platform. Maximum values of about 3.5×10^{-13} m^2 were estimated in production tests after acidizing operations that enhanced the transmissivity by up to 400 %. This observation reflects the high chemical reactivity of the carbonate minerals. Due to the basic assumptions and data quality, the permeabilities obtained are first order-of-magnitude estimates.

2.3 Temperature constraints

Temperature measurements from the five deep boreholes and one shallow borehole ("Lacedonia") are available and provide a total of eleven temperature measurements at various depths. The most promising well ("Bonito1Dir") shows a thermal gradient of about 50 K km^{-1}. The temperature observations are used to constrain the calibration of the simulation model.

3. HYDROTHERMAL SIMULATION

3.1 Simulation model

The geological model (Figure 2) with a size of 43 km (North-South) × 28 km (East-West) × 7.2 km (depth) was discretized in 109 × 69 × 71 uniform blocks (block size is 400 m × 391 m × 100 m). This simulation model incorporates the fractured carbonate reservoir rocks as well as the overlying sedimentary cover. Since the geological strata above the Apulia platform mainly consist of mainly little permeable calcareous pelagic rocks and cannot be distinguished in the seismic data, only two units were defined, a reservoir and a sedimentary cover.

The rock properties used in the simulation are based on the petrophysical analysis discussed in Section 2 and shown Table 1. Note that the sedimentary cover is assumed to be impermeable. Rock permeability is primarily caused by fractures which have been assumed to result in an isotropic, depth-dependent permeability (Manning & Ingebritsen, 1999) the dependence on depth resulting from of fracture sealing due to the overburdenpressure. Hence, the permeability k can be expressed as an exponential function of overburden thickness $\tilde{z}$, a maximum permeability k_0, and a scaling factor d.

$$k = k_0 e^{-\tilde{z}/d} \tag{1}$$

The scaling factor d is approximated roughly as 1000 m.

Table 1: Simulation parameters (the permeability decreases exponentially with depth).

	Symbol	Carbonate reservoir	Sedimentary cover
Matrix thermal conductivity [W/(mK)]	λ_m	2.53	2.36
Heat production rate [µW/m^3]	H	0.43	0.70
Porosity [-]	ϕ	0.05	0.15
Max. permeability [m²]	k	4.5×10^{-14}	0

3.2 Equations and simulation code

The numerical simulation is based on two transport equations for heat and fluid flow, in a porous medium. The equations are solved with the code SHEMAT-Suite (Rath, et al., 2006) based on a finite-difference scheme for a three dimensional Cartesian domain. The flow equation is given by

$$\nabla \cdot \left[\frac{\rho_w g k}{\mu_w} \left(\nabla h + \rho_r \nabla z \right) \right] + Q = S_s \frac{\partial h}{\partial t} \tag{2}$$

where h is the hydraulic head [m], z the vertical in space coordinate [m] (positive upward), ρ_w the water density [kg m^{-3}], μ_w the dynamic viscosity of water [kg $(m\ s)^{-1}$], g gravity [m s^{-2}]; $\rho_r = (\rho_W - \rho_0)/\rho_0$ accounts for the difference between water density ρ_w and a reference density ρ_0 (at atmospheric conditions), Q is a specific flow rate [s^{-1}] and S_s is the specific storage coefficient [m^{-1}]. Note that $v = \frac{\rho_w g k}{\mu_w}(\nabla h + \rho_r \nabla z)$ equals the specific discharge [m s^{-1}]. Accordingly, assuming local thermal equilibrium, the heat transport equation is given by

$$\nabla \cdot \left(\rho_w c_w T\, v - \lambda_e \nabla T \right) + H = (\rho c)_e \frac{\partial T}{\partial t} \tag{3}$$

where T is temperature [°C], c_w the specific heat capacity of water [J $(kg\ K)^{-1}$], and H the heat generation rate [W m^{-3}]. The effective thermal conductivity of the fluid-filled matrix, λ_e [W $(m\ K)^{-1}$], is calculated as $\lambda_e = \lambda_w^{\phi} \lambda_m^{(1-\phi)}$, where λ_w and λ_m are the thermal conductivities of water and solid matrix, respectively, ϕ is porosity, and $(\rho c)_e$ is the effective volumetric heat capacity of the water-saturated and rock. Pressure p is calculated from these primary variables as $p(z) = \int_0 \rho_w g (h(\dot{z}) - \dot{z}) d\dot{z}$. There is a non-linear coupling between eq. (2) and (3) since water viscosity and density depend on temperature, heat transport on flow, and thermal conductivity and heat capacity on pressure. These dependencies are considered for $\lambda_w(T)$ as in Phillips et al. (1981) and for

$\rho_w(T,p)$, $\mu_w(T,p)$, and $c_w(T,p)$ as in Zylkovskij et al. (1994). For further information on the simulator SHEMAT-Suite, see Rath, et al. (2006).

3.2.1 Boundary conditions

The temperature boundary condition at the top of the domain (i.e. at the land surface) is related to surface air temperature (Galgaro, et al. (2012)). Boundary conditions are obtained by adding a constant of 10 °C to the air temperatures which was determined such that the simulation result fits the shallowest available borehole temperature value available (i.e. 33.5 °C in the borehole Lacedonia at a depth of 324 m).

At the bottom of the domain, we apply a constant specific heat flow q. Its value is initially unknown and was determined as 66.7 mW m^{-2} by inversion assimilating the temperatures observed in the boreholes. Temperatures at the lateral boundaries are calculated for purely conductive heat transport at given q.

Due to the assumption that the sedimentary cover is impermeable, the flow boundary condition at the top is irrelevant. At the bottom, however, a no-flow boundary is applied. It accounts for the fact that rock permeability (due to fractures) is assumed to decline exponentially with depth as a result of the increasing overburden pressure. With d=1000 m in eq. (1), the fractures at the bottom of the model (at about 7.2 km depth) are all sealed. The lateral flow boundaries are open and assigned a constant head. Hence, there can be a regional flow of water through the domain. The hydraulic head at each lateral boundary is determined by inversion.

3.2.2 CO_2 cap

From seismic profiles, some information is available on the extent and thickness of the CO_2 cap beneath the sedimentary cover (see Section 2.1). However, neither the distribution nor the CO_2 saturation and mobility are known. Therefore, we account for the effect of CO_2 in a simplified manner: Driven by buoyancy, CO_2 (which is supercritical at the prevailing conditions, i.e. approximately 90 °C and 17 MPa) fully saturates the cap. Due to its high mobility (i.e. low viscosity) and relatively high coefficient of thermal expansion, it is assumed to circulate in convection cells within the cap, effectively equilibrating temperature. Therefore the CO_2 region is assumed to be isothermal with no water flow.

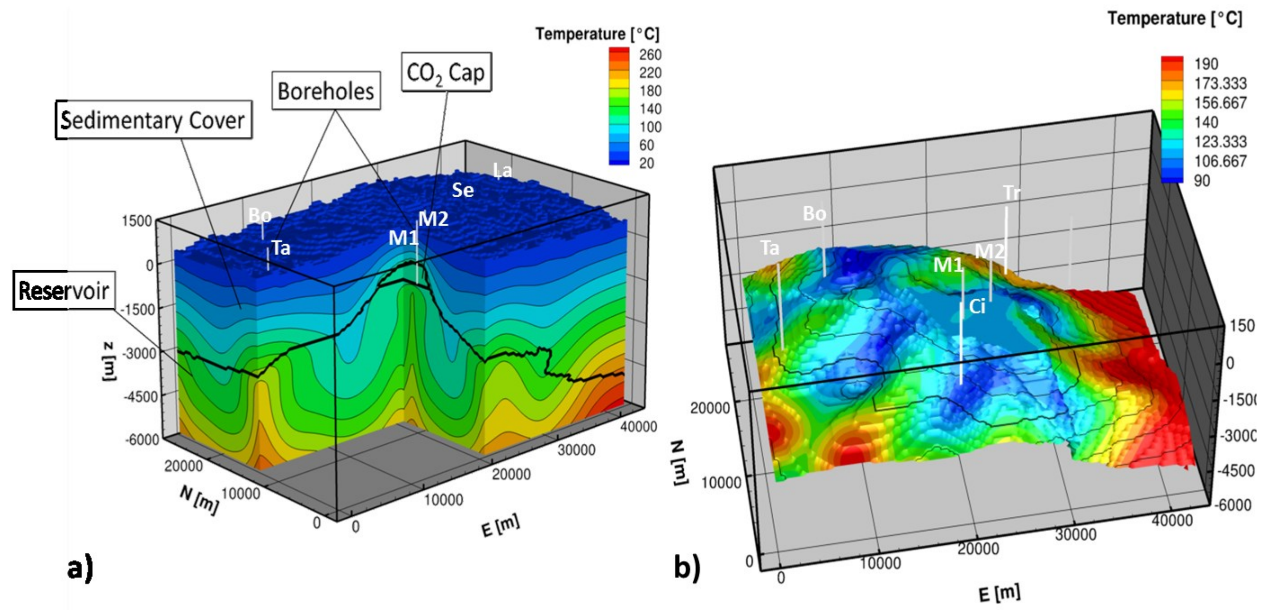

Figure 3: Simulated temperature field in the Guardia dei Lombardi carbonate geothermal reservoir. a) Vertical section removed to illustrate the up- and downgoing plumes. The black line marks the top of the Apulia platform. b) Temperature at the top of the Apulian platform. Boreholes are indicated by white vertical lines: Taurasi (Ta), Bonito (Bo), Ciccone 1 (Ci), Monte Forcuso 1 (M1), Monte Forcuso 2 (M2), Trevico 1(Tr), Serroni 1 (Se), Lacedonia 1 (La). Depth of the Apulian platform is marked by isolines.

4. RESULTS

4.1 Large scale reservoir

For the large scale reservoir we calculated the steady-state temperature field (Figure 3). Since the Apulian platform forms a relatively thick layer, free convection cells establish with a strong upward flow in the center of the region due to the geometry of the anticlinal structure. The size of the convection cells is considerably smaller than the model area and therefore the convection pattern is not influenced by boundary effects or the finite size of the model. In Figure 3b we illustrate the temperature at the top of the Apulian platform, the geothermal target layer. The depth from the ground surface to the top of the Apulian platform varies considerably in this area between 700 m and 4500 m. Accordingly, the temperature is lowest where this depth is the least, i.e. in the center of the model. Indicating the contour line for 2500 m below mean sea level, the thick black line shows temperature variations between 100 °C and 170 °C. This heterogeneous situation clearly demonstrates the importance of a careful choice for geothermal borehole locations.

Since effective permeability of the carbonates of the Apulian platform is not very well known, we also run a purely conductive heat transport model for comparison. A comparison of the temperature-depth profiles at the location of five boreholes with simulated temperature is shown in Figure 4a (conductive-advective transport) and Figure 4b (conductive transport only). Available temperature measurements in the five boreholes are color-coded. Temperature data from greater depth exist only from the Bonito 1 Dir and the Taurasi 1 borehole. The temperature data of the Bonito 1 Dir borehole yield a nearly constant temperature gradient which is in agreement with purely conductive heat transport, whereas data from the Taurasi 1 borehole show a signature of advective heat transport with a reduced vertical temperature gradient.

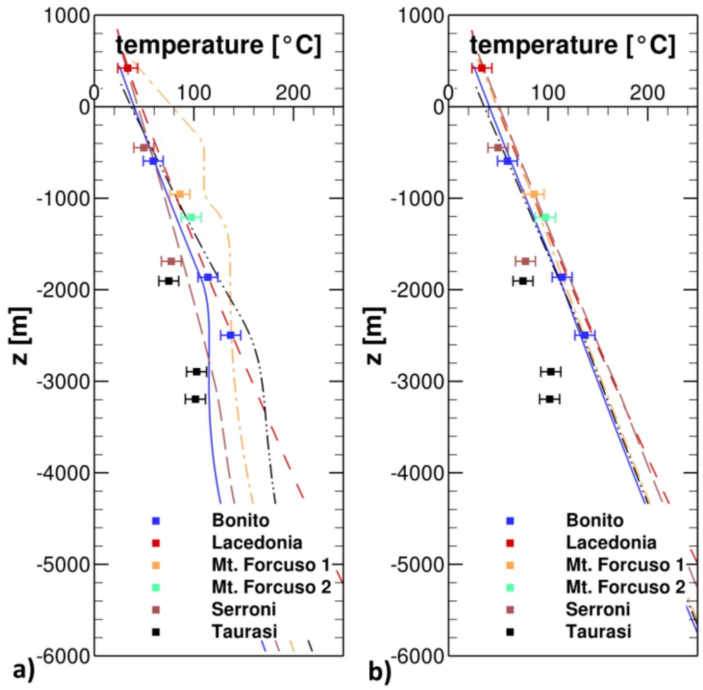

Figure 4: Comparison of borehole temperature data (colored symbols) and simulation results: a) Vertical temperature profiles from the simulation shown in Figure 3 (i.e. a steady-state simulation of conductive and advective heat transport) b) Vertical temperature profiles of purely conductive heat transport.

For the Guardia Lombardi region our conductive-advective model yields a number of convection cells in the geothermal target layer, as discussed above. In such a case, the type of vertical temperature profile which is observed at a particular location depends on the position of the borehole relative to the convection cells. We compare the temperature depth profiles resulting from the conductive-advective transport model with the observations for the Bonito 1 Dir and Taurasi 1 boreholes (Figure 4a). For both boreholes the model predicts temperatures clearly influenced by advective heat transport, but they do not agree well with data, in particular for the Taurasi 1 borehole. The reason for this discrepancy is presumably the assumption of a uniform permeability in the Apulian carbonate platform and the fact that our model does so far not resolve well potentially open fractures.

4.2 Scenarios for geothermal utilization

In a second step we modeled the performance of a geothermal doublet system in the Guardia Lombardi area. For selecting a site for the simulation of a geothermal installation we considered multiple factors as decision guidance. Amongst other things, these include the position of villages in the region as living environment of potential consumers, infrastructure, areas with preferential simulated temperatures at depth and natural restrictions (see Figure 5).

Three areas were selected, the most promising area located close to the Bonito 1 Dir borehole at the NW edge of the Guardia Lombardi region. The area was chosen due to the vicinity of a number of small villages, a temperature above 100 °C at 2500 m below ground surface (measured and predicted from our model). At this depth, drilling cost is at an acceptable level. The location is also far away from natural conservation areas and the site of the CO_2 emanation which may pose problems when drilling through the gas cap. Further, indicators for high permeability were found while drilling the Bonito 1 Dir borehole. Here we show the results for a numerical simulation of a geothermal doublet system installed close to the Bonito 1 Dir borehole.

For excluding boundary effects on the simulation, we chose the sub-model to be 7 km (North – South) × 7 km (East-West) × 2.5 km (depth). Note that the sub-model does not include the immediate subsurface below ground, and extends from a depth of 1.5 km down to 4 km. The discretization of the sub-model was refined to 140 × 140 × 50 nodes (cell size of 50 m × 50 m × 50 m). At the position of the sub-model, values for temperature and hydraulic head were extracted from the regional model, linearly interpolated from the coarser to the finer grid, and applied as boundary conditions to the sub-model. They are assumed to be constant over the simulation time. This type of boundary condition implies that all lateral boundaries are open with respect to heat and mass transport.

As initial thermal condition, we assessed the steady-state temperature field within the sub-model. At the center of this model we implemented a geothermal doublet system, roughly at the position of the Bonito 1Dir borehole. The producing borehole is situated at a depth of 2.6 km and the injector is placed at 2.4 km depth, with a lateral distance of 700 m among the two boreholes. Significant mud-losses had been recorded often at the top of the reservoir, indicating high natural permeability. Therefore a first implementation of a doublet system is situated close to the top of the reservoir. We simulated the production for 50 years with an average flow rate of 40 l/s.

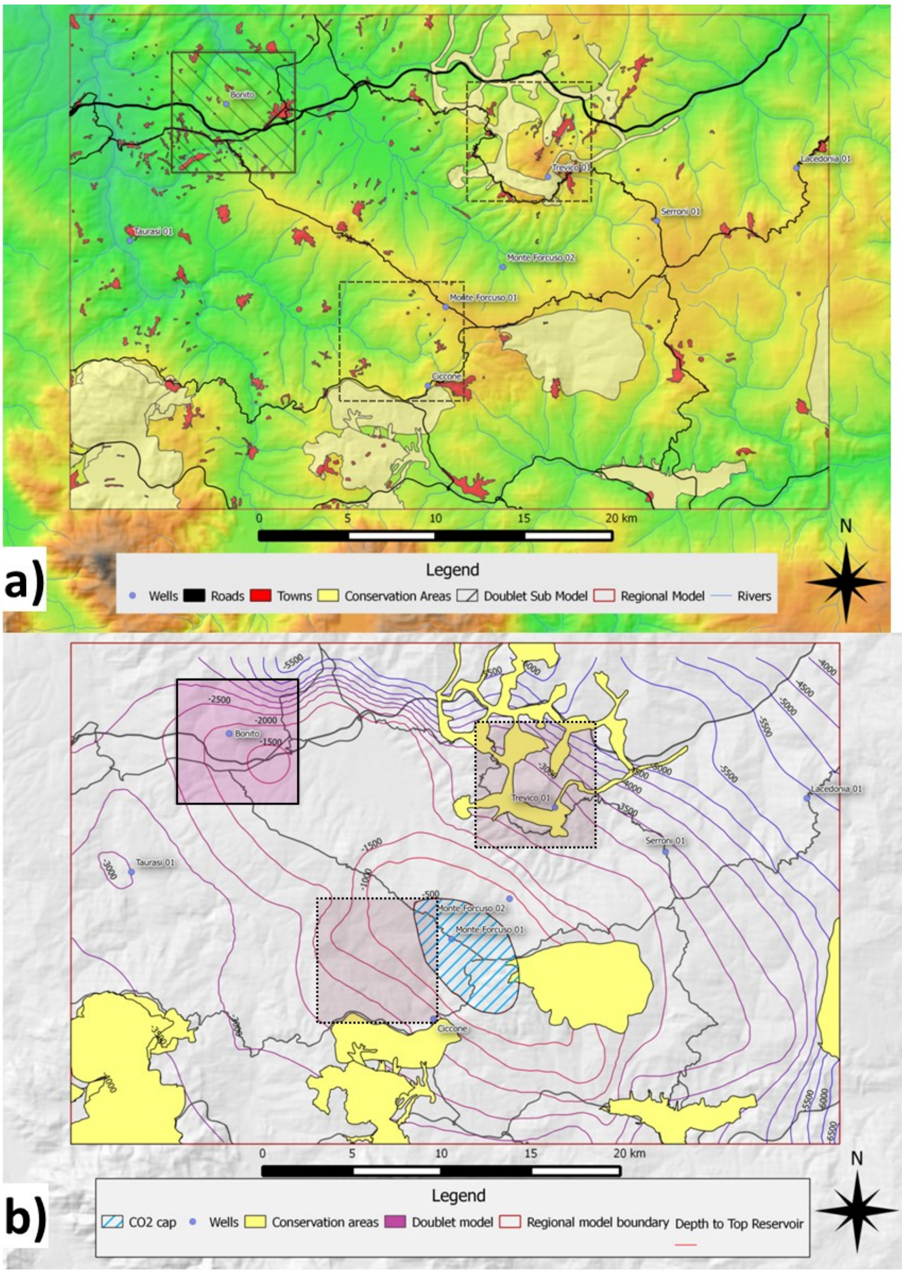

Figure 5: Data for decision making regarding geothermal use of the Guardia dei Lombardi area: a) Villages, natural conservation areas, and traffic paths. b) Top of the Apulia platform (i.e. top of the reservoir), extent of the area presumably filled with CO_2 (“CO_2 cap”) and natural conservation areas. The areas chosen for simulation of a geothermal doublet system are indicated by squares. Here we show the results for the most promising area located around the Bonito 1 Dir borehole in the NW corner of the region.

Figure 6 shows an idealized sketch of the hypothetical doublet system scenario within our model. A number of monitoring points was are placed in the vicinity of the producing borehole and in between producer and injector for monitoring the propagation of a cooling front with time. Here we show the temperature variation with time at the producer, half-way between producer and injector and close to the injector.

With the currently simulated flow rate of 40 l/s, no thermal breakthrough is observed at the producing borehole during 50 years of simulation time and only a very small temperature drop in the range of 1 K. However, halfway between producing and injecting boreholes, a notable thermal breakthrough occurs at 25 to 30 years of production. Considering the vicinity between the boreholes, this indicates that there is no dominant direct flow path between producing and injecting borehole. Inspection of streamlines suggests that fluid is produced from greater depth (Fig. 7). This may be attributed to the boundary condition which map a stable region of up-flow from the large scale model to the sub-model, in conjunctions with lateral boundaries which are open for flow and high reservoir permeability. Such a flow pattern can be expected for a thick reservoir layer with free natural convection as we observed in the large scale model.

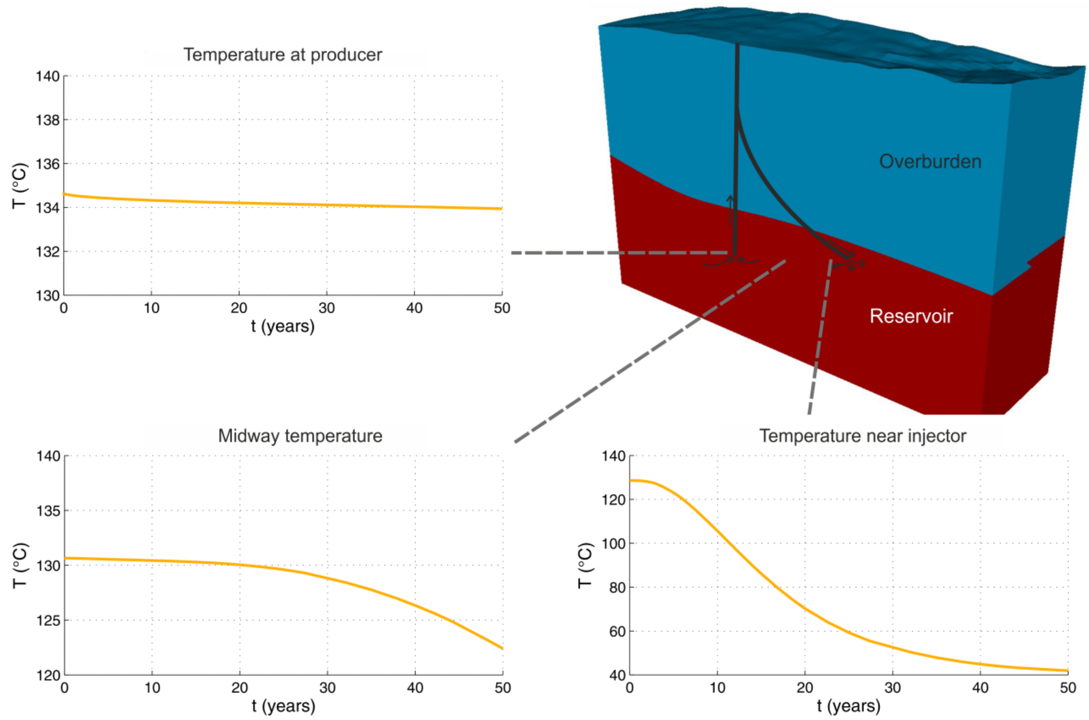

Figure 6: Sketch of the simulated doublet system and variation of temperature with time. The distance between injector and producer is 700 m. a) Temperature at the producing borehole, stable over 50 years of production. b) Temperature variation midway between producing and injecting boreholes, showing a significant thermal breakthrough at around 25 years. c) Temperature variation near the injecting borehole showing a large temperature drop already after 4 years.

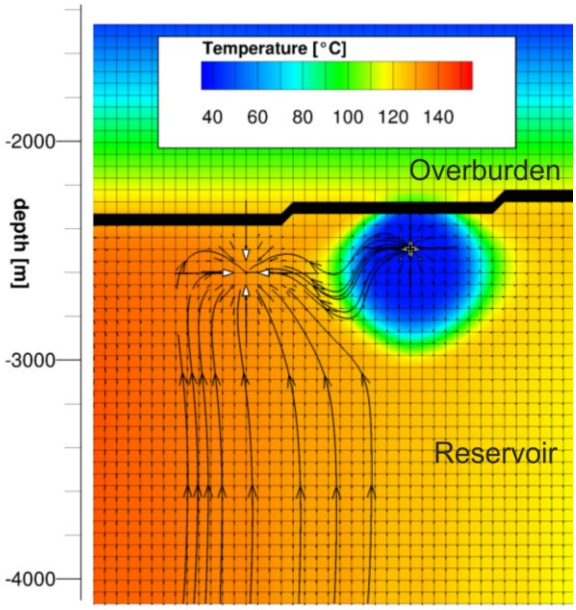

Figure 7: 2D slice of the sub-model at position of the geothermal doublet. The figure shows the temperature distribution after 50 years of simulation time. Streamlines indicate the major directions of flow. Note that the producing borehole is clearly supplied by water from greater depth. However, as streamlines and temporal temperature variations show, there is a hydraulic interaction between producing and injecting borehole.

5. CONCLUSION

We performed numerical simulations of natural fluid flow and heat transport in a fractured carbonate reservoir in the region Guardia Lombardi in Campania, Southern Italy for evaluating the reservoir's potential for geothermal use. Simulations were performed usingthe software SHEMAT-Suite. The model accounts for heat transport due to conduction and advection. Borehole temperature measurements were used for model calibration. The structural reservoir model includes the main lithological units, surface topography, and a number of large scale normal and thrust faults. Thermal conductivity and porosity were attributed to the rock units based on measurements on cores and published information. Permeability was estimated from reported results of drill-steam tests and productions tests in a number of (now abandoned) hydrocarbon exploration wells. Permeability was assigned uniformly to the entire reservoir, with no particular permeability attributed to the faults.

Given this model geometry, permeability, and specific basal heat flow of the Apulian carbonate platform, a significant impact of advection on the temperature distribution was observed in our large-scale model. We found lateral temperature variations at a depth of about 3 km (below m.s.l.) as high as 100 K. Therefore, an accurate prediction of location and extent of the convective cells is necessary for determining promising areas for geothermal exploitation.

However, some shortcomings of the large-scale model need to be considered, the most important being the influence of the faults, especially the steep normal faults. Clear evidence from field studies indicates, that some fault act as flow paths for rising CO_2, feeding the Mefite d'Ansanto surface emanation. From well logging reports it is known that in some wells significant losses of drilling fluid were encountered at the top of the Apulian platform or just below. This is a clear indication of at least locally increased permeability which might be due to an old karst surface. Hence, increased permeability related to some structural units is very probable in the reservoir. These structures may also act as large-scale flow paths for reservoir water and may be important for the thermal regime. Until now, these structures of enhanced permeability have not been considered and this is a task for future work.

Despite some shortcomings to be tackled, we provided a comprehensive evaluation of the resource in an area showing a large potential for economic use of geothermal energy. In a sub-model we evaluated a geothermal doublet system operation at a depth of 2400 m and 2600 m with a distance between injector and producer at depth of 700 m, which can be considered the lower limit of a feasible range. With these specifications a fluid flow rate of 40 l s^{-1} can be produced for a very long time (after 50 years of operation no thermal break-through occurred) at a temperature slightly above 130 °C. While this seems to be a promising result, the sustainability of the high temperature at the producer has to be considered with care. Since the water extracted by pumping at the producer stems from a depth greater than the lower end of the borehole, the temperature considered in our simulation is not realistic since it reflects the lower boundary temperature. This point has to be considered in more detail in the future, e. g. with a deeper model.

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