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Simulation of Flow and Heat Transport in a High-Enthalpy Reservoir in Tuscany, Italy

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ABSTRACT

The choice of injection/extraction or exploratory borehole positions and depths in geothermal fields of high enthalpy is a key issue in ensuring the success of the exploitation of such fields. These have to be chosen based on a very limited amount of information, making a proper handling of uncertainties inevitable.

The area of interest in this study spans an area of 22 km × 15 km, encompasses a largely unexploited geothermal field in southern Tuscany, Italy, and is characterized by geothermal gradients of over 100°C/km. Even though a relatively large amount of data from seismic profiles, boreholes, and laboratory measurements is available, the geological model, which comprises two target horizons in fractured metamorphic and sedimentary rocks as well as several faults, suffers from a large amount of uncertainty. For example, rock permeability distribution and fault location/type are crucial for the proper description of advective heat transport.

This work: 1) establishes a realistic reservoir model based on various interpretations of reflection seismic data and petrophysical core and cutting studies; 2) reproduces temperature measurements at various depths in a numerical simulation; 3) determines promising locations for production boreholes within the reservoir.

1. INTRODUCTION

Tuscany can be considered the birthplace of geothermal power generation. Thermal anomalies cause temperature gradients to exceed 100 °C/km locally, reaching maximum values of up to 300 °C/km (Della Vedova, 2008; Romagnoli, 2010). Situated in the hinterland of the northern Apennines, the Mt. Amiata region is an important geothermal resource in Italy. Operating geothermal fields in the region generate around 60 MW of electrical energy (Dini, 2010), exploiting the high heat flow of up to 100 mW/m².

An area (22 km × 15 km) within this region has been chosen by Enel Green Power, Italy for geothermal exploitation. The area is characterized by a high thermal gradient, presumably due to the presence of a young granite pluton at a depth ranging between about 4.5 km and 6 km. The variations in depth of this heat source cause strong differences in thermal gradient within the area. Fluid flow through the heterogeneously fractured sedimentary and metamorphic rocks further complicates and distorts the distribution of temperature. Such heterogeneity heavily influences the productivity and longevity of geothermal production installations, making the right positioning of boreholes crucial. With limited geophysical data, a high degree of uncertainty makes the choice of borehole positions difficult. Flow and heat-transport simulations, as presented in this study, can make a significant contribution at reducing uncertainty and improving the understanding of dominant processes and mechanisms.

The study presented here is part of the work program of the interdisciplinary MeProRisk ("Novel Methods for Exploration, Development, and Exploitation of Geothermal Reservoirs - a Toolbox for Prognosis and Risk Assessment") group and has been performed in a collaborative way involving working groups from universities and commercial firms. The MeProRisk approach combines interpretations of geological and geophysical field and borehole log data, with laboratory data and hydrothermal numerical simulations. In a companion paper to the WGC 2015 (Rabbel et al., 2015) the interpretation of seismic and gravity data from the area under investigation is discussed.

2. GEOLOGICAL BACKGROUND

The collision of the African (Adriatic microplate) and European plate gave rise to major fold-and-thrust belts such as the northern Apennines. This orogen consists of various thrust-related lithologies, ranging from marine and continental sediments to metamorphites. Compression due to continent-plate collision gave rise to an eastward stacking of these tectonic units (Brogi, 2008b). They comprise: a) Quaternary and Neogene sediments, accumulated in young graben systems and unconformably overlying pre-Neogene units; b) Ligurian and Subligurian units, which consist of remnants of the oceanic crust and its marine to pelagic sedimentary cover; c) Tuscan Nappe units, represented by continental margin deposits (Triassic to Miocene) of the Adria paleomargin, comprising basal evaporites, overlain by carbonate and pelagic-turbiditic successions (Batini et al, 2003; Brogi 2008a and references therein). The compressional regime transitioned into an extensional stress regime, as is indicated by two generations of normal faults (low- and high-angle normal faults) throughout the inner zone of the northern Apennines. The units in the area under consideration in this work, which is in southern Tuscany, are situated in this inner zone and, hence, affected by these tectonic phases, i.e. compression followed by extension.

Integrated studies in the inner zone of the northern Apennines yielded the hypothesis that, during the extensional phase, the Tuscan Nappe units were affected by mega-boudinage (e.g. Brogi, 2006, 2008b); see Fig. 1. The resulting mega-boudins (also called

extensional horses) are “isolated” patches of Tuscan Nappe successions separated from other strata by low-angle normal faults (LANFs), whereas high-angle normal and transtensional faults reflect the youngest stage of extension and displace previously developed structures (Brogi, 2008c). While this hypothesis explains geologic field data, it primarily considers the sedimentary complex above a detachment horizon. During deformation, shear strain was accumulated in incompetent units, e.g. the basal evaporitic layer of the Tuscan Nappes: the Burano formation. It served as a detachment during the tectonic evolution of the target area and separates the upper sedimentary complex from the deeper Tuscan metamorphic complex. During the compressional tectonic setting, units belonging to the metamorphic complex were affected by high-pressure/low-temperature (HP/LT) metamorphism. The metamorphic complex consists of the Monticiano-Roccastrada unit (MRU) which is usually divided into three sub-units (MRU1–3). From top to bottom, these are: The Verrucano unit (MRU1, Triassic), comprising metasandstones and metaconglomerates; a phyllite succession (MRU2, Carboniferous), which consists of graphitic phyllites and metasandstones; a micashist group (MRU3). The MRU1 as well as a deeper gneiss complex known from other geothermal areas in Tuscany are not encountered in boreholes close to the study area, but found as xenoliths in Quaternary lavas in the area (van Bergen, 1983).

As deformation affected both sedimentary cover and metamorphic complex (Fig. 1), the occurrence of duplex structures and thrust-related repetitions of units do also occur in the metamorphic units, e.g. the MRU2 units (Brogi, 2008b). Brogi (2008) considers deformation in the metamorphic complex and its lateral segmentation during the extensional phases as connected to a migration of the brittle-ductile transition to greater depths.

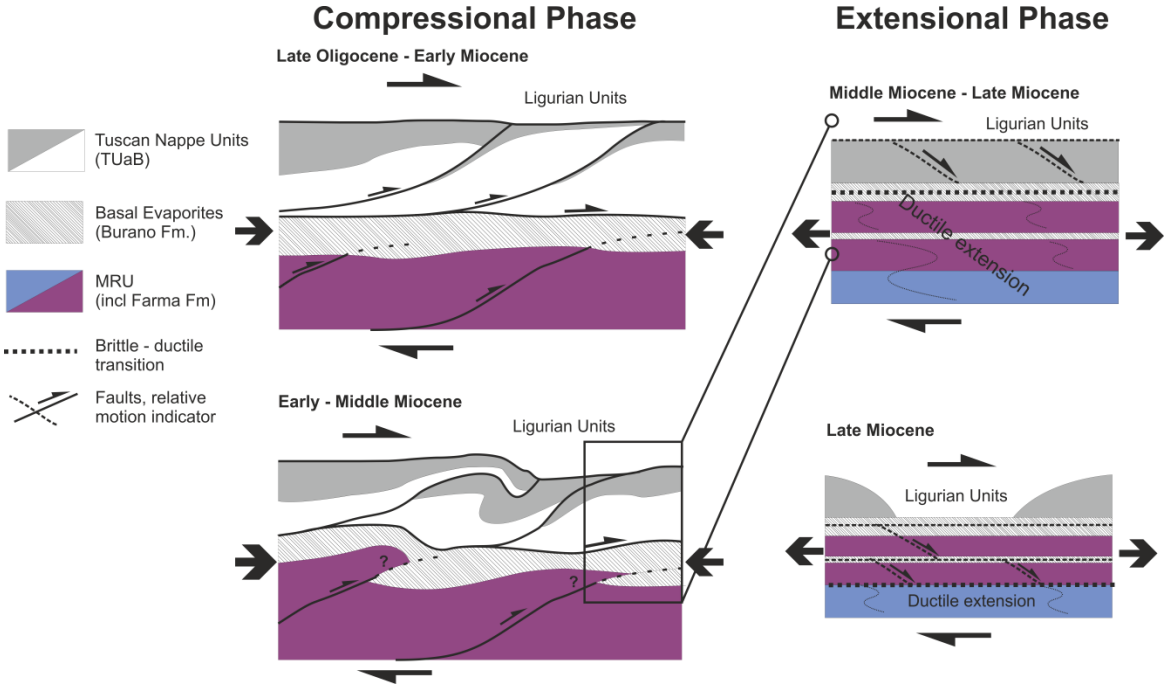

Figure 1: Schematic illustration of the possible evolution of compressional and extensional structures which affected the sedimentary and metamorphic complexes. During the compressional stage, eastward stacking of Ligurian units onto the Tuscan Nappe units and MRU occurred with a contemporaneous development of duplex structures. During middle to late Miocene, the stress regime transitioned from compressive to primarily tensile, causing the segmentation of units by step-wise low angle normal faults above the brittle-ductile transition and ductile extension beneath it (modified from Brogi, 2006; 2008b).

Accepting the described mega-boudinage of the Tuscan Nappe units of the sedimentary complex, several implications for the structural interpretation of the subsurface of our study area can be deduced:

1) During the compressional tectonic setting, an eastward stacking of the sedimentary units (Ligurian down to Tuscan Nappe units) is contemporaneous to eastward thrusting and the generation of duplex structures within the Monticiano-Roccastrada units (Brogi, 2008b; Carmignani et al., 2001, and references therein).

2) Shear strain was concentrated in more plastic layers, resulting in detachment horizons such as the phyllite succession in the MRU or the basal evaporites of the Tuscan Nappe units (Burano Formation). As a consequence, the Burano formation and MRU3/MRU2 formed repeating sequences with more competent units. Alternation of Burano formation and Phyllite sequences was found in some deep boreholes outside the sudy area.

3) During the extensional tectonic setting, lateral segmentation of the sedimentary cover by means of boudinage and the development of LANFs led to the generation of extensional horses, i.e. isolated patches of Tuscan Nappe units. Ligurian units fill the arising accumulation space by segmentation.

4) Segmentation of the sedimentary complex predates segmentation of the metamorphic complex and connected crustal thinning due to migration of the brittle-ductile transition to greater depths. As a consequence, it is assumed that extension in the MRU

transitioned from ductile extension to an extensional duplex system (Brogi 2008b), i.e. the duplex structures formed during compression are separated by LANFs during subsequent extension.

5) Due to high strain rates, the lateral thickness of the Burano formation is highly variable.

In our structural model, those key features are represented by: (1) stacking of the Burano formation (basal evaporites) and palaeozoic phyllites (referred to as the Farma formation) deduced from seismic interpretation; (2) Modeling the Tuscan units above Burano (TUaB) as extensional horses, i.e. mega-boudins bound by LANFs; (3) Implementation of high-angle normal faults as structural elements, displacing older strata.

The structural model (Fig. 2) was developed using an implicit modeling approach (Lajaunie, 1997) implemented in the software 3D GeoModeller. Structural interpretation of five seismic sections in the study area and geological data from the surface constitute the main sources of input data for our geometrical model. Three strong reflectors in the seismic sections were attributed to the tops of the Burano formation and the K horizon. This horizon (Fig. 2) is a prominent feature in geothermal areas in Tuscany, whose nature is still a major point of discussion (reflector of the top of recent granitoid intrusion, shear zone at the top of the brittle-ductile transition, or a horizon/part of carapace penetrated by supercritical fluids) (Batini, 2003; Bertani, 2005; Bertini 2006; Romagnoli, 2010)..Even though the nature of the K horizon is not clear, experience from operating geothermal fields (e.g. Larderello and Travale) suggest that the K horizon corresponds to an isotherm of between 400 °C and 450 °C. This is a crucial assumption for our numerical model.

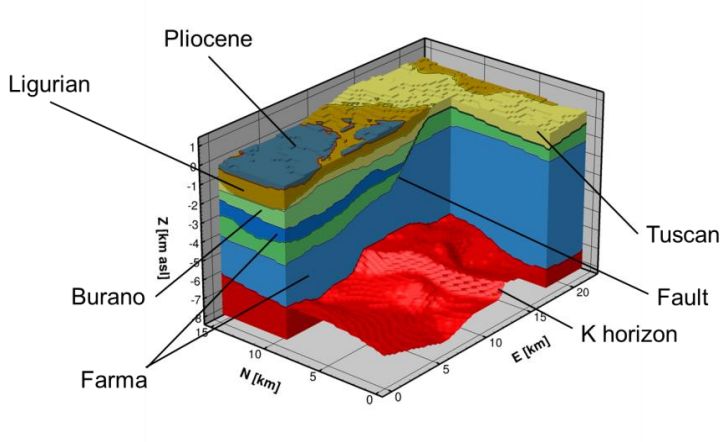

Figure 2: Geological model of the area of interest. Ligurian units fill accumulation space between separated patches of the Tuscan Nappe unit. Since there are no clear demarcations in seismic sections, the MRU was not divided into its subgroups and will henceforth be referred to as the Farma formation. Stacking of the MRU and Burano formations is inferred in the western side of the model.

In addition to the five seismic sections, accessible input data for our models comprise:

- A gravity survey over the whole model area;
- Magnetotelluric measurements;
- Temperature data and geophysical logs from 3 boreholes;
- Core and cutting material for laboratory measurements on thermal conductivity, density, and matrix porosity (only on core).

This integrated database not only provides the geometric input for the structural model, but also the possibility of calibration and the definition of rock properties which are assigned to the corresponding units in the numerical model (Table 1).

3. HYDROTHERMAL SIMULATIONS

The structural model shown in Fig. 2, of dimensions 22 km × 15 km × 9 km in *E* (East), *N* (North), and *z* (depth) directions, respectively, has been discretized in a hexagonal grid with block is of dimension 250 m × 250 m × 100 m. Based on this model we performed flow and transport simulation with the code SHEMAT-Suite, a simulator based on the finite-difference scheme and capable of modeling steady-state and transient hydro-geothermal reservoirs.

Two coupled equations (flow, Eq. (1), and heat transport, Eq. (2)) are solved iteratively in steady state to obtain hydraulic head h [m] and temperature T [°C].

$$\nabla \cdot \left[\frac{\rho_w g \mathbf{K}}{\mu_w} \left(\nabla h + \rho_r \nabla z \right) \right] = 0 \tag{1}$$

Here, **K** is permeability [m²], h is the hydraulic head [m], z is the vertical coordinate in space [m] (positive upward), ρ_w is water density [kg/m³], μ_w is the dynamic viscosity of water [kg/(m s)], g is gravity [m/s²] and $\rho_r = (\rho_W - \rho_0)/\rho_0$ accounts for the difference between water density and a reference density (at atmospheric conditions).

$$\nabla \cdot \left(\rho_w h_w \mathbf{v} - \lambda_e \nabla T \right) = H \tag{2}$$

where h_w is the specific enthalpy of the fluid [J/(m³ K)], **v** is the Darcy flux [m/s], λ_e is the tensor of effective thermal conductivity [W/(m K)] and H the radiogenic heat production [W/m³]. The simulator comprises several constitutive relationships which relate fluid and rock properties to temperature and pressure. In particular, the physical properties of supercritical water (i.e. density, enthalpy, viscosity, and thermal conductivity) are calculated using the correlations provided by the International Association for the Properties of Water and Steam (Wagner, et al., 2000). It should be noted that the physical conditions that prevail in the reservoir do not allow for the existence of two-phase (water/steam) conditions. For further information on the simulator SHEMAT-Suite, see Rath, et al. (2006).

Table 1 lists rock properties of the various geological units in the simulation model. These properties are obtained from a petrophysical analysis of rock cores and cuttings from boreholes in the area and well-logging data. The values highlighted in grey are estimated from literature, whereas those in bold face are adjusted to fit the available borehole temperature data. Note that thermal conductivity decreases with temperature (Zoth & Haenel, 1988). Rock permeability is primarily caused by fractures which have been assumed to lead to an isotropic, depth-dependent permeability (Manning & Ingebritsen, 1999); the dependence on depth being as a result of fracture sealing due to the overburden. Hence, the permeability K is expressed as an exponential function of overburden thickness z_b, a maximum permeability K_0, and a scaling factor d.

$$K = K_0 e^{-z_b / d} \tag{3}$$

The value of the scaling factor is unknown. It has, in combination with the maximum permeability, been fit to the temperature measurements as 1000 m. However, since very little information is available on the values of K_0 and d, a large amount of uncertainty persists in the model, making a detailed study of the influence of these parameters on uncertainty essential in future work.

Table 1: Simulation parameters

Parameter/property	Farma	Burano	TUaB[c]	Ligurian	Pliocene
Matrix thermal conductivity [W/(m K)][a]	4.10	4.73	4.10	2.54	1.30
Heat production rate [μW/m^3]	1.42	0.16	0.32	0.14	0.14
Porosity	0.03	0.02	0.10	0.1	0.1
Permeability [10^{-15} m^2][b]	**0.60**	**10.0**	**1.00**	0.1	0.1

[a] Value at surface. Thermal conductivity is decreases with temperature.
[b] Maximum value for given unit within domain. Permeability is depth-dependent.
[c] TUaB: Tuscan units above Burano.

3.1 Boundary Conditions

At the top of the domain, i.e. at the land surface, the temperature is dependent on air temperature, and thus topography. The values are determined using a set of shallow-well temperature measurements with temperatures ranging from 22 °C to 41 °C at depths between 147 m and 200 m below the ground surface. The hydraulic head at the land surface is set to be equal to the elevation of the land surface (topography).

As mentioned in Section 2, the K horizon is assumed to represent a 450 °C temperature isotherm, thus providing a boundary condition at the bottom of the domain. There is no flow across the K horizon.

In order to obtain lateral boundary conditions for temperature, a steady-state simulation is run with no-flow lateral boundaries (top and bottom boundaries are as described above), producing a temperature distribution which accounts for conductive and convective heat flow. The results of this simulation are stored and used as the lateral boundary conditions for temperature. The hydraulic head at the lateral boundaries are chosen to be equal to the land-surface elevation.

3.2 Simulation Results

The steady-state temperature distribution in the model domain in Fig. 3 depicts the general conductive flow of heat from the 450 °C isotherm at the K horizon to the surface and the deviation thereof as a result of advective heat transport due to the regional groundwater flow and free convection. As such, the distribution of temperature is primarily influenced by the depth of the K horizon in that area and the direction and magnitude of fluid velocities.

Lateral flow through the domain occurs mainly in the Burano formation due to their relatively high permeability. The general direction of flow is from NE to SSW. This can be seen in Fig. 4 which depicts the Darcy flow at a depth 1 km below sea level.

A comparison of simulation results with available borehole measurements (exclusively in the eastern part of the domain) shows a good fit at depths down to approximately 1.5 km below msl (see Fig. 5). The change in temperature gradient with depth in Borehole°2 (of Fig. 5), which occurs in the highly permeable Burano formation, is also represented. At greater depths, temperatures are underestimated. This is most probably due to the presence of a zone or zones of increased permeability (due to an increased

fracture density) in the Farma formation which, for lack of adequate data, has not been incorporated in the model yet. The temperature distribution particularly in Borehole 2 shows an area with a steeper temperature gradient which could be due to increased convection in that area. A reinterpretation of seismic profiles in which one correlates areas of high reflectivity with high fracture density could help account for this phenomenon in the model.

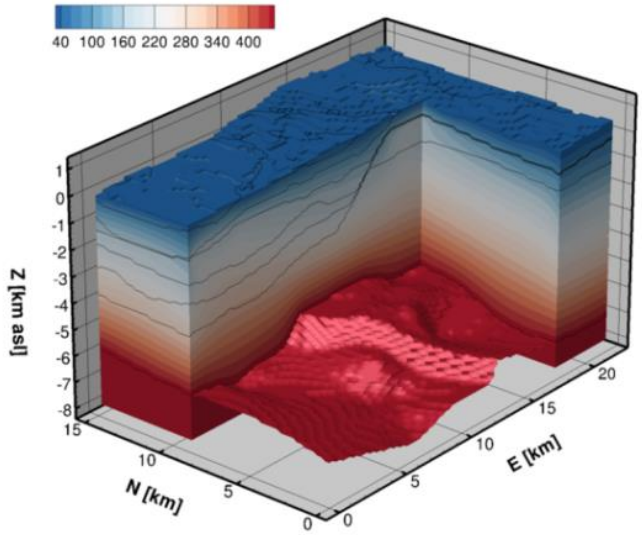

Figure 3: Steady-state temperature distribution in °C in the simulation domain. The K horizon is shown as an isosurface near the bottom.

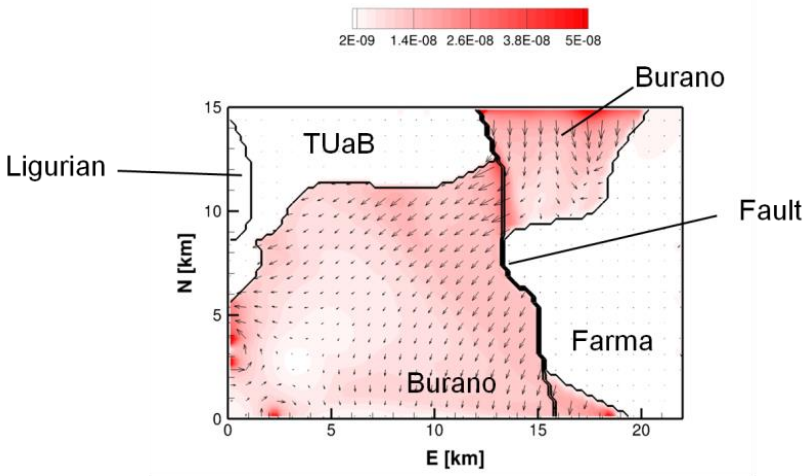

Figure 4: Magnitude (in color) and direction (arrows) of the Darcy-flow vector 1 km below mean sea level (in m/s). Due to the permeabilities of the units, flow occurs mainly within the Burano formation.

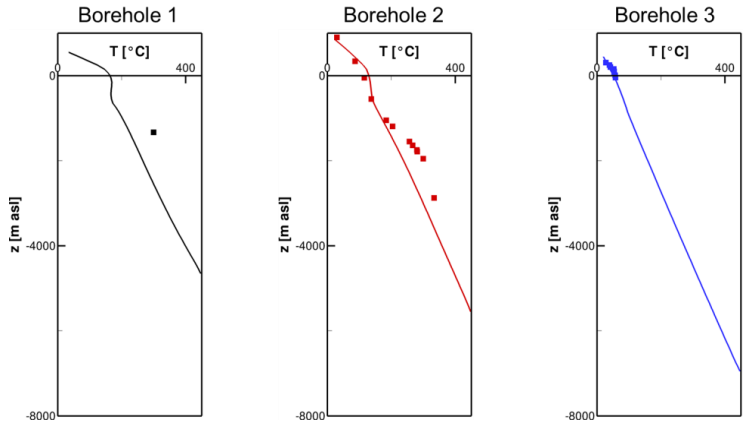

Figure 5: Comparison of temperature profiles from simulation (lines) with borehole measurements (symbols).

3.3 Discussion of Results

These steady-state simulations provide a useful tool with which one can study the thermal regime and identify promising areas for geothermal production. In Fig. 6, 250 °C and 200 °C isotherms within the model domain are shown and overlaid with a permeability color map. The highest temperatures are achieved where the heat source (K horizon) is shallowest, i.e. in the northeast and where the strata of permeable rocks are thickest, i.e. in the northwestern part. A thick geothermal reservoir (in this case composed of the Tuscan units – Burano and TUaB) produce larger amounts of convection, transporting hot water to shallower regions. Hence, further exploration and/or exploitation of the reservoir would most likely be successful in the northern part of the reservoir. That notwithstanding, there are several sources of uncertainty, the adequate quantification of which is a prerequisite for accurate predictions regarding the selection of suitable sites for geothermal exploitation. Uncertainties stem mainly from the lack of precise information with respect to rock-permeability distribution as well as location and shape of the heat source. Further, the geological interpretation of seismic profiles and logging data from boreholes to obtain a geological model (e.g., as shown in Fig. 2) leaves room for different interpretation. Some of the choices in interpretation of geophysical data may have significant consequences for the flow and heat-transport processes and ultimately on the simulation results.

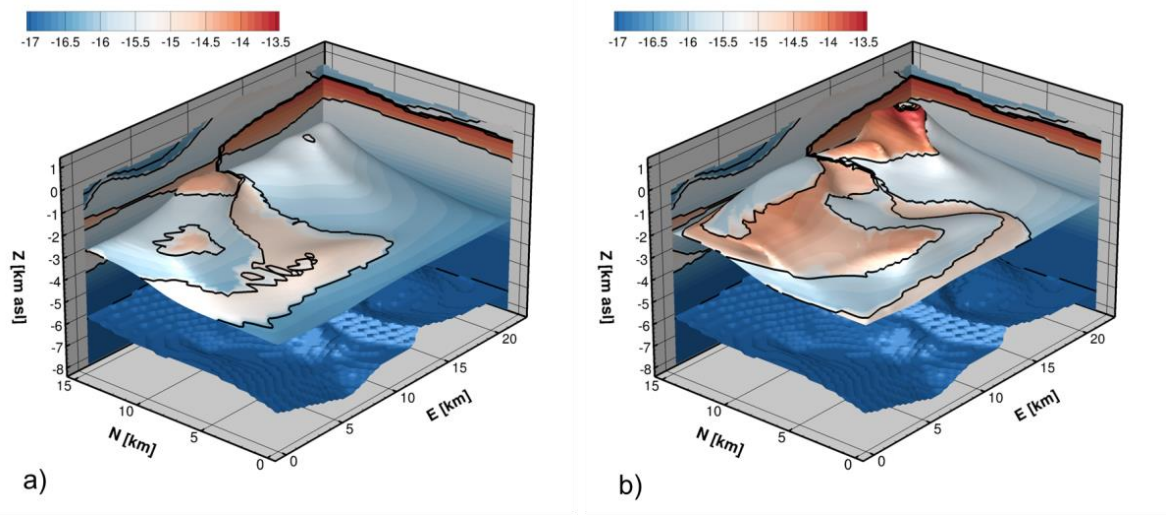

Figure 6: 250 °C (a) and 200 °C (b) isothermal surface. Logarithm of permeability (in m²) is shown in color. Black lines demarcate rock unit boundaries.

4. CONCLUSIONS

The largely unexploited, high-enthalpy geothermal reservoir in southern Tuscany presented here is characterized by relatively large variations in temperature gradients presumably due to the varying shape and depth of the young granitic intrusion (heat source) and the heterogeneous flow field. A successful geothermal exploitation relies on the proper choice of borehole positions. Due to the limited amount of geophysical data, a high degree of uncertainty makes this a difficult task. Flow and heat-transport simulations help in understanding dominant processes and in the handling of uncertainty.

A realistic reservoir model based on interpretations of reflection seismic data and petrophyscial core and cutting measurements is established and is the basis of the simulation model. It comprises a metamorphic basement and basal evaporites overlain by Tuscan Nappe and Ligurian units. The simulation model reproduces temperature measurements at various depths. The temperature distribution predicted in the simulations provides crucial information on rock strata of high permability and fluid flow direction, and on locations where high temperature gradients can be expected at shallow depths. Considering the model results the most appropriate region for geothermal exploitation is in the northern part of the study area.

The temperature data hints at possible zones of high permeability within the metamorphic basement not captured by the simulation model. A reinterpretation of seismic reflection data with the aim of identifying areas of high fracture density could aid in accounting for such zones.

The handling of uncertainty as introduced, e.g. by interpretation of geophysical data or heterogeneous parameter distributions (particularly permeability and thermal conductivity) will be tackled by the use of various stochastic approaches such as inverse modeling, Monte Carlo simulations, and the application of the “optimal-experimental-design” approach.

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