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Geothermal resources characterization of two areas in southern Tuscany

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1 - INTRODUCTION

Based on a joint analysis of geothermal indicators (e.g. temperature map at different depth, surface heat flux) and practical features (e.g. restricted areas, existing research lease), two promising areas in southern Tuscany were identified to perform a more detailed geothermal resource characterization. An area is located on the north-east of the Larderello-Travale geothermal field, and the other one is located on the west of the Mt. Amiata geothermal field.

A quantitative geothermal resources assessment was performed in the aforementioned areas of Tuscany by solving numerical thermo-fluid dynamic models and by computing the geothermal potential using the 'ThermoGIS' code, as further developed for the Italian case (Trumpy et al., 2016).

The resource assessment was carried out in two areas of the southern Tuscany (Italy). First area (of about 67 km^2) is located between **Larderello and Travale** while the second (of about 165 km ^{2}) is nearby **Mt. Amiata**, Figure 1.

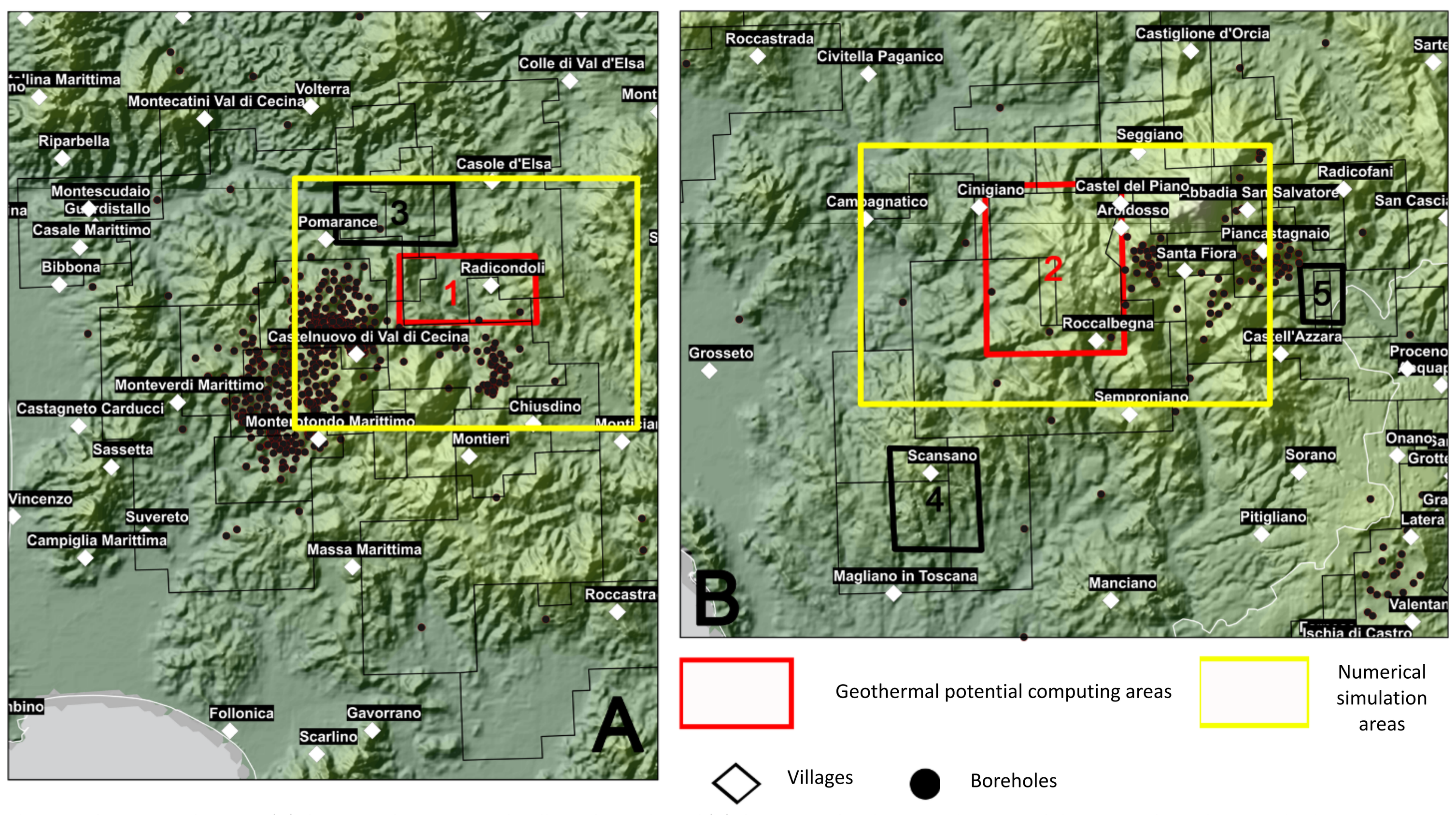

Figure 1: the two study areas: (A) the sector between Larderello and Travale and (B) the sector closeby M. Amiata. In red the areas where the quantitative geothermal resources assessment was performed. In yellow the extension of the numerical thermo-fluid dynamic models for the characterization of the underground thermal field. The white diamonds are the locations of the main villages and the black dots denote the distribution of the used deep borehole in the assessment.

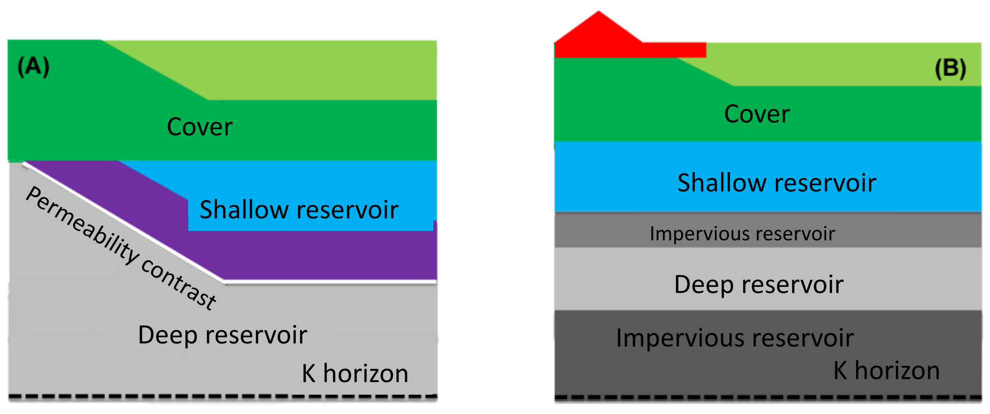

Figure 2: Conceptual models of the A) Larderello – Travale and B) M. Amiata geothermal system.

2 - METHODOLOGY

The applied methodology for the geothermal resource assessment relies on the **volume method** (Muffler & Cataldi 1978, Cataldi et al. 1978, Trumpy et al. 2016). With this approach is possible to compute the **Heat in Place**, H_{TOT} (in Joule, J), which is the maximum theoretically available heat from the reservoir.

Moreover, it is then possible to derive the power (in electrical Watt, W_e) producible by the same reservoir in relation to the used technology, so called **Technical Potential**, TP (in Mwe). We discretise the geothermal reservoir in 3D cells (voxel) 1 x 1 x 0,1 km^3. The H value for each cell, H_i, of the 3D grid results from the equation:

$$H_i\ [PJ/km^2h] = V_i * \rho_{rock\ I} * Cp_{rock\ I} * (T_i - Ts) * 10^{-15}$$

where V_i is the volume (m^3), r_{rock} is the density (kg m^3), Cp_{rock} is the specific heat (J kg^{-1} K^{-1}), Tx is the temperature at depth x, and Ts is the surface temperature, Table 1.

The TP value for each cell, Tp_i of the grid results from the equation:

$$Tp_i\ [MW/km^2] = \frac{H_i\ \eta\ R\ 10^{15}}{30\ year\ (second\ per\ year) 10^6}$$

where η is the electrical efficiency, the factor H_i is computed as the previous heat in place but instead of the surface air temperature a re-injection temperature is considered and R is the recovery factor depending on the fractured of rocks, permeability and rocks temperature.

The map of H and TP is calculated as the vertical sum of the grid cells divided over the surface area of the grid cells in km^2.

Table 1 – Used values	Tuscany	
Reservoir	Shallow reservoir	Deep reservoir
Density ρ (kg/m^3)	2600	2700
Specific heat Cp (J/(kg K))	836	877
Water density ρ (kg/m^3)	1078	1078
Water specific heat Cp (J/(kg K))	4250	4250
Minimum production temperature (°C)	120	120
Re-injection temperature	107	107
Recovery factor	10%	2%

3 – GEOLOGICAL SETTING AND CONCEPTUAL MODEL:

The Appenine chain is the result of the recent Pliocen-Quaternary continent-continent collision, where silicic batholitic are emplaced at shallow level in the crust, during the late extensional orogenic tectonic.

The Larderello-Travale geothermal system is located in the inner sector of the Norther Apennines. This region is affected by eastward migrating extensional tectonics subsequent to a migration of compressional tectonics at the front of the belt.

The geothermal system in southern Tuscany present two main geothermal reservoirs. The **shallower reservoir** is hosted in the sedimentary carbonatic and evaporitic rocks belonging to the Tuscan nappe and the tectonic wedge complex where the permeability is mainly related to the karst and tectonic processes (in cyan and violet in Figure 2). The **deeper reservoir** is in the metamorphic basement units that are characterised by a a permeability due to fractures and tectonic discontinuity (in light grey in Figure 2). The geothermal systems are seated under impervious rocks mainly made by neogenic sediments and Ligurian units (green and light green in Figure 2).

4 - MODELLING

First of all, geological and geophysical data required for geological and thermo-fluid dynamic modelling were collected and organised. The geological data were used to build a **3D geological model** of the two areas of interest suitable for numerical simulations. The **thermo-fluid dynamic simulations** were carried out starting from a steady state conductivity model solution and considering an hydrostatic pressure. The velocity fields was considered as null. The numerical models of the Larderello-Travale and Mt. Amiata are limited to the bottom with the brittle-ductile transition at a temperature varying between 450 and 550 ° C.

The shallow reservoir has a permeability between 10^{-16} e 10^{-14} m^2 while the deep reservoir has a lower values of 10^{-18} e 10^{-16} m^2.

As boundary conditions for the solution of the heat-transport equations the surface average air temperature per year was considered together with the aforementioned bottom temperature.

Static temperature data gathered from the Italian National Geothermal Database together with site-specific heat flow measurements were used to calibrate the simulated temperature distribution, Figure 3.

Temperature maps @ 1, 2, 3, 4, 5 km depth (sea level) were extracted from the thermal models of the two areas and allow to define the minimum exploration depth for the mining target, Figure 4 and 5.

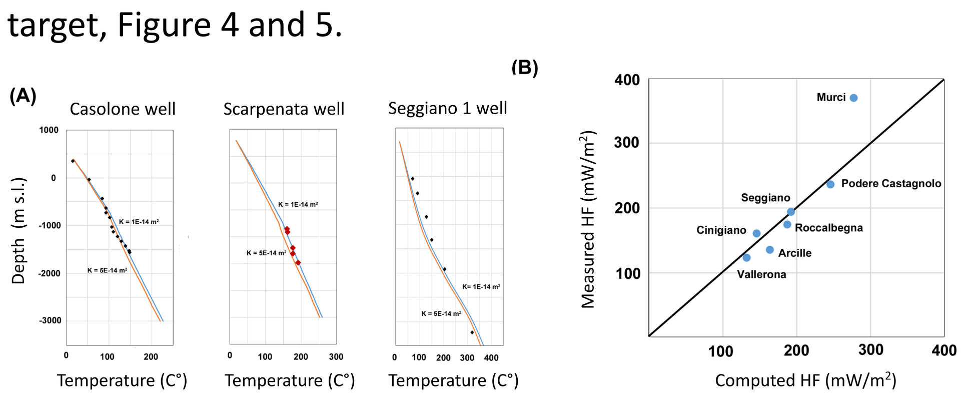

Figure 3: Thermal Model calibration in Tuscany, A) comparison between the measured and computed thermal profiles for the selected deep boreholes for the Larderello – Travale and Mt. Amiata areas. The reported geotherms are computed considering the permeability values of 5 10^{-14} e 1 10^{-14} m^2 for the shallow reservoir and 1 10^{-16} m^2 for the deep reservoir. B) Comparison between the measured and computed for the M. Amiata area.

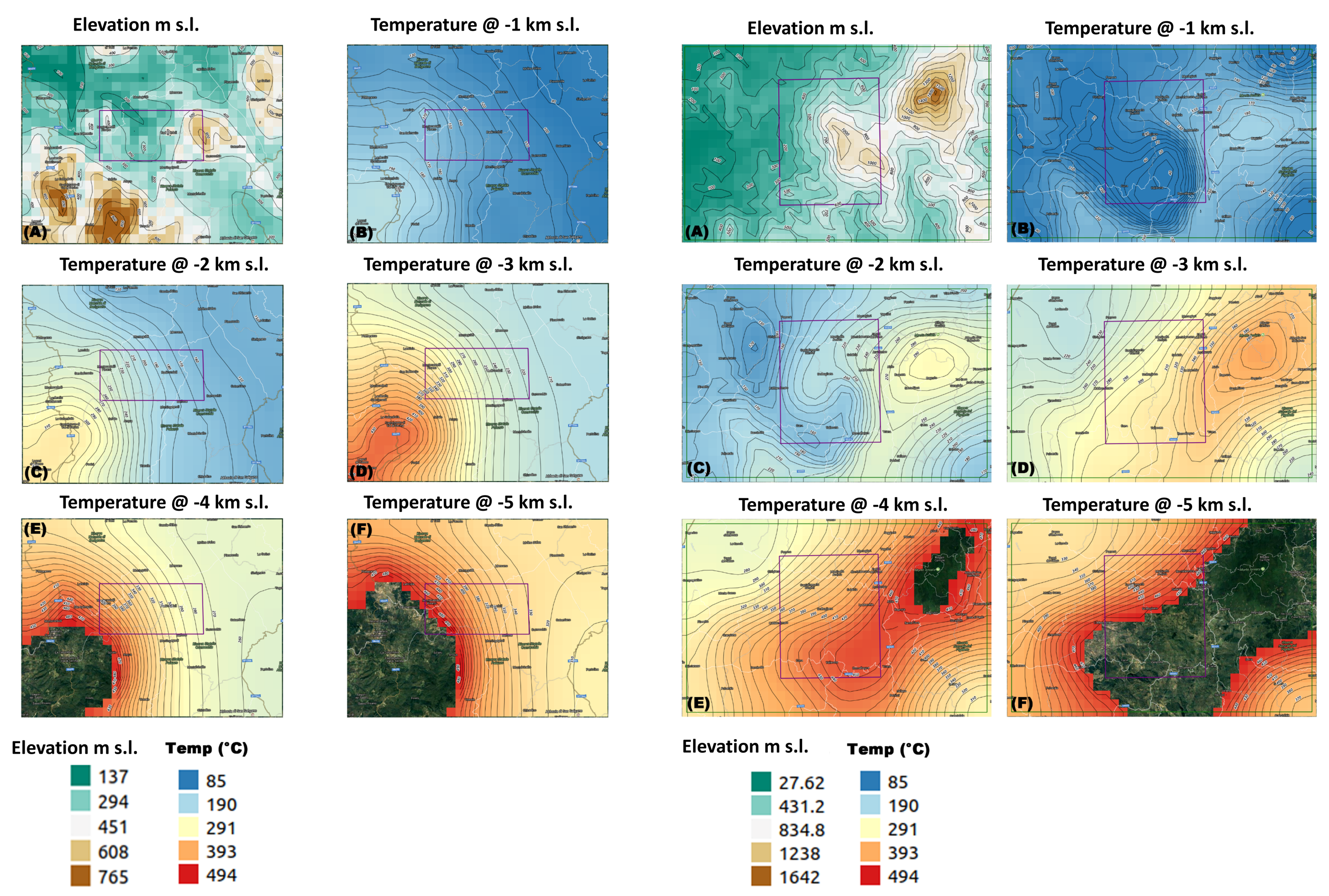

Figure 4: Maps of the distribution of the temperatures at different depths referred to the sea level in the area of Larderello – Travale (on the left side) and Mt. Amiata (on the right side). A) ground level elevation, B) temperature @ -1000 m sl.m., C) temperature @ -2000 msl.m., D) temperature @ -3000 m s.l.m, E) temperature @ -4000 m sl.m., F) temperature @ -5000 m sl.m.

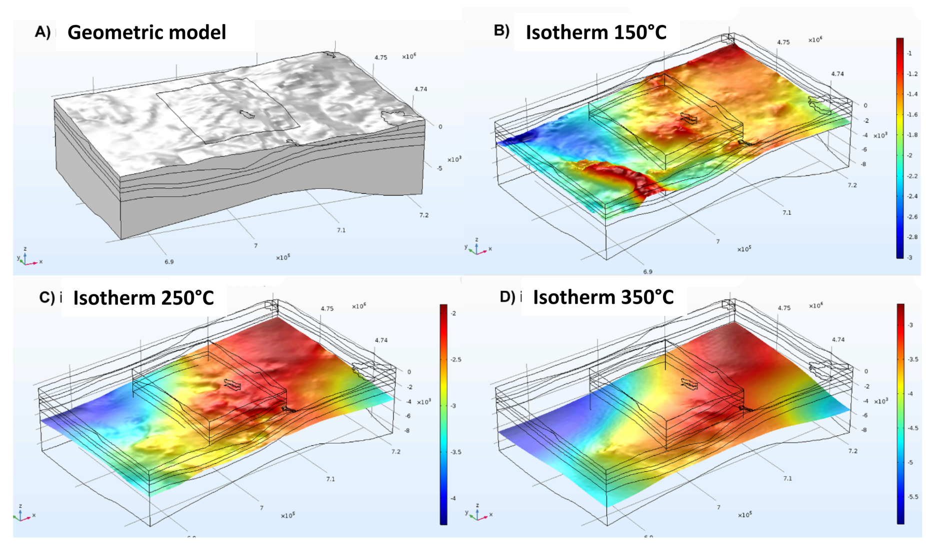

Figure 5: Example of the numerical model of Larderello – Travale: A) Geometric model of the litho thermal units, B) 150°C isotherm, C) 250°C and D) 350°C.. Elevation referred to the sea level.

5 - RESULTS

The geothermal potential computed by integrating geological, thermal and petro-physical information implementing the volume method used in ThermoGIS provided estimates of the **heat in place** and the geothermal **technical potential** maps, Figure 6 and 7. The resulting technical potential in the area close to Larderello –Travale is 330 MWe and in the Mt. Amiata sector is 44 MWe, Table 2 A and B.

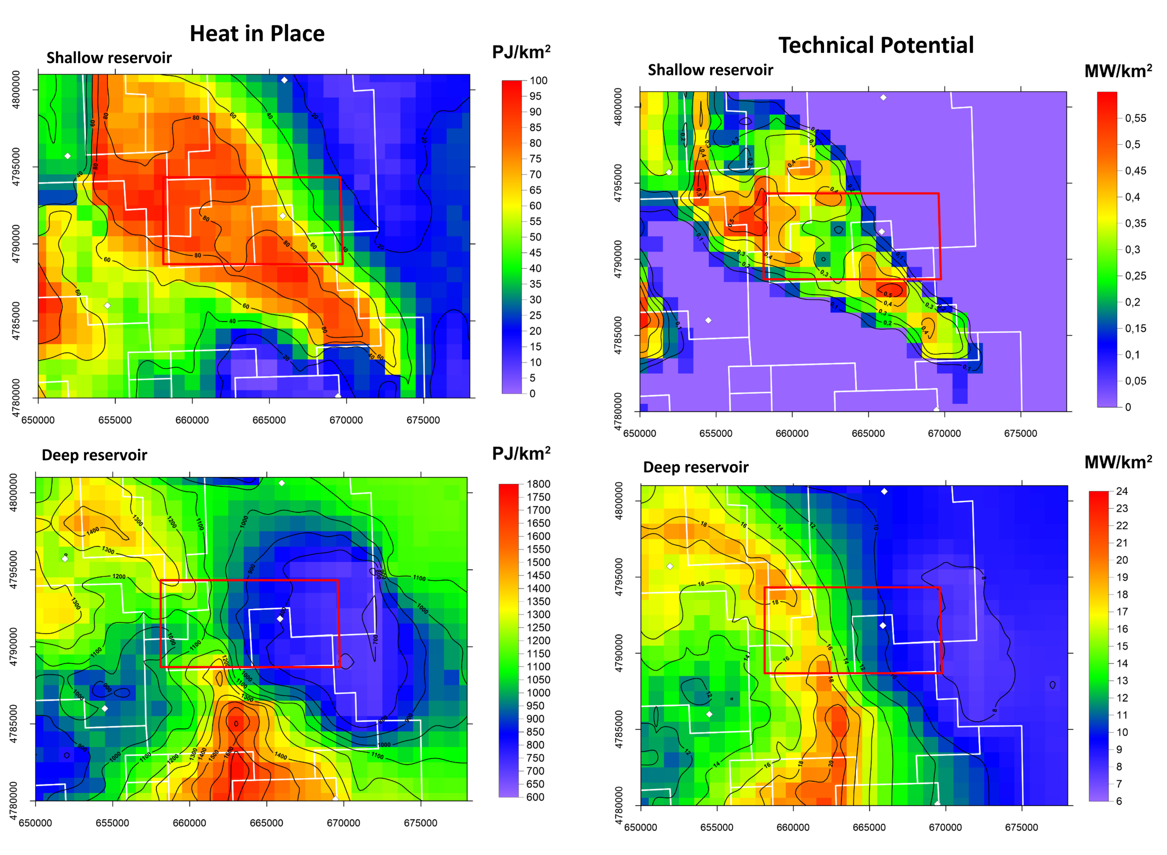

Figure 6: Heat in place and technical potential resulting maps for the Larderello – Travale area

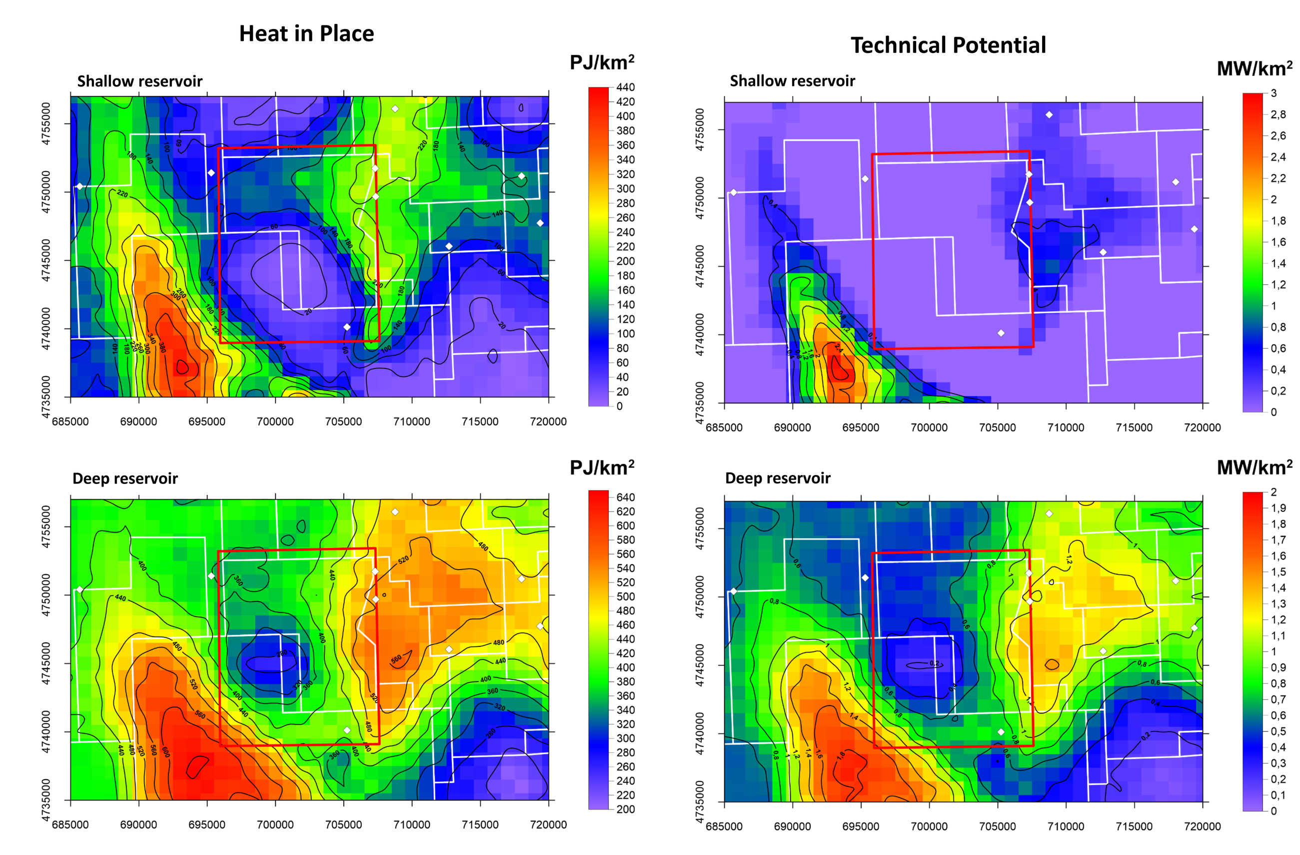

Figure 7: Heat in place and technical potential resulting maps for the M. Amiata area

Table 2A – Heat in place and technical potential for the Larderello – Travale area		
Potential	Shallow reservoir R=10%	Deep reservoir R=2%
Heat in Place [PJ]	7169 (15 – 95)	97390 (679 – 1438)
Technical potential [MWe]	23 (0 – 0.6)	1322 (7.5 – 19.9)
Usable Technical potantial [MWe]	5.75	330.5

Table 2B – Heat in place and technical potential for the M. Amiata		
Potential	Shallow reservoir R=10%	Deep reservoir R=2%
Heat in Place [PJ]	26578 (5.8 – 345)	100098 (258 – 643)
Technical potential [MW_e]	22 (0 – 2.0)	179 (0.2 – 1.9)
Usable Technical potantial [MW_e]	5.5	44.75

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