Mapping super-critical geothermal resources in Europe

Adele Manzella[1], Serena Botteghi[1], Olafur Flovenz[2], Gianluca Gola[1], Gylfi Páll Hersir[2], Jon Limberger[3], Domenico Liotta[4], Alessandro Santilano[1], Eugenio Trumpy[1], Jan Diederik van Wees[5]

[1] CNR-IGG, Pisa Italy

[2] ISOR, Reykjavik, Iceland

[3]Utrecht University, Utrecht, The Netherlands

[4]University of Bari, Bari, Italy

[5]TNO, Utrecht, The Netherlands

manzella@igg.cnr.it

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ABSTRACT

The compilation of a European database of favourable indicators of the presence of super-critical geothermal resources has been a main task in the European project IMAGE. The objective was to define areas in Europe where rocks and fluids are at super-critical condition and can be accessed by drilling. After defining three main indicators, i.e. the depth of 400 °C isotherm, the crustal thickness, and the earthquake density combined with the estimated depth of the Brittle-Ductile Transition in Europe, their spatial correlation was established by Geographic Information System (GIS) models, and a super-critical resource database was organized for Europe. By prioritizing favourable conditions using GIS spatial analysis methods, the "favourability" map of geothermal resources at super-critical condition was then obtained. The map provides a clear overview of the distribution of potential resources in Europe, based on analytical data.

1. INTRODUCTION

Very high-temperature reservoirs are a possible target for future geothermal exploration either through the direct exploitation of super-critical fluids or as a potential high-temperature reservoir for Enhanced Geothermal Systems. As stated by IEA Technology Roadmap 2011, by exploiting subsurface fluids at super-critical conditions, i.e. high temperature (>375 °C) and high pressure (>22 MPa), the energy output per well is expected to increase by a factor of ~10. This will reduce development costs by decreasing the number of wells needed.

In order to contribute to the EU strategic energy and climate targets for 2020 and 2050 by fostering increased growth in the geothermal energy market through enhanced awareness of the potential of geothermal energy production, a database of potential super-critical resources has been launched by the IMAGE project.

Super-hot and super-critical resources are expected in the surrounding of still hot magmatic intrusions in the crust. A large part of the IMAGE activity focused on understanding favourable conditions for shallow magmatic emplacement at a few km depth, besides improving exploration and investigation techniques for their detection. In a typical crust with an average thermal gradient of the order of 30-35 °C/km the critical temperature of a brine (temperature above 450 °C) is reached at depths greater than 12-15 km. However, in many sites around the world (e.g. Larderello and Phlegraean Fields in Italy, Reykjanes in SW-Iceland, The Geysers in California) where exploratory boreholes were drilled in high-temperature geothermal system (T > 370 °C), reservoir pressures above super-critical conditions (>22.1 MPa) were encountered. These sites/occurrences confirm that geothermal reservoirs in super-critical conditions, both in temperature and pressure, exist in the vicinity of cooling magmatic intrusions. Volcanic rifts, extensional basins and/or subduction zones with related shallow crustal magma emplacements, are the most promising environments in which super-critical conditions may be found in the upper to middle crust levels.

2. SUPER-CRITICAL CONDITIONS AT SHALLOW DEPTH AND FAVOURABILITY MAPPING

Focusing on Iceland, where these resources have been searched and studied in the last decade (Fridleifsson and Elders, 2017), and using the research experience in Tuscany, Italy (Bertani et al., 2018), the indicators applicable over broad areas have been defined, in search of potentially exploitable super-critical resources in continental Europe.

2.1 Indicators of super-critical condition at shallow depth

Since temperature is the key parameter controlling the presence of super-critical reservoirs at (relatively) shallow depth, mapping of super-critical resources was mainly driven by thermal models derived from crustal and lithospheric constraints and data interpolation from available deep wells. Other information providing indirect indication of crustal thinning and shallow magmatic emplacement have been searched and analysed. In particular, the following indicators were chosen and their spatial correlation was established by Geographic Information System (GIS) models:

- the depth of 400 °C isotherm;
- the crustal thickness;
- the earthquake density combined with the estimated depth of the Brittle-Ductile Transition in Europe (Fig. 3).

The depth of the isotherm 400°C was computed using the crustal thermal model based on Limberger et al., (2018) and following an already established practice, as describe in Trumpy et al., (2015). The choice of the reference temperature (400 °C, i.e. slightly above the super-critical point of pure water, which is 374 °C) should not be taken as an absolute reference: we are just interested in the isotherm's depth distribution, which would be essentially the same for isotherms of similar value (374-450 °C). The map is shown in Fig. 1.

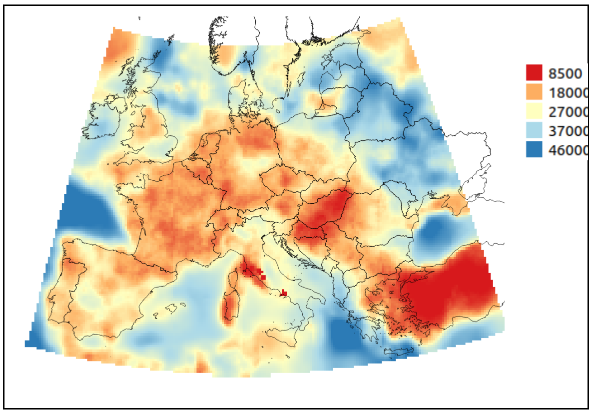

Figure 1: Distribution of the depth of 400 °C isotherm calculated from the thermal model, and, in the legend, depth colour code (m b.g.l.)

The second parameter taken into account is the crustal thickness, represented by the MOHO discontinuity depth, considering the relationship between thinned crust (and therefore shallower MOHO depth) and anomalous thermal regimes. The map was based on data from Tesauro et al. (2008) and is shown in (Fig. 2).

We then performed a combined analysis of two sources of data available at European scale: the depth of the brittle-ductile transition (BDT) in the strike-slip regime and the seismicity. The concept here explored is that the movement of magma and the related hydrothermal circulation is associated with a certain amount of seismicity, usually having high frequency and low magnitude. On the other hand, very shallow depth of the BDT may indicate the presence of igneous intrusion. At the scale of interest, we think that a combination of frequent seismicity and shallow BDT provides a good indication of geodynamic conditions favourable to shallow magmatic emplacement.

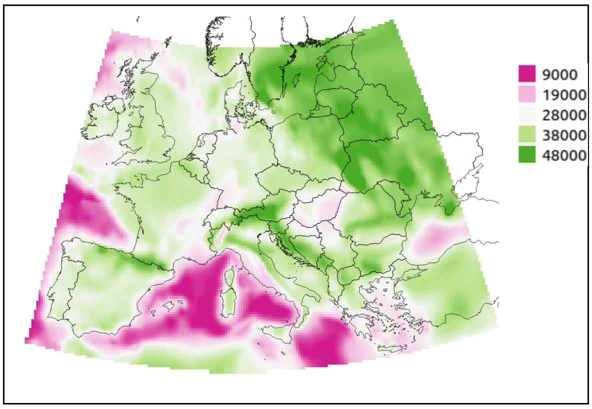

Figure 2: Distribution of MOHO thickness (after Tesauro et al., 2008) and, in the legend, thickness colour code (m).

To compute the earthquake density we used the hypocentre location map of the Earthquake Catalogue (from the SHARE project http://www.share-eu.org), and the earthquake densities at each cell of 20x20 km^2 size was then computed using a quadratic kernel function smoothing. The BDT was computed from the European strength model (Limberger et al., 2018) considering a reference and constant strain-rate of 10^{-15}, essentially comparable to background intraplate deformation rates, and strike-slip regime. All events of the earthquake density map that are located in cells where the BDT depth results deeper than 9.5 km were then filtered out, obtaining the map in Fig. 3.

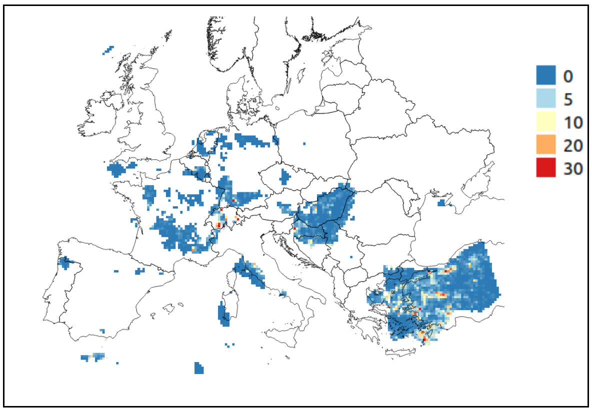

Figure 3: Earthquake density (from Earthquake Catalogue) for events located where the BDT depth is shallower than 9.5 km. In the legend, number of earthquake per cell (20x20 km^2).

Other interesting indicators, e.g. $^3He/^4He$ ratio values from which fluids of crustal origin may be inferred, or Curie Point depth that refers to deep temperature regime, were considered but then discarded as they are available only for local areas, and too restricted to be of use at regional and European scale. The same limits apply to other numerous but sparse data, e.g. magnetotelluric, gravimetric and seismological data, that are used to characterize the heat (and possibly metasomatic fluid) source of the system at local scale We explored the possibility to use large scale gravimetric data, in particular local and relative minima of the Bouguer anomaly, as index of low density anomalies at depth due fractional melting. Such an approach would have required an extensive modelling of the European crust to filter out other causes of low density, which required an effort beyond the scope of this work. The only dataset of dispersed data that was considered of use is the location of recent (Pleistocene-Holocene) volcanism, which was superimposed to the favorability map to provide external indication. Due to its local meaning, however, this parameter was not used in the computation of final maps.

2.2 Computing favourability

To produce favourability maps for super-critical geothermal resources in Europe, we used a GIS model to combine the geological and geophysical evidence previously described. The score and weight in each layer have been estimated on the basis of expert opinion, following a "knowledge-driven" model and using the Index Overlay (IO) method (Bonham-Carter et al., 1994). IO provides a flexible way to apply a common scale of values to non-uniform inputs, thus creating an integrated analysis. When information is organized in thematic maps (e.g., raster layers) with diverse value scales and importance, the values can be classified and scored before being overlaid. In addition, each information layer receives a defined weight. The average, weighted, score of the resulting map is obtained by summing the ratio between the sum of the scores and the related weight of each thematic map (Bonham-Carter, 1994).

Before combining them, the three maps described in 2.1 were classified, scored and weighted. The classifications consisted of identifying five ranges of values (classes) for each map. The classes were scored from 1, i.e "Very low" (least favourable area), to 5, i.e. "Very high" (most promising area) (Table 1). Reclassified maps were then obtained by weighting each map with a value ranging from 0 to 1 (Table 1, Fig. 4-6).

The three thematic maps were eventually combined by IO computation to produce the final map (Fig. 7), scored as in Table 1.

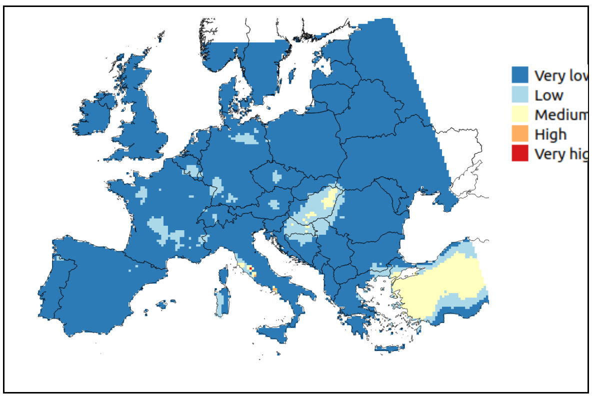

Figure 4: Reclassified map of the 400 °C isobaths.

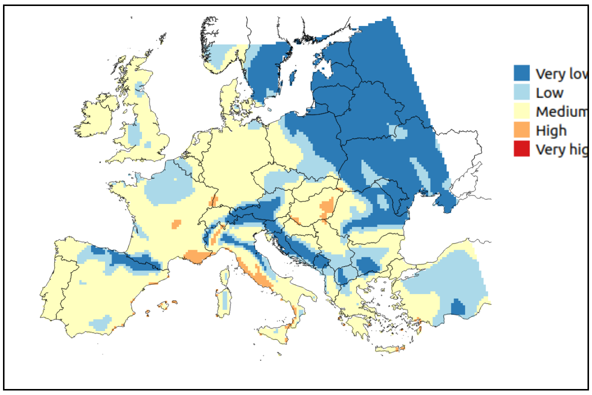

Figure 5: Reclassified map of the MOHO depth.

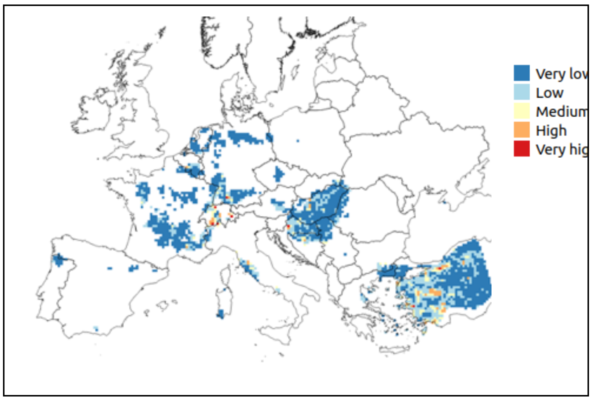

Figure 6: Reclassified map of the earthquake density for events located where BDT is shallower than 9.5 km

3. CONCLUSIONS

The favourability map of super-critical resources in Europe have been produced, and a database of favourable indicators built.

Low favourability values (in blue), are located in Turkey, Greece, Italy, the Pannonian Basin, and partially in Germany (Rhine Graben in particular), France. Some small areas in Switzerland, Belgium, Portugal and Spain are also included. The map highlights medium and highly favourable areas in small areas in Italy and Pannonian Basin, and large areas in Turkey. Recent volcanic areas, highlighted with triangles, are also preferential sites.

The approach here described exploits modern geostatistical and GIS techniques and integrates indirect information related to super-critical condition at depth. The reliability of the favourability map relates to the availability and accuracy of data.

Besides mapping resources, we have made a step towards a more detailed and systematic resource reporting system in Europe related to super-critical geothermal resources.

Table 1: Scores of classes and weights for thematic maps used in the favourability analysis

Thematic map	Weight	Score				
		5 (Very high)	4 (High)	3 (Medium)	2 (Low)	1 (Very low)
Depth of 400 °C isotherm	0.5	0-3.5 km	3.5-5 km	5-10 km	10-15 km	15-53 km
Depth of MOHO	0.2	0-10 km	10-25 km	25-35 km	35-40 km	40-58.5 km
Filtered earthquake density	0.3	30-112	10-30	5-10	0.9-5	0-0.9
Favourability map of super-critical resources in Europe		**4.2-5**	**3.4-4.2**	**2.6-3.4**	**1.8-2.6**	**0-1.8**

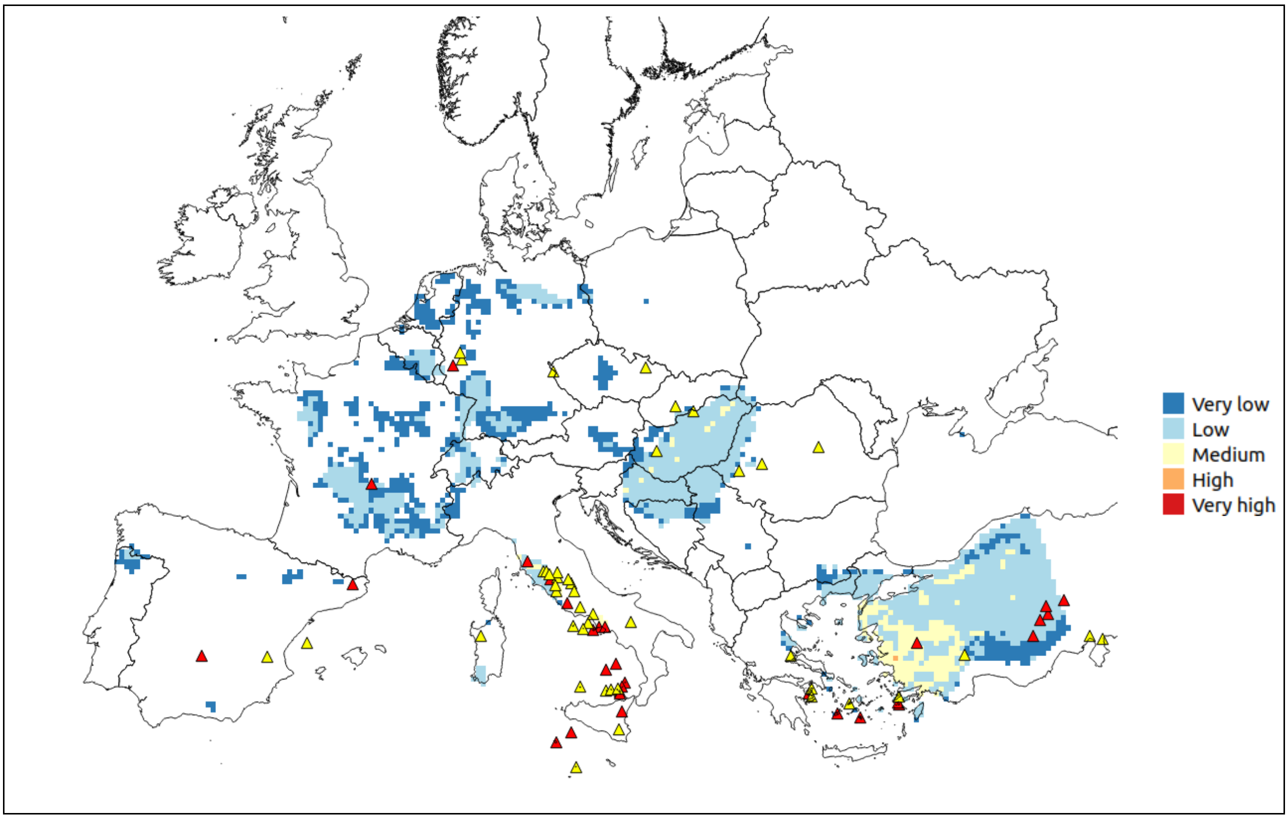

Figure 7: Map of favourability to host super-critical resources. In the legend, favourability ranking. Red triangles: Holocene volcanoes. Yellow triangles: Pleistocene volcanoes.

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