# The geothermal potential at Colli Albani caldera (Roma, Italy)

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## ABSTRACT

The Quaternary Roman Volcanic Province extends for over 200 km along the Tyrrhenian margin of the Italian peninsula and is composed of several caldera complexes with significant associated geothermal potential. In spite of the massive programs of explorations conducted by the then state-owned ENEL and AGIP companies between the 1970s and 1990s, and the identification of several high enthalpy fields, this resource remains so far unexploited, although it occurs right below the densely populated metropolitan area of Roma capital city. The main reason for this failures is that deep geothermal reservoirs are associated with fractured rocks, the secondary permeability of which is difficult to be predicted thus making it uncertain the identification of the most productive volumes of the reservoirs and the localization of productive wells. In facts, almost half of the many deep bore-holes that were drilled in the area reached a dry target. This work proposes a review of available data and a re-assessment of the geothermal potential in caldera-related systems in Central Italy, by analysing in detail the case of the Colli Albani caldera system, the closest to Roma capital city. A GIS based approach is implemented for the identification of areas corresponding to reservoir volumes most promising in terms of geothermal exploitation, to improve the well established volume method approach to the exploration of geothermal resources. The identification is based on a three dimensional matrix of georeferenced spatial data; the A axis accounts for the modeling of the depth of the top of the reservoirs based on geophysical and direct data; the B axis accounts for the thermal modeling of the crust (i.e. T with depth) based on measured thermal gradients. Both A and B data are necessary but not sufficient to identify rock volumes actually permeated by geothermal fluids in fractured reservoirs. We therefore discuss the implementation of a C axis that aims at evaluating all surface data that are evidence of actual geothermal fluid circulation in the geothermal reservoir. We considered datasets on: i) distribution and density of tectonic lineaments; ii) temperature and iii) electric conductivity of shallow groundwaters; iv) partial pressure of dissolved CO2 in shallow groundwaters. The geothermal potential of Colli Albani is then discussed, and implications for caldera-related geothermal systems in Central Italy are discussed based on the role of the geometry and structure of reservoirs in relationship with volcano-tectonic structures associated with calderas and deep geothermal fluid migration paths.

## 1. INTRODUCTION

Geothermal reservoirs are usually associated with fractured rocks. The calculation of the energetic potential in geothermal areas suffers of the large uncertainties associated with definition of secondary permeability (e.g. Giordano et al., 2013). For example, the widely used Volume Method for the evaluation of the first order geothermal potential (Muffler and Cataldi, 1978) needs the definition of an average porosity of the reservoir, which gives no information on the effects of the fracture network complexity on the anisotropic distribution of secondary permeability.

Geothermal exploration for high and medium enthalpy fluids in Italy has concentrated in areas of active or recent magmatism along the Tyrrhenian margin, from Tuscany to Sicily (Cataldi et al., 1995). These areas are characterised by the highest heat-flow values in Europe (Fig. 1) and by extensive urbanisation, including Roma Capital City and its metropolitan area, which host more than 5 millions people. In spite of the very high heat flow values, the geothermal fields in Latium region (Central Italy)(Fig.1), associated with shallow Meso-Cenozoic carbonate reservoirs located in correspondence of the main Quaternary caldera systems and generally capped by impermeable Miocene-Pliocene syn- and post-orogenic marine sediments, are not exploited, even though several tens of 1-5 km-deep bore-holes had been drilled between the 1970s and the 1990s (Barberi et al., 1994 and references therein). The main reason for this unsuccess is that the geothermal potential of the identified geothermal fields, and consequently the locations for the deep-drillings, used to be defined taking into account mainly two parameters, that are the depth of the reservoir and the temperature at its top; the reservoirs were largely modeled by the inversion of gravity and geoelectric data; these allowed the reconstruction of only the top of the reservoir but not of the internal structure and stratigraphy, even where and when stratigraphies from deep drillings had become progressively available. Several maps had been produced over the years illustrating the top of the reservoirs and the temperature gradients (maps are today available online on the site of the Italian Ministry for Economic Development (http://unmig.sviluppoeconomico.gov.it/unmig/geotermia/inventario/inventario.asp); however those maps could not further detail the volumes effectively permeable. This resulted in a series of failures and many deep-wells found randomly the same reservoirs both dry and unproductive or very productive in very narrow areas (e.g. Vulsini, Torre Alfina, Sabatini, Buonasorte et al., 1988; Chiodini et al., 2007), or either sealed and filled with hot-brines (e.g. the Cesano field in the Sabatini area; Funiciello et al., 1979).

Recent technological advances in exploration and exploitation of geothermal energy have changed the previous evaluation of the potential of geothermal reservoirs, extending to lower enthalpies and greater depths. At present (October 2012), 108 new research permits have been requested by private companies in less than one year in Italy, and of these 34 in Latium region, including the Colli Albani area (Buonasorte and Franci, 2011, http://www.unionegeotermica.it; http://unmig.sviluppoeconomico.gov.it/unmig/istanze), indicating the significant interest of the industry for the development of this renewable resource.

The main aim of this paper is to demonstrate the importance of identifying and utilizing at best the indirect evidence at surface of secondary permeability in the reservoirs, as well as the structural modeling of the reservoir. This approach is applied at the re-appraisal of the geothermal potential of the Colli Albani caldera geothermal system, in view of the huge amount of new geological and geophysical data produced in the last 20 years (Funiciello and Giordano, 2010 and references therein) and discussed in the frame of the Volume Method for fractured reservoirs. Implications are then discussed on the possible revision of the geothermal potential of the entire geothermal region associated with peri-Tyrrhenian Quaternary calderas taking into account the interplay between deep caldera-structures and reservoirs in focusing lateral migration of geothermal fluids and in the formation of distal blind resources.

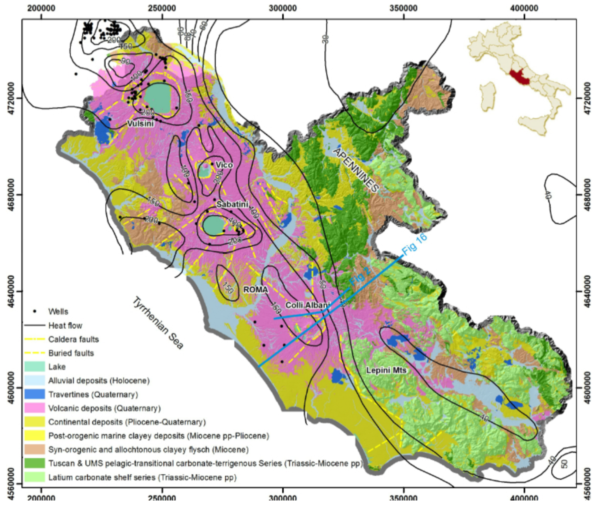


**Fig. 1 Geological setting and heat flow in Latium region**

## 2. PREVIOUS STUDIES

Research of geothermal resources in the Colli Albani volcano was performed between the 1970s and 1990s by Agip and Enel State-owned companies (Barberi et al., 1994 and references therein). The research involved the acquisition of geological, geophysical and geochemical data and the drilling of four wells for the measure of the geothermal gradient and one deep-drilling (Fig. 1 for location). In spite of the great economic interest for the Colli Albani, being the closest geothermal area to Roma capital city, the resulting data were not considered promising, because of the relatively low geothermal gradients reconstructed (between 5 and 7.5 °C/100 m) and the difficulty of using the geochemical geothermometers for the definition of equilibrium temperatures inside the deep reservoir. The electric resistivity and gravimetric data, together with the study of the xenoliths in the Colli Albani volcanic rocks (Funiciello and Parotto, 1978; De Benedetti et al., 2010; Danese and Mattei, 2010) allowed to reconstruct the first order geometry and stratigraphy of the reservoir associated with the Mesozoic-Cenozoic sedimentary carbonate rocks at a minimum depth of about -1.000 m as well as the presence of cap rocks made of hundreds of meters thick Pliocene marine clays. The low geothermal gradient was associated with a fast and vigorous recharge of meteoric water in the carbonate reservoir from the karstic systems of the nearby Apennine Mountains (Duchi et al., 1991).

The geothermal ranking of the Colli Albani area in the frame of the National Resource Inventory was based on the assumption of a top of the reservoir at -1600 m and an average T of 90°C (ENEA, 1993). Bono (1981) calculated the geothermal potential based on the Volume Method (Muffler and Cataldi, 1978), by taking into account an area of 1780 $km^2$ approximately equal to that of the volcano, an average effective porosity of the reservoir of 5%, a maximum thickness of 1 km, and a T range of 75-175°C. Doveri et al.

(2010) recently stressed that the "old" approach to the geothermal potential based only on the depth of the reservoir and the temperature should be corrected for the evidence of effective presence of circulating fluids, thus introducing the $CO_2$ surveyed in the regional aquifers as a tracer for reservoir productivity. Numerical modeling of the Colli Albani geothermal reservoir pointed also to the primary importance of geometry and continuity of the cap rocks (Todesco and Giordano, 2010).

## 3. REVISION OF THE COLLI ALBANI GEOTHERMAL POTENTIAL

The Colli Albani reservoir is inhomogeneous based on its stratigraphy, and in terms of internal fracture intensity based on the deformation history. We here now explore data that can be used to image the fluid circulation in geothermal reservoirs based on indirect evidence at surface, or at shallow depths, and how these data can be treated spatially in order to define the most promising area for geothermal exploration and location of productive wells.

### 3.1 Structural lineaments

The identification and mapping of lineaments from aerial photographs and satellites images derives from previous studies and original data. The 9072 identified lineaments have been analysed for their areal density and orientation. The most frequent lineament orientations are NE-trending (N050°, N025°), NW-trending (N135°) and meridian (N180°). The analysis of the orientation of long lineaments shows a marked difference, with N135°±11.25° lineaments being by far the most frequent.

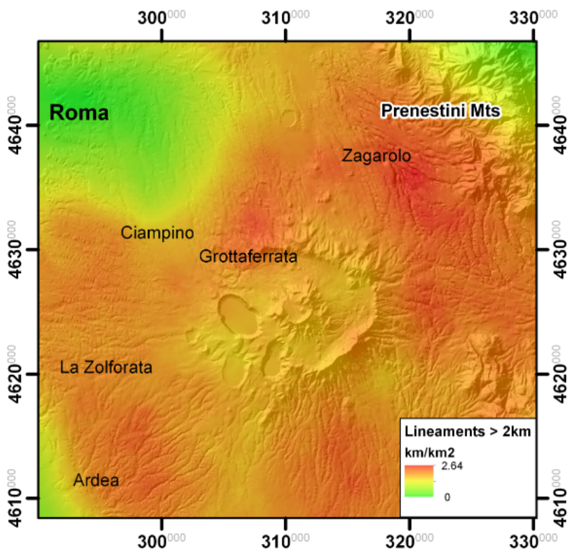


**Figure 2: Regional lineament density distribution.**

By contrast, the short lineaments show a scattered orientation distribution with a peak around the NE. We suggest that the short lineament density dominantly reflects the shallow state of fracturing and likely that of the cap rock-formations, whereas the density map of the longer lineaments in Fig. 2 more likely reflects regions of deep fracturing possibly associated with the reservoir.

### 3.2 Temperature and electrical conductivity of groundwaters and springs

In the study area groundwater temperatures range from 13°C to 40°C (Capelli et al., 2005). Anomalous areas are widespread along the NW and SW sides of volcano. The areas with the highest thermal anomaly (40 - 24°C) are near Ciampino town, and near La Zolforata (Fig. 3).

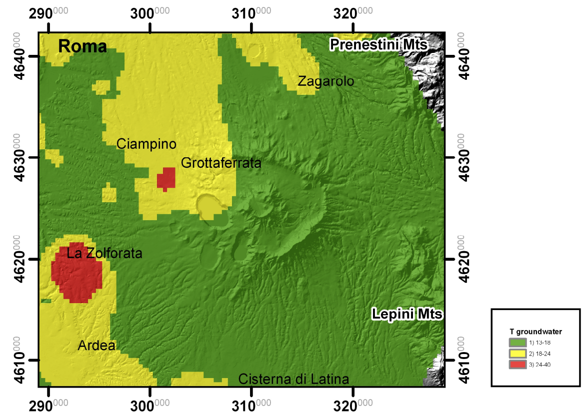


**Figure 3: Groundwater temperatures (elaborated from Capelli et al., 2005).**

Distribution of electrical conductivity roughly mirrors the groundwater T distribution. Marked anomalies are present near the town of Ciampino and Cisterna di Latina (Fig. 4).

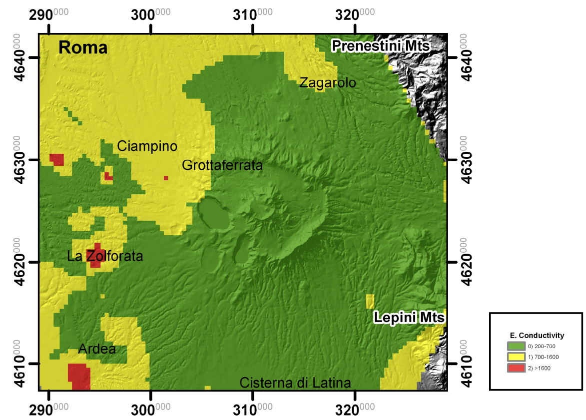


**Figure 4: Electrical conductivity of groundwaters (elaborated from Capelli et al., 2005).**

### 3.3 Partial pressure of $CO_2$ in groundwaters

Figure 5 shows the distribution of the partial pressure of $CO_2$ in groundwaters (Chiodini and Frondini, 2001). Areas with high values of $P(CO_2)$ are near the town of Ciampino, in the La Zolforata, Ardea and Grottaferrata areas.

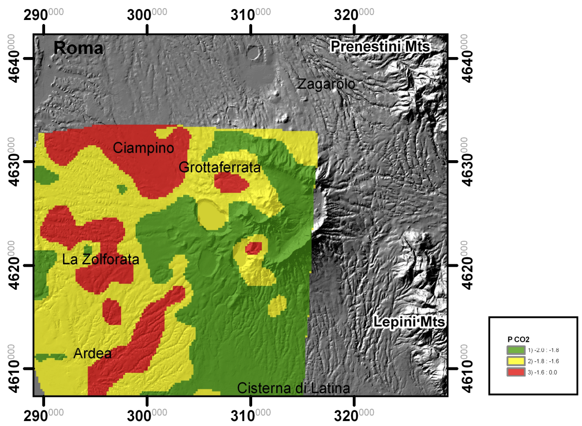


**Figure 5: Partial pressure of $CO_2$ in groundwaters (elaborated from Chiodini and Frondini 2001).**

## 4. ZONING OF GEOTHERMAL FIELD

The analysed datasets, once reclassified have been summed and further reclassified into 5 classes (Fig.6). Class 5 identifies areas where all (or most) surface indicators of reservoir permeability converge and are interpreted as indicative of presence of reservoir secondary permeability and deep fluids circulation. Our results indicate that the areas with the best surface evidence for a permeable reservoir are comprised between Ciampino and Grottaferrata, La Zolforata and Ardea.

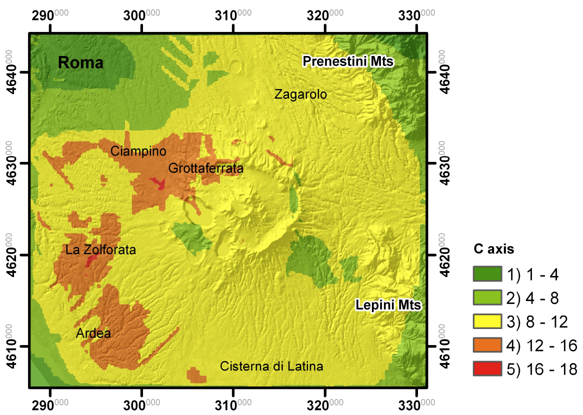


**Figure 6: Classification of the surface indicators of permeability in the geothermal reservoir. Values associated to classes 1-5 indicate the sum of reclassified datasets**

Fig. 7 shows the results of the spatial application of the conceptual matrix, i.e. areas with the highest possibility to find high temperatures (B values) in a shallow (A values), permeable reservoir (C values). Results are expressed as percentage of the maximum possible value of the matrix product, which is an expression of the spatial convergence of data. At Colli Albani the maximum spatial convergence is 80% and we consider that the interval between 60% and 80% is representative of high potential, which is reached only around Grottaferrata for an area of 24 $km^2$. By extending to 50%, the Grottaferrata area increases of another 45 $km^2$, for a total of 69 $km^2$.

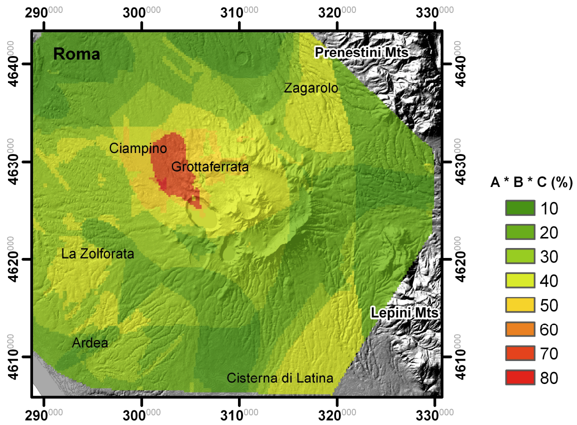


**Figure 7: Classification as a function of depth of the reservoir (A), T in the reservoir (B) and probability of a permeable reservoir (C).**

## 3. DISCUSSION

Estimation of geothermal resource potential is generally approached with the volume method (Muffler and Cataldi 1978; Doveri et al., 2010). This approach is based on the definition of a reservoir volume, of an associated effective porosity and an average fluid temperature. The misevaluation of the reservoir permeability may result in significant economic losses, especially where dealing with highly anisotropic secondary permeability. However, for Colli Albani and in general for most of the areas of geothermal interest during exploration, a deterministic definition of the fracture network in the reservoir is not available, hence the wide use of the volume method with the approximation of guessing an average effective porosity. To calculate the geothermal potential we applied the approach proposed by Doveri et al. (2010) to areas where the convergence of favourable factors accounted by the evaluation matrix AxBxC exceeds 60% and 50% in indicating the presence of a shallow, fractured geothermal reservoir. As a whole our data indicate for the Grottaferrata-Ciampino area an average potential productivity of up to 6210 t/h. It must be also noted that the Grottaferrata area has not been interested by extensive hydrothermal deposition and this may indicate that the cap rocks are still efficient in sealing the reservoir.

As previously said, the reservoir temperature at Colli Albani may be underevaluated due to the paucity of available thermal data. By projecting the expected temperatures with depth (http://unmig.sviluppoeconomico.gov.it/unmig/geotermia/inventario/) we can evaluate temperatures ranging 100-150°C for the shallower RES1 in the structural highs and higher T for RES2, on average 175°C, the latter of course to be found at greater depths (Todesco and Giordano, 2010). Since at Colli Albani the reservoir top is everywhere at accessible depths (> -2000 m), according to current drilling technologies, we also calculate the geothermal potential for all areas where most surface indicators converge in indicating deep fluids circulation (classes 5 and 4 of Fig. 6) and irrespectively of reservoir depth. The calculations indicate that three areas at Grottaferrata-Ciampino (82 $km^2$), La Zolforata (44 $km^2$) and Ardea (48 $km^2$) have a substantial geothermal potential.

It has to be underlined that while the Colli Albani geothermal system can certainly be classified as a medium enthalpy, liquid-dominated resource, the potential expected flow rates from the entire field sum up to over 25000 t/h which, in consideration of the high urbanisation of the area, may play a great role in the future sustainable development of the area, both for direct use and potentially also for electric power generation and co-generation with ORC technologies.

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