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Application of the Revised Volume Method for the Evaluation of the Geothermal Potential in the Vicano-Cimino Hydrothermal Reservoir (Central Italy)

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ABSTRACT

The revised Volume Method is used here to evaluate the geothermal potential of the practically exploited Vicano-Cimino hydrothermal reservoir. This method is based on the distribution of pCO_2 (partial pressure of CO_2) in shallow and deep-originated waters to define areas of geothermal interest, according to the hypothesis that anomalous degassing zones of endogenous CO_2, from either soil degassing and spring and well waters, are spatially related to deep fluids raising up from underlying hydrothermal reservoirs.

On the whole, 333 fluid discharges (cold waters, thermal waters and bubbling pools) were collected within the Vicano-Cimino Volcanic District (VCVD) for chemical and isotopic compositions, in an area of approximately 1,400 km^2. From this large hydro-geochemical dataset the pCO_2 values were computed and then processed to obtain a map of its distribution by using geostatistical techniques (kriging). The resulting thematic map was then used to draw up the boundaries of high pCO_2 areas within the VCVD, potentially corresponding to the exploitable sectors of the deep hydrothermal reservoir.

The estimated potential productivity and the total extractable thermal power of the VCVD are approximately of 10×10^3 t/h and 517-979 MW, respectively. This makes the VCVD suitable both for direct and indirect exploitation of the geothermal resources, in view of the target to reduce electricity generation from conventional and poorly sustainable energy sources.

1. INTRODUCTION

Starting from the pioneering experiment of power generation from a geothermal source in 1904 at Larderello, extensive exploration surveys for geothermal energy exploitation were carried out in Italy in the last century. Geothermal exploration mainly focused along the peri-Tyrrhenian sector of central Italy, where active or recent magmatism and high heat flow occur (Barberi et al., 1994; Cataldi et al., 1995). In the VCVD, exploration geophysical and geochemical surveys were carried out from 1951 to the 1990's, resulting in the drilling of numerous test-holes and some wells whose depth was up to 3,000 m. However, despite the significant potential (a maximum temperature of 218°C at the depth of 2,153 m in the Cimini 1 well; Figure 1), operations always stopped at the preliminary phases. In the last years, Italy is experiencing a renewed interest for geothermal energy, favored by the recent technological advances and encouraged by the growth of energy demand and the need to reduce CO_2 emissions to the atmosphere (Procesi et al., 2013). At present, 108 new research permits have been requested by private companies in Italy, and 34 of these are in the Latium region, including the VCVD (http://unmig.sviluppoeconomico.gov.it/unmig/istanze).

A revised version of the classical Volume Method (Muffler and Cataldi, 1978) was recently applied on a regional scale for estimating the geothermal potential of the volcanic areas of Latium region (Doveri et al., 2010). Based on a larger and more detailed geochemical dataset, the aim of this contribution is to refine the estimates of potential productivity and total extractable thermal power on a bigger scale, in order to identify the best areas within the VCVD for high-to-low enthalpy resources exploitation.

2. AREA DESCRIPTION

The VCVD is characterised by Pleistocenic volcanic products overlying a sedimentary sequence constituted, from top to bottom, by Plio-Pleistocene clays, Cretaceous-Oligocene flyschoid sediments (Ligurian s.l.) and a thick Mesozoic carbonate-Triassic evaporite formation (Barberi et al., 1994). The Cimino and Vicano volcanic complexes belong to two distinct magmatic cycles: the acid cycle (1.35-0.94 Ma) of the Tuscan Magmatic Province and the silica-undersaturated K-alkaline cycle (0.42-0.09 Ma) of the Roman Magmatic Province (Sollevanti, 1983; Peccerillo, 1985; Cimarelli and De Rita, 2006; Aulinas et al., 2011), respectively. Extensional tectonics, which interested the peri-Tyrrhenian sector of central Italy during the Neogene (Barberi et al., 1994), formed preferentially formed by NW-SE oriented horst and graben structures with clastic marine sediments filling the structural lows.

The main hydrogeological pattern is related to a pressurized hydrothermal reservoir, of regional extension, hosted in the carbonate-evaporite unit, which is separated from a shallow, mainly unconfined, regional cold aquifer hosted in the volcanic products by low-permeability Plio–Pleistocene deposits and/or the Ligurian Units s.l. acting as aquicludes (Capelli et al., 2005). Perched aquifers of limited and discontinuous extent are also present in the more permeable strata of the sedimentary sequences.

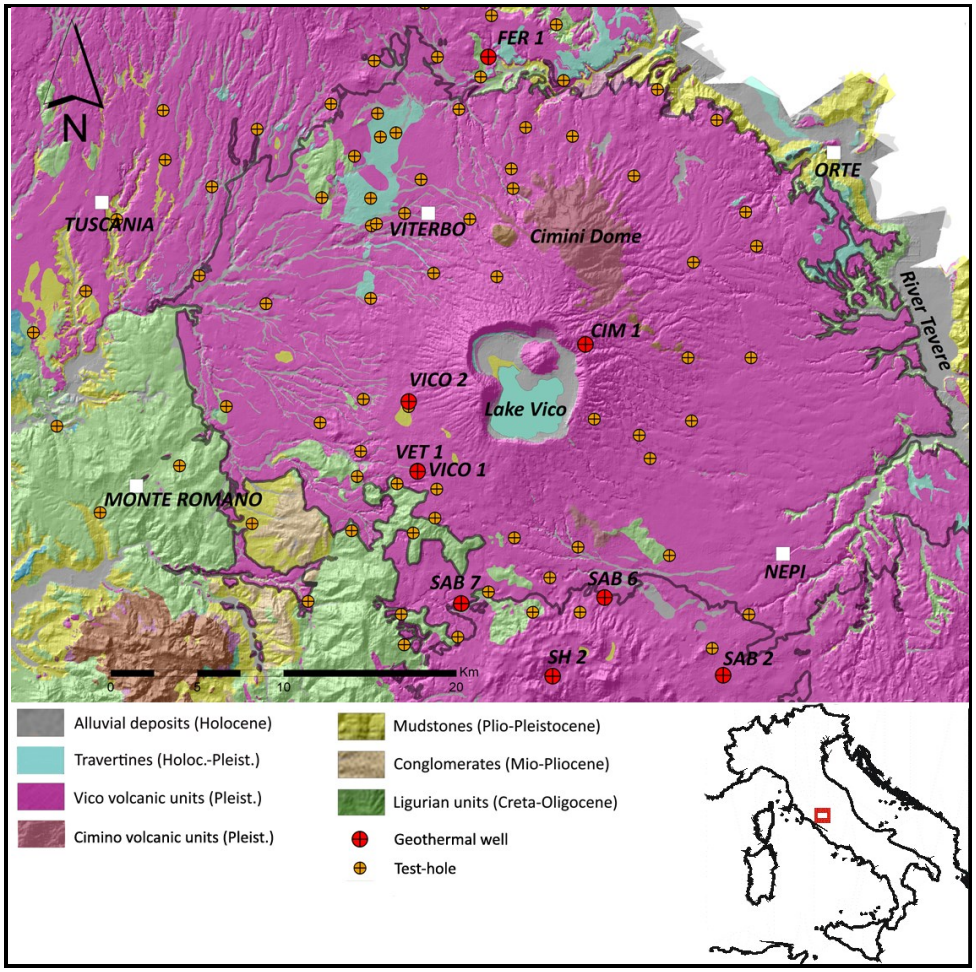

Figure 1: Geological sketch map of the VCVD and location of the wells drilled for geothermal purposes.

3. METHODS

The revised Volume Method (Doveri et al., 2010) was inspired by the good correspondence observed in geothermal areas between zones of high CO_2 fluxes of deep provenance and heat flux (Mahon et al., 1980; Marini and Chiodini, 1994). In particular, in the peri-Tyrrhenian sector of central Italy buried structural highs of the carbonate formations were considered as both geothermal reservoirs and traps for deep-originated CO_2, from which fluids (thermal waters and gases) migrate towards the surface along preferential pathways such as faults (e.g., Chiodini et al., 1995, 1999, 2007; Minissale, 2004; Frondini et al., 2009; Cinti et al., 2011, 2014). Consequently, the extension of deep structures of potential geothermal interest can be evaluated at the surface based on the distribution of pCO_2 of emerging cold and thermal waters.

A large geochemical dataset consisting of 333 water samples collected within the VCVD (Cinti et al., 2014), in an area of approximately 1,400 km^2, was used to compute pCO_2 data by means of the Phreeqc code v. 2.12 (Parkhurst and Appelo, 1999). A statistical analysis was then carried out to describe the population of water samples with respect to pCO_2. Experimental data were finally processed as contour maps by using a geostatistical approach (variogram analysis and kriging estimation) (Matheron, 1971; Goovaerts, 1997).

4. APPLICATION OF THE REVISED VOLUME METHOD

The volume (V) of the geothermal reservoir potentially exploitable is computed by multiplying the surface extension (A) of the deep geothermal reservoir and its average thickness (h), according to the equation:

$$V = A \times h$$

where A is evaluated on the pCO_2 distribution of emerging waters and h is calculated according to available information on the geological structure at depth.

The frequency distribution of pCO_2 relative to 333 sampled waters resulted from a log-normal transformation (Figure 2), in order to improve the symmetry of the highly-skewed normal distribution (not shown). The histogram shows a bimodal shape and highlights the presence of two maxima in the intervals from -2.0 to -1.6 log bar and from -1.0 to -0.2 log bar, respectively. The first maximum characterize waters with low pCO_2 values (< 0.06 bar), which can generally be interpreted as the normal enrichment in soil derived-CO_2 of infiltrating waters from zones of low CO_2 flux. The second maximum characterize those waters with medium-to-high pCO_2 values (> 0.06 bar), reflecting the input of deeply derived CO_2. Consistently, $\delta^{13}C$ isotopic values of dissolved CO_2 have confirmed

a twofold origin of carbon dioxide, from shallow organic processes and production at depth (through thermo-metamorphic reactions and mantle degassing), respectively (Cinti et al., 2014).

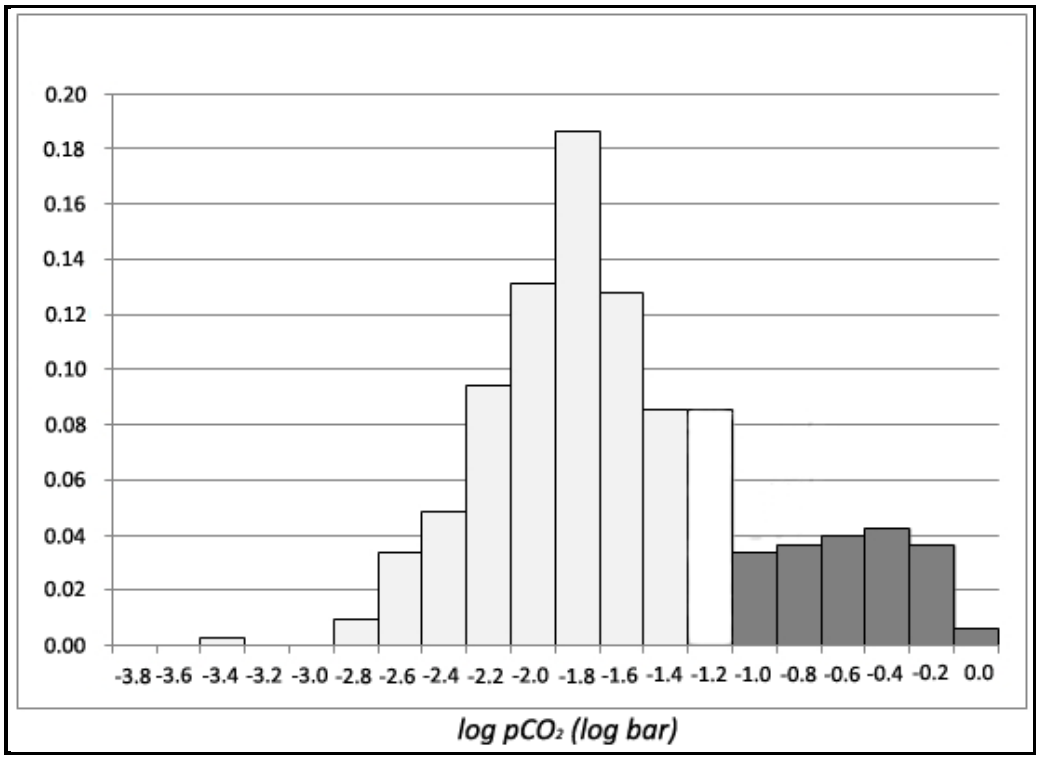

Figure 2: Histogram of pCO_2 values for the sampled waters.

After basic statistic analysis, data of pCO_2 were processed to obtain a map of its distribution. The geostatistical technique applied herein involves the use of kriging (Matheron, 1971; Goovaerts, 1997) through semi-variogram computation and modeling. The experimental semi-variograms of the log-transformed dataset (Figure 3) are referred to the main directions of anisotropy of the spatial distribution. Within a specific radius of influence (range), semi-variance values rise with the separation distance, while over that distance they tend to remain pretty constant around a value (sill) approximately close to variance of the variable.

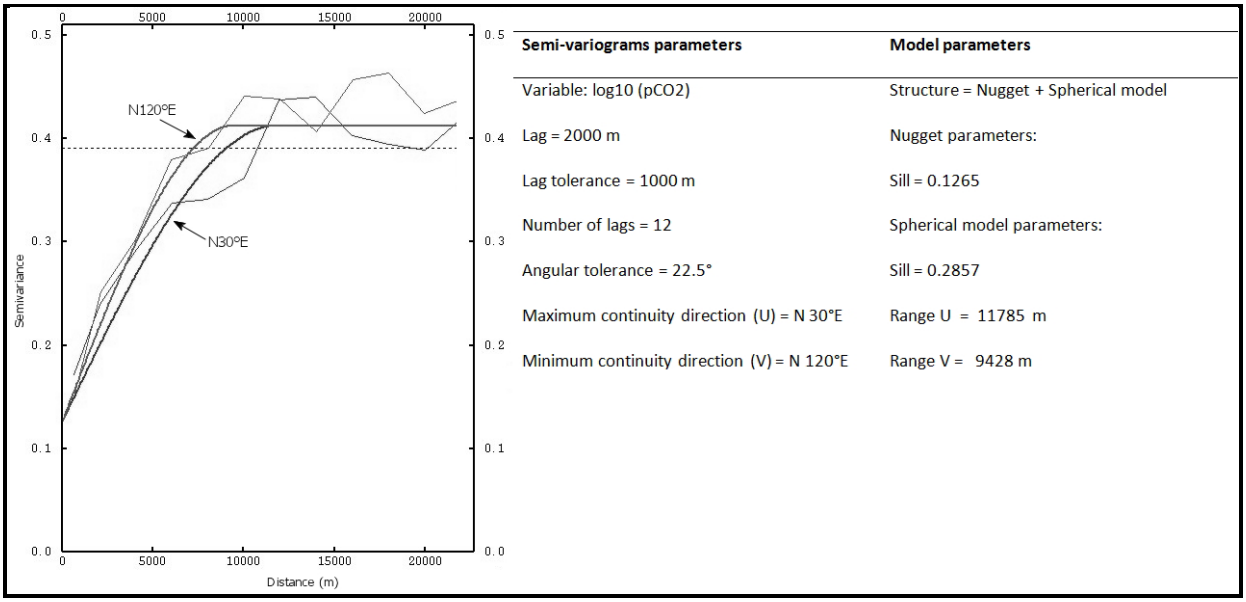

Figure 3: Experimental semi-variograms of the log-transformed pCO_2 data.

The map of pCO_2 distribution obtained from ordinary kriging is reported in Figure 4. The pCO_2 distribution is not homogeneous, being affected from the complexity of the structural setting of the area and the fracture-related upraise of deep-originated fluids from the active hydrothermal system. Eight areas characterized by pCO_2 values >0.06 bar, correspond to the second maximum of the frequency distribution plot (Figure 2), were highlighted. They are related to both thermal waters uprising from the deep reservoir, where the gas phase is originally dissolved, and to dissolution into shallow aquifers of CO_2 separated from the parent deep fluid and uprising as a single gas phase. These areas are located in correspondence with positive gravity zones, which were

interpreted as buried structural highs of the carbonate basement (Cinti et al., 2014), where the top of the geothermal reservoir is located at shallower depths. Conversely, lower pCO_2 values are associated with gravity lows and are typical of shallow waters circulating within the shallow aquifers, which have no relation with the tectonic framework. The size of the areas computed from the distribution of pCO_2 anomalies (>0.06 bar) in the collected waters is reported in Table 1.

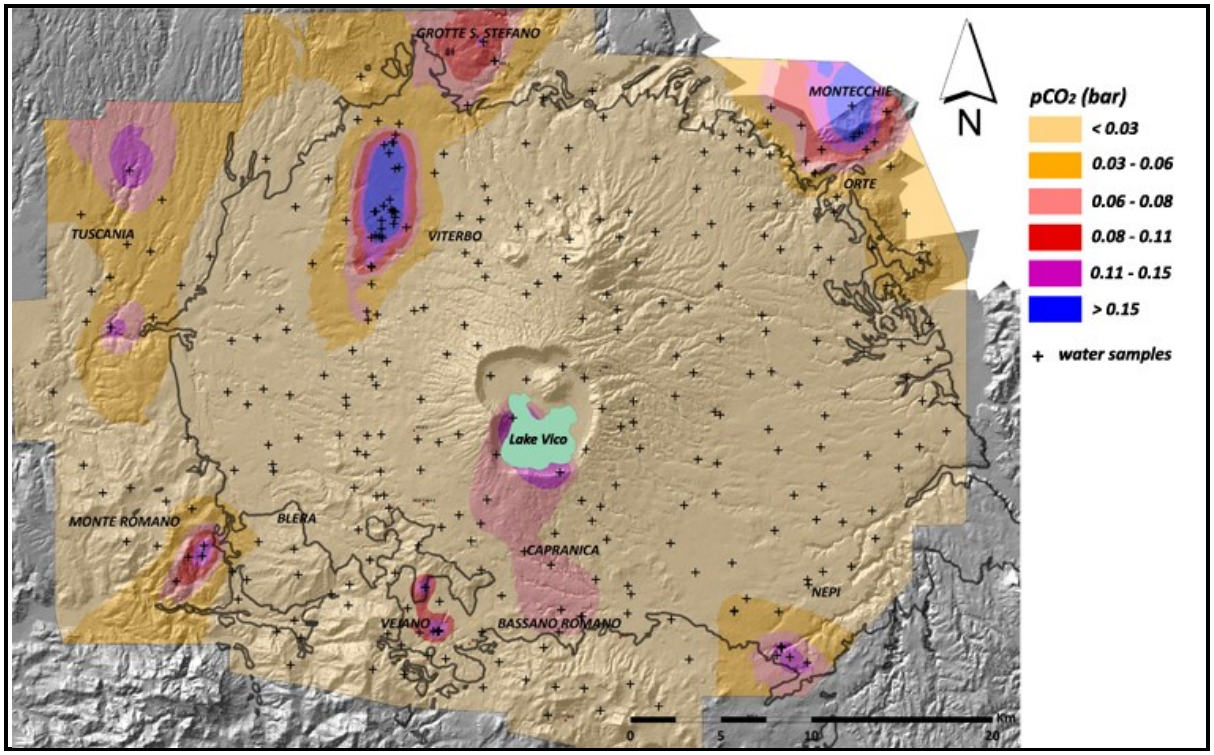

Figure 4: Map of pCO_2 distribution for the sampled waters from Ordinary kriging.

The thicknesses of the so defined areas of potential geothermal interest (Table 1) were calculated as the difference between the depth of the potential reservoir top (Procesi et al., 2013) and the depth of 3 km, which was adopted as the maximum depth for an economically exploitable geothermal resource (Doveri et al., 2010). The information on the depth of the potential reservoir top was aquired from the maps of the underground temperatures at 1,000, 2,000 and 3,000 m (Cataldi et al., 1995), the gravity map of Italy (http://www.isprambiente.gov.it), on the basis of deep drilling data (http://unmig.sviluppoeconomico.gov.it) and from the interpretation of all available information on the geological structure at depth (Barberi et al., 1994).

The average specific productivity of 40 t/h km^3, calculated for the liquid-dominated geothermal systems of Latium by Doveri et al. (2010), was used to estimate the hourly production rate (Q) of geothermal fluids by multiplying it with the calculated volumes within the VCVD. Finally, the thermal power (W) potentially extractable from the Vicano-Cimino geothermal reservoir was computed (Table 1) according to the following equation (Doveri et al., 2010):

$$W = \left(\frac{1000}{3600}\right) \times Q \times C_w \times \left(T - 298.15\right)$$

where (C_w=4.2 J/kg K) is the specific heat capacity of fluids contained in the geothermal reservoir, (T) is the reservoir temperature (in K) and 1000/3600 is a conversion factor. The values of T were derived taking into account the maps of the underground temperatures at different depths (Cataldi et al., 1995), the map of temperature of the potential reservoir top (Procesi et al., 2013), deep drilling data (i.e. the reservoir temperature of 218°C measured at the Cimini 1 well) and geothermometric evaluations based on chemical equilibria of gas species (Cinti et al., 2014). Minimum and maximum temperatures (Table 1) were considered in the calculation of the extractable thermal power as a function of the depth of the reservoir top.

Calculated volumes, discharge rates and thermal power estimates (Table 1) show that the sector extending southward from the western side of Lake Vico to Capranica seems to be the most promising area in terms of expected productivity for medium-to-high enthalpy geothermal resource. However, according to Doveri et al. (2010) it should be classified as sub-economic due to the considerably depth of the reservoir top. The Viterbo thermal basin highlighted considerable expected productivity and high potentially extractable thermal power in an area with low temperatures (up to 75°C) at relatively shallow depths (350-400 m), suggesting good perspectives for low enthalpy geothermal resource. The peripheral sectors of Grotte S. Stefano, Tuscania and Monte Romano-Blera can be classified as sub-economic for low enthalpy geothermal resource, due to moderate production rates and expected power extractable and to depth (about 700 m) and temperatures (<100°C) of the reservoir top. Concerning Grotte S. Stefano, it's worth noting that the Ferento well (FER 1 in Figure 1), drilled in 1989 for geothermal resources exploitation, was soon abandoned after a CO_2-rich gas phase eruption, with no associated thermal water, at the interception of the reservoir top. Lower

productivities and high reservoir depths characterize the sectors of Vejano and Nepi although moderate-to-high temperatures at the reservoir top (100-150°C) suggest a sub-economic interest for low-to-medium enthalpy geothermal resource.

AREA	A (km^2)	h (km)	V (km^3)	Q (t/h)	Tmin (°C)	Tmax (°C)	Thermal Power (MW)
Viterbo	30.8	2.5	77	3080	50	75	90 - 180
Capranica-Lake Vico	41	1.1-1.9	61.5	2460	100	170	215 - 416
Grotte S. Stefano	13.4	2.3	30.8	1233	50	80	36 - 79
Tuscania	13	2.3	29.9	1196	75	100	70 - 105
Monte Romano-Blera	8.9	2.0	17.8	712	90	120	54 - 79
Vejano	5	1.7	8.5	340	80	100	22 - 30
Nepi	6.7	1.3	8.7	348	100	150	30 - 51
Orte-Montecchie	23	1.5	34.5	1380	25	50	0 - 40
Totals	141.8		268.7	10749			517 - 979

Table 1: Evaluation of fluid production rate and thermal power extractable obtained using the revised volume method (Doveri et al., 2010) for calculated areas within the VCVD. A = area of the geothermal reservoir calculated by kriging; h = average thickness of the geothermal reservoir; V = volume of the geothermal reservoir; Q = discharge rate of the geothermal fluid; Tmin-max = minimum and maximum temperatures of the geothermal reservoir; W = thermal power potentially extractable.

5. CONCLUSIONS

The revised Volume Method was used to define areas of geothermal interest and estimate the productive potential within the minimally exploited Vicano-Cimino hydrothermal reservoir. The delimitation of these areas was obtained on the basis of pCO_2 values of 333 waters collected within the VCVD and computed by using geostatistical techniques (kriging). By assuming a specific productivity of 40 t/h km^3, a potential productivity of about 10,000 t/h and a total extractable thermal power of 517-979 MW was estimated. This makes the exploitation of the geothermal resources in the VCVD very suitable for both generation of electric power and direct uses and can play a significant role in reducting of the CO_2 emissions. Within the VCVD, the Lake Vico-Capranica sector and Viterbo thermal basin were regarded as the most promising area in terms of expected productivity for medium-to-high and low enthalpy geothermal resource. The presence of many potential users (municipalities, industrial sites, agricultural and touristic infrastructures) can further promote the exploitation of these resources, both for generation of electric power and for direct uses.

REFERENCES

Aulinas, M., Gasperini, D., Gimeno, D., Macera, P., Fernandez-Turiel, J.L. and Cimarelli, C.: Coexistence of calc-alkaline and ultrapotassic magmas at Mounts Cimini: evidence for transitino from the Tuscan to the Roman Magmatic Provinces, *Geologica Acta*, **9**, (2011), 103-125.

Barberi, F., Buonasorte, G., Cioni, R., Fiordalisi, A., Iaccarino, S., Laurenzi, M.A., Sbrana, A., Vernia, L and Villa, I.M.: Plio-Pleistocene geological evolution of the geothermal area of Tuscany and Latium, *Memorie Descrittive della Carta Geologica d'Italia*, **49**, (1994), 77-134.

Capelli, G., Mazza, R. and Gazzetti, C.: Strumenti e strategie per la tutela e l'uso compatibile della risorsa idrica nel Lazio: gli acquiferi vulcanici. Pitagora (Ed.), (1995), pp. 191.

Cataldi, R., Mongelli, F., Squarci, P., Taffi, L., Zito, G. and Calore, C.: Geothermal ranking of Italian territory, *Geothermics*, **24**, (1999), 115-129.

Chiodini, G., Baldini, A., Barberi, F., Carapezza, M.L., Cardellini, C., Frondini, F., Granieri, D. and Ranaldi, M.: Carbon dioxide degassing at Latera caldera (Italy): evidence of geothermal reservoir and evaluation of its potential energy, *Journal of Geophysical Research*, **112**, (2007), doi: 10.1029/2006JB004896.

Chiodini, G., Frondini, F., Kerrick, D.M., Rogie, J., Parello, F., Peruzzi, L. and Zanzari, A.R.: Quantification of deep CO_2 fluxes from central Italy. Examples of carbon balance for regional aquifers and of soil diffuse degassing, *Chemical Geology*, **159**, (1999), 205-222.

Chiodini, G., Frondini, F. and Ponziani, F.: Deep structures and carbon dioxide degassing in central Italy, *Geothermics*, **24**, (1995), 81-94.

Cimarelli, C. and De Rita, D.: Structural evolution of the Pleistocene Cimini trachytic volcanic complex (central Italy), *Bulletin of Volcanology*, **68**, (2006), 538-548.

Cinti, D., Procesi, M., Tassi, F., Montegrossi, G., Sciarra, A., Vaselli, O. and Quattrocchi, F.: Fluid geochemistry and geothermometry in the western sector of the Sabatini volcanic district and the Tolfa Mountains (central Italy), *Chemical Geology*, **284**, (2011), 160-181.

Cinti, D., Tassi, F., Procesi, M., Bonini, M., Capecchiacci, F., Voltattorni, N., Vaselli, O. and Quattrocchi, F.: Fluid geochemistry and geothermometry in the unexploited geothermal field of the Vicano-Cimino volcanic district (central Italy), *Chemical Geology*, (2014), doi: 10.1016/j.chemgeo.2014.02.005.

Doveri, M., Lelli, M., Merini, L. and Raco, B.: Revision, calibration, and application of the volume method to evaluate the geothermal potential of some recent volcanic areas of Latium, Italy, *Geothermics*, **39**, (2010), 260-269.

Frondini, F., Caliro, S., Cardellini, C., Chiodini, G. and Morgantini, N.: Carbon dioxide degassing and thermal Energy release in the Monte Amiata volcanic-geothermal area (Italy), *Applied Geochemistry*, **24**, (2009), 860-875.

Goovaerts, P.: Geostatistics for natural resources evaluation. New York, Oxford University Press (1997).

Mahon, W.A.J., McDowell, G.D. and Finlayson, J.B.: Carbon dioxide: its role in geothermal systems, *New Zealand Journal of Science*, **23**, (1980), 133-148.

Marini, L. and Chiodini, G.: The role of carbon dioxide in the carbonate-evaporite geothermal systems of Tuscany and Latium (Italy), *Acta Vulcanologica*, **5**, (1994), 95-104.

Matheron, G.: The theory of regionalized variables and its applications. Cahiers du Centre de Morphologie Mathematique, Fontainbleau (1971).

Minissale, A.: origin, transport and discharge of CO_2 in central Italy, *Earth-Science Reviews*, **66**, (2004), 89-141.

Muffler, P. and Cataldi, R.: Methods for regional assessment of geothermal resources, *Geothermics*, **7**, (1978), 53-89.

Parkhurst, D.L. and Appelo, A.A.J.: User's guide to PHREEQC (version 2) – a computer program for speciation, batch-reaction, one dimensional transport and inverse geochemical modeling. *U.S. Geological Survey Water-Resources Investigations Reports*, **99-4259**, (1999), pp. 312.

Peccerillo, A.: Roman comagmatic province: evidence for subduction-related magma genesis, *Geology*, **13**, (1985), 103-106.

Procesi, M., Cantucci, B., Buttinelli, M., Armezzani, G., Quattrocchi, F. and Boschi, E.: Strategic use of the underground in an Energy mix plan: synergies among CO_2, CH_4 geological storage and geothermal Energy, *Applied Energy*, **110**, (2013), 104-131.

Sollevanti, F.: Geologic, volcanologic, and tectonic setting of the Vico-Cimino area, Italy, *Journal of Volcanology and Geothermal Research*, **17**, (1983), 203-217.