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Probabilistic Assessment of Temperature in the Euganean Geothermal Area (Veneto Region, NE Italy)[1]

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In the geothermal Euganean area (Veneto region, NE Italy) water temperatures range from 60 to 86°C. The aquifer considered is rocky and the production wells in this study have a depth ranging from 300 to 500 m. For exploitation purposes, it is important to identify zones with a high probability that the temperature is more than 80°C and zones with a high probability that the temperature is less than 70°C. First, variographic analysis was conducted from 186 temperature data of thermal ground waters. This analysis gave results that are consistent with the main regional tectonic structure, the NW-SE trending "Schio-Vicenza" fault system. Then indicator variograms of the second, fifth, and eighth decile were compared to identify the spatial continuity at different thresholds. The unacceptability of a multigaussian hypothesis of the random function and the necessity to know the cumulative distribution function in any location, suggested the use of a nonparametric geostatistical procedure such as indicator kriging. Thus, indicator variograms at the cutoffs of 65, 70, 73, 75, 78, 80, 82, and 84°C were analyzed, fitted, and used during the indicator kriging procedure. Finally, probability maps were derived from postprocessing indicator kriging results. These maps identified scarcely exploited areas with a high probability of the temperature being higher than 80°C, between 70 and 80°C and areas with high probability of the temperature being below 70°C.

KEY WORDS: Euganean fields, variographic analysis, indicator kriging, local uncertainty.

INTRODUCTION

The hydrothermal Euganean area extends on a plain band of about 20 km^2 immediately east of the Euganean Hills (Fig. 1), comprising the territories of Abano Terme, Montegrotto Terme, Battaglia Terme, and Galzignano Terme (Veneto region, NE Italy). In this area about 100 mining claims and more than 400 wells have been drilled. At present, about 250 wells are active and the total average flow rate of thermal fluids in Abano and Montegrotto is about 0.7–0.8 m^3/sec. The Euganean aquifer is rocky and confined.

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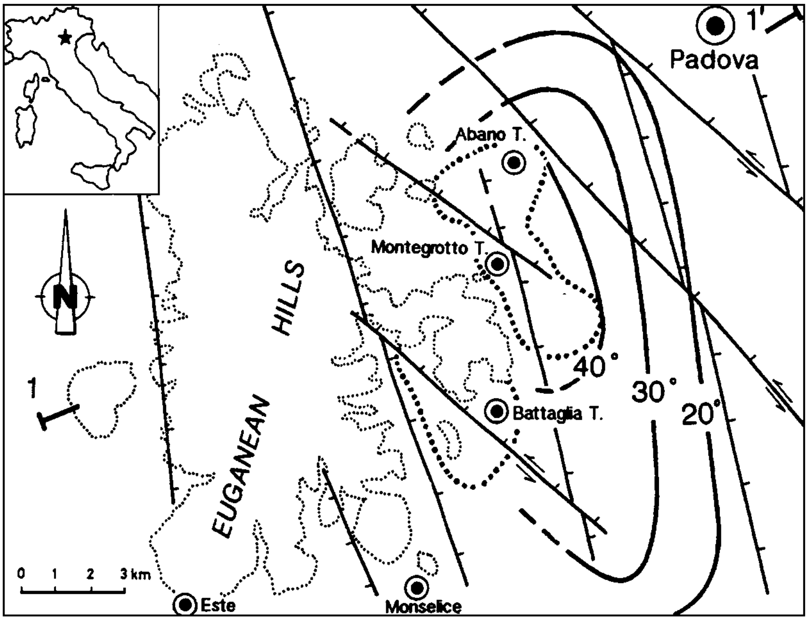

Figure 1. Structural situation of geothermal Euganean area (from Antonelli and others, 1995).

Most of these exploitation wells extend for several hundred meters into bedrock; however, well casing is usually placed only in the quaternary cover. The depth of the wells ranges from about 300 to more than 1000 m. Recently, wells 1000 m in depth have been drilled in the Abano field.

The temperature of thermal waters ranges from 60 to 86°C, and their TDS (total dissolved solids) is about 6 g/l, with the primary constituents being those of Cl^- and Na^+ (70 wt. %) and secondarily of SO_4^{2-}, Ca^{2+}, Mg^{2+}, HCO_3^-, and SiO_2.

A conceptual model of the Euganean geothermal basin was first presented by Piccoli and others (1973), and it has recently been confirmed by Dal Piaz and others (1994). This geothermal system has its recharge zone located in the pre-Alps area (Piccole Dolomiti), where meteoric waters infiltrate at about 1500 m a.s.l. (above sea level) reaching a depth of more than 3000 m, where they are thermalized by a normal geothermal gradient. From this recharge zone, the waters descend southeastward for roughly 80–100 km until reaching the Abano and Montegrotto fields. Tritium data suggest this travel path occurs in the order of more than 30 years (Norton and Panichi, 1978). Recent studies, now in progress, regarding the residence time of the Euganean fluids made by ^{14}C AMS (accelerator mass spectrometry) and tritium measurements, indicate a residence time of much more than 60 years (Sartori and others, 1997).

In the Euganean geothermal area, the fluids rise naturally by favorable tectonic conditions (Fig. 1). Particularly, in the Abano and Montegrotto fields, fluids rise from localized deep fracture zones. Moreover, when a relatively shallow, highly fractured, carbonatic reservoir (of about 300–500 m) is achieved, horizontal hot water movement occurs. The thermal fluids are partially stored inside this known fractured reservoir and partially rise again into the alluvial cover until some 10 m from the surface, eventually mixing with the cold water present in the quaternary cover.

In Figure 2, a geological cross-section of the geothermal Euganean area is reconstructed by geological, structural, lithostratigraphic knowledge, and geophysical investigations in the subsurface between the Euganean Hills and the city of Padova. The structural situation is connected with the activity of the extensional tectonics controlled by different fault systems of regional importance, the "Schio-Vicenza" being the most significant one.

As mentioned before, recent drillings have reached more than 1000 m in depth. Thus, new geological and hydrogeological data have increased the knowledge of this rocky thermal aquifer. Most of these artesian wells reach the "Dolomia Principale" (Upper Triassic) formation composed by dolomite.

The analysis of the piezometric data indicates two periods (spring and autumn) of intense exploitation and two (winter and summer) of low exploitation; at present, the level is on average 7–10 m in depth. The comparison between the water level in the deeper and more recent wells and those in the other wells (300–500 m in depth) shows a very different piezometric level. However, the piezometric variation of artesian wells is in agreement with the seasonal artificial variation (due to the exploitation), showing a hydraulic connection between different aquifer zones. Thus, all the wells are thought to produce from different levels of the same thermal aquifer.

The water level differences are linked to the high exploitation of the shallower carbonatic reservoir, essentially located in the "Biancone" formation, and to its modest transmissivity (generally ranging from 13 to 500 m^2/day) (Fabbri, 1997).

A similar hydraulic connection was identified in the sandy aquifer at about 60 m in depth in the quaternary cover (Antonelli and others, 1995). In fact, its piezometric level has the same regime as the rocky aquifer, but it is only a few meters below the surface. Thus, it is possible to affirm that all the different productive levels in the geothermal aquifer from depths of 60–1000 m are locally interconnected and the piezometric difference is related only to the unequal exploitation of different water bearing units of the same aquifer.

DATA AND VARIOGRAPHIC ANALYSIS

The temperatures considered in this paper concern only the shallower carbonatic reservoir ranging from 300 to 500 m in depth. The small amount of deeper temperature data available precludes analysis below a depth of more than 500 m.

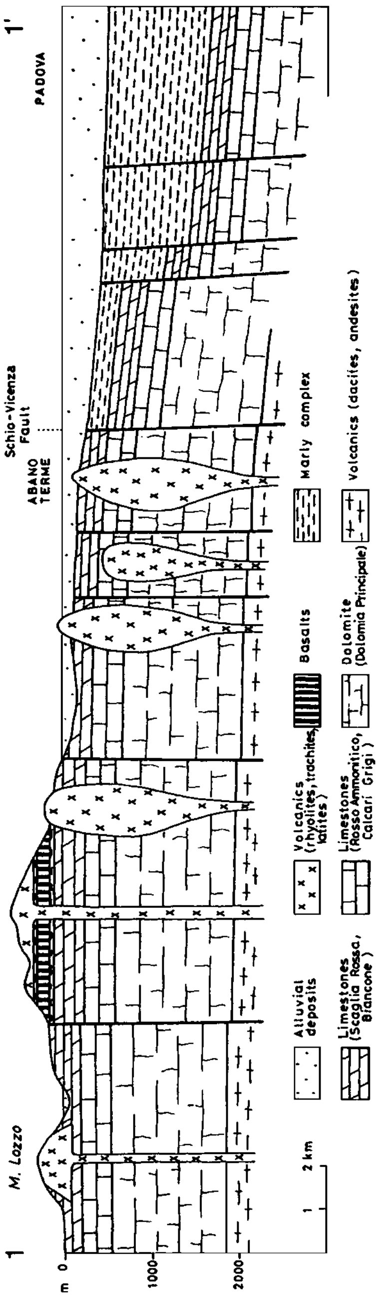

Figure 2. Cross-section of geothermal Euganean area (from Antonelli and others, 1995).

Figure 3A indicates the temperature distribution in the geothermal Euganean area, showing the necessity to decluster the 186 temperature data available. In Figure 3B and 3C, the histograms and the principal statistics before and after declustering are shown. In performing this analysis the code named *declus* (Deutsch, 1989) was used. Then the analysis continues with the calculation of the experimental surface variogram to identify eventual anisotropies (Isaaks and Srivastava, 1989; Pannatier, 1996). In Figure 4A, it is possible to pick out a middle scale anisotropy at about 290° (N70°W), and above all, a large scale anisotropy along 340° (N20°W). Figure 4C shows the experimental omnidirectional and directional variograms of temperature along and orthogonal to the principal anisotropies. Identification of a large-scale anisotropy is very interesting because it identifies an important regional geological structure represented by the "Schio-Vicenza" fault system, which is the main tectonics structure present in the studied area (Fig. 1). This fault system has a direction of roughly 340° (N20°W), as the large scale anisotropy indicates in the experimental surface variogram of Figure 4A and in the experimental directional variograms along 340° and 20° of Figure 4C.

The variographic analysis is useful to quantify the regional spatial variation in temperature, but it can also be used to analyze the differences in spatial variability with respect to different thresholds. Such a procedure involves the determination of omnidirectional indicator variograms, for example, of three statistical characteristic thresholds of univariate temperature distribution (second, fifth, and eighth decile) and their consequent comparison (Fig. 5A). This comparison indicates a nugget effect in the standardized indicator variograms increasing from the second to the eighth decile. Thus, the standardized frequency in meeting temperatures together above and below the considered threshold is less for "low" (67°C) temperatures than that for "high" temperatures (82°C) for a distance of about 0.065 km. The indicator variograms can be also interpreted as a frequency of transition from one state (below threshold) to another (above threshold), and so inform on the spatial clustering of values above or below the threshold.

The objective of this work is to assess a local uncertainty of temperature in the geothermal Euganean area and thus to identify the local probability that the temperature exceeds the threshold of 80°C and does not exceed the threshold of 70°C. With this scope in mind, it is necessary to know the cumulative distribution function in any location. Thus, the first step is to check if a multigaussian assumption of the random function model is appropriate.

Such a parametric hypothesis considers the random function model as being multivariate Gaussian. Analyzing Figure 5B, the hypothesis of multigaussianity is difficult to accept, since bigaussianity is not evident. In fact, the figure shows not only differences between the omnidirectional indicator variograms with regard to the first and the third quartile thresholds, but also the incorrect position of the indicator variogram at the third quartile with respect to that of the median. Indeed, the

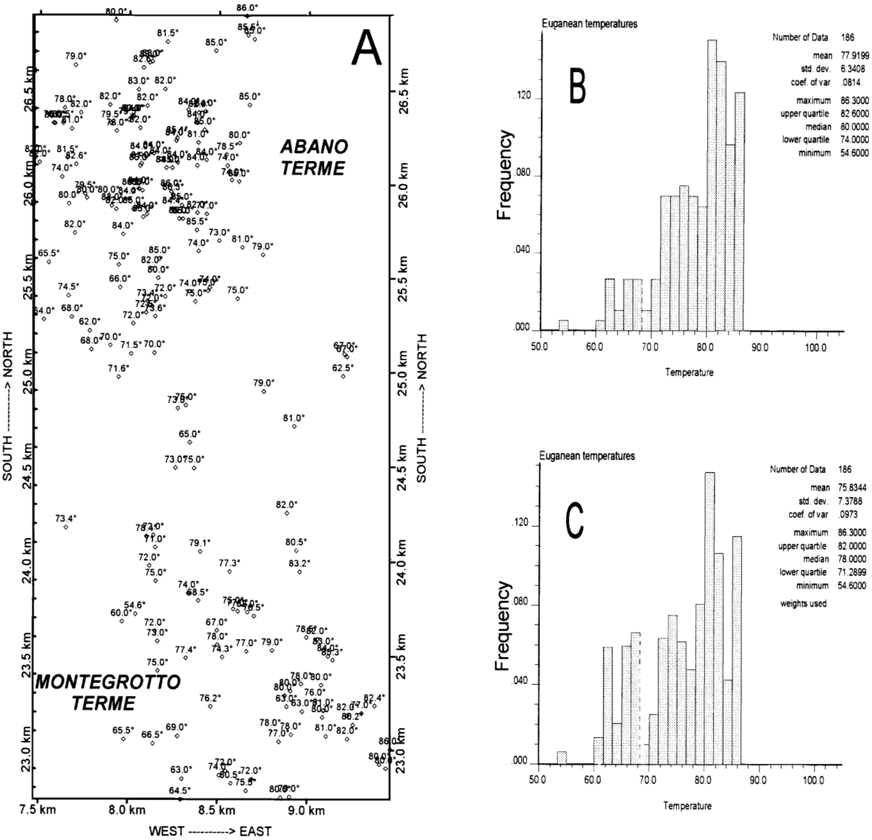

Figure 3. (A) Temperatures in the Abano and Montegrotto fields, (B) temperature frequency distribution in the Abano and Montegrotto fields before declustering, and (C) weighted temperature frequency distribution in the Abano and Montegrotto fields after declustering.

omnidirectional indicator variograms of any pair of symmetrical quartiles (here the first and the third) in presence of bigaussianity should be similar. However, as multi-Gaussian approach is a relatively simple procedure, it has to introduce the strong hypothesis of multigaussianity, and this presents some problems (Goovaerts, 1997).

In our case the best approach may be that of an indicator kriging (Deutsch and Journel, 1998). This nonparametric technique will allow the data to be analyzed outside of the strong hypothesis noted above.

Therefore, after the previous geostatistical identification of structures from surface analysis, and if possible, their tectonics interpretation, the next step is the inference process, necessary for the indicator kriging procedure. In fact, variogram structure identification is important but not sufficient for the goal of this work.

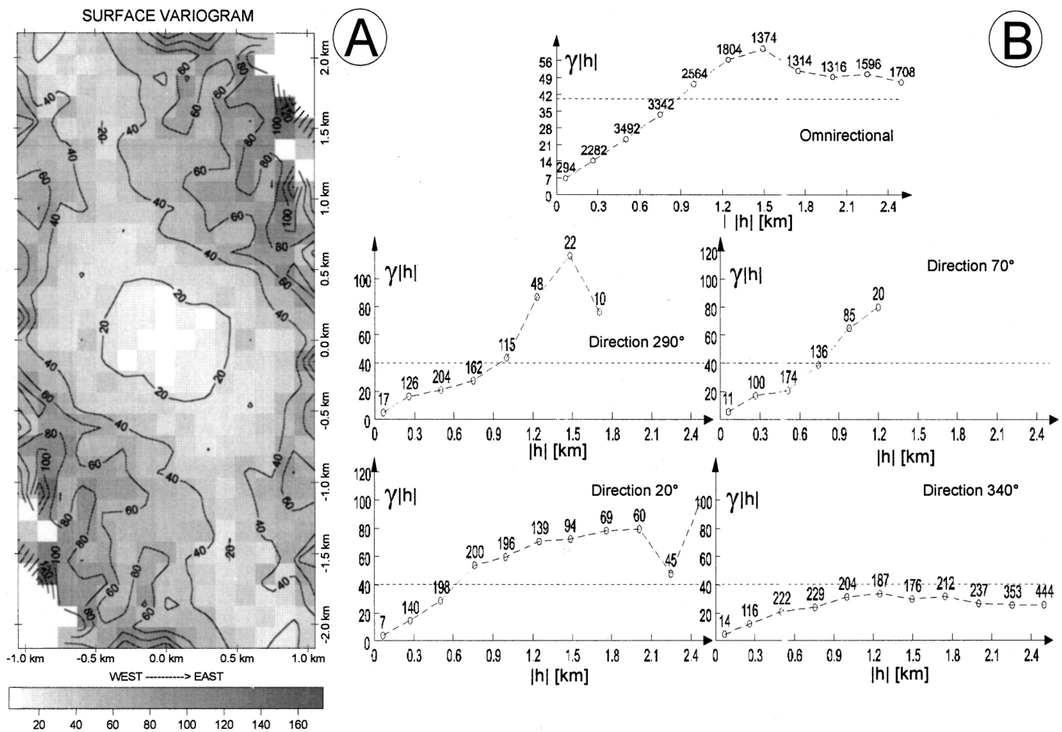

Figure 4. (A) Experimental surface variogram of temperature in the geothermal Euganean area; (B) experimental omnidirectional and directional variograms of temperature along and orthogonal to the principal anisotropies.

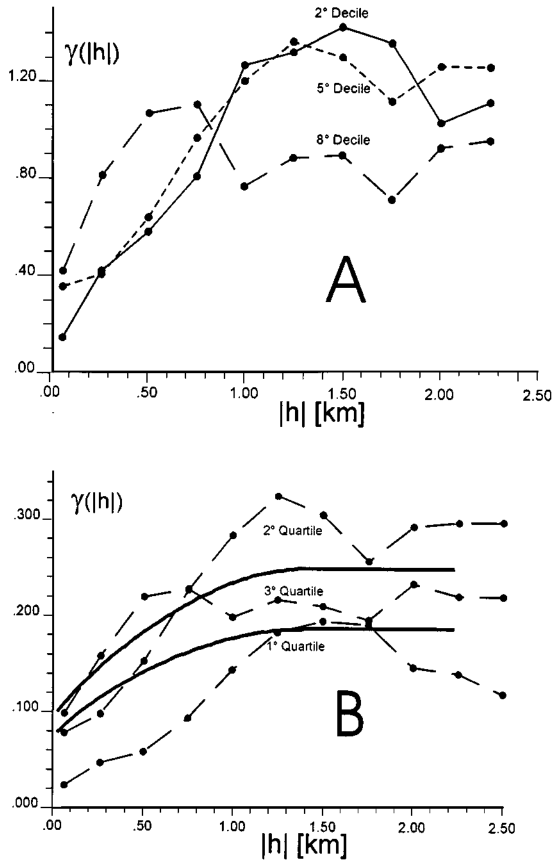

Figure 5. (A) Experimental standardized omnidirectional indicator variograms for the second, fifth, and eighth decile; (B) experimental omnidirectional indicator variograms (dashed line) for the first, second, and third quartile compared with the theoretical ones in presence of bivariate normality (solid line).

Hence, it is also necessary to infer theoretical variograms needed during indicator kriging procedure. It must be remembered that it is not possible to reproduce exactly the complex structures shown in the experimental variograms by a theoretical one. On the other hand, this is not the aim of the inference. The inference process must transfer as best as possible, both the principal bivariate characteristics of the studied indicator variable in the experimental variogram and those eventually deduced from other complementary information of the analyzed variable in a theoretical variogram.

Analysis of the cumulative distribution function of temperature individuates eight possible cutoffs at 65, 70, 73, 75, 78, 80, 82, and 84°C. Here only two indicator variograms will be treated in detail among the eight utilized during the indicator kriging procedure. The second indicator variogram (threshold 70°C) presents a geometrical anisotropy (0.8) along 330° and its theoretical equation is composed by a nugget effect plus a spherical variogram. Here the nugget effect represents 10% of the variability and the sill of the spherical variogram 90%. The inference results are visible in Figure 6B and the theoretical variogram is represented by

$$\gamma(h) = 0.017 + \begin{cases} 0.154\left[\frac{2}{3}\left(\frac{|h|}{1.97}\right) - \frac{1}{2}\left(\frac{|h|}{1.97}\right)^3\right] & h \leq 1.97 \\ 0.154 & h > 1.97 \end{cases}$$

The sixth indicator variogram (threshold 80°C) is composed of a nugget effect (10%) and an exponential variogram, whose sill explains the 90% variability with a geometrical anisotropy (0.6) along 30°. The corresponding complete theoretical equation is represented by:

$$\gamma(h) = 0.03 + 0.26[1 - \exp(-3|h|/1.53)]$$

The inference results are shown in Figure 7B.

Figures 6 and 7 also show the other six theoretical indicator variograms and the experimental ones. Moreover, all the results of the eight theoretical indicator variograms are summarized in Table 1.

Particularly, in Table 1 and in Figures 6 and 7, an increase in the nugget effect from the threshold 80 to 84°C is evident. In fact, at a threshold of 84°C, 27% of the variability of the indicator transform is not structured.

Table 1. Properties of the Theoretical Indicator Variograms at the Eight Thresholds

z_k	Nugget	Sill	Range (km)	Direction	Anisotropy	Variogram
I–65°C	0.006 (10%)	0.056 (90%)	2.04	330°	0.8	Spherical
I–70°C	0.017 (10%)	0.154 (90%)	1.97	330°	0.8	Spherical
I–73°C	0.020 (9%)	0.200 (91%)	1.97	330°	0.8	Spherical
I–75°C	0.033 (10%)	0.300 (90%)	1.57	Isotropic		Spherical
I–78°C	0.033 (10%)	0.282 (90%)	1.50	45°	0.8	Spherical
I–80°C	0.030 (10%)	0.261 (90%)	1.53	30°	0.6	Exponential
I–82°C	0.034 (15%)	0.200 (85%)	0.68	30°	0.8	Spherical
I–84°C	0.041 (27%)	0.111 (73%)	0.54	Isotropic		Exponential

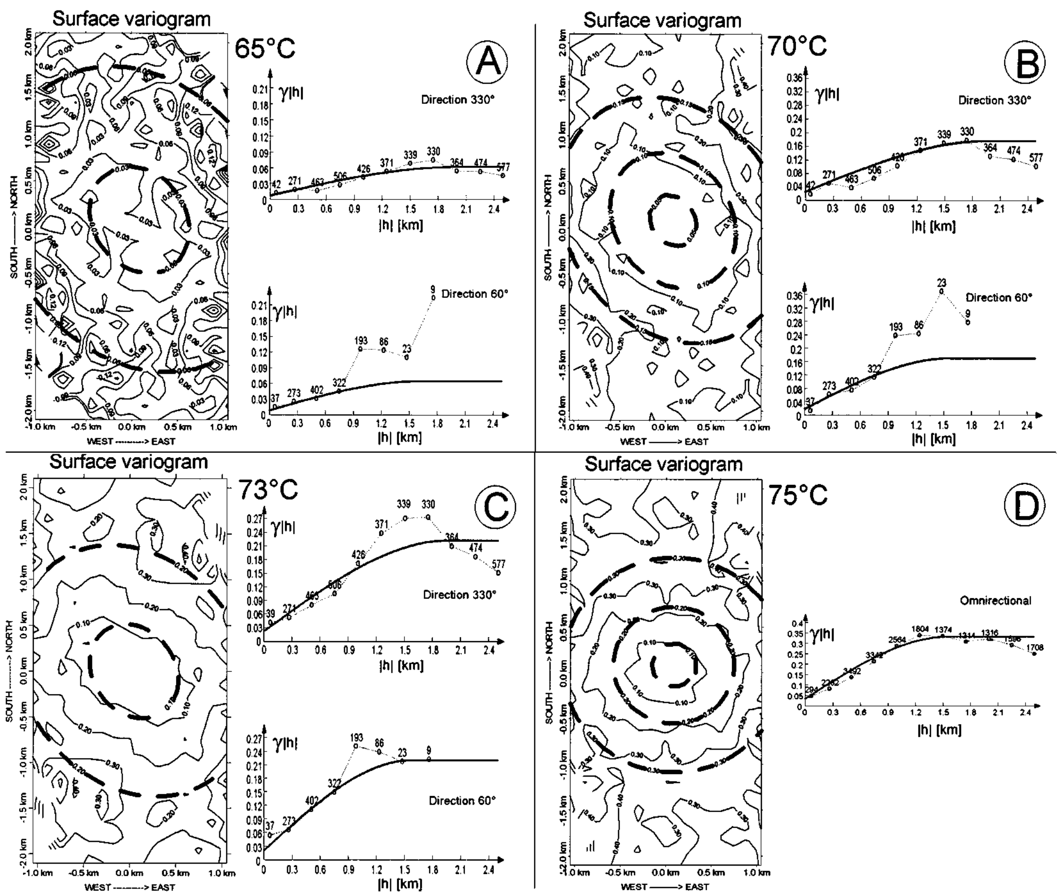

Figure 6. Experimental surface indicator variogram and the superposed theoretical one (dashed line); directional indicator variograms and theoretical ones (solid line) along and orthogonal to the principal anisotropy. Thresholds (A) 65°C, (B) 70°C, (C) 73°C, and (D) 75°C.

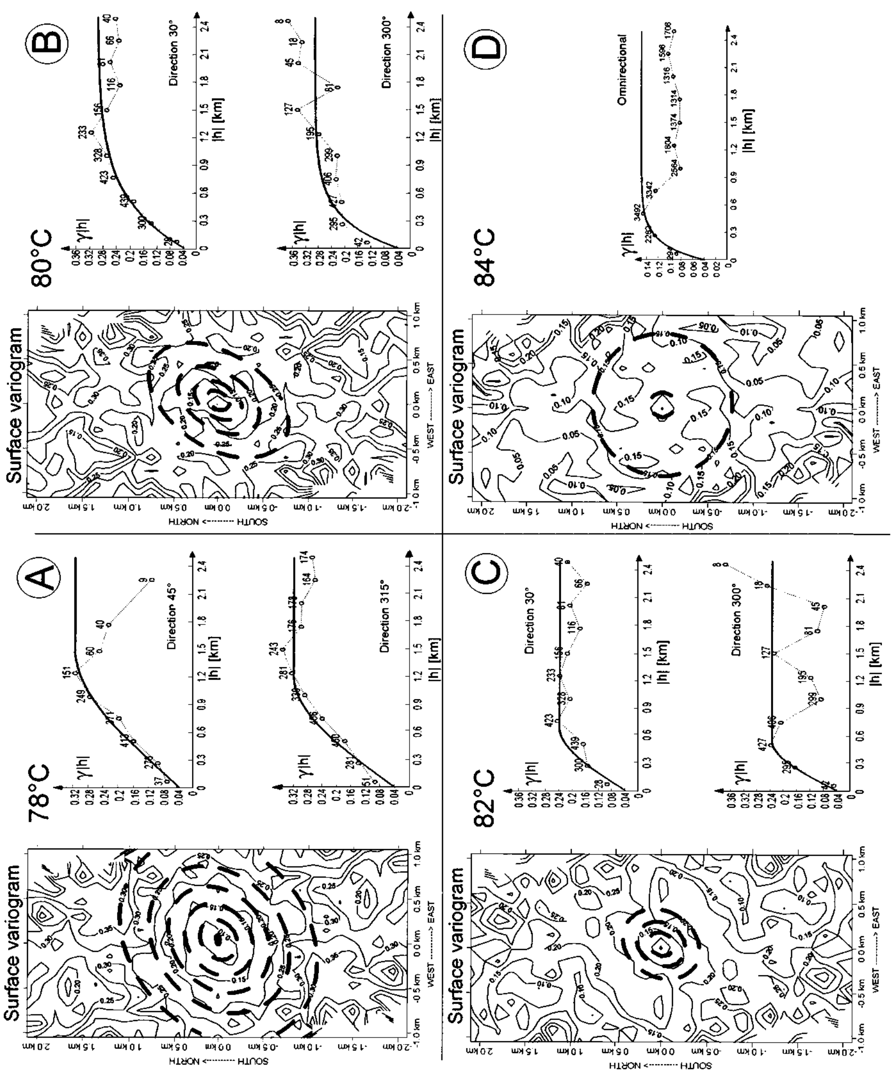

Figure 7. Experimental surface indicator variogram and the superposed theoretical one (dashed line); directional indicative variograms and theoretical once (solid line) along and orthogonal to the principal anisotropy. Thresholds (A) 78°C, (B) 80°C, (C) 82°C, and (D) 84°C.

After a detailed variogram analysis and the inference process, the next step is indicator kriging using the theoretical indicator variograms at the eight thresholds of temperature identified in the geothermal Euganean area.

RESULTS OF INDICATOR KRIGING

Outputs obtained using the *ik3d* code (i.e., conditional probability values for each threshold) must be then postprocessed with the code *postik*, which performs various statistical computations, (Deutsch and Journel, 1998). The results are georeferenced maps of probability that the temperatures in the geothermal Euganean area is in excess of 80°C (Fig. 8A), between 70 and 80°C (Fig. 8B) and not in excess of 70°C (Fig. 8C). Moreover, Figure 9A shows the median estimates of temperature and Figure 9B the interquartile range of such areas. The interquartile range of temperature distribution produces a robust measure of spread of the conditional probability distribution in any location, particularly with regards to the presence of an asymmetric distribution. Map coordinates are shown in kilometric units (UTM). Along the *north-south* direction, 5000 km (e.g., 24.50 = 5.024.500) must be added to the value shown on the map, and 710 km to the value for east-west.

A detailed analysis of Figure 8 reveals zones with very probable high temperatures (more than 80°C) and zones that are highly likely to have temperatures of less than 70°C. In the area of mining claims called "Aponus," "Smeraldo," and "Menegolli," of the Abano field, the probability is near 1 (Fig. 8A). Also, in a zone not presently exploited around the "Menegolli" mining claim, there is 0.7–0.8 probability that the temperature at about 500 m in depth is more than 80°C. Here, median temperature ranges between 80 and 84°C (Fig. 9A), and the interquartile range is from 3 to 6°C (Fig. 9B). In the Montegrotto field, the probability is very high in the mining claims called "Mioni." Then, in direction NNW from the mining claim "Venere" to "S. Giusto," there is a zone little exploited with a high probability (0.6–0.8) that the temperature is more than 80°C (Fig. 8A), a median temperature of about 80°C (Fig. 9A), and an interquartile range less than 3°C (Fig. 9B).

Figure 8B shows a central zone between Abano and Montegrotto fields where there is a high probability that the temperature is between 70 and 80°C (mining claim "Rigati" and "Antoniana").

Figure 8C shows the probability that the temperature is less than 70°C. Here, there are several areas showing high probability, including the region between the Montegrotto and the Abano field in the mining claims called "Massaggio" and "Cecchinato," and in the south west area of the mining claim "Cristallo" of the Montegrotto field.

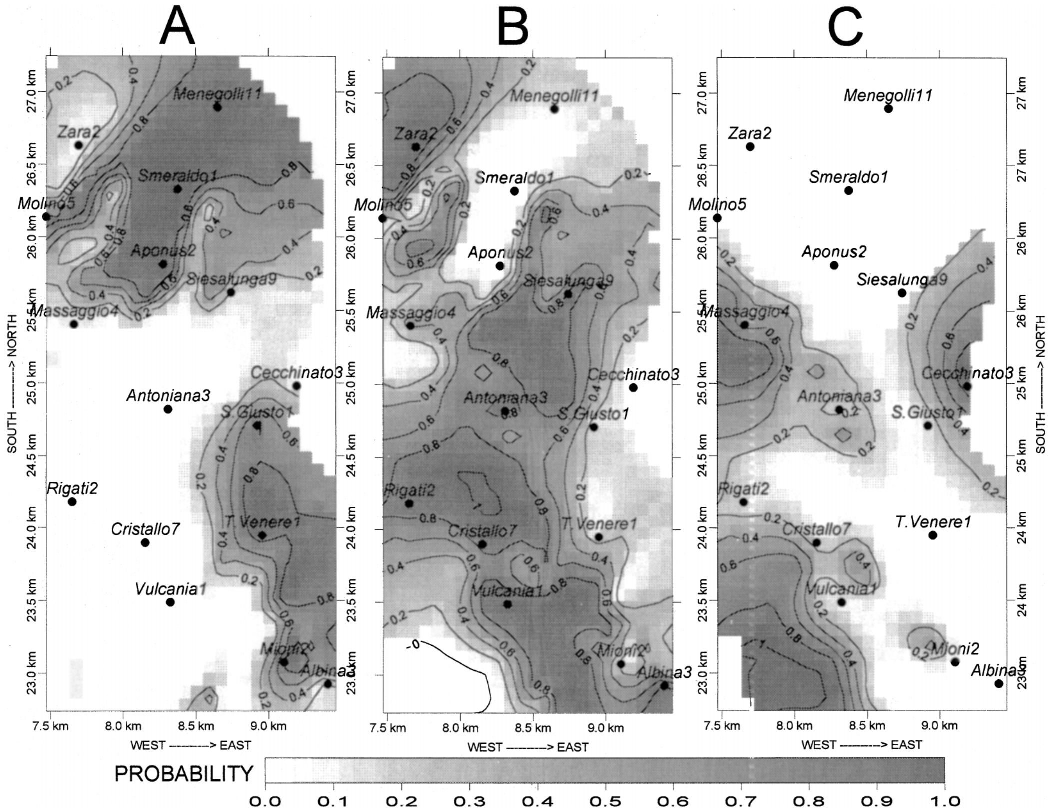

Figure 8. Georeferenced maps of probability that the temperature in the geothermal Euganean area is (A) higher than 80°C, (B) between 70 and 80°C, and (C) below 70°C.

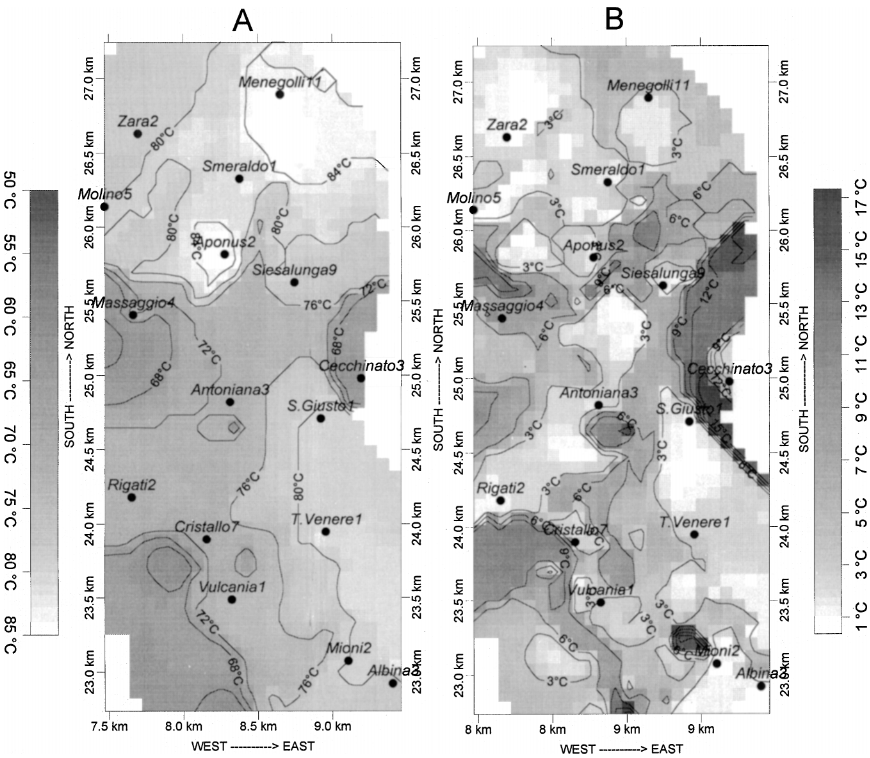

Figure 9. (A) Georeferenced map of median estimates of temperature and (B) of interquartile range of temperature representing the distribution spread.

CONCLUSIONS

In this paper the use of the indicator kriging procedure to determine conditional cumulative distribution functions at each of 24 × 53 grid nodes allows a local uncertainty assessment. The results of indicator kriging with respect to eight thresholds of temperatures in the geothermal Euganean field are postprocessed and discussed. Thus, the probability that the temperature is more than 80°C, between 70 and 80°C and less than 70°C in the geothermal Euganean area is shown. Here, the importance of detailed variographic studies finalized to the structural variable analysis and to the objective work (e.g., temperature thresholds) is pointed out, focusing the study on the hydrogeological point of view; thus the variogram analysis is not only an automatic fit problem. Indeed, the variogram analysis and successive inference steps are fundamental, not only to obtain correct geostatistical results, but also to extract useful hydrogeological information.

The temperature variogram is able to identify a general geostatistical structure but not the structure in a particular temperature cutoff. The structural analysis, confirmed by stratigraphic information and seismic profiles, indicates that general geological situation of the geothermal Euganean area (Fig. 1) includes the following:

- a middle scale anisotropy with a direction 290° (N70°W);
- a large scale anisotropy with a direction 340° (N20°W), indicating the "Schio-Vicenza" regional fault system.

Finally, the choice of a indicator kriging procedure is able to assess a local uncertainty, very useful during decision-making regarding future geothermal exploitation areas.

The resulting maps of probability that the temperature is higher than 80°C, between 70 and 80°C and below 70°C (Figs. 8A–C) reveal some practical hydrogeological information, including what follows:

- identification of an interesting unexploited zone of very probable high temperature in the Abano field near to the "Menegolli" mining claim (Fig. 8A).
- identification of a zone little exploited in the Montegrotto field with a high probability that the temperature is more than 80°C (above all between the mining claims "T. Venere" and "S. Giusto") (Fig. 8A).
- identification of a zone with high probability (0.8–1) that the temperature is between 70 and 80°C in a little exploited area between Abano and Montegrotto (mining claim "Rigati" and "Antoniana") (Fig. 8B).
- identification between the Abano and the Montegrotto field (mining claim "Massaggio," and "Cecchinato") of areas with high probability that the temperature is less than 70°C (Fig. 8C).

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