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ENVIRONMENTAL AND ENERGETIC IMPLICATIONS OF THE GEOTHERMAL ANOMALIES IN THE EASTERN PO PLAIN

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EXTENDED ABSTRACT

La ricerca presentata in questa nota vuole contribuire alla caratterizzazione delle risorse geotermiche a bassa e media entalpia esistenti nel più ampio territorio ferrarese-modenese, in Italia settentrionale. Per il raggiungimento dell'obiettivo, è stato adottato un approccio metodologico suddiviso in più fasi. In primo luogo, sono stati analizzati i dati di temperatura misurati durante la perforazione di pozzi profondi per l'esplorazione di idrocarburi (Fig. 1). Sulla base di queste informazioni è stato possibile stimare i parametri termofisici del sottosuolo a diverse profondità. A questo proposito è stata fondamentale un'analisi preliminare atta a discriminare l'influenza dei fluidi di circolazione (utilizzati durante le operazioni di perforazione) sulle misure di temperatura in simili contesti sperimentali. A tal fine sono stati quindi applicati diversi approcci metodologici per stimare i valori reali di temperatura delle rocce circostanti. In questo modo, per ogni pozzo sono stati ricavati i profili di temperatura versus la profondità. In secondo luogo, sono stati attentamente analizzati diversi profili di sismica a riflessione profonda eseguiti dall'ENI per l'esplorazione di idrocarburi. Tali profili consentono di ricostruire in profondità le principali unità litologiche e l'assetto tettonico generale. In particolare, su tali profili sono state tracciate le temperature corrette dei pozzi (Fig. 4) e ciò ha consentito l'interpolazione delle distribuzioni di temperatura in profondità e la ricostruzione di alcune principali isoterme lungo i profili. A seguito di questo passaggio, è stato possibile enfatizzare la variabilità del gradiente termico, sia verticale che laterale (Fig. 6). In terzo luogo, per una migliore valutazione del possibile impatto ambientale e per stimare l'influenza dei fluidi geotermici profondi sulle caratteristiche geochimiche delle acque sotterranee, sono stati analizzati dei dati isotopici e idrochimici (ottenuti da misurazioni di pozzo e log di temperatura) relativi ai sistemi acquiferi confinati A1 e A2 (Fig. 2). Tali dati hanno messo in evidenza l'assenza di una comunicazione idraulica diretta tra i fluidi geotermici e gli acquiferi. Infine, l'analisi integrata di tutti i dati suggerisce chiaramente che le variazioni di temperatura, sia orizzontali che verticali, sono una diretta conseguenza dell'evoluzione geologica, idrogeologica e tettonica del settore orientale della Pianura Padana. Proprio la mappatura di tali variazioni laterali permette di riconoscere le aree ad alto potenziale geotermico (Fig. 5). L'analisi dei gradienti geotermici ottenuti suggerisce chiaramente che la conduttività termica (cioè il flusso conduttivo) da sola non potrebbe giustificare tali variazioni verticali. D'altra parte, queste variazioni potrebbero essere attribuite all'instaurarsi di flussi convettivi che interessano principalmente le rocce carbonatiche del Mesozoico (Fig. 6), generando quindi una forte diminuzione del gradiente geotermico attraverso queste unità e un aumento nei depositi sovrastanti (Fig. 4). Questo modello termico potrebbe ovviamente funzionare solo nel caso in cui in profondità sia presente una fonte di calore e una sufficiente permeabilità tali da consentire la circolazione verso l'alto dei fluidi più profondi. Da un punto di vista ambientale, i dati geochimici analizzati suggeriscono che i serbatoi geotermici e il loro sfruttamento non hanno interazioni con le falde acquifere poco profonde. Di conseguenza, il serbatoio a 1000-2000 m di profondità potrebbe essere considerato idraulicamente isolato dai sistemi acquiferi A1 e A2. In altre zone, come ad esempio nella area vicino al pozzo Marrara, ad una profondità di circa 400 m, dove il calore si trasmette per convezione e la temperatura raggiunge circa 35-40°C, il sottosuolo potrebbe essere sfruttato per il riscaldamento urbano attraverso un sistema a circuito chiuso. Come ultimo commento, va sottolineato che la presenza di un gradiente geotermico 'normale' potrebbe comunque consentire lo sfruttamento delle risorse geotermiche a bassa entalpia praticamente su tutta l'area indagata e probabilmente su gran parte della Pianura Padana.

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ABSTRACT

The present research is devoted to contributing on the characterization of the low-to-medium enthalpy geothermal resources existing in the broader Ferrara-Modena territory, Northern Italy. To achieve the goal, first, we analysed temperature data in selected deep boreholes to estimate the local thermophysical parameters of the underground. In order to discriminate the influence of the circulation fluids and then estimate the real temperature values of the surrounding rocks, we applied different methodological approaches. Secondly, different deep seismic reflection profiles for hydrocarbon exploration were analysed to evaluate the main lithological formation and tectonic assessment. Thirdly, we elaborated hydrochemical data obtained from borehole and temperature logs measurement to estimate the influence of the deep geothermal fluids on the shallow aquifer systems. Finally, the integrated analysis of all data allowed to infer both the horizontal and vertical temperature distributions, which are clearly strongly affected by the geological, hydrogeological and tectonic evolution of the eastern sector of the Po Plain, and especially to recognize the area with a highest geothermal potential within the region.

Keywords: *geothermal anomalies, aquifers, Po Plain*

INTRODUCTION

In the European and Integrated National Energy and Climate Plan possible pathways to achieve "climate neutrality" by 2050 have been proposed. In particular, for the period 2021-2030, specific actions for the growth of renewable sources have been identified together with the improvement of energy efficiency and the reduction of greenhouse gas emissions respectively of 32%, 32.5% and 40% compared to the 1990 values. While the final goal of the Energy and Climate Plan is the reduction, by the 2050, of the greenhouse gas emissions over 80% with respect to the 1990. Also, according to the latest report of the World Health Organization in Global (ambient air pollution report; 09/2016) in Western Europe, Italy has the worst air, in terms of concentrations of PM2.5, while in the Po Valley the concentrations exceed the value of 25 µg/mq.

In order to achieve these goals, the request, the exploitation, the use and the diffusion of renewable energies should greatly increase in the next future. Due to the recent evolution of technological plants, like district heating, the low-to-medium enthalpy geothermal plants could fulfil the above needs with important environmental, economic, societal, and health benefits. In general, the geothermal resources, by their reservoir temperatures, have been classified into high, medium and low (or shallow) enthalpy resources. However, the average reservoir temperature is used as the classification parameter because it is considered as one of the simplest parameters. In Tab. 1, some of these classifications are presented.

Also based on temperature, Sanyal (2005) has classified the geothermal resources into seven categories focusing on the prevailing/possible use by the geothermal developer: non-electrical grade (<100°C), very-low temperature (100°C to <150°C), low temperature (150°C to 190°C), moderate temperature (190°C to <230°C), high temperature (230°C to <300°C), ultra-high temperature (>300°C) and steam fields (approximately 240˚C with steam as the only mobile phase).

Lee (2001) with reference to Specific Exergy Index (or available work; SEI) proposed the classification of the geothermal resources in high exergy (SEI ≥ 0,5), medium-high (0,5 > SEI > 0,2), medium-low (0,2 > SEI > 0,05) and low exergy resources (SEI ≤ 0,05).

In the EU, civil buildings are responsible for about the 36% of CO2 emissions and the 40% of energy consumption, while as much as the 35% of the buildings are older than 50 years and almost 75% of them are not energetically efficient (http://www.efficienzaenergetica.enea.it/allegati/RapportoDirettiva2018_844.pdf). Moreover, based on Eurostat data relative to the 2017, 8% of the European population was unable to sufficiently heat their home; while in Italy this percentage was as high as 15%. Accordingly, the exploitation of low-medium enthalpy geothermal resources can contribute to the energy transition because a) it is a renewable energy source; b) by means of a district heating system, it can provide both heating and cooling in large residential areas; c) it can contribute to the reduction of atmospheric emissions; and d) it can contribute to the improvement of the microclimate reducing the creation of 'hot air bubbles' in urban areas during the summer season due to the use of air-to-air heat pumps.

Following the above considerations, with the present research, we want to contribute to the national energetic transition project and particularly a) to the characterization of the geothermal reservoirs existing in the broader Ferrara-Modena territory, Northern Italy, which hosts in the subsoil some major tectonic structures with a high geothermal potential, like for example the Casaglia and the Mirandola anticlines (Fig. 1); and b) to preliminary evaluate the environmental impact on the shallow aquifer systems, due to the presence of the deeper high temperature fluid.

Classification/enthalpy	Muffler & Cataldi (1978)	Hochstein (1990)	Benderitter & Cormy (1990)	Haenel, Rybach & Stegena (1988)	Axelsson & Gunnlaugsson (2000)
low	<90 °C	<125 °C	<100 °C	≤150 °C	≤190 °C
medium	90 -150°C	125 – 225 °C	100 – 200 °C	---	
high	>150 °C	>225 °C	>200 °C	>150 °C	>190 °C

Tab. 1 - Classification of geothermal resources by temperature

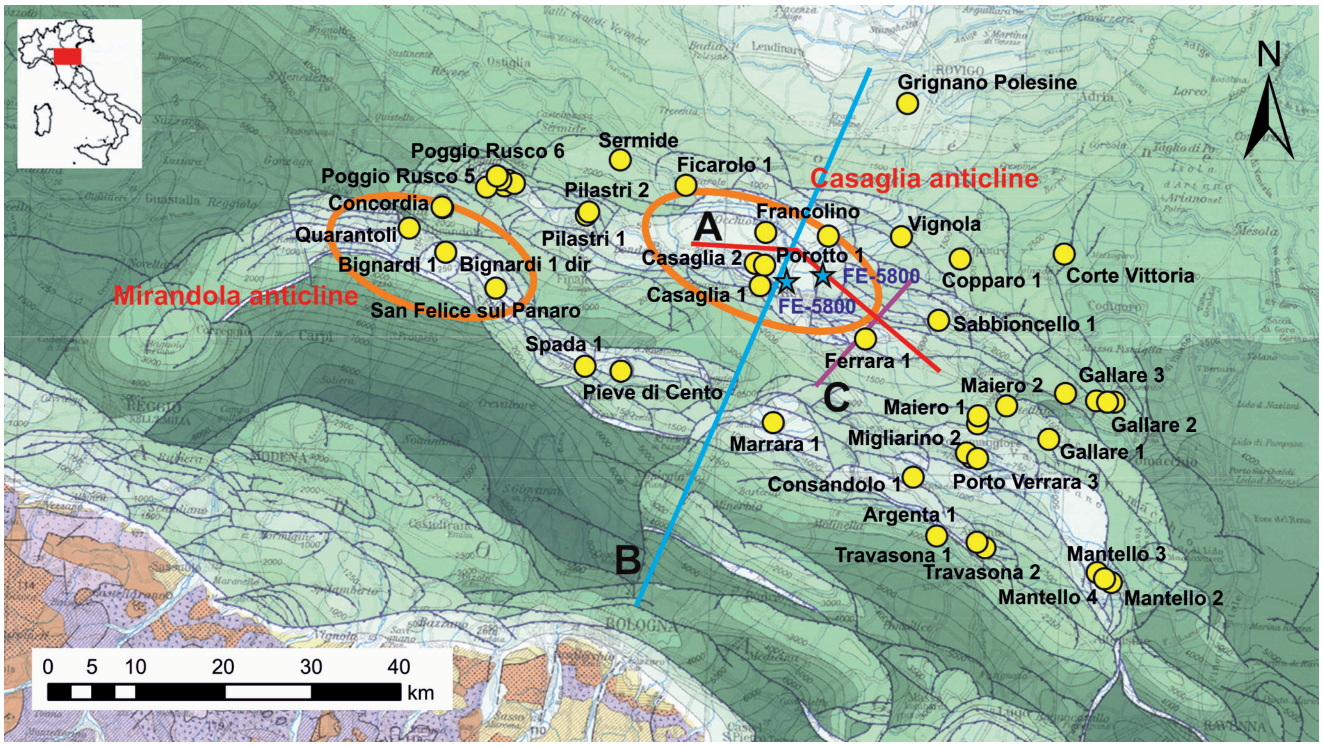


Fig. 1 - Study area showing the distribution of the analysed boreholes (yellow circles); hydrostratigraphic section (continuous red line; A); seismic reflection profiles (continuous blue and purple lines; B and C) and shallow wells (blue asterisk). The base map is extracted from the structural model of Italy (Bigi et alii, 1990)

GEOLOGICAL SETTING

Although the southern Po Plain is morphologically flat, it hosts in the subsoil the external sector of the Northern Apennines fault-and-thrust belt, whose persistent tectonic activity is well documented by both historical and instrumental seismicity (e.g. Caputo *et alii*, 2016). The buried accretionary wedge is partitioned in some major salients, one of which is the so-called Ferrara Arc. The latter basically corresponds to the investigated area. In the frame of the persisting regional shortening clearly confirmed by geodetic data, contractional deformation affecting this major tectonic feature is further partitioned in several minor-order structures (Caputo & Tarabusi, 2016), consisting of a system of low-to-medium angle reverse faults and associated folds. In these tectonic conditions, crustal scale volumes are characterized by differential vertical movements and particularly by localized uplift in correspondence of the hanging-walls blocks and especially of the hinge areas of these blind faults. On the other hand, the broader geodynamic setting is characterized by a regional-wide subsidence of the Adria foreland undergoing subduction and the consequent orogenic load on both north and south sides (i.e. Southern Alps and Northern Apennines, respectively). This in turn creates accommodation space in this wide intermountain region, which is continuously filled by the clastic deposits of the Po Plain. Accordingly, the competing role of the two tectonic processes affecting the subsoil of the investigated area (i.e. regional subsidence and local anticlinal uplift) together with the sedimentary process generated a complex geological setting in the subsoil with carbonate Mesozoic units locally at few hundred meters depth relatively close to pluri-kilometre thick Neogene clastic deposits. As we will see in the following sections, the consequent lithological lateral variability has a strong impact on the heat flow distribution across the region.

HYDROGEOLOGICAL SETTING

In the eastern Po Plain, the geometrical (thickness and lateral distribution), geochemical and hydrodynamic characteristics of the aquifers strongly depend on the lateral and vertical facies variations of the sedimentary successions, which in turn are a consequence of the tectonic structures and the continuously varying depositional environments especially in the most recent times. As a consequence, the Pliocene-Quaternary deposits are characterised by silty-muddy layers alternating with sandy and sometimes gravel lenses (Bortolami *et alii*, 1978; Regione Emilia-Romagna-ENI-AGIP, 1998).

At the regional scale, based on a hydrogeological perspective of the depositional sequences during the last 4 Ma, two major sedimentary cycles could be distinguished (Regione Emilia-

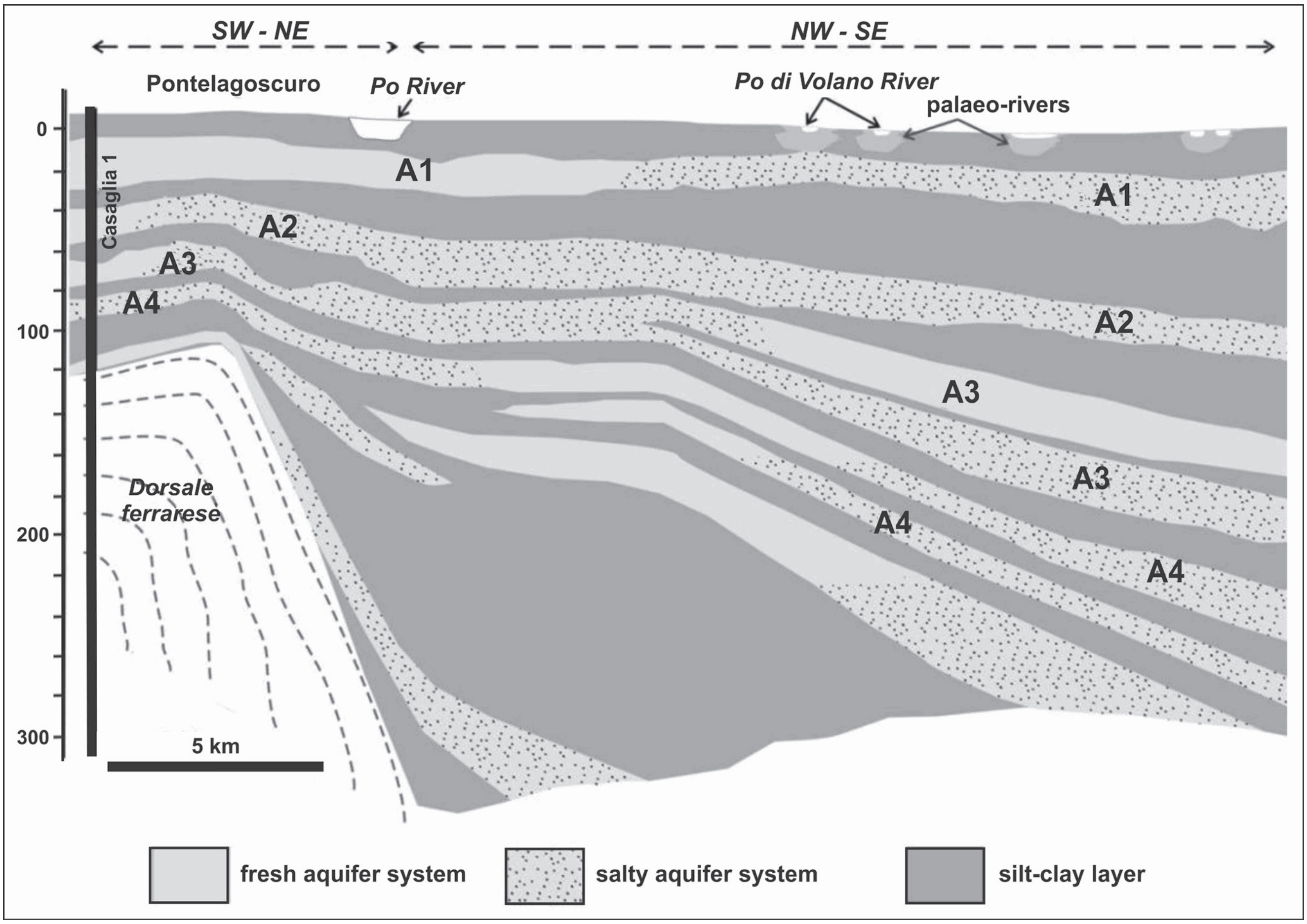
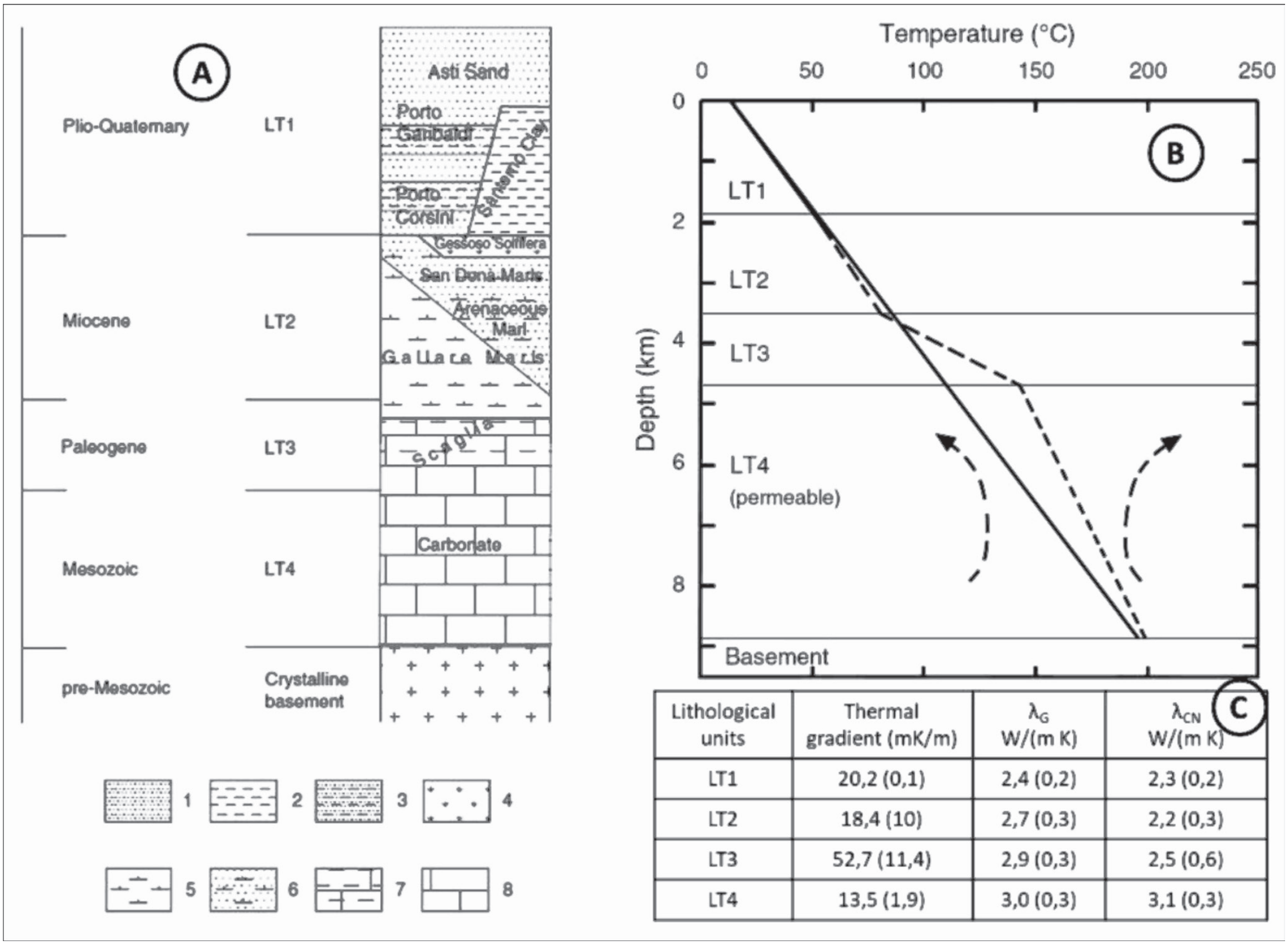


Fig. 2 - Synthetic hydrostratigraphic section (A1 to A4: aquifer systems; from Rapti-Caputo & Martinelli, 2009; for the position see Fig. 1)

Romagna-Eni-Agip, 1998). They correspond to a) the deepest marine Quaternary cycle (Qm; up to 0.65 Ma) containing the aquifer group C, and b) the continental Quaternary cycle (Qc) divided into the Lower Emiliano-Romagnolo System (Qc1; Middle Pleistocene 650-350 ka) containing the aquifer group B, and the Upper Emiliano-Romagnolo System (Qc2; Middle-Holocene Pleistocene) characterized by cyclic alternations of fine-grained material (silts and clays) and coarser deposits with sands and gravels texture where the aquifer group A is developed. Within the latter, the permeable intervals correspond to aquifer systems referred to as A1, A2, A3 and A4. In the present paper, we focus on the aquifer system A and particularly, due to the lack of a geochemical monitoring network and the availability of borehole data (Agip, 1977) used for the temperature and salinity analyses, on the upper zone of the aquifer system A (A1 and A2). Figure 2 clearly shows the influence of the deep tectonic structures, like the Casaglia anticline, on the thickness and depth of the diverse aquifer systems.

It should be noted that the salinity of aquifers and consequently their natural chemical composition are mainly attributable to the different depositional environments (continental, lacustrine or marine) developed within the low delta Po plain. For example, in the hinge area of the fold (Casaglia 1 borehole; Underground water reserves of the Emilia-Romagna Region, 1988), it is possible to distinguish the Aquifer Group B and A within the first 130 m. They mainly consist of sandy material with variable granulometry. In particular,

- the top of Group B is located at a depth of 120 m and its thickness is about 10 m and it is saturated with fresh water;
- the top of the aquifer system A4 is located at a depth of about 90 m, showing a thickness of about 18-20 m; it is saturated in salt/brackish water, while the total porosity varies between 34 and 41%;
- at 70 m depth has been identified the top of the aquifer system A3, saturated in fresh water with a thickness of about 15 m. The total porosity varies between 32 and 38%;



Lithological units	Thermal gradient (mK/m)	λ_G W/(m K)	λ_{CN} W/(m K)
LT1	20,2 (0,1)	2,4 (0,2)	2,3 (0,2)
LT2	18,4 (10)	2,7 (0,3)	2,2 (0,3)
LT3	52,7 (11,4)	2,9 (0,3)	2,5 (0,6)
LT4	13,5 (1,9)	3,0 (0,3)	3,1 (0,3)

Fig. 3 - Eastern Po Plain basin A) synthetic representative stratigraphic column: 1) sand and sandstone, 2) clay and shale, 3) clayey and marly sand, 4) evaporite, 5) marl and silty shale, 6) silty and arenaceous marl, 7) argillaceous and marly limestone, 8) carbonate; B) Temperature versus depth; continuous and dashed lines indicate regional thermal gradient, while arrows represent likely thermal convection phenomena; C) Thermal gradients and thermal conductivity for each lithologic unit (λG: Gallare; λCN: Cascina Nuova borehole); standard error in brackets (from Pasquale *et alii, 2013)*

- the top of the aquifer system A2 is at a depth of about 40 m and its thickness is 15 m; the total porosity is between 32 and 46%; the water electrical conductivity is about 1500 µS/cm and these values are likely to be attributed to the strong depression cones of the piezometric level caused by the water extraction in the industrial area of Ferrara (30 l/s) and Mirabello (9 l/s) in addition to the salinization phenomena affecting the northern sector of the A2 aquifer system;
- at 10 m depth is the top of the aquifer complex A1 which has a thickness of about 20 m; the total porosity is between 33 and 42%, while the water electrical conductivity is about 1000 µS/cm. The general flow direction is from NW to SE; influenced by the extraction in the industrial area north of Ferrara.

In order to define possible mixing phenomena due to intrusion of the deep geothermal fluids to the shallow confined aquifers, hydrochemical data from monitoring wells near the area of the Casaglia reservoir were analysed.

HYDROTHERMAL SETTING

Surface heat flux depends essentially on the concurrent role of sedimentation (e.g. aggradation rate) and tectonics (fault and folds growth) phenomena. Based on numerical calculations, Pasquale *et alii* (2012) suggested that heat-flow differences among the different tectonic units in the western Po Basin are due mainly to tectonothermal processes that have taken place in the basin and the surrounding areas. By assuming a constant sedimentation rate, the same Authors applied the simplified approach proposed by Von Herzen & Uyeda (1963) in order to evaluate the thermal effect of the most recent and important deposition cycle (Pliocene-Quaternary), which strongly affected the Miocene formations acting as a basement; calculated that the decrease of surface heat flow is significant when sedimentation rate is >0.1 mm/a. In particular, the authors estimated the increase of the average heat flow (about 39%) is due, above all, to the improved estimate of thermal conductivity, which accounts for by 24%.

Finally, the surface heat flow in the areas where heat conduction phenomena play an important role for heat propagation is characterized by values in the range 54 and 78 m·W/m2 (Haenel, 1974; Pasquale & Verdoya, 1990) while, lower heat flux values (<60 m·W/m2) suggest convective heat transport due to the presence and circulation of groundwater.

In particular, in the eastern sector of the Po Plain, Pasquale *et alii* (2013) analyse the sedimentary sequence grouping the several units in terms of lithology and density proprieties as follows (Fig. 3): LT1 (marine sands, clayey sands and clays), LT2 (marls, silty marls and arenaceous marls whose upper limit is marked by minor deposits of lake-sea clays and evaporites and marly limestones), LT3 (manly formed by argillaceous and marly limestones) and LT4 (mudstone, wackestone, packstone, dolostone deposited on the crystalline basement. Accordingly, the estimated regional thermal gradient has an average value of about 20.6 m·K/m varying between 13.5 (LT4) and 52.7 m·K/m (LT3). Also. the vertical strong variation of the thermal gradient cannot be ascribed to thermal conductivity variations of the geological formations, and a possible explanation could lie in the heat transported by water flow in the permeable deep carbonate unit (LT4). The permeability and the water flow of this unit mainly depends on the secondary porosity due to the development of fracture systems associated with the tectonics processes affecting these rocks. This water flow could cause a decrease of thermal gradient in LT4 (thermal convection mechanism) and a significant increase in the overlying impermeable unit (LT3).

MATERIAL AND METHODS

For the characterization of the low-to-medium enthalpy geothermal resources existing in the broader Ferrara-Modena territory, firstly, several deep seismic reflection profiles for hydrocarbon exploration were analysed, in order to evaluate the main lithological formation and tectonic setting (until 6-10 km). Secondly, we analysed the stratigraphic data available from the VIDEPI database (www.unmig.it) for 55 deep boreholes drilled all over the investigated area for hydrocarbon explorations (Fig. 1; 800-6000 m depth). The temperature data of these boreholes have been published in the inventory of the national geothermal resources edited by Agip (1977). The analysis of temperature data in selected deep boreholes allowed to estimate the local thermophysical parameters of the underground.

It is noteworthy that the available values of the measured temperatures were affected by the fluids (water and mud) used during the drilling operations. The difference between the temperature of the mud and that of the drilled host rock depends on several factors like the borehole depth, the time required by the muds for a complete circulation cycle, the thermal gradient, the porosity of the stratigraphic units, the time lag of the measurement, fluid flow, exothermic reactions like setting cement and mineral oxidation (Zschocke, 2005; Lachenbruch & Brewer, 1959, Eppelbaum & Kutasov, 2006, Raymond, 1969, Edwardson *et alii*, 1962).

Various temperature correction methods based on different simplified physical models have been developed based for example on a constant line source method, conductive-convective cylindrical heat source model, the spherical and radial heat flow method (Ascencio *et alii*, 2006; Dowdle & Cobb, 1975; Verma *et alii*, 2006; Wong-Loya *et alii*, 2012).

In order to discriminate the influence of the circulation fluids and estimate the real temperature of the surrounding rocks, in the present research the methodological approaches proposed by Horner (1951) and Zschocke (2005) have been applied. In case at least two measurements at the same depth were available, the former method is likely the most appropriate. While in order to estimate the thermal conductivity, the Pasquale *et alii* (2008), Sekiguchi (1984) And Deming & Chapman (1988) methods have been applied.

Horner approach: Horner Method, for static formation temperatures estimation (TH), using shut-in temperature logs is analysed. In particular, the method approximates the thermal effect of the drilling as an infinitely thin and long axial heat source extracting heat at a constant rate. Accordingly, perfect conducting conditions in the well are assumed. The mathematical expression is the following:

$$BHT(t) = T_H + \frac{H}{4 \cdot \pi \cdot K_r} \cdot ln(1 + \frac{t_c}{t_e}) \qquad (1)$$

where *BHT(t)* is the borehole shut-in temperature, *TH* is the static formation temperatures, *H* is the heat extraction rate, *Kr* the thermal conductivity of the formation, tc is the mud circulation time (in hours) and te is the shut-in time (in hours). According to equation (1), a semi-logarithmic plot of *BHT(t)* against the Horner dimensionless time *ln(*1+*tc/te)* should be a straight line intercepting the ordinate axis at *TH*. The standard procedure for applying the Horner-plot method is to extrapolate this line for te → ∞ (Horner dimensionless time = 1).

Based on the analysis of temperature data from the Po Plain basin, Pasquale *et alii* (2008) showed that the application of the Horner's method for values of te <10 h, underestimates the temperature of equilibrium on average of 2 °C according to the Cooper & Jones (1959) correction method. Accordingly, this correction value has been added to all the *TH* values derived from a te <10 h.

In case of a single temperature value, it has been proposed a correction for the temperature:

$$\Delta_t = T_H - BHT(t) = (16.3 \cdot z - 2.1 \cdot z^2) \cdot ln(1 + \frac{t_c}{t_e}) \quad (2)$$

which is also a function of depth, *z* (in kilometres)

$$t_c = 1.7 + 0.005 \cdot z + 0.10 \cdot z^2 \quad (3)$$

Also in this case, for values of *te* <10 h an additional temperature correction of 2 °C is necessary.

Zschocke approach: In the absence of temperature time series, the approach proposed by Zschocke (2005) was instead applied to correct the equilibrium temperature of the rock when a single temperature value is available:

$$\Delta_t = \frac{Q}{4 \cdot \pi \cdot K_m^{(1-\varphi)} \cdot K_w^{\varphi}} \{ E_1 \left[\frac{r^2}{4 \cdot K_m^{(1-\varphi)} \cdot K_w^{\varphi} \cdot t_e} \right] - E_1 \left[\frac{r^2}{4 \cdot k_{in} \cdot (t_e + t_c)} \right] \} \quad (4)$$

where $E1$ is the exponential integral; Km and Kw the thermal conductivity of rock formation and water, respectively, with φ the porosity varying from φ_0 (surface porosity) as a function of depth (z) and a compaction factor (λ), $\varphi=\varphi_0^{(-\lambda z)}$; kin is the rock thermal diffusivity; r is the radius of the borehole; Q is the radial heat flow, which is given by (Kutasov, 1999)

$$Q = 2 \cdot \pi \cdot K_{in} \cdot (T_m - T_f) \cdot q_D\ (t_D) \quad (5)$$

where T_m is the mud temperature; T_f the formation temperature; t_D the dimensionless time $[t_D = \frac{K_{in}\, t_c}{r_b^2}]$ and q_D the dimensionless heat flow,

$$[q_D(t_D) = \frac{1}{ln(1+D\sqrt{t_D})}, \text{ with } D = \frac{\pi}{2} + \frac{1}{\sqrt{t_D}+b} \text{ and } b = \frac{2}{(2\sqrt{\pi}-\pi)}]$$

Also, the term (T_m-T_f), which controls the radial heat flow, can be estimated based on the following relationship:

$$(T_m - T_f) = -3 \cdot z^2 + 34.6 \cdot z - 30.6 \quad (6)$$

In the present research, values adopted for φ_0 and λ are 0.180 and 0.396 km^{-1} in carbonate rocks, 0.284 and 0.216 km^{-1} in sandstones and calcarenites, 0.298 and 0.461 km^{-1} in marls and silty marls, and 0.293 and 0.379 km^{-1} in shales and siltstones, respectively (Pasquale *et alii*, 2013).

The thermal conductivity of the rock formation as a function of temperature was then estimated following Sekiguchi (1984) (7)

$$K_m = 1.8418 + (K - 1.8418) \cdot \left(\frac{1}{0.002732 \cdot T + 0.7463} - 0.2485 \right)$$

where K, is the thermal conductivity at 20 °C, while for the thermal conductivity of the water, it has been considered the formula proposed by Deming & Chapman (1988)

$$K_w = 0.5648 + 1.878 \cdot 10^{-3} \cdot T - 7.231 \cdot 10^{-6} \cdot T^2 \quad (8)$$

for $T \leq 137$°C.

The thermal conductivity and thermal diffusivity values of the different formations were based on values proposed by Viganò *et alii* (2011) and Robertson (1988).

The total heat flux for each borehole was then calculated based on the thermal resistance (R) method, which correlates the temperature difference between surface, T_0, and depth, T_d, with surface heat flow, q_0, *and resistance:*

$$T_d - T_0 = q_0 \cdot R \quad (9)$$

where the latter is calculated as,

$$R = \Delta_z \sum_{z=0}^{d} \left(\frac{1}{K_{in}} \right)$$

with K_{in} the thermal conductivity estimated at different depth intervals (Δ_Z).

Finally, in order to estimate the geothermal gradient (K) and the heat flux (q), based on the Fourier law, we considered three reference geolithological intervals corresponding to: S_0 = to silicoclastic sedimentary succession down to the base of the marine Quaternary (Qm); S_1 = the stratigraphic units underlying the marine Quaternary and overlying the Scaglia formation (SF); and S_3 = from the top of the Scaglia formation to the bottom of the analysed borehole. Also, for each interval both the geothermal gradient (K_0, K_1 and K_2; Figure 3) and the heat flux (q_0, q_1 and q_2) have been calculated.

Furthermore, for estimating the influence of deep geothermal fluids on shallow aquifer systems, the hydrogeological model was reconstructed up to the maximum depth of 150 m based on the analysis of the stratigraphic data of the wells from the database of the Emilia-Romagna Region; while the determination of the qualitative characteristics of the aquifers was based on the analysis of chemical data from 18 wells filtered in the different aquifer systems (ARPAe database).

Finally, in order to estimate the influence of deep geothermal fluids on shallow aquifer systems, the hydrogeological model was reconstructed up to the maximum depth of 150 m based on the analysis of the stratigraphic data of the wells from the database of the Emilia-Romagna Region. The determination of the hydrochemical characteristics and isotopic composition of the aquifers allows to distinguish the principal geochemical facies and to recognise the occurrence of mixing phenomena between waters with different alimentation zones (Freeze & Cherry, 1979; Hounslow, 1995; Stumm & Morgan, 1981; Hem, 1985; Lloyd & Heathcote, 1985; Rapti-Caputo, 2007). The determination of the qualitative characteristics of the aquifers was based on the analysis of chemical and isotopical data from 18 wells filtered in the different A1 and A2 aquifer systems (ARPAe database).

RESULTS

The analysis of the obtained geothermal gradients clearly suggests that the thermal conductivity (viz. conductive flux) alone could not justify such vertical variations. On the other hand, these variations could be attributed to the occurrence of convective flows mainly affecting the Mesozoic carbonate rocks, therefore generating a strong decrease of the geothermal gradient across these units and an increase in the overlying deposits. This thermal model could obviously work only in case a heat source is present at depth and a sufficient permeability allows the upwards circulation of the deeper fluids.

Accordingly, we focused our attention on the carbonate sedimentary succession, which indeed represents the geothermal reservoirs. In particular, the heat transmission characterizing these rocks is a consequence of both conduction and convection phenomena. Moreover, the largest differences in geothermal gradient and heat flux characterizing successions S1 and S2 do occur in correspondence with the major structural highs, like that associated to the Ferrara Thrust. For example, in the Casaglia 1 borehole (depth: 2418 m) where the base of the marine Quaternary (Qm) and the top of the Scaglia Formation (TS) are at about 198 m and 586 m depth, respectively, the temperature varies between 48 °C at 198 m to 113 °C at the bottom of the borehole with a mean slope of about 29.4 °C/km (Figure 4; dashed blue line). In particular, within S1 unit the thermal gradient and the heat flow are 61.9 °C/km and 113.6 mW/m^2, respectively; while, in the deeper unit (S2) the thermal gradient and heat flow are 22.4 °C/km and 58.7 mW/m^2, respectively. These values confirm the occurrence and the role of the convective flow within the carbonate unit (S2) and the calculated values could be likely attributed to the upwelling of fluids across the dense fracture system extending up to shallow depths.

In other cases, like in the Marrara 1 borehole (Figure 4), in both upper units (S1 and S2), small variations of the thermal gradient and heat flow suggest that the heat flux occurs prevailingly or exclusively by means of conductive phenomena.

Geostatistical methods (Inverse Distance Weight) have been then applied to define the spatial distribution of the data. Due to non-homogeneous distribution of the boreholes and for a better representation of the processing data, within the broader investigated area we distinguished and focused on two sub areas referred to as A and B, both with internal good spatial distributions (Fig. 5).

The results of all the investigated boreholes have been plotted to generate thematic maps thus emphasizing (at least) the first order geothermal anomalies. In particular, the data analysis allowed to observe the follow (Figure 5):
from the spatial distribution of temperatures, referred to the base of the marine Quaternary (Qm) and to the top of the Scaglia formation, the influence of the stratigraphic and tectonic structure is evident. At the base of the marine Quaternary layer, in the Ferrara and Casaglia area, a geothermal anomaly is clearly observed, with temperature values around 50 °C at a depth varying between 200 and 500 m, respectively; while a few kilometres to the east (Copparo 1 borehole) the same temperature values are located at 1650 m depth (Figure 5a). Furthermore, the spatial distribution shows that, at the top of Scaglia, at a depth of about 2200-2300 m (Figure 5b), the temperature in the Vignola borehole is about 20 °C higher than that of San Felice sul Panaro (71 °C); while in other cases, similar temperature values (72-75 °C) were calculated at depths ranging from 600 m (Casaglia 1) to 1300 m (Ferrara 1).

As for the geothermal gradient (K1; Fig. 5c), high values in the S1 unit can be attributed to convective motions developed at greater depths in correspondence of unit S2 or to the intrusion of geothermal fluids across the fracture systems; the latter hypothesis seems confirmed by the heat flux difference map (q1-q2; Figure 5d). The lowest values of the geothermal

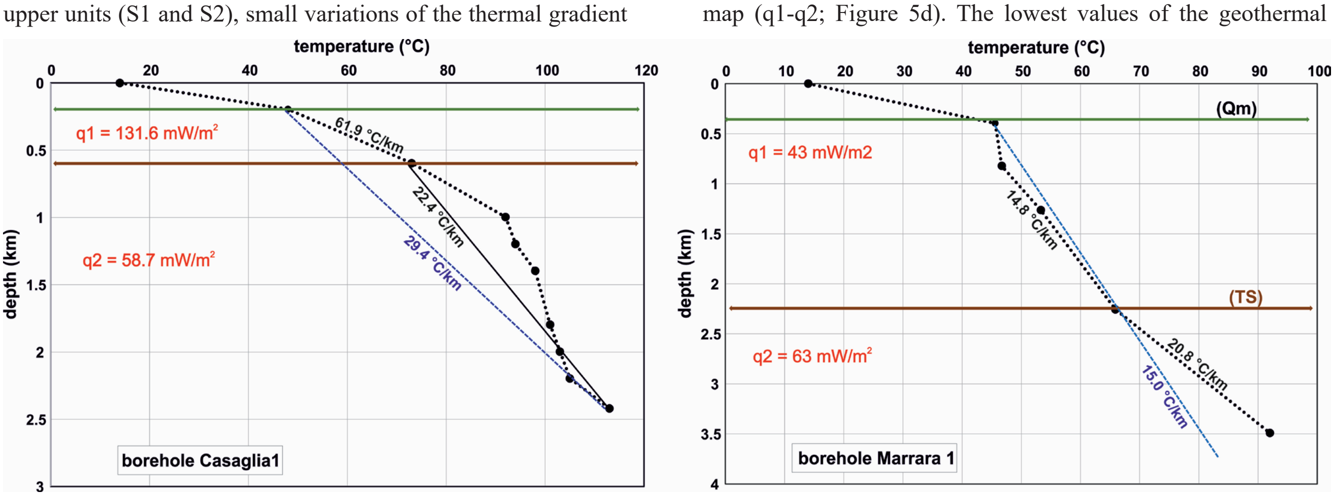


Fig. 4 - Example of geothermal gradients and heat flow calculated for the intervals S1 and S2 (see text for discussion)

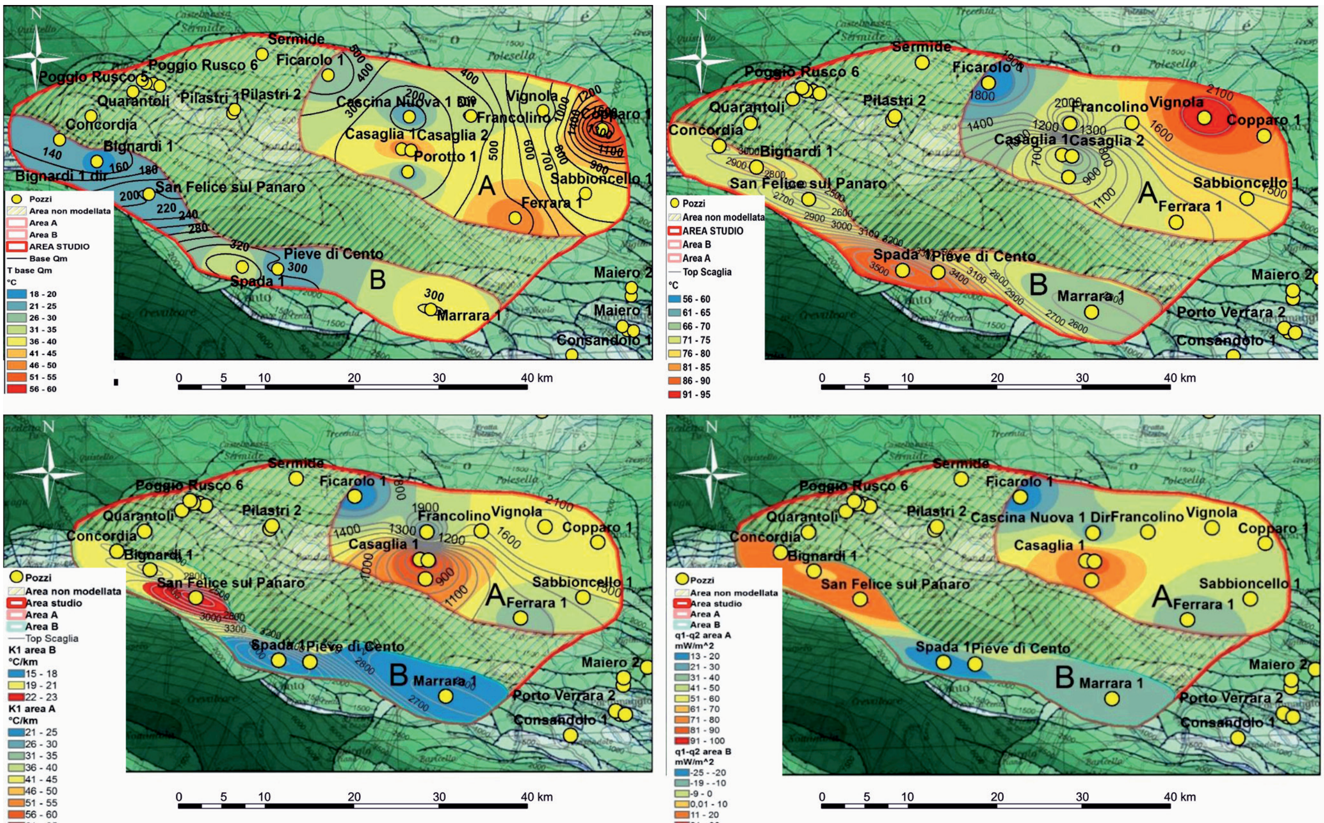


Fig. 5 - Spatial distribution of a) temperature (°C) in the base of marine Quaternary deposits (Qm); b) temperature (°C) in the top of Scaglia (TS); c) geothermal gradient (K1) in the Qm; d) differences of heat flow (q1-q2) in mW/m2. The contour lines in (a) and (b) represent the isobaths of the base of Qm and the top of Scaglia formation, respectively

gradient observed in the southern and northern parts of the study area, could be a consequence of the rapid sedimentation of the siliciclastic series and by the absence of convective motions in the S2 unit.

In order to better understand the distribution at depth of the analysed parameters, and particularly the vertical/lateral variability of the thermal gradient, deep geological sections crossing the investigated area have been considered. These sections are based on the detailed analysis of seismic reflection profiles carried out for hydrocarbon explorations, they have been carefully interpreted by means of dedicated software, stratigraphically calibrated by exploiting the available boreholes and finally depth converted (Allegra, 2016; Mistroni, 2016; Mastella, 2018). On these sections, we plotted the boreholes temperatures corrected following the previously described methodological approaches, exploiting also the spatial distributions represented in Figure 5. Based on these constraints, some principal isotherms have been reconstructed and traced along the profiles.

In Figure 6 are shown two geological profiles interpreted in terms of geothermal gradients. Both examples clearly show that the isotherms are denser in correspondence of the major anticlines where the Mesozoic carbonate units have been strongly uplifted as a consequence of the folding and faulting; conversely in the large synclines where the Neogene clastic sediments are thicker, the isotherms are more spaced and the thermal gradient lower.

As above mentioned and in order to estimate the influence of the deep geothermal fluids on the groundwater geochemical characteristics, we analysed isotopic and hydrochemical data relative to the confined aquifers A1 and A2. At this regard, aquifer A1 is certainly the most explored one due to its diffuse exploitation for aqueduct purposes.

From the isotopic point of view, the data analysis carried out in the eastern territory of the Po Valley on the A1 and A2 aquifer systems (Rapti-Caputo, 2000; Rapti-Caputo & Martinelli, 2007; 2009) allowed to document that the 18O/16O ratio has values between -10.86 and -7.44; while the D/H isotope ratio shows values between -72.79 and -48.99. The waters of the A2 aquifer appear to be characterized by the most negative values in δ18O, documenting an age greater than 20,000 years and in general greater than those found in the first confined aquifer (A1).

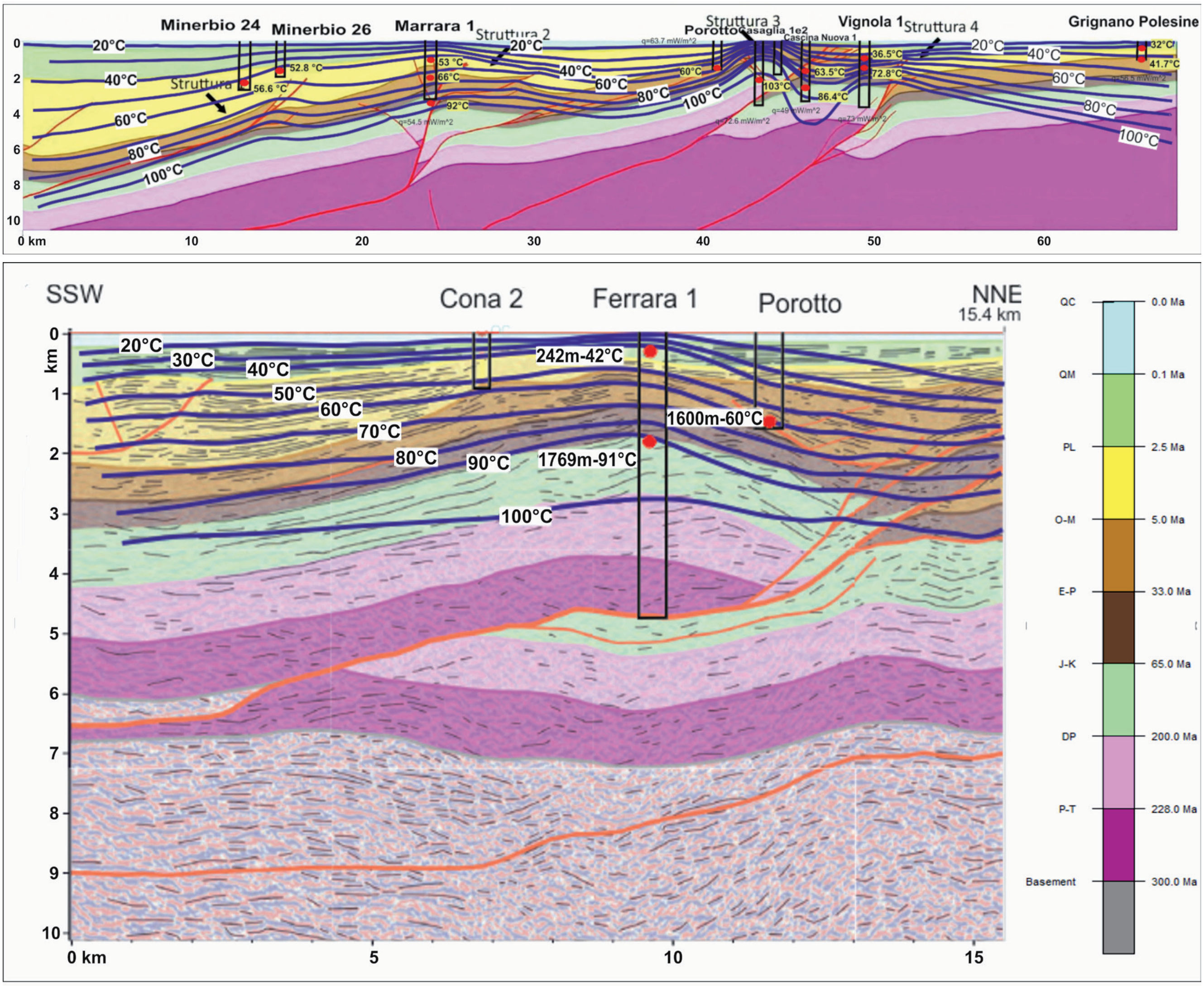


Fig. 6 - Lateral and vertical variations of the geothermal gradient emphasized by the isothermal distribution along two geological sections reconstructed from seismic reflection profiles for hydrocarbon exploration. Top and bottom sections from Mistroni *(2016) and* Allegra *(2016), respectively (for the position see Fig. 1)*

All values are aligned along a straight line analytically expressed by the equation:

$$\delta D = 7.3007 \cdot \delta 18O + 4.2452 \quad (10)$$

whose correlation coefficient is $r^2 = 0.9$.

The distribution of isotopic values relating to δ18O-δD generally reflects the presence of waters of multiple origins, from the Alps, the Northern Apennines as well as from 'local' waters due to mixing phenomena between meteoric or surface water with underground ones.

From the distribution of the hydrochemical data on the diagram of Piper (1944), we observe how in the A1 and A2 confined aquifer systems, the Ca-HCO_3 water type generally prevails, while the waters from the deep geothermal reservoir (about 1000 m-deep) are characterized by a facies Na-Cl (Figure 7). In the same Figure 7b, it is evident a decrease in chloride concentrations from the first confined aquifer A1 to the deeper on (A2). Accordingly, the processed isotopic and hydrochemical data are indicative of not direct hydraulic communication between deep waters and surface aquifers.

FINAL REMARKS

The integrated analysis of deep seismic reflection profiles (Figure 6) paired with the estimation of the thermophysical parameters down to a depth of ca. 3 km allowed to infer both the horizontal and vertical temperature distributions, which are

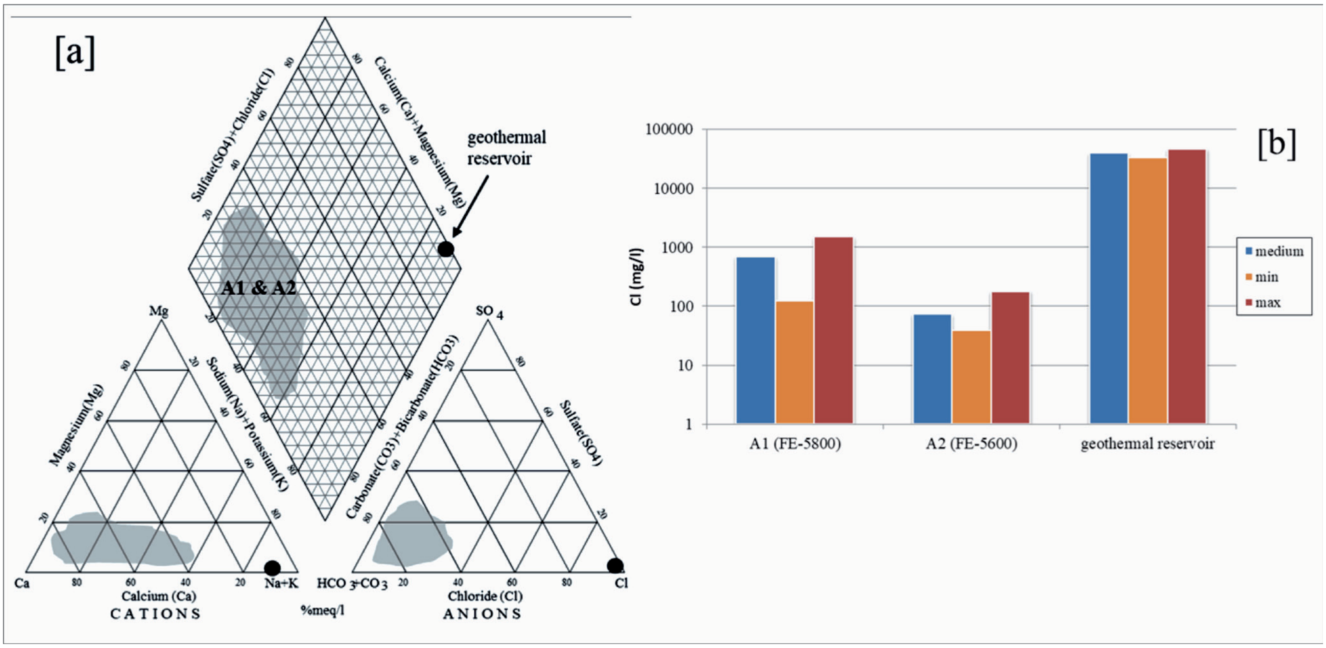


Fig. 7 - a) Piper (1944) diagrams showing the distribution of the chemical composition of the shallow confined aquifer (A1 and A2) and the geothermal reservoir of Casaglia; and b) Comparison between the chloride concentrations in the shallow aquifers (A1 and A2; ARPAe database) and the geothermal reservoir (the wells FE-5800 and Fe-5600 are close to the Casaglia anticline; for the position see Fig. 1)

clearly strongly affected by the geological, hydrogeological and tectonic evolution characterizing the region. Accordingly, the most promising areas in terms of potential geothermal reservoirs and their exploitation have been recognized in a sector of the eastern Po Plain.

For the calculation and mapping of the geothermal gradients and the heat flow for each borehole, two reference levels were considered corresponding to the base of the marine Quaternary, Qm, and the top of the Scaglia, SC. Significant variations in the geothermal gradient (Figure 5c) have been attributed to the development of convective flows within the carbonate sedimentary succession. Following this approach, areas with greater geothermal potential have been identified due to the higher temperatures. For example, near the Casaglia and Vignola wells (Figure 5), where at 1000 m-depths the geothermal fluid reaches ca. 90° C and 50°C, respectively. Both areas are in correspondence of buried structural highs. The exploitation of this geothermal resource could take place through an open circuit system that includes a withdrawal well and one or two for reinjection. Currently in the Casaglia area, the fluid contained in the geothermal reservoir is exploited with a flow rate of 400 m^3/h, providing a renewable thermal energy power of approximately 14 MWth.

From an environmental point of view, the geochemical data analyzed suggest that the geothermal anomalies and their exploitation have no interactions with the shallow aquifers. Accordingly, the 1000-2000 m-deep reservoir could be considered hydraulically isolated from A1 and A2 (Figure 7). In other areas, such as for example in the area near the Marrara well (Figures 5 and 6), at a depth of about 400 m, where heat is transmitted by convection and the temperature reaches about 35-40°C, the subsoil could be exploited through a close circuit system for building heating. As a final comment, it should be stressed that the presence of a 'normal' geothermal gradient could allow the installation of low enthalpy geothermal systems basically all over the investigated area and likely most of the Po Plain.

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