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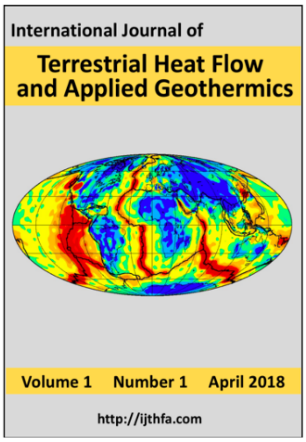

Subsurface temperature measurements for detecting tectonic dislocations

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Abstract

An example of characterization of a tectonic zone by using underground temperature measurements is presented. A tectonic discontinuity, located in NW Italy, was investigated by precision temperature measurements by means of the analysis of thermal data recorded in a monitoring well along the northern part of Torrente Traversola Deformation Zone. Moreover, we investigated the lateral extension of the deformed zone by means of the analysis of thermal logs recorded in three control wells located at some distance from the tectonic structure. The monitoring well and the three control wells show completely different thermal pattern. The former exhibits advection and a thermal profile that can be well matched with a model of fluid flow within a sub-vertical fracture. The control wells instead reveal prevailing conductive thermal regime. This might be evidence that the deformation zone has little lateral extension. Our study showed that high-precision temperature logs can be a valuable tool for detecting fractured zones and delimit their lateral extent.

1. Introduction

The analysis of precision thermal logs in boreholes, coupled with geologic-structural and hydrogeological investigations, can represent a diagnostic tool to recognize fractured zones -or important buried tectonic discontinuities - and to deduce the groundwater flow in different hydrogeological environments. The validity such an analysis depends on how much the effect of fluid circulation in a porous medium is discernible and how much is its effect on the thermal regime. Two theoretical models of advective heat transport are often used: (i) vertical flow in semi-confined layers, as proposed by (Bredehoeft and Papadopulos, 1965), (ii) horizontal flow in an aquifer as developed by (Bodvarsson, 1973) and (Ziagos and Blackwell, 1986).

These models well describe the mechanisms of mass and heat transfer in semi-confined and confined aquifers. In fractured rocks, the measured temperature profile in wells can show sudden vertical variations caused by the circulation of fluids inside zones of localized fractures, whose dimensions can vary between few meters to some hundred meters. Despite they were observed in many wells, so far these temperature anomalies, have been rarely studied due to their very local significance and also because the use of high resolution tools and very tight sampling are needed for their evaluation. This work presents an example of characterization of a tectonic structure by using underground temperature measurements.

A well-known tectonic discontinuity, located in NW Italy, the Torrente Traversola Deformation Zone - TTDZ (Gattiglio e tal, 2015) was investigated by means of the analysis of thermal data recorded in a monitoring well along the northern stretch of the TTDZ.

Figure 1a shows the geological setting and the location of TTDZ, which lies in the central sector of the Piedmont hilly area. This structure was responsible for the differential translation to the north of the Poirino Plateau (240-325 meters above sea level) with respect to the Asti Reliefs (130-330 m). The TTDZ is formed by numerous sub-parallel tectonic fractures, which would be responsible for the deformation of the whole sequence. Morphologically, it is represented by an evident step, with a height of one hundred meters, length of about 30 km. The deformation zone mainly involves the Plio-Pleistocene successions (Forno et al, 2015). TTDZ is structurally organized in various N-S-directed sub-vertical faults, mainly characterized by right strike-slip movement. The northern part of the TTDZ, involves Messinian sediments (Figure 1b).

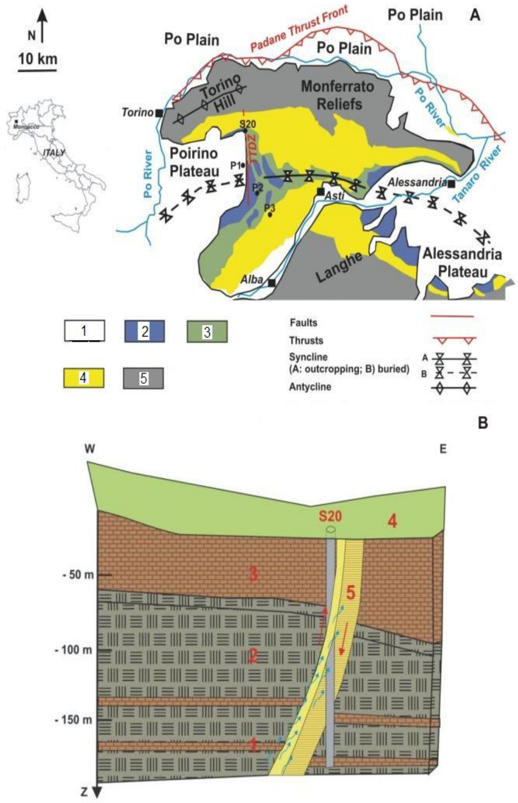

Figure 1 - A) Geological background and location of the Torrente Traversola Deformation Zone (TTDZ) in NW Italy. (after Forno et al, 2015, modified); 1 – Middle Pleistocene-Holocene deposits; 2 – Villafranchian Upper Complex (Lower Pleistocene); 3 – Villafranchian Lower Complex (Pliocene); 4 – Deep-shallow marine facies (Asti Sand and Lugagnano Clay, Pliocene); 5 – Late Eocene-Miocene succession. (B) Structural and hydrogeological model at the northern edge of the TTDZ: 1– marl levels within fractured gypsum; 2– fractured gypsum; 3– marl; 4– ground level; 5– main fault connected to the deformation zone. Location of boreholes S20, P1, P2 and P3 is shown. Blue arrows, groundwater flow along the deformation zone; red arrows, relative displacement related to the TTDZ.

2. Stratigraphic features

In the investigated area, the stratigraphic succession includes (upwards) evaporitic sediments, covered by re-sedimented gypsum and then by clayey and marly continental sediments (Irace, 2004). Pliocene marine clay and Quaternary fluvial clayey silt from the upper part of the sedimentary sequence (Dela Pierre, 2003). Litho-stratigraphic information derived from borehole stratigraphy (the monitoring well S20, in Fig. 1b). The borehole cut silt, clay and marl from the ground level to 66 m. Below, a body of fractured gypsum was found with a thickness of about 110 m and again marly-silty-clayey layers to 174 m depth.

A passive seismic survey was performed in the vicinity of the S20 monitoring well to refine stratigraphic information in the shallower part likely affected by a fracture zone. The ambient noise horizontal-to-vertical spectral ratio (HVSR) technique was used to obtain a one-dimensional model of shear-wave velocity. We used a Tromino® seismic digital data logger equipped with three velocity sensors, and data processing was carried out by means of the software Grilla supplied by the manufacturer (MoHo s.rl., 2011).

The recording time was 20 min and the sampling frequency 128 Hz. Two datasets were retrieved and processed: (i) the H/V curves and (ii) the velocity spectrum curves of the three directions of seismic waves motion (vertical, north-south, east-west), derived after the analysis of (i).

The H/V curves represent the value of the ratio between the average spectral amplitudes of the ambient vibrations (referred to the vertical and horizontal components of the motion) according to the frequency.

The peaks of the H/V curve at a given frequency may be more or less evident and interpretable, depending on the magnitude of the seismic impedance contrast between the rigid substrate and the most superficial layers. The modelling of the H/V curves was carried out through an inversion procedure that compares the single spectra and the H/V ratios measured with synthetic ones. The optimal interpretation was the one with the best match between measured data and synthetic ones.

The peak at the highest frequency (about 30 Hz) was assumed to be representative of the boundary between the agricultural soil and the silty clayey level and is located at a depth of about one meter. Assuming this superficial constraint, the synthetic curve that best approximates the observed one is reported in Figure 2. The seismic data processing provided a seismic stratigraphy (Figure 2) that in general shows a reasonable congruence with the stratigraphy of the S20 monitoring well (Table 1). Seismic layers correspond to facies in which the greatest contrasts of impedance were observed. The velocity increase at 14 m depth well correspond to the transition from clayey silt to marly clay, whereas the increase at 76m mark the transition from fractured macro-crystalline gypsum marl with gypsum clasts.

Table 1 - Stratigraphy of S20 monitoring well.

Depth (m)	Lithology
0.0-0.50	Soil
0.50-10.50	Brown clayey silt
10.50-22.3	Marly clay locally clayey marl
22.3-66.3	Clayey grey marl, locally marly clay
66.3-73.9	Fractured macro-crystalline gypsum
73.9-76.3	Grey marl with gypsum clasts
76.3-79.0	Fractured macro-crystalline gypsum
79.0-79.4	Grey clayey marl
79.4-109.0	Fractured macro-crystalline gypsum
109.0-110.1	Grey marl with gypsum clasts
110.1-174.0	Grey marl

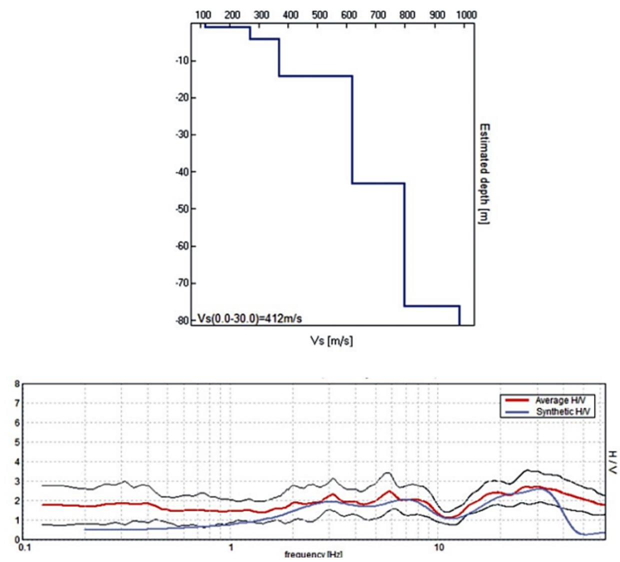

Figure 2 - Velocity-depth model) obtained from a passive seismic study next to borehole S20 site (above). Comparison between the experimental (red) and synthetic (in blue) H/V curves (below). Black curves denote 95% confidence interval.

3. Thermal logs

The borehole S20 was accessible for temperature measurements to 100 m depth. Downhole temperature logs were performed, using a 2-m spacing starting from the depth of 50 m, where the groundwater level was observed. The thermal probe consisted of a platinum resistance (Pt 100) with a sensitivity of 0.01 °C (Pasquale et al, 2017). The recorded temperature-depth data and the plot of the thermal gradient versus depth are shown in Fig. 3. Thermal gradient is nearly null or negative in the shallower part that is close to the contact between marl and gypsum. Then, the gradient assumes a linear trend with a value of about 16mK m^{-1} as far as 80 m depth. Below this depth, the temperature profile clearly shows a concavity, departing from the linear trend. This concavity may indicate an upward warm water flow along a fracture zone.

This temperature distribution might be interpreted as presence of upward fluid circulation along the fracture referring to the TTDZ. Figure 1b depicts the conceptual model: it may be hypothesized that a fault system, more extended in depth than the S20 borehole, encounters a deep aquifer containing slightly warmer groundwater.

Other temperature logs were carried out in three wells (P1, P2 and P3) located in the surrounding (1-8 km apart) of the TTDZ (Figure 1), to assess whether the fluid circulation highlighted by the thermal log in well S20 is restricted to the deformation zone or somehow extends further. The recorded thermal profiles, measured with the same temperature probe of the S20 log are presented in the top (a) and bottom (b) panels of Fig. 3. The qualitative analysis of the temperature-depth data may help to put into evidence possible local fractured zones which may be related to the TTDZ.

The well P1 is located in the Poirino Plateau, on the left side of TTDZ, in terraced fluvial deposits of Middle-Upper Pleistocene age. These deposits, with a thickness between 10 and 30 meters, constitute tabular bodies of connected and abandoned meanders, variously reshaped, more or less wedged (Forno, 1982). From the hydrogeological point of view, this area is characterized by the presence of a medium-permeability shallow aquifer hosted in silty-gravelly river deposits, underlain by a confined multi-aquifer system, hosted in Villafranchian succession (Bortolami et al, 1989; Canavese et al, 1999; Lasagna et al, 2011; Lasagna et al, 2014; Boano and Forno, 1999). Litho-stratigraphic reconstruction of the subsoil, retrieved from borehole log, displays the predominance of compacted clayey silt to a depth of 93 m beneath ground level, and coarse-medium sand with varying compaction grade to the hole bottom.

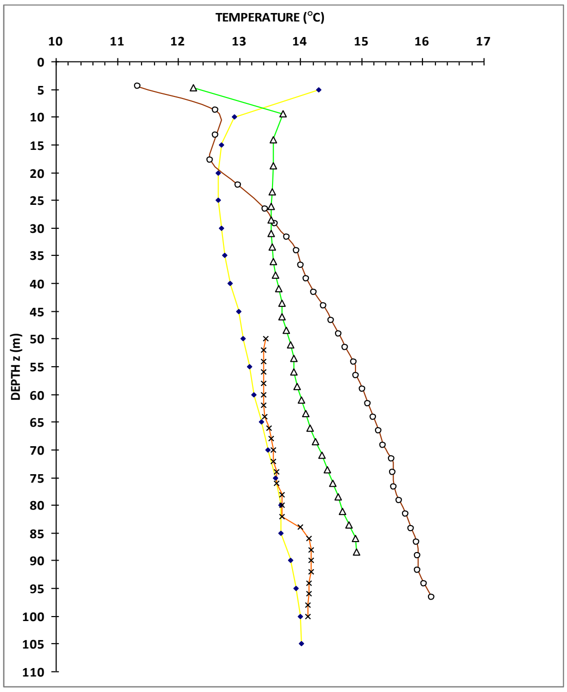

Figure 3a - Temperature profiles of S20, P1, P2 and P3 wells. See Fig. 1 for borehole locations.

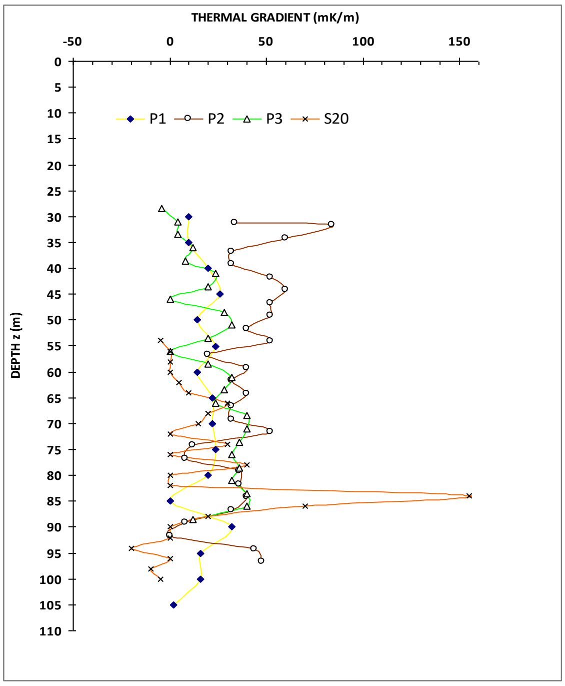

Figure 3b - Thermal gradient profiles of S20, P1, P2 and P3 wells See Fig. 1 for borehole locations.

4. Thermal Models

To obtain quantitative information on the water flow velocity within the fractured zone, we used the analytical solution (Ge, 1998):

$$\frac{T-T_t}{T_b-T_t}=\frac{z}{L}+\frac{\delta}{2}\left(\frac{z}{L}-1\right)\frac{z}{L} \qquad (1)$$

where z is the depth, L the thickness of the fractured area along the vertical direction, and T_t and T_b are temperatures at the surface and at the base of the fractured area, respectively. The quantity δ is given by the product between $sin(\omega)$ and α, where ω is the average inclination of the fracture zone relative to the horizontal plane and $\alpha = (\rho c v L)/k$ is the Peclet number, where v average Darcy velocity of the fluid along the fracture direction, ρ the density of the water and c the specific heat.

This model is based on various assumptions, among which the most important are: (i) uniform thermal conductivity; (ii) conductive and convective heat propagation take place under steady-state conditions; (iii) rocks are hydraulically and thermally homogeneous and isotropic, except in the fracture zone where the permeability of the fracture can significantly increase; (iv) the convective heat transfer is along the main direction of the fracture zone; (v) the convective heat transfer takes place along the main direction of the fracture zone; (vi) convective heat propagating along the fracture zone is localized in space and does not significantly alter the temperature range outside the fracture zone (Ge, 1998). The parameters assumed for our model are: $\omega = 70°$, $T_t = 14.0$ °C, $T_b = 14.10$°C, $L = 18$ m, $k = 1.54$ W m^{-1} K^{-1}, ρ=1000 kg·m^{-3} and c= 4186 J·kg^{-1}·K^{-1}.

Figure 4 shows a comparison between the theoretical temperature profile, calculated by means of Eq. 1, and the temperature data observed in the monitoring well S20. The theoretical model that best approximates the observed data is for δ values ranging from -9 to -6. Assuming a fracture inclination of 70°, as suggested by surface geological data, it results point to Peclet numbers between -7 and -10. The negative value of α suggests an upward-directed flow of warmer water, and the velocity along the fracture zone may range from 1 to 2x10^{-7} m·s^{-1}.

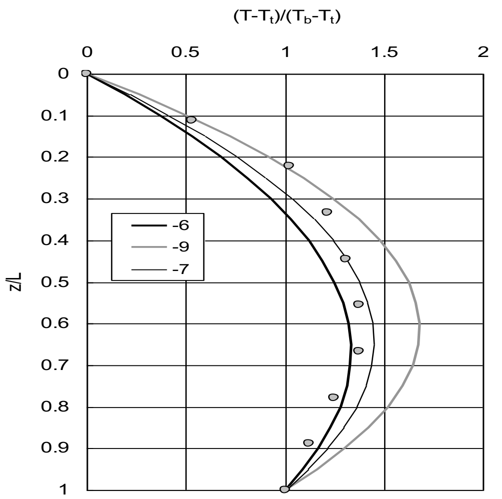

Figure 4 - Comparison between temperatures modeled with Eq. 1 (curves) and temperatures measured in the borehole S20 (dots). The curves corresponding to δ values ranging from -9 to -6 are shown.

5. Discussion

The geothermal gradient of P1 well is on average 17mK m^{-1}. The qualitative analysis of the temperature log shows that within the uppermost 25-30 m, the hole is influenced by seasonal temperature oscillations. At 50 m depth, the geothermal gradient decreases significantly. This is likely due to the presence of groundwater flow. The most important gradient variation is located at 85 meters depth, highlighted by a break in the thermal profile. This feature may be correlated with change of facies from silty-clay (characterized by lower thermal conductivity values (Pasquale et al, 2017), to compact fine-grained sand. Sand also allows easier water circulation than clay, which would further contribute to the reduction of the geothermal gradient. Below the depth of 95 m, the temperature profile assumes a typical conductive trend.

Well P2 is located in the Asti Reliefs, a few kilometres away from the TTDZ, and affects the Villafranchian succession (Boano and Forno, 1999; Forno et al, 2015). The well crossed alternating fossil-bearing silt with flat-parallel lamination and cross-laminated sand originated in a delta-plain environment and overlying fluvial sediments (Piacenzian and Calabrian). These deposits lay on the Asti Sand (Zanclean), comprising sand with plane-parallel stratification of grey colour, intercalated by silty-clayey levels, arenaceous/calcarenitic levels and medium-coarse sands. The litho-stratigraphic log displays the predominance of silty clay and sandy silt from the surface to a depth of 33 m and, finally, coarse, weakly compact medium sand with compact fine sand, with intercalations of silty and compact sand (Asti Sand) at the hole bottom.

From the hydrogeological point of view, there are two main facies forming a typical multilayer confined aquifer. The sandy levels host groundwater. But the prevalently silty-clayey levels, almost impermeable, constitute the confining layer, limiting the vertical communication between the litho-types below. The hydraulic conductivity contrast between the two facies makes vertical water flow difficult.

The hydrogeological features are reflected by perturbations in the geothermal gradients caused by advection (Fig. 3). The geothermal gradient is mostly uniform with an average value of 38mK m^{-1}. At 50 m depth the geothermal gradient significantly decreases, likely due to the presence of large groundwater flow. The most prominent gradient variation is located at 70 meters depth and it may be closely connected to the presence of the sandy levels of the multilayer aquifer, which foster a larger water circulation. The thermal profile is characterized as a whole by a predominantly conductive regime.

The P3 well is also located in the Asti reliefs, a few kilometres away from TTDZ, in the Lugagnano Clay Zanclean (Forno et al, 2015). These deposits correspond to homogeneous grey-blue silty clay and are overlain by recent sandy fluvial deposits, with a thickness of some tens of meters.

The fluvial deposits host an aquifer, while clay forms a geological body with very low or negligible permeability. The geothermal gradient in P3 (Fig. 3) is on average 22mK m^{-1}. In the 40-50 m depth range, the geothermal gradient varies, likely because the contrast in thermal properties at the boundary between the fluvial deposits and the Lugagnano Clay. From 60 meters to the hole bottom, the temperature profile shows a typically conductive trend.

6. Conclusions

The temperature-depth data recorded in a borehole located along the TTDZ well match a conceptual model that envisages the fracture zone as a preferential path through which fluids at higher temperature flow upwards. This evidence is in accordance with the results of recent geological studies which demonstrate that the study area is characterized by a tectonic dislocation extending N-S over a regional-scale and significantly deforming surrounding sedimentary sequence.

The thermal log analysis and the inferred groundwater circulation indicate that this tectonic dislocation has considerable vertical continuity and represents the surficial manifestation of a deeper tectonic structure. An analytical model of fluid and heat transport suggest that the fluid velocity in tectonic feature is of ~ 10^{-7} m s^{-1}, i.e. approximately three orders of magnitude higher than the value reached in similar rocks having only primary porosity and permeability.

The analysis of another set of thermal logs in boreholes located at both sides of the deformation zone showed completely different thermal patterns. This might be interpreted as evidence that the deformation zone has little lateral extension. In summary, this study show that the analysis of high-precision temperature profiles measured in shallow boreholes can be a valuable tool for detecting fractured zones, as well as areas affected by buried tectonic discontinuities, which host localized underground water flow.

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