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Hydrothermal circulation in the Acqui Terme district, Tertiary Piedmont Basin (NW Italy)

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ABSTRACT

We investigated the deep hydrothermal circulation of the Acqui Terme district, Tertiary Piedmont Basin (TPB), which is characterised by hot springs, with a maximum temperature of about 70 "C. A thermal gradient increasing from about 70 to 90 mK m^{-1} towards the hot spring area was determined in two conduction-dominated boreholes. Calculations on convection-dominated boreholes again yielded anomalously high thermal gradients compared to those expected for TPB. The hydrothermal circulation mainly affects the crystalline basement beneath the impermeable sedimentary cover. The maximum depth of the hydrothermal system is 3400 m, and the top of the permeable zone ruled by convection is at a depth of about 1000 m. Models of ascending flow show that the water rises from the reservoir through a relatively narrow fracture zone.

KEYWORDS

Geothermal system, medium enthalpy reservoir, convective heat transfer, hot springs

1. Introduction

The Acqui Terme district, located in the Tertiary Piedmont Basin (TPB), NW Italy, is known for its thermal springs since historical times (Fig. 1). The most recent geochemical and geothermal investigations are by BORTOLAMI et al. (1983) and PASQUALE et al. (1986), respectively. The latter presented the first thermal data for the southwestern sector **of** the Po plain, with particular reference to the Acqui hydrothermal system. They concluded that albeit the regional geothermal gradient is 29 mK m^{-1}, it remarkably increases close to the area affected by hydrothermal activity.

In this paper we propose a more detailed interpretation of the geothermal system based on new borehole temperature logs. In order to deduce the undisturbed geothermal gradient and information on the permeability of shallow and deep aquifers, we investigated not only temperature-depth profiles unperturbed by fluid flow, but also boreholes affected by water circulation and inflows from the underlying basement.

2. Thermal logs

Figure 1 shows the location of the investigated boreholes and the main springs superimposed on a geological sketch map. The stratigraphic sequence consists of the Quaternary cover (Bormida river alluvial deposits), the Oligo-Miocene sedimentary sequence, and the underlying crystalline basement which crops out south of the investigated area. The basement is formed by Mesozoic ophiolites (lherzolitic and basal metamorphic complexes) and the metamorphic covers (calc-schists) of the Voltri Massif, together with paragneisses and fine-grained gneisses alternated with carbonatic-silicic rocks of the Valosio Massif (VANOSSI et al. 1984).

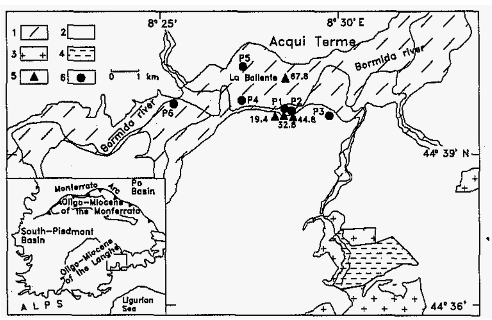

Figure 1: Geological sketch map and main hydrothermal features of the Acqui Terme district. 1) Alluvial deposits; 2) Oligo-Miocene sedimentary sequences of TPB; 3) Mesozoic metamorphic basement (Voltri Massif); 4) pre-Triassic crystalline basement (Valosio Massif); 5) thermal springs (digits denote the water temperature in °C); 6) borehole sites.

Six boreholes drilled for water exploration were examined (Fig. 2). The thermal profiles revealed remarkable water circulation at some boreholes, which may bias the inference of the undisturbed geothermal gradient. We calculated the undisturbed temperature gradient in the cover of the geothermal system, after identifying those sections of the boreholes which were not affected by groundwater circulation. This analysis allowed also the recognition of minor aquifers within the cover.

2.1 Water flow

Figure 2a-2d shows stratigraphic and thermal data of boreholes P1-P4 in the surrounding of the hot spring area. Generally, the Oligo-Miocene cover initiates with conglomerates at its base (Middle Oligocene), followed by marls and sandstones (Middle-Upper Oligocene - Lower Miocene). The uppermost layers consist of limestones (Aquitanian) with overlying calcareous marls (Lower Miocene). P2, P3 and P4 encountered also the crystalline basement.

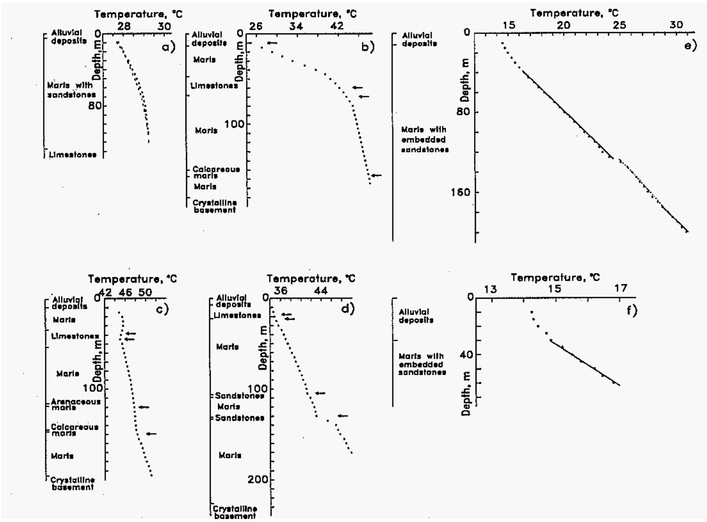

Figure 2: Temperature-depth data (full dots) and stratigraphy of boreholes denoting convection-dominated (a-d) and conduction-dominated (e,f) heat transfer. a) Borehole P1: water enters at 110 m depth and flows vertically. The theoretical temperature curve is hatched. In boreholes P2 (b), P3 (c) and P4 (d) the horizontal arrows represent inflows from minor aquifers. In borehole P5 (e) the solid line is the undisturbed thermal gradient extrapolated from the 40-125 m and 175-200 m depth intervals, and the hatched line is the calculated temperature-depth distribution. In borehole P6 (f), the solid line is the thermal gradient extrapolated from the lowermost (> 30 m) section.

The temperature in borehole P1 (30 cm in diameter) was measured 16 minutes after removing the borehole cap. The water enters at the hole bottom and flows vertically to the surface at a rate of 1.4 l s^{-1}. By assuming a thermal conductivity of 2.2 W m^{-1} K^{-1} and a diffusivity of 1 10^{-6} m^2 s^{-1} (PASQUALE et al. 1986), we calculated the expected temperature distribution in this borehole by means of the relation by **RAMEY** (1962). The difference between the calculated and measured temperatures is very small at any depth, and the undisturbed thermal gradient is 80 mK m^{-1}. This also indicates that there is no thermal perturbation due to shallow aquifers (Fig. 2a).

A vertical groundwater flow also occurs in boreholes P2-P4 which have quite low discharges of 0.10 (P2), 0.08 (P3) and 0.03 l s^{-1} (P4), respectively. The thermal profiles (Fig. 2b, 2c and 2d) are clearly affected by perturbations due to water circulation within minor shallow aquifers. Since the boreholes have a casing, water can enter the borehole only through the bottom and no contribution to the total discharge is yielded by the shallow aquifers. Under these conditions, it is not possible to apply the model by Ramey, and we can only draw information on the hydrogeological characteristics.

Borehole P2 cuts alluvial deposits, beneath which there are stratified arenaceous marls and Miocenic limestones, highly fractured and affected by shallow, non-mineral colder aquifers. In the 68-180 m depth range there are compact marls, interrupted at 150 m depth by a 6 m thick layer of calcareous marls affected by water flows. At 180 m depth the hole reached porous Miocenic conglomerates overlying fractured ophiolitic rocks. The temperature data were recovered down to 160 m depth, since the hole bottom was not accessible to the probe. The water at 160 m depth is thermal (maximum temperature 48.0 °C) and mineral. The water flowing out contains much more gas than that of the other boreholes, and has a temperature of 22.2 °C.

Borehole P3 crossed limestones, marls and sandstones overlying the ophiolitic crystalline basement. Limestones are present only in the uppermost layers and are affected by a shallow cold aquifer. Marls are crossed by thin sandstone layers denoting thermo-mineral, artesian water flows. The water temperature is 51.1 °C at the hole bottom and 31.1 °C at the collar.

The maximum accessible depth in P4 was 170 m against a maximum drilling depth of 239 m. The stratigraphic sequence and the shallow cold aquifer are similar to P3. At 106 and 131 m depth there are permeable sandstone layers with thermal water circulation. The temperature increases almost linearly in the uppermost section down to 130 m, where it is perturbed by lateral flows, which sensibly rise the thermal gradient. The water temperature decreases from 49.8 at the bottom to 34.1 °C at the top of the borehole.

2.2 Conduction-dominated heat transfer

Boreholes P5 and P6 showed a mainly pure conductive temperature gradient (Fig. 2e and 2f). These boreholes were drilled entirely in the Tertiary sedimentary rocks beneath the Quaternary alluvial cover. P5 reached a depth of 500 m, but the temperature was recorded only down to 200 m, as the lowermost section was not accessible. The thermal profile shows a water inflow at 175 m depth. The water vertically moves and then flows out at

125 m depth through a thin permeable layer, thus generating a thermal perturbation. The velocity of the rising water was calculated by means of RAMEY (1962) for a radius of 0.15 m and by considering a circulation time since 1989. Under these conditions, the calculated temperature fits well the data, thus demonstrating that the thermal gradient in 40-125 and 175-200 m depth ranges is undisturbed. On the other hand, the permeability in the 125-175 m depth interval is so low that water cannot circulate in the surrounding rock.

Considering that the surface temperature is 12.5 °C (average value determined from data at the Acqui Terme meteorological station in the period 1992-1996 and reduced to the borehole elevation), one obtains a temperature gradient of 91.5 mK m^{-1}, which is in agreement with that of borehole P1. We expect no large variation in thermal conductivity as the logged section does not show remarkable lithological variation.

The uppermost 30 m of borehole P6 are affected both by the annual variation and the water circulation in the permeable alluvial deposits. Below this depth the thermal gradient appears undisturbed down to the hole bottom (60 m) and it is slightly lower (69.3 mK m^{-1}) than that of the borehole P5. However, it should be stressed that P6 is less close to the hot spring area than P5.

3. Modelling of the geothermal system

3.1 Chemical and physical constraints

The Acqui Terme hydrothermal system is located at the western edge of the Po plain, which is characterised by geothermal gradients of 20-25 mK m^{-1} (PASQUALE & VERDOYA 1990). Away from the thermally anomalous area, previous studies found values of 29 mK m^{-1} in TPB (cf. PASQUALE et al. 1986). Our results indicate that in borehole P5, close to the hot spring area, the purely conductive thermal gradient is anomalously high as well as in P1.

The temperature of the most important spring (La Bollente, 65-71 °C) and the rock-water equilibrium temperatures deduced from the Na^+, K^+, Ca^{++} and SiO_2 geothermometres (FOURNIER et al. 1974) are additional constraints to the geothermal model. Geothermometry of the La Bollente spring, whose water is believed chemically closer to the water of the reservoir, indicates a temperature range of 101-119 °C. The reliability of this estimate depends, of course, on whether chemical exchanges between the water and rocks have occurred during its ascent or whether dilution and precipitation due to cooling have taken place.

If the recharge of the hydrothermal system occurs at areas with a normal regional temperature gradient (29 mK m^{-1}) and an average rock-water equilibrium temperature of 110 °C is assumed, the maximum circulation depth should be 3400 m. Conversely, if the temperature of the reservoir is closer to that of the hottest spring, the circulation depth should be 1900 m. The latter hypothesis corresponds to the more conservative case that geothermometry gave widely overestimated temperatures for the deepest section of the hydrothermal system.

On the other hand, the thermal profile extrapolated from the thermal gradient of **P5** fits the case that the top of the fractured, convection-dominated zone is at a depth of ahout 600 m (with a temperature of about 70 °C) as well as that of a depth of about 1100 m with a temperature of 110 °C. The foregoing information does not allow **us** to cbaracterise the reservoir, but only to outline two possible models: (i) a reservoir which extends from the top of the fractured zone to the maximum circulation depth, (ii) a reservoir which is located at intermediate depths. The latter hypothesis implies an upward flow of water towards the reservoir zone which is accompanied by a more or less remarkable heat loss. In view of the small width of the Acqui Terme thermal anomaly, it seems more likely that the reservoir is located somewhere at intermediate depth.

3.2 Cooling curves

The La Bollente spring exhibits geological and geothermal features which resemble other thermal springs known in the literature (e.g. ANDREWS et al. 1982). Water heating excludes the contribution of additional sources such as recent magmatic intrusions, but is due to a deep circulation of meteoric water within a permeable system. The temperature of the outflowing water depends on the possible mixing with cold surface water during the rise from the deep system. If such a phenomenon is negligible, cooling of rising water within fractures can be analytically described (BODVARSSON 1969).

Under the assumption that water of the La Bollente spring is practically unaffected by mixing of shallow water, we calculated the expected ratio between the temperature T at the spring and the water temperature T_0 at the beginning of the uprising flow. On the basis of structural data, we considered the fracture as nearly vertical, so that its length h corresponds to the depth of the reservoir. The residence time for the hydrothermal circuit water is estimated to be 80 years from isotopic data (BORTOLAMI et al. 1983). Therefore, we assumed that the water takes times of the order of ten years to rise through fractures. Figure 3 shows some possible models for values of the fracture width L varying from 600 to 75 m. T_0 may range between the temperature estimated from the geothermometers and that of the La Bollente spring.

If the temperature at the top of the reservoir were 110 °C, the T/T_0 ratio should be 0.62. For times of the order of 10 years and L of 300-600 m, such a cooling would occur only on condition that the top of the reservoir were at a depth of only 150-300 m. This model is not consistent with the data observed in **P5,** as it would imply geothermal gradients in the cover even higher than 300 mK m^{-1}. A fracture zone of 75-150 m in width yield values of h = 650-1300 m, with thermal gradients very close to that observed. **This** indicates that the fracture zone through which water rises towards the bot springs should be relatively narrow.

On the other hand, we cannot exclude the case that T/T_0 tends to 1, i.e. a negligible cooling. Among the several possible solutions we can accept only those yielding a thermal gradient of about 90 mK m^{-1}. Since the crystalline basement in the hot spring area was intercepted by drilling at a minimum depth of **200** m, the possible range of h is between 200 and 1100 m.

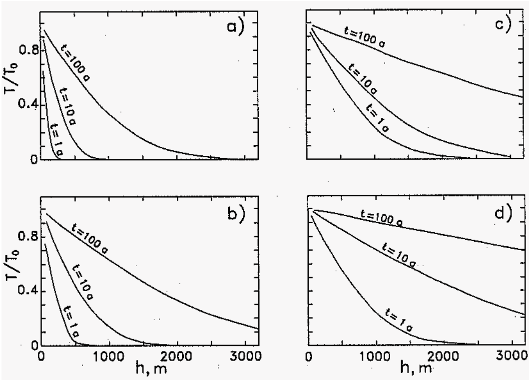

Figure 3: T/T_0 as a function of the fracture length h for the La Bollente spring. t is the time for water rising within the fractured zone for width L of 600 m (a), 300 m (b), 150 m (c) and 75 m (d), respectively.

4. Discussion and conclusions

New determinations of geothermal gradient in the Acqui Terme district allow us to define a local thermal anomaly. The observed temperature gradient is higher close to the main hot springs and tends to decrease within a few kilometres. The high thermal gradient and the hot springs are attributable to the presence of a reservoir with medium-low enthalpy geothermal fluids, whose top should be at relatively shallow depth in the crystalline basement. The colder water at some boreholes and minor springs is also chemically different from that of the main hot springs and, consequently, belong to or is mixed with shallower aquifers within the sedimentary cover.

The cooling models applied to the La Bollente spring show that water could in principle rise from the top of the reservoir, at a depth of 200-1100 m, through a relatively narrow fracture zone. By considering that the recharge zone lies at some 15 km south of the thermal area, the average velocity of the thermal fluid is in the order of 10^{-5}-10^{-6} m s^{-1}. If the top of the reservoir were at depths of some 100 m and the time for water rise in the order of 10 years, the corresponding velocity for the uprising flow should be lower by 1-2 orders of magnitude. As the cooling models indicate that the ascent occurs through a rather narrow fractured zone, we expect that the water velocity should, instead, increase. In order to have a water velocity equal to or higher than 10^{-6} m s^{-1} and a thermal gradient of about 90 mK m $^{-1}$ in the cover, we should restrict the possible range for the depth of the reservoir top and temperature to values of the order of 1000 m and 100 °C, respectively.

A possible interpretation of the TPB geothermal system, based on all the foregoing considerations and data, accounts for the recharge zone at the southern sector of the basin, in the outcropping crystalline massifs, where meteoric waters sink through a system of normal faults down to a depth of 3400 m. The water should circulate and warm up in the fractured basement. Since the width of the thermally anomalous zone is relatively small, we can hypothesise that the main reservoir is located at an intermediate depth, between 1000 and 2500 m. If the water rose from the deepest part of the hydrothermal system directly to the surface, we should expect extremely low values of T/T_0, of the order of 0.1-0.2. This would imply that the temperature at the thermal springs should be much lower than that observed. Therefore, water rises from the maximum circulation depth to the reservoir at intermediate depth, with possible small heat loss (some 10-20 °C).

The main hot spring is directly connected to the reservoir through very narrow fracture systems. The other springs and boreholes with lower temperatures and minor discharges scattered in the Acqui Terme district are evidence of minor loss of fluids from the reservoir. Their waters escape from the system and mix with shallow colder aquifers changing the original chemical composition and temperature.

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