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Groundwater flow analysis using different geothermal constraints: The case study of Acqui Terme area, northwestern Italy

Vincenzo Pasquale *, Massimo Verdoya, Paolo Chiozzi

Dipartimento Territorio e Risorse, Settore di Geofisica, Università di Genova, Viale Benedetto XV 5, I—16132 Genova, Italy

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ABSTRACT

We review some analytical techniques that use underground thermal data as tracers of groundwater flow. These techniques allow the evaluation of the Darcy velocity in shallow aquifers of mid-low permeability and the evaluation of heat gain/loss by conduction in deeper aquifers. Examples of application are then given for the Acqui Terme hydrothermal system, located in the Tertiary Piedmont Basin (northwestern Italy). The analysis of borehole temperatures allowed the inference of the hydraulic features of the sedimentary cover of the hydrothermal system. The results show the presence of a relatively weak flow, with upward and horizontal components, only in conglomerates occurring at the base of the marly impermeable cover. The analysis of the heat transported in the deep parts of the hydrothermal system was approached by splitting the water path into different sections, each with given shape, slope and hydraulic properties. The recharge area is situated in the upland, south of the discharge area. Meteoric water initially descends and then flows horizontally within the fractured metamorphic basement of the basin, heating by conduction. Finally, from a reservoir positioned at intermediate depths, hot water reaches rapidly the surface through a sub-vertical fault. This scheme of deep water flow is constrained by the regional surface heat flow and the local geothermal gradient, and it is consistent with data of rock–water equilibrium temperature.

1. Introduction

The study of groundwater flow and heat transport mechanisms is vital in understanding and exploring geothermal resources. Within any aquifer, the analysis of the thermal effects of groundwater flow should be carried out on a wide variety of scales and quantitative descriptions may become a difficult task. For these reasons, several strategies have been developed to explore the heat transport associated with groundwater flow, which involve the use of more or less sophisticated models. A common approach is to apply numerical groundwater flow models that are constrained by borehole data, including measurements of temperature, head, hydraulic conductivity and tracer concentrations, in addition to geologic information (e.g., Haenel et al., 1988; Beck et al., 1989; Anderson and Woessner, 1992; Swanson and Bahr, 2004). However, water and heat transfer analytical solutions are still a benchmark for the formulation of more complex numerical simulations.

This paper reviews some analytical techniques for the study of underground heat and water flows, focusing on those of particular interest in the investigations of hydrothermal systems. As a case study, these techniques are applied to the hydrothermal system of Acqui Terme located in the Tertiary Piedmont Basin (Fig. 1). This basin, placed at the suture between the Alps and the Apennine belts (northwestern Italy), consists of a thick Oligo-Miocenic sedimentary cover of marls and embedded sandstone layers. There is evidence of a positive thermal anomaly centred on the Acqui Terme district, where numerous thermal springs with a total flow of more than 15 l s^{-1} give a thermal yield of 3 MW (Pasquale et al., 1986; Chiozzi et al., 1998). The main hot spring has maximum temperature of 70 °C. The regional context of the basin is non-volcanic and of normal surface heat flow. The water flow path, the heating mechanism and the structure of the hydrothermal system is still poorly known (Bortolami et al., 1983; Verdoya et al., 1999, 2008).

We first attempt to deduce information on the hydraulic features of the sedimentary cover of the Acqui Terme hydrothermal system from borehole thermal data. The heat transfer of a deep groundwater flow through fractured medium is then discussed. This approach is used to formulate a model of the groundwater flow path in the metamorphic basement of the basin. The discharge temperature at the main spring, the local geothermal gradient and the regional surface heat flow are considered as fundamental constraints to assess the relative scale of groundwater flow.

2. Hydrothermal regime of the sedimentary cover

Temperature–depth data from saturated porous layers contain quantitative information on groundwater flow (see, e.g., Anderson, 2005; Pasquale et al., 2010). We show how such information can be extracted by means of some analytical solution for heat and water

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* Corresponding author.
E-mail address: pasquale@dipteris.unige.it (V. Pasquale).

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flow. These solutions, generally used to study aquifers of mid-low permeability, are then applied in fully saturated porous layers of the sedimentary cover of the Acqui Terme hydrothermal system.

2.1. General basis of heat and water transport

The basic theory of groundwater flow in porous media is similar to other diffusion theories. The driving force is the pressure gradient or hydraulic potential gradient and the resistance is due to the combination of the water viscosity and interstices through which water flows. This behavior is described by the Darcy law, in which the volumetric flow rate of water per unit area u, referred to as the Darcy velocity, is connected with its pressure in the form

$$u = \frac{k}{\eta_w}\nabla(p + \rho_w gz) = \frac{k\rho_w g}{\eta_w}\nabla h = K\nabla h \tag{1}$$

where k is permeability, η_w and ρ_w are the water viscosity and density, respectively, p is the pressure, $h = z + p/(\rho_w g)$ is the hydraulic head, z is the elevation above a datum, g is the acceleration due to gravity, and $K = k\,\rho_w\,g/\eta_w$ is the hydraulic conductivity.

The energy equation, which governs convective heat transfer, is discussed in several textbooks (e.g., Goguel, 1976; Jessop, 1990; Turcotte and Schubert, 2002), and first analytical solutions for porous media are given by Stallman (1963, 1965) and Bredehoeft and Papadopulos (1965). In terms of total heat flow, i.e., the sum of the conductive and convective components, this equation was integrated by Lubimova et al. (1965), Laschenbruch and Sass (1977) and Mansure and Reiter (1979). The heat transferred from the rock to water depends on u, the volumetric heat capacity of water $\rho_w c_w$ and the thermal gradient ∇T, in the direction of u. The heat equation is thus expressed as (Bredehoeft and Papadopulos, 1965)

$$\rho c\frac{\partial T}{\partial t} = \kappa\,\nabla^2 T - \rho_w c_w(\mathrm{u}\cdot\nabla T) \tag{2}$$

where c_w is the specific heat of water, c, ρ and κ are the specific heat, density and thermal conductivity of the water–rock matrix, respectively, and t is the time. Further assumptions are the absence of heat sources and thermal conductivity to be isotropic and temperature-independent.

Flow in an aquifer may be caused by externally applied pressure gradient, a condition known as forced convection (advection), or by buoyancy effect of density gradient caused by thermal gradient, i.e., free convection. If the horizontal thermal gradient is negligible and the flow of heat and water is steady, the substitution of Eq. (1) into Eq. (2) gives

$$\frac{d^2T}{dz^2} = \frac{\rho_w c_w k}{\kappa\,\eta_w}\left(\frac{d}{dz}(p + \rho_w gz) + gz\frac{d\rho_w}{dz}\right)\frac{dT}{dz} \tag{3}$$

where ρ_w is a function of depth z. Introducing in this equation the hydraulic head and the volumetric thermal expansion coefficient $\alpha_v = (d\rho_w/dT)/\rho_w$, we find that

$$\frac{d^2T}{dz^2} = \frac{\rho_w^2 c_w gk}{\kappa\,\eta_w}\left(\frac{dh}{dz} + \alpha_v z\frac{dT}{dz}\right)\frac{dT}{dz}. \tag{4}$$

This equation contains terms expressing conductive heat transfer, forced convection and free convection. Forced and free convection represent two limiting conditions. In the former case, the buoyancy forces are assumed to be negligible; in the latter case, water motion is expressed entirely in terms of buoyancy. In this study, we ignore free convection and use the term advection to mean forced convection.

2.2. Flow driven by hydraulic gradient

For combined conductive and advective heat transfer, Eq. (4) becomes

$$\frac{d^2T}{dz^2} - \frac{c_w\rho_w u_z}{\kappa}\frac{dT}{dz} = 0 \tag{5}$$

where u_z is the Darcy velocity in the direction z. The solution of Eq. (5) in dimensionless form is

$$\theta(\zeta) = \frac{\exp(\beta_z\,\zeta) - 1}{\exp\beta_z - 1} \tag{6}$$

where $\theta(\zeta) = (T(z) - T_1)/(T_2 - T_1)$ and $\zeta = z/L$, L is the vertical distance between two points at temperature $T_{1(z=0)}$ and $T_{2(z=L)}$. The quantity $\beta_z = c_w\rho_w u_z L/\kappa$ is a dimensionless parameter, which is positive or negative, depending on whether u_z is positive (downward) or negative (upward). Fig. 2 shows the dimensionless temperature θ versus the dimensionless distance ζ for different values of β_z. Notice that the larger the vertical flow, the larger the curvature of the

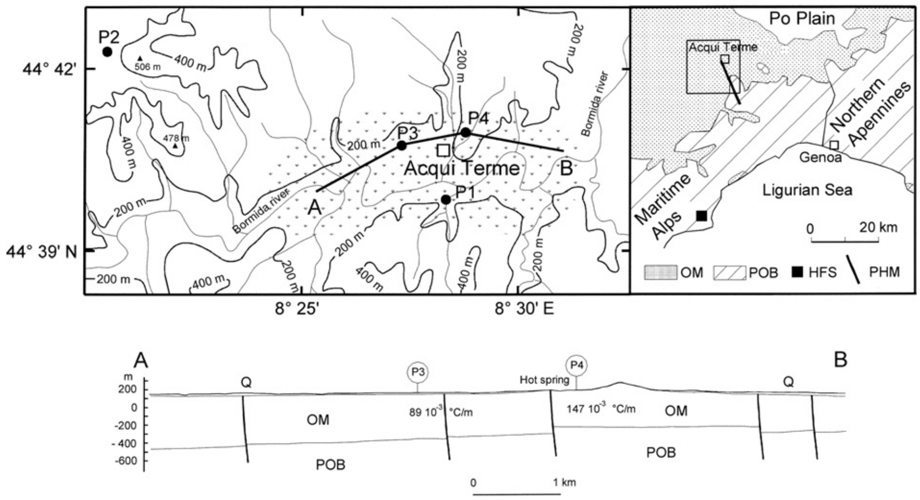

Fig. 1. Acqui Terme geothermal district (dotted area), location of boreholes P1-P4 and geological section AB. Q: quaternary sediment; OM: Oligo-Miocene sedimentary sequences of the Tertiary Piedmont Basin; POB: pre-Oligocenic basement; HFS: heat-flow site; and PHM: profile of the hydrothermal model. The thermal gradient of the sedimentary cover at boreholes P3 and P4 is shown.