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Evidence for thermal convection in the deep carbonate aquifer of the eastern sector of the Po Plain, Italy

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A B S T R A C T

Temperatures recorded in wells as deep as 6 km drilled for hydrocarbon prospecting were used together with geological information to depict the thermal regime of the sedimentary sequence of the eastern sector of the Po Plain. After correction for drilling disturbance, temperature data were analyzed through an inversion technique based on a laterally constant thermal gradient model. The obtained thermal gradient is quite low within the deep carbonate unit (14 mK m^{-1}), while it is larger (53 mK m^{-1}) in the overlying impermeable formations. In the uppermost sedimentary layers, the thermal gradient is close to the regional average (21 mK m^{-1}). We argue that such a vertical change cannot be ascribed to thermal conductivity variation within the sedimentary sequence, but to deep groundwater flow. Since the hydrogeological characteristics (including litho—stratigraphic sequence and structural setting) hardly permit forced convection, we suggest that thermal convection might occur within the deep carbonate aquifer. The potential of this mechanism was evaluated by means of the Rayleigh number analysis. It turned out that permeability required for convection to occur must be larger than 3 10^{-15} m^2. The average over-heat ratio is 0.45. The lateral variation of hydrothermal regime was tested by using temperature data representing the aquifer thermal conditions. We found that thermal convection might be more developed and variable at the Ferrara High and its surroundings, where widespread fracturing may have increased permeability.

1. Introduction

Italy is one of the most important countries in the world with regard to the availability of geothermal resources, a large part of which is already extracted at relatively low cost (see e.g. Bertani, 2010; Pasquale, 2011). Temperatures often exceeding 200 °C at 2—3 km depth occur west of the Apennines mountain chain (Fig. 1), within a wide and several hundred kilometer long belt, affected by lithosphere extension and recent magmatism (Pasquale et al., 2010). This belt includes several geothermal fields mainly exploited for electricity generation. (e.g. Allegrini et al., 1995; Gianelli et al., 1988; Sommaruga and Verdiani, 1991). By excluding the volcanic belt, the deep aquifer hosted in the carbonate rocks of the Po Plain, the region extending between the Alps and Apennines, is probably the most important thermal water resource (Carella and Sommaruga, 2000). Such a general picture has been well established through numerous geophysical investigations and drillings.

In the Po Plain, exploration for hydrocarbons has given the main contribution to the knowledge of the structure and the stratigraphic setting of the sedimentary sequence. Generally, up to ten exploratory wells were drilled annually during the 1930s and 1940s, and both exploration and development operations intensified in the 1950s when the analysis of seismic reflection data was refined. Early exploration was focused on the shallow Tertiary anticlines, identified from seismic data. The deeper Mesozoic, folded and faulted carbonate successions were targeted in the 1970s and 1980s, with improved success rates achieved by the new seismic techniques (Pieri and Groppi, 1981). Since then, well logs, which often included temperature records, and regional seismic sections were integrated with magnetic and gravimetric modeling to obtain several geological cross-sections extending to the pre-Mesozoic crystalline basement (Cassano et al., 1986, 1990).

Despite the extensive structural information, the knowledge of the thermal water resources in the deep aquifer of the Po Plain is still rather poor. In this paper, we focus on the eastern sector of the plain and try to gain a better knowledge of the thermal regime in the sedimentary sequence. We will argue that the deep aquifer in the carbonate rocks, to some degree karstified, may probably host thermal convection. Analyses of available temperature data from hydrocarbon exploration wells together with structural information supply basic constraints for investigating the occurrence of this process. Thermal convection is considered to be a major mechanism for heat transfer in many geological environments, spanning from sedimentary basins (see e.g. Anderson, 2005; Pestov, 2000, and references therein), to geothermal fields (Hanano, 1998) and fractured rocks (Kühn et al., 2006; Murphy, 1979; Zhao et al., 2003).

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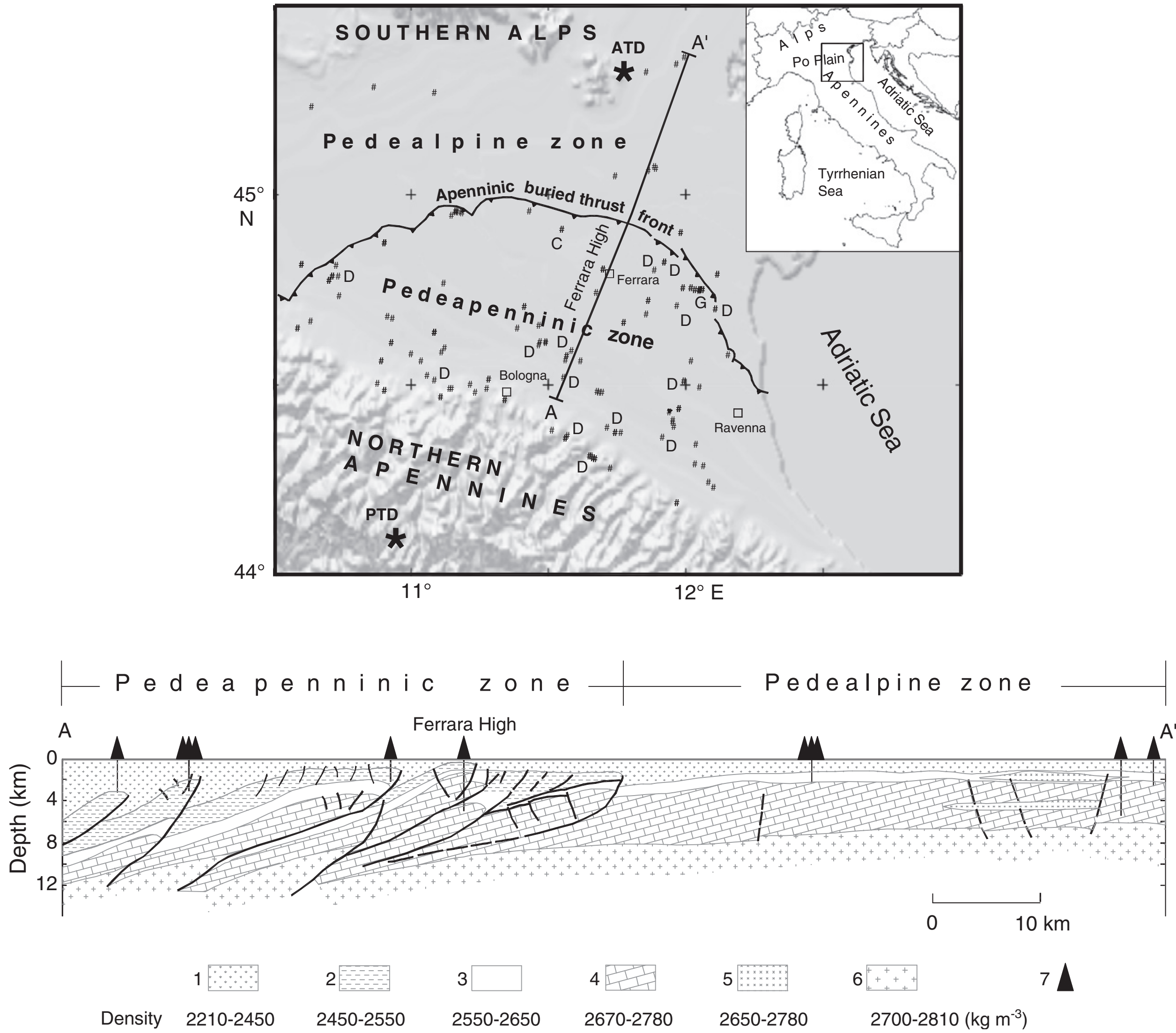

Fig. 1. Position of wells (full circle) providing BHTs and DST temperatures in the eastern sector of the Po Plain. D, wells with available DST temperatures; C and G position of Cascina N. and Gallare wells. Location of the thermal districts of Abano (ATD) and Porretta (PTD) is also shown. Below: cross-section AA′ based on geological and geophysical data by Cassano et al. (1986); 1 — sands, clayey sands, clays, 2 — marls, silty marls, arenaceous marls, 3 — argillaceous and marly limestones, 4 — mudstone, wackestone, packstone, dolostone, 5 — volcanic bodies, 6 — crystalline basement, 7 — exploratory wells. Density values of the lithotypes are indicated.

2. Geological and hydrothermal setting

The Po Plain is characterized by the deposition of a large thickness of clastic sediments since the Paleocene within a general tectonic context of Africa—Europe convergence. After the region experienced Mesozoic extensional events, which led to the formation of a wide carbonatic platform, the tectonic regime turned into compressive. This caused the formation of south-verging thrusts during the Neo-Alpine phase in the Southern Alps and north-verging thrusts since the Oligocene in the Northern Apennines. The huge sediment deposition can be thus considered as a result of continental lithosphere flexure in response to load increase caused by stacking of the thrust sheets. The Mesozoic carbonatic platform is at present deeply buried beneath the clastic sediments deposited during Tertiary and Quaternary times (Pieri and Groppi, 1981).

The eastern sector of the Po Plain can be structurally split into the Pedeapenninic and Pedealpine zone (Fig. 1). The sedimentary sequence of the Pedeapenninic zone includes the Apenninic buried thrusts and folds. The most outstanding feature is the overlapping of the Apennines thrust front on the rather uniform structure (homocline) of the Pedealpine zone. Such a structural setting has been produced by the migration of a chain—foredeep system since the end of Miocene to lower Pleistocene times, through several tectonic episodes that caused shortening and overthrusting to migrate progressively towards northeast (see e.g. Ori and Friend, 1984; Pasquale et al., 1993).

The main structural elements that characterize the sedimentary sequence and the crystalline basement of the Po Plain are depicted by the cross-section of Fig. 1. The buried Apennines thrusts consist of reverse faults with dextral arrangement (Costa, 2003), affecting the whole sedimentary sequence and the underlying crystalline basement. Thrusting is a result of progressive shortening caused by the opening of the Tyrrhenian Sea (e.g. Pasquale et al., 2003; Verdoya et al., 2005, and references therein). The sedimentary sequence consists mainly of terrigenous rocks, deposited on the Mesozoic carbonate successions cropping out in the Southern Alps. This denotes an important detrital contribution and remarkable subsidence, which have taken place through two major cycles in Tertiary and Quaternary times (Dondi, 1985). Thrust front culminates in a structural high, known as the Ferrara High, which is characterized by a reduced thickness of the Tertiary and Quaternary cover overlying the carbonate rocks.