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Incorporating surface indicators of reservoir permeability into reservoir volume calculations: Application to the Colli Albani caldera and the Central Italy Geothermal Province

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ABSTRACT

The Quaternary Roman Volcanic Province extends for over 200 km along the Tyrrhenian margin of the Italian peninsula and is composed of several caldera complexes with significant associated geothermal potential. In spite of the massive programs of explorations conducted by the then state-owned ENEL and AGIP companies between the 1970s and 1990s, and the identification of several high enthalpy fields, this resource remains so far unexploited, although it occurs right below the densely populated metropolitan area of Roma capital city. The main reason for this failure is that deep geothermal reservoirs are associated with fractured rocks, the secondary permeability of which has been difficult to predict making the identification of the most productive volumes of the reservoirs and the localisation of productive wells uncertain. As a consequence, almost half of the many exploration deep bore-holes drilled in the area reached a dry target. This work reviews available data and re-assesses the geothermal potential of caldera-related systems in Central Italy, by analysing in detail the case of the Colli Albani caldera system, the closest to Roma capital city. A GIS based approach identifies the most promising reservoir volumes for geothermal exploitation and uses an improved volume method approach for the evaluation of geothermal potential. The approach is based on a three dimensional matrix of georeferenced spatial data; the A axis accounts for the modelling of the depth of the top of the reservoirs based on geophysical and direct data; the B axis accounts for the thermal modelling of the crust (i.e. T with depth) based on measured thermal gradients. Both A and B data are necessary but not sufficient to identify rock volumes actually permeated by geothermal fluids in fractured reservoirs. We discuss the implementation of a C axis that evaluates all surface data indicating permeability in the reservoir and actual geothermal fluid circulation. We consider datasets on: i) distribution and density of tectonic lineaments; ii) temperature and iii) electric conductivity of shallow groundwaters; iv) partial pressure of dissolved CO_2 in shallow groundwaters. The geothermal potential of Colli Albani and the implications for caldera-related geothermal systems in Central Italy are discussed based on the role of the geometry and structure of reservoirs in relationship with volcano-tectonic structures and deep geothermal fluid migration paths.

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1. Introduction

Geothermal reservoirs are usually associated with fractured rocks (Grant and Bixley, 2011). The common approach to the definition of secondary permeability is the wide use of high-resolution methods such as active seismic and structural modelling of reservoirs and cap rocks; however, while extensively used in oil-exploration, such approaches are less common in geothermal exploration (e.g. Brogi et al., 2003), both because of technical and cost limitation. Nevertheless the circulation of hot fluids has allowed the successful development of lower resolution geoelectric, magnetotelluric, geochemical methods (e.g. Newman et al, 2008; Cinti et al., 2011), as well as remote sensing (e.g. Vaughan et al., 2012). The calculation of the energy potential in geothermal areas suffers from the large uncertainties associated with definition of secondary permeability (e.g. Chiodini et al., 2007; Jafari and Babadagli, 2011; Giordano et al., 2013). For example, the widely used Volume Method for the evaluation of first order geothermal potential (Muffler and Cataldi, 1978) needs a definition of average porosity of the reservoir, but does not take into account the effects of the fracture network complexity on the anisotropic distribution of secondary permeability.

Geothermal exploration for high and medium enthalpy fluids in Italy has concentrated in areas of active or recent magmatism along the Tyrrhenian margin, from Tuscany to Sicily (Buonasorte et al., 1995; Cataldi et al., 1995). These areas are characterised by the highest heat-flow values in Europe (Fig. 1) and by extensive urbanisation, including Roma, and its metropolitan area, with more than 5 million people. However, the only active electric-power plants are those associated with shallow granitic bodies at Larderello-Travale and Amiata (e.g. Romagnoli et al., 2010). Despite of the very high heat flow values, the geothermal fields in the Latium region (Central Italy)(Fig. 1), associated with shallow Meso-Cenozoic carbonate reservoirs located in correspondence of the main Quaternary caldera systems and generally capped by impermeable Miocene–Pliocene syn- and post-orogenic marine sediments, are not exploited, even though several tens of 1–5 km-deep bore-holes were drilled between the 1970s and the 1990s (Baldi et al., 1974; Barberi et al., 1994 and references therein). The main reason for this is that the geothermal potential of the identified geothermal fields, and consequently the locations for the deep-bore-holes, were based mainly on two parameters: the depth of the reservoir and the temperature at its top (e.g. Cataldi et al., 1995). The reservoirs were largely modelled by the inversion of gravity and geoelectric data, which allowed only reconstruction of the top of the reservoir but not of the internal structure and stratigraphy, even where and when stratigraphies from deep bore-holes were progressively available. Several maps had been produced over the years illustrating the top of the reservoirs and the temperature gradients (maps are available online at the Italian Ministry for Economic Development (2012). These maps do not detail the permeable volumes, as permeability of the reservoirs is associated with fractures, and not evenly distributed; accordingly, no modelling of the potential geothermal flow paths was attempted, nor discussion of the potential role of volcano-tectonics on fluid migration has been published. This resulted in a series of failures and many deep-wells found the same reservoirs both dry and unproductive or very productive in very narrow areas (e.g. Vulsini, Torre Alfina, Sabatini)(Buonasorte et al., 1988; Chiodini et al., 2007), or either sealed and filled with hot-brines (e.g. the Cesano field in the Sabatini area; Funiciello et al., 1979).

Recent technological advances in exploration and exploitation of geothermal energy have changed the previous evaluation of the potential of geothermal reservoirs, extending to lower enthalpies and greater depths. At present (October 2012), 108 new research permits have been requested by private companies in less than one year in Italy, and of these 34 are in Latium region, including the Colli Albani area (Buonasorte and Franci, 2011, http://www.unionegeotermica.it; http://unmig.sviluppoeconomico.gov.it/unmig/istanze), indicating the significant interest of industry for the development of this renewable resource.

The main aim of this paper is to demonstrate the importance of utilising indirect evidence at surface of secondary permeability in the reservoirs, as well as the structural modelling of the reservoir. This approach is applied to the re-appraisal of the geothermal potential of the Colli Albani caldera geothermal system, in view of the huge amount of new geological and geophysical data produced in the last 20 years (Funiciello and Giordano, 2010 and references therein) and discussed in the frame of the Volume Method for fractured reservoirs. Implications are then discussed on the possible revision of the geothermal potential of the entire geothermal region associated with peri-Tyrrhenian Quaternary calderas, taking into account the interplay between deep caldera-structures and reservoirs in focusing lateral migration of geothermal fluids and in the formation of distal blind resources.

2. Geologic framework

The Colli Albani volcano is one of the Quaternary volcanoes in the Roman Magmatic Province (Fig. 1; Mattei et al., 2010), active since >600 ka and characterised by mafic K-alkaline compositions (Boari et al., 2009; Conticelli et al., 2010 and references therein). The minimum total volume of the Colli Albani deposits is estimated at approx. 290 km^3 (Diano et al., 2010), mostly made of ignimbrites associated with the formation of the 10 × 10 km^2 central caldera (Giordano et al., 2006, 2010; Giordano and the CARG Team, 2010). The most recent volcanic activity (≤33 ka; Cross et al., 2013 and references therein) produced several maars associated with the interaction of magma with the hydrothermal system. Phreatic activity at Colli Albani occurred in historical times (Funiciello et al., 2003; De Benedetti et al., 2008). The geothermal system at Colli Albani is active and able to produce surface and deep manifestations. The frequent shallow seismic swarms indicate the occurrence of periodic fracturing in the reservoir that thus maintain high permeability over time (Amato et al., 1994; Chiarabba et al., 1994, 1997, 2010). The presence of widespread manifestations of deep-degassing (Carapezza et al., 2003, 2010a, 2010b; Carapezza and Tarchini, 2007; Chiodini et al., 2012), and of areas with hypo-and meso-thermal spring-waters (Capelli et al., 2005), in association with ground deformation (Chiarabba et al., 1997; Salvi et al., 2004; Anzidei et al., 2008, 2010 and references therein), also indicate an active geothermal system. Colli Albani volcano is also site of the impulsive release of gases and thermal waters, which have been related to seismic events, indicating that deep fluids can reach the surface when cap rocks fracture