Update of Heat Flow Data in the Geothermal Areas of Tuscany, Italy

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ABSTRACT

Tuscany is the region of Italy where geothermal energy production started, first in the world, in the early years of 20th century. With an installed capacity of 915 MW, today the totality of Italian geothermal electricity production is concentrated in Tuscany, in the well-known high enthalpy fields of Larderello-Travale and Mount Amiata, owned and managed by ENEL (National Electricity Board). A Legislative Decree of 2010 liberalized the geothermal market, allowing new operators to request exploration leases. As of today, 24 new research permits are active in Tuscany, all of them in the surrounding areas of the two main geothermal fields. The foreseen target of the exploration should be a geothermal resource sufficient at least to allow the construction of binary technology power stations (or better, depending on the quality of the resource). A huge amount of exploration and production data exist in the geothermal areas, and new campaigns have been planned or already started to acquire site-specific information in the new research permits. We present the results of heat flow (HF) measurements carried out in new 200-250 m gradient wells drilled in areas West of Mount Amiata, and regional HF and geothermal gradient maps updated by gathering all well thermal data that became recently available. A comparison with different parameters (e.g. Bouguer gravity anomaly) allows a better definition of the geothermal features of the new areas of exploration.

1. Introduction

The lithospheric extension affecting the Tuscan-Tyrrhenian domain represents one of the most relevant and recent tectonic processes within the entire Alpine-Mediterranean area. The

heat input from the mantle is responsible for the presence of large geothermal resources at accessible depths in the crust, as testified by temperature and heat flow anomalies, locally extremely high. The extensional stage produced a crustal thinning, with depth to the Moho of 20-25 km and emplacement of large plutons at shallow crustal levels, associated with local magmatic activity, in a wide belt of Tuscany, stretching between the Tyrrhenian coast and the Northern Apennines (Nicolich, 1989; Carmignani et al., 1994; Locardi and Nicolich, 2005). In the post–Pliocene the entire Tuscan-Tyrrhenian belt underwent a widespread uplift (i.e. 400-600 m in the Larderello area, Marinelli et al. (1993)). A further effect of the extensional tectonics was the emplacement of sedimentary basins (i.e. the Volterra Basin). The geothermal fields of Larderello and Mt. Amiata are located in this area (Fig. 1), with maximum HF values up to 1000 mWm^{-2} at Larderello and 350 mWm^{-2} at Mt. Amiata. The background long wavelength heat flow anomaly of the whole geothermal area of Tuscany has average values of 120-150 mWm^{-2} (Bellani et al., 2005).

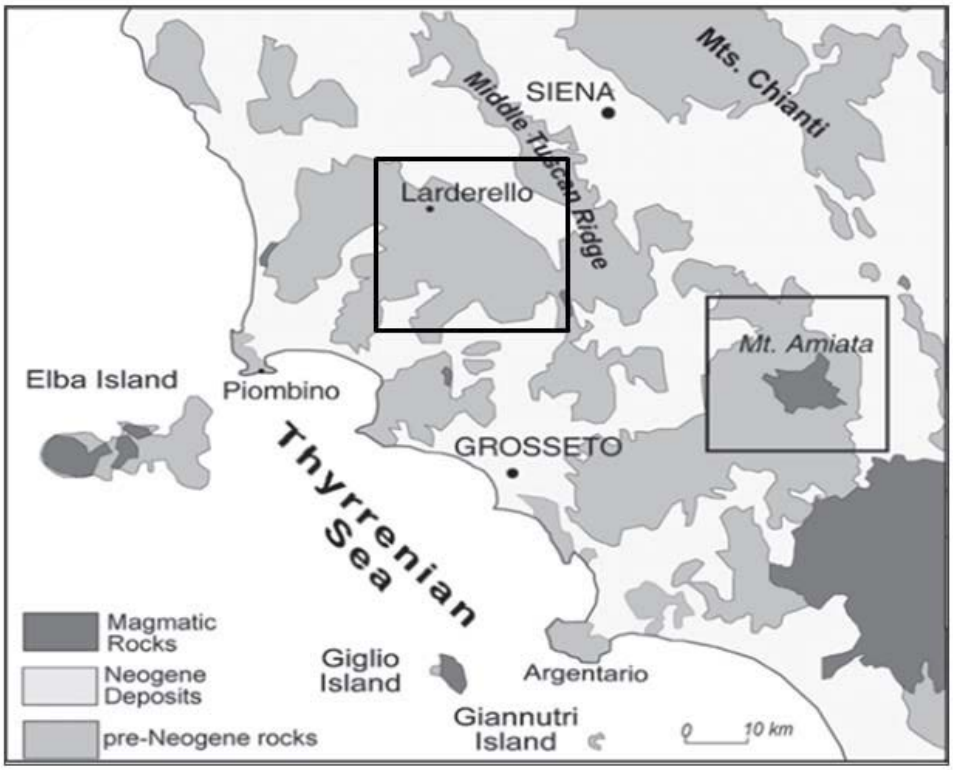

Figure 1: Location map of Larderello and Mt. Amiata geothermal fields.

The industrial exploitation of geothermal energy started in Tuscany in 1818, when the world's first facility capable of extracting boric acid from geothermal vapor, in order to produce boron for pharmaceutical and chemical use, was created. Again, in 1904 the first five light bulbs of history were lighted with a generator consisting of a dynamo running on geothermal steam. Today, with an installed capacity of 915 MW, the whole Italian geothermal electricity production is in Tuscany, in the fields of Larderello-Travale and Mount Amiata, owned and managed by

ENEL. Since 2010, the deregulation of the geothermal market has allowed new operators to request exploration leases. Currently, 24 new research permits have been granted, in areas surrounding the productive fields; further requests are under evaluation, in Tuscany but also in northern Latium, in the surroundings of Bolsena lake, an area intensively explored by ENEL in the 80s'.

2. Geological setting

The two geothermal fields show considerable geological-structural and thermal similarities, with some important differences. The geological structure of Larderello-Travale and Mt. Amiata fields is similar (Fig.2), with two geothermal reservoirs recognized and industrially exploited (Batini et al., 2003; Baldi et al., 1995; Bertini et al., 1995): a shallower one (700-1000 m depth), located in the cataclastic horizon (Late Triassic evaporites and overlying Jurassic carbonates); and a deeper one, consisting of fractured metamorphic rocks at depths ranging between 2000 and 4500 m. The impervious cover of the shallower geothermal reservoir is made up of Cretaceous–Early Miocene terrigenous formations ("Tuscan Nappe"), "Ligurian Units" (remnants of Jurassic oceanic crust and its sedimentary cover, and Cretaceous–Oligocene flysches) and Miocene-Pliocene sediments (Brogi et al., 2010). The caprock is continuous and effective at Mt. Amiata, while it is discontinuous at Larderello-Travale, where several steam and gas natural manifestations exist. A fundamental difference between the two fields regards the fluid characteristics: Larderello-Travale is one of the few vapor-dominated geothermal systems in the world producing superheated steam, while Mt. Amiata is a water-dominated field. Mt. Amiata is an extinguished Quaternary volcano (0.3-0.19 Ma), while no extrusive rocks outcrop at Larderello.

3. Short summary of the previous studies in the area

A vast amount of data has been gathered throughout the years during the exploration and the exploitation of the geothermal fields of Tuscany, in all the possible fields related to geology and geothermics. Hundreds of wells with depth up to 4500 m allowed a detailed reconstruction of an area that underwent complex tectonic activity (Fig.2). The available data sheds light not only on currently productive areas, but also on some part of the fields' neighboring zones, that today are enclosed in the new research permits. Many references can be cited to describe the geothermal area, a very minimal list includes: Calamai et al. (1970), Gianelli et al. (1988), Baldi et al. (1995), Gianelli et al. (1997), Brogi et al. (2003), Bellani et al. (2004), and Barelli et al. (2010); all of them include further references therein. Aside from the collection and study of experimental data, several 2D and 3D models of the geothermal fields of Tuscany have been published, including for Larderello: Della Vedova et al. (2008), Romagnoli et al. (2010), Bellani and Gherardi (2013), and for Mt. Amiata: Bellani and Gherardi (2009), Fulignati et al. (2014), Ebigbo et al. (2016), Girolami et al. (2017).

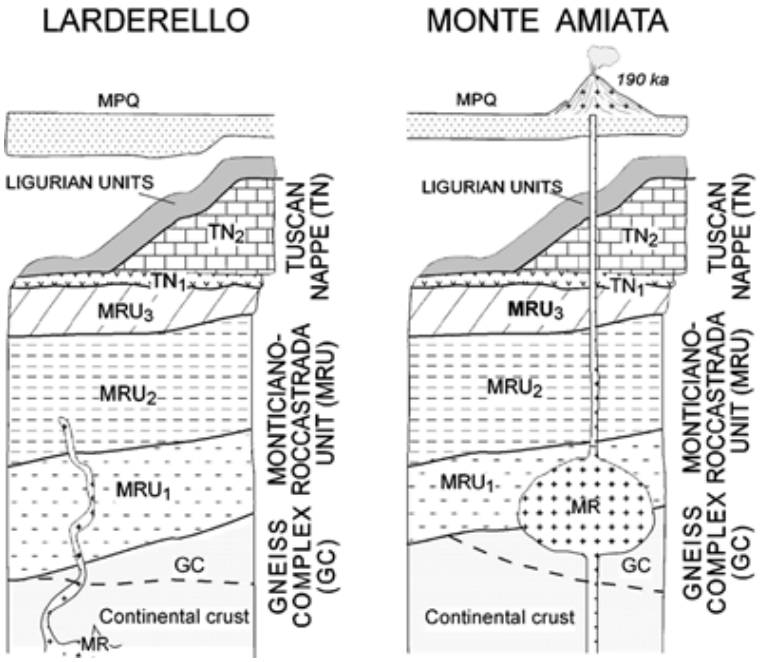

Figure 2: Tectonostratigraphic units in the Larderello and Mt. Amiata geothermal areas (not to scale). MPQ: Miocene, Pliocene and Quaternary sediments; Tuscan Nappe (TN): TN2—Early Miocene–Rhaetian carbonates; TN1—Late Triassic evaporites; Monticiano–Roccastrada Unit (MRU): MRU3—Mesozoic–Palaeozoic Group: dolostones and limestones (Late Triassic), quartz metaconglomerates, quartzites and phyllites (Verrucano Group, Middle–Early Triassic), sandstones, phyllites (Middle–Late Carboniferous–Early Permian); MRU2—Phyllitic–Quartzitic Group; MRU1—Paleozoic Micaschist Group; GC—Gneiss Complex; MR— magmatic intrusions (after Batini et al., 2003).

4. New data and discussion

Proximity to the developed geothermal fields has allowed the companies willing to invest in geothermal exploration to estimate the resource potential of the exploration leases based on the known features of the operating fields and on the aforementioned abundance of data regarding the geological conditions of the area. Several companies started in recent years exploration programs to collect new data specific for the areas enclosed in the new research permits. Due to the very strict regional legislation of Tuscany currently in force related to geothermal exploration and development, and to the general attitude of environmentalist associations in Italy, that consider geothermal energy as pollutant as fossil-fuel based energy sources, the path to the fulfillment of the "geothermal endeavor" in the new areas is still long. Nevertheless, some results have already been published, mainly about geophysical surveys (MT, Bouguer gravity, and seismic): Caranova et al.(2015), and modeling of production/reinjection systems (Stacey et al., 2016). Further activity is in progress but the data are still confidential. The CNR-IGG (former CNR-IIRG) operated for several years in the 80s' and 90s' on behalf of ENEL to carry out heat flow surveys in the peripheral areas of the two main fields: most of the shallow wells (generally 150-250m deep) fall now in the zones included in the new research permits (Fig. 3) represented

by the colored areas around the Larderello-Travale field and, to the southeast, the Mt. Amiata field (Bagnore and Piancastagnaio areas).

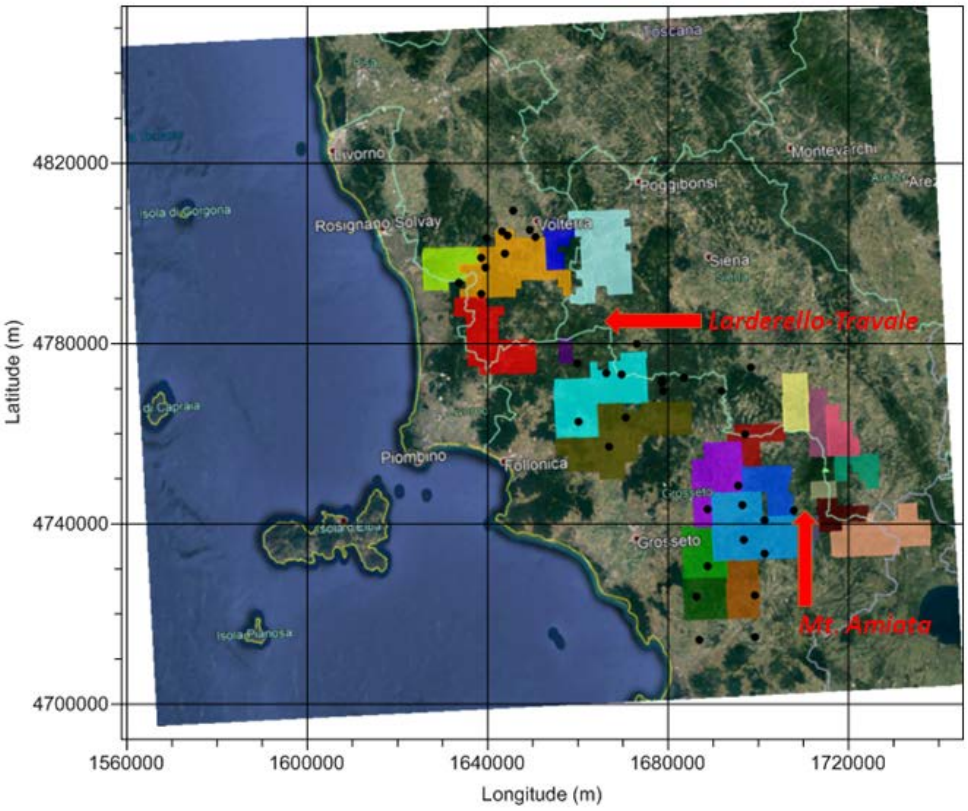

Figure 3: Base map from Tuscany Region official site http://www.regione.toscana.it/-/permessi-concessioni-e-impianti (accessed May 28th 2018). Colored areas: exploration leases issued after 2010. Black dots: geothermal gradient wells logged by CNR-IGG (except two deeper ENEL wells in the Volterra area, N of Larderello: see Fig. 4 for location).

CNR-IGG, by appointment of two private companies, recently logged up to thermal stabilization in two new wells (no.18, 238 m and no.19, 205 m deep, location in Fig. 4) on the southwest side of Mt. Amiata, measuring thermal conductivity (K) on core samples, and logged a 310 m deep well (no. 17), located S of Larderello in collaboration with another private company. In addition, the data from three more wells (21, 25, 26) that were logged in the late 1990s, but were never accounted for in map contouring, were used to update the latest map shown in Figure 4. The extensive database of K available for the Tuscan cover lithologies allowed a correct calculation of HF values for the latter wells. The regional heat flow map, originally based on more than 300 values (mostly gradient wells with some deep ENEL wells) published in Baldi et al. (1995), and updated in Bellani and Gherardi (2013) in the northern part of Larderello, has been integrated with the new data, merging the contouring grids (realized using natural neighbor method to account for the uneven distribution of data points in the map). The geothermal gradient map underwent a similar process, and is directly compared with HF in Figure 4. The general trend of

the contour maps is confirmed with the new data: the thermal anomaly extends with relatively high values north- and southwards of the Larderello field. It seems to decrease in the area between the fields, but it must be said that historically this area has been scarcely investigated due to the presence of outcrop of the same formations that represent the fields reservoir, which allows the infiltration of meteoric water, and there are no cover formations where gradient wells could be profitably drilled. The thermal anomaly recovers strongly around Mt. Amiata, particularly on its west side. The no. 19 well, for example, on the southwestern-most side of the new research permits, where the thermal anomaly appears to fade far from Mt. Amiata, still shows gradients around 50 °Ckm^{-1} and has HF close to 140 mWm^{-2}, values undoubtedly promising at least for medium enthalpy geothermal applications. Figure 5 shows the thermal logs of selected wells located inside the new research permits, chosen among the most representative in the zones of high thermal anomaly around the geothermal fields.

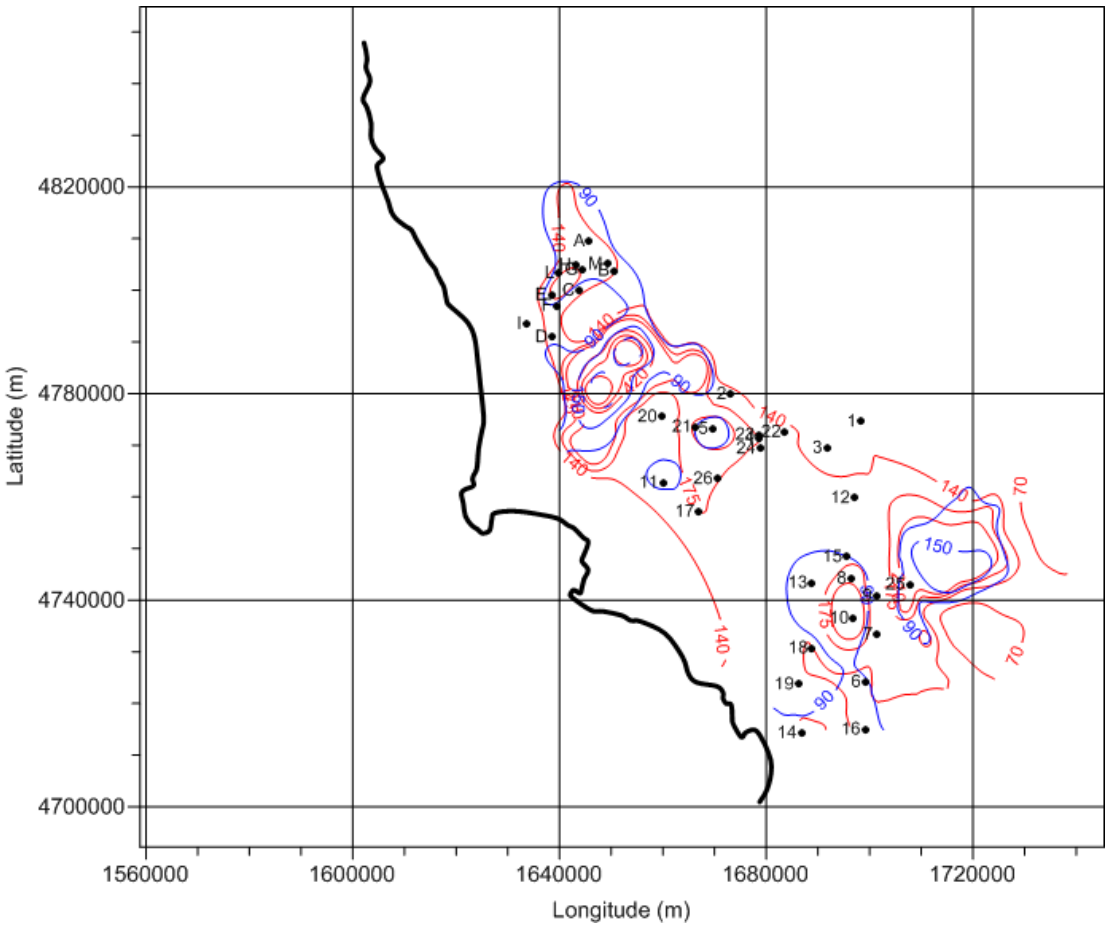

Figure 4: Updated heat flow (mWm^{-2}, red contours) and geothermal gradient (°Ckm^{-1}, blue contours) map of the area under study. Black dots: geothermal gradient wells logged by CNR-IGG (except two deeper ENEL wells in the Volterra area, N of Larderello, named L, M on the map).

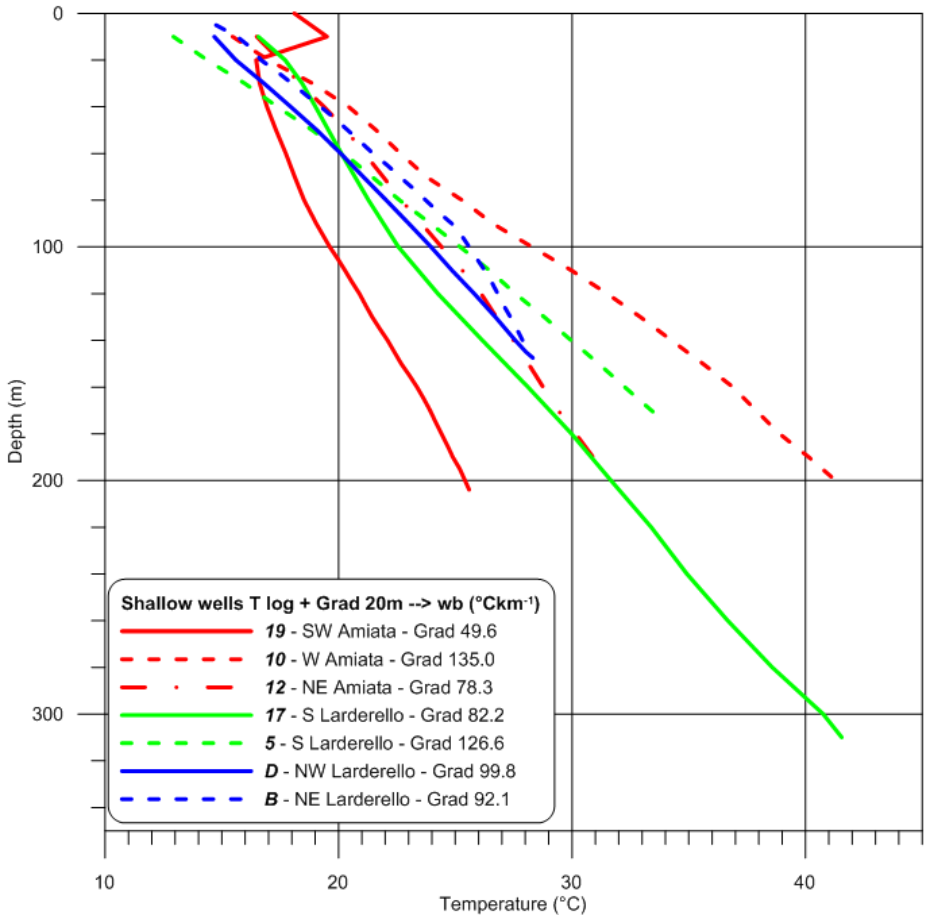

Figure 5: Thermal logs of selected wells located inside the new research permits in the surroundings of Larderello-Travale and Mt. Amiata. The legend shows also geothermal gradients (between 20 m and well bottom). Well location in Figure 4.

The Bouguer gravity anomaly shows peculiar features in Tuscany: the main gravimetric structures are aligned northwest-southeast (sub-parallel to Apennine range), with evident correlation between gravimetric minima and the neogenic grabens that dot the region as a result of the extensional regime. The general correspondence between gravimetric relative maxima and the outcrop of carbonatic and metamorphic formations finds an exception in the broad areas of the two main geothermal fields, characterized by relative minima despite the diffused outcrop of the same denser formations. This is ascribed to the presence of large light bodies (namely hot acidic intrusions) at depth (Gianelli et al., 1988; Baldi et al., 1995). In Figure 6 we superimpose the updated HF map to the Bouguer map (digitized from Baldi et al., 1995): There seems to be a strong correspondence between the relative gravity minima that elongate south of Larderello and west of Mt. Amiata, and values of the HF anomaly that are still in excess of 150 mWm^{-2}. We consider these as positive indicators of the existence of a large thermal anomaly spread over a large part of Tuscany, inside the area of the new research permits but also beyond them, that allows for optimism about the technical possibilities of a further development of geothermal energy in Tuscany.

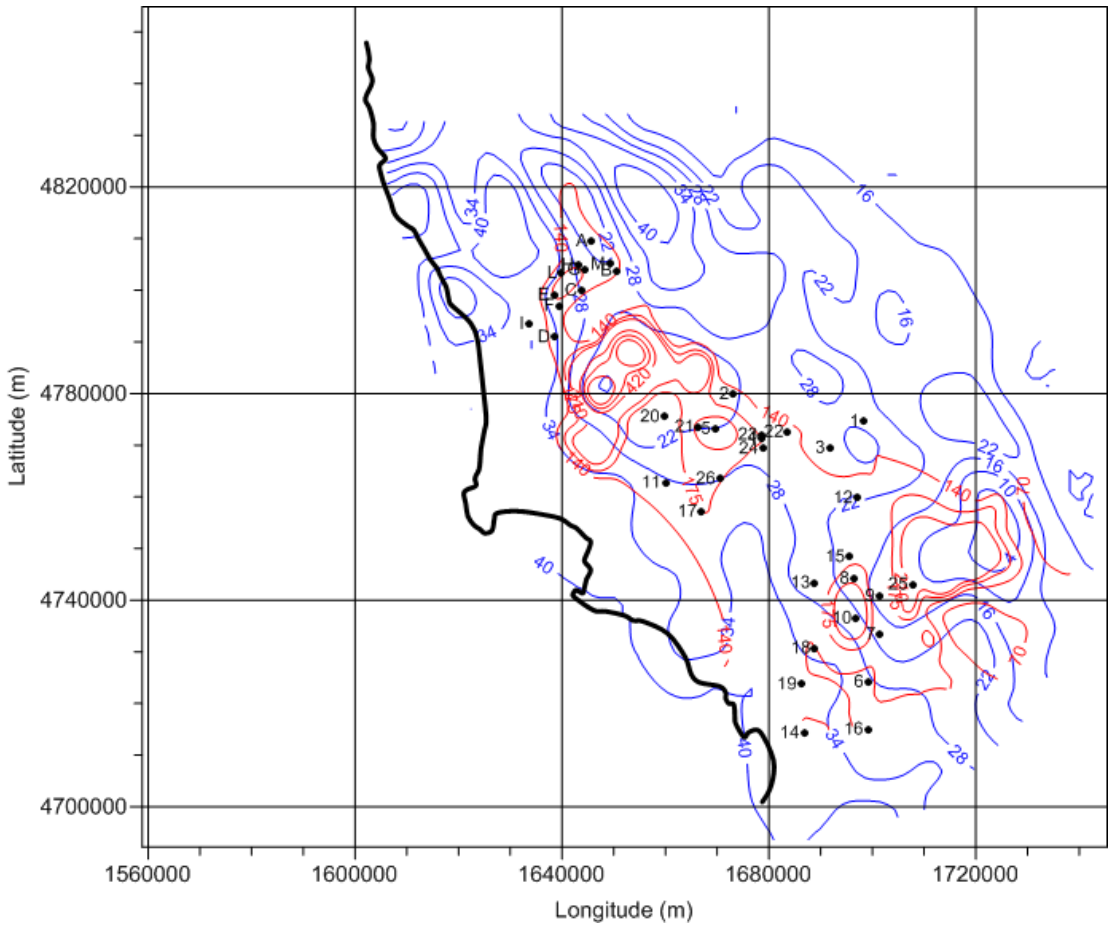

Figure 6: Comparison of HF contours (red, mWm^{-2}) and Bouguer gravity anomaly contours (blue, mgal; values from Baldi et al. 1995, digitized and redrawn). Black dots: geothermal gradient wells (see Fig. 4).

5. Concluding remarks

The law, that in 2010 liberalized the geothermal market in Italy, along with the increasing demand for renewable sources of energy, has generated a strong recovery of interest for several companies willing to invest in geothermal exploration, beyond the long-time management by ENEL of the main geothermal fields of Larderello-Travale and Mt. Amiata. The extensive amount of data available after more than a century of geothermal exploration and exploitation represents a solid base to rely on to define the features of the new areas. In addition, specific programs have been set up by the various companies to acquire geological, geophysical and geochemical data, preliminary to the industrial phase of the geothermal projects. As a first activity, we present the results of thermal logging in some new wells, and the update of the thermal maps covering the new lease areas, largely explored by CNR-IGG in a recent past. The comparison of the results with the peculiar shape of the Bouguer gravity anomaly in Tuscany confirms the general correspondence between the thermal and gravimetric parameters existing in these areas. Although the intensity of the thermal anomaly in the new exploration areas appears

lower compared to the exceptional values at Larderello-Travale and Mt. Amiata, it is surely strong and diffused on a wide surface extension. Considering that the first exploitation projects presented for these zones are based mostly on binary cycle power plants, which are suitable for medium-to-low enthalpy sources, should the hydraulic features of the reservoirs be satisfactory, there could be a high possibility for industrial development, also with water temperature in a range of 100°C to 200°C. The results of further exploration in progress or scheduled will help to define more precisely the extension and the quality of the geothermal resource.

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