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Geoscientific Feature Update of the Larderello-Travale Geothermal System (Italy) for a Regional Numerical Modeling

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ABSTRACT

The Larderello-Travale geothermal model has been updated with all the available geoscientific data to provide input parameters for a regional numerical modeling. Data analysis has been extended over an area of 70 x 70km, which is more than ten times wider of the about 400km^2 covered by the geothermal mining leases, to include the involved hydrographic basins and to minimize the boundary effects. The huge amount of existing geological and geophysical data allowed an accurate definition of the main features of the geothermal system from surface to a depth of several km.

Larderello-Travale is one of the few superheated steam geothermal systems in the world, i.e. with a reservoir pressure that is much lower than the hydrostatic gradient. This peculiarity is the consequence of a natural evolution of the system from the initial water-phase to the current steam-phase. The geothermal field is characterized by widespread nearly impermeable formations constituting the "cover" of the system. The underlying geothermal reservoir is made of carbonate-anhydrite formations in the upper part and in the deeper one by metamorphic rocks of the Paleozoic basement. Usually, the shallow carbonate-anhydrite reservoir shows temperature of 220-250°C and pressure of about 20bar at 1000m depth, while the deep metamorphic reservoir has temperature of 300-350°C and pressure of about 70bar at 3000m depth.

The top of the productive reservoir was set in correspondence of the first fractured level in the central areas of the field, where a great amount of well data are available. In the peripheral areas instead, where well data are lacking, it was set in correspondence of the 250°C isotherm. The seismic K horizon, strictly related to temperature of about 400°C, was considered as the bottom of the geothermal reservoir. Furthermore, on the base of the geoscientific data analyses just very local and reduced interactions can be present between the shallow geothermal reservoir and the phreatic aquifers. Also these elements have been utilized as input data for the numerical model.

1. INTRODUCTION

The use of superheated steam for electricity production started more than one century ago in the Larderello area, and about 60 years ago at Travale (Barelli et al., 1995a and c; Barelli et al., 2000; Batini et al., 2003). The present running capacity at Larderello-Travale is 632MW$_e$ out of 711 total geothermal MW$_e$ in Italy (Bertani, 2007; Buonasorte et al., 2007). Up to the '80s the steam was exploited from a shallow reservoir made up of Mesozoic carbonate-anhydrite formations and located at 500–1500m depth. Afterward, and still at present days, the steam has been extracted also from a reservoir deep more than 3000m, hosted in metamorphic rocks. The almost constant pressure and composition of the geothermal fluid, over a drilled area of approximately 400km^2 (Bertani, 2005), support the hypothesis of a huge reservoir characterized by fracture permeability (Bertini et al., 2006).

The elaboration of a regional numerical model for the Larderello-Travale geothermal system must be included into a wider context. In fact, a general conceptual model of the area has to account for both the geothermal system and the hydrologic circuits. The final target of the model is represented by the evaluation of the possible interactions between the geothermal field, during its exploitation, and the hydrologic basins in the area.

A numerical model capable of describing all the various system parameters requires significant efforts and long times. This is due to the huge extent of the system to be modeled, to the poor available information, in particular for the shallow aquifers, and also to the use of a single tool for the simulation of different physical phenomena. Further complexities arise from anisotropic lateral and depth distribution of permeability, and from different exploitation history.

All the geoscientific data available in an area of 70 x 70km (Figure 1) have been considered and updated to provide input parameters to the numerical model of the system. The main target of the model is to give a macro-description of the geothermal system associated with its boundary interactions (Barelli et al., 2010 in press).

2. SHORT PRODUCTION HISTORY OF THE GEOTHERMAL FIELD

The industrial exploitation of geothermal resources in the Larderello area started at the beginning of XIX century with the extraction of boric acid.

In 1913 the first 250kW geothermoelectric unit started operating and, for this, Larderello, and Italy in general, is considered the "birthplace of geothermal energy". The comparison between the geothermal production trend in Italy and the first geothermal activities in other countries evidences this event (Figure 2). In fact, the first power plants were installed only at the end of '50s in New Zealand and U.S.A., at the end of '60s in Iceland and an important increase of geothermal energy production worldwide was achieved just in the '80-'90s.

In 1926 some wells drilled in the Larderello field found a large amount of steam in a very restricted area inside a shallow reservoir. Between 1926 and 1940, 136 wells were drilled in an area of only 4km^2 and the 82% of them resulted productive. Between 1940 and 1950 the explored area was enlarged to about 7km^2, with additional 69 wells, and again up to the 180km^2 at the end of '70s. During this period the exploitation interested the shallow carbonate reservoir characterized by temperature of about 220-230°C and pressure of 20-40bar (Bertani et al., 2005).

In 1961 a first experimental deep well was drilled up to 2700m depth. Only during the ‘80s a complete deep exploration program have found industrially productive and exploitable levels into the metamorphic basement between 2500 and 3000m depth. This deep reservoir is characterized by temperature greater than 300°C and pressure around 60-70bar (Barelli et al., 1995c).

In the Travale field, located some 10-15km SE of Larderello, the exploration activities began in the ‘50s. The first drillings were performed to depths of few hundred meters in the surroundings of the natural manifestations to the NE of Travale. During the ‘70s new drillings were deepened up to 1000m. At the beginning of ‘80s the exploration and exploitation activities spread northward in the Radicondoli area with drillings 1300-2500m deep (Barelli et al., 1995a).

In its deeper portion the shallow Travale reservoir is similar to the Larderello one, with temperature of about 250°C and pressure of 50-60bar. Analogously to Larderello, it is hosted inside rocks with medium to high permeability belonging to the Tuscan Nappe carbonate formations and to the Tectonic Wedge Complex (Pandeli et al., 1991).

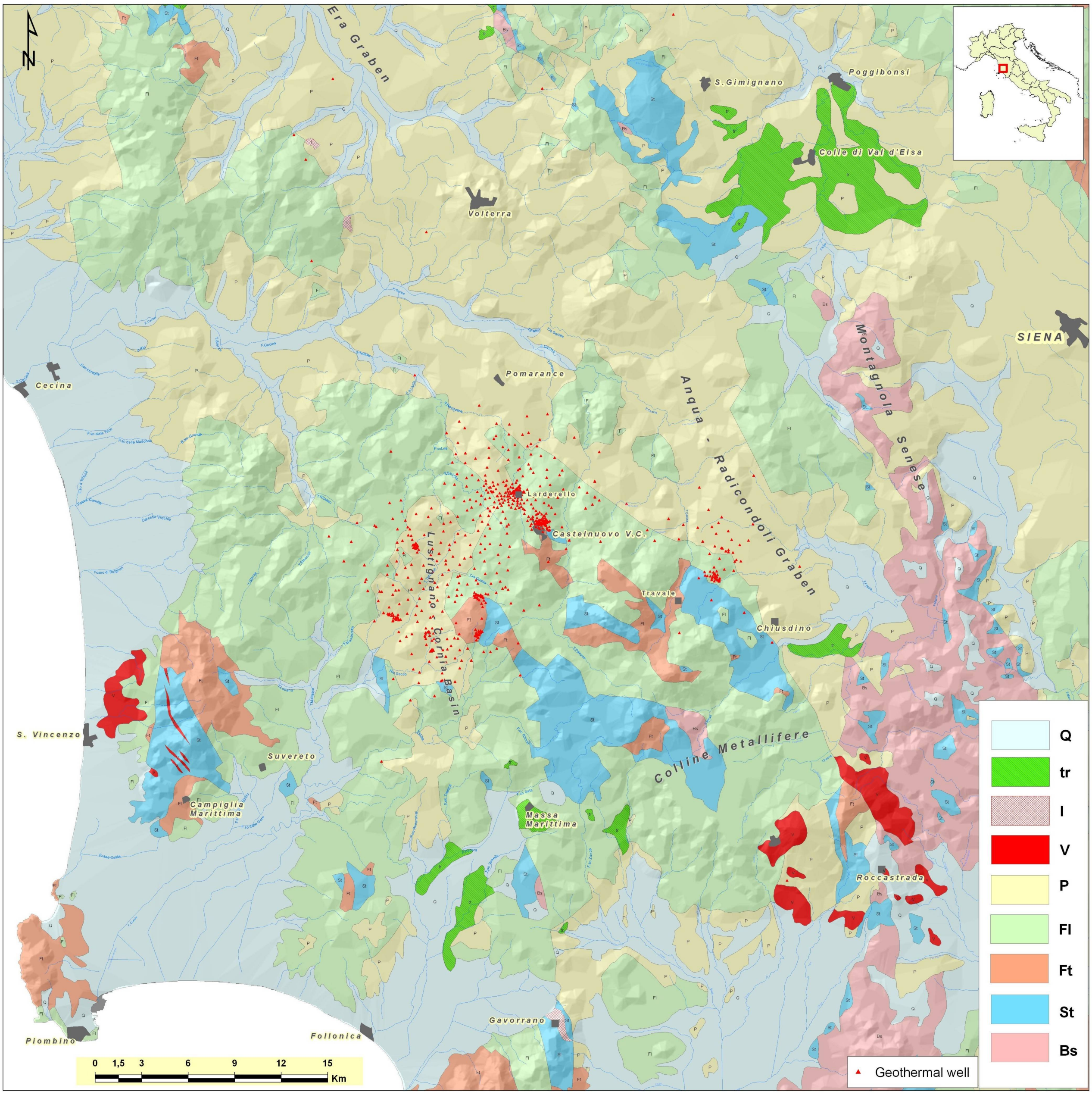

Figure 1: Schematic geology of the area of the numerical model. Geologic legend from top to bottom: Q) Quaternary deposits; tr) Plio-Quaternary Travertines; I) Intrusions; V) Vulcanites; P) Neoautochthonous terrigenous deposits (Lower Pliocene – Upper Miocene); Fl) Ligurian and Sub-Ligurian Complex (Jurassic -Eocene); Ft) Terrigenous formations of Tuscan Units (Upper Cretaceous – Lower Miocene); St) Mainly carbonate formations of Tuscan Units (Upper Trias - Malm); Bs) Crystalline basement (Upper Carboniferous). Geologic base simplified from Giannini et al., 1971

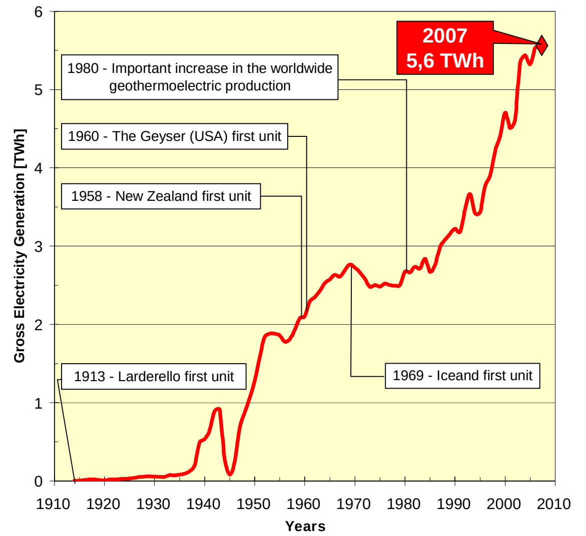

Figure 2: Gross electricity generation from geothermal in Italy and new power plant operation in foreign countries. Modified from Buonasorte et al., 2007

At the beginning of the ‘90s, as already seen for the Larderello field, a deep exploration program to over 3500m was developed in the Travale field too, encountering the same deep superheated steam reservoir. This is hosted in the metamorphic basement, has temperature over 300°C and original pressure of 60-70 bar. It resulted to be in a vapor-static equilibrium with the shallow reservoir (Barelli et al., 1995a and c).

Larderello and Travale fields, initially considered separate, turned out to belong to the same geothermal system when drilling was extended to 3-4 km depth. Temperature and pressure distribution shows that the whole system is steam dominated with some 50°C of superheating (Barelli et al., 1995c; Barelli et al., 2000), although a liquid phase is present where the meteoric water seeps into the carbonate rock outcrops (Figure 3).

In the Larderello field, steam production had been progressively increasing from the ‘20s to the beginning of ‘60s up to a maximum value of 3000t/h (Figure 4). The boundaries of the shallow reservoir had been reached in the ‘70s and two innovative strategies were developed to sustain production:

- Reinjection of waste fluids from geothermal power plants;
- Steam extraction from deep productive horizons.

Reinjection started as an experimental strategy in the central sector of the Larderello field (Valle Secolo) that was considered the most favorable area in terms of reservoir permeability and superheating conditions (Barelli et al., 1995b; Cappetti et al., 1995). As a consequence of the re-evaporation of injected water, steam production increased in Valle Secolo area, reaching a steady production level. Furthermore, the gas/steam ratio decreased improving turbine specific consumption (Figure 5), and the reservoir pressure was recovered in the absence of any appreciable temperature change in the produced fluid (Barelli et al., 1995b).

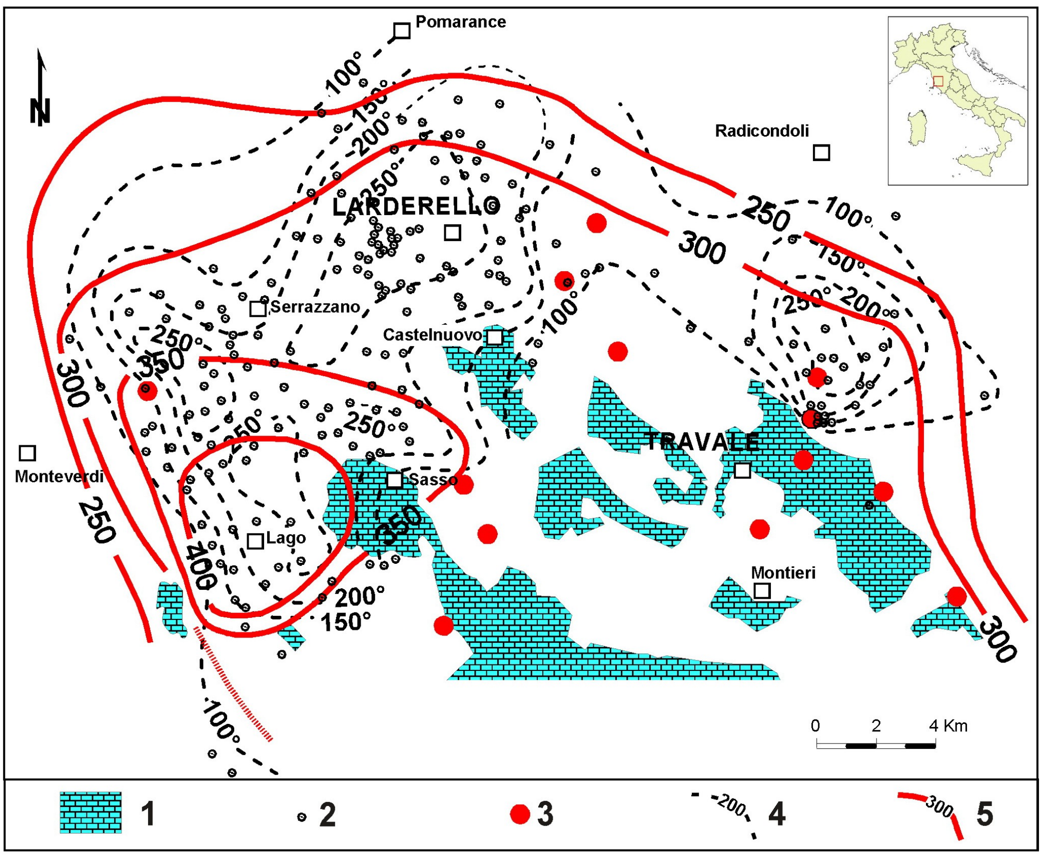

Figure 3: Temperature distribution in the Larderello-Travale geothermal field. 1) Outcrop of permeable formations; 2) Shallow wells; 3) Deep and recent wells; 4) Temperature at the top of the shallow reservoir; 5) Temperature at 3000m b.s.l.. Modified from Cappetti et al., 2005

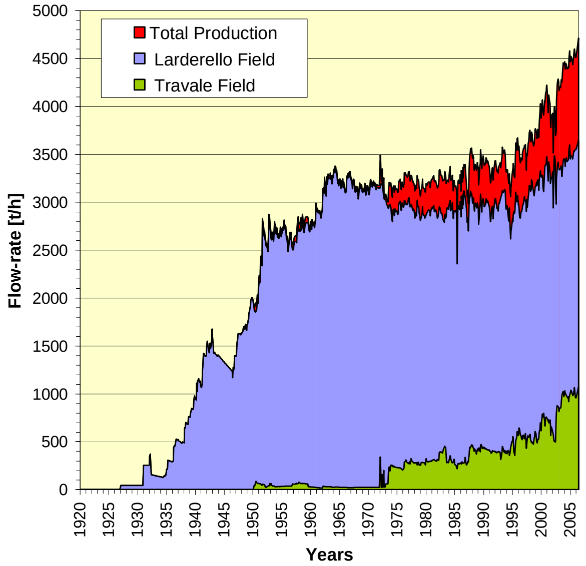

Figure 4: Production history of the Larderello-Travale geothermal fields. Updated from Cappetti and Stefani, 1994.

Nowadays, a total of more than 1500m^3/h of water is reinjected into the whole Larderello-Travale system. The joint action of reinjection, and of widening and deepening of the exploration allowed a significant recover of fluid production that, in the Larderello field, rose up to the current 3700t/h (see Figure 4). At the beginning of '70s the deepening of drillings in the Travale field gave rise to a sharp and instantaneous increase of produced flow rate that reached 500t/h in mid '90s (see Figure 4). In 1995, and more recently in 2003, the positive outcomes of the first deep drillings further increased the production flow rate up to the current 1000t/h. At present, the total steam flow rate produced in the whole Larderello-Travale geothermal system is over 4700t/h.

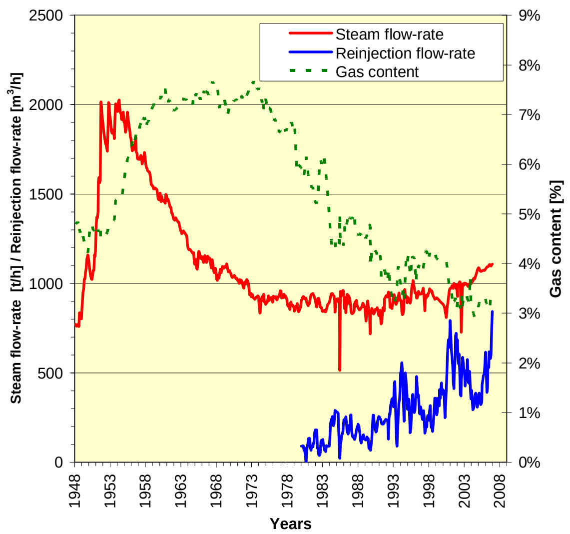

Figure 5: Steam production and reinjection flow-rate in the Valle Secolo area (Larderello). Updated from Cappetti et al., 1995

3. GEOLOGIC OUTLINE

The updated geologic outline covers the same 4900km^2 considered for the numerical model (see Figure 1). The choice of an area remarkably larger than the one covered by geothermal exploited area (about 400km^2) was required by the modeling to reduce boundary effects to negligible values.

3.1 Regional Geology

The studied area is located in southern Tuscany, extending from the coastline to the Montagnola Senese, fully encompassing the Colline Metallifere area where Quaternary to Paleozoic rocks outcrop. The most recent sediments are the Quaternary marine and continental deposits that spread respectively on the coastal plain and on the alluvial valley of the main streams (see Figure 1). These sediments lie over the Neoautochthonous Complex that is mainly constituted by clays and subordinately sands, conglomerates and detrital limestones. Neoautochthonous formations were originated by Mio-Pliocene marine ingression and outcrop widely in the northern part of the area (Era Graben, Anqua-Radicondoli Graben, Lustignano-Cornia Basin). Plio-Quaternary volcanic rocks (intrusive and effusive) outcrop along the coast and inland around Roccastrada, testifying a recent magmatic activity likely connected to the geothermal phenomena. Moreover, rocks of Ligurian/Sub-Ligurian Complex (Mesozoic-Tertiary clayey-marly units) extensively outcrop. These Flysch facies formations overlapped the Tuscan Nappe Complex (Tertiary and Mesozoic). This latter is made of arenaceous and clayey-marly formations, calcareous-siliceous rocks, Triassic dolostone and anhydrites up to shale metamorphic rocks of the Paleozoic Basement (Bertini et al., 2006). Evidences of the hydrothermal circulation are represented by various travertine beds.

Present-day structural setting results from complex geodynamic processes, both compressive and extensive, that have occurred over the last 30 million years (Alpine Orogenesis). From Oligocene to Lower Miocene, the compressive phase caused the collision between the European continental margin and the African one. The consequent over-thrusting and overlapping of different tectonic complexes originated the present nappe structure of the Apennine chain (Carminati and Doglioni, 2004).

From Lower Miocene the extensive tectonic regime caused two important structural phenomena: the formation of the so-called "reduced series", and the development of NW-SE trending sub-parallel tectonic basins. The "reduced series" is a typical phenomena in southern Tuscany (Signorini, 1949; Decandia et al., 1993a and b). It consists of a tectonic lamination process by low angle normal faults (flat-ramp-flat geometry) that caused the direct contact of the allochthonous Flysch facies complexes on the basal calcareous-anhydrite formations of the Tuscan Sequence (Costantini et al., 2002 and references therein; Bertini et al., 2006).

The Graben, sometimes bordered by normal faults, are wide basins filled by Neoautochthonous sediments deposited directly over the Ligurian and Sub-Ligurian Complex (Batini et al., 2003). This tectonic style produced also crustal thinning and favored the upwelling of magmatic bodies with the consequent increase of heat flow. In fact, the whole southern Tuscany is characterized by a regional thermal anomaly with heat flow values over 100mW/m^2 (Figure 6). The greatest values of heat flow (1000mW/m^2) and of thermal gradient (>300°C/Km) mark the geothermal areas of Larderello and Travale (Baldi et al., 1995).

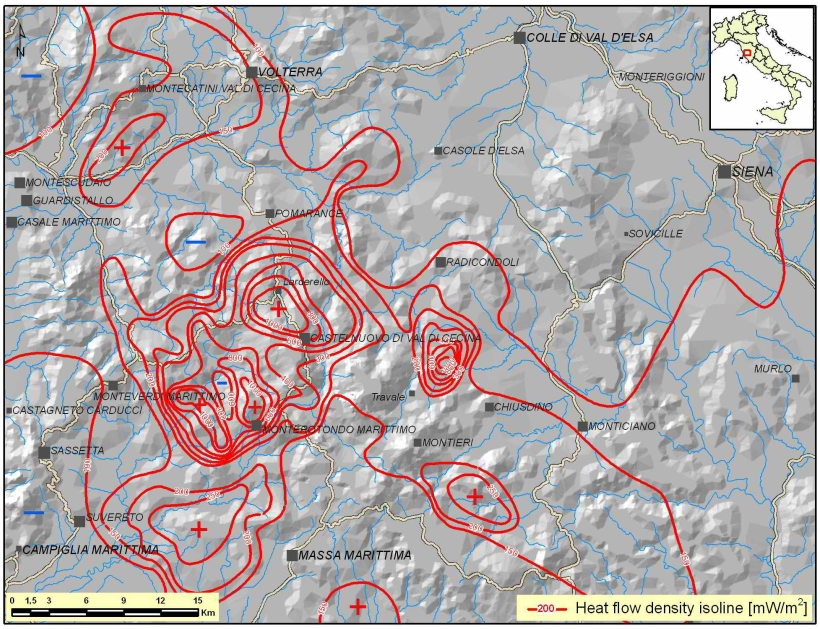

Figure 6: Heat flow density map of the Larderello-Travale geothermal field. Redrawn and detailed from Baldi et al., 1995

The presence of intrusive granite bodies in correspondence of the main Italian geothermal fields had been already hypothesized in the past. More recently, deep drillings have reached granitoid intrusions at depth over 2000m thus confirming this hypothesis (Gianelli and Laurenzi, 2001). On regional scale, the most ancient anatectic magma bodies, including insular archipelagos, date back to about 7Ma. The intrusions related to the geothermal fields are comprised between 3.5 and 0.5Ma, evidencing younger magma emplacements from west to east as a response to the rollback of the subduction hinge during the opening of the Tyrrhenian sea (Doglioni, 1991; Rosenbaum and Lister, 2004).

3.2 Local Geology

Neogene sediments, allochthonous Ligurian/Sub-Ligurian Flysch Complex, and Tuscan Sequence are the main outcrops in the Larderello-Travale area. The most likely geological setting has been reconstructed at depth (Figure 7) on the basis of deep drilling data and with the aid of several geophysical surveys (Bertini et al., 2006).

The cover of the geothermal system is guaranteed by the poorly permeable formations of Flysch and Neoautochthonous clayey deposits. The first geologic input for the numerical model is the distinction between cover and reservoir formations (Barelli et al., 2010 in press).

Starting from this geological boundary, a further difference was evidenced by well data in order to better define the reservoir top. This, in fact, was associated to the top of the main productive layer, i.e. characterized by high permeability, and referred in depth to the first fractured level identified by production wells. This element was reconstructed in detail for the already explored area, and just extrapolated at its boundaries because of the few available data (Barelli et al., 2010 in press). On the other hand, in the marginal areas of the field, where well data are lacking, the limit between potential and productive reservoir was identified with the 250°C isotherm (Figure 8). In fact, this temperature represents the average value expected at the top of the productive reservoir.

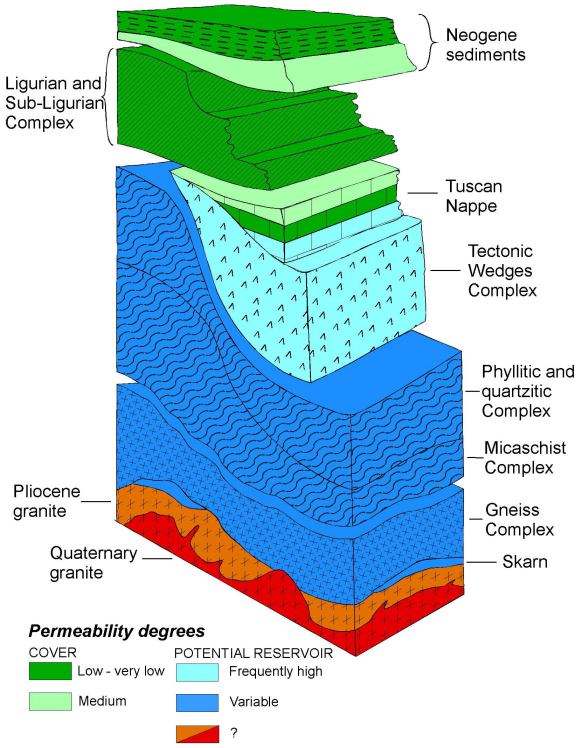

Figure 7: Structural-stratigraphic and hydrogeologic sketch of the geothermal area. Modified from Bertini et al., 2006

A great help to the reservoir bottom definition derives from geophysical surveys (Batini et al., 1983; Brogi et al., 2005; Gianelli et al., 1997). Reflection seismic data have highlighted the presence of an intense and continuous reflecting horizon inside the crystalline basement. This is the so-called K horizon, (Figure 9) the meaning of which is still under debate (brittle/ductile change, recent granitoid intrusions carapace permeated by supercritical fluids, etc.). The depth of the K horizon is normally around 8-10km, and is reduced to only 3-4km in the westernmost sector of the geothermal area (Bertini et al., 2006).

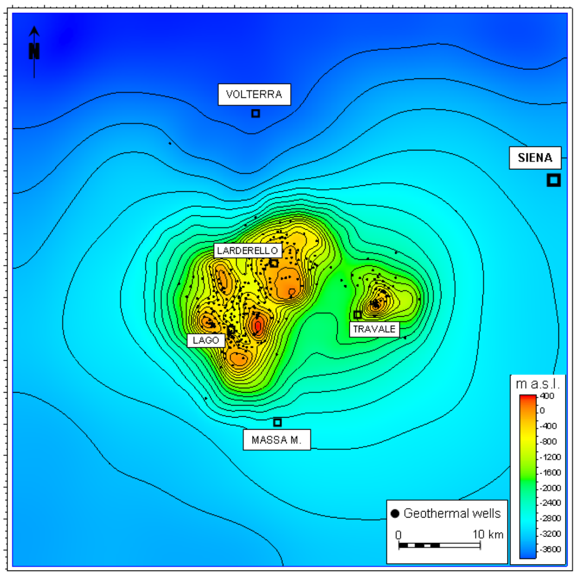

Figure 8: Map of the envelope between 250°C isotherm and first productive fractures [m a.s.l.]

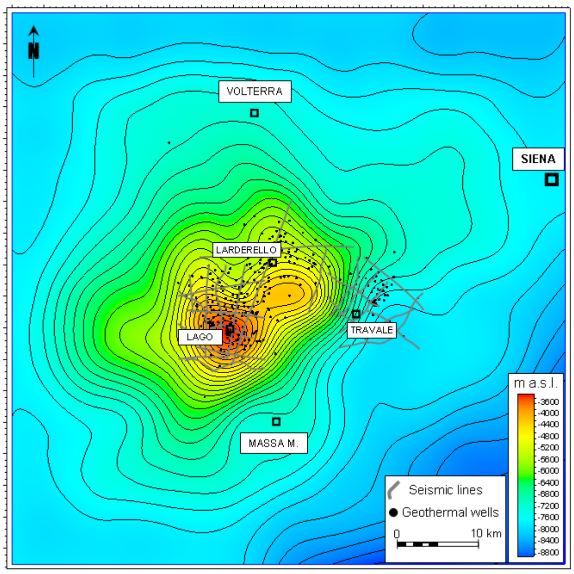

Figure 9: Map of the K horizon [m a.s.l.]

Since the inferred temperature of this horizon is in the order of 400-450°C, at present it represents the lower boundary of the geothermal system industrially exploitable. This is the reason why it was considered the base of the numerical modeling. Due to numerical modeling requirements, such surface was suitably simplified, considering the 400°C isotherm at the fixed depth of 4000m in the Lago area, and at 7000m in the Travale one.

4. HYDROGEOLOGIC OUTLINE

Larderello-Travale is one of the few steam-dominated geothermal systems in the world, showing a pressure lower than the normal hydrostatic gradient. This situation arises from the natural evolution of the system. In fact, the thermal and structural context allowed the geothermal system to pass from an initial water phase to the current steam condition. The depressurization of the reservoir happened prior to the industrial exploitation of the geothermal resource, as verified by the first drilling data in the area (Celati et al., 1975).The liquid phase is currently only in correspondence of a few local structural situations (see Figure 3) where the meteoric waters seep into the reservoir through the permeable outcrops (Barelli et al.,1995c).

From a hydrogeologic point of view, the whole Larderello-Travale field is characterized by wide outcrops of nearly impermeable formations (Neoautochthonous and Flysch of the Ligurian/Sub-Ligurian Complex). These sedimentary rocks have a thickness up to 1000m and constitute the "cover" of the geothermal system, since they seal the underlying carbonate-anhydrite formations of the Tuscan Sequence and the deepest rocks of the metamorphic basement. Nowadays, the shallow carbonate geothermal reservoir displays temperatures of 220-250°C and pressures around 20bar at 1000m, while the deep metamorphic one has temperatures of 300-350°C and pressures around 70bar at 3000m.

Both the reservoirs have a secondary permeability due to fractures. The high fracture variability, both in size and density, determines a wide range of permeability values that are in any case greater than 5mDarcy (Bertani and Cappetti, 1995). Otherwise, the primary porosity of all the reservoir rocks is homogeneous and very low (1-5%) (Cataldi et al., 1978).

The fracture system is in general present and homogenously distributed in the shallow carbonate-anhydrite formations, with higher density in correspondence of structural highs. On the other hand, the fracturing in the rocks of the metamorphic basement is inhomogeneous and localized showing a wide range of permeability (see Figure 7).

4.1 Cover and Shallow Aquifers

The cover lithologies can locally host shallow aquifers that feed a number of springs with seasonal regime. Only thermal conduction effects could locally affect these aquifers (Duchi et al., 1992).

Permeable lithotypes are represented by valley alluvia, detrital limestones of the Neoautochthonous formations, carbonate levels in the Flysch and sandstones of the underlying Macigno. These last two formations are turbidity sequences, generally with a scarce permeability, and usually separated from the underlying geothermal reservoir by the interposition of clayey-marly lithotypes (so-called “Tuscan Scaglia”). Only in an area near Castelnuovo V.C., the Macigno formation is in direct contact with the reservoir and supplies a minimum feeding to the system (Calore et al., 1982).

Moreover, the thermal springs within the geothermal area (Figure 10) produce waters of shallow origin, with low salinity values (TDS generally <1000mg/Kg), that have circulated exclusively in the cover formations and have been heated by thermal conduction (Duchi et al., 1992). In the schematization required by the numerical model, the cover of the geothermal reservoir is considered nearly impermeable.

4.2 Geothermal Reservoir and Recharge Aquifers

In the southern part of the field reservoir formations outcrop along a ridge with Apennine direction (see Figure 10). Their prevailing carbonate-anhydrite nature allows the infiltration of meteoric water at depth thus partially feeding the reservoir (Ceccarelli et al., 1987).

The possible interference zones between meteoric water infiltration and geothermal fluids have been evidenced by wells that encountered a water level instead of steam. In the past these zones were considered as boundaries of the shallow geothermal field (Ceccarelli et al., 1987). This hydrogeological situation and all the geological elements used in the numerical model are shown in the map of Figure 10 and in the cross sections of Figure 11.

The deep circuit is fed by carbonate-anhydrite outcrops and has natural outflows in springs that display high flow rate and medium-low thermal characteristics. These springs are located at the southern boundaries of carbonate ridges (Figure 12).

At the north-western end of the ridges a mixing between the inflowing water and the geothermal steam occurs, and at times is evidenced by thermal inversion observed in wells at field boundaries. This water represents the so-called local recharge of the geothermal system. Otherwise, the aquifer is perched and separated with respect to the steam phase as verified by some deep wells that crossed it.

Deep drillings evidenced that Larderello-Travale is a one single system at the level of the metamorphic reservoir with temperatures greater of 300°C at 3000m depth. It is also important to underline that permeable outcrops have no thermal influence on the deep system that is open southward (see Figure 3).

A preliminary evaluation of local recharge amounts in the whole Larderello-Travale system has been defined by means of gas/steam ratio analyses. The total steam flow rate from local recharge was estimated as 390-580t/h, i.e. 3.3-5.0*$10^6 m^3$/y. These values are consistent with the results of the numerical modeling (Barelli et al., 2010 in press).

Prior to the beginning of exploitation activity a strong pressure disequilibrium among the geothermal steam dominated reservoir and the peripheral aquifers should have existed (Celati et al., 1975). This testifies the occurrence of permeability boundaries that drastically limit the interaction among geothermal reservoir and surrounding aquifers. Without such barriers, a steam-dominated field could not exist (Barelli et al., 2010 in press) as evidenced by steep horizontal thermal gradients near the outcrops of the permeable reservoir rock (see Figure 3).

In the framework of the geoscientific data analyses for the numerical modeling a detailed study of the hydrogeologic characteristics has been performed with a specific focus on the recharge aquifers. Two main aquifers, locally feeding the geothermal reservoir, have been recognized within the carbonatic formation of Tuscan Units: a base aquifer with a piezometric level at 160m a.s.l. and a second aquifer (see Figure 12). These large water bodies are characterized by high permeability, moderate piezometric gradients typical of karstic aquifers, medium-low temperatures (20-25°C) induced by the regional thermal anomaly and main outflows of underground waters southward.

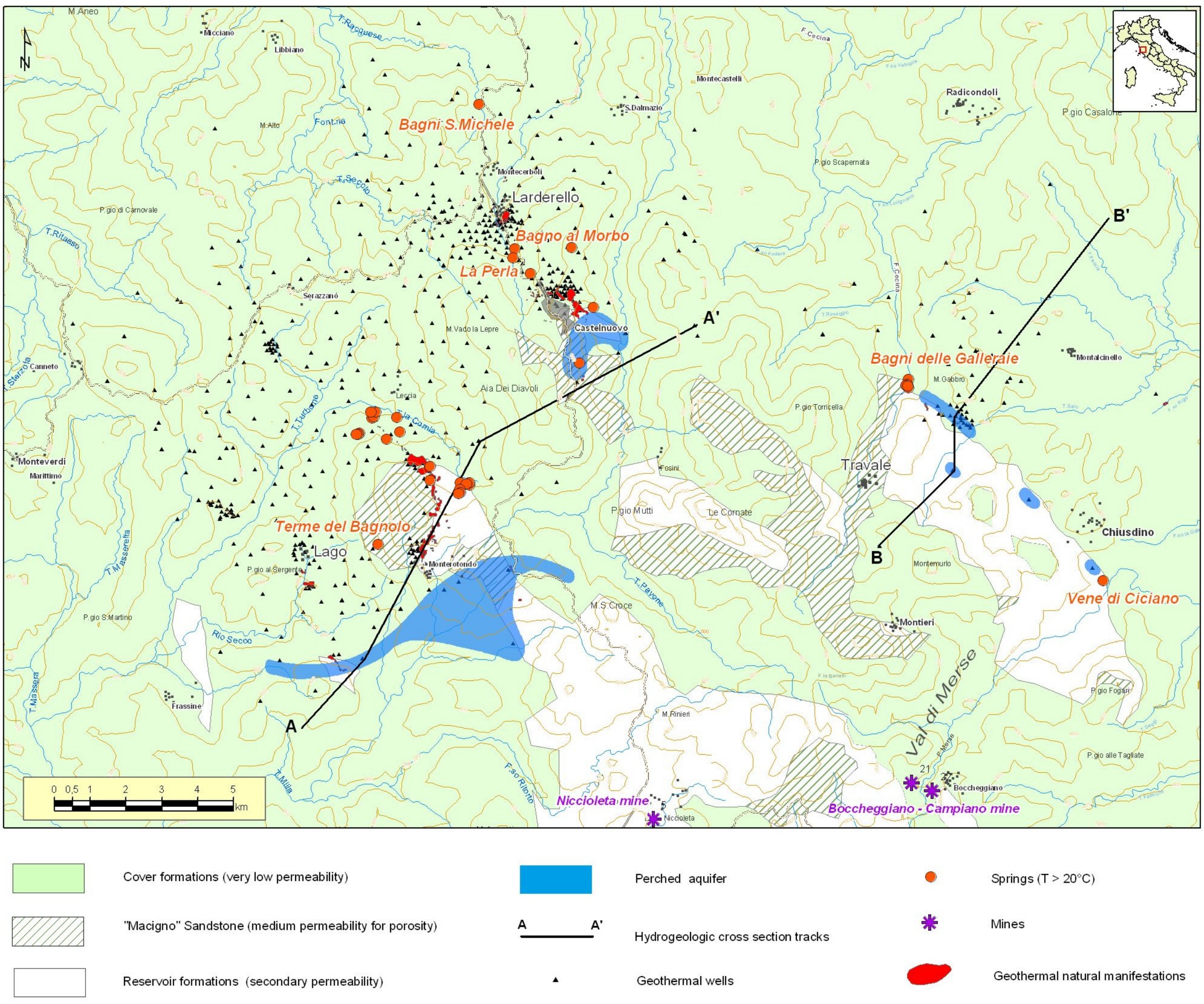

Figure 10: Hydrogeologic map of the Larderello-Travale area

The carbonate outcrop to the North of Monterotondo has not been investigated by wells. In this case, due to the significant local heat flow a sudden evaporation of meteoric waters could be inferred as shown by numerous local natural manifestations (see section A-A' in Figure 11).

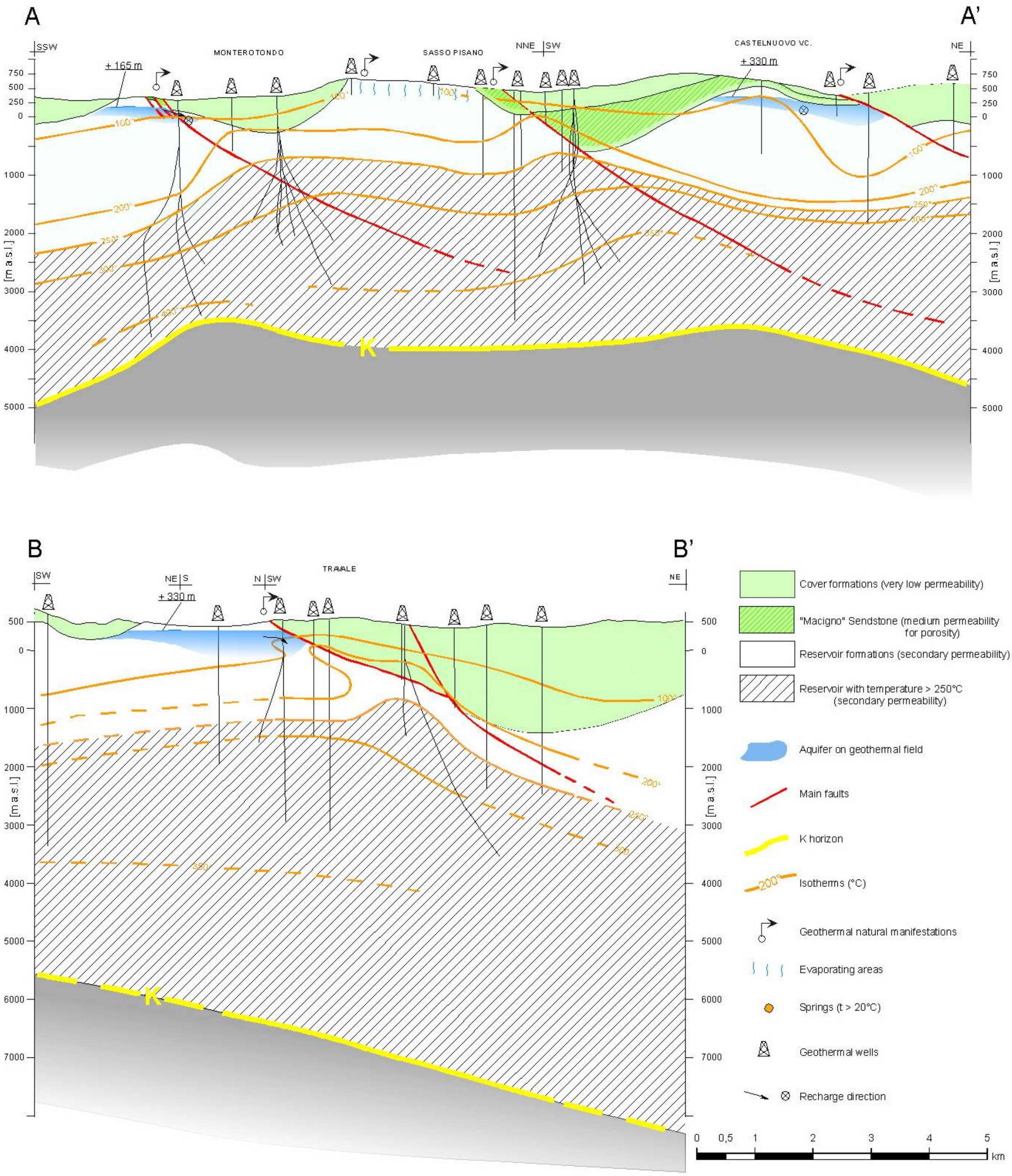

Figure 11: Hydrogeologic cross sections of the Larderello-Travale area. Tracks as in Figure 10

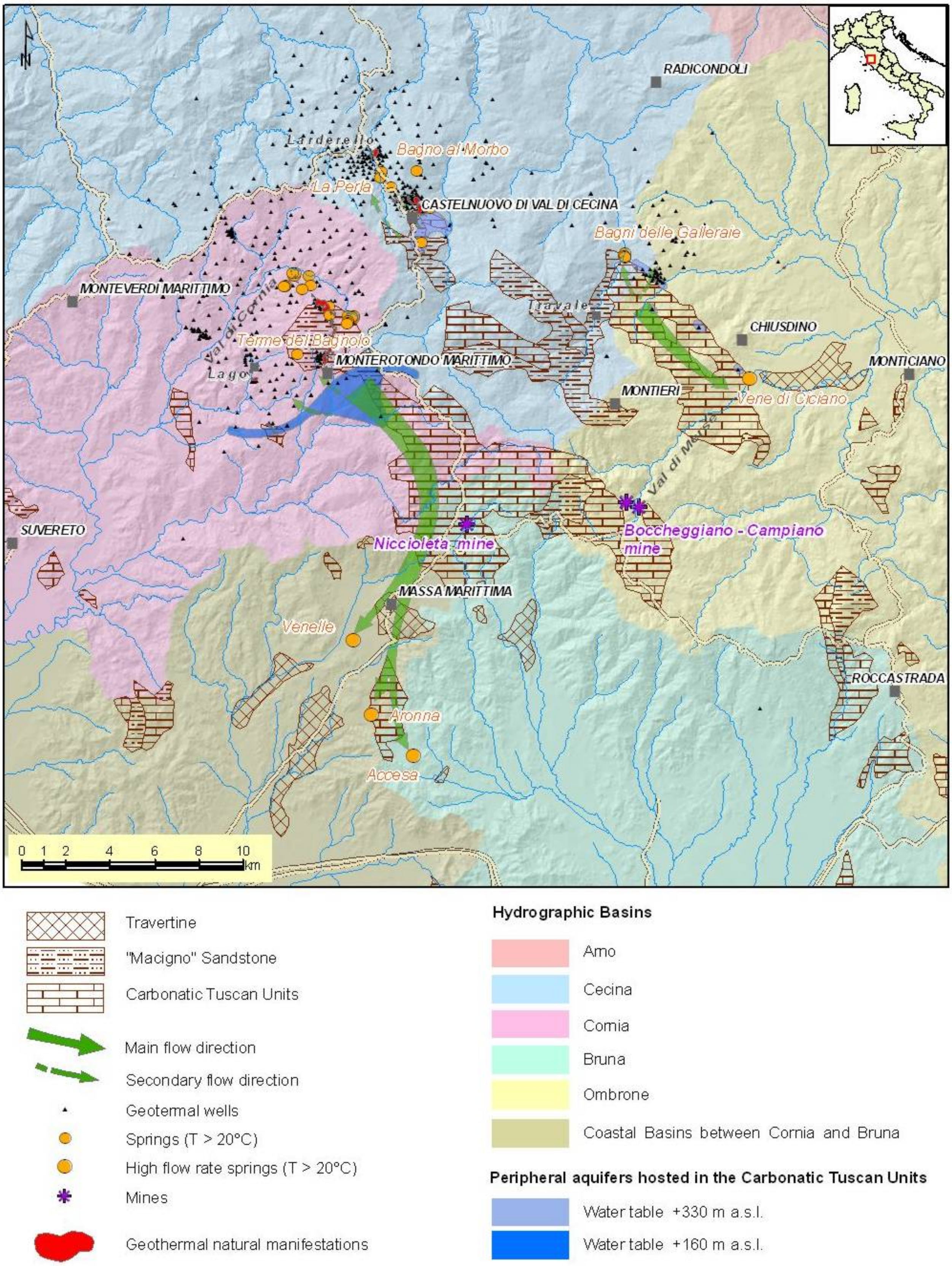

Figure 12: Interpretative hydrogeologic map

CONCLUSIONS

The update analysis of all the available geoscientific data in the Larderello-Travale geothermal system allowed defining the main elements for the numerical model.

The first layer represents the cover of the system constituted by low permeability Flysch formation. Its thickness is from a minimum of 400m to about 1000m and it is characterized by really low permeability values, i.e. impermeable to mass flux but that guarantees a conductive heat transfer.

As for the modeling, the top of the productive geothermal reservoir has been referred to the first fractured level met in the wells of the central part of the field. In the peripheral areas, where stratigraphic well data are lacking, such limit was hypothesized as coincident with the 250°C isotherm which is the expected temperature at the reservoir top. The merging of the first fractured/productive levels and the 250°C isotherm surface are substantially coincident in the central part of the field as ascertained by drillings.

The bottom of the geothermal system has been considered as coincident with the K seismic horizon. This latter could correspond to the 400°C isotherm that can represent the ductile/brittle transition zone and should imply the lack of fractured/permeable structures at greater depths. The depth of the K horizon varies from 8-10km in the eastern sector of the geothermal system and from 3-4km in the western one.

The lower limit of the system represents the heat source that, together with the different permeability areas allows the temperature distribution into the reservoir.

In the natural state condition the model boundaries had been characterized by a pressure consistent with the hydrostatic gradient.

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