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An updated numerical model of the Larderello–Travale geothermal system, Italy

Paolo Romagnoli, Alessia Arias*, Antonio Barelli, Maurizio Cei, Michele Casini

Enel Green Power S.p.A., Via A. Pisano 120, 56122 Pisa, Italy

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ABSTRACT

Larderello–Travale is one of the few geothermal systems in the world that is characterized by a reservoir pressure much lower than hydrostatic. This is a consequence of its natural evolution from an initial liquid-dominated to the current steam-dominated system. Beneath a nearly impermeable cover, the geothermal reservoir consists of carbonate-anhydrite formations and, at greater depth, by metamorphic rocks. The shallow reservoir has temperatures in the range of 220–250 °C, and pressures of about 20 bar at a depth of 1000 m, while the deep metamorphic reservoir has temperatures of 300–350 °C, and pressures of about 70 bar at a depth of 3000 m. The 3D numerical code "TOUGH2" has been used to conduct a regional modeling study to investigate the production mechanism of superheated steam, the interactions between the geothermal field and the surrounding deep aquifers, and the field sustainability. All the available geoscientific data collected in about one century of exploration and exploitation have been used to provide the necessary input parameters for the model, which covers an area (4900 km^2) about 10 times wider than the Larderello–Travale geothermal field (400 km^2). The numerical model explains the origin of the steam extracted in about one century of exploitation and shows that, at the current level, the production is sustainable at least for the next 100 years.

1. Introduction

The generation of electricity from geothermal resources in Italy started at the beginning of the 20th century in the Larderello and Travale geothermal fields (Barelli et al., 1995a,c, 2000; Batini et al., 2003) with the exploitation of a shallow reservoir at a depth of 500–1500 m which consists of carbonate-anhydrite formations of Mesozoic age. Since the mid-1980s, drilling technology improvements enabled geothermal fluid production from a deeper reservoir, which is hosted in metamorphic rocks at depths greater than 3000 m.

Pressure, temperature, and composition of the geothermal fluids are almost constant over the exploited area, supporting the hypothesis of a single, very large fractured geothermal system (Bertini et al., 2006). The deep Larderello–Travale reservoir has temperatures in the range of 300–350 °C and pressures of 40–70 bar. It is one of the few examples of superheated steam system on earth with about 50 °C of superheating (Bertani, 2005). At present, the installed capacity in the entire Larderello–Travale geothermal area is 722 MWe, that is 89% of the total (810.5 MWe) installed capacity in Italy (Cappetti et al., 2010).

To forecast the future evolution of the field and its production sustainability, a numerical modeling effort has been carried out covering an area of 70 km × 70 km (Fig. 1). This large areal extent requires the availability of a large amount of data to determine the various system parameters. The poor quality of available information particularly for the shallow aquifers, a varied field exploitation history, and complexities arising from anisotropic distribution of permeability, make the numerical modeling of the Larderello–Travale geothermal system an extremely difficult task. Further challenges arise in explaining how a superheated and depressurized geothermal system, with negligible recharge from local meteoric waters could produce such an enormous amount of steam.

To develop a detailed model of the Larderello–Travale system, all the geoscientific data collected up to the end of 2009, were considered and analyzed (Arias et al., 2010). In this way, reliable input parameters were generated for the numerical model with the goal of producing a macro-description of the geothermal system (Barelli et al., 2010). The final objective of the model is the evaluation of the possible interactions between the geothermal field, during its exploitation, and the hydrologic basins in the area.

For this reason, the numerical model must take into account both the geothermal system and the regional hydrology. Although the producing area is only 400 km^2, an area of 4900 km^2 was chosen for the simulation to include both the geothermal system and the surrounding aquifers.

* Corresponding author at: Enel Green Power S.p.A., Renewable Energies Division, Via A. Pisano 120, 56122 Pisa, Italy. Tel.: +39 050 6185866; fax: +39 050 6185504.
E-mail address: alessia.arias@enel.com (A. Arias).

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Nomenclature

G_D	steam discharge from deep circulation (t/h)
G_L	steam discharge from local recharge (t/h)
G_T	total rate of steam discharge (t/h)
A	gas/steam ratio in the total discharge
B	gas/steam ratio in the fluid of deep origin
V_{steam}	available volume for the steam storage (m^3)
V_{res}	reservoir volume (m^3)
M_{steam}	steam mass (t)

Greek symbols

ϕ	reservoir porosity
$\rho_{(T;P)}$	steam density (kg/m^3)

2. Historical field exploration

Exploration and exploitation of the Larderello field started at the beginning of the 20th century, and were later extended to the Travale field in the 1950s. Initial drilling work in both fields only reached a shallow carbonate-anhydrite reservoir. But a deep exploration program, that was carried out in Larderello during the 1980s and in Travale in the 1990s, found an exploitable steam-dominated system in the metamorphic basement at a depth of about 2.5–4 km. Data from the deep reservoir revealed that Larderello and Travale fields belong to the same geothermal system (Fig. 2). At present, the total steam production from the Larderello–Travale geothermal system is over 4700 t/h.

2.1. Larderello field

The first well was drilled in Larderello in 1926, tapping the shallow carbonate formations (Barelli et al., 2000; Batini et al., 2003). Between 1926 and 1940, 136 wells were drilled over an area of 4 km^2 with a high success rate of 82%. In the following 10 years, the exploitation area was doubled with another 69 wells. All these wells tapped the carbonate reservoir with a maximum pressure of 32 bar and a temperature of 220–230 °C (Bertani et al., 2005). From the 1950s to 1980s, the drilled area was further extended to about 100 km^2.

The boundaries of the shallow reservoir were reached by exploitation in the 1970s, and two innovative strategies were successfully developed to sustain production namely, injection of condensate from geothermal power plants, and steam extraction from new deep productive horizons.

Injection started in 1979 as an experimental strategy in the central part of the Larderello field ("Valle Secolo") which was considered the most favorable area in terms of reservoir permeability and superheated conditions (Barelli et al., 1995b; Cappetti et al., 1995). As a consequence of the re-evaporation of injected water, steam production increased in the "Valle Secolo" area, reaching a steady production level of about 1500 t/h. Furthermore, the gas/steam ratio decreased, improving the power plant specific consumption (i.e., steam requirements per MW), and the reservoir pressure was recovered without any substantial temperature change in the produced fluid (Barelli et al., 1995b). Currently, more than 1500 t/h of water are injected into the Larderello system.

In the early 1980s, a deep exploration program began with wells reaching some 3500 m which encountered productive layers in the metamorphic basement. This reservoir contained superheated steam with an average pressure of 40 bar and temperature of 300–350 °C (Barelli et al., 1995c). As a result of injection, and expansion of the drilled area both vertically and laterally, fluid production increased in the Larderello field and is now about 3700 t/h.

2.2. Travale field

The geothermal exploitation of the Travale field began in the early 1950s, when 20 wells were drilled near the natural manifestations to a depth of a few hundred meters and penetrated a water-dominated Mesozoic carbonate reservoir that is different from that in the Larderello area (Barelli et al., 1995a; Batini et al., 2003). Production caused the surface manifestations to disappear and triggered the inflow of meteoric water that quickly flooded the wells.

In the 1970s, the exploration was extended northward, targeting a deeper and hotter reservoir, named "Horst". Permeable rocks were encountered at a depth of 500–1000 m in the Mesozoic carbonate formation (see above) with a pressure of 60 bar and a temperature of 280 °C (Barelli et al., 1995a). This reservoir hosts a saturated steam-dominated system that is in pressure equilibrium with the previously discovered water-dominated one.

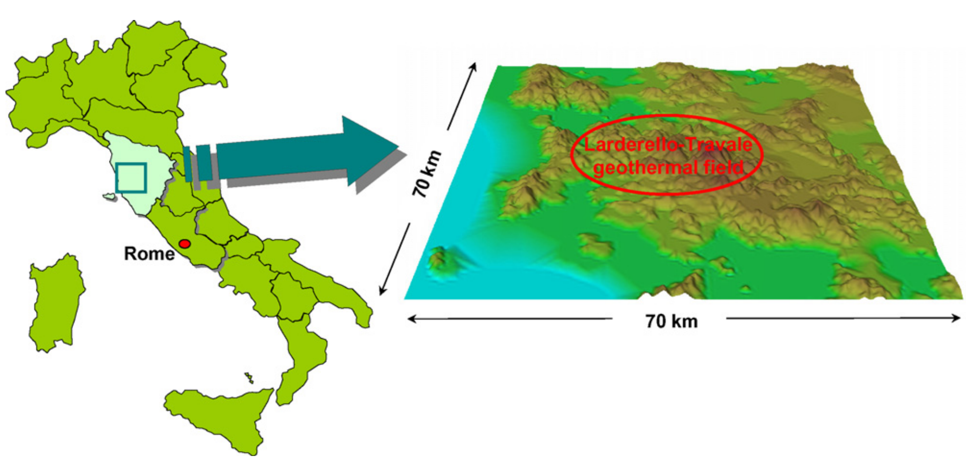

Fig. 1. Location of the 70 km × 70 km numerical modeling area (Tuscany Region, Italy).

At the beginning of the 1980s, production was extended deeper (1300–2000 m) and northward in the same 60 bar "Horst" reservoir that, in this case, is named "Graben" (Barelli et al., 1995a). A continuous flow-rate decline without substantial changes in the steam quality and gas content was observed as a result of the exploitation of this deeper layer.

After 1992, about 30 deep wells were drilled up to depths of 4000 m in a wider area to investigate a deeper reservoir hosted in the metamorphic basement and in the granite intrusions. This reservoir contained superheated steam in vaporstatic equilibrium with all the previously discovered shallower reservoirs (Barelli et al., 1995c), had a temperature of about 300–350 °C and had an initial pressure of 70 bar. The success of the deep exploration program increased the steam production up to 1000 t/h. An injection strategy has not been adopted for the Travale area because of its high pressure (50–60 bar).

3. Geologic outline

Extensive geologic data from the 4900 km^2 area chosen for the Larderello–Travale numerical simulation have been collected, reanalyzed, and interpreted. In the following, the stratigraphic-structural setting, the hydrogeologic, and the physical characteristics of the area are described with particular attention to the outlines of the geothermal system. An evaluation of the local recharge of the system is also presented.

3.1. Stratigraphic-structural setting

The present-day geologic setting is the result of compressive and extensional geodynamic processes that began 30 Ma ago (Oligocene) with the Alpine-Apennine orogenesis (Carminati and Doglioni, 2004). From Lower Miocene, the extensional tectonic regime resulted in the formation of NW–SE tectonic basins, crustal thinning with consequent upwelling of magma bodies and increased heat flow. The geothermal gradient in the Larderello–Travale system is greater than 100 °C/km and reaches maximum values of 300 °C/km (Baldi et al., 1995).

The most recent outcrops correspond to the Quaternary marine and continental deposits on the coastal plain and in the alluvial valley, while the oldest ones are represented by the metamorphic rocks of the Paleozoic Basement (Bertini et al., 2006). The presence of travertine beds and volcanic rocks is suggestive of hydrothermal circulation, and recent magmatic activity, likely connected to the geothermal phenomena. The main and most widespread outcrops in the Larderello–Travale area are:

- *Neoautochthonous complex*: Clays, with minor sands, conglomerates and detrital limestones;
- *Ligurian/sub-Ligurian complex*: Jurassic-Eocene clayey-marly units in flysch facies; and
- *Tuscan Nappe complex*: Triassic-Lower Miocene arenaceous and clayey-marly formations, calcareous-siliceous rocks, dolostone and anhydrites.

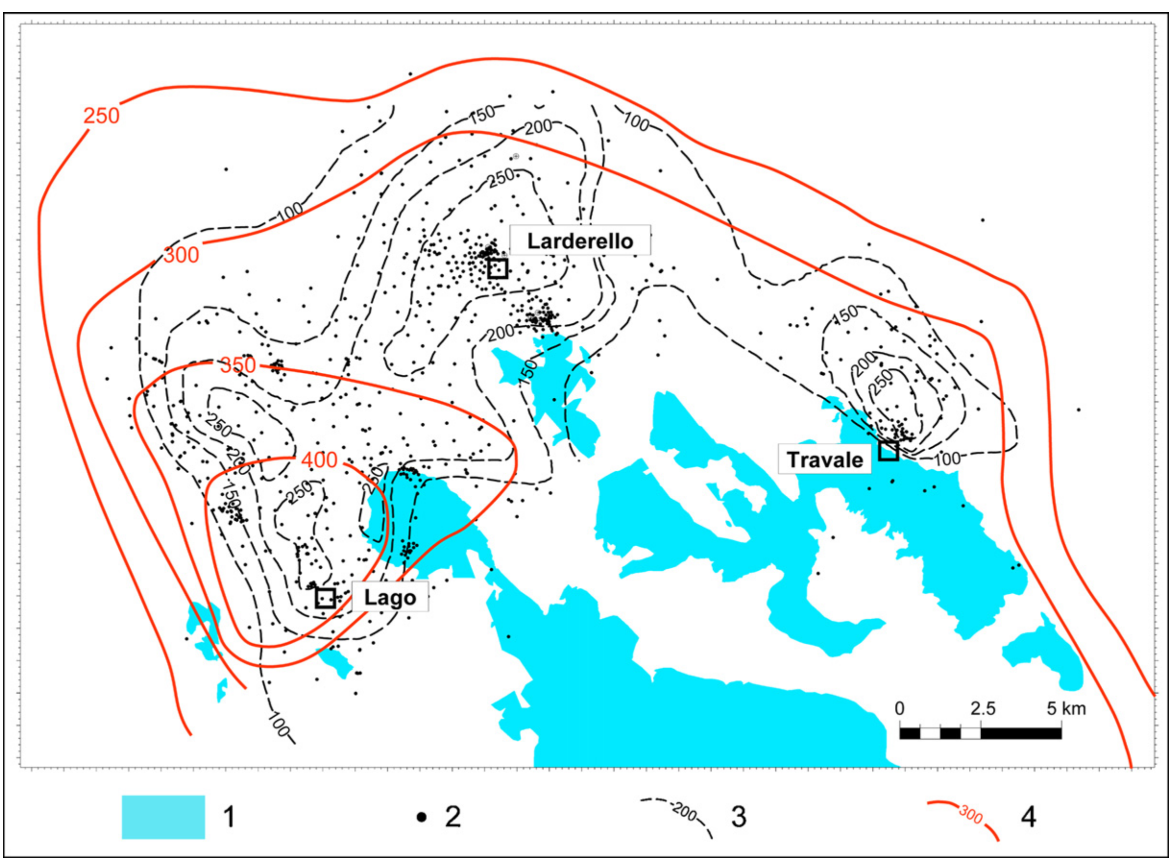

Fig. 2. Temperature distribution in the Larderello–Travale geothermal field. (1) Outcrops of permeable formations; (2) geothermal wells; (3) temperature at the top of the shallow reservoir; (4) temperature at 3000 m b.s.l. Figure modified from Cappetti et al. (2005).

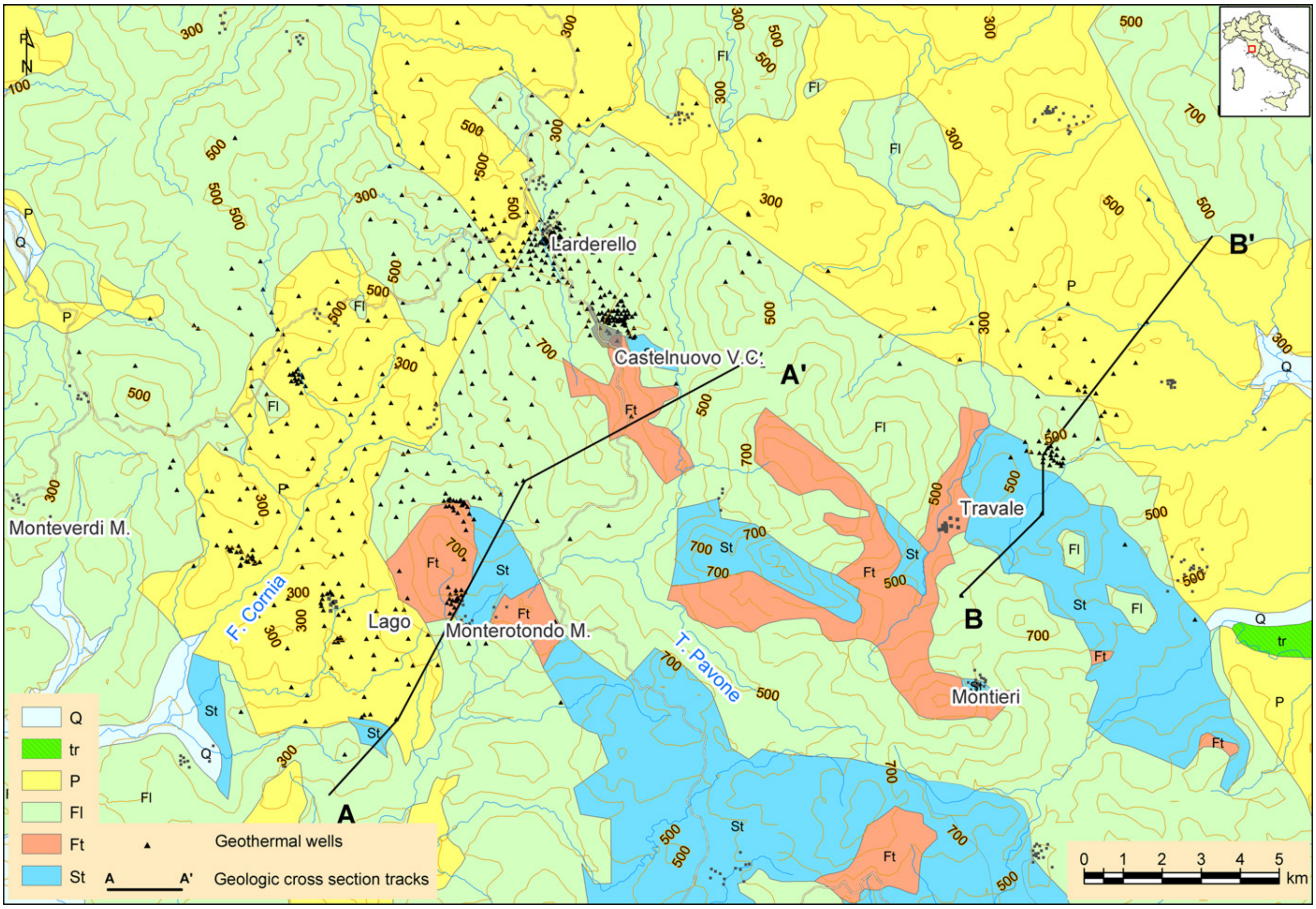

Fig. 3. Schematic geology of the Larderello–Travale geothermal area simplified from Giannini et al. (1971). Q: Quaternary deposits; tr: Plio-Quaternary Travertines; P: Neoautochthonous terrigenous deposits (Lower Pliocene–Upper Miocene); Fl: Ligurian and sub-Ligurian Flysch complex (Jurassic – Eocene); Ft: terrigenous formations of Tuscan Units (Upper Cretaceous–Lower Miocene); St: mainly carbonate formations of Tuscan Units (Upper Trias – Malm).

A reconstruction of the geological setting at depth (Figs. 3 and 4) has been carried out using data from deep wells and geophysical surveys (Bertini et al., 2006).

3.2. Hydrogeologic outline

Larderello–Travale is one of the few steam-dominated geothermal systems in the world and has a sub-hydrostatic pressure gradient. The thermal and structural setting of the system allowed its natural evolution from an initially liquid state to its current superheated steam condition. The liquid phase is presently confined to a few local structures (Fig. 5) that, for the presence of permeable outcrops, facilitate the seepage of meteoric waters into the reservoir (Barelli et al., 1995c). The depressurization of the reservoir occurred prior to industrial exploitation of the geothermal resource as verified by the first drilling data in the area (Celati et al., 1975). A strong pressure disequilibrium should have existed between the steam-dominated reservoir (with 60–70 bar at 4000 m depth) and the regional peripheral aquifers (with hydrostatic pressure of 300–400 bar at 3000–4000 m depth). This requires the presence of a very low permeability boundary in order to limit the interactions among the geothermal system and peripheral aquifers, and consequently allow the existence of the system itself.

From a hydrogeologic point of view, the field is characterized by nearly impermeable formations (Neoautochthonous and Flysch Units) having a thickness of up to 1000 m which act as a caprock for the geothermal system (Fig. 6) hosted in the Mesozoic carbonate-anhydrite formations (shallow reservoir) and in the Paleozoic metamorphic basement (deep reservoir).

The formations constituting the caprock locally exhibit permeable lithologies that host shallow aquifers of limited areal extent. These permeable lithotypes are mainly represented by valley alluvia, detrital limestones in the Neoautochthonous formations, carbonate levels in the Flysch and the underlying "*Macigno*" sandstones. The latter two formations are turbidite sequences that generally exhibit low permeability, and are usually separated from the underlying geothermal reservoir by clayey-marly lithotypes (so-called "*Scaglia Toscana*"). Only in an area near Castelnuovo V.C., the "Macigno" formation is in direct contact with the steam reservoir and can supply a minimum recharge to the system (Calore et al., 1982).

In any case, the aquifers hosted in the overlying formations are underlain by impermeable rocks that prevent interactions with the geothermal system. These aquifers can feed a number of seasonal thermal springs (i.e., Bagno al Morbo, La Perla, Terme del Bagnolo, Bagni San Michele in Fig. 5) which are heated by thermal conduction (Duchi et al., 1992) and are characterized by low salinity values (TDS generally <1000 mg/kg).

The reservoir formations crop out in the southern part of the field along a ridge with a NW Apennine direction. The infiltration of meteoric water to a deeper level is made possible by the carbonate-anhydrite outcrops that represent zones of interference

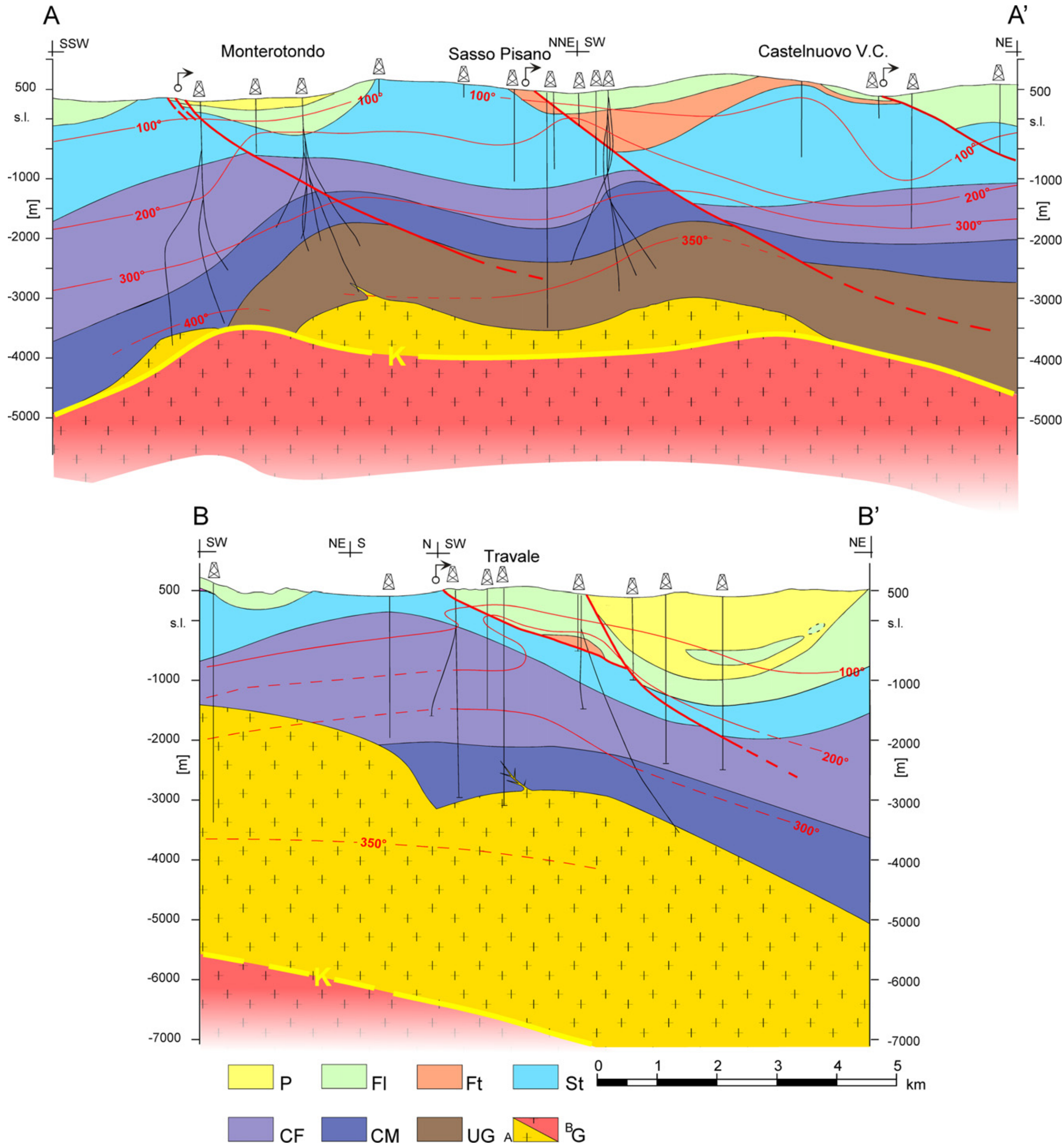

Fig. 4. Geologic cross-sections of the Larderello–Travale geothermal area. See Fig. 3 for locations of cross-sections. P: Neoautochthonous terrigenous deposits (Lower Pliocene–Upper Miocene); Fl: Ligurian and sub-Ligurian Flysch Complex (Jurassic – Eocene); Ft: terrigenous formations of Tuscan Units (Upper Cretaceous–Lower Miocene); St: predominantly carbonate formations of Tuscan Units (Upper Trias – Malm); CF: Phyllites and Quartzites complex (Upper Cambrian – Ordovician); CM: Micaschist complex (Precambrian – Lower Paleozoic); UG: Gneiss Unit (Precambrian – Lower Paleozoic); G: Granite A. Pliocene; B. Quaternary (?).

with the shallow geothermal reservoir. A few wells have encountered water rather than steam (see Fig. 6) and hence these areas have been considered as the boundaries of the shallow geothermal field (Ceccarelli et al., 1987).

The carbonate outcrops feed a deep circulation system that supplies the springs at the south-eastern boundaries of the carbonate ridges. These springs (i.e., Vene di Ciciano, Venelle, Aronna) display high flow rates with medium to low temperatures (around 25 °C). A mixing between the incoming water and the geothermal steam occurs at the northwestern end of the ridges (Fig. 7). This inflow represents the so-called local recharge of the geothermal system and the phenomenon is sometimes evidenced by thermal inversion in a few wells at the field boundaries. Otherwise, the shallow aquifers are perched and separated from the steam reservoir, as verified by some deep wells that have penetrated these aquifers (see Fig. 6), and by the horizontal temperature distribution at the top of the shallow geothermal reservoir. In fact, a strong horizontal thermal gradient, caused

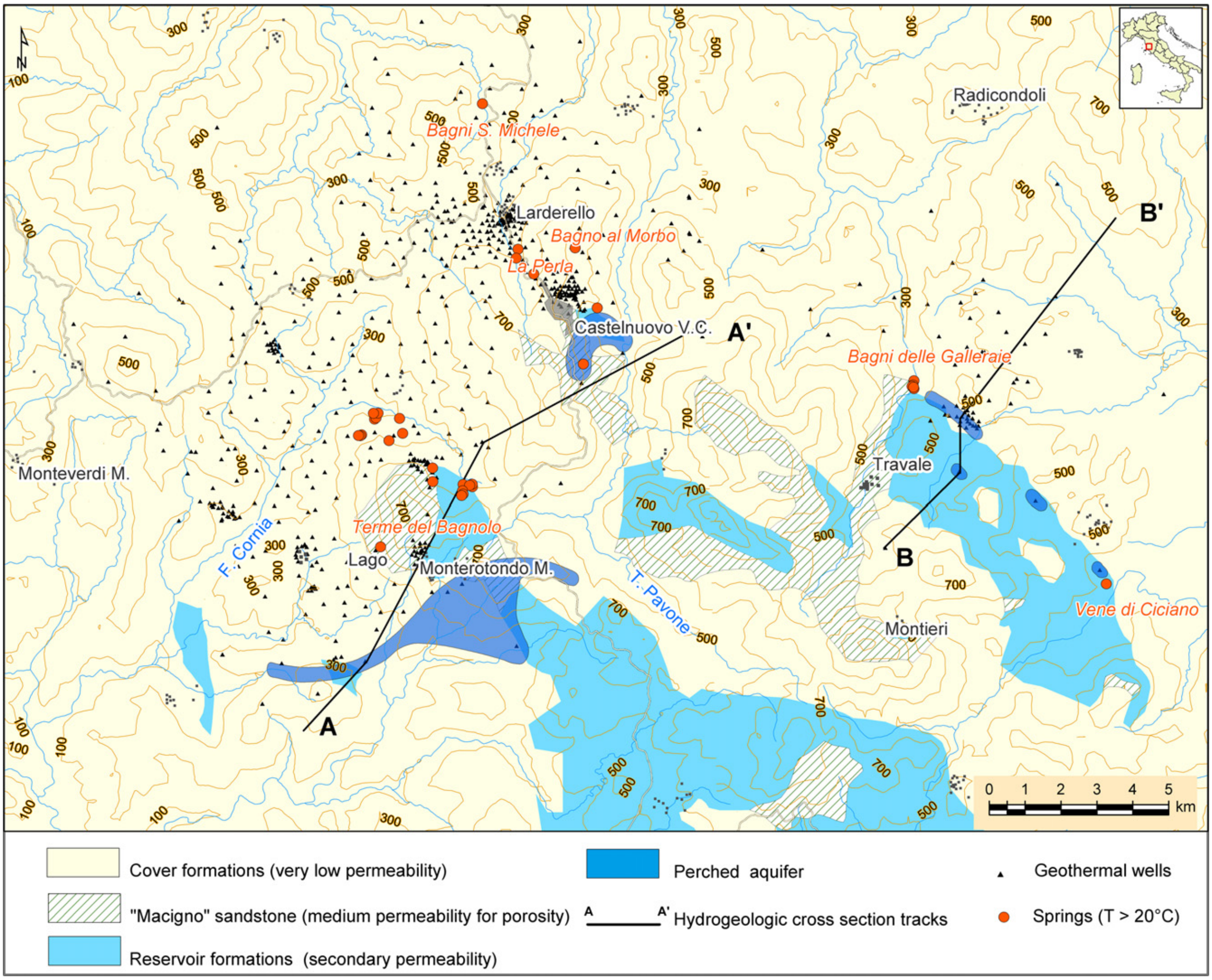

Fig. 5. Hydrogeologic map of the Larderello–Travale area.

by the interference of cold water inflow, occurs only in outcrops of the shallow reservoir. The contribution of the shallow aquifers constitutes only a part of the total natural recharge in the Larderello–Travale system, and has been preliminary estimated, from gas/steam ratio analyses, to be 390–580 t/h (i.e., $3.3–5.0 \times 10^6\,m^3$/year).

Deep drilling shows no thermal influence on the deep metamorphic system due to the above-mentioned permeable outcrops. This is supported by the thermal anomaly being open in the south (see Fig. 2) where these outcrops are widely present.

Two main perched aquifers with piezometric levels of 160 m (base aquifer) and 330 m a.s.l. have been identified within the carbonate formation of the Tuscan Units that can locally feed the geothermal reservoir. These large aquifers are characterized by high permeability, very small piezometric horizontal gradients (typical of karst aquifers), medium–low temperatures (20–25 °C), and a southward outflow (see Fig. 7).

The primary porosity of the geothermal reservoir rocks is very low (1–5%) and homogeneous (Cataldi et al., 1978), while a highly variable fracturing results in a wide range of possible secondary permeability values (Bertani and Cappetti, 1995). Generally, the shallow reservoir is characterized by a homogenously distributed fracture system that can be denser in structural highs. The metamorphic basement however exhibits a large permeability variation due to the nonhomogeneous and localized fracturing (Fig. 8).

3.3. Geologic and physical characteristics of the model

The geoscientific features used as inputs for the numerical model are described below and are shown graphically in Fig. 9. The caprock for the geothermal system consists of the low permeability formations of Flysch Units and Neoautochthonous clayey deposits. Its thickness varies from 200 to 400 m in the central part of the modeled reservoir to about 1000 m in the boundary zones, and its permeability has been chosen to be negligibly small ($10^{-21}\,m^2$).

In order to distinguish the caprock from the reservoir, both stratigraphic and production well data were analyzed. From a geological perspective the top of the reservoir corresponds to the base of the Flysch (Fig. 10), while from a production point of view it is determined by the first fractured layer encountered in the exploited area. Outside the geothermal system, the reservoir top was assumed to coincide with the 250 °C isotherm which is the average temperature value at the reservoir top. The drilling data indicate a substantial

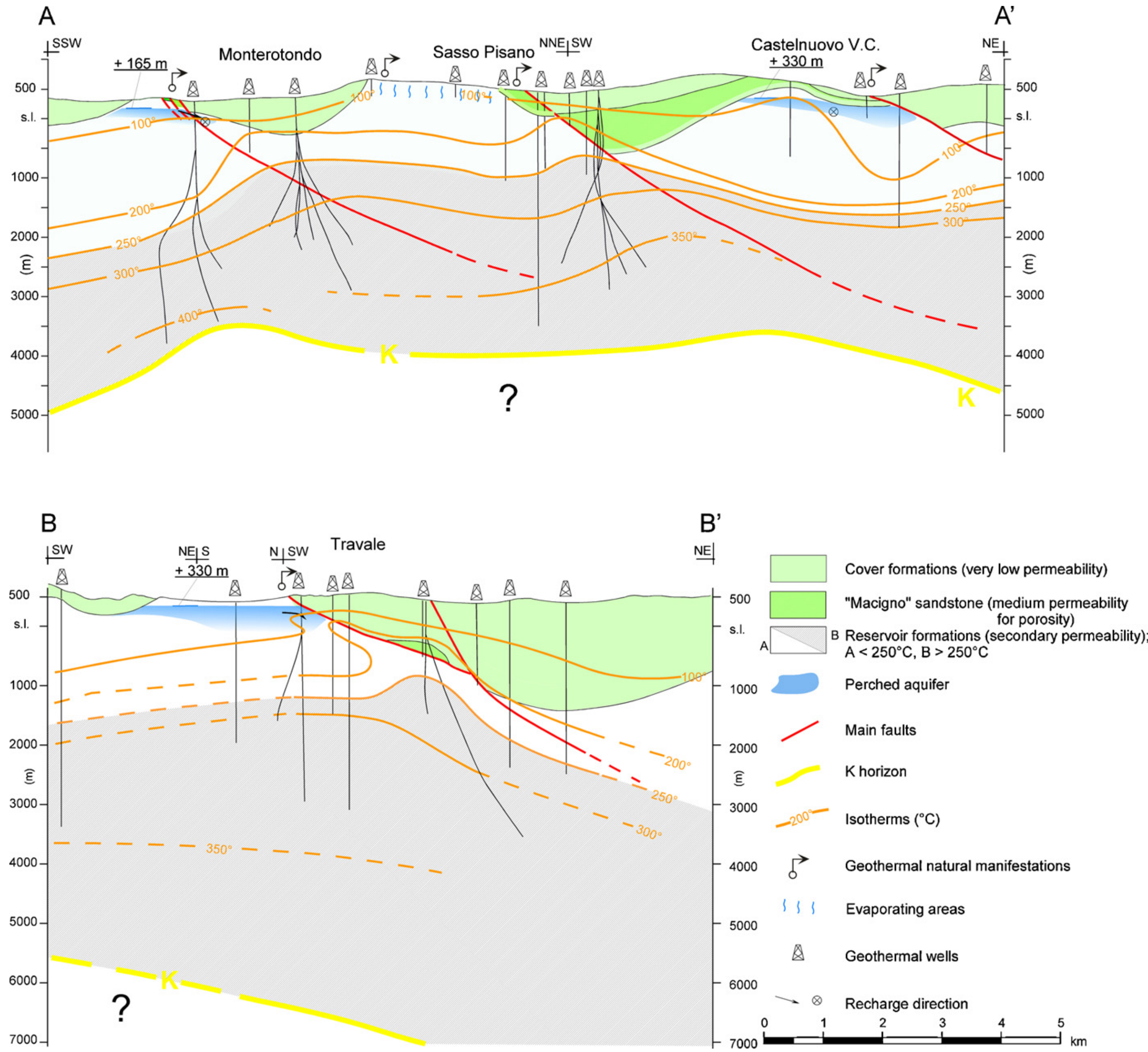

Fig. 6. Hydrogeologic cross-sections of the Larderello–Travale area. See Fig. 5 for locations of cross-sections.

coincidence of the first fractured/productive levels with the depth of the 250 °C isotherm in the central part of the field (Fig. 11).

The boundary between the potential reservoir (the geological formation that can host a reservoir) and the productive formation is considered as the reservoir top in the numerical simulation, thus distinguishing two different bodies:

- an *intermediate layer* in the uppermost part of the potential reservoir, characterized by unfractured low permeability rocks (3×10^{-20} m^2) with a maximum porosity value of 2%, and
- the *productive geothermal reservoir* with permeabilities ranging from 10^{-13} to 10^{-15} m^2, porosity from 2% to 4%, and temperature in the range of 250–320 °C.

As mentioned previously, the Larderello and Travale are part of the same 300–350 °C geothermal system at depths greater than 3000 m. Nevertheless, a low permeability (10^{-16} m^2) section was inserted in the numerical model between Larderello and Travale areas, to simulate the different pressure response of the two fields as evidenced by exploitation (see Fig. 9).

Reflection seismic data (Batini et al., 1983; Brogi et al., 2005; Gianelli et al., 1997) highlighted the presence of an intense and continuous reflector inside the Palaeozoic crystalline basement, the so-called K-horizon (Fig. 12). Its nature is still a subject of debate (brittle/ductile transition, recent granitoid intrusions, carapace permeated by supercritical fluids, etc.) and its depth varies between 3–4 km in the western zone and 8–10 km in the Travale geothermal area (Bertini et al., 2006). The K-horizon is associated with the 400 °C isotherm and is considered the *base of the reservoir*

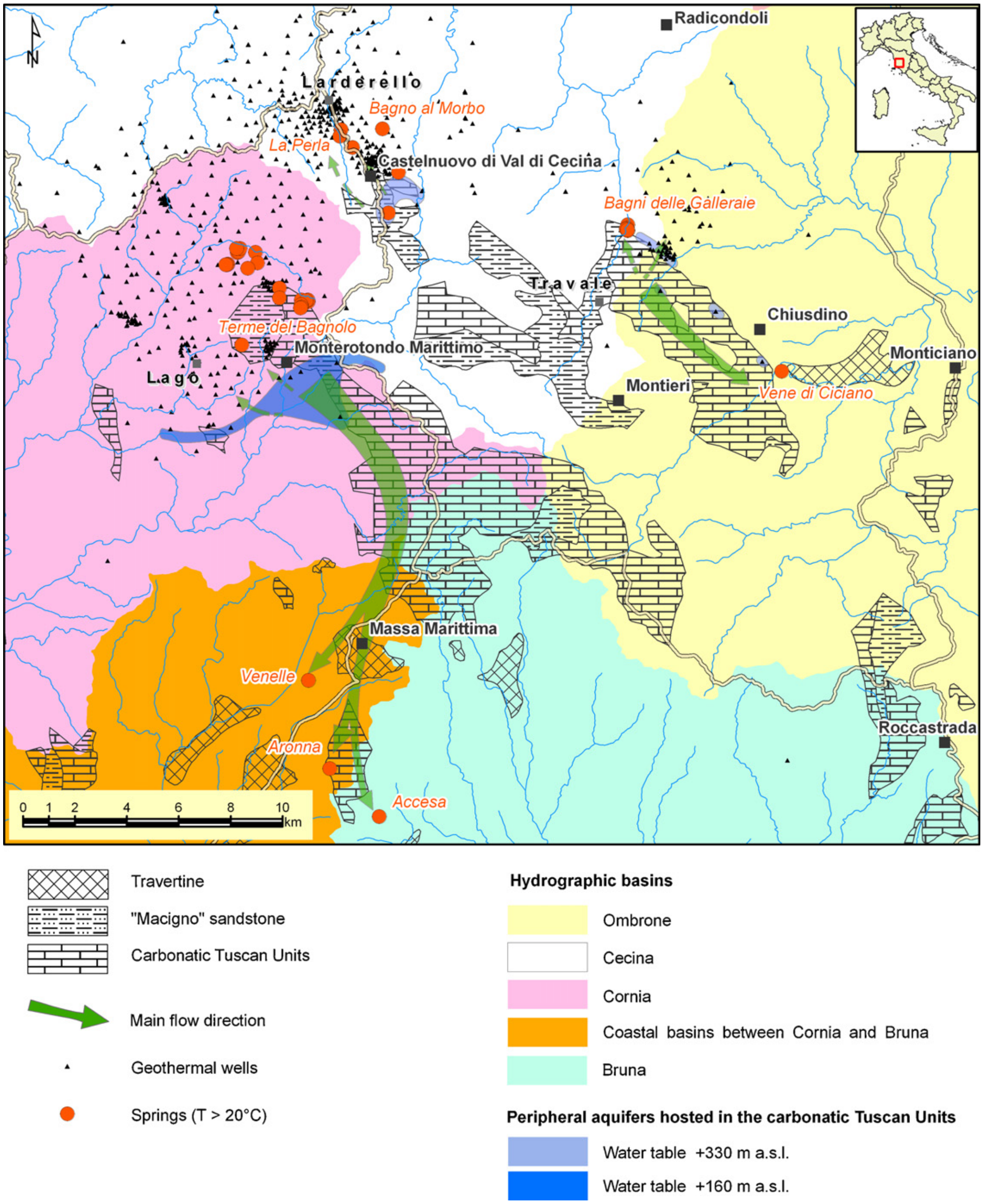

Fig. 7. Interpreted hydrogeologic map of the Larderello–Travale area.

in the numerical model (i.e., it is believed to be the lower boundary of the exploitable geothermal system). At this temperature, the rock ductility should be sufficiently high to prevent natural fracturing. Due to numerical modeling constraints, the shape of this seismic marker was simplified and was set at a depth of 4000 m in the Lago area, and at 7000 m in the Travale one. In order to allow for heat flow but no mass flow from the bottom, the K-horizon was modeled by using impermeable ($k = 0$) and constant temperature cells.

The *lateral boundaries* of the geothermal reservoir are treated in the model as low permeability zones (1.5×10^{-18} m^2) in order to hydraulically separate the surrounding deep aquifers from the steam dominated reservoir. The permeability of these boundaries was estimated from the peripheral well data.

In the numerical model, the caprock is nearly impermeable, but some cells are considered permeable in order to simulate the interaction zones between the geothermal reservoir and the environment. As previously mentioned, the only interactions are the natural manifestations and some perched aquifers. The natural manifestations were modeled by inserting three virtual wells, one for each of the three main zones of outflow, and their productivity index (PI) was chosen to match the estimated historical production. In order to connect these virtual wells to the reservoir, three permeable blocks were introduced in the model. As for the perched

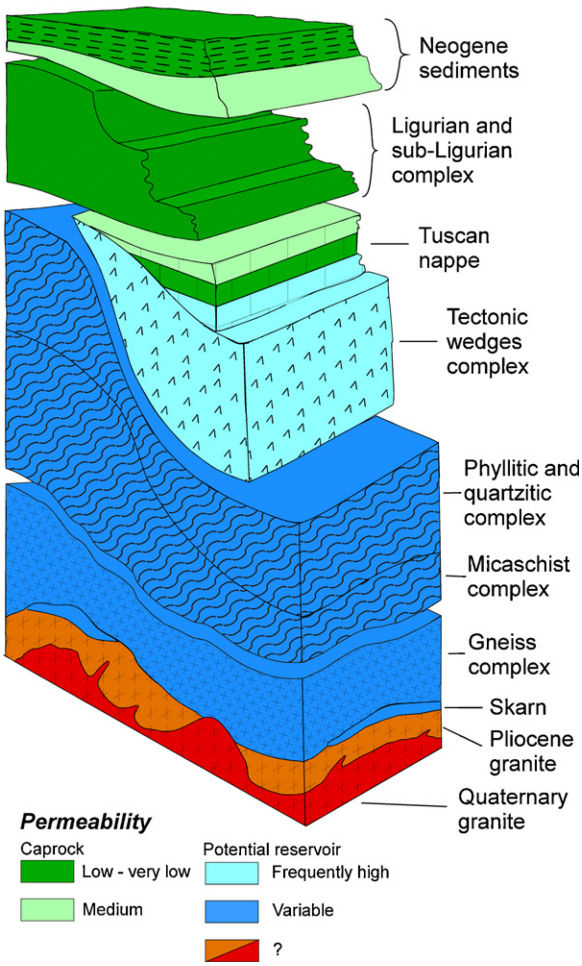

Fig. 8. Structural-stratigraphic and hydrogeologic sketch of the geothermal area (Arias et al., 2010).

aquifer, a number of cells with constant pressure were introduced to simulate the reservoir outcrops (Barelli et al., 1995c; Ceccarelli et al., 1987).

The numerical model has sixteen rock types, twelve for the reservoir, two for the impermeable caprock, and two others for the lateral boundaries where the regional aquifer is hosted. The petrophysical parameters are summarized in Table 1 for the main rock types used in the model.

3.4. Evaluation of the geothermal system local recharge

Prior to industrial exploitation, the geothermal system was recharged by deep regional inflows with long circulation times. The progressive increase of steam production from wells located near the carbonate outcrops (shallow reservoir), triggered a local influx of water (Fig. 13). The local recharge results in a lowering of the non-condensable gas content, and at times in the production of a two phase fluid. In fact, the steam from local recharge is gas free because of the short circulation times (less than 50–70 years based on isotopes; internal unpublished data). The variation with time of the steam extraction rate and of the gas/steam ratio allows the evaluation of local recharge. This is done using a mixing model between the superheated steam derived from deep circulation (primary steam) and that from local recharge (Fig. 14). The total steam production and the gas/steam ratio were analyzed for the so-called "Horst" sector of the Travale area, for the "Castelnuovo V.C." and "Valle Secolo" sectors of the Larderello area, and for the "Monterotondo" and "Lago" sectors of the Val di Cornia area (Fig. 15).

Table 1
Petrophysical parameters for main the rock types.

Rock types	Permeability (m^2)	Porosity (%)	Thermal Conductivity (W/m °C)
Reservoir (12 rock types)	10^{-16} to 10^{-13}	2–5	2
Caprock (2 rock types)	0–10^{-20}	0.1–2	2
Lateral aquifers (2 rock types)	10^{-18} to 10^{-16}	2	2

The evaluation of the primary steam fraction is based on a mass balance and can be performed only for geothermal wells not affected by water injection and with a constant production rate. The wells that showed production decline and lowering of the steam gas content were not considered in this evaluation.

Assuming that the gas content in steam from local recharge is negligible, and defining:

$$G_T = G_L + G_D \tag{1}$$

where G_T is the total steam discharge rate, G_D the steam from deep circulation (primary steam), and G_L the steam from local recharge , there follows:

$$G_T \times A = G_D \times B \quad \text{and} \quad G_D = \frac{G_T \times A}{B} \tag{2}$$

Here A is the gas/steam ratio in the total discharge and B the gas/steam ratio in the fluid of deep origin. Substituting for G_D from Eq. (2) into Eq. (1), results in:

$$G_L = G_T - \frac{G_T \times A}{B} \quad \text{and} \quad G_L = G_T \left(1 - \frac{A}{B}\right)$$

Assuming the gas content of the primary steam (B) remains unchanged from its original value of 10.7% by weight (based on data from the early wells), steam flow derived from local recharge was computed, taking into account the lowering of the non-condensable gas content from the beginning of the industrial exploitation up to present time. This analysis was applied to those areas of the Larderello–Travale system most affected by the mixing between primary steam and local recharge fluids (shallow carbonate reservoir):

- *Travale area* ("Horst" reservoir)
- *Larderello area* ("Castelnuovo V.C." and "Valle Secolo")
- *Val di Cornia area* ("Monterotondo" and "Lago")

The mixing model input parameters and the results of the computation for each sector are summarized in Table 2. Since these recharge values are based on indirect evaluation, higher local recharge values (+10–40%) have been tentatively adopted for comparison with the results of the numerical model where water inflow is simulated using constant pressure grid blocks. The total steam production from local recharge is in the range of 390–580 t/h (3.3–5.0 × 10^6 m^3/year) and Table 3 shows the recharge values for each of the three areas (Travale, Laderello, Val di Cornia).

4. Numerical modeling

The Larderello–Travale system was simulated using the numerical simulator TOUGH2, a general-purpose code for modeling multi-dimensional, multiphase/multi-component flow and heat transport in porous and fractured media (Pruess et al., 1999).

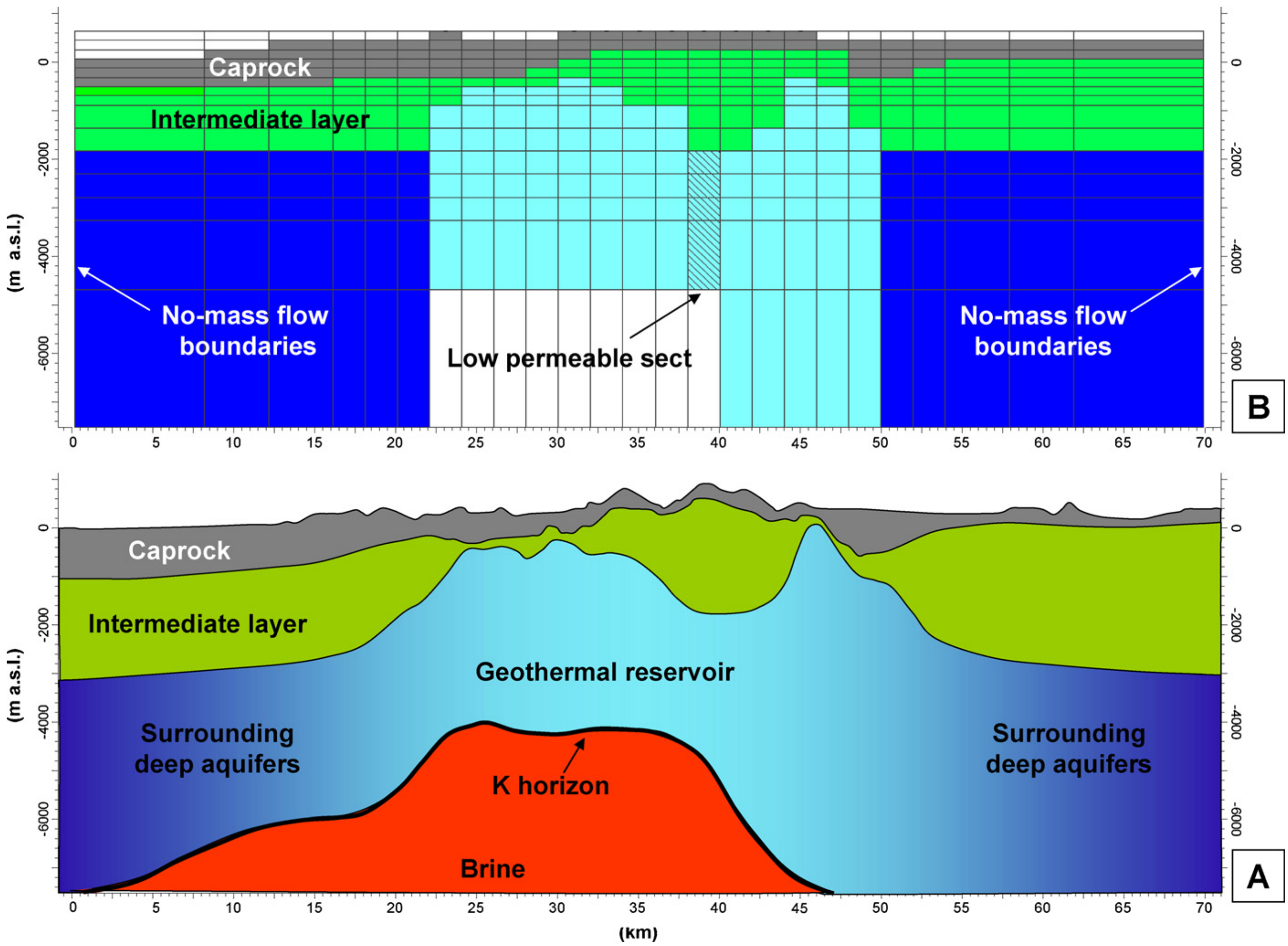

Fig. 9. Comparison of geology (A) and numerical model (B) on a W–E cross-sections.

The modeling was performed using the "equation of state" module (EOS1) for pure water. All water properties (density, specific enthalpy, viscosity, and saturated vapor pressure) are supplied by the International Formulation Committee steam equation tables (1967). While Corey curves were adopted for the relative permeability, capillarity, adsorption, and double porosity were not considered.

Although the Larderello–Travale geothermal system at depths greater than 3000 m is a single superheated steam-dominated system with temperature of 300–350 °C, a low permeability section is inserted between the Larderello and Travale areas (see Fig. 9) to simulate the pressure response to production. Furthermore, the lateral boundaries between the high-permeability reservoir core and the surrounding low-permeability deep regional aquifers are assumed to be at 250 °C which is believed to be the minimum reservoir temperature.

4.1. Conceptual model and natural geothermal system evolution

The numerical simulation is based on a conceptual model for the Larderello–Travale system that explains the origin of the steam produced over a century. The permeable portion of the geothermal system could not have contained the total amount of superheated steam extracted since the beginning of the exploitation. The main features of the conceptual model can be summarized as follows:

- a clayey-shaley caprock (from 0 to 500 m)
- a fractured carbonate reservoir (from 500 to 1000 m)
- a metamorphic reservoir (from 1000 to 4000–5000 m)
- a granitic intrusion as the heat source of the system

Before the emplacement of granitic intrusions, temperature, and pressure, distributions at depth are assumed to be given by the average geothermal gradient and the hydrostatic pressure gradient. Initially, the entire reservoir volume was liquid saturated (Fig. 16). Subsequent to granitic intrusions (3.0–0.5 Ma), the temperature gradually increased in the reservoir and the pressure started to decrease due to the onset of natural manifestations (Celati et al., 1975) that were triggered by the fluid evaporation process. The steam-dominated zone initially developed at the top of the reservoir and then spread all over the reservoir volume (Fig. 17). Complete vaporization of the reservoir water, resulted in a superheated and depressurized system long time before the start of exploitation (Fig. 18).

The main reservoir recharge, particularly during exploitation, comes from the surrounding low permeability regional aquifers in response to pressure drop. A two-phase zone

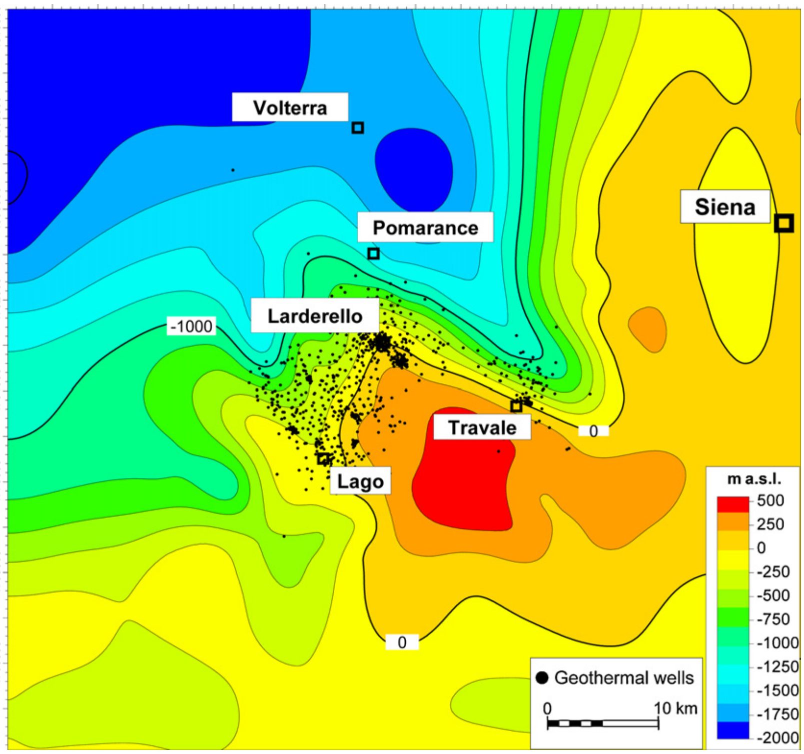

Fig. 10. Map of the Flysch formations base (m a.s.l.).

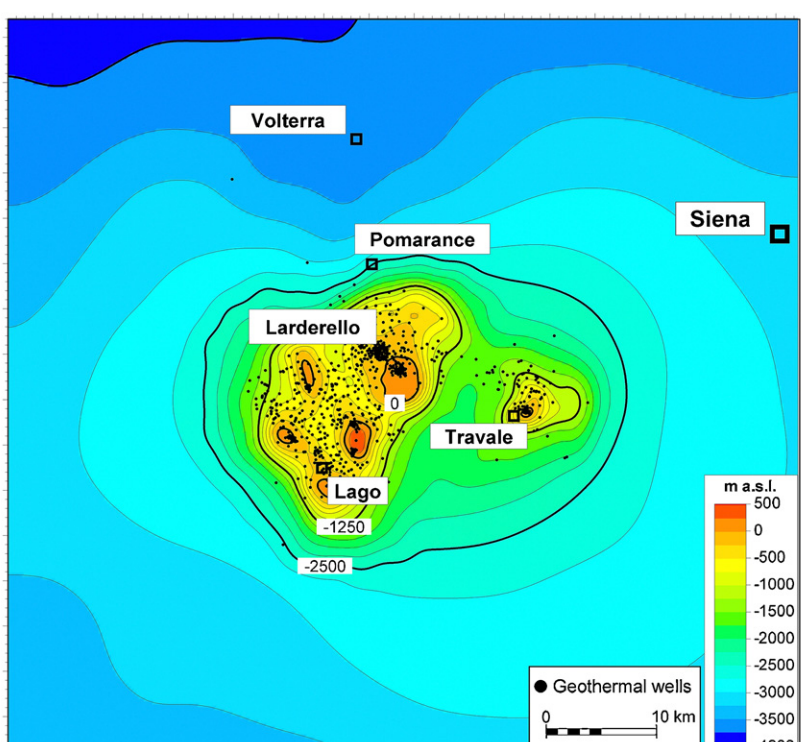

Fig. 11. Map of the top of productive reservoir (m a.s.l.).

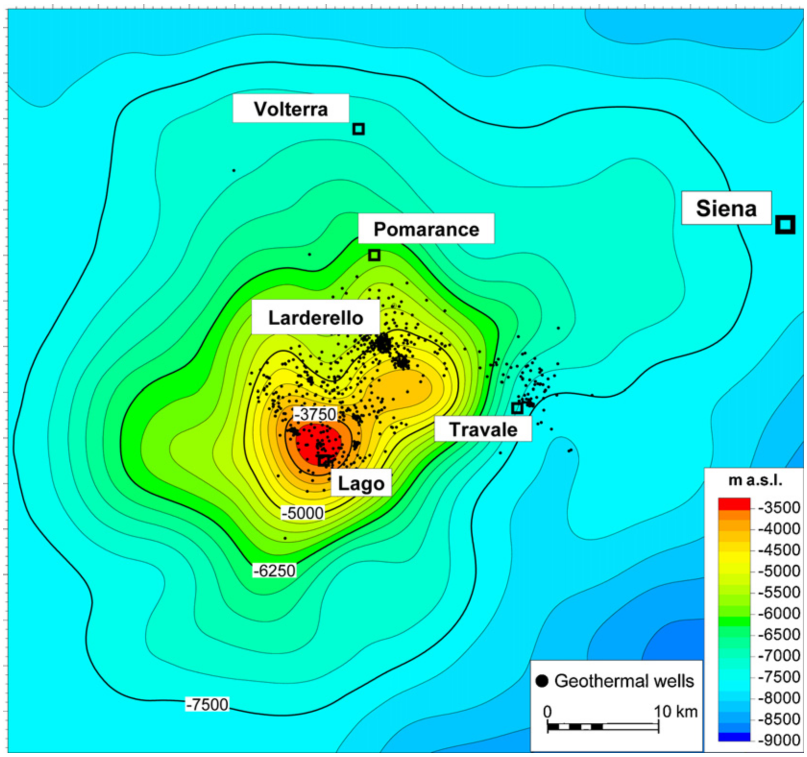

Fig. 12. Map of the seismic K-horizon (m a.s.l.).

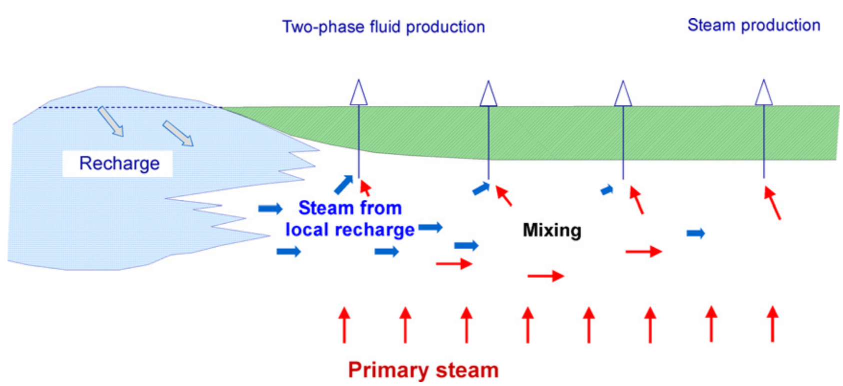

Fig. 13. Schematic cross-section of the interference between the local recharge and the deep primary steam.

is likely to exist near the boundaries between the superheated reservoir and the regional aquifers. Only this type of recharge can explain the large amount of steam extracted over a century of exploitation, i.e., 1.8×10^9 t. It is also possible to evaluate the maximum amount of steam that could be contained in the geothermal system. Since the Larderello–Travale system has an area of about 400 km^2 and an average thickness of about 2 km, the total reservoir volume (V_{res}) is 800 km^3. Assuming a porosity (ϕ) of about 2%, the available volume for the steam storage in the reservoir (V_{steam}) is:

$$V_{steam} = V_{res} \cdot \phi = 16\,\text{km}^3.$$

Thus, the maximum steam amount (M_{steam}) which could be contained in the Larderello–Travale geothermal system is:

$$M_{steam} = V_{steam} \cdot \rho_{(300\,^\circ\text{C};\ 50\,\text{bar})} = 16\,\text{km}^3 \cdot 22.075\,\frac{\text{kg}}{\text{m}^3} = 0.35 \times 10^9\,\text{t}$$

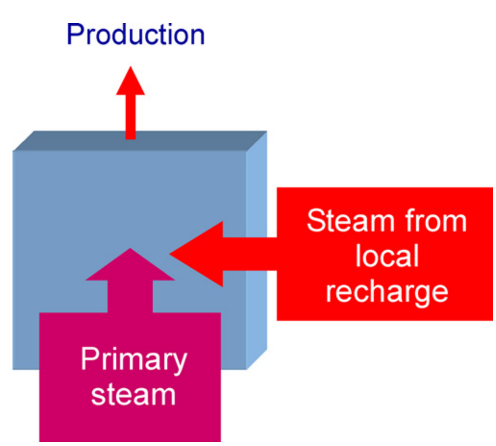

Fig. 14. Mixing recharge model.

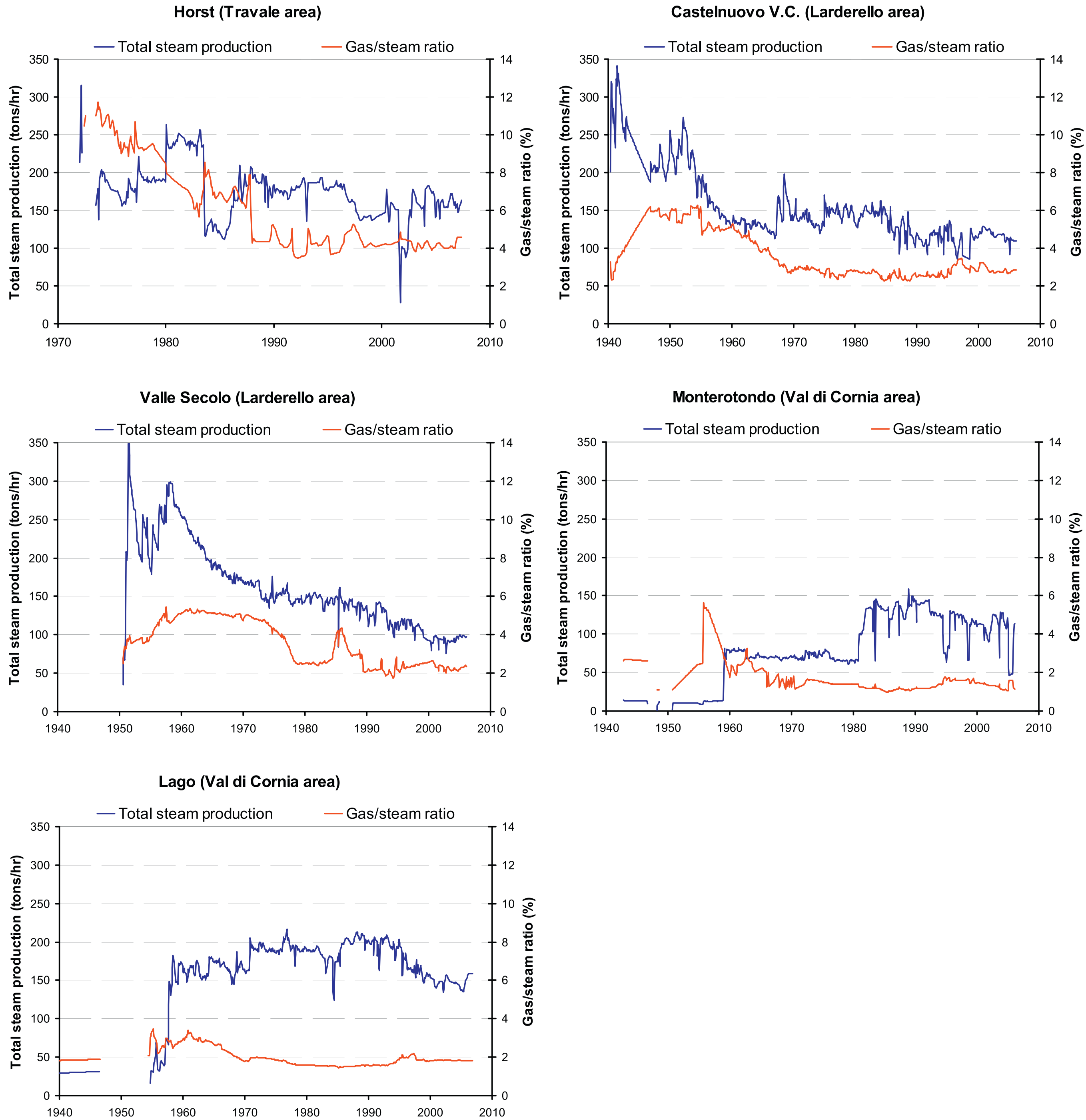

Fig. 15. Production history for the different areas of Larderello–Travale geothermal field.

where $\rho_{(300\,^{\circ}\mathrm{C};50\,\mathrm{bar})}$ is the steam density evaluated at a temperature of 300 °C and a pressure of 50 bar, which is the average pressure and temperature in the reservoir. The total steam extracted to date is more than five times the storage capacity of the Larderello–Travale geothermal system. Even the assumption of an equivalent porosity of 10% to account for the amount of adsorbed water, cannot explain the amount of the steam extracted from Larderello–Travale geothermal system. The continuous evaporation of water in the boundary zone, between the superheated reservoir and the surrounding regional water-dominated aquifers, recharges the reservoir at a rate that certainly is much higher than the shallow local recharge (390–580 t/h).

4.2. Simulation grid and boundary condition

The simulation domain has an area of 4900 km^2 (70 km × 70 km) and a maximum total vertical thickness of nearly 7500 m (from 500 m a.s.l. to 7000 m b.s.l.). The depth to the bottom of the reservoir (K-horizon in Fig. 9) varies between 4000 m in the western zone and about 7000 m in the Travale area. The numerical grid is subdivided into 16 layers and consists of about 10,000

Table 2
Input data and results of the mixing model for the local recharge zones.

Local recharge zone	Original gas/steam ratio B (%)	Present gas/steam ratio A (%)	Total steam capacity G_T (t/h)	Computed recharge (t/h)
Horst (Travale area)	10.70	4.60	160	91
Castelnuovo V.C. (Larderello area)	6.00	2.95	110	56
Valle Secolo (Larderello area)	5.00	2.40	100	52
Monterotondo (Val di Cornia area)	2.85	1.18	110	64
Lago (Val di Cornia area)	3.00	1.80	160	64

cells; each horizontal layer consists of 625 (25 × 25) cells with variable sizes (Fig. 19). A cell size of 2 km × 2 km is used in the central part where greater detail is necessary. Along the domain boundary, a 8 km × 8 km cell size has been adopted. The layer thickness varies with depth from a maximum of a few thousand meters (deep layers) to only 200 m (shallow layers).

To demonstrate the field sustainability, a no-mass flow condition (see Fig. 9) is imposed over all the domain boundaries. The large distance between the grid boundaries and the producing area guarantees that the field behavior is not affected by the assumed boundary conditions.

Temperatures and pressures are assumed to be time invariant in the cells at the top and bottom of the simulation grid. A fixed temperature of 15 °C and atmospheric pressure were set for cells along the upper boundary. The temperatures varied between 350 °C and 400 °C for cells in the bottom layer inside the producing reservoir. The TOUGH EOS1 is not applicable at temperatures above the critical point of water. Temperatures above the critical point are associated with impermeable blocks along the bottom boundary that act as heat sources without allowing mass flow. Outside the producing area, the temperatures in the bottom boundary cells were set to values calculated according to the average earth thermal gradient.

The only interactions between the geothermal reservoir and the external environment are the natural geothermal manifestations and the inflow of cold water from shallow aquifers, where the caprock is absent (see Section 3.4). The natural manifestations were modeled by three virtual wells with a productivity index (PI) chosen to match the historical flow rate. The PI was estimated from the production data of the chemical industry (boric acid extraction) that began in the early 19th century.

As for the interaction with the shallow aquifer, fixed pressure cells were used where the reservoir outcrops are present. The fixed pressure cells are connected via permeable blocks to the geothermal reservoir. The permeability values for these blocks were chosen to match the results of the mixing model (see Table 2).

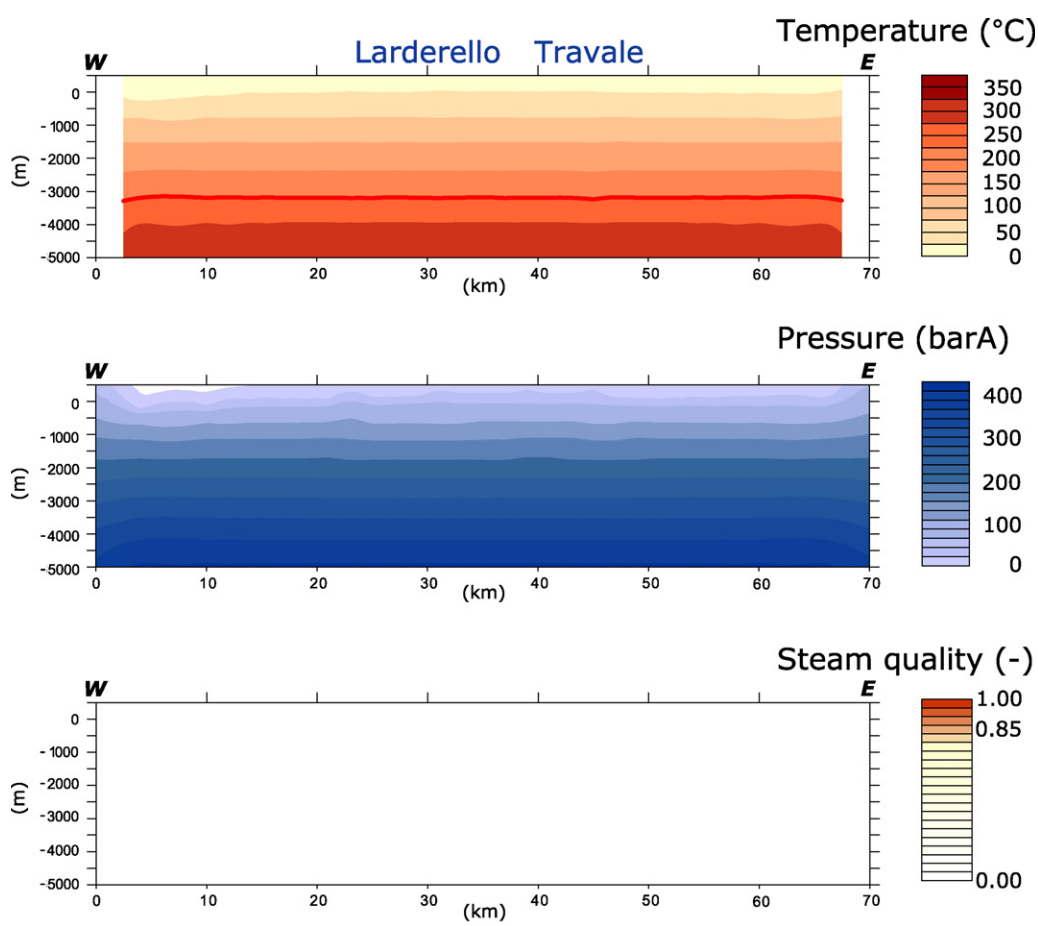

Fig. 16. Temperature, pressure and steam quality distribution along a W–E section before the emplacement of magmatic bodies (~3.0 Ma).

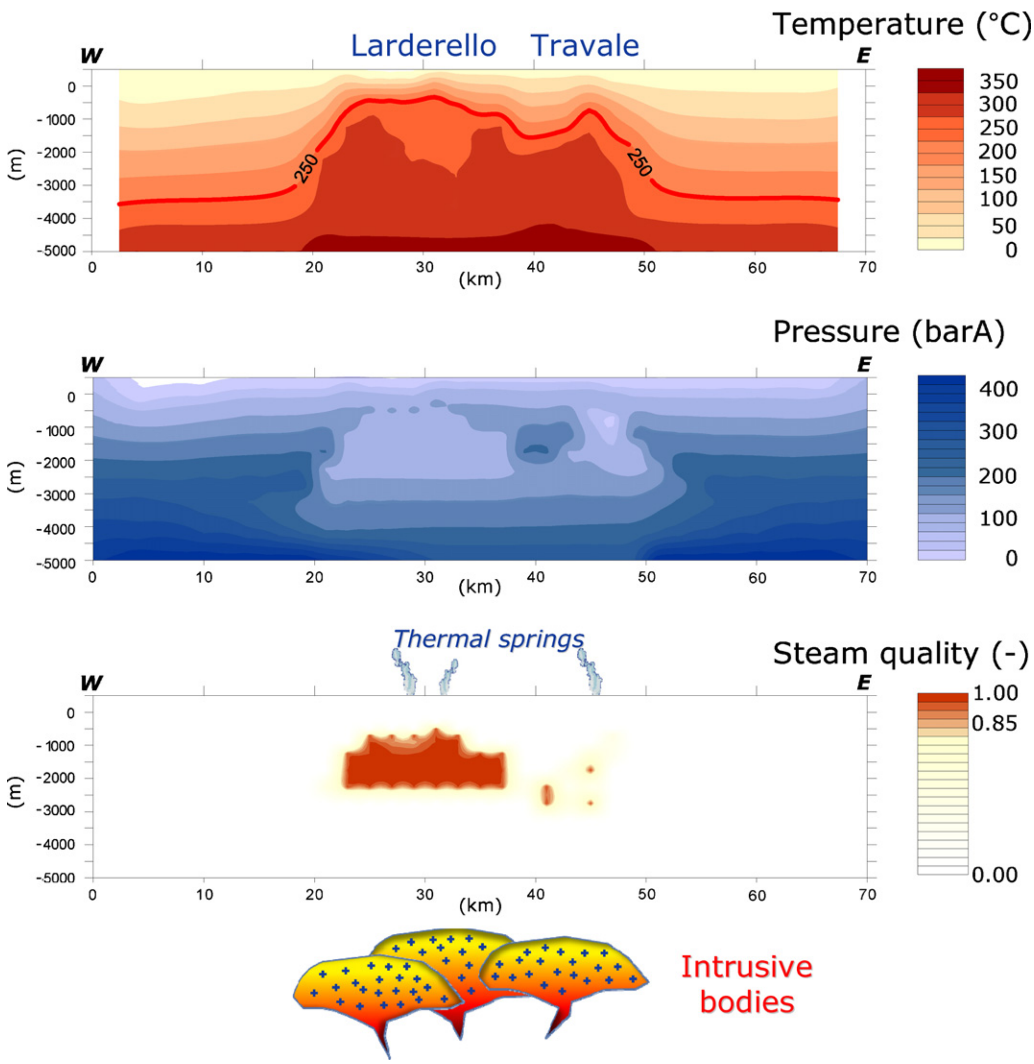

Fig. 17. Temperature, pressure and steam quality distribution along a W–E section after the emplacement of magmatic bodies (3.0–0.5 Ma).

Table 3
Local recharge values adopted for a comparison with the numerical model.

Local recharge area	Total recharge (t/h)
Travale area	90–130
Larderello area	150–210
Val di Cornia area	150–240

5. Natural state simulation

During simulation of the natural state that covers a period of about 3 Ma, the permeability and porosity values were tuned to match the temperature distribution at depth. To verify the reliability of the natural state simulation, the areal distributions of the simulated values of temperature, pressure, and steam quality were compared with the measurements at different depths. Satisfactory agreement was found, particularly for the temperature (Fig. 20). Additionally, simulated well temperature profiles were compared with observed data from the early wells. To this end, the Larderello area (Fig. 21) was subdivided into four zones (Monteverdi, Larderello, Val di Cornia, and Selva) and the Travale area (Fig. 22) into two zones (Travale and Montieri) on the basis of their thermal characteristics.

The total natural manifestations flow rate was calculated to be 120 t/h. This is the same order of magnitude as the estimate based on boric acid production at the beginning of the 20th century. The natural state inflow from the shallow aquifers in the three areas previously considered (Larderello, Travale and Val di Cornia) was computed to be 300 t/h. The evaporation of the surrounding deep aquifer (regional) has been considered in the numerical modeling which guarantees the recharge of the geothermal. The computed natural state simulation was used as the initial condition for production history simulation.

6. Production history simulation and system sustainability

Once a satisfactory match for the natural state was achieved, the same three-dimensional distributions of permeability and porosity, obtained during the natural state simulation, were used to simulate field production history and to predict the future sys-

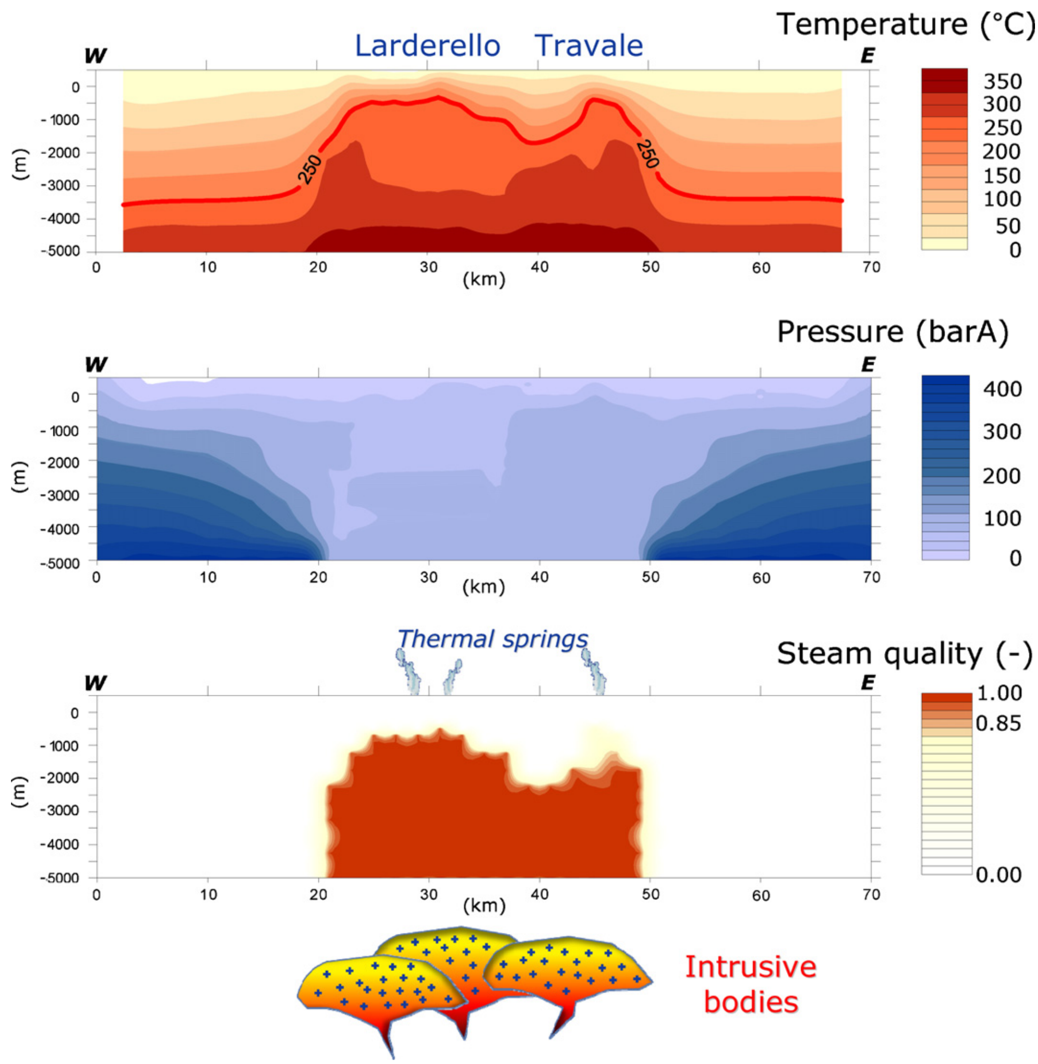

Fig. 18. Temperature, pressure and steam quality distribution along a W–E section before the exploitation of the system (1900).

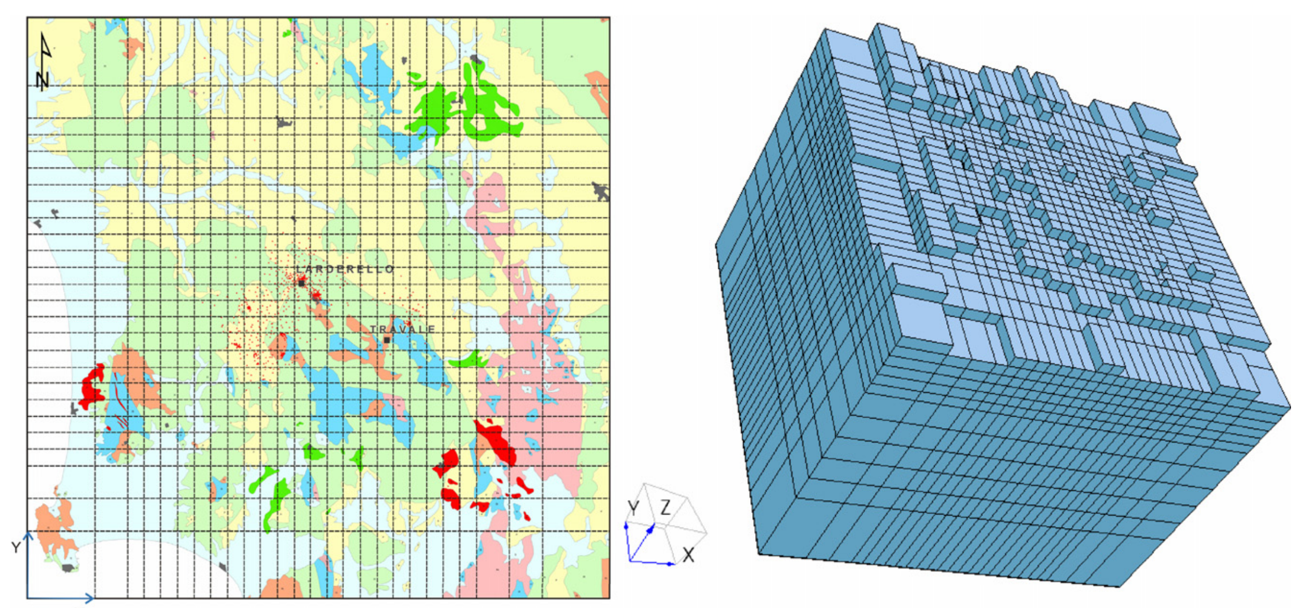

Fig. 19. 2D horizontal and 3D simulation grids.

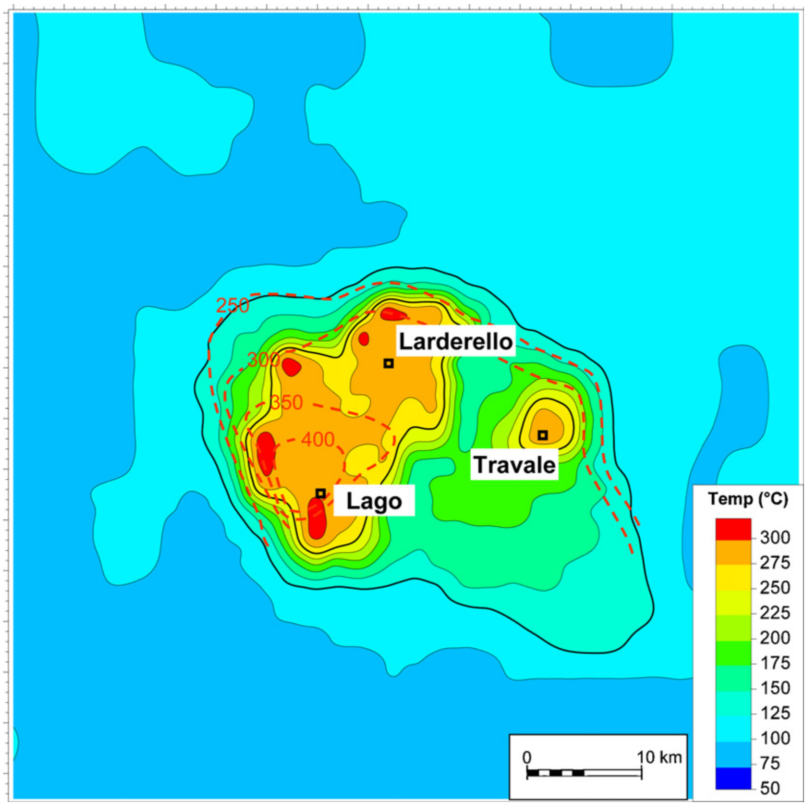

Fig. 20. Observed (dashed lines) and simulated temperature distribution (continuous lines) at 3000 m b.s.l.

tem evolution. The exploitation history was modeled using the production and injection data (1927–2009) collected in more than 700 wells grouped into 20 "virtual" wells accordingly to their location and depth. The system evolution due to production was simulated by comparing the computed pressure decline with the observed pressures obtained from static wellhead measurements (Fig. 23). Fairly good agreement was obtained both for shallow and deep reservoir pressure histories, with the only exception being the shallow Travale reservoir ("Graben") where the simulated pressure is higher than the historical data. This difference is probably due to local permeability variations that cannot be estimated in the framework of a current regional modeling.

The horizontal distributions of the simulated temperature, pressure and steam quality were compared with measurements at different depths, yielding satisfactory results. To quantify the effects of exploitation, the simulation results for temperature and pressure corresponding to the natural state and the present state are compared in Figs. 24 and 25, respectively. Each dot in the graphs represents one of the 625 cells at 3000 m b.s.l. There is only a slight reduction in pressure in cells located inside the reservoir. A pressure draw-down takes place in the central part of the reservoir, while the pressure of the surrounding deep aquifers is only slightly affected. A small pressure decrease can be noticed at the interface between the steam dominated reservoir and the surrounding aquifers. This small pressure decrease causes the evaporation of liquid water near the steam/water interface. No significant temperature variations are evident during exploitation in the reservoir (Cappetti et al., 1995). Only two-phase cells display a sizeable temperature decline because these cells are placed at the boundary between steam reservoir and water aquifers.

Our simulation demonstrates that the contribution of the shallow aquifers, which are separated from the geothermal system by a thick impermeable caprock, is not necessary for sustainable geothermal production. The contribution of the perched aquifers is only local, as they partially feed the geothermal reservoir at small outcrops of carbonate formations. The total local inflow is around 300 t/h, less than 10% of the total production flow rate (Fig. 26). The discharge of the geothermal fluids through natural manifestations decreases with time (Fig. 27) as the reservoir pressure is reduced during exploitation.

In conclusion, the numerical modeling illustrates that only very few changes from the natural state of the geothermal system have been induced by the exploitation (Fig. 28). Good agreement between the measurements and the simulated results for the natural state and the production history allows a confident prediction of the reservoir response to future exploitation. Results show current production from the Travale–Larderello geothermal system is sustainable for at least 100 years.

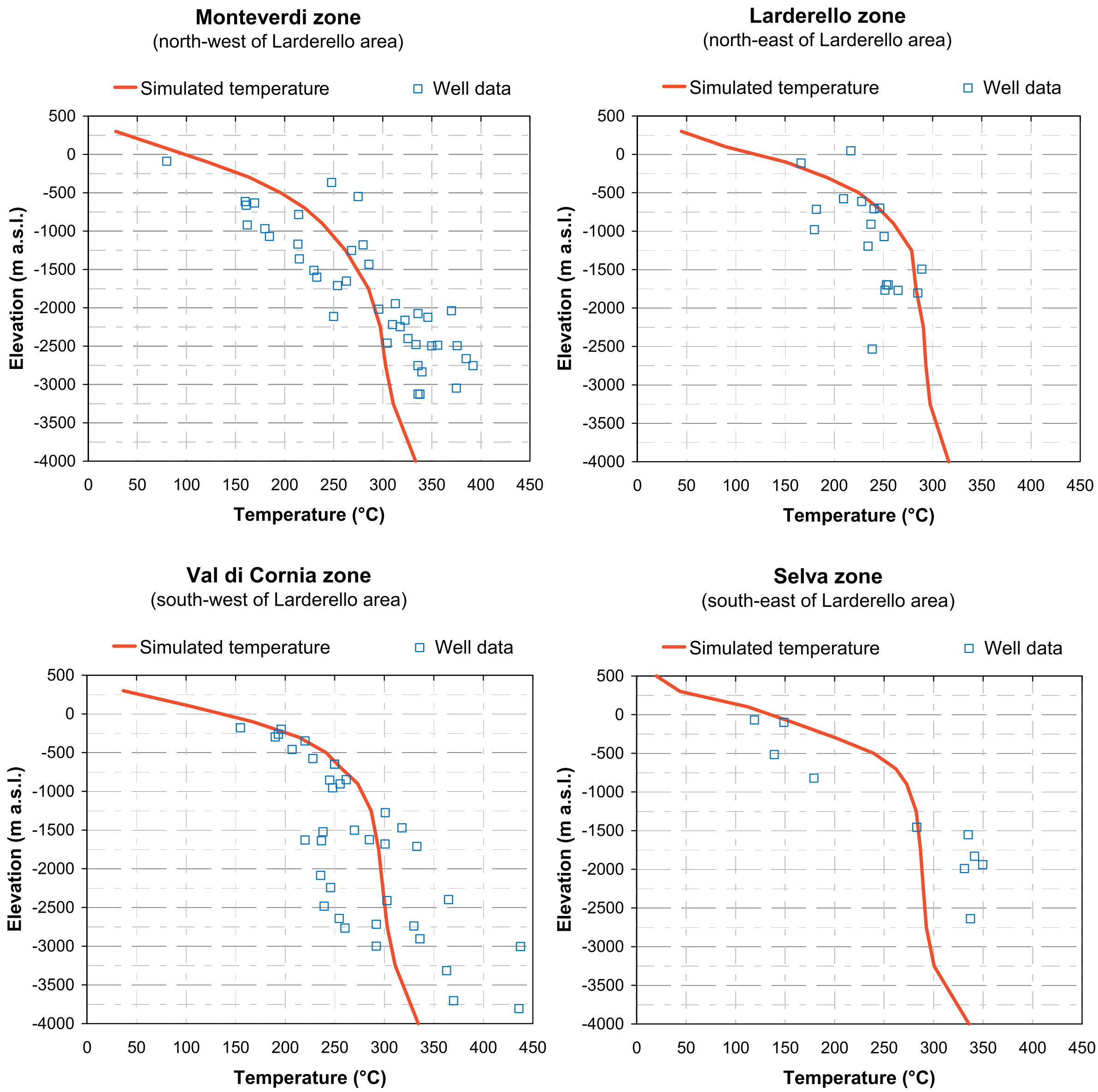

Fig. 21. Observed and simulated well temperature profiles in the Larderello area.

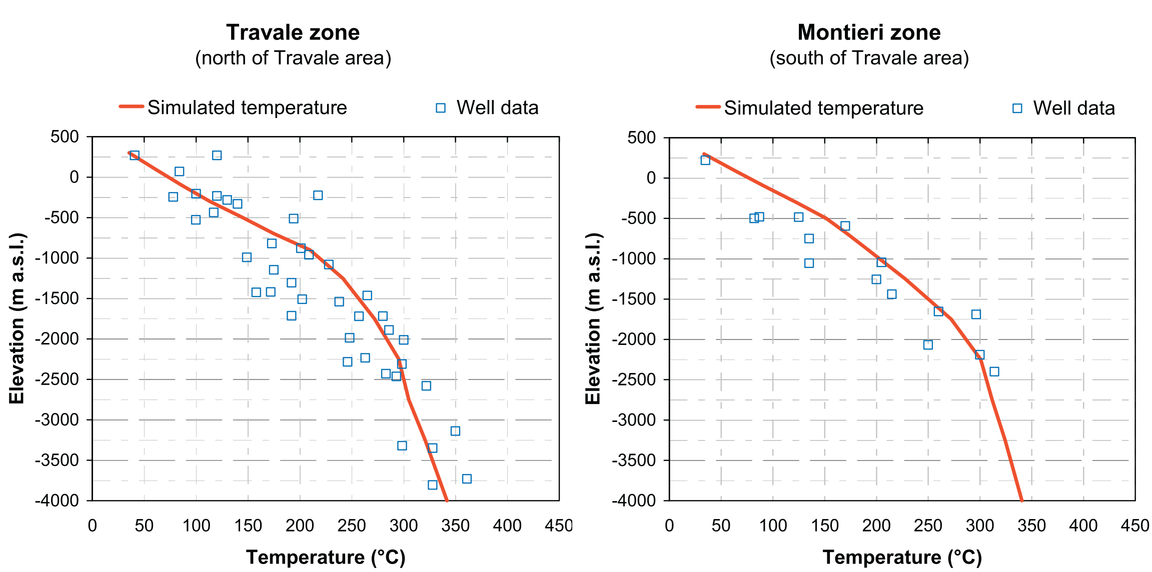

Fig. 22. Observed and simulated well temperature profiles in the Travale area.

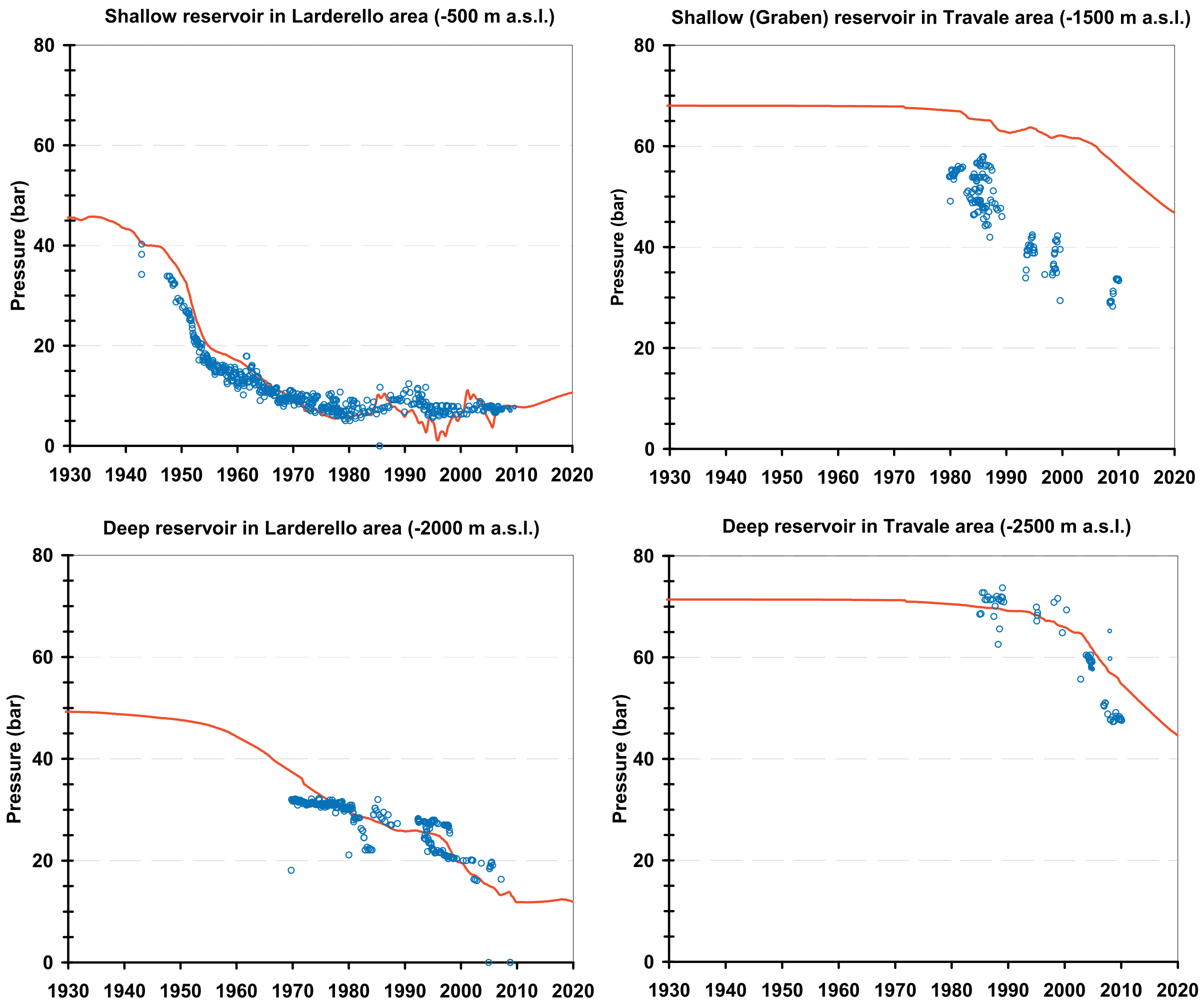

Fig. 23. Observed and simulated pressure decline in the Larderello and Travale reservoirs.

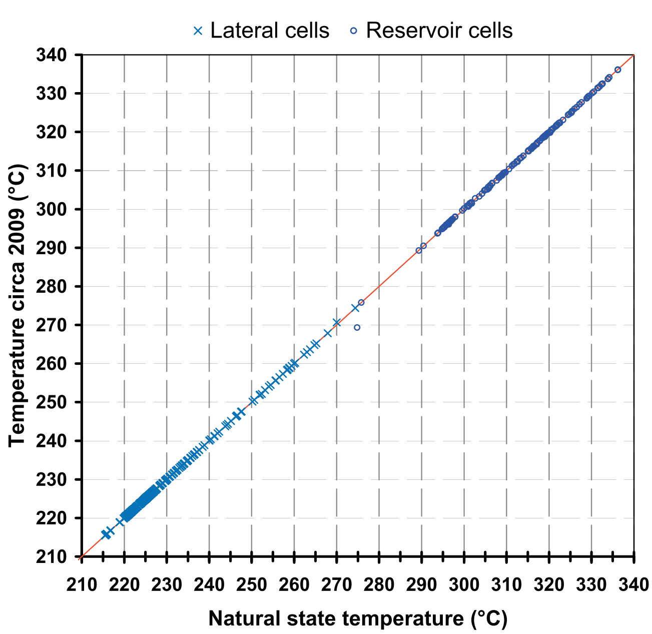

Fig. 24. Comparison between natural and present state temperature at 3000 m b.s.l.

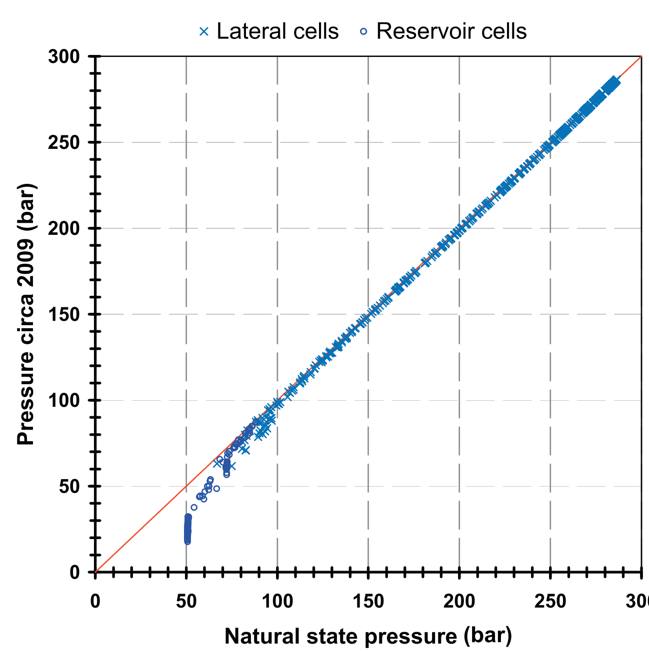

Fig. 25. Comparison between natural and present state pressure at 3000 m b.s.l.

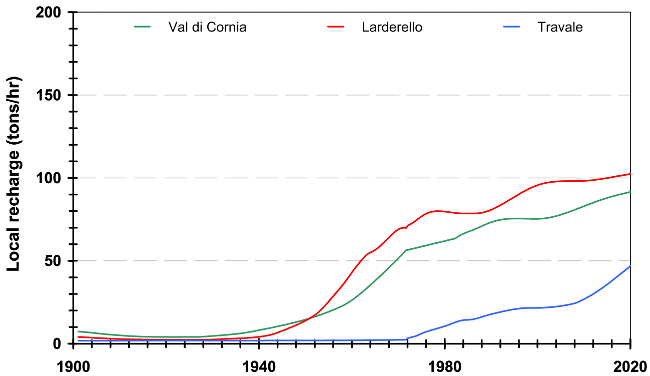

Fig. 26. Simulated system recharge from local influx.

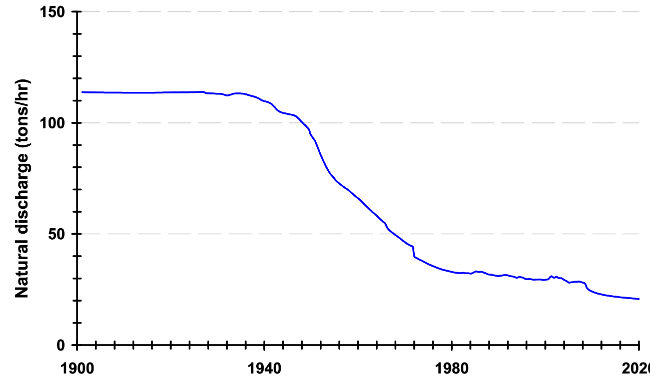

Fig. 27. Simulated total discharges from natural manifestations.

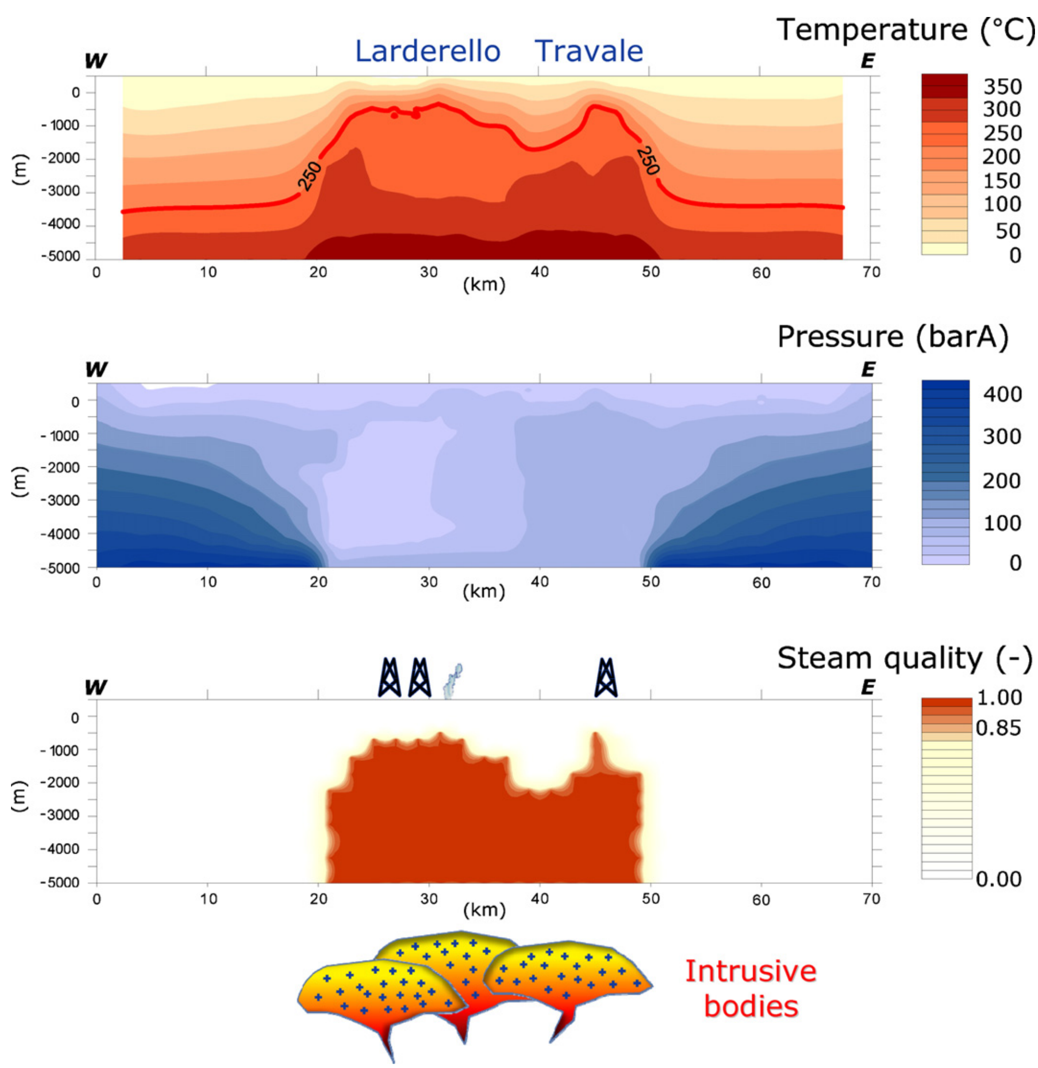

Fig. 28. Simulated temperature, pressure and steam quality distribution along a W–E section at the end of 2009.

7. Conclusions

Based on an updated analysis of all the available geoscientific data from the surface surveys and wells, a numerical model of the Larderello–Travale geothermal system has been developed. The main elements of this model can be summarized as followed:

- A low-permeability caprock consisting of Neogene and Flysch formations, and with thickness ranging from about 200 to 1000 m, overlies the geothermal reservoir.
- The productive geothermal reservoir comprises both carbonate-anhydrite and metamorphic formations. In the central part of the field the reservoir top was inferred from the first fractured level encountered in the wells, while in the peripheral areas, where well data are lacking, it was assumed to be coincident with the 250 °C isotherm which is the temperature at the top of the reservoir.
- The bottom of the geothermal system is taken to be coincident with the K-seismic horizon, since it could correspond to the 400 °C isotherm. A ductile/brittle transition at about 400 °C implies the lack of fracture permeability at greater depths. The depth of K-horizon varies from 8–10 km in the eastern sector of the geothermal system to 3–4 km in the western sector.

All of the above-mentioned elements, as well as the average formation density, porosity, and permeability values have been defined for an area of about 5000 km^2 centered around the geothermal system. Then, a simulation of the field evolution has been carried out for a time interval of about 3 Ma, starting from the emplacement of the magma bodies up to the present. The main results of the numerical modeling are:

- Computed temperature and pressure distributions for the natural state are in fairly good agreement with the observed values. The pressure evolution at different reservoir depths during the exploitation displays satisfactory agreement with the simulation results.
- No significant temperature variations are observed during exploitation, while pressure draw-down is observed in the central part of the geothermal system.
- Generally, the pressure in the surrounding deep aquifers is not affected by production; only a slight pressure decrease, caused by the evaporation of liquid water, is noticed at the interface with the steam dominated reservoir.
- The steam generated by evaporation in the surrounding deep aquifers provides most of the system recharge and explains the enormous productive capacity of the geothermal system; the recharge from local shallow inflows accounts for less than 10% of the total production flow rate.
- A conceptual model, that explains the origin of the steam extracted in almost 100 years of exploitation of the Larderello–Travale system, is for the first time supported by a numerical model. The conceptual model assumes the presence of a two-phase zone along the lateral boundaries between the geothermal reservoir and the surrounding regional water dominated aquifers. The vaporization of the water takes place in response to pressure drop and guarantees the main recharge of the reservoir.
- The numerical model was used to predict the future evolution of the Larderello–Travale geothermal system; the current level of production is sustainable for at least another 100 years. The regional dimensions of the model may limit the accuracy of predictions on a local scale, and more work is needed to refine the model for localized applications.

Current plans include, up-dating the model in the next 3–4 years. If the produced steam flow rate increases significantly, the CO_2 role can be evaluated by using EOS2 equations in the model.

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