Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Numerical Modeling for the Larderello-Travale Geothermal System (Italy)

Antonio Barelli, Maurizio Cei, Ferdinando Lovari and Paolo Romagnoli

via Andrea Pisano, 120 – 56100 Pisa

antonio.barelli@enel.com

Keywords: Numerical modeling, TOUGH2, Larderello, Travale, Italy

ABSTRACT

The Larderello-Travale field was simulated via the three-dimensional numerical model TOUGH2.

This work was mainly aimed at investigating:

- The superheated steam production mechanism;
- The interactions between the geothermal field and the surrounding deep aquifers including their long distance pressure draw-down;
- The field sustainability.

The simulated area is 5000km^2, abundantly covering the geothermal fields of Larderello and Travale, whose area totals “only” 300km^2. This choice was made to evaluate the pressure draw-down induced in the faraway aquifers by production exploitation.

To fulfill the work aims, no constant pressure boundaries (i.e. mass sources) were introduced.

The depth of the domain was set to 7000 m according to a seismic reflection horizon which is believed to represent the reservoir bottom. This bottom is impermeable, but allows the natural heat flow to take place. The reservoir top is modeled as an impermeable layer of rock that acts as a cover. The only interactions with the environment are natural manifestations and some well known shallow aquifers where the cover is absent.

The natural state was successfully simulated assuming a natural manifestation flow-rate of some 10% of the present extraction rate.The rock permeability was tuned to match the initial pressures and temperatures.

The history of the industrial exploitation was then introduced and the resulting pressure distribution was compared with the actually recorded data achieving satisfactory results.

The production mechanism resulted to be not only the steam expansion in the superheated reservoir core, but also and mainly the liquid evaporation in the steam-water contiguous zones.

The field production results to be sustainable at least for the next 100 years.

1. WORK AIMS

The numerical modeling of the Larderello-Travale geothermal system (Figure 1) represents a challenging task, because of both the unhomogeneous permeability and the different field production histories.

Although the producing area is 300km^2 (Bertani et al., 2005), a simulated area of 4900km^2 (70×70km) was chosen so as to include the whole geothermal system and also the surrounding aquifers. This was done to investigate the possible interaction between them.

Another important scope was to explain how a superheated and depressurized geothermal system, with negligible meteoric water recharge, could produce such an enormous amount of steam.

Forecasting the future evolution of field production was an important work aim too.

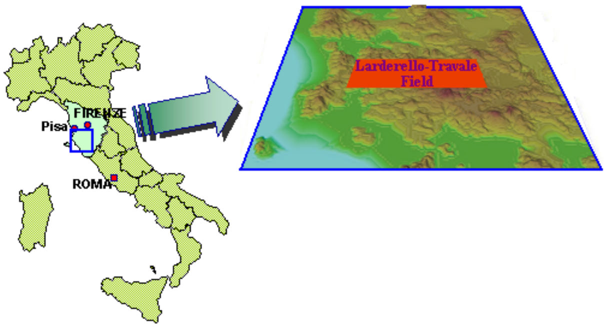

Figure 1: Larderello-Travale field location.

2. HISTORICAL FIELD EXPLORATION

2.1 Larderello field

At Larderello first wells were drilled 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 4km^2 with a high success ratio (82%).

In the following ten years, the exploitation area was doubled with another 69 wells. All these wells tapped the steam carbonate reservoir with a maximum pressure of 32bar (Bertani et al., 2005). From the 1950s to 1980s the drilled area was further extended to about 100km^2.

In the early 1980s, a deep exploration program began with some 3500m wells, which encountered productive layers in the metamorphic basement. This reservoir was characterized by an average pressure of 40bar and 300-350°C temperature (Barelli et al., 1995b). At present the total Larderello production is about 3300t/h.

2.2 Travale field

The geothermal exploitation of the Travale field began in the early 1950s when some 20 wells were drilled to the depth of a few hundred meters near the natural manifestations, in a water-dominated system (Barelli et al., 1995a; Batini et al., 2003). Production caused the surface manifestations to disappear and triggered the inflow of meteoric water causing these wells to be soon watered out.

In the 1970s, the exploration was extended northward aiming at a deeper and hotter reservoir, named "Horst". The permeable rocks were met at a depth of 500-1000m in carbonate formations with a pressure of 60bar and a temperature of 280°C (Barelli et al., 1995a). These formations hosted a steam-dominated system. This reservoir and the previous water-dominated one are somehow interconnected.

At the beginning of the 1980s, the exploitation was extended further northwards to a deeper layer (1300-2000m), named "Graben" (Barelli et al., 1995a). This reservoir had an initial reservoir pressure of about 60bar and experienced a continuous flow-rate decline without substantial changes in steam quality and gas content.

After 1992, some 4000m deep wells were drilled in an extended area, investigating a deeper reservoir hosted in the metamorphic basement and in the granite intrusions. The abundant reservoir fluid was superheated steam with an initial pressure of 70bar, in vaporstatic equilibrium with the previously discovered reservoirs (Barelli et al., 1995b). The temperature has been about 300°C-350°C.

The good results of the deep exploration allowed for an increase of steam production up to 1000t/h.

3. NUMERICAL MODELLING OF LARDERELLO-TRAVALE GEOTHERMAL FIELD

Larderello-Travale field was simulated via the three-dimensional numerical simulator TOUGH2, which is a general-purpose code for multi-dimensional fluid and heat flows of multiphase, multicomponent fluid mixtures in porous and fractured media (Pruess et al., 1999)

The simulated area covers about 5000km^2 in southern Tuscany. This area has been chosen substantially larger than the producing geothermal area (Figure 2) in order to obtain results independent from the assumed boundary conditions.

3.1 Larderello-Travale Conceptual Model

Larderello-Travale geothermal system is a superheated dominated one. The main hydrogeological features are: a clayey-shaley cap rock (from 0m to 500m), a fractured carbonatic formation (from 500m to 1000m), a metamorphic basement (from 1000 to 3000m) and granite intrusion.

At depths greater than 3000m, Larderello and Travale are part of a one only geothermal system root at 300-350°C (Barelli et al., 1995b). However, during model tuning, a low permeable sect has been inserted between Larderello and Travale areas to simulate the peculiar pressure response to exploitation.

The boundaries between the high-permeability reservoir core and the low-permeability deep surroundings geothermal aquifers (aquicludes) have been identified with the 250°C isotherm, which is believed to be the minimum possible reservoir temperature.

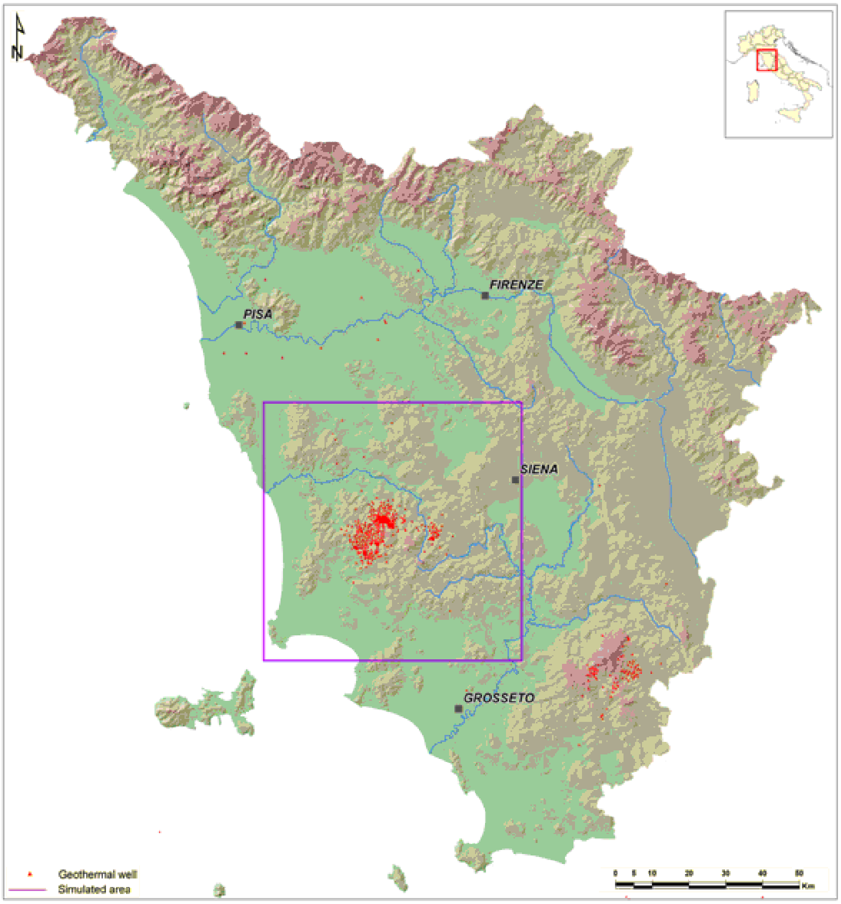

Figure 2: Larderello-Travale simulation domain.

The recharge of the superheated reservoir core may occur through these aquicludes. A two-phase zone is envisaged between the superheated reservoir and the water-dominated boundaries. In this way, the natural liquid water, which is present in the deep aquicludes, can recharge the reservoir in response to the pressure drop induced by exploitation.

3.2 Geological schematizations for the Larderello-Travale field

In this numerical modeling some geological features have been used as an input. The field geology is described in a companion paper (Arias et al., 2010, in press). The geological schematization used in this paper is described below:

- COVER – The reservoir cover is made of Neogene sediments in flysh facies. Cover thickness vary from 200m in the central part of the reservoir to 1000m in the external zones. Its permeability is practically null;
- INTERMEDIATE LAYER – Due to the lack of fractures in the field periphery, the rocks are not very permeable in the uppermost part of the potential reservoir as a whole. These volumes have been given a low permeability value. The boundary between these unproductive layers and the actual reservoir has been identified with the first fractured layer encountered by drillings. Where this information is lacking, the 250°C isotherm was adopted.
- GEOTHERMAL RESERVOIR – Different values of permeability have been used according to well testing results. The reservoir bottom is identified by the K-horizon and it is impermeable;
- K HORIZON – K horizon is believed to be the reservoir bottom, because it could be associated to the 400°C isotherm which could hinder fracturation. K horizon depth varies between 3000-4000m in the western zone and 8000-10000m in the Travale area (Bertini et a.l, 2006). To allow heat flow, but avoid the mass flow from the bottom, the K horizon has been modeled with fixed temperature cells, associated with no permeability rocks;
- LATERAL BOUNDARIES – Outside the geothermal reservoir, low permeability zones have been introduced. Its permeability and porosity have been calculated using the peripheral wells draw-down.

In total, 16 rock types have been used in this simulation.

3.3 Interactions with the environment

The only interactions between the geothermal reservoir and the environment are the natural manifestations and some well-known shallow aquifers where the cover is absent.

As for the natural manifestations, three permeable blocks were introduced to allow for their flow rate. Their productivity index (PI) has been chosen to match the estimated historical production.

As for the shallow aquifer interactions, some cells with imposed constant pressure have been introduced where are reservoir outcrops (Barelli et al., 1995b; Ceccarelli et al., 1987).

3.4 Domain and Simulation Grid

The simulation grid is made of about 10000 cells, subdivided into 16 vertical layers. The simulation area is 4900 km2 (70×70 km) and total vertical thickness is nearly 7500 m (from +500 m a.s.l. to -7000 m a.s.l.).

Each horizontal layer is formed by 25×25 cells with different sizes. A greater details is necessary in the inner simulation domain where cell size is 2×2 km. In the bordering area, 8×8 km cell size has been adopted (Figure 3). The cell thickness varies with depth; the deeper cells are some thousand meters thick, while the shallow ones are only 200 m (Figure 4).

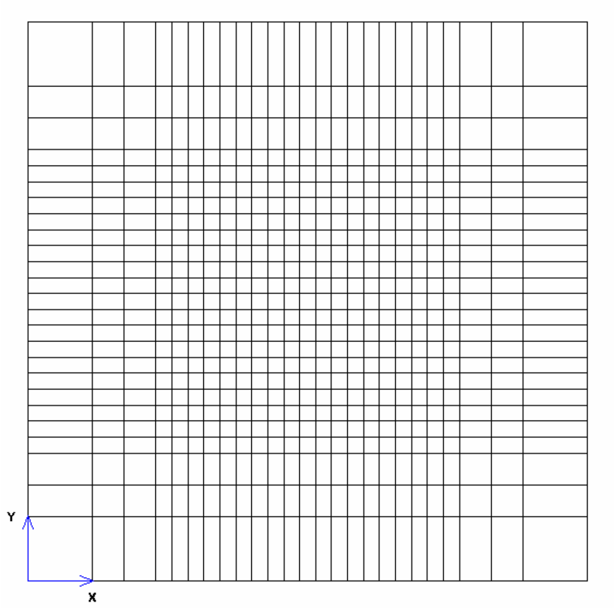

Figure 3: Simulation horizontal layer.

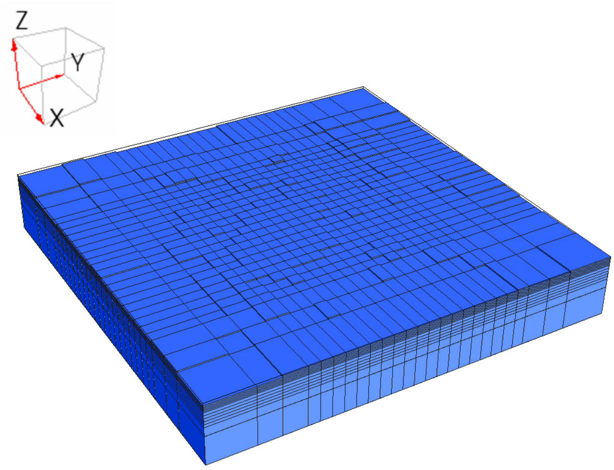

Figure 4: 3D simulation grid.

3.5 Boundary Conditions

To simulate Larderello-Travale geothermal field, no-mass sources have been introduced as boundary conditions. Consequently, all the borders have been set as no-flow boundaries. However, the distance from the producing area is so large that this choice has little impact on the results. The results of the natural-state simulation have been used as the initial condition for production history simulation.

At the top and bottom of the simulation grid, boundary conditions have been imposed as fixed temperatures.

As for the bottom cells, where the reservoir is present, temperatures vary between 250 °C and 320 °C, according to temperature distribution data. Outside the producing reservoir, the bottom temperature is defined by a natural gradient.

4. NATURAL STATE SIMULATION

Model tuning in the natural state was based on comparison between simulated and actual temperature and pressure distributions. Simulated temperature, pressure and steam quality distributions have been obtained by modeling Larderello-Travale natural state, while the actual data come from static temperature and pressure well profiles.

During model tuning, rock parameters such as porosity and permeability were changed to optimize the simulation. These three-dimensional distributions were subsequently used to simulate field production history and to evaluate the future system evolution.

In order to simulate the natural state, the thermal evolution of Larderello-Travale system has been reconstructed from the time of the magmatic intrusion to historical times. In the initial condition of this propedeutic simulation ($3.5\text{-}0.5\times10^6$ years), temperature and pressure gradients were respectively the average earth temperature gradient and hydrostatic pressure. The whole reservoir volume was initially filled with liquid water (Figure 5).

The magmatic intrusion prompted reservoir temperatures to increase and pressure began to decrease because of the onset of natural manifestations. Initially the vaporization process took place initially at the reservoir top (Figure 6), and then spread all over the reservoir volume (Figure 7).

During this phase (Figure 6), the two main reservoirs (Larderello and Travale) differentiated from the surrounding aquicludes. These latter underwent a lesser temperature increase and, in general, were also depressurized to a lesser degree. The extent of such phenomena was an inverse function of the distance from the reservoir.

Natural manifestations produced a complete reservoir vaporization (Celati et al., 1975) prior to the beginning of the industrial exploitation (early 1900s).

To check the reliability of the natural state simulation, the simulated and observed temperature and pressure horizontal distributions have been mapped at different depths, yielding satisfactory results. The comparison between simulated vertical temperature profiles and well data has been made subdividing the Larderello area (Figure 8) into four zones (Monteverdi, Larderello, Val di Cornia and Selva) and the Travale area (Figure 9) into two zones (Travale and Montieri) on the basis of their thermal characteristics.

Natural state three dimensional distributions of temperature, pressure and steam quality are shown in Figure 10, Figure 11 and Figure 12. For a better visualization of these figures, vertical dimension (z axis) is exaggerated by a factor of 5.

Total natural manifestation flow rate resulted to be 120t/h, in accordance with the order of magnitude estimated on the basis of boric acid production at the beginning of the 20th century, while the natural state inflow from the three well-known aquifers resulted to be some 30t/h. The remaining 90t/h were supplied by evaporation of liquid water which was present in deep confining aquicludes. The relevant heat flow which was needed for water vaporization was supplied by the magmatic body through the bottom boundary.

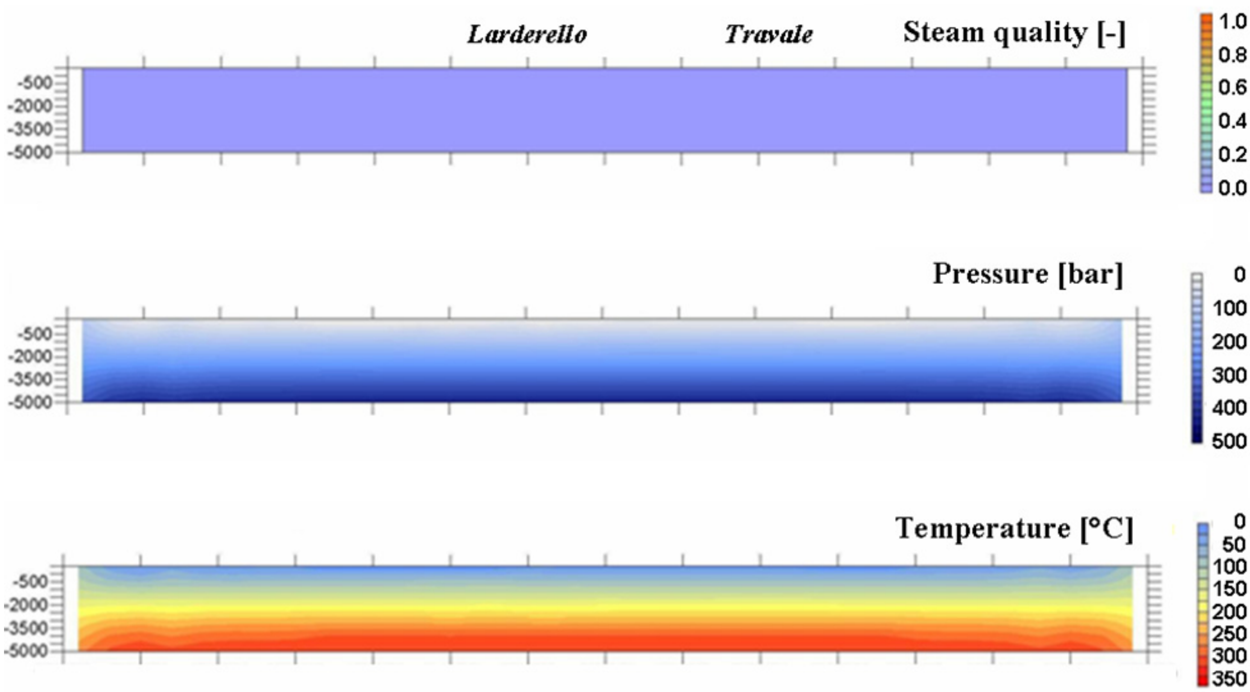

Figure 5: Steam quality, pressure and temperature distributions before the intrusion of the magmatic body.

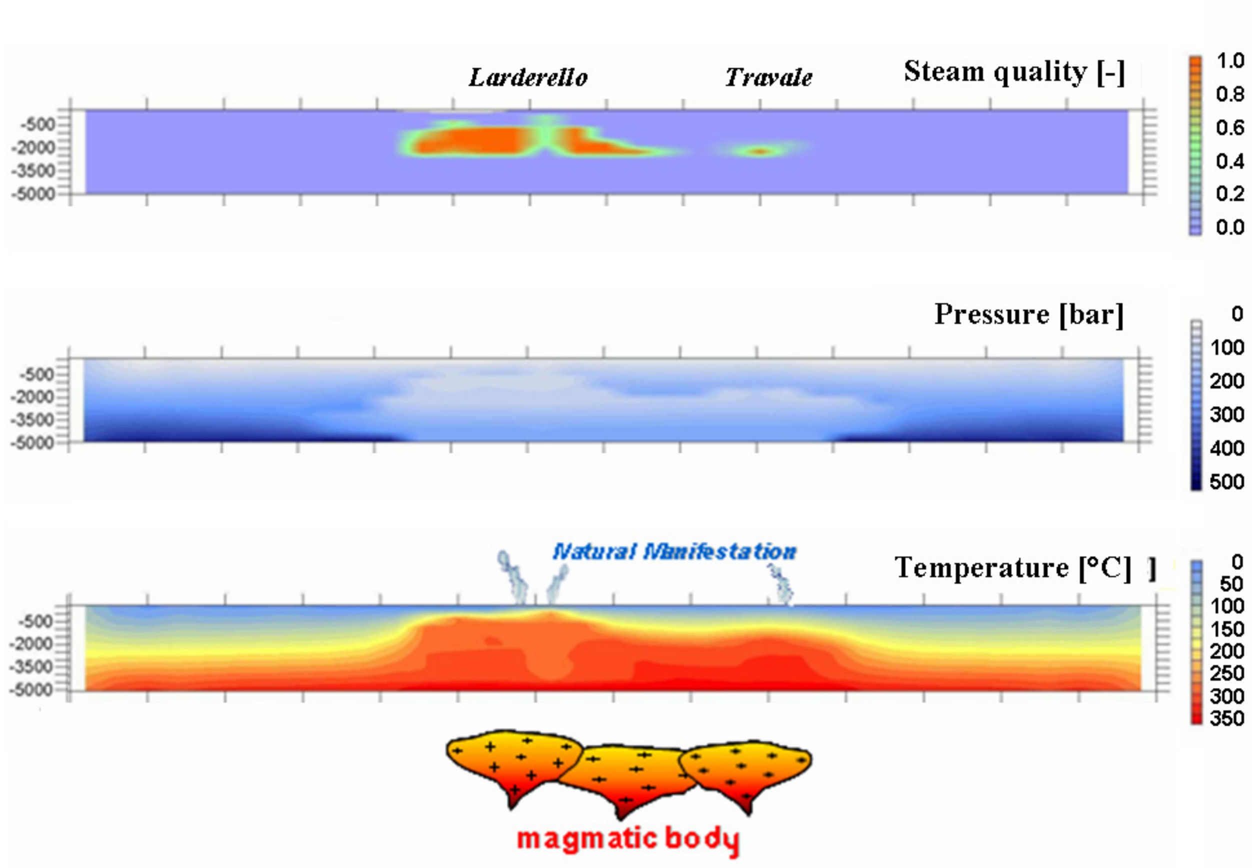

Figure 6: Steam quality, pressure and temperature distributions after the intrusion of the magmatic body.

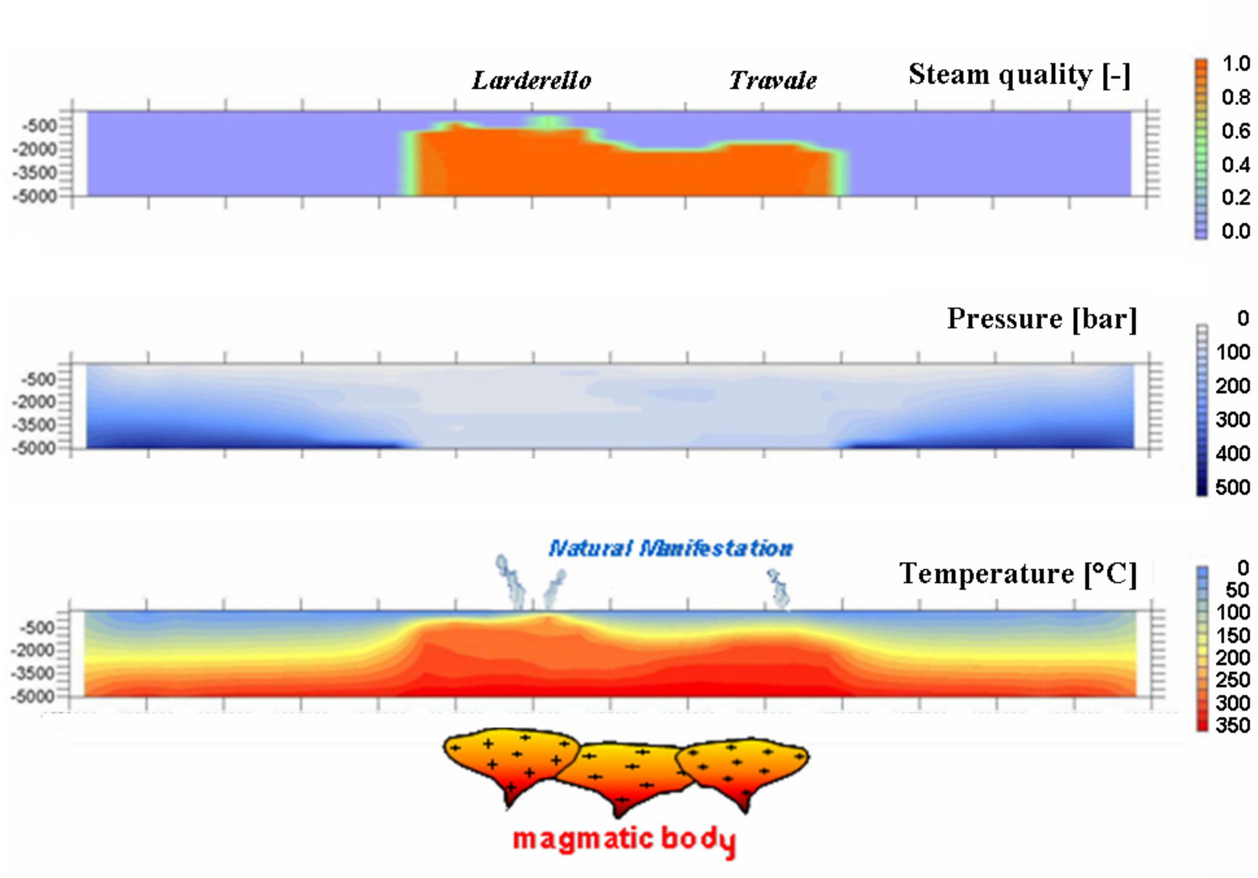

Figure 7: Steam quality, pressure and temperature distributions at natural state.

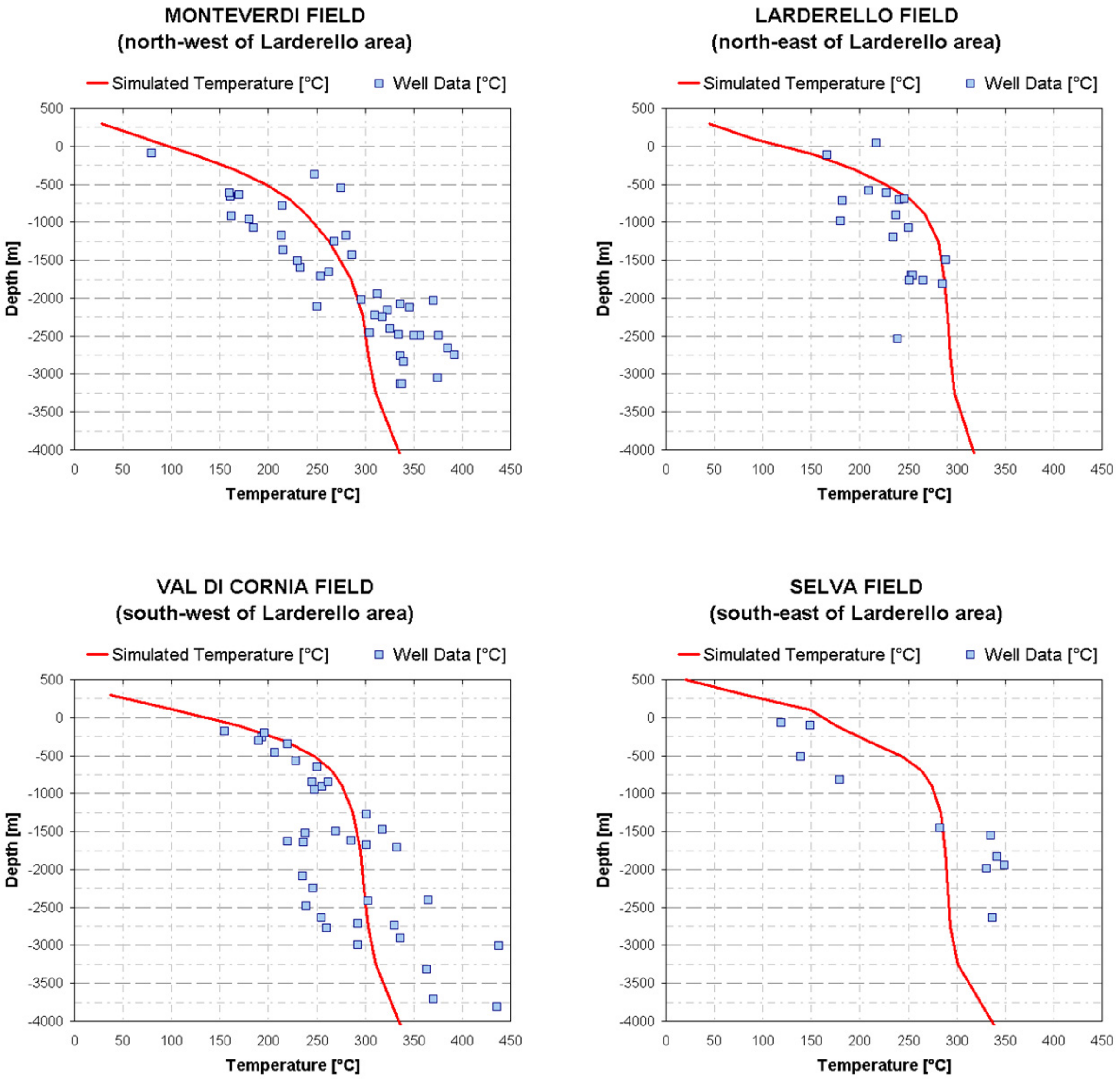

Figure 8: Simulated and observed temperature vertical profiles for Larderello area.

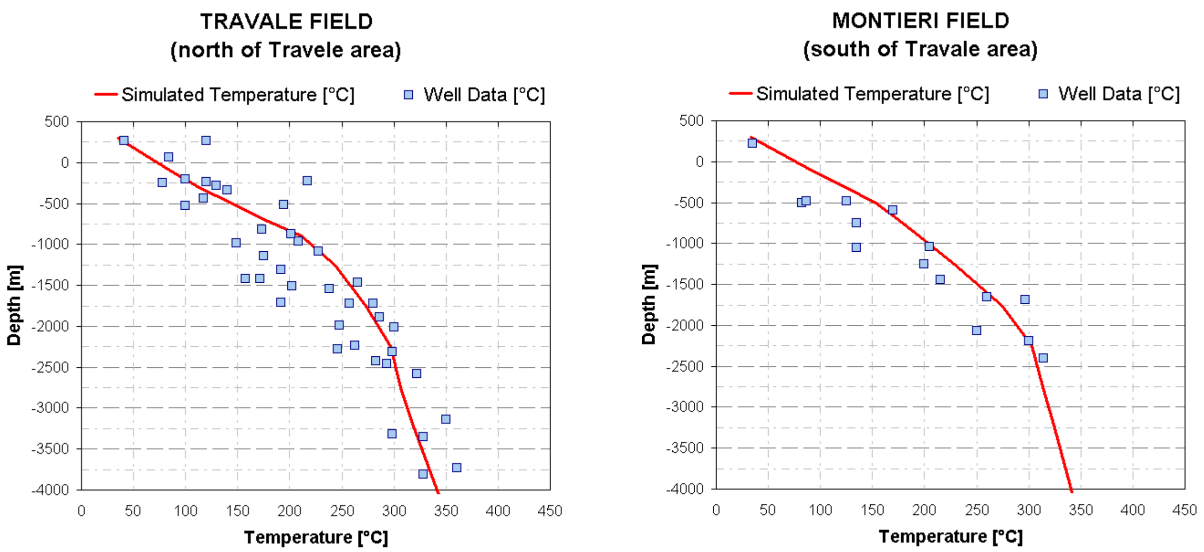

Figure 9: Simulated and observed temperature vertical profiles Travale area.

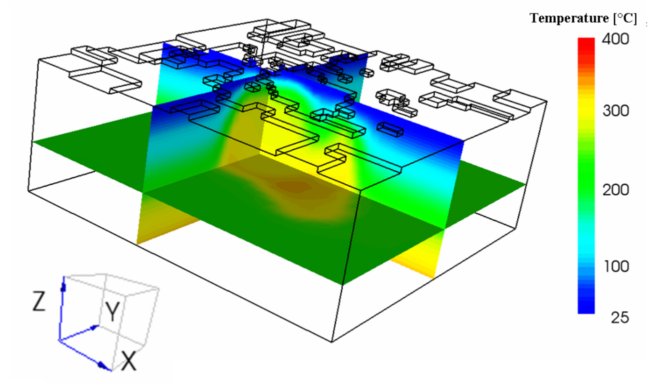

Figure 10: Temperature 3D distribution for natural state (vertical dimension is exaggerated by factor of 5).

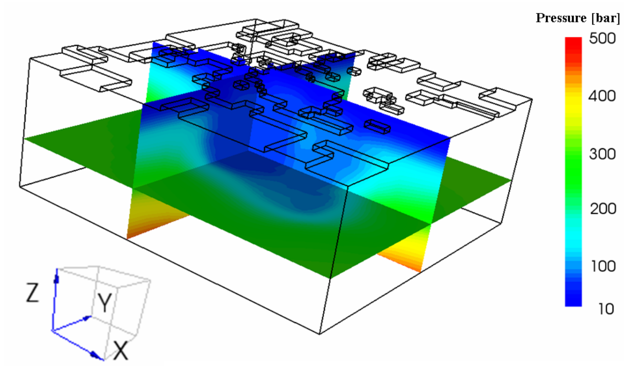

Figure 11: Pressure 3D distribution for natural state (vertical dimension is exaggerated by factor of 5).

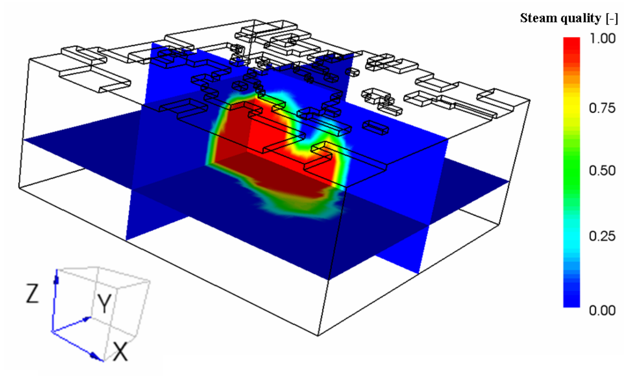

Figure 12: Steam quality 3D distribution for natural state (vertical dimension is exaggerated by factor of 5).

5. PRODUCTION HISTORY SIMULATION

Once a satisfactory match for the natural state was achieved, the industrial production was simulated.

The main objectives of this simulation were to develop a numerical model which could simulate the observed data for about 80 years of production and reiniection (from 1927 to 2008) and to analyze the reservoir behavior during industrial exploitation. Once a plausible numerical model of the Larderello-Travale system has been developed, it was used to envisage future development scenarios and to assess their sustainability. For sake of simplicity the productive wells (more than 100) have been grouped in some equivalent ones (about 20 wells) according to their location.

The simulated decline in field pressure was compared with the data (Figure 13). To improve the match, slight variations of rock parameters were introduced.

Fairly good results have been obtained both for shallow reservoir pressure histories and for deeper ones, with the only exception of the deep Travale area, where the simulated pressure resulted a little higher than the historical data. This is probably due to the fact that the data were relevant to wellhead, whilst the simulated ones were relevant to the actual depth. The difference is due to the weight of the steam/gas column which, in this case, is not negligible.

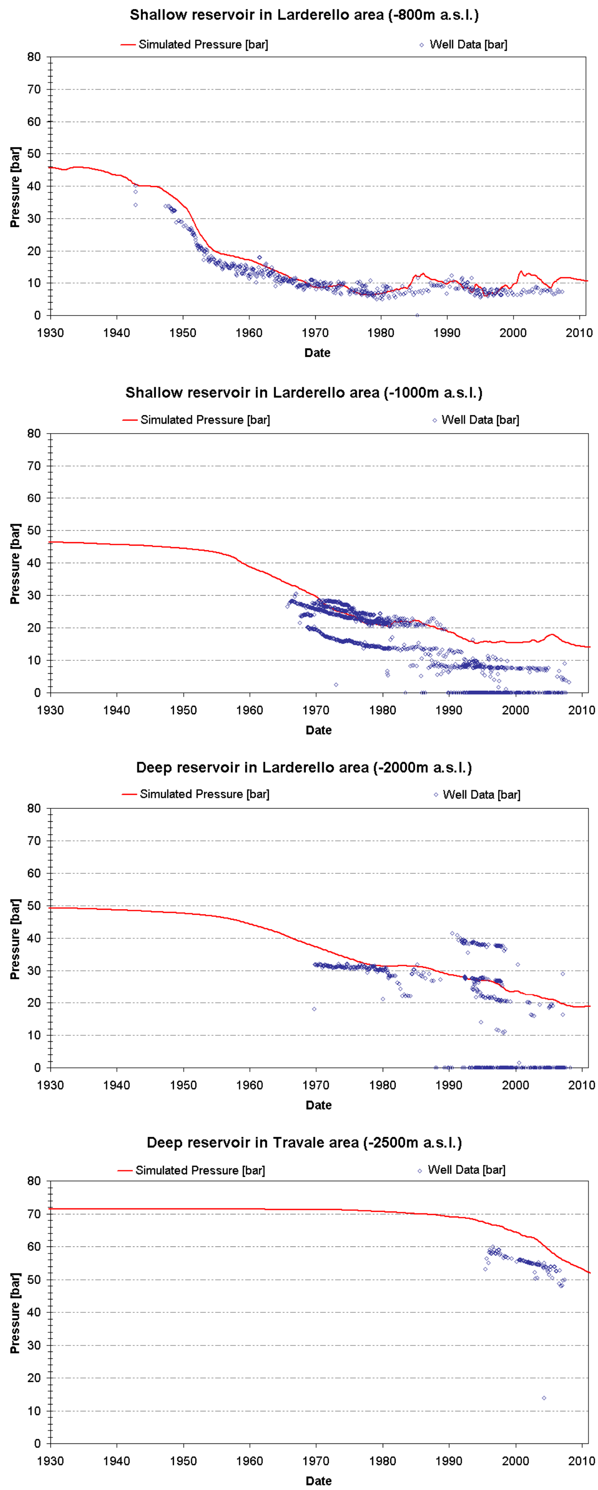

Figure 13: Well pressure evolution with time.

6.1 General results and future field performance

The most important achievements resulting from production history match are:

- No significant temperature variations are evident during industrial exploitation in the reservoir core (Cappetti et al., 1995). Natural state and present temperatures at -3000m depth are very close (Figure 14). Only two-phase cells display a sizeable temperature loss because they are placed at the boundary between steam reservoir and water aquicludes. In these zones, steam is generated at the expenses of the rock sensible heat. This observation gives an insight into the production mechanism. At the reservoir top, where reiniection takes place, temperatures locally decrease substantially. In these spots too, steam is generated by means of the heat supplied by rocks.

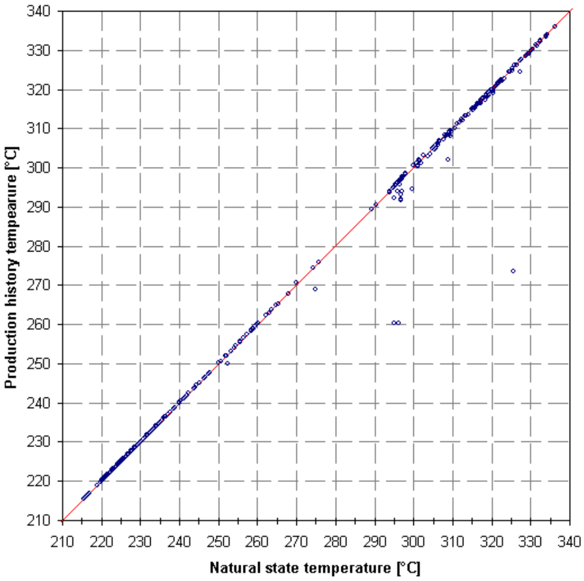

Figure 14: Temperature comparison between natural state and production history at -3000m depth.

- A pressure draw-down takes place in the central part of the reservoir, while the pressure of the surroundings deep aquicludes pressure is only very slightly affected: only a small pressure decrease can be noticed at the interface between the steam dominated reservoir and the surrounding aquicludes. This pressure decrease causes the evaporation of liquid water in the nearness of the steam dominated reservoir. Natural state and present pressures for each cell at -3000m depth are shown in Figure 15.

- Our simulation demonstrated that the geothermal production does not need the contribution of the potable aquifers which are not involved in the recharge mechanism. They are also separated from the geothermal system by a thick impermeable layer of cap rock.

- The reservoir is fed only by three well-known aquifers in correspondence of local outcrops of carbonate formations at a depth of some 500m. Their total flow resulted around 300t/h, less than 10% of total production flow rate.

- Natural discharge of geothermal fluid through fumarolic areas became less and less important with time (Figure 16) because of the reduction in reservoir pressures during exploitation.

- The good results, achieved by the simulation of natural state and the production history, have allowed a confident prediction of the future exploitation. Current production resulted to be sustainable for at least 100 years.

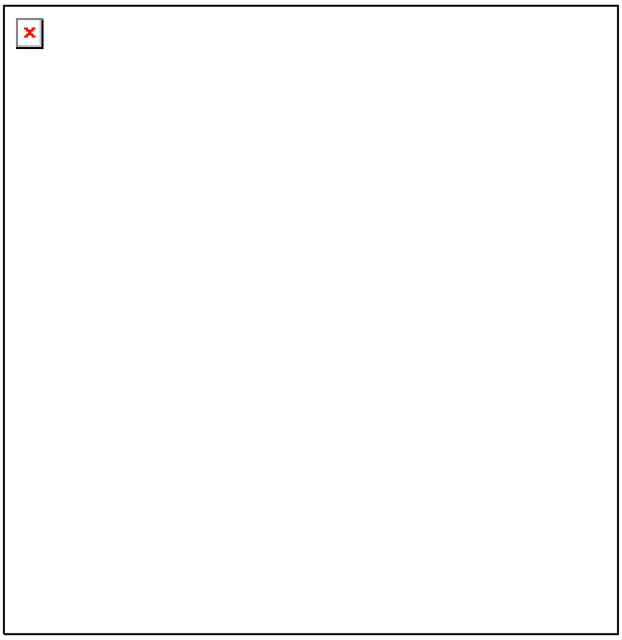

Figure 15: Pressure comparison between natural state and production history at -3000m depth.

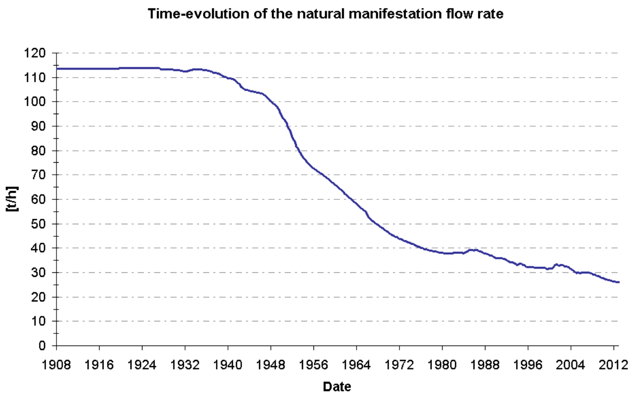

Figure 16: Natural manifestation flow rate with time during industrial exploitation.

6. CONCLUSIONS

A successful simulation of the field evolution from the emplacement of the magmatic body to present (3 million years) has been carried out.

Temperature and pressure distributions in the simulated natural state fit reasonable well with data.

Fairly good results have been obtained from the comparison between the simulated and observed pressure evolution at different reservoir depths during the industrial exploitation. Horizontal temperature distributions obtained by production history simulation have shown that no significant temperature variations are apparent during industrial exploitation. On the contrary, pressure draw-down is sustained in the central part of the reservoir.

The pressure of the surrounding deep aquicludes are not generally affected by production, but a slight pressure decrease can be noticed at the interface between the steam dominated reservoir and the surrounding aquicludes. This is caused by the evaporation of liquid water in the nearness of the steam dominated reservoir. This steam generation supplies most of the system recharge explaining the enormous productive capacity of the geothermal system.

This numerical simulation has allowed understanding the geothermal processes that are at the basis of the continuous steam production in the Larderello-Travale system.

The good simulation results have allowed the prediction of future evolution. Field exploitation resulted sustainable for at least 100 years.

REFERENCES

Arias, A., Dini, I., Casini, M., Fiordalisi, A., Perticone, I., and Dell'Aiuto, P.: Geoscientific feature update of the Larderello-Travale geothermal system (Italy), for a regional numerical modeling *Proceedings*, World Geothermal Congress, Bali, Indonesia (2010), in press.

Barelli, A., Bertani, R., Cappetti, G., and Ceccarelli, A.: An update on Travale – Radicondoli geothermal field, *Proceedings*, World Geothermal Congress, Florence, Italy (1995a).

Barelli, A., Cappetti, G., and Stefani, G.: Results of deep drilling in the Larderello-Travale/Radicondoli geothermal area, *Proceedings*, World Geothermal Congress, Florence, Italy (1995b).

Barelli, A., Bertini, G., Buonasorte, G., Cappetti, G., and Fiordelisi, A.: Recent deep exploration results at the margins of the Larderello-Travale geothermal system, *Proceedings*, World Geothermal Congress, Kyushu-Tohoku, Japan, (2000).

Batini, F., Bertini, G., Gianelli, G., Pandeli, E., and Puxeddu, M.: Deep structure of the Larderello field: contribution from recent geophysical and geological data, *Soc. Geol. Ital. Mem.*, **25**, (1983), 219–235.

Batini, F., Brogi, A., Lazzarotto, A., Liotta, D., and Pandeli, E.: Geological features of the Larderello-Travale and Mt. Amiata geothermal areas (southern Tuscany, Italy), *Episodes*, **26**, (2003), 239-244.

Bertani, R.: World Geothermal power generation in the period 2001-2005, *Geothermics*, **34**, (2005), 651-690.

Bertani, R., Bertini, G., Cappetti, G., Fiordelisi, A., and Marocco, B.M.: An update of the Larderello-Travale/Radicondoli deep geothermal system. *Proceedings*, World Geothermal Congress, Antalya, Turkey (2005).

Bertani, R.: World Geothermal Generation in 2007, *Proceedings*, European Geothermal Congress, Unterhaching, Germany, (2007).

Bertini, G., Casini, M.. Gianelli, G., and Pandeli E.: Geological structure of a long-living geothermal system, Larderello, Italy, *Terra Nova*, **18**, (2006), 163-169.

Bjornsson, G., Hjartarson, A., Bodvarasson, GS., and Steingrimsson B.: Development of 3-D geothermal reservoir model for the greater hengill volcano in sw-iceland, *Proceedings*, Tough Symposium 2003, Lawrence Berkeley National Laboratory, Berkeley, California (2003).

Bodvarsson, G.S., Lippmann, M.J., and Pruess K.: Modeling of Geothermal Systems. Geothermal Resources Council. - Vol. 23, n.4, pp. 144-160. (1994).

Buonasorte, G., Cataldi, R., and Passaleva, G.: Geothermal development in Italy: from Present to Future, *Proceedings*, European Geothermal Congress, Unterhaching, Germany (2007).

Cappetti, G., and Stefani, G.: Strategies for sustaining production at Larderello, *Transactions*, Geothermal Resources Council, Salt Lake City, U.S.A., (1994).

Cappetti, G., Parisi, L., Ridolfi, A., and Stefani, G.: Fifteen years of reinjection in the Larderello-Valle Secolo area: analysis of the production data. *Proceedings*, World Geothermal Congress, Florence, Italy (1995).

Cappetti, G., Fiordelisi, A., Casini, M., Ciuffi, S., and Mazzotti, A.: A new deep exploration program and preliminary results of a 3D seismic survey in the Larderello-Travale geothermal field (Italy), *Proceedings*, World Geothermal Congress, Antalya, Turkey (2005).

Ceccarelli, A., Celati, R., Grassi, S., Minissale, A., and Ridolfi, A.: The southern boundary of Larderello Geothermal field, *Geothermics*, **16**, (1987), 505-515.

Celati, R., Squarci, P., Taffi, L., and Stefani, G.C.: Analysis of water levels and reservoir pressure measurement in geothermal wells, *Proceedings*, 2nd U. N. Symposium on the Development and Use of Geothermal Resources, San Francisco, CA (1975).

Celati, R., Cappetti, G., Calore, C., Grassi, S., and D'Amore, F.: Water recharge in Larderello geothermal field, *Geothermics*, **20**, (1991), 119-133.

Fiordelisi, A., Moffat, J., Ogliani, F., Casini, M., Ciuffi, S., and Romi, A.: Revised Processing and Interpretation of Reflection Seismic Data in the Travale Geothermal Area (Italy), *Proceedings*, World Geothermal Congress, Antalya, Turkey (2005).

Pruess, K.: TOUGH2-A general purpose numerical simulator for multiphase fluid and heat flow, Lawrence Berkeley Laboratory report LBL-29400 .(1991).

Pruess, K., Oldenburg, C., and Moridis, G.: TOUGH2-User's Guide, Version 2.0, Lawrence Berkeley Laboratory report LBNL-43134 (1999).