Numerical Modeling for Resource Management at Ribeira Grande, São Miguel, Azores, Portugal

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ABSTRACT

A numerical simulation model of the Ribeira Grande geothermal reservoir, São Miguel Island, Azores, has been developed to support the ongoing development and management of the resource for generating electric power. This model has been calibrated using data obtained since startup, including the results of new deep wells drilled during 2005, operations of the Ribeira Grande and Pico Vermelho power plants, logging, testing and sampling of the various wells, and the results of a tracer test conducted during 2007-2008.

The numerical model of the reservoir has been calibrated first by matching the initial subsurface temperature distribution interpreted from temperature-profile measurements in the deep wells. With iterations back to the initial state, the model was then calibrated to the historical production/injection data and to the new tracer data. Following calibration, the model was used to forecast field performance under various operating conditions.

The results of forecasts indicate that significant cooling of the Pico Vermelho production sector could occur if the present injection configuration is maintained, with or without a planned increase in the level of power generation. Fluid injected into the existing injection wells returns quickly to the production wells, causing a relatively high rate of cooling. This high rate of cooling can be reduced significantly if injection is relocated to the northeastern part of the field, and based on the results of the model forecasts, a plan for drilling alternative injection sites during 2009 was put into place, in zones that are more distant from the production area than the existing injection wells.

Introduction

Sociedade Geotérmica dos Açores (SOGEO) has requested that GeothermEx develop a numerical model of the Ribeira Grande geothermal reservoir, located in the central part of the island of São Miguel (Figure 1). The model is used to support SOGEO's ongoing development and exploitation of the reservoir for the generation of electric power. This report presents the results of the numerical simulations, which have been undertaken during 2007-2008.

The numerical model has been created using data obtained from SOGEO (or collected directly by GeothermEx in the course of its assistance to SOGEO) since 2003. These include, the results of new deep wells drilled in the Ribeira Grande field during 2005, data from the continued operation of the Ribeira Grande power plant, data from the operation of the new plant at Pico Vermelho that began operation in 2006, and the results of logging, testing and sampling of the various wells in the field.

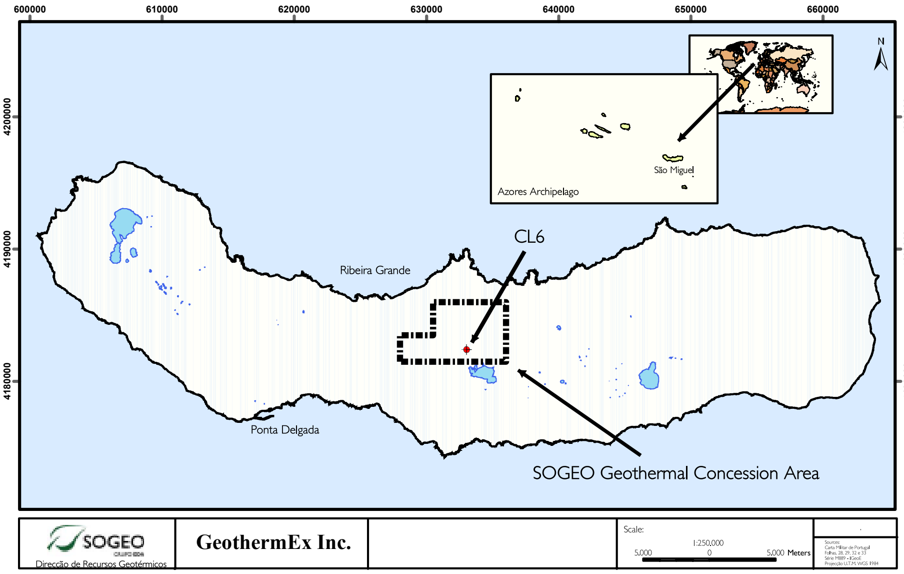

Figure 1. Location of SOGEO Geothermal Concession Area on São Miguel.

Conceptual Hydrogeologic Model

The Ribeira Grande geothermal field is an extensive, high-temperature geothermal system hosted by volcanic rocks (mainly lavas and pyroclastic units) on the northern flank of the Fogo volcano. The geothermal reservoir is elongated in a northwestern direction, and may have southwestern and northwestern boundaries that follow this trend, particularly at lower elevations. However, the field is insufficiently delineated by drilling to be certain of its limits, and recent geoelectrical surveys suggest a possibility that the field extends further to the northeast than was thought previously to be the case.

Geothermal water with a maximum temperature of at least 250°C enters the reservoir in an upflow zone that is probably located in the southeastern part of the field. The ultimate source of heat for the hot water is presumably the body of magma or young intrusive rock associated with the activity of the Fogo volcano.

The principal flow direction into and within the reservoir at deeper levels is upward and northwestward, though there is probably some lateral flow toward the margins of the reservoir as well. The available data do not strongly indicate the presence of more than one upflow zone, but they do not preclude it either. At shallower levels (particularly near about -400 m elevation), lateral, northwestward flow appears to predominate over upward flow, forming an extensive, relatively shallow reservoir in the Pico Vermelho sector.

Tracer Test of 2007-2008

In part because fluids chemistry trends are inadequate for evaluating injection returns in the Ribeira Grande reservoir, SOGEO, with assistance from GeothermEx, designed and contracted services for conducting a tracer test of the reservoir starting on October 10, 2007.

The test comprised injecting 100 kg of three different isomers of naphthalene di-sulfonic acid into three different injection wells, CL4, PV5 and PV6. Production wells monitored were CL1, CL2, CL5, CL6, PV2, PV3 and PV4. Injection water at CL4 and PV6 (same as injection to PV5) was also sampled routinely.

There was very little return of the tracer injected into well CL4, and this appeared only at well CL5 (never above ~4 ppb) and, after 186 days, at CL6 in very small amounts. In contrast, tracer injected into PV6 returned to PV-sector production wells at levels as high as 88 ppb, and tracer injected into PV5 returned to PV-sector production wells at levels as high as 20 ppb.

Initial-State Numerical Model

The numerical modeling study of the Ribeira Grande geothermal reservoir was undertaken in order to evaluate existing and potential new field management strategies. It has included evaluation of the impacts of injection into existing wells on the production wells in both the Pico Vermelho and Ribeira Grande sectors. The model has been created using the "dual porosity, dual permeability" [1] formulation in the commercially available geothermal reservoir simulator TETRAD, with the aim of providing adequate resolution for the matching of data obtained since 2003, particularly the new tracer data gathered during the 2007-2008 tracer test.

Description of the Initial-State Model

The simulation grid for the numerical model of Ribeira Grande field covers an area of 40 km^2 (8.0 km x 5.0 km), and is oriented northeast to southwest, encompassing both the Ribeira Grande and Pico Vermelho project areas (Figure 2). Each layer of the model is divided into 21 by 31 blocks, or 651 blocks. The grid block dimensions range from 150 by 200 m in the productive portion of the field to 400 by 500 m on the periphery of the field.

Vertically, the model has 11 layers and extends from an elevation of 0 m above mean sea level (msl) to -2,000 m msl. The top layer, used to represent the cap rock, is 150 m thick. The next four layers are 100 m thick each, while layers 6, 7, 8, 9, 10, and 11 are 150, 200, 200, 200, 250, and 450 m thick, respectively.

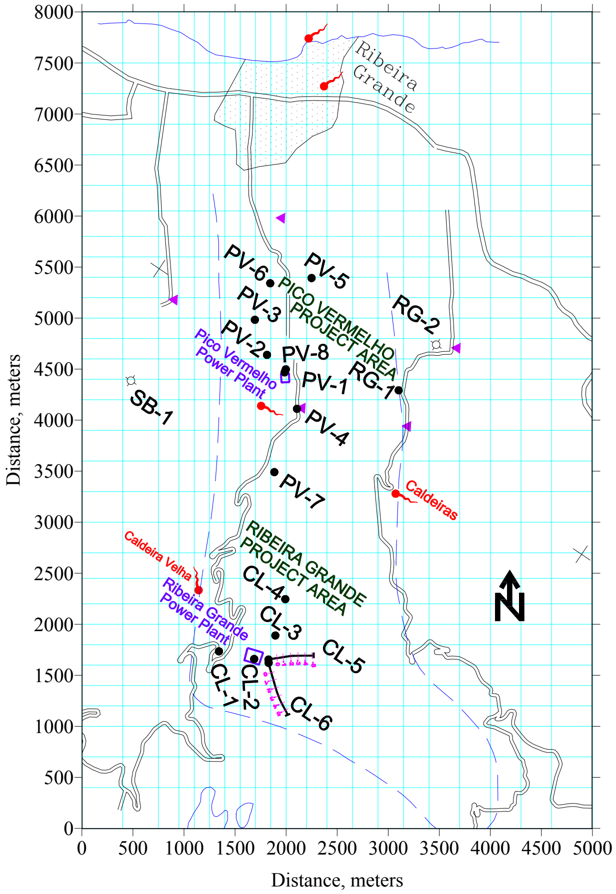

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Figure 2. Grid blocks arrangement in the numerical model.

Results of the Initial-State Model

The main set of data used to calibrate the model at this stage is the subsurface temperature distribution, deduced from temperature profiles measured in wells before they went into operation for production or injection. The objective of the initial-state modeling effort is to match the calculated temperature distribution from the model to the observed temperature distribution by trial and error.

Figure 3 shows the subsurface temperature match obtained for one of the layers in the main production zone of the reservoir. Overall, the model has correctly calculated the shape and

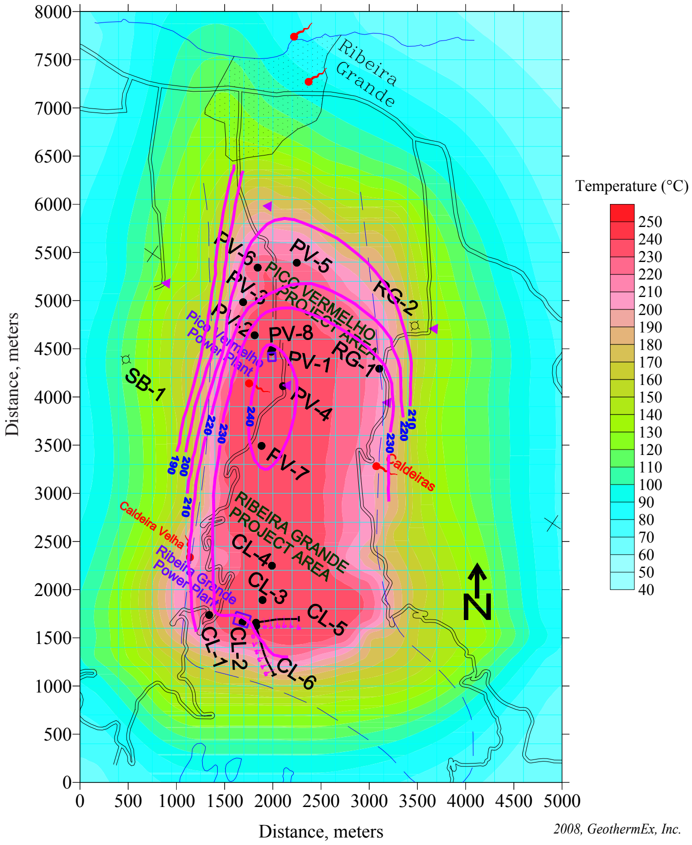

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Figure 3. Subsurface temperature matching, layer 3, at -300 meters, msl.

location of the high temperature lobes. The difference between measured and calculated temperatures is typically less than 10ºC. Considering the typical uncertainties associated with the measured temperatures, this level of agreement between measured and calculated temperatures are considered very good. Equally good subsurface temperature matches were also achieved for all the remaining layers where data were available. In the interest of brevity, these matches are not described here.

After numerous trial-and-error iterations, the numerical model of the Ribeira Grande was successfully calibrated against the interpreted original subsurface temperatures. The initial-state model was therefore considered ready to be used to match the dynamic historical production data.

Historical Data Matching

The results of the initial-state modeling indicated that the overall fluid and heat flow patterns in the Ribeira Grande geothermal system were reasonably represented. Because the initial-state model does not provide detailed information on localized reservoir conditions at and near the wells, these parameters are ascertained by matching the historical data obtained from the field. Detailed production and injection rate data were input into the model, and the measured historical data trends were matched.

History Matching Procedure

Typically, for a two-phase reservoir such as Ribeira Grande, downhole pressure data from observation wells and production enthalpy changes are used as calibrating parameters for the history matching phase of numerical modeling. Production enthalpy data from the start of the project to present were available, but downhole pressure data were not available due to instrument malfunctions.

To enhance the understanding of the overall hydraulic connection in the reservoir, SOGEO and GeothermEx jointly designed and conducted a comprehensive chemical tracer test in the Ribeira Grande field during 2007-2008. Three separate tracers (1,6NDS, 2,6 NDS and 2,7 NDS) were injected into wells PV6, PV5, and CL4, respectively, on October 10, 2007. Routine sampling for analysis of tracer returns was conducted at production wells CL1, CL2, CL5, PV2, PV3, and PV4 over a period of several months.

It would have been very difficult to obtain a clear picture of the effect of injection on the production wells based on the measured enthalpy data alone. Fortunately, excellent tracer return data were obtained from the production wells, and the tracer data from the production wells were used together with enthalpy data as calibration parameters for the numerical model of the Ribeira Grande field.

History Matching Results

All the production-well enthalpy data provided to us were matched. The enthalpy match of two representative wells are discussed here. The first enthalpy trend matched was for well CL1, as shown on Figure 4. There are four items in each plot: the triangles show the measured total flow rate (tons/hr), the solid line denotes the flow rate used by the model, the circles represent the measured fluid enthalpy, and the broken line is the fluid enthalpy calculated by the model. As seen in the figure, the model was able to duplicate the fluid enthalpy trend measured from this well. The enthalpy of this well has remained constant over its production history, at about 940 kJ/kg.

The enthalpy match for production well CL5 is shown on Figure 5, overleaf. This well also produced a significant proportion of steam at the start of its history. Measured enthalpy was initially about 1,900 kJ/kg in 2001, but has declined gradually to about 1,300 kJ/kg by mid-2005. Later on, production from CL6 was combined with this well. An excellent match to the measured enthalpy has been achieved as shown in the figure. Both the

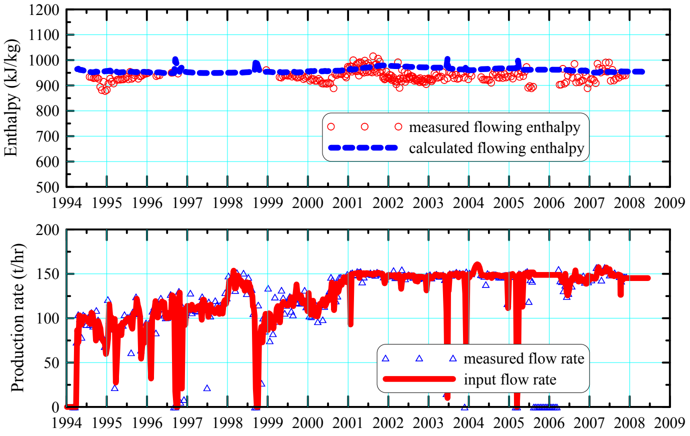

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Figure 4. Production parameters matching, well CL1.

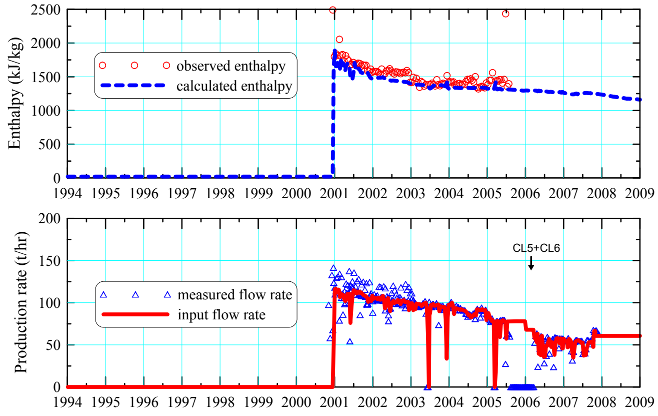

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Figure 5. Production parameters matching, well CL5.

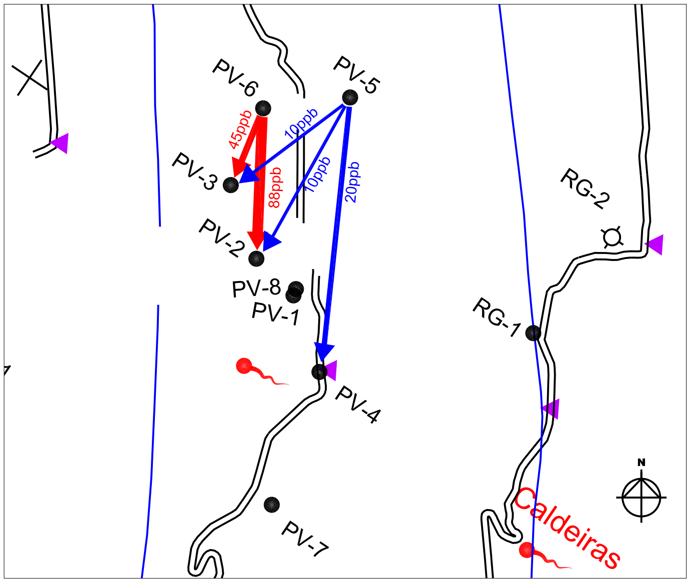

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Figure 6. Tracer return pattern at Pico Vermelho.

magnitude and trend of the measured enthalpy has been closely matched by the model-calculated enthalpy values.

Excellent enthalpy match was also obtained for each of the remaining wells in the field. The model was able to duplicate measured enthalpy throughout the production history. Typical different between measured and calculated enthalpies is less than 50 KJ/kg for all the wells.

In addition to the enthalpy data, the analyzed tracer return data have been used to further calibrate the numerical reservoir model. Overall tracer returns pattern is shown on Figure 6, and matches to tracer returns by the model are plotted on Figures 7 to 9.

Overall, an excellent match to the tracer return was obtained for each of the wells where sampling was carried out; both the magnitude the timing of the tracer returns were closely duplicated. The rapid and relatively large-magnitude return of the tracer injected into well PV6 to wells PV2, PV3 and PV4 indicates that PV6 injection can be expected to have a detrimental effect on the fluid production temperature of these producers at some point. It may also be anticipated that PV8 will also eventually be negatively

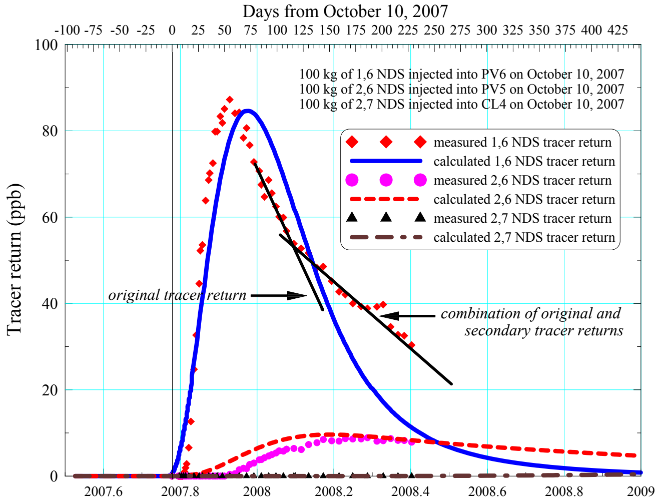

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Figure 7. Tracer returns matching, well PV2.

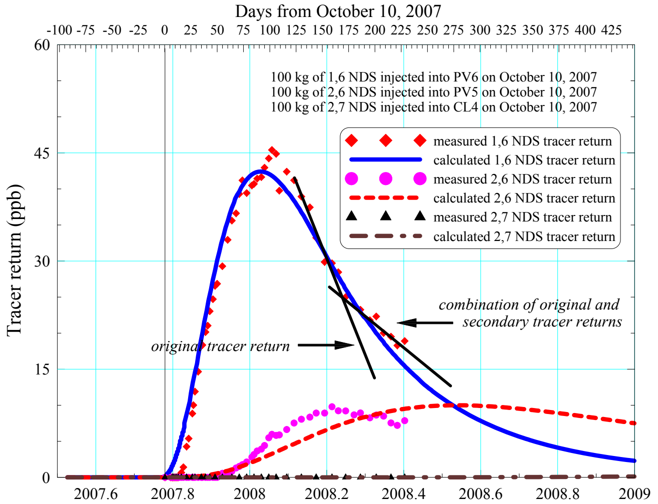

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Figure 8. Tracer returns matching, well PV3.

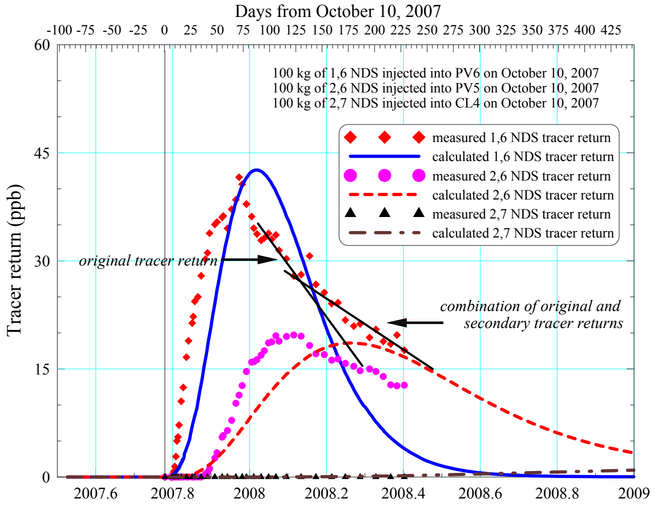

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Figure 9. Tracer returns matching, well PV4.

impacted by the injection into PV6, because this well is close to PV2 and PV4. Injection into PV5 may also negatively impact the temperature of the produced fluid of the Pico Vermelho wells, but to a lesser degree than PV6. Very little of the tracer injected into CL4 was found in the Ribeira Grande production wells, suggesting that injection into CL4 should not have a significant negative impact on the wells' thermal characteristics.

In summary, the three-dimensional numerical model of the Ribeira Grande field has been successfully calibrated against the measured enthalpy and tracer return data. We therefore believe that the model provides a good representation of the Ribeira Grande reservoir and can be used with reasonable confidence in forecasting future reservoir changes in response to exploitation.

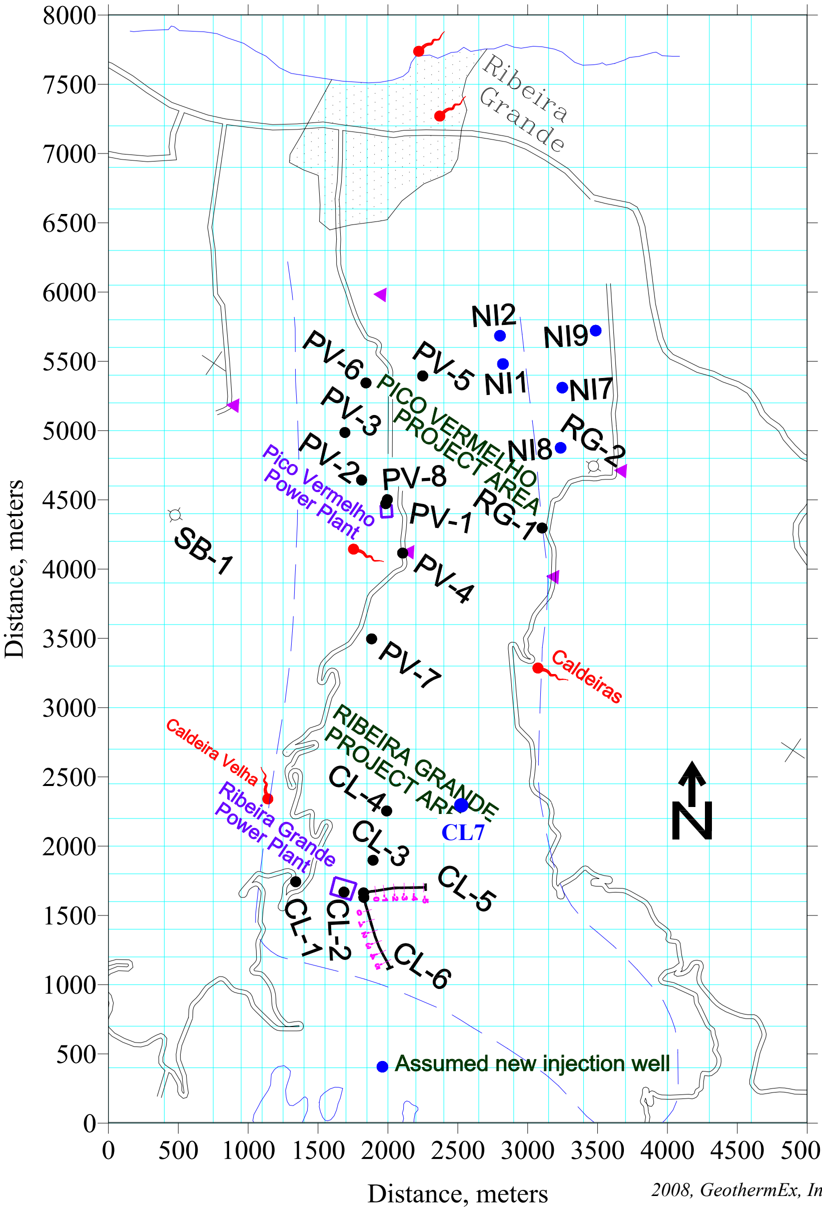

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Figure 10. Well locations used in the forecasts.

Field Performance Forecasts

One of the main objectives of the performance forecasts was to examine various possible injection configurations in order to optimize power production while minimizing potential detrimental impacts caused by injection return from existing injection wells.

Six forecast scenarios are presented and discussed here. In the first three scenarios (A, B, and C), the amount of power generated is kept constant at both the Ribeira Grande and Pico Vermelho power plants (8 MW and 10 MW net, respectively). The last three scenarios (D, E, and F) assume that 10 MW (net) of additional power is to be generated at the Pico Vermelho project area using existing PV wells. Well locations used in these scenarios are shown on Figure 10.

Non-Expansion Scenarios

- Scenario A: In this scenario, the current production and injection scheme is maintained for the entire forecast period of 30 years. Production wells CL1, CL2, CL5, and CL6 supply geothermal fluid to the Ribeira Grande power plant, and the waste brine is injected back into the reservoir using injection well CL4. The Pico Vermelho plant is supplied by production wells PV2, PV3, and PV4. The separated brine and condensate are sent to injection wells PV5 and PV6. The production and injection rates for each of the active wells were specified based on actual data reported by SOGEO for the month of November 2007. The total production from the Ribeira Grande area during this month was about 400 tons/hr, with a corresponding generation of approximately 8 MW (net). The total production from the Pico Vermelho wells was about 500 tons/hr, with a corresponding generation of about 10 MW (net).
- Scenario B: In this scenario, the current generation capacity in the field remains unchanged, but instead of injecting into PV5 and PV6, the waste brine from the Pico Vermelho plant is sent to the two new injection wells, NI7 and NI9.
- Scenario C: In this scenario, the current generation capacity in the field remains unchanged, but instead of injecting into PV5 and PV6, the waste brine from the Pico Vermelho plant is sent to the two new injection wells, NI7 and NI8.

10 MW (net) Expansion Scenarios

- Scenario D: The existing injection configuration at the field remains unchanged. In addition to the current production level at Pico Vermelho, PV7 and PV8 are put online with an assumed combined production rate of 500 tons/hr (corresponding to an increase of 10 MW net power production), for a total production rate of 1,000 tons/hr at Pico Vermelho. To dispose of the additional waste brine, two new injection wells are assumed, NI1 and NI2.

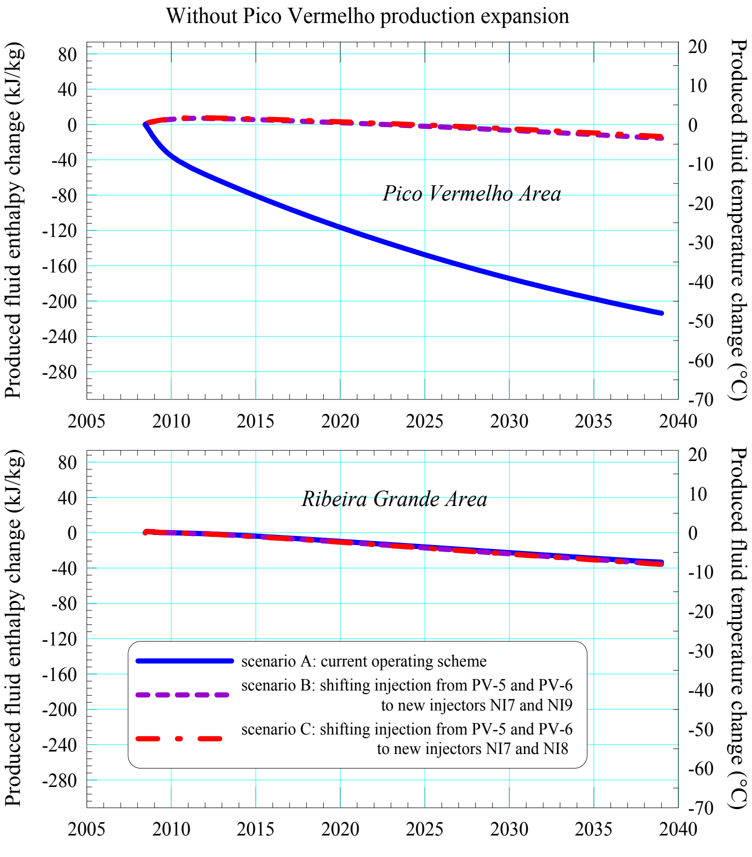

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Figure 11. Production enthalpy forecast, scenarios A, B, and C.

- Scenario E: Similar to scenario D, but instead of using PV5 and PV6 as injectors, the entire waste brine volume is shifted toward the eastern side of the Pico Vermelho project area using new injection wells NI1, NI7, NI8, and NI9.
- Scenario F: Similar to scenario D, but instead of using PV5 and PV6 as injectors, the entire waste brine is shifted toward the eastern side of the Pico Vermelho project area using new injection wells NI2, NI7, NI8, and NI9.

Forecast Results

Non-Expansion Scenarios

The results of the three non-expansion forecasts for the Pico Vermelho area are shown in Figure 11. The calibrated numerical model suggests that significant cooling of the Pico Vermelho production area could occur if the present injection configuration is maintained. Fluid injected into PV5 and PV6 returns quickly to the production wells (with PV6 having a larger impact), causing the average fluid enthalpy to decline by about 220 kJ/kg (corresponding to a reservoir temperature decline of about 50°C) over the 30 years of production. This represents a temperature decline rate of about 1.7°C per year, which is very high for a geothermal field. The model results indicate that this potential high cooling rate can be reduced significantly if injection at PV5 and PV6 is shifted to the area east of PV5. If injection is shifted by 1,000 meters, to new injection wells at locations NI7 and NI9, or to NI7 and NI8 (Figure 10), the model predicts a total enthalpy decline of about 14 kJ/kg over the next 30 years, or a total temperature decline of about 4°C. This corresponds to an annual decline rate of 0.13°C per year, a low decline rate.

For the Ribeira Grande area, the predicted enthalpy decline is relatively small (Figure 11). The model calculates a total 30-year decline of only about 35 kJ/kg under each of the three scenarios. This corresponds to a total decrease of about 7.5°C in the produced reservoir fluid temperature, or a decline rate of 0.25°C per year, which is fairly low. This small decline in the fluid enthalpy suggests that cooling due to injection water encroachment should not be a significant problem in the Ribeira Grande sector, if the current production/injection scheme is continued.

10 MW (net) Expansion Scenarios

The model also calculates significant cooling of the reservoir if an additional 10 MW (net) is produced from the Pico Vermelho area (Figure 12). The total enthalpy decline for the 30-year production period is predicted to be about 240 kJ/kg, corresponding to a fluid temperature decline of about 54°C. This fluid temperature decline rate is slightly higher (1.8°C per year) than the decline predicted under scenario A, where the status quo is maintained.

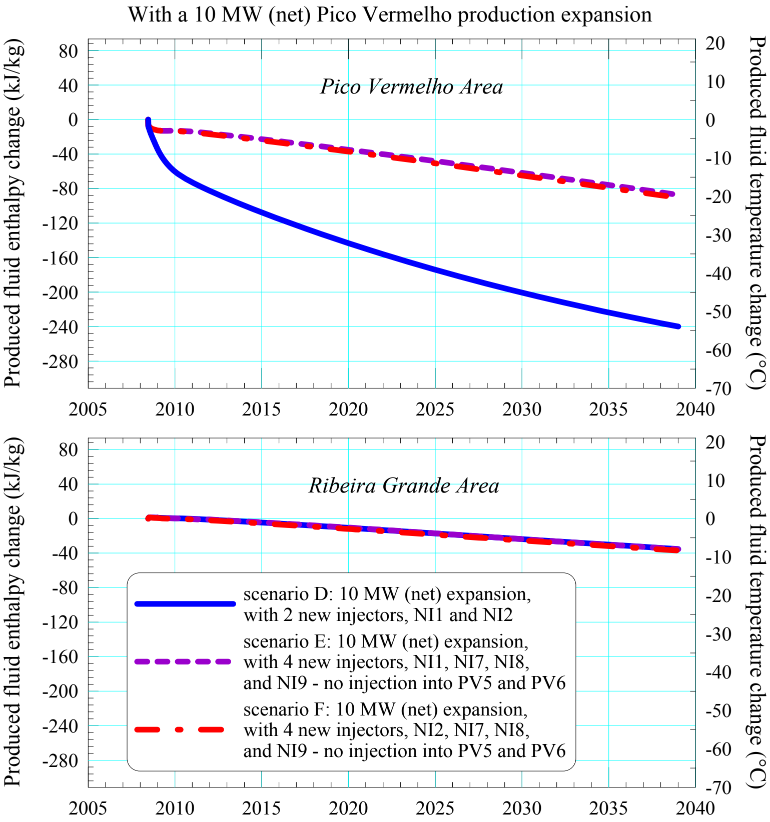

Figure 12. Production enthalpy forecast, scenarios D, E, and F.

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The fluid temperature decline rate can be significantly reduced if the waste brine from the Pico Vermelho sector is moved completely toward the eastern side of the PV5, to wells NI1, NI7, NI8, and NI9 (scenario E), or to wells NI2, NI7, NI8, and NI9 (scenario F). The results for these scenarios are also shown on Figure 12. It is calculated that fluid temperature will decline at a rate of about 0.66°C per year.

For the Ribeira Grande area, very little change in the fluid thermal characteristics is seen (Figure 12) even when an additional generation of 10 MW (net) is imposed on the Pico Vermelho area. Fluid temperature declines at a low rate of about 0.26 °C per year for the entire duration of the forecast.

Conclusions and Recommendations

The numerical model of the Ribeira Grande geothermal field has been successfully calibrated against all available data, and can be now used to provide forecasts of future reservoir behavior under various production/injection schemes.

Under the current scheme of exploitation, the model predicts that existing injection at PV5 and PV6 will cause significant cooling of the reservoir in the Pico Vermelho sector, at a rate of about 1.7°C per year. This high cooling rate can be reduced significantly by relocating injection from the two existing wells to the area east of PV5.

It appears that the reservoir can sustain a doubling of the existing level power generation (10 MW net) in the Pico Vermelho area, provided that the anticipated problem of injection-related cooling can be addressed adequately. Without relocating injection from wells PV5 and PV6, the fluid temperature decline rate is predicted to be about 1.8°C per year. If injection is relocated from PV5 and PV6 to a zone further from the production area, the fluid temperature decline rate can be reduced to a more manageable rate of less than 1°C per year. This decline rate is not low, but is manageable in many geothermal fields. One or more make-up wells may be needed in the future to compensate for the anticipated reduction in fluid temperature.

No significant cooling of the resource is predicted in the Ribeira Grande area under any of the scenarios examined. The model calculates a fluid cooling rate of only about 0.26°C per year, a low rate for a typical geothermal field.

Injection-related reservoir cooling in the Pico Vermelho sector is therefore the principal field management problem indicated by the numerical reservoir model, and represents the main risk associated with expansion of generation at Pico Vermelho. Based on the results of the model forecasts, we strongly recommend that SOGEO investigate potential alternative injection sites in the Pico Vermelho sector, in zones that are more distant from the production area than the existing injection wells PV5 and PV6.

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