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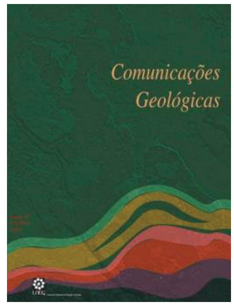
# Sustainable use of geothermal resources in the Ribeira Grande geothermal field, São Miguel, Azores




# Aproveitamento sustentável de recursos geotérmicos no campo geotérmico da Ribeira Grande, São Miguel, Açores

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**Abstract:** The use of geothermal resources for power production on São Miguel Island has almost 40 years of accumulated experience. In the last decade, the stable power output from Pico Vermelho and Ribeira Grande geothermal plants have been providing up to 44% of the electricity needs of São Miguel Island. Throughout the history of the project, EDA RENOVÁVEIS has been carefully monitoring the Ribeira Grande reservoir conditions and well discharges to assess the resource response to the production load. The results from the last 10 years of monitoring data indicate that production did not cause any significant impact on the reservoir pressure or temperature and it can be maintained in the long-term without the risk of over-exploiting the geothermal resource.

**Keywords:** Geothermal energy, sustainable development, geothermal reservoir, Ribeira Grande.

**Resumo:** O uso de recursos geotérmicos para produção de eletricidade na ilha de São Miguel tem quase 40 anos de experiência acumulada. Na última década, a estabilidade da produção das centrais geotérmicas do Pico Vermelho e da Ribeira Grande tem garantido até 44% das necessidades de energia elétrica da ilha de São Miguel. Ao longo da história do projeto, a EDA RENOVÁVEIS tem promovido a monitorização do reservatório geotérmico da Ribeira Grande, bem como dos parâmetros de produção dos poços geotérmicos, com vista a avaliar a resposta do recurso ao esforço de exploração. Os resultados dos últimos 10 anos de monitorização indicam que a exploração do recurso geotérmico não causou impacto significativo quer na pressão, quer na temperatura do reservatório, prevendo-se que esta poderá manter-se a longo prazo sem o risco de sobre-exploração do recurso geotérmico.

**Palavras chave:** Energia geotérmica, desenvolvimento sustentável, reservatório geotérmico, Ribeira Grande.

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## 1. Introduction

Since the 1970s, the geothermal development in São Miguel Island has been in the Ribeira Grande field, emplaced in the northern flank of Fogo Volcano (Fig. 1). The geothermal power production started in 1980, with the 3 MW Pico Vermelho pilot plant (Meidav, 1981), but the commercial use of the resource only started with the Ribeira Grande power plant, installed in two stages – 5 MW in 1994, and expanded to 13 MW in 1998 (Ponte, 2002). Meanwhile, in 2006, the 3 MW pilot plant was dismantled and replaced by the 10 MW Pico Vermelho power plant (Kaplan *et al.,* 2007), installed at the same location.

Over the past decade, the production from the geothermal plants has been consistently providing up to 44% of the electricity needs of São Miguel Island. Here, geothermal power production is considered a case study, where all the distinctive features of this energy source from other renewables are demonstrated, with geothermal operating at the base of the load diagram, providing a highly predictable and stable power output.

The response of the geothermal reservoirs to the production load is quite variable and different geothermal systems often respond differently to production, depending on their geological setting and nature. Therefore, comprehensive management is essential for the sustainable use of the resource, with careful monitoring, modeling and reinjection corresponding to the main tools used in modern geothermal resource management (Axelsson *et al.,* 2004).

To assess the reservoir response to the production load and to predict its evolution in the long-term, EDA RENOVÁVEIS has been implementing a comprehensive resource monitoring program, which includes borehole temperature and pressure measurements, and monitoring of well discharges over time, particularly fluid enthalpy, wellhead pressure and mass flow rates, as well as the fluid chemistry. In this paper, we present the physical monitoring results, integrating these with the reinjection strategy implemented in the Ribeira Grande geothermal field.

## 2. Production rates and reservoir pressure

The discharge parameters from the individual production wells have been continuously monitored by the control system of the power plants, providing valuable data to assess the reservoir response to the production load, particularly fluid enthalpy, total flow rates and wellhead pressure (WHP).

When discharge enthalpy and flow rates are stable over time, the evolution of reservoir pressure can be inferred from the WHP

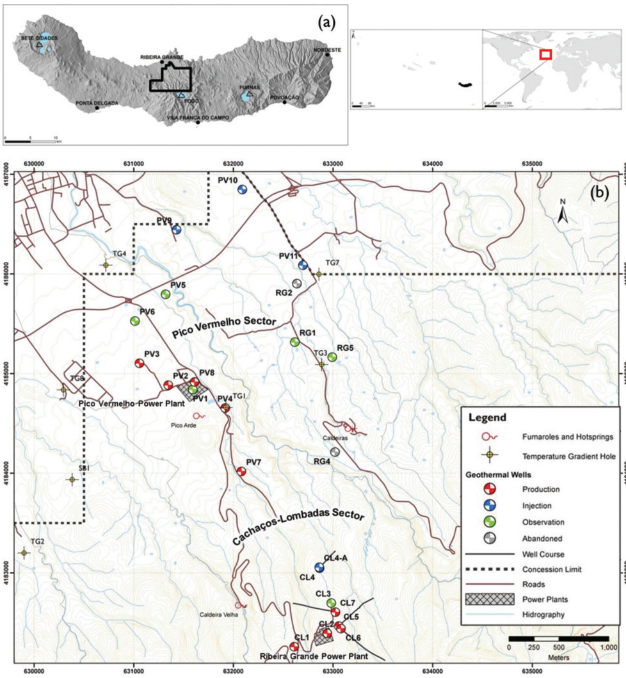


Figure 1. Geothermal project area (a) and well field (b) (provided by EDA RENOVÁVEIS).

Figura 1. Área de concessão geotérmica (a) e parque de poços geotérmicos (b) (fornecido pela EDA RENOVÁVEIS).

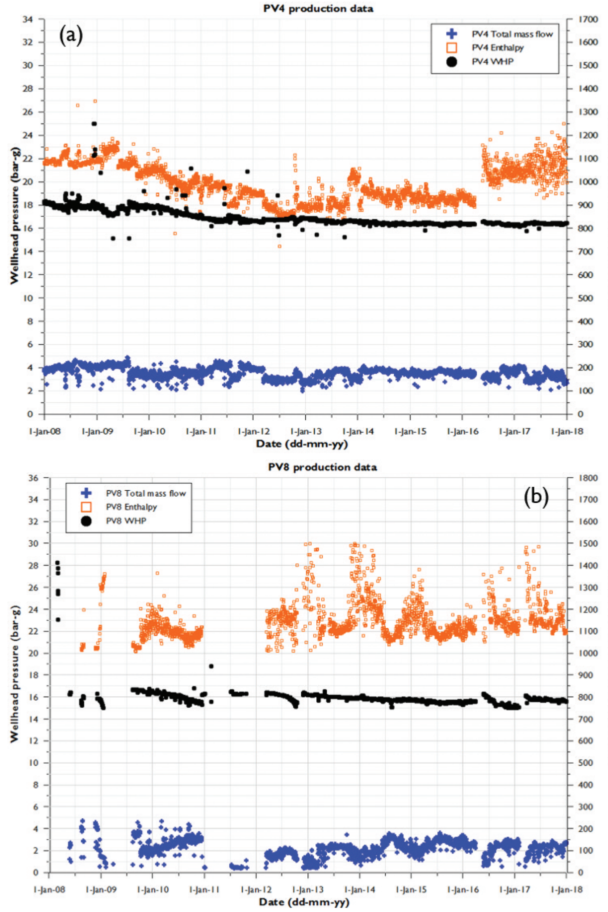


Figure 2. History of PV4 (a) and PV8 (b) well discharge parameters.

Figura 2. Histórico dos parâmetros de produção dos poços PV4 (a) e PV8 (b).

trends observed in production wells. In the northern part of the field, wells PV4 and PV8 show relatively constant fluid enthalpy and flow rates, and very little changes have been observed in the WHP over time (Fig. 2). Likewise, wells CL1 and CL6, in the southern part of the field, show stable WHP trends for the given enthalpy and flow rate values (Fig. 3), indicating that reservoir pressure has been rather stable.

To complement the well discharge trends, reservoir pressure has been directly measured in observation wells (shut-in), using downhole pressure transients (Figs. 4 and 5). The results are depicted along with the production rate history in Pico Vermelho (PV sector) and Ribeira Grande (CL sector) power plants to evaluate the impact of production on reservoir pressure.

Since Dec-2006, the power production at Pico Vermelho has been very stable (Fig. 6), with the power plant operating at full capacity over time, fed by a relatively constant supply of 350-450 t/h of geothermal fluid (Fig. 4). The production rate shows seasonal fluctuations, as the power plant needs less fluid in the winter (because lower ambient temperatures decrease the condensing pressure of the generating unit, thus increasing its efficiency). Reservoir pressure was logged from Aug-2014 to Feb-2015 in well PV2 and it was observed to be very stable at 50.8 bar-g (Fig. 4).

The power production history of the Ribeira Grande plant has been more oscillatory (Fig. 6), and this is mainly related to insufficient supply of geothermal fluid to meet the plant generation capacity, with the production rates varying from 400 to 550 t/h. Reservoir pressure has been measured in well CL3 since 2008 and it has remained relatively stable over time, ranging from 44.5 to 45.5 bar-g (Fig. 5), with only a minimal decline of approximately 0.1 bar/year. Based on the experience from other geothermal projects worldwide, this is considered low. In addition, there is a good correlation between the production and the observed reservoir pressure, as pressure recovered when production was lower (related with the periodic closing of individual wells or with outage periods of the power plant). On the other hand, high production rates do not seem to originate any abrupt decline in reservoir pressures.

## 3. Reinjection strategy in Ribeira Grande

In the Ribeira Grande field, reinjection is mandatory due to environmental constrains, ensuring the adequate disposal of the hot saline geothermal water downstream the power plants. In addition, as in many other geothermal systems worldwide, reinjection is an important tool for the sustainable use of the resource (Axelsson, 2012), contributing to minimize the reservoir pressure decline and thus preventing over-exploitation.

According to Axelsson *et al.* (2004), the effect of small production is so limited that it can be maintained for a very long time (hundreds of years). Based on data compiled by Diaz *et al.* (2015), the mass withdrawal in Ribeira Grande (compared to most geothermal projects worldwide) is very small but the reinjection rate is amongst the highest practiced in the geothermal industry, with more than 94% of the produced fluids being reinjected back into the deep reservoir. Furthermore, reinjection in the Ribeira Grande field is divided by 5 injection wells, which enhances the operational flexibility of the well field.

The results from a tracer test conducted in 2015 revealed a limited hydraulic communication between reinjection and production

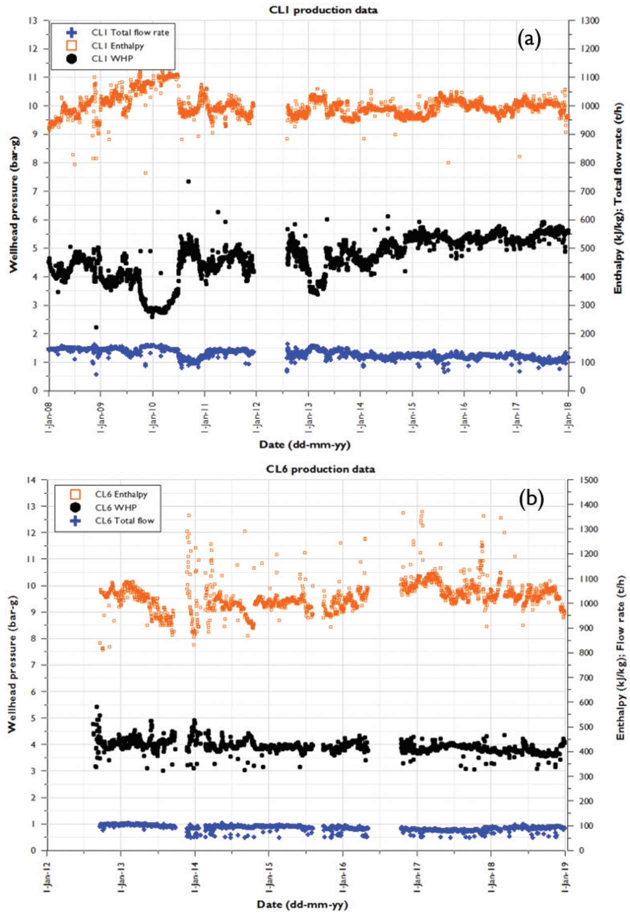


Figure 3. History of CL1 (a) and CL6 (b) well discharge parameters.

Figura 3. Histórico dos parâmetros de produção dos poços CL1 (a) e CL6 (b).

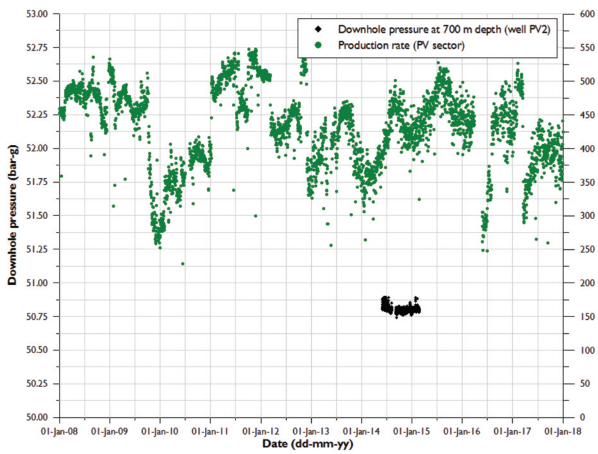


Figure 4. Reservoir pressure measured in well PV2 and production registers in the Pico Vermelho sector.

Figura 4. Histórico de produção no sector do Pico Vermelho e da pressão no reservatório, medida no poço PV2.

areas, as only weak returns (in both timing and magnitude) of reinjected fluids were observed in the production wells (Rangel *et al.*, 2017). This minimizes the risk of cooling the production areas, due to the reinjection of the colder fluids. The reservoir temperature measured at the main feed zones of individual production wells confirms minimal temperature changes over time (Fig. 7). In the Pico

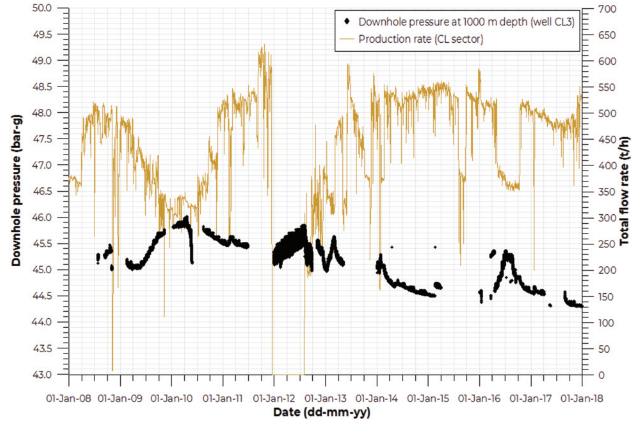


Figure 5. Reservoir pressure measured in well CL3 and production registers in the Cachaços-Lombadas sector.

Figura 5. Histórico da produção no sector de Cachaços-Lombadas e da pressão no reservatório, medida no poço CL3.

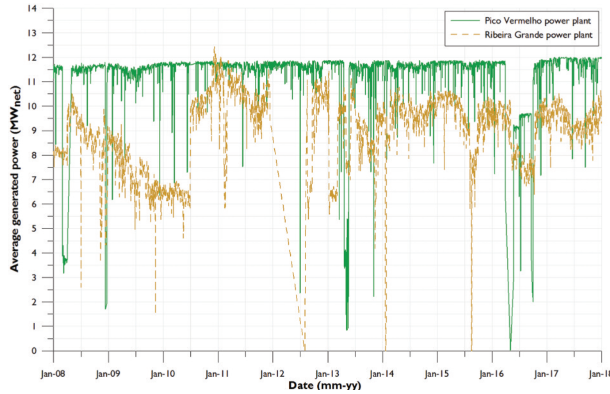


Figure 6. Power generation history in the Ribeira Grande geothermal field.

Figura 6. Histórico de produção de eletricidade no campo geotérmico da Ribeira Grande.

Vermelho sector, this tendency is more evident since 2014, after reinjection was relocated farther away from the production area.

In addition, based on the stable reservoir pressures over time, the tracer test results suggest that most of the discharge is being replaced by the natural recharge. Nonetheless, the small returns from reinjection add to the natural recharge, contributing to the sustainable use of the resource.

## 4. Conclusions

The resource management results have shown that geothermal power production in São Miguel did not cause any significant impact in the Ribeira Grande geothermal resource and it is forecasted that production can be maintained in the long-term without any significant reservoir pressure or temperature decline.

In addition, the tracer test conducted in 2015 indicated only small partial returns of the reinjected fluids to the production areas. Thus, considering that reservoir pressure has been quite stable throughout the production history, it seems that most of the discharge is being replaced by the natural recharge. Nonetheless, the small returns from reinjection add to the natural recharge and contribute to guarantee the sustainable development of the geothermal resource in Ribeira Grande.

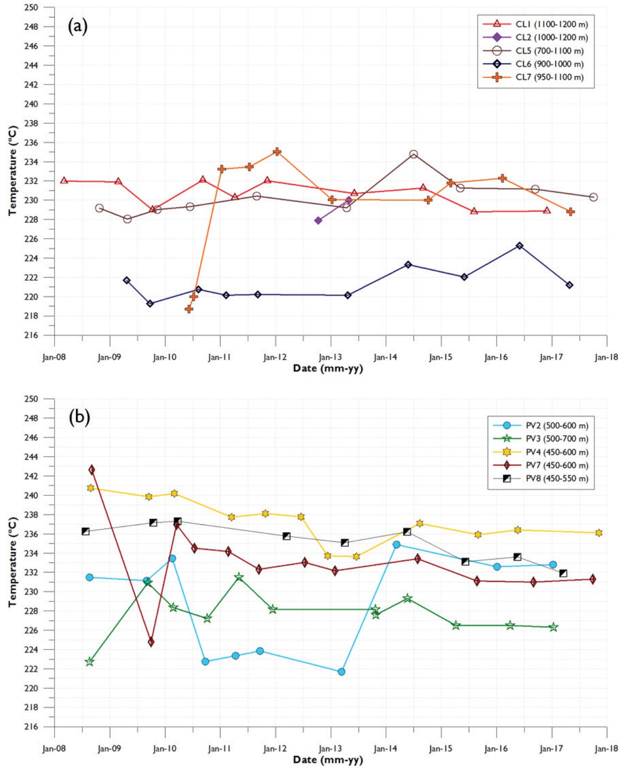


Figure 7. History of reservoir temperature at the main feed zones in CL (a) and PV (b) production wells.

Figura 7. Histórico da temperatura no reservatório, medida nas principais zonas produtivas nos poços CL (a) e PV (b).

The efficient management of the geothermal resource, combined with careful monitoring and comprehensive modelling, have been the essential ingredients for the success of the Ribeira Grande project, ensuring the sustainable use of the resource. Maintaining this strategy in the future will enhance the chances of project success in the long-term, particularly looking to the possibility to increase the geothermal contribution to the energy self-sufficiency of São Miguel Island.

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