Direct uses as environmental mitigation measure in Ribeira Grande Geothermal Field (S. Miguel, Azores Islands, Portugal)

José Martins Carvalho[1,4], João Carlos Nunes[2,4]* and Maria do Rosário Carvalho[3,4]

[1] TARH, Lda. & Laboratório de Cartografia e Geologia Aplicada, School of Engineering (ISEP), Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal

[2] Universidade dos Açores, Departamento de Geociências, Rua Mãe de Deus, 9501-801 Ponta Delgada & INOVA Institute, Estrada de S. Gonçalo, 9504-540 Ponta Delgada, Azores, Portugal

[3] Faculdade de Ciências da Universidade de Lisboa, Departamento de Geologia, CeGUL, Campo Grande, Edifício C6, 3º Piso, 1749-016, Lisbon, Portugal

[4] Consultant, EDA RENOVÁVEIS, SA – IMAGE Project, Ponta Delgada, Azores, Portugal

*jcnunes@uac.pt

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ABSTRACT

Within the 2009/2010 drilling campaign on the NE part of the Ribeira Grande Geothermal Field, in São Miguel island, a geothermal well (RG4) intercepted a shallow thermal aquifer at about 230-250 meters depth, causing high levels of superficial steaming activity and geologic and environmental problems in the nearby areas, including houses located at Caldeiras da Ribeira Grande, at a distance of about 250 m away, were a traditional fumarolic field and an old thermal bath building exists since 1811. The well was sealed and abandoned.

Afterwards, a new fumarolic field and strong CO_2 diffuse discharge developed in an NW-SE trending area, initially about 200,000 m^2 around well RG4. Aiming the mitigation of its effects, a monitoring and intervention program was established, that included wells for temperature monitoring, spatial distribution of the diffuse CO_2 emissions and soil temperature, isothermal imaging with a thermal camera, monitoring of water composition and gas of fumaroles and soil emissions and reflection seismic studies, among others.

Overall interpretation of the investigations revealed that hot water and steam originating from a depth of about 240 m was entering a shallow trachyte lava flow through fracturing channels mostly controlled by local tectonics. Thermal groundwater and steam are inferred to circulate mainly through the upper part of the trachyte lava flow, which develops about 10-30 m below surface covered by tuffs and pyroclastic pumice fall deposits. Chemical and isotopic signature of the new degassing area indicates close similarity with the fumaroles ever known in Caldeiras da Ribeira Grande site.

Among the several mitigation and remediation measures accomplished in the area, it was decided to implement non invasive mitigation measures and to develop approaches to promote the new fumarolic field as a thermal resource, does trying to convert a problem into an opportunity. Among those measures was the creation of leisure and recreational structures for direct uses of geothermal fluids, including traditional “geothermal cooking” spots, most appreciated by the local population.

1. INTRODUCTION

The S. Miguel Island, located 400 km east of the Mid-Atlantic-Ridge (MAR), is the largest island of the Azores Archipelago and comprises three active stratovolcanoes (Furnas, Fogo and Sete Cidades) to which various thermal springs, fumaroles, boiling mud-pools and steam ground-emissions are related.

The Fogo poligenic silicic volcano, whose most recent eruptions occurred in 1563 A.D. (Booth et al. 1978), occupies the central part of the S. Miguel Island and has a summit caldera partly occupied by a lake (Figure 1). Current volcanic activity is expressed by fumarolic and hydrothermal activity and a strong thermal gradient that sustains a high-enthalpy geothermal field. The main hydrothermal vents are located along the northern flank of the Fogo Volcano and apparently follow various structural discontinuities, most of them related to the NW-SE fault system associated with the Ribeira Grande Graben (Forjaz, 1986; 1994).

The degassing manifestations, characterized by low-temperature fumaroles, thermal and CO_2-rich mineral springs, as well as gas ground-emissions, are concentrated in three main sites/areas: Caldeira Velha, Caldeiras da Ribeira Grande and Pico Vermelho (Figure 1).

The high-enthalpy geothermal field is presently exploited by EDA RENOVÁVEIS, SA for electricity production. The Ribeira Grande Geothermal Field (RGGF) is located on the northern flank of Fogo Volcano, being presently exploited by 10 production wells and 7 re-injection wells in two different sectors: the Pico Vermelho (PV) and the Cachaço-Lombadas (CL) sectors. The installed generation capacity of 23 MW net allowed an annual production of 185 GWh in 2011, that represents about 44% of the electrical consumption of S. Miguel, and 23% of the total demand of the archipelago (Carvalho et al 2015). On the third sector of the RGGF – the Caldeiras sector – there are four wells, the RG4 and RG5 wells being drilled in 2009-2010.

Well RG4 was planned as one of several deep wells to be drilled by SOGEO (now EDA RENOVAVEIS, SA) for the investigation of reservoir conditions in the Caldeiras sector of the RGGF. It was drilled on a large open area used for cattle grazing, approximately 300 m southwest of the Caldeiras da Ribeira Grande small village (Figure 1) and historic thermal Spa. The Spa has been using the traditional fumarolic field to heat water for bathing and therapeutic applications since 1811, which is provided by a large concrete enclosed mud pool.

The drilling operations in well RG4 were carried out in 2009-2010 (till a depth of about 470 m), and the well intercepted a shallow thermal aquifer at 230-250m. RG4 well caused high levels of steaming activity in the surroundings and triggered a number of environmental and related geotechnical disturbances. Given the occurring difficulties, the well was plugged and abandoned.

After May 2010, a new fumarolic field was development in the nearby areas of RG4 wells, including near the Caldeiras da Ribeira Grande houses and old thermal Spa building, where a former fumarolic field ever existed.

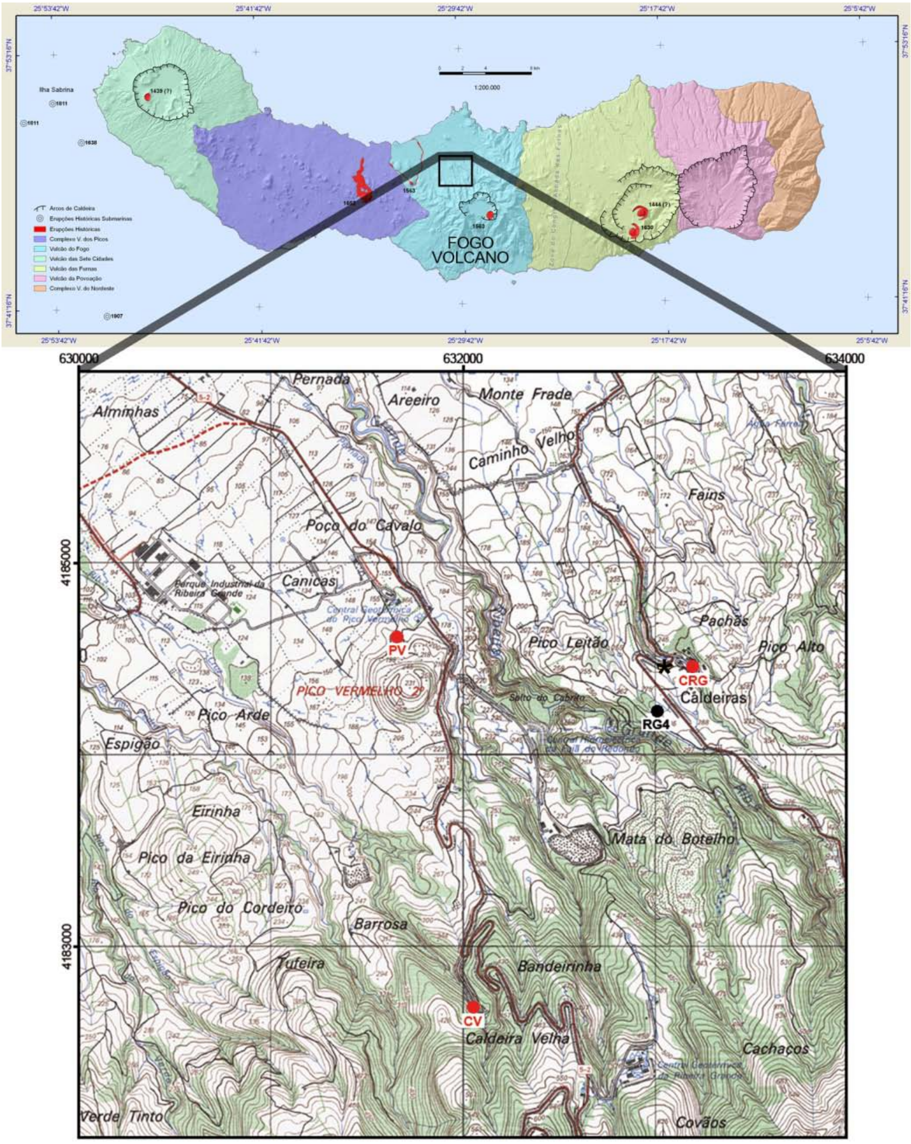

Figure 1. Location of well RG4, new site of direct uses on the Ribeira Grande Geothermal Field (*) and the Pico Vermelho (PV), Caldeira Velha (CV) and traditional Caldeiras da Ribeira Grande (CRG) fumarolic fields. Volcanological map by Nunes (2004). Topographic base map by IGeoE.

2. GEOLOGICAL SETTING

The Fogo stratovolcano occupies the central part of S. Miguel Island, extending east-westwards for about 11-13 km. The volcano's summit is occupied by a 3.4 × 2.2 km in diameter and 400 m deep caldera, formed about 15 ka and presently covered by a small lake (Nunes et al. 2004).

The volcano consists mainly of an accumulation of trachyte lava flows, domes and pyroclastic deposits developed in the course of various (plinian) eruptions (Castro 1888, Zbyszewski et al. 1958, Assunção 1961). Alkaline and hyper-alkaline trachyte rocks form thick *coulées* and domes, pumice-fall deposits, pyroclastic flows and *lahars* (Wallenstein 1999). These are complemented by ankaramites, basanitoides, alkali olivine basalts, hawaites and mugearites (Assunção and Canilho 1970, Girod and Lefévre 1972, Moore 1991).

Five trachyte explosive eruptions occurred over the last 5,000 years generating extensive deposits of pumice, pyroclastic flows and *lahar* deposits (Booth et al. 1978, Wallenstein 1999) that, in some places reach more than 50 m thickness. The last event, a sub-plinian intra-caldera eruption, was recorded in 1563 and deposited considerable amounts of tephra on the eastern half of the island; it was followed, 4 days later, by a basaltic flank eruption (Fructuoso 1926, Agostinho 1960, Machado 1955, Weston 1964) at Pico Queimado. Geological, geochemical and geophysical studies are consistent with a magma chamber below the volcano at 4 km depth (Duffield and Muffler 1984); there is also evidence for several intrusive bodies along the Ribeira Grande Graben, due to volcanic activity along the flanks of the volcano (Forjaz 1994).

The Fogo Volcano is affected by a range of active fault zones. The main structures include: (i) circular and sub-circular fractures related to caldera collapses; (ii) NW-SE to NNW-SSE structures controlling the Ribeira Grande and the Vila Franca do Campo Grabens, sub-parallel to the Congro fault system (Forjaz 1986, 1988, 1994, Oliveira et al. 1990); (iii) NE-SW to ENE-WSW trending fractures, and (iv) recently developed WNW-ESE minor alignments/lineaments.

The hydrothermal system coupled to the Fogo Volcano comprises an aquifer with boiling water (water, water + steam, and steam) and the productive formation seems to be composed of pillow lavas at about 800 m depth (Forjaz 1994); the measured fluid (water + vapour mix) temperature in the reservoir varies between 220 and 250°C (Forjaz 1994, Carvalho 1999, Carvalho et al. 2006). Meteoric waters infiltrating through Fogo's Lake and the volcano flanks are the primary source of recharge to the geothermal system (Carvalho 1999); the main up-flow zone is controlled by the caldera structure at the top of the volcano and limited to the Ribeira Grande Graben (Carvalho 1999, Carvalho et al. 2006). These thermal fluids have excess enthalpy (boiling fluid) and, separated at atmospheric pressure, are characterised by mineralisation of the sodium-chloride type up to 6-7 g/l.

The most notable superficial expressions of the hydrothermal system are located in the northern flanks of the Fogo Volcano, chiefly controlled by structures related to the Ribeira Grande Graben (Forjaz 1986). These comprise: (i) dry steaming ground at Pico Vermelho and fumarole-bearing ground at Caldeira Velha and Caldeiras da Ribeira Grande (CRG) (cf. Figure 1); (ii) two thermal springs, one placed nearby the Caldeira Velha fumarole site and another (Ladeira da Velha) at sea level, emerging at ≈ 34ºC and 30ºC, respectively; (iii) cold CO_2-rich mineral water springs in the Lombadas valley (e.g. Água das Lombadas with ≈ 2 g/l of total CO_2); and (iv) diffuse emissions of CO_2 (Ferreira et al. 2005). According to Jean-Baptiste et al. (2009), the nearly pure CO_2-composition of the gas emanations is consistent with a continuous gas supply from deep magmatic sources through a CO_2 oversaturated hydrothermal system, allowing almost direct gas transit towards the surface.

The geothermal well RG4 was drilled on a sequence of pumice deposits at surface (with thickness of 10 – 30 m), deposited over a thick sequence of trachytic lava flows which extends to about 100 m depth.

3. OLD CRG FUMAROLIC FIELD

The CRG fumarolic field (Figure 1) is located to the NE of the Ribeira Grande Graben and includes boiling mud-pools besides small groups of fumaroles, some of them confined in an artificial tank built up to supply the existing thermal Spa "Banhos da Coroa". The fumaroles emerge from fractures affecting a trachyte lava flow covered by variably altered trachyte pumice deposits. The fractures can be defined through several alignments inside the tank, the most important ones running NW-SE and WSW-ENE (Carvalho et al 2015).

The CRG fumarole emissions result from hydrothermal steam mixed with volcanic gases all separated from the geothermal aquifer at about 800 m depth (e.g. Carvalho et al. 2006). The emerging aqueous fluids are acidic (pH < 3), hot (≈ 70ºC-90ºC) and display variable mineralisation as a result of mixing of deep vapours/gases with surface waters and progressive hydrothermal alteration of host rocks. This acid fluid displays large contents of sulphate, aluminium and silica attained under oxidising conditions at high gas/water ratios.

The gas composition of fumarole discharges is CO_2 dominated (94 to 99.6 mol%); H_2S and H_2 are two other major components, representing 0.1 to 3 mol% of the total gas, and N_2 concentration rests below 1.5 mol% (e.g. Ferreira et al. 2005). Considering the relative concentrations of minor reactive compounds (CO, H_2 and CH_4), the geothermal system feeding the thermal emissions at the CRG site should be characterised by a boiling saline solution coexisting with a vapour having 8 mol% CO_2 and 92 mol% H_2O (CO_2/H_2O ratio around 0.087) – Carvalho et al. (2015).

The cooling and oxidation of steam released from deep hydrothermal fluids, under boiling, result in the formation of acidic condensates and strong alteration of the hosting volcanic rocks. The acidic condensates are further mixed with surface and shallow groundwater and subjected to a relatively focused flow, promoting variable chemical leaching of rocks and ruling the precipitation of secondary mineral phases (Carvalho et al. 2015). The thermal fluids are retained in a tank, feed by a natural spring and specifically designed to accumulate the clay-rich sediments used in the nearby thermal Spa.

4. NEW FUMAROLIC FIELD

Since the first anomalies detection, in the end of February 2010, it was implemented by EDA RENOVÁVEIS, SA a monitoring program including: temperature measurements in monitoring wells; discrete and continuous measurement of soil temperature and CO_2 degassing; isothermal imaging with a thermal camera; water and gas analysis; seismic reflection survey.

Between May and September 2010 the anomalies increased in number and extension. The new degassing/fumarolic field seems to be stabilized since March 2013 and remain confined to an area of about 39 hectares.

The degassing area is not uniform, and it includes small zones with fumarolic activity of low intensity, very localized and often over small cracks in the soil. In this new fumaroles the temperature sometimes exceeds 90°C, leading to progressive burning of vegetation and continuous hydrothermal alteration of the pumice soil into clay materials (Figures 2 and 3).

Figure 2. General view of the new fumarolic field and degassing area in CRG.

The gas and temperature anomalies define an area of elongated shape along a general NW-SE direction, concordant with the main alignment of the Ribeira Grande Graben (Figure 4). Its spatial distribution is conditioned by tectonic structures already recognized in the area (cf. Forjaz, 1986), which individualize blocks limited by dominant directions NW-SE and E-W to ENE-WSW (TARH 2012).

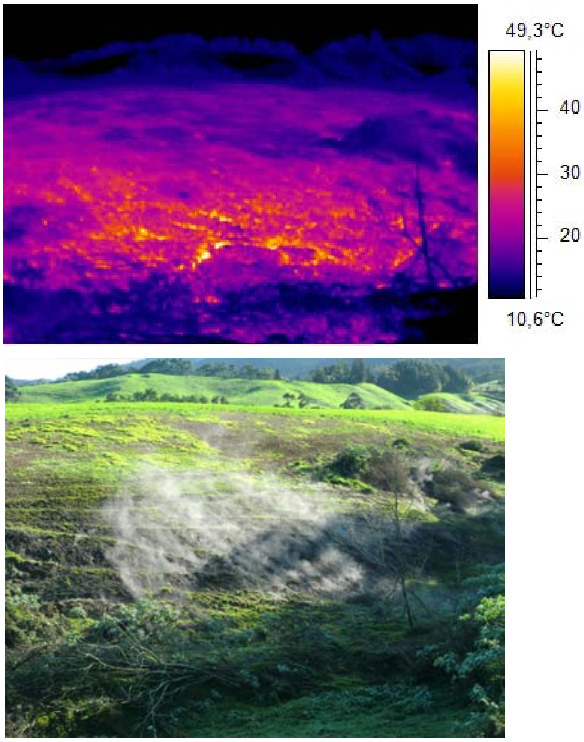

Figure 3. New fumarolic activity at CRG and isothermal imaging with a thermal camera. In: INOVA (2012).

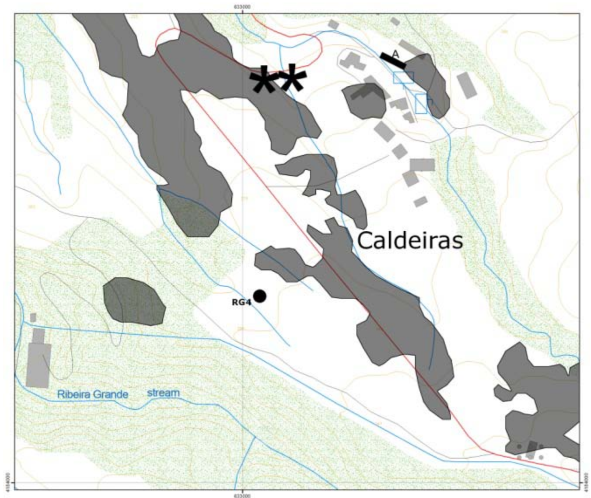

Figure 4. Location of well RG4, new site of direct uses on the Ribeira Grande Geothermal Field (*), the "Banhos da Coroa" thermal Spa building (A) and main CO_2 soil anomalies (in gray), with an elongated shape and a general NW-SE direction.

Fumarolic vents and hydrothermal alteration of soil, causing the loss of the cohesive properties of the soil, were also detected on the slopes of fluvial valeys (Figura 5), namely at the Ribeira Grande stream valey. This thermal activity leads to the occurrence of slope instabilities phenomena, namely through small slumps in the affected area.

Despite heterogeneous mixing/dilution with rain and runoff, the chemical affinities of the new fumarolic emissions established with the thermal fluid emerging at CRG old fumarole are evident.

The gas samples from soil are characterized with high CO_2 contents, with more than 90% mole percent, and relevant concentration of minor compounds such as H_2, CO and CH_4 typical of gases from the geothermal system. They show a chemical composition similar to the natural emission from CRG and CV sites (INOVA 2012).

The relative concentrations of minor reactive compounds (CO, H_2 and CH_4) have been used for geothermometry and geobarometry calculation at equilibrium conditions in the system H_2O-CO_2-H_2-CO-CH_4-O_2. The data are consistent with a geothermal system characterized by a boiling saline solution, with temperatures between 200°C and 340°C, coexisting with a vapour having 8 mol% CO_2 and 92 mol% H_2O (CO_2/H_2O ratio around 0.087) – INOVA (2012).

The gases of the new fumarolic field and those from the traditional CRG fumarolic field have a common origin: deep geothermal fluids originated in the deeper geothermal reservoir. Modest changes in the steam chemistry must be related to climate changes (rainfall, humidity in the air and soil, atmospheric pressure, wind, evapotranspiration), groundwater mixing and outflow channels change due to soil alteration.

Figure 5. CRG new fumarolic emission affecting the slopes stability (top) and mitigation measures (bottom). In: INOVA (2012).

Overall interpretation of the investigations done (TARH 2012) revealed that hot water and steam originating from a depth of about 240 m was entering a shallow trachyte lava flow through fracturing channels, mostly controlled by the local tectonics. Thermal water and steam moves through the upper part of the trachyte lava flow, which develops about 10-30 m below surface and covered by tuffs and pyroclastic pumice fall deposits.

5. DIRECT USES OF THE GEOTHERMAL FLUID

Ancient and modern direct uses in balneology and cooking are well known around the world in geothermal areas. In Azores (particularly in S. Miguel island) there is a strong tradition of cooking in the fumaroles as in Furnas fumaroles and even in Caldeiras da Ribeira Grande.

Following the RG4 drilling, several monitoring and mitigation and remediation measures were accomplished in the area of Caldeiras da Ribeira Grande to contain damages in buildings, account for slopes instability and increase the overall safety in the new fumarolic field area. In a later stage, given the quasi-stabilization of the phenomena, it was decided to implement non invasive mitigation measures and to develop approaches to promote the new thermal resource in the area, does trying to convert a problem into an opportunity.

Among these, new balneological facilities and other recreational and touristic uses, the rehabilitation of the old thermal Spa, as well as the heating of some houses are under scrutiny. Meanwhile it seemed evident the immediate construction of leisure and recreational structures for direct uses of the geothermal fluids, namely by traditional “geothermal cooking” spots, most appreciated by the local population.

Thus, in the second semester of 2014 a set of 9 new “geothermal cooking” spots were implemented by EDA RENOVÁVEIS, SA in the Caldeiras da Ribeira Grande area (Figures 6 and 7), taking profit of the new fumarolic vents and degassing areas.

This new attraction – now very popular and with growing attention, namely due to the increasing of the tourism activity in S. Miguel – constitutes an important anchor for the local income and the rehabilitation and valuing of the Caldeiras da Ribeira Grande village and its thermal Spa.

6. FINAL CONSIDERATIONS

The passive geothermal cooking spot facilities now developed are the first step for the rehabilitation of the area of the CRG new fumarolic field.

Further developments needs exploration activities in order to determine where the new resource is located, and its temperature, areal extent and depth (Lund 2013; TARH 2012). Furthermore, if the resource is developed and utilized, what is the expected sustainability in temperature and heat flow?

Figure 6. Direct uses in the CRG new fumarolic field: remediation measures through traditional "geothermal cooking" spots.

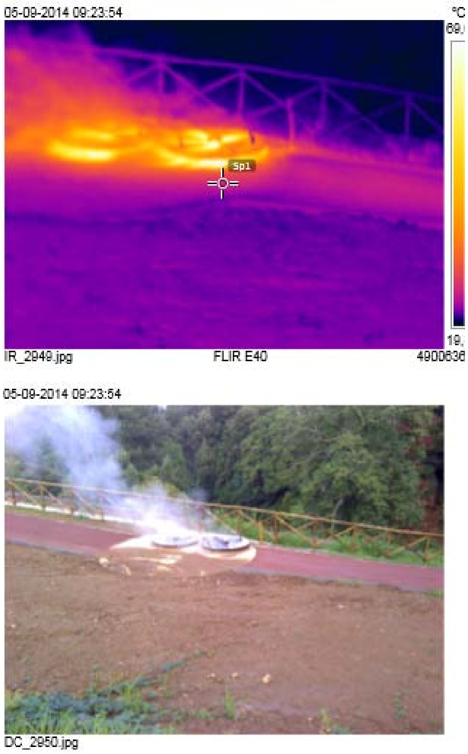

Figure 7. Direct uses in the CRG new fumarolic field: remediation measures through traditional "geothermal cooking" spots and its isothermal imaging with a thermal camera. Photos by EDA RENOVÁVEIS, SA (Sep., 2014).

Also, as heating/cooling developments can be envisaged in the future, an important issue is the heating and cooling demand to be satisfied. That is, can the investment in development(s) justify the capital and maintenance expenditure over a reasonable period of time?

In theory several developments, generating employment and income and following the Lindal Diagram (Lindal 1973), could be thought for this site, depending on the available resource and its sustainability. However it seems advisable a step by step approach trying to look for a hypothetical increasing demand using tailor made solutions exchanging: this is the case of designing surface exchangers using the local water resources or thermal swimming pools for balneological and other recreational and touristic uses.

REFERENCES

Agostinho, J.: Actividade vulcânica nos Açores. Açoreana, **v.5**, (1960), 362-478.

Assunção, C.F.T.: Estudo petrográfico da ilha de S. Miguel (Açores). Com. Serv. Geol. Portugal, **Tomo XLV**, (1961), 81-177.

Assunção, C.F.T., Canilho, M.H.: Notas sobre petrografia comparada das ilhas Atlânticas (Arquipélagos dos Açores e de Cabo Verde). Bol. Museu Lab. Minerlog. Geolog. da Fac. Ciências, **11(2)**, (1970), 305-342.

Booth, B., Croasdale, R., Walker, G.P.L.: A quantitative study of five thousand years of volcanism on São Miguel, Azores. Phil. Trans. R. Soc. Lond., **228**, (1978), 271-319.

Carvalho, J.M., Coelho, L., Nunes, J.C., Carvalho, M.R., Garcia, J. and Cerdeira, R.: Portugal Country update 2015, *Proceedings of the World Geothermal Congress 2015*, Melbourne, Australia, (2015), paper #01065, 11 pp.

Carvalho, M.R.: Hidrogeologia do Maciço Vulcânico de Água de Pau/Fogo (S. Miguel – Açores). Dissertação para obtenção do grau de Doutor em Geologia, na Especialidade de Hidrogeologia. Universidade de Lisboa, Lisboa, (1999), 445 pp.

Carvalho, M.R., Forjaz, V.H., Almeida, C.: Chemical Composition of Deep Hydrothermal Fluids in the Ribeira Grande Geothermal Field (São Miguel, Azores). Special Issue "Volcanic Geology of the Azores Islands", of Jour. Volcanol. Geothermal Research, **156 (1-2),** (2006), 116-134.

Carvalho, M.R., Mateus, A., Nunes, J.C., Carvalho, J.M.: Origin and chemical nature of the thermal fluids at Caldeiras da Ribeira Grande (Fogo Volcano, S. Miguel Island, Azores). Environ Earth Sci., **73**, (2015), 2793-2808.

Castro, E.V.P.C.: Recherches micrographiques sur quelques roches de l'Ile de San Miguel, (Açores). Imprimerie Nationale, (1888), 7-91.

Viveiros, F., Ferreira, T., Marques, R., Silva, R., Medeiros, A.R., Pacheco, P., Silva, C., Pacheco, J.E., Medeiros, B., Gaspar J.L.: Monitorização da área envolvente à plataforma do furo geotérmico de avaliação RG4 (Campo Geotérmico da Ribeira Grande). Relatório anual - 2014. DTC 23/CVARG/CIVISA/15, (2015)., 61 pp.

Duffield, W.A., Muffler, L.J.P.: Geothermal Resources of São Miguel Island, Azores, Portugal. U.S. Geol. Survey Open-File Report **84-287**, (1984), 21 pp.

Ferreira, T., Gaspar, J.L., Viveiros, F., Marcos, M., Faria, C., Sousa, F.: Monitoring of fumarole discharge and CO2 soil degassing in the Azores: contribution to volcanic surveillance and public health risk assessment. Ann. Geophys., **48**, (2005), 787–796.

Forjaz, V.H.: Ilha de S. Miguel (Açores) - Carta tectónica na escala 1:50.000. Doc. Int. CV/INIC, 09/86, (1986).

Forjaz, V.H.: Azores study tour: Field tripe guide. In Seminar on the prediction of earthquakes. Econ. Comm. for Europe, U.N. Lisbon, (1988), 36 pp.

Forjaz, V.H.: Geologia económica e aplicada da ilha de S. Miguel (Açores): recursos vulcanogeotérmicos. Dissertação para Provas de Doutoramento. Universidade dos Açores, Ponta Delgada, (1994), 599 pp.

Fructuoso, G.: Saudades da Terra. Vol. IV. Reimpresso de 1563. Diário dos Açores. Ponta Delgada, (1926).

Girod, M., Lefévre, C.: A propos des "andesites" des Açores. Contrib. Mineral. Petrol., **15,** (1972), 159-167.

Jean-Baptiste, P., Allard, P., Coutinho, R., Ferreira, T., Fourré, E., Queiroz, G., Gaspar, J.L.: Helium isotopes in hydrothermal volcanic fluids of the Azores archipelago. Earth and Planetary Science Letters, **281 (1-2**), (2009), 70-80.

INOVA: “Projecto TERMAZ – Monitorização dos sistemas hidrogeológicos das Caldeiras da Ribeira Grande e Lombadas”, Relatório de Progresso. Documento interno INOVA (2012).

Lindal, B.: Industrial and other applications of Geothermal Energy. In: ARMSTEAD H. C. H., ed., Geothermal Energy, UNESCO, Paris, (1973).

Lund, J.W.: Recommendations for the Development and Utilization of the Fumarole Area. SOGEO Report (2013). 11 pp.

Machado, F.: Alguns Aspectos da Sismicidade dos Açores. Mem. Ordem Eng., **107**, (1955), 1-6.

Moore, R.: Geology of three late Quaternary stratovolcanoes on São Miguel, Azores. U.S.G.S. Bulletin, **1900**, (1991), 1-26.

Nunes, J.C.: Geologia, in: Atlas Básico dos Açores, Forjaz, V.H. (Ed.), 60-62, *Observatório Vulcanológico e Geotérmico dos Açores*, Ponta Delgada, (2004).

Nunes, J.C., França, Z., Forjaz, V.H., Macedo, R., Lima, E.A.: Poligenetic volcanoes of Azores archipelago (Portugal): size, nature, eruptive styles and related volcanic hazard. Poster – 32nd International Geological Congress – Abstracts (part 1), August. Firenze. Itália, (2004), p. 336.

Oliveira, C.S., Costa, A.C., Forjaz, V.H., Nunes, J.C.: Seismic Hazard Analysis in Zones of Time and Space Interdendence: An Application to São Miguel Island, Azores. Natural Hazards, **3**, (1990), 15-29.

TARH: Intervenção na Área das Caldeiras da Ribeira Grande. Relatório Final 020412, Maio 2012, (2012), 46 pp.

Wallenstein, N.: Estudo da história recente e do comportamento eruptivo do Vulcão do Fogo (S. Miguel, Açores), Avaliação preliminar do Hazard. PhD thesys. Universidade dos Açores, Ponta Delgada, (1999), 255 pp.

Weston, F.S.: List of recorded volcanic eruptions in the Azores with brief reports. Bol. Museu. Lab. Mineralog. Geolog. da Fac. Ciências de Lisboa, 10 (1), (1964), 3-18.

Zbyszewski, G., Almeida, F.M., Ferreira, O.V., Assunção, C.T.: Carta Geológica de Portugal na escala 1:50.000. Notícia explicativa da folha B, S. Miguel (Açores). Serv. Geol. Port., Lisboa, (1958), 37 pp.

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