Geothermal Geology of the Outflow Zone of the Ribeira Grande Geothermal System, São Miguel Island, Azores

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ABSTRACT

The Ribeira Grande geothermal system has a 245ºC two-phase liquid dominated reservoir whose limits have been only partially defined by deep drilling. The positions of its southern and western boundaries were inferred with reasonable confidence from older wells, but its eastern and northern limits had not been defined previously. In this study, we have investigated geological and geothermal data from recent exploratory wells drilled in the northern part of the field, interpreting these along with surface geological data and geothermal data from nearby wells to improve the local conceptual model of the geothermal system. The results allowed us to delineate the extent of the outflow zone of the high-temperature reservoir, which is restricted laterally to the western side of the scoria cone of Pico das Freiras. This suggests that the Pico das Freiras eruptive fissure may be a volcano-tectonic flow barrier that limits northeastward outflow.

1. Introduction

The Ribeira Grande geothermal system is located on the northern flank of the Fogo volcano on the island of São Miguel in the Azores archipelago (Figure 1). The system has a 245ºC two-phase liquid-dominated reservoir that can be tapped by relatively shallow wells (1000-1300 m deep). The system is elongated in a northwesterly direction, and has western and southern boundaries that have been reasonably well defined by existing wells, but its eastern and northern boundaries have not been yet confirmed (Pham et al., 2010; Ponte et al., 2010; Rangel et al., 2011).

The reservoir upflow zone is inferred to be in the southeastern part of the geothermal field. From there, the high-temperature fluid moves northwestward, following the slope of the Fogo volcano and probably with some degree of control by fracture zones associated with the graben of Ribeira Grande (Duffield, 1984; Gandino et al., 1985; Henneberger & Nunes, 1990; Granados et al., 2000; Pham et al., 2010). It appears that the thermal water discharges from the system offshore of the city of Ribeira Grande (Figures 1 and 2), but the extent of the discharge is not fully understood.

In 2009, 3 new reinjection wells were drilled in the northern part of the field to relocate the reinjection from the Pico Vermelho power plant. Well PV11 was drilled close to well RG2, whereas PV9 and PV10 were step-out wells, intended to explore the area near the scoria cone of Pico das Freiras, where high reservoir permeability was expected. The results of the step-out wells, complemented by data from the nearby TG4 (a 1972 exploratory temperature gradient well drilled by the University of Dalhousie, as described Muecke et al., 1974 and McGraw, 1976), allow for evaluation of the reservoir conditions within the Pico das Freiras area and assessment of the extent of the outflow zone.

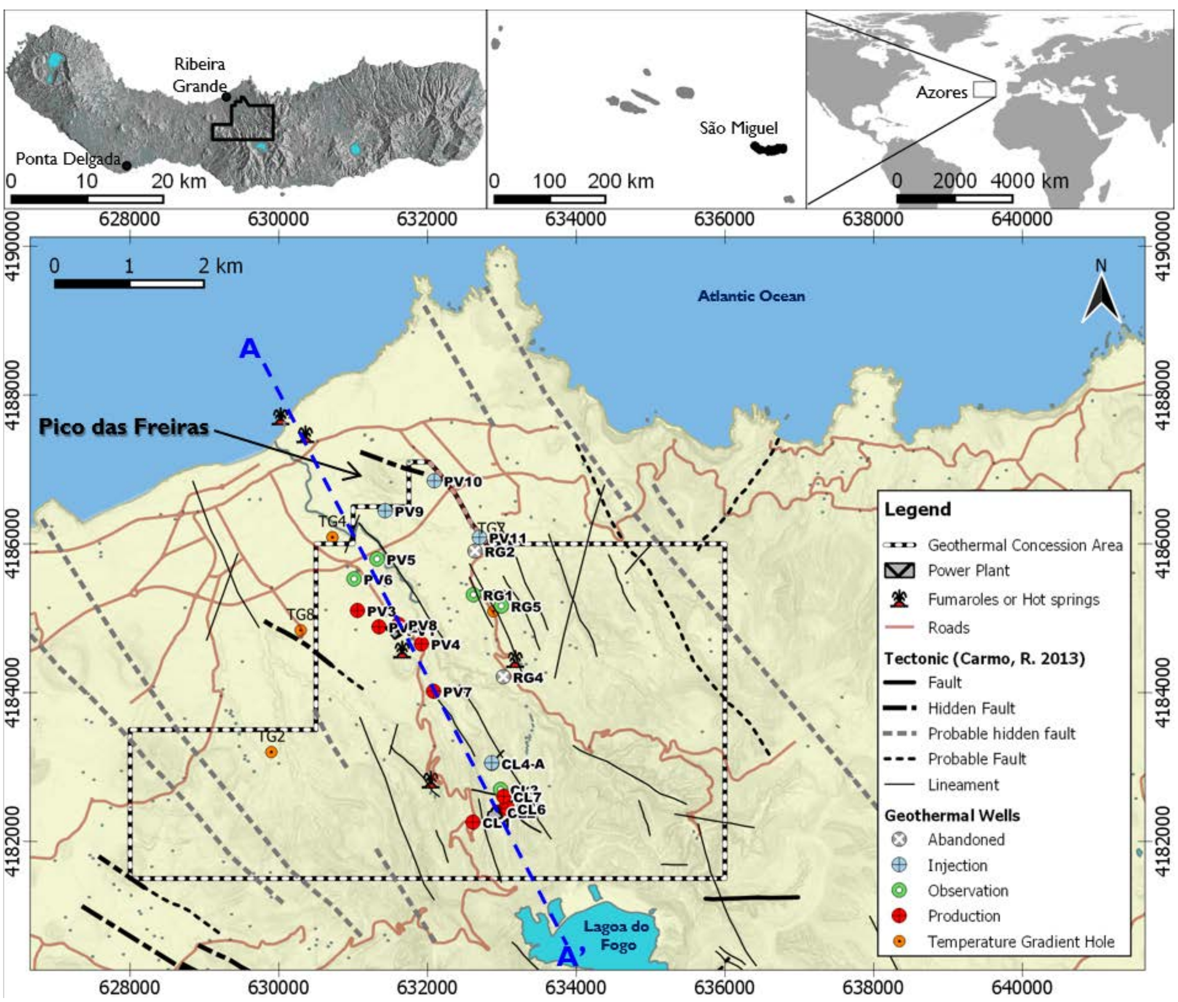

Figure 1: Location of the Ribeira Grande geothermal field and the study area

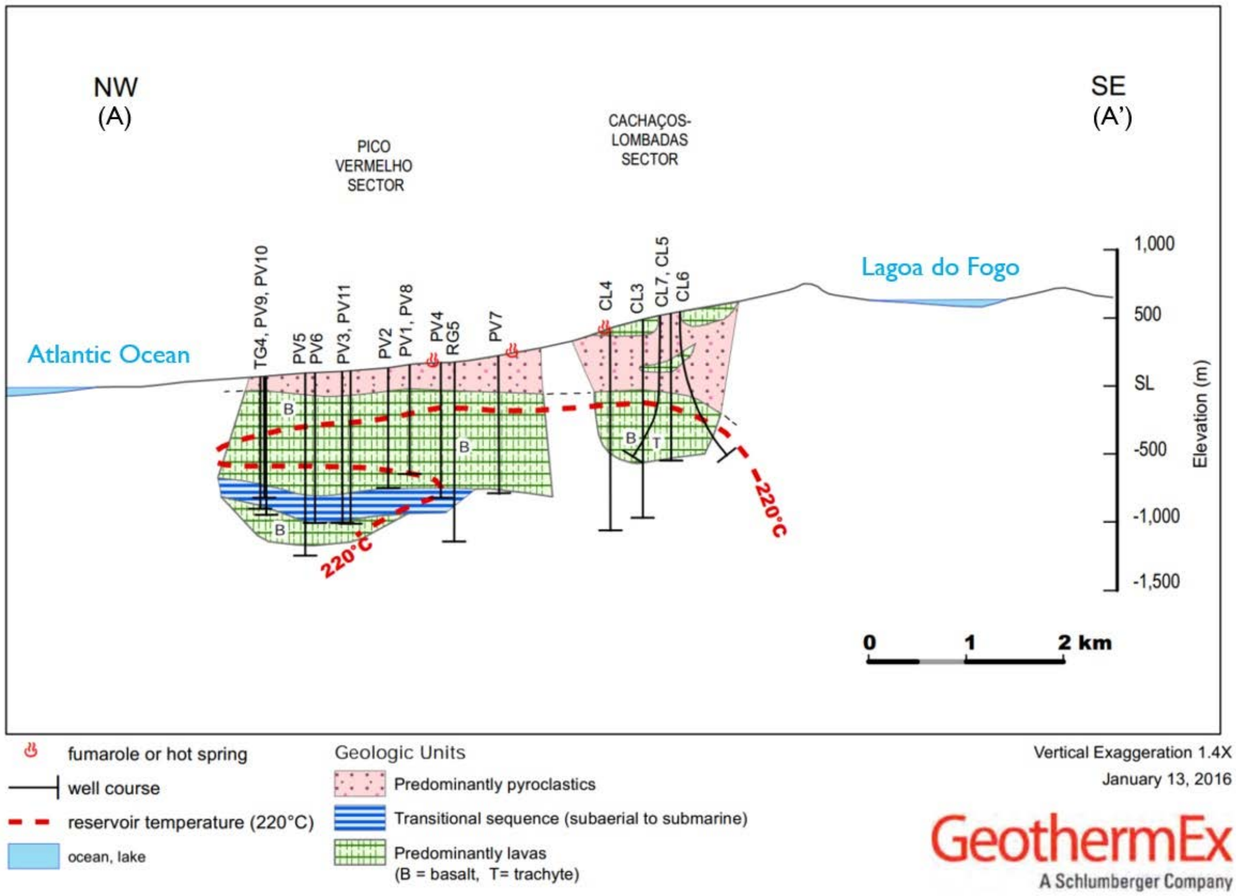

Figure 2: Generalized cross-section A-A' (Figure 1) of Ribeira Grande geothermal system (GeothermEx, 2016).

2. Geothermal geology of the Pico das Freiras area

Pico das Freiras is a spatter cone dated at between 5 and 10 thousand years of age (Moore, 1991a and 1991b). It was built by basaltic scoria and lapilli ejected while still hot enough to agglomerate around the eruptive fissure, increasing the height of the cone to a maximum height of 107 m a.s.l, with a NW-SE elongation. The main crater is open to the east, and Carmo (2013) has identified a second crater that forms a NW-SE alignment with the main crater, defining the lineament of the eruptive fissure. Beds of different grain sizes can be observed within the scoria deposits in a quarry at Pico das Freiras, suggesting that the cone was built by more than one eruptive event, or by different pulses within a single event (Wallenstein, 1999). Like other scoria cones in the Ribeira Grande geothermal field, the eruptive fissure of Pico das Freiras could affect reservoir permeability in the geothermal system, and thereby have an influence on the pattern of outflow.

The subsurface geology of the Pico das Freiras area was interpreted based on the binocular analysis of drill cuttings recovered during drilling of PV9 and PV10, and on the detailed petrographic descriptions of drill cores recovered from TG4 (McGraw, 1976). Geothermal data from these and other nearby wells were investigated to improve the local conceptual model of the geothermal system. The results are schematically depicted in Figures 3 and 4 and the main findings are summarized below.

2.1 Subsurface geology and hydrothermal alteration

The subsurface geology in the Pico das Freiras area (Figure 4) is consistent with what is observed in other parts of the Ribeira Grande geothermal system (Figure 2). At shallower levels, pyroclastic deposits of mainly trachytic composition are predominant – these include air fall deposits (tuffs, lithic tuffs and pumice) and flow deposits (ignimbrites). The pyroclastic sequence is locally interrupted by lava flow units, mostly of trachyte and trachybasalt compositions. In some places, the lava flow units can be traced over distances of a few hundreds of meters, allowing for a few generalized well-to-well correlations.

Beneath the pyroclastic-rich sequence, basalt lavas predominate over an interval of several hundreds of meters. These lavas are fractured and they host the high-temperature reservoir of the Ribeira Grande system. The bottom limit of the reservoir appears to coincide with the transition to submarine rock formations (hyaloclastite units, pillow lavas and submarine breccias). These are found in TG4 and PV10, respectively, at -600 m and -950 m a.s.l.. The submarine sequence was not identified in PV9, likely because the well was drilled without returns below -550 m a.s.l., but its identification in PV10 corroborates the high subsidence rate proposed by Muecke et al. (1974) for the graben of Ribeira Grande.

No intrusive rock units were identified in the new PV wells, but this does not preclude their presence, because reliable identification of such units by simple binocular analysis of drill cuttings cannot be assured, and, as noted, the deeper part of PV9 was not sampled because it was drilled without returns.

The hydrothermal alteration observed in the wells of the area is consistent with the proposal from Franco (2016) for the wells in the southern part of the field. A shallow unaltered zone extends from the surface to about -50 to -150 m a.s.l., followed by a zone of intense alteration to clay from about -50 to -350 m a.s.l., accompanied by the appearance of secondary silica minerals. Silicification increases with depth in the latter interval (in a sequence of opal – chalcedony – quartz), and zeolites, pyrite and chlorite appear. This interval forms the cap rock of the geothermal system. The transition to reservoir conditions occurs at -250 to -350 m a.s.l.; this zone is marked by the disappearance of low temperature clays, and an alteration mineral assemblage dominated by chlorite, quartz, calcite and pyrite.

Based on the secondary mineralogy observed in TG4, PV9 and PV10, the top of the cap rock is interpreted to be at -150 to -200 m a.s.l. (Figure 3). In more detail, the top of the cap rock is found at a slightly shallower level in wells TG4 and PV9 than PV10, suggesting that PV10 area was (and likely still is) located in the periphery of the high-temperature reservoir.

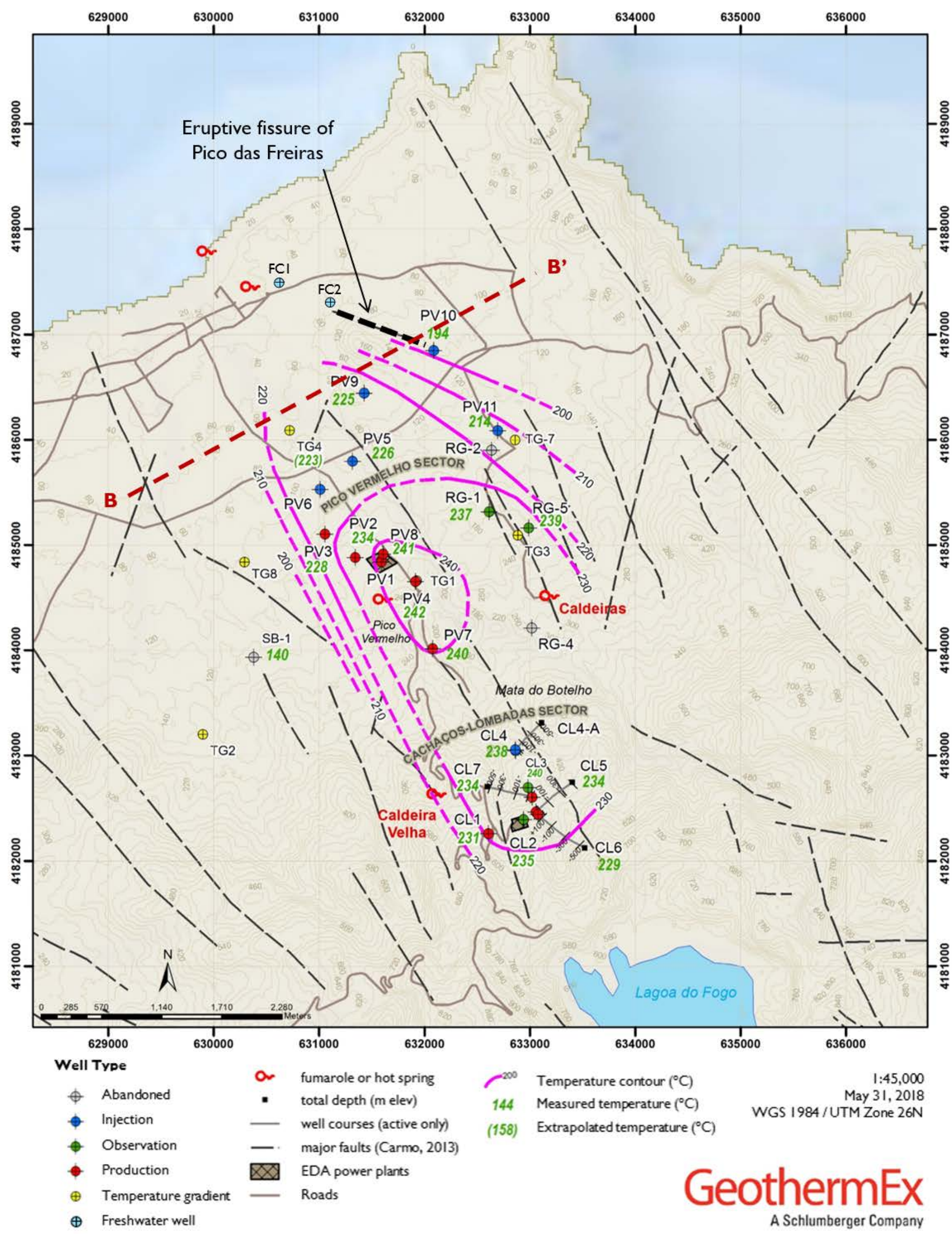

Figure 3: Temperature contours at -400 m a.s.l. (adapted from GeothermEx, 2016).

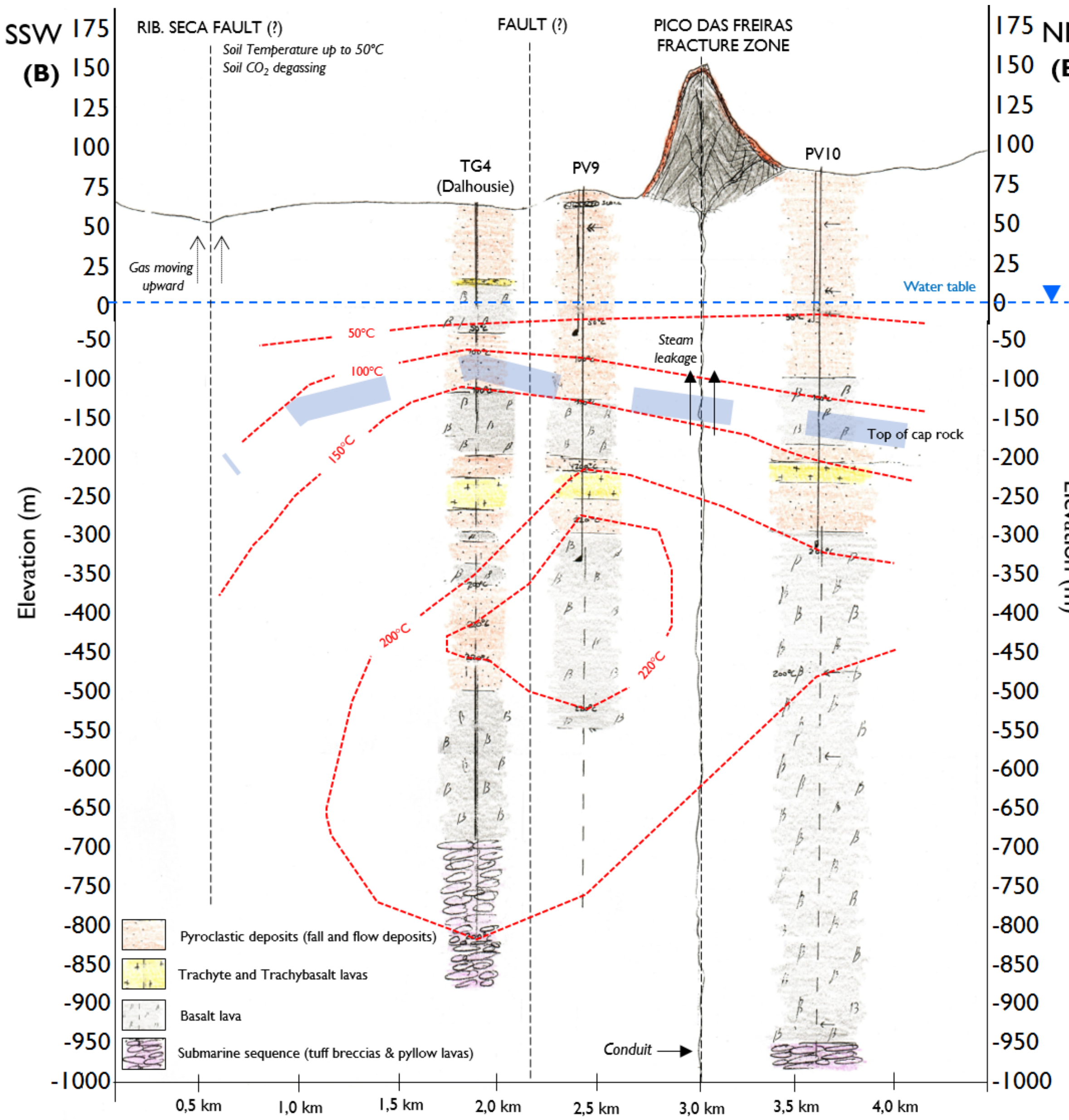

Figure 4: Conceptual model of the Ribeira Grande geothermal system at Pico das Freiras area (cross section A-A' from Figure 3)

2.2. Permeability

Migration through fractures is the most efficient means of transporting magma through the earth's crust (Watanabe et al., 1999). Therefore, the NW-SE eruptive fissure of Pico das Freiras (Carmo, 2013 & 2015) represents the most likely source of concentrated fracture permeability in the study area, either in the form of pre-existing fracture zones or as fractures along the chilled margins of the intrusives that moved upward through the crust and formed the plumbing system of this scoria cone. This implies that this sector of the geothermal system had (and might still have) significant vertical permeability. The geometry of the intrusives that fed the volcanic activity is uncertain, but the genesis of monogenetic cones is often associated with steeply dipping (>70°) fault systems (Kereszturi and Németh, 2013), so the Pico das Freiras conduit (and related dykes) is probably near-vertical, parallel to its eruptive fissure.

Other, more indirect, evidence of permeability is given by the warm temperatures (up to 40ºC) observed in the coastal aquifer of Ribeira Grande, which is tapped by the freshwater wells FC1 and FC2 (Freire, 2006 & 2013; Costa, 2006; Cruz et al., 2010 & 2015), located, respectively, 600 and 300 m northwest of Pico das Freiras (Figure 3). This aquifer may be heated by geothermal steam breaching the cap rock and venting upward wherever there is adequate vertical permeability, or simply by conductive heating from the high-temperature reservoir. In either case, the heat transport is probably facilitated by the pre-existing fracture zones or the chilled margins of the intrusives associated with the NW-SE eruptive fissure of Pico das Freiras, with these providing highly permeable pathways for fluid flow.

In addition, Caniaux (2003) has reported gas emissions offshore of the city of Ribeira Grande and these may be manifestations of an undersea extension of the Ribeira Grande system. The offshore gas emissions and the warm water wells FC1 & FC2 are aligned with the NW-SE eruptive fissure of Pico das Freiras (Figure 2), indicating that this volcano-tectonic structure might be a vertical permeable pathway feeding these manifestations.

The vertical displacement between the top of the submarine formations found at -700 m in TG4 and at -950 m a.s.l. in PV10 may also be related to reservoir permeability. The displacement suggests the presence of a tectonic structure between the two wells, with the most immediate candidate being the fault system associated with the eruptive fissure of Pico das Freiras.

Both PV9 and PV10 found major permeable zones at shallow levels (from the surface and down to sea level). At deeper levels, PV9 found a major permeable zone at -550 m a.s.l., whereas PV10 found only very limited permeability, suggesting that it may be in the periphery of the reservoir.

2.3. Subsurface temperatures

Analysis of temperature distribution is a key tool to assess the patterns of fluid movement within the geothermal reservoirs (Grant & Bixley, 2011). Stabilized temperature profiles measured in PV9, PV10 and other nearby wells were therefore interpreted to characterize the temperature distribution in the northern part of the geothermal system and thereby evaluate the extent of the outflow zone.

In Pico das Freiras area, the temperature distribution at shallow levels is not well known, particularly to the north of this scoria cone. Nevertheless, temperatures up to 50ºC were measured close to sea level in PV9 and PV10, and these are consistent with what is observed in the nearby freshwater wells FC1 and FC2. Below sea level, the temperature profiles (Figure 5) show a conductive zone, in which temperatures progressively increase with depth until the top of the reservoir (inferred to be at -220 m); this is consistent with the limited permeability found in this interval.

The transition to reservoir conditions is marked by an isothermal zone (indicating convection), which seems to be confined to a relatively narrow vertical interval of a few hundreds of meters

(-200 to -550 m). Below this zone the temperature declines, with PV9 and PV10 showing a distinct temperature reversal at the bottom. This feature confirms that they intersect the lateral outflow of the reservoir, and is consistent with that observed in other PV wells (GeothermEx, 2016).

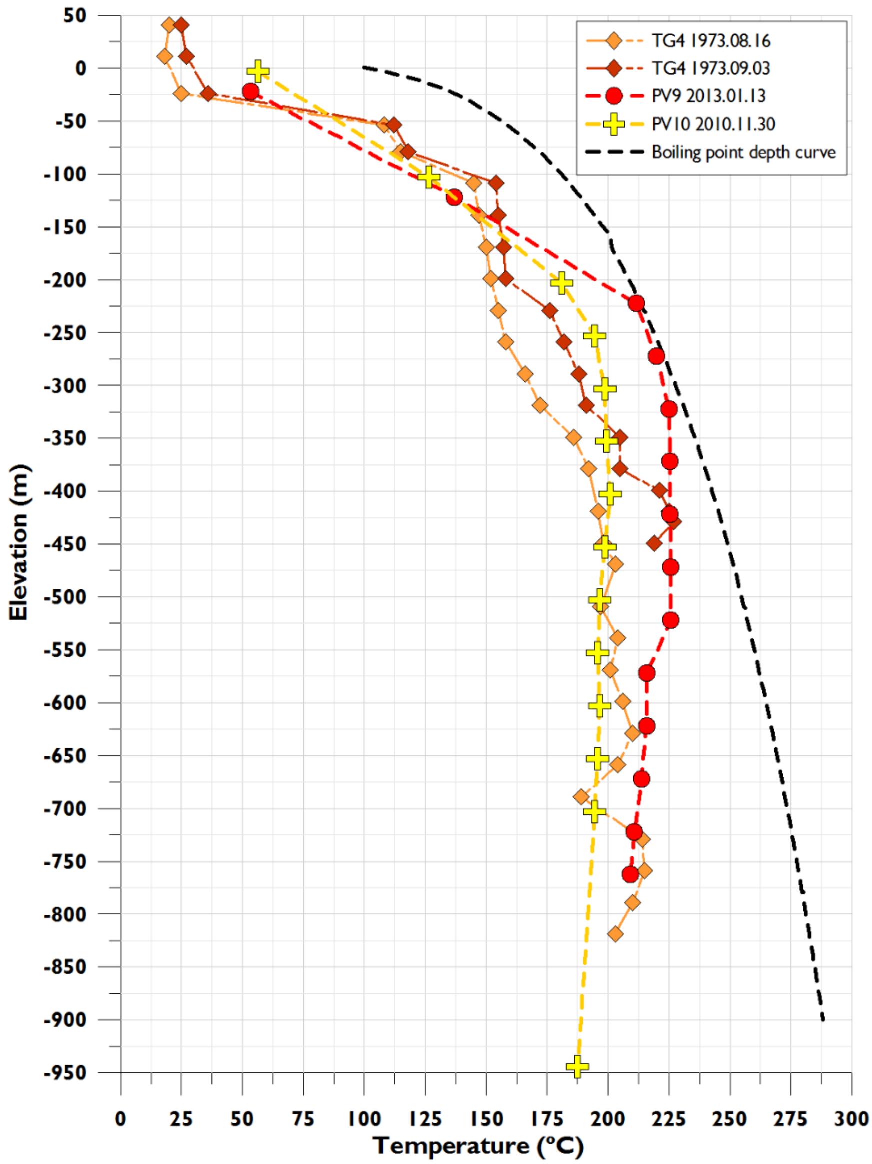

Figure 5: Stabilized temperature profiles measured in PV9, PV10 and TG4

Reservoir temperatures are distinctly lower in PV10 than in PV9, which may reflect the influence of the NW-SE Pico das Freiras eruptive fissure, acting as a local impermeable barrier or as a main fluid conduit deflecting most of the flow towards the northwest. A similar type of structural control on hydrothermal flow is described by Rowland and Sibson (2004) for the Taupo geothermal system in New Zealand. In either case, the eruptive fissure seems to limit the flow towards the northeast. Moreover, lower reservoir temperatures are also found in TG4 (compared to PV9), suggesting that most of the outflow likely occurs along the western part of Pico das Freiras, through a narrow area where PV9 is located. The temperature profiles shown in Figure 4 confirm that PV9 intersects a hotter part of the reservoir, providing further evidence that the main outflow occurs through the PV9 area.

3. Conclusions

The results of the recent step-out wells PV9 and PV10 have allowed for improvement of the conceptual model of the Ribeira Grande geothermal system, providing valuable data about the subsurface geologic and geothermal conditions within the northern part of the system.

Our investigation indicates that the main outflow from the geothermal system takes place within a narrow zone to the west of the scoria cone of Pico das Freiras, where well PV9 is located, and that the lateral outflow occurs within a confined vertical interval of 200-300 meters. The eruptive fissure of Pico das Freiras likely limits the lateral outflow of geothermal fluid towards the northeast, either by acting as an impermeable barrier and/or by deflecting most of the outflow in a northwesterly direction. Thus, the eruptive fissure of Pico das Freiras probably corresponds to the northeastern limit of the high-temperature Ribeira Grande reservoir.

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