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New geologic insights for the Pico Alto Geothermal Field (Terceira Island, Azores, Portugal) as a key tool for its conceptual modelling

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ABSTRACT

The Pico Alto Geothermal Field (PAGF) is emplaced on a high volcanological complexity area in the central part of Terceira Island (Azores archipelago, Portugal), where Pico Alto and Guilherme Moniz silicious polygenetic volcanoes with caldera and the Basaltic Fissural Zone formations outcrop and interact. At depths, the geothermal system interacts also with the Santa Bárbara central volcano with nested caldera formations that outcrop further east.

Through information from a detailed 1:10,000 geological mapping and new insights on the associated surface geology, volcanostratigraphy, morpho-tectonics and absolute ages on the PAGF and its surrounding areas, this work presents relevant geologic and volcanological inputs to the building up of a comprehensive and robust conceptual model to the Pico Alto Geothermal Field, where a pilot geothermal power plant 3.5 MW is under construction and should be running in the first semester of 2017.

To built up a well constrained and robust conceptual model, the geologic mapping and interpretative profiles produced were coupled with temperature distribution, AMT anomalies, geophysic (e.g. microgravimetric), boreholes data (cuttings, lithological logs) and hydrogeological characterization of the deep geothermal system. This integrated, multi-disciplinary approach to understand the "plumbing" of the Pico Alto Geothermal Field also raised relevant key issues about the deep geology of Terceira Island and the evolution of its active central volcano systems, Santa Bárbara and Pico Alto, the latest silicious in composition and the younger volcanic centre of Terceira Island.

The geosciences data gathered about the PAGF are considered essential information within the framework of the IMAGE Project (Integrated Methods for Advanced Geothermal Exploration) to built a 3D model representation and visualization of this geothermal system.

1. INTRODUCTION: GEOMORPHOLOGY OF TERCEIRA ISLAND

The morphology of the Terceira Island reflects its volcanic nature and the tectonic events that occurred on the island since its formation: the presence of four composite volcanoes with subsidence caldera, the scoria cones fields in its central and SE sector and the NW-SE trending Lajes Graben, at the northeastern sector of the island, are key features on its landscape (Figure 1).

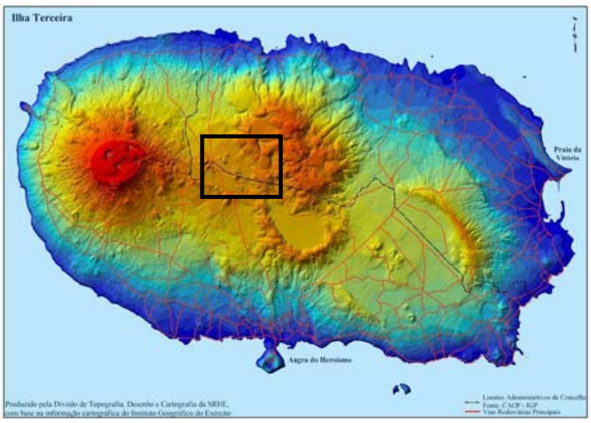

Figure 1. Digital elevation map of the Terceira Island. Source: Azores Government (SRHE/DTDC). Rectangle indicates the actual exploration area.

The morphology of the central part of the islands is dominated by the Guilherme Moniz and Pico Alto massifs that correspond to two polygenetic siliceous volcanoes with caldera, the later caldera almost completely flooded by trachyte *s.l.* domes and *coulées*, including the Biscoito Rachado and Biscoito da Ferraria *coulées* (Figure 2). To west of these central volcanoes, it is the flatten area of the Basaltic Fissural Zone and the eastern flanks of the Santa Bárbara polygenetic volcano with caldera that dominates the landscape.

The geomorphology of the PAGF area and its vicinity can be characterized by two main sectors (Nunes, 2015):

i) the western sector, as a gentle slopes and flattened area, that reaches maximum elevation of 530 m and is dominated by several scoria cones and associated lava flows of the Basaltic Fissural Zone (BFZ). These eruptive centers are located mostly on the axial part of the BFZ, defining volcano-tectonic alignments with a general WNW-ESE trend, as it is the case of the fissure system of the Pico Gaspar. To the north and to the south of these alignments/axial part, the lava flows poured down along the slopes in direction of the north and/or south coast of the island.

ii) the eastern sector, a more vigorous and rugged terrain, with altitudes greater than 700 m (namely at Biscoito Rachado, Biscoito da Ferraria and Terra Brava), that corresponds to the domes and *coulées* associated with the Pico Alto volcano. These trachyte *s.l.* flows are either flooding the caldera floor, either overflowing the caldera walls and moving along the flanks of the volcano, as it is the case of the Pico das Pardelas and Pico Alto *coulées*.The Rocha do Chambre-Juncal, Serra do Labaçal, Caldeira da Agualva and Quinta da Madalena rocky steep cliffs are the nowdays expression of the Pico Alto caldera wall.

Figure 2. Pico Alto Volcano caldera, with the caldera wall (Serra do Juncal) and the intra-caldera coulée of Biscoito da Ferraria.

This morphological contrast has a similar contrast in terms of vegetation and human occupation: the western sector is dominated by grassland and higher density of paths and roads, while the eastern sector is dominated by forested land (including important areas of native laurel forest and bushes) and less paths and roads, due to topographic and environmental constrains. In certain high altitude areas, the surface formations are deeply weathered (e.g. soils) and especially in flatten areas and where detritical/pyroclastic material allows it, there are several bogs and temporary wetlands.

2. VOLCANIC AND GEOLOGICAL FRAMEWORK OF THE PICO ALTO GEOTHERMAL FIELD

The detailed 1:10,000 geological mapping of the central part of Terceira Island (Nunes et al., 2014) and the PAGF area (Nunes, 2015) show that the Pico Alto Geothermal Field is emplaced on a high volcanological complexity area in the central part of Terceira Island (Append 1). In that area, the Pico Alto and Guilherme Moniz polygenetic volcanoes and the Basaltic Fissural Zone formations outcrop and interact. Furthermore, at depths, they also interact with the Santa Bárbara Volcano formations that outcrop further east (Figure 3).

Thus, and unlike the Fogo Volcano Geothermal Field (in S. Miguel Island) – where the geothermal system is emplaced on the northern flanks of a single volcanic system – the characterization and understanding of the PAGF impose different, new and creative approaches, at all levels.

A detailed characterization of the geology and volcanology of the PAGF is presented in Nunes (2015, 2016), which is summarized here with special emphasize on relevant aspects of the volcanic and geological conditions of that area that impact on the conceptual model of the geothermal field.

It is worth mentioning that the more common rock types in Pico Alto Volcano are trachytes, rhyolites and trachydacites, and with minor quantities of trachybasalts, either as pumice fall deposits and pyroclastic flows/ignimbrites, either as lava flows (*coulées* and domes), the later clearly dominant on Holocene times.

A similar pattern is true for the Guilherme Moniz Volcano (in this case with the pyroclastic deposits being dominant), but this polygenetic volcano has a basaltic “root” at sea level (Nunes et al., 2001), only observed on its south shoreline, namely at the Angra do Heroísmo sea cliffs underneath the surtseyan tuffs of Monte Brasil. On its north shoreline, those formations are concealed by the trachytic younger rocks of Pico Alto Volcano, that when extruded overlapped them and increased the size of Terceira Island towards north (Figure 4).

That basaltic *s.l.* sequence is also present at the base of the Santa Bárbara Volcano, around almost all its base at sea level, sometimes reaching highs of about 100 meters, as it is the case in the western and northwestern coast, from Doze Ribeiras to Serreta (e.g. Zbyszewskiet al., 1971), with thick compound lava flows outcropping on the shoreline.

Similar basaltic *s.l.* formations associated with basic volcanism are present in the area of the PAGF only associated with the Basaltic Fissural Zone (BFZ) and has a thin sequence of basaltic *s.l.* lava flows and scoria deposits overlapping, “flooding” and burying the area between the Guilherme Moniz and Pico Alto volcanoes, on the east and the eastern flanks of Santa

Bárbara volcano, on the west (cf. Figures 1, 3 and 4, and Nunes et al., 2014).

Self (1976) identified a caldera at Pico Alto Volcano, which general topographic expression and boundaries are outlined in Nunes (2015), as a 3.5 x 2.4 km and NW-SE oriented depression (Append 2). Its topographic expression is discontinuous and the caldera rim is overflowed/buried by domes and *coulées* (many of them Holocene) giving a depression of horseshoe shape which is hidden to the southeast (cf. Figures 3 and 4).

The caldera is elongated in the general direction of the Pico Alto volcanic system and it has produced (almost) exclusively trachytic s.l. rocks, among them sheets of ignimbrite (e.g. the Lajes-Angra ignimbrite, Self, 1976), dated at 19,000 and 23,000 years BP. Post 23,000 years basalts have been erupted on the distal part of the Pico Alto central plumbing system, what might suggest the presence of a layered high level magma chamber.

The volcanostratigraphic unit corresponding to the period post-Lajes-Angra ignimbrite (e.g. younger than 23,000 years BP) was designated as the “Upper Terceira Group (UTG)” by Self (1976). That unit, in the case of the Pico Alto volcano includes exclusively eruptive episodes of silicious magmas and dominantly as effusive volcanism, with the formation of domes and coulées.

Based on the stratigraphic and morphological relationships observed in situ and inferred from aerial photos interpretation, and also the available radiometric age determinations on the area, the Upper Terceira Group (UTG) was subdivided in 3 sub-units (Nunes, 2015):

- (A) Upper sub-unit, with ages younger than 5,000 years;
- (B) Intermediate sub-unit, with ages between 5,000 and 10,000 years;
- (C) Lower sub-unit, with ages older than 10,000 years and post-Lajes-Angra ignimbrite.

The mapping of the UTG in the area of the Pico Alto Geothermal Field and its vicinity is presented in Append 2.

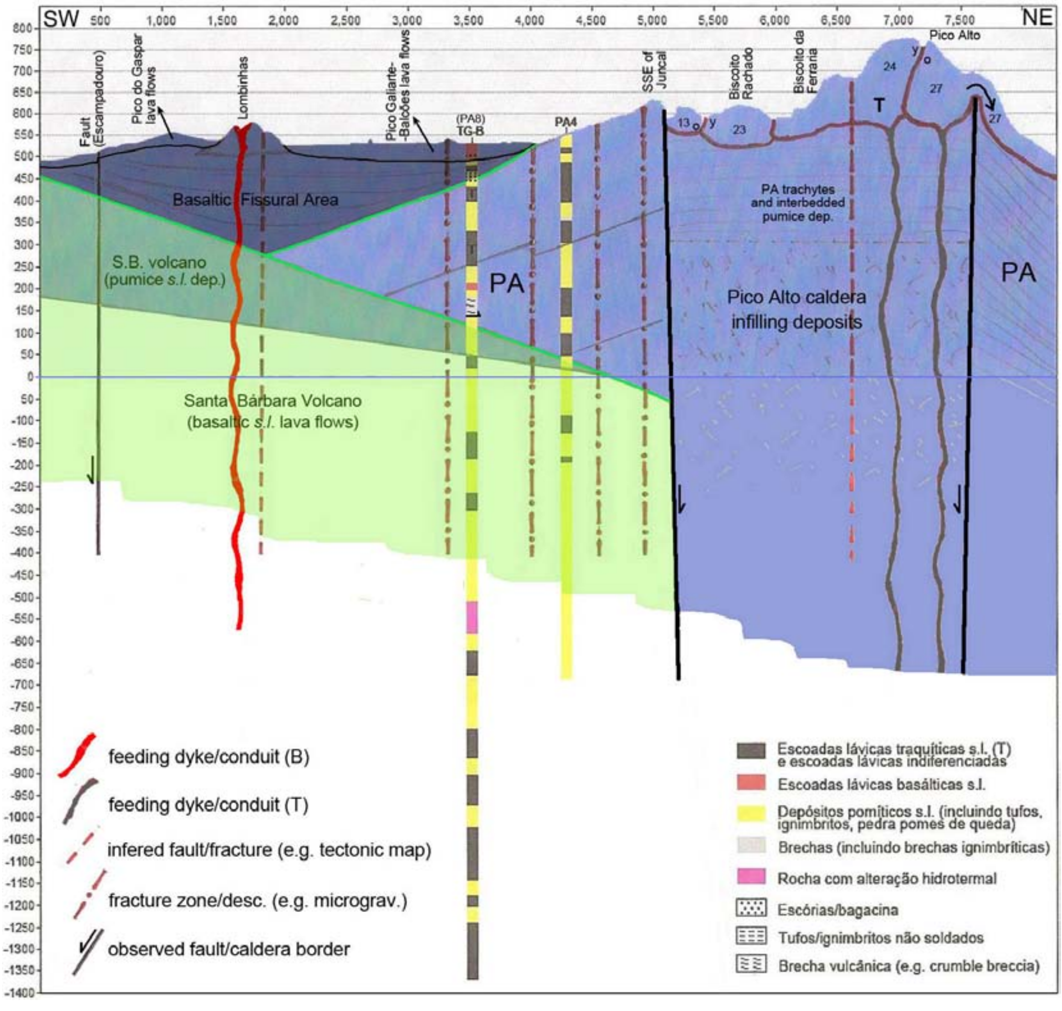

Figure 3: Interpretative SW-NE geological cross-section of the Pico Alto Geothermal Field (PAGF), Terceira Island, Azores archipelago. *In:* TARH & ISOR (2016).

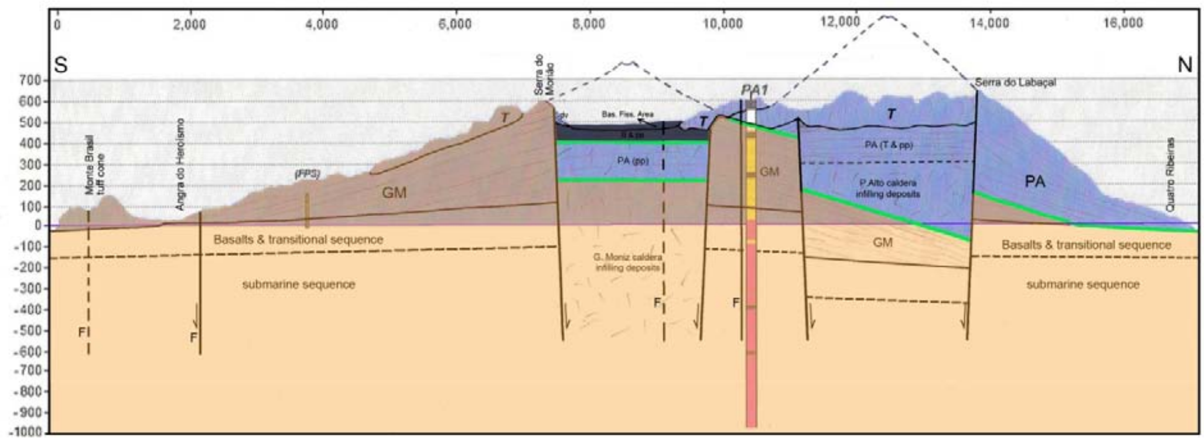

Figure 4. Interpretative S-N geological cross-section of Terceira Island and the PAGF. ***In:*** **TARH & ISOR (2016).**

From the above framework it can be concluded that even some geothermal wells are emplaced at the surface on the Pico Alto volcano formations (or on the BFZ, e.g. PA8 well – Figure 3), its deep sectors and the associated geothermal system – or at last a significant part of them – should develop on the deep roots of the Guilherme Moniz, or Santa Barbara volcanoes.

The type and quality of lithologic logging information on the wells (e.g. cuttings) and the extensive hydrothermal alteration that affects some sectors of the wells does not allow us to better clarify that regional framework. Namely, the presence of a basaltic transitional (subaerial to submarine) sequence or submarine formations (e.g. pillow lavas, breccias, hyaloclastites) is not obvious on the well loggings, in spite the several "undifferentiated lavas" occurrences and some breccias occurrences (e.g. at PA2 well, ~1,600 m depth) that may correspond to these transitional or submarine sequences. And the drilling by diamond coring done at the TG-B hole (cf. Figure 3 and Nunes, 2015) did not proceed to deeper levels, and into the geothermal system.

Nevertheless, it should be emphasized that accordingly to the wells logs and the study of Mateus et al. (2014), trachytic *s.l.* type rocks (including pyroclastic/pumice deposits) were recognized at depth and well below the sea level, what is contradictory with the expectable conceptual evolution of such volcanic systems in oceanic volcanic islands as the Azores.

As a way to solve these incongruence's we might think on a general subsidence phenomena (or flank collapse?) of a few hundred meters, affecting the area to NE of the Terceira Rift alignment in this part of the island. And besides the eventual (?) collapse of the NE sector of the Guilherme Moniz caldera rim (not visible today), what evidences do we have on such potential subsidence? And why is it not obvious a gravimetric signature of such subsidence (cf. Montesinos et al., 2003; 2014)?

The subsidence phenomena identified in Terceira Island by Marques et al. (2015) – with peak rates of about 5 mm/year – may justify the presence of trachytic *s.l.*rocks in the geothermal reservoir area, but does not give a full answer to the above mentioned incongruence, since it is stated that the whole island is subsiding.

Thus, to a more sustainable answer for those and other questions and open issues, it is recommendable that future drilling operations care for different and more detailed petrographic and geochemical studies of the cuttings and, desirable, a drilling by diamond coring be envisaged, namely to target specific sectors of the geothermal system. And the systematic re(analysis) and revision of the existing wells cuttings may also be a strong tool to better understand the deep geology of the PAGF.

3. GENERAL TECTONICS OF THE PAGF AREA

Accordingly with Nunes (2015), three major fault systems are present in the PAGF area (Appends 1 and 2):

- NW-SE to WNW-ESE volcano-tectonic lineaments, dominant in the Basaltic Fissural Zone (BFZ) and Santa Bárbara volcano, as it is the case of the "Pico do Gaspar Fissural System" and the "Algar do Carvão Formation" lineaments at the BFZ, and several domes/*coulées* lineaments at Santa Bárbara volcano flanks; it is also the trend of the Santa Bárbara Graben (e.g. its northeastern "Escampadouro Fault" boundary – Figure 5);

- NNW-SSE volcano-tectonic lineaments, mainly as domes and *coulées* lineaments located inside the caldera of the Pico Alto volcano, as it is the case of the Biscoito Rachado and the Biscoito da Ferraria-Pico Alto lineaments;

- ENE-WSW to NE-SW volcano-tectonic lineaments, as the major fault system defined by the lineaments (and associated extensional fractures) of Furnas do Enxofre-South of Biscoito Rachado fracture zone.

The WNW-ESE trend (usually as N110° faults with oblique striations – normal dextral – Marques et al., 2015) is related with the Terceira Rift direction, a major tectonic feature of the Azores Triple Junction, as a hyper-slow, hotspot-dominated oblique spreading axis, with a 4 mm/year extensional component (Figure 6 – Vogt & Jung, 2004).

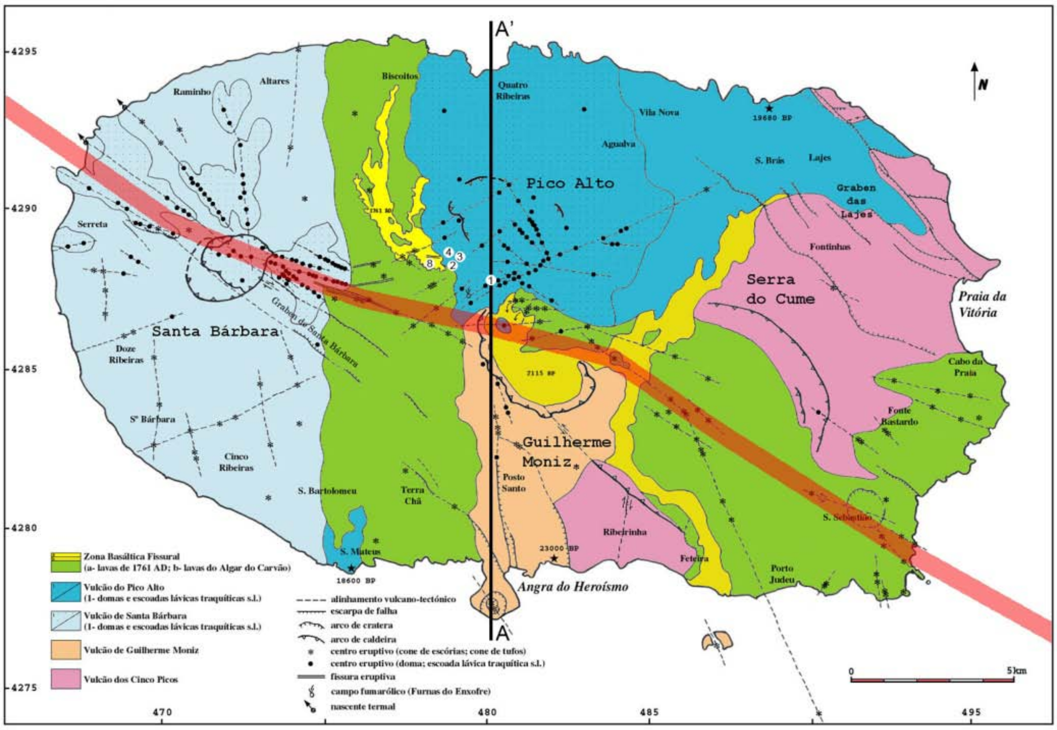

Figure 5. Volcano-tectonic map of Terceira Island (Nunes, 2000). The axis of the Terceira Rift is indicated as a red band. A-A' line indicates the location of the S-N cross section of Figure 4. Location of Pico Alto geothermal wells is also indicated (white circles).

The ENE-WSW major lineament across the Terceira Island (e.g. the Furnas do Enxofre-South of Biscoito Rachado fracture zone) runs obliquely to the Terceira Rift implying a transtensional opening. Accordingly with Marques et al. (2015), this N70° faults system indicates the transform direction related to the Africa/Nubia-Eurasia plates boundary (cf. Figure 6).

The Furnas do Enxofre fumarolic field conforms with the conjugate NE-SW general trend, that has the most clearly expressed faults in the area of the PAGF, as a volcano-tectonic lineament extending roughly from Pico da Bagacina scoria cone till an area south of the Biscoito Rachado *coulée*. This fracture zone might act as the south-easternmost boundary of the PAGF, while the "Pico do Gaspar Fissure System" marks its south-westernmost boundary.

4. FINAL CONSIDERATIONS

A conceptual model must be understood has an integrated, multi-disciplinary approach to understand the "plumbing" of geothermal systems (Robertson-Tait, 2013). Thus, it is a joint geologic model (framework of the area), hydrologic model (fluid flow and permeability), geochemical model (fluid flow and mixing), and heat resource model (temperature distribution). Being always "a work in progress" issue, building up a conceptual model implies a process of integrating data, especially interpreted data. This tool is also a method of visualizing the resource and, besides being and a risk reduction tool it is a useful way to convey resource information to experts and non-experts.

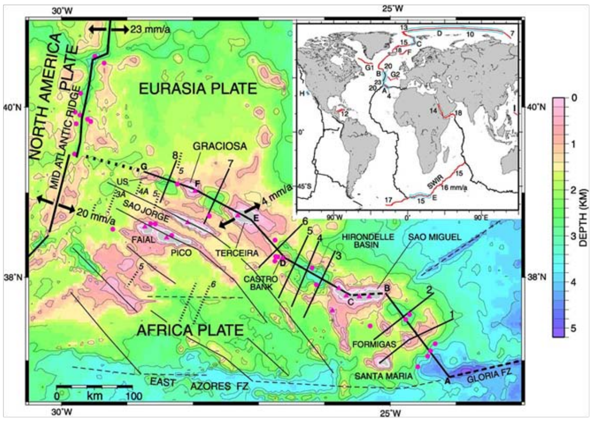

Figure 6. Terceira Island regional tectonic framework at the aim of the Azores Triple Junction. *In:* Vogt & Jung (2004).

A comprehensive and robust conceptual model is, than, made from a all set of reliable information, including publications, inventory of thermal features, interpreted geological (e.g. stratigraphy, structure), geochemical and geophysical data, temperature distribution, drilling parameters (e.g. lithology, alteration minerals, completion, circulation losses, test data, fluid chemistry, etc.), well logging and well testing data, produced fluid chemistry data … and experience and imagination (Robertson-Tait, 2013). And non-resource data are important too, like licensed areas, ownership (private versus public areas), and "off limits" areas for environmental or other reasons.

Given this context, it is considered that the geological data gathered in recent studies on the Pico Alto Geothermal Field and above presented is a relevant input to the building up of a comprehensive and robust conceptual model to the PAGF. Which have to be coupled with temperature distribution, AMT anomalies, geophysics (e.g. microgravimetric), boreholes data (cuttings, lithological logs) and hydrogeological characterization of the deep geothermal system of the PAGF.

That joint and multi-disciplinary interpretation is also part of the IMAGE Project (Integrated Methods for Advanced Geothermal Exploration), where the geosciences data gathered about the PAGF is considered essential information to built a 3D model representation and visualization of this geothermal system.

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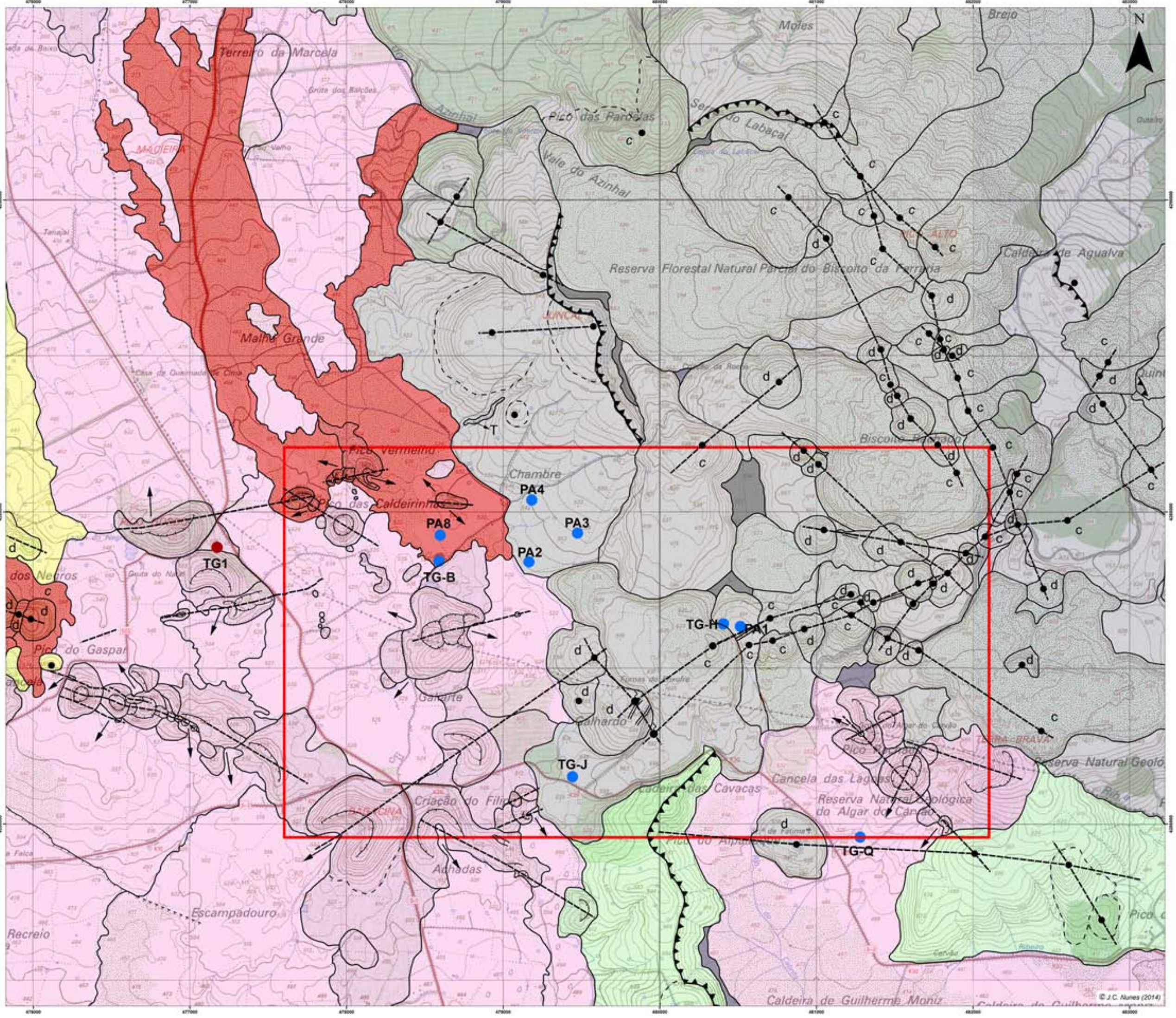
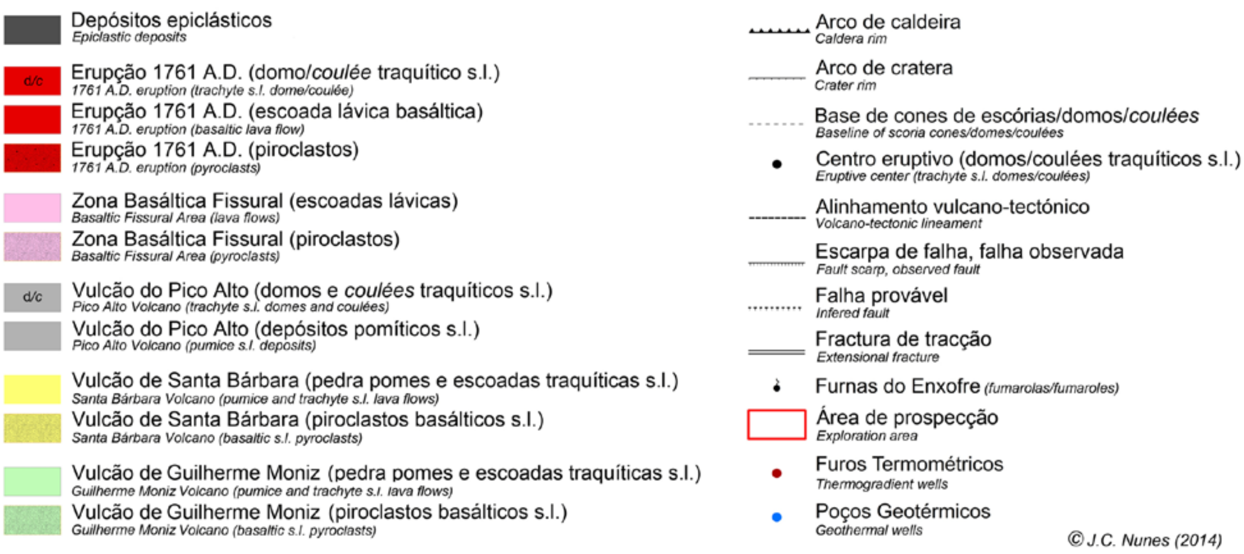
APPEND 1: Volcanostratigraphic map of the Pico Alto Geothermal Field (PAGF) and its vicinity, located in the central part f Terceira Island, Azores archipelago (top) and its captions (bottom). Topographic base map by IGeoE. *In:* Nunes (2015).





APPEND 2: Mapping of the sub-units A, B and C established for the "Upper Terceira Group" formations in the area of the PAGF. See also text.