Geothermal resource assessment in volcanic islands - Fogo Island, Cape Verde

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Cape Verde archipelago depends greatly on imported fossil fuel for electricity generation, but the use of their renewable energy resources can reduce their dependency. Under the renewable energy plan for Cape Verde were studied two islands (Fogo and Santo Antão) that apparently showed high geothermal potential, but that had to be confirmed. Fogo Island showed the best results.
Fogo Island is an active volcano island, with almost perfect conical shape rising up to 2829 m above sea level and with intense historical volcanic activity. The last eruptions occurred in 1951 and 1995, along a line of fractures in the base of Pico do Fogo creating two small cones at the basis of the main volcanic building.
Despite the existence of volcanic eruptions in Fogo Island in a recent past there are no surface geothermal manifestations and it was necessary perform geochemical and geophysical campaigns to characterize the geothermal potential of the island. Several water samples were collected from springs and wells that were analyzed for dissolved solids, stable isotopes of oxygen and hydrogen in water, and the unstable isotopes tritium and 14C.
A geophysical survey with 299 MT soundings on the Fogo Island was carried out to characterize the three-dimensional distribution of electrical resistivity in the subsurface.
The integration of all geological, geochemical and geophysical surveys was able to define several drillings sites and the location of a small geothermal power plant in Fogo Island.
Development of shallow geothermal resources with small units, as binary cycle turbines can offer a reliable source of baseload electricity for small and isolated islands.

INTRODUCTION

This work was conducted under the Renewable Energy Plan of Cape Verde, developed by Gesto Energy (consulting company) for the Department of Energy, between January 2010 and January 2011. On this project during the year 2010, was performed the analysis and characterization of the geothermal resources of the Cape Verde archipelago, with a focus on the two islands with the greatest potential.

The Republic of Cape Verde is a group of islands situated in the North Atlantic about 600 km off the western coast of Africa, approximately at latitudes between 15º and 17ºN and longitudes between 21º and 25º W of Greenwich Fig. 1.

The archipelago comprises ten islands but just nine are inhabited, hosting a population of approximately 450.000 inhabitants, with a combined area of 4.000 km^2, resulting in one of the highest population densities among the West African nations. The majority of the population resides in rural areas and just a small part of the population living in the cities has access to electricity.

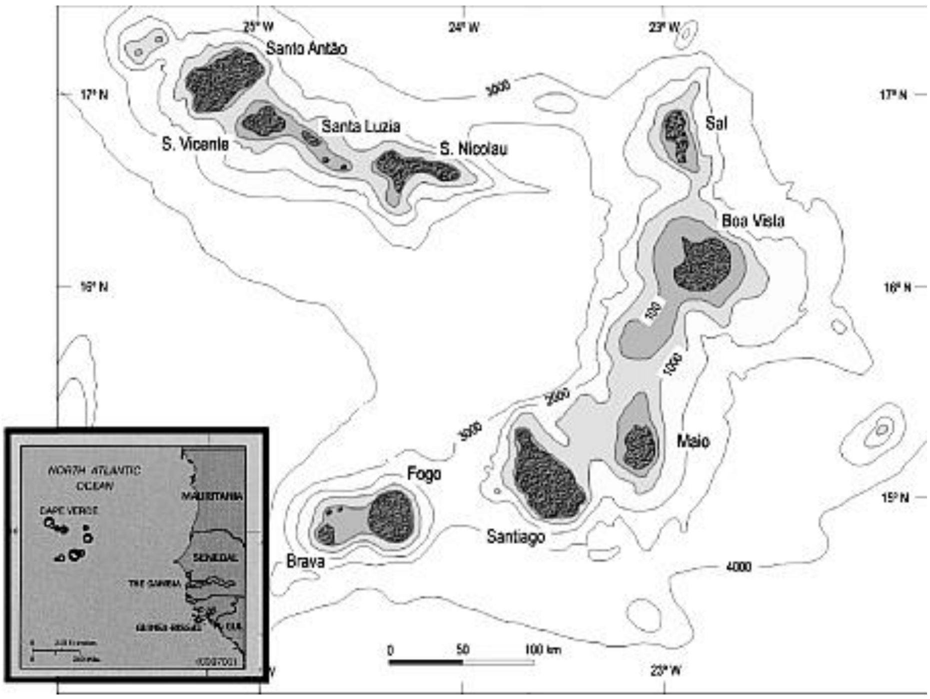

Fig. 1 – Map of Cape Verde Archipelago.

Cape Verde islands are volcanic and therefore met all conditions to provide relevant geothermal resource specially the Fogo Island because it's active volcanism, and Santo Antão, one of the latest Islands of the Archipelago and the one that has the greatest amount of ground and surface water. Historical volcanism (<500 y) is known only on Fogo Island, whose latest's eruptions occurred in 1951 and 1995, but most islands exhibit products erupted during the Quaternary. Age determinations on several islands (Mitchell *et al*., 1983; Plesner *et al*., 2002) suggest that most of the volcanic activity took place from 16 Ma until the present.

Still no geothermal manifestations were recognized in a preliminary screening in a field campaign carried out to collect water or gas samples. Water samples collected in Fogo and Santo Antão allowed characterizing best areas to perform a geophysical campaign. The integration of all geochemical and geophysical data showed no evidence of geothermal resources, except for an area on Fogo Island (the volcano caldera), which presented some features likely to be connected to a high temperature geothermal system.

GEOLOGICAL SETTINGS

The volcanic history of numerous of the islands is poorly documented, but the island chain has a history of volcanic activity extending back over several 10 millions of years, with an age progression from east (old) to west (young), consistent with a hotspot origin. Fogo is one of the most active oceanic volcanoes on Earth with almost 30 eruptions since its discovery in the 15th century (Ribeiro 1960; Torres et al. 1997).

Fogo is the only Cape Verde island exhibiting historic volcanic activity, whereas Brava is seismically more active (Heleno 2003). Fogo has a diameter of 25 km and reaches its maximum height at Pico do Fogo stratovolcano (2829 m above sea level) that is encircled to the west by the steep, up to 1000 m high Bordeira cliff Fig. 2.

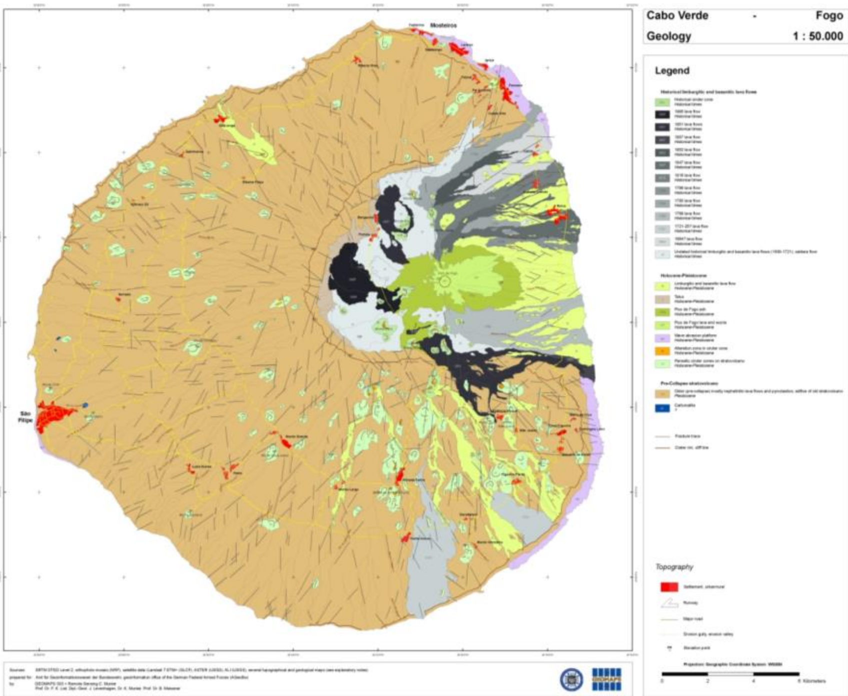

Fig. 2 - Geological map of Fogo (List *et al*., 2009)

According to Day et al. (1999) and Foeken et al. (2009), the evolution of Fogo can be subdivided into four phases: 1) The uplifted Seamount Series (~4.5 Ma) consists of carbonatites and alkaline basalts. The basement rocks are also cut by a dense network of igneous dikes, reducing their permeability. 2) The first subaerial lavas of the Principal Eruptive Complex, overlies unconformably the carbonatites, these basalts have prominent columnar jointing (Barmen et al 1990). 3) The main phase of intense volcanism, the 2-3 km thick, consists mainly of highly alkaline basic to intermediate lavas and scoria cones.

These rocks may be entirely of Quaternary age. 4) The post-collapse Chã das Caldeiras Group (62 ka to present) consists mainly of alkaline basanites to tephrites. This group includes a ~2 km thick sequence infilling the collapse scarp (Chã das Caldeiras plain) to where most historic eruptions were restricted, and the Pico do Fogo.

The geology of the 770 km^2 island of Santo Antão was investigated by Bebiano (1932), who identified a wide variety of rock types. The island is almost entirely of subaerial volcanic origin, stratovolcanoes with numerous lateral vents, and several scoria-cones Fig. 3. Strombolian to Hawaiian eruption products are typical and created the basic morphology of the island (Holm et al. 2006). Volcanoclastic fluviatile sediments and lahars occur locally, and are widespread in the Chã de Morte depression and SE towards the coast. Very minor amounts of aeolian sediments occur in the north.

Most of the central part of the island is more than 1300 m asl. This highland is dissected, mainly to the N and NE, by deep and steep valleys. The southern part of the island is covered by young volcanic products and is less deeply dissected.

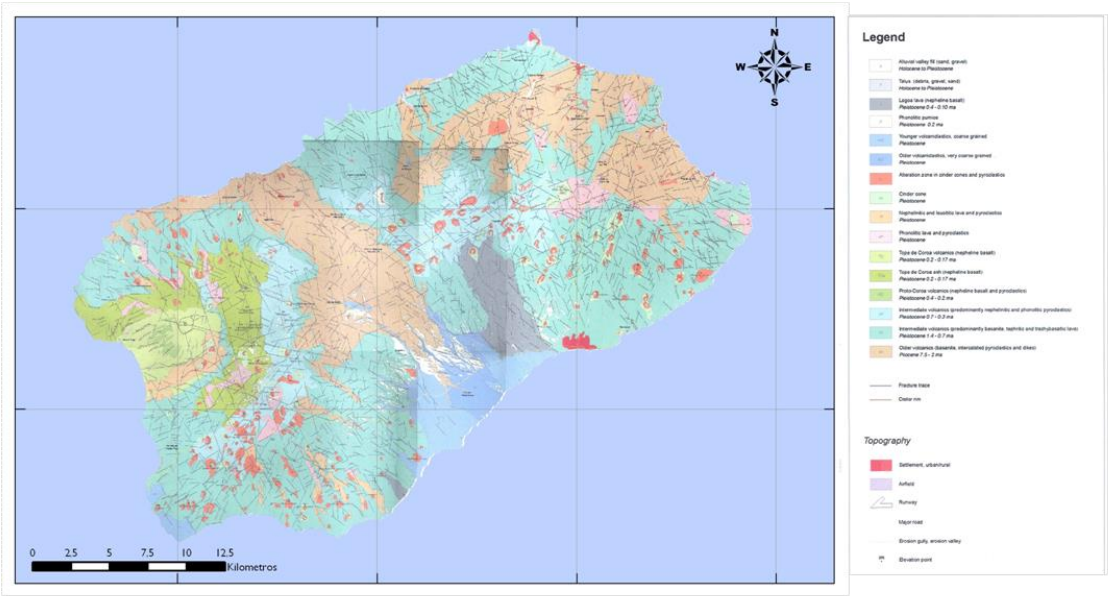

Fig. 3 - Geological map of Fogo (List *et al*., 2009)

GEOCHEMICAL EXPLORATION

The surface activity offers a possibility to obtain information on the subsurface chemical composition of the fluid in the geothermal system under evaluation and can be used to estimate the temperature of possible reservoir as well as the source of the fluid and to locate active upflow zones.

In March and April 2010, Gesto Energy collected water samples from a variety of wells and springs and a few spring-fed surface water sources on Fogo Island and on Santo Antão Island of Cape Verde (Fig. 4). 13 water samples from Fogo Island and 24 water samples from Santo Antão Island were analyzed for dissolved solids, and a selection of the same samples was analyzed for the stable isotopes of oxygen and hydrogen in water, and the unstable isotopes tritium and 14C.

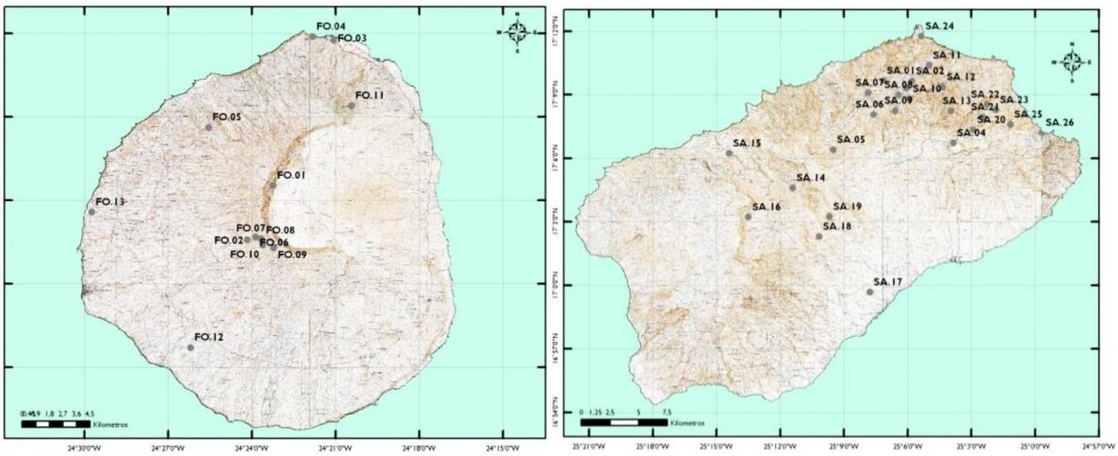

Fig. 4 – Water samples location on Fogo Island (left) and Santo Antão Island (right)

At each spring or well, 4 samples were collected, two filtered for ion chromatography and isotopic analyses, one filtered but acidified with nitric acid to pH=2 for chemical elements, and one filtered but treated with 3-4 drops of mercury chloride solution for 14C. The filtered samples were performed using a 40µm filter. Other physical parameters measurements were performed in the field such as temperature, pH, TDS and conductivity.

The analytical data have been studied in relation to questions of hydro-geochemistry and in particular to see whether any of the samples show signs of geothermal activity, either by direct heating underground or possibly by mixing of geothermal water into shallower cool ground water.

Subsurface reservoir temperatures are estimated with the help of geothermometers that are based isotope ratios on the composition of thermal waters. Geothermometers are often subdivided in two groups, chemical geothermometers (water and gas geothermometers) and isotope geothermometers. The first ones can be describe as either univariant (SiO_2, CO_2, H_2S and H_2) or based on ratios of elements (Na/K; CO_2/H_2, CO_2/N_2 and CO_2/Ar).

GEOPHYSICAL EXPLORATION

The knowledge of the reservoir can be improved by a geophysical survey, permitting to understand the structures thanks to the identification of resistivity and underground thickness.

As part of the study of the geothermal resources of Cape Verde being carried out by Gesto Energy, a Magneto Telluric (MT) and Time-Domain Electro Magnetic (TEM) survey was conducted on the islands of Fogo and Santo Antão during 2010.

The survey consisted of 299 MT soundings on the island of Fogo, and 90 on Santo Antão. In addition, 31 TDEM sounding were performed on Fogo, and 39 TDEM soundings on Santo Antão, for use in making static-shift corrections to the MT results (Fig. 5 and 6). As noted in the survey report, the fundamental objective of an MT survey of this type is to characterize the three-dimensional distribution of electrical resistivity in the subsurface, within the volume that is effectively penetrated by the soundings.

The TDEM data were processed by one-dimensional (1D) inversion, and resistivity cross-sections (pseudosections) were constructed along a number of lines selected within the distribution of survey stations (5 lines on Fogo and 6 lines on Santo Antão). The MT soundings were processed by 2D modeling along 11 lines on Fogo and 6 on Santo Antão, and a resistivity cross-section was constructed along each line.

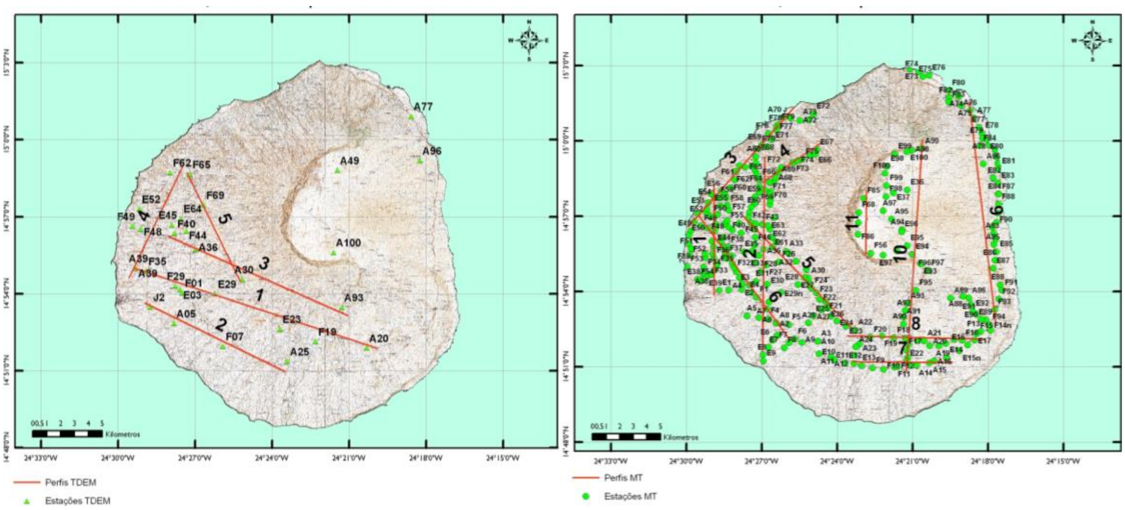

Fig 5 - Location of the TDEM sites (on the left) and MT soundings (on the right) and identification of profiles made on Fogo Island

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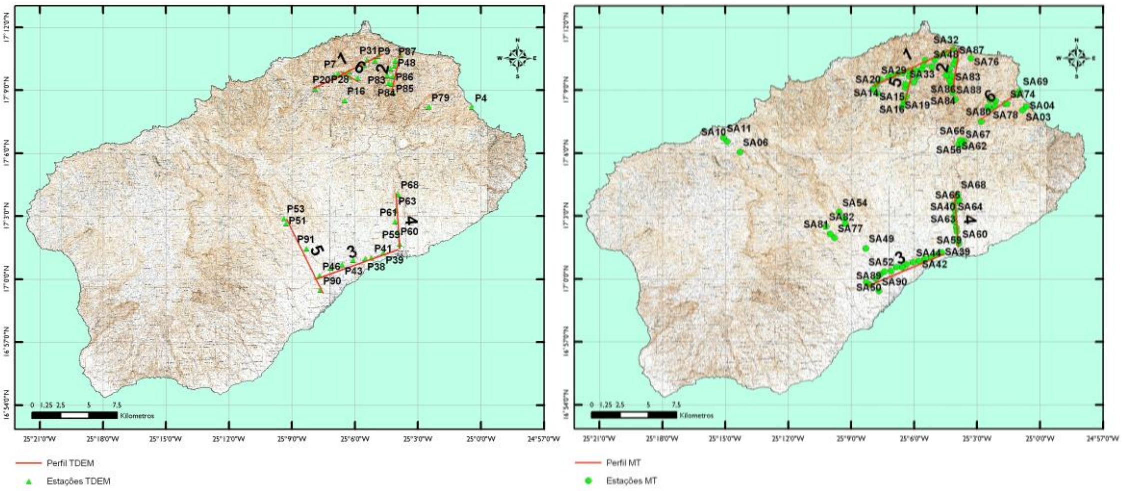


Fig 6 - Location of the TDEM sites (on the left) and MT soundings (on the right) and identification of profiles made on Santo Antão Island

EXPLORATION RESULTS

The samples are in general not unusual for meteoric waters found in volcanic rocks. Dilute bicarbonate (HCO_3) is the principal anion and sodium (Na) and potassium (K) tend to be the principal cations, but there are deviations and occasional strong outliers: see the diagrams on Fig. 7. The bicarbonate is formed as a result of rock-weathering (decomposition) reactions caused by carbon dioxide (CO_2) that is dissolved in meteoric water.

These trends have several sources:

• Variations among the principal cations that doubtlessly reflect variations in local (volcanic) rock composition. Along the spectrum of possible volcanic rock compositions, the volcanic rocks of Fogo tend to be relatively enriched in Na and K but locally there will be higher Ca and Mg. Small amounts of chloride (Cl) and sulfate (SO_4) can also come from these rocks.

• Addition of Na-Cl to a dilute mixed-cation-bicarbonate-dominated composition. Most of this Na-Cl is probably sea salt that is carried as very fine particulates in rain clouds. Its presence is most obvious in samples F3 and F5 (see Cl vs. Na, diagram in Fig. 7).

• Addition of a stronger bicarbonate component, seen most strongly at well F12 where HCO_3 exceeds 600 mg/l and to a small extent at well F13, which has the highest HCO_3 otherwise. The level of HCO_3 at F12 is significantly higher than likely to be generated by routine weathering reactions. Instead, it is likely that F12 represents an addition to meteoric water of upward-moving carbon dioxide (CO_2) that is released from a very deep-seated cooling body of magma.

Release of deep-seated CO_2 is not unusual in volcanic settings. At the deepest levels there may also be some release of steam, but this does not necessarily ascend to commercially exploitable levels. Heilweil and others (2006) studied the gases dissolved in trace amounts in the ground waters of a northeastern sector of Fogo and found helium of deep-seated origin, also not unusual in this setting.

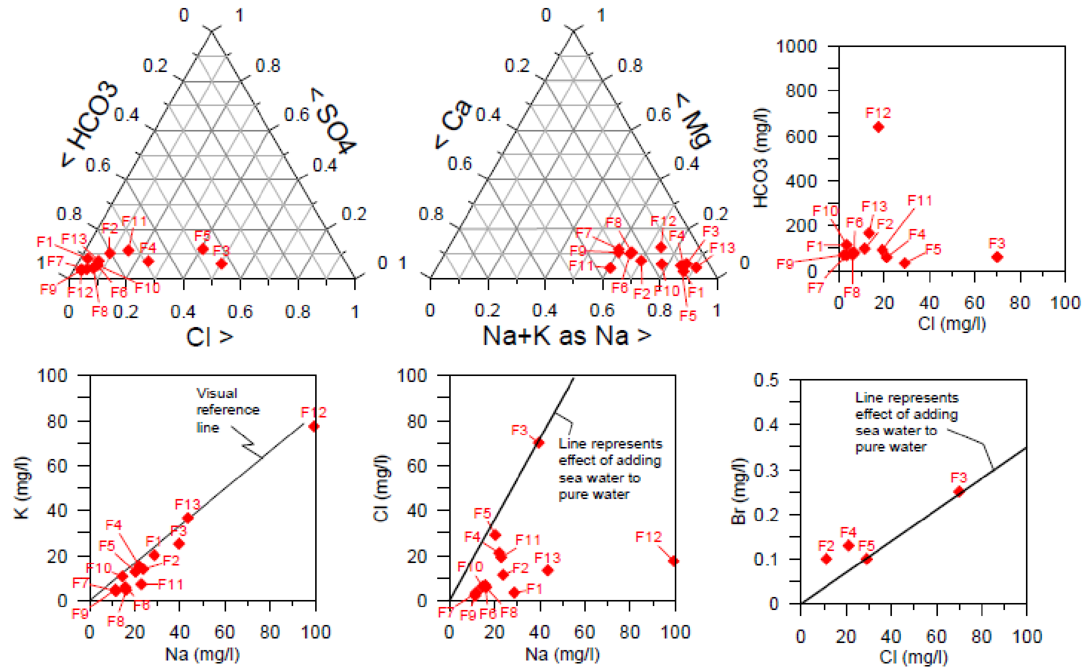


Fig. 7 - Chemical relationships among ground water samples from Fogo Island, Cape Verde.

As on Fogo, the samples are in general not unusual for meteoric waters found in volcanic rocks. Bicarbonate at 500 mg/l or less is the principal anion and sodium and potassium tend to be the principal cations, but the deviations and outliers are somewhat stronger than among the Fogo samples: see the diagrams on Fig. 8. The Santo Antão waters also tend to be more saline, as there are few samples from Fogo that have more than ~150 mg/l bicarbonate. The higher bicarbonate on Santo Antão may be a result of longer residence times (although this is not clearly suggested by the tritium data) and/or a stronger and more general addition of CO_2 from depth (possibly suggested by the 14C data).

There are particularly well-defined relationships between Cl and Na and Br and Cl that match the effects of adding sea water to pure water, with Cl reaching almost 250 mg/l.
The sample with highest Cl (S1) comes from a 64 m – deep well at 150 m elevation in the northern sector of the island, so direct sea water contamination is a less likely source than are the sea salts carried in rain. These may have been concentrated by evapo-transpiration and it is also possible that the volcanic sequence includes evaporate deposits.

• Two samples are strong outliers of elevated HCO_3, with about 2,500 mg/l. One of these (S12) is the gassy, 34°C water from the site of a reported well blow-out during drilling. The other (S_20) is a 24°C spring several km away from the first. The unstable isotope 14C is very low in both of these waters as a result of dilution by 14C-free CO_2 from a very deep (probably magmatic) source. Tritium was not measured in S12, but shows the presence of S_20 at least in some younger ground water.

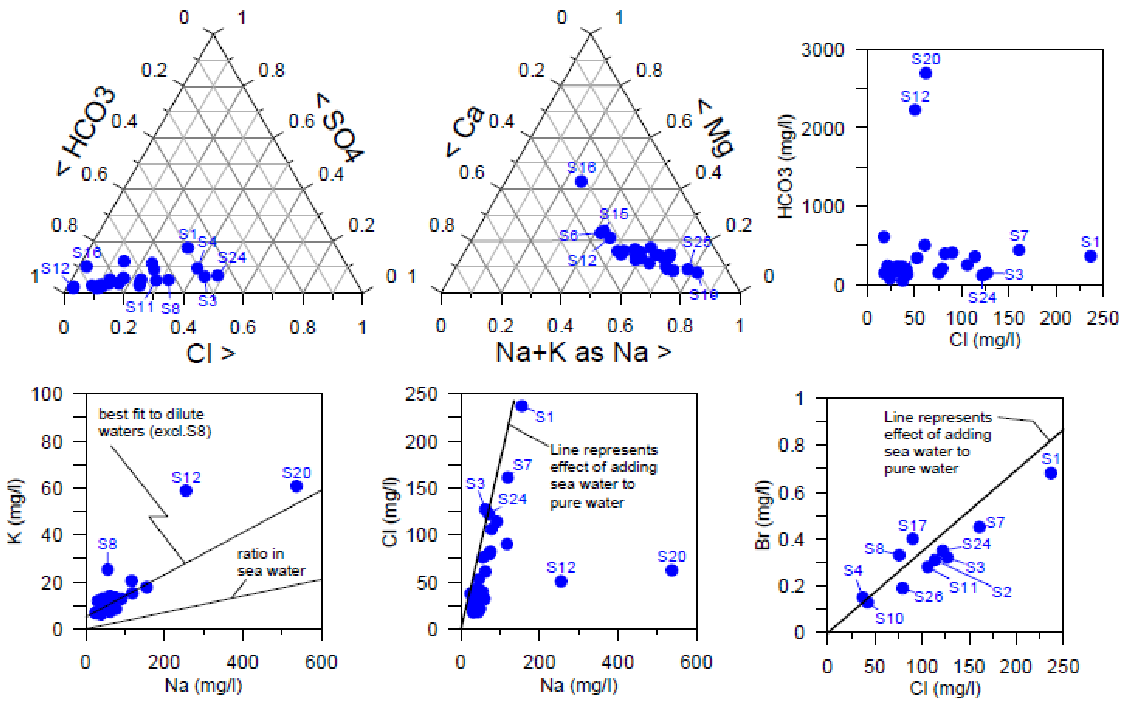


Fig. 8 - Chemical relationships among ground water samples from Santo Antão Island, Cape Verde

The 5 TDEM resistivity cross-sections constructed from the survey on Fogo all show a structure of decreasing resistivity with depth, from greater than 800 ohm-m in about the first 100-200 m below the surface to less than about 40 ohm-m at deeper levels; this is modeled either as two distinct layers or as three layers (each decreasing in characteristic resistivity with depth). None of the sections shows a low-resistivity layer underlain by higher resistivity (as is normally observed in active geothermal reservoirs); in addition, there is little variation in resistivity structure from section to section, indicating that none of the sections traverse a zone of distinctly anomalous conditions. However, the effective depth of penetration of the TDEM soundings is insufficient to show the resistivity structure over the interval where a geothermal system is likely to be present.

It must be concluded that the TDEM results on Fogo do not show any specific anomalies that might be related to geothermal activity, but that this does not preclude their presence at deeper levels.

Of the 11 MT resistivity cross-sections constructed for Fogo, about half show low-resistivity layers near or above sea level, with the general form (of a relatively thin but extensive cap that is elevated in its central part) that is sometimes associated with a geothermal reservoir. However, none of the sections shows a low-resistivity layer with the degree of continuity and widespread, very low resistivity that is usually seen when intense, high-temperature geothermal activity is present. It is therefore more likely that the low-resistivity zones are associated with other features such as aquifers.

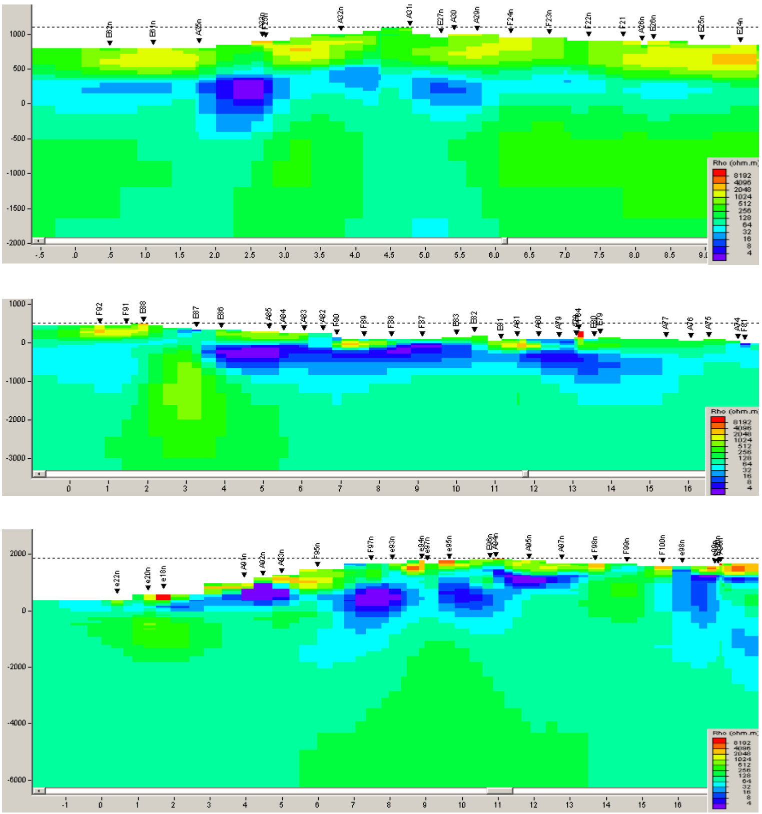
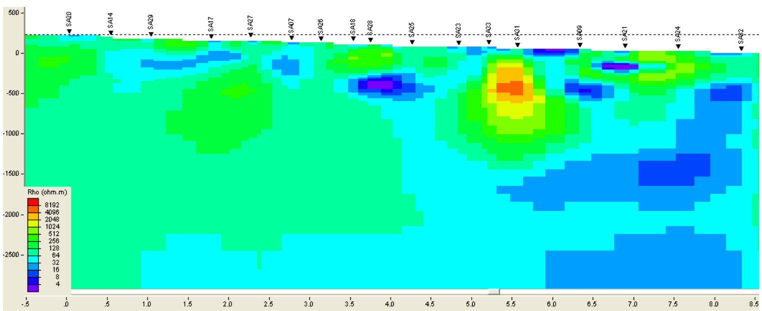


Fig. 9 - 2D MT resistivity profiles in Fogo Island (from top to bottom profiles MT5, MT 10 MT11).

The TDEM pseudo-sections constructed along 6 profile lines from the Santo Antão survey showed similar results to those obtained on Fogo, and a fairly small range of resistivity variations overall.

As on Fogo, resistivity decreases with depth, and there are no obvious strong anomalies from which specific subsurface features might be inferred. Again, the depth of investigation is insufficient to determine whether or not anomalies that might be related to geothermal systems are present.

None of the 7 resistivity sections based on MT soundings (which, on both Santo Antão and Fogo, provide an effective depth of investigation of at least 1,000 to 2,000 m) shows evidence of a continuous low-resistivity layer of the type that is typically associated with a geothermal reservoir (Fig. 10). The other sections show either fairly uniform resistivities, or smaller and more localized anomalous zones (of both high and low resistivity).



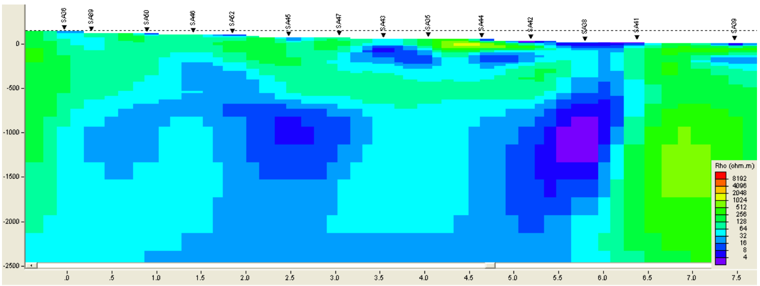


Fig.10 - 2D MT resistivity profiles in Santo Antão Island (from top to bottom profiles MT1, MT3).

Overall, the MT/TDEM results on Santo Antão do not show any significant anomalies that are likely to be associated with geothermal activity.

CONCLUSIONS

The results of the MT/TDEM survey conducted on the islands of Fogo and Santo Antão in Cape Verde do not show any resistivity anomalies that strongly suggest the presence of high temperature geothermal activity.

On Santo Antão, there are no significant anomalies that would serve to prioritize one area over another in terms of the likelihood of the presence of a geothermal system.

On Fogo, interpreted low-resistivity layers in the island's west-northwestern and east-northeastern sectors make these two areas somewhat more prospective than other parts of the island, though alternative origins for the anomalies appear at least as likely as a geothermal origin.

In the absence of other indications of geothermal activity, the caldera area (east-northeast sector) on Fogo would be the first choice as a location for exploratory drillholes to seek possible geothermal anomalies

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