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Underground Temperature Measurements as a Tool for Volcanic Activity Monitoring in the Island of Tenerife, Canary Islands

A. Eff-Darwich,[1] J. Coello,[1] R. Viñas,[1] V. Soler,[2] M. C. Martin-Luis,[1] I. Farrujia,[3]
M. L. Quesada,[1] and J. de la Nuez[1]

Abstract—The spatial distribution of groundwater temperatures in the volcanic island of Tenerife, Canary Islands, has been inferred through measurements of water temperatures collected in the vast network of wells and subhorizontal tunnels, locally called "galleries," which constitutes the main water supply of the island. The spatial coverage of the network of galleries allows us to reach from depth almost any geological feature of the island. The complex spatial distribution of temperatures in the interior of Tenerife is the result of the complex geological evolution of the island. Groundwater temperatures are greatly affected by groundwater flow and are considerably warmer in those galleries located in areas where water circulation is reduced due to the low permeability of materials and/or to the low infiltration rate of cooling meteoric water. In this sense, groundwater temperature should be characterized in quiescent conditions (background level), in order to facilitate monitoring changes in heat flow, such as those induced by ascending gases expected with an increase in volcanic activity.

Key words: Tenerife, groundwater, volcanic eruption, thermal precursors.

1. *Introduction*

The implementation of a volcanic activity monitoring network in the island of Tenerife, Canary Islands (Spain) has to take into account the complex geological evolution of the island. In this sense, recent eruptive activity includes a sub-plinian eruption that took place approximately 2000 years ago in the central part of the island, as well as six strombolian eruptions in the last 300 years that were scattered over a large portion of the island. This dispersion in the frequency and location of eruptive activity makes it difficult to run a monitoring network and hence, simple and robust observational methodologies have to be considered.

Groundwater monitoring reveals as a promising option in Tenerife, since the saturated zone could be reached through more than 1000 galleries and more than 400

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[1] Departamento de Edafología y Geología, Universidad de La Laguna, Av. Astrofísico Francisco Sánchez s/n., La Laguna, 38206 Tenerife, Spain. E-mail: adarwich@ull.es
[2] IPNA-CSIC, Volcanological Station of the Canary Islands, Tenerife, Spain.
[3] Consejo Insular de Aguas, Cabildo Insular de Tenerife, Tenerife, Spain.

wells. Galleries are horizontal tunnels, usually several kilometres long depending on the excavated distance needed to reach the general saturation level. Water flows through one or several outcrops (that may be separated up to several hundreds of meters), being transported to the entrance into pipes or channels. The location of the entrance of these tunnels varies from a few meters above sea level to approximately 1800 meters. Galleries are optimal locations to study the geodynamical processes occurring in the interior of the island. On one hand, they penetrate the different stratigraphical units that conform the interior of the volcanic edifice, providing valuable information on the location and evolution of the general water table, the regional water balance, the groundwater flow pattern and the geology of the island (CUSTODIO, 1987; NAVARRO, 1991). On the other hand, galleries are very stable locations that are ideal to monitor gaseous dynamics, since the effect of most atmospheric variables is negligible. Air-temperature variations are very small and the only recordable environmental parameters that may affect gas flows are barometric pressure and temperature differences between the air inside and outside the galleries (MARTÍN *et al.*, 2002; EFF-DARWICH *et al.*, 2002).

Systematic monitoring of groundwater in active volcanic regions is one of the tools used in early detection of volcanic eruptions. Indeed, groundwater could trap the main components of fluids released from magma, providing information on temporal and spatial changes in heat and gas transfer within the volcanic edifice (TEDESCO, 1995; FEDERICO *et al.*, 2002). It is expected that magma ascent towards the surface modifies the temperature distribution inside the volcanic edifice, as the result of heat transfer between magmatic gases, cracks and groundwater. In this sense, it may occur that temperature in wells and springs could change during the early stages of volcanic eruptions. This has been reported in many examples in the literature, e.g., temperature changes in crater lakes (SIGURDSSON, 1977; BADRUDIN, 1994), in hot springs (SATO *et al.*, 1992), wells and springs (BONFANTI *et al.*, 1996; MARTÍN DEL POZZO *et al.*, 2002). YAMASHINA and MATSUSHIMA (1999) also reported variations on ground temperature outside the geothermal area at Unzen volcano prior to the phreatic eruption in November 1990. In the case of volcanic islands, the connection between groundwater and hot magmatic fluids is poorly understood, since the available volcanologic and hydrologic data are limited (VIOLETTE *et al.*, 1997). In the case of Tenerife, the interaction between volcanic activity and groundwater is represented by fumarolic gaseous emissions (ALBERT *et al.*, 1989) and by the presence of thermal and hydrochemical anomalies (i.e., BRAVO *et al.*, 1976; CUSTODIO, 1987; NAVARRO, 1991; FARRUJIA *et al.*, 1994).

In this work, we have obtained the spatial distribution of temperatures in the groundwater system of the Island of Tenerife. We attempted to show how temperature is a proxy for the dynamics of the groundwater system, as well as for volcanic activity in Tenerife. In this sense, this work provides valuable information for setting up an instrumental network (e.g., temperature and radon) in galleries and wells that could become an essential part of any early detection system of volcanic activity in the island.

2. *Geology and Hydrology of Tenerife*

Tenerife is the largest island (2034 km^2) of the Canarian Archipelago and one of the largest oceanic islands in the world. It is located between latitudes 28–29°N and longitudes 16–17°W, 280 km away from the African coast. The construction of the island has been brought about by the accumulation, during the last millions of years, of volcanic materials with different compositions. The stratigraphic units conforming the emerged part of Tenerife may be placed in three groups (Fig. 1). The first group is conformed by the Old Basaltic Edifices or Shield Edifices, dated from 12 Ma to approximately 3.3 Ma (Guillou *et al.*, 2004). The second group, the Central Volcanic Edifice (compressing the so-called Cañadas Edifice and Teide-Pico Viejo Complex), has been dated from 3.5 Ma to present (Ancochea *et al.*, 1999; Martí *et al.*, 1994; Huertas *et al.*, 2002). The most representative structures of the Central Volcanic Edifice are a large elliptical depression measuring 16 × 9 km^2, known as Las Cañadas Caldera and, in the northern sector of the

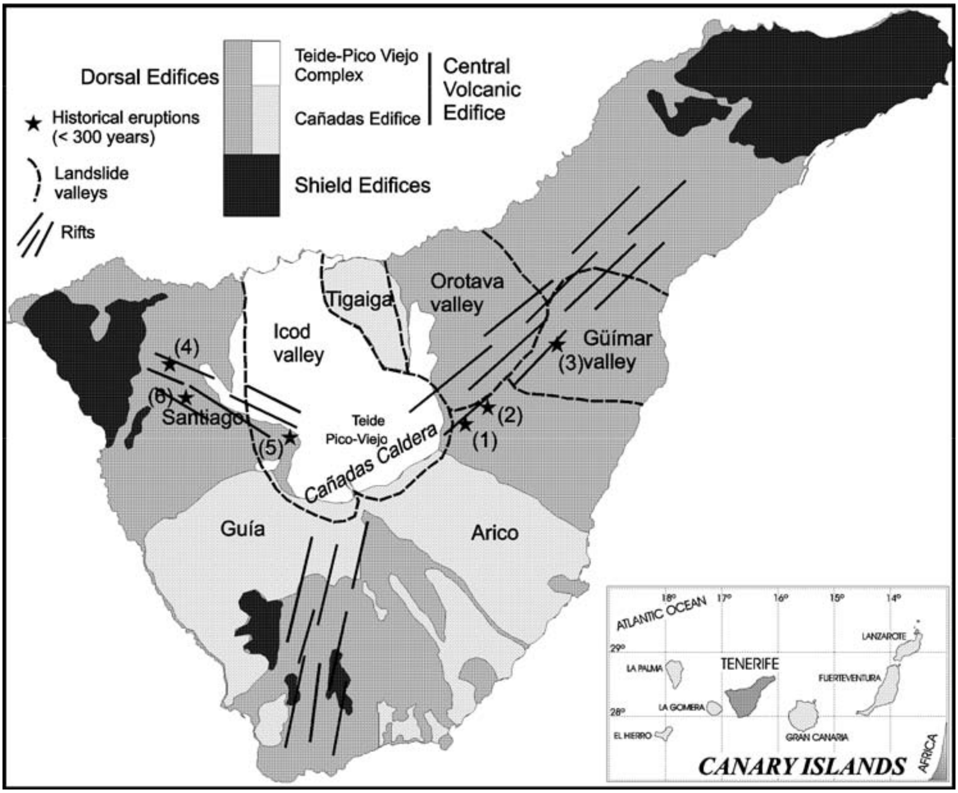

Figure 1

Simplified geological map of Tenerife, including the main volcanic edifices and recorded historical eruptions (stars), namely Siete Fuentes (1), Fasnia (2), Arafo (3), Arenas Negras (4), Chahorra (5) and Chinyero (6).

caldera, the Teide-Pico Viejo strato-volcano. Finally, the third group is conformed by three basaltic ridges or Dorsal Edifices (NE, NW and S ridges), that overlap in time with the Central Volcanic Edifice. These ridges converge at the center of the island where the strato-volcano Teide-Pico Viejo is located (Fig. 1).

The growth of the island has not been homogeneous, occasionally concentrating volcanic activity in some areas where there has been an excessive vertical accumulation of materials. This accumulation has induced gravitational instabilities that have led to giant landslides and to the generation of gravitational depressions (valleys), being the Icod, La Orotava and Güímar valleys the largest (CANTAGREL *et al.*, 1999; ABLAY and HURLIMANN, 2000; WALTER *et al.*, 2005). A portion of the Central Volcanic Edifice did not collapse during the formation of the Icod and La Orotava valleys, conforming the present Tigaiga massif. Recorded eruptive activity has consisted of six strombolian eruptions (CABRERA and HERNÁNDEZ-PACHECO, 1987), namely Siete Fuentes (1704), Fasnia (1705), Arafo (1705), Arenas Negras (1706), Chahorra (1798) and Chinyero (1909). The last three eruptions occurred in the NW ridge, the most active area of the island together with El Teide-Pico Viejo Complex for the last 50,000 years (CARRACEDO *et al.*, 2003).

The hydrological behavior of the island is defined by three different aspects that characterize the insular edifice, namely the stratigraphic accumulation of materials, the dorsal ridges and the gravitational depressions (NAVARRO, 1991). Indeed, the deeper the volcanic edifices are located in the stratigraphic sequence, the more compact and altered they are and hence, the less permeable. In this sense, the permeabilities in the Shield Massifs and Cañadas Edifice are gradually reduced with increasing depth until they become nearly impervious, whereas the more recent edifices are less compact and altered and hence, they constitute highly permeable units.

The dorsal ridges play an important role in the hydrodynamics of the island. In the central strip of the ridges, where the dike swarm density is greater, the open fractures attenuate the differences in the original permeabilities of the different stratigraphic units, significantly increasing vertical interconnection. Dikes and fractures are usually parallel to the ridges, facilitating longitudinal flow and considerably reducing transversal flow. This induces a super-elevation of the saturated zone and the transversal profile of the water table becomes stepped.

The valleys are formed by an impervious basement (debris avalanche deposit), known as “Mortalón” (CANTAGREL *et al.*, 1999), covered by high permeability post-landslide lavas, where the saturated zone is located. Infiltrated water cannot be retained by the lava fill-in and circulates down to the basement, where it begins to flow towards the sea.

3. *Observational Methodology*

The Water Council Board (hereafter WCB) of the local Government, the Cabildo de Tenerife, manages a large database, consisting of physico-chemical measurements of water samples collected in more than 1000 galleries and wells spread out all over the

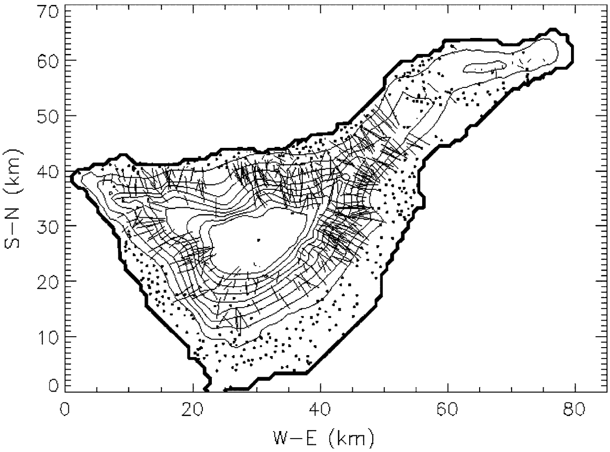

Figure 2
Map of Tenerife indicating the location of the galleries (solid lines) and wells (filled circles) that constitute the main water exploitation system of the island. Contour lines for the position of the general water table are plotted every 200 meters.

island. We took from this database 390 measurements of groundwater temperatures collected from 1998 to 2004. Moreover, we also used 91 water temperature measurements collected by Coello (1976) at water outcrops in galleries between 1969 and 1973. Neither galleries nor wells have reached the saturated zone in the central part of Las Cañadas Caldera. Hence, information on the temperature of the aquifer is provided by two scientific boreholes drilled in this area by the WCB. The Water Council has also measured the location of water outcrops in galleries and water level in wells, obtaining in this way the shape of the groundwater system (see Fig. 2), that at large scale retains the pyramidal-like shape of the island.

WCB data were collected at the entrance of the galleries and hence this may not exactly reflect the actual conditions at the saturation level, because of changes in temperature during the transport of water into the pipes or channels. Comparison of the data sets revealed differences in the temperatures measured of up to 4°C at a given sampling point. This prevented us from performing a quantitative analysis of the data and hence, a qualitative study of the temperature distribution has been carried out.

4. Results

The distribution of groundwater temperature is highly heterogeneous, as illustrated in Figure 3. The mean temperature for groundwater is 23°C, being 21.6°C and 24.4°C for galleries and wells located in the northern and southern slopes of the island, respectively. Four different aspects have to be considered when analyzing the spatial distribution of

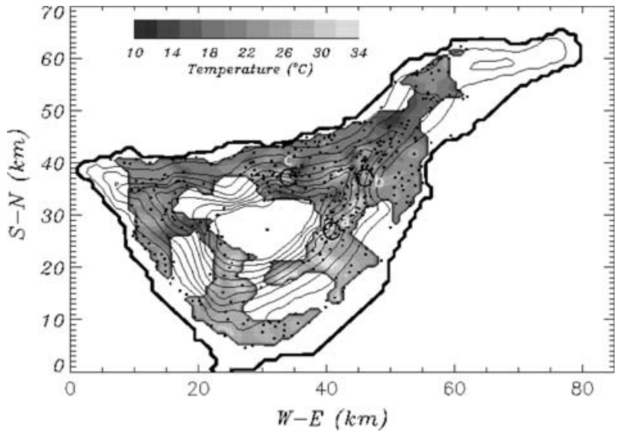

Figure 3
Distribution of temperatures for the groundwater system of the island of Tenerife. Contour lines, plotted every 200 meters, indicate the position of the general water table. Filled circles indicate both the location of wells and the deepest part of the galleries.

temperatures, namely meteorology, permeability of volcanic materials, water flow from Las Cañadas Caldera and volcanic activity.

Rainfall varies from less than 200 mm/year at low altitudes in the southern part, up to 1000 mm/year at altitudes between 1000 and 1500 m, specially in the NE ridge. Some snow percolates El Teide-Pico Viejo and Las Cañadas Caldera, helping to recharge the aquifer in the central part of the island. The larger precipitation rate in the northern part of the island is a consequence of the N and NE wet trade winds.

Larger permeabilities are found in the northern slope of the island, namely the lava fill-in of La Orotava and Icod valleys, as well as the NE and NW ridges. Those areas located in the southern flank of Las Cañadas Caldera are well defined geologically by the presence above the saturated zone of a thick and extensive pile-up of scarcely permeable phonolitic lavas. Groundwater is nearly stagnant and the cooling effect of infiltrated meteoric water is insignificant due to the presence of this low-permeable layer, as well as to the low precipitations recorded in the area.

Cold meteoric water collected in the very permeable lavas of the Las Cañadas Caldera easily flows down through the lava fill-in of La Orotava and Icod valleys, as well as through the NW ridge and that part of the Tigaiga massif in direct contact to Las Cañadas Caldera, acting as a refrigerating agent. The effect of this flow from Las Cañadas aquifer is also illustrated in Figure 4, where it is represented by the distribution of HCO_3^- content in water. These data were also taken from the WCB database. Groundwater in direct contact to Las Cañadas Caldera presents substantial values for the content of HCO_3^- and relatively cold temperatures, reflecting the conditions found in the Caldera aquifer, namely cold temperature (approximately 15°C) and high contents of CO_2

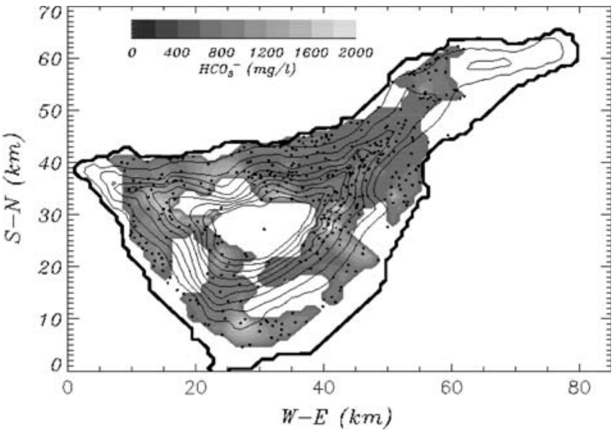

Figure 4
Distribution of HCO$_3^-$ content in water for the groundwater system of the island of Tenerife. Contour lines, plotted every 200 meters, indicate the position of the general water table. Filled circles indicate both the location of wells and the deepest part of the galleries.

dissolved in water (Soler *et al.*, 2004). Since there are no sedimentary carbonates in Tenerife, HCO$_3^-$ originates in the dissolution of volcanic CO$_2$ in water (Custodio, 1987). The warmer groundwaters of the southern slope of the island are not refrigerated by the Caldera aquifer, since the southern wall of the caldera behaves as an impermeable barrier (Navarro, 1991).

Volcanic activity could also play an important role in the temperature distribution of groundwater. It has been postulated that some anomalously high water temperature areas may be associated with the cooling of shallow magma chambers that fed historical eruptions (Valentín *et al.*, 1990) as occurs in the areas closer to Fasnia, Siete Fuentes, Chinyero and Arafo volcanoes. This idea is supported by the fact that groundwater located in this areas presents high temperatures and geo-chemical anomalies. Heat upflow may also be induced by convective ascent of hot endogenous gases from a deep source through preferential paths, such as dike swarms or fracture systems. The existence of a large-scale upflow of gases in the central part of the island has already been proposed by Bravo *et al.* (1976) and Pérez *et al.* (1996), based on measurements of the concentration of CO$_2$ in the air of the galleries and the ratio of ^{3}He/^{4}He, respectively.

There are some areas where the density of galleries is large enough to study the dependence of groundwater temperature with depth and altitude. These areas are shown in Figure 3 as circles and labelled as *a, b* and *c*. Area *a* is located in the southern slope of the island, where both precipitation rates and permeabilities are low. The dependence of temperatures with depth below topographic surface and altitude of the measuring point above sea level (panel *a* of Figs. 5 and 6) shows no significant trend. In the case of area *b*, located in the NE ridge closer to the Güimar valley, we found a significant increment of temperature with depth and altitude (panel *b* of Figs. 5 and 6), being more evident in the case of altitude. The better match between temperature and altitude may be a geometrical effect caused by rapid variations in the altitude of the topographic surface relative to the altitude of the sampling points. The variation of temperature with depth is approximately 0.02°C/m, being closer to the value of the standard geothermal gradient, 0.03°C/m. Area *c* is located in the Tigaiga Massif, however it is not in direct contact with the Las Cañadas Caldera aquifer. Groundwater reserves are negligible when compared to other areas. In this sense, water flow does not play an important role in controlling the vertical distribution of temperatures and hence, an increase in temperature with depth of approximately 0.05°C/m is observed (panel *c* of Figs. 5 and 6). This is larger than the standard geothermal gradient, however the lack of precision in the temperature measurements prevents us from making further conclusions.

In summary, it has been shown that the combination of larger precipitation rates, larger permeabilities and the cooling effect of the cold flow from Las Cañadas aquifer may explain the lower groundwater temperatures found in the northern slope of Tenerife, relative to the southern slope. It is still not clear whether recent volcanic eruptions or large scale heat upflow or a combination of both could explain the temperature distribution in the southern slope of the island. It is evident that more precise measurements are necessary to better understand the thermal regime of the groundwater system in Tenerife, in particular the temperature gradient in Tigaiga, the temperature

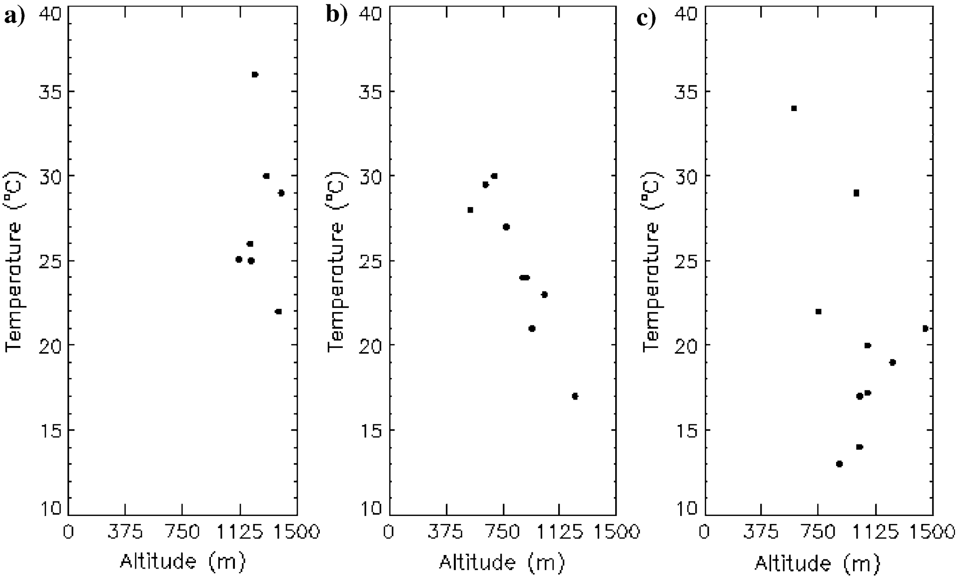

Figure 5
Panels a), b) and c) represent the distribution of groundwater temperature relative to altitude above sea level of the temperature measuring points for the areas *a*, *b* and *c* that are shown in Figure 3.

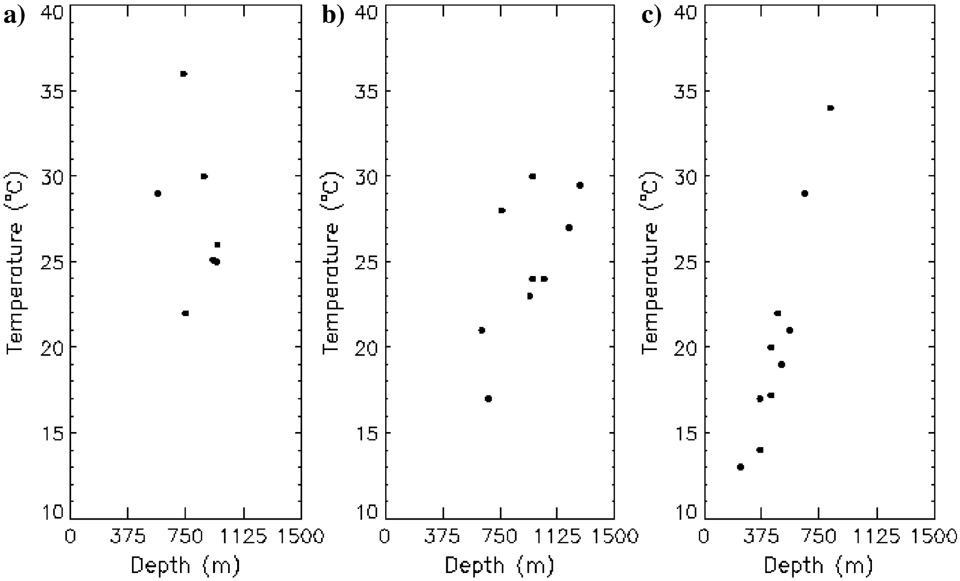

Figure 6
Panels a), b) and c) represent the distribution of groundwater temperature relative to depth below topographic surface for the areas *a, b* and *c* that are shown in Figure 3.

distribution in the southern slope of the island or some high temperature spots in the Orotava valley.

5. *Conclusions*

We have carried out a qualitative analysis of the regional distribution of groundwater temperature for the volcanic island of Tenerife. This analysis was thought as a first step for setting up a network of water temperature monitoring stations that could become part of an early detection system of volcanic activity. Groundwater temperature is greatly affected by groundwater flow, being warmer those galleries located in areas where water circulation is reduced. The cold-water aquifer in Las Cañadas Caldera is connected to highly permeable areas, such as the NW ridge, La Orotava and Icod valleys in the North, but it is disconnected from the warmer areas of the southern slope of the island, since the southern wall of the Cañadas Caldera acts as an impermeable barrier to water flow.

Although the origin and spatial distribution of heat flow remains uncertain, it seems reasonable to characterize the spatial and temporal evolution of groundwater temperatures. In this way, it will be possible to define the temperature distribution in quiescent conditions (background level) from where changes in the heat flow could be monitored, such as those induced by the ascending gases expected with an increase in volcanic activity.

During the elaboration of this work, Prof. Juan Coello passed away after a fatal car accident. Undoubtedly, he has been one of the most prominent geologist in the Canary Islands and his work greatly improved our understanding on the structure and evolution of this volcanic archipelago.

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