Volcanic Activity in Costa Rica in 2012
Official Annual Summary

Turrialba volcano on January 18th, 2012: central photo, the 2012 vent presents flamme due to the combustion of highly oxidant magmatic gas (photo: J.Pacheco). On the right, ash emission by the 2012 vent at 4:30am the same day (photo: G.Avard).On the left, incandescence is visible since then (photo: G.Avard 2-2-2012, 8pm).

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OVSICORI-UNA

I_ Introduction

At 8:42 a.m. on September 5th, 2012, a Mw = 7.6 earthquake occurred 20 km south of Samara, Peninsula de Nicoya, Guanacaste. The maximum displacement was 2.5 m with a maximum vertical motion about 60 cm at Playa Sa Juanillo (OVSICORI Report on September 11th, 2012).

The fault displacement continued until the end of September through postseismic motions, slow earthquakes, viscoelastic response and aftershocks (> 2500 during the first 10 days following the Nicoya earthquake). The seismicity spread to most of the country (Fig.1)

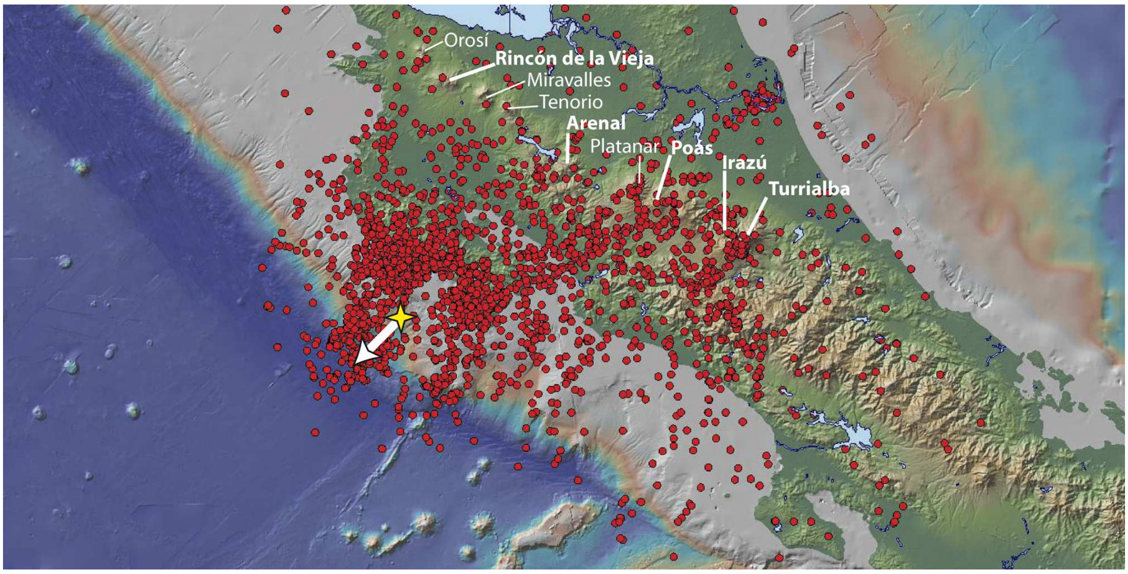

Figure 1: Seismicity in September 2012 and location of the main volcanoes. Yellow star: epicenter of the Nicoya seism on September 5th, 2012 (Mw = 7.6). White arrow: direction of the displacement due to the Nicoya seism (map: Walter Jiménez Urrutia, Evelyn Núñez, y Floribeth Vega del grupo de sismología del OVSICORI-UNA).

Regarding the volcanoes, the seism of Nicoya generated an important seismic activity especially in the volcanic complexes Irazú-Turrialba and Poás as well as an unusual seismic activity mainly for Miravalles, Tenorio and Platanar-Porvenir. No important change in the superficial activity was noticed, but an unusually high seismic activity continued for few weeks.

Volcanically speaking, the main effect observed was the activation of tectonic faults associated to the volcanoes, either in Costa Rica or in Nicaragua. The seism of Nicoya generated swarms of volcano-tectonic events nearby most active and some resting volcanoes. However no significant change in the volcanic seismicity strictly speaking was noticed, neither external signs (phreatic eruptions, unusual gas emission, etc) for any of the active costarrican volcanoes. Important changes happened at some volcanoes of Nicaragua (San Cristóbal, Telica, Apoyeque), however these cannot be directly attributed to the seism of Nicoya even if it probably contributed as they were intermittently active these last years. Volcanic changes can occur after an important earthquake because it modifies the static and dynamic field of stress. While passing, the seismic waves induce dynamic fluctuations, and the strain induced by the fault dislocation produces static changes. In both case, a volcanic system responds with delay due to its viscoelastic property and to the constants of diffusion of the fluids involved (*Brodsky et al*, 2003). In order to generate a volcanic reaction, a magmatic body must be saturated in gas within a shallow magma chamber. Hence only a few magmatically active volcanoes showed modification of their activity with the occurrence of a high magnitude earthquake nearby (*Cannata et al*., 2010).

II_ Turrialba Volcano

II_1 Turrialba V.: Summary of the main events in 2012

On January 12th, 2012, 3 p.m., Turrialba volcano emitted ash for a few hours due to the opening of a vent, the 2012 Vent, on the southwest inside slope of the Central Crater (Fig.2a). The next day a less than 1m-diameter conduit was visible. On January 18th, 2012, 3 p.m., the same vent emitted ash again for a few hours (Fig.2b), widening the conduit to ~3m diameter. Since then, the 2012 Vent is an active contributor to the plume generation of the volcano, which travels large distances sometimes reaching Nicaragua, the Pacific or Atlantic Oceans. The gas is expelled from the 2012 Vent at temperatures around 800°C.

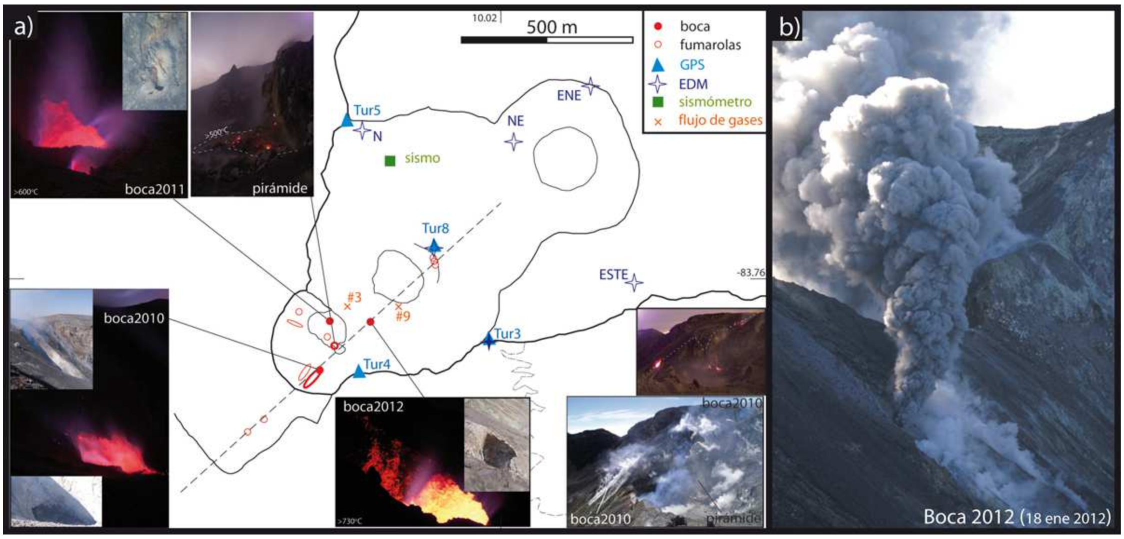

Figure 2: a) Map of the summital craters of Turrialba volcano with the main thermal anomalies indicated, especially the active vents (2010 Vent, 2011 Vent and 2012 Vent). b) Second ash emission on January 18th, 2012, which widened the conduit of the 2012 Vent one week after its opening. (photos: G.Avard)

II_2 Turrialba V.: Seismic Activity

In 2012, the seismic activity at Turrialba volcano was dominated by a shallow seismicity related to the hydrothermal activity and the water-gas-rock interaction (fluids motion in the aquifers, rock fractioning due to the injection of hot and pressurized fluids). The volcano-tectonic seismicity of Turrialba volcano contrasts with the one of Irazú volcano

(Fig.3). Irazú has seismicity in its whole edifice between -5 km and the sea level whereas VTs at Turrialba volcano are concentrated in the upper part of the edifice with low seismicity in faults around. The seismicity of Irazú volcano is most likely related to the fault system which is activated by changes in the local and regional stress field, whereas the activity at Turrialba volcano is related to rock fractioning due to fluids injection, i.e. hydrofractioning due to the interaction water-gas-rock as a result of the desgasification of a relatively shallow magmatic body.

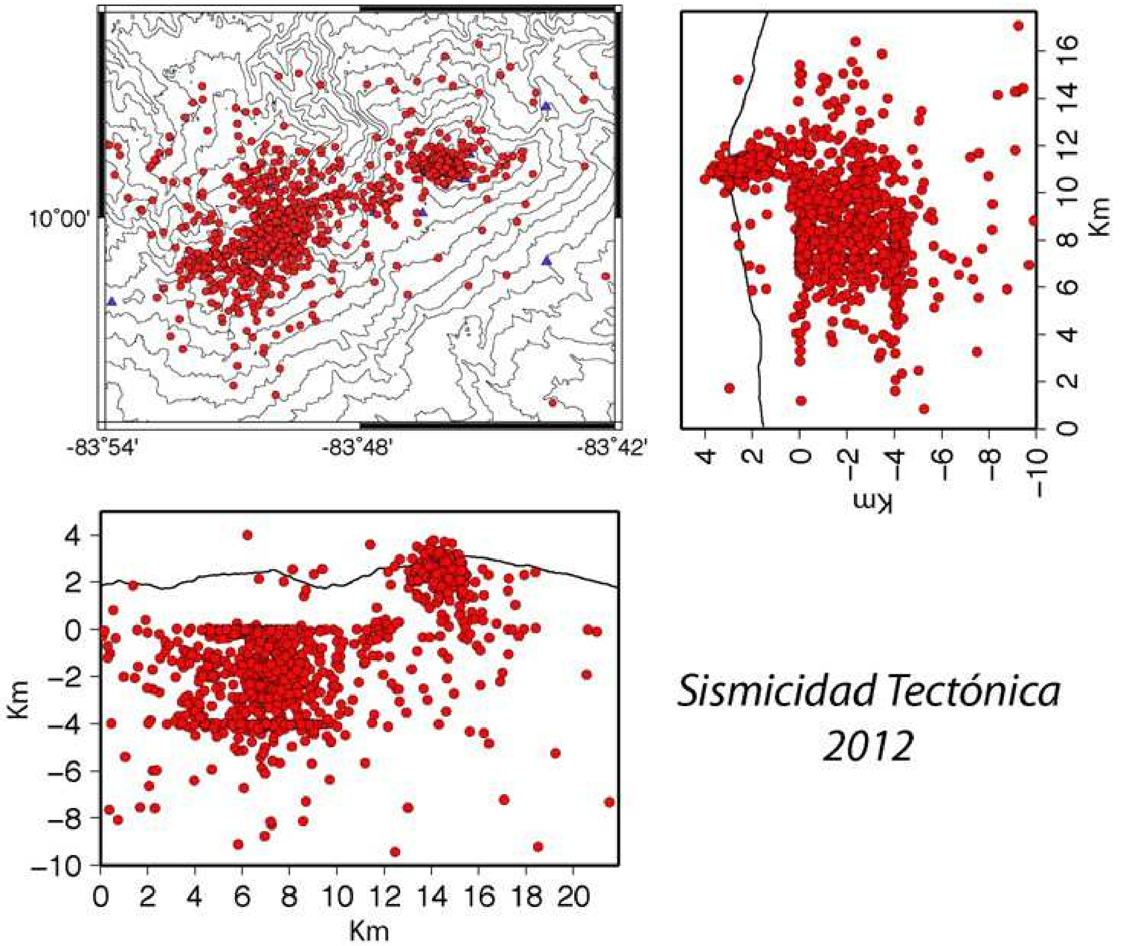

Figure 3: Tectonic seismicity recorded at Irazú and Turrialba volcanoes in 2012.

In general, the volcanic seismicity was lower in 2012 than the previous years 2011 and particularly 2010. Figure 4 shows the daily number of seismic events between January and December 2012. A small increase occurred in January followed by a decrease after the opening of the 2012 Vent on the internal southwest wall of the Central Crater. The decrease was interrupted by a seismic swarm mid-March characterized by up to 250 shallow amplitude events per day on March 15th. This swarm lasted 4 days then the activity came back to less than 100 events per day on March 18th. Activity below 50 events per day kept going most of the year until early September when a slow increase reached more than 100 events per day between mid-October and mid-November before decreasing again to less than 50 events per day at the end of November, and one single digit event per day at the end of December (Fig.4).

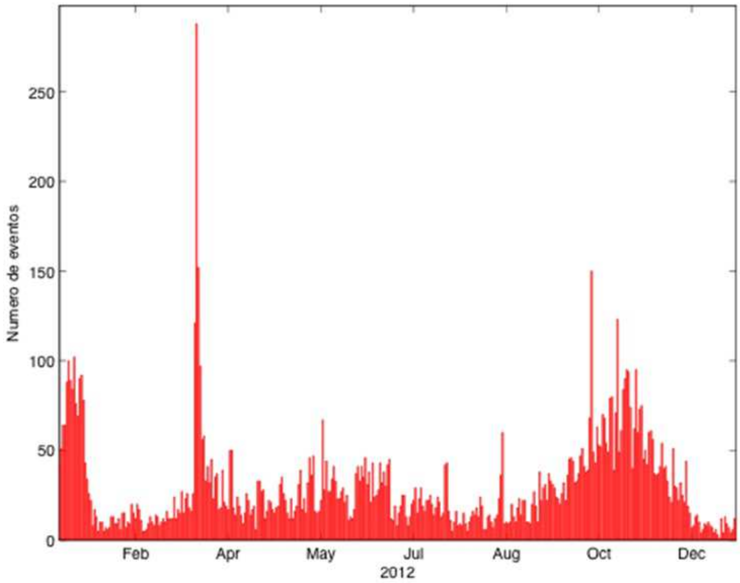

Figure 4: Number of daily volcanic seisms recorded at Turrialba volcano in 2012.

II_3 V.Turrialba: Deformation

A network of Electronic Distance Measurements (EDM) is regularly repeated at the top of Turrialba volcano (Fig.5a) as part of the monitoring to determine deformations of the edifice, its upper part and the craters.

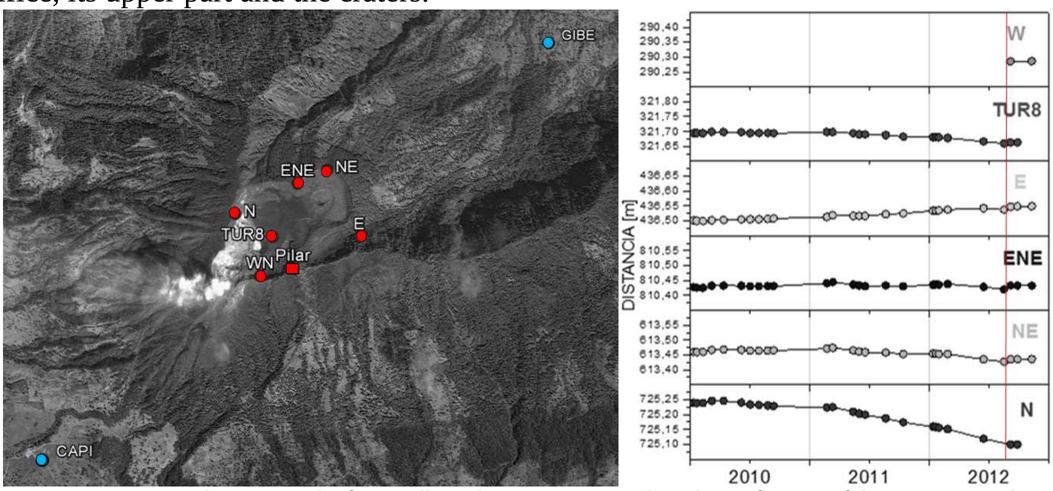

Figure 5: a) Geodesic network of Turrialba volcano in 2012. Red circles: reflectors of the EDM network measured from the Pilar (red square). Blue circles: permanent GPS stations (CAPI and GIBE). b) Longitudes of the EDM lines as defined Fig.5a. in 2010-2012. The red line marks the Mw 7.6 earthquake of Nicoya on September 5th, 2012. Generally a contraction of the distances is noticed in 2012.

In 2012 was noticed a general contraction of the distances in the summital network. The most significant contraction was about 7 cm/yr on the line from the pilar to the northern point N (Fig.5). The NE reflector has 3.6 cm/yr contraction while TUR8 has 3 cm/yr. The ENE and NE reflectors have less than 2 cm/yr contraction. The red line marks the Nicoya earthquake on September 5th, 2012, which generated an expansion of the lines (*Estado de los volcanes, setiembre del 2012*).

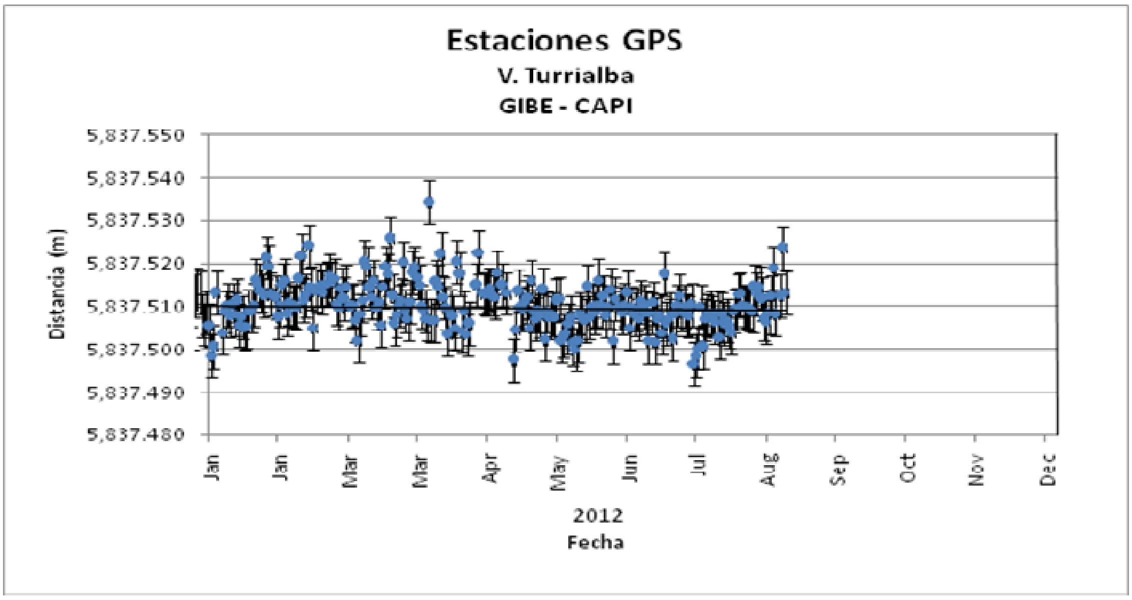

Figure 6: Geometrical distance between the 2 permanent GPS stations CAPI and GIBE for 2012.

The geometrical distance between the 2 permanent GPS stations CAPI and GIBE varies within a 2 cm range interval in 2012. A few measurements are beyond this range due to changes in the ionosphere and ambient humidity with the alternation of the dry and wet seasons. Looking at Figure 6, the general tendency is a contraction, with a non-significant magnitude of 2 mm which is within in the uncertainty of measurements (± 5 mm). Taking into account the results from the EDM network and the base of the longitude between the GPS stations CAPI-GIBE, we can infer that no deep magma intrusion occurred in 2012. A recent GPS field campaign, as part of the university training, determined that the main measured displacement occurred on the east component (9cm) of the Pilar.

II_4 Turrialba V.: Magmatica-hydrothermal Activity

The opening of the 2012 Vent was not associated to any new magmatic activity. As well as the 2010 and 2011 vent openings, we consider it corresponds to the opening of a conduit or superficial fracture through the summital shallow hydrothermal system under its pressurization. The similar temperatures of the 2010 (estimated at ~600°C), 2011 (580-620°C with a thermocouple) and 2012 Vents (750-805°C with a thermocouple, Fig.7) suggest a common magmatic source of heat and volatiles.

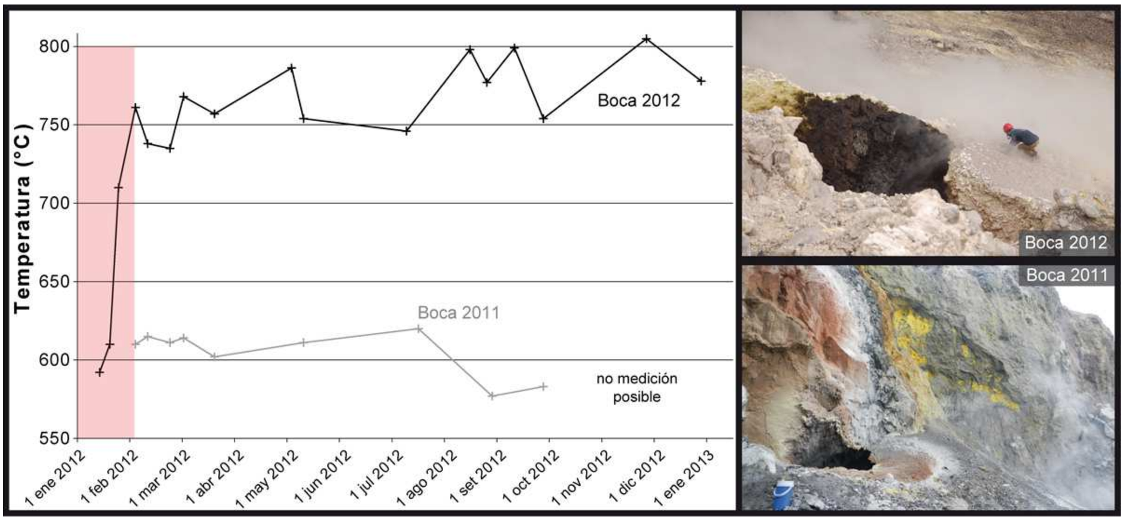

Figure 7: Temperature evolution of the 2011 and 2012 Vents measured thanks to a thermocouple. The measurements were affected by the difficulty to access to the 2012 Vent in January, and the 2011 Vent at the end of 2012 (Photos: C.Muller and G.Avard)

Since May 2012, a permanent mini DOAS station is working again at La Central school, ~2.2 km SW of the West Crater as part of the NOVAC project. It allows measurements of the SO_2 concentration in the volcanic plume (Fig.8a). The lack of knowledge on the wind properties (speed and direction) as well as on the plume height is responsible for an important uncertainty on the SO_2 flux, estimated up to a factor 2. However, the measurements from the mini DOAS and from the NASA satellite AURA are consistent and of the same magnitude (Fig.8b). In 2012, both methods to monitor the SO_2 emission consistently showed a low flux fluctuating between 300 $t{\cdot}d^{-1}$ in May and 800 $t{\cdot}d^{-1}$ in July and November (mini DOAS data) and between 20 and 580 $t{\cdot}d^{-1}$(OMI-AURA data). Such values are low in comparison to the flux measured in 2009-2010 (up to 4000 $t{\cdot}d^{-1}$ of SO_2).

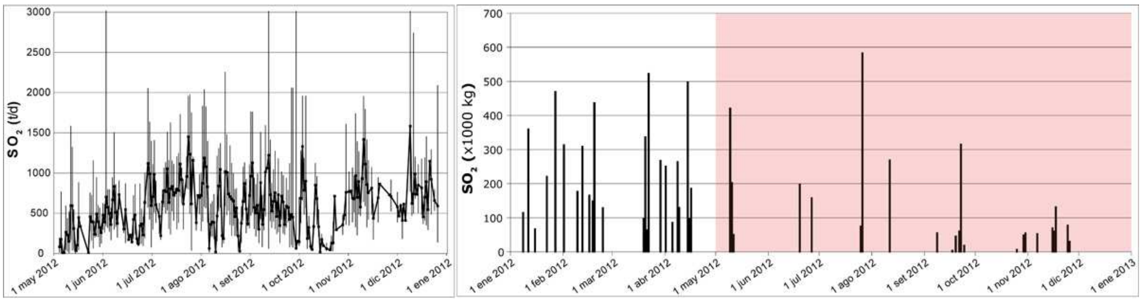

Figure 8: a) Daily flux of SO2 measured by a mini DOAS station at La Central. B) SO2 mass emitted by Turrialba volcano measured by OMI-AURA satellite image from NASA between October 2008 and December 31st, 2012. The SO2 mass corresponds to the total mass detected by the OMI sensor in the Central America area at 6-7 p.m. UTC, it is not corrected for any noise. http://so2.gsfc.nasa/.

II_5 Turrialba V.: Hydrothermal Activity

The hydrothermal activity corresponds to the activity generated by fluids circulations. Most fluids are originally meteoric and interact with the heat and gases released by a magmatic body underneath. This fluids circulation through cracks in the superficial hydrothermal system generates vibrations and rock fracturing which represent the main seismic activity at Turrialba volcano in 2012 (Figs. 3 and 4). The hydrothermal system traps and transports heat and magmatic volatiles up to the surface, and it absorbs fast changes in the composition and heat flux that could potentially generate the magmatic activity. Regular measurements of the CO_2 and H_2S fluxes that diffuse through the ground along a profile from the West Crater to the Central Crater showed a gas flux increase in this area prior to the opening of the 2012 Vent (Fig.9). This increase was followed by a flux drop with the 2 ash emissions on January 12th and 18th. After this opening, the diffuse flux of CO_2 and H_2S remained stable to even a slight tendency to decrease. This observation is consistent with the reduction of the magmatic volatiles transfer to the atmosphere according to the SO_2 flux in the volcanic plume (Fig.8). Hence, the measurements generally support the hypothesis of a magmatic body that intruded between 2001 and 2007 (*Vaselli et al.*, 2010) which would be crystallizing and depleting in volatiles.

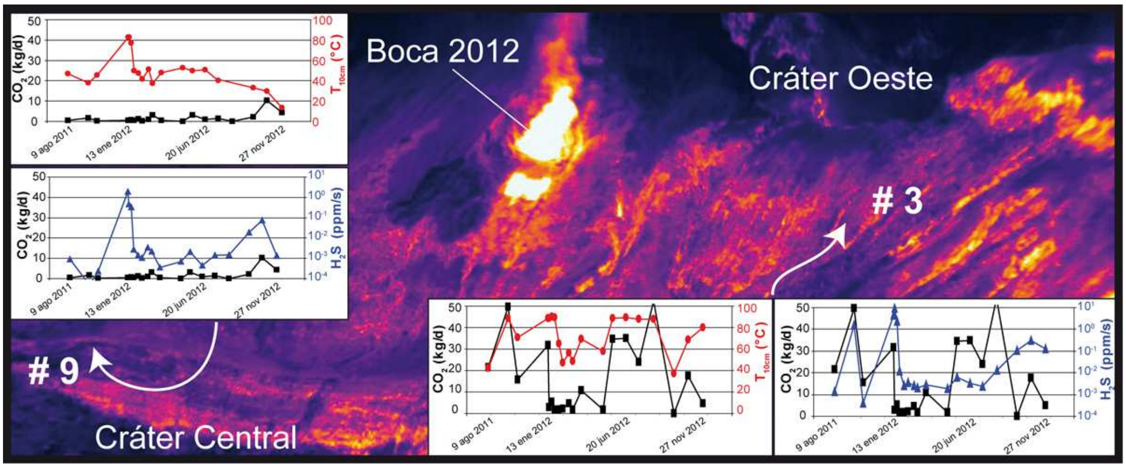

Figure 9: Thermogram of the west wall of the Central Crater on October 27th, 2012 (Image: G.Avard). Time sequence of the temperature at 10cm depth (in red), of diffuse CO2 (in black) and H2S fluxes (in blue) for the points #3 and #9 of the profile (Fig.2)

II_6 Turrialba V.: Environmental impact and erosion

II_6.1 Environmental impact

The acid rain and fog combined with the direct interaction with the volcanic gases continued affecting the vegetation, the soil and the infrastructures near the volcano. In 2012, the forest did not recover in the sectors affected by the dominant wind (SW-N sector, Fig.10).

Figure 10: Turrialba volcano on August 26th, 2012. The vegetation on the top and on the flanks (zone 1) of the edifice shows severe affectation such as necrosis (death of the vegetal tissue). The pastures (zone 2) used for milk production shows clorosis (the vegetation turned yellowish). It is interesting to notice that part of the native vegetation such as the tall trees Quercus sp show a better resistance to the environmental acidification (Photos: G.Avard)

In 2011 and 2012, the humid and dry acid deposit collected at different station around the volcano showed pH values with a positive slope which indicates a reduction of the acidity of the total deposit (Fig.11). This general tendency suggests a decrease of the magmatic gas input in the atmosphere during the last 2 years in opposition to the measurements in 2009 and 2010. However, without any more magmatic intrusion the volcano will continue degassing at an important level for several years before the shallow magmatic body cools down enough to show a dominant hydrothermal activity such as the years 2005-2007.

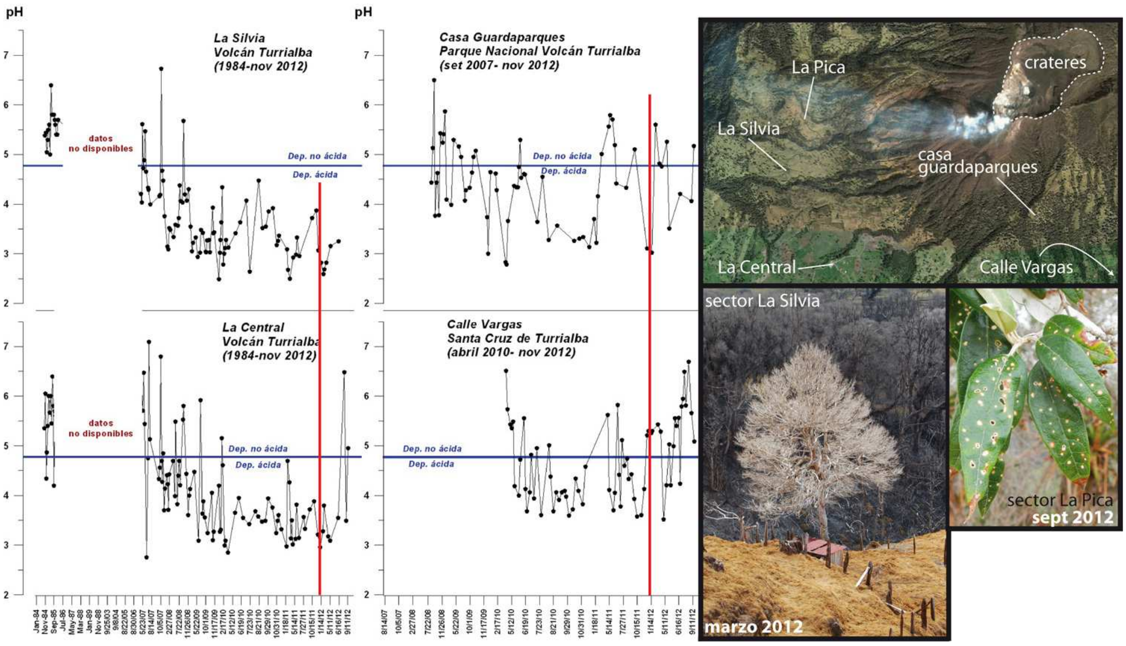

Figure 11: pH (acidity level) of the total deposit (humid + dry) collected at the stations: La Silvia (2.6 km W of the summit), La Central (2.2 km SW of the summit), Casa Guardaparques y Calle Vargas. Values of $pH \leq 5.6$ correspond to an acid deposit (blue line). Data: Programa de Vigilancia Volcánica – Laboratorio de Geoquímica Volcánica "Dr. Eduardo Malavassi Rojas" del OVSICORI-UNA.

II_6.2 Changes due to the erosion process

The hydrothermal activity modifies the mineralogy and decreases the cohesion of the rocks in contact with the fluids, which alter and reduce the stability of the slopes of the volcanic edifice, triggering gravitational collapses, rock falls and strong erosion during the main rainy events. Such implications were noticed after the storms on August 15th and in November, 2012, when coarse and fine material was transported from the walls to the bottom of the Central Crater, deepening the west and northwest gullies.

III_ Irazú Volcano

III_1 Irazú V.: Summary of the main events in 2012

Irazú volcano did not show noticeable changes whether for the degassing level of the fumaroles nor the geochemistry of the thermal springs in 2012, except for the tectonic seismic activity following the September 5th Mw 7.6 Nicoya earthquake. The level of the lake in the Main Crater stayed low all year with fluctuations and reached a minimum at the end of the year.

III_2 Irazú V.: Seismic Activity

Irazú volcano kept having an important tectonic-seismic activity possibly reflecting changes in the local and regional field of stress. The seismic peak occurred immediately after the Nicoya seism on September 5th, 2012 (Mw 7.4). Figure 3 shows the location of the volcano-tectonic seisms in 2012. The current network does not allow enough precision in the location to associate the events with the identified fault systems in the volcanic range. The seisms are uniformly spread in the whole range with a peak under the summit of the volcano, between the surface and 5 km depth.

Seismic activity was recorded all year with 3 peaks on January 9th, June 27-28th and September 5-8th (Fig.12). In January, the events were located southest of the Main Crater, in June they were north and northeast of the crater, and in September they were mostly under the summit area of the volcano.

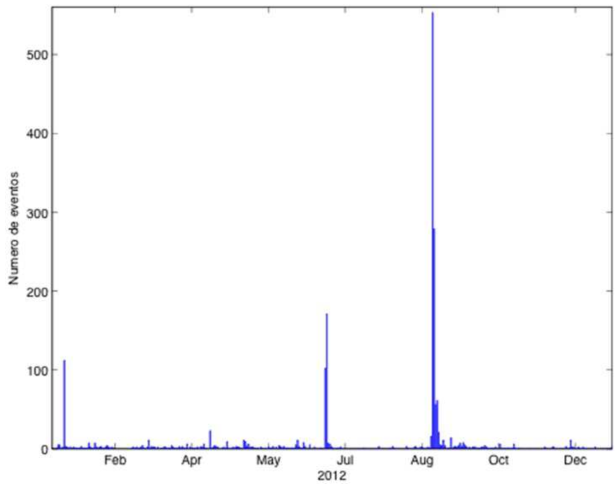

Figure 12: Number of daily volcano-tectonic seisms recorded at Irazú volcano

The volcanic seismic activity was dominated by LPs. This seismicity showed an almost – stable periodicity pattern until September 2012, then volcanic seisms occurred more frequently. These seismic events were LP type with a dominant frequency at 1.56 Hz and variable amplitude (Fig.13). The amplitude ranged between 1 and 30 microns, and the time interval between 2 events was around 15 hours at the end of November and in December. This variation indicates a slow increase of the hydrothermal activity, probably associated to the September 5th earthquake of Nicoya. The associated seismo-tectonic activity to this event could have opened new deep fractures allowing more heat to reach the hydrothermal system.

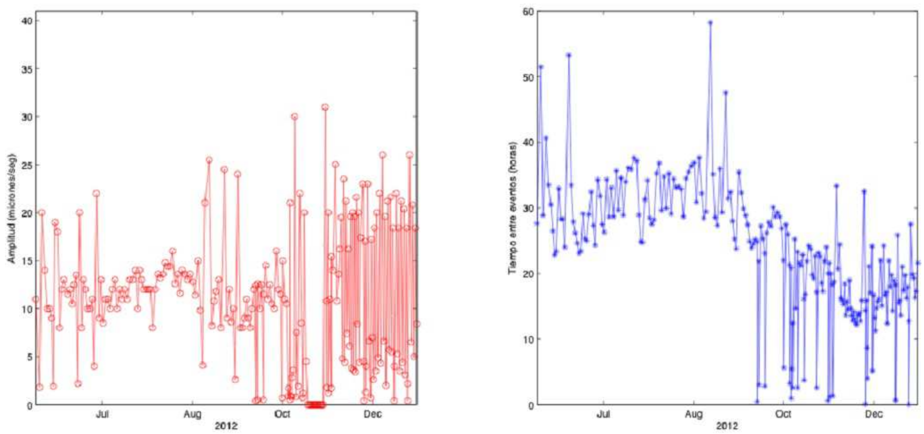

Figure 13: a) Variation of the mplitude in microns of the volcanic seisms vs. Time at Irazú volcano. B) Variation of the frequency of occurrence of the volcanic seisms vs. time.

III_3 V.Irazú: Deformation

In 2012, the deformation was determined using a network of Electronic Distance Measurements (EDM, Fig.14a). The result shows a general tendency between 3 and 5 mm contraction (Fig.14b). This result is in opposition to the tendency from mid-2008 to the end of 2011 when inflation was noticed.

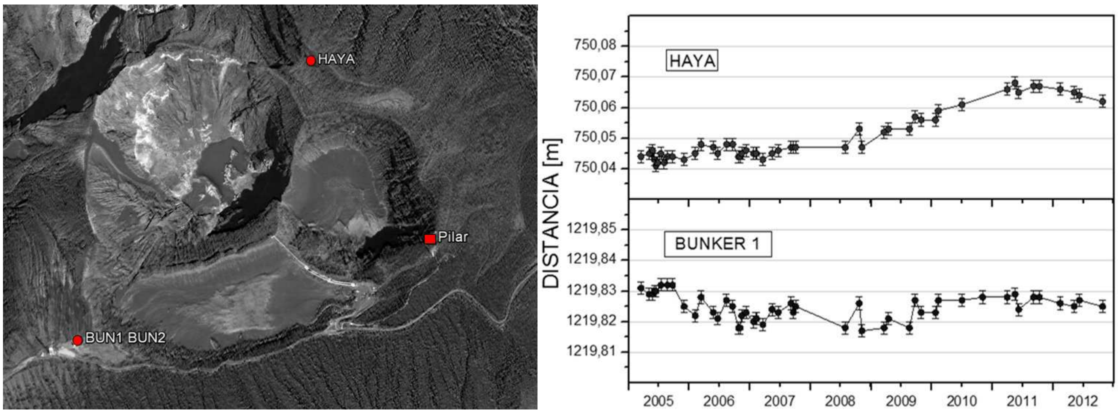

Figure 14: a) EDM Network at Irazú volcano (BUN1, BUN2, HAYA), measured from Pilar. b) Longitude lines of EDM, observed from Pilar at the summit of Irazú volcano.

III_4 Irazú V.: Magmatic-hydrothermal activity

III_4.1 Irazú V.: Lake in the Main Crater

The nivel of the lake in the Main Crater stayed low during the whole year 2012. In December 2012 it was reduced to a pond (Fig.15). The rainy deficit in Costa Rica in 2012 affected this level of the lake. The tectonic activity in the volcanic range may have also affected the stability of the crater lake.

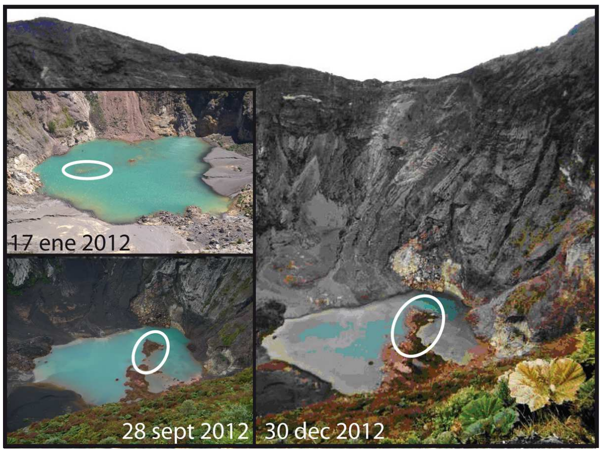

Figure 15: Evolution of the level of the lake in the Main Crater of Irazú volcano (photo on Dec. 30th, 2012: Alejandra Muñóz Chacón, other photos: G.Avard)

III_4.2 Irazú V.: Fumaroles and Thermal Springs

In 2012 Irazú volcano had a secondary hydrothermal activity with weak low temperature fumaroles (<90°C), sulfur and minerals deposit, and hot springs. The irregular monitoring of physic-chemical parameters such as acidity (pH), electrical conductivity and temperature of the northern hot springs did not show any significant change in the hysdrothermal system feeding them. The springs Río Aguacaliente and Quebrada Gata A have a stable composition, temperature and acidity with minor fluctuations (Fig.16) most likely due to meteorological affectation. Río Aguacaliente's geochemical characteristics suggest a deeper origin of the agua than Quebrada Gata.

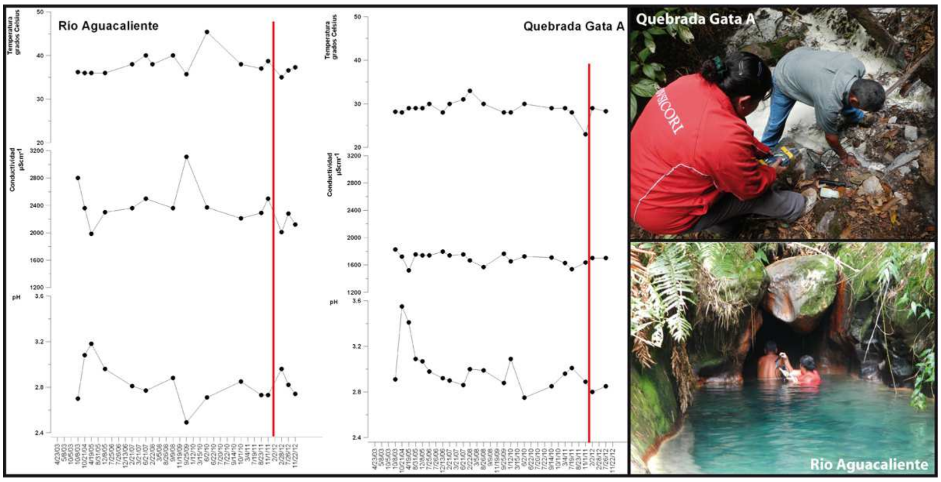

Figure 16: Geochemical parameters monitored for Río Aguaclaiente and Quebrada Gata A hot springs at Irazú volcano between 2003 ans 2012. The red line marks the beginning of 2012. Data: Laboratorio de Geoquímica Volcánica del Programa de Vigilancia Volcánica del OVSICORI-UNA.

IV_ Poás Volcano

IV_1 Poás V.: Summary of the main events in 2012

Poás volcano had unusual high temperaturas on the cryptodome between June and October 2011 (700-890°C), with incandescence visible by day between July and September of 2011. After the temperature peak in August 2011, the heat input in the cryptodome decreased constantly during the whole year 2012. Sporadic phreatic eruptions occurred all year in 2012 with a short pause between August 4th and October 17th, 2012, followed by stronger ones between October 18th and 27th. Various active convection cells have been observed at the surface of the lake since May 2011, sometimes vigorous.

IV_2 Poás V.: Seismic Activity

The volcano-seismic activity was dominated by small and shallow low frequency (LP) events, as well as phreatic eruptions in the lake (Fig.17a). These last ones can be gas bubbles reaching the surface to large phreatic eruptions throwing fine to coarse material, water and vapor from the bottom of the lake.

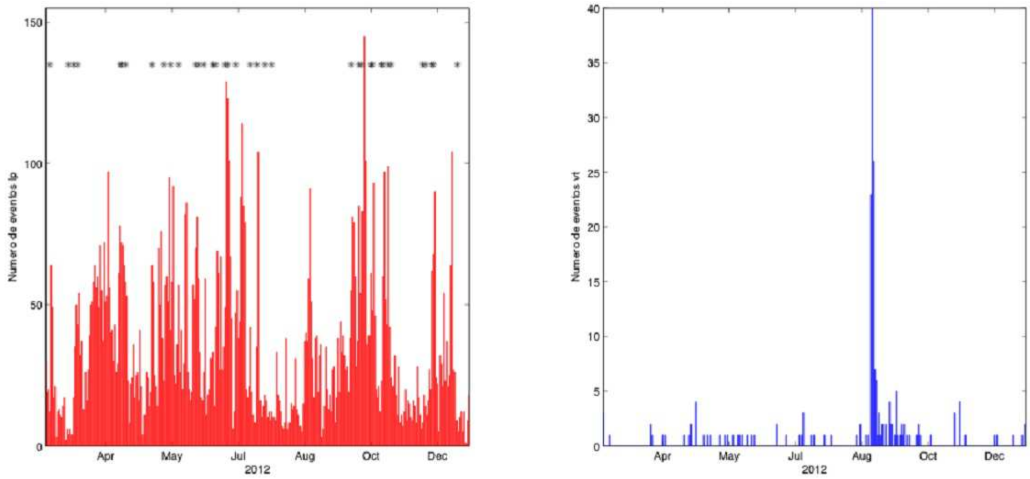

Figure 17: a) Volcanic seismicity: number of daily events. The asterix represent phreatic eruptions. b) Number of volcano-tectonic events per day.

The volcano-tectonic activity stayed low at Poás volcano. Most of these events were associated to fault responsible for the Cinchona earthquake in January 8th, 2009. A few tectonic seisms were recorded under the crater at shallow depth, which indicates an association with the hydrothermal system. The main activity occurred between September 5th and 7th (Fig.17b), following the September 5th, 2012, Nicoya earthquake (Mw 7.4), which suggests it is a response to the Nicoya event.

The phreatic eruptions reached a peak in amplitud and occurrence in October, especially between the 18th and the 27th (Fig.18). In January 2012 there was no data, and no phreatic eruption was recorded in September.

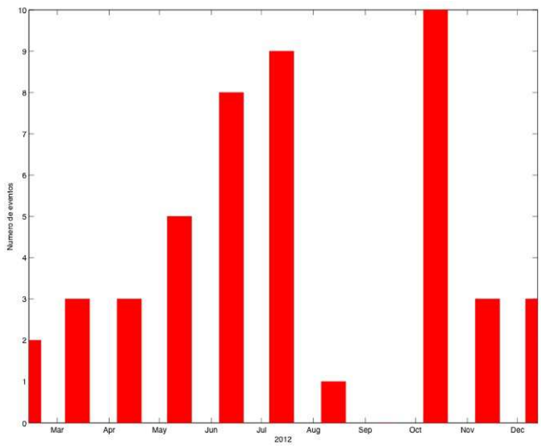

Figure 18: Number of phreatic eruptions per mes in 2012.

IV_3 V.Poás: Deformation

The general tendency in the distances of the network of Electronic Distance Measurements (EDM) at Poás volcano (Fig.19a) is contraction, only affected by the Mw 7.6 Nicoya earthquake on September 5th, 2012. Following this tectonic event, marked by the red line (Fig.19b), the distances continued decreasing as seen for the S and N reflectors. The displacement attributed to the Nicoya earthquake corresponds to 1 to 3 cm expansion.

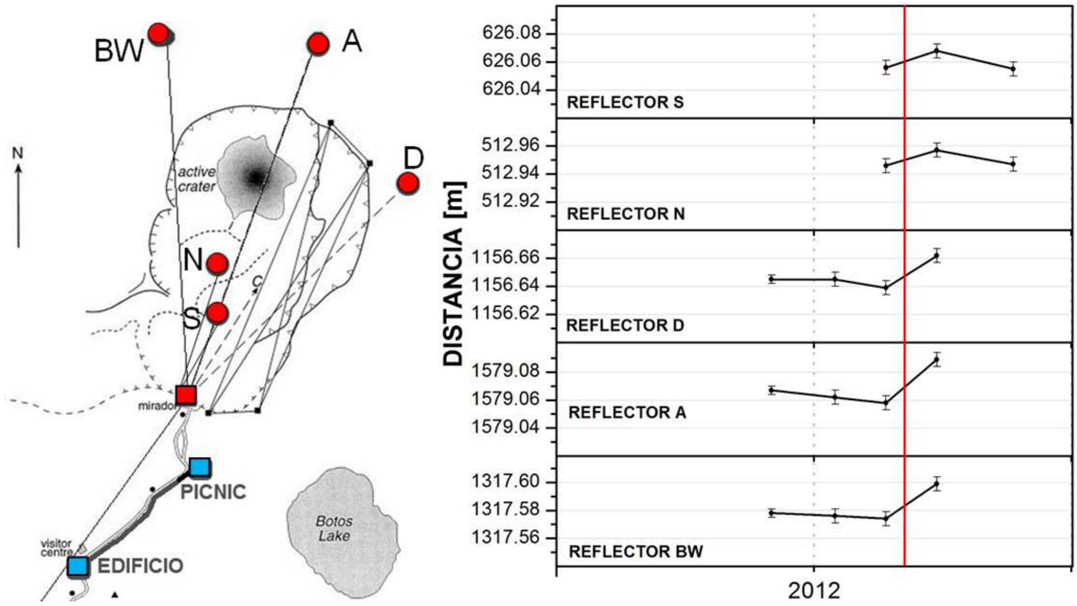

Figure 19: a) Geodesic network at Poás volcano. Red circles: EDM reflectors for which the distance is measured from the Pilar (red square). In blue are the 2 marks of the geometrical leveling. b) Longitude lines of the EDM network, observed from the Pilar at the Mirador of Poás volcano. A contraction was generally observed until the September 5th Nicoya earthquake. The S and N reflectors present the same tendency after this tectonic event.

In 2012, the geometric line of leveling Picnic-Edificio matches the general deflation tendency measured at the rate of 1.6 µrad/yr (Fig.20), which is represented by the green line. Such tendency is interpreted as the superficial response to the permanent and continuous release of gas and vapor from the magma chamber.

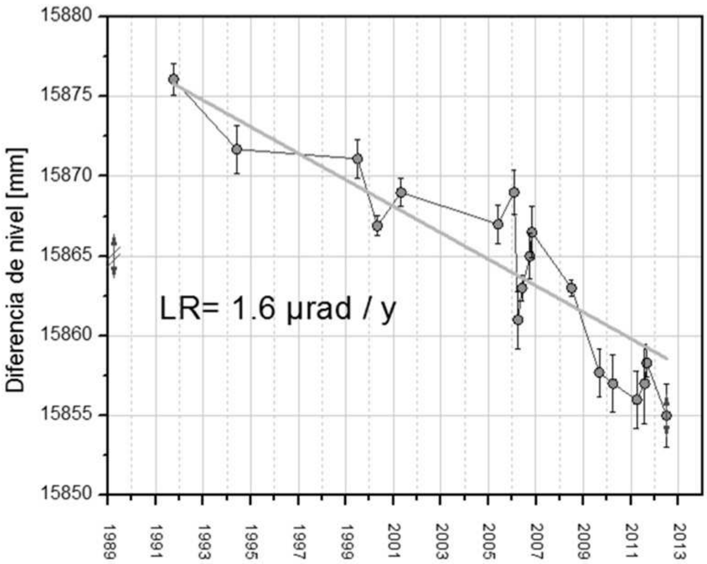

Figure 20: Level difference between Picnic and Edificio (Fig.19a.). A clear tendency of deflation at the rate of 1.6 µrad/yr is noticeable since 1991.

IV_4 Poás V.: Magmatic-hydrothermal activity

IV_4.1 Poás V.: Fumaroles of the cryptodome

The temperaturas of the fumaroles on the cryptodome decreases during the whole year 2012 from ~700°C to ~100°C (Fig.21), as well as their strength. These changes on the cryptodome suggest an important reduction of the fluids and heat transport from the magmatic-hydrothermal system toward the surface.

The cryptodome is a structure on the south edge of the ultra-acidic lake of Poás, and one of the most important site in the active crater where frequent intense degassing occurred in the history of the volcano. The temperatures of the fumaroles of the cryptodome were around 80°C in the 70s until December 1980, between 730°C and 1020°C in 1981-1983 with a maximum of 1000-1020°C between April and June 1981, between 275°C and 690°C in 1984-1988, and back to ~93°C between 1989 and 2008 (*Martínez et al.*, 2000; *Martínez*, 2008). Between May 2008 and February 2012, the fumeroles had a strong flux of vapor and magmatic volatiles and a slow increase of temperature from 109°C to ~900°C.

One can notice that the heating up of the cryptodome 1) occurred after 20 years at low stable temperatures (<93°C), 2) started 2 years after the beginning of a new period of phreatic eruptions in the lake which started in March 2006 until today, and 3) took place 8 months **before** the cinchona earthquake on January 8th, 2009.

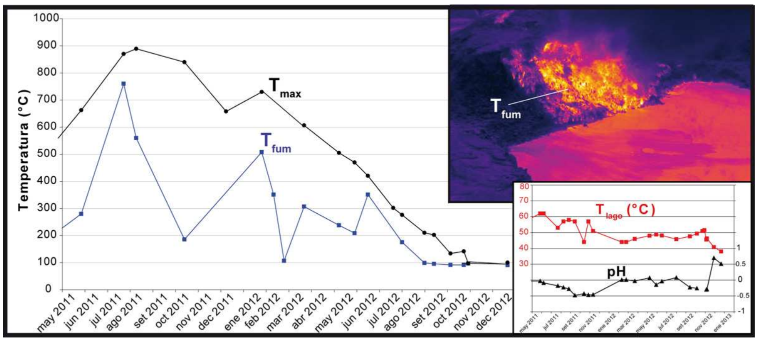

Figure 21: Evolution of the temperature of the fumaroles on the cryptodome since May 2011. The inserted figure shows the temperature and pH of the ultra acidic lake during the same period.

IV_4.2 Poás V.: Ultra acidic Lake

Since March 2005, Poás volcano has been in a phase of sporadic phreatic eruptions and vigorous convective activity in the ultra acidic lake with a peak of activity at the beginning and particularly in March 2006.

At least 44-47 phreatic eruptions were observed in 2012 either way by the rangers of the National Park Poás Volcano or in the seismic recordings (Fig.18). Sometimes they consist on large bubbles of gas+liquid, sometimes they are phreatic eruption of moderate energy (<500m high). A frequency and magnitude peak in phreatic eruptions occurred between October 18th and 27th. Important transport of molten sulfur from the bottom of the acidic lake to the surface was also noticed during the same period of October (Fig.22), due to the strength of the subaquatic fumeroles (>150°C, *Takano et al.*, 1994). This increase in the phreatic activity in October could possibly result from the disturbance of the hydrothermal system underneath the active crater after the September 5th Nicoya earthquake.

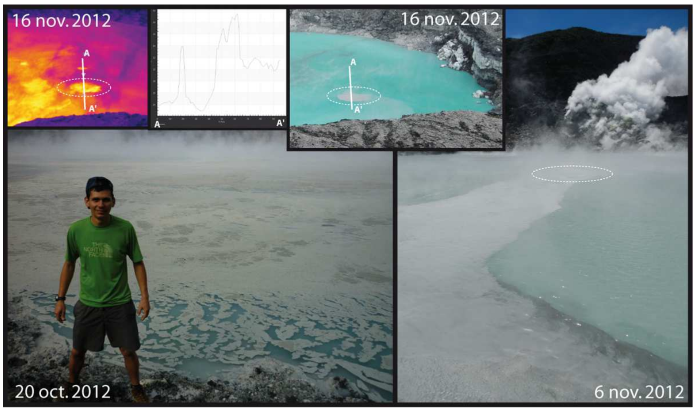

Figure 22: Photo of the lake on October 20th, 2012, showing an important quantity of molten sulfur on the surface of the lake, and covering most of its surface (photo: Fabián Murillo S.). The November 6th and 16th, 2012, photos show a sulfur streak that originates from a convection cell which temperature profile AA' is extracted from the thermogram and photo on November 16th (photos: G.Avard).

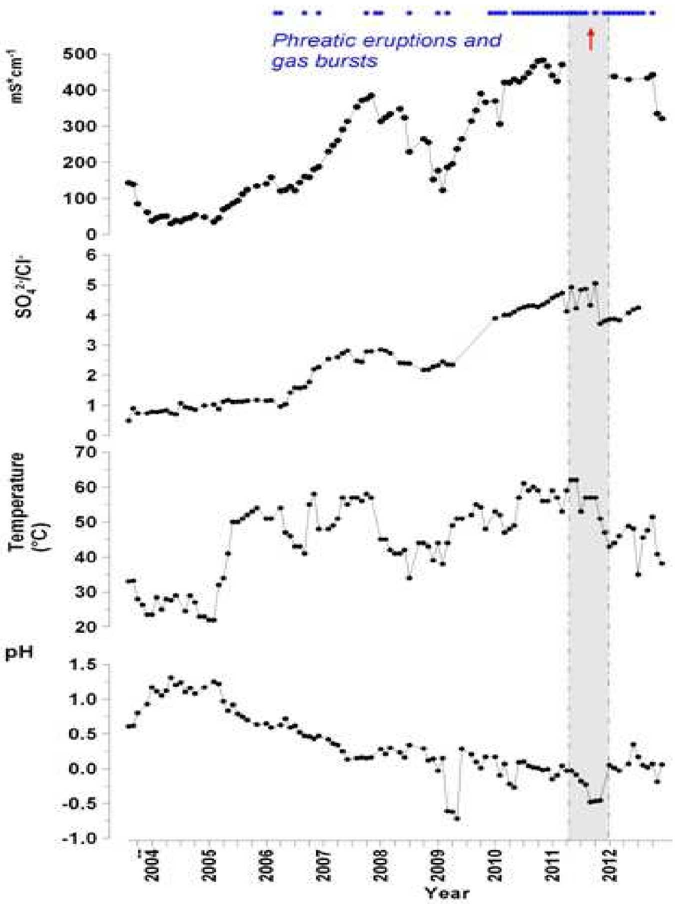

Figure 23: Time series for the electric conductivity, sulfate/chloruro ratio, temperature and pH of the ultra acidic lake of Poás volcano. The red arrow means the electrical conductivity was beyond 500 mS/cm, period (April-November 2011, in pink) where the pH was minimum and the cryptodome was recording the highest temperature of the fumaroles for the last 20 years.

The level of the lake decreased ~4m between January and October 2012 and recovered the same level in November-December 2012 due to the high precipitations common at this period of the year.

Figure 23 shows abrupt geochemical changes in the lake as well as unusually high values of electric conductivity (>500 mS/cm) and low pH in April-November 2011. On the same time the cryptodome was recorded with its highest temperatures of fumaroles in 20 years (up to ~900°C). Finally variations on the SO_4^{2-}/Cl^- ratio between November 2011 and March 2012 suggest the possibility of a deep injection of fluids rich in magmatic volatiles, such as hydrogen chloride, HCl, in the lake.

IV_5 Poás V.: Environmental impact and erosion

IV_5.1 Poás V.: Environmental impact

In 2012, the total acid deposit collected at the Mirador of the National Park registered pHs between 3.4 and 4.3 which suggest a strong impact level on the environment by the degassing of the active crater. A study realized in October-November 2012 showed that the fog has a much stronger power of affectation on the environment than rain due to a pH more extreme. At the Mirador, the pH was around 4.25 for the rain and 2.95 for the fog during the same period. It was still 3.17 and 4.01 for the fog at the Visitor Center and at the ranger station respectively (*personal communication from Dr. Jorge Herrera M., 2012*).

IV_5.2 Poás V.: Changes in the Main Crater due to erosion processes

The erosion process was more visible where persistent intense fumarolic activity occurs due to the alteration of the minerals and the decrease of the cohesion between particles as a result of chemical reaction between the rock and the hydrothermal fluids. The strong rain events in November eroded the north flank of the cryptodome, and the mobilized material buffered a few existing fumaroles and cracks, which affected the apparent fumarolic flux. Rock falls were also noticed from the steep edges of the crater east and northeast of the lake.

V_ Arenal Volcano

V_1 Arenal V.: Summary of the main events in 2012

The main event in 2012 was the collapse of a moderate volume of rocky material from the unstable upper northeast part of the edifice, most likely under the vibrations of the September 5th Nicoya earthquake. No reactivation of the magmatic system was noticed after this event.

V_2 Arenal V.: Seismic Activity

2012 was one of the years of lowest activity for the Arenal volcano since it woke up in 1968. No volcano-tectonic seisms were recorded, neither volcanic seisms nor tremors associated to the Aernal volcano. The September 5th Nicoya earthquake (Mw 7.4) did not generate seismicity inside the volcanic edifice, nor fault motions associated to the volcano. The closest seismic events recorded were located near Monteverde and near Tenorio volcano.

V_3 V.Arenal: Deformation

The electronic Distance Measurement (EDM) network is located on the west flank of Arenal volcano (Fig.24a). It shows a contraction of most lines (Fig.24b). Such a behavior was already noticed between 1992 and 2007 thanks to an EDM network on the south flank of the volcano that was destroyed by lava and pyroclastic flows. At the end of 2011 the rate of contraction started decreasing and no deformation occurred in 2012.

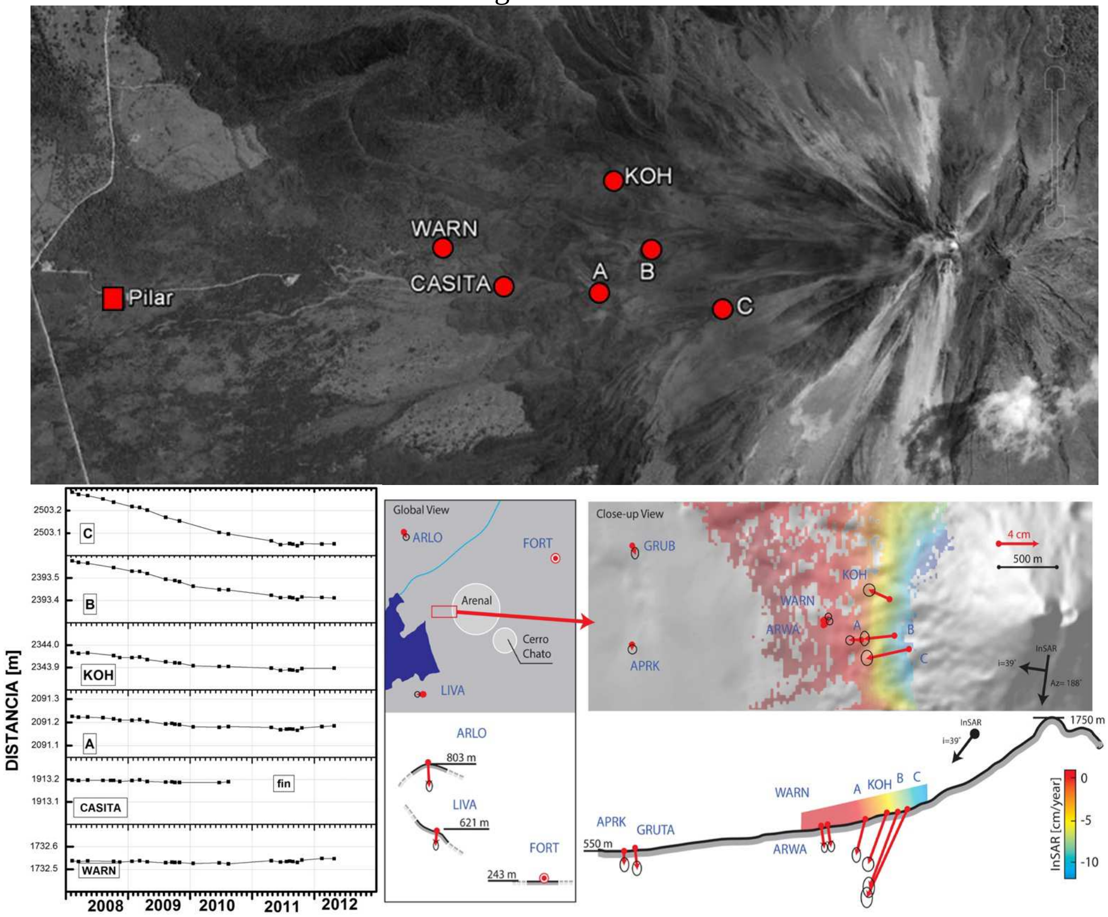

Figure 24: a) The geodesic network at Arenal volcano in 2012. Red circles: EDM network measured from Pilar. b) EDM results for the west flank of the volcano. c) Calculation of speed of deformation between 2008 and 2009 using EDM, GPS and 2005-2009 InSar techniques (Muller et al., 2011*).*

The Figure 24c combines GPS and EDM results over the period 2008-2012 with InSar over the period 2005-2009 (*Muller et al.*¸2011). It shows a contraction of 75±7 mm/yr of the lines, which is consistent with results from "dry inclinometry".

V_3 Arenal V.: Magmatic Activity

No magmatic activity was noticed in 2012.

V_4 Arenal V.: Hydrothermal Activity

V_4.1 Arenal V.: Fumaroles

The hydrothermal activity remained low with the presence of few diffuse fumaroles mostly on the north flank of the C cráter (Fig.25). No incandescence was observed by night, even with long exposure pictures which suggests low temperature in these fumaroles.

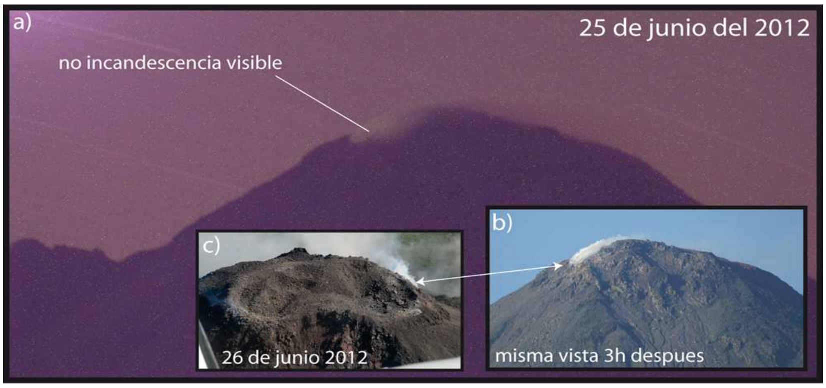

Figure 25: a) Night long exposure picture (~12min, iso800) of the northeast flank of the C cráter of Arenal volcano, and b) same view by day 3h later (Photos: G.Avard, on June 25th, 2012). c) Aerial photo of the C crater seen from south (Photo: F.Chavarría-Kopper, June 26th, 2012).

V_4.2 Arenal V.: Tabacón Thermal Spring

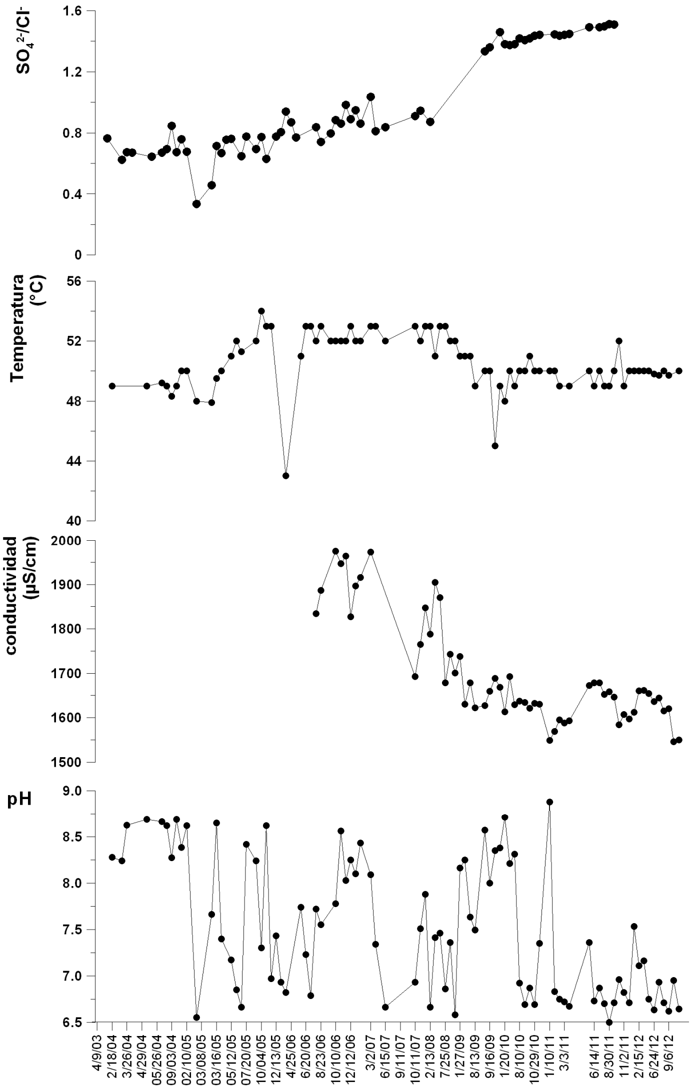

Figure 26: pH (acidity), temperatura, and sulfate-clorure ratio of the waters of Tabacón spring, Arenal volcano, from the end of 2007 to the end of 2013. Data: Programa de Vigilancia Volcánica - Laboratorio de Geoquímica Volcánica "Dr. Eduardo Malavassi Rojas"- OVSICORI-UNA.

The Tabacón thermal spring (site A), located NW of the Arenal volcano, had salina-chloridic waters until 2007. These water seem to originate from the fast infiltration of meteoric water in recent basaltic-andesitic calco-alkalin lava flows and old pyroclastic deposits. Since 2008, the waters of Tabacón are showing physico-chemical changes associated to the end of lava extrusion and the drastic drop in the degassing levels observed during the last 5 years. The SO_4^{2-}/Cl^- ratio, the temperature and the pH are especially showing (Fig.26) changes interpreted as the reduction of the input of heat, magmatic volatiles, and rock-formers elements through the hydrothermal system at the origin of the the Río tabacón.

V_5 Arenal V.: Environmental Impact and erosion

V_5.1 Arenal V.: Environmental Impact

The total acidic deposit (humid an dry) monitored by OVSICORI-UNA around the Arenal volcano show a sistematic increase of the pH up to values near the acid rain reference: pH 5.6 (Fig.27). The total deposit is considered acid for pH≤5.6. Such an evolution since 2010 especially reflects the significant reduction of any magmatic activity at Arenal volcano.

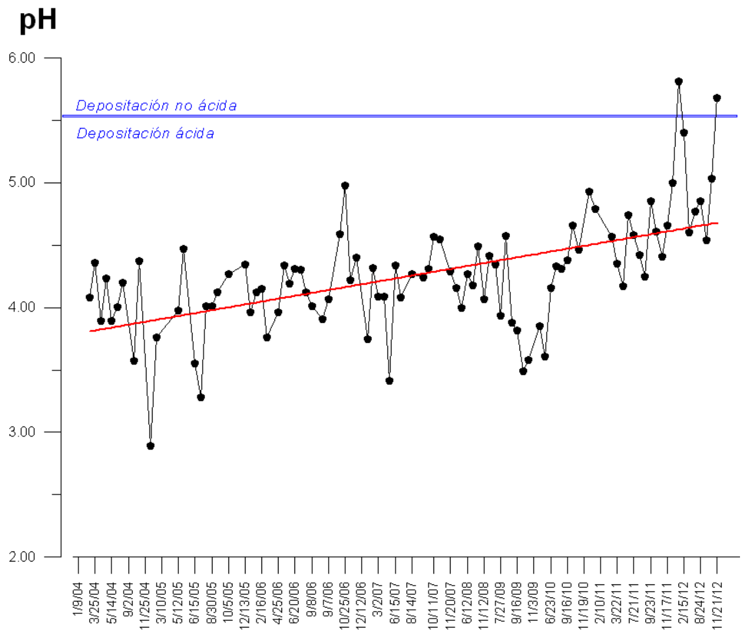

Figure 27: Evolution of the pH (acidity) of the toal acid deposit [humid and dry] at the entrance of the National Park. The blue line represents the acid rain limit. The red line is the average tendency of the data.. Data: Programa de Vigilancia Volcánica - Laboratorio de Geoquímica Volcánica "Dr. Eduardo Malavassi Rojas"- OVSICORI-UNA

V_5.2 Arenal V.: Changes due to erosion processes

Rock falls were observed and reported by inhabitants and park rangers in September-October 2012, and particularly in September 5th, day of the Nicoya earthquake. They originated from the summit of the volcano, on the north and northwest sides (Fig.28). The seism caused a noticeable fall of unstable rocky material and the weather conditions pursued this fast erosion process.

Figure 28: Northwest view of the edifice in May 2012 (Photo: C.Müller) and 24 hours after the September 5th earthquake of Nicoya (Photo: G.Avard).

VI_ Rincón de la Vieja Volcano

VI_1 Rincón de la Vieja V.: Summary of the main events in 2012

In 2012 Rincón de la Vieja volcano maintained a low activity with low seismicity. The most important phreatic eruption occurred on April 14th, 2012, and was moderate with small amplitude. It did not generate lahars.

VI_2 Rincón de la Vieja V.: Seismic Activity

In 2012, the seismic activity stayed low. The main activity was volcano-tectonic events that occurred between September 5th and 8th, with a total of 58 events, most likely as a consequence of the September 5th earthquake ofNicoya (Mw 7.4). Few volcanic seisms and sporadic tremors of very low amplitude and short duration were also recorded. Small phreatic eruption were recorded on February 19th and 20th, on april 14th, and on October 17th, 2012. The April 14th moderate phreatic eruption was recorded by the seismographs, visually observed and heard as an explosion and generated a column of vapor and sediments visible from Buenos Aires and Aguas Claras de Upala, ~7km north of the crater (Fig.29). The material ejected did not generate lahars.

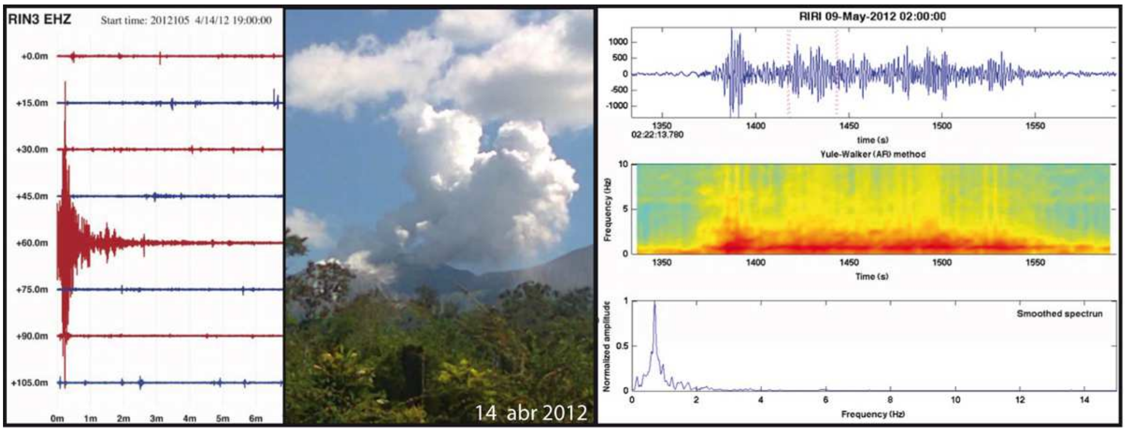

Figure 29: a) Seismograph of the April 14th, 2012, phreatic eruption b) Photo of the vapor-rich volcanic plume generated by the phreatic eruption as seen from Aguas Claras de Upala on April 14th, 2012 (Photo: Yanela Zamora Ugarte), c) Monochromatic tremor recorded May 9th, 2012: seismograph on top, spectrogram in the middle and spectrum of frequencies at the bottom.

VI_3 Rincón de la Vieja V.: Magmatic-Hydrothermal Activity

VI_3.1 Rincón de la Vieja V.: Ultra Acidic Lake

Few data are available for Rincón de la Vieja volcano because of the difficulty to access the crater and to the generally poor weather conditions. These data do not show any significant change for the physico-chemical parameters measured in the ultra acidic lake in 2012. In March and December 2012, the temperature was 29°C and 33°C, the electric conductivity was 125 mS/cm and 151 mS/cm, the pH was 0.42 and 0.37 respectively. Since 2000, the Figure 30 shows a decrease of the temperature, of the quantity of dissolved ions, and an increase of pH between September 2011 and December 2012, possibly due to a combination of a reduction of the volume of the lake due to sporadic phreatic eruptions with the dilution of the water lake due the input of meteoric water. In both March and December 2012 was observed molten sulfur floating on the surface of the lake.

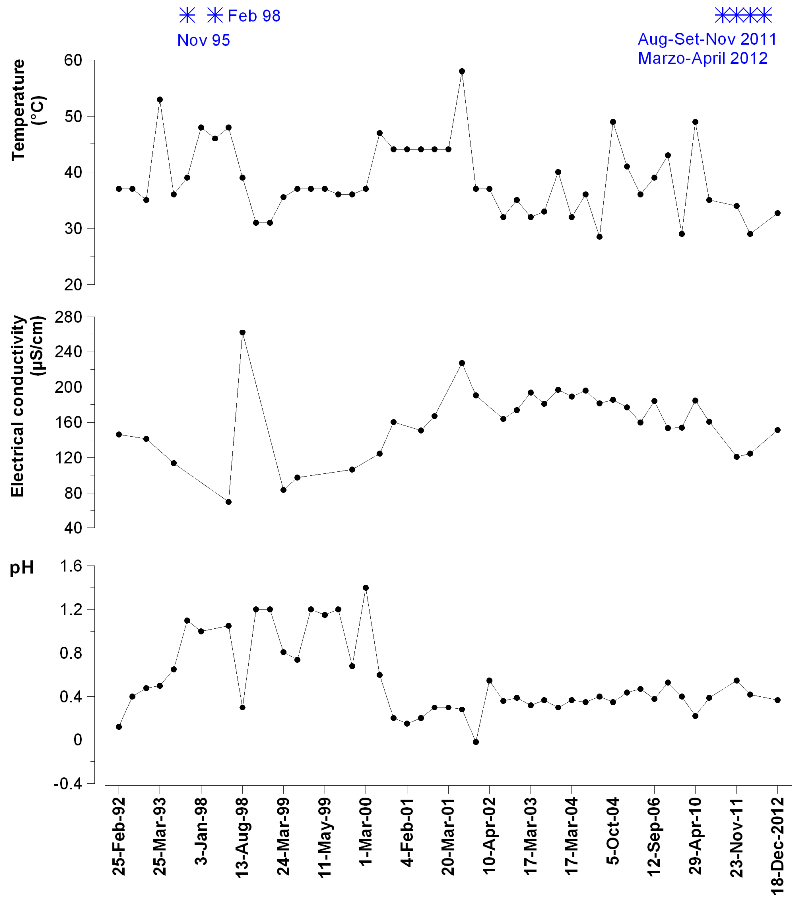

Figure 30:Physico-chemical parameters profiles of the ultra acidic lake of Rincón de la Vieja volcano: pH (acid level), and electrical conductivity compared to the temperature. The asterix indicate periods of reported phreatic eruptions.

VI_3.2 Rincón de la Vieja V.: Fumaroles, and Mud Volcanoes

The temperatures of fumaroles on the north flank of the edifice stayed around 90-91°C in 2012. And the mud volcanoes of the sector Las Pailas, southwest of the active crater, were measured at 96-100°C (Fig.31).

Figure 31: Left: Mud volcano on the sector Las Pailas, and infrared thermogram of a mud volcano. Right: temperature profile of the mud volcano corresponding to the AA' line on the left thermogram. The red and plue triangles locate the maximum and minimum temperature of the AA' profile respectively.(Photos: G.Avard on March 13th, and December 17th, 2012).

VII_ Barva Volcano

Barva volcano is monitored since 1992 through the thermal spring Huacalillo, 5.3 km southeast of the crater lake, 1846 m a.s.l. Huacalillo is a small acidic tributary of Ciruelas Río (Fig.32a). The water of the spring is low temperature (26.3°C-33.5°C), very acidic (pH 1.74-2,51), rich in sulfate (1,600-9,000 mg/kg), chloride (225-1,580 mg/kg) and fluoride (13-45 mg/kg). It contains a decent quantity of rock-forming elements such as Al (570 mg/kg), Fe (280 mg/kg), Na (190 mg/kg), Ca (162 mg/kg), K (166 mg/kg), Mg (58 mg/kg) and Si (73 mg/kg). It also contains trace elements such as B (3,5 mg/kg), P (9,7 mg/kg), Zn (963 µg/kg), Cd (29 µg/kg), Ba (37 µg/kg), Pb (15 µg/kg), La (451 µg/kg), Ce (854 µg/kg), etc. This water is considered saline, rich in $Cl^{-}+SO_4^{2-}$ y $Ca^{2+}+Mg^{2+}$, and are the result of the mix between meteoric water and a hydrothermal fluid derivated from the water–magmatic gas–rock interaction (OVSICORI data). Around the spring are vapors and a hydrogen sulfide, H_2S, smell. A pinky café deposit made of hydrous ironic oxides is noticeable over several meters toward the Río Ciruelas.

Figure 32b shows the variations of acidity (pH), temperature and SO_4^{2-}/Cl^{-} ratio for the last 10 years. Generally, the water of Huacalillo spring evolves toward a less chloride-rich composition, less acidic and colder water. This general trend suggests a slow decrease of the magmatic input in the hydrothermal system of barva volcano whether it is heat or volatiles, and less water-gas-rock interaction.

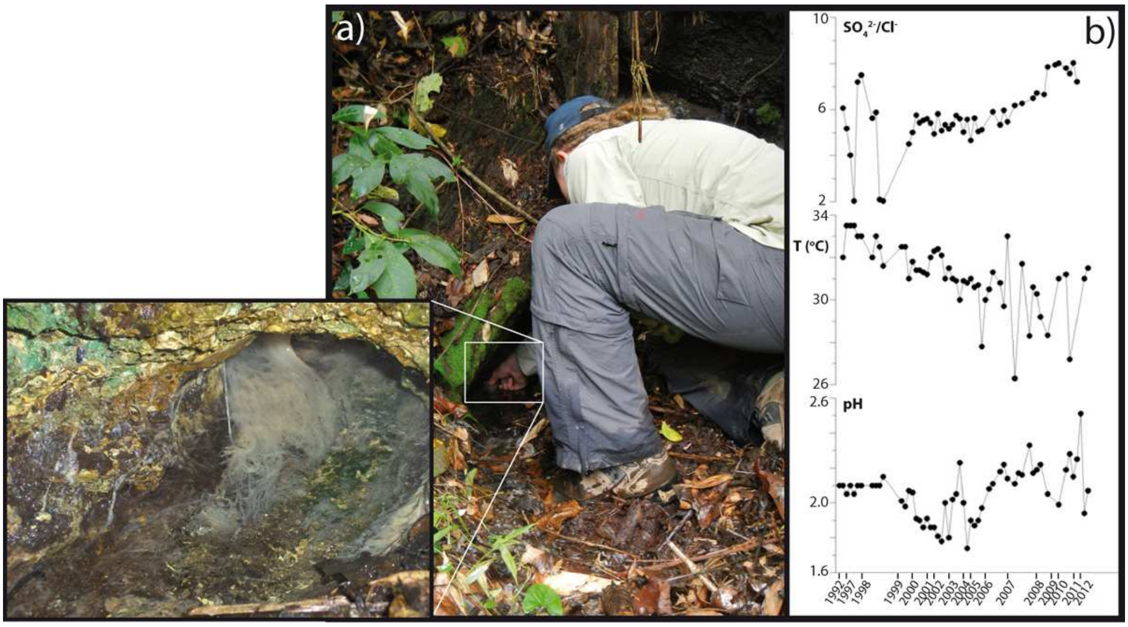

Figure 32: a) Huacalillo termal spring of barva volcano. The spring has filaments made of bacteria colonies which are currently studied at Utrecht University, Netherlands (Photos: M.Martínez, April 19th, 2010, and G.Avard, July 30th, 2012). b) pH (acidity), temperature and SO_4^{2-}/Cl^- ratio of Río Huacalillo (Data: OVSICORI-UNA)

Aknowledgements:

We thank the officials of the Costa Rica National Parks Conservation System, and to all the workers who helped the lab and field work to obtain data presented in this document.

Previous information about the monitoring of the volcanoes by OVSICORI-UNA are available following these links:

- Mensual bulletin about the volcanic activity in Costa Rica (in Spanish):
  http://www.ovsicori.una.ac.cr/index.php?option=com_phocadownload&view=section&id=3&Itemid=73

- Videos:
  http://www.ovsicori.una.ac.cr/index.php?option=com_content&view=article&id=55&Itemid=79

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