Turrialba volcano: Opening of a new fumarolic vent on the southeast flank of the West Crater on January 12th, 2012, as a consequence of a shallow decompression

View from the overlook on the 2012 vent on February 9th, 2012. Inserted pictures are:
1) on the left, incandescence after 6pm on the 2012 vent as seen on February 2nd, 2012; and 2) on the right, the second ash emission of the 2012 vent on January 18th, 2012.
(photos: G.Avard, OVSICORI-UNA).

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Abstract

Since May 1996, Turrialba volcano has shown an important increase in activity, which can possibly be interpreted as precursory of a new eruptive phase. The volcano-tectonic activity and degassing increase is particularly noticeable since 2007, and even more since the opening of the first fumarolic vent in the West Crater in January 2010, which suggested a magmatic intrusion between 2005 and 2007 as well as the beginning of a new eruptive phase. A new vent opened on January 12th, 2012, (Boca 2012 or 2012 vent) on the southeast external flank of the West Crater, with few hours of ash emission, followed by a second ash emission from the same vent on January 18th, 2012. Seismic recordings, deformation and diffused gas fluxes measurements allowed the conclusion that the opening of the 2012 fumarolic vent is not due to a change in the magmatic activity but to an excessive shallow accumulation of gas. Similar openings occurred at Turrialba volcano prior to the 1864-66 eruption and at Irazú volcano prior to the 1963-65 eruption, hence other openings of fumarolic vents can be expected in the future, especially along the fractures and weak zones aligned in a direction SW-NE that passes by the three upper craters of Turrialba volcano.

I_ Introduction

Turrialba volcano is a 3,349 m.a.s.l. basaltic-andesitic volcano. It is the furthest oriental volcano of the Central Volcanic Range of Costa Rica, ~30 km ENE of the capital San Jose. In its upper part are located three craters (East Crater, Central Crater and West Crater) aligned on a northeast-southwest direction, inside a depression opened toward the northeast, with normal faults on the edge oriented SW-NE (Fig.1). The last identified magmatic activity corresponds to explosive eruptions between 1864 and 1866. These explosions were preceded by at least 20 years of fumarolic activity, with opening of vents, and resulted with the formation of the West Crater, which has hosted most of the recent fumarolic activity since 1996 [1,2].

II_ Observations

II_1 Chronology

- *1996*: increase in the seismic and fumarolic activities (hydrothermal stage) [1,2].
- *2001, 2003-2005 and 2007*: seismic swarms and increase in the fumarolic activity with the apparition of magmatic gases (hydrothermal/magmatic stage) [1,2]. This stage was characterized by the extension of the fumarolic area and clear environmental effects (burnt vegetation, corrosion of metallic infrastructure, and health effects on human beings and animals).
- *2007:* increase in the fumarolic activity at the bottom of the West Crater, forming a plume up to 2 km high. Apparition of fumaroles in the Ariete Fault [2].
- *2007-2012:* increase in the fumarolic activity with a strong magmatic component and high temperatures [1].

- *January 5-6th, 2010*: phreatic eruption and opening of the 2010 vent on the west flank inside the West Crater accompanied by **ash emission** [3,4].
- *January 14th, 2011*: small ash emission, no juvenile [5].
- *Beginning of 2011*: first notice of a roaring sound from the 2011 vent located on the north side of the bottom of the West Crater [6]. This vent may have opened at the beginning of the rainy season, around May 2011, however no confirmation is possible.
- *January 12th, 2012:* opening of the 2012 vent on the southeast flank of the West Crater accompanied by an **ash emission**, no juvenile [7,8].
- *January 18th, 2012:* second **ash emission** at the 2012 vent, no juvenile [9].

II_2 Visual and physical observations

The opening of the 2012 vent occurred on January 12th, 2012, triggering a small ash emission for several hours. This ash was transported mostly W and NW by the dominant wind, and was reported up to Tres Ríos (~27 km southwest of the volcano) [8]. The following day a new vent about 3x5m with a ~1m diameter conduit inside was observed [10]. On January 18th, 2012, for the second time, a slightly larger volume of ash was emitted for several hours from the same vent. This ash was also transported mostly W and NW by the dominant wind. This second emission did not change the area of the vent but the diameter of the conduit increased to ~3m. Following the ash emission an important gas jet audible from the overlook (~350m away) was noticed, it still occurred at the end of March 2012. During these first 2 months of activity, gas temperature has been measured within the range of 700-765°C, inducing the calcinations of the rocks that form the conduit. The high temperature of the rock is responsible for radiation in the red-yellow visible spectrum by night, and the combustion of volcanic gases in contact with the atmospheric oxygen produces blue flames.

The main features presenting incandescence by night are: 1) the 2010 vent (estimated at >600°C), 2) the 2011 vent (>610°C), 3) the 2012 vent (>730°C) and 4) numerous spots at the bottom and in the south flank of the West Crater where yellow to red liquid sulfur is observed (500-730°C). Most hot spots are on or near a SW-NE line also noticeable thanks to the presence of various fumaroles that extend to the southwest outside the West Crater (Fig. 1).

A shallow accumulation of water first observed at the bottom of the West Crater in June 2011 [6] disappeared between January 13th and January 24th, 2012 [11] and was observed again at the end of March 2012.

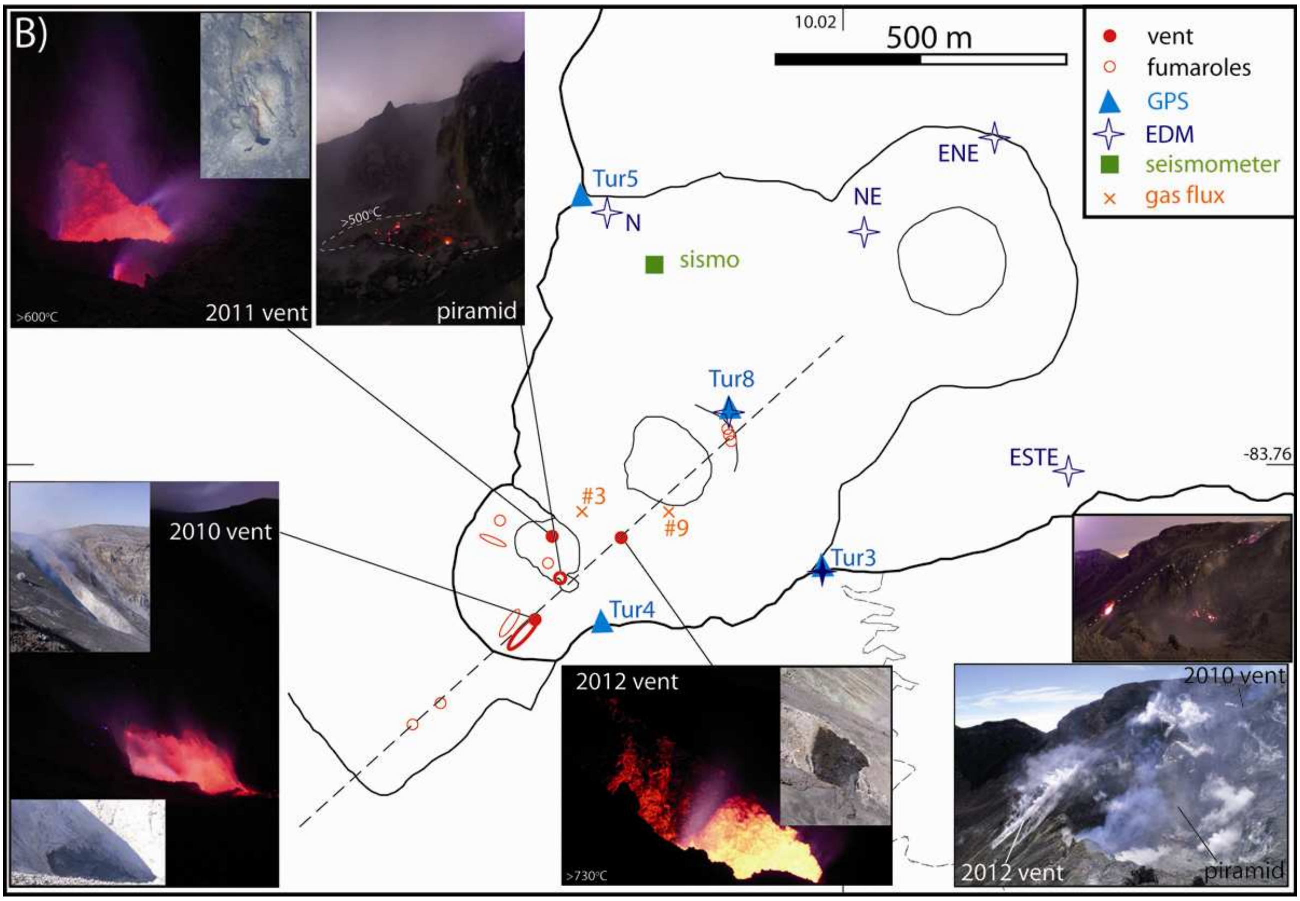

Figure. 1: A) General view to the north from the south rim of the West Crater

B) Map of the top of Turrialba volcano with its 3 craters and the northeast "grabben". The fumarolic and thermic activity is mostly located inside or around the West Crater, especially along a SW-NE line that passes through the southern areas of the West and Central Craters. Geodesic, seismic, and diffused gas flux points of measurement presented in this document are also reported. (photos: G. Avard)

II_3 Seismic activity

In 1990 the OVSICORI-UNA set up a short period and vertical component (Ranger SS1) analogical seismic station at the top of Turrialba volcano. Since 1999 a network of 3 short period analogical seismic stations has been built as part of the Volcano Disaster Assistance Program of the United States Geological Survey (VDAP-USGS). The network includes 1) two vertical component seismographs (Mark L-4C sensors), and 2) one two-horizontal component seismograph (Mark L-4D sensors) and a vertical sensor Ranger SS1. The stations are located on the west, south and east flanks of the volcano. Data are transmitted after modulation in Very High and Ultra High Frequencies (VHF and UHF). After 1999 the acquisition was done using the free kit Earthworm, first developed by the USGS and maintained by the users (www.isti.com/products/earthworm). Since 2010 the acquisition system of seismic data Antelope (www.brtt.com) has been used. In April of the same year 3 digital stations at the top of Turrialba volcano were installed, in conformity with the Nanometrics 24 bits Taurus digitalizers and Trillium Compact 3 components large band sensors from Nanometrics. The signal is transmitted in real time through free frequency radios.

Figure 2 shows the volcano-seismic signal counting between November 2011 and February 2012 recorded by the reference digital station VTUN, which is located northeast of the Central Crater (Fig. 1). The counting was done using a simple algorithm STA/LTA [12] provided with the Matlab volcanic signal analysis kit from Philippe Lessage (2009) [13]. The seismicity stayed stable with 40 to 80 events per day between November and December 2011, except on December 31st when 155 volcanic seismic events were counted. Most of these seisms occurred in 1.5 hours, between 11:30 am and 1:00 pm (local time), with an average of 3 seisms per minute. Due to their small magnitude and non-tectonic character, it was not possible to locate these events. Other volcano-tectonic events occurred the same day indicating shallow depths (less than 1 km below the summit), which suggests that the seismicity originated close to the surface and was due to the opening of a crack, to the decompression and fluid ascent through it.

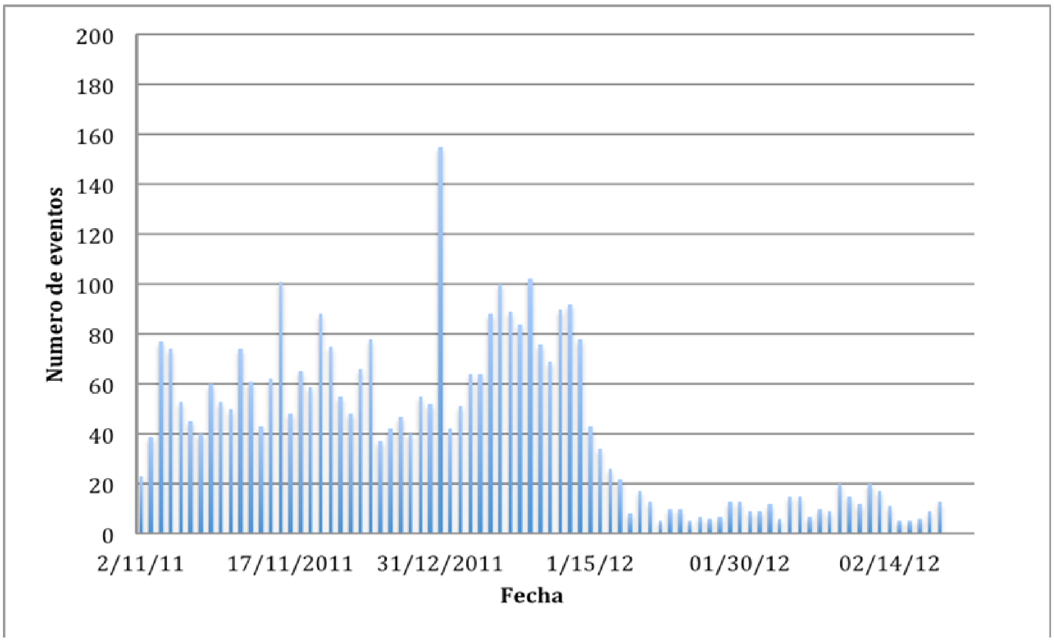

Figura 2. Número de sismos volcánicos diarios registrados en la estación sísmica VTUN ubicada al noreste del Cráter Central.

After January 1st, 2012, the seismicity increased until reaching a minimum of 80 per day between January 6th and January 13th, and decreased to stabilize below 20 per day after January 18th.

On January 12th, 2012, no unusual seismic activity was observed, just the usual low amplitude volcanic seisms [14]. Moreover, none of these events coincided with either the beginning of the opening of the 2012 vent, which occurred a few minutes before 3 pm on January 12th, or with the ash and gas emission (Fig. 3A). Even if shallow activity was noticed in the morning of January 12th (resonances), most of the information coincided with the beginning of the ash emission few minutes before 3 pm. However, the small volcanic seisms of various amplitudes recorded do not present any systematic pattern. [14].

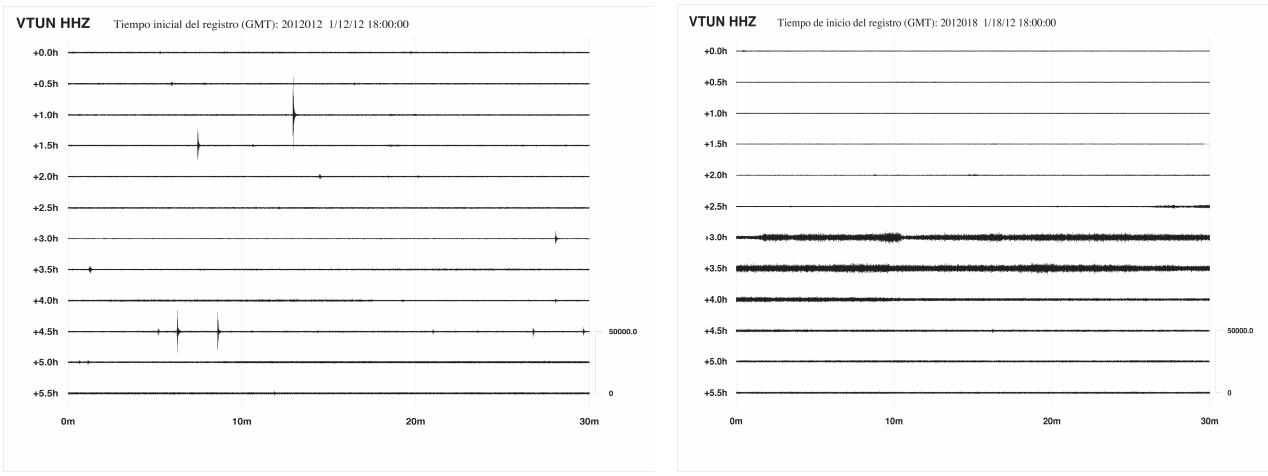

Figure 3. A) Seismic recording of January 12th, 2012. The recording starts at 12 am and ends at 6 pm (local time). The first reports of activity occur a few minutes before 3 pm. The events observed are "hybrid" volcanic seisms.
B) Seismic recording on January 18th, 2012. The recording starts at 12 am and ends at 6 pm (local time).

By contrast, recordings on January 18th show a seismic tremor that coincides with the beginning of the ash and blocs emission through the 2012 vent, and lasts as long as the intense eruptive phase (Fig. 3B). Even if the beginning of the signal is diffused, one can determine the arrival of the tremor around 5 minutes before 3 pm. The most intense phase occurred between 3:02 pm and 4:10 pm. The amplitude of the tremor stays low until the end of the recording.

Figure 4 shows 5,000 seconds of recording with the most intense part of the tremor. We observe variations of the amplitude, especially at the beginning of the activity, but the main frequencies remain constant (Fig. 4B). The signal is high frequency with the main ones between 5 and 15 Hz (Fig. 4C). Even after the intense phase, the frequencies remain the same until the end of the recording.

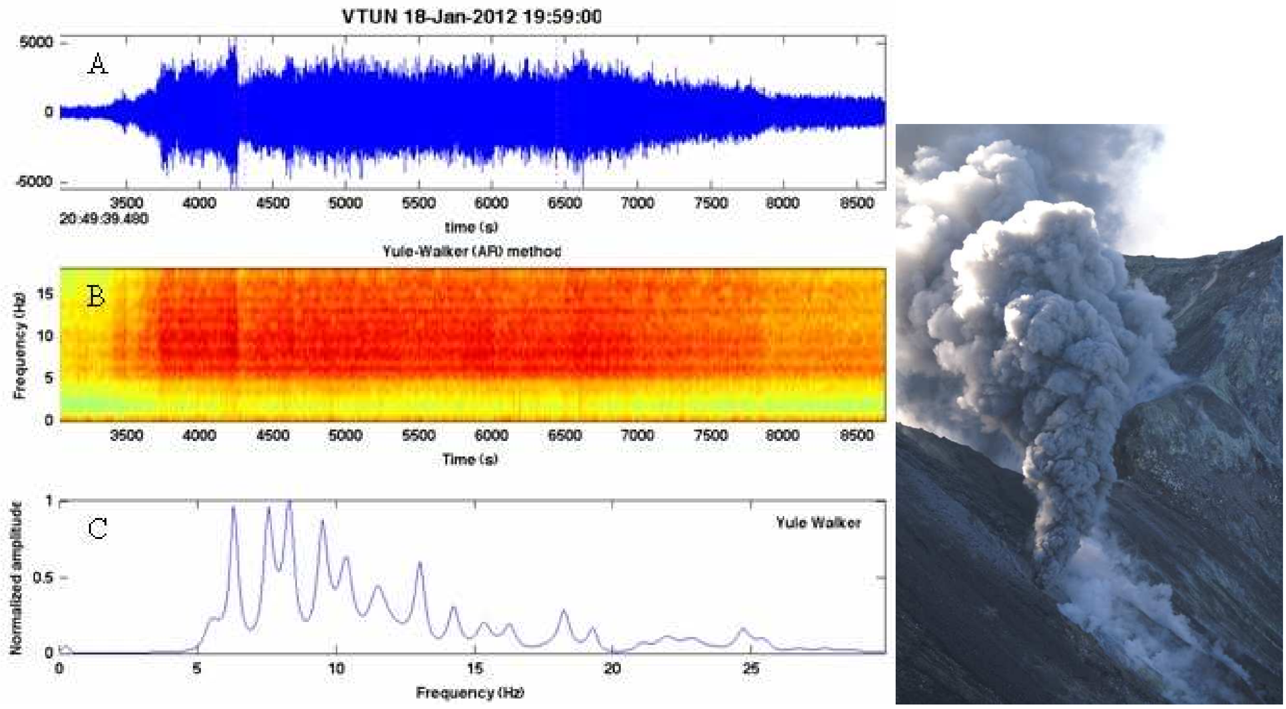

Figure 4: A) Seismic recording of the most intense phase of the tremor. B) Spectrogram of the recording shown in A). C) Frequencies spectrum of the seismic recording (red represents high amplitude and green low amplitude signal). (Photo: ash emission on January 18th, 2012. G. Avard)

II_4 Deformation of the volcanic edifice

- *Electronic Distance Measurements technique (EDM)*

The geodetic monitoring of Turrialba volcano includes a network of EDM at the top, with 5 prisms around the East, Central and West Craters and a reference point at the overlook (Fig. 1). The distances have been regularly measured since the end of March 2009 thanks to an automatic Trimble station that takes into account atmospheric temperature and pressure fluctuations which allows measurements with ± 2-4 mm uncertainty. Such an error is generally due to local variations in the trajectories because of the ambient conditions such as atmospheric temperature, pressure and relative humidity.

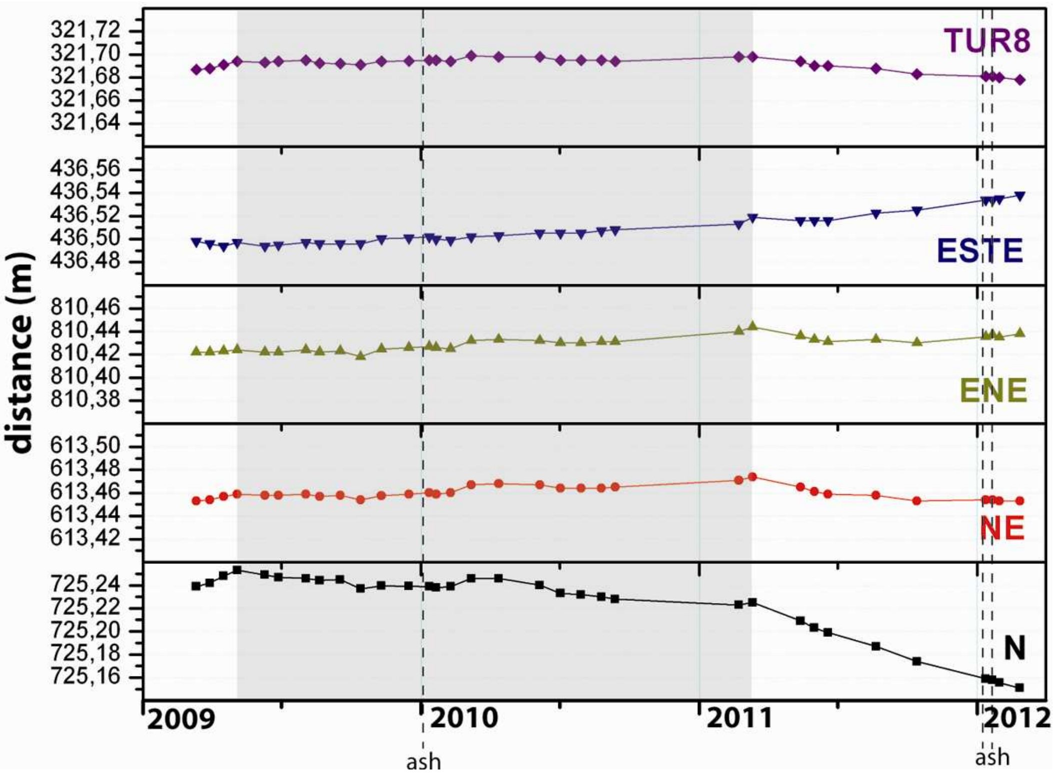

Figure 5: Electronic Distance Measurements between the overlook and various prisms (Fig. a) since early 2009.

Figure 5 shows variations from 35 mm (NE reflector) to 95 mm (North reflector) on the tilted direction toward the overlook during the 2009-2012 period. Vectorial processing, GPS campaigns and dry tilt technique in the Central Crater are currently going on in order to complete the EDM network and to determine whether these changes are related to any volcanic activity or if they correspond to local displacements of the sites. However, no significant variation of the distances was noticed that could potentially coincide with the ash emissions of 2010 and 2012 (Fig. 5). Looking at the general tendency of these curves, 3 main periods can be defined: 1) before May 2009 with an extrapolated increase of the distance up to 95 mm per year (in the north direction), 2) between May 2009 and March 2011 with slower changes, and 3) after March 2011 with a decrease of the measured distance up to 76.9 mm per year (in the north direction). The last period is characterized by a fast contraction of the distance mainly in the north direction while small variations are observed in the other directions, which suggests a local deformation incompatible with the hypothesis of a superficial or deep source, and also incompatible with the hypothesis that the source could potentially increase the stress without any detection from the existing network.

➢ *Global Positioning System technique (GPS)*

Two permanent GPS stations, type Trimble NetRS, record their position every 30 seconds on the northeast and southwest flanks of the volcano. One, called CAPI, is placed on the old abandoned chapel of La Central, and the other, called GIBE, is on a rock in the Bajos de Bonilla sector. Both have been working since April 2010, however, the presence of trees triggers problems of satellite coverage which prevents a Precise Point Positioning (PPP) processing [15] necessary for a vectorial interpretation. However, it allows a precise measure of the distance between the 2 stations (more than 5,837 m away) to monitor deep or large scale deformations along the line.

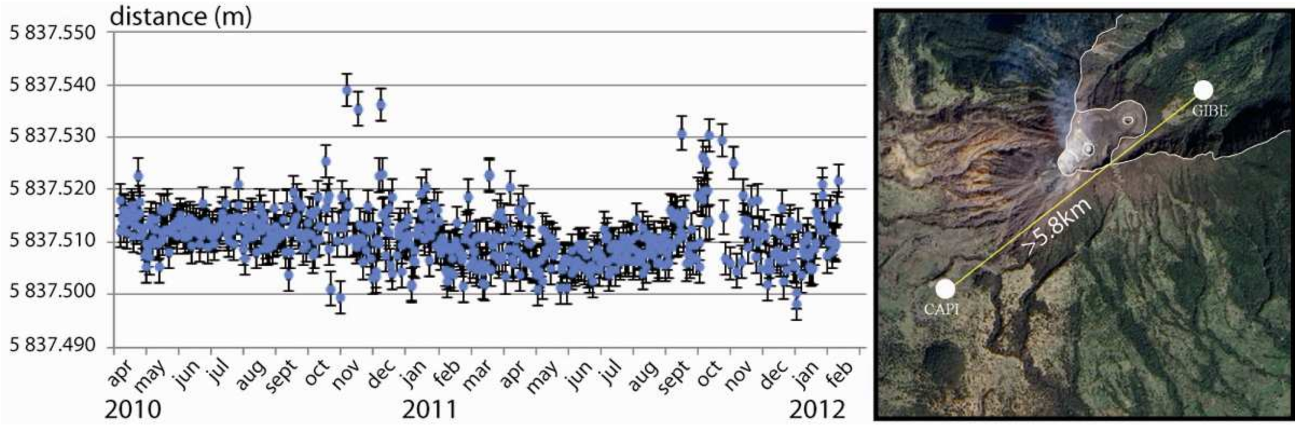

Figure 6: Distance time series between the 2 permanent GPS stations CAPI (southwest of the volcano) and GIBE (northeast of the volcano)

Figure 6 shows that the distance between the 2 GPS stations progressively decreases by about 5 mm between April 2010 and July 2011, which corresponds to the standard deviation of the database (±5 mm). A systematic dispersion of the data is noticed at the end of the years (November-December 2010 and October-December 2012) which are the result of discontinuous recording of GIBE because of problems in the solar recharge of the batteries due to climatic reasons. This dispersion prevents any interpretation on small changes of the distance, especially during January-February 2012. However, any significant variation would reflect a large scale or deep source of deformation. The small but continuous trend of decreasing distance observed during the whole period of observation (figure 5) shows that no accumulation or ascent of an important volume of magma has occurred in the volcanic edifice since 2010. Hence this information is a valuable baseline for future volcanic activity.

II_5 Geochemical parameters profiles

➢ *Variation of diffused CO_2 and H_2S fluxes in the ground*

Profiles of diffused CO_2 and H_2S fluxes in the ground have been repeated since September 2011, completed with temperature measurements at 10 cm depth thanks to a fluxmeter West Systems and a thermocouple. The geochemical profiles start on the east rim of the West Crater and end on the southeast rim of the Central Crater. They were determined based on 2 maps of the upper part of the volcano made by scientists from INGV, Italy in 2008 and 2011 [T. Ricci, personal com.]. Due to weather conditions, no measurements were possible between November 8th, 2011, and January 11th, 2012, but high values are noticeable (Fig. 7) for CO_2 and H_2S the day before the opening of the 2012 vent, in the whole east flank of the West Crater as shown Figure 7 (site #3 is located in the upper part) as well as in the west and south area of the Central Crater (site #9). Temperatures at 10 cm depth were measured around 90°C, which correspond to the boiling temperature of water at this elevation (~3,300 m.a.s.l.). These data were consistent with the observation the same day of an important fumarolic activity on the whole east flank of the West Crater (convective flux of gas), and with the observation of a 115 m-long liquid sulfur flow exiting from the “channel” La Quemada (on the east side of the West Crater) and flowing inside the Central Crater. Moreover, an increase of the fumarolic activity was reported on the same flank at the end of December 2011, which suggests a slow increase of gas emission in the area before the opening of the new fumarolic vent on January 12th, 2012.

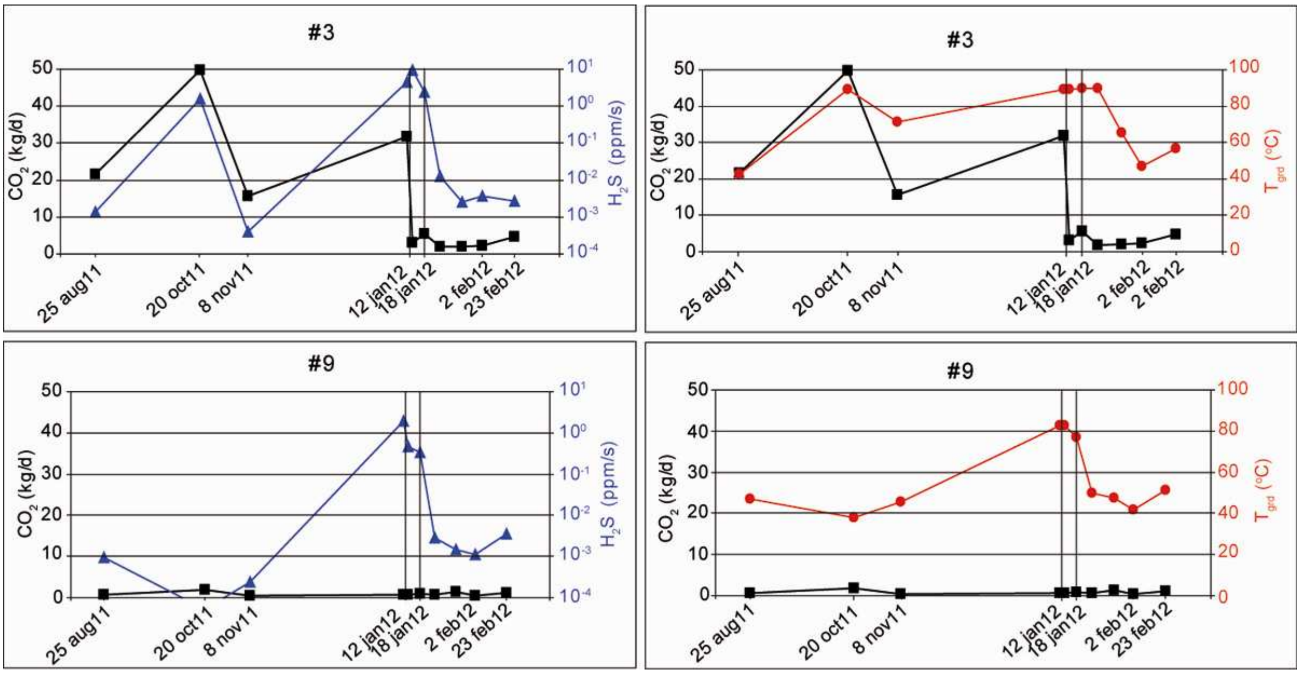

Figure 7: Measurements of passive diffused CO_2 and H_2S flux through the ground, and temperature at 10 cm depth for the sites #3 and #9 (Fig. 1) of the profile.

The opening of the vent on January 12th, 2012, triggered an ash emission. The day after, on January 13th, 2012, a strong decrease of the fluxes was noticed up to 1 order of magnitude for the CO_2 and of various orders of magnitude for the H_2S compared to January 11th, 2012, on the southeast flank of the West Crater and the west rim of the Central Crater. However, such a pattern did not repeat with the second ash emission on January 18th, 2012. Since then the fluxes of diffused gas in the ground stabilized at a level comparable to November 2011, and the ground temperature slowly decreases (Fig. 7).

- *Condense phase of fumaroles in the West and Central Craters*

After the last magmatic period of activity of Turrialba volcano in 1864-66 and until the 90s, two small permanent fumarolic fields maintained a low activity on the inside SW flank of Central Crater and on the inside of the north flank of the West Crater. It corresponded to vapor emission and temperatures at the boiling point of the aquifer (i.e. 90°C) [1,16], and a chemical composition dominated by H_2O, CO_2, and H_2S, characteristic of a water-gas-rock interaction in a developed and stable hydrothermal system [17,18].

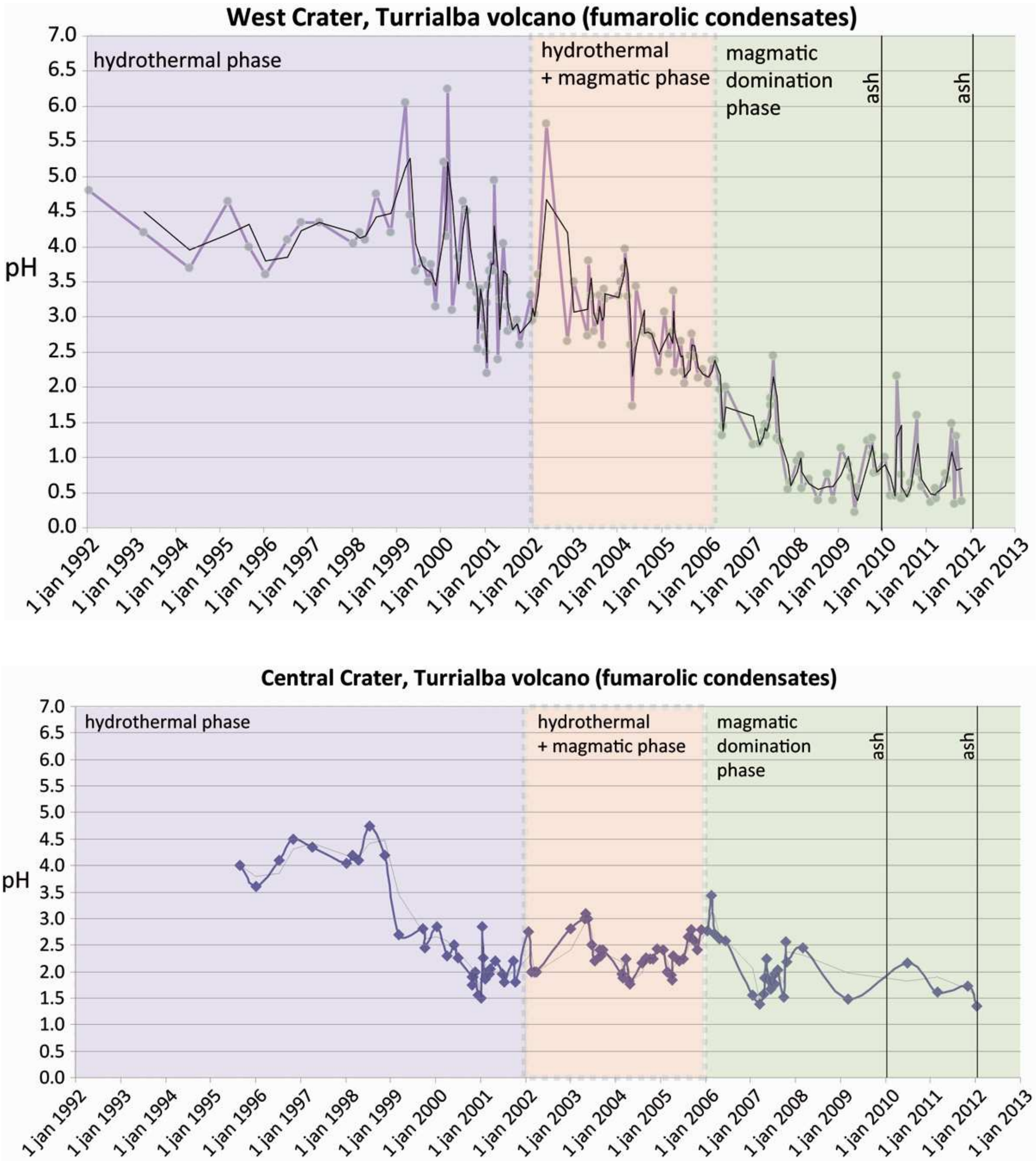

Figure 8: Time change of the pH of fumaroles condensed phase sampled 1) in the West Crater, and 2)in the Central Crater of Turrialba volcano between January 1992 and January 2012. Data from the Laboratorio de Geoquímica Volcánica "Dr. Eduardo Malavassi Rojas" at OVSICORI-UNA.

A significant gradual and systematic acidification of the condensates sampled in various fumaroles of the West and Central craters has occurred since March 1999 (Fig. 8). Both craters show the same decreasing pH pattern with a more pronounced decrease since 2006. These changes mark the beginning of a new phase of fumarolic activity of the volcano, in terms of chemical composition as well as in gas flux, in agreement with the geochemical evolution of the gas described by Vaselli *et al.* [1]: 1) A hydrothermal phase between 1992 and 2001 with pH of the condensates relatively high, 2) a progressive increase of the acidity of the condensates due to the presence of a magmatic component between 2002 and 2005; 3) a stronger increase of the acidity of the condensates due to fluids dominated by magmatic components since 2006.

- *SO_2 total flux estimated from OMI/ASTER images, and environmental effect*

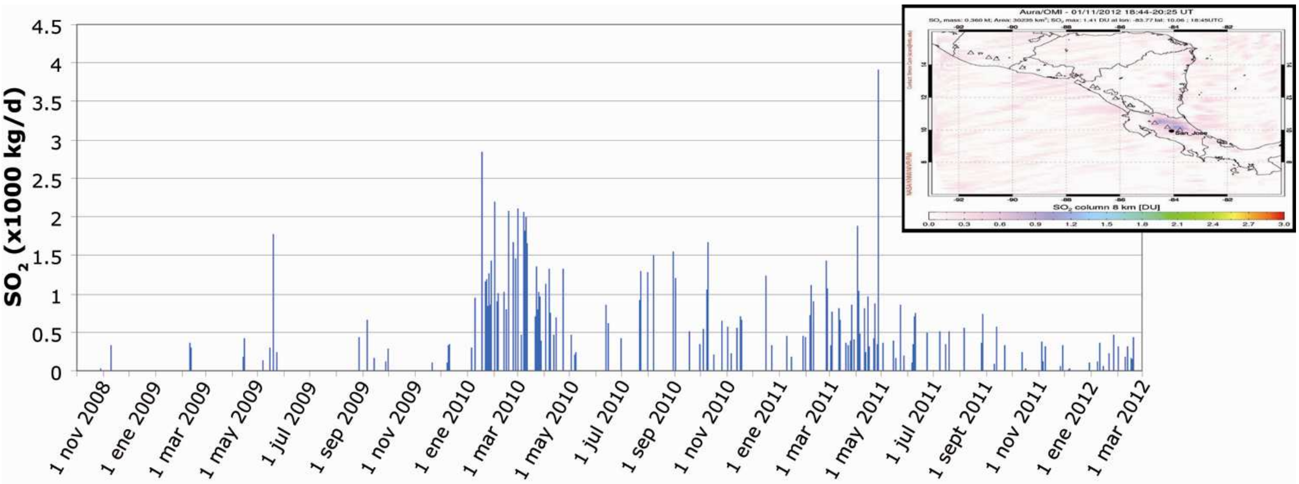

Figure 9: SO_2 mass flux of Turrialba volcano plume determined from the analysis of AURA/OMI satellite images of NASA between October 2008 and February 2012. The data correspond to the total SO_2 detected by the OMI instrument of the AURA satellite in Central America, no "noise" correction is applied. Detection is possible when the satellite passes above the Central American isthmus between 18:00-19:00 UTC. .Source: http://so2.gsfc.nasa

The comparison of data from the satellital instruments OMI/ASTER between December 2011 and February 2012 does not show any significant change in the mass of SO_2 emitted by the volcano (Fig. 9). The same observation is noticed with the pH of the rain regularly collected in La Central, 2.1 km SW of the edifice which also does not show any significant change with the opening of the 2012 vent (Fig. 10). However, precipitation at La Central has shown an extreme decrease of pH since 2007 as the consequence of a gradual acidification of the atmosphere around the volcano, which generates acidic deposition with fairly low pH. Average values are 4.11, 3.98 and 3.12 for the periods January-February of 2010, 2011 and 2012, respectively.

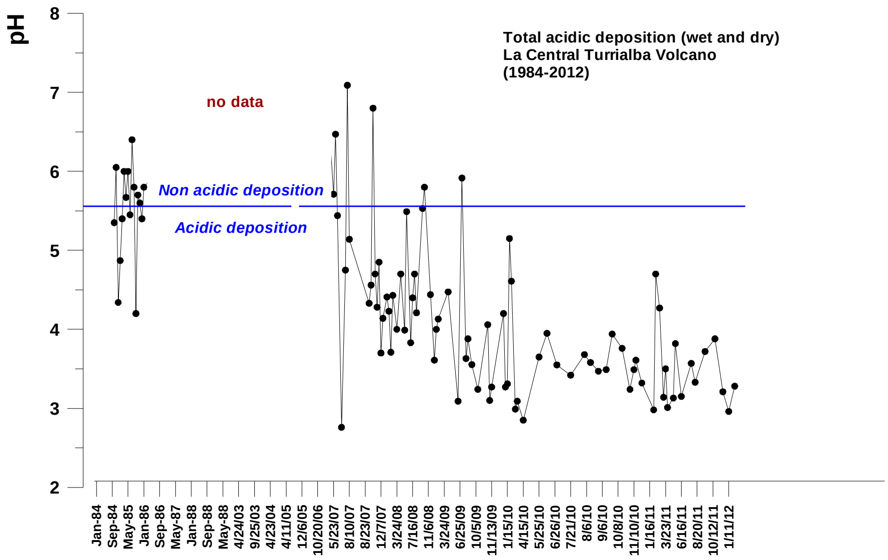

Figure 10: Time series of the pH of the total acidic deposition collected since 1984 near the school of La Central, 2.1 km SW of the West Crater.

The pH profile of the total acidic deposition collected in La Central (Fig. 10) shows a similar tendency as the pH profiles of the condensates from fumaroles (Fig. 8).

III_ Interpretation

In December 2011 were reported discrete changes that can be considered as precursors of the January 2012 activity. Among them was an increase of the fumarolic activity on the east flank of the West Crater and more fumaroles in the Central Crater. Moreover an unusual seismicity occurred on December 31st, 2011, with many shallow volcanic seisms in a short time.

The absence of tremor or explosion in the seismic recording for the opening of the new fumarolic vent on January 12th, 2012, indicates that its formation process was not associated to an interaction heat-water (phreatic eruption). Neither was seismically recorded rock fracturing nor vibrations that would have been interpreted by high pressure fluids motion in the edifice. Finally no juvenile material was found in the ash deposit. Therefore there is no evidence of new magmatic activity associated with the opening of the 2012 fumarolic vent. The quick change in the diffuse CO_2 and H_2S flux in the ground observed between January 11th and the 13th suggests that a shallow accumulation of gas increased the internal pressure. A small opening triggered the decompression and sudden exit of the confined gas, ripping out solid material of different size, and forming the 2012 fumarolic vent. The absence of specific seismic signals or deformation suggests that the accumulation of gas was very superficial.

By contrast, the second ash emission on January 18th through the same 2012 vent presented an associated seismic signal. The coincidence of the beginning of the ash emission with the generation of a high frequencies volcanic tremor indicates that the high pressure fluids motion (gas and vapor that escaped through the narrow vent) originated it. Therefore the tremor was generated by the sudden decompression triggered by the escape of gas and vapor through a narrow vent. [14]. However, contrary to the 11th, no diffuse gas flux increase was noticed prior to the 18th ash emission, which suggests that the gas that escaped the second time accumulated slightly deeper than on January 12th. As on January 12th, no significant deformation related to a deep pressure change was measured. Hence the emission of ash, lapilli, rock fragments, and gas through the new vent is not due to an explosion or fracturing of the volcano interior but to a superficial event [14].

It is likely that the January 12th decompressions that opened the 2012 vent triggered favorable conditions to a deeper decompression on January 18th, but not deep or large enough to destabilize the magmatic isostatic equilibrium in the magma chamber (depth unknown). Until the end of March 2012, no signal triggered by magma motion associated with these two decompressions was recorded, i.e. no evidence of intrusion and/or volcanic eruption. This new gas exit did not increase significantly the gas flux in the plume which suggests that the degassing volume of magma did not change, and neither the kinetic of exsolution. Hence the opening of the 2012 vent is part of the permanent degassing activity of the deep magma, which gases pass through the weakest areas of the edifice. The apparition of the new vent on the southeast flank of the West Crater shows that weaknesses on the edifice rocks propagate toward the Central Crater.

The disappearance of the shallow water accumulated in the West Crater between January 13th and 24th can be explained by a simple water deficit in the rain-evaporation balance with the beginning of the dry season (January). No evidence allows a link between the presence of water first noticed on June 2011 [6] about 10 m from a 500-730°C area (temperature measurements at the end of January 2012) and the remarkable fumarolic activity on January 2012. A new accumulation of water was noticed again on March 20th, 2012, after several days of rain.

IV_ Conclusions

The opening of the 2012 fumarolic vent corresponds to a spectacular but normal degassing process for Turrialba volcano, for which no interaction, motion or destabilization of magma occurred. On January 5th, 2010, the 2010 vent initiated similar activity with a phreatic eruption and a moderate emission of ash [3]. Today this vent is ~70x25m with a ~4x2m vent and canalizes most of the magmatic gas flux that forms the plume. The 2011 vent opened in 2011 without any direct or instrumental observation and today is ~1m diameter. For reference, many comparable fumarolic vents appeared on the top of Turrialba volcano prior to the 1864-66 phreatomagmatic eruptive phase [19]. A similar pattern was observed at Irazú volcano with the opening of dozens of vents emitting high pressure gas prior to the 1963 eruption. Therefore, openings of other fumarolic vents is likely to happen in the future, with or without explosions, especially along fractures and weak zones where aligned thermal anomalies are noticed through the craters along a west-east direction.

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Illustrative video:

http://www.ovsicori.una.ac.cr/videos/Turrialba_2012_apertura-boca2012-crisis.mp4