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Crater Lake Temperature Changes of the 2005 Eruption of Santa Ana Volcano, El Salvador, Central America

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Abstract—A sudden eruption at Santa Ana occurred on 1 October 2005, producing an ash-and-gas plume to a height in excess of 10 km above the volcano. Several days before, thermal infrared images of the crater provided precursory signals of the eruption. A significant increase in the extent and intensity of the fumarolic field inside the crater rim and of the surface temperature of the crater's lake was observed. Changes in energy input was also estimated to explain the increase in lake temperature based on energy/mass balance calculations.

Key words: Santa Ana, crater lake, volcanic eruption, thermal precursors.

1. *Introduction*

Santa Ana volcano is located 40 km west of San Salvador, in Central America. This massive stratovolcano rises 2,381 m above mean sea level (Fig. 1) and forms a part of the Central American volcanic chain, which results from the convergence of the Cocos and the Caribbean plates. It is located at the intersection of a NW-SE system of regional faults (Williams and Meyer-Abich, 1955) and the southern boundary of the so-called 'Central American Graben', an extensional structure parallel to the Pacific coastline of El Salvador (Rotolo and Castorina, 1998). The NW-SE system of faults is considered a major structural feature of El Salvador's geology (Wiesemann, 1975), found over the entire country, and expressed in the Santa Ana region by fissures and alignments of volcanic edifices and eruptive centers. This volcanic complex consists of the Coatepeque collapse caldera, a 6.5 $\times$ 10.5 km elliptical depression about 0.22 Ma (Pullinger, 1998), the Santa Ana and Izalco volcanoes, as well as numerous cinder cones and explosion craters (Fig. 1).

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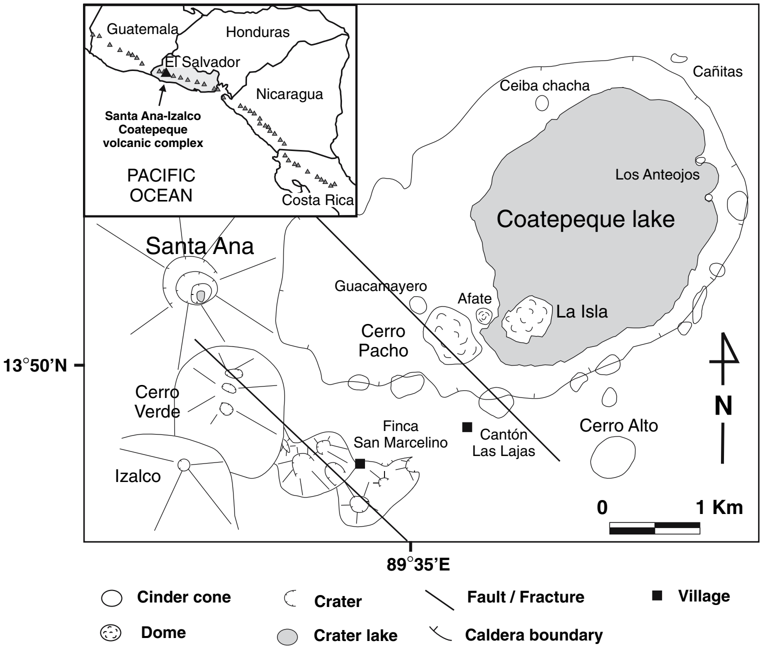

Figure 1
Simple morphological and structural map of Santa Ana volcano complex and its surroundings, El Salvador, Central America. In the map of Central America, closed triangles represent active volcanic systems of the Central American Volcanic Belt.

The activity during the last few thousand years has been characterized by phreatic or phreatomagmatic eruptions at the central summit vent (PULLINGER, 1998), suggesting the existence of a large and permanent hydrothermal system beneath the Santa Ana volcano. With 12 historic eruptions, it is one of the most active volcanoes in El Salvador. Its summit contains an acid lake with an average surface temperature of 18–20°C within a 0.5-km diameter explosion crater that was formed during the most recent eruption in 1904. Hot springs, gas bubbling and intense fumarolic emissions are observed along the shoreline of this crater lake. A volcanic gas plume, usually driven by the NE trades, may be seen rising to 500 m from the summit crater of the Santa Ana volcano.

The presence of a lake in the crater represents an interesting opportunity for long-term monitoring since it acts as a calorimeter and chemical condenser, integrating most of the heat flux and volatiles released by the shallow magma (BERNARD *et al.*, 2004). The physico-chemical characteristics of a volcanic lake depend largely on the magnitude of the volcanic/hydrothermal heat and mass influx and the capacity of the lake to dissipate the heat. BERNARD *et al.* (2004) observed changes in the depth and volume of the crater's lake between 2000 and 2002 from 27 m to 20 m and from 4.5×10^5 m^3 to 3.10^5 m^3, respectively. Changes of the temperature and chemical and physical parameters of the volcanic gases and volcanic lakes have been observed before volcanic eruptions and became useful tools to monitor the activity of the volcanoes (Giggenbach, 1974, 1983; Takano, 1987; Rowe *et al.*, 1992; Badrudin, 1994; Pasternack and Varekamp, 1997; Vandermeulebrouck *et al.*, 2000; Hernández *et al.*, 2001; Varekamp *et al.*, 2001, Dehn *et al.*, 2002).

In the beginning of July 2005, the seismic network of the Servicio Nacional de Estudios Territoriales (SNET) of El Salvador at Santa Ana volcano detected an anomalous seismic activity (09/2005, BGVN 30:09). After the detection of these possible volcanic precursors, a monitoring of the SO_2 emission in the volcanic plume of Santa Ana by means of remote sensors (COSPEC and miniDOAS) started. University of El Salvador (UES) scientists carried out most of the measurements under a collaborative scientific project UES-ITER (Institute of Technology and Renewable Energy) financed by the Spanish Aid Agency (AECI), finding a significant increase of the SO_2 emission rate at the beginning of September 2005 (Olmos *et al.*, 2007). Subsequently, a more intensive survey was carried out at Santa Ana volcano several days before the volcanic eruption on October 1, 2005. A thermal survey of the summit crater fumaroles and the volcanic lake together with intensive monitoring of the volcanic plume before and after the volcanic eruption provided information on precursory signals of the pending volcanic eruption.

This paper reports the thermal precursors detected before the 2005 eruption of Santa Ana and estimates the energy/mass balance associated with the volcanic heat transfer during the volcanic unrest.

2. *Chronology of the Volcanic Eruption*

Based on the monthly Smithsonian reports of the volcanic activity of Santa Ana (04/2001, BGVN 26:04; 09/2005, BGVN 30:09) since June 2005, strong degassing occurred at the summit area with an ash emission on 16 June. A slight increase in the seismicity together with a significant increase in the gas emission rate were observed from 27 July until at least 30 August. SNET scientists recorded on a daily basis surface temperature at the center of the lake, documenting an increase of the from 20°C to 25°C during the period April–June 2005. No more data are available since then due to accessibility problems. Observations made by SNET scientists on 29 August revealed incandescent rocks in the fumarolic fields inside the summit crater, effects attributed to hot gases heating the rocks. At that time, a significant increase in SO_2 emission was recorded (Olmos *et al.*, 2007), together with a gas-and-steam plume rising 500–1,000 m above the volcano's crater. After these volcanic unrest signals, seismicity and gas emissions continued above normal levels. During the first two weeks of September, the SO_2 flux was over 1,000 metric tons per day and from 5 September, satellite imagery detected a thermal anomaly. On 16 September SO_2 flux reached a maximum of 3,320 metric tons per day (14–20 September/2005, BGVN; Olmos *et al.*, 2007). Microseismicity remained at relatively high levels and incandescence was visible inside some cracks. During 21–26 September, seismicity and gas emissions showed the highest values (1000–4000 tn SO_2; BARRANCOS, 2005; OLMOS *et al.*, 2007), indicating the possibility of the occurrence of a volcanic eruption.

On 1 October 2005, a volcanic eruption occurred at Santa Ana, producing a plume of 14 km of altitude and several lahar deposits as far as 2 km SE of the volcano (28 September – 4 October/2005, BGVN). Following the eruption of 1 October, small explosions, degassing, and low-to-moderate seismicity occurred at Santa Ana during 5–11 October. Surprisingly, during an aerial inspection of the volcano by the scientific staff of SNET on 11 October, no important changes were observed at the crater. On 11 October, SO_2 measurements were around 600–700 metric tons per day.

The volcanic activity of Santa Ana remained high until February 2006, with relatively high SO_2 emission rates (500–1000 *t/d*) (Barrancos, personal communication), seismicity above background levels, and strong evaporation of the summit crater lake.

3. *Procedures and Methods*

With the aim to detect thermal precursors of the volcanic eruption of Santa Ana volcano, a handheld thermal camera FLIR (Forward Looking Infrared Radiometer) model P65 was used to collect thermal images from the crater's lake and fumarolic area at the summit of the volcano. FLIR data were collected on a daily basis between September 19 and 26, 2005, and between February 20 and 26, 2006. This type of handheld thermal camera has been used at other volcanoes such as Etna and Stromboli volcanoes (DEHN *et al.* 2002, CALVARI and PINKERTON, 2004; CALVARI *et al.* 2005) and other volcanic areas (CALVO *et al.*, 2006, PADRÓN *et al.*, 2006). The FLIR consists of an uncooled microbolometer detector with a thermal sensitivity of 0.05°C (50/60 Hz 50 mk at 30°C) which allows us to clearly see the smallest temperature differences. A total of 76,000 pixels provide real-time, crisp, high-resolution 16-bit thermal images. The built-in visual camera provides digital images linked with corresponding thermal images. The field of view/min focus distance is $19 \times 14°/0.3$ m with a spatial resolution (IFOV) of 1.1 mrad. Internal calibration together with an atmospheric correction based on user input for reflected ambient temperature, distance, relative humidity, atmospheric transmission, and external optics allow the FLIR to calculate realistic digital source temperatures. Ambient temperature and relative humidity were measured every ten minutes at the start of the thermal measurements with specific sensors, whereas an emissivity correction factor was taken at 0.95 for hot rocks at the fumarolic areas and at 0.96 for the lake water surface. Accuracy of the instrument (% of reading) was $\pm$ 2 °C or $\pm$ 2%.

Depending on the lens installed in the camera, different ranges of temperature are available: −40°C to +120°C, 0°C to +250°C, +150°C to +500°C, and up to +1500°C, which we did not have at the time of the September 2005 survey. During the collection of

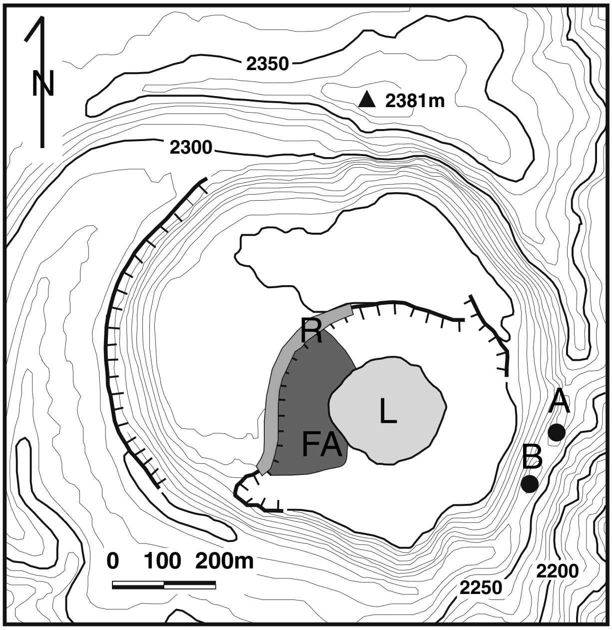

Figure 2
Summit area of Santa Ana volcano showing the sites (A and B) from where the thermal IR images were recorded in both surveys, September 2005 and February 2006. Abbreviations are as follows: FA, Fumarolic Area; L, Lake; R, NE Rim of inner crater.

images, it is very important to select the correct range as well as the long line-of-sight. Since the distances from the measuring points to the crater's lake were about 400 m (Fig. 2), we used the low-temperature range (−40°C to +120°C) for the detection of small temperature gradients. Solar reflection was avoided since most of the measurements were carried out after sunset. To check if reflection on the lake surface due to the thermal energy radiated from the high temperature fumarolic field was affecting the observed thermal anomalies, several pictures were taken from the west side of the rim. The results were similar to the images taken from A and B sites (Fig. 2). The middle temperature range (+150°C to +500°C), which can measure extrapolated temperatures up to +850°C, was used for observing the incandescent fumarolic areas. To minimize the effect of gas and aerosols absorption, most of the measurements were carried out from the opposite side of the crater where the volcanic plume occurred. We assumed following CALVARI *et al*. (2005), the associated errors to the thermal images collected during this field work to be between 6–20%, depending mainly on the wind direction during the measurements. Once measurements in the field were completed, images were optimized with the software ThermaCAM at the field lab.

SO_2 flux measurements were taken by means of two different remote sensors, mini-DOAS and COSPEC. Mini-DOAS was used in all the measurements whereas COSPEC was used only during several days to compare the fluxes obtained with both instruments (Barrancos, 2005).

Mini-DOAS is based on an Ocean Optics USB2000 spectrometer, taking the light caught by the telescope and guided through an optical fiber to the spectrometer. The detector, which can operate at ambient temperature, is a CCD-array of 2048 elements (13 μm (width) × 200 μm (height)) treated for enhanced sensitivity below 360 nm resolution, a 50 μm slit and spectal resolution of ~0.6 nm over the wavelength range of 245–380 nm. The COSPEC is a correlation spectrometer designed for vertical or slant column measurements of SO_2 concentration using zenith sky-scattered sunlight. The calibration always was performed *in situ* by placing cells containing known amounts (ppm•m) of gas in the path of the radiance dispersed by the instrument ('high and low'). The detection limit of the COSPEC is lower than 5 ppm with short time constants (1 s), and higher than 10% during adverse meteorological conditions which affect the intensity of light.

Measurements by COSPEC and mini-DOAS were carried out as mobile measurements by placing the instruments on a car and traversing beneath and roughly perpendicularly to the volcanic plume of Santa Ana (Barrancos, 2005). Total integrated concentration cross-sections of SO_2 were obtained and later multiplied by the estimated plume velocities to yield the total source emission rates (ton/day).

4. Summit Crater's Lake and Fumarole Temperatures

Measurements of temperature were focused at the summit crater lake and the active fumarolic areas by means of a thermal camera FLIR. During the September 2005 survey, a significant increase in the extent and intensity of the fumaroles and the surface temperature of the lake was observed. For several years, the fumarolic area located at the west side of the lake has been present, with temperatures of 532°C measured in January 2000, 875°C in June 2002 due to a sudden increase in the fumarolic activity (Bernard *et al.*, 2004) and decreasing in December 2003 to 264°C and January 2004 to 360°C (SNET, Monthly Report). Due to technical and accessibility problems, no more temperature measurements in the high temperature fumarolic area have been carried out since February 2004.

Surface temperature of volcanic lakes is a good indicator of volcanic activity. During periods of low volcanic activity, temperatures of the water at the crater's lake of Santa Ana volcano range near ambient atmospheric values (17–21°C). Heating episodes increase the temperature of the lake water and reflect changes in the flow rate or in the enthalpy of hot fluids entering the lake (Bernard *et al.*, 2004). The only way to obtain temperature data of the fumarolic area and crater's lake at the time of both surveys was the use of a handheld thermal camera. For this reason thermal IR images were taken at the lake's surface during September 2005 and February 2006 surveys. During both thermal

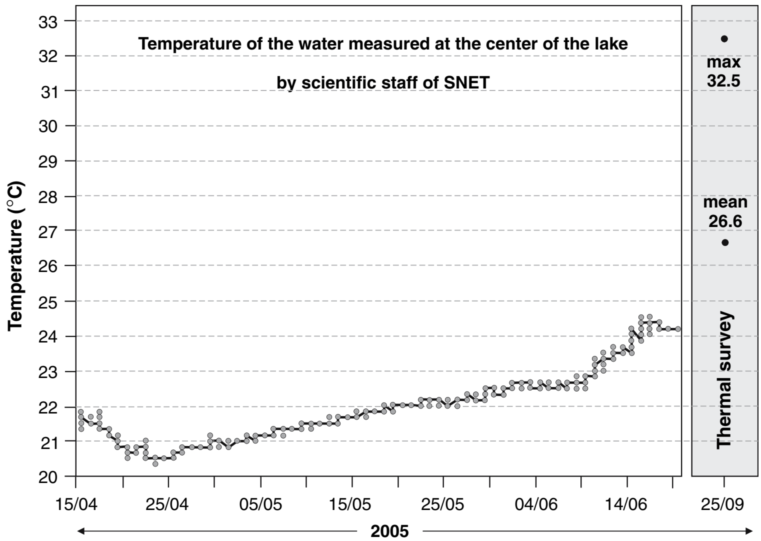

Figure 3
Time series of temperature measured at the center of Santa Ana volcano crater's lake by scientific staff of SNET (El Salvador) during the period April to July 2005. Also shown are the maximum and average temperatures measured at the center of the crater's lake with the thermal camera FLIR in September 25, 2005.

surveys, measurements were carried out under stable weather conditions, avoiding cloudy days and rain.

During the measurements carried out in September 2005, we used an average value of 65% for atmospheric humidity, 22°C for atmospheric temperature and 0.88 for atmospheric transmission. The viewing distance for the measurements was 400 m, resulting in a pixel size of 50 cm; such a small pixel size can reduce apparent peak temperatures. One of the most important observations was the significant increase of the temperature at the center of the lake surface‘s, compared to the temperatures measured at the same area by the SNET scientific staff until July 2005 (Fig. 3). This increase was higher in those areas closer to the fumarolic field, where bubbling was also observed, indicating changes in the flow of hot gases entering the lake. These observations, together with the increase in the seismicity and the relatively high SO_2 flux emission rates measured during this survey, indicated precursory signals of renewal magmatic activity at Santa Ana and suggested the possibility of an incoming high volcanic activity in the immediate future. From the observed temperature gradient at the lake's surface in 20 September 2005, we distinguished four areas characterized by different colors (different temperatures) which we called areas 1, 2 3, and 4 (Fig. 4). Table 1 shows the average and maximum surface temperatures of the four colored areas selected at the lake during the September 2005 thermal survey. The maximum apparent temperature measured at the surface of the lake at that time was 58°C and close to the fumarolic field with an average temperature of 29°C for the lake surface.

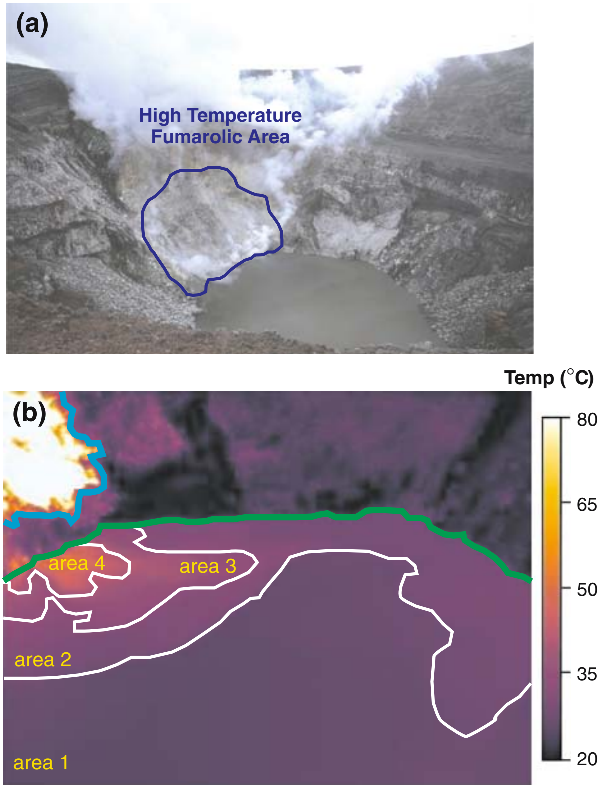

Figure 4
(a) View of Santa Ana's summit crater and hosted crater's lake taken September 20, 2005, from the southeast rim. Dark blue line indicates the area affected by intensive fumarolic activity. (b) Thermal image of the lake's surface taken from the southeastern rim of Santa Ana volcano on 20 September 2005. White lines indicate separately the four different thermal areas selected in this study. Green line denotes the crater's lake shore line. The yellow bright spot at the high left end of the image is the high temperature fumarolic area.

Thermal images of the fumarolic field were taken on 20, 21 and 25 of September 2005, the last one five days before the volcanic eruption (Figs. 5a, 5b and 5c). These three images have been corrected with the atmospheric and internal parameters of the FLIR for comparison. The IR images show the concentric and incandescent fractures which

Table 1

Surface lake's apparent temperatures measured at Santa Ana crater lake on September 20, 2005

Area	Average Temperature (°C)	Maximum Temperature °C)
1	27	33
2	29	37
3	36	47
4	46	58

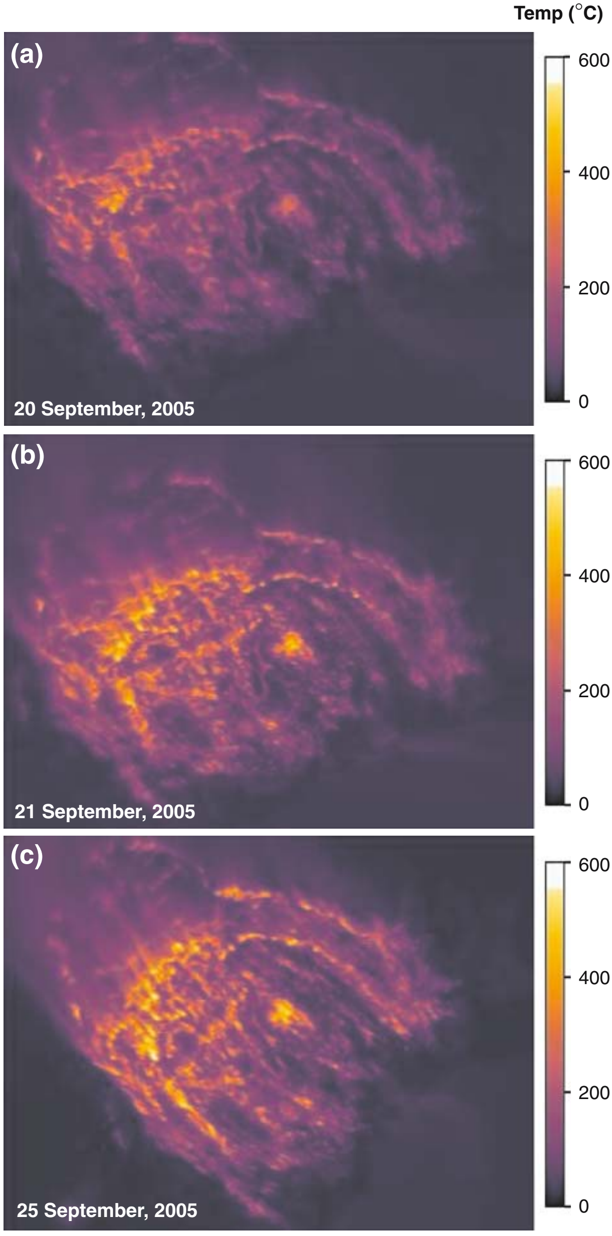

Figure 5
Thermal images taken on the high temperature fumarolic area (FA) on (a) 20 September 2005, (b) 21 September 2005 and (c) 25 September 2005, just few days before the volcanic eruption of Santa Ana volcano.

resulted from inflation of the fumarolic field due to the high pressure of endogenous hot gases. An increased intensity of the hotter areas is observed, indicating the increase of the hydrothermal activity beneath Santa Ana volcano a few days before the volcanic eruption.

In February 2006, four months after the volcanic eruption, a new thermal survey was performed at Santa Ana summit crater. At this time the crater's lake showed a continuous lowering of the water lake level. Thermal IR images were recorded at the same sites as those in September 2005. A significant decrease in the apparent temperature of the remaining fumaroles at the summit crater was observed. As was mentioned above, the area affected by hot degassing and incandescence was "cut" and disappeared with the volcanic explosions during the eruption, leaving just a vertical escarpment. During this second thermal survey, the remaining vertical escarpment showed no significant high temperature (Fig. 6a). At the time of the volcanic eruption, the incandescent area disappeared due to the volcanic explosions that occurred inside the summit crater. This fact, together with the decreasing hydrothermal activity, explains the observed relatively low fumarolic temperatures. However, a different behavior was observed at the surface lake temperature. At the time of the February 2006 thermal survey, a significant increase in the water lake surface temperatures was observed, this time quite homogeneous over the lake (Fig. 6b). The maximum recorded apparent temperature was about 67°C, close to a small island that formed on the east

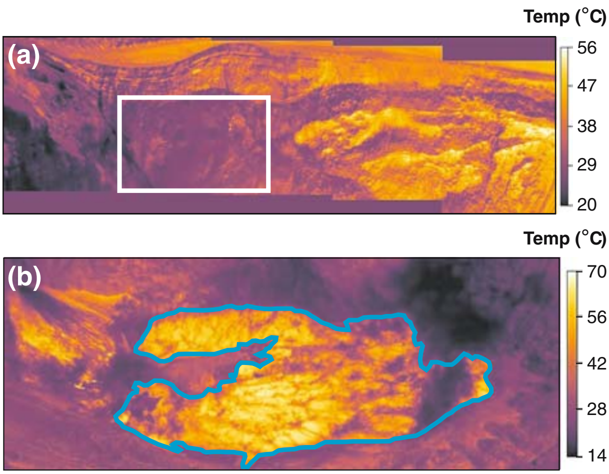

Figure 6
(a) Thermal image of the remaining vertical escarpment left after the volcanic eruption taken during the February thermal survey (R in Fig. 2). White square indicates the location of the Fumarolic area before the volcanic eruption. No significant thermal anomalies are observed. (b) Thermal image of the lake's surface taken from the southeastern rim of Santa Ana volcano on 24 February 2006, blue line shows the crater's lake shore line.

side of the lake due to the strong evaporation. The fast evaporation process occurring at the crater lake of Santa Ana after the volcanic eruption was possibly due to the residual heat in hot rocks remaining beneath the volcano.

Lack of evidence regarding the presence of "fresh rocks" suggests that the anomaly that led to the explosion was fed by a shallow, strongly degassing magma body. The closeness to the surface was responsible for the high measured temperatures, and possibly water that drained into heated cracks served as the trigger of the eruption. Seismic data provided by SNET shows that banded as well as polychromatic tremor, and also LP and VT events were indicating the ascent of magmatic gases, however no evidence of extruding magma has been provided. In 2002, 875 °C was measured in the fumarolic field without an eruption, consequently we can assume a vertical oscillation of a magmatic body beneath the volcano. Thermal imagery is then essential for detecting future changes in the dynamics of Santa Ana volcano.

5. *Energy and Mass Balance Calculation*

The observed increase of temperature at the surface of the lake of the Santa Ana volcano during the volcanic unrest of 2005 indicated the existence of changes in the heat input into the lake system of the volcano. To evaluate the magnitude of volcanic energy input during the volcanic crisis, we used a box model developed by Pasternack and Varekamp (P&V, 1997). Since the physico-chemical characteristics of a volcanic lake depend largely on the magnitude of the volcanic/hydrothermal heat and mass influx and the capacity of the lake to dissipate the heat, the P&V model uses outgoing energy and mass fluxes as a function of lake temperature, basin geometry and atmospheric parameters. Water mass balance with inputs of meteoric water and geothermal vapor or liquid and outputs of water lost by evaporation, seepage, or stream outflow determine whether a lake will maintain its volume or not (Brantley *et al.*, 1993). For a steady-state, energy balance is expressed as:

$$E_{\mathrm{cond}}^{\mathrm{volc}} + E_{\mathrm{rad}}^{\mathrm{sun}} + E_{\mathrm{volc}} + E_{\mathrm{rad}}^{\mathrm{atm}} = E_{\mathrm{rad}}^{\mathrm{lake}} + E_{\mathrm{evap}} + E_{\mathrm{cond}}^{\mathrm{lake}} + E_{\mathrm{meteoric}} \tag{1}$$

This equation shows that the energy inputs expressed as the sum of conductive heat input from a shallow magma body ($E_{\mathrm{cond}}^{\mathrm{volc}}$), the short-wavelength solar flux ($E_{\mathrm{rad}}^{\mathrm{sum}}$), the enthalpy of the volcanic/hydrothermal flux (E_{volc}) and the long-wavelength radiative input from the atmosphere ($E_{\mathrm{rad}}^{\mathrm{atm}}$) must equal the lake surface long-wavelength radiation ($E_{\mathrm{rad}}^{\mathrm{lake}}$), heat loss due to surface evaporation (E_{evap}), lake surface conduction ($E_{\mathrm{cond}}^{\mathrm{lake}}$) and heating of meteoric influxes up to the lake's temperature (E_{meteoric}). To yield a conceptual and generic model Pasternack and Varekamp made several simplifications and assumptions (see P&V, 1997).

The model currently runs in Mathematica 5.2 and solves simultaneously all the energy and mass-balance statements. Atmospheric parameters such as average annual air temperature, cloudiness and precipitation rate were entered, based on local observations or derived from the geographical location (latitude) and altitude. The temperature of the volcanic gas input is expressed as a function of the gas mass flux, using a step function (a small flux of gas cools rapidly whereas a big gas flux maintains magmatic temperatures). Following P&V (1997), we used a 'standard arc gas' with the composition of 2% SO_2, 5% CO_2 and 93% of H_2O. Gas inputs were expressed in MW as well as in equivalent SO_2 fluxes (*t/d*) for comparison with COSPEC data (Barrancos, J., 2005; Olmos *et al.*, 2007). Ultimately, since the main energy input comes from the conversion of steam to liquid water (enthalpy of condensation), gas temperature and gas composition are not critical parameters (P&V., 1997). The current version of the P&V model uses the evaporation expressions after Sill (1983) conformed to Stevenson (1992), nonetheless an important difference is the phrasing of the long wavelength heat input from the atmosphere. The P&V model uses an empirical expression that relates measured long wavelength heat fluxes to the surface temperature (following Linacre, 1992), whereas most other models simply use Boltzman's Law with the surface temperature (Stevenson, 1992, Bernard *et al.*, 2004). The latter approach creates larger atmospheric heat inputs into a lake (up to 30%), with resulting smaller volcanic heat inputs needed to obtain a given temperature.

Running the model with various air surface temperatures at different elevations from El Salvador, we calculated the surface temperature from the latitude and the elevation of Santa Ana volcano (using a lapse rate of 6°C per km), getting a satisfactory relation between elevation and air temperature. With this fitting we used a mean September 2005 temperature for the town of Santa Ana of 26.1°C (http://www.tutiempo.net/en/Climate/Santa_Ana_El_Palmar/09-2005/786550.htm) which gave an air temperature in the crater

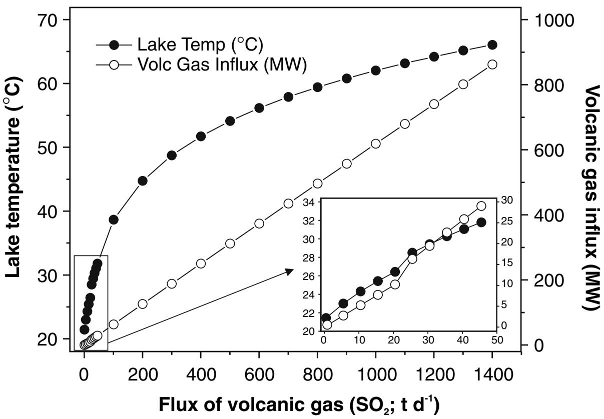

Figure 7
Energy model results for a volcanic gas input and the resulting lake water temperature, with parameters specific for Santa Ana volcano. The flux of volcanic gas is expressed in MW as well as in equivalent SO_2 fluxes (*t/d*). Also shown in more detail are the results for lake water temperature range 20–34°C.

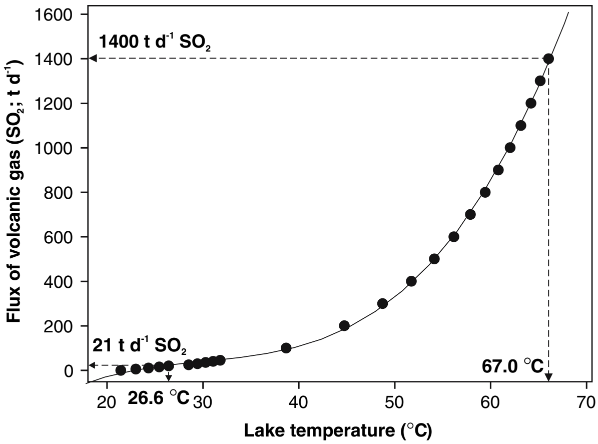

Figure 8
Relationship between the calculated flux of volcanic gas (SO_2, *t/d*) and surface lake's temperature for September 2005.

of 16.6°C, very close to locally measured temperatures *in situ*. We used a gas temperature of 875°C, as measured in 2002 in the crater. The results of the model calculations are shown in Figure 7.

Assuming an average temperature of 26.6°C for the entire lake's surface during our field work in September 2005, we estimated the flux of volcanic gas necessary to maintain the observed lake temperature. Our calculations yielded a total of 21 *t/d* of SO_2 (Fig. 8) or 10 MW for Santa Ana volcanic lake (20 m depth and 200 m of diameter), a value in the range of similar volcanic lakes (PASTERNACK and VAREKAMP, 1997). BERNARD *et al.* (2004) reported an energy flux of 16 MW when the lake surface was at its peak temperature (30°C) in July-August 2000, which would give with the P&V model an energy flux of 24 MW (using a crater air temperature of 15.7°C for June 2000), a slightly larger value for model specific reasons that were discussed above. These values reflected changes in the dynamics of the volcanic gas entering the lake and a clear sign of volcanic unrest. Most of reported values of SO_2 flux measured with COSPEC and miniDOAS during our thermal measurements (OLMOS *et al.*, 2007) were in the range of 500–1500 *t/d*, which are considerably higher than the calculated values for the lake. In situ observations at the crater area during our measurements showed that most of the volcanic gas (volcanic plume) escaped through the fumarolic field and not from the lake's surface. Only part of this gas was heating the water of the lake to the observed temperature. Those areas of the lake showing higher temperatures (max. of 54°C) were located close to the fumarolic field, indicating that only these areas of the lake (areas 3 and 4 in Fig. 4) were affected by the hot gases entering the lake.

During the volcanic eruption which occurred on October 1, part of the lake was "ejected" due to the phreatic explosion. Since the meteorological conditions did not allow scientists to make visual inspections of the summit crater, later on (November 2005) again a volcanic lake with slight changes in the color (light green), shape, level of water and with a strong bubbling at its center (SNET, Informe mensual N°7) was observed. Our observations made in February 2006 indicated a higher lake temperature (67°C) and a fast evaporation rate indicating that the lake was not going to keep its mass for a longer period of time. The loss of mass was so fast that during the 10-days field work the level of the lake decreased about 1 meter. The volcanic input required to create a lake temperature of 67 °C is 1400 *t* SO_2/day or 860 MW energy input (Fig. 8).

6. *Conclusions*

Two thermal surveys conducted before and after the occurrence of a volcanic eruption of Santa Ana volcano on 1 October 2005 enabled detection of crater's lake temperature changes related to the eruption. The strong degassing observed before the eruption seems to be responsible for the recorded thermal anomalies at the crater's lake surface. The observed changes in the apparent temperatures in the fumarolic field and lake, together with the magnitude of volcanic energy input, reflected changes in the dynamics of the volcanic gas entering the lake and were a clear sign of a volcanic unrest. The use of a thermal imaging system at Santa Ana volcano provides a clear potential for detecting changes in the dynamics of active volcanic systems.

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