Mazot, A.; Taran, Y.
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Geofísica Internacional, vol. 48, núm. 1, enero-marzo, 2009, pp. 73-83
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Available in: http://www.redalyc.org/articulo.oa?id=56813222006
**CO₂ flux from the volcanic lake of El Chichón (Mexico)**

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Received: July 1, 2008; accepted: September 19, 2008

**Abstract**

Carbon dioxide flux was measured in March 2007 at the surface of the volcanic lake of El Chichón volcano, Mexico using the floating accumulation chamber method. The results of 162 measurements and the application of a standard statistical approach developed for these studies showed that the total CO₂ flux from the crater lake is relatively high. The total emission rate calculated by sequential Gaussian simulation was 164 ± 9.5 t.d⁻¹ from the 138,000 m² area of the lake. Two different mechanisms of degassing (diffusion through the water-air interface and bubbling) are well resolved by a graphical statistical approach (GSA). The highest fluxes were observed along inferred fault traces. Elevated degassing was also observed along main basement faults in the area. The average flux of CO₂ over the entire crater floor of El Chichón (~ 308,000 m²) is inferred to exceed 370 t.d⁻¹. Thus the total emission rate of CO₂ from El Chichón crater is five times higher than at Kelud volcanic lake, Indonesia, but is similar to emission rates from other passively degassing active volcanoes worldwide.

**Key words:** CO₂ flux, accumulation chamber, crater lakes, El Chichón.

**Introduction**

Geochemical monitoring of active volcanoes generally includes a periodical or continuous study of the chemistry and/or fluxes of fluids released from the volcano crater or from the volcano edifice where active hydrothermal manifestations are present. In addition to spectroscopic remote sensing of volcanic plumes and direct sampling of fumaroles and hot springs, measurements of the soil diffuse CO₂ degassing by using the method of “accumulation chamber” has become a standard monitoring tool in volcanic and geothermal environments over the last 20 years (e.g. Chiodini et al., 1998). Temporal variations in CO₂ fluxes can be related to changes in the volcanic activity and may be important for the mitigation of the volcanic risk (Hernández et al., 2001a, Notsu et al., 2005). Fluxes of volcanic CO₂ by diffuse degassing through crater floors (Koepenick et al., 1996) or volcanic flanks can be comparable with plume degassing (Wardell et al., 2001). Volcanic craters occupied by a lake include Ruapehu in New Zealand, Poas in Costa Rica, Santa Ana in El Salvador, Kelud in Indonesia and El Chichón in Mexico. In order to measure the gas flux from crater lakes it is necessary to measure fluxes at the water lake surface. Degassing through the lake surface occurs by bubbles (convective/advective degassing) or by diffusion through the water/air interface. Early measurements of diffuse degassing from lakes by using the “floating accumulation chamber” method were made by Kling et al. (1991) for studying biogenic CO₂ production from an Arctic lake. Bernard et al. (2004) and Mazot (2005) were the first to use this method in a volcanic lake (Santa Ana in El Salvador and Kelud in Indonesia).
In this work, we report the first data on CO$_2$ flux from the surface of the crater lake of El Chichón volcano, Mexico, obtained in March 2007. The aims of this work were (1) to quantify the total CO$_2$ output from the volcanic lake and the whole crater, (2) to discriminate between mechanisms of degassing (diffusive or by bubbling); (3) to build a CO$_2$ flux map of degassing patterns from the lake bottom and relate them to local tectonics.

Finally, the total emission rate of CO$_2$ from El Chichón volcano is compared with those from other volcanic sites.

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**General setting**

The El Chichón dome complex (17.36N, 93.23W; 1,100 m.a.s.l.) is located in the northwestern part of the State of Chiapas in southeastern Mexico and halfway between the southeastern end of the Trans-Mexican Volcanic Belt (TMVB) and the northwestern end of the Central American Volcanic Arc (CAVA) (Fig. 1A). Prior to the 1982 eruption, the volcanic structure consisted of two nested andesitic lava domes (maximum elevation of 1260 m a.s.l.) inside a somma crater (Macías et al., 2003; Layer et al., this issue). The 1982 eruption of El

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![Map of El Chichón volcano](image)

Fig. 1a) Location map of El Chichón volcano in southern Mexico. Modified from Capaccioni et al. (2004). Abbreviations are: TMVB= Trans-Mexican Volcanic Belt, CAVA= Central American Volcanic Arc, CVA= Chiapanecan Volcanic Arc.

b) A sketch map of El Chichón crater with the lake (in gray) as it was in March 2007. The points of measurement are also shown by dots (modified from N. Varley - pers. comm.) Contour interval = 10 m. The 900 m level was chosen for the estimation of the crater floor area (bold-dashed line).
Chichón volcano ejected 1.1 km$^3$ of anhydrite-bearing trachyandesite pyroclastic material to form a new 1-km-wide and 200-m-deep crater (Rose et al., 1984). Currently, intense hydrothermal activity, consisting of fumaroles (mainly at the boiling point), steaming grounds, a soap-pool and an acidic (pH=2.3) and warm lake (~30 °C) occur in the summit crater (Fig. 1B; Taran et al., 1998). With the low pH of the lake, CO$_2$ is mainly present as a gaseous phase and dissolved in water. So, at this range of pH, the other carbonate species HCO$_3^-$ and CO$_3^{2-}$ are not present in the water for which we were sure to measure the whole CO$_2$ emitted from the lake.

El Chichón lies within an area of folded Jurassic evaporates, Cretaceous limestones, and Tertiary terrigenous rocks (Canul and Rocha, 1981; Duffield et al., 1984). The region is affected by two faults systems oriented approximately N-S and E-W. The most significant fault of the latter system is the San Juan Fault (Fig. 2). Furthermore, the area is characterized by a series of N45°E faults (Chapultenango Fault System) on top of which El Chichón has been emplaced (García-Palomo et al., 2004).

**Procedure and method**

In March 2007, a total of 162 randomly distributed CO$_2$ flux measurements, covering an area of 138,000 m$^2$ of the lake surface, were carried out (Fig. 1B). The GPS position of each measurement point represents the average of two readings (resolution ± 6 m) taken before and after each CO$_2$ flux measurement (duration 40-60 sec). The drift between these two readings depended greatly on the wind and could attain 40 m. The accumulation chamber method (Chiodini et al., 1998) was modified in order to work on a lake by using a floating chamber (Fig. 3). Gas flux was measured by using a chamber equipped with a LICOR LI-8100-103 infrared CO$_2$ analyzer (IRGA). The measurement accuracy of the CO$_2$ flux measurements method is assumed to be ~12.5% (Evans et al., 2001). As the original method from Chiodini et al. (1998), the CO$_2$ gas coming from the water lake passes through the chamber and the infra-red sensor, it returns to the chamber where it accumulates with the new CO$_2$ entering the chamber. The flux is derived by obtaining the increase of the CO$_2$ concentration with time (ppmvol.s$^{-1}$). Each measurement takes about 40 to 60 seconds. In order to

Fig. 2. Structural map of the El Chichón volcano showing main structural features. Modified from Garcia-Palomo et al. (2004).
convert volumetric concentrations to mass concentrations (g.m\(^{-2}\).d\(^{-1}\)), atmospheric pressure, temperature and total volume (sum of the chamber, IRGA connection tube, and the floating device) were taken in account. The fieldwork was undertaken under dry and stable meteorological conditions.

The mapping of degassing areas and estimation of the total CO\(_2\) discharge from the lake and the uncertainty of this estimation, were performed by using the sequential Gaussian simulation (sGs) that is an interpolation algorithm (Deutsch and Journel, 1998). The basic idea of the sGs is to generate a set of equiprobable representations of the spatial distribution of the simulated values, reproducing the statistical (histogram) and spatial (variogram) characteristics of the original data. According to Goovaerts (2001), the differences among all simulated maps (from 100 to 500 realizations) are used to compute the uncertainty of the flux estimation. The sGs approach has already successfully been used for soil CO\(_2\) degassing at other volcanic systems e.g. Chiodini et al., 2007 and details about the method in Cardellini et al., 2003.

**Results and discussion**

**Probability distribution of the CO\(_2\) flux data**

Fig. 4a shows the histogram of log \(F_{\text{CO}_2}\) (where \(F_{\text{CO}_2}\) is CO\(_2\) flux in g.m\(^{-2}\).d\(^{-1}\)) versus its frequency. The distribution of CO\(_2\) flux differs from a log-normal distribution indicating that there are at least two different mechanisms of degassing through the lake surface. According to the GSA approach (Sinclair, 1974), the histogram must be transferred to a log probability plot (Fig. 4b). This plot indicates that the CO\(_2\) flux data are separated into two different populations recognizable by the inflection point on the curve corresponding to the 83 cumulative percentile. On the plot we can individuate a high CO\(_2\) population (A in fig. 4b) corresponding to the 17 % of the data and a low CO\(_2\) population (B in fig. 4b) corresponding to the 83 % of \(F_{\text{CO}_2}\). The two-population percentages must be checked and validated by combining both populations in the proportion of 17 % A and 83 % B at various levels of log \(F_{\text{CO}_2}\). The checking procedure uses the following relationship: \(P_M = f_A^P_A + f_B^P_B\), where \(P_M\) is the probability of the “mixture”, \(P_A\) and \(P_B\) are cumulative probabilities of population A and B from the plot of Fig. 4b at a specified x value; \(f_A\) and \(f_B\) are the proportions of populations A and B. In fig. 4b, the points of the “mixture” are represented by gray triangles. Afterwards, parameters of the individual partitioned populations can be estimated. To estimate the arithmetic mean value of CO\(_2\) flux and the central 90% confidence interval of the mean in the original data units (in g.m\(^{-2}\).d\(^{-1}\)) for each population, we used, according to Chiodini et al. (1998), the Sichel’s t estimator (David, 1977).

A summary of the estimated parameters of partitioned distributions (populations A and B) is reported in Table 1. Population A is characterized by a mean of 6,702 g.m\(^{-2}\).d\(^{-1}\) with a 90% confidence interval of 5,154-10,429 g.m\(^{-2}\).d\(^{-1}\). Population B is characterized by a mean of 464 g.m\(^{-2}\).d\(^{-1}\).
with a 90% confidence interval of 442–490 g.m⁻².d⁻¹. We suggest that population A corresponds to the flux resulting from bubbles rising through the lake and population B represents the CO₂ degassing by diffusion through the water-air interface (see paragraph 4.3 for details).

The total flow rate of CO₂ released by the lake, calculated by the GSA method, is \((6,702 \text{ g.m}⁻²\text{.d}⁻¹ \times 0.17\% + 464 \text{ g.m}⁻²\text{.d}⁻¹ \times 0.83\%) \times 138,000 \text{ m}² = 210 \text{ t.d}⁻¹\) with a 90% confidence interval of 172-301 t.d⁻¹.

### Mapping and sgs estimation of the CO₂ flux from the lake

Another statistical method for the estimation of the CO₂ fluxes and the total flow rate is the sequential Gaussian simulation (sGs) (Deutsch and Journel, 1998) method. The 162 measured CO₂ fluxes in randomly distributed points on the lake surface were interpolated by a distribution over a grid of 5,523 square cells (5x5 m²) covering an area of 138,075 m² using the so-called exponential variogram model. Then, 100 simulations

<table>
<thead>
<tr>
<th>Population of CO₂ flux</th>
<th>Mean flux of CO₂ (g.m⁻².d⁻¹)</th>
<th>90% confidence interval (g.m⁻².d⁻¹)</th>
<th>Proportion (%)</th>
<th>Total CO₂ output for each population (t.d⁻¹)</th>
<th>90% confidence interval (t.d⁻¹)</th>
<th>Total CO₂ output (t.d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6702</td>
<td>5,154-10,429</td>
<td>17</td>
<td>921</td>
<td>708-1433</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>464</td>
<td>442-490</td>
<td>83</td>
<td>64</td>
<td>61-67</td>
<td>210</td>
</tr>
</tbody>
</table>

Table 1

Proportions of each population with a mean CO₂ flux (in g.m⁻².d⁻¹) and a total CO₂ output (in t.d⁻¹) obtained by statistical graphical approach.

Fig. 4. Histogram (a) and probability plot (b) of CO₂ flux data. Population A is indicated by open squares, population B by open triangles and the “mixture” by gray triangles. The inflection point is indicated by an arrow.
of the CO$_2$ fluxes with the obtained distribution were performed. For each simulation, the CO$_2$ flux estimated at each cell is multiplied by 25 m$^2$ and added to the other CO$_2$ fluxes estimated at the neighborhood cells of the grid to obtain a total lake CO$_2$ output. The mean of the 100 total simulated CO$_2$ outputs, 164 t.d$^{-1}$, represents the estimation of the total CO$_2$ output from the lake area with a standard deviation of 9.5 t.d$^{-1}$. The total CO$_2$ output determined using GSA method is higher (210 t.d$^{-1}$) than the mean simulated by the sGs method (164 t.d$^{-1}$). In the calculation of the mean of F$_{co2}$, GSA approach does not take into account the spatial correlation between the data, resulting generally in an overestimation of the uncertainty.

The obtained map (Fig. 5) shows that the highest CO$_2$ flux “spots” are located close to the eastern shore of the lake near the active fumarolic area. Two linear zones of high flux can be clearly recognized on the map, together with several intensively bubbling “funnels” observed during the campaign. These arrangements along NNW-SSE and W-E alignments may be correlated to the regional faults and the E-W San Juan Fault, respectively (García-Palomo et al., 2004).

Estimation of the CO$_2$ diffusion through the lake-air interface

Our suggestion that the population of data with lower CO$_2$ fluxes is provided by the diffusion of CO$_2$ through water-air interface can be checked using the thin boundary layer model (Liss and Slater, 1974). The flux $F$ between water and air may be calculated by the empirical equation (e.g. McGillis and Wanninkhof, 2006):

$$F (mg.cm^{-2}.h^{-1}) = k_{CO2} \times (C_{w/a} - C_w)$$  \hspace{1cm} (1)

where $k_{CO2}$ is the gas exchange coefficient (in cm.h$^{-1}$) for CO$_2$, $C_w$ and $C_{w/a}$ refers to the concentration of CO$_2$ in water, and in water film at the water-air interface, respectively.

The value of $k_{CO2}$ was calculated by using the relationship between windspeed and $k_{CO2}$ derived from tracer techniques studies on a small lake (Crusius and Wanninkhof, 2003):

$$k_{CO2} = 0.93u_1 \times [600/Sc_{CO2}]^{1/3}$$  \hspace{1cm} (2)

where $u_1$ is the windspeed measured at 1 m height and Sc is defined as the kinematic viscosity of water at measured temperature divided by the diffusivity of the gas at that temperature. Transfer velocity was adjusted to a Schmidt number of 600 that corresponds to the value for the dissolved atmospheric CO$_2$ in fresh water at 20°C. The value of Sc$_{CO2}$ at 30°C was calculated according to Wanninkhof (1992):

Fig. 5. CO$_2$ flux map (in g.m$^{-2}$.d$^{-1}$) as a mean of 100 sequential Gaussian simulations (see text for explanation). Gray zones indicate fumarolic areas and very high CO$_2$ fluxes are highlighted. White crosses correspond to the flux measurement sites.
**ScCO2 = 1911.1-118.11×t + 3.4527×t^2 - 0.04132×t^3 (3)**

At a mean windspeed $u_1$ of 2 m.s$^{-1}$, $Sc_{CO2} = 360$ and $k_{CO2} = 1.39$.

At saturation conditions of 30 °C and 1 atmosphere, $C_w$ of the CO$_2$ gas is 1.32 mg.cm$^{-3}$ (Eq. 1). The concentration of CO$_2$ in the air-water ($C_{aw}$) interface can be approximated to the concentration of CO$_2$ in the air-saturated water and corresponds to $C_{aw} = 1.39$. From the equation (1) and with values for $k_{CO2}$ of 1.39 and $C_w$ of 1.32 mg.cm$^{-3}$ we estimated a CO$_2$ flux by diffusion of 442 g.m$^{-2}$.d$^{-1}$ that is very close to the mean value of $F_{CO2}$ (464 g.m$^{-2}$.d$^{-1}$) for the low flux of data points (population B).

**Estimation of the heat power and comparison with other volcanoes in the world**

The area of the whole crater floor corresponding to the isohypse 900 m (Fig. 1b) was estimated to be as 308,000 m$^2$. Hypothesizing that mains NNW-SSE and W-E alignments are recognized on the lake and that there are not so important variations in $F_{CO2}$ in soil and water due to the low depth of the lake (average depth 3 meters see Taran and Rouwet, 2008), a rough estimate of the total CO$_2$ output for the whole crater floor yields ~370 t.d$^{-1}$.

The high CO$_2$ fluxes plotted on figure 6, show that high CO$_2$ degassing is not necessarily related to active volcanoes. Three different sources of CO$_2$ degassing are likely: (1) CO$_2$, directly coming from a magma chamber, escapes to the surface with other magmatic gases such as SO$_2$, H$_2$S, HCl and HF, as this is the case for volcanoes Masaya, Nicaragua (Pérez et al., 2000), Miyakejima and Usu, Japan (Hernández et al., 2001a,b), Stromboli, Italy (Carapezza and Federico, 2000), San Salvador, El Salvador (Pérez et al., 2004), Santa Ana, El Salvador (Bernard et al., 2004) and Galeras, Colombia (Williams-Jones et al., 2000). (2) CO$_2$ coming from a magma chamber but with a possible contamination due to the crustal carbonate decomposition and subsequent CO$_2$ release. This type of the CO$_2$ release could be the case for Solfatara and Vesuvio, Italy (Cardellini et al., 2003; Frondini et al., 2004), Santorini and Nisyros, Greece (Chiodini et al., 1998; Cardellini et al., 2003), Yellowstone, USA (Werner et al., 2000) and Kelud, Indonesia (Mazot, 2005). (3) CO$_2$ degassing at low temperature and coming from carbonate metamorphism, not related to magmatism. Sites that released this kind of CO$_2$ are for example Dixie Valley, USA (Bergfeld et al., 2001) and central Italy (Rogie et al., 2000).

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Fig. 6. Comparison of CO$_2$ flux (in Mt/y) among El Chichón crater lake and other volcanic and geothermal sites in the world: Vulcano (Baubron et al., 1990), Stromboli (Carapezza and Federico, 2000), Solfatara (Cardellini et al., 2003), Ischia (Chiodini et al., 2004), Vesuvio (Frondini et al., 2004), Central Italy (Rogie et al., 2000), Pantelleria, Italy (Favara et al., 2001); Dixie Valley (Bergfeld et al., 2001), Mammoth Mountain (Sorey et al., 1998), Yellowstone, USA (Werner et al., 2000); Santa-Ana (Bernard et al., 2004), San Salvador, (Pérez et al., 2004), Ilopango lake, El Salvador (López et al., 2004); Santorini, (Chiodini et al., 1998), Nisyros, Greece (Cardellini et al., 2003); Usu (Hernández et al., 2001a), Miyakejima, Japan (Hernandez et al., 2001b); Kelud, Indonesia (Mazot, 2005); Masaya, Nicaragua (Pérez et al., 2000); Galeras, Colombia (Williams-Jones, 2000).
The total CO₂ output from El Chichón crater is 1.5 times higher than the diffusion rates reported for the summit area at Stromboli (mean flux: 246 t.d⁻¹; area: 357,500 m²; Carapezza and Federico, 2000) and little lower than those reported for the soil CO₂ flux at Mammoth Mountain in Long Valley Caldera, USA (mean flux: 411 t.d⁻¹; area: 420,000 m²; Sorey et al., 1998).

The CO₂ degassing from the volcanic lake of El Chichón was compared (Fig. 6) with that of Kelud crater lake (Indonesia) and Santa Ana crater lake (El Salvador). In the Kelud crater lake, where CO₂ flux measurements have been carried out since 2001 (Mazot, 2005), the total CO₂ output ranges from 100 t.d⁻¹ with a mean of 1020 g.m⁻².d⁻¹ (2001) to 35 t.d⁻¹ with a mean of 335 g.m⁻².d⁻¹ (2006) and a constant area of 103,600 m². In Santa Ana, where measurement was performed in 2002, CO₂ output corresponds to 7 t.d⁻¹ in 2002 with a mean of CO₂ flux of 220 g.m⁻².d⁻¹ and an area of 30,000 m² (Bernard et al., 2004). Among these three volcanic lakes, the total CO₂ output at El Chichón in 2007 was up to 5 times higher (164 t.d⁻¹) than Kelud volcano and 23 times higher than Santa Ana (Fig. 4).

Fumarolic gas of El Chichón volcano contains about 90 wt% of H₂O (steam) and 10 wt% of CO₂ (Taran et al., 1998; Tassi et al., 2003). Assuming that all the CO₂ released from the crater floor is the result of separation of these gases caused by shallow condensation of hydrothermal steam at ~100 °C, beneath the crater floor of the volcano we have ~3,700 t/day or ~43 kg/s of steam flux and beneath the lake we have ~1,640 t/day or ~19 kg/s. Using a value for steam enthalpy at 100 °C due to steam condensation (~2.257 MJ/kg) we can estimate the heat power due to fumarolic output from the crater floor as 100 and from the lake 43 MW. This heat output is up to 3.5 times higher than the output estimated by Taran and Rouwet (2008) using the heat and chemical balance approach at El Chichón lake. Our estimation based on the direct measurements of fluxes seems to be more realistic.

The heat output corresponding to El Chichón lake (43 MW) is comparable with the heat power of other crater lakes of active volcanoes. In Kelud lake, Mazot (2005) calculated values of heat power ranging from 45 to 180 MW in the period 2004-2007 (Table 2) by using the heat and chemical balance model of Stevenson (1992). The heat power was estimated on other crater lakes as Kawah Ijen (Indonesia; Delmelle, 1995), Taal (Philippines; Poussielgue, 1998), Poas (Costa Rica; Stevenson, 1992), Yugama (Japan; Ohba et al., 1994), Ruapehu (New Zealand; Stevenson, 1992) and Copahue (Argentina; Varekamp et al., 2001). The heat output of 100 MW from El Chichón crater is relatively small in comparison with the heat power observed at hot (>40 °C) crater lakes, where values as high as several hundred MW were estimated (Table 2).

Table 2

<table>
<thead>
<tr>
<th>date</th>
<th>Eₚₒₙ (MW)</th>
</tr>
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<tr>
<td>Santa Ana</td>
<td>2002</td>
</tr>
<tr>
<td>Yugama</td>
<td>1988-1993</td>
</tr>
<tr>
<td>Copahue</td>
<td>1997-1999</td>
</tr>
<tr>
<td>El Chichón</td>
<td>1997-2007</td>
</tr>
<tr>
<td>Kelud</td>
<td>2001-2007</td>
</tr>
<tr>
<td>Taal</td>
<td>1989-1995</td>
</tr>
<tr>
<td>Poas</td>
<td>1978-1989</td>
</tr>
<tr>
<td>Ruapehu</td>
<td>1966-1989</td>
</tr>
</tbody>
</table>

Conclusion

CO₂ flux measurements made by using the floating accumulation chamber method allowed to estimate the total CO₂ emission from the crater lake of El Chichón (138,000 m²) to be close to 164 t.d⁻¹. For the total area of the crater floor of 308,000 m² the total CO₂ emission was estimated at 370 t.d⁻¹. This level of the total CO₂ emission and the estimated heat output are comparable with other volcanic and geothermal areas worldwide.

Continuous monitoring of CO₂ flux from the crater lake of El Chichón could improve our understanding of the hydrothermal system. This would be complementary to other geochemical investigations and it would be particularly important for detecting possible changes in the activity of the volcano.

Bibliography


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