

Dynamics and mass balance of El Chichón crater lake, Mexico

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RESUMEN

El balance de masa en el lago del cráter del Chichón es controlado por la precipitación y la evaporación, así como por la infiltración en el fondo del lago. La fuente principal no meteórica de agua y Cl de este lago es un manantial en ebullición (Soap Pool) que descarga aguas salobres y neutras dentro del cráter con una tasa de flujo que varía entre los 0 y 30 kg/s. Las variaciones temporales en el volumen del lago fueron determinadas aproximadamente mediante fotografías digitalizadas del lago y una relación empírica entre la profundidad del lago y su superficie, que se obtuvo con cuatro levantamientos batimétricos. La mejor correlación entre los cambios observados en el volumen del lago, el contenido de Cl y la tasa de flujo medido en el manantial Soap Pool se logró con un modelo de caja para el balance de Cl. Se propone un modelo de lago "enterrado" basado en la tendencia en el contenido de Cl en el agua de Soap Pool.

PALABRAS CLAVE: Lago cratérico, balance de masa, el volcán Chichón.

ABSTRACT

The mass balance of El Chichón crater lake is controlled by precipitations, evaporation and seepage through the lake bottom. The main non-meteoric source of water and Cl for the lake is a boiling spring (Soap Pool) discharging saline and neutral water with a variable flow rate from 0 to 30 kg/s inside the El Chichón crater. Variations in lake volume over time were approximately determined from digitized photographic views of the lake using an empirical relationship between depth of the lake and surface area, obtained after four bathymetric surveys. The best correlation between the observed changes in lake volume, Cl content and the measured flow rate of Soap Pool was obtained by a box-model for the Cl mass balance. Based on a trend in the Cl content of the Soap Pool water a model of a "buried" initial crater lake is proposed.

KEY WORDS: Crater lake, mass balance, El Chichón volcano.

1. INTRODUCTION

Lakes in craters of active volcanoes are condensers of volcanic gases and volcano-hydrothermal fluids formed in the deeper zones of a volcanic edifice. Variations in chemical flux from the magma can cause significant changes in the temperature, composition and volumes of these lakes. Thus, monitoring of crater lakes is a useful tool for volcanic surveillance (Giggenbach and Glover, 1975; Takano, 1987; Rowe *et al.*, 1992; Ohba *et al.*, 1994). Crater lakes are also good objects to apply models of heat and mass balance (Brown *et al.*, 1989; Hurst *et al.*, 1991; Ohba *et al.*, 1994; Rowe *et al.*, 1992, 1995; Sanford *et al.*, 1995).

El Chichón volcano in Mexico erupted violently in March-April 1982 with ejection of fresh magma and material of the old central dome. A crater lake was formed soon after the eruption. By November 1982 it attained a maximum surface area of 1.4×10^5 m² and a volume of 5×10^6 m³ (Casadevall *et al.*, 1984). In this paper we examine the physi-

cal and chemical data collected at the lake and hot springs in El Chichón crater over the period 1983 – 2003 on the basis of water and chlorine balance models for the crater lake system and a simple remote method for the determination of the volume of the lake and its mass budget.

2. BACKGROUND INFORMATION AND CHEMICAL CHANGES IN THE LAKE WATER

El Chichón is a trachyandesite complex volcano rising about 1000 m above sea level with a relative elevation of 600 m. The volcano is located between the Mexican Volcanic Belt and the Central American volcanic chain (Figure 1). Its tectonic setting is being debated (Espíndola *et al.* 2000 and references therein). El Chichón crater lake appeared soon after the 1982 eruption, when a 1-km wide and 200-m deep crater was formed after explosion of the central extrusive dome. According to Casadevall *et al.* (1984) in 1983 the crater lake was filled with ultra-acidic (pH=0.5), hot (55°C) and mineralized (TDS=34 g/L) water with a Cl

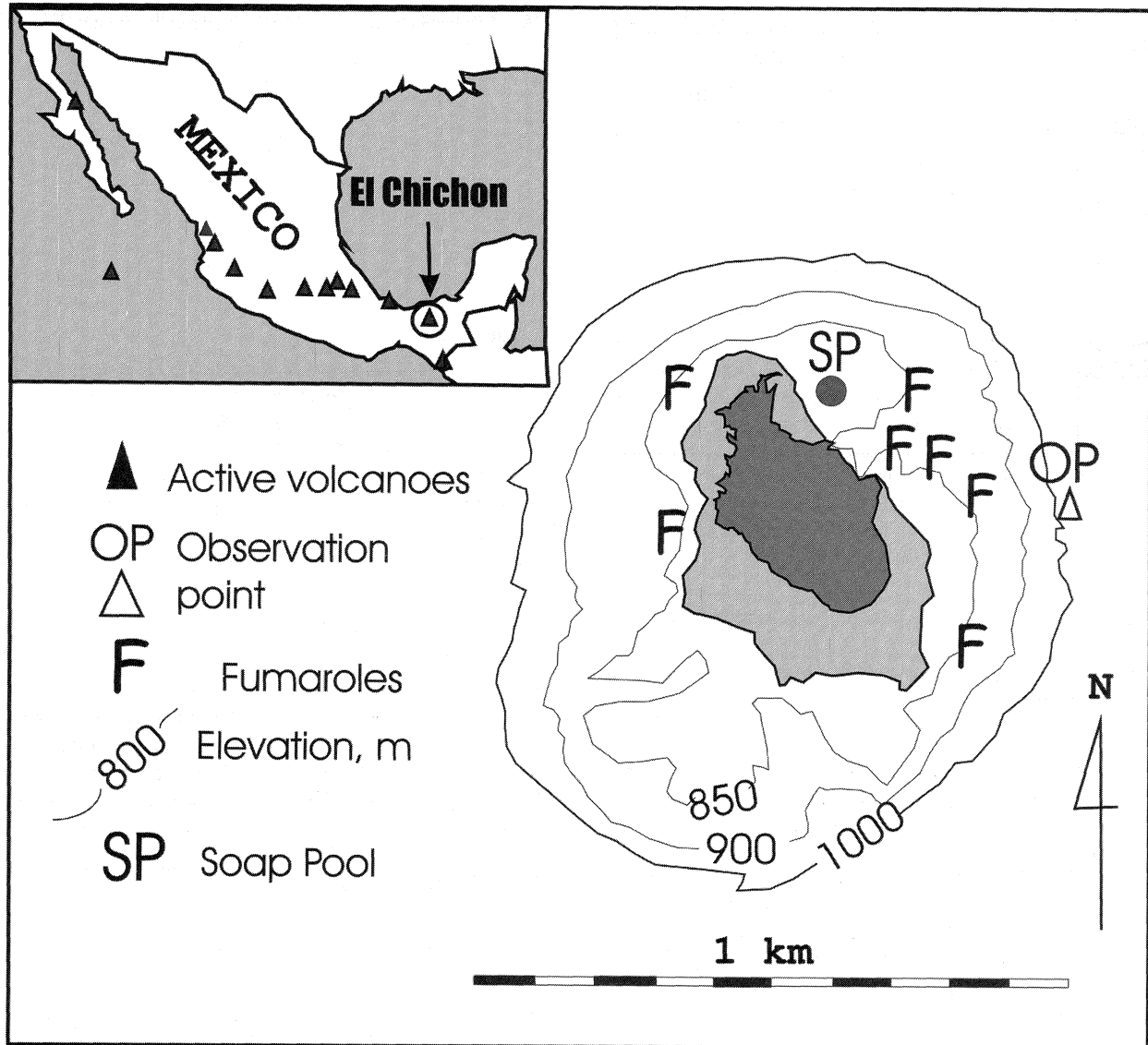


Fig. 1. The El Chichón crater and lake (light-shaded) in November 1982 according to Casadevall *et al.* (1984), contour (dark-shaded) of the lake in March 2003 made by GPS measurements, and location of the Soap Pool springs and fumarolic fields in the crater.

content of about 24 000 ppm. Taran *et al.* (1998) reported strong hydrothermal activity in the crater in 1995-1997: numerous boiling-point fumaroles, water and drainless mud pools, gas bubbling in the lake, "fried pans" and a boiling spring (Soap Pool) with a total discharge of 10-30 kg/s of saline Na-Ca-Cl water with Cl > 10 000 ppm, low sulfate (<250 ppm) and a surprisingly high pH (>6.5). Casadevall *et al.* (1984) reported that there were no springs in the crater in 1983. The lake in 1995-1997 had a temperature of 30°-34°C, pH~2.5 and Cl content between 1000 and 4000 ppm. In November 1998 the Soap Pool spring became a vigorous wet fumarole, and the Cl content was quite low in the crater lake (<20 ppm). This supported the preliminary idea of Taran *et al.* (1998) that the Soap Pool is the only source of Cl in the lake water. The Soap Pool reappeared a

year later, but as a group of boiling springs with fountains up to 0.5 m high. It disappeared again before January 2002. Soon after the Soap Pool disappeared, the lake became almost free of Cl, which means that the recharge and dilution processes were very intense.

Figure 2 shows the changes in Cl content of the lake water starting from 1983, and water from the Soap Pool starting from 1995. The lake composition does not show seasonal variations but apparent cyclical changes with 3-4 year intervals. The Soap Pool water started with 13 100 ppm of Cl in 1995 (no data about this spring prior to this date), and decreased to 5300 ppm in 2002. The extrapolation of Soap Pool data to 1983 gives a value close to 24 000 ppm that agrees with the initial Cl concentration in the lake (Figure 2).

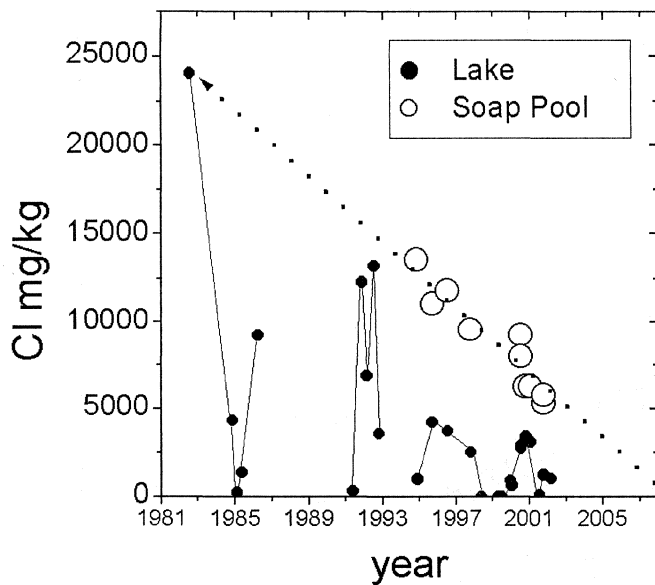


Fig. 2. Chlorine concentration in the lake and Soap Pool over time. Data before 1995 are from Taran *et al.* (1998). A few data points for the lake after 1995 not presented in Table 1 are added to the plot. We don't have photos from those visits. Extrapolation of data for Soap Pool to 1983 gives exactly the Cl-concentration in the lake reported by Casadevall *et al.* (1984).

3. CHANGES IN LAKE VOLUME

We performed bathymetry surveys in April 1998, November 1998, January 2001 and April 2002 to estimate the lake volume (Taran and Varley, 2000). The surveys revealed a shallow, flat-bottomed topography with a flat part of approximately 20 000 m² and average depths of 1.3 m to 3.3 m. The lake surface area was estimated from photographs taken from a fixed site on the crater rim (OP, Figure 1). The lake contour was digitized and transformed from a perspective view to a normal view using Corel Draw and Origin software. The reference contour (March 2003) and four reference lines on the crater floor were obtained from "Garmin" GPS device (Figure 1). Changes in the lake surface area, the lake shape and Cl content of lake water since 1983 are shown in Figure 3.

The volume increments of crater lakes are often estimated assuming a cylindrical shape – using changes in the water level only (e.g. Rowe *et al.*, 1992). Ohba *et al.* (1994) derived an empirical equation between water level and volume of the Yugama crater lake. In the case of El Chichón, the shape of the lake is close to an elliptical truncated cone, and the depth-area dependence should be: $d = a + bS^{1/2}$ where a and b are constants depending on the area of the flat floor and the shore inclination. Figure 4 shows that this is a good approximation. Thus, the volume of the lake can be estimated from values a , b and the lake surface area. Table 1 summa-

rizes the data on areas, measured and calculated depth, volumes and volume changes between measurements, as well as the Cl content in the lake and the Soap Pool springs.

4. WATER BALANCE; INPUT AND OUTPUT PARAMETERS

Calculations of the water content and energy balance in crater lakes have been done by several authors (see Pasternack and Varekamp (1997) for a review). The mass balance for a lake requires

$$\frac{dM}{dt} = Q_i - Q_o, \quad (1)$$

where M is the mass of the lake water, Q_i is the rate at which water is added to the lake and Q_o is the output rate. The input rate is the rate of precipitation (Q_p) and rate of the Cl source. For El Chichón the latter is the Soap Pool flow (Q_{sp}), assuming that the steam input from the bottom of the lake and the steam condensate from fumaroles are negligible; thus: $Q_i = Q_p + Q_{sp}$. The output is due to evaporation from the lake surface (Q_e) and seepage through the lake bottom (Q_s); thus $Q_o = Q_s + Q_e$. The evaporation flux is an uncertain parameter because it strongly depends on wind velocity and difference between temperature of the lake surface and ambient air temperature (Adams *et al.*, 1990; Brown *et al.*, 1989). For an average annual wind speed of 2 m/s, an air temperature of 22.5°C (from the Meteorological Survey of Mexico for this region) and an average lake temperature of 31°C the evaporation flux can be estimated as $F_e = (6 \pm 4) \times 10^{-5}$ kg/m²s, using the Brown *et al.* (1989) expression and relative errors. The next uncertainty is the catchment area for the precipitation. If the total crater area is the catchment area, the net input flow rate into the lake can be expressed as

$$Q_i = S_c F_p - (S_c - S_L) F_s + Q_{sp}, \quad (2)$$

where F_p and F_s are fluxes of precipitation and seepage (infiltration) in kg/m²s, S_L and S_c are the lake and crater areas in m². The total balance is then:

$$\frac{dM}{dt} = Q = S_c (F_p - F_s) - S_L F_e + Q_{sp} \text{ (if } F_p > F_s \text{)} \quad (3)$$

$$\frac{dM}{dt} = Q = S_L (F_p - F_s) - S_L F_e + Q_{sp} \text{ (if } F_p < F_s \text{)} .$$

We have three measurements of the flow rate of the Soap Pool spring by the float method in March 1996 (16 kg/s), January 2001 (24 kg/s) and April 2002 (14 kg/s), plus four visits with zero discharge. Using the average distribu-

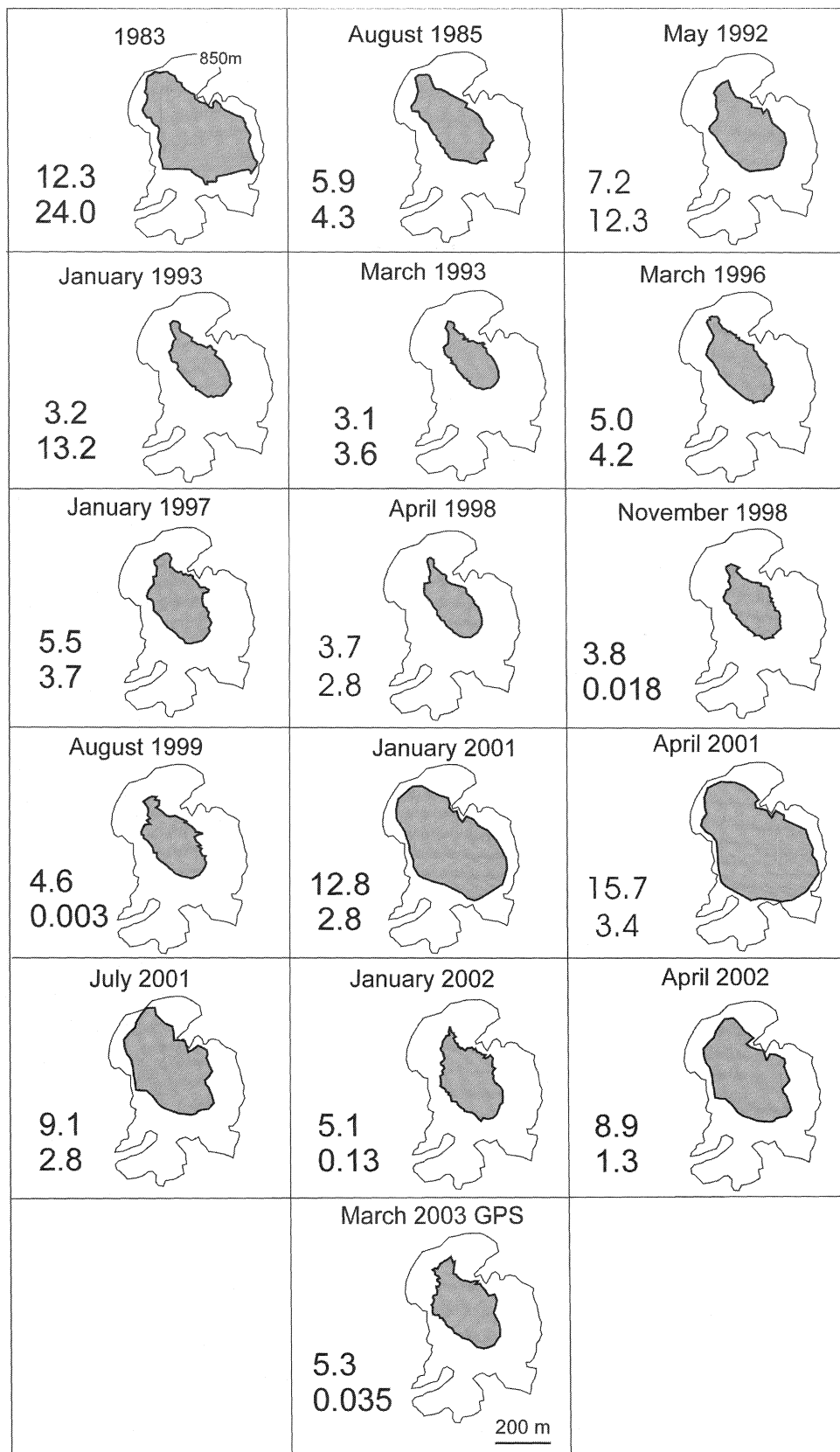


Fig. 3. Contours of the El Chichón crater lake transformed from perspective photo shots to the orthogonal view. The “March 2003” contour was made by the 10m-step GPS measurements and was used as a reference. Upper numbers indicate the lake surface area in m^2 divided by 10^4 and lower numbers show Cl content of the lake water in g/kg. Also the contour of the 850 m elevation is shown.

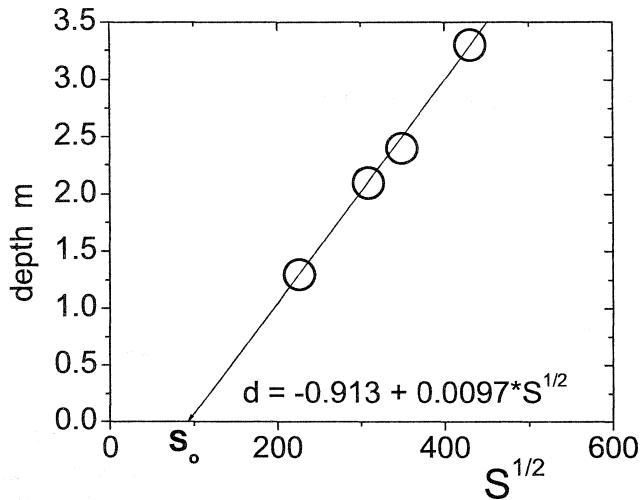


Fig. 4. Correlation between measured depth of the flat lake floor and calculated areas (see text).

tion of precipitation over 25 year at the village of Chapultenango, 8 km east of the volcano, and variations in the volume (mass) of the lake, we estimate the infiltration flux, F_s as $(2.0 \pm 0.8) \times 10^{-4}$ kg/m²s. The average annual precipitation is 1.34×10^{-4} kg/m²s (4243 mm/year) with a maximum of 2.3×10^{-4} kg/m²s in November and a minimum of 0.69×10^{-4} kg/m²s in April. Thus, El Chichón crater lake without the Soap Pool spring has a negative average annual mass balance, so it possibly would only exist after rainy seasons. The infiltration (seepage) flux estimated for El Chichón crater lake is close to the average value found by Ohba *et al.* (1994) for the Yugama lake, and more than one order of magnitude lower than values calculated by Rowe *et al.* (1992) for the crater lake of Poás volcano.

5. CHLORINE BALANCE

Assuming constant rates of in- and outflow, the chlorine balance in the system (lake+Soap Pool) can be found from the ordinary differential equation

$$\frac{d(MC)}{dt} = C_{sp}Q_{sp} - CQ_s, \quad (4)$$

where C is Cl concentration in the lake water, Q_s is the seepage (infiltration) rate, C_{sp} is Cl in the Soap Pool water and Q_{sp} is the outflow rate of the Soap Pool.

From $d(MC)/dt = C(dM/dt) + M(dC/dt)$, $d/dt = d/dM(dM/dt)$ and $dM/dt = Q$ we may write

$$MQ \frac{dC}{dM} + CQ = Q_{sp}C_{sp} - Q_s C. \quad (5)$$

Table 1

Surface area of the lake calculated from the photo images, S ; depth, d ; estimated volume, V , and the total flow rate Q calculated from volume changes between two dates. The surface area in March 2003 was estimated from a contour obtained by GPS measurements.

Date	S $\times 10^{-4}$ m ²	d m	V $\times 10^{-4}$ m ³	Q kg/s	Cl Lake g/kg	Cl SP g/kg
20.05.95	-	-	-	-	0.98	13.6
24.03.96	5.0	1.6	6.4	-1.7	4.20	11.0
16.01.97	5.5	1.8	7.4	0.4	3.7	11.8
07.04.98	3.7	1.3*	4.6	-0.7	2.8	9.54
20.11.98	3.8	2.1*	10.5	3.0	0.018	-
10.08.99	4.6	1.5	5.7	-2.1	0.003	9.25
22.01.01	12.8	3.3*	26.0	4.7	2.8	8.0
19.04.01	15.7	3.7	34.4	11.1	3.4	6.29
05.07.01	9.1	3.1	23.1	-16.5	2.8	6.24
10.01.02	5.1	2.0	9.6	-8.2	0.13	-
24.04.02	8.9	2.4*	13.2	3.8	1.3	5.3
10.03.03	5.3	1.8	8.0	-1.9	0.035	-

* measured depths.

The solution at $Q \neq 0$ can be written down as

$$\frac{C_{sp}Q_{sp} - C_o(Q_s - Q)}{C_{sp}Q_{sp} - C(Q_s - Q)} = \left(\frac{M}{M_o} \right)^{\frac{Q_s + Q}{Q}}, \quad (6)$$

where C_o and M_o are initial values.

The flow rates are not constant, but we can use Equation (6) for estimation of the average flow rate of the Cl source (Soap Pool) between two observations using two M -values such as M_o and M . The infiltration flow rate can be estimated as the seepage from the lake using the surface area as the average between S -values. Thus, $Q_s = F_s(S_o + S)/2$, using the average F_s calculated in the previous section, and $Q = (M - M_o)/t$ (kg/s) where t is the time interval between observations. It gives:

$$Q_{sp} = (Q + Q_s) \frac{BC - C_o}{C_{sp}(B - 1)}, \quad (7)$$

where $B = (M/M_o)^{(Q_s + Q)/Q}$. The advantage of the Cl balance model is that Q_{sp} depends only on Q_s and Q , and the seepage outflow is calculated only for the lake surface. There is no need to make assumptions about the catchment area, the wind speed and other meteorological parameters.

6. RESULTS AND DISCUSSION

The water mass balance and the Cl balance may be used separately for estimations of flow rate of the chlorine

source. From the water balance we can calculate Q_{sp} using only photographs of two consecutive visits and meteorological data (precipitation, wind speed and ambient temperature) between visits. The Q_{sp} value obtained in this way includes all non meteoric sources of water: Soap Pool, steam condensate and seepage from the lake bottom into the lake. Sources of errors include volume estimation, meteorological data, choice of catchment area, and the assumption of a constant and homogenous infiltration. Each one requires special investigation and an estimation of its magnitude.

The Cl balance model with Equation (7) can be used after chemical analyses of the lake water and SP for determinations of C_{sp} , C_o and C . This method yields the average flow rate of a chlorine source between two observations. Results are presented in Table 2 together with the measured outflow rates at the Soap Pool. There is a large difference in calculated values between the water mass balance model and the Cl balance model. The water mass balance gives at least three erroneous values of Q_{sp} for the 1998-1999 and 2002-2003 periods when the SP spring did not discharge water. This means that neither the averaged meteorological data for the estimation of rainfall and evaporation nor the choice of the catchment area are correct. In contrast, the Q_{sp} calculated from the Cl balance model agrees with the observed behavior of the Soap Pool. The model calculates average flow rates between two dates and this may be the reason for the significant difference between measured and calculated Q_{sp} . El Chichón lake was almost free of Cl from November 1998 (17 ppm) through December 1999 (3 ppm), as well as in January 2002 (130 ppm), and in March 2003 (30 ppm), when the Soap Pool spring did not discharge water but Cl-free steam. It can be seen from Figure 2 that the first drop of Cl content in the lake was observed in 1985 (243 ppm), and then in 1991 (320 ppm). There was no information about the existence of the Soap Pool spring before 1995, but a variable source of Cl must have existed at that time. A significant decrease in Cl occurred also in 1995 (980 ppm against 3600 ppm in 1993). The behavior of the Soap Pool spring (or any other source of Cl before 1995) seems to be geyser-like but with a long (3-4 years) and irregular period, and a variable flow rate of brine. For example, in April 2002 the lake had the largest surface and Cl concentration was ~3500 ppm. April is the driest month after at least four low-rainfall months when the rain water balance in the lake is negative. Water was supplied by the Soap Pool, with a flow rate higher than 30 kg/s. The Cl content of the Soap Pool (Figure 2) has a tendency to decrease over time, and the extrapolated “zero-time” concentration in 1983 is very close to the initial Cl concentration in the lake (Casadevall *et al.*, 1984).

7. MODEL

These observations suggest that the Soap Pool springs discharge saline water from an aquifer of limited size. The

Table 2

Infiltration (seepage) flow rate, Q_s , and flow rate of the Soap Pool springs (kg/s): Q_{sp} – measured; Q_{sp}^* – from the box (chlorine budget) model; Q_{sp}^{**} – from the water mass balance

Date interval	Q_s	Q_{sp}	Q_{sp}^*	Q_{sp}^{**}
05.95-03.96	15.6	16	4.2	4.7
03.96-01.97	13.4	-	4.8	6.3
01.97-04.98	11.7	-	2.7	4.9
04.98-11.98	13.6	0	0.0	7.1
11.98-08.99	14.8	0	1.4	5.6
08.99-01.01	22.2	24	8.9	12.2
01.01-04.01	36.3	-	25	34.4
04.01-07.01	35.3	-	7.4	-1.4
07.01-01.02	23.7	0	-1.4	-1.9
01.02-04.02	18.7	14	5.9	18.8
04.02-03.03	17.7	0	0.0	6.8

brine in the aquifer had an initial Cl concentration of 24 g/kg, which is the Cl content in the lake just after the eruption. Therefore it can be assumed that the initial mass of the brine in the aquifer was “buried” by landslides and fluvial flows from the walls of the crater lake with an initial volume, according to Casadevall *et al.* (1984), of 5×10^6 m³. For the dilution of this amount of water from 24 g/kg of Cl to 5.5 g/kg (Cl content of in the Soap springs in 2000) during 20 years without any supply of Cl from a deeper (magmatic) source, a discharge of 12 kg/s of brine is needed. This value is close to the Soap Pool average discharge rate over the time of observation.

As for the origin of the Soap Pool, discharge of neutral saline water from the bottom of a 20-year old crater formed after one of the largest eruptions of the 20th century does not appear likely. Crater lakes and hot springs in craters of active volcanoes are usually fed by an ultra-acid mixture of magmatic fluid and meteoric water, where the acidity is provided by magmatic SO₂, HCl and HF. Some examples are the crater lakes of Ruapehu, New Zealand; Poás, Costa Rica, and Yugama, Japan and the hot acid springs in the crater of White Island, New Zealand (Hurst *et al.*, 1991; Christensen 2000; Rowe *et al.*, 1995; Ohba *et al.*, 1994; Giggensbach *et al.*, 2003). We propose the model of a “buried” lake – a local, boiling, shallow hydrothermal system with a very fast magmatic-to-hydrothermal transition due to intensive water-fresh rock interaction and a geometry responsible for the geyser-like discharge of the Soap Pool. If chlorine concentration over time in the Soap Pool is extrapolated to zero Cl

(Figure 2), this condition will occur in 2008±2. A future increase in Cl concentrations in the Soap Pool or lake water, above the values constrained by the Cl balance model, could indicate an impending reactivation of the volcano.

8. CONCLUSIONS

Water and chlorine balance of the lake in the crater of El Chichón volcano is controlled by precipitation, seepage, evaporation and the flow rate of Soap Pool – a boiling spring with variable discharge of near-neutral saline water feeding the lake. If the meteorological data of precipitation, wind speed and ambient temperature are known, the water balance of the lake and the flow rate of the only Cl source, the Soap Pool, can be estimated from the changes in the lake volume. The volume of the lake can be approximately estimated from digitized perspective photographs of the lake and the empirical relationship between average depth of the lake flat floor and its surface area. Therefore, taking photographs of the lake surface on a regular basis represents a useful tool for surveillance of the volcano. The trend in the Cl content of the Soap Pool spring over 8 years of observation could be explained if the only source of Cl for Soap Pool is the initial crater lake, which was deep and saline, but was subsequently buried by landslides and fluvial sediments.

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