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The Mayotte seismo-volcanic crisis of 2018-2021 in the Comoros archipelago (Mozambique channel) / *La crise sismo-volcanique de 2018-2021 de Mayotte dans l'archipel des Comores (Canal du Mozambique)*

Impact of the seismo-volcanic crisis offshore Mayotte on the Dziani Dzaha Lake

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Abstract. Since May 2018, an unexpected long and intense seismic crisis started offshore Mayotte (Indian Ocean, France). This ongoing seismic sequence is associated with the birth of a newly discovered submarine volcano 50 km east of Petite Terre. Here, we investigate the indirect impact of this crisis on the stability of an atypical ecosystem located in Mayotte, the Dziani Dzaha Lake. This lacustrine system presented physical, chemical and biogeochemical characteristics that were distinct from those classically observed in modern lakes or seawater, e.g. high salinity (up to 70 psu), lack of nitrate, sulfate content below 3 mM, and permanent water column anoxia below ca. 1.5 m depth (2012–2017 period). Based on three surveys conducted in 2020 and 2021, we documented an episode of water column oxygenation, a significant pH decrease and an impressive change in the carbon isotope signatures. These preliminary data suggest that the functioning of biogeochemical cycles in the Dziani Dzaha Lake is impacted by increased CO₂ inputs and the changes in the lake mixing dynamics, which is an indirect consequence of the ongoing seismo-volcanic crisis.

Keywords. Dziani Dzaha Lake, Mayotte, Seismo-volcanic crisis, Carbon isotopes, Nitrogen isotopes, Volcanic CO₂ degassing.

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1. Introduction

Mayotte Island is one of the four main volcanic islands of the Comoros Archipelago located in the

Indian Ocean. The earliest step of magmatic activity is around 11 Ma [Debeuf, 2004, Pelleter et al., 2014], and the last eruptive events are estimated to have occurred between 7 and 4 ka [Zinke et al., 2003]. Until the present seismo-volcanic crisis offshore Mayotte that started in May 2018, the volcanic islands of

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the Comoros Archipelago were known for their diffuse and moderate seismicity with few historically felt events. The ongoing seismic sequence is thus unexpected and remarkable with regard to its duration and intensity (i.e. earthquakes of magnitude 5.9 on 15 May 2018). After the first two months of intense seismicity at the beginning of the crisis, seismicity still persisted a long time with numerous small earthquakes [Bertil *et al.*, 2019], and ground deformation was observed [Lemoine *et al.*, 2020]. A new submarine volcano was discovered at 50 km east of Petite Terre [Feuillet *et al.*, 2019, 2021], and significant subsidence of Mayotte Island (up to 20 cm) was attributed to the drainage of a deep magma chamber near the coast [Foix *et al.*, 2021]. This long-term seismic sequence and the associated new active volcano offshore Mayotte led the scientific community to investigate further the seismo-volcanic hazard in this area [Feuillet *et al.*, 2019, Cesca *et al.*, 2020, Darnet *et al.*, 2020, Lemoine *et al.*, 2020, Berthod *et al.*, 2021, Foix *et al.*, 2021, Saurel *et al.*, 2022]. This seismo-volcanic crisis has been monitored since the beginning of May 2018; numerous studies were performed and many others are in progress to gain further information about the deep volcanic system, to better constrain the seismo-volcanic hazard for Mayotte and its population (e.g. seismicity, slope instability, tsunami, island subsidence or even new volcanic activity onshore).

On the Petite Terre Island in Mayotte, one of the latest eruptive events proposed at around 7 and 4 ky is probably at the origin of the Dziani Dzaha Lake formation [Zinke *et al.*, 2003]. For the last decade, this atypical lacustrine system has been extensively studied [Leboulanger *et al.*, 2017, Cellamare *et al.*, 2018, Gérard *et al.*, 2018, Milesi *et al.*, 2019, Aucher *et al.*, 2020, Jovovic *et al.*, 2020, Sala *et al.*, 2022]. Based on its water chemistry, the lake was most likely initially filled with seawater [Sarazin *et al.*, 2021], and has since evolved as a closed system. Before the seismo-volcanic crisis, the physical, chemical and biological features of this ecosystem were far from those observed in a modern oceanic or lacustrine environment (details in Study site section). The ongoing seismo-volcanic crisis offshore Mayotte could have a significant impact on the stability and the functioning of this ecosystem through the reactivation of fractures in the crater/basement, the infiltration of fresh/sea water and/or the increase in magmatic

bubbling and degassing through its waters [Liuzzo *et al.*, 2021].

In order to investigate the impact of the perturbations related to the growth of the submarine volcano offshore Mayotte on this lacustrine system, we conducted three field trips in 2020 and 2021 on the Dziani Dzaha Lake. We documented the evolution of the physical and chemical properties in the water column (e.g. $[O_2]$, pH, salinity, T), as well as the carbon and nitrogen isotopic signatures of dissolved inorganic carbon (DIC) and suspended particulate matter (SPM) within it (i.e. $\delta^{15}N_{SPM}$, $\delta^{13}C_{DIC}$, $\delta^{13}C_{SPM}$). The comparison of these results with those obtained before the seismo-volcanic crisis illustrates the response of this lacustrine system to this kind of geological perturbations.

2. Study site

The Dziani Dzaha Lake is a shallow maar lake located on the Petite Terre Island of Mayotte (Figure 1). This lake is small (i.e. $2.36 \times 10^5 \text{ m}^2$), close to sea level and separated from the nearby seashore by a 220-m-thick crater wall [Rouwet *et al.*, 2021]. The lake watershed is restricted to the volcanic crater (i.e. $\sim 1 \text{ km}$ in diameter and 50–100 m height). The average depth of the Dziani Dzaha Lake is about 3 m with a narrow depression reaching 18 m depth (Figure 1), likely related to the chimney of the phreatomagmatic eruption at the origin of this lake. Magmatic gases bubble through the water column in several locations [Milesi *et al.*, 2020, Liuzzo *et al.*, 2021] mostly in shallow areas of the lake, with one bubbling site in the central part for which a strong increase in the bubbling activity has been observed since 2020 compared to our last observations from 2012 to 2017 (Figure 1).

From 2010 to 2017, i.e. before the beginning of the seismo-volcanic crisis in May 2018, the lake water column showed an atypical combination of physical and chemical features for a modern lacustrine system [e.g. Sarazin *et al.*, 2021]. Salinity measured was between 35 and 70 psu (practical salinity unit), nearly twice the usual salinity of seawater. The alkalinity was also very high, with values ranging from ca. 0.1 to 0.2 M (nearly 100 times the alkalinity of seawater), and pH ranged between 9 and 9.5. The water column was periodically stratified with a sharp halocline at ca. 2 m depth about half of the year, driven by the salinity decrease in surface waters as a result

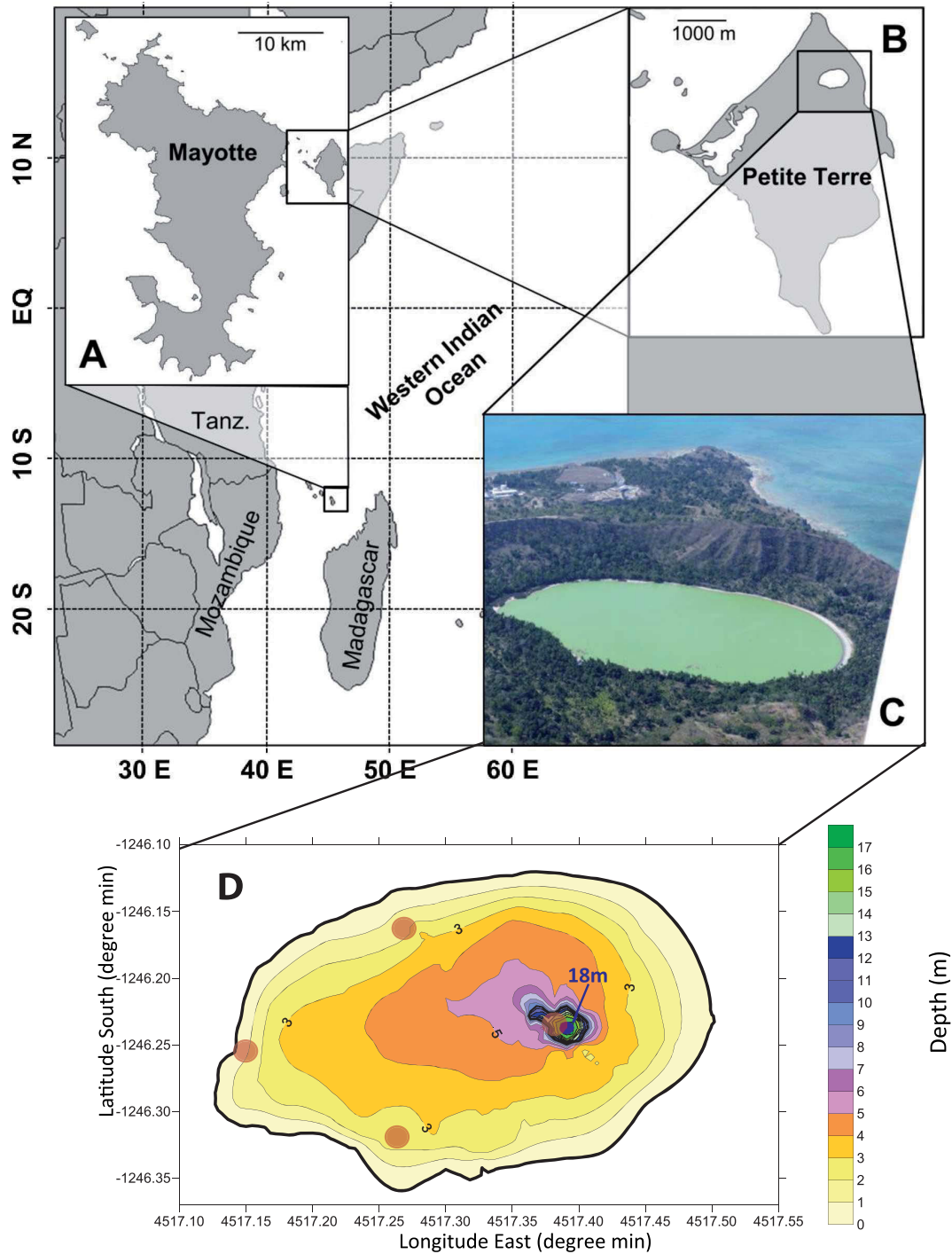


Figure 1. Location and bathymetric maps of the Dziani Dzaha Lake on Mayotte Islands (Indian Ocean). (A) Mayotte Islands in Western Indian Ocean, (B) Dziani Dzaha Lake in Petite Terre Island on Mayotte, (C) Picture of the lake taken in October 2014, and (D) Bathymetric map of the lake, with blue circle representing the water column sampling location and the red circles representing the identified bubbling areas at the water–air interface (modified from Le Boulanger *et al.* [2017] and Cadeau *et al.* [2022]).

of increasing precipitation during the rainy season. A permanent chemocline was also present at ca. 14 m depth in the narrow depression [Sarazin *et al.*, 2021]. Importantly, the lake was permanently anoxic below ca. 1.5 m depth despite seasonal variations in its water column structure, and was strongly euxinic (sulfides $\text{H}_2\text{S}/\text{HS}^-$ concentration ranging from 2 to 6 mM) below 2 m depth when the halocline is present (during the stratified period), or only below a 14 m depth when it is not [during the non-stratified period, Sarazin *et al.*, 2021]. Details on the evolution of the physical and chemical parameters according to stratification are available in previous works [e.g. Leboulanger *et al.*, 2017, Cadeau *et al.*, 2020, Sarazin *et al.*, 2021]. All our field trips done since the beginning of the crisis were conducted during non-stratified periods (i.e. from August to December). Before the crisis, these non-stratified periods were characterized by the absence of halocline (except at ca. 14 m depth). As a result, most physical, chemical and biological parameters were constant with depth down to the deep chemocline at 14 m depth, except for the dissolved oxygen that was only present down to a maximum of 1.5 m depth depending on the photosynthetic activity. The fact that O_2 saturation values fluctuate widely (from 0 to 350%) is related to large nycthemeral fluctuations in the balance between the activities of photosynthesis (which produces O_2) and respiration (which consumes it) in this biologically very active lacustrine system [e.g. Leboulanger *et al.*, 2017, Cadeau *et al.*, 2020]. The salinity was close to 60 psu, the alkalinity close to 0.14 M, the pH close to 9.2, the $[\text{SO}_4^{2-}]$ content close to 3 mM, $[\text{H}_2\text{S}]$ content close to 0.1 mM, and a relatively homogeneous diversity of cyanobacteria, bacteria, and archaea was observed along the water column [Hugoni *et al.*, 2018]. Below the 14 m deep chemocline, the salinity and alkalinity increased to 70 psu and 0.2 M, respectively, the pH decreased to a value close to 9, no SO_4^{2-} was observed while H_2S accumulated up to 6 mM. Our previous work has demonstrated that the characteristics of non-stratified seasons have remained stable since 2010 [e.g. Leboulanger *et al.*, 2017, Hugoni *et al.*, 2018, Bernard *et al.*, 2019, Sarazin *et al.*, 2021].

3. Materials and methods

The isotope signatures in this study were acquired on samples from surveys conducted in November 2020,

September 2021 and December 2021. A nomenclature consistent with previous publications was used to identify each sample taken during the different surveys. For example, for the sample “DZ21-9 2m,” “DZ” indicates the Dziani Dzaha Lake, “21-9” indicates the year (2021) and month (September) of the survey, “2m” refers to sampling depth of the water column station called “18m” as shown on Figure 1.

Water samples were collected using a horizontal 1.2 L Niskin bottle along a vertical profile at the 18 m depth station for each survey. For each sampling depth, samples were taken in 500 mL plastic bottles. Each sample was then filtered onto pre-combusted Whatman GF/F glass fiber filters (0.7 μm) and quartz Millipore AQFA (size cut-off ca. 3 μm) for $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PON}}$ analysis, and a 12 mL Labco Exetainer glass tube was filled with the filtrate and fixed with 0.2 mL of saturated HgCl_2 solution for DIC and $\delta^{13}\text{C}_{\text{DIC}}$ analyses. The GF/F filters with SPM were decarbonated by exposure to concentrated HCl fumes in a desiccator for 12 h to avoid loss of material.

3.1. Physical and chemical *in situ* measurements

In situ profiling were performed with a CTD multiparameter EXO2 probe (temperature, conductivity/salinity, pH, ORP, O_2 , turbidity, chlorophyll, phycocyanine (PC) and fDOM) and a turbidity AQUAlogger 210 TYPT Aquatec probe. The pH electrode was calibrated using pH 4.00, 7.01 and 10.00 NBS-NIST buffers; O_2 optode was calibrated at 100% saturation in wet air; salinity sensor was calibrated with a 34.271 psu seawater. Other sensors have not been calibrated and the corresponding parameters are used as relative values; nevertheless, most of these sensors offer quite stable response (especially T, turb., chl., PC, fDOM), at the exception of oxidation-reduction potential (ORP) electrode which can only be used as relative values. In addition, two O_2 NKE SDOT optodes were deployed at 0.25 m depth from 10/09 to 13/12 2021 near the central gas bubbling zone (at ca. 1–3 m from the outlet, respectively), and a water level probe (OTT Orpheus Mini) was installed in September 2021 in the NO part of the lake.

3.2. Carbon and nitrogen isotope measurements

DIC and $\delta^{13}\text{C}_{\text{DIC}}$ were measured using an AP2003 mass spectrometer. Phosphoric acid (100% H_3PO_4)

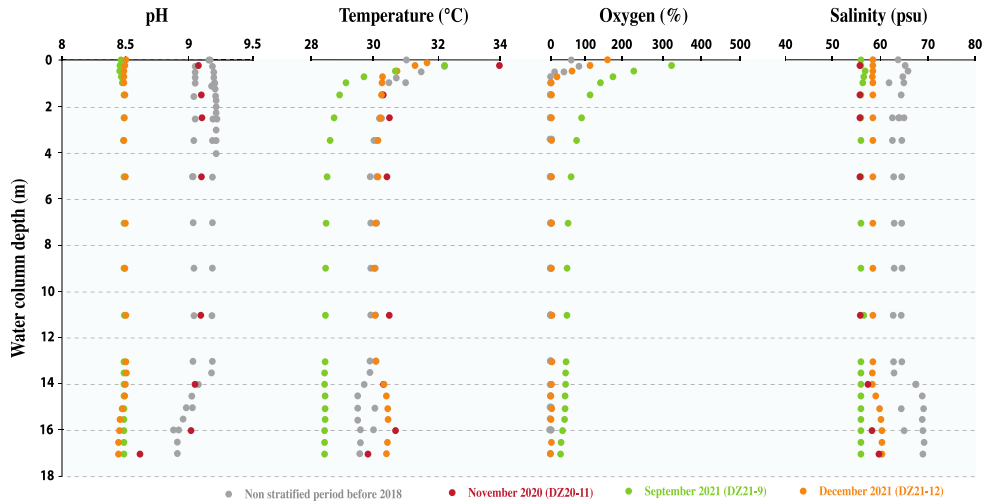


Figure 2. Vertical profiles of physical and chemical parameters recorded during each survey including salinity (psu), temperature (°C), pH and dissolved oxygen (%). The grey profiles correspond to previous data obtained before 2018 from Cadeau *et al.* [2022].

was injected into 12 mL Labco Exetainer tubes that were then flushed with helium. For each sample, 0.1 mL water was sub-sampled and transferred into the acidified Labco Exetainer tubes. The samples were agitated for 15–24 h so that CO_2 in the water was in equilibrium with the CO_2 in the headspace. The CO_2 in the headspace gas was then separated by gas chromatography with helium as a carrier gas and analyzed using the AP2003 mass spectrometer. Solutions presenting a range of DIC were prepared using sodium hydrogen carbonate for DIC calibration. Three internal carbonate standards with known isotopic compositions (Across, Merck and Rennes II) were used for isotopic composition calibration. The standard carbonate powder was loaded into 12 mL Labco Exetainer tubes with 0.1 mL distilled water before being flushed with helium and then analyzed in the same way as DIC. DIC values are expressed in $\text{mol}\cdot\text{L}^{-1}$ with a reproducibility of $\pm 0.01 \text{ mol}\cdot\text{L}^{-1}$, and $\delta^{13}\text{C}_{\text{DIC}}$ values are expressed in ‰ relative to Vienna Pee Dee Belemnite (VPDB) with a reproducibility of $\pm 0.1\text{‰}$ (1σ).

The $\delta^{13}\text{C}_{\text{POC}}$ and $\delta^{15}\text{N}_{\text{PON}}$ of the decarbonated filters were measured using a Flash EA1112 elemental analyzer coupled to a Thermo Finnigan Delta-plus XP mass spectrometer via a ConFlo IV interface (Thermo Fisher Scientific, Waltham, MA, USA). The decarbonated samples were loaded into tin capsules

and heated to 1200 °C in a combustion tube with a mixture of chromium oxide and silver cobalt oxides. The combustion gases were carried by helium through a reduction column and a gas chromatography column to separate CO_2 from N_2 and from the other gases. CO_2 and N_2 were successively injected into the mass spectrometer for isotopic analysis. For the isotope calibration, four internal standards of organic-rich soil or sediment were analyzed in the same way. $\delta^{13}\text{C}_{\text{POC}}$ values are expressed as ‰ relative to VPDB with a reproducibility of $\pm 0.2\text{‰}$ (1σ) and $\delta^{15}\text{N}_{\text{PON}}$ are expressed as ‰ relative to air with a reproducibility of $\pm 0.3\text{‰}$ (1σ).

4. Results

4.1. Physical and chemical features of the water column

In September 2020, salinity was constant down to 14 m depth with an average value close to 55.6 psu and increased below this depth up to 59.7 psu (Figure 2, Table 1). pH was constant down to 14 m depth with an average value of 9.1 and decreased below this depth down to 8.6. Temperature decreased in surface waters from 34 °C to 30.3 °C at 1.5 m depth, and remained constant with depth down to the lake bottom. In September 2021, salinity, pH and temperature significantly decreased in the water column.

Table 1. Salinity (psu), temperature (°C), pH and dissolved oxygen (%) measured in November 2020, September 2021 and December 2021 in the Dziani Dzaha Lake

Sample (name)	Depth (cm)	Temperature (°C)	pH	[O ₂] (%)	Salinity (psu)
DZ20-11	0.25	34	9.07		55.6
DZ20-11	1.5	30.3	9.09		55.6
DZ20-11	2.5	30.5	9.095		55.6
DZ20-11	5	30.4	9.093		55.6
DZ20-11	11	30.5	9.083		55.8
DZ20-11	14	30.3	9.038		57.3
DZ20-11	16	30.7	9.009	0.2	58.1
DZ20-11	17	29.8	8.610		59.7
DZ21-9	0.25	32.2	8.6	327	55.1
DZ21-9	0.50	30.4	8.6	212	55.8
DZ21-9	0.75	29.5	8.6	149	55.6
DZ21-9	1.01	29.1	8.6	128	55.3
DZ21-9	1.25	29.0	8.6	116	55.2
DZ21-9	1.50	28.9	8.6	100	55.2
DZ21-9	1.75	28.8	8.6	93	55.1
DZ21-9	2.01	28.8	8.6	91	55.1
DZ21-9	2.26	28.7	8.6	84	55.1
DZ21-9	2.51	28.7	8.6	80	55.1
DZ21-9	2.76	28.7	8.6	73	55.1
DZ21-9	3.01	28.6	8.6	70	55.1
DZ21-9	3.26	28.6	8.6	67	55.1
DZ21-9	3.51	28.6	8.6	65	55.1
DZ21-9	3.76	28.6	8.6	64	55.1
DZ21-9	4.00	28.6	8.5	61	55.1
DZ21-9	4.50	28.5	8.5	53	55.1
DZ21-9	5.00	28.5	8.5	51	55.1
DZ21-9	5.51	28.5	8.5	48	55.2
DZ21-9	6.61	28.5	8.5	47	55.2
DZ21-9	7.01	28.5	8.5	45	55.2
DZ21-9	7.47	28.5	8.5	43	55.2
DZ21-9	8.18	28.5	8.5	43	55.2
DZ21-9	8.50	28.5	8.5	43	55.2
DZ21-9	8.86	28.5	8.5	42	55.2
DZ21-9	9.58	28.5	8.5	42	55.2
DZ21-9	10.00	28.5	8.5	42	55.2
DZ21-9	11.04	28.5	8.5	41	55.2
DZ21-9	11.51	28.5	8.5	40	55.2
DZ21-9	12.01	28.5	8.5	39	55.2

(continued on next page)

Table 1. (continued)

Sample (name)	Depth (cm)	Temperature (°C)	pH	[O ₂] (%)	Salinity (psu)
DZ21-9	13.01	28.4	8.5	39	55.2
DZ21-9	13.51	28.4	8.5	37	55.2
DZ21-9	14.51	28.4	8.5	36	55.2
DZ21-9	15.00	28.4	8.5	35	55.2
DZ21-9	16.00	28.4	8.5	29	55.2
DZ21-9	17.01	28.4	8.5	23	55.2
DZ21-12	0.25	31.4	8.6	152	57.9
DZ21-12	0.50	30.4	8.6	58	58.2
DZ21-12	0.75	30.3	8.6	22	58.1
DZ21-12	1.00	30.3	8.5	7	58.1
DZ21-12	1.25	30.2	8.5	5	58.1
DZ21-12	1.50	30.2	8.5	4	58.1
DZ21-12	1.75	30.2	8.5	2	58.1
DZ21-12	2.00	30.2	8.5	2	58.1
DZ21-12	2.25	30.2	8.5	2	58.1
DZ21-12	2.50	30.2	8.5	2	58.1
DZ21-12	2.75	30.2	8.5	2	58.1
DZ21-12	3.00	30.2	8.5	1	58.1
DZ21-12	3.25	30.1	8.5	1	58.1
DZ21-12	3.50	30.1	8.5	1	58.1
DZ21-12	3.75	30.1	8.5	1	58.1
DZ21-12	4.01	30.1	8.5	1	58.1
DZ21-12	4.50	30.1	8.5	1	58.1
DZ21-12	4.99	30.1	8.5	1	58.1
DZ21-12	5.51	30.1	8.5	1	58.1
DZ21-12	6.00	30.1	8.5	1	58.1
DZ21-12	6.50	30.1	8.5	1	58.1
DZ21-12	7.01	30.1	8.5	1	58.1
DZ21-12	7.50	30.0	8.5	1	58.1
DZ21-12	8.01	30.0	8.5	1	58.1
DZ21-12	8.51	30.0	8.5	1	58.1
DZ21-12	9.00	30.0	8.5	1	58.0
DZ21-12	9.50	30.0	8.5	1	58.1
DZ21-12	10.00	30.0	8.5	1	58.1
DZ21-12	10.49	30.0	8.5	1	58.1
DZ21-12	11.01	30.0	8.5	1	58.1
DZ21-12	11.50	30.1	8.5	1	58.1
DZ21-12	12.01	30.1	8.5	0	58.1

(continued on next page)

Table 1. (continued)

Sample (name)	Depth (cm)	Temperature (°C)	pH	[O ₂] (%)	Salinity (psu)
DZ21-12	12.49	30.1	8.5	0	58.1
DZ21-12	13.01	30.1	8.5	0	58.1
DZ21-12	13.50	30.1	8.5	0	58.1
DZ21-12	14.01	30.3	8.5	0	58.2
DZ21-12	14.50	30.4	8.5	0	58.7
DZ21-12	15.02	30.4	8.4	0	59.5
DZ21-12	15.50	30.4	8.4	0	59.8
DZ21-12	16.00	30.5	8.4	0	60.0
DZ21-12	16.50	30.5	8.4	0	60.2
DZ21-12	17.00	30.4	8.4	0	60.2

Salinity and pH values were still constant with depth throughout the whole water column but with average values close to 55 psu and 8.5, respectively. Temperature decreased from 32 °C in surface water to 28.2 °C at about 2 m depth, and then remained constant with depth down to the lake bottom. Dissolved oxygen was present throughout the whole water column. Surface waters showed very high O₂ saturation values (i.e. up to 327%, Figure 2) that are related to the high photosynthetic activity similar to before the volcanic crisis. Surprisingly however, the deeper part of

