INSTITUT DE FRANCE
Académie des sciences

Comptes Rendus

Géoscience

Sciences de la Planète

Pierre Cadeau, Didier Jézéquel, Alexis Groleau, Andrea Di Muro and Magali Ader

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

Volume 354, Special Issue S2 (2022), p. 299-316

Published online: 9 December 2022
Issue date: 17 January 2023

https://doi.org/10.5802/crgeos.172

Part of Special Issue: The Mayotte seismo-volcanic crisis of 2018-2021 in the Comoros archipelago (Mozambique channel)

Guest editors: Jérôme Van der Woerd (Institut Terre Environnement de Strabourg, UMR 7063 CNRS / Université de Strasbourg, 67084 Strasbourg, France), Vincent Famin (Laboratoire Géosciences Réunion, Université de La Réunion - IPGP, 97744 Saint-Denis, France) and Eric Humler (Professeur Université de Nantes, Laboratoire de Planétologie et Géosciences, UMR 6112, Faculté des Sciences et Techniques, Nantes Université, 44322 Nante, France)

CENTRE MERSENNE

Les Comptes Rendus. Géoscience — Sciences de la Planète *sont membres du Centre Mersenne pour l'édition scientifique ouverte*
www.centre-mersenne.org
e-ISSN : 1778-7025

Comptes Rendus
Géoscience — Sciences de la Planète
2022, Vol. 354, Special Issue S2, p. 299-316
https://doi.org/10.5802/crgeos.172

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

Pierre Cadeau *, [a, b], **Didier Jézéquel** [b, c], **Alexis Groleau** [b], **Andrea Di Muro** [b, d] **and Magali Ader** [b]

[a] Sorbonne Université, CNRS, EPHE, PSL, UMR METIS, F-75005 Paris, France

[b] Université Paris Cité, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France

[c] UMR CARRTEL, INRAE & Université Savoie Mont Blanc, 74200 Thonon-les-Bains, France

[d] Observatoire Volcanologique du Piton de la Fournaise, Institut de physique du globe de Paris, 97418, La Plaine des Cafres, France

E-mails: pierre.cadeau@gmail.com (P. Cadeau), jezequel@ipgp.fr (D. Jézéquel), groleau@ipgp.fr (A. Groleau), dimuro@ipgp.fr (A. Di Muro), ader@ipgp.fr (M. Ader)

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 CO_2 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 CO_2 degassing.

Published online: 9 December 2022, Issue date: 17 January 2023

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

* Corresponding author.

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. 2.36×10^5 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. ~1 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

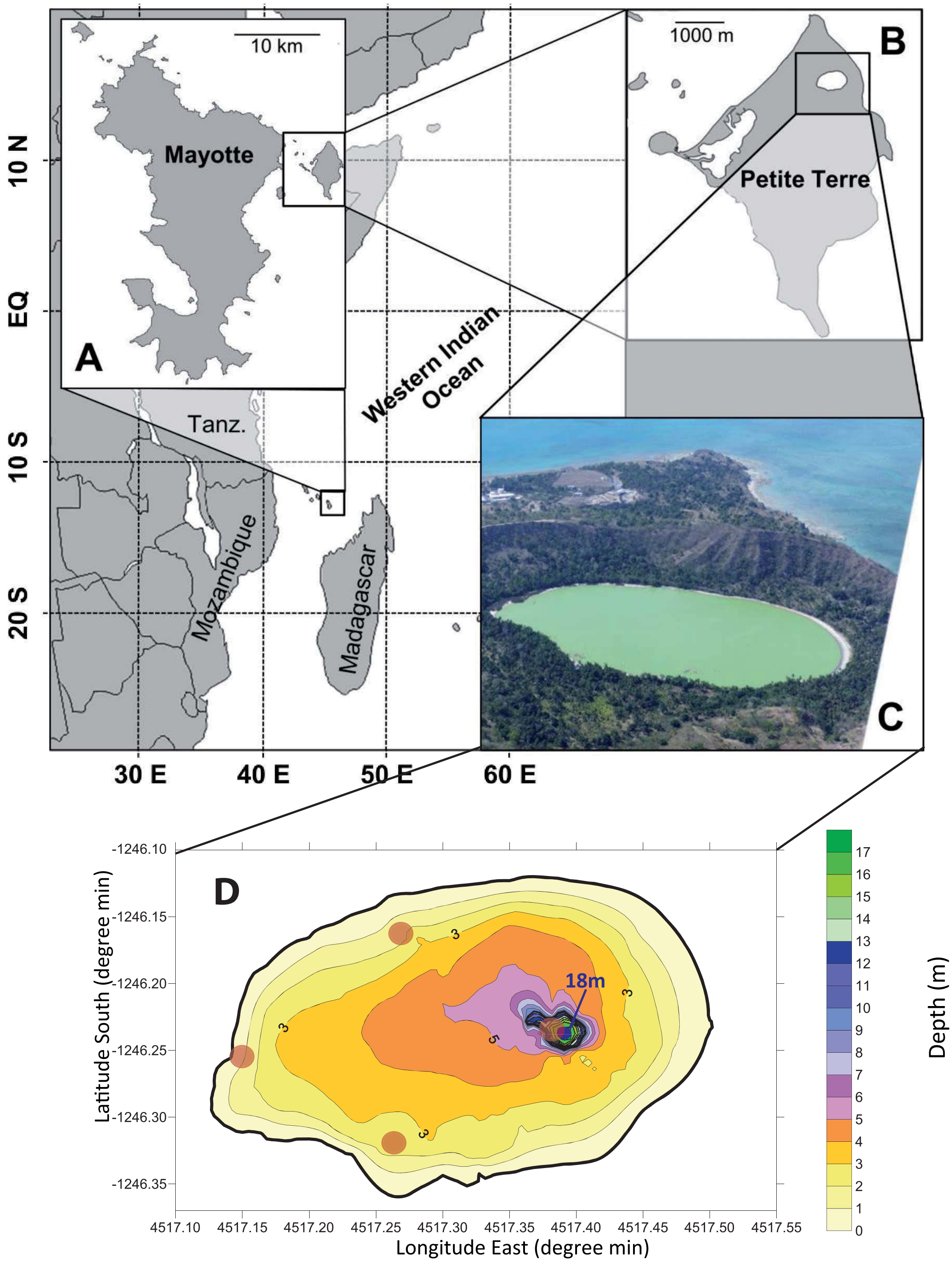

Figure 1. Location and bathymetric maps of the Dziani Dzaha Lake on Mayotte Islands (Indian Ocean). (A) Mayotte Islands in Western Indian Ocean, (B) Dziani Dzaha Lake in Petite Terre Island on Mayotte, (C) Picture of the lake taken in October 2014, and (D) Bathymetric map of the lake, with blue circle representing the water column sampling location and the red circles representing the identified bubbling areas at the water–air interface (modified from Leboulanger 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 H_2S/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 $[SO_4^{2-}]$ content close to 3 mM, $[H_2S]$ 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 precombusted Whatman GF/F glass fiber filters (0.7 μm) and quartz Millipore AQFA (size cut-off ca. 3 μm) for $\delta^{13}C_{POC}$ and $\delta^{15}N_{PON}$ 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 $\delta^{13}C_{DIC}$ 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 $\delta^{13}C_{DIC}$ were measured using an AP2003 mass spectrometer. Phosphoric acid (100% H_3PO_4)

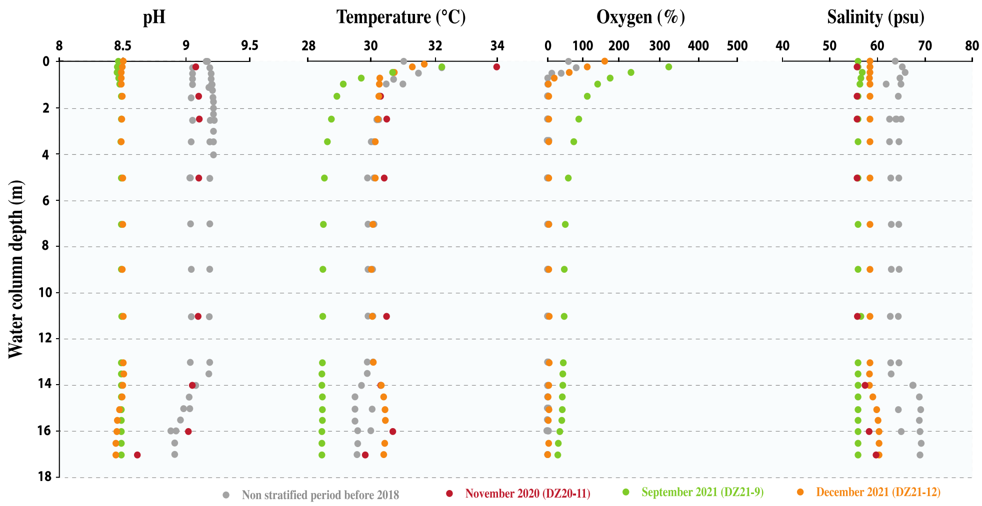

Figure 2. Vertical profiles of physical and chemical parameters recorded during each survey including salinity (psu), temperature (°C), pH and dissolved oxygen (%). The grey profiles correspond to previous data obtained before 2018 from Cadeau et al. [2022].

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 $mol \cdot L^{-1}$ with a reproducibility of ± 0.01 $mol \cdot L^{-1}$, and $\delta^{13}C_{DIC}$ values are expressed in ‰ relative to Vienna Pee Dee Belemnite (VPDB) with a reproducibility of ± 0.1‰ (1σ).

The $\delta^{13}C_{POC}$ and $\delta^{15}N_{PON}$ of the decarbonated filters were measured using a Flash EA1112 elemental analyzer coupled to a Thermo Finnigan Deltaplus 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. $\delta^{13}C_{POC}$ values are expressed as ‰ relative to VPDB with a reproducibility of ± 0.2‰ (1σ) and $\delta^{15}N^{PON}$ are expressed as ‰ relative to air with a reproducibility of ± 0.3‰ (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 O_2 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 the lake, which was anoxic all year long before the crisis was oxygenated at 20% of O_2 saturation. In December 2021, the temperature decreased from about 32 °C in surface waters to 30 °C at about 2 m depth. Temperature then remained constant down to 14 m and increased to values close to 30.5 °C below 14 m depth. Salinity was constant down to 14 m depth with an average value close to 58 psu and increased below this depth up to 60.2 psu. pH was constant with depth throughout the water column with an average value close to 8.5. Dissolved oxygen was only present in surface water down to 0.8 m; below this depth the water column remained completely anoxic.

Physical and chemical features of the water column in September 2020 were similar to those observed during the surveys conducted before the seismo-volcanic crisis offshore Mayotte (Figure 2), except for the salinity which was already lower than those observed previously. In contrast, salinity and pH values were significantly lower in September 2021 compared to the pre-seismo-volcanic crisis values observed, whereas dissolved oxygen was distributed in the water column, which had never been observed before. In December 2021 the pH still remained as low as in September 2021, the salinity increased by 2.8 psu compared to September 2021 (up to about 5 psu in the deeper part of the lake), and the water column was anoxic again below 1.5 m depth. In addition, based on O_2 optode placed in the central part of the lake, monitoring of dissolved oxygen content indicates that oxygenation of the entire water column lasted for several months between September and December 2021 (Figure 3).

4.2. *Carbon and nitrogen isotopic signature in the water column*

In the Dziani Dzaha Lake water column, the DIC concentrations ranged from 0.15 to 0.21 M with an average value of 0.19 ± 0.02 M in November 2020, from 0.16 to 0.22 M with an average value of 0.20 ± 0.02 M in September 2021, and from 0.17 to 0.23 M with an average value of 0.21 ± 0.02 M in December 2021 (Figure 4, Table 2). An increasing trend with depth was observed below the deep chemocline at 14 m depths in November 2020 from 0.15 to 0.21 M. In September and December 2021, the DIC concentrations decreased between 6 and 12 m depths. Overall, these concentration data show some variability but remain around an average value close to 0.2 M throughout the water column, which is similar to the DIC concentrations observed before the seismo-volcanic crisis (Figure 4).

The DIC isotopic compositions ($\delta^{13}C_{DIC}$) ranged between 12.2 and 13.0‰ with an average value of

Table 2. [DIC], $\delta^{13}C_{DIC}$, $\delta^{13}C_{POC}$ and $\delta^{15}N_{PON}$ measured in November 2020, September 2021 and December 2021 in the Dziani Dzaha Lake

Sample (name)	Depth (cm)	[DIC] (M)	$\delta^{13}C_{DIC}$ (±0.2‰)	$\delta^{13}C_{POC}$ (±0.2‰)	$\delta^{15}N_{PON}$ (±0.2‰)
DZ20-11	0.25	0.17	12.36	−14.01	7.86
DZ20-11	0.25	0.18	13.01	−14.13	8.10
DZ20-11	1.5	0.20	12.41	−14.01	8.14
DZ20-11	2.5	0.19	12.66	−13.78	8.14
DZ20-11	3.5	0.21	12.59	−13.95	8.17
DZ20-11	5	0.18	12.73	−13.82	7.83
DZ20-11	11	0.19	12.55	−13.55	7.92
DZ20-11	14	0.15	12.19	−13.04	8.68
DZ20-11	16	0.18	12.51	−12.24	9.03
DZ20-11	17	0.21	12.94	−9.99	10.70
DZ20-11	17	—	—	−10.33	10.46
DZ21-9	0.25	0.21	9.93	−18.74	7.71
DZ21-9	0.75	0.21	9.73	−18.68	7.78
DZ21-9	1.5	0.19	9.94	−18.77	7.73
DZ21-9	1.5	0.22	9.63	—	—
DZ21-9	2	0.20	9.88	−18.57	7.63
DZ21-9	2.5	0.21	9.77	−18.68	7.72
DZ21-9	5	0.20	9.78	−18.63	7.80
DZ21-9	7	0.16	9.93	−18.38	7.54
DZ21-9	11	0.21	9.89	−18.40	7.65
DZ21-9	14	0.21	9.85	−18.37	7.83
DZ21-9	16	0.21	9.92	−18.55	7.36
DZ21-9	17	0.21	9.78	−18.01	7.43
DZ21-12	0.25	0.18	9.78	−18.07	7.55
DZ21-12	0.75	0.21	9.51	−17.89	8.01
DZ21-12	1.5	—	—	−17.96	8.02
DZ21-12	2.5	0.23	9.43	−17.91	7.83
DZ21-12	5	0.21	9.56	−17.91	7.94
DZ21-12	7	0.19	9.66	−17.92	7.99
DZ21-12	11	0.17	9.73	−17.85	7.97
DZ21-12	13	0.23	9.51	−17.79	8.06
DZ21-12	14	0.22	9.44	−17.90	8.01
DZ21-12	15	0.22	9.57	−17.79	8.35
DZ21-12	16	0.22	9.50	−17.86	7.90
DZ21-12	17	0.21	9.32	−17.50	8.24
DZ21-12	17	0.21	9.46	−16.93	8.42

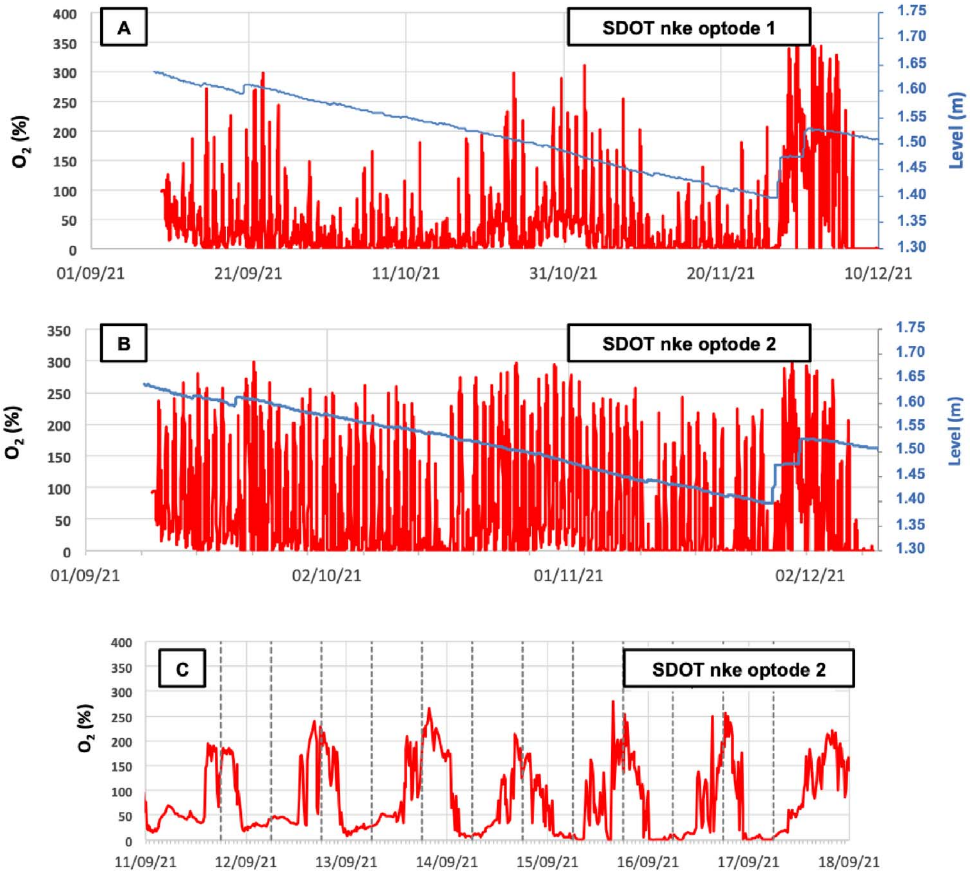

Figure 3. Evolution of dissolved oxygen content at 25 cm depth at station 18 m (in red) and relative water column level (in blue) from September to December 2021 ((A, B) two NKE SDOT optodes, (C) zoom on several nycthemeral cycles from the NKE SDOT optode 2).

12.6±0.2‰ in November 2020, between 9.6 and 9.9‰ with an average value of 9.8 ± 0.1‰ in September 2021, and between 9.3 and 9.8‰ with an average value of 9.5 ± 0.1‰ in December 2021 (Figure 4). The $\delta^{13}C_{DIC}$ was constant with depth during these three surveys. The $\delta^{13}C_{DIC}$ observed in November 2020 was similar to the $\delta^{13}C_{DIC}$ measured before 2018 (i.e. average value of 12.1‰, Figure 4), while the isotopic signatures observed in September and December 2021 were depleted in ^{13}C by almost 3‰ compared to the $\delta^{13}C_{DIC}$ measured before 2018.

The particulate organic carbon (POC) isotopic signatures ($\delta^{13}C_{POC}$) ranged from −14.1 to −10‰ with an average value of −13 ± 1.5‰ in November 2020, from −18.8 to −18‰ with an average value of −18.5 ± 0.2‰ in September 2021, and from −18 to −16.9‰ with an average value of −17.8 ± 0.3‰ in December 2021 (Figure 4). In November 2020, the $\delta^{13}C_{POC}$ was constant with depth from the surface water to the deep chemocline at 14 m depth with an isotopic signature close to −14‰, and significantly increased below it to −10‰. These isotopic signatures and this isotopic pattern with depth are similar to the $\delta^{13}C_{POC}$ observed before 2018 (i.e. average value of −14‰, Figure 4). In contrast, the $\delta^{13}C_{POC}$ in September and December 2021 were constant with depth throughout the whole water column and strongly depleted in ^{13}C compared to the $\delta^{13}C_{POC}$ observed before 2018.

The particulate organic nitrogen (PON) isotopic signatures ($\delta^{15}N_{PON}$) ranged from 7.8 to 10.7‰ with an average value of 8.6 ± 1‰ in November 2020, from 7.4 to 7.8‰ with an average value of 7.7 ± 0.1‰ in

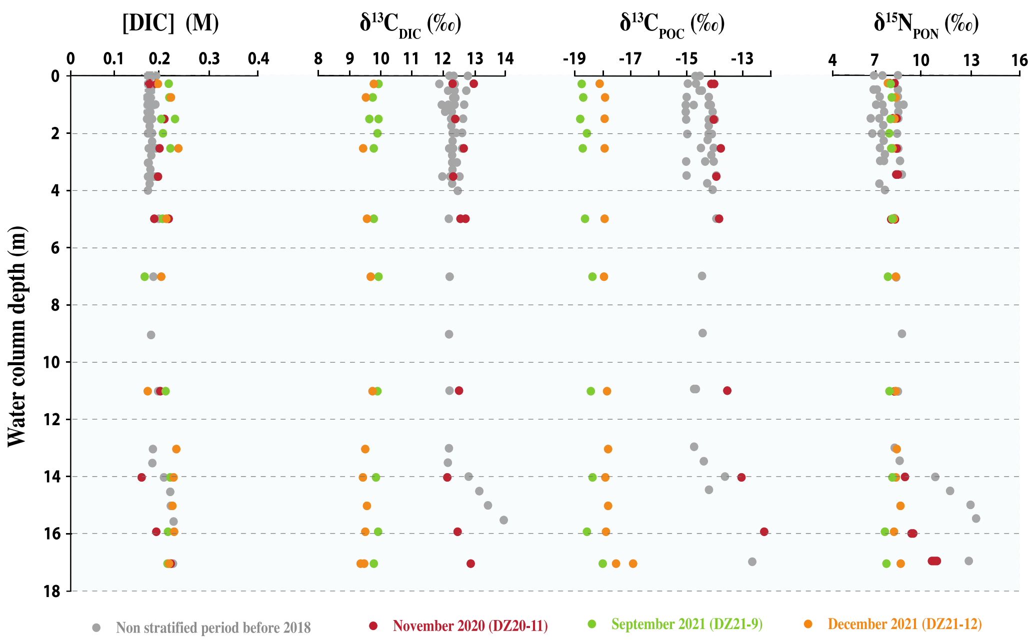

Figure 4. Vertical profiles of [DIC], $\delta^{13}C_{DIC}$, $\delta^{13}C_{POC}$ and $\delta^{15}N_{PON}$ in the Dziani Dzaha Lake water column. The grey profiles correspond to previous data obtained before 2018 from Cadeau [2017] and Cadeau et al. [2020, 2021, 2022].

September 2021, and from 7.5 to 8.4‰ with an average value of 8 ± 0.2‰ in December 2021 (Figure 4). Overall, during these three surveys the $\delta^{15}N_{PON}$ values were close to 8‰ and constant with depth throughout the water column, except in November 2020 when a significant isotopic enrichment was observed below 14 m depth, up to a value of 10.7‰. This isotopic enrichment is similar to the isotopic enrichments observed before 2018 ($\delta^{15}N_{PON}$ values up to 13‰), and contrasts with the constant isotopic values observed in September and December 2021 (Figure 4).

5. Discussion

5.1. *Physical and chemical features in the water column*

The evolution of the physical and chemical parameters observed in the Dziani Dzaha Lake water column during the surveys conducted after the beginning of the seismo-volcanic crisis illustrates significant modifications of the water column characteristics. Indeed, before 2018, one of the main features of this lacustrine system was its great stability (since it was first studied in 2010), with a permanent anoxia of the water column below ca. 1.5 m depth [sometimes shallower depending on photosynthetic activity in surface water, e.g. Sarazin et al., 2021]. The oxygenation of the whole water column, as well as a significant decrease in salinity and pH values, had never been observed. These represent major perturbations of this lacustrine system. Two distinct processes related to the seismo-volcanic crisis may be invoked to explain these observations: (i) an impact of seawater or freshwater infiltration into the lake in response to the subsidence, and (ii) an intensification of volcanic degassing into the lake (with physical, chemical and biological impacts).

Water chemistry of the Dziani Dzaha Lake and the ocean are very different. A contribution of an oxygenated, more neutral and less salty water from the ocean (or from groundwater) into the lake could have a consistent impact with what is observed in the Dziani Dzaha Lake water column in September 2021. However, firstly, after infiltration into bedrock, ocean or groundwater is unlikely to remain well-oxygenated. Moreover, given the very high organic matter content in the water column [Leboulanger et al., 2017, Cadeau et al., 2020], an oxygen supply from episodic water inputs into the lake would probably be quickly consumed through oxygenic organic matter degradation. Secondly, to significantly change the chemistry of the whole water column in the Dziani Dzaha Lake, water inputs would have to be significant, which seems unrealistic. Considering seawater and freshwater inputs with a salinity of 35 psu and 0 psu ($\text{Salinity}_{\text{input}}$ in (1)), respectively, and a lake salinity before the seismo-volcanic crisis near 63.5 psu ($\text{Salinity}_{\text{pre-2020}}$ in (1)), the impact of water input on salinity can be tested using mass balance equations as follows:

$$V_{\text{post-2020}} \times \text{Salinity}_{\text{post-2020}} = V_{\text{input}} \times \text{Salinity}_{\text{input}} + V_{\text{pre-2020}} \times \text{Salinity}_{\text{pre-2020}}. \quad (1)$$

For instance, based on water volume calculations [e.g. Cadeau et al., 2022], an increase of the water level of about 20 cm (corresponding to the subsidence of Mayotte Island) would represent a water input of about 7.2% of the total water volume (V_{input} in (1)). From this, the calculated salinities considering seawater or freshwater inputs are close to 61.4 psu or 58.9 psu, respectively. In September 2021, salinity was close to 55 psu. According to the mass balance equation, to obtain a calculated salinity of 55 psu it would be necessary to consider a freshwater input representing 12.7% of the total water volume. In addition, the origin of potential freshwater inputs is difficult to constrain, because it could also be related to an increase of precipitation water inputs as observed in surface waters during the period when the lake is stratified [e.g. Sarazin et al., 2021]. Although oceanic or freshwater inputs cannot be dismissed, it seems unrealistic to assume that this process alone could be responsible for all the modifications observed in the physical and chemical features in 2020 and 2021, but could at least in part explain the salinity decrease.

Before the beginning of the seismo-volcanic crisis offshore Mayotte, several bubbling areas were identified at the water–air interface of the Dziani Dzaha Lake. The volcanic origin of these degassing into the atmosphere was confirmed by the CO_2 carbon isotopic composition, which was typically of magmatic origin [around −3‰, Milesi et al., 2020, Liuzzo et al., 2021]. Yet, since a large part of these degassing was ebullitive, the contribution of this carbon source to the lake water column was difficult to estimate [Cadeau et al., 2020]. In addition, degassing areas were mainly located in the shallow parts of the lake (<2 m depth, Figure 1), with only one weakly bubbling area in the central part of the lake. An intensification of volcanic degassing through the Dziani Dzaha Lake water column related to the seismicity associated with the submarine volcano growth offshore Mayotte could impact both the oxygenation state and the pH of the water column. Indeed, an intense and permanent degassing in the central part of this lacustrine system, as observed during the surveys conducted in 2020 and 2021, could generate a convective plume that would significantly increase the mixing of the water column, favoring oxygenation events throughout the water column. Based on $[O_2]$ data from two O_2 NKE SDOT optodes deployed at 0.25 m depth between September 10th and December 10th 2021 near the central plume, long-term water column oxygenation is highlighted (Figure 3). From 10th September to 7th December, day–night cycles of oxygenation are observed, which reflect the relative variations of photosynthesis and respiration activity in this highly productive lacustrine system [e.g. Leboulanger et al., 2017]. As the optodes are under the central plume influence, water comes from the bottom part of the lake (ca. 5 m depth at this point), which suggests the presence of dissolved oxygen at depth at least part of the day (O_2 decreases according to the respiration activity at night). Since magmatic gases do not contain O_2, the only explanation for the presence of O_2 in the deeper part of the lake (at least at 5 m depth) would be a more active water column mixing (i.e. which was never observed before 2018) introducing O_2 from the surface waters to the deep waters. This increase of the mixing dynamics probably results from the water uplift induced by the more active central degassing in the absence of strong salinity gradient. After December 7th, these day–night cycles of oxygenation stopped, indicating a reduction of the water column mixing dynamics. We assume here that the water uplift due to the central degassing zone was not strong enough to fight the onset of the water column stratification. This is consistent with an increase in precipitation water inputs in late November and early December leading to a rise of the lake level (Figure 3), and the beginning of haline stratification. In addition to the water column mixing, this intense and long-term central plume could also increase the dissolution of volcanic CO_2 in the lake waters, decreasing the pH. Although this process might explain both the dissolved oxygen content increase (i.e. physical mixing of the water column) and the pH decrease (i.e. dissolution of CO_2), the volcanic CO_2 contribution to the dissolved inorganic pool in the lake is difficult to constrain and it seems unrealistic to propose that the significant pH decrease is entirely related to it. In addition, pH value represents the balance of many processes, such as photosynthesis/respiration or sulfate reduction, which may also have changed.

Based on the three surveys conducted in 2020 and 2021, physical and chemical properties in the Dziani Dzaha Lake water column have already been impacted by the seismo-volcanic crisis offshore Mayotte. It is probably related to a combination of a dilution by precipitation water (explaining the salinity decrease), an infiltration of low salinity groundwater and an intensification of volcanic degassing (explaining both the oxygenation of the whole water column, through a mixing process, and at least a part of the pH decrease). These results provide a first assessment of the extent to which the Dziani Dzaha Lake functioning is impacted by the consequence of the birth of this submarine volcano.

5.2. *The Carbon biogeochemical cycle*

Since the beginning of the seismo-volcanic crisis offshore Mayotte, the three surveys conducted in the Dziani Dzaha Lake indicate: (i) similar but more variable DIC concentrations, and (ii) a significant depletion in ^{13}C since 2021 of about 3‰ (Figure 4). These results could be explained by (i) an input of a carbon source isotopically lighter than the DIC pool, or (ii) a modification in the respective influence of the processes that regulate the carbon cycle in the Dziani Dzaha Lake.

Two main parameters related to the seismo-volcanic crisis offshore Mayotte need to be considered to discuss the potential impact of an isotopically lighter carbon source in the lake: the subsidence of Mayotte and the seismicity affecting these islands for 4 years now. This combination of parameters might favor both water input through the bedrock and an increase of volcanic CO_2 input in the lake. Based on the chemical and physical parameters (e.g. salinity, pH, $[O_2]$), no seawater input has been identified since the study of the Dziani Dzaha Lake in 2010 and until 2018. In contrast, volcanic CO_2 inputs have already been highlighted by previous studies [Cadeau et al., 2020, Milesi et al., 2020], mostly thanks to the observation of several bubbling areas at the water/air interface. The contribution of volcanic CO_2 to the Dziani Dzaha Lake carbon cycle was difficult to constrain, and CO_2 dissolution in the water could be limited by a mainly ebullitive degassing through the water column. In addition, since 2018 the activity of the degassing area located in the central part of the lake has strongly increased, which must have increased water column mixing and CO_2 dissolution. These carbon sources present a significantly lighter $\delta^{13}C$ value compared to the $\delta^{13}C_{DIC}$ values in the Dziani Dzaha Lake, i.e. close to 0‰ and −3‰ for seawater DIC and volcanic CO_2, respectively [Cadeau et al., 2020]. Considering the strong modifications of the physico-chemical parameters observed in the lake since 2018 (e.g. $[O_2]$, pH, Figure 2), both water inputs and increased CO_2 inputs through old fractures in the volcanic basement are strongly suspected. However, considering the very high DIC concentrations in the lake (i.e. about 100 times seawater concentrations), it is unlikely that these two sources alone are responsible for the ^{13}C depletion observed in September and December 2021. The impact of these sources can be tested using isotopic and mass balance equation as follows:

$$X_{\text{post-2020}} \times \delta^{13}C_{\text{DIC-post-2020}} = X_{\text{input}} \times \delta^{13}C_{\text{DIC-input}} + X_{\text{pre-2020}} \times \delta^{13}C_{\text{DIC-pre-2020}}. \tag{2}$$

With X representing the amount of DIC considering the concentrations and water volumes, and $\delta^{13}C$ the calculated or measured carbon isotopic compositions of DIC. Based on the (2), considering the concentrations and isotopic signatures of the lake and ocean DIC (i.e. 200 mM and 12‰ for the lake, and 2 mM and 0‰ for the ocean), an input of seawater equivalent to 7.2% of the lake volume as mentioned previously would modify the lake $\delta^{13}C_{DIC}$ by less than 0.1‰. The effect of an increase of volcanic CO_2 dissolution with a $\delta^{13}C$ of −3‰ would have a similar impact.

As mentioned previously, water input or most likely an intensification of CO_2 volcanic input through the central plume have the ability to strongly and quickly impact the oxygenation state of the water column, which is a key parameter in the regulation of the carbon cycle by exercising a strong control on the organic matter degradation pathways.

Previous studies have shown that the strongly positive $\delta^{13}C_{DIC}$ in the Dziani Dzaha Lake was the consequence of organic matter degradation by methanogenesis associated with methane degassing into the atmosphere, which results from the complete sulfate consumption in an anoxic water column [Cadeau et al., 2020, 2022]. In contrast to other lacustrine systems in which methanogenesis has been suggested to explain ^{13}C enrichment observed in the sediment record or in the water column [Talbot and Kelts, 1986, Valero-Garcés et al., 1999, Gu et al., 2004, Anoop et al., 2013, Zhu et al., 2013, Birgel et al., 2015], the Dziani Dzaha Lake exhibits similar carbon isotope signatures in the lake waters and in the sediment, as well as a long-term steady state [Cadeau et al., 2020]. Oxygenation of the water column necessarily modified the carbon cycle functioning by limiting the methanogenesis activity in favor of an aerobic degradation of the organic matter, and by fostering methane oxidation in the water column, hence limiting methane degassing into the atmosphere. Using the isotopic and mass balance equation described below, the impact of methane oxidation in the water column can be tested with the following equation:

$$\delta^{13}C_{\text{DIC-post-2020}} = X_{\text{CH}_4\text{-pre-2020}} \times \delta^{13}C_{\text{CH}_4\text{-pre-2020}} + X_{\text{DIC-pre-2020}} \times \delta^{13}C_{\text{DIC-pre-2020}}. \quad (3)$$

With X representing the amount of DIC or CH_4 considering the concentrations and water volumes, and $\delta^{13}C$ the calculated or measured carbon isotopic compositions of DIC or CH_4. Based on the (3) and considering a methane concentration close to 2 mM (i.e. hundred times lower than DIC which is of 200 mM) and its isotopic signature close to −65‰, as observed in the water column before 2018 [e.g. Cadeau et al., 2020, Sarazin et al., 2021], methane oxidation would decrease the $\delta^{13}C_{DIC}$ by only 0.8‰. This illustrates that punctual and complete methane oxidation in the water column (i.e. simulating an extreme oxygenation episode) would have a limited impact on $\delta^{13}C_{DIC}$.

Although such punctual perturbation has a limited impact on the $\delta^{13}C_{DIC}$, a modification of the Dziani Dzaha Lake steady state related to seismo-volcanic crisis perturbations could easily explain the $\delta^{13}C_{DIC}$ decrease. Based on the steady state box model proposed in Cadeau et al. [2020], a decrease in methane degassing into the atmosphere of about 10% of methane generated, a decrease of about 10% of the amount of organic matter degradation through methanogenesis, or a combination of both, would be sufficient to explain 3‰ decrease in $\delta^{13}C_{DIC}$ as observed in September and December 2021. The $\delta^{13}C_{DIC}$ significantly depleted in ^{13}C is thus most probably the consequence of the limitation in both organic matter degradation by methanogenesis and methane degassing to the atmosphere related to the oxygenation of the water column.

Based on the three surveys conducted in 2020 and 2021, the carbon cycle in the Dziani Dzaha Lake seems to be significantly impacted by the seismo-volcanic crisis offshore Mayotte most likely because of the intensification of volcanic CO_2 degassing into the lake, resulting in water column oxygenation and modifications of the organic matter degradation pathways within it. Future work is needed to determine the spatial extent and the persistence of these processes, as well as determine whether the carbon cycle is temporarily or permanently modified.

5.3. *The nitrogen biogeochemical cycle*

The particulate organic nitrogen isotope signatures ($\delta^{15}N_{PON}$) observed since 2018 are very similar to those observed before the beginning of the seismo-volcanic crisis offshore Mayotte, i.e. close to 8‰ and constant with depth (Figure 4). The only difference is the absence of significant isotopic increase below 14 m depth for the samples collected in September and December 2021.

In a previous study, we have suggested that the isotopic enrichment observed in the $\delta^{15}N_{PON}$ evolution in the deeper part of the water column or in the surface sediments results from a ^{15}N-enriched ammonium (NH_4^+) assimilation, which itself results from NH_4^+ dissociation to ammonia (NH_3) associated with a strong isotopic fractionation under basic and anoxic conditions [Cadeau et al., 2021]. As also shown for other modern basic lacustrine environments [Menzel et al., 2013] and sedimentary records of past lacustrine environments [Stüeken et al., 2020, 2019, 2015], pH and oxygenation state are thus major parameters in the regulation of the nitrogen cycle in the Dziani Dzaha Lake.

The oxygenation state of the water column controls the speciation of dissolved nitrogen into ammonium *versus* nitrate. Water column oxygenation, as observed in September 2021, should prevent any NH_4^+ accumulation by inducing its oxidation. In addition, even when the water column remains anoxic as observed in December 2021, the significant decrease in pH can be predicted to limit the dissociation of NH_4^+ into NH_3. Based on the average pH value of 8.5 and on the isotopic fractionation associated with the NH_4^+/NH_3 dissociation reaction [Li et al., 2012], only about 15% of the NH_4^+ dissociates into NH_3, resulting in an isotopic enrichment of the residual NH_4^+ of only about 7‰. These predicted amounts of dissociated NH_4^+ and isotopic enrichment of residual NH_4^+ are significantly lower than those estimated before the seismo-volcanic crisis event [i.e. about 45–72% of NH_4^+ dissociated with an isotopic enrichment of residual NH_4^+ comprised between 20 and 32‰, Cadeau et al., 2021]. The perturbations related to the seismo-volcanic crisis 2018 should therefore have had a significant impact on the $\delta^{15}N_{PON}$ in the Dziani Dzaha Lake.

Surprisingly however, nitrogen isotope signatures are quite similar to those observed before the beginning of the ongoing crisis. The only difference is that in September and December 2021, $\delta^{15}N_{PON}$ values are constant over the whole water column, including the deeper part of the water column, while up until 2020 a marked isotopic increase was observed in the deep part of the water column. These constant nitrogen isotopic signatures observed in September and December 2021 are probably related to the assimilation of NH_4^+ only slightly enriched in ^{15}N as a consequence of a less basic condition in the deeper and NH_4^+-rich part of the water column. We predict that this minor change in the $\delta^{15}N_{PON}$ pattern represents the premise of bigger changes, should the lower pH and the periods of oxygenation persist or aggravate in the future.

6. Conclusion

Since the beginning of the lake study in 2010 and until the beginning of the seismo-volcanic crisis in 2018, the Dziani Dzaha Lake presented an atypical combination of physical, chemical and biological features, as well as a high stability. Among them, the permanent anoxia of the water column and the pH exerted a strong control on the carbon and nitrogen cycles through: (i) an organic matter degradation by methanogenesis coupled to methane degassing into the atmosphere following the quantitative sulfate consumption in the water column, and (ii) a ^{15}N-enriched NH_4^+ assimilation in the deeper part of the lake related to the dissociation of NH_4^+ to NH_3 under basic conditions. Three years after the onset of the seismo-volcanic crisis, the submarine volcano growth and its associated perturbations are already having an impact on the biogeochemical functioning of the lake. Through water infiltration into the lake or/and an increase of volcanic CO_2 degassing into the lake, the water column oxygenation and the strong decrease of the pH value have: (i) modified the organic matter degradation pathways by limiting both the methanogenesis activity and methane degassing into the atmosphere, which is illustrated by a significant decrease in the $\delta^{13}C_{DIC}$, and (ii) limited the NH_4^+ dissociation into NH_3 and the isotopic enrichment of the residual NH_4^+, which is illustrated by the absence of $\delta^{15}N$ increase with depth. These results constitute a first assessment of the present-day impact of the seismo-volcanic crisis on the lake. Although the perturbations affecting the Dziani Dzaha Lake are difficult to constrain now, studying this lacustrine system is an exciting opportunity to explore the resilience of these ecosystems to such geological disturbances.

Data availability

All the data generated and analyzed in this study are available in the paper.

Conflicts of interest

The authors declare no competing financial interests.

Author contributions

MA designed the study. MA, DJ and AD collected the samples. DJ and AG measured the physical and chemical parameters on the Dziani Dzaha Lake. PC performed the isotopic analyses and took the lead in the interpretation and writing the original draft. All authors provided critical feedback in shaping both the research results and the manuscript.

Acknowledgements

Research was supported by the Réseau de Surveillance Volcanologique et Sismologique de Mayotte (REVOSIMA), a partnership between the Institut de Physique du Globe de Paris (IPGP), the Bureau de Recherches Géologiques et Minières (BRGM), and the Observatoire Volcanologique du Piton de la Fournaise (OVPF-IPGP), the Centre National de la Recherche Scientifique (CNRS), and the Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors also wish to thank the Conservatoire du littoral for their support.

References

Anoop, A., Prasad, S., Plessen, B., Basavaiah, N., Gaye, B., Naumann, R., Menzel, P., Weise, S., and Brauer, A. (2013). Palaeoenvironmental implications of evaporative gaylussite crystals from Lonar Lake, central India. *J. Quat. Sci.*, 28, 349–359.

Aucher, W., Delafont, V., Ponlaitiac, E., Alafaci, A., Agogué, H., Leboulanger, C., Bouvy, M., and Héchard, Y. (2020). Morphology and ecology of two new amoebae, isolated from a Thalassohaline Lake, Dziani Dzaha. *Protist*, 171, article no. 125770.

Bernard, C., Escalas, A., Villeriot, N., Agogué, H., Hugoni, M., Duval, C., Carré, C., Got, P., Sarazin, G., Jézéquel, D., Leboulanger, C., Grossi, V., Ader, M., and Troussellier, M. (2019). Very low phytoplankton diversity in a tropical saline-alkaline lake, with co-dominance of Arthrospira fusiformis (Cyanobacteria) and Picocystis salinarum (Chlorophyta). *Microb. Ecol.*, 78, 603–617.

Berthod, C., Médard, E., Bachèlery, P., Gurioli, L., Di Muro, A., Peltier, A., Komorowski, J.-C., Benbakkar, M., Devidal, J.-L., Langlade, J., Besson, P., Boudon, G., Rose-Koga, E., Deplus, C., Le Friant, A., Bickert, M., Nowak, S., Thinon, I., Burckel, P., Hidalgo, S., Kaliwoda, M., Jorry, S., Fouquet, Y., and Feuillet, N. (2021). The 2018-ongoing Mayotte submarine eruption: Magma migration imaged by petrological monitoring. *Earth Planet. Sci. Lett.*, 571, article no. 117085.

Bertil, D., Roullé, A., Lemoine, A., Colombain, A., Hoste-Colomer, R., Gracianne, C., Meza-Fajardo, K., Maisonhaute, E., and Dectot, G. (2019). MAYEQSwarm2019: BRGM earthquake catalogue for the Earthquake Swarm located East of Mayotte. May 2018–May 2019. http://ressource.brgm.fr/data/data/937d4fef5c0b-4580-b1ad-2723393b68b6.

Birgel, D., Meister, P., Lundberg, R., Horath, T. D., Bontognali, T. R. R., Bahniuk, A. M., de Rezende, C. E., Vasconcelos, C., and Mckenzie, J. A. (2015). Methanogenesis produces strong ^{13}C enrichment in stromatolites of Lagoa Salgada, Brazil: a modern analogue for Palaeo-/Neoproterozoic stromatolites? *Geobiology*, 13, 245–266.

Cadeau, P. (2017). *Cycles biogéochimiques du carbone, de l'azote et du soufre dans un analogue des océans précambriens : le lac Dziani (Mayotte)*. PhD thesis, Université Sorbonne-Paris Cité.

Cadeau, P., Ader, M., Jézéquel, D., Chaduteau, C., Sarazin, G., Bernard, C., and Leboulanger, C. (2021). Nitrogen isotope discrepancy between primary producers and sediments in an anoxic and alkaline lake. *Front. Earth Sci.*, 9, article no. 787386.

Cadeau, P., Cartigny, P., Thomazo, C., Jézéquel, D., Leboulanger, C., Sarazin, G., and Ader, M. (2022). The Dziani Dzaha Lake: a long-awaited modern analogue for superheavy pyrites. *Geobiology*, 20, 444–461.

Cadeau, P., Jézéquel, D., Leboulanger, C., Fouilland, E., Le Floc'h, E., Chaduteau, C., Milesi, V., Guélard, J., Sarazin, G., Katz, A., d'Amore, S., Bernard, C., and Ader, M. (2020). Carbon isotope evidence for large methane emissions to the Proterozoic atmosphere. *Sci. Rep.*, 10, article no. 18186.

Cellamare, M., Duval, C., Drelin, Y., Djediat, C., Touibi, N., Agogué, H., Leboulanger, C., Ader, M., and Bernard, C. (2018). Characterization of phototrophic microorganisms and description of new cyanobacteria isolated from the saline-alkaline crater-lake Dziani Dzaha (Mayotte, Indian Ocean). *FEMS Microbiol. Ecol.*, 94, article no. fiy108.

Cesca, S., Letort, J., Razafindrakoto, H. N. T., Heimann, S., Rivalta, E., Isken, M. P., Nikkhoo, M., Passarelli, L., Petersen, G. M., Cotton, F., and Dahm, T. (2020). Drainage of a deep magma reservoir near Mayotte inferred from seismicity and deformation. *Nat. Geosci.*, 13, 87–93.

Darnet, M., Wawrzyniak, P., Tarits, P., Hautot, S., and D'Eu, J. F. (2020). Mapping the geometry of volcanic systems with magnetotelluric soundings: Results from a land and marine magnetotelluric survey performed during the 2018–2019 Mayotte seismovolcanic crisis. *J. Volcanol. Geotherm. Res.*, 406, article no. 107046.

Debeuf, D. (2004). *Étude de l'évolution volcano-structurale et magmatique de Mayotte (archipel des Comores, océan Indien)*. Université de la Réunion, Réunion.

Feuillet, N., Jorry, S., Crawford, W. C., Deplus, C., Thinon, I., Jacques, E., Saurel, J. M., Lemoine, A., Paquet, F., Satriano, C., Aiken, C., Foix, O., Kowalski, P., Laurent, A., Rinnert, E., Cathalot, C., Donval, J.-P., Guyader, V., Gaillot, A., Scalabrin, C., Moreira, M., Peltier, A., Beauducel, F., Grandin, R., Ballu, V., Daniel, R., Pelleau, P., Gomez, J., Besançon, S., Geli, L., Bernard, P., Bachelery, P., Fouquet, Y., Bertil, D., Lemarchand, A., and Van der Woerd, J. (2021). Birth of a large volcanic edifice offshore Mayotte via lithosphere-scale dyke intrusion. *Nat. Geosci.*, 14, 787–795.

Feuillet, N., Jorry, S., Rinnert, E., Thinon, I., and Fouquet, Y. (2019). MAYOBS. In *French Oceanographic Cruises*. Sismer, Paris.

Foix, O., Aiken, C., Saurel, J.-M., Feuillet, N., Jorry, S. J., Rinnert, E., and Thinon, I. (2021). Offshore Mayotte volcanic plumbing revealed by local passive tomography. *J. Volcanol. Geotherm. Res.*, 420, article no. 107395.

Gérard, E., De Goeyse, S., Hugoni, M., Agogué, H., Richard, L., Milesi, V., Guyot, F., Lecourt, L., Borensztajn, S., Joseph, M.-B., Leclerc, T., Sarazin, G., Jézéquel, D., Leboulanger, C., and Ader, M. (2018). Key role of alphaproteobacteria and cyanobacteria in the formation of stromatolites of Lake Dziani Dzaha (Mayotte, Western Indian Ocean). *Front. Microbiol.*, 9, article no. 796.

Gu, B., Schelske, C. L., and Hodell, D. A. (2004). Extreme ^{13}C enrichments in a shallow hypereutrophic lake: implications for carbon cycling. *Limnol. Oceanogr.*, 49, 1152–1159.

Hugoni, M., Escalas, A., Bernard, C., Nicolas, S., Jézéquel, D., Vazzoler, F., Sarazin, G., Leboulanger, C., Bouvy, M., Got, P., Ader, M., Troussellier, M., and Agogué, H. (2018). Spatiotemporal variations in microbial diversity across the three domains of life in a tropical thalassohaline lake (Dziani Dzaha, Mayotte Island). *Mol. Ecol.*, 27, 4775–4786.

Jovovic, I., Grossi, V., Adam, P., Simon, L., Antheaume, I., Gelin, F., Ader, M., and Cartigny, P. (2020). Quantitative and specific recovery of natural organic and mineral sulfur for (multi-)isotope analysis. *Org. Geochem.*, 146, article no. 104055.

Leboulanger, C., Agogué, H., Bernard, C., Bouvy, M., Carré, C., Cellamare, M., Duval, C., Fouilland, E., Got, P., Intertaglia, L., Lavergne, C., Le Floc'h, E., Roques, C., and Sarazin, G. (2017). Microbial diversity and cyanobacterial production in Dziani Dzaha Crater Lake, a unique tropical thalassohaline environment. *PLoS ONE*, 12, article no. e0168879.

Lemoine, A., Briole, P., Bertil, D., Roullé, A., Foumelis, M., Thinon, I., Raucoules, D., de Michele, M., Valty, P., and Hoste Colomer, R. (2020). The 2018–2019 seismo-volcanic crisis east of Mayotte, Comoros islands: seismicity and ground deformation markers of an exceptional submarine eruption. *Geophys. J. Int.*, 223, 22–44.

Li, L., Lollar, B. S., Li, H., Wortmann, U. G., and Lacrampe-Couloume, G. (2012). Ammonium stability and nitrogen isotope fractionations for –NH3(aq)–NH3(gas) systems at 20–70 °C and pH of 2–13: applications to habitability and nitrogen cycling in low-temperature hydrothermal systems. *Geochim. Cosmochim. Acta*, 84, 280–296.

Liuzzo, M., Di Muro, A., Rizzo, A. L., Caracausi, A., Grassa, F., Fournier, N., and Italiano, F. (2021). Gas geochemistry at Grande Comore and Mayotte volcanic islands (Comoros archipelago), Indian Ocean. *Geochem. Geophys. Geosyst.*, 22(8), article no. e2021GC009870.

Menzel, P., Gaye, B., Wiesner, M. G., Prasad, S., Stebich, M., Das, B. K., Anoop, A., Riedel, N., and Basavaiah, N. (2013). Influence of bottom water anoxia on nitrogen isotopic ratios and amino acid contributions of recent sediments from small eutrophic Lonar Lake, central India. *Limnol. Oceanogr.*, 58, 1061–1074.

Milesi, V. P., Debure, M., Marty, N. C. M., Capano, M., Jézéquel, D., Steefel, C., Rouchon, V., Albéric, P., Bard, E., Sarazin, G., Guyot, F., Virgone, A., Gaucher, É. C., and Ader, M. (2020). Early diagenesis of lacustrine carbonates in volcanic settings: the role of Magmatic CO_2 (Lake Dziani Dzaha, Mayotte, Indian Ocean). *ACS Earth Space Chem.*, 4, 363–378.

Milesi, V. P., Jézéquel, D., Debure, M., Cadeau, P., Guyot, F., Sarazin, G., Claret, F., Vennin, E., Chaduteau, C., Virgone, A., Gaucher, E. C., and Ader, M. (2019). Formation of magnesiumsmectite during lacustrine carbonates early diagenesis: study case of the volcanic crater lake Dziani Dzaha (Mayotte—Indian Ocean). *Sedimentology*, 66, 983–1001.

Pelleter, A.-A., Caroff, M., Cordier, C., Bachelery, P., Nehlig, P., Debeuf, D., and Arnaud, N. (2014). Melilite-bearing lavas in Mayotte (France): an insight into the mantle source below the Comores. *Lithos*, 208–209, 281–297.

Rouwet, D., Nemeth, K., Tamburello, G., and Calabrese, S. (2021). Volcanic lakes in Africa: the VOLADA_Africa 2.0 Database, and implications for volcanic hazard. *Front. Earth Sci.*, 9, article no. 717798.

Sala, D., Grossi, V., Agogué, H., Leboulanger, C., Jézéquel, D., Sarazin, G., Antheaume, I., Bernard, C., Ader, M., and Hugoni, M. (2022). Influence of aphotic haloclines and euxinia on organic biomarkers and microbial communities in a thalassohaline and alkaline volcanic crater lake. *Geobiology*, 20, 292–309.

Sarazin, G., Jézéquel, D., Leboulanger, C., Fouilland, E., Le Floc'h, E., Bouvy, M., Gérard, E., Agogué, H., Bernard, C., Hugoni, M., Grossi, V., Troussellier, M., and Ader, M. (2021). Geochemistry of an endorheic thalassohaline ecosystem: the Dziani Dzaha crater lake (Mayotte Archipelago, Indian Ocean). *C. R. Géosci.*, 352, 559–577.

Saurel, J.-M., Jacques, E., Aiken, C., Lemoine, A., Retailleau, L., Lavayssière, A., Foix, O., Dofal, A., Laurent, A., Mercury, N., Crawford, W., Lemarchand, A., Daniel, R., Pelleau, P., Bès de Berc, M., Dectot, G., Bertil, D., Roullé, A., Broucke, C., Colombain, A., Jund, H., Besançon, S., Guyavarch, P., Kowalski, P., Roudaut, M., Apprioual, R., Battaglia, J., Bodihar, S., Boissier, P., Bouin, M. P., Brunet, C., Canjamale, K., Catherine, P., Desfete, N., Doubre, C., Dretzen, R., Dumouche, T., Fernagu, P., Ferrazzini, V., Fontaine, F. R., Gaillot, A., Géli, L., Griot, C., Grunberg, M., Guzel, E. C., Hoste-Colomer, R., Lambotte, S., Lauret, F., Léger, F., Maros, E., Peltier, A., Vergne, J., Satriano, C., Tronel, F., Van der Woerd, J., Fouquet, Y., Jorry, S. J., Rinnert, E., Thinon, I., and Feuillet, N. (2022). Mayotte seismic crisis: building knowledge in near real-time by combining land and ocean-bottom seismometers, first results. *Geophys. J. Int.*, 228, 1281–1293.

Stüeken, E. E., Buick, R., and Schauer, A. J. (2015). Nitrogen isotope evidence for alkaline lakes on late Archean continents. *Earth Planet. Sci. Lett.*, 411, 1–10.

Stüeken, E. E., Martinez, A., Love, G., Olsen, P. E., Bates, S., and Lyons, T. W. (2019). Effects of pH on redox proxies in a Jurassic rift lake: implications for interpreting environmental records in deep time. *Geochim. Cosmochim. Acta*, 252, 240–267.

Stüeken, E. E., Tino, C., Arp, G., Jung, D., and Lyons, T. W. (2020). Nitrogen isotope ratios trace high-pH conditions in a terrestrial Mars analog site. *Sci. Adv.*, 6, article no. eaay3440.

Talbot, M. R. and Kelts, K. (1986). Primary and diagenetic carbonates in the anoxic sediments of Lake Bosumtwi, Ghana. *Geology*, 14, 912–916.

Valero-Garcés, B. L., Delgado-Huertas, A., Ratto, N., and Navas, A. (1999). Large ^{13}C enrichment in primary carbonates from Andean Altiplano lakes, northwest Argentina. *Earth Planet. Sci. Lett.*, 171, 253–266.

Zhu, Z., Chen, J., and Zeng, Y. (2013). Abnormal positive $\delta^{13}C$ values of carbonate in Lake Caohai, southwest China, and their possible relation to lower temperature. *Quat. Int.*, 286, 85–93.

Zinke, J., Reijmer, J. J. G., Thomassin, B. A., Dullo, W.-C., Grootes, P. M., and Erlenkeuser, H. (2003). Postglacial flooding history of Mayotte Lagoon (Comoro Archipelago, southwest Indian Ocean). *Mar. Geol.*, 194, 181–196.