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INITIAL TIME OF TWO HIGH ALTITUDE CRATER LAKES (NEVADO DE TOLUCA, CENTRAL MEXICO) RECORDED IN SUBFOSSIL CLADOCERA

Krystyna Szeroczyńska, Edyta Zawisza, Marta Wojewódka

Institute of Geological Sciences, Polish Academy of Sciences, Twarda 51/55, Warsaw, Poland; kszerocz@twarda.pan.pl

Abstract

The objective of this study was the recognition and reconstruction of the origin of two high altitude lakes and the ecological conditions of their early existence based on subfossil Cladocera and chemical analyses. The study focused on the oldest lacustrine sediments from Lake Sol and Lake Luna, located in the crater of Volcano Nevado de Toluca (Central Mexico). The Nevado de Toluca crater developed approximately 12 ka yr BP. According to the literature, the volcano was last active approximately 3.3 ka yr BP, and the lakes developed after that eruption. The remains of nine Cladocera species were found in the bottom sediments of both lakes. The most dominant taxa were two endemic littoral species: *Alona manueli* and *Iliocryptus nevadensis*. The total frequency of Cladocera specimens in both of the sediment cores was very low. No Cladocera remains were recorded in the sediment layer at depths between 123–103 m from Lake Luna. The results of the lithological and geochemical analyses showed that this sediment layer was composed of allochthonous material, probably originating from slid down from the volcanic cone. This was suggested by the content of silica (up to 13%), iron (up to 12%), and titanium (up to 4%). The Cladocera remains recorded in the bottom sediments suggested that both reservoirs developed as freshwater lakes at the beginning of the sedimentation. The calibrated radiocarbon dates obtained for the bottom samples were 4040 to 3990 yr BP for Lake Luna (129 cm) and 4485 to 4485 yr BP for Lake Sol (89 cm). The obtained ages were older than the dates of the last eruption, which occurred approximately 3300 yr BP. This result was likely related to the type of radiocarbon dated materials (charcoals).

Key words: crater lakes, Sol and Luna Lakes, palaeolimnological studies, Cladocera and chemical components, Nevado de Toluca, Central Mexico.

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INTRODUCTION

Lakes are frequently the objects of both limnological and palaeolimnological studies. Their genesis and ages are a subject of interest for many researchers around the world (McNamara, 1979; Soper, N.J. and Numan, N.M.S., 1974; Więckowski, 2009). The majority of studies focused on high latitude and lowland lakes. Little research, particularly on high altitude tropical lakes, has been conducted. High altitude lakes of volcanic origin were rarely the subjects of investigations, due to their isolation and inaccessibility. Therefore, those lakes constitute an important element for the reconstruction of both the lacustrine environment and climatic changes.

In general, research on climate changes in Central Mexico dates back to the 1940s. Palaeoenvironmental data were primarily based on palaeolimnological research on lakes located in Michoacan (e.g., Patzcuaro Lake, Deevey, 1944, Hutchinson *et al.*, 1956). This research provided a basis for interpretation of the Holocene climatic changes in Central Mexico. However, the studied lakes were strongly impacted by humans (Xelhuantzi-Lopez, 1994; Metcalfe *et al.*, 2000). Central Mexico was occupied by prehistoric human populations approximately 3500 years ago. The presence of human settlers considerably changed the ecological state of the lakes, and the results recorded changes in the overlapping of natural and anthropogenic factors (Deevey, 1944; Lozano Garcia and Ortega Guerrero, 1997; Metcalfe *et al.*, 2000).

Authors of presented study were looked for isolated lakes located in an area largely inaccessible, where their development may have mainly been influenced by climatic changes. The choice led to two high altitude lakes separated from human activity: Lake Sol and Lake Luna, located in the crater of Volcano Nevado de Toluca (Central Mexico).

Geological research on Volcano Nevado de Toluca dates back to the first decade of the 20th century (Ordoñez, 1902; Flores, 1906). These studies were particularly concerned about the morphology and structure of this volcano. The first eruption of Volcano Nevado de Toluca occurred approximately 2.6 Ma years ago, and eruptions continued during the

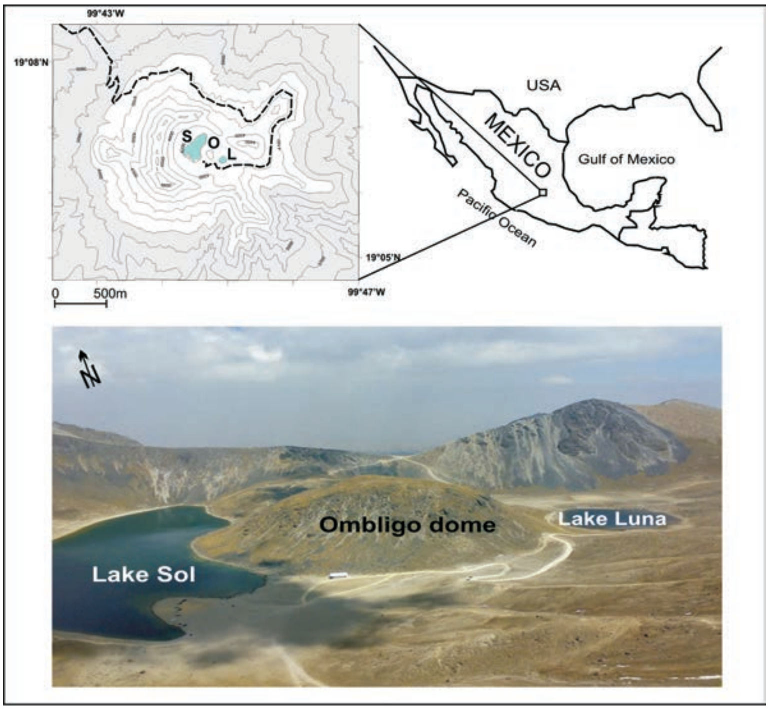

Fig. 1. Geographical location of the study Lake Sol and Lake Luna – located in the Volcano Nevado de Toluca crater keeping apart by volcanic dome. S – Lake Sol, L – Lake Luna, O – Ombligo dome, dotted line – access road to the crater.

Pleistocene-Holocene (Bloomfield *et al.,* 1977; Garcia-Palomo *et al.*, 2000; 2002; Capra *et al.*, 2008). The occurrence of several eruptions during the late Pleistocene were occurred approximately 37 ka yr BP, 32 ka yr BP, 28 ka yr BP, 26 ka yr BP, 14 ka yr BP, 10.5 ka yr BP, 8.5 ka yr BP, and 3.3 ka yr BP (Heine and Heide-Weise, 1973; Heine, 1988; Armienta *et al.*, 2000; Garcia-Palomo *et al.*, 2002; Macias *et al.*, 1997, Quesada *et al.,* 2007). The largest eruption of the volcano likely occurred approximately 37 ka BP (Caballero *et al.*, 2001).

The first scientific studies of the lakes in the Nevado de Toluca crater were conducted in the 1990s. They focused on the limnological description of the lakes and were based on macro- and micro-floristic analyses (Caballero-Miranda, 1996; Caballero-Miranda and Ortega Guerrero, 1998). The first studies on subfossil zooplankton were performed by Zawisza *et al.* (2012), Siniev and Zawisza (2013) and Cuna *et al.* (2014).

This paper presents the results of research in which the primary aim was to define the time of origin and ecological character of the early existence of Lake Luna and Lake Sol, located in the Nevado de Toluca crater. The time of the origin of the lakes and their characteristics during their early development time were estimated based on C-14 dating, changes of the Cladocera species composition and abundances, and the chemical composition of sediment (from the depth interval 103–123 cm in Lake Luna). Another important objective of the study was to trace local climate changes that occurred during the deposition of the oldest sediment layer (Late Holocene).

MATERIALS AND METHODOLOGY

Study area

The study area included the two tropical high altitude lakes (Tab. 1), Lake Luna (Lake of the Moon) and Lake Sol (Lake of the Sun), located in the crater of Volcano Nevado de Toluca (4680 m a.s.l., Central Mexico). This volcano is located 23 km SW of the City of Toluca and approximately 90 km SW from Mexico City (Fig. 1). Nevado de Toluca is recognized as a dormant stratovolcano of the Pliocene-Holocene age, developed on a sequence of metamorphic and sedimentary formations, particularly from dacitic lava (Bloomfield and Valastro, 1977; Macias *et al.*, 1997; Quesada *et al.*, 2007). The crater has an oval shape, which is elongated on the E–W axis. Its dimensions are approximately 2 km × 1.5 km.

The time of the last eruption of volcano, the origin of the crater and the origin of the lakes are controversial. Research by Macias *et al.*, (1997) suggested the occurrence of a major Plinian event in Nevado de Toluca ca. 10.5 ka yr BP. Macias and Siebe (2005) stated that the age of the last eruption of the volcano was ca. 3.3 ka yr BP, based upon C-14 dating from the ash (charcoal). The last eruption was a minor magnetic eruption, resulting in a surge and pyroclastic flow of deposits on its north-west flank (Garcia-Palomo *et al.*, 2002).

The ecology of the studied lakes is largely influenced by the lakes' catchment areas, geology (andesic-dacitic subsoil) and boulders, and poor vegetation (alpine meadow) (Caballero-Miranda, 1996; Gonzalez, 1984). The climate of the Nevado de Toluca is quite cold, with a summer rainy season. The mean annual temperature amount is approximately 4°C, with the maximum in May (approximately 19°C) and the minimum in January (approximately –9°C) (Mexican Meteorology Service, data 1970–2000). Cuna *et al.*, (2014) showed that the studied lakes had a positive water balance,

Table 1

Geographical coordinates and general morphometric data of the stufied lakes

Lake	Coordinates	a.s.l.	Max depth	Surface area	Conductivity*	pH*	Fish
Sol (Spanish: El Sol)	19° 06'13" N 99° 45'20" W	4200 m	12 m	175 000 m^2	18–24.6 µS/cm	5.6–5.9	YES
Luna (Spanish: La Luna)	19° 06'13" N 99° 45'20" W	4200 m	8 m	25 000 m^2	17–20 µS/cm	4.7–6.2	NO

* - after (Caballero-Miranda 1996; Armienta *et al.*, 2000; Cuna *et al.*, 2014)

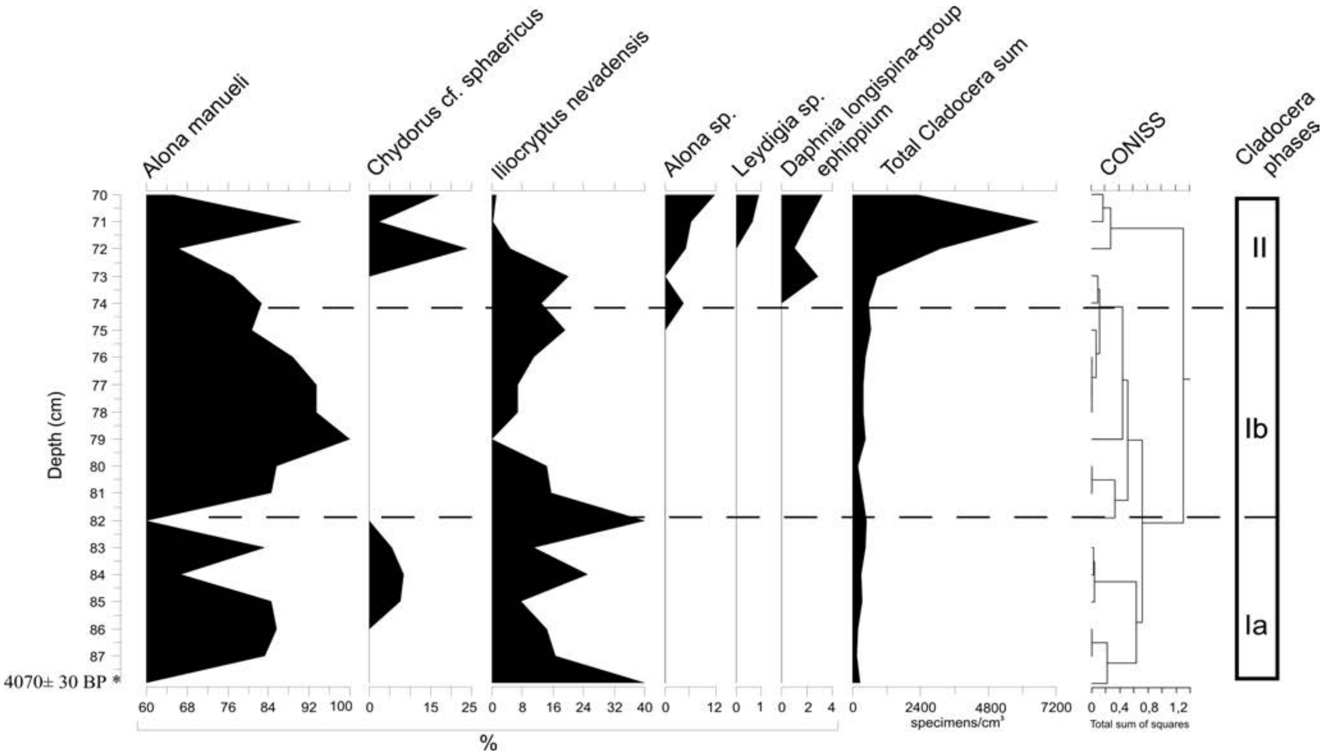

Fig. 2. Diagram of percentage composition and the total sum of Cladocera specimens in sediments of Lake Sol. * (dating, 4070±30 BP) – 2 sigma calibration: (cal BP 4785 to 4765), (cal BP 4625 to 4515), (cal BP 4485 to 4445).

with the average annual precipitation (1213 mm/yr) concentrated during the summer months that exceeded the annual evaporation (824 mm/yr). Water in the lakes is cold and clear and originates primarily from precipitation. The lakes are classified as oligotrophic, and they are distinguished by low alkalinity and low content of minerals (Caballero-Miranda, 1996; Armienta *et al.*, 2000; Alcocer *et al.*, 2004; Dimas-Flores *et al.*, 2008).

Methods

Sediment cores were recovered in 2013 from the central parts of Lake Luna (129 cm long) and Lake Sol (89 cm long) using a Livingstone corer. The cores were sealed plastic tubes and transported to the laboratory of the Geophysics Institute (UNAM, Mexico), where they were cut in half lengthwise, photographed, described (sediment colour, texture, etc.), and subsampled. Samples for the cladoceran analysis were taken in 1 cm intervals. The sediment layers from the depths between 128–93 cm (silty clay with fine sand) from Lake Luna and from the depths between 88-70 cm (clay and silty clay) from Lake Sol were subjected to the Cladocera analysis. Sediments from Lake Luna (layer of depth: 123–103 cm) were also subjected to a geochemical analysis.

Dating

Radiocarbon dating from the first bottom samples of the sediments from both lakes were determined by AMS dating. For the dating, c.a. 12 cm^3 of sediment (from 129 cm in Lake Luna and 89 cm in Lake Sol) were used. The pollen was extracted according to the standard procedure and concentrated by sieving through a 50 µm mesh. The pollen samples were sent to BETA ANALYTIC INC. in Miami, Florida, for AMS radiocarbon dating using the IntCal 13 database (Reimer *et al.*, 2013).

Cladocera analysis

Samples of 1 cm^3 were prepared according to the standard procedure (Frey, 1986). The sediment was heated in 10% KOH for 20–30 minutes using a magnetic stirrer to deflocculate the organic material. Samples were sieved through a 33 µm screen and transferred into distilled water. Before counting, the samples were coloured with safranin dye and glycerin solution. Approximately 200 remains of Cladocera were counted (3–4 slides were examined for each level) only for the bottom sediment samples less, due to a very low Cladocera remains frequency. The percentage composition and the total concentration of Cladocera per 1 cm^3 were calculated. The identification of cladoceran taxa was performed using an OLYMPUS microscope and based on the papers by Elias-Gutierrez *et al.*, (2008), Cervantes-Martinez *et al.*, (2000), and Sinev and Zawisza (2013). The results were plotted in a relative abundance diagram using the C2 software (Juggins, 2005, 2007) (Figs 2, 3).

Chemical analysis

There was a lack of Cladocera remains and other organisms' remains at the depths between 123–103 cm from Lake Luna. Because of this result, the major and trace elements

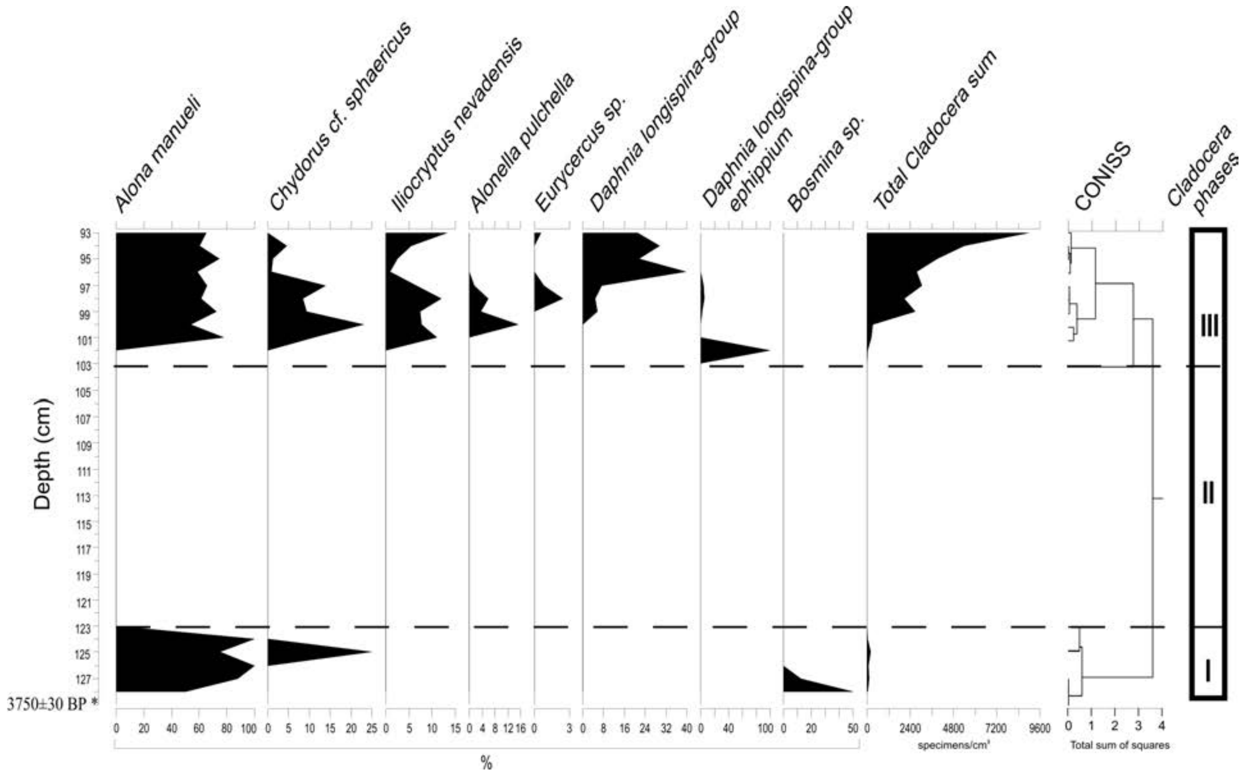

Fig. 3. Diagram of percentage composition and the total sum of Cladocera specimens in sediments of Lake Luna. * (dating, 3750±30 BP) – 2 sigma calibration: (cal BP 4225 to 4200), (cal BP 4175 to 4170), (cal BP 4160 to 4070), (cal BP 4040 to 3990).

were determined by an X-ray fluorescence (XRF) analysis (Singh and Agrawal, 2012; Kalnicky and Singhvi, 2001; Gonzalez-Fernandez *et al.*, 2007; Mendoza-Rosas and De la Cruz-Reyna, 2008). The measurements were performed using an energy-dispersive X-ray fluorescence spectrometer (EDXRF), model Genius 7000 EDX Pocket IV with SDD detector. The resolution of the detector was 139±5 eV. The X-ray source was an X-ray tube with a Ag-anode and U_{max} and I_{max}, equal to 40 kV and 100 μA, respectively. The calibration was performed on lake sediments to limit the errors resulting from the high level of complexity of the matrix of the geological samples (Boyle, 2000).

The measurements were made on dry and homogenized sediment samples. In Lake Luna (sediment layer: 123–103 cm), the concentrations of 8 elements (Al, Si, Ti, Fe, Sr Y, Rb, and Zr) were measured. The samples were placed in a cup with foil, placed on the EDXRF and then measured for 100 s. The light elements (Al and Si) were determined using a helium washer (flow 50 ml/min). Each sample was measured four times, and the mean value was calculated. The data results are reported in Tab. 3 and Fig. 4.

RESULTS

The results of the C-14 dating are presented in Table 2.

Subfossil cladoceran analysis

The subfossil Cladocera analysis was performed using the sediments from lakes Sol and Luna. The samples were analysed in 1 cm intervals.

Table 2

Radiocarbon dating – calibration on radiocarbon age to calendar years (Talma and Vogel, 1993)

Lake	Material	Lab. no.	Conventional ^{14}C BP(*)	Calibrated Results (Probability) 95 %	Calibrated Results (Probability) 68%
Sol (Spanish -El Sol)	pollen	403149	4070±30	Cal BC 2835 to 2815 (Cal BP 4785 to 4765) Cal BC 2675 to 2565 (Cal BP 4625 to 4515) Cal BC 2535 to 2495 (Cal BP 4485 to 4445)	Cal BC 2830 to 2820 (Cal BP 4780 to 4770) Cal BC 2650 to 2570 (Cal BP 4575 to 4520) Cal BC 2510 to 2505 (Cal BP 4460 to 4455)
Luna (Spanish -La Luna)	pollen	4031488	3750±30	Cal BC 2275 to 2250 (Cal BP 4225 to 4200) Cal BC 2225 to 2220 (Cal BP 4175 to 4170) Cal BC 2210 to 2120 (Cal BP 4160 to 4070) Cal BC 2090 to 2040 (Cal BP 4040 to 3990)	Cal BC 2200 to 2135 (Cal BP 4150 to 4085)

*Measured 13C/12C ratios (Sol: -20.2 ‰, Luna: -25.4 ‰) were calculates relative to the PDB-1 standard

Lake Sol

Nineteen samples of bottom sediment (from depths between 88–70 cm) were analysed. Six Cladocera species were identified: *Alona manueli*, *Alona* sp., *Iliocryptus nevadensis*, *Chydorus* cf. *sphaericus*, *Daphnia longispina*-group, and *Leydigia* sp. The relative abundance diagram and total Cladocera sum are shown in Fig. 2. The changes in the Cladocera species composition and the total Cladocera sum distinguished three phases, which were confirmed by the CONISS analysis.

Phase I (89–82 cm) was characterized by a very low Cladocera frequency (below 400 specimens/cm^3). The remains of three species were present in the sediments: *Alona manueli, Chydorus* cf. *sphaericus*, and *Iliocryptus nevadensis*. This phase was dominated by two endemic species: *Alona manueli* (60–85%), and *Iliocryptus nevadensis* (8–40%). The remains of *Chydorus* cf. *sphaericus* were only recorded in the depths between 85.5–82.5 cm, and their percentage was very low (0–10%).

Phase II (82–74 cm) was characterized by the presence of only two Cladocera species: *Alona manueli* and *Iliocryptus nevadensis*. *Chydorus* cf. *sphaericus* remains were not recorded in this phase. The frequency of Cladocera zooplankton was also low and did not exceed 800 specimens/cm^3 sediments.

Phase III (74–70 cm) was characterized by the presence of six Cladocera species in the sediments. The remains of *Daphnia longispina*–group, *Leydigia sp.* and *Alona sp.* (head with three head pores) were recorded for the first time. *Chydorus* cf. *sphaericus* was also present. The frequency of Cladocera during phase III significantly increased and was recorded at a maximum of >7200 specimens per 1 cm^3 of sediments.

Lake Luna

A total of 36 bottom sediment samples (layer depth: 128–93 cm) from Lake Luna were analysed. Seven Cladocera species were identified: *Alona manueli*, *Alonella pulchella*, *Iliocryptus nevadensis*, *Chydorus* cf. *sphaericus*, *Eurycercus sp.*, *Daphnia longispina*-group, and *Bosmina* sp. The relative abundance diagram and total Cladocera sum are presented in Fig. 3. The frequency and species composition drastically changed over time and three Cladocera phases were distinguished.

Phase I (128–123 cm) was characterized by the presence of three Cladocera species: *Alona manueli* (50–100%)*, Chydorus* cf. *sphaericus* (0-25%), and the planktonic species *Bosmina* sp. (0–50%). The remains of *Bosmina* sp. were present only in the lowest sediment layer (depth: 128–125 cm) of the studied core. The frequencies of all of the specimens were very low.

Phase II (123–103 cm), no Cladocera remains were recorded. The samples had a mineral character with no Cladocera and other organic remains detected.

Phase III (103–93 cm) was characterized by the presence of six Cladocera species. The dominant species were *Alona manueli* and *Daphnia longispina*–group. The new species that occurred were *Alonella pulchella* and *Eurycercus* sp. The total Cladocera sum gradually increased, reaching a value of 9,000 specimens/cm^3 sediments in the top sample (93 cm).

Table 3

Concentrations (% or ppm) of 8 geochemical elements in the sediments of the Lake Luna (layer from depth: 123–103 cm)

	Al	Si	Ti	Fe	Sr	Y	Rb	Zr
	(%)				(ppm)			
Minimum	0.0	8.1	0.5	3.6	597.3	41.5	50.4	258.9
Maximum	2.5	13.0	3.6	11.3	879.1	52.7	84.1	372.0
Mean	1.5	10.6	1.5	6.8	766.5	48.9	69.3	327.9

Geochemical analysis

The analysed sediment layer in Lake Luna (depth: 123–103 cm, Cladocera phase II), had no traces of organic matter. This layer was distinguished in two geochemical units (Ia, Ib and II) by a considerable increase in the concentration of chemical elements (confirmed by CONISS analysis), the major elements (titanium and iron), and trace elements (strontium and yttrium, Tab. 3, Fig. 4).

Unit Ia

The trace elements, strontium (Sr) and yttrium (Y), were observed at the maximum concentrations of 879.1 ppm and 52.7 ppm, respectively (depth – 122 cm). In this unit, the concentration of zirconium ranged from 258 ppm to a maximum concentration of 372.0 ppm (depth of 118 cm). In unit Ia, the lowest concentration of titanium was recorded (0.5%).

Unit Ib

The highest concentrations of Si and Fe, amounting to 13.0% and 11.3%, respectively, were recorded in sediment at a depth of 114 cm. At this depth, the maximum contribution of Al was also recorded (2.5%). In the case of titanium, a double increase in the percentage contribution was observed at a depth of 114 cm (~3%) and 106 cm (3.5%).

Unit II

From the beginning of this unit (depth of 105 cm), there were decreases in the concentrations of most of the geochemical elements.

DISCUSSION

The study of the bottom sediments of the two crater lakes (Sol and Luna) provided insight into the conditions of the early existence of the lakes. The lakes undoubtedly developed as a result of the last eruption of Volcano Nevado de Toluca. According to literature data, the eruptive sequence covered a phreatomagmatic surge deposit dated at ~ 3.3 ka BP (Macias *et al*., 1997; Capra *et al.*, 2008). The deposit of the last eruption was described as a dark grey colour, up to 1 m thick, lithic rich, and with a laminated basal layer. This deposit only occurred in one place on the western flank of the volcano.

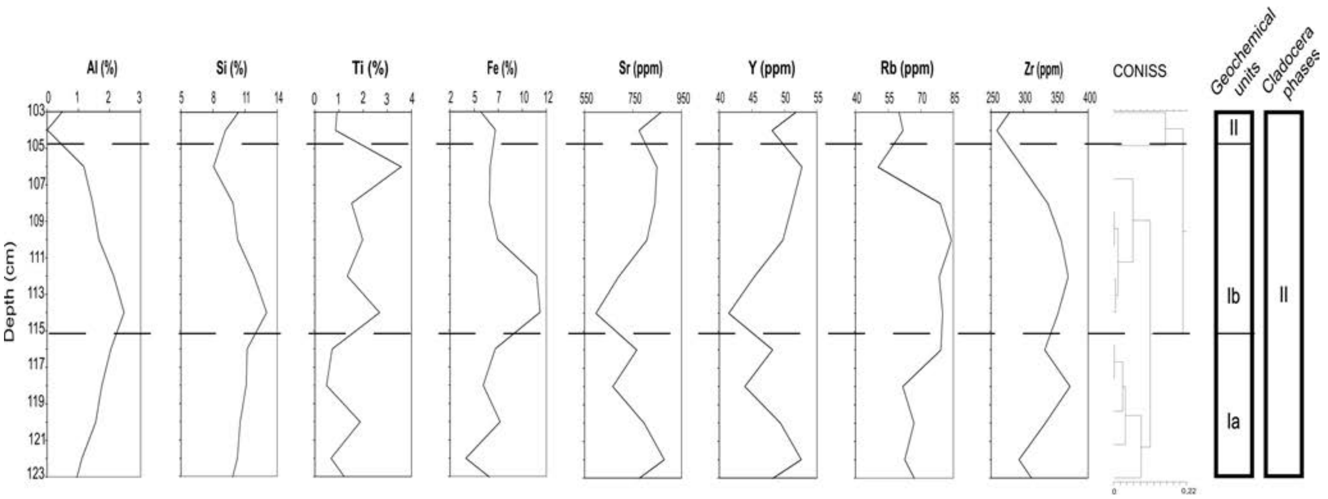

Fig. 4. Content of selected chemical elements in sediments of the Lake Luna (layer from depth: 123–103 cm).

The lacustrine sedimentation in the "Toluca basin" was greatly influenced by volcanic activity (Caballero *et al.*, 2001; Capra *et al.*, 2008). Ash deposits were also recorded below the bottom of the lacustrine sediments from lakes Sol and Luna. Their presence presumably indicated the presence of the ashes of the last eruption of Volcano Nevado de Toluca.

The presence of the endemic species *Alona manueli* and cosmopolitan species *Chydorus* cf. *sphaericus*, as well as very low total Cladocera abundances, were recorded in the oldest sediment layer (3–7 cm thickness) of both lakes, suggesting that the lakes were very poor in biogenic substances at the beginning of their existence (phase I). Both of the lakes were likely extremely ultraoligotrophic at that time. After phase I, drastic changes in the lakes ecosystems occurred. At phase II, one species, *Alona manueli*, dominated in Lake Sol (depth: 82–74 cm) and reached as high as 90–100%, but the number of Cladocera individuals was very low. During phase II the sedimentation of the layer (depth: 123–103 cm) at Lake Luna, a complete absence of cladoceran remains was observed. Both layers (phase II at Lake Luna and Lake Sol) were presumably the same age because after their deposition, the rapid development of zooplankton occurred (Figs 2, 3). This significant change (rapid Cladocera development) was marked as phase III and was documented by the increase in both the number of species and the frequency of Cladocera specimens. At that time in both lakes, new littoral species appeared (*Alonella pulchella*, *Leydigia* sp., *Eurycercus* sp., and *Alona* sp.) as well as the planktonic *Daphnia longispina* - group. The total Cladocera abundances significantly increased and reached almost 10,000 individuals per 1 cm^3 of sediment. Such changes in the structure of zooplankton suggested an important transition in the lakes' environment. These changes were likely related to considerable climate change and an appearance of favourable edaphic conditions for zooplankton. The period preceding the expansion of Cladocera (phase II) was presumably more severe and dry, and the water level in the lakes was probably lower. The climate condition during phase II was suggested by both the very low frequency of Cladocera fauna in Lake Sol and the presence of a volcanic ash layer in the deposit of Lake Luna. In Lake Luna, the contents of the chemical elements in the deposits evidently changed (Tab. 3, Fig. 4). A considerable increase in the contributions of chemical elements, such as Si, Fe and Ti were recorded in this sediment layer from Lake Luna. The results of the geochemical analysis, particularly those of Fe and Ti, suggested substantial supply of material from the catchment of the lake. The mean values obtained for the elements in the layer depth of 103–123 cm were considerably increased and may confirm the volcanic origin of the sediment (Ortega-Guerrero and Newton, 1998; Weitz *et al.*, 1999; Garcia-Palomo *et al.*, 2002; White *et al.*, 2004). The Ombligo dome likely contained the unconsolidated material on its surface that was deposited by the last small phreatomagmatic explosion (Capra, *et al.*, 2008). This unconsolidated material slid down the slope and was deposited as a mineral layer in Lake Luna. A similar process was observed by Dean *et al.*, (2004), who studied the sediments deposited in two basins in the central Gulf of California. The authors interpreted the high concentration of Ti, Mn, and Fe in the sediment samples as mafic volcanic debris from the Sierra Madre.

The C-14 dating of the deposited pollen (from a depth of 129 cm in Lake Luna and from a depth of 89 cm in Lake Sol) right above the volcanic ash showed dates of 4040 to 3990 cal BP for Lake Luna and 4485 to 4445 cal BP for Lake Sol. The obtained ages were older by ca. 600–1000 years compared to the date of the last eruption, estimated at 3.3 ka yr BP (Macias *et al.*, 1997; Garcia-Palomo *et al.*, 2002; Capra *et al.*, 2008). This problem was observed in many lakes in the Mexican highland and might be a result of volcanic activity. However, it should also be considered that the date of the last eruption of the volcano might be imprecise, especially the datings based on charcoal deposits. The C-14 age of charcoal from the ashes of the last eruption of Volcano Nevado de Toluca was estimated to be from 4300 to 3000 years ago, according to Gracia-Palomo *et al.*, (2002). Irrespective of the precision of the datings, the history of the development of the studied lakes was certainly closely related to the activity of Volcano Nevado de Toluca.

Nonetheless, this study demonstrated that despite the close proximity of both lakes, their ecological development was somewhat different. These differences were likely determined by the presence of the Ombligo dome, which developed just after the Upper Toluca Pumice (UTP) eruption. The Ombligo dome is located in the centre of the crater and separates both lake basins. According to Capra *et al.*, (2008), the majority of the block and ash flow deposits recorded in the crater of the volcano were probably generated by discrete collapses of the central dome. The lacustrine mineral layer identified in Lake Luna (depth: 123–103 cm) had no traces of organic elements, and this layer likely originated from the slid down of material from the western part of the Ombligo dome.

It is uncertain whether the volcanic material deposited in Lake Luna was a result of a single episode of the runoff of a 20 cm sediment layer, or if this layer was deposited gradually as a result of dry strong winds. It was more likely that the volcanic material (with no elements of organic matter) was the result of a single episode. There was a high probability that sliding sediment could have removed or disturbed the limnic sedimentation. However, this sediment layer could have been created as an effect of dry strong winds. The existence of a climate drier than the current climate in Central Mexico during the periods of 3700-3300 yr BP, 2950 yr BP, and 2700 yr BP was suggested by a number of studies, including Metcalfe *et al*., (2000), Park *et al.,* (2010), and Wanner *et al*., (2008).

CONCLUSION

The results, discussion, and mentioned problems presented above indicate the difficulties in the paleo-interpretation and reconstruction of the volcano crater lakes. This study will be continued, and the presented material will be supplemented by new precise dating of the lacustrine sediments, which will aid in determining the correct dating despite current conflicts in the literature dates. Nevertheless, the results aiding in forming the following conclusions:

1. The species composition of Cladocera was unusual and likely documented the tropic status of the cold, oligotrophic, isolated and high-altitude lakes (with endemic forms).
2. During the initial development period, the lakes were likely ultraoligotrophic, with a low water level and a very low frequency of Cladocera.
3. During the time and development of the catchment area, the lakes were enriched with nutrients and thus achieved better conditions for the development of zooplankton.
4. Changes in the assemblages of Cladocera were related to climate changes (water temperature, trophic status and/or pH).
5. Lake Sol and Lake Luna were created after the last eruption of Volcano Nevado de Toluca.
6. The obtained ages from AMS C-14 dating were different from the dates of the last eruption, which occurred ca. 3.3 ka yr BP.

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