Environmental change since AD 1080 in the Grijalva watershed, Mexico, inferred from Lake Chicuacan sediments

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Little research has been done on recent environmental and climatic change in Mexico. This study presents an environmental reconstruction since the Postclassic Era (~ AD 1080) for the southeastern part of Mexico. A lacustrine core from laguna Chicuacan, located in the Grijalva watershed, Tabasco, Mexico has been analyzed on diatom and pollen content. The diatom and pollen data have been used to reconstruct variations in lake level as well as changes in trophic state of the lake. An age-depth model for the core was established by the use of radiocarbon dates. Laguna Chicuacan experienced fluctuations in water depth, suggested by varying *Aulacoseira spp.* abundances. Ever since the formation of laguna Chicuacan at the end of the 11th century, water levels have slightly decreased. Shallowest lake levels probably occurred around AD 1660. After AD 1800, the relative abundance of *Aulacoseira spp.* and *Cyperaceae* pollen increased, indicating a slight increase in water depth. These variations in lake level are presumably caused by precipitation changes. This study shows evidence for several phases of nutrient supply to laguna Chicuacan as well, suggested by the varying occurrences of *Staurosira spp.* and *Staurosirella pinnata*. This enhanced nutrient supply occurred in the time period between approximately ~AD 1080 and 1505. More recent anthropogenic eutrophication occurred from AD 1950 until recent. Current flora on the lakeshore supports the finding that laguna Chicuacan is a eutrophic lake at present.

Keywords: Diatoms; Paleolimnology; Environmental reconstruction; Pollen; Grijalva watershed; Eutrophication; Lake level

Introduction

Mexico is an area of particular interest for paleoenvironmental and archeological studies and the interaction between them (e.g. Metcalfe et al., 2000). During the last decades, an increasing amount of paleoclimate studies has documented climatic fluctuations in Central America during the late Holocene. These studies were performed in order to gain insight in changing environments and the impact on the Maya population, which ruled the area for more than 1000 years. Hence, most of these paleoclimatic studies are focused on the Maya Classic Period, lasting from AD 250-900 (e.g. Curtis et al., 1996; Douglas et al., 2015; Haug et al., 2003; Vélez et al., 2005; Wahl et al., 2014). Furthermore, these studies are mainly concerning $d^{18}O$ data or pollen records and based on records from Central Mexico, the Yucatan peninsula or other parts of Central America. Few lake sediments in Central America have been used for the reconstruction of more recent environmental change.

In this paper, a paleolimnologic study from laguna Chicuacan, located in the Grijalva watershed, Tabasco, Mexico, will be presented. The lacustrine core has been studied on fossil diatom and pollen content and sedimentological characteristics. The main goals of this research are to 1) report environmental change in the area during the past 950 years and 2) contribute to our knowledge of diatoms from this region. Changes in lake trophic state since the end of the 11th century are reconstructed from fossil diatom assemblages. Furthermore, lake level variations are reconstructed using fossil diatom assemblages and pollen. An overview of the diatom assemblages of the sediment core from laguna Chicuacan will be presented. Relationships between the environmental parameters and diatom content will be discussed and the results will be compared to other paleo-environmental studies from Central America.

Study site

Laguna Chicuacan is located in the Grijalva watershed (Fig. 1 and appendix 5). The Grijalva watershed is situated in the state of Tabasco in southeastern Mexico. The Grijalva River drains into the Gulf of Mexico and has its source in the mountains of the Chiapas highlands. The Grijalva flows approximately 750 kilometers through the state of Chiapas before the river unites with the Usumacinta River in Tabasco. There, the two rivers confluence and flow into the Gulf of Mexico (Rhoda and Burton, 2010).

The climate in Mexico is influenced by the occurrence of El Niño and La Niña years and coherent the position of the Inter Tropical Convergence Zone (ITCZ). During an El Niño summer, the ITCZ shifts a few degrees southwards. This leads to fewer tropical cyclones and droughts in most of Mexico. During La Niña summers on the other hand, precipitation increases to normal or even extreme situations (Magaña et al., 2003). The climate of Tabasco is strongly seasonal. In winter, westerly winds are responsible for dry conditions in the area. During the summer, easterly winds bring moist air from the Gulf of Mexico and the Eastern pacific to the country (Metcalfe et al., 2000). The dry period lasts from November-May, while the wettest month is July, with mean precipitation of 150mm/month. Average high temperatures range from 23 ˚C in January to 32˚C in May (Servicio Meteorológico Nacional, 2015).

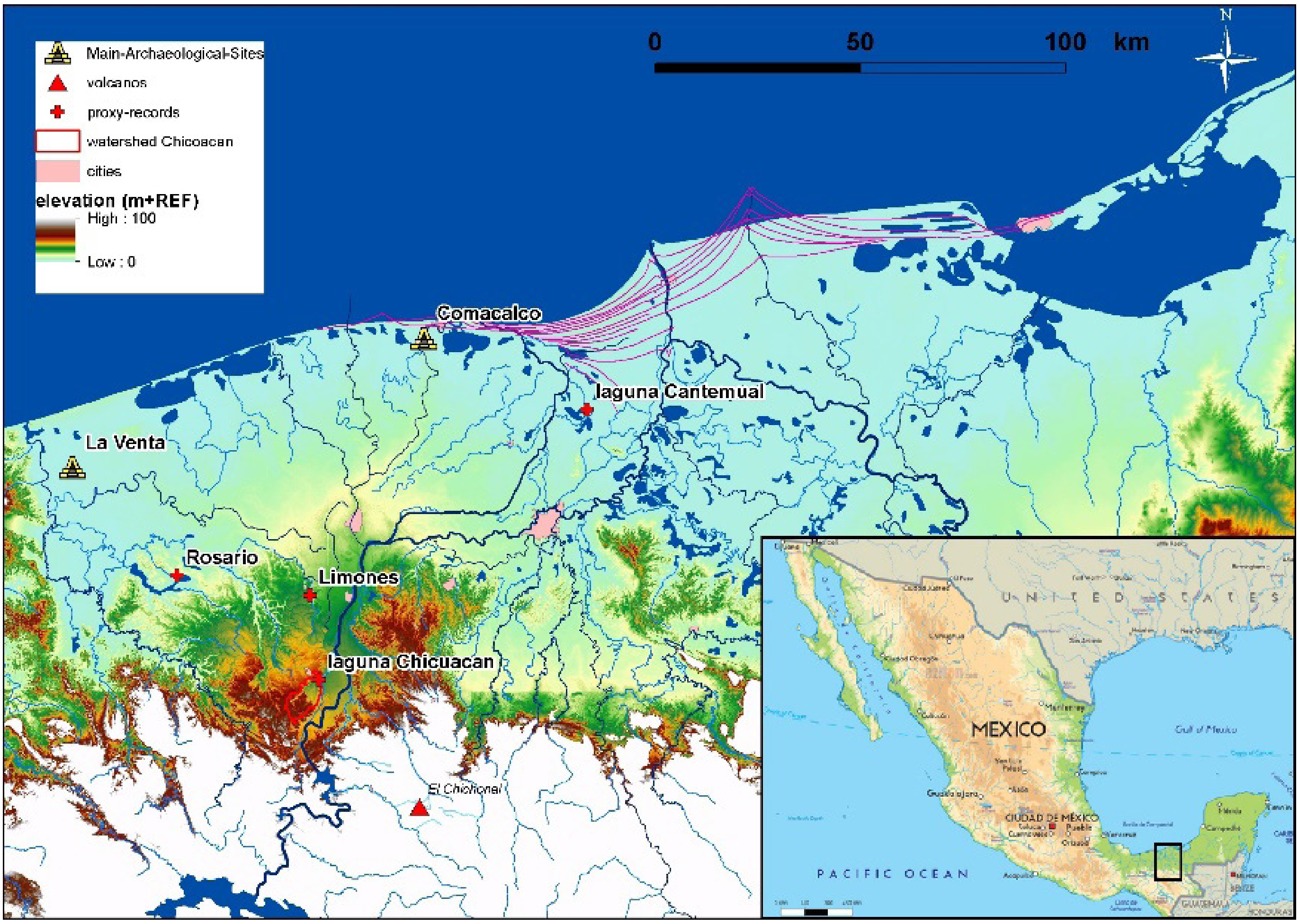

Fig. 1 Location of laguna Chicuacan. Bottom right: Overview of Mexico, area of interest is marked with the black square.

Laguna Chicuacan

Laguna Chicuacan (17˚38"56'N, 93˚27"26'W, 33 m.a.s.l.) is located 7 kilometer west of the Mezcalapa (Grijalva) river, nearby the town of Huimanguillo. The lake has a surface area of approximately 0.65 km^2 and a maximum water depth of 1.6 m. The catchment has an area of approximately 51.2 km^2 and consists of two Pleistocene terraces (appendix 5).

Methods

Sampling methods

In March 2015, a core of 295 cm was recovered from the central part of laguna Chicuacan. The core was collected by the use of a piston corer. The 295 cm core from laguna Chicuacan was sectioned at first. Since the upper 13 cm of the sediment were not preserved, the top of the sediment column was at 13 cm depth below lake level. Therefore, the core depth represents the depth below water level. Sections of 5 cm were taken from the deepest part of the core (295-100 cm depth), while the upper part (100-13 cm depth), which shows more variation in lithology, was sectioned per centimeter. Eighteen sediment samples were removed from the core for diatom analysis. From the deepest part of the core, one sample per roughly every 20 centimeter was taken. From the shallowest part, one sample per roughly 10 centimeter was taken. Since the core consists of alternations between clayey and more organic layers, sampling took into account variations in sediment composition. A high resolution set of samples was taken from the upper, organic part of the core. Every centimeter in the interval from 39-29 centimeter depth was prepared for diatom analysis as well. Furthermore, two samples from water plants were taken from laguna Chicuacan for the identification of modern floras for reference data. Finally, samples from the core were prepared for pollen analysis by Kees Nooren.

Laboratory methods

First, the samples were freeze dried and weighed. The samples were treated subsequently with 10% hydrochloric acid, 30% hydrogen peroxide and 30% hydrochloric acid. Excess acid was removed by four sedimentation processes using deionized water. Afterwards, the samples were diluted with deionized water and evaporation trays (Battarbee, 1973) were used for the settling of diatoms on the coverslips. Permanent diatom slides were made using Naphrax®. Since the slides of laguna Chicuacan contained a lot of clastic material, heavy liquid separation was done using liquid with a density of 2.5 g/cm^3 in order to remove the excess of heavy particles. After sampling, the amount of organic material in the samples was estimated using Loss on Ignition (LOI) (Heiri et al., 2001; Dean, 1974). At the Royal Netherlands Institute for Sea Research (NIOZ), XRF analysis was performed using an Avaatech XRF core-scanner and magnetic susceptibility was measured on the top part of the core (98-13 cm). X-ray images from this part of the core were made as well.

Furthermore, seven samples were used for ^{14}C dating for the establishment of a detailed chronological framework. Dating was done using Accelerator Mass Spectrometry (AMS) radiocarbon dating at the Centre for Isotope Research in Groningen. The radiocarbon ages were calibrated using the IntCal 13 calibration curve (Reimer et al., 2013) within OxCal v.4.2.

Counting and identification

Diatoms were counted and identified at 500x magnification using an optical microscope. A minimum of 300 valves was counted per slide. All diatoms in the field of view were counted, moving along a horizontal traverse to the next field. A valve was only counted if it was for more than half in the field of view and if both the central area and one pole were recognizable. The poles of *Nitzschia spp.* and *Eunotia spp.* were counted and divided by two if the diatoms were incomplete. Standard diatom floras were used for classification of the diatoms (e.g. Krammer and Lange-Bertalot, (1991-1997) and Patrick and Reimer (1966 and 1975)). The software C2 (Juggins, 2003) was used to transfer the counts into a visual representation of the diatom abundances. Diatom taxa were assigned to environmental categories using ecological information given in literature.

Statistical methods

Principal Component Analysis (PCA) was performed on all the samples, taking the major species (>5% occurrence in at least one sample) of the record into account. The data were root square transformed before the analysis was performed, aiming to obtain a better spread of the values. Species values as well as sample scores were calculated. The axis values of axes 1 and 2 were plotted in stratigraphic order. This PCA analysis was applied to the records in order to create a zonation of the core. A description and overview of these PCA analyses can be found in appendix 8.

Results

Lithology

The deepest part of the core (295-100 cm) consists of clayey sediments. A darker, almost black interval is visible at a depth of 250-245 cm. The upper part of the core shows more variation. At 93 cm core depth, an abrupt transition from grey clayey material to black organic material is present. This organic material alternates with thick clayey intervals. This clay layers occur at the following depths: 73-68 cm; 62-60 cm; 50-40 cm. In appendix 9, the results from the XRF-analysis of the core are given. The XRF results show that aluminium concentrations are enhanced within the clay layers. Other elements like iron, silicon, titanium and potassium are enhanced as well. Nickel is also enhanced, except for the flood layer at 73-68 cm depth. Aluminium is primarily allogenic in most lakes and usually viewed as an indicator of clastic input and erosion intensity in the watershed (Jenny et al., 2002 op. cit. Engstrom and Wright, 1984). The clay intervals are for this reasons interpreted as flood layers.

Chronology

The radiocarbon-based chronology of the sediment core is measured on seven organic samples. The measured radiocarbon ages are shown in table 1. The establishment of an age-depth model (Fig.2) is complicated since the upper three radiocarbon samples show comparable ages. It is assumed that the flood layers are catastrophic events, indicating that similar ages of the sediment occur just below and above the flood layers, occurring in the upper two radiocarbon samples.

Table 1 Radiocarbon dates from laguna Chicuacan. Oxcal v.4.2.(IntCal13; Reimer et al., 2013) was used for the calibration of the measured 14C dates. Samples were analyzed at the Centre for Isotope Research in Groningen.

Name	Code	Depth (cm)	Material	14C yr BP	Cal yr AD (2σ)	Age in age model
Chic 39-40-L	63134	39.5	leaf fragments	145 ± 30	1668-1948	1950
Chic 49-50-L	63135	49.5	leaf fragments	265 ±30	1516-1950	1950
Chic 73-74-L	63433	73.5	leaf fragments	110 ±30	1681-1938	1800
Chic 73-74-T	64330	73.5	1 thorn	230 ± 35	1526-	1800
Chic 92-93-L	63137	92.5	leaf fragments	240±30	1526-	1660
Chic 185-190-S	64336	187.5	1 seed from an unidentified species	855±45	1043-1264	1211
Chic 240-245-L	63139	242.5	leaf fragments	935±30	1026-1162	094

Figure 2a and 2b show possible age-depth models for laguna Chicuacan. In figure 2b, a hiatus occurs at a core depth of 93 cm. This implies that almost 250 year would be missing in the sedimentary record. Figure 2a shows a model which lacks a hiatus. Both models show possible age-depth relationships. A hiatus could be possible since reconstructed lake levels are extremely low around 93 cm core depth and the lake probably expierenced swamp-like conditions. Therefore, constant sedimentation and preservation could be disturbed. However, since no clear evidence for the presence of hiatus has been observed, the model shown in figure 2a is assumed to show a correct age-depth relationship. The age-depth model shown in figure 2a is therefore used for the age interpretation of the sedimentary record.

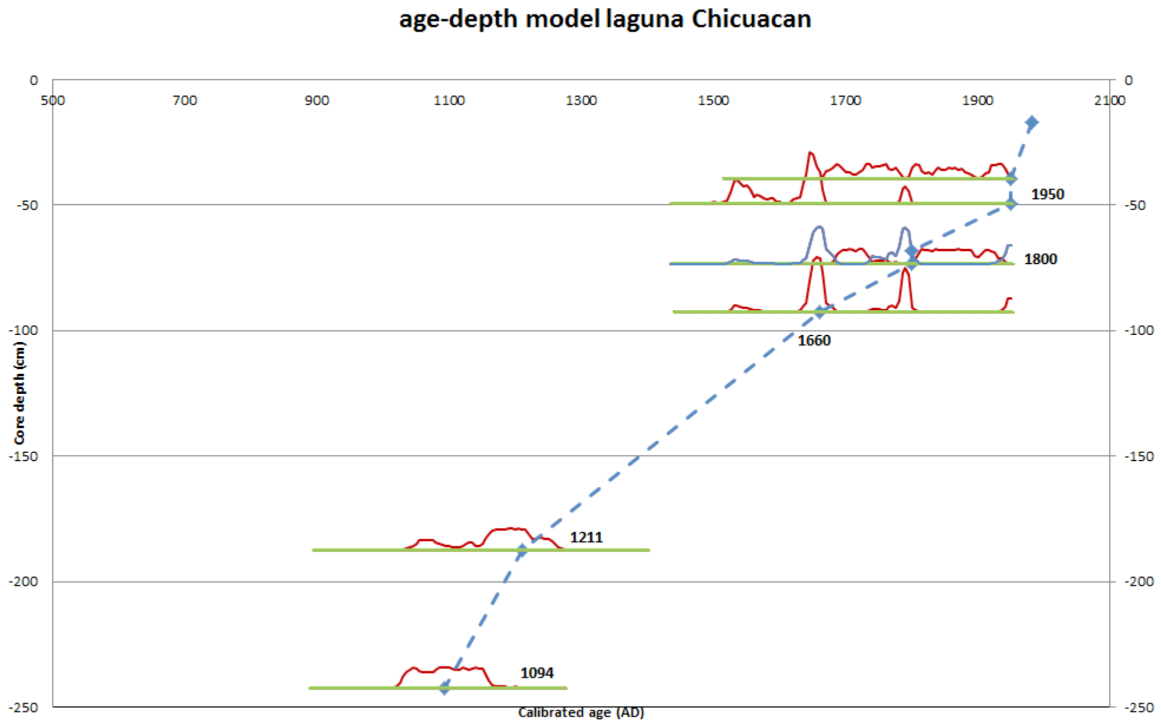

Fig. 2a Possible age-depth model for the sedimentary record from laguna Chicuacan. Red lines indicate the ^{14}C probability distribution. The purple line indicates the probability distribution for sample Chic 73-74-T.

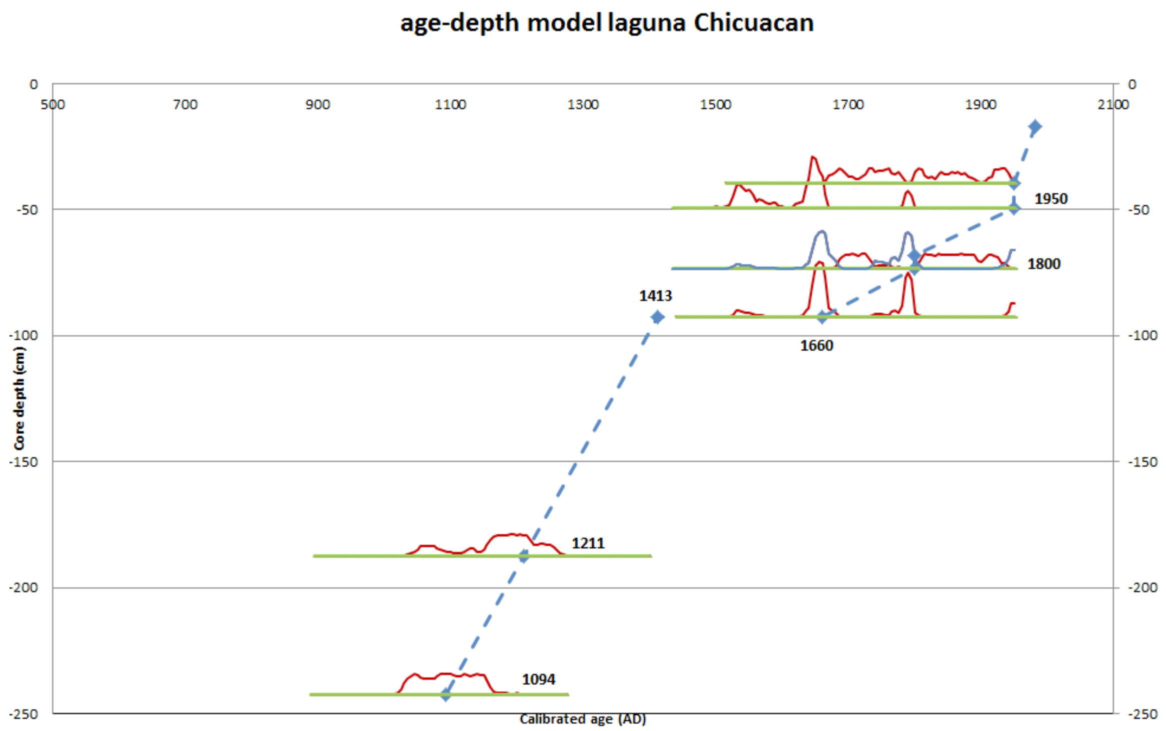

Fig. 2b Possible age-depth model for the sedimentary record from laguna Chicuacan. Red lines indicate the ^{14}C probability distribution. The purple line indicates the probability distribution from sample Chic 73-74-T.

Diatoms

Apart from the clayey flood layers, diatoms were found in almost all of the prepared samples and they were well preserved. A total of 103 diatom taxa was identified. A list and overview of all the taxa can be found in appendices 10, 11 and 13. The main diatom taxa present in this core (occurrence of >5% in a sample) are shown in Figure 3. In this figure, diatoms are ordered on the basis of the PCA, meaning that species that are placed together in figure 3 showed comparable axis values in the PCA biplot (appendix 8). Diatom zones are identified on the basis of the sample scores on the PCA axes and the chemical and lithological properties of the core (LOI and magnetic susceptibility), described in appendix 8. Grey intervals represent the flood layers within the sediment core. These layers correspond well to low (around 10%) LOI values and high magnetic susceptibility values.

Diatom zone 1 is characterized by high percentages of species belonging to the genera *Aulacoseira* and *Eunotia*. The abundance of *Aulacoseira* gradually declines in zone 2 until a depth of 100 cm. Zone 2 is characterized by a variety of diatom taxa. *Eunotia* species make up a significant percentage, as well as *Staurosira* species and Unknown 1. A description of this unknown species can be found in Appendix 14. The transition to zone 3 coincides with the shift in lithology, at 93 cm depth. Zone 3a is characterized by LOI values higher than 30% and a diatom assemblage consisting mainly of *Frustulia saxonica*, *Achnanthes brevipes, Navicula contenta* and *Eunotia* species. Diatom zone 3b is characterized by lower LOI values and the occurrence of some *Nitzschia* species. A gradual increase in *Aulacoseira* species is observed within zone 3 as well. Zone 4 consists mainly of *Aulacoseira* species, together with *Diadesmis confervacea* and *Achnanthes oblongella*. *Staurosira* and *Staurosirella* re-appear as well. Furthermore, a dramatic increase in diatom concentration is recorded in zone 4.

Modern flora

Vegetation on the Pleistocene terraces in the watershed consists mainly of *Terminalia amazonia* (Roble Coral Tropical Hardwood) and *Sweetia panamensis* (flowering tree, only found in Belize, Colombia, Mexico and Venezuela). Nowadays, the area surrounding the lake has been transformed to grassland and the lakeshore has been invaded by the non-native eutrophic species *Eichhornia crassipes*.
Vegetation at the lakeshore consists mainly of water ferns and water hyacinths. Two samples from a water fern and a water hyacinth were counted on diatom content. Modern diatom assemblages seem not to differ substantially from the fossil assemblages. Common species living on the vegetation are *Aulacoseira* and *Sellaphora pupula*. Besides, *Cymbella*, *Gomphonema* and *Diadesmis confervacea* are well represented. Species that are not very common in the modern flora, in contrast to the paleoflora, are *Eunotia camelus* and *Pinnularia* species. *Staurosira* and *Staurosirella* are also not very common in the modern flora. These species have been found on the water plants, but their occurrences do not reach a relative abundance of more than 5%.

Pollen and macro-remains

Phytoliths are present in the record below 250 cm depth, but pollen, spores and charcoal fragments are completely absent. Above 250 cm depth, low amounts of charred plant remains have been found, as well as a few *Cyperaceae*, *Cephalantus* and *Ludwigia* seeds. Above 93 cm depth, large amounts of *Hypomycetes* spores appear. Pollen content remains very low, but is dominated by *Cephalantus occidentalis* pollen. Concentration of charred plant fragments remains low as well. Above the flood layer between 73-68 cm depth, the percentage of *Cephalanthus* pollen gradually decreases, while the percentage of *Cyperaceae* pollen increases. Furthermore, pollen from *Cecropia*, *Trema*, *Celtis*, *Hyptis* and *Ambrosia* is present above this depth.

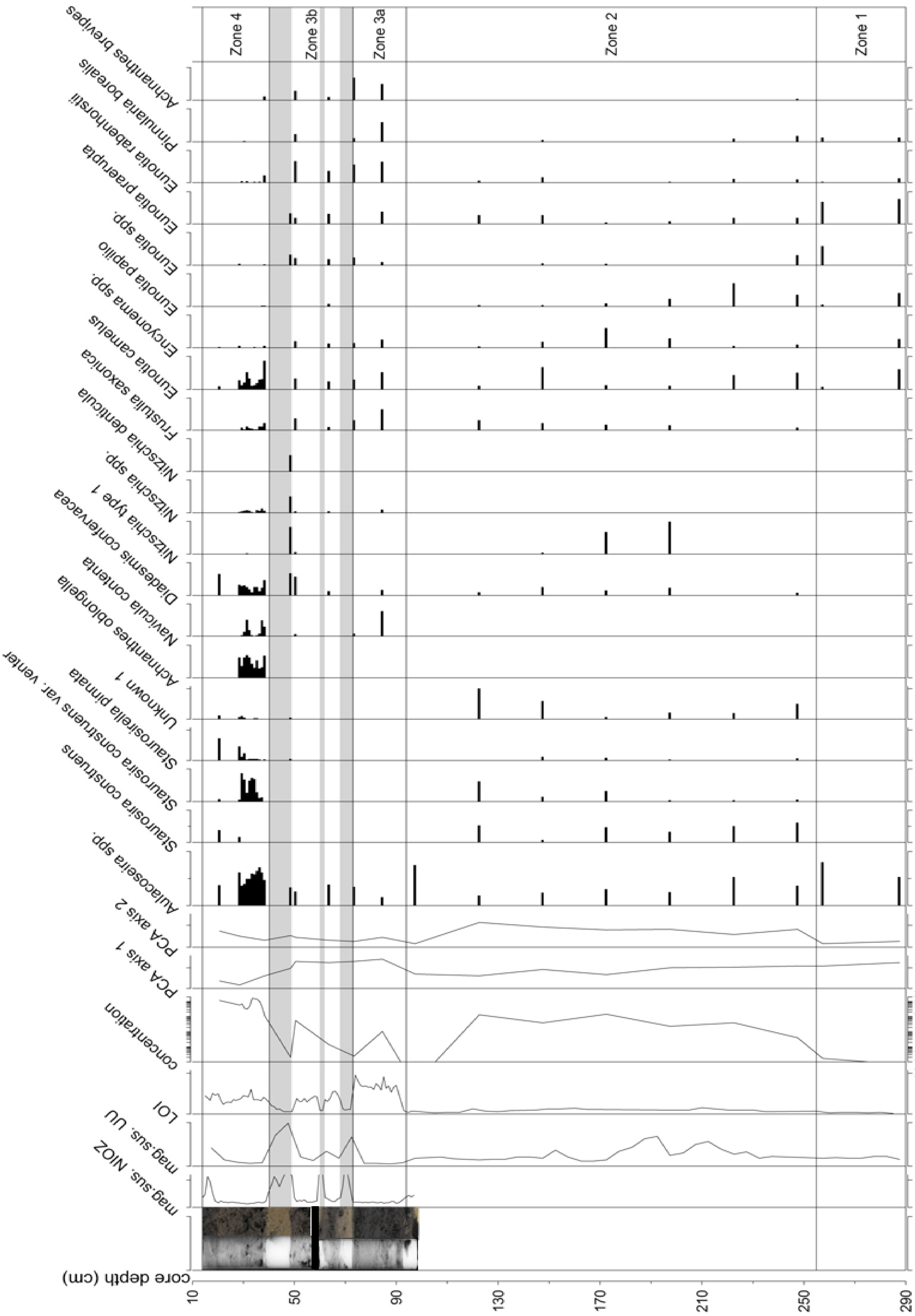

Fig. 3 Relative abundance of diatoms in the Chicuacan core. Depth is given in cm below water level. Diatom abundances are in percentages, concentration is given in million diatoms per gram dry sediment, plotted on logarithmic scale. Grey intervals are clayey intervals. A description of *Nitzschia type 1* can be found in appendix 15.

Interpretation and discussion

Each diatom zone is interpreted based on ecological information of the diatom species, according to literature. Zone 1 is characterized by an extremely high abundance of *Aulacoseira* species, together with some *Eunotia* species. Since the core lacks pollen below 250 cm (~ AD 1080), it is assumed that the lake had not formed before ~ AD 1080. This is supported by the diatom data. The diatom concentration is extremely low below 250 cm core depth and the occurrence of few species indicates that few diatoms have been preserved. Only the most resistant diatoms have preserved at this depth. *Aulacoseira* species show a strong resistance.

Diatom zone 2 is characterized by the occurrences of a lot of different diatom taxa. Pollen has been found in zone 2, indicating that a small lake had formed. Since *Aulacoseira* is a planktonic genus and prefers slightly deep and turbulent water (Kilham and Kilham, 1975; Owen and Crossley, 1992), fluctuations in *Aulacoseira spp.* abundances are interpreted as showing varying water depths. From 255-93 cm depth (~ AD 1080-1660), a gradual decline in *Aulacoseira* is observed, indicating a slight shallowing of the lake. This shallowing is presumably caused by a decrease in precipitation. Furthermore, *Aulacoseira* flourishes where nutrients are abundant. The high occurrences of *Aulacoseira* in the record indicate that *Aulacoseira* growth was not limited by nutrients, but occurrences of *Staurosira* and *Staurosirella* in zone 2 indicate that periods of enhanced nutrient supply have occurred, since these species prefer meso- to eutrophic conditions (Brenner et al., 1999; van Dam et al., 1994; Whitmore, 1989).

The transition of zone 2 to zone 3 coincides with a transition in lithology. Pollen analysis shows that at this time large amounts of *Hypomycetes* spores appear, gradually declining upwards. *Hypomycetes* are funghi, growing in a very shallow, swamp-like environment. The pollen content in this part of the core is very low, but *Cephalanthus* (small swamp shrubs) pollen is well represented. Zone 3a is therefore indicative of a very low lake level. This is supported by the relatively low *Aulacoseira* abundances, but also by the occurrence of *Achnanthes brevipes*. *Achnanthes brevipes* is a species that tolerates brackish waters (Smith, 2012). The low lake level might have increased the concentration of dissolved salts in the water, causing desirable conditions for *Achnanthes brevipes*. Above the occurrence of a flood layer between 73-68 cm depth (~AD 1800), the percentage *Cephalanthus* pollen gradually decreases while the percentage *Cyperaceae* pollen increases, indicating a gradual increase in water level since *Cyperaceae* generally grow in wet environments. This is also supported by a gradual increase in *Aulacoseira* species above this flood layer. An increased water level might be explained by the occurrences of La Niña-like events or shifts in the ITCZ, which are related to an increase in precipitation. Zone 3 is also characterized by high abundances of *Eunotia camelus*, which is a species preferring low to moderate pH and a reduction in nutrient concentrations (Vélez, 2005).

Zone 4 shows low magnetic susceptibility values, but very high diatom concentrations. This zone is characterized by the meso-eutrophic *Staurosira* and *Staurosirella* species, as well as *Diadesmis confervacea* and *Achnanthes oblongella*. The occurrence of *Staurosira* and *Staurosirella pinnata* as well as the high diatom concentrations, indicate that intensified nutrient supply to the lake has taken place. Furthermore, *Staurosira* species are indicators of shallow water (Bradbury, 1971; Metcalfe et al., 1997), suggesting that lake levels were still low, even though a slight lake level rise has taken place within zone 3b. Modern diatom flora consists of a slightly different diatom assemblage, compared to the assemblage in zone 4. In the modern flora, *Sellaphora*, *Aulacoseira* and *Gomphonema* are the dominant genera that have been observed. This suggests that the environmental conditions in zone 4 are not totally equal compared to current environmental lake conditions. However, the current presence of the eutrophic species *Eichhornia crassipes* (water hyacinth) on the lakeshore supports the hypothesis that laguna Chicuacan is a very eutrophic lake at present.

Lake level variation in laguna Chicuacan

The changes in diatom assemblages together with the occurrence of pollen, allows a rough lake level reconstruction of laguna Chicuacan. The decline in *Aulacoseira spp.* abundance from ~ AD 1080-1660 is regarded as a lowering of the lake level. The occurrence of *Hypomycetes* spores from ~ AD 1660 together with the occurrence of *Achnanthes brevipes* within zone 3a, supports the assumption that the lake experienced very shallow lake levels from ~ AD 1660. An increase in water level is noted in zone 3b, from AD 1800. Zone 4 is characterized by slightly increased lake levels. However, they were still low, indicated by the occurrences of *Staurosira* and *Staurosirella*. Zone 4 comprises the time interval from 1950 until recent, indicating that the lake level was comparable to the current lake level, which is approximately 1.6 meter at the deepest point.

Pérez et al. (2010) did a study to the recent lake level variations in Lago Petén Itzá, Guatemala. Lake levels since ~ AD 1500 were reconstructed, based on ostracod assemblages. Wet periods and high lake levels occurred in the early 1580s and around AD 1650. A shallowing in lake level from AD 1730-1850 was reconstructed, with lowest water depths occurring around AD 1800-1850. After this time period, a slight increase in lake level was noted and recent lake levels occur after 1950. This reconstruction shows some similarities to the reconstruction based on the sediments from laguna Chicuacan. However, lowest lake levels in laguna Chicuacan have been found already from AD 1660-1800, 100 years earlier than in Lago Petén Itza. Reasons for this offset are probably different precipitation rates between Guatemala and the Grijalva-watershed in Mexico. Different positions of the ITCZ might be responsible for varying precipitation rates. Furthermore, the core from Lago Petén Itzá was studied on much higher resolution than the core from laguna Chicuacan, allowing a very detailed lake level reconstruction.

Recent eutrophication in laguna Chicuacan

The occurrences of *Staurosira* and *Staurosirella pinnata* from 250-125 cm depth (~AD 1080-1505), indicate that several periods of enhanced nutrient supply to the lake have occurred. Since this part of the core lacks charcoal, anthropogenic activities are not supposed to be responsible for this nutrient supply. The extreme high abundances of *Staurosira* and *Staurosirella* in zone 4, from AD 1950 until recent, show recent eutrophication caused by anthropogenic activities. Pérez et al. (2010) concluded that recent cultural eutrophication started at ~AD 1930, inferred from geochemical data and chironomid abundances. Another study based on Lago Petén Itzá sediments was done by Rosenmeier et al. (2003). They showed that increased nutrient accumulation started at ~AD 1930 and intensified eutrophication occurred in the lake after AD 1965, based on elemental analyses. This was confirmed by the dominance of eutrophic and hypereutrophic diatom species at that time. The authors keep agricultural activities as well as ranching and commercial logging operations responsible for this eutrophication.

An allocation plan, the Plan la Chontalpa, named after the village of Chontalpa (appendix 5) nearby laguna Chicuacan, was developed by the Mexican federal government in the 1960s. Aim of this plan was to develop the hydroelectric potential of the rivers in the area and to promote agricultural activities. For these reasons, 60,000 hectares of land were deforested and turned into farm lands. Furthermore, roads, bridges and new villages were built (Tortajada and Contreras-Moreno, 2007). The implementation of this plan has probably led to extremely high erosion rates in the Grijalva watershed, leading to enhanced recent eutrophication of laguna Chicuacan.

Suggestions for further research

The Chicuacan record shows promising information about the late Holocene environmental conditions in the Grijalva watershed. In order to provide a more detailed lake level reconstruction, additional samples could be studied on diatom content. Especially the deepest part of the core could be studied in more detail. Furthermore, laguna Chicuacan is the one of the two lakes in the watershed that has been studied in great detail. Other lakes might provide valuable information about the late Holocene environmental change in the area as well. Not only diatoms and pollen could be studied, but also other proxies like oxygen isotope data. Furthermore, transfer functions for Mexican diatoms are still under construction, but could possibly be applied to this data. The use of transfer functions could provide new insights in the climatic and environmental development of the Grijalva watershed.

Conclusions

The results from this study show recent environmental changes in the Grijalva watershed, based on lake sediments from laguna Chicuacan. Laguna Chicuacan has been formed since ~ AD 1080. Since the formation, shallowing of the lake has taken place. Around AD 1660, the lake experienced its shallowest conditions. Possible cause for this low lake level is a dry climate. From ~AD 1800, water level increased, caused by increased precipitation presumably related to shifts in the ITCZ. The reconstructed lake levels correspond quite well to lake level reconstructions in Guatemala, however timing of maximum droughts is slightly offset. Furthermore, laguna Chicuacan has experienced several periods of enhanced nutrient supply. Recent eutrophication since AD 1950 is caused by anthropogenic activities. The use of transfer-functions or a multiproxy study in this area may give further clarification on the paleoenvironment of the Grijalva delta during the past 950 years.

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References

Battarbee, R.W. (1973). A new method for the estimation of absolute microfossil numbers, with reference especially to diatoms. *Limnology and Oceanography* 18, 647-653.

Bradbury, J.P. (1971). Paleolimnology of lake Texcoco, Mexico. Evidence from diatoms. *Limnology and Oceanography* 16, 180-200.

Brenner, M., Whitmore, T. J., Lasi, M. A., Cable, J. E., and Cable, P. H. (1999). A multi-proxy trophic state reconstruction for shallow Orange Lake, Florida, USA: Possible influence of macrophytes on limnetic nutrient concentrations. *Journal of Paleolimnology* 21 (2), 215–233.

Curtis, J. A., and Hodell, D. A. (1996). Climate Variability on the Yucatan Peninsula (Mexico) during the past 3500 Years , and implications for Maya cultural evolution. *Quaternary Research* 47, 37–47.

van Dam, H., Mertens, A., and Sinkeldam, J. (1994). A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. *Netherlands Journal of Aquatic Ecology* 28 (1), 117–133.

Dean W.E. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of sedimentary petrology* 44, 242–248.

Douglas, P. M. J., Pagani, M., Canuto, M. A., Brenner, M., Hodell, D. A., Eglinton, T. I. and Curtis, J. H. (2015). Drought, agricultural adaptation, and sociopolitical collapse in the Maya Lowlands. *Proceedings of the National Academy of Science* 112 (18), 5607-5612.

Engstrom, D.R. and Wright, H.E. (1984). Chemical stratigraphy of lake sediments as a record of environ mental change. In: Haworth, E.Y., Lund, J.G. (Eds.), Lake sediments and environmental history. Leicester University Press, Leicester, UK, 11–67.

Espinosa, M.A. (1994). Diatom paleoecology of the Mar Chiquita lagoon delta, Argentina. *Journal of Paleolimnology* 10, 17-23.

Haug, G. H., Gunther, D., Peterson, L. C., Sigman, D. M., Hughen, K. A., and Aeschlimann, B. (2003). Climate and the collapse of Maya Civilization. *Science* 299, 1731-1735.

Heiri, O., Lotter, A. F., and Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology* 25 (1), 101–110.

Jenny, B., Valero-Garcés, B.L., Urrutia, R., Kelts, K., Veit, H., Appleby, P.G. and Geyh, M (2002). Moisture changes and fluctuations of the westerlies in Mediterranean Central Chile during the last 2000 years: The Laguna Aculeo record (33˚50'S). *Quaternary international* 87, 3-18.

Juggins, S. (2003). C2 User guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle upon Tyne, pp.1-72.

Kilham, S. S. and Kilham, P. (1975). Melosira granulata (Ehr.) Ralfs: morphology and ecology of a cosmopolitan freshwater diatom. *Verhandlungen des internationalen Verein Limnologie* 19, 2716-2721.

Krammer, K., Lange-Bertalot, H. (1991–1997). Bacillariophyceae süsswasserflora von Mitteleuropa, vol. 2. Fischer, Stuttgart.

Magaña, V. O., Vázquez, J. L., Párez, J. L., and Pérez and J. B. (2003). Impact of El Niño on precipitation in Mexico. *Geofisica Internacional* 42 (3), 313–330.

Metcalfe S.E., Bimpson A., Courtice A.J., O'Hara S.L. and Taylor D.M. (1997). Climate change at the monsoon/Westerly boundary in northern Mexico. *Journal of paleolimnology* 17, 155–171.

Metcalfe, S. E., O'Hara, S. L., Caballero, M., and Davies, S. J. (2000). Records of Late Pleistocene-Holocene climatic change in Mexico - A review. *Quaternary Science Reviews* 19 (7), 699–721.

Owen, R. B., and Crossley, R. (1992). Spatial and temporal distribution of diatoms in sediments of Lake Malawi, Central Africa, and ecological implications. *Journal of Paleolimnology* 7 (1), 55–71.

Patrick, R. (1977). Ecology of freshwater diatoms and diatom communities. In: The Biology of Diatoms (ed. D. Werner). Biological Monographs vol. 13. Blackwell Scientific Publications, Oxford, 284-332.

Patrick, R. and Reimer, C.W. (1966). The Diatoms of the United States, vol. 1. Academy of Natural Sciences of Philadelphia, Philadelphia.

Patrick, R. Reimer, C.W. (1975). The Diatoms of the United States, vol. 2. Part 1. Academy of Natural Sciences of Philadelphia, Philadelphia.

Rao, V.S. (1977). An ecological study of three freshwter ponds of Hyderabad-India IV. The phytoplankton (Diatoms, Eugleninae and Myxophyceae). *Hydrobiologia* 53 (1), 13-32.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hattz, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and van der Plicht, J. (2013). IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years cal BP. *Radiocarbon*, 55(4).

Rhoda, R. and Burton, T. (2010). Geo-Mexico; the geography and dynamics of modern Mexico. Sombrero Books, Vancouver, Canada.

Smith, K.E.L. (2012). Paleoecological study of coastal marsh in the chenier plain, Louisiana: Investigating the diatom composition of hurricane-deposited sediments and diatom-based quantitative recon struction of sea-level characteristics. University of Florida, 203 pp.

Tortajada (Fellow), C. and Conteras-Moreno, N. (2007). Institutions for River Basin Development in Mexico, 1947-1986. *Water International* 32 (1), 91-104.

Vélez, M. I., Hooghiemstra, H. and Metcalfe, S.E. (2005). Fossil and modern diatom assemblages from the savanna lake El Pinal, Colombia: An environmental reconstruction. *Diatom research* 20 (2), 387-407.

Wahl, D., Byrne, R., and Anderson, L. (2014). An 8700 year paleoclimate reconstruction from the southern Maya lowlands. *Quaternary Science Reviews* 103, 19–25.

Whitmore, T. J., (1989). Florida diatom assemblages as indicators of trophic state and pH. *Limnology and Oceanography* 34, 882– 895.

You, Q., Kociolek, J.P. and Wang, Q. (2015). Taxonomic studies of the diatom genus Halamphora (Bacillariophyceae) from the mountainous regions of southwest China, including the description of two new species. *Phytotaxa* 205 (2), 75-89.

Oxcal software retrieved on 09-11-2015 from: http://c14.arch.ox.ac.uk/oxcal.html.

Servicio Meteorológico Nacional, Mapas Diarios de Temperaturas y Lluvia, retrieved on 06-11-2015 from: http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=12:temperaturas-y-llu via&catid=12:climatologia&Itemid=77.

Appendices: Table of contents

Appendix 1: Description of the four studied lakes

In order to investigate environmental and climatic changes in the Grijalva watershed, a total of four lacustrine cores was studied. Two of these cores have been studied in great detail. During a fieldwork in the Usumacinta-Grijalva delta in June 2013, one lake (laguna Cantemual) was cored. One of the goals of the fieldwork in Mexico in March 2015, was to core a supplementary lake that could provide a climate record for the late Holocene (~past 6000 years). The lake had to be located in the Grijalva watershed in the state of Tabasco, Mexico. The fieldwork of 2015 has resulted in sediment cores from three different lakes; laguna Chicuacan, laguna del Rosario and laguna de los Limones. This meant that four lacustrine cores from Tabasco, Mexico could be used for climate and environmental reconstruction. Figure 1 shows the location of these four lakes.

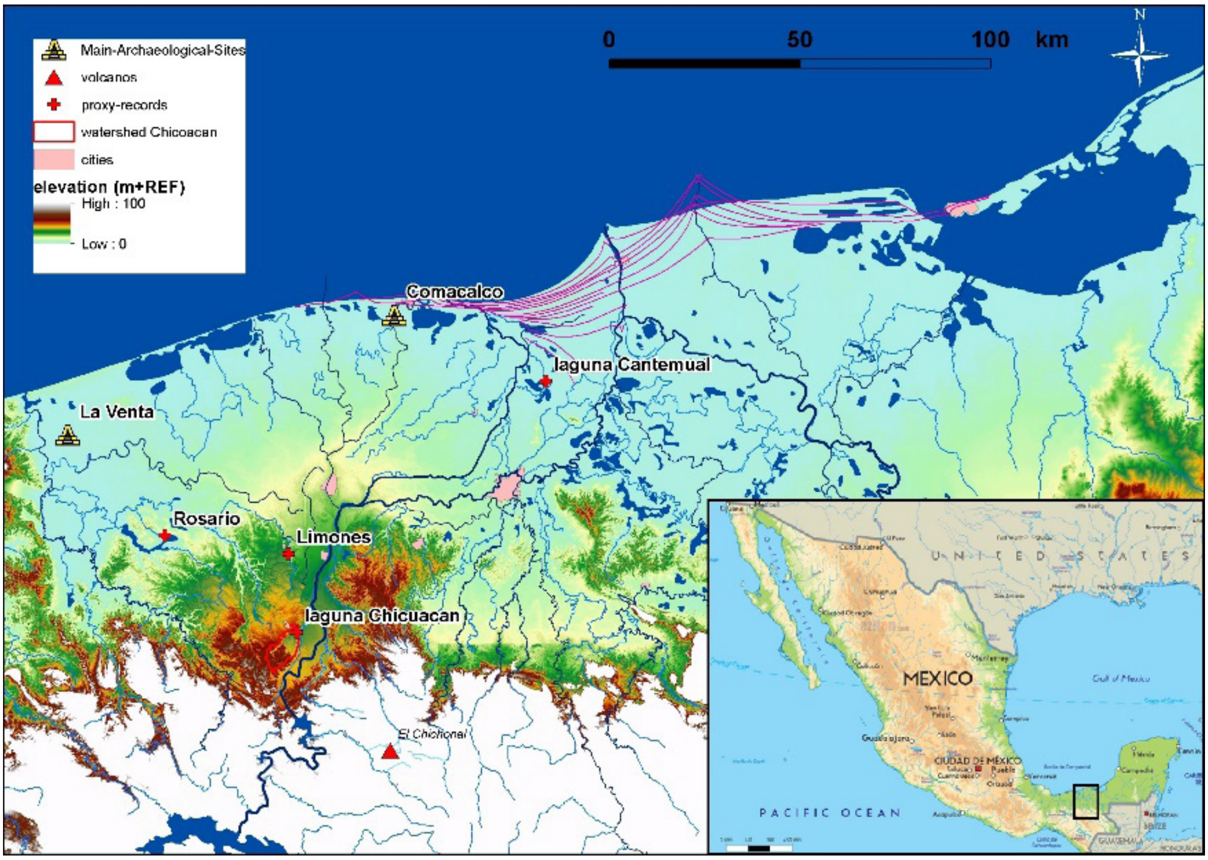


Fig. 1 Locations of the four lakes are marked with a red cross. Bottom right: Overview of Mexico, area of interest is marked with the black square.

The environmental reconstruction was mainly done on the basis of diatom content of the cores. From laguna Chicuacan and laguna Cantemual however, also sediment characteristics were measured using XRF-analysis and pollen analysis was performed. The records from laguna Chicuacan and Cantemual were chosen for detailed analysis, since the sedimentary records were supposed to be long enough to cover the time period of interest. For this reason, the analyses done on the cores from laguna del Rosario and laguna de los Limones are limited.The coring, sampling and diatom content of the lacustrine records will be discussed in the next appendices.

Appendix 2: Laguna del Rosario

Site description

Laguna del Rosario (17˚52”39’N, 93˚47”03’W) is situated in the western part of the Tabasco state and located 4 m above sea level. The depth of the lake varies from 1.5 m near the lakeshore to a maximum of 3.0 m in the center of the lake. The lakeshore and the water are covered by a lot of vegetation. Four dominant types of vegetation could be distinguished in and around the lake. Water ferns and *Ludwigia sedioides* (Mosaic flower) are growing in the lake. Especially *Ludwigia sedioides* is extremely dominant. Along the lakeshore, marsh plants and cane are growing (Fig 2).

Fig. 2 From left to right: *Ludwigia sedioides* (yellow flowers) and water fern, marsh plant and cane.

Methods

A core of 90 cm was recovered from the bottom of the lake at a depth of 1.80 m below water level. The core was subsampled in 2 cm sections in the field. Five samples from the core were prepared in the laboratory for diatom analysis. These samples were taken from the following depths: 87 cm, 67 cm, 47 cm, 27 cm and 7 cm below water level. Furthermore, four samples from the four types of vegetation and a water sample were prepared for diatom analysis. Chemical preparation of the samples was done as described on page 5 of this thesis. Diatoms in the samples were not counted but quickly identified in order to observe the major changes in diatom assemblages. Radiocarbon dating was done as described on page 5.

Results

Lithology and chronology

The sediment of the core consists of uniform dark brown/black organic material. Since this core was initially supposed to be too short to provide a 6000 year old detailed climate record, this record was not chosen to be analyzed in great detail. However, one radiocarbon date from this core was measured. At a depth of 85 cm, a radiocarbon age of 5320 ± 40 was measured. Since only one radiocarbon date was obtained, an age depth model could not be constructed. However, this measured age probably corresponds to an age between 4316 and 4042 (2σ) calibrated years B.C. (Fig 5).

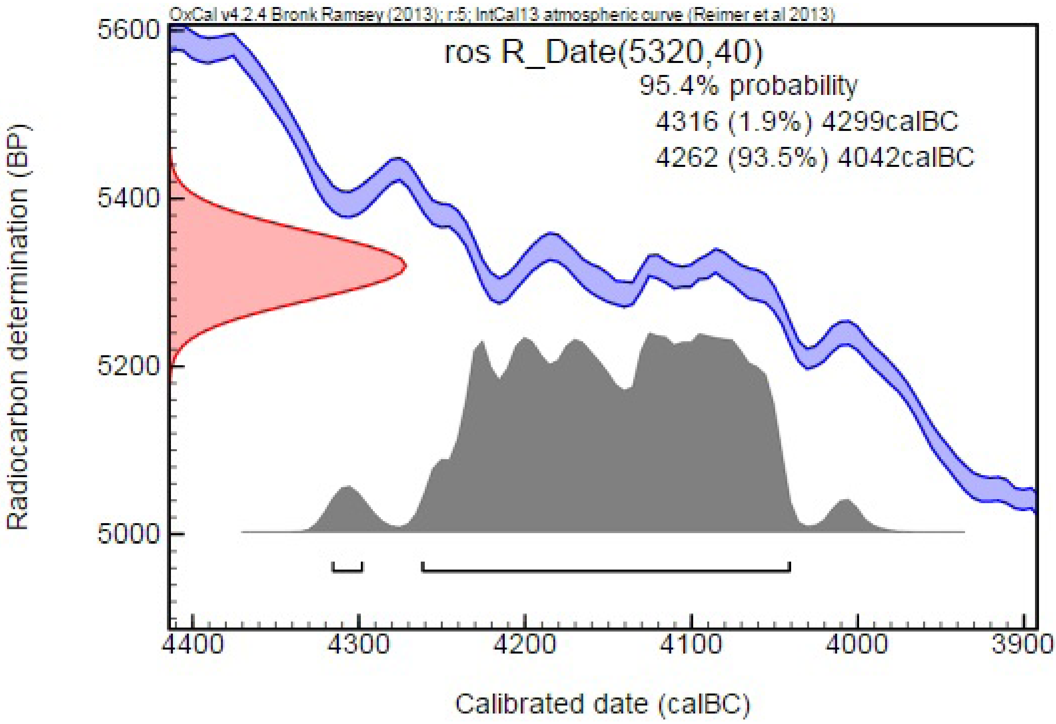


Fig. 3 Calibrated radiocarbon age from laguna del Rosario.

Diatoms

Diatoms were well preserved in the prepared samples, but hardly visible since a lot of organic material was still present in the sediment samples after chemical preparation. The concentration of diatoms in the sample taken from the *Ludwigia sedioides* was extremely high. The assemblage consists mostly of *Gomphonema* and *Cymbella* species. The other three samples from the plants (cane, fern and swamp vegetation) are very similar to each other. Concentrations of diatoms is low in all three samples and *Gomphonema*, *Cymbella*, *Eunotia* and *Pinnularia* make up the assemblage. The deepest sample of the core (87 cm) contains too much organic material in order to identify any diatoms. Sample 67 contains a lot of diatoms which are well preserved. Major genera in this sample are *Eunotia*, *Frustulia*, *Gomphonema* and *Aulacoseira*. Sample 47 shows a high concentration of diatoms as well, but the diatoms are obscured by a lot of organic material. Sample 27 is comparable to sample 67, showing a high diatom concentration and a variety of diatom species. The concentration of diatoms in the shallowest sample (7 cm) is extremely high. Diatoms are well preserved and a lot of different taxa are present amongst which *Gomphonema*, *Aulacoseira*, *Neidium*, *Sellaphora*, *Surrirella* and some large *Pinnularia*. The water sample lacks diatoms.

Appendix 3: Laguna de los Limones

Site description

Laguna de los Limones (17˚50”04’N, 93˚28”43’W) is situated ten kilometer west of the town of Huimanguillo and located 24 m above sea level. Water depth at the coring location is 0.8 m. Both length and width of the lake are approximately 600 m.

Methods

A sediment core was recovered from the bottom of the lake at a depth of 0.8 m below lake level. The length of the sediment core was almost 25 cm. The core was sectioned in the laboratory in sections of 1 cm. Four samples were removed from the core for diatom analysis; at 19.5 cm, 14.5 cm, 9.5 cm and 4.5 cm below lake level. Furthermore, a sample from the water was taken and sieved at 8 µm. Chemical preparation of the samples was done as described on page 5.

Results

Lithology and chronology

The sediment of the core consists of uniform grey clayey material. Radiocarbon dates from the core were not measured.

Diatoms

Since the record of laguna de los Limones was not expected to cover the time period of interest, the diatom content of the samples was quickly determined. The prepared water sample lacks diatoms. Sample 19.5 and 14.5 are comparable: A lot of diatom fragments are present in these samples, but the presence of clastic material hinders a detailed identification of the diatoms. Major genera that could be identified were *Eunotia*, *Sellaphora*, *Gomphonema* and *Cymbella*. Diatom concentration increases slightly in sample 9.5. Mainly *Aulacoseira* are present, but also *Pinnularia*, *Eunotia*, *Surrirella* and *Gomphonema*. The concentration of diatoms in sample 4.5 is extremely high in contrast to the deeper samples. Especially *Aulacoseira* species are abundant. Other identified genera are *Pinnularia* and *Sellaphora*.

Appendix 4: Laguna Cantemual

Site description

Laguna Cantemual (18˚14"38'N, 92˚50"27'W, 1 m.a.s.l.) is situated in the Usumacinta-Grijalva delta, approximately 20 kilometers out of the coastline. The lake is very shallow with a maximum depth of 1.5 m. Length of the lake is approximately 4 kilometers and maximum width is 2.5 kilometers.

Methods

Coring of the lake was done in June 2013. A core of almost 3.5 m was recovered near the central part of this lake, taken at a depth of 1.20 m below water level. Due to an inconsistency in the registration of the core depth, a core depth of 55 cm corresponds to the top of the core, consisting of sediment directly below the water level. Ten 1 cm-samples from laguna Cantemual were chosen for diatom analysis. Since the deepest part of the core from Laguna Cantemual lacks diatoms (appendix 6), analysis was concentrated on the upper 60 cm of the core, from 115-55 cm core depth. One sample in approximately every 5 cm was chosen for diatom analysis The samples were chemically prepared as described on page 5 of this thesis and counted according to the method described at page 5 of this thesis. LOI of the core was measured and XRF analysis was done at the NIOZ. Furthermore, X-ray images were made at the NIOZ as well. Five samples were chosen for the measuring of radiocarbon dates. PCA analysis was performed on the samples as described on page 5. Finally, samples from both cores were prepared for pollen analysis, performed by Kees Nooren.

Results

Lithology

The core of laguna Cantemual is characterized by alternations between organic layers and layers containing more clayey material. The boundaries between these intervals however are not very sharp. Organic intervals have an LOI value above 60%, while the more clayey intervals have an LOI around 35%. In the shallowest part of the record that was used for diatom analysis, a distinct interval with clastic material is present. The clayey intervals above this distinct interval are less clear, except for a clear clayey interval around 88 cm depth (Fig. 5).

Chronology

Five radiocarbon dates from laguna Cantemual are measured. The measured dates can be found in table 1. An age-depth model for the core can be found in Figure 4.

Table 1 Radiocarbon dates from laguna Cantemual

Name	Code	Depth (cm)	Material	14C yr BP	Cal yr BC/ AD 2σ	Age in age model
Lca 172-173-S	62996	107	Seed (1 Passifloraceae)	1220 ± 40	684-892 (AD)	830 AD
Lca 194-195-S	62958	144	Seeds (22 Cladium, 20 Asteraceae seeds)	1385 ± 30	605-676 (AD)	650 AD
Lca 232-233-S	62959	182	Seeds (17 Cladium ,1 Asteraceae)	2425 ± 30	749-403 (BC)	460 BC
Lca 338-350-S	64315	344	Seeds (26 Asteraceae)	4095 ± 50	2872-2493 (BC)	2600 BC
Lca 420-425-L	62960	422.5	leaf fragments	4190 ± 35	2892-2666 (BC)	2800 BC

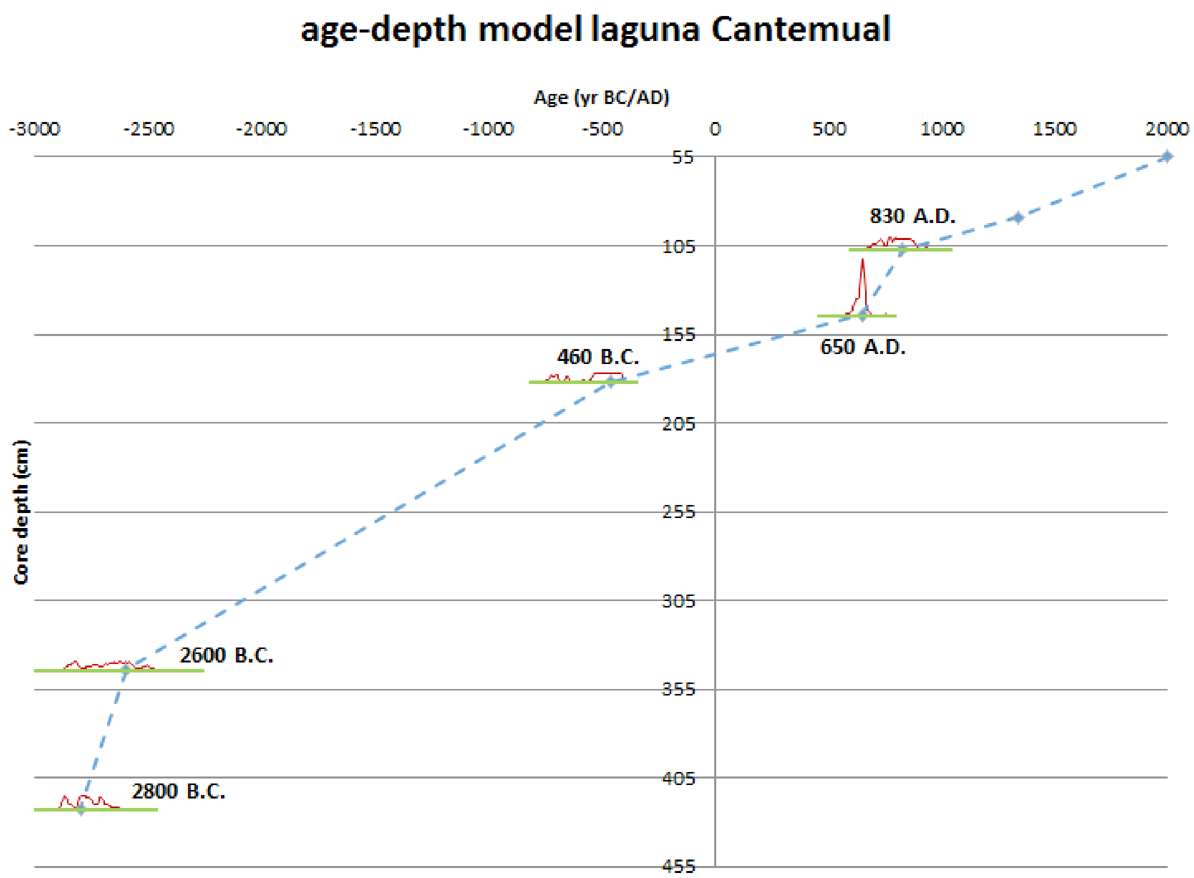


Fig. 4 Age-depth model for laguna Cantemual. Red lines indicate the ^{14}C probability distribution.

Diatoms

Diatoms were well preserved in all prepared samples. A total of 87 diatom taxa was identified. A list and overview of all the taxa can be found in appendices 12 and 13. The relative abundances of the main taxa (>2% at a certain depth) are given in Figure 5. Zonation is based on the sample scores on PCA axis 1 and 2 and on changes in magnetic susceptibility and LOI (appendix 8). Zone 1 consists mainly of *Aulacoseira* species, together with a minor abundance of *Rhopalodia musculus*. The assemblage shifts in zone 2a to an assemblage consisting of various species, amongst which *Halamphora coffeaeformis*, *Cyclotella meneghiniana*, *Diadesmis confervacea* and *Nitzschia spp*. are abundant. A clear maximum in magnetic susceptibility is observed at a depth of 88.5 cm. At the same time, diatom concentration increases dramatically. In zone 2b, *Sellaphora pupula*, *Navicula elginensis* and *Diploneis spp*. appear in larger percentages. Diatom zone 3 is mainly dominated by *Staurosira* species and *Staurosirella pinnata*.

Pollen and macro-remains

Until a depth of 111 cm (~AD 810), vegetation on the lakeshore consists of *Poaceae* (grass), *Cyperaceae* (cypergrass) and *Typha* (bulrush). At 111 cm core depth, a sudden transition in pollen content is observed. Pollen at this depth is mainly mangrove pollen and *Acrostichum* ferns. Charcoal is present in the core below 111 cm depth, the core lacks charcoal above this depth.

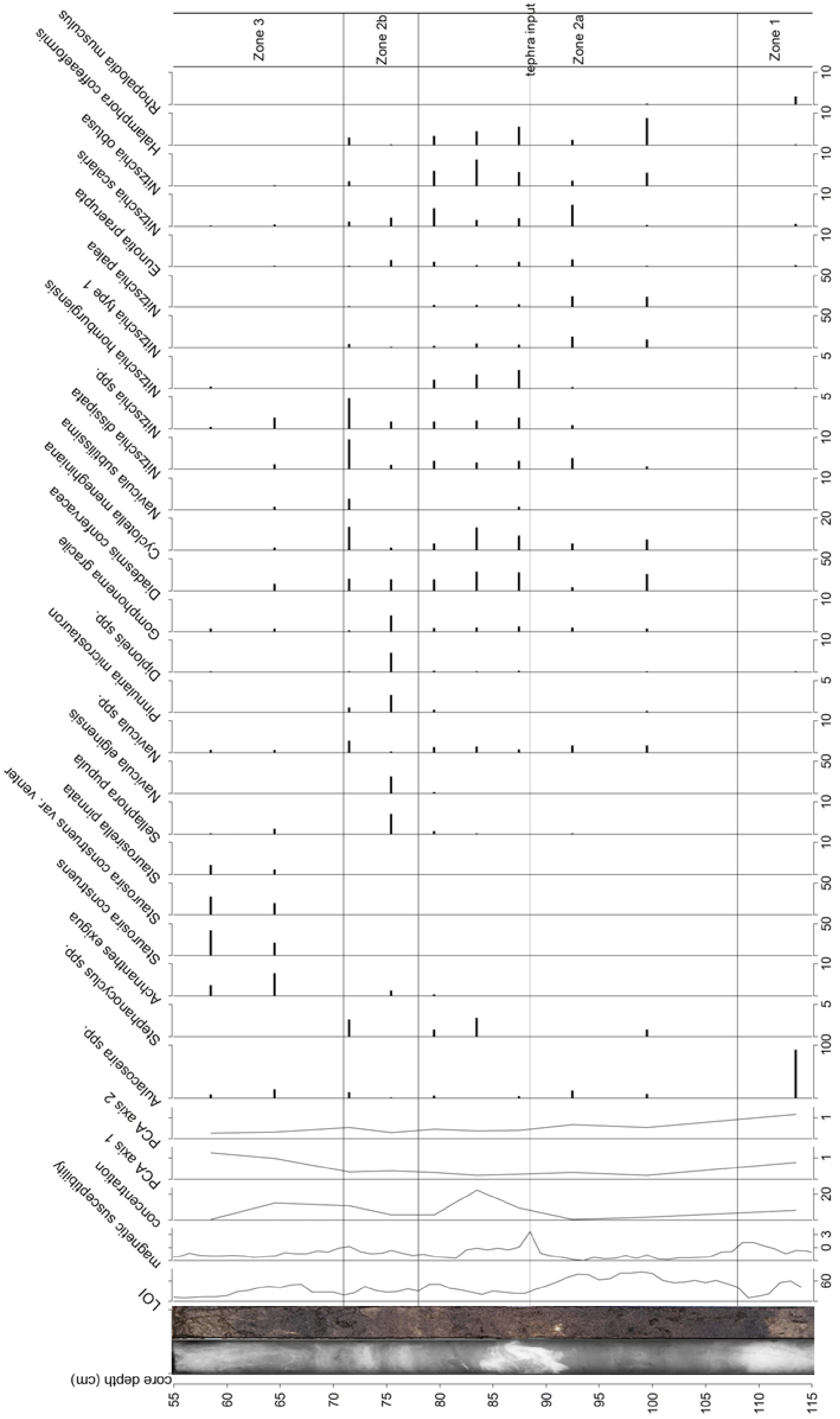


Fig. 5 Abundance of diatoms in the Cantemual core, including diatom zonation. Diatom abundances are in percentages, concentration is given in million diatoms per gram dry sediment. 55 cm depth corresponds to the top of the core, directly below water level.

Interpretation

Variations in diatom content of laguna Cantemual are probably caused by changes in salinity of the water, based on the presence of brackish- and fresh water preferring diatoms. Since the lake is situated in a coastal area, input of brackish and/or salt water is reasonable.

Diatom zone 1 comprises one sample that almost totally consists of *Aulacoseira* species. Another species that is represented in this sample is *Rhopalodia musculus*. *Rhopalodia musculus* prefers brackish water (Espinosa, 1994; Smith, 2012). The lithology of zone 1 is characterized by clayey material. The transition of zone 1 to zone 2a is dated at approximately AD 830. This means that zone 1 comprises the Classic Maya Period, the time interval in which the Maya culture flourished and the Maya were widespread over the area. This anthropogenic influence in the area is confirmed by the presence of charcoal in the record. The clayey material however, is probably deposited by the Samario-Gonzalez River. The course of this river was close to laguna Cantemual during this time interval. At the transition of zone 1 to zone 2, there is a shift from clastic to organic material in the core. This indicates that the river was less active after this transition. Indeed, indications for an avulsion of the Samario-Gonzalez River have been found in the beach ridges at the coast of the Gulf of Mexico (Nooren, in prep.). This avulsion might have initiated inflow of saline waters from the Gulf of Mexico to the lake. This avulsion probably started already before AD 830, allowing the inflow of saline waters already before this time. This explains the occurrence of *Rhopalodia musculus* in zone 1. At the transition of zone 1 to zone 2, the Samario-Gonzalez River had shifted its channel, indicated by the presence of organic material and the common presence of species that tolerate saline waters like *Halamphora coffeaeformis* and *Nitzschia obtusa* (You, 2015; Rao, 1977) in zone 2. This avulsion coincides with the Classic Maya Collapse, supported by a lack of charcoal in zone 2. The salinization of the lake probably hindered the surrounding agricultural activities, leaving the Maya people no choice than to abandon the lake.

Zone 2a is characterized by a major peak in magnetic susceptibility at 88.5 cm depth (Fig 5). In the sample just above this depth, a lot of tephra has been found. This indicates that a major volcanic eruption occurred around AD 1350, probably originating from the El Chichón volcano, located more than hundred kilometers south of Laguna Cantemual. After this tephra input, the total concentration of diatoms increases dramatically. Diatoms are favored by nutrient and especially silica input, explaining the increase in diatom concentration. In zone 2b, the water of the lake becomes less saline. The saline tolerant species are gradually replaced by fresh water species like *Sellaphora pupula* and *Gomphonema gracile* (Mann and Droop, 1996 op. cit. Gasse, 1986; Sanchéz et al., 2002). This inflow of fresh water again might be initiated by closure of the coast.

Diatom zone 3 of laguna Cantemual shows some similarities with zone 4 of laguna Chicuacan. Zone 3 is characterized by high abundances of *Staurosira spp.* and *Staurosirella pinnata*, indicating eutrophic conditions, probably caused by recent anthropogenic activities.

Appendix 5: Images of laguna Chicuacan

The following images show the measured water depths of laguna Chicuacan and the catchment area of the lake in more detail. Figure 6 shows the transect at which water depths have been measured. The image shows clearly a lot of vegetation in the lake. At the time of coring however, less vegetation was present in the lake. Figure 7 shows the catchment area of the lake with the corresponding elevations.

Fig. 6 Depth measuring points in Laguna Chicuacan. Depths are given in meters. The red dot represents the coring location.

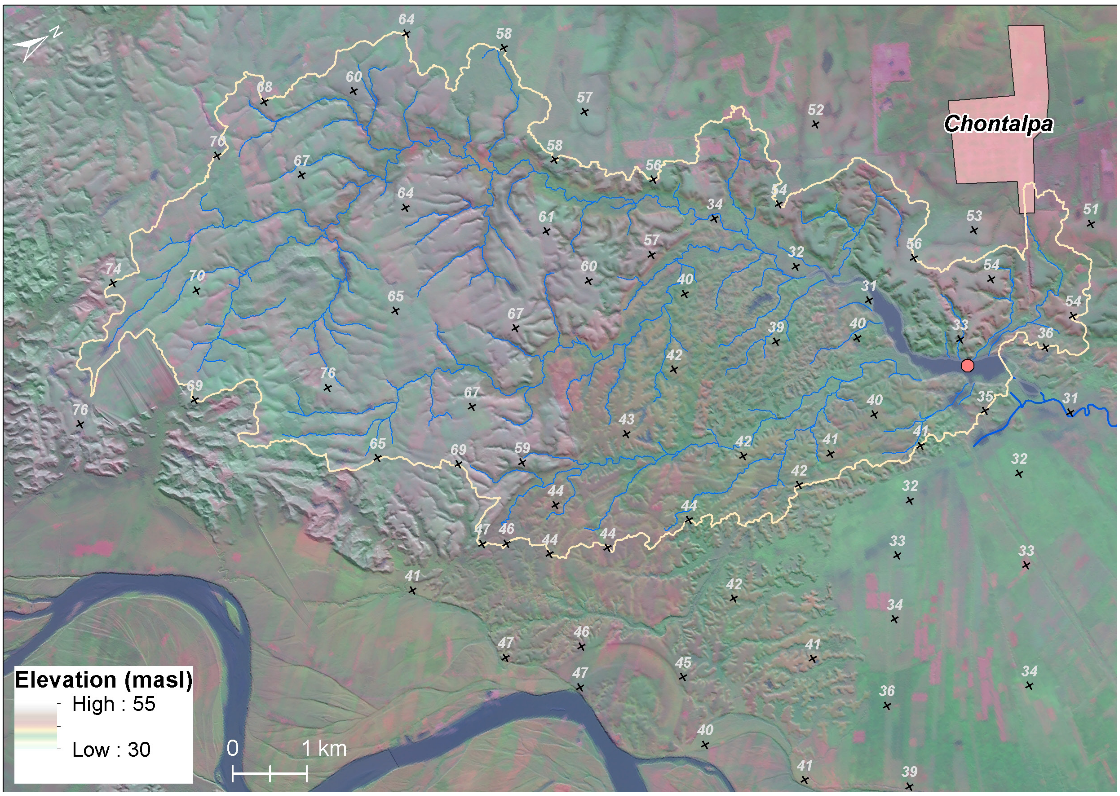


Fig. 7 Catchment area of laguna Chicuacan.

Appendix 6: Use of LOI residues for diatom extraction

Diatoms can be directly extracted from the dry or wet lacustrine sediment using chemical preparation techniques. However, diatoms could possibly be extracted from the LOI residues as well, meaning that fewer samples have to be removed from the sediment core. From laguna Cantemual, diatoms were extracted in both ways.

Methods

All the diatoms in the samples from laguna Cantemual and laguna Chicuacan that were counted, were chemically prepared using the method described on page 5 of this thesis. Freeze dried sediment samples were used for this preparation. From laguna Cantemual however, a total of 27 samples (at approximately every 5 cm) were at first prepared using the LOI residues instead of the freeze dried sediment samples. A few drops of HCl were added to this residues in order to dilute the present carbonates. Furthermore, H_2O_2 was added. Afterwards, samples were warmed in a water bath and prepared using the technique of Battarbee (1973). These samples were very quickly analyzed using an optical microscope, 500 times magnification.

Results

The samples taken at a depth below 115 cm, hardly contained any diatoms or even lacked diatoms. However, sponge needles and tephra particles were present in these samples. Shallower samples (115-55 cm core depth) contained diatoms, indicating that a warming of 500 ˚C in the oven does not destroy all diatoms. Although a lot of diatoms were broken and incomplete, they were still recognizable. These shallowest samples contained a lot of diatoms as well as tephra fragments. The shallow interval in the core that contained diatoms was therefore chosen for further sampling and chemical extraction of the diatoms. Since a lot of diatoms were broken and since not all samples could be prepared using the LOI residues (some clayey samples were turned into 'brick' after heating in the oven, making diatom extraction impossible), freeze dried sediment samples were preferred for the preparation of the final diatom slides.

Appendix 7: Diatoms as proxy for paleo-environment

Diatoms are often used in paleo-environmental studies. They are widely used for a couple of reasons. At first, diatoms are relatively easy to recognize. They are one of the best characterized microalgae groups because of their unique features. Besides, their cell wall is made of silica, which can preserve very well. Thirdly, the first diatoms already appeared in the Triassic age. Since then, the diatom classes have diverged and diatoms became widespread algae. This means that diatoms can be used in paleo-environmental studies concerning different time periods. Last and perhaps most important reason is the fact that diatoms very quickly adapt to changing environmental conditions. Diatoms respond to different limnological parameters like water depth, salinity, pH, conductivity, nutrient availability, turbidity and temperature. Hence, interpretation of diatom assemblages must be done carefully. It might not be always clear what parameter was responsible for the changing assemblages and often a combination of the parameters influences the assemblages. Nevertheless, diatoms have proven to be successful in reconstructing past environments.

References

Anderson, J.N. (2000). Miniview: Diatoms, temperature and climatic change, *European Journal of Phycology,* 35 (4), 307-314.

Medlin, L.K. (2009). Diatoms. From: The Timetree of Life. New York: Oxford University Press, 2009. 572 pp.

Appendix 8: Principal Component Analysis (PCA) and diatom zonation

Figure 8 and figure 10 show the results of the PCA, performed on both cores. Vectors represent the species, the samples are represented by the blue dots. Acute angles between two vectors indicate a positive relation between both species, obtuse angles indicate a negative correlation.

Laguna Chicuacan

Correlation

Figure 8 shows the results of the PCA. The biplot of axis 1 versus axis 2 is shown. A clarification of the abbreviations is given in table 2. The biplot indicates that *Staurosira construens var. venter*, *Staurosirella pinnata* and *Diadesmis confervacea* are positively correlated to each other. Also *Staurosira construens* and Unkown 1 are positively related to these species. These species are all positively correlated with axis 2. In contrast, *Aulacoseira* together with *Achnanthes oblongella* is negatively associated with both axes 1 and 2. *Aulacoseira* plots in the biplot almost orthogonal to *Staurosira construens* and Unkown 1, indicating that there is hardly any relation between these species. The species that is most positively correlated to *Aulacoseira* is *Navicula contenta*. Furthermore, *Eunotia* species plot close to each other, indicating that a positive relation exists amongst the *Eunotia* species.

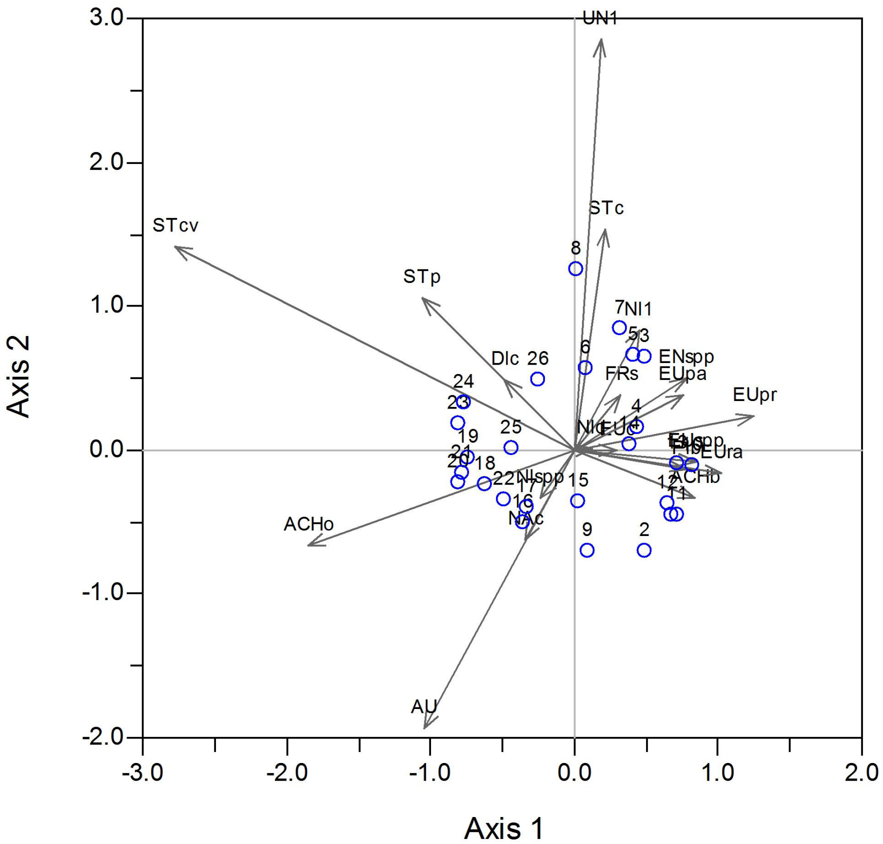


Fig. 8 PCA-biplot for laguna Chicuacan. Species with an occurrence of more than 5% are incorporated in the analysis. Eigenvalues λ for axis 1 and 2 are respectively 0.30 and 0.24.

Table 2 Abbreviations and sample numbers

Abbreviation	Species	Sample nr.	Core depth (cm)
ACHo	*Achnanthes oblongella*	1	287.5
AU	*Aulacoseira spp.*	2	257.5
STc	*Staurosira construens*	3	247.5
STcv	*Staurosira construens var. venter*	4	222.5
STp	*Staurosirella pinnata*	5	197.5
Achb	*Achnanthes brevipes*	6	172.5
NAc	*Navicula contenta*	7	147.5
Enspp	*Encyonema spp.*	8	122.5
UN1	*Unknown 1*	9	97.5
DIc	*Diadesmis confervacea*	10	84.5
EUspp	*Eunotia spp.*	11	73.5
EUpa	*Eunotia papilio*	12	63.5
Eupr	*Eunotia praerupta*	13	50.5
EUc	*Eunotia camelus*	14	48.5
EUra	*Eunotia rabenhorstii*	15	38.5
FRs	*Frustulia saxonica*	16	37.5
NIspp	*Nitzschia spp.*	17	36.5
PIb	*Pinnularia borealis*	18	35.5
NI1	*Nitzschia type 1*	19	34.5
NId	*Nitzschia denticula*	20	33.5
		21	32.5
		22	31.5
		23	30.5
		24	29.5
		25	28.5
		26	20.5

Zonation

The record of laguna Chicuacan is subdivided into 4 diatom zones. The boundary between zones 1 and 2 is positioned at the base of an increase in values on PCA axis 2 at a depth of 255 cm (Fig 9). The boundary between zone 2 and 3a (93 cm depth) is based on the lithology. At this boundary, the sudden transition between clay and organic material occurs. Also PCA axis 1 shows higher values above this depth. The transition to zone 3b at 73 cm depth is placed at the transition from high (>30%) to lower LOI values. PCA values for axis 1 are constantly high in zone 3. Zone 4 starts at the point where the values for PCA axis 2 increase at a depth of 40 cm.

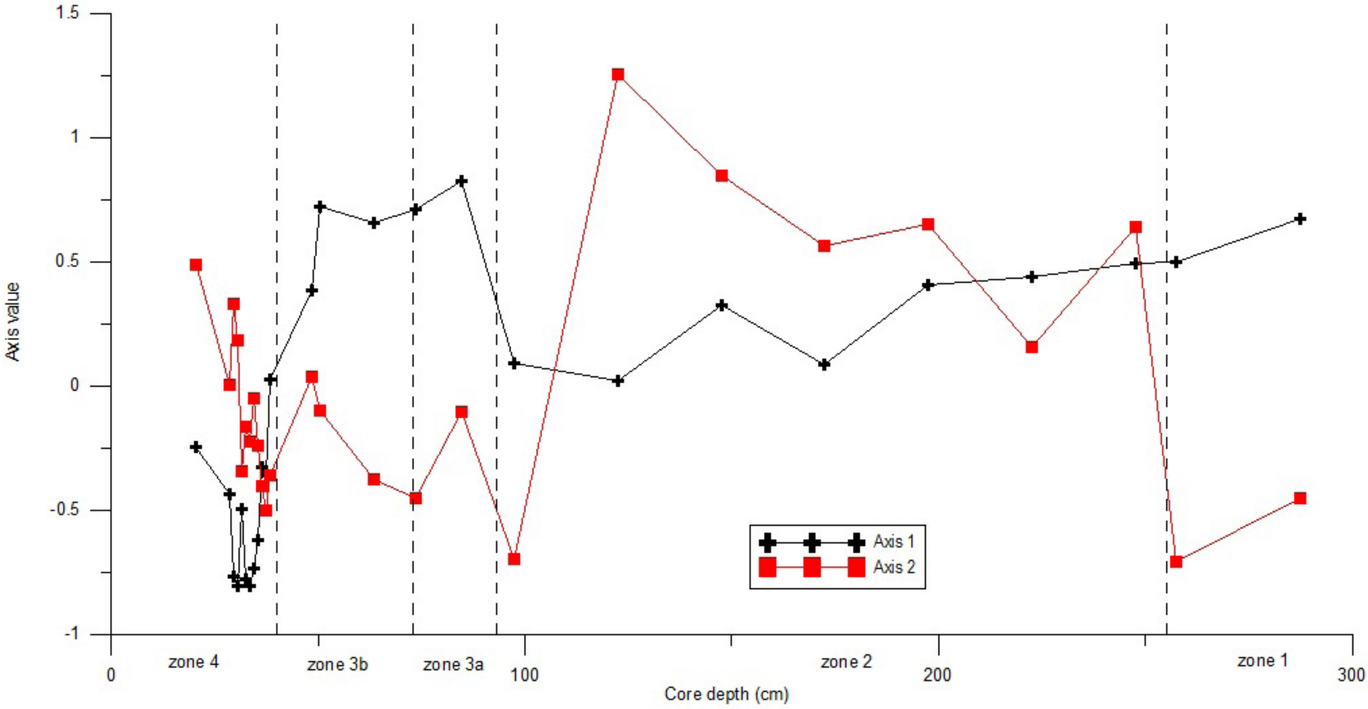


Fig. 9 Values of PCA axes 1 and 2 plotted in stratigraphic order. The dotted lines represent the zone boundaries.

Laguna Cantemual

Correlation

In figure 10, the biplot of axis 1 versus axis 2 is shown. A clarification of the abbreviations and sample numbers is given in table 3. *Aulacoseira* seems mainly to be positively associated with axis 2. In the biplot, *Aulacoseira* shows a strong positive correlation with *Rhopalodia musculus*. The angle between the vectors representing *Staurosira construens*, *Staurosira construens var. venter* and *Staurosirella pinnata* is 0, indicating that these species are extremely positive correlated to each other. Furthermore, *Nitzschia* species plot close to each other, indicating that the *Nitzschia* species are positively correlated.

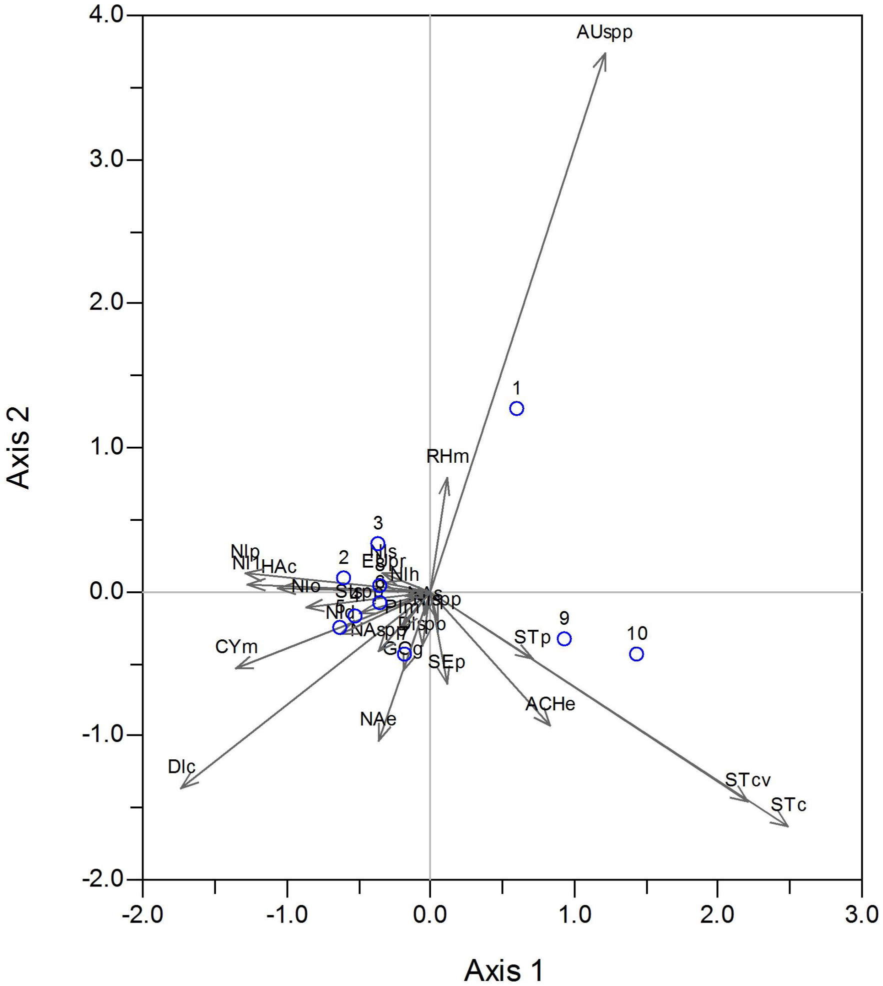


Fig. 10 PCA-biplot for laguna Cantemual. Species with an occurrence of more than 2% are incorporated in the analysis. Eigenvalues λ for axis 1 and 2 are respectively 0.49 and 0.24.

Table 3 Abbreviations and sample numbers.

Abbreviation	Species	Sample nr.	Depth (cm)
CYm	*Cyclotella meneghiniana*	1	113.5
AU	*Aulacoseira spp.*	2	99.5
STc	*Staurosira construens*	3	92.5
STcv	*Staurosira construens var. venter*	4	87.5
STp	*Staurosirella pinnata*	5	83.5
ACHe	*Achnanthes exigua*	6	79.5
HAc	*Halamphora coffeae-formis*	7	75.5
DIspp	*Diploneis spp.*	8	71.5
GOg	*Gomphonema gracile*	9	64.5
DIc	*Diadesmis confervacea*	10	58.5
EUpr	*Eunotia praerupta*		
NAspp	*Navicula spp.*		
NAs	*Navicula subtillissima*		
NIs	*Nitzschia scalaris*		
NI1	*Nitzschia type 1*		
NIo	*Nitzschia obtusa*		
NIp	*Nitzschia palea*		
NAe	*Navicula elginensis*		
RHm	*Rhopalodia musculus*		
SEp	*Sellaphora pupula*		

Zonation

The record of laguna Cantemual is subdivided into 3 diatom zones. The boundary between zones 1 and 2a (108 cm depth) is positioned on the base of an increase in LOI values, reaching values around 60%. The boundary between zone 2a and 2b is purely based on the diatom content. Above this boundary at 78 cm depth, *Sellaphora pupula*, *Navicula elginensis* and *Diploneis spp.* appear. The boundary from zone 2b to zone 3 (71 cm depth) is based on the values of both PCA axes. Axis 1 shows increasing values in zone 3, while axis 2 shows decreasing values (Fig. 11).

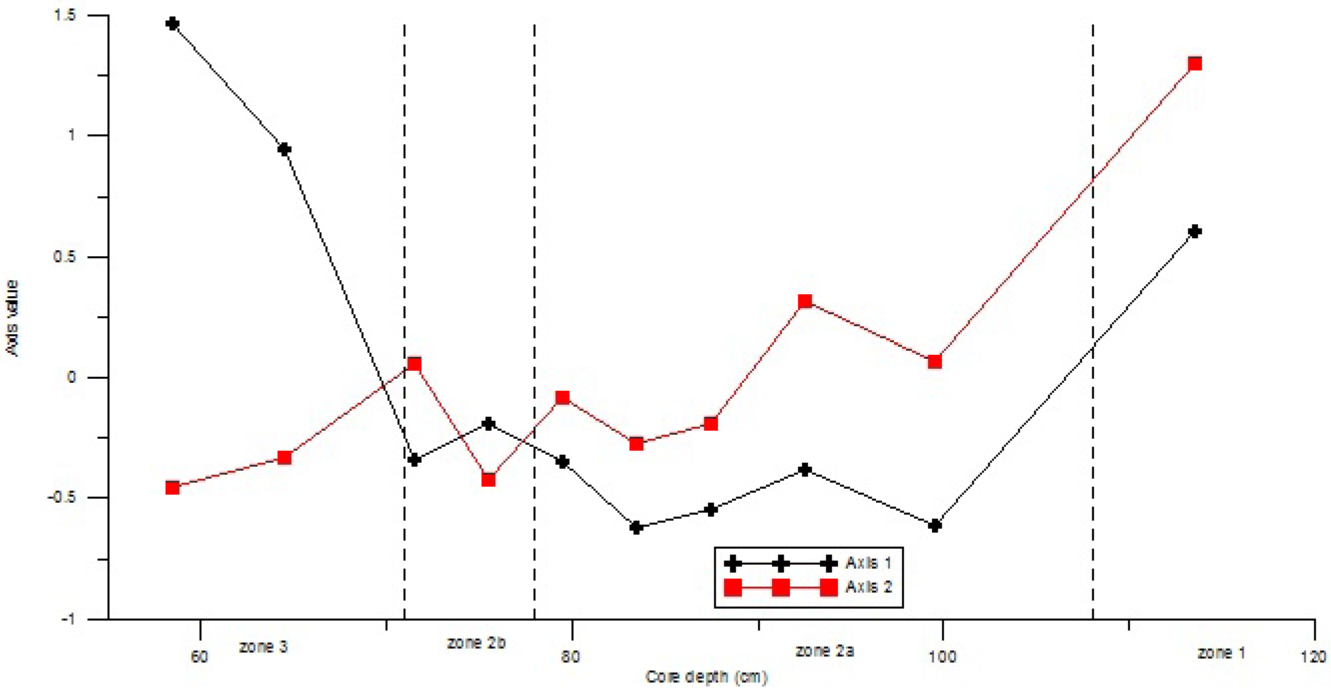


Fig. 11 Values of PCA axes 1 and 2 plotted in stratigraphic order. The dotted lines represent the zone boundaries.

Appendix 9: X-Ray Fluorescence (XRF) analysis

Laguna Chicuacan

Figure 12 shows the results from the XRF analysis that was performed at the NIOZ in May 2015. It is clearly visible that the flood layers contain increased values of aluminium and some other metals like nickel and zinc.

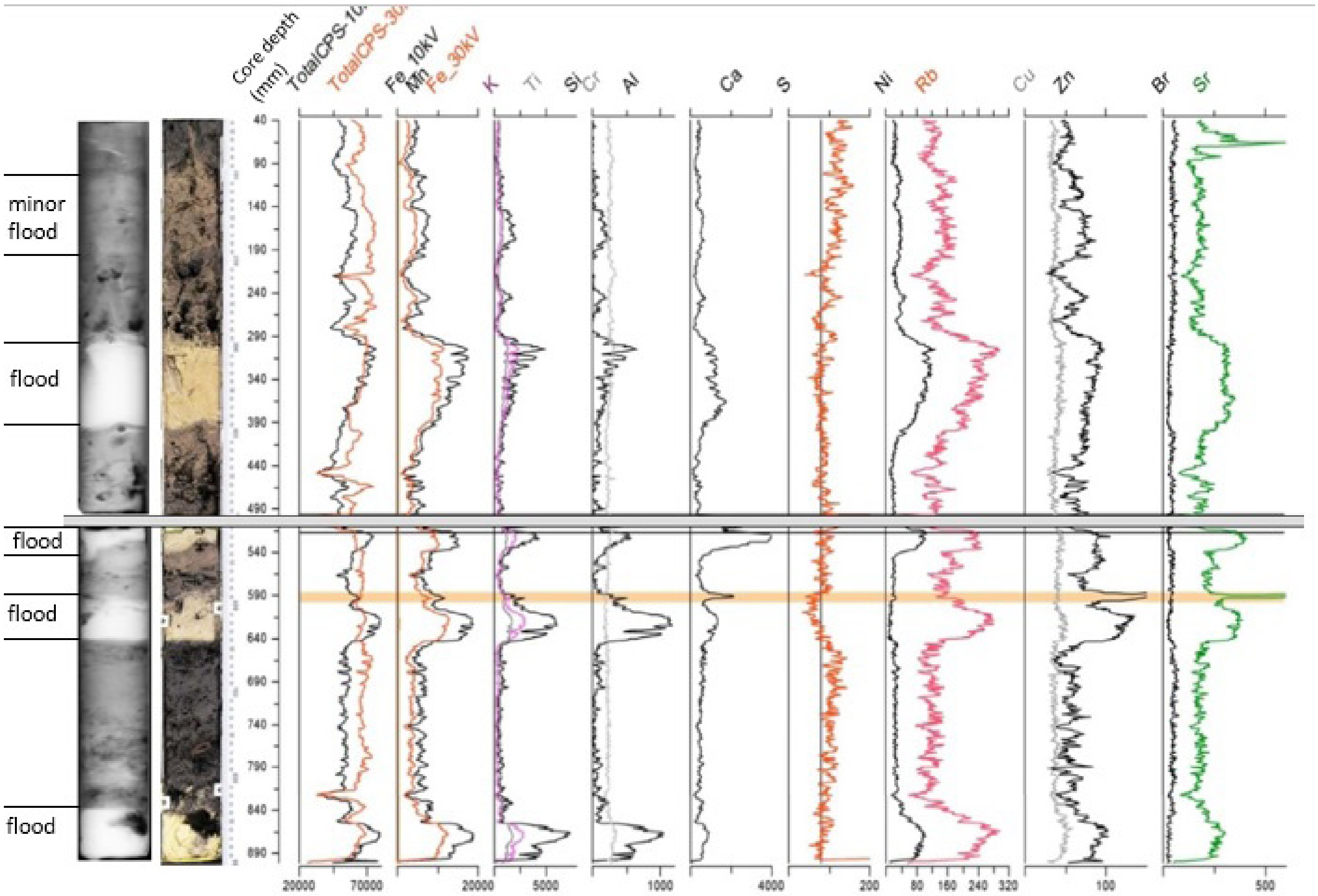


Fig. 12 XRF results from laguna Chicuacan. Top of the core (40 mm) corresponds to a depth of 13 cm below water level. Figure made by Kees Nooren.

Laguna Cantemual

Figure 13 shows the results of the XRF analysis from the upper part of the Cantemual core. The lighter intervals are enhanced with several elements amongst which silicon and strontium. Furthermore, tephra particles have been observed in the samples at 87.5 cm and 83.5 cm depth. The yellow bar is therefore regarded to show a tephra layer. Since no tephra has been found in the deepest and shallowest samples, the other white intervals in the core are not supposed to be tephra layers but small flood layers possibly deposited by the Samario-Gonzalez River.

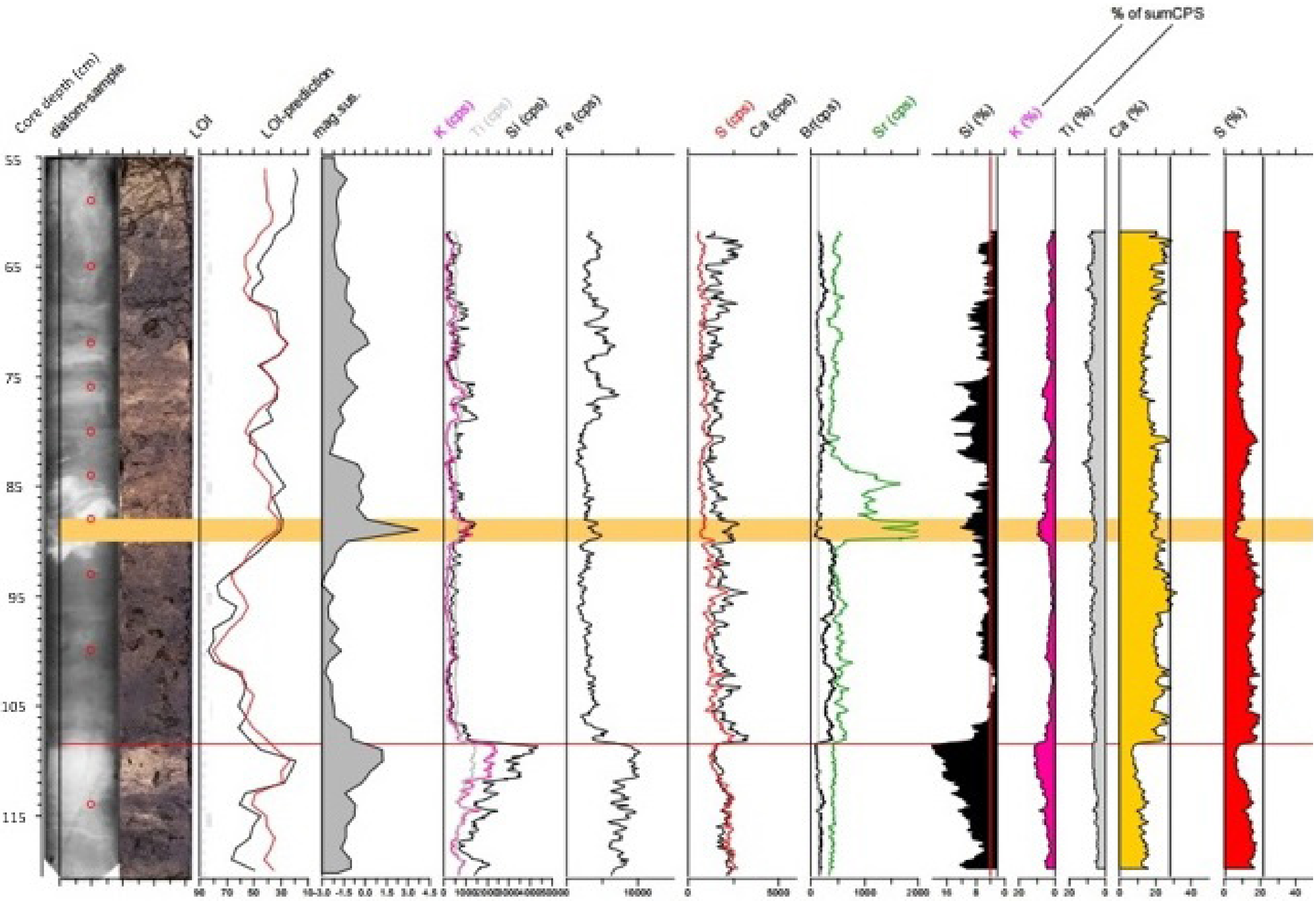


Fig. 13 XRF results from laguna Cantemual. A depth of 55 cm corresponds to the top of the core, which is directly below water level. Figure made by Kees Nooren.

Appendix 10: Raw diatom counts laguna Chicuacan

Table 4 Raw counts from laguna Chicuacan. Samples are given in cm core depth.

Genus	Species	287.5	257.5	247.5	222.5	197.5	172.5	147.5	122.5	97.5	84.5	73.5	63.5	50.5	48.5	38.5	28.5	20.5
Aulacoseira		74	229	131	6										20	222	345	241
	ambigua				118	41	86	84	41	3	52	57	113	93				
	granulata (italica)				83	52	36	41	36		49	28	24	12				
Terpsinoe	musica			1														
Cyclotella	meneghin-iana										1			2			1	
Staurosira	spp.				9	4	12											
	construens			22	14	9	14	5	21								10	25
	construens var. venter			7	3	5	32	24	74		3			1		3	12	18
Staurosire-lla	pinnata			8	3	5	10	21	1		1			1	1	4	80	138
Achnantes	inflata	1	2	2	1	1		3	1		8		4	2				
	exigua			4	4	8	9	11	4					3		5	2	25
	brevipes			2							31	18	4	12		6		
Navicula	contenta										47	2		3		14	1	1
Anomoneis	sphaerofor-ma										2	2			1			
Brachysira	brebissonii											1						
Encyonema	spp.	4		4	3	11	24	10	2		16	4	5	8		3	4	2
Cymbella	spp.				2	6		1						1		6		
Craticula	cuspidata					1	1		1									
Unknown 1				55	24	24	8	99	120		2			1	1	5	13	23
Diadesmis	confervacea			3		9	6	13	4		11		5	23	4	22	19	42
Denticula	sp.														3			
Diploneis	spp.			2	4	8	8	1		1	8	3	4	1		2		5
Epithemia	adnata					3												
	turgida							1										

Table 4 continued

Genus	Species	287.5	257.5	247.5	222.5	197.5	172.5	147.5	122.5	97.5	84.5	73.5	63.5	50.5	48.5	38.5	28.5	20.5
Eunotia	spp.		17	11	1		2	4	1		6	6	7	9	2	2	3	
	camelus	13	4	27	26	7	8	53	7		48	12	13	20		61	24	10
	papilio	6	2	13	28	9	4	3	2				3	1		2		
	praerupta	11	20	7	8	3	2	14	11		24		11	8	2	1	1	1
	type 1	5	1		5			2				3				1		1
	minor	2		4	6	5		6	5		27	8	17	7		4		
	diadema	1	1	1	2						16	4	1					
	type 2					7	2	2	4		8	1		5		4		
	type 3					4	6	9	5		16	8	12	12		5	3	3
	flexuosa	1											5	2	1		1	
	formica	4		6	2	1	3	1	2		3	2						
	rabenhorstii	2	1	4	5	1		9	3		41	15	13	27		11		
	triodon					1												
	ventriosa var. brevis										3			5		5	1	1
	zygodon	1		1	1	1	1				4	1	1	3			1	1
	soleirolli												3	2		2		
	veneris													16		2	2	1
Frustulia	saxonica			3		6	7	12	13		40	8	4	15		11	1	1
Gompho-nema	gracile	1			2	3		1	3					1		2	2	
	affine			4				2			9	6						
	parvulum					6	1	2			1	3						
	angustum						4											
	sp.												2					
Gomph-osphenia	sp.					1		2	1									
Hippodonta	capitata														1			
Halampho-ra	coffeae-formis															1		
Mastogloia	sp.															1		
Navicula	type 1														1	1	1	5
	type 2													1		1	2	
	elginensis			1	2	2	5		2		10	2		2	2	3	3	6

Table 4 continued

Genus	Species	287.5	257.5	247.5	222.5	197.5	172.5	147.5	122.5	97.5	84.5	73.5	63.5	50.5	48.5	38.5	28.5	20.5
Neidium	dubium	2			3	1	3		1		2		2	1			3	5
Hantzschia	abundans	2						3				2			1	2	1	
	cf. elongata							1			2							
Nitzschia	spectabilis												7					
	scalaris	3		1												1	2	1
	recta															1		2
	spp.				1						6		2	2	3	3	2	
	type 1					42	27	3	1					3	5			
	homburgien-sis							1										
	dissipata											2						
	nana											2						
	sigma											1						
Fragilaria	ulna var. ulna					8	7	3				3	5					1
Pleurosigma	spp.														1		1	1
Pinnularia	spp.	4	3	6	2	2	2	9	4		4	6	13	10	1	3	1	3
	acrosphaeria										3							
	borealis	2	4	7	4			4			37	3		11		1		
	gibba				2	3	1		1									
	neomajor							1									1	
	nobilis	1		1					1									
	nodosa				1	1								3	1			
	major			4	2	1	5	3			4		4	2			1	5
	microstauron				2	3		2	3		3	2	3	4			3	5
	saprophila						1				2			6		8	1	1
	sinistra						1									8		
	stoermeni							2	4		3	2	4	1				
	subgibba				6	5	4	3			3	1	8		3	5	1	1
	subrupestris					1	4	2	1			1	5	5		1		1
	tropica												6		1			
	sp.											1	1	1				1
	divergens															1		12
Caloneis	sp.						1					3						

Table 4 continued

Genus	Species	287.5	257.5	247.5	222.5	197.5	172.5	147.5	122.5	97.5	84.5	73.5	63.5	50.5	48.5	38.5	28.5	20.5
Rhopalodia	gibba			2		15	7	2	2			1	2					1
	musculus															1		
Sellaphora	pupula			3		12	5	10	7		20	8	10	16	1	7	6	20
	bacillum				3	9	11							6	1		1	4
Stauroneis	phoenicen-teron					2		2					5	2	1			
	gracilis			3				8			8	2	1	2	1	5	2	5
Surirella	spp.			2	3	8	10	9	7		5	5	3	7		1	1	3
	linearis					1		1			1					1		
	robusta					1	7	2					11	4				
Stenopter-obia	sp.										9	3	10	1			1	1
Ulnaria ulna													1	3	1			

Appendix 11: Raw diatom counts laguna Chicuacan (37.5-29.5 cm depth)

Table 5 Raw diatom counts of laguna Chicuacan. Sample depths are given in cm core depth.

Genus	Species	37.5	36.5	35.5	34.5	33.5	32.5	31.5	30.5	29.5
Aulacoseira	spp.	369	483	523	490	588	343	379	260	223
Cyclotella	meneghiniana	2		3		2	2		2	1
Staurosira	construens								1	1
	construens var. venter	24	26	71	178	221	136	63	133	157
Staurosirella	pinnata	4	6	14	13	19	11	10	46	22
Achnantes	inflata	1					1	3		
	exigua	1	5	5	8	19	10	5	15	14
	oblongella	20	20	45	27	44	45	55	41	23
Navicula	contenta	30	6	3	2	3	13	40	9	2
Cocconeis	sp.				1					
Encyonema	spp.		1		3	1	1	1		
Cymbella	spp.	1	2	5	2	2	5	3	1	1
Craticula	sp.	1				1			1	
Craticula	cuspidata									2
Diadesmis	confervacea	15	9	21	22	11	13	20	20	18
Halamphora	coffeaeformis									2
Unknown 1			4	10	8		1		12	
Diploneis	sp.	2	1	2	2	2	4	1		1
Eunotia	spp.					1		1	1	
	camelus	29	30	23	18	17	34	61	20	13
	papilio	2	1							
	praerupta	1						1	1	
	minor			2			1	3		
	formica	2	6	3	4	1	4	7	4	2
	type 2	4	4	4				1	3	1
	type 3	8	4	2		1	7	7	1	1
	rabenhorstii		2	1	3	1	1	4		3
	triodon		1	1						
	ventriosa var brevis	12	9	3	1		9	10	1	1
	zygodon	3		1			1	1		1
	veneris				1		5	5	3	3

Table 5 continued

Genus	**Species**	**37.5**	**36.5**	**35.5**	**34.5**	**33.5**	**32.5**	**31.5**	**30.5**	**29.5**
Frustulia	saxonica	8	9	3	3	5	5	9	2	5
Gomphonema	gracile	1	2	2	2	1		4	2	1
	affine		1							
	parvulum			1	2	1				
Navicula	radiosa	8	6		2		1	7	7	10
	elginensis	7		2	3	4	2	4	4	2
	sp							1	3	
Neidium	dubium		1	4	2	6	1	1	1	1
Nitzschia	scalaris	1	1	1	2	1	1		1	1
	recta		6	3	4		1	4		
	spp	8	5	7	2	3	5	7	4	3
	homburgiensis					1	3	1		
	linearis					1				
	brevissima							7		3
Pleurosigma										3
Pinnularia	spp.		2	1	2	2	2	1	1	1
	borealis	1	1						2	1
	gibba		2	2	1					
	neomajor	2								
	nodosa					1				
	major					1				
	microstauron	1				1			1	
	saprophila	6	1	7	3	3	4	5	4	4
	sinistra					2	3	8	4	4
	subgibba	1				3	2			4
	subrupestris	5		3		3		6	5	6
	sp.	1							1	
	divergens			2	1				2	2
Caloneis	sp.		4	3	4					
Rhopalodia	musculus		1							1
Sellaphora	pupula	8	5	7	14	6	3	3	12	12
	bacillum			3	6	2	2		4	13
Stauroneis	phoenicenteron			1				1	2	1
	gracilis						1	3		
	spp.	6	4	2	2	1	2	3	2	1
Surirella	spp.	1	1	1	2	1	1	1	2	2
	linearis	1			2		1	1		2
	robusta			2		3	1			
Stenopterobia	sp.	2		2	1	3		1		1

Appendix 12: Raw diatom counts laguna Cantemual

Table 6 Raw diatom counts from laguna Cantemual. Samples are given in cm core depth.

Genus	Species	113.5(1)	113.5(2)	99.5	92.5	87.5	83.5	79.5(1)	79.5 (2)	75.5	71.5	64.5	58.5
Aulacoseira		334		32	51	15	5	12	30	6	42	82	24
Terpsinoe	musica	3											
Cyclotella	meneghiniana		1	26	15	37	53	17	17	6	54	9	
Thalassiosira	sp.	2	7		7	5							
Centric	type 1	4	8		2	1							
Stephanocy-clus	spp.			4			11	4	4		10		
Staurosira	construens											102	123
	construens var. venter											91	92
	brevistriata											6	7
	construens var. binodis											8	4
Staurosirella	pinnata											9	10
Achnantes	inflata		3					1		6	3		
	exigua					1		3	1	6		35	11
	brevipes	1	7	3	27	10	3	2	4				
Achnanthid-ium	duthiei					1							
Anomoneis	sphaerophora		1									3	
Halamphora	coffeaeformis		7	31	6	22	16	12	9	1	9		
Cymbella	spp.			1		1		1	5	1		3	3
Craticula	cuspidata		1			1		1	1				
	sp.					5							
Unkown 1			1	3							2	1	3
Diadesmis	confervacea	4	14	96	21	114	115	132		62	73	54	2
Diploneis	spp.	3	6	1		2	2		4	20	1	1	1
Epithemia	adnata												1

Table 6 continued

Genus	Species	113.5(1)	113.5(2)	99.5	92.5	87.5	83.5	79.5(1)	79.5(2)	75.5	71.5	64.5	58.5
Eunotia	spp.	5	2		4	2	2	2	2	3	1	1	1
	camelus					1		1				2	1
	papilio											1	
	praerupta	4	11	1	8	6	2	5	7	7	1	2	
	minor	1	2	3	3	6	2	2	3	2		2	
	type 2									5			
	type 3					1	2			5			
	flexuosa		2						10	1			
	implicata						1			4			
	pectinalis	3	2	1						3			
Gomphone-ma	gracile		3	4	5	7	5	4	5	17	2	5	3
	affine									4	3	1	
	sp.			1									
Hippodonta	capitata			1		5		5	8			3	
Mastogloia	klein			1		1		3					
	sp.					2			1				
	smithii												5
	elliptica												2
Navicula	spp.			9	7	5	9	6	8	2	14	5	3
	angusta			6	1	1	4	3	2		7	3	
	digitoconver-gens				5								
	oligotrophen-ta										1		
	subtillissima					4					13	5	
	aurora											1	
	contenta				2	3	4						
	elginensis					5		6	11	91	3	1	
	type 1										3		

Table 6 continued

Genus	Species	113.5(1)	113.5(2)	99.5	92.5	87.5	83.5	79.5(1)	79.5(2)	75.5	71.5	64.5	58.5
Nitzschia	scalaris	6	18	2	23	10	8	9	13	9	6	3	1
	recta			2	1	7	7	3	4	2	7		
	spp.	1	2		2	7	5	9		4	18	9	1
	type 1	1	2	47	58	21	27	14	14	7	24	5	
	homburgiensis	1	3		1	11	8	6	4				1
	dissipata			3	12	10	8	10	9	5	35	8	
	nana				3								
	sigma							1			1		
	obtusa		3	15	6	17	30	13	21		6	2	
	palea			62	59	22	16	17	14	2	5	2	
	gracilis			5	3	8	7	4	6				
	fossilis											1	
	denticula												2
Fragilaria	ulna var. ulna	2	1	1	1					1	2	2	
Pinnularia	spp.		1		1				1	3		2	
	neomajor									1			
	nodosa									1	1		
	microstauron			1				1	2	9	3		
	saprophila								1	1	1	1	
	sinistra										3		
	subgibba									2			
	subrupestris					2	2	2	3	6	2		
	tropica									1			
Denticula	sp.							1					
Caloneis	spp.							2			1	2	
Cocconeis	placentula										2		4
Rhopalodia	gibba							1				5	3
	musculus	19	48	1									
Sellaphora	pupula	1			1	1	3	5	3	21		9	1
	bacillum							1	1				

Table 6 continued

Genus	Species	113.5(1)	113.5(2)	99.5	92.5	87.5	83.5	79.5(1)	79.5(2)	75.5	71.5	64.5	58.5
Stauroneis	sp.							3	4		10		
	phoenicen-teron									1			
	gracilis							1	1	1			
	kriegeri					4							
Tabularia	sp.						7	2	2	1	1	1	
Stenopterobia	sp.				1		2						

Appendix 13: All counted taxa with reference

Species	**Reference**
Achnanthes brevipes	Agardh 1824
Achnanthes exigua	Grunow in Cleve and Grunow 1880
Achnanthes inflata	Grunow 1867
Achnanthes oblongella	Ostrup 1902
Achnanthidium duthiei	Edlund 1994
Anomoeoneis sphaerophora	Pfitzer 1871
Aulacoseira spp.	Thwaites 1848
Brachysira brebissonii	Bréb ex. Kützing 1849
Caloneis spp.	Cleve 1894
Cocconeis placentula	Ehrenberg 1838
Cocconeis sp.	Ehrenberg 1837
Craticula cuspidata	Mann in Round, Crawford and Mann 1990
Cyclotella meneghiniana	Kützing 1844
Cymbella spp.	Agardh 1830
Denticula sp.	Kützing 1844
Diadesmis confervacea	Kützing 1844
Diploneis spp.	Cleve 1894
Encyonema spp.	Kützing 1833
Epithemia adnata	Kützing 1833
Epithemia turgida	Ehrenberg 1832
Eunotia camelus	Ehrenberg
Eunotia diadema	Ehrenberg 1837
Eunotia didyma	Hustedt 1913
Eunotia flexuosa	Kützing 1849
Eunotia formica	Ehrenberg 1843
Eunotia implicata	Nörpel, Lange-Bertalot and Alles 1991
Eunotia minor	Grunow in van Heurck 1881
Eunotia papilio	Grunow 1868
Eunotia pectinalis	Rabenhorst 1864
Eunotia praerupta	Ehrenberg 1843
Eunotia rabenhorstii	Cleve and Grunow
Eunotia triodon	Ehrenberg 1837
Eunotia soleirolli	Rabenhorst 1864
Eunotia veneris	Kützing 1892
Eunotia ventriosa var. brevis	Metzeltin and Lange-Bertalot
Eunotia zygodon	Ehrenberg 1843
Fragilaria ulna var. ulna	Lange-Bertalot 1980
Frustulia saxonica	Rabenhorst 1853
Gomphonema affine	Kützing 1844
Gomphonema angustum	Agardh 1831
Gomphonema gracile	Ehrenberg 1838
Gomphonema parvulum	Kützing 1849
Gomphosphenia sp.	Lange-Bertalot 1995

Halamphora coffeaeformis	Agardh 1827
Hantzschia abundans	Lange-Bertalot 1993
Hantzschia cf. elongata	Hantzsch 1869
Hippodonta capitata	Ehrenberg 1838
Unknown species 1	
Mastogloia elliptica	Cleve in Schmidt et al. 1893
Mastogloia smithii	Thwaites ex W.Smith 1856
Mastogloia sp.	Thwaites in Smith 1856
Navicula aurora	Sovereign 1958
Navicula angusta	Grunow 1860
Navicula contenta	Grunow in Van Heurck 1885
Navicula digitoconvergens	Lange-Bertalot 1999
Navicula elginensis	Ralfs in Pritchard 1861
Navicula oligotraphenta	Lange-Bertalot and Hofmann 1993
Navicula radiosa	Kützing 1844
Navicula subtillissima	Cleve 1891
Neidium dubium	Cleve 1894
Nitzschia brevissima	Grunow in van Heurck 1880
Nitzschia denticula	Grunow in Cleve and Grunow 1880
Nitzschia dissipata	Rabenhorst 1860
Nitzschia homburgiensis	Lange-Bertalot 1978
Nitzschia linearis	Smith 1853
Nitzschia nana	Grunow in van Heurck 1881
Nitzschia obtusa	Smith 1853
Nitzschia palea	Smith 1856
Nitzschia recta	Hantzsch ex. Rabenhorst 1862
Nitzschia sigma	Smith 1853
Nitzschia scalaris	W.Smith 1853
Nitzschia spectabilis	Ralfs 1861
Pinnularia acrosphaeria	Smith 1853
Pinnularia borealis	Ehrenberg 1843
Pinnularia divergens	Smith 1853
Pinnularia gibba	Ehrenberg 1843
Pinnularia neomajor	Krammer 1992
Pinnularia nobilis	Ehrenberg 1843
Pinnuaria nodosa	Smith 1856
Pinnularia major	Rabenhorst 1853
Pinnularia microstauron	Cleve 1843
Pinnularia saprophila	Lange-Bertalot, Kobayasi and Krammer 2000
Pinnularia sinistra	Krammer 1992
Pinnularia stoermeri	Metzeltin and Lange-Bertalot
Pinnularia subgibba	Krammer 1992
Pinnularia subrupestris	Krammer 2000
Pinnularia tropica	Ehrenberg 1843
Pleurosigma sp.	Smith 1852
Rhopalodia gibba	Ehrenberg 1895

Rhopalodia musculus	Müller 1900
Sellaphora bacillum	Mann 1989
Sellaphora pupula	Mereschkowsky 1902
Stauroneis gracilis	Ehrenberg 1843
Stauroneis phoenicenteron	Nitzsch 1843
Staurosira construens	Ehrenberg 1843
Staurosira construens var. venter	Ehrenberg 1854
Stauroneis kriegeri	Patrick 1945
Staurosirella pinnata	Ehrenberg 1843
Stenopterobia sp.	Brébisson ex Van Heurck 1896
Stephanocyclus sp.	Skabitschevsky 1975
Surirella linearis	Smith 1853
Surirella robusta	Ehrenberg 1885
Thalassiosira sp.	Cleve 1873
Terpsinoë musica	Ehrenberg 1843
Ulnaria ulna	Compere 2001

Appendix 14: Description of Unknown species 1

Observations

Length: ~7 – 10 µm
Width: ~5 – 7 µm
Striae in 10 µm: ~16

Characteristics

1. Elliptical valves
2. Ends are broadly rounded, not protracted
3. Striae are radiate and punctuated
4. Distal raphe ends externally curved
5. Proximal raphe has a straight ending
6. Wide axial area

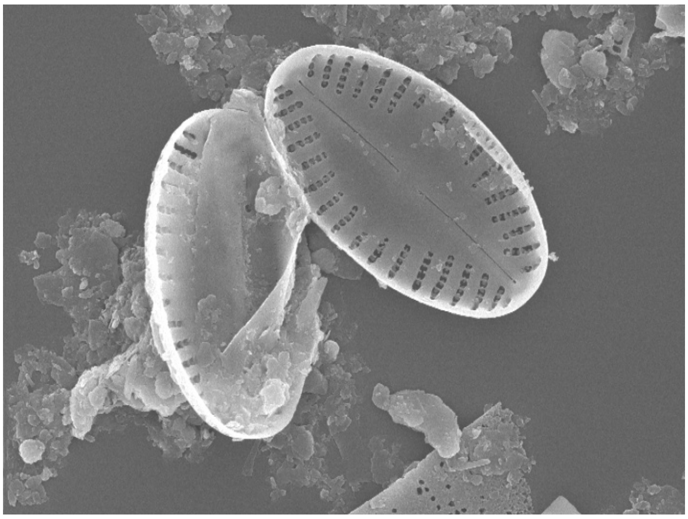


Fig. 14 SEM image of Unkown species 1, both valves visible.

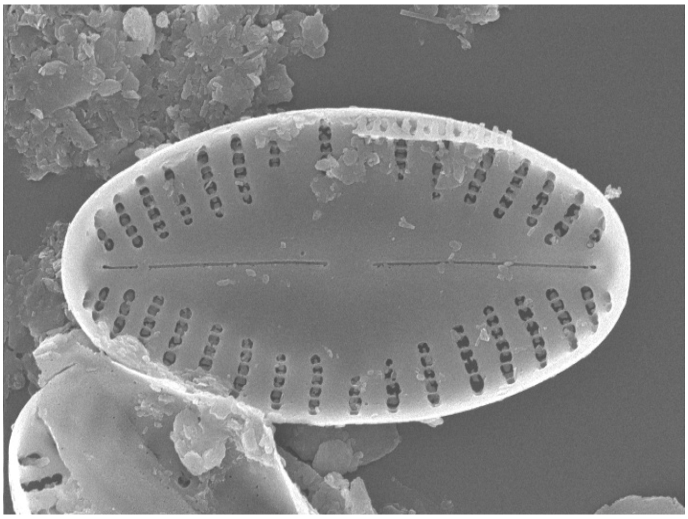


Fig. 15 SEM image of Unknown species 1, front view. The other valve is partly visible.

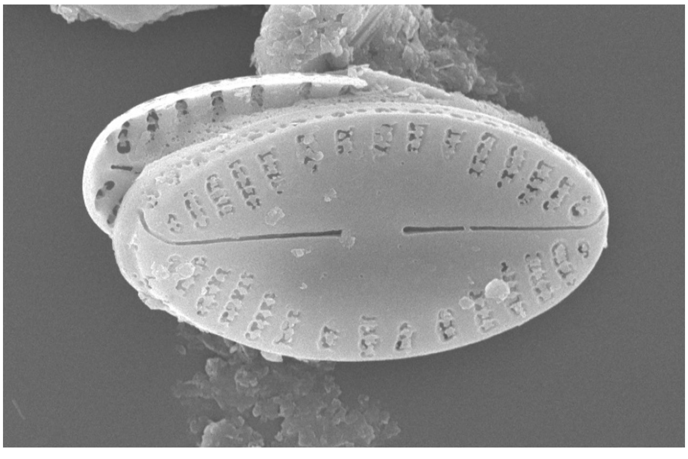


Fig. 16 SEM image of Unknown species 1, clearly visible is the curve of the external raphe.

Fig. 17 Optical microscope image of Unknown species 1, 1500x magnification. The valve on the picture has a length of ~10 µm.

Appendix 15: Description of *Nitzschia* type 1

Description

Nitzschia type 1 is a *Nitzschia* species with a length of ~10µm. Valves are linear to linear-lanceolate shaped. Ends are protracted and striae are finely punctuated.

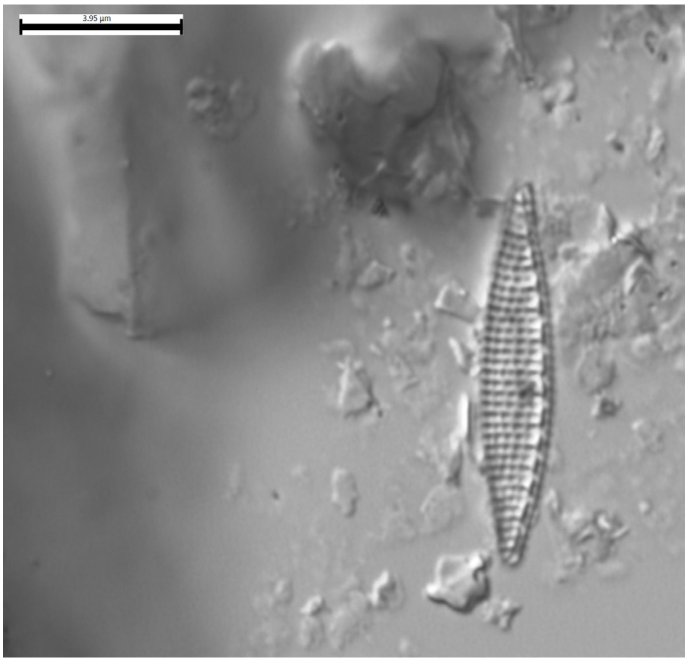


Fig. 18 Microscope image of Nitzschia type 1, 1500x magnification.

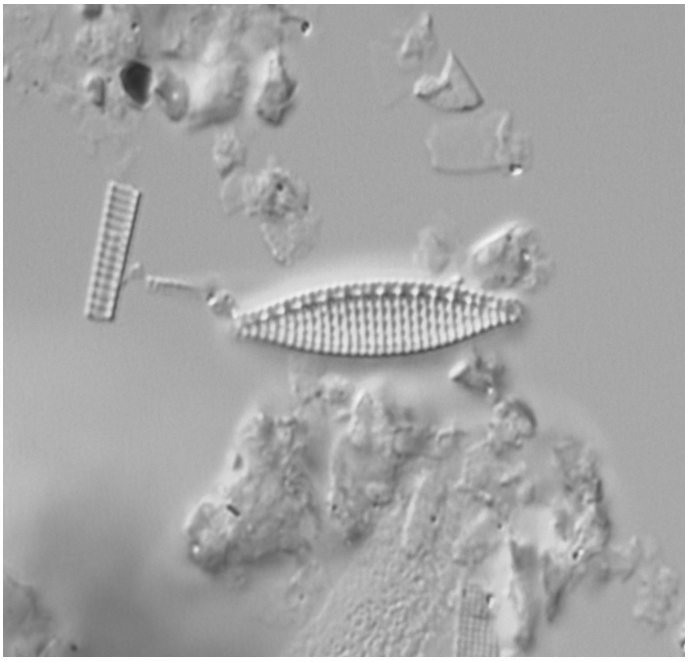
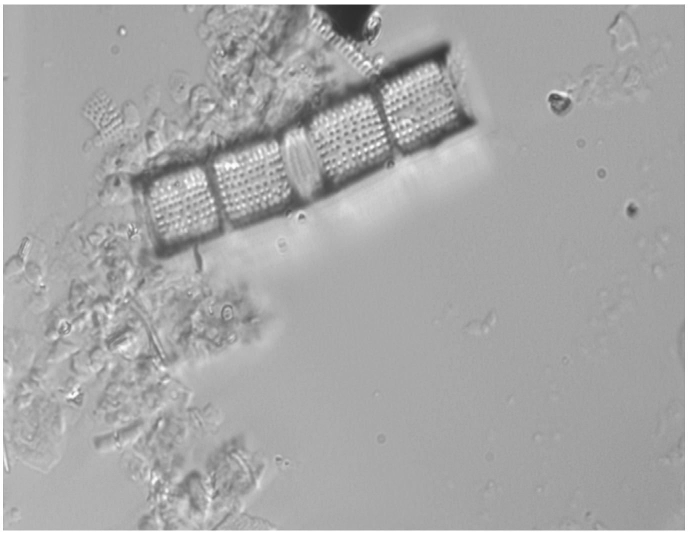


Fig. 19 Microscope image of Nitzschia type 1, 1500x magnification. Valve on the image has a length of ~8µm.

Appendix 16: Overview of major diatom taxa



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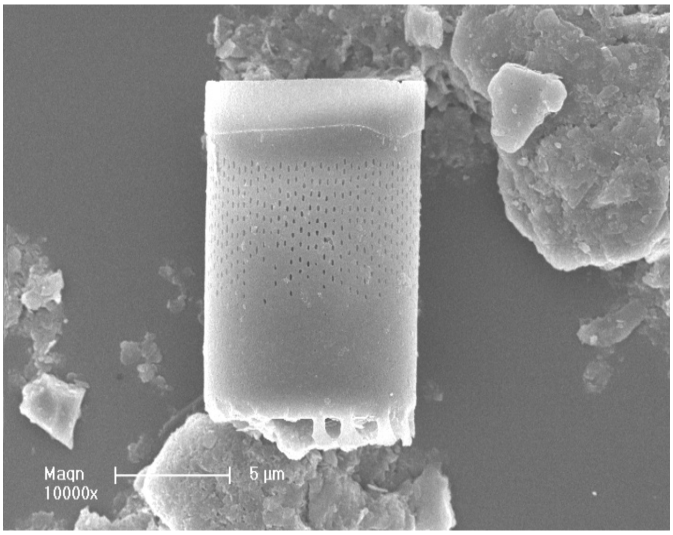

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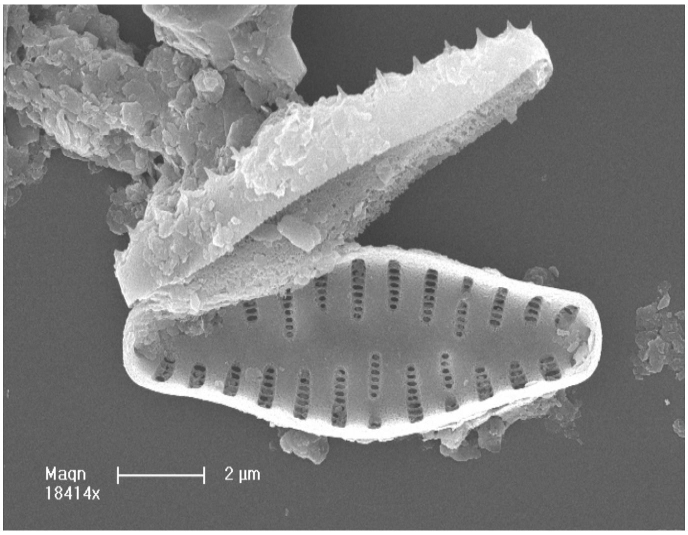

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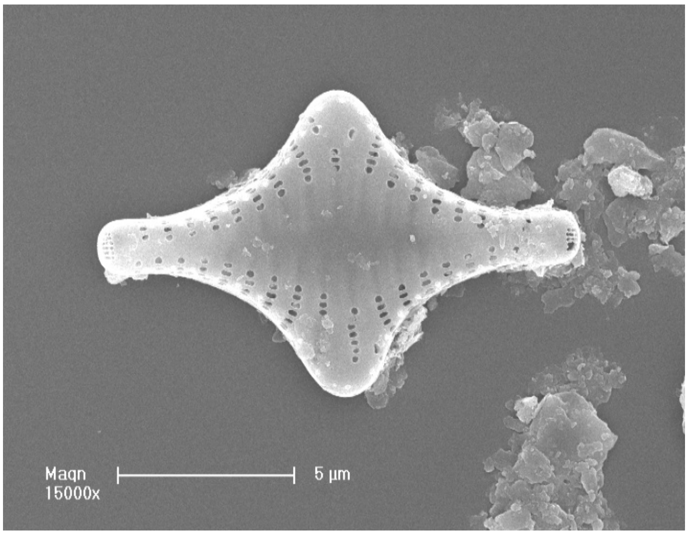

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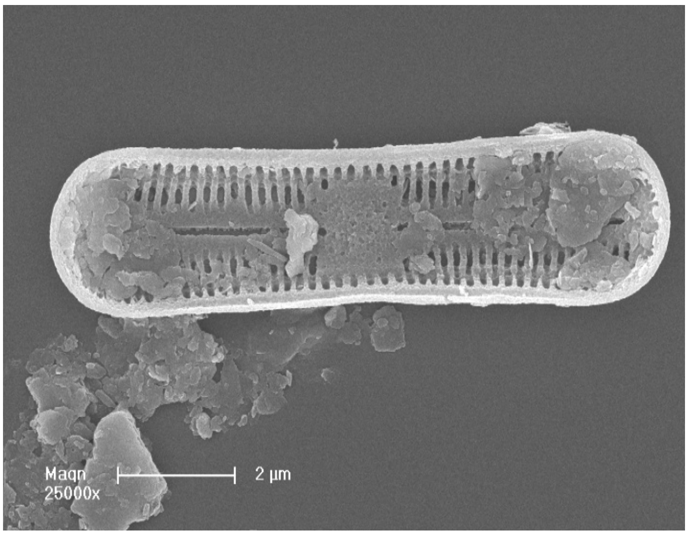

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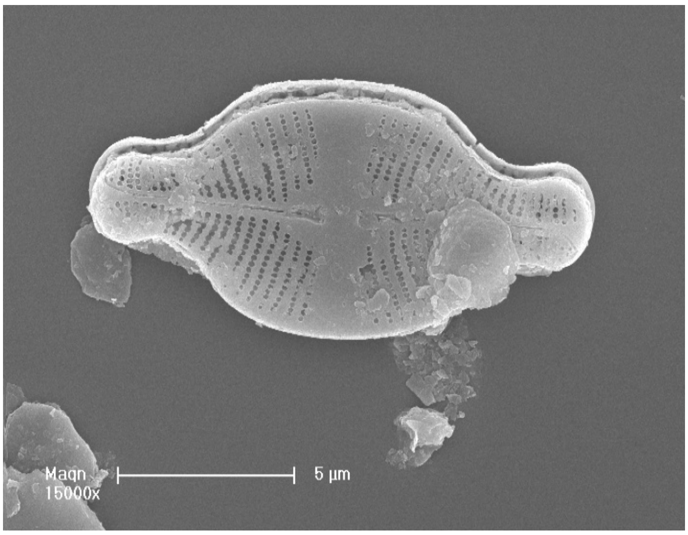

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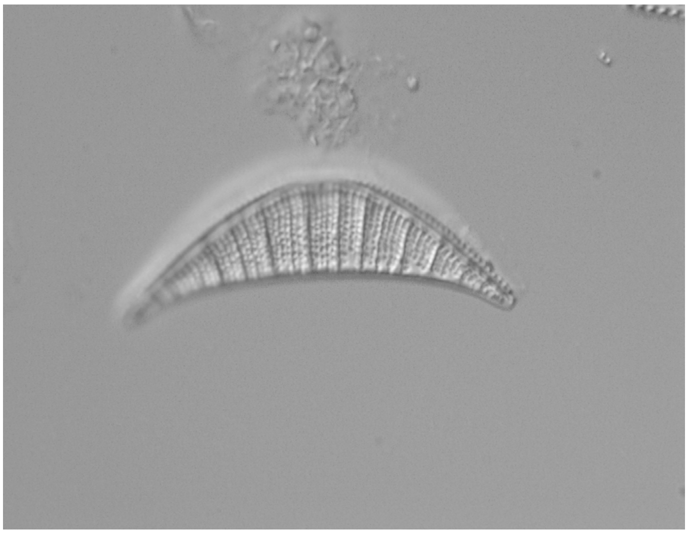

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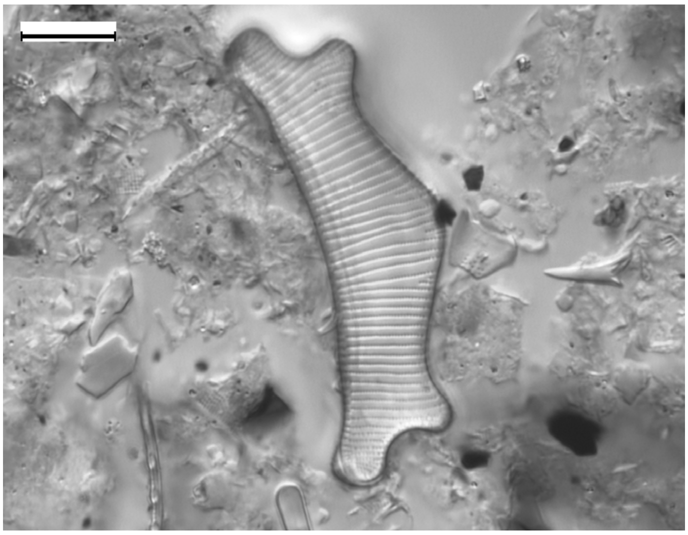
8.



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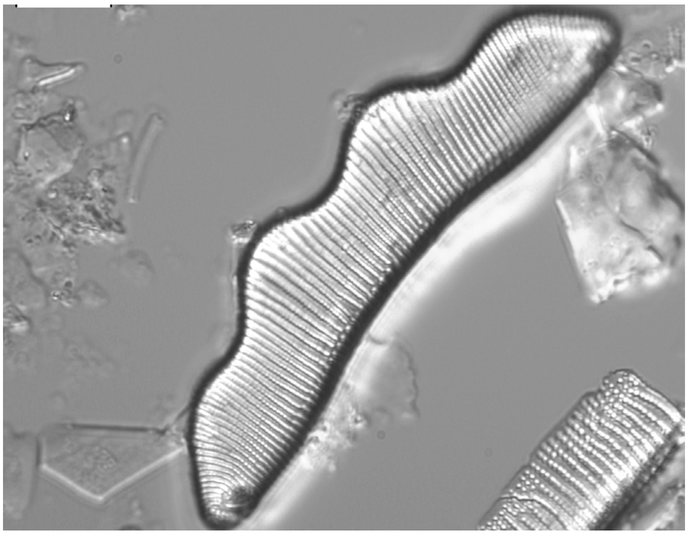

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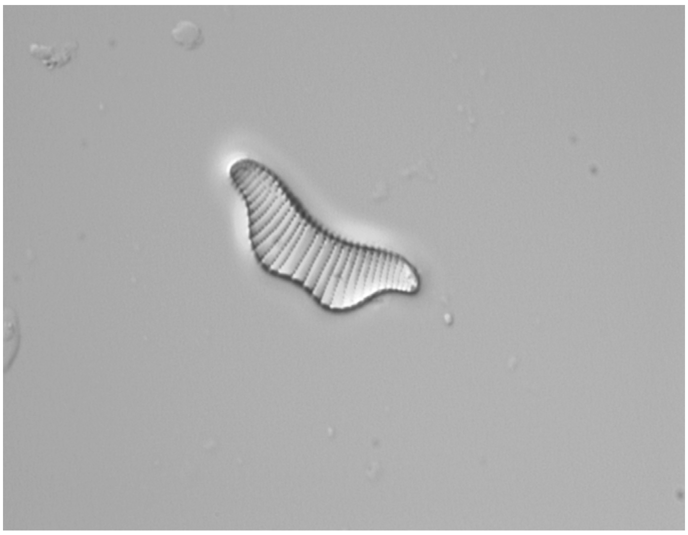

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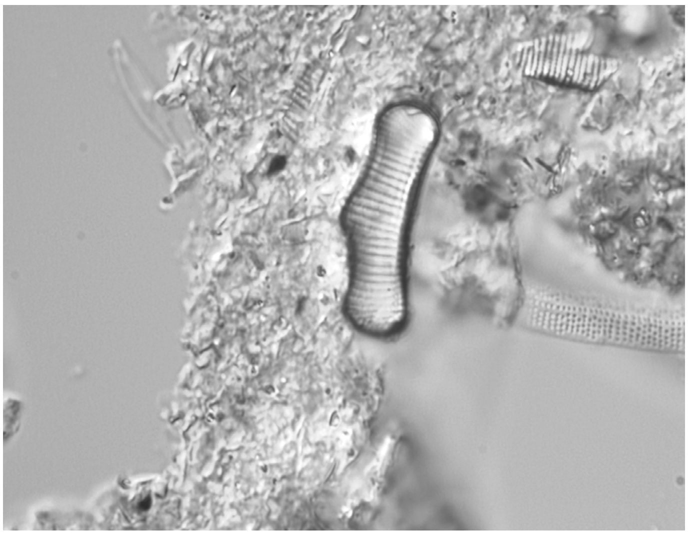

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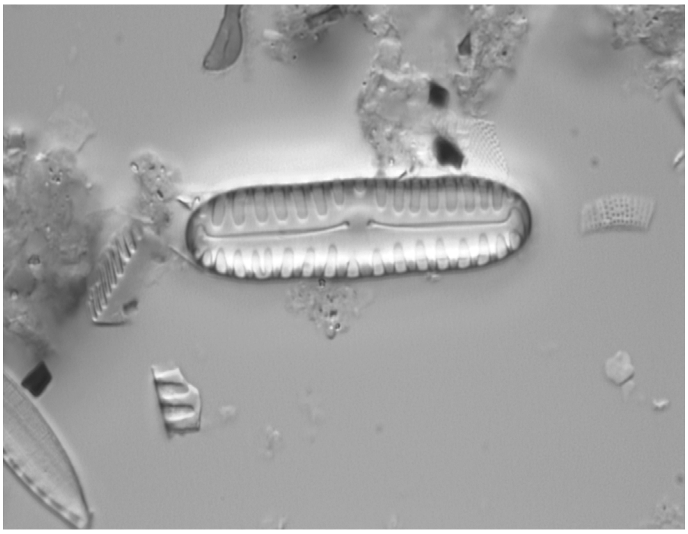

13.

List of species

1: *Aulacoseira sp.;* magnification: 1500x, length individual species: ~10 μm
2: *Aulacoseira sp.*
3: *Staurosira construens var. venter*
4: *Staurosira construens*
5: *Navicula contenta*
6: *Achnanthes exigua*
7: *Rhopalodia musculus;* magnification: 1500x, length: ~30 μm
8: *Rhopalodia gibba;* magnification: 1500x, length: ~100 μm
9: *Eunotia diadema;* magnification: 1500x, length: ~50 μm
10: *Eunotia zygodon;* magnification: 1500x, length: ~50 μm
11: *Eunotia camelus;* magnification: 1500x, length: ~15 μm
12: *Eunotia rabenhorstii;* magnification: 1500x, length: ~20 μm
13: *Pinnularia borealis;* magnification: 1500x, length: ~30 μm