A 6,000-year record of environmental change from the eastern Pacific margin of central Mexico

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Abstract

The transition from the mid- to late-Holocene in MesoAmerica saw increasing complexity in spatial patterns of change. Records from the western part of the region are sparse, with lacustrine sequences affected by long term anthropogenic disturbance or lacking chronological resolution. Here, we present a continuous palaeoecological and geochemical record from Laguna de Juanacatlán, a remote lake in the mountains of the western TMVB. Diatom assemblages, XRF scanning data and bulk organic geochemistry from a well-dated, 7.25-m laminated sequence were combined with summary pollen data from a 9-m partially laminated core to provide a continuous record of catchment and lake ecosystem changes over the last c. 6,000 years. Relatively humid conditions prevailed prior to c. 5.1 cal ka, which supported dense oak-pine forest cover around a deep, stratified lake. A trend towards drier conditions began c. 5.1 cal ka, intensifying after 4.0 cal ka, consistent with weakening of the North American Monsoon. Between 3.0 and 1.2 cal ka, lower lake levels and variable catchment run-off are consistent with increasing ENSO influence observed in the Late Holocene in the neotropics. From 1.2 to 0.9 cal ka, a marked change to catchment stability and more intense stratification reflected drier conditions and / or reduced rainfall variability and possibly warmer temperatures. After 0.9 cal ka, conditions were wetter, with an increase in catchment disturbance associated with the combined effects of climate and human activity. In recent decades, the lake ecosystem has changed markedly, possibly in response to recent climate change as well as local catchment dynamics.

Keywords: Holocene; Palaeolimnology; North America; diatoms; geochemistry; pollen.

1. Introduction

The broad pattern of climatic change across Mexico over the Holocene has become better understood over the last 20 years (c.f. Metcalfe et al., 2000 and Metcalfe et al., 2015), but the spatial distribution, sampling resolution and chronological control of paleoclimate records from the region are highly variable. Generally wetter conditions in the early to mid-Holocene were driven by insolation forcing, and are associated with northward movement of the intertropical convergence zone (ITCZ) and strengthening the North American Monsoon (NAM). This was followed by a change around 4 cal ka, when the role of insolation declined. The ITCZ moved southward and the NAM weakened, leading to drier conditions over much of Mexico. A more complex set of climate forcings then seem to have become more evident, especially those associated with the tropical and sub-tropical Pacific, such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Differences between southern and northern, and perhaps eastern and western Mexico, became more apparent. Some of this variability seems to be explained by spatially different responses to forcings such as the Atlantic Multi-Decadal Oscillation (AMO), the PDO and ENSO. The highlands of central Mexico, the Trans-Mexican Volcanic Belt (TMVB) (at about 20^{o}N), appear to lie in the transition zone in terms of some of these responses (Stahle et al., 2012).

The many lake basins of the TMVB have long been a focus for palaeoclimate studies, particularly in and around the Basin of Mexico and in the states immediately west (Estado de Mexico, Michoacán). However, the number of continuous, high-resolution Holocene records from this part of Mexico remains small as sedimentation rates in basins are often quite low or discontinuous due to volcanic/tectonic activity, periodic desiccation and deliberate drainage (Caballero et al., 1999; Vázquez-Castro et al., 2008; Ortega et al., 2010). The situation is further complicated by the strong imprint of human activity on many Holocene records from the area, with *Zea mays* (domesticated maize) appearing in pollen records from around 4 ka (Watts and Bradbury, 1982; Lozano-García et al., 2013). Large increases in sedimentation rates also occurred, coincident with the onset of sedentary agriculture (O'Hara et al., 1993; Metcalfe et al., 1994; Vázquez-Castro et al., 2010). In some cases, it has been difficult to develop reliable radiocarbon chronologies because of inwash of old carbon from catchments (Metcalfe et al., 1994). Only sites at very high elevations, close to the modern timberline, seem to have been immune from anthropogenic influence (Lozano-García and Vázquez-Selem, 2005). Development of continuous, high-resolution palaeoclimate records from maar lakes across the TMVB, which often preserve laminated sediments, is now being realised (Sosa-Nájera et al., 2010; Bhattacharya et al., 2015; Rodríguez-Ramírez et al., 2015; Park et al., 2017) and new, high-resolution sequences have been produced for the southern Mexican highlands (Goman et al., 2018), though these show clear evidence of long-term human impact.

Here we present a record from remote highland lake Laguna de Juanacatlán, on the western fringe of the TMVB, which spans the mid-late Holocene. Laguna de Juanacatlán (Fig. 1) lies close to the area that is often considered to be the 'core' of the North American Monsoon (Douglas et al., 1993; Ropelewski et al., 2005). The site was first investigated in 1990, and its often-laminated sediments demonstrated the potential for development of a high-resolution palaeoclimatic record (Byrne et al., 1996). Our initial research at the site used diatoms from the last few hundred years, in a suite of short cores, and highlighted rapid, recent changes in the aquatic ecosystem (Davies et al., 2005). Collection of longer cores (see below) and application of micro-XRF scanning of the finely laminated sediment sequence enabled development of an annually resolved rainfall reconstruction for the last 6,000 years, based on the titanium record (Metcalfe et al., 2010; Jones et al., 2015). This long-core sequence provides a complete, high-resolution sequence from this part of Mexico for the last 6 cal ka. In this paper, we synthesise the geochemical (XRF scanning, bulk organic geochemistry) and palaeoecological (diatoms, pollen) evidence from Juanacatlán to explore links between Holocene climate variability, including the NAM, lake dynamics and vegetation change, providing insights into the complex drivers of change from a uniquely well-dated sequence.

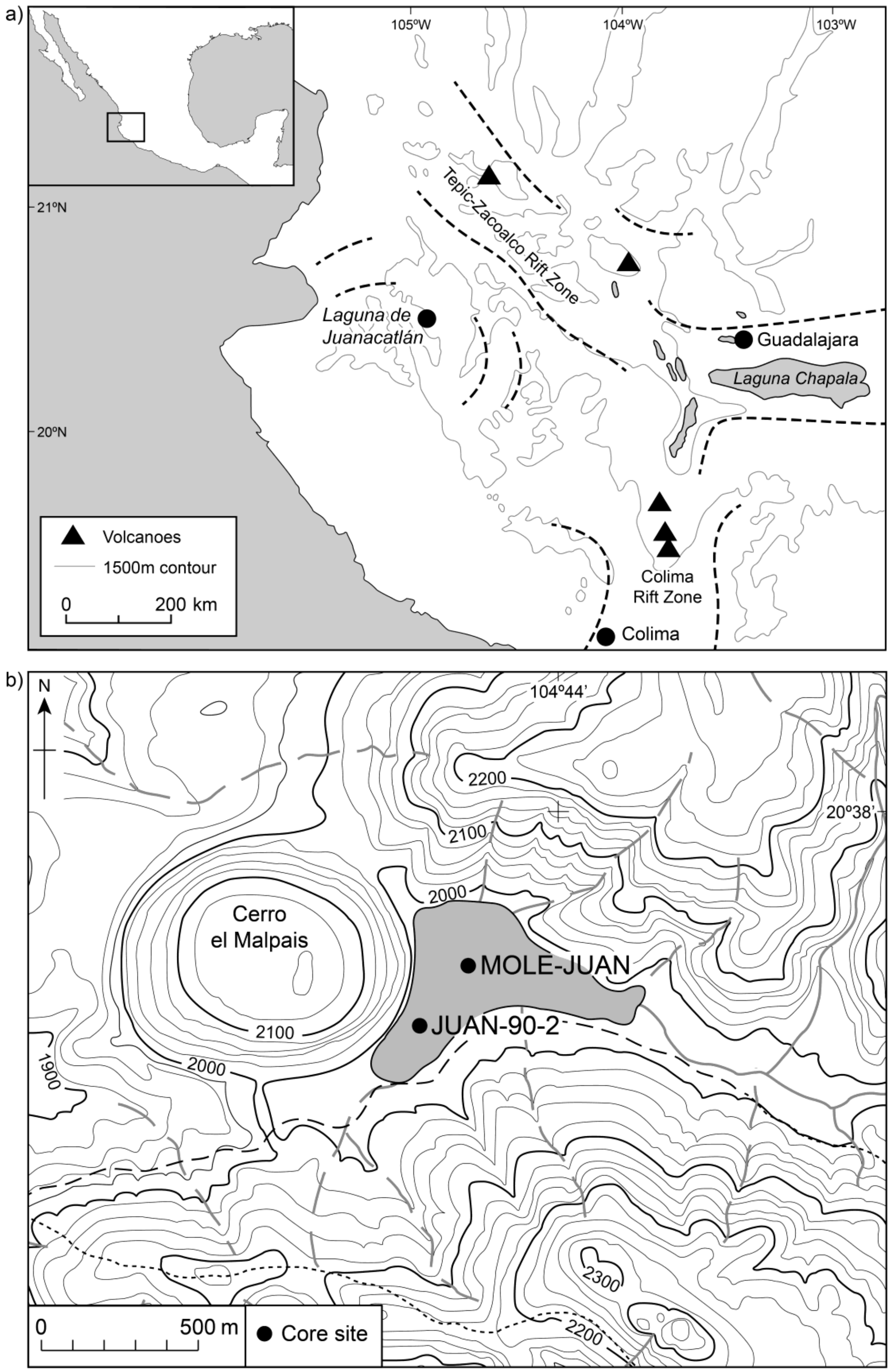

Figure 1: a) Regional setting of Laguna de Juanacatlán and b) the local catchment, illustrating core locations.

2. Regional Setting

Laguna de Juanacatlán (20°37´N, 104°44´W) is a lava-dammed lake situated in a remote location in the Sierra de Mascota (Fig. 1) at ~2000 m a.s.l, approximately 52 km east of the Pacific Coast at Puerto Vallarta. It lies within the Mascota Volcanic Field (MVF), in the Jalisco Block (Fig. 1a), which is bounded to the northwest by the Tepic-Zacoalco Rift Zone and to the east by the Colima Rift Zone (Carmichael et al., 1996). The MVF is characterised by an unusual diversity of volcanic rocks, dominated by potassic and hydrous types that range in composition from minettes to andesites. Potassium-argon dating of volcanic deposits in the MVF indicates an age range from c. 5 ka to 2.48 Ma (Carmichael et al., 1996; Ownby et al., 2008).

The lake surface area is approximately 0.5 km^2 within a 10 km^2 catchment, and the water body is surrounded by steep slopes that rise to a maximum of 2,300 m a.s.l. The closest meteorological station is at Mascota, 800 m lower and 12 km away from the lake. Average annual temperature at Mascota is 21.8°C and average annual precipitation is 1026 mm (IMTA, 1996). Lake water has a calcium-magnesium bicarbonate composition (Davies et al., 2002), with a pH range of 7.8-8.8 and electrical conductivity from 100 to 150 $\mu S\ cm^{-1}$. Thermal stratification of the water column was evident on each field visit between 1998 and 2006, with seasonal variation in depth. In July 2005 (wet season) the thermocline was observed between 3 and 6 m depth, whilst at the end of the following dry season (April 2006), the thermocline was between 6 and 8 m depth. Results of more recent sampling in October 2011 (Sigala et al., 2017) were consistent, with the onset of the thermocline observed at 7 m depth.

Pine (*Pinus*) or pine/oak (*Quercus*) forests are typical of west-central Mexico at elevations between 1200 and 3000 m (Ortega Rosas et al., 2008; Lozano García et al., 2013). In a study of modern vegetation just north of Juanacatlán, Guerrero-Hernandez et al. (2014) reported *Quercus obtusata*, *Q. scytophylla*, *Q. candicans*, *Pinus devoniana* and *P. lumholtzii* as dominant forest species. These authors also described *Abies* (fir) forest (mainly *A. flinckii*), but noted its rather restricted distribution. The area shows a high level of endemism, with an estimated 35% of forest species being endemic to Mexico, nearly 5% endemic to the state of Jalisco and 4% endemic to the western highlands within the state (Guerrero-Hernandez et al., 2014). Within the Juanacatlán Basin, there is a concentration of oak on an apparently recent volcanic dome (Cerro el Malpais) at the west end of the lake (Fig. 1b). Prior to recent development of the catchment for tourism, *Salix* (willow) was common along the lake shore and particularly in the southwest, where there is an extensive area of flatter land. Core JUAN-90-2 was taken close to this area (see below).

The regional archaeological context of western Mexico is characterised by shaft tomb cultures, represented at various sites in Michoacán, Nayarit and Jalisco, the earliest dating from around 1400 BCE. The Late Formative and Classic (300 BCE – 500 / 600 CE) was a period of population growth and expansion and saw the development of ceremonial architecture represented by distinctive circular, stepped pyramids as found at Guachimontones (Beekman, 2010), c. 150 km from Juanacatlán. Little is known about the prehistory of the immediate surroundings of Laguna de Juanacatlán, but middle-Formative (c. 800 BCE) burial sites have been the subject of recent investigations in the Mascota Valley (Rhodes et al., 2016), where there are also numerous Pre-Hispanic petroglyphs (Mountjoy, 2012). Colonial silver and gold mining was established in the 17th century in the Sierra de Mascota, but it is unclear if there were operations within the catchment itself (Davies et al., 2005). During the 1950s, a channel was dug at the southwest end of the lake to supply irrigation water to small farms in the adjacent valley. Until the late 1990s, catchment disturbance was very low in comparison with other central Mexican lake basins, and there was little maize cultivation. Settlement was restricted to several small hamlets close to, but outside the basin. A major change occurred around the year 2000 when an 'ecotourism' complex was established near the edge of the lake, with construction of buildings, infrastructure and landscaping.

3. Materials and Methods

Two parallel sediment cores were retrieved from 23.5 and 24.4 m water depth in Laguna de Juanacatlán in October 2003 using a Kullenberg system (Fig. 1b). The sediment-water interface was recovered simultaneously with a gravity corer attached to the trigger arm of the Kullenberg. MOLE-JUAN03-1A and -2A were 987 cm long and 946 cm long respectively. Cores were recovered in polycarbonate liners of 70mm diameter, cut into section lengths ≤ 150cm, transported to the LacCore Facility at the University of Minnesota and refrigerated at 4^{o}C. Cores were scanned on whole- and split-core multisensory loggers, split in half lengthwise, and photographed with a DMT CoreScan Colour linescan camera. Lithological core descriptions were completed following LacCore protocols (Schnurrenberger, 2003) and used to create an initial composite sequence (splice) of 779 cm to avoid stratigraphic disturbances evident in the laminated sediments. Magnetic susceptibility was analysed on split cores at 0.5-cm resolution using a Bartington MS2E point sensor on a Geotek MSCL-XYZ automated core logger. The composite splice was sub-sampled into u-channels and scanned using an Itrax® XRF core scanner (Croudace et al., 2006) at Aberystwyth University at 200-μm resolution, with settings at 30kV and 30mA and a 10-second count time. The chronology for the composite sequence is based on 26 AMS radiocarbon dates, with additional age control based on ^{137}Cs peaks that correspond to weapons testing (1963 CE) and the Chernobyl nuclear accident (1986 CE). Details of the dates and age model are reported in Metcalfe et al. (2010) and Jones et al. (2015). A laminae count was based on visual inspection of the u-channel samples and the core photographs and the laminae types were classified based on both the visual stratigraphy and examination of example thin sections from each unit identified.

Samples were taken from the splice at 5-cm intervals for total organic carbon (TOC), total nitrogen (TN) and bulk organic carbon stable isotope (δ^{13}C) analysis. Sediment samples were washed in 5 % hydrochloric acid to remove calcite, rinsed in deionised water, dried at 40^{o}C, then ground with an agate pestle and mortar. Carbon isotope measurements were carried out by combustion in a Carlo Erba 1500 on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer. δ^{13}C values were calculated to the VPDB scale using within-run laboratory standards. Replicate analysis of standard materials indicated a precision of +/– 0.1 ‰ (1 SD) (n=37). TOC and TN concentrations were measured as a by-product of the same process, calibrated against an Acetanilide standard. Replicate analysis of samples indicated a precision of ~ 0.4 ‰ (2 sigma).

Diatom species assemblages were analysed at 10-cm resolution through the composite sequence. Samples were digested in hydrogen peroxide using standard protocols described in Battarbee (1986), with aliquots mounted onto slides using Naphrax™ resin. Diatoms were counted at 1000x magnification using an Olympus BX50 microscope or a Zeiss Axioskop2 Plus microscope. At least 400 valves were counted for each sample and identifications were made with reference to published floras (Krammer and Lange-Bertalot, 1986, 1988, 1991a, 1991b; Gasse, 1986) and online databases (e.g. https://westerndiatoms.colorado.edu/).

We also report results of pollen analysis of a 900-cm core (JUAN-90-2) retrieved in 1990 from 11.5 m water depth, using a Livingstone corer (Fig. 1b). Calibrated ages from six AMS ^{14}C dates on plant fragments were used to create a linear age model to enable comparison with palaeoenvironmental data from the MOLE-JUAN cores. Pollen samples were taken at approximately 10-cm intervals, yielding a total of 93 samples, and a known quantity of Lycopodium spores was added to each sample as a control. Pollen was extracted using standard techniques (Faegri and Iversen, 1989), including hydrochloric acid (10 %), KOH (10 %), hydrofluoric acid (49 %), nitric acid (50 %) and acetolysis. Residues were stained with safranin and mounted in silicone oil (2000 centistokes). In samples from diatom-rich levels, oil released during the hydrofluoric treatment often caused clumping at later stages of the extraction. This problem was minimized by washing with isopropanol immediately after the HF treatment, i.e., without an intervening water wash. The isopropanol wash was repeated several times if oil remained in the sample. After the final isopropanol wash, the sample was washed in water to avoid an explosive reaction with nitric acid. Pollen slides were counted on a Zeiss Photomicroscope with a 40x planachromat objective. Identifications were made with the aid of the University of California Museum of Paleontology Pollen Reference Collection and published keys

(Palacios-Chávez, 1968, 1985). The mean pollen count was 837, with a minimum of 471. A total of 60 known pollen types were recognised and for most samples, unknowns accounted for less than 2% of the pollen sum.

4. Results and Interpretation

4.1 Stratigraphy and Chronology

The sedimentary sequence was largely laminated, consisting of greenish organic, diatomaceous layers with occasional fine-grained clastic layers. Five types of laminae were observed through the composite sequence (Fig. 2):

1. Organic laminae couplets of different shades, both with a clotted (ie. irregular, clumped) appearance.
2. Organic laminae couplets, one clotted, one not. Contained distinct, bright green laminae.
3. Dark brown and greenish-white non-clotted laminae.
4. Clotted organic laminae with fine-grained pink clastic laminae.
5. Non-clotted organic laminae with fine-grained pink clastic laminae.

A total of 2732 laminae pairs were counted. The basal age of 5.79 cal ka for the sequence (Jones et al., 2015) implies that the laminae were not deposited annually, even considering that lamination was less clear in some sections of core. The composite sequence was divided into six units, characterised by laminae type. Unit 6 (779-710 cm) was dominated by type 1 laminae. Unit 5 (710-445 cm) was dominated by type 3 laminae, which were about 2 – 3 mm thick. Unit 4 (445-265 cm) contained a mixture of clastic type 5 and entirely organic, type 3 couplets. Unit 3 (265-225 cm) was characterised by type 1 organic couplets. Unit 2 (225-17 cm) was dominated by type 4 and type 5 couplets. Unit 1 (0-17 cm) was dominated by type 1 organic couplets with a lower clastic content than Unit 2.

There were six non-laminated sections of different thicknesses, characterised by fining-upwards sequences, some with basal sands (Fig. 2; Table 1). These were interpreted as turbidite deposits that represent instantaneous events, possibly related to tectonic or storm activity (Metcalfe et al., 2010; Jones et al., 2015). Turbidites were removed from the composite sequence, consistent with our previous work, and given the focus here on identifying patterns of change over time. The final composite sequence was therefore 725 cm long.

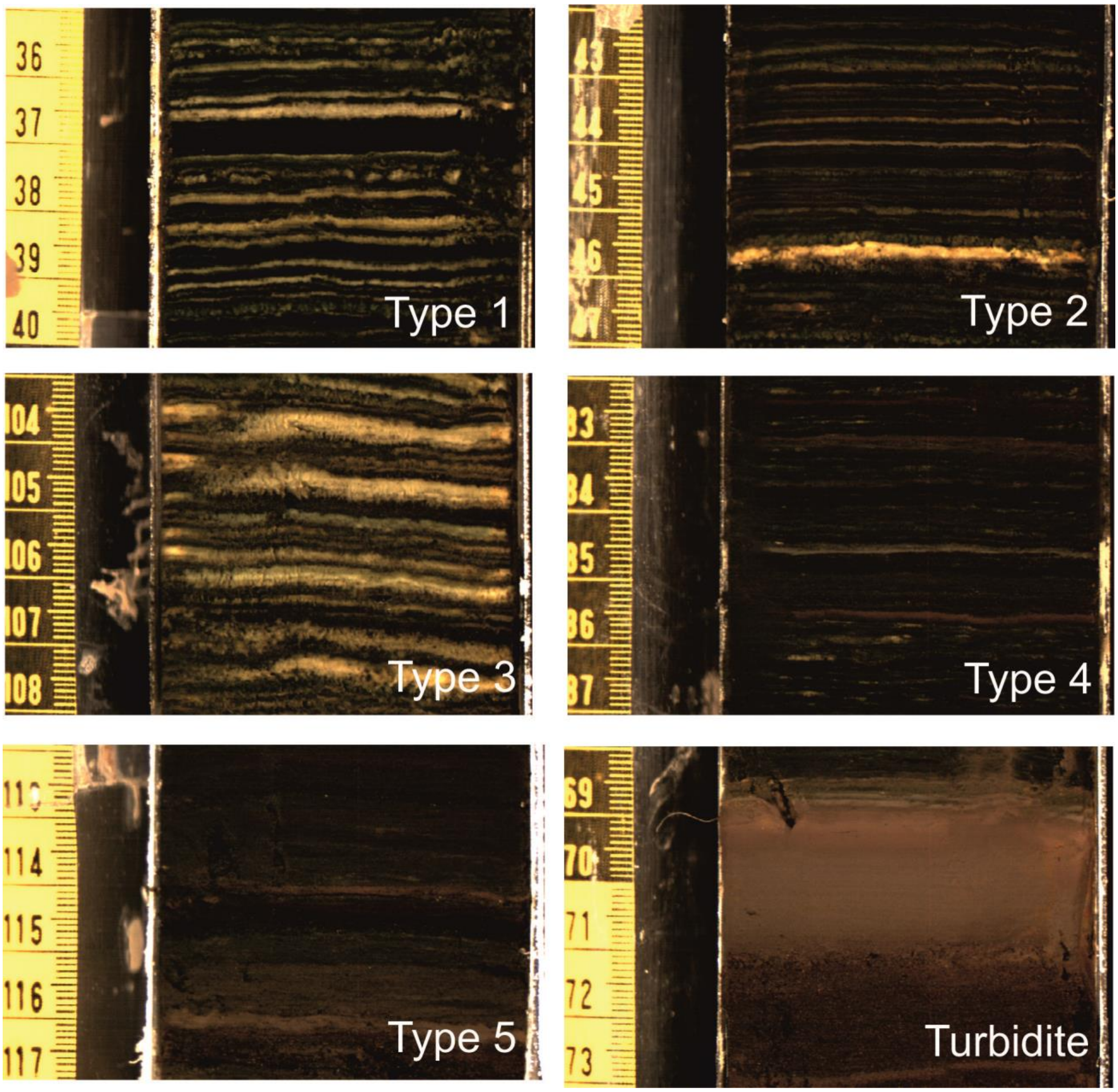

Figure 2: Examples of the five laminae types identified in the MOLE-JUAN cores and an example of one of the turbidite layers (4 in Table 1) which were removed from the composite sequence for the purposes of this study.

Table 1: Depth and age of turbidite layers in the MOLE-JUAN composite sequence.

Turbidite	**Upper depth (cm)**	**Lower depth (cm)**	**Age (cal ka)**
1	92	105.1	221
2	166.4	184.9	585
3	203.8	210	727
4	570	573.7	4231
5	601.6	613.6	4453
6	683.4	680.7	4912

The 900-cm Livingstone core (JUAN-90-2) retrieved in 1990, on which pollen analysis was performed, was moderately to well-laminated for most of the sequence. Non-laminated intervals were observed from 820 cm to the base and at 640-600, 450-430 and 300 – 150 cm. A possible black tephra layer was found at 650 cm. A number of oxidised clay layers/flood deposits (turbidite layers) were also observed. These showed a similar pattern of distribution as the MOLE-JUAN sequence, with the turbidite layers in the upper 200 cm and below 450 cm depth. Radiocarbon dates on plant macrofossils (Table 2) were used to develop an age-depth model for JUAN-90-2, based on linear interpolation. Dates were calibrated using Intcal04 (Reimer et al., 2004), for consistency with the MOLE-JUAN chronology. The resulting basal age for the full sequence was 7.3 cal ka. Here we only present data from the last 6 cal ka, to provide temporal overlap with MOLE-JUAN.

Table 2: Radiocarbon dates from core JUAN-90-2 used to construct the linear age-depth model.

Depth (cm)	Lab. Code	^{14}C yr BP	Cal yr BP (2σ)
203	CAMS-27561	1140 ± 60	932 – 1228

288	CAMS-29428	2320 ± 50	2155 – 2655
490	CAMS-10223	3660 ± 45	3862 – 4144
678	CAMS-29426	5030 ± 60	5649 – 5910
694	CAMS-29430	5080 ± 60	5661 – 5796
873	CAMS-27559	5960 ± 80	6568 – 7138

4.2 Magnetic Susceptibility and XRF scanning

Results of magnetic susceptibility and XRF core scanning are presented against age for the MOLE-JUAN composite sequence (Fig. 3). Between 5.8 and 5 cal ka, magnetic susceptibility values were at their lowest in the sequence, with frequent negative values indicating diamagnetic properties of the sediment. Magnetic susceptibility remained low between 4.95 and 1.0 cal ka, with a mean of 4.4 SI × 10^{-5}. Notable peaks, coinciding with increases in Ti, occurred at 5.2 and 4.2 cal ka, with smaller peaks at 3.6, 2.8, 2.5, 2.1, 2.0, 1.9 and 1.2 cal ka. These all corresponded to pink clay layers that were thicker than typical type 4 or 5 clastic/organic laminae couplets. Higher magnetic susceptibility values were observed during the last 1.0 cal ka, with mean values of 12 SI × 10^{-5} and a series of large peaks between 60 and 110 SI × 10^{-5}.

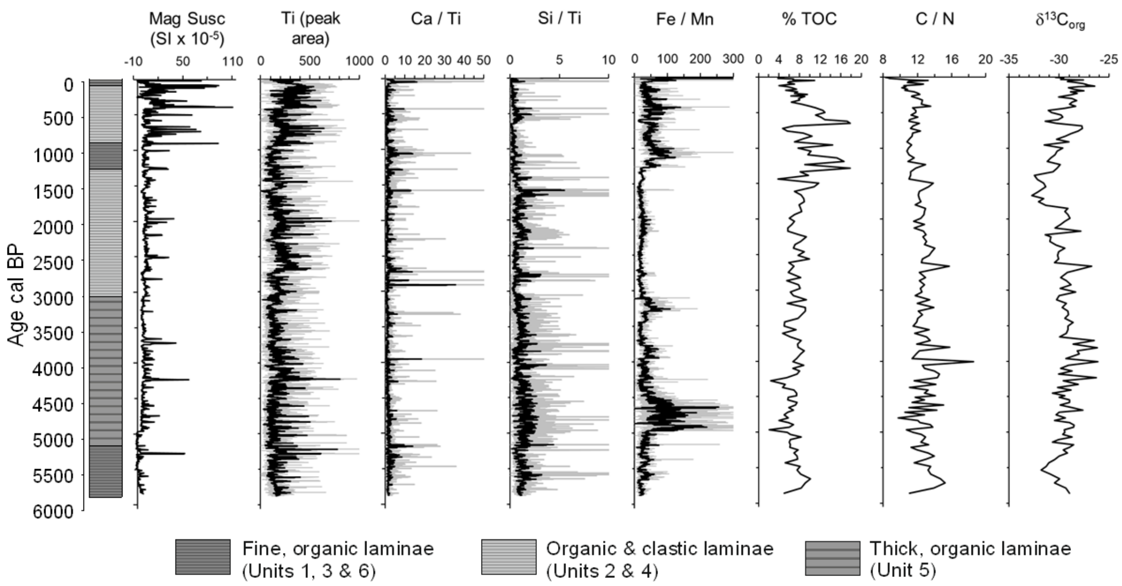

Figure 3: Magnetic susceptibility, summary of XRF scanning and bulk organic geochemistry profiles for the MOLE-JUAN composite sequence. Numbers on the stratigraphic column refer to units described in section 4.1 based on dominant laminae type.

Titanium (Ti) co-varied with magnetic susceptibility throughout the sequence. We previously established Ti as a proxy for catchment run-off related to rainfall (Metcalfe et al., 2010; Jones et al., 2015). Some Ti peaks may represent individual inwash events. Other elements that would also be expected to represent allochthonous, minerogenic inputs, such as potassium, were strongly correlated with Ti ($R^2 > 0.8$; Metcalfe et al., 2010) and are not shown here.

In-lake processes can be explored by normalisation of key elements to Ti, which is an unambiguous indicator of external inputs. Ca/Ti ratios indicate authigenic processes such as evaporative concentration or biogenic calcite production (Davies et al., 2015). Both mechanisms are possible at Juanacatlán, a Ca Mg HCO_3 lake which could be expected to precipitate carbonate through evaporative concentration. Higher Ca/Ti ratios were observed at the base of the core, between c. 5.7 and 5.1 cal ka, with short-lived peaks centred around 3.2, 2.9, 2.7, 1.5 cal ka. In the upper part of the core, additional periods of higher Ca / Ti were evident, from 1.1 to 0.9 cal ka and from 0.6 to 0.4 cal ka, with another rise around 50 years ago.

Si/Ti ratios can be used to examine changes in biogenic silica, with increases in Si/Ti usually related to enhanced diatom productivity (Brown et al., 2007). The silica peak area values were low (mean < 110) and should be treated with caution. The 25-point moving-average data, however, showed generally higher values between 5.5 and 4 cal ka and lower values over the last 3.0 cal ka. Peaks in the upper part of the core were observed from 2.8 to 2.6, 2.3 to 2.1, 1.6 to 1.5, 0.5 to 0.4 cal ka and in the last 60 years.

Cluster analysis of downcore geochemical variations was previously carried out on the record of the last 2,000 years (Metcalfe et al., 2010). This indicated that iron (Fe) was not consistently related to Ti and therefore unrelated to catchment inputs (Metcalfe et al., 2010). Along with manganese (Mn), Fe can reflect changing redox conditions (Mackareth, 1966; Engstrom and Wright, 1984; Boyle, 2001). We explored this using the Fe/Mn ratio. Greater Fe/Mn indicates more reducing conditions at the sediment-water interface and enhanced lake stratification. Fe/Mn ratios were generally low between 5.8 and 1.26 cal ka, but punctuated by a significant increase between c. 5.0 and 4.4 cal ka. Smaller peaks were also observed between 3.9 and 3.7 cal ka and 3.2 and 3.1 cal ka. Fe/Mn ratios increased after 1.3 cal ka, with a major peak in the last 60 years.

Catchment inputs, indicated by magnetic susceptibility and Ti values, were low through most of the sequence, but increased substantially after c. 0.9 cal ka. Earlier peaks occurred at c. 5.2 and 4.2 cal ka and more generally between 2.8 and 1.9 cal ka, but with less intensity than in the uppermost sediments. Peaks in Ca/Ti and Si/Ti ratios coincide, indicating that when biogenic silica production was higher, endogenic calcite production also increased. Si/Ti ratios (25-pt moving average) were generally higher in the lower part of the core, especially between 5.5 and 4 cal ka. This coincided with increased Fe/Mn ratios, indicating that increased biogenic silica production was associated with more reducing conditions and a stable catchment, the latter evidenced by low magnetic susceptibility and Ti values. Within the last 0.9 cal ka, lake conditions appear to have been more variable, with periods of increased catchment inwash alternating with more reducing conditions and enhanced lake stratification.

4.3 Bulk organic geochemistry

The ratio of carbon to nitrogen (C/N) in the organic component of lake sediments, combined with $\delta^{13}C$ values of the organic matter, can provide information on the source of organic matter and the amount of biological productivity (Meyers and Lalliers-Verges, 1999). Bulk organic geochemical data are presented in Figure 3. The variation in C/N ratios and $\delta^{13}C_{org}$ values through the core was relatively small, indicating rather subtle changes in catchment vegetation and/or productivity (increased productivity can lead to higher $\delta^{13}C_{org}$; Leng and Marshall 2004). Total organic carbon content (% TOC) of the sequence ranged from 2.1 % to 17.9 %. Percent TOC remained relatively stable through the core from 5.8 until 1.6 cal ka, fluctuating between 2.1 and 9.9 %, with a mean of 7 %. Between 1.6 cal ka and present, the mean increased to 8.9 %, with greater variability, from 3.9 to 17.9 %. Two distinct peaks in % TOC were observed between 1.2 to 0.9 cal ka and at c. 0.6 cal ka.

C/N ratios were less variable, exhibiting a slight declining trend through the core. The C/N ratio of algae is generally between 4 and 10, and higher in terrestrial plants, usually > 20 (Meyers, 1994). The lower part of the sequence, between c. 5.8 and 3.4 cal ka, was more variable than the most recent 3,000 years, with a return to increased variability in the last 150 years. Values in the MOLE-JUAN core ranged from 18.6 (at 3.9 cal ka), characteristic of mixed algal and terrestrial composition, to 8.3 (core top), indicating an algal source.

The sediments were diatomaceous throughout all the organic laminae, and it is therefore likely that diatoms were the main source of organic matter. No data are available on the $\delta^{13}C$ composition of modern diatoms in Laguna de Juanacatlán, but algae (including diatoms) usually range between –20 and –30 ‰ (Galimov, 1995; Meyers and Teranes 2001). The $\delta^{13}C$ of bulk organic matter from the sequence fluctuated between –26.4 and –32.8 ‰. Between 5.8 and 2.5 cal ka, the mean value was –29.3 ‰, with a period of lower values between 5.6 and 5.3 cal ka, and increased variability between 4.6 and 3.6 cal ka. A trend towards lower values was observed after 2.5 cal ka, reaching about –32 ‰ between 1.7 and 1.3 cal ka, before increasing again towards the top of the sequence. There is no indication in the $\delta^{13}C_{org}$ record of the presence of C4 plants, which typically have substantially higher $\delta^{13}C$ values than algae or C3 terrestrial plants (Meyers, 1994). A number of modern vegetation samples collected around the lake margins and catchment slopes have values within the range of the sediments, including the emergent aquatic macrophyte *Juncus* (C/N 12; $\delta^{13}C$ –30.5 ‰) and herbaceous *Salvia* (C/N 10.4; $\delta^{13}C$ –31.8 ‰) (Aston, 2008). The predominance of C3 plants was confirmed by pollen analysis (see below).

Taking the % TOC, C/N and $\delta^{13}C$ data together, four key periods can be identified. At the base of the core, between c. 5.8 and 5.1 cal ka, declining % TOC and C/N, combined with tendency towards higher $\delta^{13}C_{org}$ values, suggest that algal sources were dominant and there was increasing productivity over this period. Between 5.1 and 4 cal ka, % TOC remained stable, but C/N ratios and $\delta^{13}C$ values co-vary and generally increase, with both reaching their highest values in the core. This is consistent with increased, but variable inputs from catchment sources. From 3.6 to 1.3 cal ka, stable and slightly lower C/N ratios and $\delta^{13}C_{org}$ point to an increased algal contribution to lake sediment organic matter. After 1.3 cal ka, the nature of the relationship between the sediment variables changed, indicating a shift in underlying causes. C/N ratios remained stable, indicating a consistent organic source, whilst % TOC and $\delta^{13}C_{org}$ values were variable and anti-phased. Higher $\delta^{13}C_{org}$ values, reaching –26.4 ‰, but stable C/N ratios, suggest increased algal productivity.

4.4 Diatom assemblages

Diatom species assemblage data are summarised in Figure 4. The planktonic *Discostella stelligera* (Cleve and Grunow) Houk and Clee, was common throughout the core, accompanied by a smaller form, < 5 μm in diameter, possibly *Discostella glomerata*, but it is problematic to distinguish when counting under light microscopy and is referred to as 'stelligeroid group (< 5 μm)'. Between c. 5.8 and 5.1 cal ka, *Discostella* species dominated the assemblage, mainly the larger *stelligera* type, accompanied by *Aulacoseira granulata* (Ehrenberg) Simonsen, making up to 20 % of the total. A distinctive feature of this period was the presence of *Fragilaria crotonensis* var. *oregona* Sovereign, with relative abundance up to 40 % at c. 5 cal ka.

Urosolenia spines were well preserved between 5.4 and 5.1 cal ka, their only occurrence in the record.

Between c. 5.1 and 1.2 cal ka BP, the diatom record continued to be dominated by *Discostella stelligera*, with *Synedra* species present in small amounts. The relative importance of *Discostella stelligera* and *Aulacoseira granulata* fluctuated through this period. A distinct peak of *Nitzschia paleacea* Grunow in Van Heurck occurred at c. 4.7 cal ka. Above this, *A. granulata* were present in higher numbers, up to 60 %, between 4.6 and 3.5 cal ka. The epiphytic species, *Cocconeis placentula* Ehrenberg also increased in abundance between c. 4.0 and 3.6 cal ka. A single peak of *S. acus* var. *radians* (Kützing) Hustedt was observed at 3.23 cal ka, followed by the reappearance of *N. palaecea* in large numbers at c. 3.1 cal ka. *A. granulata* increased in abundance between 3.0 and 2.4 cal ka. Two peaks of the small *Discostella* 'stelligeroid group' occurred at c. 2.9 and 2.3 cal ka.

Between 2.3 and 1.6 cal ka, *A. granulata* abundance was very low, rising again between 1.6 and 1.3 cal ka. A number of tychoplanktonic species were also present in low numbers through this period, including *Staurosirella pinnata* (Ehrenberg) Williams and Round, *Staurosira construens* Ehrenberg and *Pseudostaurosira brevistriata* (Grunow) Williams and Round. *Cocconeis placentula* was also present in small amounts, with a peak at 1.3 cal ka.

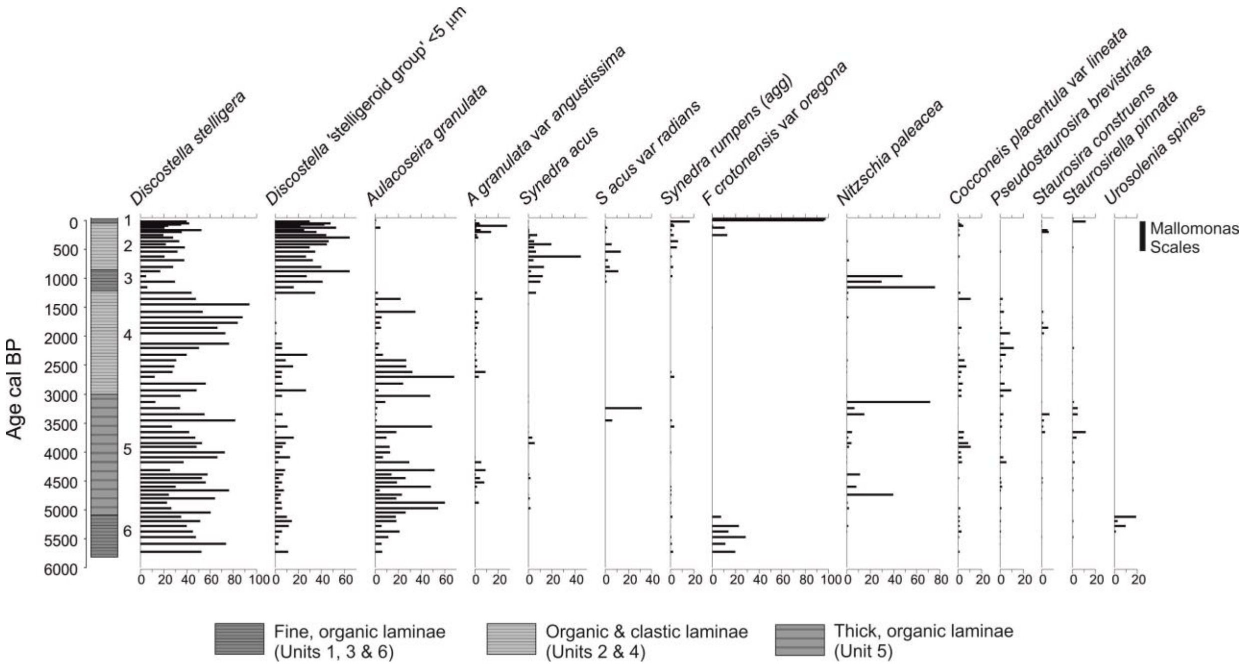

Figure 4: Summary of diatom species assemblages from the MOLE-JUAN composite sequence (species with at least 3% abundance are plotted).

A notable shift in the diatom assemblage occurred during the last 1.2 cal ka. Between 1.2 and 0.9 cal ka, *Nitzschia paleacea* dominated the assemblage at values of up to 80 %, having been absent from the record for the previous 2,000 years. Whilst *Discostella stelligera* was still present at values of c. 40 %, the proportion of the smaller *Discostella* species increased substantially to between 30 and 60 % of the total. *Synedra* species were also common, at values of 5 – 20 %. Over the last 300 years, the relative abundance of *Aulacoseira granulata* var. *angustissima* (Müller) Simonsen reached its highest level in the sequence. Also present in diatom samples over the last 500 years were abundant *Mallomonas* scales, tentatively identified as *M. pseudocoronata* Prescott.

The most striking change in the entire MOLE-JUAN sequence was observed in the uppermost sediments, where the dominant *Discostella* species were completely replaced by monospecific blooms of *Fragilaria crotonensis* var. *oregona* in the last 20 – 30 years. *Mallomonas* scales were not found within these uppermost samples.

The diatom species in the MOLE-JUAN sequence do not reflect major changes in ionic concentration of lake waters, with the major taxa in the MOLE-JUAN sequence found in Mexican lakes with circumneutral to alkaline waters of low conductivity (Davies et al., 2002). The most common species in the core, *Discostella stelligera*, has been interpreted as an indicator of recent warming and enhanced lake stratification in Arctic and temperate environments (Rühland et al., 2015). Saros et al. (2012) found that nutrient availability also plays an important role in its response to changes in mixing depth. In Mexico, it has been found in deeper freshwater lakes of the volcanic highlands (Davies et al., 2002) and occurs in numerous Holocene and Late Pleistocene records from the region (Bradbury, 2000; Caballero et al., 2006; Metcalfe et al., 2007). In contrast, *Aulacoseira granulata*, a more heavily silicified diatom requires nutrient-rich, well-mixed waters to remain buoyant (Bradbury, 2000). A diatom-based interpretation of limnological change is outlined for key time periods below, the forcing mechanisms behind which are considered in the synthesis.

Between 5.8 and 5.1 cal ka, dominance of *D. stelligera* over *A. granulata* suggests enhanced stratification and shallower mixing depth. *Fragilaria crotonensis* var. *oregona* is also present in substantial numbers. The ribbon-like chains formed by this species probably increases its ability to compete for nutrients (Rühland et al., 2015). *F. crotonensis* is widely acknowledged as an indicator of nutrient enrichment (Bradbury, 1975; Yang et al., 1996). The presence of delicate *Urosolenia* spines reflects exceptional preservation, indicating a very stable water column and high silica availability.

After 5.1 cal ka, the increase in *A. granulata* relative to *D. stelligera* suggests a change in the mixing regime to less well-stratified conditions or more regular overturning. Two distinct peaks in *Nitzschia paleacea* occur within this period (c. 4.74 and 3.1 cal ka). Whereas these sudden increases may represent the tendency of this species to bloom (Woodbridge and Roberts, 2011), the samples averaged multiple laminations and these occur only in specific parts of the core. *N. paleacea* was associated with periphytic assemblages in modern samples from Laguna Zacapu

(Metcalfe, 1988) and has been interpreted as indicating warm, alkaline and shallow conditions, representing less turbid waters than *A. granulata* (Metcalfe, 1995). However, the water must have been deep enough to be stratified during these episodes. One explanation is that *N. paleacea* peaks may indicate periods of enhanced stratification, with increased phosphorus availability relative to silica (Kilham et al., 1986). After 2.3 cal ka, the return to dominance of *C. stelligera*, but lack of *A. granulata*, indicates continued stratification, with further intensification of these conditions between 1.2 and 0.9 cal ka inferred from another *N. paleacea* peak. After 0.9 cal ka, the increase in *Synedra* species suggests a further shift in nutrient availability. Kilham et al. (1986) demonstrated that *Synedra* spp. are more effective competitors in systems with a limited phosphorus supply, and reflect high Si/P ratios. The peak in abundance of *Aulacoseira granulata* var. *angustissima* after 0.2 cal ka represents a shift to this morphological form instead of the nominate variety. The reason for this is difficult to interpret as the two forms have similar ecological requirements, although the rise in numbers of this genus does indicate increased turbidity. The very recent and dramatic change in the diatom assemblage to one entirely dominated by *Fragilaria crotonensis* var. *oregona* was previously interpreted in short cores as a response to recent anthropogenic disturbance in the catchment and associated eutrophication (Davies et al., 2005). The nominate variety is known to compete well where nitrogen concentrations are increased relative to phosphorus (Saros et al., 2005, 2011), and could indicate both local and regional signals. Nevertheless, because this species is also found at the base of the core, prior to the likely influence of human activities, natural drivers probably produced favourable conditions for this species during the Holocene.

4.5 Pollen assemblages

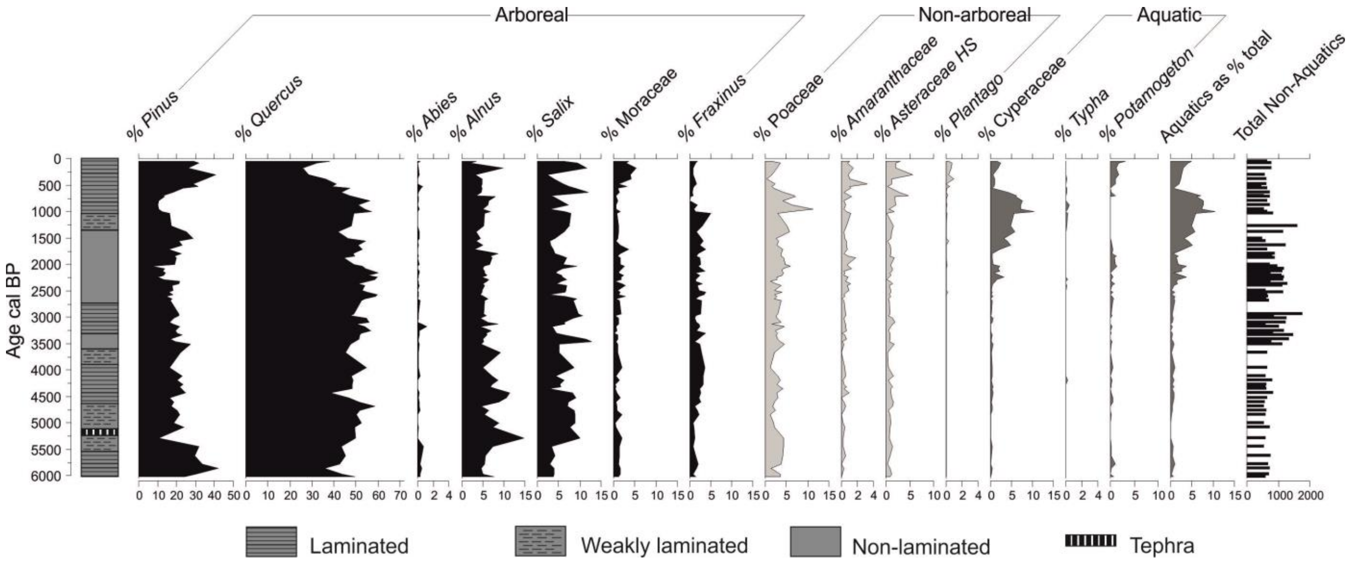

Figure 5: Summary pollen diagram for Core JUAN-90-2.

Pollen data from JUAN-90-2 are plotted as percentages of the total pollen sum in Fig. 5. Although aquatic pollen are sometimes excluded from the total, here they generally account for < 5 % of the total, except for the interval between about 1.3 and 0.65 cal ka when there are higher percentages of Cyperaceae. As the inclusion of aquatic pollen makes little difference to the percentages of non-aquatic pollen types, here we include them in the total pollen sum. *Pinus* (pine) and *Quercus* (oak) account for between 52% and 77 % of the total pollen sum in JUAN-90-2. Before c. 5.4 cal ka, *Pinus* and *Quercus* are co-dominant (together > 70 %), with low percentages of other tree species such as *Alnus* (alder) and *Salix* (willow). Grasses and herbs comprise a low percentage of the total pollen count. Between c. 5.4 and 0.5 cal ka, oak is present at higher percentages than pine. The pollen assemblage through this interval is marked by higher percentages of alder (up to 14.8 %) and willow (up to 12.8 %). From about 2 cal ka there is an increase in pollen percentages of emergent aquatic plants, including *Typha* (cattails), and Cyperaceae (sedges), which reach 10.4 % of the total pollen count at 0.95 cal ka. The top part of the core is marked by a switch back to pine > oak, with a clear increase in Moraceae (up to 5.3 %), a group that includes *Ficus* and *Morus* (Ramos Zamora, 1977). Amongst the non-arboreal pollen, there are increases in high-spine Asteraceae and *Plantago*. In the aquatic pollen, there is a decline in Cyperaceae and *Typha* and an increase in

Potamogeton (pond weed), which forms 3.2 % of the total pollen sum at the top of the core.

The interpretation of the pollen evidence from the highlands of Central Mexico has been complicated because of the dominance of taxonomically difficult taxa such as pine, oak, and alder, and the overlapping effects of climate change, human-induced disturbance and volcanic activity. Different species of pine and oak form different communities that occupy rather different environments with respect to moisture availability and temperature, but are difficult to distinguish using standard palynological techniques (Lozano García and Xelhauntzi Lopez, 1997; Lozano-García and Ortega-Guerrero, 1998). They also produce very large amounts of pollen. In contrast, *Abies* (fir), which may be a component of these pine-oak forests (increasingly so at higher elevations), has low pollen productivity and may be under-represented by its pollen (Watts and Bradbury, 1982; Lozano-García, 1989). The changing ratios of pine and oak, or pine to oak + alder + fir, have been used in Mexican pollen studies to try and elucidate the nature of past climate. Unfortunately, interpretations of these ratios, and of switches between pine and oak more generally, have not been consistent (Deevey, 1944; Sears, 1952; Watts and Bradbury, 1982; Ortega Rosas et al., 2008; Park et al., 2010; Lozano-García et al., 2013).

The early part of the pollen record (prior to about 5.4 cal ka) indicates a catchment dominated by pine-oak woodland. Fir reaches its highest percentage in the last 6000 years, but is still under 1%. *Salix* and *Alnus* are often found as riparian taxa in the Mexican volcanic highlands (Lozano-García et al., 2013) and their limited presence here may reflect a lack of suitable habitat when the lake was higher than it is today. After about 5.4 cal ka, there is a distinct decline in the percentage of pine, while the percentage of oak remains fairly stable (40 – 50 %). Such high percentages of oak pollen are rarely recorded in the TMVB, but have been recorded further north (~28^{o}N) in the Sierra Madre Occidental (Ortega-Rosas et al., 2008). Although aquatic pollen remains poorly represented until about 2.5 cal ka, this part of the pollen diagram is marked by clear increases in alder and willow and a slight increase in

Fraxinus (ash). *Fraxinus* is described by Rzedowski (1994) as riparian or occupying valley bottoms in oak woodlands. This increase suggests a slight decline in lake level, which would have created a wider riparian zone, although the continuously laminated sediments throughout this part of the JUAN-90-2 core would seem to indicate at least 7-8 m of water at the coring site, based on comparison with a core taken in 7.35 m depth in 1990 but not analysed in detail. That core, like JUAN-90-2 also preserved laminations in the surface and recent sediments. This depth is also consistent with measured thermocline depths (see above). It has been suggested that increasing predominance of oak relative to pine can be a result of succession, a more dominant summer precipitation regime or warming (Figueroa-Rangel et al., 2008; Ortega-Rosas et al., 2008; Correa-Metrio et al., 2012). Park et al. (2010) suggested that percentages of oak + alnus > pine (as here) are indicative of wet conditions. After about 2.5 cal ka, the arboreal pollen record remains stable, but there is a clear increase in the percentage of Cyperaceae (sedge) to a maximum of > 10% of total pollen about 0.9 cal ka. Although sedges can grow in a wide range of habitats, these emergent aquatics have been reported as being very common around lakes in the TMVB (Bonilla-Barbosa and Novelo Retana, 1995). The expansion of sedges and the switch from laminated to unlaminated sediments in core JUAN-90-2 seem to indicate a fall in lake level and hence drier conditions. The peak in Poaceae (grasses) at about the same time, may confirm this. After about 0.9 cal ka an increase in high-spine Asteraceae and the presence of large (> 80 µm) Poaceae (possibly *Zea mays* (maize), although not recorded as such) may indicate anthropogenic catchment disturbance. More distinct changes in the pollen record at about 0.5 cal ka, when there is an increase in Moraceae (up to 5.3%), persistently higher percentages of Amaranthaceae, and an increase in *Plantago*, seem to confirm this interpretation. High-spine Asteraceae and *Plantago* have both been interpreted as indicators of human disturbance (Almeida-Lenero et al., 2005; Bhattacharya et al., 2015). Amongst the Moraceae, *Ficus* are particularly common in this part of Mexico and many occur in moderately to strongly disturbed sites (Serrato et al., 2004). Moraceae in general and *Ficus* in particular, are also found mainly in warm and wet climate zones in Mexico. At the same time as this disturbance occurs, pine recovers to the percentages found near the base of the sequence, Cyperaceae declines, and the submerged aquatic/floating mat-forming *Potamogeton* becomes more abundant. Taken together with a return to the deposition of laminated sediments in JUAN-90-2, it seems possible that the catchment was experiencing both more disturbance and higher water levels, although percentages of willow remain quite high.

5. Discussion

5.1 Paleoenvironmental synthesis

Proxy palaeoenvironmental data from Laguna de Juanacatlán demonstrate variations in the mixing regime of the lake over the last 5.8 cal ka. This may have been caused by changes in water depth, temperature and wind speed, or a combination of these, but individual sediment variables cannot be used readily to identify which factors were responsible at any one time. Here, we synthesise the multiple sediment variables (Fig. 6) for key time periods and consider the likely forcing mechanisms behind the observed limnological and catchment changes. Detrended Correspondence Analysis (DCA; Hill and Gauch, 1980) was used to explore the environmental gradients in the pollen and diatom datasets.

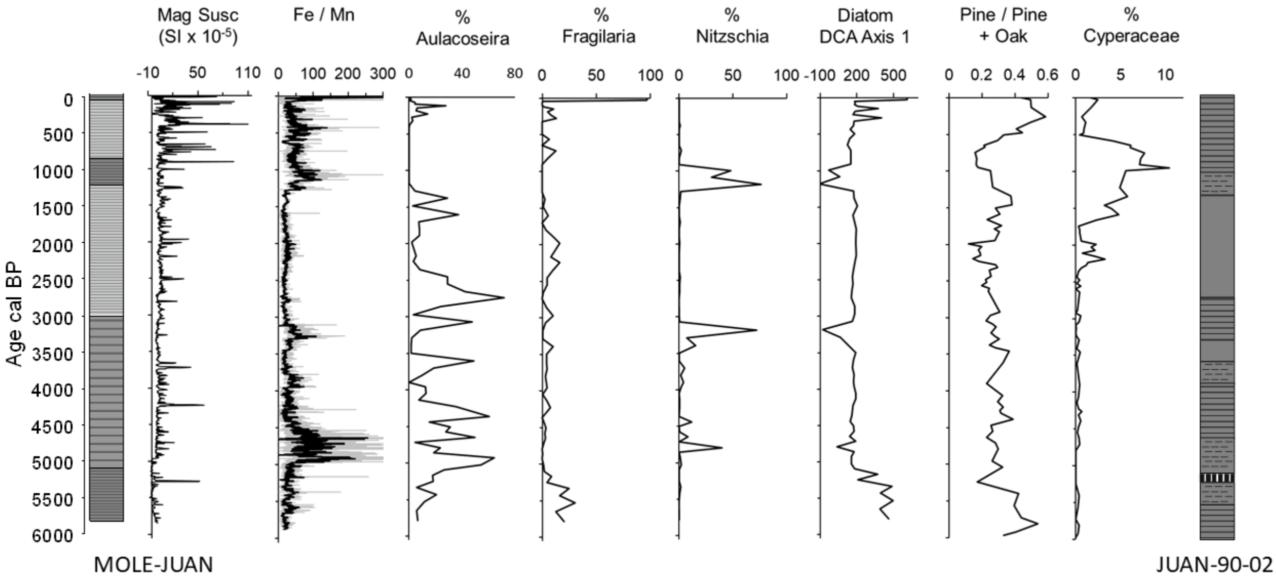

Figure 6: Summary of palaeoenvironmental data from the MOLE-JUAN composite sequence and core JUAN-90-2 pollen analysis.

5.1.1 ~ 5.8 to 5.1 cal ka

This period is characterised by low catchment inputs, with type 1 organic laminae couplets. The diatom assemblage, represented by *D. stelligera* with *F. crotonensis* var *oregona*, indicates a stratified and stable water column and mesotrophic conditions that were similar to present. High positive scores on Diatom DCA Axis 1 (eigenvalue 0.64) during this period are driven by *F. crotonensis* var *oregona*. This taxon was encountered previously only in the uppermost sediments at this site and suggests high nitrogen concentrations relative to phosphorus and silica. Algae were the main source of organic matter, with $\delta^{13}C$ values suggesting an increasing trend in lake productivity. Pollen DCA Axis 1 (eigenvalue 0.038) mirrored the pine profile (and pine/pine +oak ratio) through the sequence and is therefore not presented. Up to c. 5.3 cal ka, pollen data point to wetter conditions, with increased pine/pine + oak ratios and the presence of *Abies* at its highest concentrations in the sequence (but still in low numbers). Together, these data suggest that generally moist conditions maintained relatively high water levels and stable lake stratification. Some catchment disturbance around 5.2 cal ka, with higher Ti and magnetic susceptibility values, marks a change in the record after this point.

5.1.2 ~ 5.1 to 4.0 cal ka

This period is marked by the onset of more variable conditions, with episodic periods of catchment instability and an increase in C/N to its highest levels in the entire record, indicating increased inputs of higher plant material into the lake. The predominant laminae type changed in the deeper water core and in the shallower water core sediments changed from laminated to weakly laminated sediments. The increasing abundance of riparian vegetation (willow and alder, Fig. 5) probably indicates a lowering of lake level, consistent with the change in lamination at this site. The increasing importance of the diatom *A. granulata* and high Si:Ti indicate productive, silica rich conditions. Warm conditions could account for the predominance of oak in the terrestrial vegetation, periodic intense stratification (high Fe:Mn) and high levels of *N. paleacea*, particularly at ca. 4.7 cal ka (Figs 4 & 6).

5.1.3 ~ 4.0 to 1.2 cal ka (2050 BCE – 750 CE)

This continues the general drying of the earlier period. Catchment conditions appear to have been generally stable until around 3.0 cal ka. After this, there is an increase in sediment inputs from the catchment. The change to clastic laminae in the deeper water core confirm this trend. Shallower water is indicated by an increase in the proportions of epiphytic and periphytic diatoms (small Fragilaroid taxa, *C. placentula*; Fig 4) and the deposition of unlaminated sediments in the shallower water core. Willow and alder remain important components of the pollen flora, while towards the end of this period there is a marked increase in aquatic pollen, (e.g. Cyperaceae) possibly indicative of further shallowing (Figs 5 & 6).

5.1.4 ~ 1.2 to 0.9 cal ka (750-1050 CE)

The represents a brief period of catchment restabilisation, with a lack of clastic laminae at the deeper water site. The diatom record shows the last peaks of *N. paleacea* indicated by a shift to negative values on Diatom DCA Axis 1 and the start of higher proportions of *Synedra* spp (Diatom DCA Axis 2). *Nitzschia* species have been linked with increased nutrient availability from cyanobacteria which would be consistent with higher productivity indicated by the increase in % TOC and $\delta^{13}C_{org}$ values (Fig. 3). Cyperaceae continues to increase through this period. We interpreted the Ti record as an indicator of drier conditions (Metcalfe et al., 2010; Jones et al., 2015). The signal from the palaeoecological evidence however is less clear. *N. paleacea* likely indicates warmer conditions and has been associated with lake shallowing in central Mexico (Metcalfe, 1995). However, the return from non- to weakly-laminated sediments in core JUAN-90-2 does not support a lake level decline. The major change in the diatom flora does indicate a substantial change in limnological conditions and may be representing intensified stratification due to warming rather than any significant lake level lowering.

5.1.3 ~ 0.9 to –50 cal ka (1050 – 2000 CE)

Following the period of drier conditions which ends at c. 0.9 cal ka (1050 CE), a switch to higher values of magnetic susceptibility and Ti indicates a substantial increase in catchment inputs. Clastic laminae dominate in the MOLE-JUAN core. The generally greater catchment inwash is punctuated by periods of lower catchment inputs, between 0.6 and 0.4 cal ka (1350 – 1550 CE) and from 0.3 to 0.1 cal ka (1680 - 1850). Within these time periods are several known historical multi-year droughts that are associated with lower Ti values (Metcalfe et al., 2010). There is a substantial shift in the JUAN-90-2 pollen record over the last 0.9 cal ka, with pine increasing to its highest percentages. Oak is still common, at 30 % of the count, higher than in many other central Mexican sequences. Forest elements clearly remain dominant, but the increase in Poaceae, which begins around 0.9 cal ka, high-spine Asteraceae and Moraceae indicate anthropogenic disturbance of the catchment vegetation. This is the first clear signal of human influence in the record. The increase in pine over the last 500 years could be interpreted as a shift to wetter conditions, with similar conditions to those prior to 5.3 cal. ka. This is also combined with a drop in Cyperaceae and higher abundance of *Potamogeton*, suggesting a modest increase in water level. Diatom DCA Axis 2 scores are higher, which reflects a shift towards the dominance of the smaller form D. 'stelligeroid group' and also an increase in *Synedra* species. Laminated sediments at both core sites suggest increased water depth. A switch from the presence of *Synedra* species to *Aulacoseira granulata* var. *angustissma* around 300 years ago, suggests increased mixing after this point, related to the combined influences of catchment disturbance and wetter conditions. The very recent and dramatic change to the diatom flora recorded since the 1990s, to a total dominance of *F. crotonensis* var *oregona* (high DCA Axis 1 scores; Fig. 6) signals a further strengthening of stratification and an increase in concentrations of nitrogen relative to phosphorus. Fine organic laminae dominate in the MOLE-JUAN core. We interpret this as a local anthropogenic signal, but there may also be a broader, regional influence from nitrogen deposition and anthropogenic warming. Combined impacts of ENSO events and recent warming have been linked to phytoplankton changes in a central Mexican crater lake (Caballero et al., 2016) Further high-resolution sampling resolution of surface cores and detailed limnological monitoring at Juanacatlán could be used to investigate these relationships further.

5.2 Implications for Holocene monsoon variability

The data presented here cover the period after the peak intensity of the North American Monsoon, which occurred around 6 cal ka (Metcalfe et al., 2015). The transition from relatively wet to drier conditions begins c. 5.1 cal ka intensifying after c. 4.0 cal ka and is consistent with the weakening of the NAM as the ITCZ moved south. A number of records across Mexico indicate variable conditions between 6 and 5 cal ka BP, as the declining influence of orbital forcing led to increased prominence of other forcing mechanisms (Metcalfe et al., 2000). The timing of the transition to a weaker monsoon is consistent with records across the TMVB indicating a shift to drier conditions around 4 cal ka (Bernal et al., 2011, Lozano García et al., 2013; Metcalfe et al., 2015).

An increase in the influence of ENSO and greater hydrological variability is inferred at several sites beginning c. 4 cal ka, including Pátzcuaro (Metcalfe et al., 2007) and Zirahuén (Ortega et al., 2010; Vázquez-Castro et al., 2010; Lozano et al., 2013) (Figure 1a). At Juanacatlán, dominance of a 20-25 year cycle in the Ti record after 3 cal ka was interpreted as an increasing Pacific influence (Jones et al., 2015). This is reflected in the stratigraphy of the JUAN-MOLE composite as clastic laminae become common in Unit 4 (Fig 3). The palaeoecological record at Juanacatlán is of insufficient resolution to capture the decadal variability observed in the high resolution Ti record but does indicate a shift to drier and more variable conditions. Increasingly distinct fluctuations in moisture availability are also observed at some TMVB lakes, such as those in the Valle de Santiago (Park et al., 2010) over the late Holocene. The more intense human occupation history at sites like Pátzcuaro (Metcalfe et al., 2007) and Zirahuén (Lozano-García et al., 2013) probably sensitized the catchment response to hydrological changes, making it difficult to interpret the recent parts of these records strictly in terms of climate variability, at least compared to the pre-disturbance parts of the sequences.

We interpret the changes observed in the Juanacatlán record between 1.2 and 0.9 cal ka (750 – 1050 CE) as indicating generally drier and warmer conditions. However, the record at this point may also reflect reduced rainfall variability and / or intensity, given the absence of any clastic laminations. The regional picture at this time is complex. Drier conditions are observed a little earlier than at Juanacatlán in high-resolution records from southwest Mexico. The Juxtlahuaca speleothem shows the onset of drought at 1.25 cal ka (~ 700 CE), peaking at 750 CE (‘Epiclassic Drought), with a switch to wetter conditions (Postclassic Pluvial) associated with increased La Niña influence (Lachniet et al., 2017). At Laguna Minucúa drought conditions are inferred between 1.28 and 1.16 cal ka (670 – 790 CE), followed by variable but wetter conditions. The laminated sequence from Santa Maria del Oro, north of Juanacatlán captures drought conditions between 1.5 and 1 cal ka (450 – 950 CE). The most intense phase, between 1.35 and 1.15 cal ka (600 - 800 CE) (Rodríguez Ramírezet al., 2015), peaks earlier than at Juanacatlán. The distinct period of reduced run-off at Juanacatlán coincides with records elsewhere across Mesoamerica, which record prolonged drought conditions, the so-called Terminal Classic Drought (Hodell et al., 1995; 2005; Douglas et al., 2015), also clearly expressed across the TMVB (Metcalfe et al., 1991; Metcalfe and Davies 2007; Bhattacharya et al., 2015).

Previous work suggested that the intense dry phase observed across Mesoamerica was caused by a shift in the strength and position of the Bermuda-Azores High and related to southward movement of the ITCZ (Metcalfe et al, 2000). Recent modelling confirms a strong North Atlantic imprint on drought across the region, with a positive North Atlantic Oscillation (Bhattacharya et al., 2017), whilst in the Pacific Ocean, La Niña-like conditions prevailed during the Medieval Climate Anomaly (Metcalfe et al., 2015). Lachniet et al. (2017) emphasise the complex interactions between East Pacific (ENSO) and Atlantic (NAO) forcings that are probably involved. Persistent La Niña conditions brought drier conditions to the region north of Juanacatlán but increased rainfall to the south (Metcalfe et al., 2015). One possibility is that the catchment stability observed at Juanacatlán between 1.2 and 0.9 cal ka linked more closely to reduced rainfall variability rather than absolute values as lower Pacific sea surface temperature would result in fewer tropical storms. This period also coincides with reduced ENSO frequency recorded in the sediments of El Junco Lake in the Galapagos (Conroy et al., 2008).

The major shift in the diatom assemblage to *N. paleacea* dominance between 1.2 and 0.9 cal ka was also observed earlier in the record, at 4.7 cal ka and 3.1 cal ka. These may also represent equivalent periods of drying / catchment stability and also coincide with low ENSO frequency in the El Junco record (Conroy et al., 2008). Comparison with other lakes in the TMVB is problematic for these two earlier *N. paleacea* phases as other records lack sufficient chronological resolution. Caballero et al. (2002) report a dry phase at Sta Cruz Atizapan at c. 4.5 cal ka, but timing of dry episodes at Zirahuén and Pátzcuaro in Michoacán only coincides with the 1.2-0.9 cal ka phase (Davies et al., 2004; Metcalfe et al., 2007; Ortega et al., 2010). More high resolution lacustrine sequences extending back to the mid-Holocene are needed to explore these earlier episodes.

The Juanacatlán record fits the model of a two-part Medieval Climate Anomaly (Rodysill et al., 2018). The phase discussed above between 1.2 and 0.9 cal ka (750 - 1050 CE) is quickly followed by a shift to substantially wetter conditions, although this signal may be enhanced by the onset of anthropogenic disturbance. The climate of the Little Ice Age (1400 – 1850 CE) also varied across the region, with a continued shift to markedly wetter conditions than during much of the record, but punctuated by drier periods corresponding to historic droughts (Metcalfe et al., 2010). Increasing regional variability during the last few hundred years is evident from a regional synthesis of records (Metcalfe et al., 2015). Drier conditions between 0.6 and 0.35 cal ka (1350 and 1600 CE) and the earlier one at 1.2 – 0.9 cal ka (750 – 1050 CE) are antiphased with the Juxtlahuaca speleothem record (Lachniet et al., 2012; 2017), but in phase with the nearest lake record at Santa Maria del Oro (Sosa Najera et al., 2010; Rodríguez Ramírez et al., 2015). The lake and cave records have different levels of chronological resolution, but may also record different aspects of the climate system (Lachniet et al., 2017). The position of Juanacatlán at the boundary between northern and southern regions in relation to Pacific forcings adds to the complexity.

5.4: Human – environment interactions

The timing of the onset of human disturbance varies across central Mexico, and it has been suggested it could be as early as 5.7 cal ka in southern Guanajuato (Park et al., 2010), whilst in the Cuenca Oriental in eastern Mexico, charcoal and pollen indicate an onset of agriculture c. 2.7 cal ka (Bhattacharya and Byrne, 2016). Here, at Laguna de Juanacatlán, we see no clear evidence of human activity until much later than at many other sites, after the drought event between 1.2 and 0.9 cal ka. The peak in Poaceae at the end of the drought may be related to anthropogenic disturbance, but could also be a response to the drier conditions. Given that it occurs as the JUAN-90-2 core site becomes laminated again, signalling increased water depth, anthropogenic disturbance is the more likely explanation.

The evidence from Juanacatlán suggests that there was some minor forest clearance and cultivation in the basin during the Postclassic, but that human influence here was considerably less intense than observed at other sites across the TMVB (Metcalfe et al., 2007; Lozano et al., 2013). There is currently no archaeological evidence to support dense settlement in the area (see section 2). This highlights the rare value of the palaeoecological record from Laguna de Juanacatlán, which primarily reflects a response to climate forcing during the late Holocene.

One topic of contentious debate is the relative amount of disturbance caused by pre- and post-Hispanic populations in central Mexico (Denevan, 1992; O'Hara et al., 1993; Fisher et al., 2003). At Laguna de Juanacatlán, the minor change in forest composition began c. 1200 CE prior to the Colonial Period (1521 CE) and probably represents the combined influences of climate change and human activity. The two small peaks in disturbance indicators at c. 1300 CE and 1700 CE are similar in magnitude. There is no evidence from the Juanacatlán catchment to indicate a more intense phase of human activity following the Spanish Conquest, despite historical records of mining activity during the 17th century in the area (see section 2.1).

The most pronounced anthropogenic signal occurs within the last 30 years, with a complete change in the diatom flora of the lake, which persisted through the most recent phytoplankton sampling in 2011 (Sigala et al., 2017). This change in assemblage occurred prior to the establishment of a tourist complex on the lake shore. We previously interpreted this as a response to local catchment changes (Davies et al., 2005). The dramatic change, however, is consistent with evidence from alpine lakes in North America that phytoplankton have responded to increased atmospheric nitrogen deposition and anthropogenic warming (Saros et al., 2005; Rühland et al., 2015). Information from tropical lakes on the impact of these multiple stressors on phytoplankton composition is lacking. One problem is that it is difficult to disentangle these larger-scale driving mechanisms from local, catchment-scale impacts. Rapid turnover of the diatom flora has also been observed in recent decades at Lago de Zirahuén (Davies et al., 2004) and Laguna Zacapu (Leng et al., 2005), but these have much more intense human activity around the basin and at the lake shore, and so probably represent local changes. One possibility is that recent warming effects are more visible at Laguna de Juanacatlán, in light of the muted magnitude of human impacts. A short core retrieved in 2003 from high-altitude Lake La Luna on the Nevado de Toluca, the same year as MOLE-JUAN, showed no evidence of recent, rapid change (Cuna et al., 2014), but Lake La Luna is an oligotrophic lake at a substantially higher altitude and may not have reached a threshold to initiate a nutrient-related response.

6.1. Conclusions

The palaeolimnological record from Laguna de Juanacatlán provides new insights into the links between climate variability and lacustrine response over the last c. 6,000 years in western Mexico. The broad sequence of change is consistent with patterns observed at other sites in the Trans-Mexican Volcanic Belt. Less intense anthropogenic disturbance was evident here over the late Holocene, compared with other basins, suggesting that more subtle limnological responses to climatic change can be identified.

- Humid conditions, similar to present, are identified between 5.8 and c. 5.1 cal ka, with dense oak-pine forest, a deep, stratified lake and low catchment inputs.
- A transition to lower lake levels from 5.1 – 4.0 cal ka was observed, with drier and more variable conditions from c. 3 cal ka, consistent with increased influence of ENSO variability during the Late Holocene.
- A distinct period of drier and / or reduced rainfall variability between 1.2 and 0.9 cal ka is coincident with major hydrological changes observed across MesoAmerica. The record at Juanacatlán may reflect reduced tropical storm during a period of reduced El Niño frequency.

- A return to wetter, but more variable conditions occurred during the last c. 950 years, evident from changing catchment inputs, lake stratification and nutrient availablity.
- Although anthropogenic disturbance at Juanacatlán has always been relatively low, recent dramatic changes in the aquatic ecosystem highlight the sensitivity of the lake to multiple local and regional stressors.

Laguna de Juanacatlán is a key site for palaeoclimate research in Mesoamerica and provided an unambigious record of climate over much of the last 6,000 years. The geochemical and palaeoecological record presented here provides a framework for further work to investigate ecological responses to climate change at annual or sub-annual resolution.

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