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Discussions

Climatic variability and human impact during the last 2000 years in western Mesoamerica: evidences of late Classic and Little Ice Age drought events

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Abstract

Results are presented from biological (diatoms and ostracodes) and non-biological (Ti, Ca/Ti, total inorganic carbon, magnetic susceptibility) proxy analyses from an 8.8 m long laminated, high resolution (∼ 20 yr $sample^{-1}$) sediment sequence from lake Santa María del Oro (SMO), in western Mexico. This lake is at a sensitive location between the dry climates of northern Mexico, under the influence of the north Pacific High Pressure Subtropical Cell and the moister climates of central Mexico, under the influence of the seasonal migration of the Intertropical Convergence Zone and the North American Monsoon (NAM). The sequence covers that last 2000 years and gives evidence of two periods of human impact in the lake, shown by increases in *Achnanthidium minutissimum*, the first related with the Shaft and Chamber Tombs Cultural Tradition from 100 BC to AD 300 and a second late Postclassic occupation from AD 1100 to 1300. Both periods correspond to relatively wet conditions. The sequence also gives evidence of three dry intervals with high carbonates, ostracodes and aerophilous *Eolimna minima* concentrations. The first, from AD 500 to 1000 (most intense from AD 600 to 800), correlates with the end of the Shaft and Chamber Tradition after ca. AD 600. This late Classic dry period is the most important climatic signal for the Mesoamerican region during the last 2000 years, as it has been recorded at several sites from Yucatan to the Pacific coast. In the Yucatan area this dry interval has been related with the demise of the Maya culture between AD 850 and 950. The last two dry events correspond with the onset and late Little Ice Age (1400 to 1550 and 1690 to 1770), and follow the Spörer and Maunder minima in solar radiation. The first of these intervals (1400–1550) shows the most intense signal over western Mexico, however this pattern changes at other sites. Dry/wet intervals in the SMO record are related with lower/higher intensity of the NAM over this region.

1 Introduction

The knowledge of past climate and environmental events is critical for understanding a wide variety of modern environmental processes in order to better estimate causes and effects of future environmental changes. Records from many parts of the world have led to the recognition of climate variability in the late Holocene. However, its duration and the possible mechanisms of climate change involved at each location are not clear, especially at tropical latitudes where there are fewer paleoclimatic continental records than at higher latitudes (Maasch et al., 2005; Mann et al., 1999).

In Mesoamerica, the last two thousand years appear to have been a time of significant climatic change with a complex signal, mostly linked to moisture availability. At present, the influence of the Intertropical Convergence Zone (ITCZ) and Subtropical High-Pressure Cells (SHPCs) varies seasonally, showing latitudinal shifts associated with the tropospheric equator-pole temperature gradient in each hemisphere, and the thermal contrast between both hemispheres (Haugh et al., 2001; Nyberg et al., 2002). The seasonal shift in insolation and latitudinal location of the ITCZ and SHPCs brings shifts in moisture availability that affect most of Mesoamerica, with an intense summer rainfall season associated with the northerly location of the ITCZ and the onset of the North American Monsoon (NAM). Past changes in the amplitude, intensity and location of the ITCZ and SHPCs and in the intensity of the NAM are therefore likely explanations of the changes documented in the Mesoamerican geological record (Hodell et al., 2005a; Metcalfe et al., 2010; Haug et al., 2003; Barron et al., 2012). Long term changes in these climatic systems can be recorded in the sedimentary archives of the lakes in the region given that lakes are natural systems that are sensitive to climatic variations which can lead to changes in their stratification patterns, their water chemistry and/or their biological associations. Specifically, western Mexico is an area which precipitation is modulated by the position of the ITCZ and the intensity of the NAM, however, most of the available paleolimnological records for Mesoamerica are concentrated in the highlands of central Mexico or in the Yucatan region (Metcalfe et al., 2000).

In this paper we present a multiproxy, high resolution (~ 20 yr per sample) study of a laminated sediment~~ary~~ sequence from a closed lake in western Mexico (Santa María del Oro, Nayarit, Fig. 1) which aims to reconstruct the past climatic events that affected western Mesoamerica during the past 2000 years. This lake currently sits at the intersection between the arid climates of northern Mexico, mostly under the influence of the north Pacific SHPC, and the temperate, sub-humid to humid climates of central Mexico (García-Oliva et al., 2002), under the influence of the ITCZ and the NAM systems. This record gives clear evidence of two intense drought periods, the late Classic (AD 500 to 1000) and the onset of the Little Ice Age (AD 1400 to 1550) ~~and~~ a third, less intense around AD 1690 to 1770.

2 Site description

Santa Maria del Oro (SMO, 21°23′ N, 104°35′ W, 750 m a.s.l.) is a topographically closed freshwater crater lake at the western end of the Transmexican Volcanic Belt and only 65 km from the Pacific coast (Fig. 1). The catchment rocks are dominated by dacite-rhyolite and basaltic-andesite. Minor exposures of basaltic lava flows are present on the northern wall of the crater. There are no carbonate rock outcrops in the catchment or in the surrounding areas (Ferrari et al., 2003; Vázquez-Castro et al., 2008).

The climate at SMO is warm and sub-humid, with monthly average temperatures that range from 16.5 to 25 °C (Station 18005-Cerro Blanco – Servicio Meteorológico Nacional). This region receives an average annual precipitation of ~ 1200 mm mainly during the warm, summer months (June to September) when the ITCZ is at its most northerly location and the NAM is active (Liebmann et al., 2008; Berbery, 2001). During summer tropical storms and hurricanes can also bring moisture from the Pacific (Castro, 2010; García-Oliva et al., 2002). The rest of the year (October to May) is relatively dry, particularly during spring.

SMO is a nearly round, ~ 2 km diameter lake. It has a maximum depth of 65.5 m and a mean depth of 46 m (Serrano et al., 2002). The crater has steep slopes but

there is a small flat and shallow bay (12 m deep) where the core for this study was retrieved (Fig. 1). The lake receives inflows directly from precipitation, seasonal runoff and ground water, and loses water to evaporation and seepage. The lowest point of the crater is on the north-eastern side, where the natural sill has been anthropogenically modified and today it lies ~ 5 m above the lake level (755 m a.s.l.). The closed nature of the basin and relatively unpolluted conditions make ~~of~~ this lake an ideal paleoenvironmental research site, where lake chemistry depends mostly on the precipitation – evaporation balance. At present SMO is a freshwater, [HCO_3^-]-[Cl^-], [Na^+] > [Mg_2^+] ≫ [Ca_2^+], oligotrophic, monomictic lake, with a winter mixing period (Caballero et al., 2013); the oxycline lies between 13 to 20 m depth the rest of the year. Currently the lake ostracode fauna is dominated by *Potamocypris variegata* Brady and Norman, *Cypridopsis vidua* Müller and *Darwinula stevensoni* Brady and Robertson and the planktonic diatom flora by *Aulacoseira granulata* (Ehrenberg) Simonsen in association with *Nitzschia amphibia* Grunow.

3 Methods

Four parallel cores between 4 and 9 m long were recovered from the shallow southwestern bay (12 m depth) of SMO in 2002 (Fig. 1c) with a Usinger coring system (Mingram et al., 2007). All cores were split, described, photographed and sampled at the Instituto de Geofísica, Universidad Nacional Autónoma de México (UNAM) and except otherwise specified all analyses were performed there. The longest core (SMO02-V, 8.8 m) was sampled on average at 5 cm intervals for magnetic susceptibility (MS), biological (ostracodes, diatoms, pollen) and geochemical analyses (total inorganic carbon, total organic carbon, X-Ray Fluorescence elemental analysis). Seven samples for ^{14}C AMS radiocarbon age determinations were collected at selected levels, dried and sent without any further treatment to a commercial laboratory. Sediment stratigraphy, age model, MS and ~~total inorganic carbon (TIC)~~ data have been published in Vazquez et al., 2008. In this paper we present these data, with MS expressed in dimensionless international system units (SI) and TIC expressed as its $CaCO_3$ % equivalent, together with new diatom, ostracode, Ca and Ti analysis from the same (SMO02-V) core.

3.1 X-Ray Fluorescence

Thirty nine freeze-dried sediment samples were chosen, on average every 20 cm, for X-Ray Fluorescence (XRF) elemental analysis. Samples were homogenized and ground to 200 mesh using an agate mortar. Elemental concentrations were measured in a Siemens SRS 3000 wavelength dispersive XRF spectrometer with a precision of 5 % at the Institute of Geology, UNAM. Titanium and calcium concentrations are expressed as percentages, Ca was normalized against titanium and expressed as Ca/Ti ratio.

3.2 Diatoms

For diatom analysis 108 samples were chosen, on average at every 10 cm interval, of which 78 contained diatoms. Dry sediment (0.5 g) was successively cleaned with HCl (10 %), H_2O_2 and HNO_3. Permanent slides were made with 200 µL of clean material, with Naphrax® as mounting medium. Minimum counts of 300 valves were undertaken in most samples, but 22 had low diatom abundance and only 100 valves were counted. Diatom counts were done with an Olympus BX50 microscope with Interdifferential Phase Contrast at 1000 × . Species composition is reported as relative abundance (%), and total abundance is reported as valves per gram of dry sediment (v gds^{-1}).

3.3 Ostracodes

For ostracodes the same 108 samples were analyzed, but only 57 levels contained ostracodes. Two cubic centimeters from each sample were freeze dried, from which 1 g of dry sediment was disaggregated by standard methods (Delorme, 1990; Forester, 1988) and slowly wet-sieved (63 µm). Ostracode valves were picked under an Olympus

SZX12 stereo microscope, counted, determined to species taxonomic level and stored in micropalaeontological slides. Care was taken to pick whole adult valves to allow species identification, juvenile valves were counted separately. Ostracode counts are expressed as valves per gram of dry sediment (v gds^{-1}).

4 Results

4.1 Core description

The SMO02-V sequence consists of sand/silt laminations with intercalated woody peat layers. Individual silt layers can be of ~ 1–3 to 60 mm in thickness and either light-brown calcareous, greenish, reddish or dark-brown (Vázquez-Castro et al., 2008). A tephra layer at 4.4 m depth was identified as the Toba Jala (AD ~ 860), from nearby Ceboruco volcano. The light-brown calcareous silt layers contain either authigenic carbonates or ostracodes, and are more frequent towards the top of the core, while woody peat layers are more frequent towards the bottom. There is no evidence for hiatuses, erosion features or slumping structures in the cores.

4.2 Chronology

The seven dates (Table 1) were calibrated to calendar years with Calib 5.0 (Stuvier et al., 2005) and the IntCal04 data set (Reimer et al., 2004). The age model (Fig. 2) assumed uniform sediment accumulation rates between the dates and anchored the top sediment to the year of coring (2002) (Vázquez-Castro et al., 2008). Sedimentation rates vary between 0.21 and 1.15 cm yr^{-1} (Fig. 2). According to this model the base of the core (882 cm) is ca. 2600 years old, with an average resolution of 23 years per sample.

4.3 Non biological proxies

Magnetic susceptibility (MS) (Fig. 3) fluctuates along the core between 24 and 520 $\times 10^{-6}$ SI, with the lowest values ($< 200 \times 10^{-6}$ SI) observed between 530 and 490 cm, and between 200 and 150 cm. The highest MS values ($> 300 \times 10^{-6}$ SI) are mainly present from 600 to 530 cm~~,~~ from 490 to 420 cm. Titanium content ranges between 0.3 and 1.5 % with lower than average (< 0.8 %) values concentrated between 530 and 370 and 200 to 150 cm. The highest values (> 1.3 %) in the record ~~are present~~ between 450 and 420 cm.

TIC as its $CaCO_3$ equivalent varies along the core from 0 to 59 % (Fig. 3), in a nearly opposite way as magnetic susceptibility, showing in general terms higher values (> 20 %) between 530 and 370, 320 and 240, 200 to 150 and 120 to 100 cm. Ca/Ti ratio ranges between 1.4 and 175 and shows above average values (> 15) between 530 and 370 cm and at 200 cm.

4.4 Diatoms

Diatom abundance shows several intervals of lower than average abundance values ($< 40 \times 10^6$ v gds^{-1}, Fig. 4), but the lowest abundances are recorded between 740 to 690 cm and from 380 to 330 cm. Sixty four species are recorded in the sequence, 9 with relative abundances ~~higher~~ than 20 % in more than one sample (Fig. 3). *Aulacoseira granulata*, *Nitzschia amphibia* and small species of *Fragilaria sensu lato* (*Staurosira construens*, *Staurosirella pinnata*, *Pseudostaurosira parasitica*, *P. brevistriata*) are the dominant species along the record, *Achnanthidium minutissimum* (Kützing) Czarnecki ~~has a preferential distribution~~ between 750 and 650 cm and from 400 to 250 cm, *Amphora ~~lybica~~* Ehrenberg and *Hippodonta luneburgensis* (Grunow) Lange-Bertalot, Metzeltin and Witkowski ~~have higher abundances on~~ the top 500 cm of the core and *Eolimna minima* (Grunow) Lange-Bertalot and W. Schiller shows a distinctive distribution with maxima between 530 and 420 cm and two less important peaks between 200 and 110 and 75 to 60 cm.

4.5 Ostracodes

Ostracode total abundance shows two distinct intervals with high values (> 1000 adult v gds^{-1}), the first between 530 and 420 cm and the second between 200 and 110 cm. A smaller peak at 75 to 60 cm is also present ~~and~~ the rest of the core has very low (< 100 adult v gds^{-1}) ostracode concentration (Fig. 3). Six species are recorded in the sequence; *Candona patzcuaro* Tressler is the most abundant and constant along the core in association with *Potamocypris variegata* Brady and Norman and minor numbers of *Chlamydotheca arcuata* Sars. *Cypridopsis vidua* Müller and *Darwinula stevensoni* Brady and Robertson are also present along the core, but show a preferential distribution between the 530 and 420 cm interval. *Limnocythere verrucosa* Hoff is only present as juvenile valves, and shows maximum concentrations between 570 and 530 cm.

5 Proxy interpretation

MS generally indicates the abundance of magnetic minerals that reach a lake mainly by surface runoff from the catchment area or, ~~in occasions~~, from volcanic activity (Evans and Heller, 2003). Titanium is an element which originates from minerals in the catchment rocks and its abundance in lacustrine sediments is also indicative of surface runoff to the lake (Metcalfe et al., 2010; Sosa-Nájera et al., 2010). Both proxies can therefore be used to identify times of higher or lower precipitation and surface transport of sediments to the lake.

On the other hand, given that in this lake there are no carbonate rocks in ~~its~~ catchment, high values of TIC are indicative of times of higher authigenic carbonate precipitation. This is a process that currently occurs in SMO during the warmer part of the year (Caballero et al., 2013) and that is in general favored by high evaporation rates leading to ~~high~~ electric conductivity, alkalinity and pH (Eugster and Hardie, 1978; Gierlowski-Kordesch, 2010). Calcium ~~is an element which can~~ originate from the minerals in the catchment but is also incorporated in authigenic carbonates. Sosa-Nájera et al. (2010) demonstrated that in this lake higher Ca concentrations correlate with historical droughts during the last 700 years, supporting the interpretation that in SMO high calcium values are mostly related with carbonate deposition during times of higher evaporation. Nevertheless, Ca was normalized against Ti to down weight the detrital signal in this element. High TIC and high Ca/Ti values in this record can therefore be taken as indicators of increased carbonate deposition during times of lower precipitation and higher evaporation rates leading to relatively high lake water electric conductivity, pH and alkalinity. Given the opposite interpretation of the MS and Ti records compared to TIC and Ca, it is not surprising that they show nearly opposite patterns of downcore variations. Together these records allow ~~to identify~~ two intervals of intense evaporation and reduced surface runoff to the lake, the first from 530 to 490 cm (AD 600 to 800) and the second from 200 to 150 cm (AD 1400 to 1450).

With respect to the biological proxies, in the diatom record three ecological groups can be identified: (1) a planktonic/tychoplanktonic association dominated by *Aulacoseira granulata*, *Nitzschia amphibia* and small *Fragilaria* spp., which is abundant along most of the sequence (Fig. 3); this association includes the two main diatom species ~~that are~~ present in the modern lake plankton (Caballero et al., 2013). (2) A benthic/periphytic association where *Amphora ~~lybica~~, Hippodonta luneburgensis* and *Eolimna minima* are the main species. These periphytic genera (*Amphora*) and species (*H. luneburgensis*, *E. minima*) are currently distributed in the shallower environments of the lake (Caballero et al., 2013). *E. minima* in particular is an aerophilic species (Wolfe and Härtling, 1996; Van Dam et al., 1994) ~~that shows a~~ distinctive distribution along the record (shaded areas in Fig. 3) that suggests intervals of particularly shallow lake levels. (3) A~~n~~ eutrophication/human impact association defined by the presence of *Achnanthidium minutissimu~~n~~*, which is a species that has been considered by some authors as a colonizer in disturbed environments (Peterson and Stevenson, 1992; Hodgson et al., 1997) and that in Mexico has been recorded in the plankton of eutrophic and hypereutrophic tropical lakes which basins have been importantly altered by human activities (Caballero et al., 2006). This interpretation is further supported by the presence

of Zea mays pollen grains in the same segments of the core (S. Sosa-Nájera, personal communication, 2013).

The ostracode record ~~can be interpreted under the light of the study undertaken in this lake by~~ Caballero et al. (2013) where ostracodes were found to be most abundant in shallow water conditions with littoral vegetation and a low sediment supply. Given that the dominant species in the SMO record are the same that currently live in this lake (*P. variegata*, *D. stevensoni*, *C. vidua*) high ostracode abundances are taken to be indicative of these conditions, which are consistent with a lower surface runoff. Following the ostracode abundance record and considering the distribution of *E. minima*, three zones of lower than average lake levels can be identified from the biological record (Fig. 3): 560 to 410 cm (AD 500 to 1000), 200 to 100 cm (AD 1400 to 1550) and 75 to 56 cm (AD 1690 to 1770). The first two of these periods include the two events of intense evaporation identified in the geochemical record.

6 Paleoenvironmental history of the SMO record

Together the MS, Ti, Ca/Ti, ostracode~~s~~ and diatom records (Fig. 3) allow ~~to reconstruct~~ the environmental history of lake SMO during the last 2000 years. Low values in Ca/Ti, TIC and ostracod abundance together with the absence of benthic/periphytic diatoms in the record prior to AD 500 indicate that the conditions in SMO were generally deeper and more diluted from 100 BC to AD 500. An early phase of human impact is identified by the abundance of *A. minutissim* from 100 BC to AD 300 possibly related with the local expression of the Shaft and Chamber Tom Tradition (200 BC to AD 600) characteristic of western Mexico (Beekman, 2010; Barrera-Rodríguez, 2006).

After AD 500 the lake experienced a first low level stage defined mainly by an increase in *E. minima* and in ostracode concentrations and also by its magnetic mineralogy (Vázquez-Castro et al., 2008). This ~~low lake level period~~ extended from AD 500 to 1000, with the interval from AD 600 to 800 representing the driest conditions (lowest MS and Ti values and highest TIC and Ca/Ti ratios). This first low lake level phase in

SMO correlates with what is known as the late Classic period in the development of Mesoamerican cultures, characterized by a decline of the Teotihuacan culture in central Mexico after AD 650 (Manzanilla, 2011) and by ~~a high development of the~~ Maya cities in the Yucatan region, that ends abruptly between AD 850 and 950. In western Mexico in general and specifically in the state of Nayarit (Barrera-Rodríguez, 2006), this is a time of cultural transition as the Shaft and Chamber Tomb tradition ended by AD 600 (Barrera-Rodríguez, 2006). ~~Not surprisingly in the SMO record,~~ there is no evidence of human impact during this dry interval. This guaranties that the trend to dry climates during this period is a true climatic signal, not obscured by anthropogenic activities.

~~This late~~ Classic drought has been consistently identified in several records from Mexico, particularly from Yucatan (Hodell et al., 2005a; Metcalfe et al., 2010; Caballero et al., 2002; Lozano-García et al., 2010; Curtis et al., 1996) (Fig. 2), to the extent that it is referred to as the "Great Maya Drought" (Gill, 2001) and has been put forward as an important factor in the collapse of the May culture at the end of the Classic. The exact timing of this late Classic drought varies slightly in each region but in general it is centered in a similar time band as in SMO (AD 500 to 1000). In some records ~~it shows~~ a recurrent or cyclic ~~nature~~ (Haug et al., 2003; Hodell et al., 2001; Curtis et al., 1996) which in the SMO sequence could explain the ~~erratic values of the~~ geochemical records (alternating high and low TIC, Ti and MS) from AD 800 to 1000 and even until AD 1200.

After AD 1000 the low abundances of *E. minima* and ostracode valves suggest that the lake level in SMO recovered, however TIC, Ca/Ti and Ti still fluctuate between high and low values until AD ~ 1200. After this date, the age model (Fig. 2) also suggest that sedimentation rates increased (from ≤ 0.3 to > 1 cm yr^{-1}), in accordance with a higher surface runoff to the lake. This moister conditions after AD 1000 and especially from AD 1200 to 1400 correlate with moist conditions inferred from the Ti record from lake Juanacatlán, also in western Mexico (Metcalfe et al., 2010). Between 1000 and AD 1400, however, the presence of *A. minutissimum* points to a time of human disturbance in the system leading to higher turbidity and nutrient level. This trend in

human occupation in SMO agrees with recent archaeological findings in Nayarit that show late ~~Postlassic~~ (AD 1100–1350) occupations (Gálvez-Rosales, 2006) and is also in agreement with the late Postclassic cultural peak reached in western Mesoamerica by groups like the Purepecha or Tarascans (Pollard, 2005).

From AD 1400 to 1550 the increase in TIC, *E. minima* and ostracode abundance as well as the magnetic mineralogy (Vázquez-Castro et al., 2008) suggest that the lake level in SMO dropped again. The lowest MS and Ti values and highest TIC suggest that the reduction in moisture was most intense from AD 1400 to 1450. This second dry interval in the SMO record corresponds with the onset of the Little Ice Age. This period has also been recorded as a time of reduced moisture and lower lake levels in other Mesoamerican records (Metcalfe et al., 2010; Hodell et al., 2005b; Cuna et al., 2014) and represents the climatic scenario for the Spanish conquest of Mesoamerica in 1521.

Lake levels recovered in SMO between AD 1550 and 1690, but a third, if however less intense period of reduced moisture availability is evident from a slight increase in *E. minima* and ostracode concentrations between AD 1690 and 1770. This lighter reduction in moisture is coeval with the end of the Little Ice Age and shows a dual nature of the Little Ice Age cooling, also evident in the record from Lago Verde, eastern Mexico (Lozano-García et al., 2007).

7 Paleoclimatic implications

The data from SMO allows ~~to identify~~ two periods of human impact which follow closely the findings from recent archaeological research in the area (Barrera-Rodríguez, 2006; Gálvez-Rosales, 2006) the first related with the Shaft and Chamber Tomb tradition (100 BC to AD 300) and the second during the late Postclassic (AD 1100 to 1400). It is interesting to note that these periods correspond with times of moister conditions while there are no evidences of human impact in this lake during the dryer late Classic or in recent times.

The biological and non-biological proxies from SMO give solid evidence of three dryer than average intervals, the most intense during the late Classic (AD 500–1000) and the other two related with the onset (1400–1550) and the late (1690–1770) Little Ice Age. There is also evidence of a wetter late Postclassic period (AD 1200 to 1400). In this region, in which climate is controlled by the seasonal shift of the north Pacific SHPC, the ITCZ and the onset of the NAM, dryer than average conditions can be related with an expansion of the north Pacific SHPC, a southward migration of the ITCZ and a less active NAM. These are mechanisms that have also been used by other authors to explain drought conditions over Mesoamerica (Haug et al., 2003; Metcalfe et al., 2010). Other mechanisms that could bring wetter/dryer conditions in this region are changes in the frequency or strength of "La Niña"/"El Niño", as today "La Niña" is related with wetter than average summers (Magaña et al., 2003; Metcalfe et al., 2010). Changes in the paths or frequency of Pacific tropical storms and hurricanes could also be elements controlling the moisture balance in this area.

The data presented in this paper give further evidence that the late Classic drought (AD 500 to 1000) was the most important one in Mesoamerica during the last 2000 years, affecting the whole region, from Yucatan to the Pacific coast and not only a circum-Caribbean feature. In SMO the most intense phase is recorded from AD 600 to 800. The stochastic nature of the SMO record from AD 800 to 1200 seems consistent with the proposed recurrent nature of droughts, which has been suggested to follow cycles in solar activity (mainly 50 and 200 yr), (Hodell et al., 2001; Haug et al., 2003; Hodell et al., 2005a). This time of strong fluctuations in the SMO record also correlates with the onset of warmer than average conditions over the Northern Hemisphere from AD 830 to 1100 during the Medieval Climatic Anomaly (PAGES-2k-Consortium, 2013) that locally correlated with warmer sea surface temperatures in the Gulf of California (Barron et al., 2002).

The dry interval from 1400 to 1550 which corresponds with the onset of the Little Ice Age, correlates closely with the Spörer minimum in solar activity. The less intense dry period towards the end of the Little Ice Age (AD 1690 to 1770) correlates with

the Maunder solar minimum. This dual nature of the Little Ice Age cooling, following the two solar minima, is also present in the record from Lago Verde, eastern Mexico (Lozano-García et al., 2007). In lakes SMO and Juanacatlán (both in western Mexico, Fig. 1) the Spörer minimum shows the most intense signal, however in other records in central or eastern Mexico the Maunder minimum represents the driest and/or coldest period (Haug et al., 2003; Cuna et al., 2014). Furthermore, in others records the two periods seem to merge into a single, longer Little Ice Age drought (Hodell et al., 2005b). These Little Ice Age droughts are undoubtedly related with the Spörer and Maunder solar minima which could be the ultimate control on the intensity of the NAM system.

The good coherence of the biological and non-biological proxies, the solid chronology and high resolution nature of the SMO record gives an excellent view of the environmental and climatic processes affecting this lake during the last 2000 years, and an insight into the interplay between climatic and anthropogenic influences in this lake.

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Table 1. Radiocarbon (AMS) dates of core SMO02-V, lake Santa Maria del Oro, Nayarit. Calendar years were calculated using the program Calib 5.0 (Stuvier et al., 2005) with the IntCal04 data set (Reimer et al., 2004).

Laboratory I.D.	Depth (cm)	Material dated	Radiocarbon age (yr BP)	2σ range (cal yr)
Beta – 186 780	125.0	peat	400 ± 40	AD 1432–1526
Beta – 176 359	246.5	peat	660 ± 40	AD 1341–1397
Beta – 186 781	278.0	peat	700 ± 40	AD 1256–1327
Beta – 176 360	366.5	wood	850 ± 40	AD 1154–1275
Beta – 176 361	404.7	peat	990 ± 40	AD 983–1073
Beta – 176 362	791.8	peat	2250 ± 40	324–202 BC
Beta – 169 050	837.0	wood	2340 ± 40	520–357 BC

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

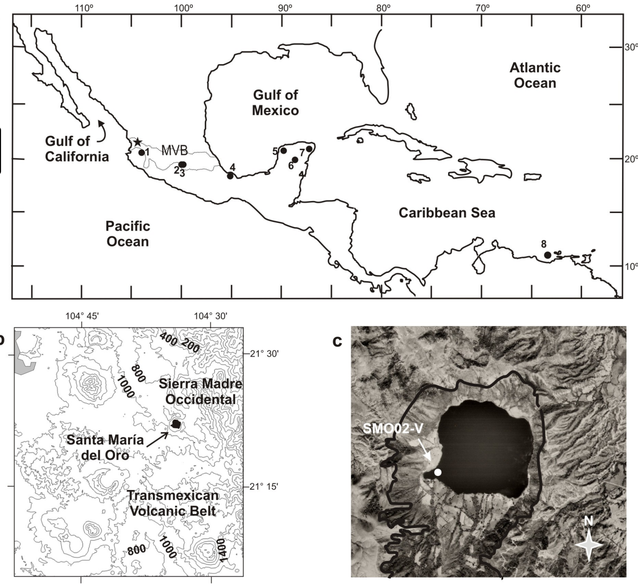

Figure 1. Location maps **(a)** Map of Mexico showing the research site (star) and locations discussed in the text from E to W: 1. Juanacatlán (Metcalfe et al., 2010), 2. La Luna (Cuna et al., 2014) 3. Chignahuapan (Caballero et al., 2002), 4. Lago Verde (Lozano-García et al., 2007; Lozano-Garcia et al., 2005), 5. Aguada X'caamal (Hodell et al., 2005b), 6. Lake Chichancanab (Hodell et al., 2001, 2005a), 7. Punta Laguna (Curtis et al., 1996), 8. Cariaco Basin (Haug et al., 2003, 2001). Dotted line delimits the Transmexcian Volcanic Belt (MVB). **(b)** Map of the research area with the location of lake Santa María del Oro, Nayarti, Mexico. **(c)** Aerial photograph showing the catchment basin (continuous black line) of lake Santa María del Oro and location of SMO02-V core site.

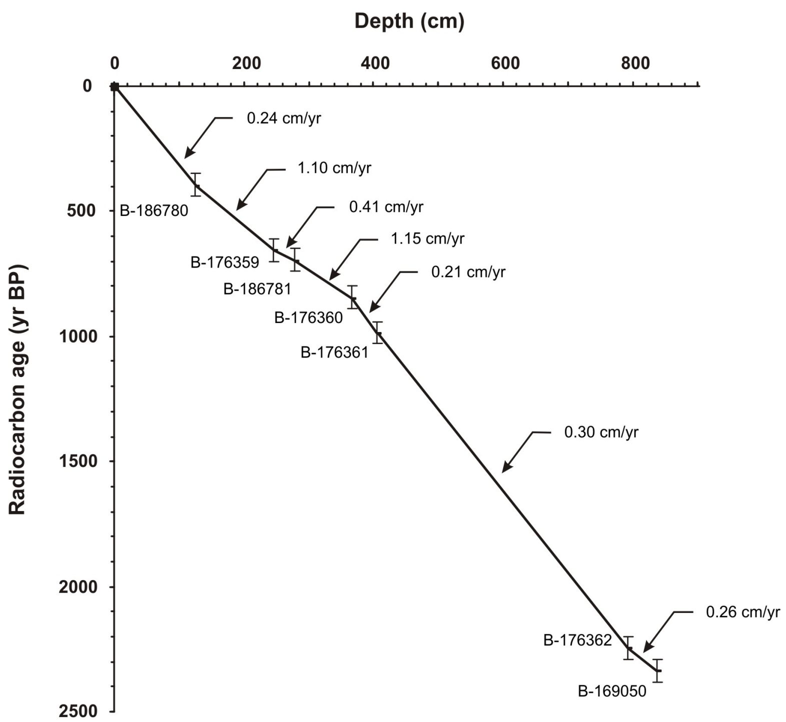

Figure 2. Age model of core SMO02-V, lake Santa Maria del Oro, Nayarit. Sedimentation rates are indicated above the line. Details of dates are listed in Table 1.

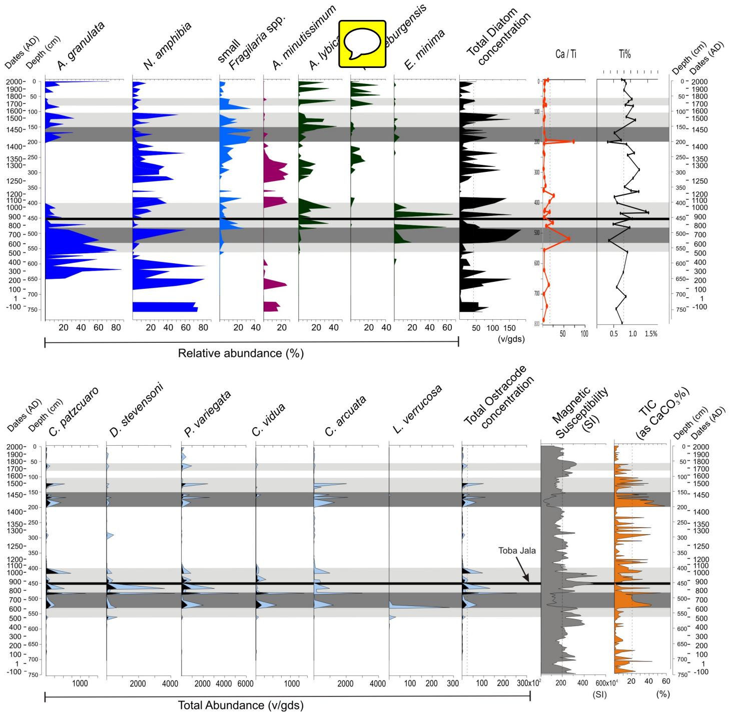

Figure 3. Biological (diatoms and ostracodes) and non-biological (Ca/Ti, Ti, magnetic susceptibility and TIC) proxies from core SMO02-V, Santa María del Oro, Nayarit, Mexico. TIC = total inorganic carbon. Small *Fragilaria* spp. includes: *Staurosira construens*, *Staurosirella pinnata*, *Pseudostaurosira parasitiaca*, *P. brevistriata*, of which only *P. brevistrata* had < 20 % abundance in the sequence.