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Paleomagnetic chronostratigraphy of Holocene Laguna Minucúa, Oaxaca, Mexico

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A R T I C L E I N F O

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A B S T R A C T

Full-vector paleomagnetic secular variation (PSV) records have been recovered from two cores (MN1, MN2) collected from Laguna Minucúa, Oaxaca, Mexico. The sediments of Laguna Minucúa are laminated, probably varved, to within 15 cm of the sediment/water interface. They may become a key paleoclimate record for Southern Mexico. However, radiocarbon dating has been equivocal at estimating the age of the lake sediments (Goman et al., 2013). The PSV records from cores MN1 and MN2 are correlatable between them and have a distinctive pattern of variability that can be correlated to well-dated PSV records from the western USA. The PSV correlations establish that the longest core (MN2) extends back ~4500 cal BP. Assuming the MN2 lamina are varves, their average thickness (1.2 mm) and core length provide an independent estimate of ~4600 cal BP, not significantly different. One radiocarbon date with an age of 1120 ± 60 cal BP, occurs at a depth in core MN2 with an equivalent paleomagnetic age of 1140 ± 50 cal BP, again not significantly different. Therefore, our estimate is that the Laguna Minucúa sediments are varved and represent a remarkable, high-resolution repository of paleoclimate information for Southern Mexico for the last 4500 years.

1. Introduction

Laguna Minucúa is a lake situated in the Sierra Madre del Sur of southwestern (Oaxaca) Mexico (Fig. 1). Two sediment cores were recovered from near the lake center in 2008 (Goman et al., 2013; MN1 – 365 cm; MN2 – 560 cm). The lake sediments are unusual in that they are laminated, probably varved, and may contain a detailed record of late Holocene climate. However, radiocarbon dating has been equivocal in determining the lake age (Goman et al., 2013). Only two other Mexican lakes (Fig. 1) are known to contain somewhat continuously laminated/varved sediments from the last ~3000+ years of Mesoamerican culture: Laguna Juanacatlan (Metcalfe et al., 2010; Jones et al., 2015) and Lago Aljojuca (Bhatacharya and Byrne, 2015; Bhattacharya et al., 2015).

This study uses paleomagnetic secular variation (PSV) recorded in the lake sediments to independently assess the age of these sediments by correlation to other well-dated PSV records from western USA (e.g., Lund, 1996; Lund and Platzman, 2015). This lake is ideally situated to record both natural climate variability (e.g., Kumaran and Limaye, 2014) and evidence for the impact of climate on human populations (e.g., Niemann et al., 2013) in southwestern Mexico for the last several thousand years. Most other paleoclimate studies related to Mesoamerican culture have focused on Central Mexico or the Yucatan Peninsula (Arnauld et al., 1997; Garcia, 2012) rather than southwestern Mexico.

2. Lake setting and lithostratigraphy

Laguna Minucúa is a small, ~0.25 ha, lake at an elevation of 2510 m. The lake is located in carbonate rocks and may be a sinkhole. Annual precipitation levels in the region are ~95 cm/yr, but the regime is highly seasonal with ~80% falling during the months of May through September. The lake was clear of aquatic vegetation at the time of coring, but had a periphery of aquatic

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grasses/and sedges; the lake is surrounded by an Oak/Pine forest. The lake has no significant inlet or outlet and is currently only 46 cm deep. Surface runoff alone should thus continuously fill the lake and provide allochthonous clastic and organic flux. Human activity in the region has been documented for at least the last 3500 years with urban development beginning at ca. 2400 cal BP (Joyce, 2010).

Sediment flux to Laguna Minucúa is derived primarily from surrounding Late Cretaceous and Tertiary arc volcanic rocks and marine forearc sediments (Nieto-Samaniego et al., 2006; Moran-Zenteno et al., 2007). Paleomagnetic studies of the Oaxaca regional rocks (Urruti-Fukugauchi and Ferrusquia-Villafranca, 2001; Molina Garza et al., 2003) indicate that magnetite is the primary magnetic mineral phase in these rocks. Laguna Minucúa is currently almost filled with sediment. The sediments are olive green to brown silts overall with clear ~1 mm laminations that alternate dark/light in detail. The dark laminations appear to be relatively coarse with silt/sand size detrital and charcoal fragments while the light laminations are more homogeneous with clay size particles. The sediments appear to have >1% organic matter and are laminated to within ~15 cm of the sediment core tops. It is reasonable to argue that the sediment porewater within the lake is anoxic almost to the sediment/water interface.

3. Magnetism methods

Both cores were sampled contiguously with 2 × 2 × 2 cm cubes for paleomagnetic and rock magnetic studies. Paleomagnetic measurements were made on all samples by first measuring their natural remanence (NRM) and then step-wise demagnetizing the NRMs at 10 mT steps in alternating magnetic fields (AF) up to 60 mT. (MN1 samples were also demagnetized at 5 mT) 60 mT AF demagnetization typically reduced the NRM intensities to less than 20% of their initial values. An artificial, anhysteretic remanence (ARM) was applied and measured (0.05 mT bias field; 100 mT alternating field). Following this the ARMs were AF demagnetized sequentially in 10 mT steps up to 60 mT. Next, a saturation isothermal remanence (SIRM) was applied in a 1 T pulsed field and measured. The SIRMs were AF demagnetized sequentially in 10 mT steps up to 60 mT. Finally, magnetic susceptibilities (chi) of the individual cubes were measured. Previously, magnetic susceptibility measurements had been carried out in sequential 0.5 cm increments on the individual push sections of both cores at LacCore (Goman et al., 2013).

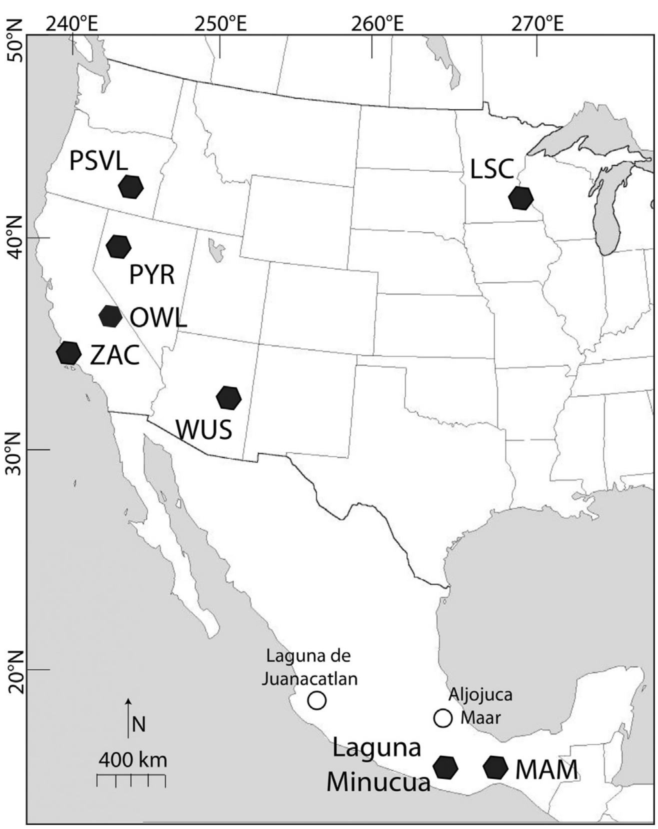

Fig. 1. Map of the western USA and Mexico showing the location of Laguna Minucúa, key PSV records considered in this paper (closed diamonds), and two other lakes (open circles) with Late Holocene laminated sediments. LSC = Lake St. Croix, PYR = Pyramid Lake, PSVL = lava flow PSV, OWL = Owens Lake, ZAC = Zaca Lake, WUS = western USA archeomagnetic studies, MAM = Mesoamerican archeomagnetic data.

4. Results

4.1. Rock magnetism

The magnetic intensities of the NRM, ARM, and SIRM for cores MN1 and MN2 are plotted in Fig. 2. The intensities have good co-variance among the three rock magnetic parameters. Individual parameter intensities vary by less than a factor of 3 over the core lengths. Under anoxic bottom water/porewater conditions, we might expect that the finest grained magnetic minerals (less than a few microns) would be dissolved (e.g., Leslie et al., 1990). However, these sediments show no evidence for such dissolution and are probably silts with mean grain sizes ~10 microns.

This inference was also evaluated by plotting the NRM, ARM, and SIRM intensities as a function of AF demagnetization (Fig. 3). The NRMs have median destructive fields (MDFs) of 15–30 mT. These values are typical of relatively coarse-grained magnetite (pseudo-single domain to multi domain; >5–10 microns in size). The ARM and SIRM coercivities also suggest that titanomagnetite minerals with coercivities less than 100 mT dominate the magnetic minerals present.

4.2. Paleomagnetism

Fig. 4 shows the directional variation of selected samples under AF demagnetization. It is clear that almost all samples have a single paleomagnetic direction that is demagnetized between 10 and 60 mT, which demagnetizes toward the origin. This simple characteristic remanence typically has maximum angles of deviation (MAD angles) less than 3°. There is commonly a 'viscous' magnetic overprint, which is demagnetized by 10 mT, but in some samples persists up to 20 mT. The simple characteristic remanence is associated normally with more than 70% of the total NRM.

Fig. 5 shows the characteristic remanences for both cores. There is a clear pattern of paleomagnetic secular variation described by the inclination and declination variability with strong serial correlation among directions located near to one another stratigraphically in each core. The inclinations and declinations have a notable oscillatory pattern, which we think we can uniquely correlate to similar paleomagnetic secular variation records elsewhere in the region. All of the paleomagnetic evidence from both cores indicates the presence of an NRM that is recorded at or soon after deposition and has strong serial correlation throughout, which we hypothesize reflects the local pattern of secular variation for this site.

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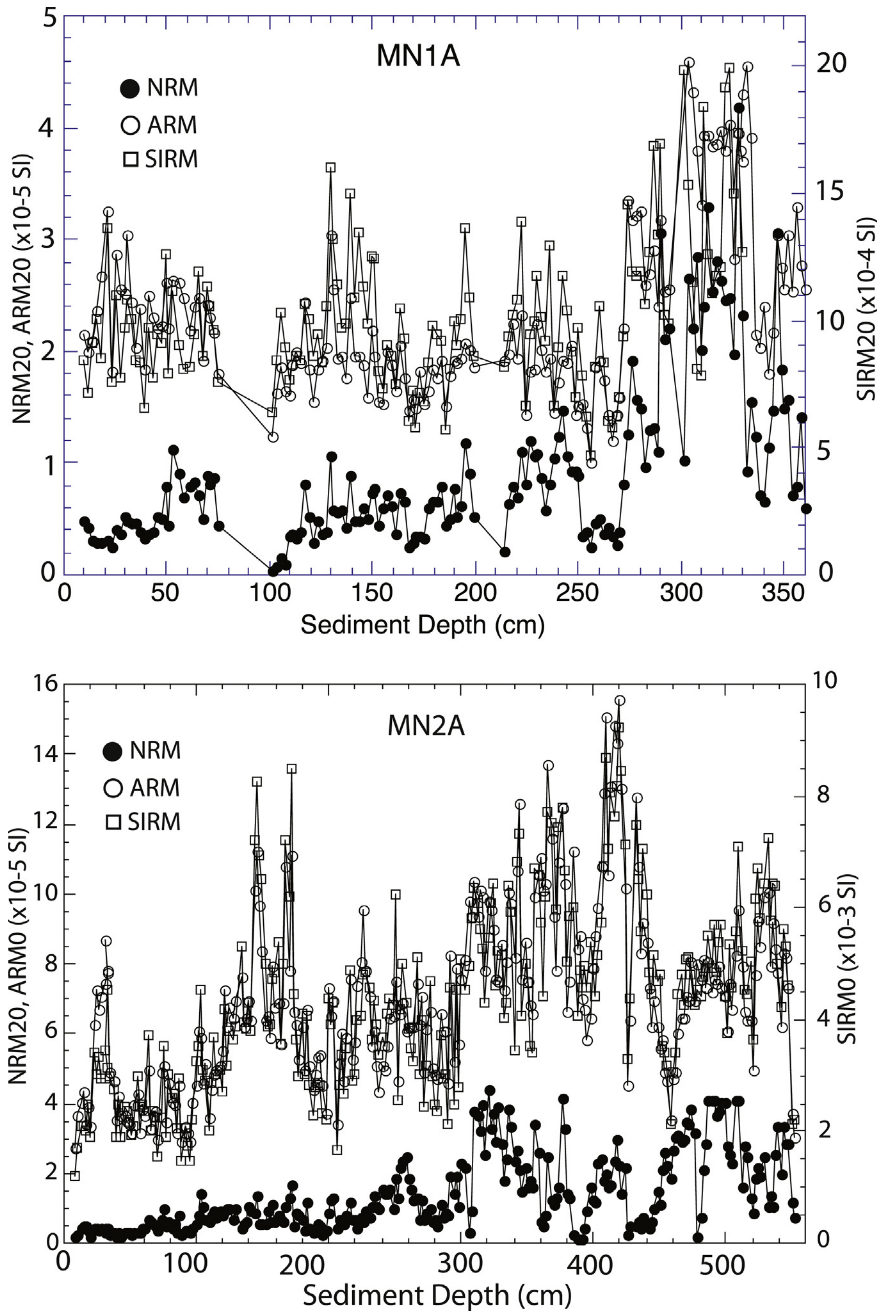

Fig. 2. NRM, ARM, and SIRM intensities within cores MN1 and MN2 after 20-mT AF demagnetization. Note the close correspondence in the ARM and SIRM intensity variability.

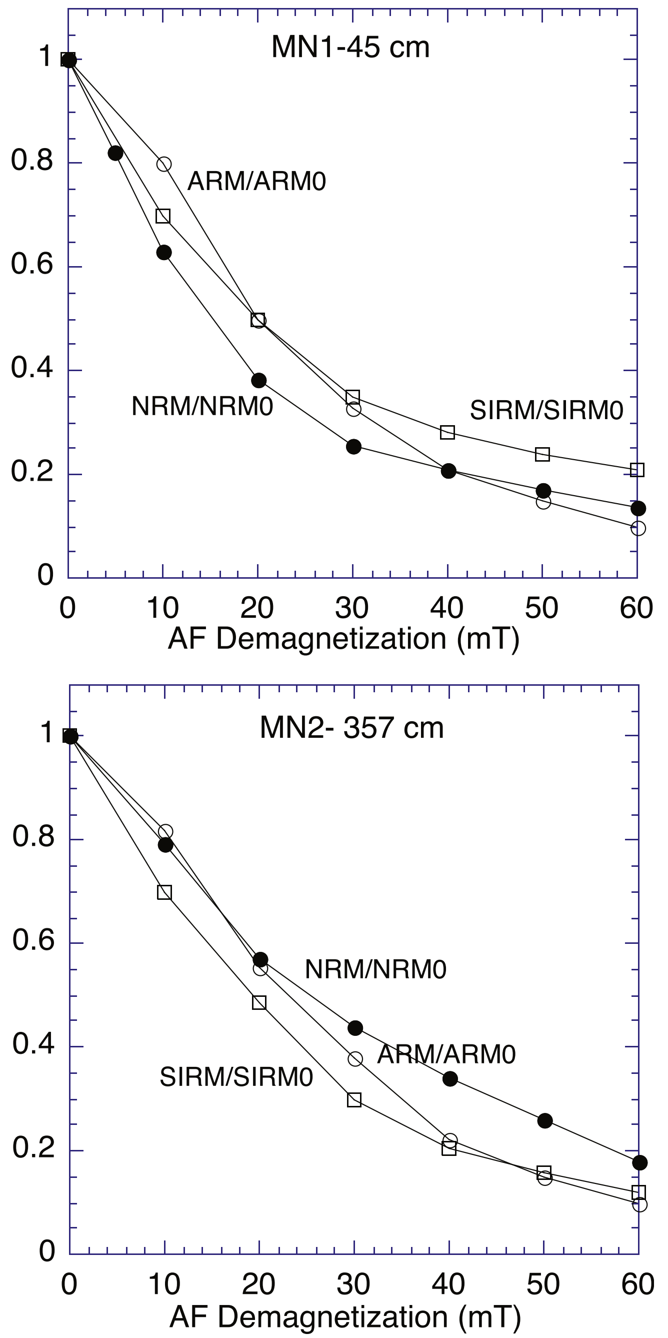

Fig. 3. NRM, ARM, and SIRM intensity variation under AF demagnetization to 60 mT for two typical horizons (MN1 45 cm and MN2 357 cm). The median destructive field (MDF, 50% intensity reduction) for the NRMS is typically 15–25 mT.

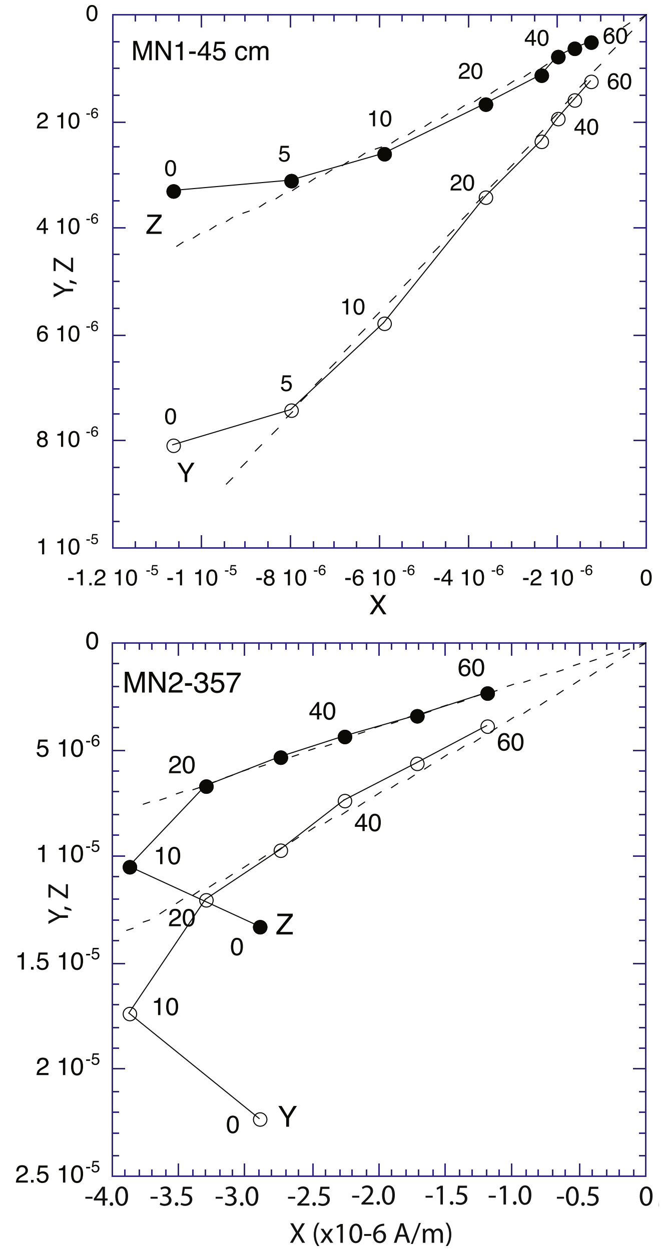

Fig. 4. Directional changes in the NRMs for two typical horizons shown in Fig. 3 (MN1 45 cm and MN2 357 cm). Each dot represents the tip of the NRM vector at each demagnetization step. Solid (open) dots indicate the vertical (horizontal) directional component. The directions demagnetize straight toward the origin after 10-mT or 20-mT AF demagnetization. X, Y, and Z are sample coordinates; X and Y are horizontal components, Z is the vertical component.

Six published Holocene PSV records from central and western USA (Fig. 1) share distinctive directional features with the Laguna Minucúa PSV records. Fig. 6 shows three representative directional PSV records from Lake St. Croix, Minnesota (LSC, 45°N; Lund and Banerjee, 1985), an archeomagnetic composite record from the southwestern USA (WUS, 35°N; summarized in Lund, 1996), and a composite lava-flow PSV record from the western USA (PSVL, 42.6°N; Hagstrum and Champion, 2002). Labels mark key PSV features that are correlatable with the Laguna Minucúa PSV records (Fig. 5). The ages of these PSV features have been estimated in the individual PSV studies and summarized in Lund (1996). Three other recent Holocene PSV studies from the California region are also consistent with these correlations: Owens Lake (OWL, Li et al., 2000), Pyramid Lake (PYR, Benson et al., 2002), and Zaca Lake (ZAC, Lund and Platzman, 2015). A shorter directional PSV composite record from southern Mexico (MAM; Wolfman, 1990) is also consistent with these correlations. Table 1 summarizes the correlatable PSV directional features, their depths in cores MN1 and MN2, and the best estimate of their ages from Lund (1996).

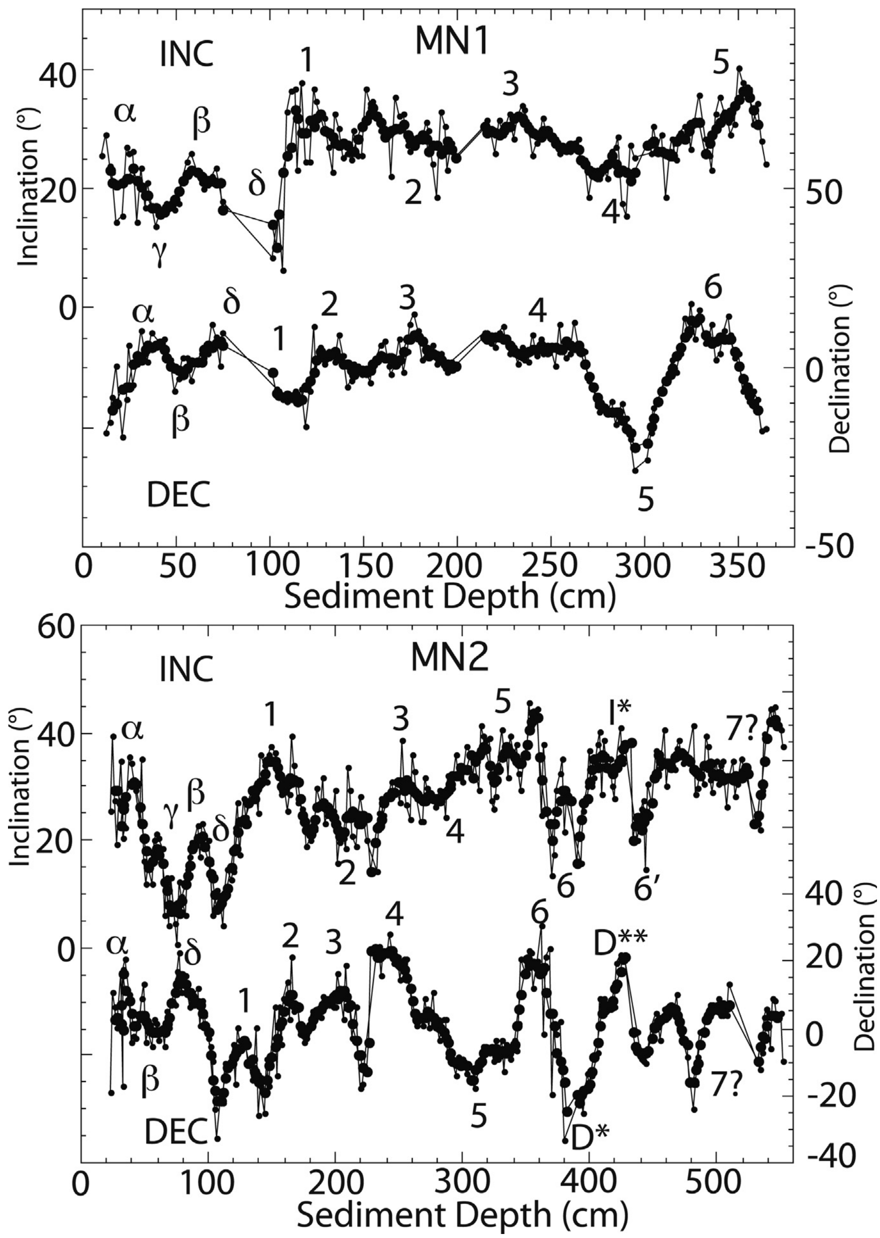

Fig. 5. Directional PSV recovered from cores MN1 and MN2. Small dots are actual data, larger dots are 3-point running averages. Selected highs/lows in inclination and east/west swings in declination are labeled for correlation to other PSV records (see Fig. 6 and Table 1).

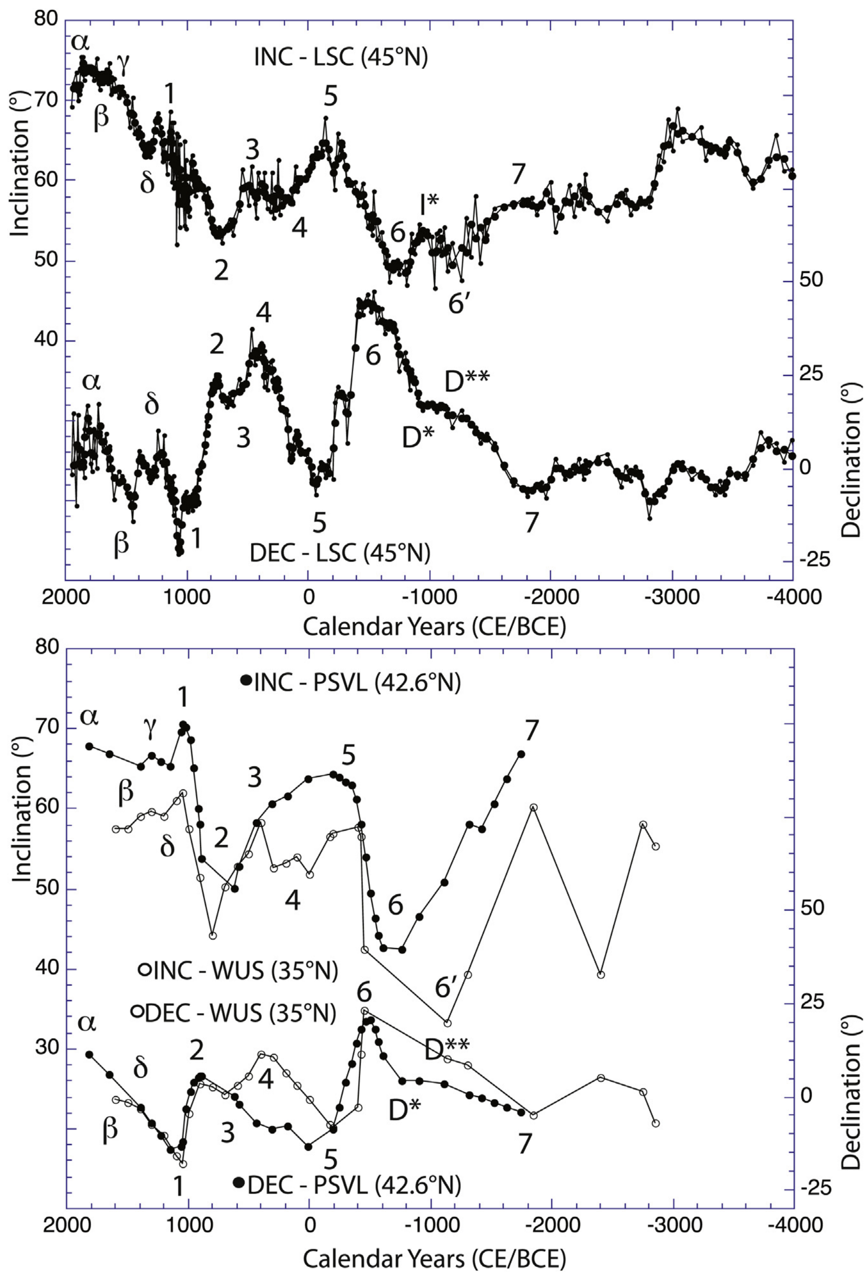

Fig. 6. Directional PSV records from Lake St. Croix (LSC, a sediment PSV record), PSVL (a summary of western USA lava-flow PSV data), and WUS (a summary of western USA archeomagnetic PSV data). See Fig. 1 for locations? Selected highs/lows in inclination and east/west swings in declination are labeled for correlation to other PSV records.

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Table 1
Age–depth relationships for cores MN1 and MN2.

Feature	Cal yrs (AD/BC)	±	MN1 dep (cm)	±	MN2 dep (cm)	±
Da	1803	50	20	10	30	10
Ia	1754	35	25	10	35	10
Db	1612	84	50	10	55	15
Ig	1578	56	45	10	70	15
int-1	1444	50	60	15	70	15
Dd	1350	100	70	10	80	15
Ib	1336	60	70	15	95	10
Id	1223	63	90	20	110	10
int-1′	1120	50			110	15
D1	1058	83	110	15	130	20
I1	1039	68	125	15	148	15
D2	820	88	135	20	163	15
int-2	831	60	160	20	169	20
I2	747	102	180	20	200	20
D3	612	68	185	20	220	10
I3	432	61	230	15	250	15
D4	400	76	240	20	250	20
int-2′	300	100	245	15	258	20
I4	161	65	270	20	280	20
D5	−43	117	290	20	310	20
int-3	−322	100	310	20	320	20
I5	−203	69	330	20	330	20
D6	−475	97	335	20	360	10
I6	−675	66			380	15
D*	−900	75			390	15
int-4	−933	100			400	20
I*	−1050	75			411.5	15
D**	−1100	75			416.5	15
I6′	−1261	100			440.5	15
int-5	−1708	100			478	30
D7?	−1740	100			501.5	30
I7?	−1791	100			510	30
int-6	−2140	100			527	20

The rock magnetic intensities noted in Fig. 2 can also be used to estimate relative paleointensity variations at Laguna Minucúa. The normal procedure is to divide the NRM intensity variability by some rock magnetic parameter, which estimates the amount of magnetic material in the sediment. We have normalized the NRM (after 10 mT af demagnetization) by the ARM and SIRM (after 10 mT af demagnetization) and bulk magnetic susceptibility. All three normalized relative paleointensity estimates are plotted in Fig. 7 after renormalizing each ratio to a mean of 1. All three relative paleointensity estimates are almost identical to one another over the entire core length. This is an added indicator of the reasonably constant rock magnetic conditions in the lake.

There are also a number of published paleointensity estimates from western USA, which share distinctive paleointensity features with the Laguna Minucúa records. Fig. 8 shows three representative paleointensity estimates from LSC (Lund and Schwartz, 1999), archeomagnetic data from WUS (Champion, 1980; Sternberg and McGuire, 1990), and lava-flow data from PSVL (Hagstrum and Champion (2002)). Key PSV paleointensity features are labeled, which are correlatable with the Laguna Minucúa PSV records (Fig. 7). Table 1 summarizes the correlatable PSV directional and relative paleointensity features, their depths in cores MN1 and MN2, and the best estimate of their ages, which is the average of the three published studies.

Fig. 9 summarizes the time/depth relationships for cores MN1 and MN2 based on the paleomagnetic directional and paleointensity correlations in Table 1. The PSV correlations to other dated records are consistent among all three paleomagnetic parameters, and, as such, should be considered a unique correlation and paleomagnetic chronostratigraphy. The PSV chronostratigraphy indicates that the longest core, MN2, encompasses approximately 4500 years.

5. Discussion

Lamination couplet counts and measurements completed on core MN2 (Goman et al., 2013) identified 3922 couplets with an average thickness of ~1.2 ± 0.09 mm. The near surface sediments were devoid of couplets and push segment tops were sometimes too disturbed to permit measurements. Using the average couplet thickness and assuming the lamina are yearly varves, we estimate the base of the core at ~4600 years old, within one hundred years of the paleomagnetic age for the core base.

One radiocarbon date at 176 cm in MN2 (Keck58020, 1200 ± 15 ^{14}C BP) returned a calibrated age range of 770–890 cal. C.E. (a median 1120 ± 60 cal BP). That horizon is identified in Fig. 9 and is not significantly different from the PSV estimated age of 1140 ± 50 cal BP. However, another nine radiocarbon dates all give ages less than a few hundred years old, which are strongly inconsistent with the PSV chronostratigraphy.

We think that the paleomagnetic chronostratigraphy for the Laguna Minucúa cores is a good estimate of the real age of these sediments and that this record does contain a laminated (varved) record of sediments for the last 4600 cal BP.

6. Conclusions

Full-vector paleomagnetic secular variation (PSV) records have been recovered from two cores (MN1 – 365 cm, MN2 – 560 cm) collected from Laguna Minucúa, Oaxaca, Mexico. The sediments of Laguna Minucúa are silts in average grain size and laminated, probably varved, to within 15 cm of the sediment/water interface. Radiocarbon dating has been equivocal at estimating the age of the lake sediments (Goman et al., 2013). The PSV records from cores MN1 and MN2 both have good serial correlation in their directions as a function of depth. The directions are correlatable between cores and have a distinctive pattern of variability that can be correlated to other well-dated, published PSV records from central/western USA and Mexico. The PSV correlations establish that the longest core (MN2) extends back ~4500 cal BP. Assuming that the laminae are yearly varves, the average lamina thickness (1.2 mm) and core length provide an independent estimate of ~4600 cal BP for core MN2, not significantly different from the paleomagnetic age estimate. One non-modern radiocarbon date with an age of 1120 ± 60 cal BP, occurs at a depth in core MN2 with an equivalent paleomagnetic age of 1140 ± 50 cal BP, again not significantly different. Our overall estimate is that the Laguna Minucúa sediments are varved and that they represent a remarkable, high-resolution repository of paleoclimate information for Southern Mexico for the last 4500 years. Given the paucity of paleoclimate data from the southern Mexican Highlands, the Laguna Minucúa core also has the potential to provide crucial data on the role of climate change associated with major cultural transformations in the region including the origins of Mesoamerican agriculture and early village life, the development of cities, and the Classic-period collapse.

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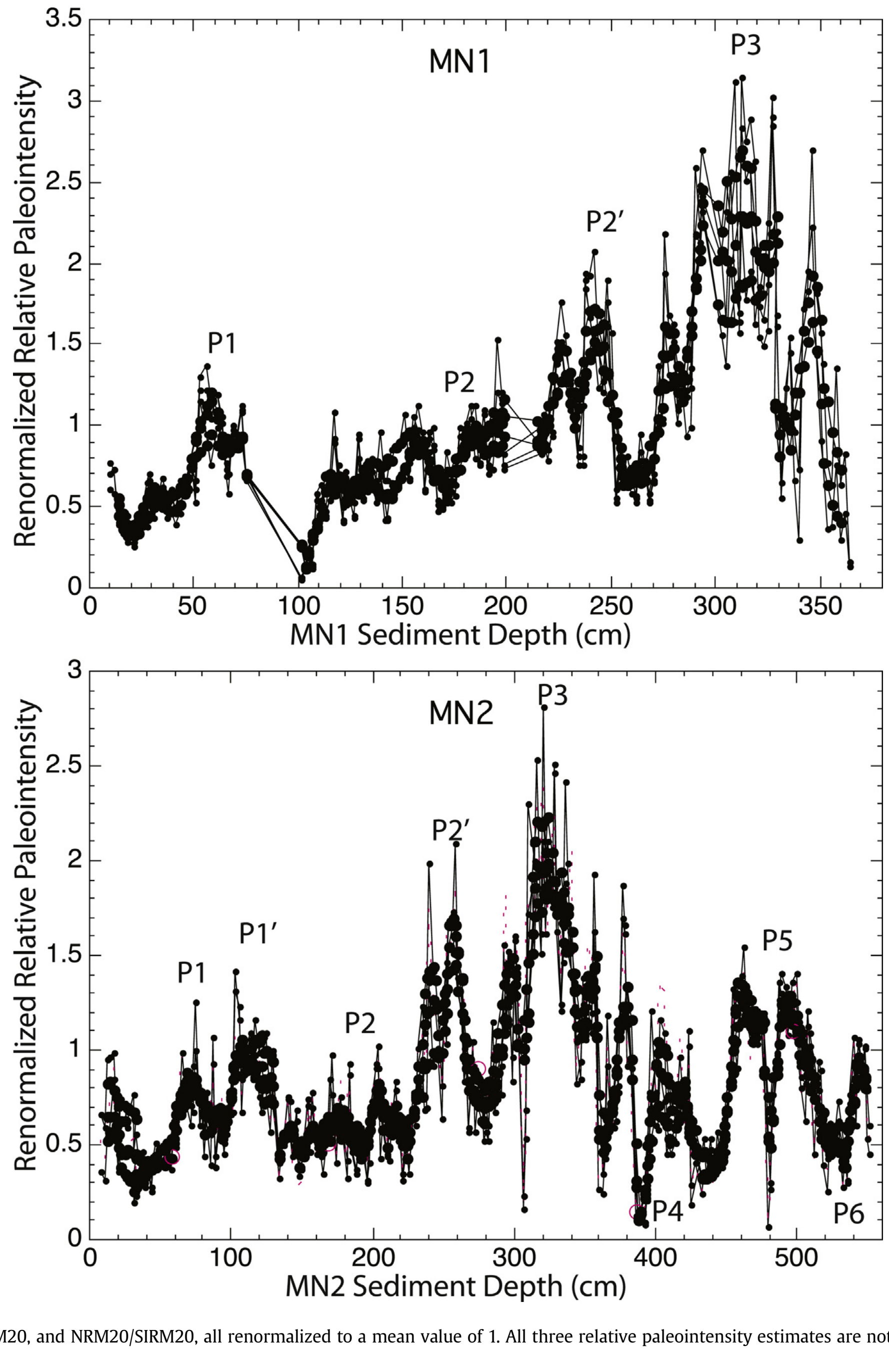

Fig. 7. NRM20/chi, NRM20/ARM20, and NRM20/SIRM20, all renormalized to a mean value of 1. All three relative paleointensity estimates are not significantly different from one another. Key high/low intensity variations are labeled for correlation to other PSV records.

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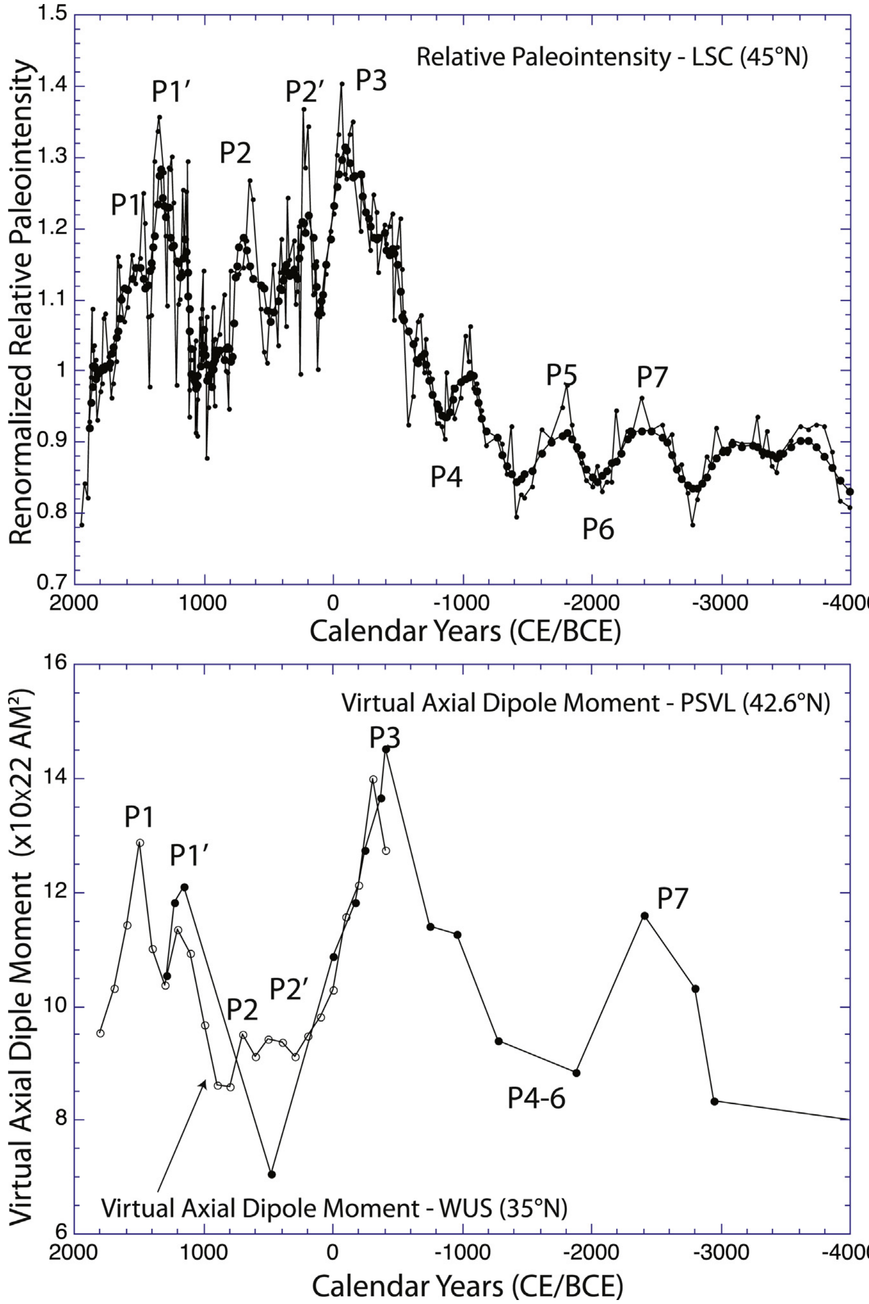

Fig. 8. (top) Relative paleointensity record for LSC. (bottom) Absolute virtual axial dipole moment (VADM) for the PSVL lava-flow data (closed dots) and WUS archeomagnetic data (open dots). Key high/low intensity variations are labeled for correlation to other PSV records.

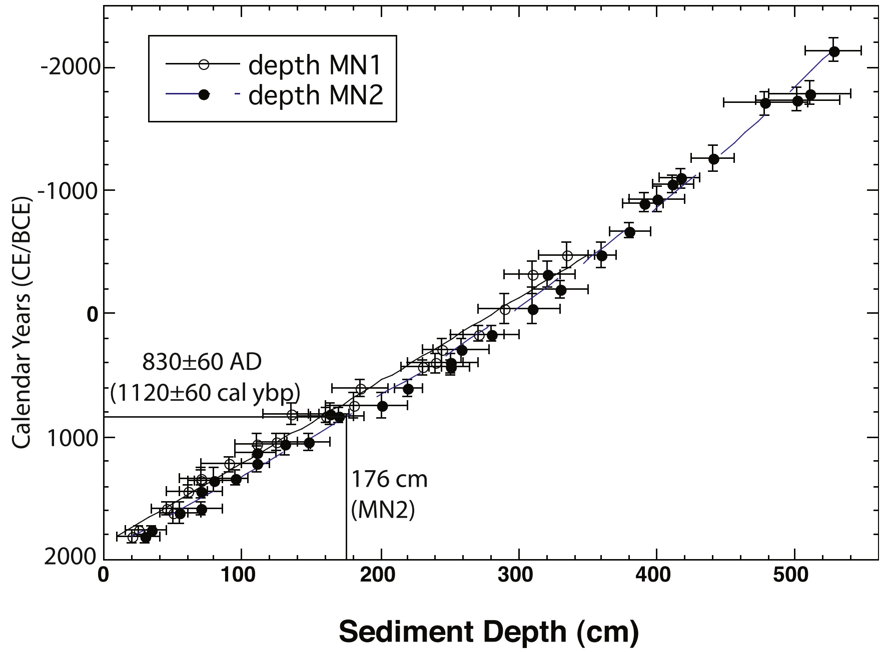

Fig. 9. Final time/depth plots for cores MN1 and MN2 based on the PSV ages and correlations summarized in Table 1. The placement of one non-modern radiocarbon date in core MN2 is noted for comparison.

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