Geofísica Internacional (1995), Vol. 34, Num, 1, pp. 33-53

Palaeomagnetic and palaeoenvironmental studies in the southern basin of Mexico - II Late Pleistocene - Holocene Chalco lacustrine record

J. Urrutia-Fucugauchi[1], S. Lozano-García[2], B. Ortega-Guerrero[1] and M. Caballero-Miranda[1]
[1] *Laboratorio de Paleomagnetismo, Instituto de Geofísica, UNAM, MEXICO*
[2] *Departamento de Paleontología, Instituto de Geología, UNAM, MEXICO*

Received: March 16, 1993; accepted: April 28, 1994.

RESUMEN

Se presentan los resultados de los estudios de paleomagnetismo (primeros 12 metros) y microfósiles (primeros 8 metros) para la secuencia lacustre del lago de Chalco. Estos se han realizado en material recobrado de cuatro perforaciones en el sector central del lago. La reconstrucción paleoambiental propuesta integra los datos de polen, diatomeas, limnología, paleomagnetismo y fechamientos de radiocarbono. La edad estimada para el fondo de la secuencia, a los 12 m, es de 25,000 años antes del presente. Los sedimentos están caracterizados por valores altos de susceptibilidad magnética, los cuales están relacionados a la ocurrencia de material volcánico (se identifican 10 tefras en esta parte de la secuencia). La paleoflora está constituida principalmente por bosques de coníferas y vegetación subacuática. Los datos limnológicos indican fluctuaciones en el nivel del lago, con correspondientes cambios en salinidad y alcalinidad. La disminución o ausencia de paleofósiles en la secuencia correlacionan con la localización de las tefras; ello sugiere una relación con la actividad volcánica.

El registro de declinación magnética muestra varias anomalías, de hasta 30 - 60 grados, para aproximadamente los 5,000 años y los 14,000 años. La variación para los 5,000 años ha sido observada también en estudios de rocas volcánicas y podría reflejar una variación del campo geomagnético. El registro de inclinación magnética muestra un patrón más homogéneo, con fluctuaciones alrededor de los 32.9 grados (inclinación dipolar es de 35.3 grados). Sin embargo se tiene también una variación para los 14,000 años, que se resalta en los valores de la anomalía de inclinación. El análisis espectral de los registros de los varios parámetros magnéticos indica varios periodos dominantes. Para la intensidad se tienen del orden de 650 a 2,900 años. Para la declinación se tienen del orden de 850 a 2,900 años. Para la inclinación se tienen del orden de 1,000 a 3,800 años.

PALABRAS CLAVE: Paleoambientes, paleoecología, paleoclimatología, paleomagnetismo, Lago de Chalco, palinología, diatomeas.

ABSTRACT

Results of a detailed palaeomagnetic and microfossil study of the first twelve and eigth meters, respectively, of the lacustrine sedimentary sequence from Chalco Lake, southern Basin of Mexico are reported. The study is based on four cores recovered from the central part of the lake. Radiocarbon dating indicates an age for the bottom of the section (12 m) of about 25,000 yr B.P. Sediments are characterized by high magnetic susceptibility values, related to the intensive and widespread volcanic and tectonic activity in and around the lake. The palaeoflora was mainly constituted by coniferous forests in the highlands and swamp vegetation closer to the lake. Palaeolimnological data document fluctuations in lake levels, with changes in salinity and alkalinity. Diminution or absence of palaeofossil populations in the sequence show a correlation with the tephra (as indicated by high magnetic susceptibilities and remanence intensities). Volcanic activity affects microfossil abundance and distribution both directly (tephra fallout in the lake area) and indirectly (e.g., through enhanced erosion, tectonism and hydrothermal alteration).

The characteristic declination shows several anomalies; large swings are observed at 5,000 and 14,000 yr B.P. The inclination varies around a mean value of 32.9°, with an apparent cyclic pattern. There are no large swings in the inclination data as compared with the declination, but the inclination anomaly shows a peak at about 14,000 yr B.P. that correlates with the declination swing. Intensity data show periodicities from 650 to 2,900 yr. Declination data show similar dominant periods in the order of 850 to 2,900 yr. Inclination data present periodicities in the range from 1,000 to 3,800 yr.

KEY WORDS: Palaeoenvironments, palaeoecology, palaeoclimatology, Chalco Lake, Basin of Mexico, palaeomagnetism, palynology, diatoms.

1. INTRODUCTION

In this paper we report initial results of an interdisciplinary study of the lacustrine sedimentary record of Chalco Lake (19.5°N) in the southern sector of the lake system of the Basin of Mexico (Figure 1). An earlier paper included results on basin structure, coring, stratigraphy of lacustrine sequence and radiocarbon dating (Urrutia-Fucugauchi *et al.*, 1994). This second paper is concerned with the palaeomagnetic and palaeoenvironmental studies.

The Basin is limited by volcanic ranges: Chichinautzin in the south; Sierras Nevada and Río Frío (including the stratovolcanos Popocatépetl and Iztaccíhuatl) in the east;

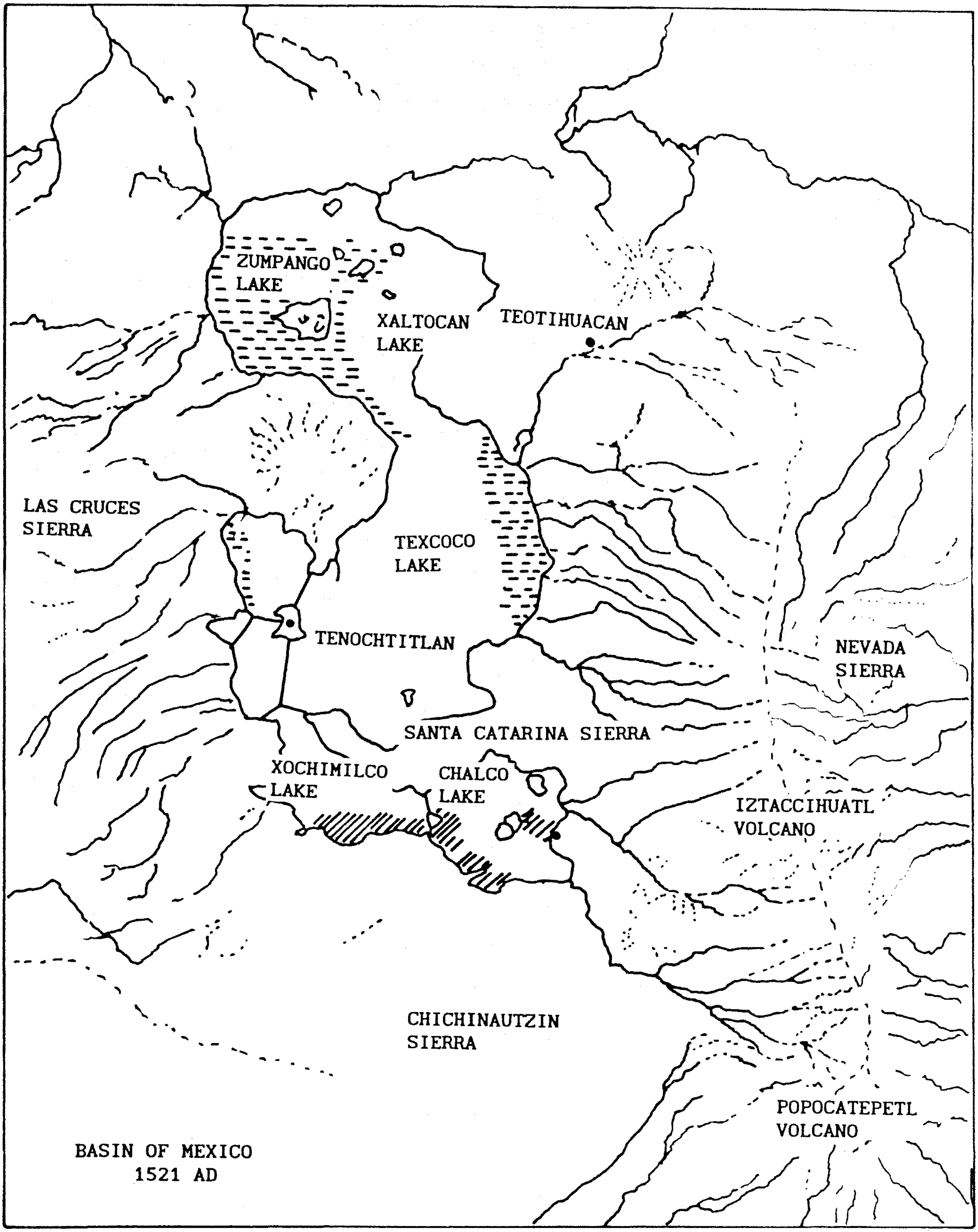

Fig. 1. Schematic reconstruction of the lake system in the Basin of Mexico at about 1521 DC. The system was composed of several interconected small basins. This study concentrates in the southeastern lake basin of Chalco. Drainage system is also shown schematically, as well as the settlements of the Mexica and other groups (major urban centers are Tenochtitlan and Tlaltelolco in the middle of Lake Texcoco).

Sierra de las Cruces in the west; Sierras Tepotzotlan and Pachuca in the north. Development of extensive shallow lakes resulted in a thick volcano-sedimentary sequence, which provides a detailed record of past limnological, ecological, and climatological conditions in the basin (e.g., Sears, 1952; Sears and Clisby, 1955; Bradbury, 1971, 1989; Watts and Bradbury, 1982; White, 1987; Lozano-García, 1989; Lozano-García *et al.*, 1993).

The continuous growth of the metropolitan and industrial area of Mexico City since the 16th century has produced severe changes in the environment and ecosystems, mainly because of the huge demand of water, the contamination of atmosphere, soils and water, microclimatological changes, reduction of green areas and accumulation of garbage and waste water. It is important to distinguish such processes from natural ones related to volcanic eruptions, climatic changes, and other geo-biological processes.

2. FIELD WORK AND CORING IN CHALCO LAKE

The study area is situated in the southeastern sector of the Basin. The lake sediments of the Chalco sub-basin have an approximate extension of 1,500 km^2. Its central part is presently covered by shallow alkaline waters at least during the summer rain season. At the time of the first coring operations in April-May 1988, the study area (Figure 2) was essentially dry. Since the end of the summer 1988 rain season, the area has remained partly covered by a shallow lake.

During two field campaigns, 4 vertical sections (Figure 2) were sampled (A to D), down to depths of 26 m. Coring was completed with a modified Livingston piston corer that permits more than 95% recovery of undeformed sediment. The presence of a 'hard' layer (one of the marker horizons in the basins; Mooser, 1967, 1975) limited the maximum coring depth (Core B).

For palaeomagnetic studies, the construction of a sampling mechanism and procedure was neccessary to collect relatively undisturbed sediment into transparent plastic cubes. The extruded half-cores were laid on an aluminum base with lateral bounds, which limited the sediment thickness to be transferred to the plastic cubes. The overlapping sediment was cut with a thin steel wire to avoid distortion. On top of the resulting sediment slab, a movable guide for the plastic cubes was positioned. The cubes were pushed into the sediments by means of a piston system that controls the sampling angle (Figure 3). Separation of individual samples was 1.25 or 2.5 cm, representing some 50% overlap.

Pollen samples were taken at 10 cm intervals in Core B. Extraction of palynomorphs was done using a volume of 2 cubic cm. Diatom samples were collected also at 10 cm

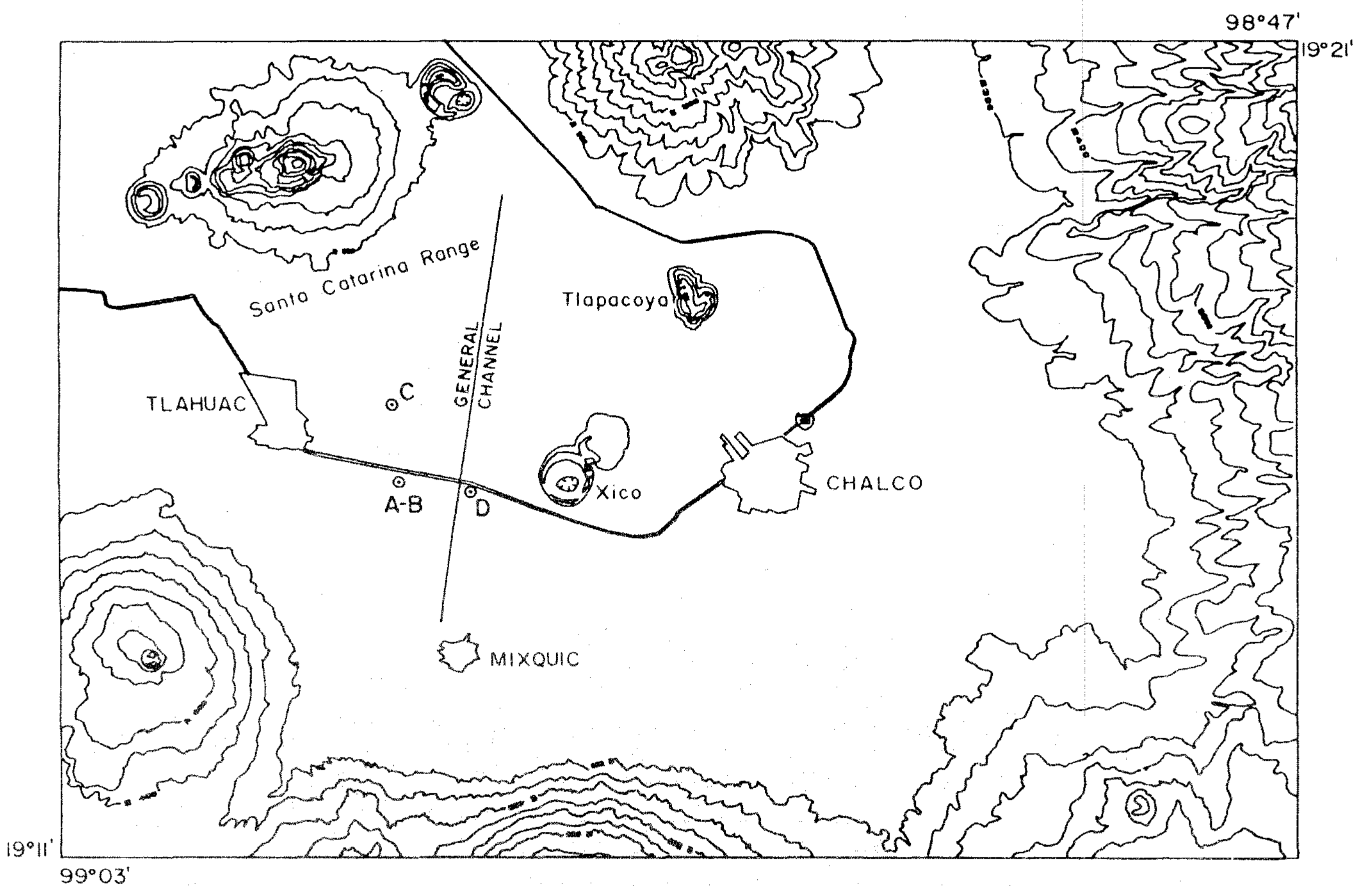

Fig. 2. Schematic topographic map of the Chalco area showing the actual situation of city settlements and the location of the coring sites (indicated by capital letters A to D).

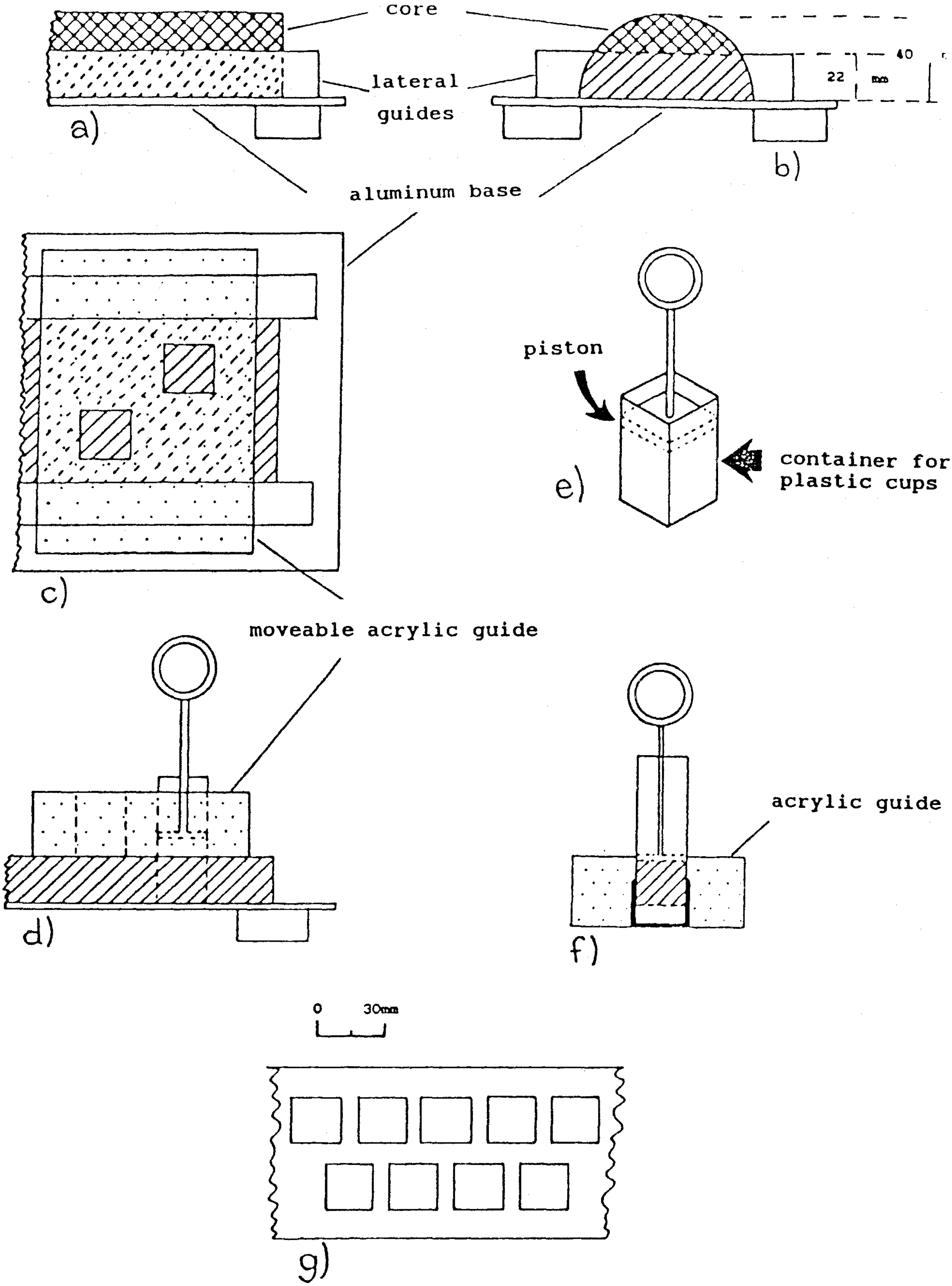

Fig. 3. Paleomagnetic sampling equipment. Schematic view of major parts used in sub-sampling: (a,b) base for half-cores (side view), (c,d) moveable guide for piston, (d,e,f) piston system for sampling, (g) sample separation (15 mm). Non-magnetic plastic cubes are about 10 cc.

ntervals in Core A. For every sample, 0.5 g of dry sediment was treated to eliminate carbonates and organic matter.

3. STRATIGRAPHY AND AGE DETERMINATIONS

The stratigraphy and radiocarbon data of the lacustrine sequence was discussed in the previous paper (Urrutia-Fucugauchi *et al.*, 1994). Based on the coring reports and detailed descriptions of each extruded core, lithostratigraphic columns were established. Figure 4 shows columns for the cores D, C, and the core A-B, which was combined for the first 12 m because of the proximity of locations A and B. We propose a subdivision into 7 major stratigraphic units, with 16 tephra layers for the 26 m thick sequence. The units and tephra layers are numbered from top to bottom with Arabic and Roman numerals, respectively.

All units were recognized in the 4 cores. The only exception is Tephra VIa, restricted to core A-B and not found in cores C and D. Observations may be summarized as follows.

The thickness of the sedimentary units decrease towards core C, most clearly for the upper 4 units.

The units in core C were deposited at shallower depths than in cores A-B and D, in agreement with present topographic differences.

The sediments recorded an intensive volcanic activity. This activity concentrates in the first 9 m of core A-B, where 9 of the 16 tephras are present.

The sedimentation rate estimated from the available ^{14}C analyses gives about 0.28 mm/y for the interval between 3.5 m and 8.13 m and a rate of about 0.80 mm/yr for the upper portion above 3.5 m. These are order of magnitude rates, since the estimations include the tephra layers, some up to 50 cm thick, which were accumulated in short intervals for the upper portion of the sequence. This gives only an upper limit of the deposition rates.

The variation of organic carbon content suggests that the first 8 m correspond to a shallow lake environment with high accumulation and preservation of organic matter (Urrutia-Fucugauchi *et al.*, 1994).

The ^{14}C date distribution may be interpreted in terms of a change in the sedimentation process at about 12,000 yr B.P., that agrees well with a change of environmental conditions from the Pleistocene to the Holocene.

The radiocarbon data has been discussed in the previous report (Lozano-García *et al.*, 1993; Urrutia-Fucugauchi *et al.*, 1994). Eleven dates were obtained for the first twelve meters of the sequence. The information is integrated in the stratigraphic column (Figure 4). The age at 8 m is about 19,000 yr B.P. and at 12 m is about 25,000 yr B.P.

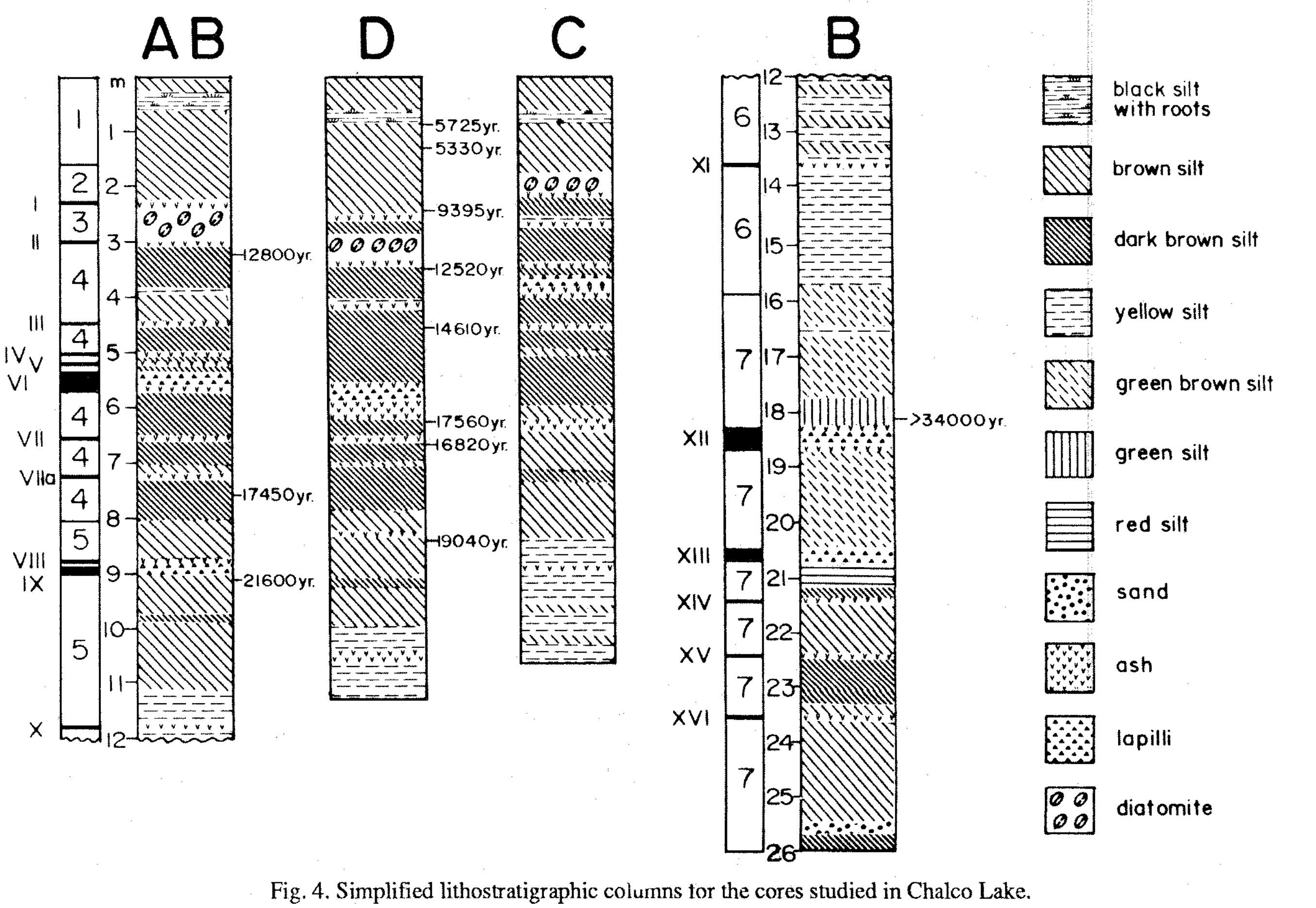

Fig. 4. Simplified lithostratigraphic columns for the cores studied in Chalco Lake.

Several widely distributed tephra layers have been used as stratigraphic markers in studies of the Basin of Mexico. They include two tephra layers originated from the Nevado de Toluca volcano (upper Toluca pumice, UTP and lower Toluca pumice, LTP) and one from the Popocatepetl volcano ('Pomez con andesita', PCA). Bloomfield and Valastro (1974) give an age of about 11,600 yr B.P. for UTP. The 'pomez tripartita' found in the Tlapacoya sequence (dated between 12,900 and 9,920 yr B.P.; García Barcena, 1986) has been correlated with UTP (Bloomfield and Valastro, 1977). The UTP likely correlates with tephra II in our cores (Figure 4). PCA was described by Mooser (1967) for the Tlapacoya sequence, and has been dated at 14,450 yr B.P. (García Barcena, 1986). This characteristic tephra is present in the Chalco cores (Tephra VI; Figure 4); however, the estimated age following the radiocarbon dates is much older, about 16,500 yr B.P. This age has been used for interpretations of the stratigraphy (Lozano-García *et al.*, 1993). Further study on the PCA age is needed. A tephra layer identified in the Tlapacoya sequence, the 'pomez marcadora superior' with an age of about 4,900 yr B.P. (Mooser, 1967; García Barcena, 1986) is not apparrently present in the Chalco cores. Lozano-García *et al.* (1993) proposed that its absence may be related to some tectonic disturbance and erosion that affected the Chalco basin.

Table 1

Magnetic susceptibility (in 10^{-5} SI-units) for tephra layers I to IX.

Tephra Unit	Core A	Core B	Core C	Core D
I	30	40	45	45
II	10	18	20	15
III	32	20	72	115
IV	87	72	100	55
V	95	75	110	142
VI	135	138	135	160
VIa	33	50	-	-
VII		132	72	128
VIII		50	25	-
IX		42	25	30

Tephra II corresponds to the upper Toluca pumice. Tephra VI corresponds to the 'pomez con andesita'.

4. PALAEOMAGNETIC RESULTS

The low-field magnetic susceptibility was measured with a Bartington MS-2 susceptibility bridge (core logging sensor and the MS2B dual frequency sensor). Direction and intensity of natural remanent magnetization (NRM) were determined with a Molspin spinner fluxgate magnetometer. The magnetic stability and vectorial composition of the NRM was investigated by detailed step-wise alternating field (AF) demagnetization. AF demagnetization was completed with a Schonstedt GSD-5 instrument (used in the static three positions method).

Magnetic susceptibility varied along the various cores, with the maxima clearly related to the occurrence of tephra layers (Urrutia-Fucugauchi, 1990). The highest values correspond to Tephra VII and VIII (Table 1). Tephra VIa was not observed macroscopically; it was inferred from the high susceptibility values measured in all cores. The susceptibility peaks of the tephra layers represent a very important support for correlation of the cores obtained at different sites, and the stratigraphic columns and correlations largely rely on that property. Figure 5 shows the variation of magnetic susceptibility with depth for the 4 cores, and assigns the observed peaks to the 10 tephra layers.

NRM inclinations could be easily determined absolutely, whereas declination could only be measured relatively within each core section. A composite declination log for the entire core sequence measured was completed by single vertical axis rotation of declination data for consecutive core sections until values from the bottom and top of given sections coincided. Variation of both parameters with depth are shown in Figure 6, together with NRM-intensity. The upper 80 cm show high dispersion, probably due to reworking of the sediments by agricultural activity. Below about 1.3 m a similar pattern was observed in all cores.

Declination with depth shows well defined consistent variations between about 90° and 30° (Figure 6b). This pattern of declination changes seems typical for lake sediment records of geomagnetic palaeosecular variation (Creer *et al.*, 1983).

The expected mean inclination for an axial geocentric dipole at the latitude of Chalco is 35°. The observed NRM inclination records for cores A and B vary around the dipolar inclination, with considerable angular dispersion (Figure 6c). High angular dispersion of NRM directions has been also observed by Liddicoat *et al.* (1979, 1981) for sediments in the nearby Tlapacoya sequence. This high angular dispersion may be due to secondary components, effects related to the sampling procedures, and also to some extent to the low magnetization intensities which result in larger measurement errors. Additionally, superparamagnetic minerals may acquire anomalous magnetizations in the ambiental magnetic field. To reduce that contribution, the samples for core D were stored in a magnetically shielded space. After AF demagnetization, the directional dispersion is reduced.

NRM intensity varies between 0.1 and 100 mA/m. As mentioned, the high intensities are related to the tephra layers and correlate with the low-field magnetic susceptibility. In contrast to the magnetic susceptibility variations, intensity variations are less pronounced: above many tephra layers, NRM intensities change gradually to lower values, possibly because of sediment reworking and the indirect effects of deposition of fine-grained ash eroded outside the lake.

Almost all samples demagnetized with AF show simple univectorial magnetization, with vector plots

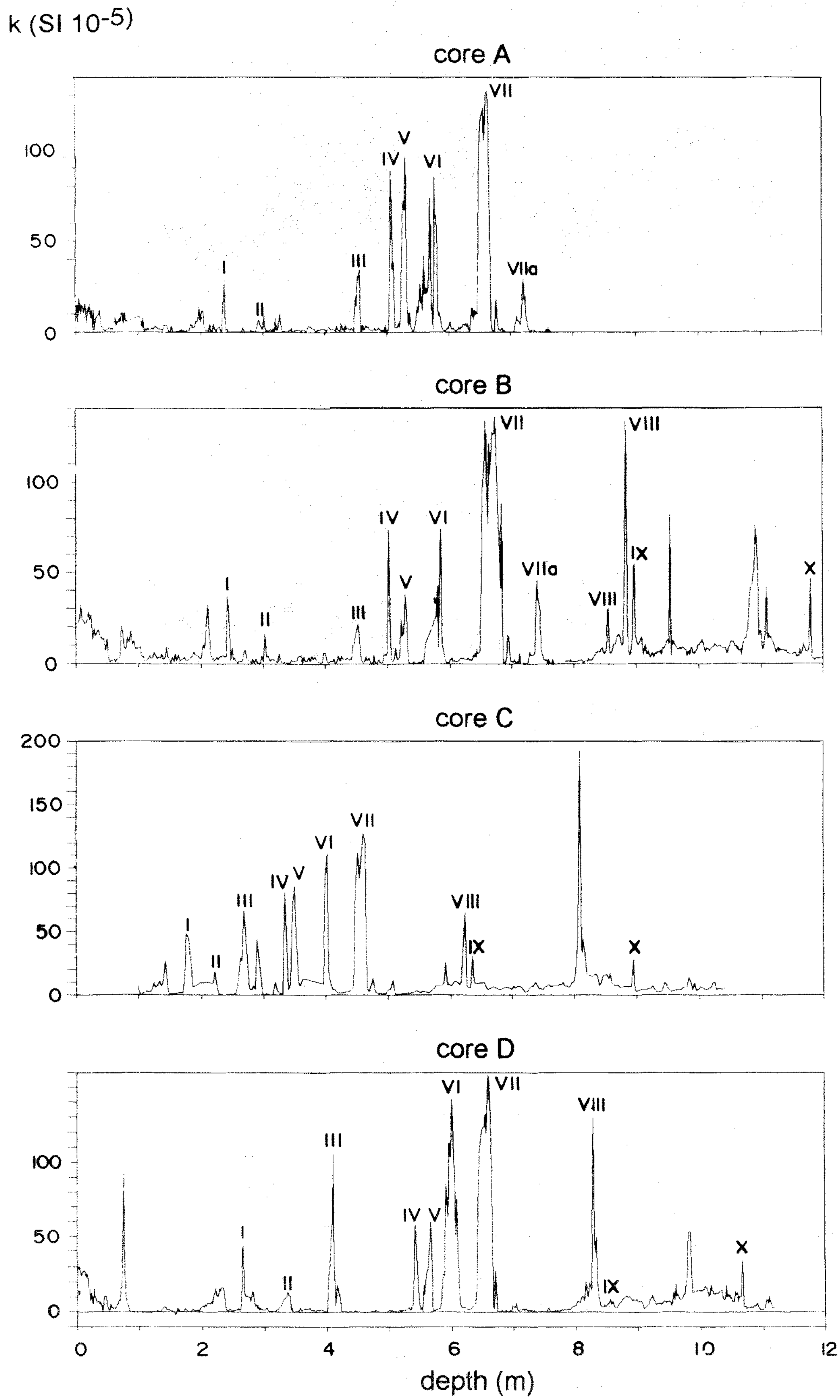

Fig. 5. Depth variation of magnetic susceptibility for the four cores from Chalco.

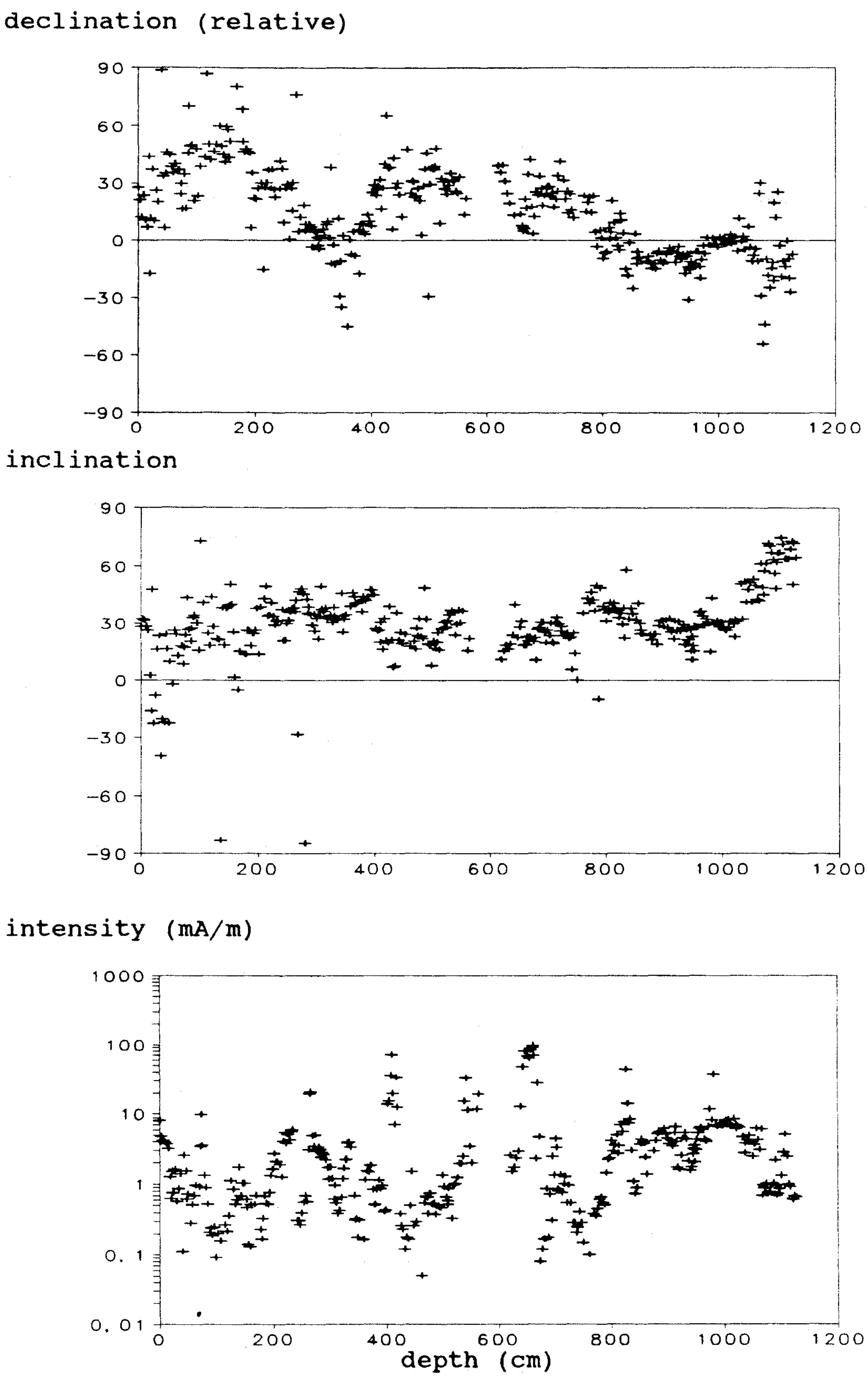

Fig. 6. Depth variation of intensity and direction of magnetization for the combined core A/B.

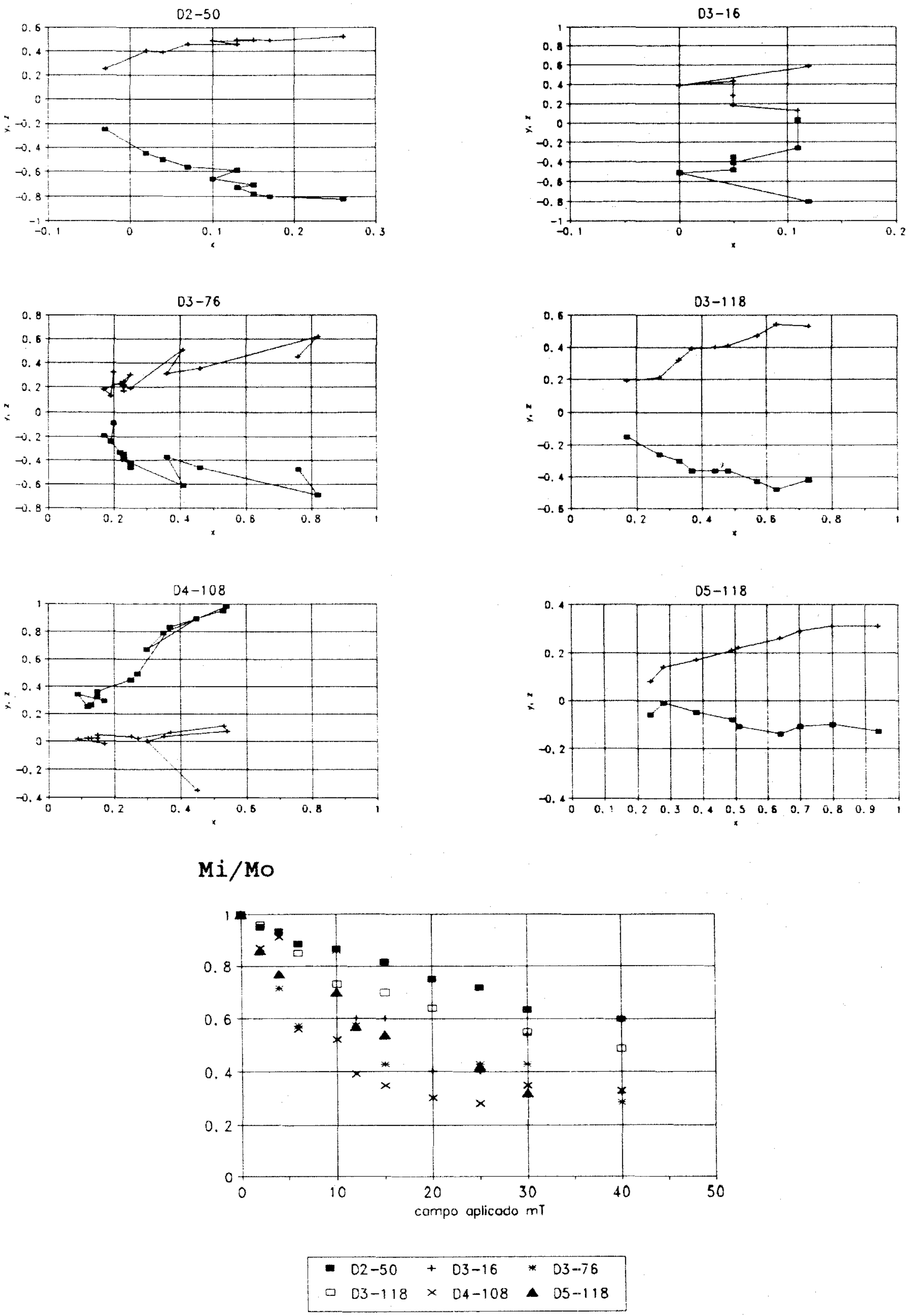

Fig. 7. Examples of vector plots for some samples (alternating field demagnetization. AF peak fields applied in mT).

(Zijderveld, 1967) directed towards the origin (Figure 7). This simple vectorial behaviour led to the decision to demagnetize the rest of the samples at one step of 15 mT (mili-Tesla).

The declination record is very smooth and shows small amplitude variations, between about 90° and -20°, with a pronounced 'swing' at a depth of 200 cm. The declination values were referred to an arbitrary declination value in the first core segment and all other core segments were rotated to adjust to that value, then obtaining a composite declination record for the entire core (Figure 8a).

There is apparently little resolution in the inclination record from the demagnetized NRM for the Chalco core examined in detail through demagnetization procedures. The variation of inclination with depth is given in Figure 8b. It shows more scatter than the declination record, with values distributed around the dipolar inclination for the sampling site which is about 35° and with a rough correspondance with the lithological variation and core segments. The inclination values mainly range from about 20° to 60° and show an increase towards the deeper part of the core. The scatter observed in the inclination data is disappointing since one of the initial objectives of the project was the documentation of the geomagnetic palaeosecular variation for central Mexico. Nevertheless, a detailed assesment of factors contributing to scatter and stacking of inclination records may still help in improving the resolution of the remanent magnetization record for Chalco Lake.

Palaeosecular variation estimates from studies of recent Brunhes volcanic units in central Mexico suggest a low non-dipole field component (Böhnel *et al.*, 1990). An earlier palaeomagnetic study of the sediment sequence at nearby Tlapacoya (Liddicoat *et al.*, 1979, 1981) indicated a small amplitude declination variation. For one of the sections studied, they reported the occurrence of a swing in the declination values that was interpreted in terms of an excursion of the geomagnetic field. This interpretation was later withdrawn since they were unable to observe the excursion in the other sections. The Tlapacoya 'excursion' was found at about 14,000 yr B.P. (Liddicoat *et al.*, 1979, 1981).

The corresponding variations in the intensity after demagnetization are also included in Figure 8c. It can be observed that an apparent cyclic variation with stratigraphic position is present in the values, similar to that in the initial NRM intensity.

5. PALYNOLOGICAL STUDIES

A total of 80 samples was studied, taken every 10 cm from core B. The palynomorphs were extracted from 2 cm^3 of sediment. To estimate the total abundance, 2-3 marker tablets (*Lycopodium clavatum*) were diluted with the sediment. After standard preparation for microscopy, 500 palynomorphs and the markers were counted in every sample, belonging to trees, bushes, herbs, aquatics, fungi, and algae.

The results of the pollen analyses in the first 8 m are presented in a summary pollen frequency diagram (Figure 9). It includes the most important taxa in terms of abundance and palaeoecological significance. The calculation of the pollen concentration, expressed in number of pollen grains/cm^3 x 1000, and the drawing of the diagram were made with the Tilia program (Grimm, 1992).

Arboreal pollen is dominated by several species of *Pinus*, *Quercus* and *Alnus*, also found elsewhere in Mexico (e.g., Brown, 1985; Xelhuantzi, 1991). This results in rather homogeneous pollen diagrams. Some other tree pollen taxa with relative low frequency were recorded, includying *Abies sp.*, Cu-Ju- type (genus *Cupresus* and *Juniperus*). Extremely low frequency (less than 2 %) pollen such as *Liquidambar*, *Carpinus-Corylus type*, *Fraxinus*, *Ulmus*, *Fagus*, *Picea*, *Podocarpus*, *Tilia* and *Populus* are present in the record. The only non-arboreal pollen curves correspond to Poacaeae, Chenopodiacae-Amaranthaceae. Other herbaceous taxa present in low frequencies correspond to *Compositae*, *Artemisia*, *Cirscium*, *Ambrosia* and *Umbelliferae*. Some elements of subaquatic vegetation such as *Cyperaceae*, *Typha sp.*, fungi spores and algae were also observed in the samples. The palynological assemblages offer indications of past vegetation communities in the basin, and changes in palaeolimnology.

Based on the variation in frequency of the taxa, it is possible to establish different periods of changes in the pollen record. From 8.0 m to 4.95 m, the pollen record is affected by the intense volcanic activity. This is observed in a reduction or even absence of pollen. Pollen concentration is low (26,000 grains/cm^3), with *Pinus*, *Quercus* and *Alnus* as dominant elements. Grasses with high values point to a more extended herbaceous cover in the vegetation. Elements of the subaquatic environment are present in low frequencies; this could reflect the unstable conditions due to volcanic activity and lake level changes. Reduction in lake levels contributes to the increase of fungi. High values of loss-on-ignition are also observed in this interval (Urrutia-Fucugauchi *et al.*, 1994).

Between 4.95 m to 3.00 m, the record with increased pollen concentration (105,000 grains/cm^3 on average) suggests more stable environmental conditions. Although the same pollen taxa are present, the low frequency taxa become more abundant. Slight reduction in grasses and the increase in arboreal pollen could indicate an expansion of the forests. The increase in Cyperaceae and *Typha* could be associated with humid conditions in the areas around the lake.

Palynological assemblages from 3.00 m to 2.10 m suggest the establishment of mixed forests with pine and oak in the area, and a consequent reduction of the herbaceous pollen, mainly grasses. Pollen concentration is about 80,000 grains/cm^3 during this period. Frequency of fungi decreases substantially probably due to a high lake level.

Arboreal pollen attains highest frequencies from 2.10 to 1.05 m. In addition to the pine, oak and *Alnus*, during

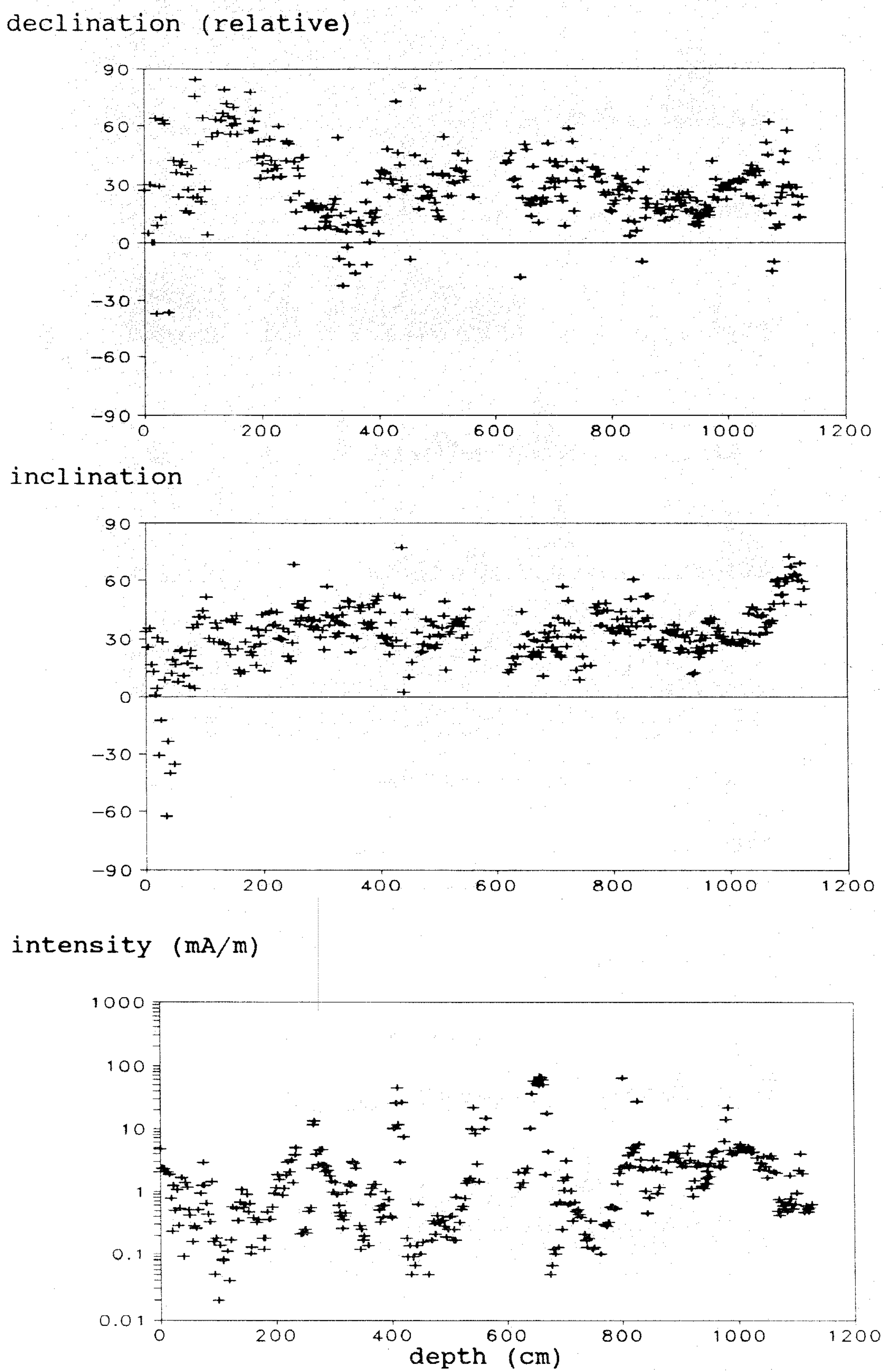

Fig. 8. Variation of characteristic remanent magnetization after AF demagnetization with a 15 mT peak field.

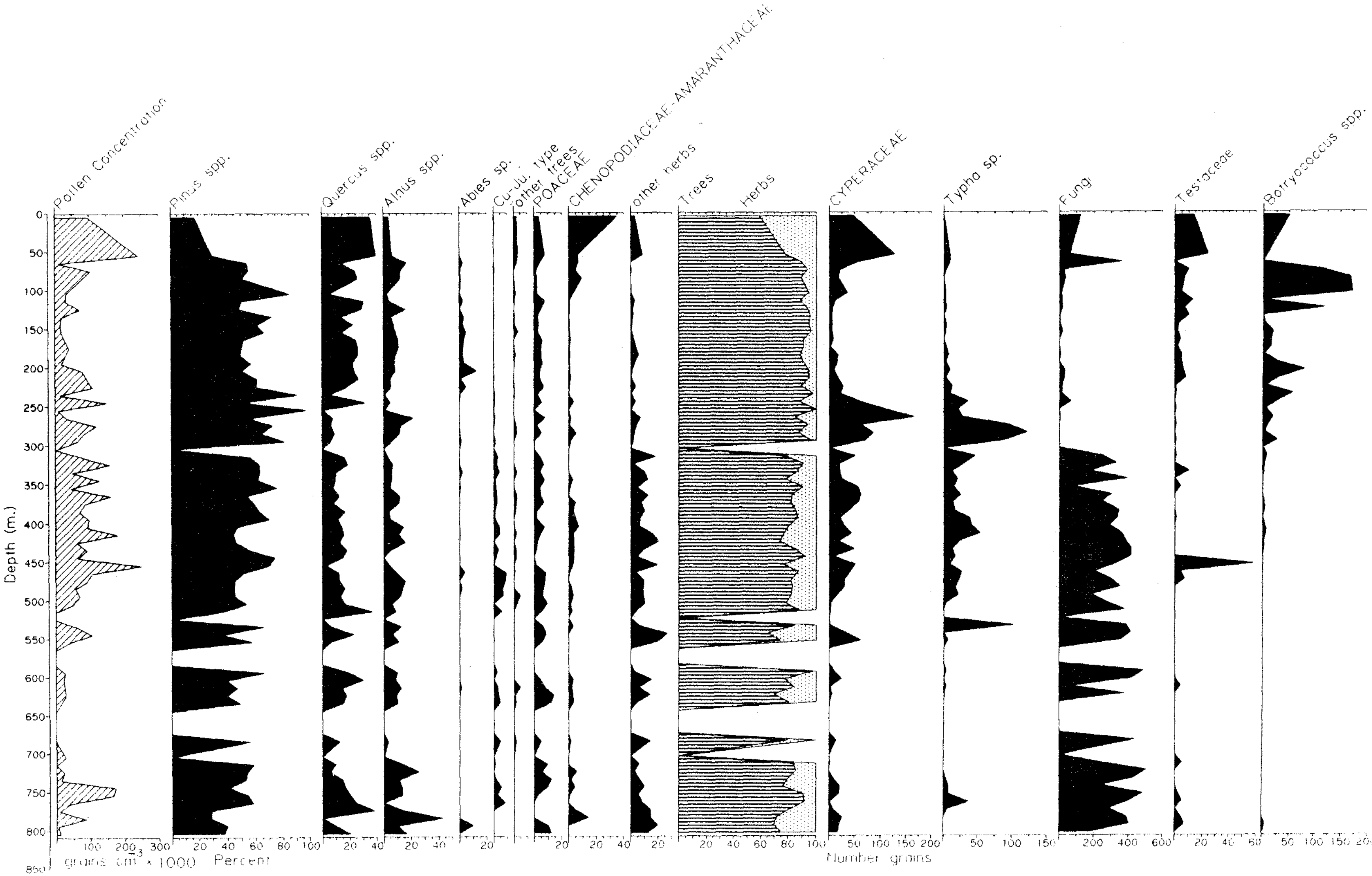

Fig. 9. Summary of pollen analyses in terms of concentration diagrams (see text for detaisl and discussion).

this time, pollen of *Abies* becomes an important element and oak shows high values. Pollen of *Picea, Podocarpus, Fagus, Juglans* are present in very low frequencies (<2%). A reduction in overall pollen concentration is observed (50,000 grains/cm^3 in average). Pollen of subaquatic vegetation decreases, and fungi record is minimal. Conditions may be more humid, as indicated by the presence of *Abies* and *Picea*, as well as the expansion of the forest.

The upper meter in the pollen record of Chalco is characterized by the occurrence of Chenopodiaceae-Amaranthaceae, associated with human activity. Deforestation is also noted in the pollen diagram with the reduction of pine. Modifications in the erosion rates are documented by increments in susceptibility values.

6. DIATOM STUDIES

Diatom samples were prepared using a constant weight of 0.5 g of dry sediment that was treated with standard methods and diluted to a constant volume of 30 µl. Diatom counts (500 valves) were performed on duplicate slides prepared with 25 µl to determine diatom taxa relative abundance. Total abundance was determined by selecting and counting an index taxa at low amplification (40 x objective) in the entire aliquote.

The detected diatom taxa can be grouped into five categories. These categories differ slightly from those reported in Lozano-García *et al.* (1993), that were based on a classification by Bradbury (1989) in which *Cocconeis placentula* is considered as indicative of alkaline environments.

1. Species representative of shallow acidic water environments like *Eunotia spp., and Pinnularia spp.*

2. Species representative of shallow fresh water environments, mostly the *Fragilaria spp.* complex.

3. Species representative of fresh to slightly alkaline swamps, like *Cocconeis placentula, Cymbella spp, Epithemia spp,* and *Navicula spp.*

4. Species representative of shallow alkaline environments, mostly *Cyclotella meneghiniana* and *Nitzschia spp.*

5. Species representative of shallow saline-alkaline environments like *Amphora veneta, Anomoeneis costata* and *Navicula elkab?*.

Chrysophyte cysts are also abundant in some samples, these cysts are representative of acid environments and because they are resting structures, are considered to represent unstable conditions probably related to changes on water levels and chemistry or to disturbances induced by volcanic activity.

Based on diatom relative and absolute abundance and on the presence of Chrysophyte cysts (Figure 10) we may interpret the limnological history of Lake Chalco during the last 18,000 yr B.P. as follows:

I. From 8 to 5.05 m (c.a. 19,000 to 15,000 yr B.P.): During the period represented by this section, Chalco lake was a fresh to slightly alkaline swamp that had alternating short events in which an acid environment was favoured (Figure 10). These events may have been related to deglaciation periods during which water inflow was higher, these events could have favoured as well the developement of acid pond diatoms on the heights surrounding the lake that were later transported into it. These deglaciation processes could have been originated either by climatic variablity or volcanic activity.

II. From 4.95 to 2.25 m (c.a. 15,000 to 9,000 yr B.P.): Along this section *Fragilaria spp.* becomes dominant, this suggests that Chalco experienced a transition, involving a small increase in water level, from a swamp to a fresh water pond (Figure 10).

III. From 2.15 to 1.00 m (c.a. 9,000 to 5,000? yr B.P.): The diatom record in this section exhibits a marked change, diatom total abundance is very low and the dominant taxa are the representative of saline-alkaline shallow environments (Figure 10). The higher abundance of *Anomoeoneis costata* in the lower part and of *Amphora veneta* in the upper part (Figure 10) indicates that during this period Chalco was a very shallow saline-alkaline swamp with a tendency towards a decreasing salinity.

IV. From 0.8 to 0.2 m (c.a. 5,000 yr B.P. to present?): In this section the diatom record exhibits a marked change again, with the disappearence of most of the varieties representative of saline-alkaline environments and an increase in the fresh and alkaline representative varieties. This can be interpreted as a recovery of the fresh to slightly alkaline swamp conditions in Chalco (Figure 10). However there may be serious alterations in this part of the record due to agricultural activities that have taken place in the area.

7. DISCUSSION AND CONCLUSIONS

7.1. Palaeoenvironmental reconstruction

On the basis of the results obtained so far, the Late Quaternary palaeoenvironments in Chalco can be described as follows.

During the late Pleistocene, the upland vegetation is dominantly open forest of pine and oak, and the grasslands seems to have been more common. Volcanic activity is intense, resulting in high values of magnetic susceptibility and low concentration of micro fossils (palynomorphs and diatoms). Lake Chalco was a swamp or pond with apparent alternating periods between fresh water (pH-7) and acid (pH<7) water. Periods of higher humidity are indicated by fresh water diatoms (*Fragilaria spp.*) an increment in fringing vegetation (*Cyperaceae* and *Thypa spp.*), phases

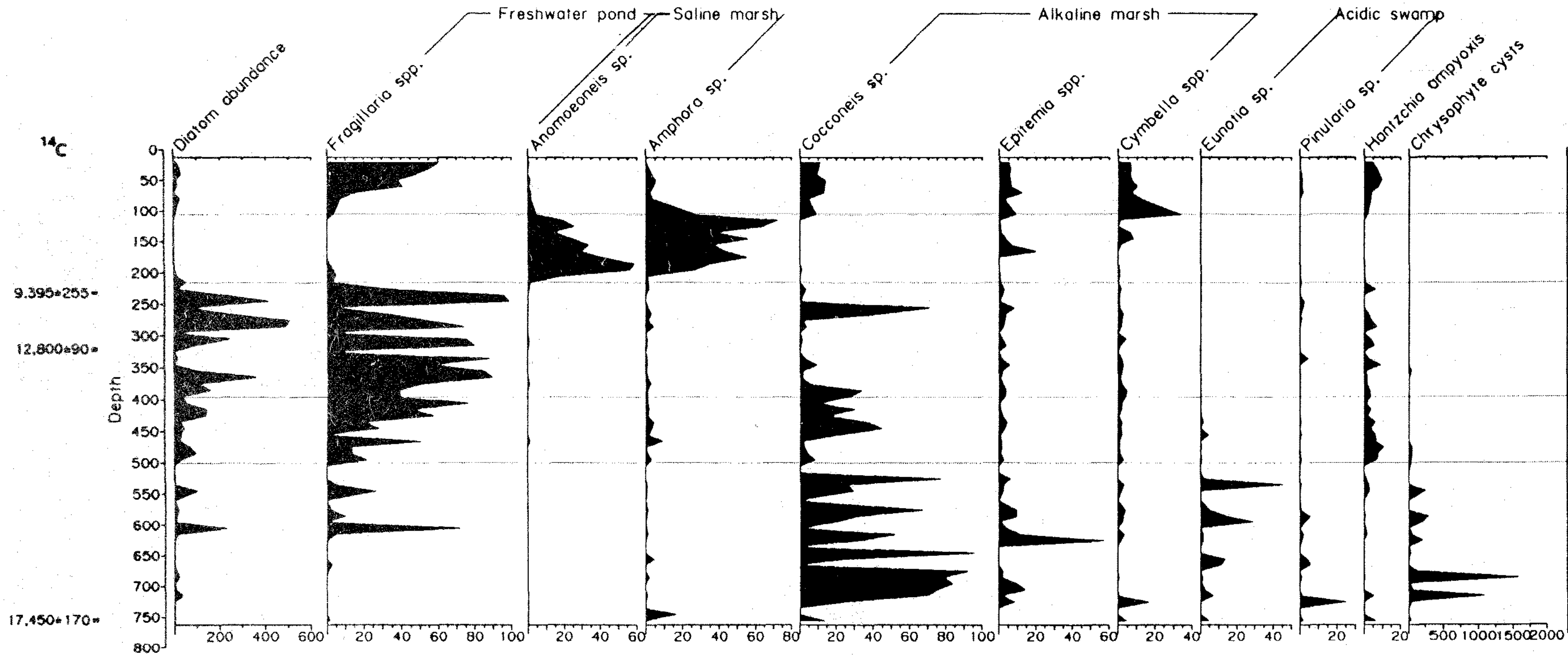

Fig. 10. Summary of diatom analyses of Chalco lake sequence.

of lower humidity by diatoms typical for shallower water and more alkaline conditions (*Cocconeis sp.*).

At the end of the Pleistocene and before the climatic change of the Holocene, a major increase of humidity is recorded. Chalco became a fresh water pond with abundant fringing and floating vegetation; in the pollen record *Abies* approached present conditions. Limnologically Chalco changed to a saline alkaline marsh (pH 8-9) and the pollen assemblages also are modified. Oak is more abundant as well as the total arboreal pollen; the reduction in humidity suggested by the diatom record is not observed in the pollen data. On the contrary, there are indications of a semidecidous forest. The late Holocene in the records is characterized by human impact, and climatic interpretations of the records are difficult.

In general terms, the lake level reconstruction proposed in this work is consistent with the results by Bradbury (1989), except for the period around 11,500 to 5,000 yr B.P. which he characterizes in terms of saline assemblages. Watts and Bradbury (1982) had interpreted the saline periods in terms of wetter conditions associated with flooding from Texcoco lake. The association by Bradbury (1989) for saline assemblages with dry periods is in better agreement with the diatom assemblage observations in our cores, where genera documented are benthic or epiphytic, suggesting shallow water levels and increasing evaporation in Chalco. Uncertainties with the chronological control may explain the apparent differences between results from our core and those summarized by Bradbury (1989), particularly if they are based on identification of tephra and lateral correlation to produce a chronological sequence. Difficulties can be observed, for instance, in the various data sets obtained in the Tlapacoya archaeological site studies (Lorenzo and Mirambell, 1986).

Most studies concerning the palaeoecological processes during the late Quaternary have been conducted in high latitudes. Water level was high in the SW of the United States during the glacial maximum, about 18,000 yr B.P. The increasing melting of the polar caps was followed by an increased aridity and reduction of the water level (CLIMAP, 1976, 1981; COHMAP, 1988; Crowley and North, 1991). This general effect is also observed in the Basin of Mexico, although less pronounced, as the water level was already much lower. During the glacial maximum, Chalco apparently was characterized by a swamp or pond with varying inflow water. The combined evidence indicates that there were no lakes of large extension. In Texcoco, towards the center of the Basin of Mexico, similar conditions were found (Lozano-García, 1989). A tendency to more arid conditions seems to have began earlier in the Basin of Mexico. A review of the palaeoclimatic records from Central and South America suggests also aridity in this region, as is shown by shallow lake levels (Markgraf, 1993).

The Holocene is characterized by warmer and more humid climate in the tropics, and increased evaporation in mid-latitudes. In Chalco, pollen data suggest a subhumid climate, but in the local records (diatoms and subaquatic vegetation) this is not observed. On the contrary, the interpretation from these records are in terms of dry environmental conditions at the beginning of the Holocene. Distinctions between early and mid-Holocene have some difficulties taking into account the uncertainties. Holocene records in the Basin of Mexico generally indicate human activity, but in the diatom data it is possible to observe an increment in lake levels suggesting humid climates in this area.

Global climatic records indicate the occurrence of a postglacial climate optimum at about 8,000 to 6,000 yr B.P. Since about 6,800 yr B.P. there has been a tendency of global cooling (e.g., Feng and Epstein, 1994). This trend was particularly accelerated during the Little Ice Age between 1700 and 1900 A.D. Street-Perrot and Perrot (1990) proposed that lake levels were high during the mid-Holocene; however, this is not observed in the Chalco records. Bradbury (1989) did not find evidence for high lake levels after 7,000 yr B.P. Although, it is necessary to obtain more records in the Basin of Mexico and in the central part of the country to achieve a better picture of the late Pleistocene palaeoenvironmental changes in this latitude, the Lake Chalco records offer new data that contribute to the understanding of climatic changes in a high-altitude subtropical region.

7.2. Palaeomagnetism

Geomagnetic palaeosecular variation for Lake Chalco shows a pattern of declination and inclination swings characteristic of lake sediment records in other latitudes. Results for core D that provides the best data over the entire depth (in terms of magnetic stability and vectorial composition) are summarized versus the C-14 chronology in Figures 11 and 12.

The intensity and susceptibility show similar patterns of changes with an apparent cyclicity. Koenigsberger Q-coefficients are generally lower than unity, in the range from 0.04 to 6 (Figure 11). The pattern may be observed by smoothing the series (e.g., Figure 12c). The directional variation pattern of the characteristic magnetization (summarized in Figure 12a,b, after application of a six-point running filter) shows several features in declination and inclination (identified by letters, Figure 12a,b). The inclination data vary around a mean value of around 32.9°, also with an apparent cyclic pattern (Figure 12b). There are no large swings in the inclination data as compared with those present in the declination pattern (Figure 12a). The dipolar inclination for the site is 35.3°, therefore the corresponding mean inclination anomaly ΔI is -2.4°. This value is similar to that determined for volcanic units from Sierra Chichinautzin that covers the last period of Brunhes chron, estimated in -3.1 degrees (Herrero-Bervera *et al.*, 1986). The inclination anomalies for Chalco lake sediments and Chichinautzin volcanics are compared with data from other localities in the world in terms of site latitude in Figure 13 (global data from Lund *et al.*, 1985). The inclination anomaly for the lacustrine sequence of Chalco (Figure 14)

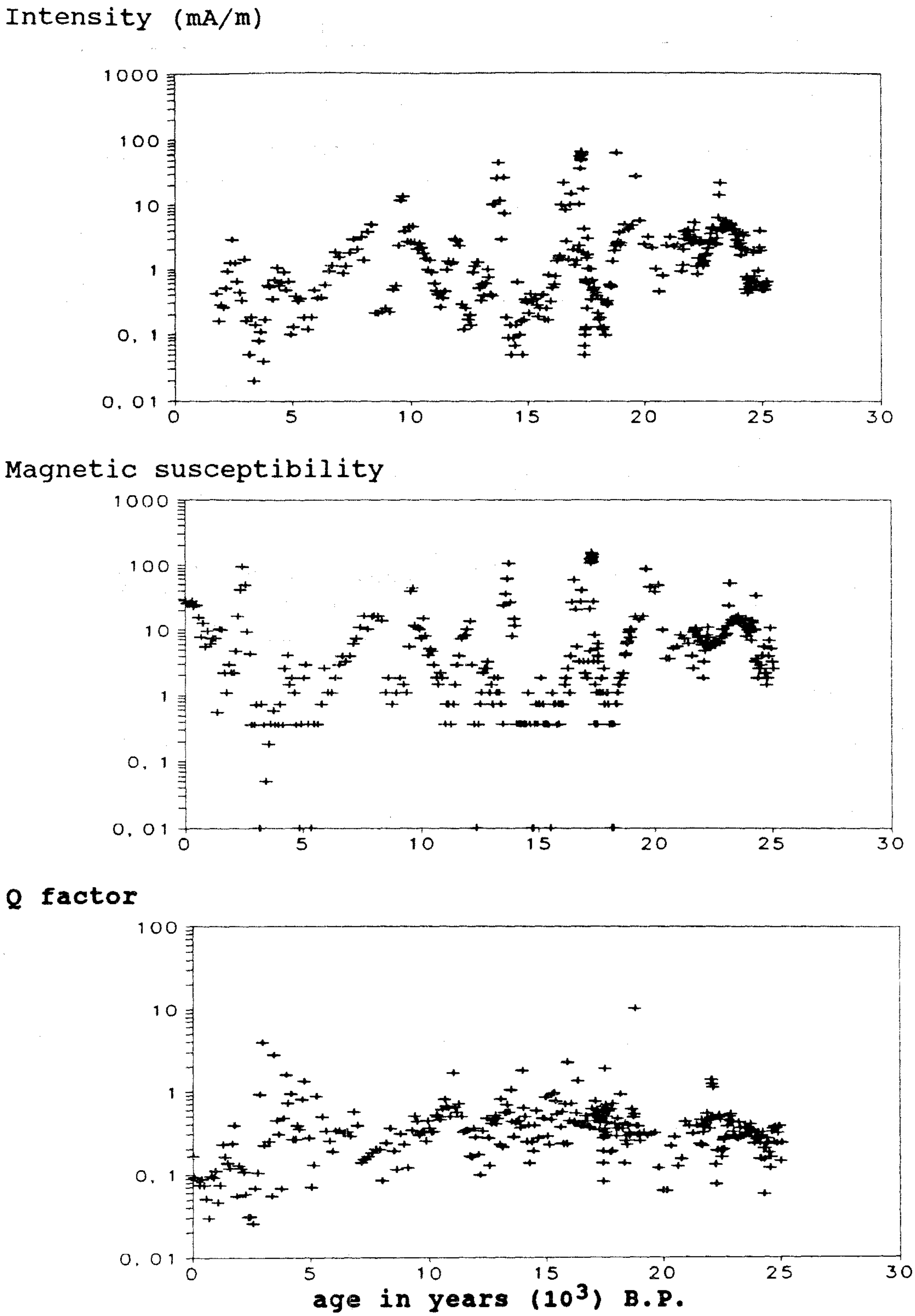

Fig. 11. NRM intensity, magnetic susceptibility and Koenigsberger Q-coefficient as a function of age for core D.

displays a marked peak at about 14,000 yr B.P. that correlates with a declination swing.

The declination record shows a marked swing (feature D; Figure 12a) of about 30 - 60 degrees for a time of around 5,000 - 6,000 yr B.P. This 'declination excursion' is also observed in the volcanic rocks record from units in the Basin of Mexico and nearby Toluca Valley (González-Huesca, 1992) and may reflect a real feature of the geomagnetic field during the recent time in the Holocene.

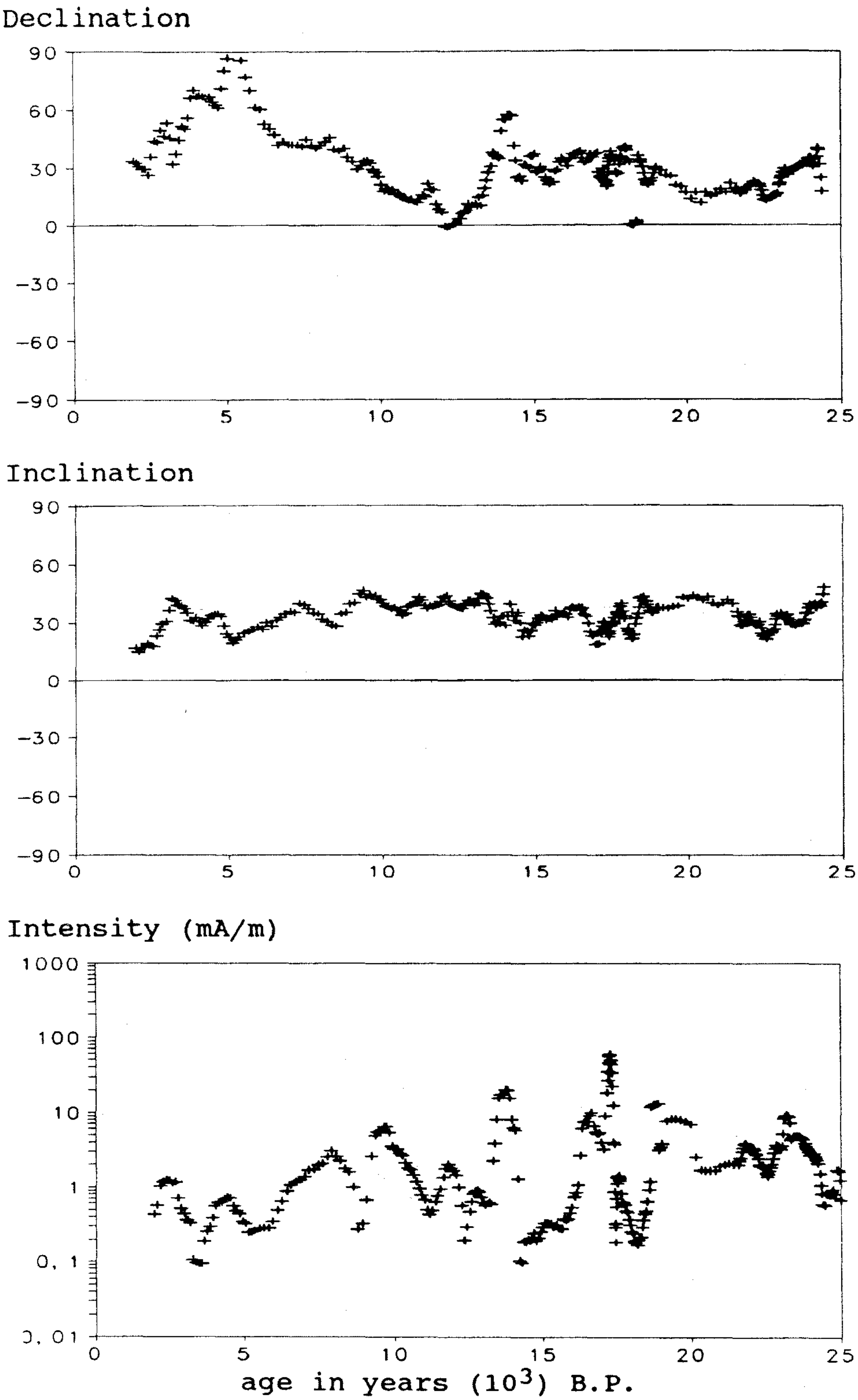

Fig. 12. Variation of characteristic remanence as a function of age for data from core D. A six-point running filter has been applied to data. Major features in the declination record have been marked with capital letters (a). Corresponding features in the inclination record are marked with lower case letters.

All major features are present in both series of data (Figures 12 and 15). The feature identified as I (Figure 12a) that shows at about 14,000 yr B.P. may correspond with a declination anomaly early reported from the sediments in Tlapacoya (Liddicoat *et al.*, 1979, 1981). These correlations and any interpretation in terms of

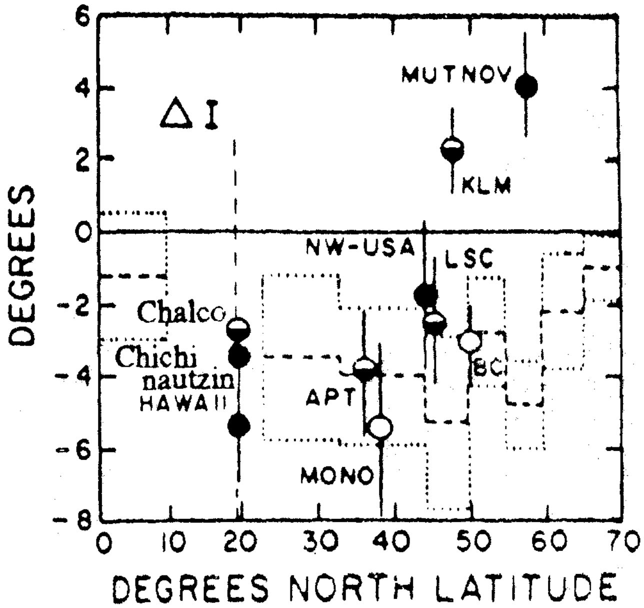

Fig. 13. Summary of inclination anomaly (ΔI) observed for various locations plotted as a function of latitude. Global data taken from Lund *et al.* (1985). Data for Chichinautzin volcanics, basin of Mexico is from Herrero-Bervera *et al.*, (1986) and data from Chalco lake sediments is from this work. Open symbols correspond to marine sediments; half-open symbols are for lacustrine sediments and closed symbols for volcanic rocks.

behaviour of the Earth's magnetic field should be considered as preliminary. Particularly in regard to possible geomagnetic excursions and additional data from nearby parallel sections should be obtained to confirm the patterns of variation.

The frequency content of the directional and rock-magnetic property data were analysed to estimate apparent periodicities. Regular spacing interpolation was completed by cubic splines approximation of the initial data referred to the radiocarbon chronological sequence. The chosen time interval is 32.5 yr, approximately corresponding to the time differences between succesive samples. Spectral analysis was carried out with the computer program of Scherbaum and Johnson (1992) that offers options for e.g., low and high pass filters. Results are summarized in Figures 16, 17 and 18 for the intensity, declination and inclination series for the characteristic magnetization observed in core D (see Figures 11 and 12). Intensity data show periodicities from 650 to 2,900 yr (Figure 16). Declination data show similar dominant periods in the order of 850 to 2,900 yr (Figure 17). Inclination data present dominant periodicities in the range from 1,000 to 3,799 yr (Figure 18).

ACKNOWLEDGMENTS

Valuable assistance has been provided by Susana Sosa, Ralph Hansen, Bernt Haverkamp, Harald Böhnel, Barry Warner, J.F.W. Negendank, Martín Espinoza, Teodoro Hernández, Oscar Campos and Claudia Mendoza. We acknowledge the critical comments by two journal referees and by the senior editor. Partial financial support for the project was provided by grants from DGAPA (project IN-103589), National University of Mexico, the VW Scientific Foundation (1988-89) and the R. J. Zevada Foundation (1991).

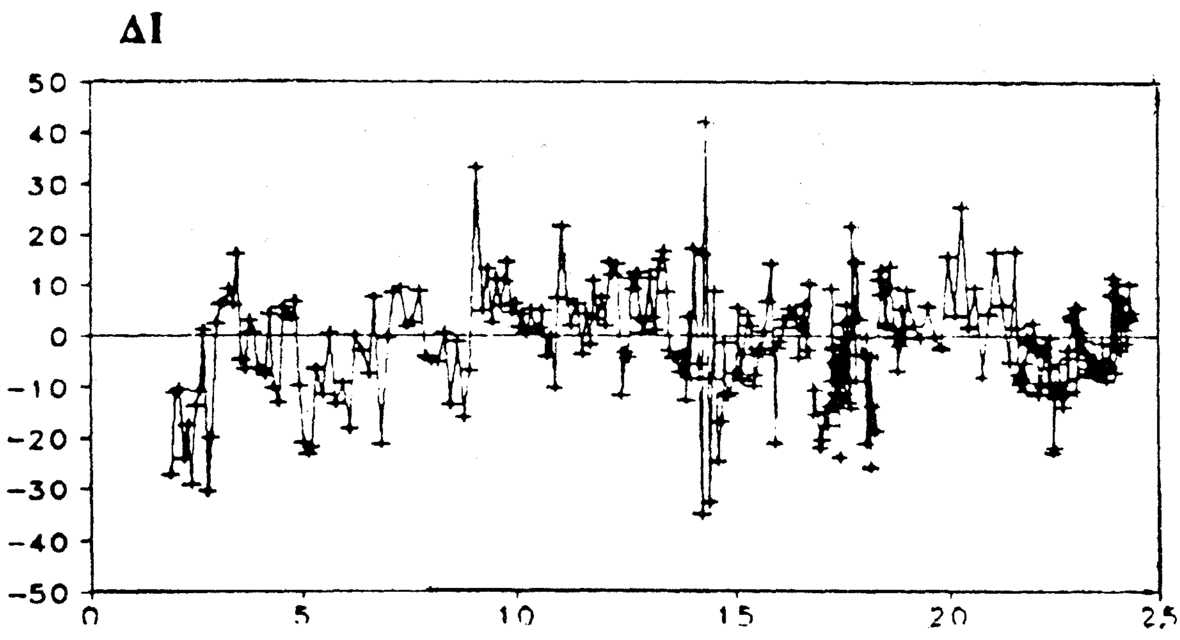

Fig. 14. Variation of inclination anomaly (ΔI) for data of core D, as a function of age in thousands of years BP.

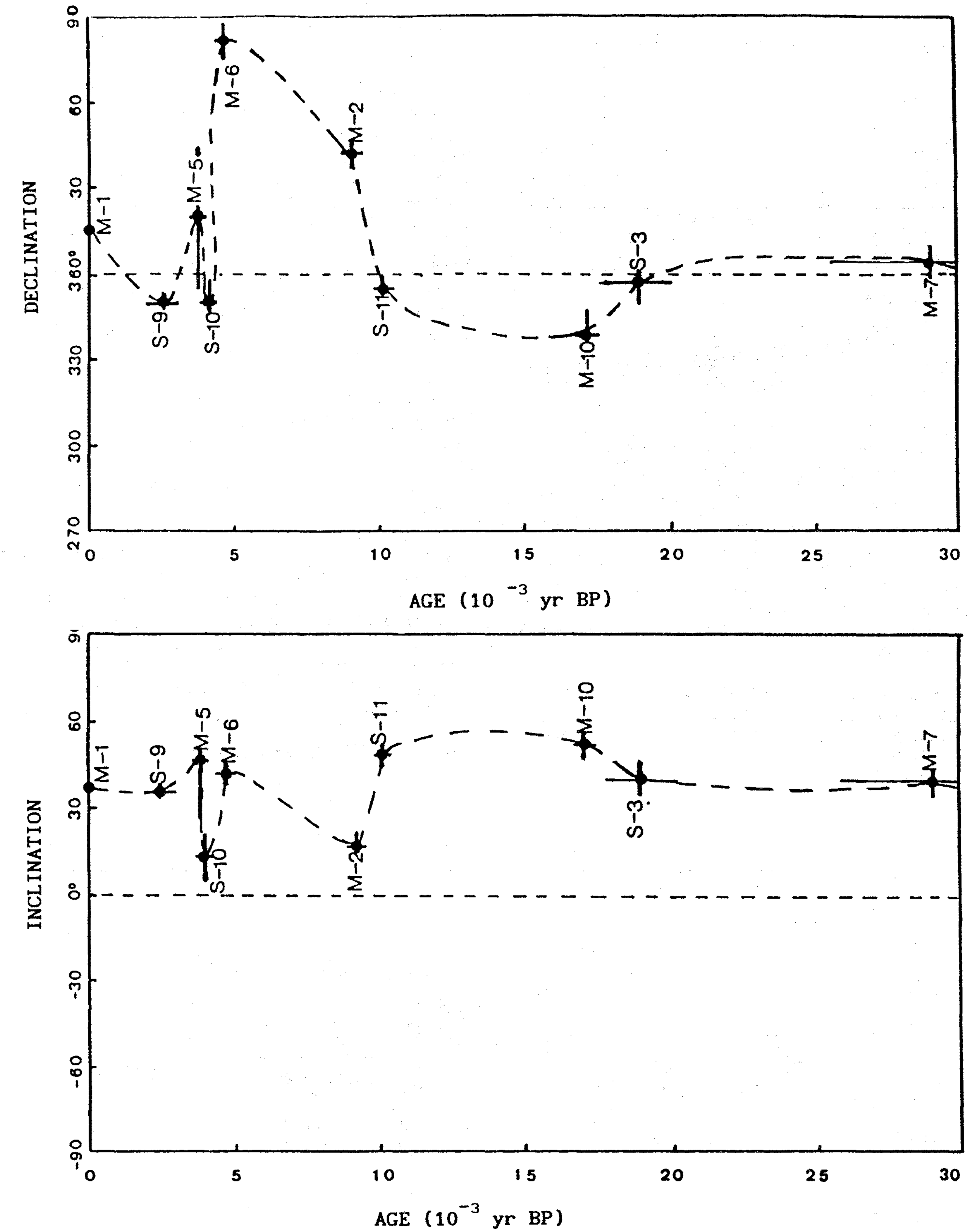

Fig. 15. Palaeosecular variation data for volcanics from central Mexico. Declination (a) and inclination (b) data as a function of C-14 dates. Diagram taken from González-Huesca, 1992). Observe the declination swing at about 5000 yr BP and the overall variation pattern (compare with Figure 12).

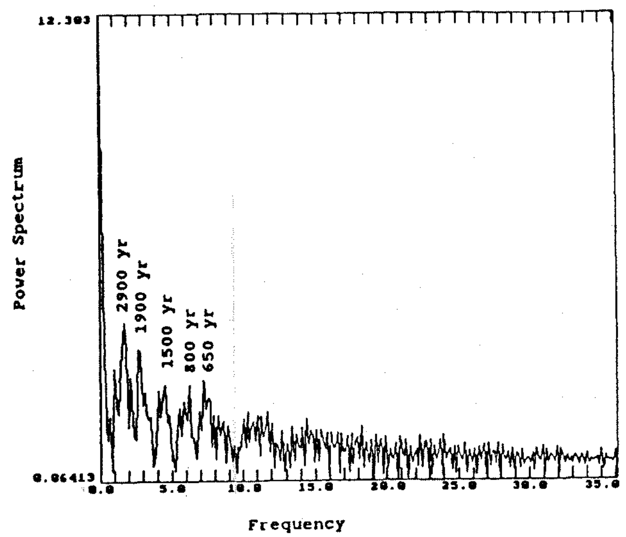

Fig. 16. Power spectrum for remanence intensity data for core D. Periods observed are marked in years BP.

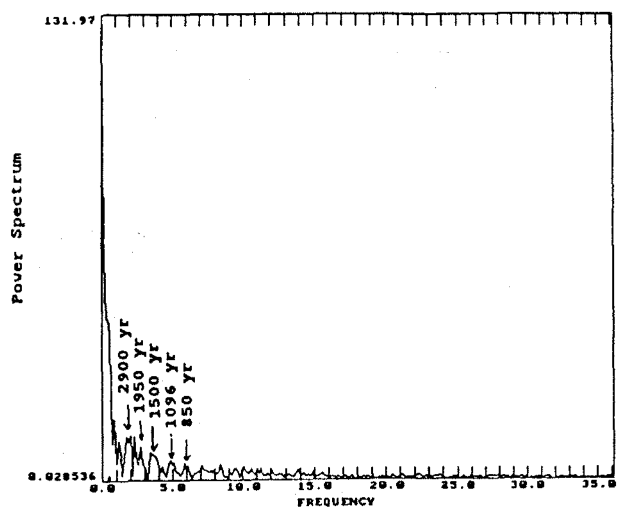

Fig. 17. Power spectrum for declination data for core D. Periods observed are marked in years BP.

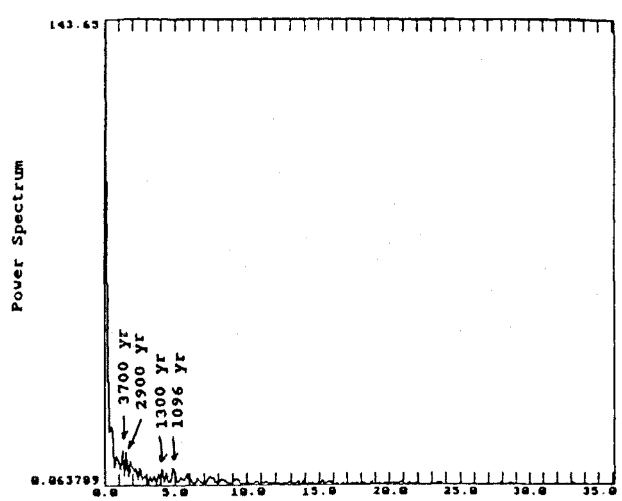

Fig. 18. Power spectrum for inclination data for core D. Periods observed are marked in years BP.

BIBLIOGRAPHY

BLOOMFIELD, K.A. and S. VALASTRO, 1974. Late Pleistocene eruptive history of Nevado de Toluca, Central Mexico. *Geol. Soc. Am. Bull.*, *85*, 901-906.

BLOOMFIELD, K. A. and S. VALASTRO, 1977. Late Quaternary tephrachronology of Nevado de Toluca volcano, central Mexico. Inst. Geol. Sci., *Overseas Geol. Miner. Resour.*, *46*, 1-15.

BÖHNEL, H., J. URRUTIA FUCUGAUCHI and E. HERRERO BERVERA, 1990. Palaeomagnetic data from central Mexico and their use for palaeosecular variation studies. *Phys. Earth Planet. Inter.*, *64*, 224-236.

BRADBURY, J. P., 1971. Paleolimnology of Lake Texcoco, Mexico: Evidence from diatomes. *Limnol. Oceanogr.*, *16*, 180-200.

BRADBURY, J. P., 1989. Late Quaternary lacustrine paleoenvironments in the Cuenca de Mexico. *Quat. Sci. Rev.*, *8*, 75-100.

BROWN, B., 1985. A summary of late Quaternary pollen records from Mexico west of the Isthmus of Tehuantepec. *In:* V. H. Bryant and R. G. Holloway (Eds.) Pollen Records of Late-Quaternary North America Sediments. Am. Assoc. Strat. Palyn. Found., p. 71-94.

CLIMAP, 1976. The surface of the ice-age earth. *Science*, *191*, 1131-1137.

CLIMAP, 1981. Seasonal reconstructions of the Earth's surface at the last glacial maximum. Geol. Soc. Am. Map and Chart Ser., MC-36, 1-18.

COHAMAP, 1988. Climatic changes of the last 18 000 years: Observations and model simulations. *Science*, *241*, 1043-1052.

CREER, K.M., P. TUCHOLKA and C.E. BARTON (Eds), 1983. Geomagnetism of Baked Clays and Recent Sediments. Elsevier Sci. Publ., Amsterdam, The Netherlands.

CROWLEY, T.J. and G.R. NORTH, 1991. Paleoclimatology. Oxford Monogr. Series, Oxford Univ. Press, Oxford, UK, 339 pp.

FENG, X. and S. EPSTEIN, 1994. Climatic implications of an 8000-year hydrogen isotope time series from bristlecone pine trees. *Science*, *265*, 1079-1081.

GARCIA BARCENA, J., 1986. Algunos aspectos cronológicos. *In:* J. L. Lorenzo and L. Mirambell (Eds.), Tlapacoya: 35,000 anos de Historia en el Lago de Chalco, Colecc. Cientif. INAH, México, 109-156.

GONZALEZ HUESCA, S., 1992. La variación secular en México central durante los últimos 30,000 años por medio del estudio magnético de lavas. Tesis Doctoral, Progr. Geofís., Univ. Nac. Aut. México.

GRIMM, 1992. Tilia software. Version 1.12.I11. State Musseum Collect. Cent.

HERRERO BERVERA, E., J. URRUTIA FUCUGAUCHI, A. L. MARTIN, H. BÖHNEL and J. GUERRERO, 1986. Normal amplitude Brunhes paleosecular variation at low-latitudes: A paleomagnetic record from the Trans Mexican volcanic belt. *Geophys. Res. Lett.*, *13*, 1442-1445.

LIDDICOAT, J. C., R. S. COE, P. W. LAMBERT and S. VALASTRO, 1979. Paleomagnetic record in late Pleistocene and Holocene dry deposits at Tlapacoya, Mexico. *Geophys. J.R. Astr. Soc.*, *59*, 367-377.

LIDDICOAT, J. C., R. S. COE, P. W. LAMBERT, H. E. MALDE and V. STEEN-McINTYRE, 1981. Paleomagnetic investigation of Quaternary sediment at Tlapacoya, Mexico, and at Valsequillo, Puebla, Mexico. *Geofís. Int.*, *20*, 249-262.

LORENZO, J. L. and L. MIRAMBELL (Coords), 1986. Tlapacoya: 35 000 años de historia del Lago de Chalco. Colecc. Cientif. INAH, México, 297 pp.

LOZANO, S., 1989. Palinología y paleoambientes Pleistocénicos en la Cuenca de México. *Geofís. Int.*, *28*, 335-362.

LUND, S., J. C. LIDDICOAT, K. R. LAJOIE, T. L. HENYEY and S. W. ROBINSON, 1985. Paleomagnetic evidence for long-term (10 000 year) memory and periodic behavior in the earth's core dynamo process. *Geophys. Res. Lett.*, *15*, 1101-1104.

MARKGRAF, V., 1993. Climatic history of central and South America since 18,000 yr B.P. Comparison of pollen records and model simulations. *In:* H.E. Wright, Jr., J.E. Kutzbach, T. Webb III, W.F. Rudiman, F.A. Street-Perrot and P.J. Bartleim (Eds.), Global Climates since the last glacial maximum. Univ. Minnessota Press, Mineapolis, 567 pp.

MOOSER, F., 1967. Tefracronología de la Cuenca de México para los últimos treinta mil años. Bol. Inst. Nac. Antropol. Hist., 30, 12-15.

MOOSER, F., 1975. Historia geológica de la Cuenca de México. *En:* Memoria de las Obras del Sistema de Drenaje Profundo del Distrito Federal, Depto. D.F., Mexico, tomo 1, p. 7-38.

SEARS, P. B., 1952. Palynology in the southern North America, 1: Archaeological horizons in the basins of Mexico. *Geol. Soc. Am. Bull.*, *63*, 241-254.

SEARS, P. B. and K. H. CLISBY, 1955. Palynology in the southern North America, 4: Pleistocene climate in Mexico. *Geol. Soc. Am. Bull.*, *66*, 521-530.

SCHERBAUM, F. and J. JOHNSON, 1992. Programmable Interactive Toolboox for Seismological Analysis, version 3.2. Rep. Inst. für Geophysik, Univ. Munich, Munich, Germany 223 pp.

STREET-PERROT, F.A. and R.A. PERROT, 1990. Abrupt climatic fluctuations in the tropics: The influence of the Atlantic ocean circulation. *Nature*, *34*, 607-612.

URRUTIA FUCUGAUCHI, J., 1990. Characterization and correlation of tephra from their magnetic properties. *EOS, Trans. Am. Geophys. Union*, *71*, 43, 1283 (abstr.).

URRUTIA FUCUGAUCHI, J., S. LOZANO-GARCIA, B. ORTEGA-GUERRERO, M. CABALLERO-MIRANDA, R. HANSEN, H. BÖHNEL and J. F. W. NEGENDANK, 1994. Palaeomagnetic and palaeoenvironmental studies in the southern Basin of Mexico-I. Volcanosedimentary sequence and basin structure of Chalco Lake. *Geofís. Int.*, *33*, 421-430.

WATTS, W. A. and J. P. BRADBURY, 1982. Paleoecological studies at Lake Patzcuaro on west-central Mexico plateau and Chalco in the Basin of Mexico. *Quat. Res.*, *17*, 56-70.

WHITE, S., 1987. Quaternary glacial stratigraphy and chronology of Mexico. *Quat. Res.*, *5*, 201-206.

XELHUANTZI, S., 1991. Estudio palinológico y reconstrucción paleoambiental del ex-lago de Zacapu, Michoacán. MA Thesis, National Univ. México.

ZIJDERVELD, J. 1967. AC demagnetisation of rocks: anaylsis of results. *In:* D.W. Collinson, K.M. Creer and S.K. Runcorn (Eds.), Methods in Palaeomagnetism, Elsevier Sci. Publ., 254-286.

J. Urrutia-Fucugauchi[1], S. Lozano-García[2], B. Ortega-Guerrero[1] and M. Caballero-Miranda[1]

[1] *Laboratorio de Paleomagnetismo, Instituto de Geofísica, Universidad Nacional Autónoma de México, D. Coyoacán, 04510 MEXICO, D. F.*

[2] *Departamento de Paleontología, Instituto de Geología, Universidad Nacional Autónoma de México, D. Coyoacán, 04510 MEXICO, D. F.*