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Palaeomagnetic and palaeoenvironmental studies in the southern basin of Mexico - I. Volcanosedimentary sequence and basin structure of Chalco lake

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RESUMEN

Se presentan los resultados de un estudio estratigráfico y de fechamiento radiométrico para los primeros doce metros de la secuencia volcano-sedimentaria del Lago de Chalco, en el sector sureste de la Cuenca de México. Para el estudio se ha analizado el material recuperado de cuatro perforaciones realizadas en la porción central del sector oeste de la cuenca. El modelado de las anomalías de Bouguer indica que la cuenca esta dividida en dos sub-cuencas por un alto estructural N-S que coincide con la estructura volcánica de Xico. El espesor máximo de la secuencia en la parte oeste es de 400 m y en la parte este de 300 m. Este estudio forma parte de un proyecto que incluye análisis del contenido de microfósiles, paleomagnetismo, sedimentología y limnología, encaminado a documentar la evolución paleoambiental y paleoclimática de la Cuenca durante el Pleistoceno tardío y el Holoceno. Cinco unidades mayores pueden ser identificadas en los primeros 12 m. Intensa actividad volcánica está representada por 10 horizontes de tefra. El control de edades se ha obtenido a partir de once determinaciones de radiocarbono. La edad a los 9 m de profundidad es alrededor de 19, 000 años. Un cambio marcado en la secuencia ocurre a los 13,000 años, indicado por los fechamientos y la presencia de una tefra y un grueso horizonte de diatomitas. Los cocientes promedio de sedimentación cambian de unos 0.80 mm/año en la parte profunda entre 3.5 y 8.13 m a unos 0.28 mm/año en la parte somera, arriba de los 3.5 m de profundidad. Análisis de las variaciones del contenido de carbón orgánico en la secuencia sugieren que entre 3 y 8 metros corresponden principalmente a un ambiente de lago somero, con acumulación alta de materia orgánica.

PALABRAS CLAVE: Pleistoceno, Holoceno, sedimentación lacustre, volcanismo, Lago de Chalco, Cuenca de México.

ABSTRACT

Results of stratigraphic and radiometric dating of the first twelve meters of the lacustrine sedimentary and volcanic sequence from Lake Chalco, southern Basin of Mexico are reported. The study is based on four cores recovered from the central part of Chalco. Bouguer gravity models indicate that Chalco basin is divided by a N-S structural high associated with the Xico volcano into two sub-basins with different sedimentary thickness. Maximum thickness is some 400 m in the east basin and 300 m in the west basin. The long-term project includes pollen, diatomes, palaeomagnetic and limnological studies and aims at a palaeoenvironmental reconstruction for the late Pleistocene and Holocene. The 12 m lacustrine sequence can be divided into five major units. Ten tephra layers are present in the sequence, indicating an intense volcanic activity in the region. Age control is provided by eleven radiocarbon determinations, with about 19,000 yr BP at 9 m depth. A change in the sequence is present at about 13,000 yr BP, indicated by the radiocarbon dates and the occurrence of a tephra layer followed by a thick diatomite horizon. Average bulk sedimentation rates vary from about 0.28 mm/yr in the upper 3.5 m to about 0.80 mm/yr in the subsequent deeper section. Organic carbon variations suggest that between 3 and 8 m, the sequence corresponds mainly to a shallow lake environment with high accumulation and preservation of organic matter.

KEY WORDS: Pleistocene, Holocene, lacustrine sediments, volcanism, Chalco Lake, Basin of Mexico.

INTRODUCTION

Most of the information concerning Quaternary climate and environments in North America comes from studies in temperate and high latitudes (higher than about 30°N). Information for low latitude regions is important for developing and testing global and regional climatic models and for understanding the environmental factors involved in the Pleistocene glaciations and subsequent Holocene interglacial warm period and their fluctuations (e.g., CLIMAP, 1976; COHMAP, 1988; Street-Perrot and Perrot, 1990). The importance of such studies has been recently stressed in interdisciplinary research programs that view the earth as a system or as a set of systems including geosphere, biosphere and hydrosphere. There is also a need for low-latitude geomagnetic secular variation data, which are critical for studies and modeling of the geodynamo (e.g., Creer, 1983).

In a sequence of two papers, we report initial results of an interdisciplinary study of the lacustrine sedimentary record of Lake Chalco (19.5°N) in the southern sector of the lake system of the Basin of Mexico, central Mexico (Figure 1). The first paper concentrates on studies of the basin structure from gravity surveys and on the lacustrine sequence stratigraphy as derived from coring, organic carbon determinations and radiocarbon dating.

BASIN OF MEXICO

The Basin of Mexico is a high-altitude site within the tropical zone (Figure 1) which has been formed by a complex series of processes in which volcanic activity has been

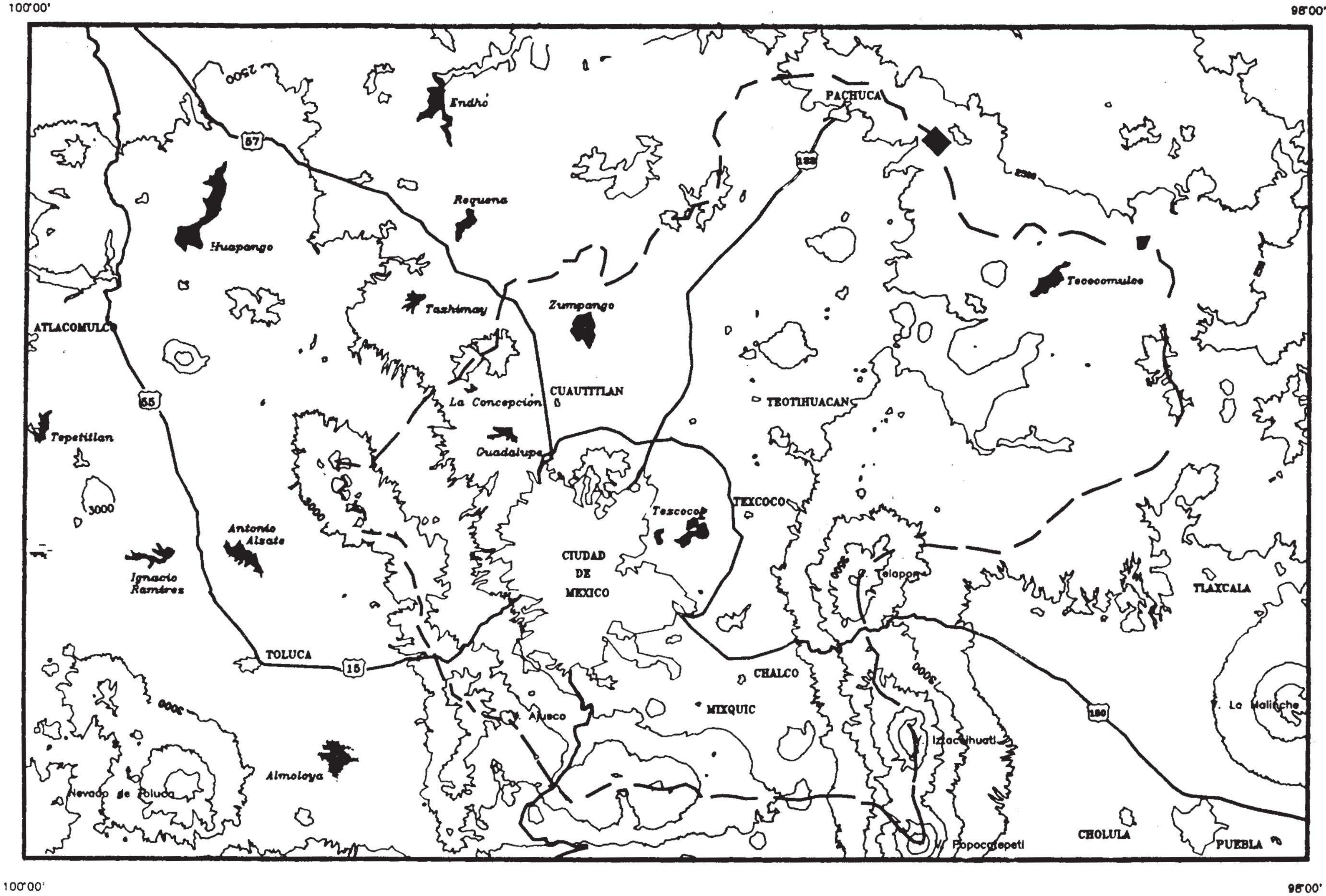

Fig. 1. Schematic topographic map of central Mexico showing approximate limits of the Basin of Mexico, Major topographic features correspond to volcanic structures that form the basin. The study area corresponds to Chalco Lake, located in the southeastern sector of the Basin.

dominant (e.g., Mooser, 1967, 1975; Mooser *et al.*, 1974; Martin del Pozzo, 1990; Mora-Alvarez *et al.*, 1991). The Basin is limited by volcanic ranges: Chichinautzin in the south; Nevada and Río Frío (including the stratovolcanos Popocatépetl and Iztaccihuatl) to the east; Sierra de las Cruces to the west; Sierra de Guadalupe, Tepotzotlán and Pachuca to the north. Apparently related to the closure of the Basin by the volcanic activity of Chichinautzin, a series of lakes developed which had a major impact on the environmental conditions (Urrutia-Fucugauchi and Martin del Pozzo, 1993). These lakes have recorded in their sediments the palaeoenvironmental, palaeoecological, and palaeoclimatological conditions during the Quaternary (e.g., Sears and Clisby, 1955; Bradbury, 1971, 1989; Watts and Bradbury, 1982; Lorenzo and Mirambell, 1986; Lozano-García, 1989).

LAKE CHALCO BASIN STRUCTURE

Lake Chalco forms the southeastern sector of the Basin. Lacustrine sediments of the Chalco sub-basin have an approximate extension of 1500 km^2 (Figure 2). The central part of the basin is presently covered by shallow waters at least during the rainy season. Excepting the volcanic composite structure of Xico, it can be simply regarded as an extended lacustrine plain.

The structure of the lake basin has been investigated by modeling of geophysical data. The available Bouguer gravity data (Hernández-Moedano, personal communication 1990) have been used to develop a preliminary model, using spectral analysis and a modified (2.5-dimensional) Talwani approach. Knowledge of the shallow structure and characteristics of the basin is important for adequately selecting the coring sites (e.g., far from the input currents, abrupt bottom topography, central sections of the basin, etc) and for interpretation of the depositional conditions through time (thickness of sediment sequence, presence of higher density volcanic units, possible uplift or compaction of sequence and faulting).

The Bouguer gravity anomaly map (Figure 3) shows a simple pattern that correlates with surface structures. Two roughly east-west orientated gravity lows coincide with the lake sediment deposits. These minima are separated by north-south orientated maxima which are due to the structure of the Xico composite volcanic complex and variations in the basal rocks below the sediments. The western gravity low extends into the Xochimilco area, indicating a continuity of the sedimentary sequence in that direction (Urrutia-Fucugauchi and Chávez-Segura, 1991).

For modeling, densities were either taken from the sampled sediments (superficial sequence), or estimated for the reported (and inferred) lithologies. Our model may be briefly summarized in Figure 4, using four of the profiles.

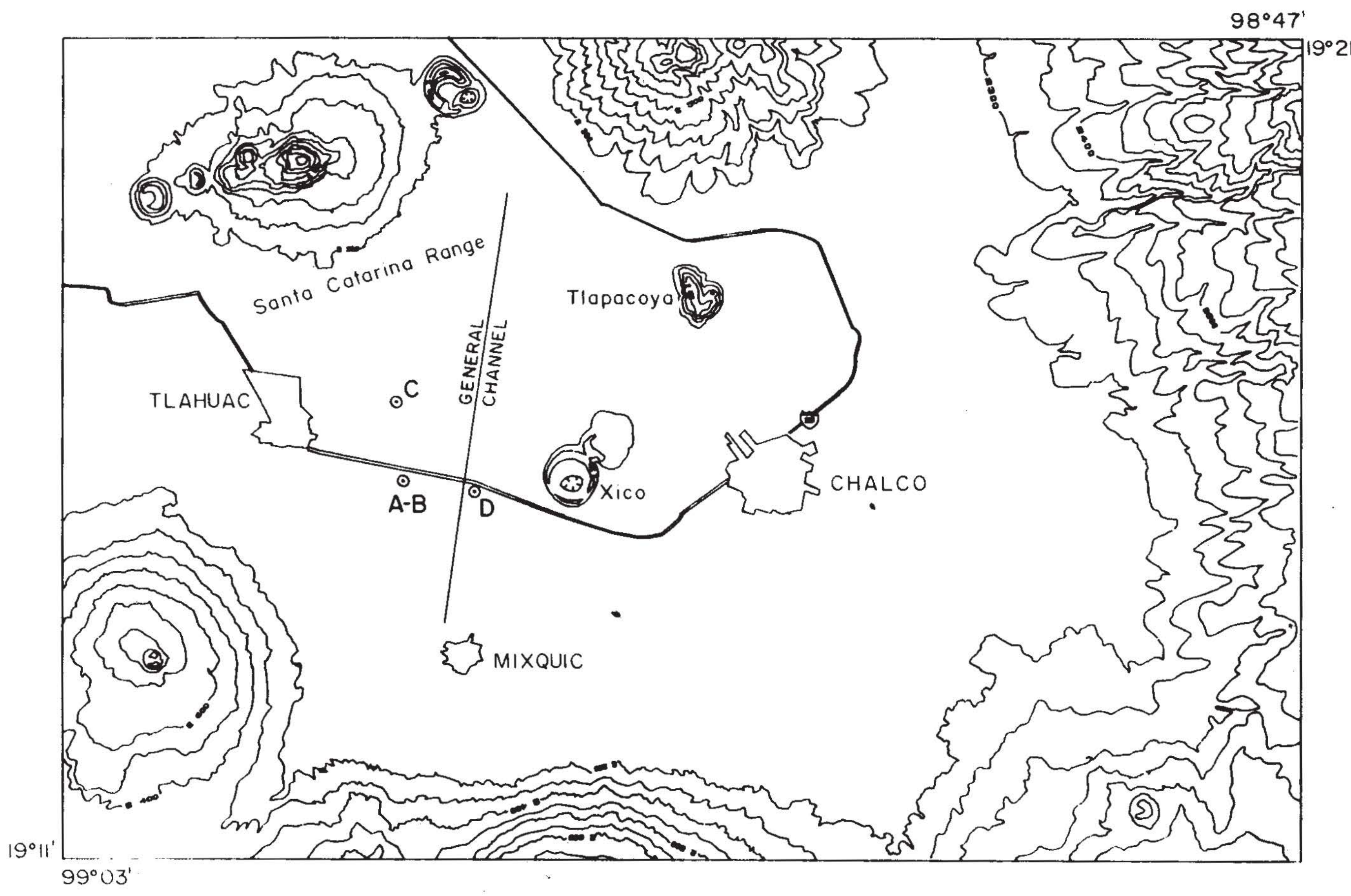

Fig. 2. Schematic topographic map of the Chalco area showing the present location of urban settlement and the location of the coring sites (indicated by letters A to D).

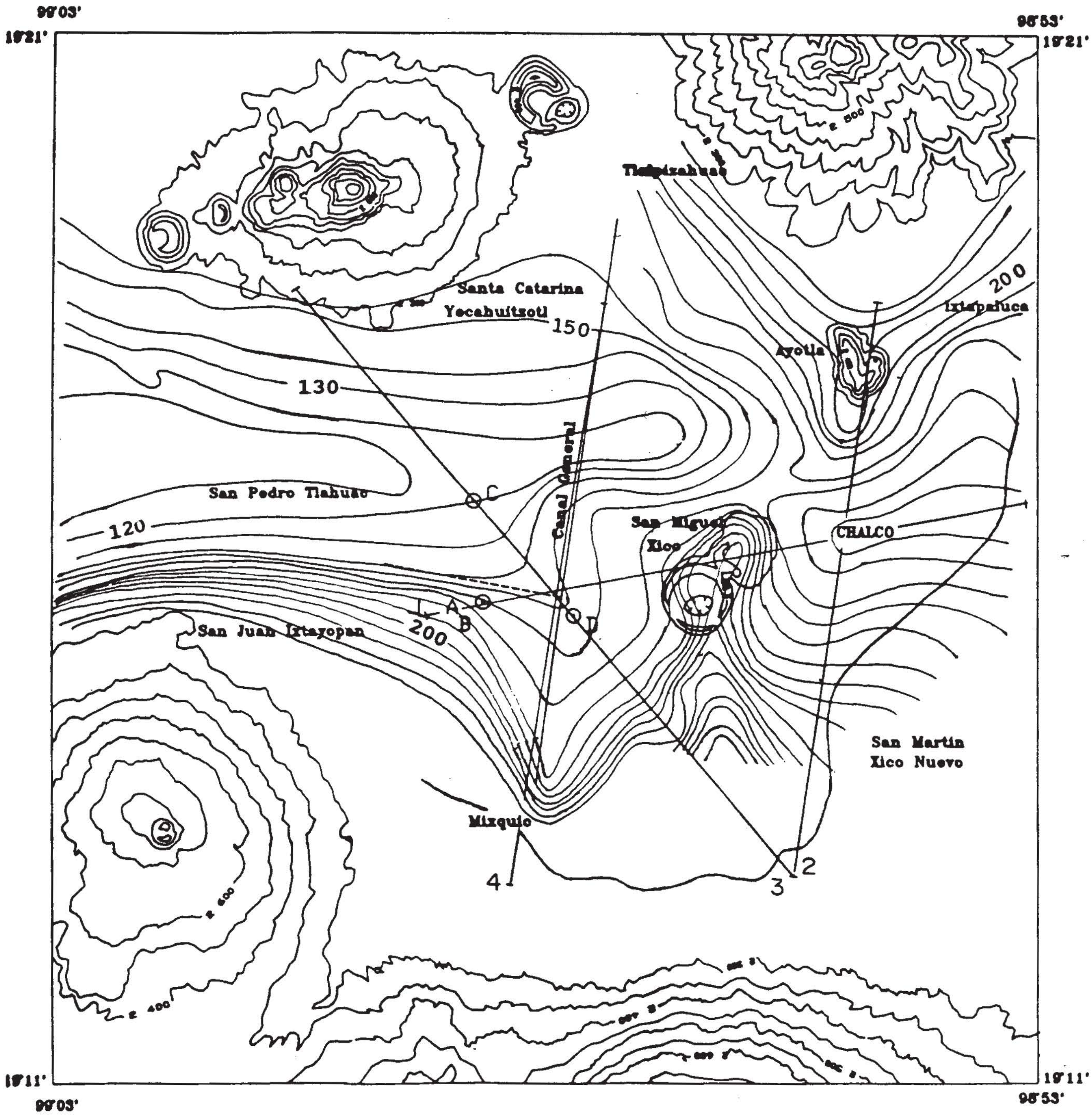

Fig. 3. Bouguer gravity anomaly map of the Chalco basin (in gravity units, gu). Location of coring sites and profiles used for modeling is indicated. Observe the gravity high oriented south-north in the central part of the basin, that coincides with the Xico volcanic structure.

Profile A-A' (Figure 4a) crosses the volcanic structure of Xico. The volcano-sedimentary sequence has a thickness of around 400 m in the eastern section and a thickness of about 300 m in the western section. The shape of the basin is distinct, with the eastern section showing an abrupt increase in sedimentary fill at the eastern side of Xico. This may partly reflect normal faulting in the area. In the eastern central part sampling sites A, B, and C (location of cores) were selected (Figure 3). Core D was taken more to the north.

The shape of the sedimentary sub-basins can be well observed from models in profiles B-B' (Figure 4b), Profile C-C' (Figure 4c) and Profile D-D' (Figure 4d). The results are preliminary because of uncertainties in density contrasts. Further modeling is needed in order to obtain a more detailed model of the shape and physical property contrasts of the lacustrine sequence.

The models correlate with the lithology from one of the deep water wells, where lake sediments were found down

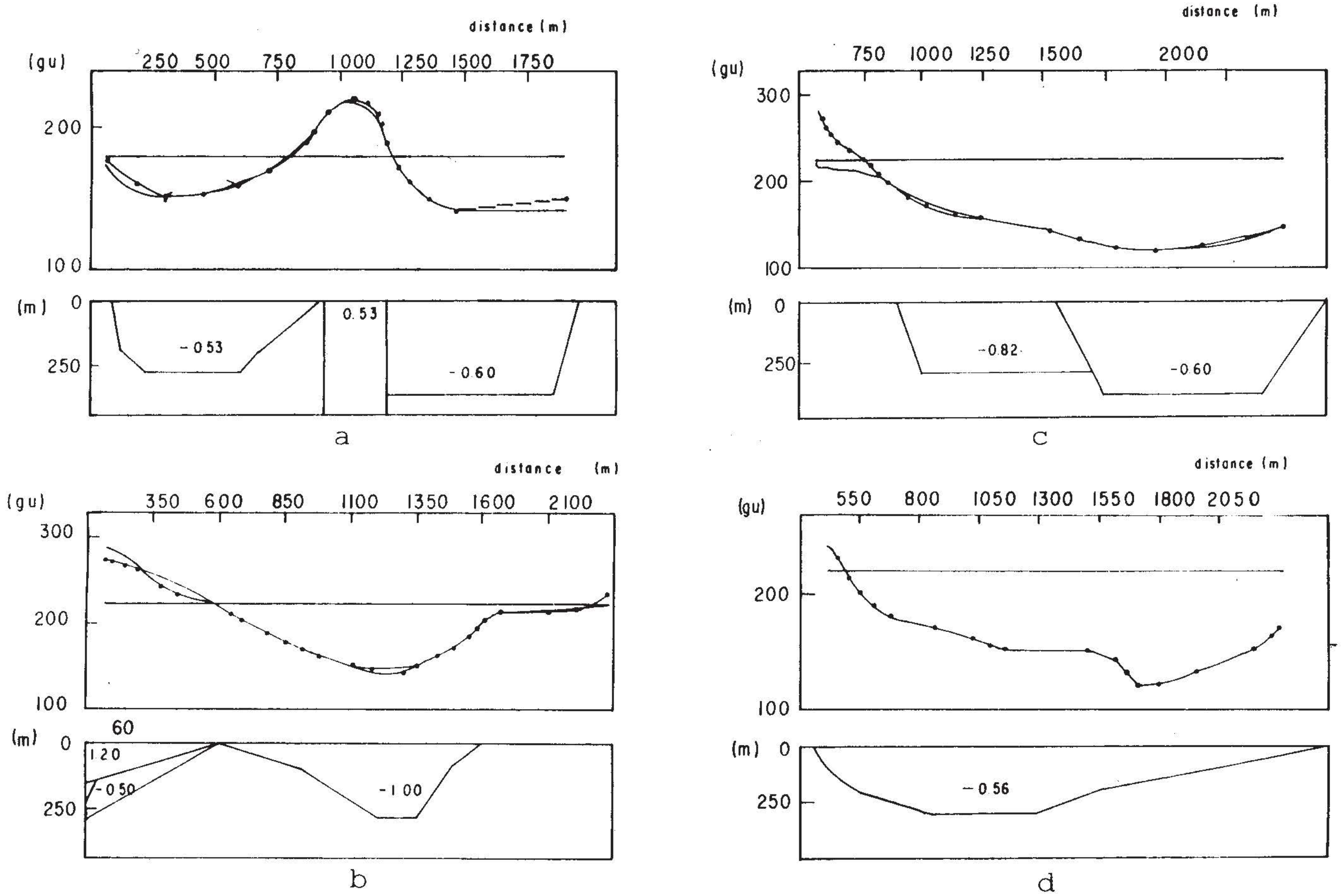

Fig. 4. Gravity models for profiles shown in Fig. 3. (a) Profile A-A', (b) profile B-B', (c) profile C-C' and (d) profile D-D'. Values correspond to density contrasts which are indicated for the model units.

to 252 m depth, followed by sand and gravel and at 387 m by basalt (Figure 5). The model is also supported by recent results from seismic refraction and electrical resistivity studies (Benhumea-León *et al.*, 1991).

CORING

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

Core A is 7.60 m long. Core B reached the maximum depth of 26 m. Core C is 10.65 m long. Core D is 11.27 m long.

STRATIGRAPHY OF VOLCANO SEDIMENTARY SEQUENCE

Based on the core descriptions, lithostratigraphic columns were established. Figure 6 shows columns for cores D, C, and combined core A-B, which was merged for the upper 12 m due to the proximity of sites A and B. We propose a subdivision of the first 12 m into 5 stratigraphic units, with 10 tephra layers. The units and tephra layers are numbered from top to bottom with Arabic and with Roman numbers, respectively.

Unit 1

Mainly brown and black silt with layers containing abundant fragments of highly altered pumiceous lapilli, sized 0.5 cm to 4 cm. The darkest layers contain remnants of roots and fissures produced by escape of gas. Unit 1 has a thickness of 170 cm in cores A-B and D, which decreases to 110 cm in core C.

Unit 2

Brown silt with light red layers and few fragments of pumaceous lapilli up to 0.5 cm in diameter. In cores A-B and C macro-remnants of moluscs are found in the lower part. The thickness of this unit varies between 80 cm (core D), 65 cm (C) and 50 cm (core A-B). The base of Unit 2 is defined by Tephra I, which is a black ash some 0.02 cm thick.

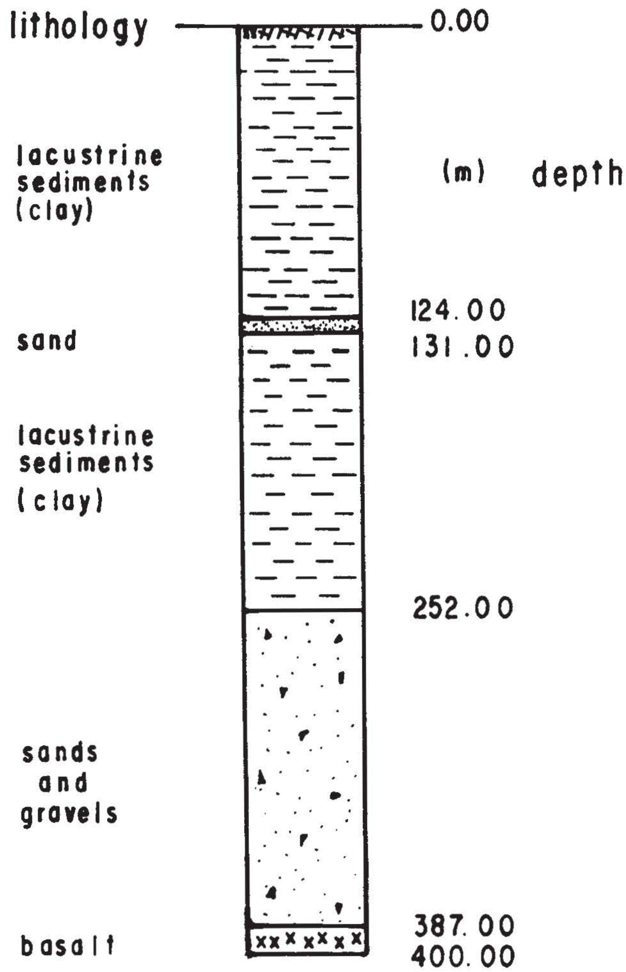

Fig. 5. Simplified lithological column for a deep borehole in Chalco Basin (drilled by Comision Nacional del Agua in the northern sector between San Miguel Xico and Tlahuac, unpublished internal report).

Unit 3

This striking core consists of a bright-grey diatomite with 55-60 cm thickness in cores A-B and D, decreasing towards the north of the Chalco Basin, reaching only 5 cm in core C. Irregular bands of dark-grey and vertical fissures filled with dark-grey material are observed. Possibly this material comes from other levels and was redeposited in the fissures by fluid circulation through the highly porous and permeable diatomite. The base of Unit 3 is defined by Tephra II, which is a 0.04 cm thick black ash.

Unit 4

This unit is composed of five layers of predominantly dark-brown silt, with thicknesses varying between 40 cm and 150 cm, separated by Tephras III to VI. The uppermost layer, delimited by Tephra III, is of dark-brown color in the upper part and light-brown color in the lower part. Thickness changes from 150 cm (core A-B) to 40 cm (core C).

The next layer is dark-brown silt with maximum thickness in core D (120 cm), reducing to 45 cm in core (A-B). It is separated by Tephra IV from an underlying dark-brown silt, which is only observed in core C with a thickness of 30 cm. In the other cores, Tephra IV lies directly on top of Tephra V, which consists in the upper part of an up to 50 cm deposit of pumaceous lapilli with diameters of 0.2 cm to 5 cm. Associated to these lapilli is a black volcanic ash of 3 cm to 5 cm thickness.

Tephra V is underlain by 40 cm to 60 cm of dark-brown silt, delimited by Tephra VI. Below that, a thin layer (2 cm to 3 cm) of grey silt is recognized in all cores. This is limited by a layer of volcanic ash, which is only observed in cores A-B and interpreted to be due to a restricted distribution in the basin. Therefore, it is named Tephra VIa.

The last silt layer again is dark-brown with an almost constant thickness of 75 cm.

Unit 5

Unit 5 is very thick, reaching some 447 cm in core D, 396 cm in core C and 323 cm in core B. It consists of dominantly brown silt and a basal unit of yellow silt. Tephra VIII and IX are located at around 9 m depth. Tephra X lies at the base of the unit and consists of pumicitic lapilli 2 to 4 mm diameter, as defined in the B core. In cores C and D it is characterized by fine grained material.

RADIOCARBON DATING

Eleven C-14 dates have been obtained for the first twelve meters of the sequence. Two samples were dated in the Radiocarbon Laboratory of the University of Waterloo, Canada (WAT-code samples) with the collaboration and under the supervision of Dr. Barry Warner. Nine additional samples were analyzed in the Geochronological Laboratories of Kruger Enterprises Inc., Massachusetts, USA (GX-code samples). Samples for radiometric dating were selected from results of loss of ignition and careful inspection of the core material. Dated material was rich in organic matter (> 15 %) and apparently free from contamination. Data are summarized in Table 1 and in the corresponding stratigraphic column (Figure 6). Eight dates come from core D and three dates come from core B.

There are two pairs of C-14 dates with apparent stratigraphic inconsistencies: samples GX-16970 and GX-16966 and samples GX-16558 and GX-16971. In both cases, inspection of material, drilling logs, etc revealed no information that may assist in evaluating/rejecting the given dates. The shallow-depth discrepancy may be related to sediment disturbance by farming. The disturbances are also documented in the rock-magnetic data that are characterized by peaks in the susceptibility, NRM intensity and saturation remanence patterns (e.g., in the Zacapu basin, Michoacán; Xelhuantzi and Urrutia-Fucugauchi, 1989). In the depth-versus-age plot (Figure 7a), the first sample date seems off the general trend defined by the other dates. This may indicate a problem with this sample, resulting in an older date. Corrected dates are 5535 and 5672 yr BP. The second group concerns samples a few centimeters apart

Table 1

Summary of radiocarbon dates for Chalco Lake cores

Laboratory Code	Depth (m)	C-14 Date yr BP	Cδ-13 pdb	Corrected Date	Core
GX-16970	0.84 - 0.92	5725 + 175	-21.0	5535+129	D
GX-16966	1.65 - 1.75	5330 + 235	-4.9	5672+196	D
GX-16969	2.53 - 2.60	9395 + 255	-16.5		D
GX-16965	3.46 - 3.56	12520 + 135	-25.5		D
GX-16972	4.27 - 4.37	14610 + 470	-27.5		D
WAT-2487	3.18 - 3.23	12800 + 90	27.5		B
WAT-2488	7.51 - 7.57	17450 + 170	-27.5		B
GX-16558	6.30 - 6.40	17560 + 330	-25.9	16903+243	D
GX-16971	6.58 - 6.67	16820 + 195	-27.3	17050+163	D
GX-16559	8.08 - 8.18	19040 + 390	-25.7		D
GX-16967	9.00 - 9.10	21600 + 1050	-19.6		B

WAT, University of Waterloo Radiocarbon Laboratory, GX, Geochron Laboratories, Krueger Enterprises Inc. Values reported in conventional radiocarbon years BP corrected by C-12.

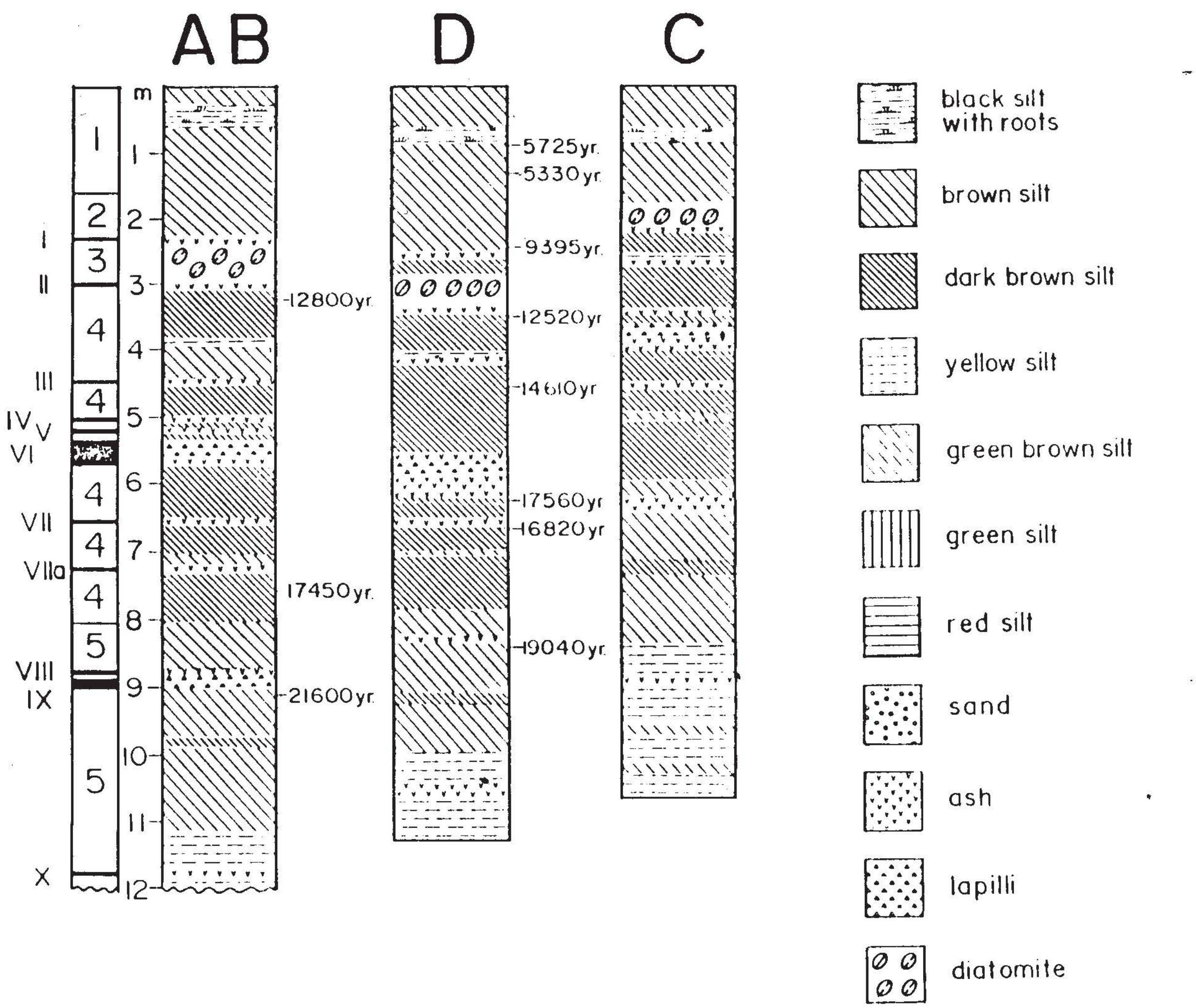

Fig. 6. Simplified lithostratigraphic columns for the cores in Chalco Lake. The sequence has been divided into five major units (referred by numbers). Ten tephra horizons have been documented in the sequence (Roman numerals). Radiocarbon dates are given for the various cores.

and the dates are not very different, within statistical uncertainties. A statistical correction in terms of Bayesian analysis (Vincent, 1988) gives 'corrected' dates of 16,904 and 17,049 yr B.P (Table 1).

A least-squares regression line fitted to all C-14 data points obtained for core D gives an intersection at about 2,700 yr BP, suggesting that the upper part of the record may be missing. This would yield an average accumulation rate of about 0.53 mm/y. Alternatively, the C-14 data distribution could be interpreted in terms of a change in the sedimentation rate with a break at around 13,000 y BP. This results in two regression lines that can be fitted to the data points (Figure 7b). The younger linear segment can be forced through the origin, yielding an average sedimentation rate of about 0.28 mm/yr for the upper 3.5 m. The C-14 date for the shallowest horizon seems anomalous and be discorded for the regression analysis. A possible explanation would be the reworking of sediments by human (agricultural) activities, as indicated by palaeomagnetic and microfossil studies discussed elsewhere (Urrutia-Fucugauchi *et al.*, second part in press). The sedimentation rate for the deeper portion is more than twice as large, about 0.80 mm/yr.

The second interpretation is preferred since it agrees with a marked change in environmental conditions from the Pleistocene to the Holocene. It does not require erosion or non deposition of any substantial portion of the sedimentary sequence, thus eliminating the need for assuming a drastic change in environmental conditions for the lake basin. There is also a marked change in C-12 data for the upper meters. Using the two regression lines, the younger line predicts an age of 3,000 yr for one meter depth, at least 2,500 yr older than expected (Figure 7b). A possible interpretation for the discrepancy is the occurrence of a hiatus between 5,700 and 3,000 yr BP. Alternatively, the date of 5,500 yr BP may represent older redeposited material in the lake. Stratigraphic and limnological data support this possibility.

ORGANIC CARBON DETERMINATION

Organic carbon was determined every 10 cm down to 12 m depth, using the method of loss of ignition. The samples were first weighted, dried for 18 hours at a temperature of 80°C and weighted again. After heating for one hour at 500°C, the difference in weight provides an estimate of the content of organic matter.

Results are shown in Figure 8. Average carbon content is around 37 % with a maximum of 65 % in Unit 4, where black silt is dominant. Unit 1 reaches up to 55 % of carbon content where root content is high, with a mean value of 30 %. Unit 2 shows lower values around 20%. This holds also for Unit 3, due to the predominance of diatomite. Below 8 m depth, values decrease notably, below to 20 %.

CONCLUSIONS

Results of Bouguer gravity anomaly modeling indicate that the Chalco basin is divided into two major sub-basins, separated by a roughly N-S high which is associated with the Xico volcanic structure. The volcano-sedimentary sequence has a maximum thickness of about 400 m in the eastern sub-basin and about 300 m in the western sub-basin. The shape of the sub-basins seems different, with the eastern sector showing an abrupt increase of thickness at the eastern edge of the Xico structure. These characteristics are attributed to normal faulting in the region. Normal faulting may have occurred contemporaneously with the lacustrine sedimentation.

The first 12 m of the lacustrine sequence of the central-western sector of Chalco Lake can be divided into five major units. Intense volcanic activity is represented by ten tephra layers, interbedded in the sequence. Results of the radiometric study provide a good age control for the sequence, with eleven radiocarbon dates covering the first 9 meters.

All units can be recognized in the 4 cores, except for one of the tephras, VIa, only found in core A-B and not in cores C and D. The thickness of the sedimentary units decrease towards core C, most clearly in the upper 4 units. The units in core C were deposited at smaller depths than in cores A-B and D, which checks with the present topographic differences.

The sediments recorded an intense volcanic activity. This activity (represented by 10 tephra layers) is concentrated in the uppermost 8-9 m of core A-B.

The sedimentation rate estimated from the available ^{14}C analyses gives about 0.28 mm/y for the shallower 3.5 meters and about 0.80 mm/y for the deeper portion of the sequence, between 3.5 m and 8.13 m. This gives only a rough idea about the deposition, since there are also several thick tephra layers (up to 50 cm), which presumably were accumulated in very short periods.

The variation of organic carbon content suggests that between about 3 and 8 m, the sequence corresponds to a shallow lake environment with high accumulation and preservation of organic matter.

The C-14 dates may be interpreted to indicate a change in the sedimentation process at about 13,000 y BP. This agrees with a change of conditions between the Pleistocene and the Holocene. A possible hiatus may have occurred between about 5,700 to 3,000 yr BP.

Most studies concerning palaeoecological processes during the Quaternary have been conducted in higher latitudes than the Basin of Mexico. Thus, water level was high in the SW United States during the glacial maximum, about 18,000 years ago. Increasing melting of polar caps was followed by an increased aridity and reduction of the water level (CLIMAP, 1976; COHMAP, 1988; Crowley and North, 1991). The same general effect is also observed

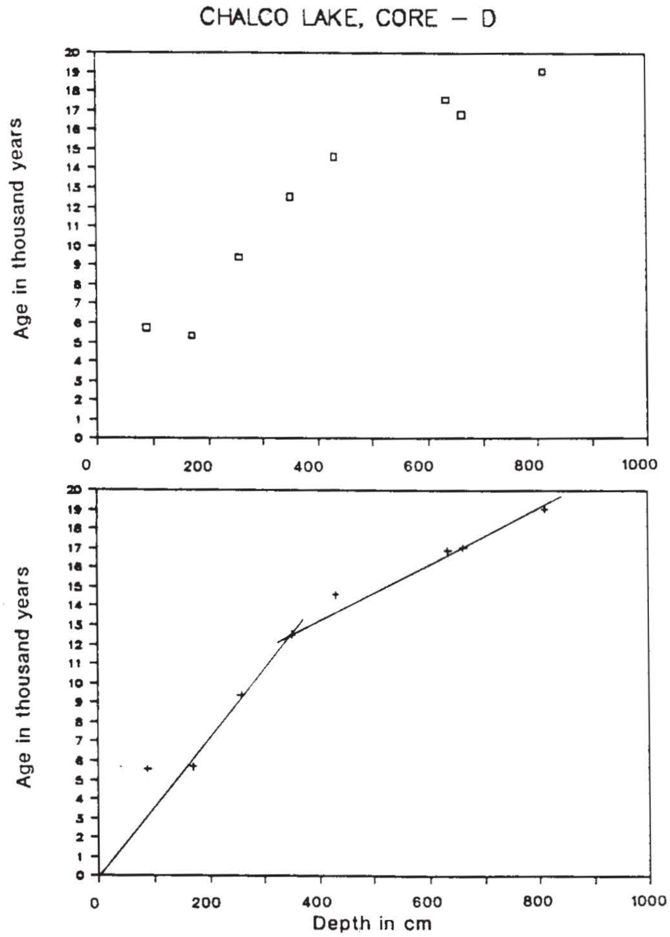

Fig. 7. Carbon-14 data for Chalco cores. (a) Initial data and (b) data pair corrected using Bayesian analysis. Linear regression lines fitted to data. Note the break at about 12,000 yr in graph (b).

in the Basin of Mexico, although less pronounced, as the water level was initially much lower. During the glacial maximum, Chalco apparently was a swamp or pond with varying inflow of water. The overall evidence suggests that there were no large lakes. In Texcoco, towards the center of the Basin of Mexico, similar conditions prevailed (Lozano-García, 1989). Thus the tendency to more arid conditions seem to begin earlier in the Basin of Mexico.

The Holocene is characterized by warmer and more humid climate in the tropics, with increased evaporation at mid-latitudes. In Chalco we suggest warmer environmental conditions at the beginning of the Holocene, with an increasing level of fresh to alkaline water toward the end of the Holocene.

The palaeoenvironmental record in Chalco has been largely affected by intense volcanic activity in the region, which modified the erosional and sedimentation processes.

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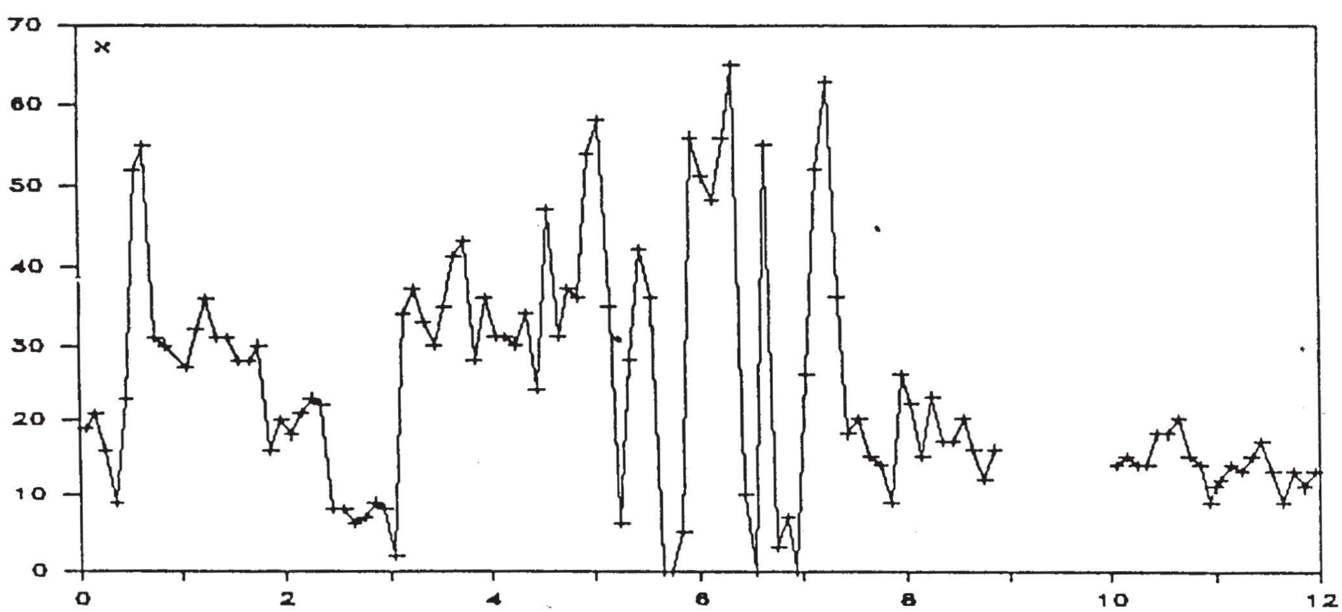

Fig. 8. Variation of organic carbon content with stratigraphic position for core B.

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