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Catchment disturbance inferred from paleolimnological studies of three contrasted sub-humid environments in Morocco

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Abstract

Paleolimnological techniques for assessing recent drainage basin disturbance are evaluated in three Moroccan lakes with catchments contrasted in terms of land-use and vegetation. Rates of sediment accumulation in the two lakes with agricultural catchments were relatively high (> 1.6 cm yr^{-1}) in the most recent past. Dilution effects prevented core dating by the ^{210}Pb method alone and post-1953 chronologies were constructed by combining ^{210}Pb and ^{137}Cs data. The recent sediment accumulation rate at the currently least disturbed site, where natural *Cedrus* forest is still abundant, was relatively low (< 0.4 cm yr^{-1}) but has increased since the mid-19th century.

Magnetic, geochemical, pollen, and diatom studies of all three lake sediment cores linked with modern field survey data show that soil erosion in the most vegetationally disturbed catchment (Dayat-er-Roumi) has been high throughout the recent past and that intensity peaks are probably associated with wetland drainage operations beginning in the 1940's. At the partially forested site (Dayat Affougah), pre-1950's woodland clearance and other land-use changes are the likely cause of past major soil erosion episodes. The site currently dominated by natural *Cedrus* forest (Lac Azigza) shows only minor disturbance during the past c. 150 years although a major soil erosion episode occurred in the 17th century.

Paleolimnological analysis has clearly demonstrated that major landscape change has occurred at all three sites. However, only at the two sites with catchment cultivation do previously accelerated soil erosion and lake sediment accumulation rates persist to the present. Information essential for formulation of appropriate management plans is presented and the importance of paleolimnology in assessing man-induced lake-catchment disturbance is stressed.

Introduction

Major human disturbance of natural environments is now a world-wide problem and if resulting habitat destruction is to be controlled the processes involved must be understood. Since the problem began in the past, usually in the last century or earlier, information about predisturbance conditions and rates of change can often only be obtained through paleoecology. Landscape degradation can be particularly acute in developing countries such as Morocco where it is exacerbated by a seasonally dry climate (Beaudet *et al.*, 1964, Heusch, 1970). Considerable circumstantial evidence suggests that in this country progressive woodland clearance followed by overgrazing has caused major vegetation change resulting in high rates of soil erosion (Mikesell, 1960). Furthermore, Morocco is a country where documentation and monitoring of environmental disturbance at the catchment level is often absent or inadequate. In this situation paleolimnological studies can potentially provide evidence of changes in catchment soils and vegetation and in water quality and aquatic biota on a variety of time-scales (Oldfield, 1977) that can be of immense value in habitat management.

In this paper we define paleolimnology as a division of paleoecology confined to the study of changes, sequential or otherwise, in lake sediment characteristics that are derived from any ecosystem process (cf. Frey, 1988). We assess the value of paleolimnology for reconstructing recent environmental histories of three Moroccan lake-catchments. The catchments differ in land-use from intensive agriculture, to semi-natural *Quercus* woodland and to natural *Cedrus* forest. The supposition that past disturbance, such as soil erosion and vegetation change has been greatest in the former and least in the latter catchment is testable by paleolimnological analysis. Consequently, we use multidisciplinary methodologies, based on magnetic, microfossil and geochemical analysis of dated lake sediment cores, combined with modern catchment survey information, to investigate each site.

Site locations, descriptions and field methods

i) Site locoations

Dayat-er-Roumi (Long. 33° 45′ N, Lat. 6° 11′ W), is located on the alluvial coastal plain between Rabat to the West and the Middle Atlas Mountains to the East (Fig. 1). Both Dayat Affougah (Long 4° 45′ Lat 33° 37′) and Lac Azigza (Long. 5° 27′ Lat. 32° 85′) lie to the east at considerably higher altitudes in the uplands of the Middle Atlas Mountains (Fig. 1). The topographic catchments of each lake are indicated in Fig. 1, though the hydrologically effective catchments are probably smaller, especially for Dayat-er-Roumi and Dayat Affougah, where substantial loss of surface runoff to subterranean systems is suspected.

ii) Geology and soils

All three sites lie on Mesozoic limestones which at Dayat-er-Roumi are mainly covered by thick deposits of Quaternary alluvium. However, at the other two sites soils are thin and rock scarps and outcrops are common. Soils show great spatial variation according to local environmental factors, but can generally be considered as fersiallitic intergrading into calcimagnesian soils with color varying from dark red to pink (see Duchaufour, 1970). Under semi-natural forest cover, notably the Cedar forest around Lac Azigza, brunified fersiallitic red soils have formed. Truncated red soils have developed on steep, deforested slopes, especially around Dayat Affougah, and in small pockets in the Dayat-er-Roumi catchment. At all sites, colluvial material derived from the red soil constitutes the parent material for calcareous brown soils in topographic depressions and at the base of slopes.

iii) Climate

The climate at all three sites is Mediterranean (Table 1). Precipitation, mostly restricted to the winter months, is considerably greater at the two higher altitude sites. Inspection of precipitation data (1931–81) from Meknes (near Dayat-er-Roumi) reveals no sustained major changes over this period, although data from Ifrane (near Dayat

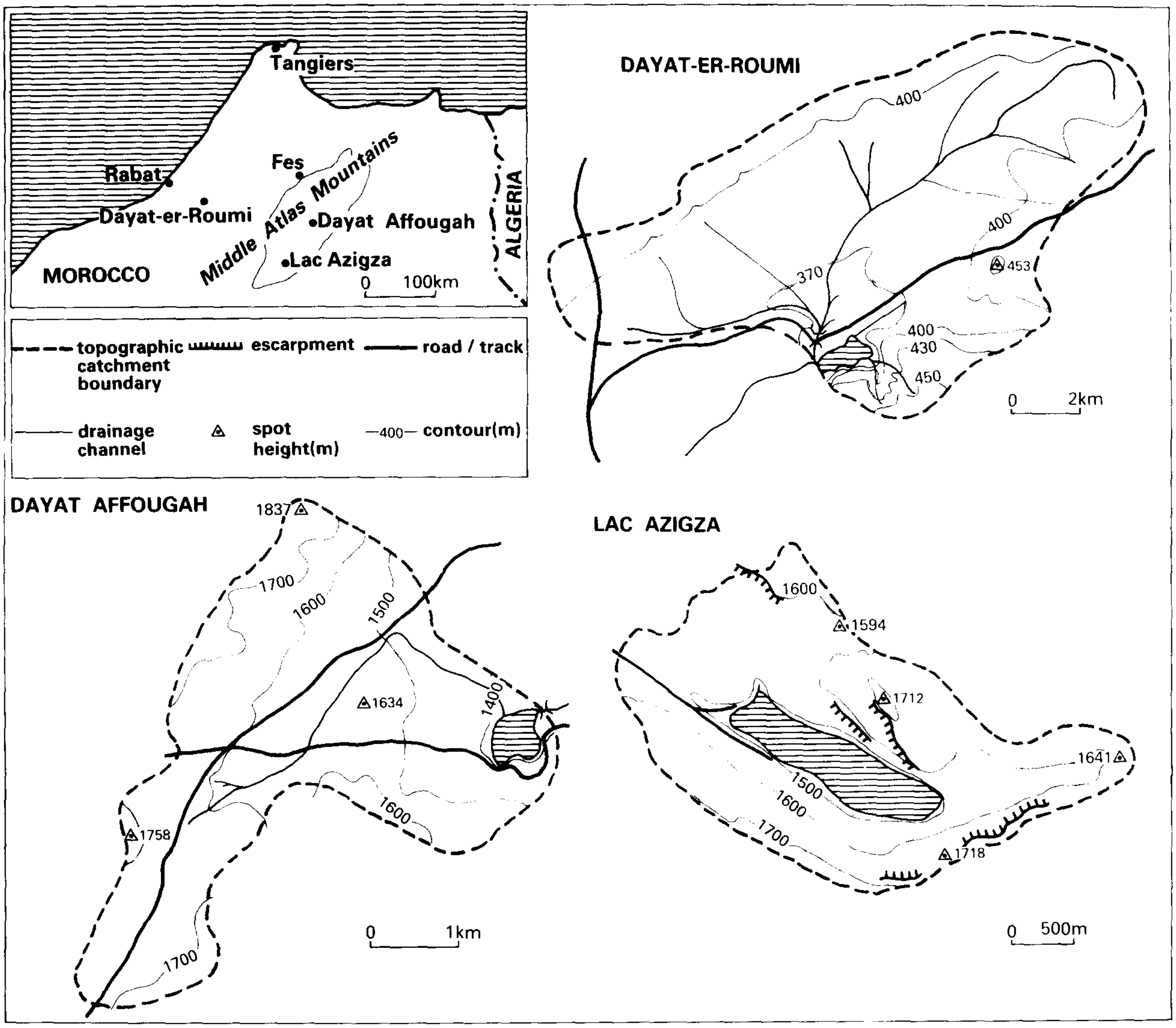

Fig. 1. The Dayat-er-Roumi, Dayat Affougah and Lac Azigza drainage basins with an inset showing site locations within Morocco.

Table 1. Some physical and climatic characteristics of the three lakes and their catchments. Annual precipitation for Dayat-er-Roumi refers to 1950–52 (Gayral, 1954), for Dayat Affougah refers to 1927–49 (Rippey, 1982) and for Lac Azigza refers to 1952–53 (Gayral & Panouse, 1954). Note, topographic catchment area is taken from published maps and is likely to be much larger than the surface water collection area for each lake (see text).

	Dayat-er-Roumi	Dayat Affougah	Lac Azigza
Catchment characteristics:			
Altitude (m)	330	1400	1800
Annual precipitation (mm)	396	1100	c. 850
Snow cover (months)	0	c. 1	1–3
Topographic catchment (ha)	1000	1400	380
Lake characteristics:			
Max. depth (m)	11.5	14.0	33.0
Lake area (ha)	85.0	6.0	37.0
Max. length (km)	1.5	0.3	1.4
Shoreline (km)	4.2	1.4	3.3

Affougah) indicates a drier period in the early 1970's (also see Rippey, 1982). Snow cover in January is usual at Dayat Affougah and Lac Azigza but neither lake ices over during the winter, although ice often forms around their margins. Strong diurnal winds occur at all three sites during summer months but are of insufficient strength to break down lake thermocline development (Flower, unpub.).

iv) Vegetation and land-use

Approximate areas of vegetation and zones of different land-use in the vicinity of each lake were mapped by combining ground surveys with information from aerial photographs (Figs 2, 3, & 4, Table 2). Over 80% of the land around Dayat-er-Roumi is under cereal and pulse production; natural forest is absent but olive plantations and small groves of *Eucalyptus* and *Pinus halepensis* have been established in several areas. On steeper slopes and hilltops intensive sheep-grazing occurs. In contrast, almost 50% of the land around Affougah is forested with oak (mainly *Quercus ilex*) and *Juniperus oxycedrus* although many trees are severely cropped for fuel by local villagers. On the flatter ground mainly to the west and south of the lake there is subsistence cereal agriculture. Sheep grazing is fairly intensive on non-arable land, especially in impoverished woodland to the north of the lake. Cedar-oak forest predominates in the Lac Azigza catchment and is protected from exploitation although grazing occurs on grassland west of the lake and some tree felling for charcoal production is permitted.

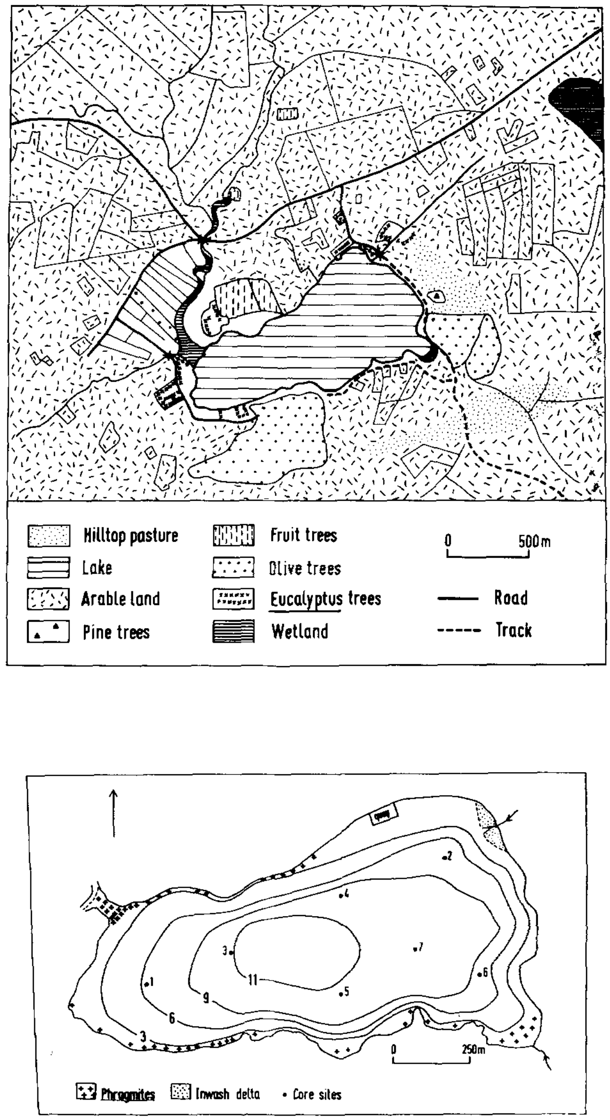

Fig. 2. Vegetation and land-use around Dayat-er-Roumi (upper), note the predominance of agricultural land. Lake bathymetry and numbered core locations (lower), note the inwash delta at the NE corner of the lake.

v) Land-use history

We have no specific documentary evidence of land-use change in the lake catchments selected for study. There are published limnological accounts of Dayat-er-Roumi and Lac Azigza (Gayral, 1954; Gayral & Panouse, 1954), but these are descriptive and do not refer to historical changes except those of lake level at Azigza. Earlier studies of Dayat-er-Roumi (Flower *et al.*, (1984) and Dayat Affougah (Rippey, 1982) showed that recent lake sediment is predominantly derived from catchment soil inwash and that at the former site the sediment accumulation rate was probably influenced by artificial drainage of surrounding wetland. Anecdotal evidence suggests that several attempts were made since the 1940's to drain this area for mosquito control. In addition, major catchment plantations of *Olea* and *Eucalyptus* were established in the Dayat-er-Roumi catchment probably between 50 and 30 years ago. All three sites are unknown palynologically but several studies on the vege-

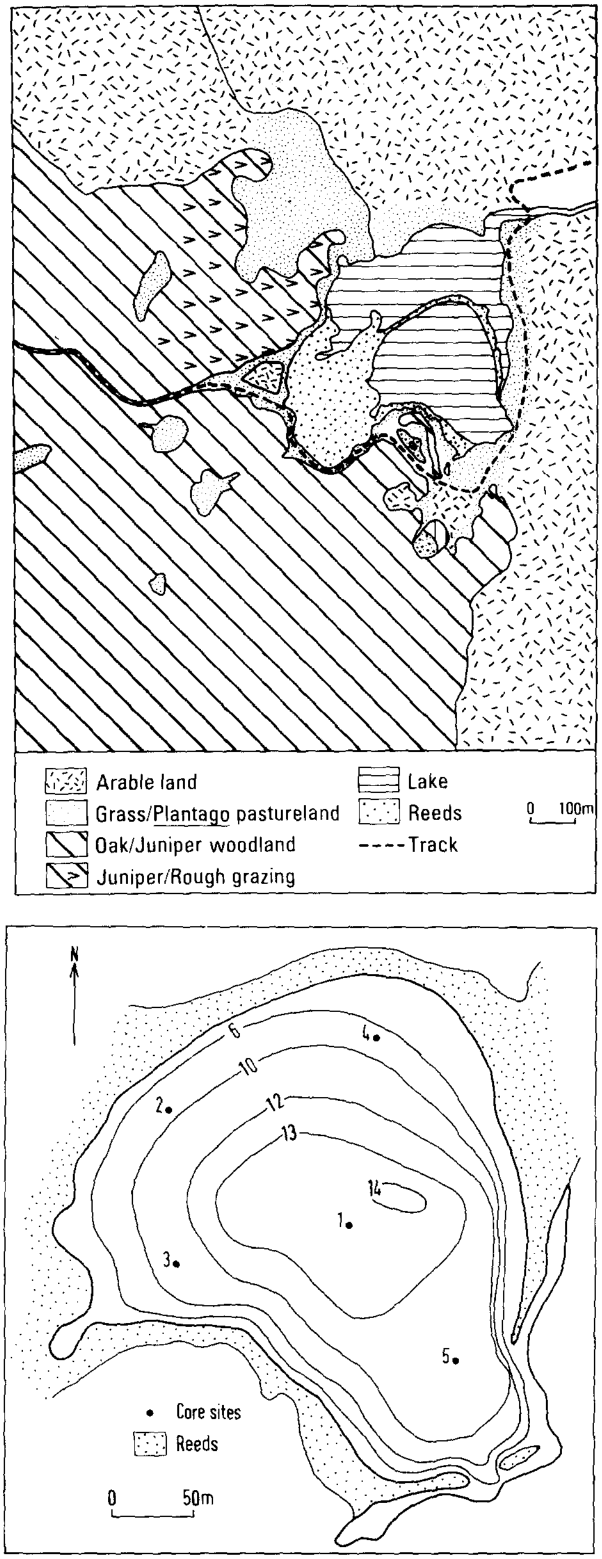

Fig. 3. Vegetation and land-use around Dayat Affougah (upper), note the combination of woodland and arable land. Lake bathymetry and numbered core locations (lower).

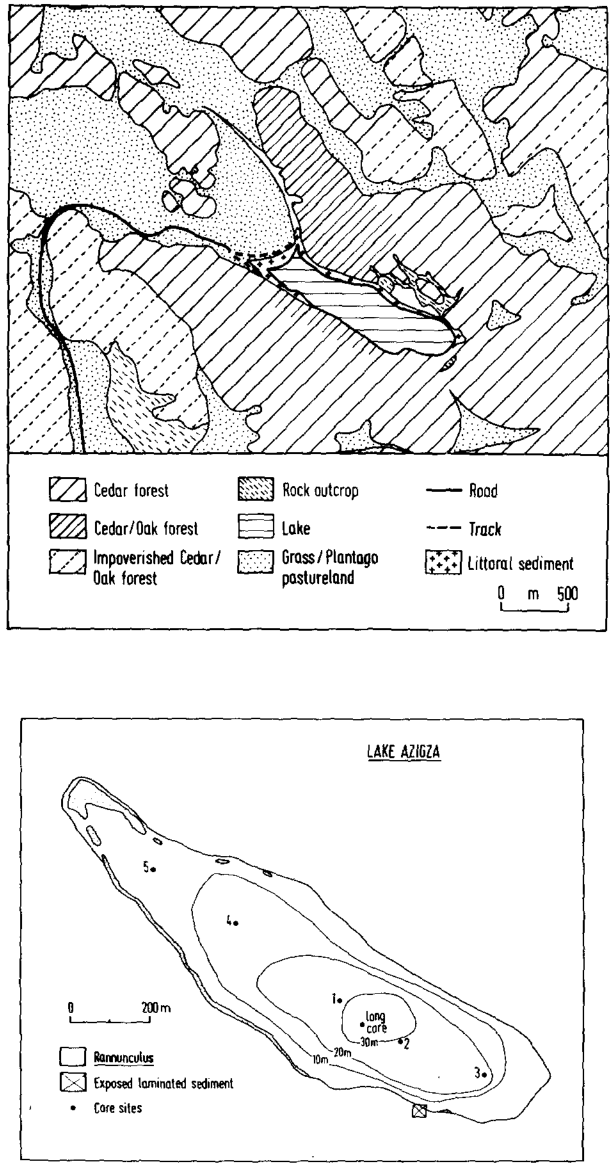

Fig. 4. Vegetation and land-use around Lac Azigza (upper), note the predominance of Cedar woodland. Lake bathymetry and numbered core locations (lower), location of a long core is also shown.

tational history of the Atlas Mountain regions have shown that the postglacial forest history of the Middle Atlas is dominated by *Cedrus* forest (Reille, 1976, 1977).

vi) Lake basin and water quality

The bathymetry of each lake was surveyed by taking depth transects across each basin between points (identified on a small-scale map) using an

Table 2. Areas and percentage land-use categories showing the major vegetation types in the vicinity of each lake. The lake area largely accounts for the category called 'other'.

	Dayat-er-Roumi		Dayat Affougah		Lac Azigza	
	ha	%	ha	%	ha	%
Arable land	961	86	66	34	–	–
Pasture land	18	16	19	10	512	34
Olive groves	40	4	–	–	–	–
Pine plantation	1	< 1	–	–	–	–
Oak/Juniper woodland	–	–	90	47	–	–
Cedar forest	–	–	–	–	577	38
Cedar/oak forest	–	–	–	–	359	24
Exposed rock	–	–	1	< 1	35	2
Reedbeds/wetland	13	1	5	3	1	< 1
'other'	90	8	13	7	39	3

echo-sounder. All bathymetric measurements (Table 1, Figs. 2, 3, & 4) relate to the time of survey (June 1984) and take no account of seasonal fluctuations in water level. In terms of area, Dayat-er-Roumi is the largest lake and possesses a simple basin morphometry with the deepest point (11.5 m) occurring towards the centre. The littoral region is composed predominantly of silts and gravels, and submerged macrophytes are uncommon. Considerably smaller than the other two sites, Dayat Affougah reaches 14 m depth in the central region and is fringed by a dense *Phragmites-Scirpus* swamp; the submerged macrophyte stems are encrusted with biogenically precipited calcite. Immediately north of the main basin and separated by a belt of vegetation there is an area of open water which is devoid of limnic sediment. Lac Azigza is the deepest lake (33 m) and has a simple single basin morphometry, it occupies a fault line and is somewhat linear in outline. Large fluctuations in water level occur in Lac Azigza (Gayral & Panouse, 1954) and the occurrence of laminated sediments exposed in 1984 on the southeast shore (Foster & Flower, unpub.) confirms the existence of a considerably higher lake level in the past. Recent water level change at the other two lakes appears to be slight.

There are no significant permanent surface inflows at the three sites although the Oued Rhaba possibly supplied Dayat-er-Roumi before it was diverted for irrigation purposes. Springs discharge into all three lakes and complicate the catchment drainage hydrology. A swamp area at the northwest end of Dayat-er-Roumi permits water outflow at times of high lake level (Gayral, 1954). Dayat Affougah has a surface outflow impeded by a low sluice in the southeast corner. Lac Azigza has no surface outflow.

Some basic water quality measurements are given in Table 3 and show that all three lakes are alkaline with pH values usually above 8. Conductivity values are relatively high for Dayat-er-Roumi and are probably mainly attributable to sodium chloride.

Methods

Several short (c. 1 m) sediment cores were collected from each lake (Fig. 2, 3, & 4) using a modified Mackereth mini-corer (Mackereth, 1969) operated from an inflatable boat. Cores from deep and shallow water locations were obtained but only one deep water core from each lake is described here. After initial magnetic measurements in the field, cores were transported to the laboratory and extruded and sectioned at 1 cm intervals. Routine measurements of bulk density, percentage dry weight (at 60 °C) and loss on ignition (at 550 °C) were carried out on each sample. Dried sub-samples of each core were then analysed in the following ways:

Table 3. Basic water chemistry results for each lake. Determinations of pH, conductivity and cations (in mg l^{-1}) were made on various occasions, September 1979, April 1981(*), and May/June 1984(**) and cation measurements refer to the 1981 sampling period.

	Dayat-er-Roumi	Dayat Affougah	Lac Azigza
pH	8.4 8.3* 8.9**	7.8 8.3* 8.2**	8.2 8.5* 8.5**
$\mu S\ cm^{-1}$	2100 1350**	750 600**	400 740* 270**
Na^+	290	88	11
K^+	–	–	1
Ca^{2+}	32	48	35
Mg^{2+}	34	57	27

i) Radiometric measurements for core dating: Selected sediment subsamples from the Dayat-er-Roumi and Lac Azigza cores were analysed for ^{210}Pb, ^{226}Ra, and ^{137}Cs by gamma spectrometry (Appleby *et al.*, 1986) using a well-type coaxial low-background intrinsic germanium detector fitted with a Na(T1) escape suppression shield. Samples from the Dayat Affougah core were analysed for ^{210}Pb by assay of the alpha-emitting grand-daughter isotope ^{210}Po using the method outlined by Eakins & Morrison (1978). ^{137}Cs activities in the Affougah core were determined by gamma assay. ^{226}Ra determinations were made using both alpha and gamma spectrometry.

ii) Magnetic measurements: Samples of dried (30 °C) sediment and soil of known mass were packed into 10 cm^3 plastic containers for measurements of magnetic susceptibility and remanent magnetism (defined in Table 4) on Bartington Instruments and Molspin equipment (see Dearing *et al.*, 1985).

iii) Geochemistry: Sediment samples from each core were analysed for calcium and magnesium by flame atomic absorption spectrophotometry (Perkin Elmer, 2380) after sediment digestion with hot hydrofluoric, nitric and perchloric acids. The residue was taken up in 0.1 M hydrochloric acid and diluted with 0.1% lanthanum chloride to remove interferences. All reagents were Analar grade. Total carbonate was measured by weight loss of sediment between 550 and 950 °C (Dean, 1974). Sediment mineralogy was determined by X-ray diffraction (Phillips) after removing organic matter by sodium hexametaphosphate (Jones & Bowser, 1978). Identification of the minerals was made using Brown (1961) and Carroll (1970).

iv) Pollen analysis: Subsamples from selected levels in each sediment core were prepared for pollen analysis by KOH digestion followed by HF and acetolysis treatments (Ertdman, 1960). The samples were mounted in glycerol jelly and at least 500 land pollen grains counted for each sample. Pollen identifications follow Moore and Webb (1978) and Stevenson (1981).

v) Diatom analysis: Subsamples of lake sediment were oxidized with hydrogen peroxide and carbonates were removed with hot 50% HCl (Battarbee, 1986). The washed diatom samples were mixed with calibrated aliquots of latex microsphere suspension to estimate the diatom concentration (Battarbee & Kneen, 1982). 0.5 ml samples of the resulting diatom-microsphere mixture were evaporated on cover slips and mounted in Mikrops for microscopic analysis at × 1000 magnification. Diatom identifications were made using published floras.

Results and discussion

i) Core dating

The ^{210}Pb and ^{137}Cs profiles in all three cores are shown in Fig. 5 and the radiometric parameters are summarized in Table 5. The irregular nature

Table 4. Definitions of magnetic parameters measured in this study.

Parameter	Definition	Symbols & Units
Magnetic suseptibility	The ratio of induced magnetization to the intensity of a low magnetic field, and commonly measures the concentration of ferrimagnetic minerals	K (dimensionless) or X_{LF}, $m^3\ kg^{-1}$ (mass specific)
Fequency dependent susceptibility	The difference between susceptibility measurements made at low and high frequencies that identifies a narrow size range of ultra fine grains which display viscous properties. It is expressed here as a percentage of X_{LF}	$X_{FD\%}$, $m^3\ kg^{-1}$
High-field isothermal remanent magnetization	The magnetism remaining in a sample exposed to a saturating magnetic field after demagnetization in 0.1 T field. The measurement approximates the conc. of haematite and geothite	HIRM, $mAm^2\ kg^{-1}$

of the unsupported ^{210}Pb profiles, none of which shows an exponential decline with depth, suggests that the CRS (constant rate of ^{210}Pb supply) model (Appleby & Oldfield, 1978) is most suitable for calculating sediment chronologies. Results of all radiometric measurements are available from the authors.

The Dayat-er-Roumi core: The CRS model ^{210}Pb dates are in reasonable agreement with the 1963 ^{137}Cs date for sediment at 30.5 cm depth,

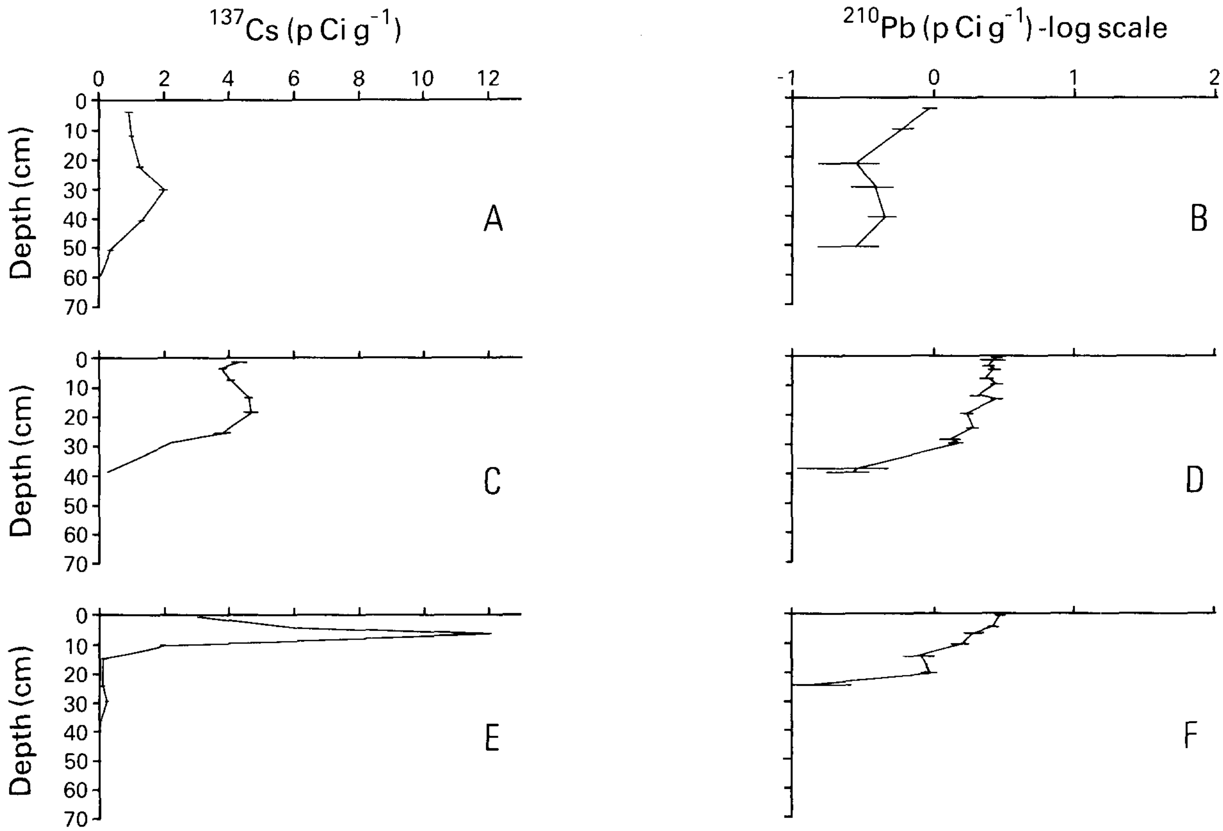

Fig. 5. ^{137}Cs and unsupported ^{210}Pb concentration ($pCi\ g^{-1}$) profiles in the Dayat-er-Roumi (A & B), Dayat Affougah (C & D), and Lac Azigza (E & F) sediment cores. Error bars are calculated from one standard deviation of the count mean. Note, the log scale ^{210}Pb concentration axis.

Table 5. A summary of the radiometric parameters of the Dayat-er-Roumi, Dayat Affougah and Lac Azigza sediment cores.

	Unsupported ^{210}Pb			^{226}Ra	^{137}Cs	
	Surface concentration pCi g^{-1}	Inventory pCi cm^{-2}	Mean flux pCi cm^{-2} yr^{-1}	Mean concentration pCi g^{-1}	Surface concentration pCi g^{-1}	Inventory pCi cm^{-2}
Dayat-er-Roumi	0.9	10.0	0.31	0.72	0.9	29.2
Dayat Affougah	2.9	17.4	0.54	0.72	4.3	29.9
Lac Azigza	3.1	18.7	0.58	1.10	3.1	29.3

Table 6. A chronology for the Dayat-er-Roumi core based on ^{210}Pb dates calculated with the CRS model using ^{137}Cs reference levels of 30 cm = 1963 and 50 cm = 1954. Percentage errors based on counting statistics alone.

Depth (cm)	Date	Age (yr)	+/−	Sedimentation rate		
				g cm^{-2} yr^{-1}	cm yr^{-1}	+/−(%)
0.0	1984	0				
5.0	1981	3	2	0.4	1.4	23
10.0	1978	6	3	0.5	1.3	26
15.0	1974	10	4	0.7	1.6	38
20.0	1971	13	4	0.9	1.9	51
25.0	1967	17	5	0.9	1.7	53
30.0	1963	21	6			
35.0	1961	23	8			
40.0	1959	25	10	1.2	2.2	–
45.0	1956	28	13			
50.0	1954	30	15			

but below this level ^{210}Pb dates are significantly older than those predicted by ^{137}Cs analysis. Because of a high rate of sediment accumulation in this core the ^{137}Cs dates are likely to be more reliable than those based on ^{210}Pb measurements alone. High sediment accumulation rates result in low unsupported ^{210}Pb activities (an assumption of the CRS model) and make accurate determination of dating parameters difficult. The low surface concentration of 0.9 pCi g^{-1} (Table 5) is such that unsupported ^{210}Pb will be undetectable beyond about two half-lives i.e. c. 40 years. For ^{137}Cs however a high accumulation rate will reduce the relative importance of ^{137}Cs diffusion, a major source of potential error in cores with slow accumulation rates. Hence, the most appropriate chronology for this core is calculated from ^{210}Pb measurements using the ^{137}Cs derived dates for 1963 (30 cm) and 1954 (50 cm) sediment as reference levels (Oldfield & Appleby 1984) and is given in Table 6. This chronology shows a high sediment accumulation rate of over 2 cm yr^{-1} in the most recent sediment.

The Dayat Affougah core: The CRS ^{210}Pb chronology calculated for this core suggested that the sediment accumulation rate had accelerated in a fairly consistent manner over the past 140 years, doubling in the past 40–50 years. A poorly defined ^{137}Cs concentration peak occurs between 13.5 and 18.5 cm depth, corresponding to 1963, and with a ^{210}Pb date of 1955–1965. Below this level however the two dating methods are contradictory. ^{210}Pb calculations put 1950 at 20 cm and 1900 at 30 cm depth. On the other hand, ^{137}Cs concentration at 26 cm is not significantly below peak values and the level should not predate 1954. Furthermore, ^{137}Cs is detectable down to 38 cm, dated by ^{210}Pb to the mid-19th century. Although differences between ^{210}Pb and ^{137}Cs dates often occur as a result of diffusion processes (Davis *et al.*, 1984), this discrepancy appears to result from a major inwash event of old sediment, as evidenced by neglible diatom microfossil concentrations below 40 cm depth (see below). This interpretation is consistent with the radiometric data in that there is no ^{137}Cs or unsupported ^{210}Pb below this depth and the rise in diatom concentration above 40 cm is paralleled by a similar and coincident rise in ^{137}Cs and ^{210}Pb activity (Fig. 5). The dilution of unsupported ^{210}Pb below 40 cm implied by this event indicates at least a tenfold increase in the accumulation rate over current values and clearly invalidates the usual chronological interpretations of the radiometric profiles. Table 7 gives a tentative chronology based on the inwash hypothesis. As the ^{137}Cs inventory is similar to those in the other two lakes (Table 5) it is likely that sediments above 38 cm span the entire period of ^{137}Cs deposition and accumulation rates above this level has been calculated using the same method as for the Dayet-er-Roumi core, using 1954 for 38 cm as a dated reference level.

Table 7. A chronology for the Dayat Affougah core based on the 1954 date for the beginning of ^{137}Cs contamination (see text). Because of the speculative nature of this chronology no error estimates are calculated and dates must be regarded as approximations only.

Depth (cm)	Date	Age (yr)	Sediment accumulation rate	
			$g\ cm^{-2}\ yr^{-1}$	$cm\ yr^{-1}$
0.0	1984	0		
5.0	1980	2		
10.0	1976	8	0.3	1.3
15.0	1972	12		
20.0	1968	16		
25.0	1964	20		
30.0	1960	24		
35.0	1958	26	0.5	1.7
38.0	1954	30		

The Lac Azigza core: The CRS ^{210}Pb dates for this core are shown in Table 8; they indicate a steady increase in sediment accumulation rate since about 1900. The ^{137}Cs profile appears to reflect fallout history for the isotope and the data give good support to the CRS ^{210}Pb dates. The well-defined ^{137}Cs peak and the onset of ^{137}Cs contamination are dated by ^{210}Pb to 1963 and the early 1950s respectively. The 99% (150 yr) ^{210}Pb

Table 8. A chronology for the Lac Azigza core based on ^{210}Pb dates calculated using the C.R.S. model. The errors are calculated from counting statistics alone. Note: the relatively high concentrations of unsupported ^{210}Pb in this core and agreement with the ^{137}Cs data enable precise dating of the uppermost sediment.

Depth (cm)	Date	Age (yr)	+/−	Sediment accumulation rate		+/− (%)
				$g\ cm^{-2}\ yr^{-1}$	$cm\ yr^{-1}$	
0.0	1984	0				
1.0	1981	3	2	0.17	0.35	8
2.0	1978	6	2	0.16	0.32	9
4.0	1972	12	2	0.14	0.28	10
6.0	1964	20	3	0.14	0.30	14
8.0	1961	27	3	0.13	0.29	15
10.0	1951	33	3	0.12	0.27	14
12.0	1943	41	4	0.12	0.27	16
14.0	1936	48	4	0.13	0.29	18
16.0	1925	59	5	0.11	0.24	21
18.0	1912	72	7	0.08	0.17	24
20.0	1899	85	9	0.04	0.10	28
22.0	1873	111	10	0.03	0.07	29
24.0	1841	143	11	0.03	0.07	32

equilibrium depth in the core occurs at about 25 cm depth.

ii) Magnetic measurements

a) Soils: Free surveys in all three catchments indicate the presence of two distinct soil types; a thin pale-yellow topsoil (Munsell color 10 YR) found on steep and convex slopes, and a red soil (2.5–5.0 YR) found at the surface in pockets and below the paler soil extending 2–3 m below ground level. The paler soil is usually associated with pasture or upland scrub vegetation; the red soil occurs under *Cedrus* forest and in some cultivated areas. The clear distinction by color is matched by their significantly different K values (see Table 4), the red soil having a K value usually 4 × higher than the pale soil. Intermediate K values, especially in cultivated areas, suggest that many topsoils are a mixture of the two types.

Table 9 shows values of specific low-field magnetic susceptibility (X_{LF}), percentage frequency-dependent susceptibility ($X_{FD}\%$), specific high field (0.1T) remanant magnetisation (HIRM) and the HIRM/X_{LF} ratio (see Table 4) for topsoil samples from both soil types at each of the three sites. Compared with the pale soils, the higher values of X_{LF} and $X_{FD}\%$ in red soils indicate higher concentrations of both ferrimagnetic minerals and ultrafine ($\ll 1\ \mu$m) grains. These ultrafine grains are typical of secondary ferrimagnetic minerals of magnetite or maghemite formed through pedogenic processes (Mullins, 1977; Dearing *et al.*, 1985). In most temperate regions, these minerals occur in topsoil horizons but here they are associated with reddened soils, particularly in the clay fraction (Table 9). Soil redness results from decarbonation of the parent material and the formation of haematite, an antiferromagnetic mineral identified by HIRM. Table 9 shows that red soils have up to 4 × more haematite than paler soils. The ratio HIRM/X_{LF} expresses the relative proportions of hamatite and magnetite/maghemite; lower values in red soils indicate lower proportions of haematite than in pale soils, although red soils have more haematite. Overall, the resuls suggest that red soils contain a higher concentration of secondary minerals (magnetite/maghemite and haematite) as a consequence of long term weathering and alteration. The HIRM/X_{LF} ratio distinguishes between different magnetic mineral assemblages and since it largely avoids problems of particle size and mineral dilution (Björck *et al.*, 1982; Dearing *et al.*, 1985) this parameter should be a useful indicator of the relative contribution of each soil type to lake sediment.

b) Lake sediments: Figure 6 shows profiles of X_{LF}, HIRM and HIRM/$_{LF}$ values for the three lake cores. Values of X_{LF} can fluctuate according to the allocthonous minerogenic content of sedi-

Table 9. Typical magnetic properties of soils in the three lake catchments. Measurements are for single bulk soil samples, except for two measurements made on clay fractions, shown in parentheses. Values of X_{LF} have been calibrated against c. 100 measurements made *in situ* and represent typical magnetic properties for the soil types shown.

Sample	Depth (cm)	X_{LF}	$X_{FD\%}$	HIRM	HIRM/X_{LF}
Roumi					
Red soil	100	1.72	13.1	0.51	0.30(0.4)
Pasture soil	0–5	0.27	6.8	0.43	1.69(2.2)
Affougah					
Red soil	0–5	3.40	10.6	1.08	0.32
Pasture soil	0–5	0.24	4.9	0.31	1.30
Azigza					
Red forest soil	0–5	3.35	6.6	1.50	0.45
Pasture soil	0–5	0.12	6.0	0.34	2.73

( ) measurements on $< 2\ \mu$m fraction.

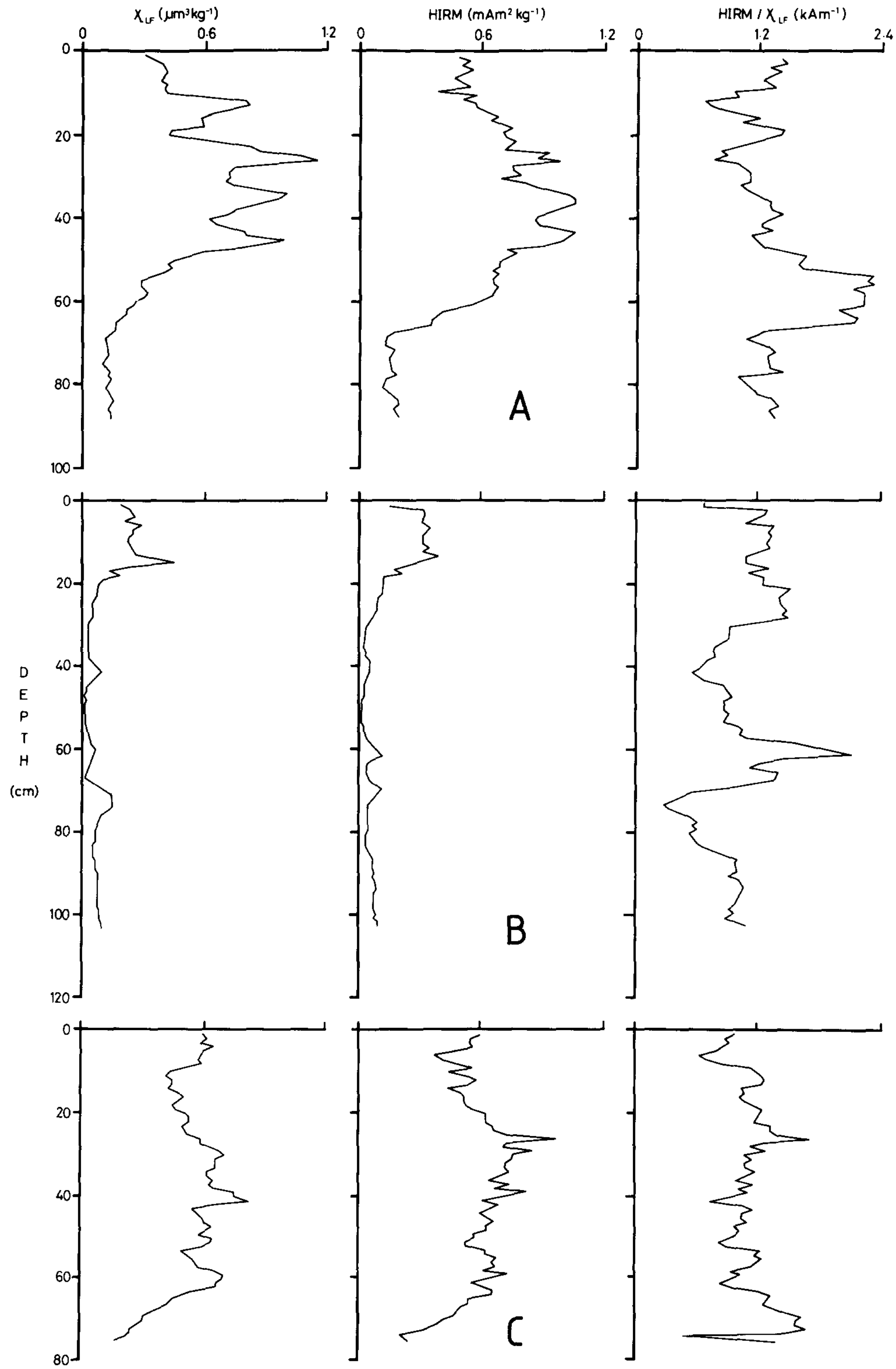

Fig. 6. Profiles of magnetic susceptibility (X_{LF}, left), high field remanent magnetism (HIRM, centre) and of the ratio of these two parameters (HIRM/X_{LF}, right) in the Dayat-er-Roumi (A), Dayat Affougah (B), Lac Azizga (C) sediment cores.

ment. Since all the catchment soils have relatively high ferrimagnetic mineral concentrations, low X_{LF} values in the cores may reflect high proportions of 'non-magnetic' organic matter, diatoms or, probably most significantly at these sites, carbonates. The concentration of ferrimagnetic minerals is generally highest but most variable in the sediments from Dayat-er-Roumi and lowest in those from Dayat Affougah, although at the base of each core, the X_{LF} values are similar.

The HIRM curves, indicative of the haematite concentration, display trends similar to the X_{LF} curves in each case. This parallelism suggests that ferrimagnetic minerals and haematite are usually associated, though not necessarily in the same proportions as indicated by variability in the three HIRM/$_{LF}$ curves. Curves of this ratio (Fig. 6) show values deviating to the right (more haematite) and to the left (more magnetite/maghemite) of the vertical line (constant proportions). Using HIRM/X_{LF} values of < 0.5 as an index of red soil (Table 8), there appear to be few periods when such material dominated the sediment composition of any of the three cores (Fig. 7). The majority of levels in each core have values exceeding 1.0, indicating that the paler soil dominates. Clearly, the sediments are derived from both soil types but the stronger magnetic signals from red soil means that, in a mixture, the bulk HIRM/X_{LF} value will be weighted towards the red soil component. Initial work on a mixing model for the two sources suggests that a 50% contribution by red soils reduces the HIRM/X_{LF} value for pure pale soil by 65% and a 10% contribution by red soils reduces the value by 40%.

These figures imply that in the Dayat-er-Roumi core the lowest HIRM/X_{LF} values of 0.6–0.8 (12 and 22 cm) may reflect a 25% contribution from red soil and that pale soil has been the major source of sediment throughout the core. In the upper 50 cm of this core, HIRM/X_{LF} minima correspond to maxima in X_{LF} suggesting that the magnetic measurements have detected a periodic influx of minerogenic material containing a substantial quantity of red soil. The most likely explanation of this record is related to the development of a large gully which feeds directly into the lake (see above), whereby progressive downcutting caused erosion, first of the pale surface soil, (evidenced by high HIRM/X_{LF} values at 55–65 cm depth) and then of the deeper red soil (evidenced by the X_{LF} maxima). The relatively low X_{LF} values in the upper 10 cm of the core probably reflect stabilisation of the gully where red soil represents an insignificant component of sediment reaching the lake.

In the Dayat Affougah core X_{LF} and HIRM values are generally lower than in the other two cores indicating either lower levels of all soil derived sediment or a dilution of the magnetic minerals by carbonates or both. Similarly, the increase in these magnetic parameters in the top 15 cm of sediment could indicate a recent increase in erosion or a reduction in dilution effects from a diminshed supply of carbonates. The HIRM/X_{LF} curve shows large fluctuations, especially in the middle section of the core, around 60 cm depth, indicating major shifts in sediment sources. There are several levels (2, 40, and 75 cm depth, where red soil predominates but elsewhere in the core pale soil appears to have contributed most to the sediment.

In the Lac Azigza core the HIRM/X_{LF} curve generally shows less variability than in the other two cores and indicates relatively constant sediment sources, except for a sharp drop in values at 74 cm which suggests an influx of red soil at this time. The increase in values for both X_{LF} and HIRM above this depth could indicate a general increase in erosion of soil material from all available sources.

iii) Basic geochemistry

The basic sediment constitution (sediment dry weight, calcium carbonate content and mole percent of magnesium in the carbonate mineral, x, where $Ca_{1-x}Mg_xCO_3$ represents the carbonate mineral) is presented in Fig. 7. Changes in these components are used to infer catchment erosion episodes at all three sites. There are four points which support this approach:

Firstly, SEM examination of sedimentary carbonate minerals revealed extensive surface pitting, which suggests that these minerals were weath-

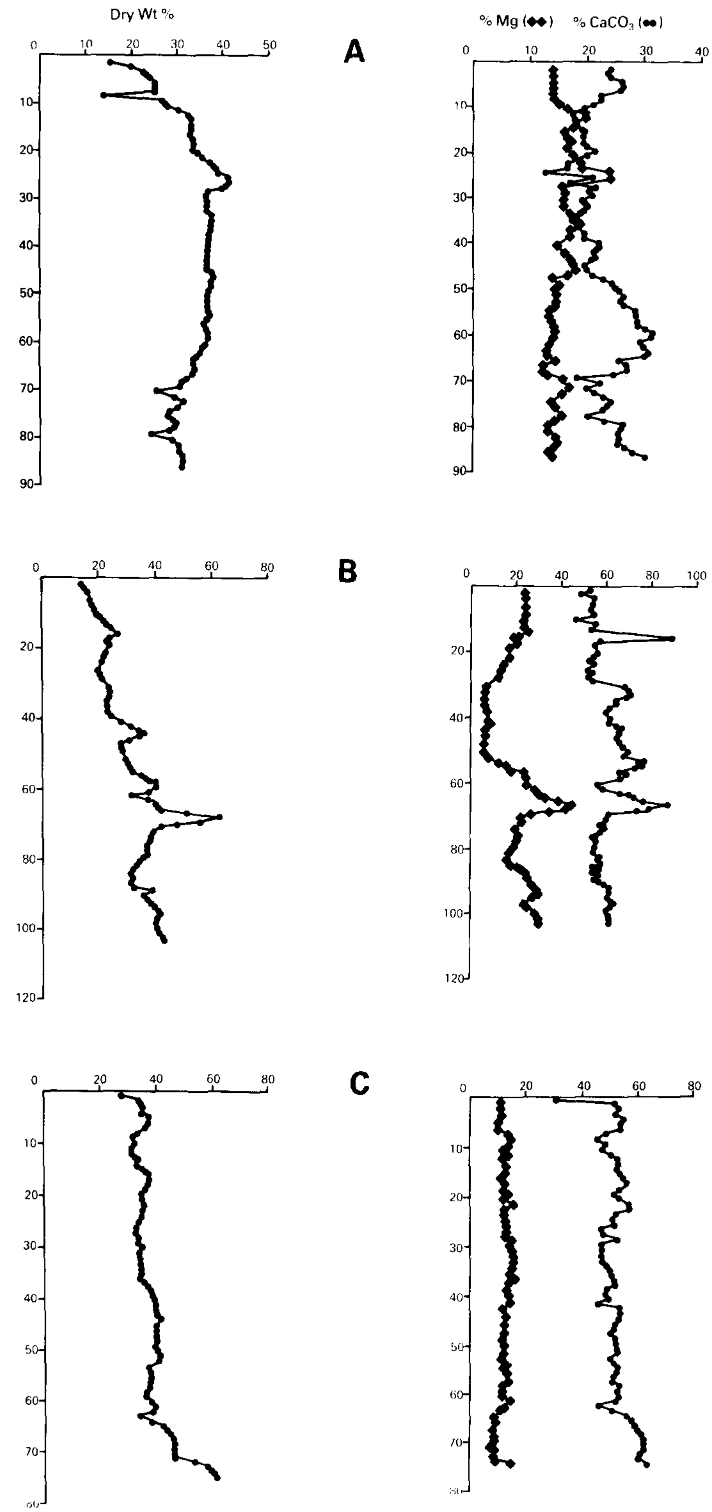

Fig. 7. The percentage dry weight profiles for the Dayat-er-Roumi (A), Dayat Affougah (B), and Lac Azigza (C) cores (left). The profiles of calcium carbonate, as a percentage of the sediment dry weight and magnesium, as mole percent x, where $Ca_{1-x}Mg_xCO_3$ represents the carbonate mineral (right).

ered on land before erosion and deposition (Rippey & Viles, unpubl.). Hence, despite some biogenic precipitation of calcite from the water column, the majority of sedimentary carbonates probably originates from erosion of catchment soils. Secondly, we found dolomite (by X-ray diffraction) present in five out of the six soil and four out of the six sediment samples from the Dayat Affougah catchment. Dolomite was not found in selected soil or sediment samples from the other two sites, where the carbonate mineral was all calcite. No gypsum was found in any of the samples. These observations suggest that in the Dayat Affougah core, variation in the mole percent of magnesium reflects changes in erosion of dolomite from the catchment. The magnesium/calcium weight ratio in water from all three lakes is around 1 (Table 3) and since ratios of 7 to 12 are required for diagenetic formation of dolomite from a primary precipitate of high magnesium calcite (Kelts & Hsu, 1978), an erosional origin for this mineral is most likely. Thirdly, changes in sediment dry weight are mainly caused by changes in sediment particle size (Berner, 1980). The major dry weight increases in all three cores are likely to indicate changes in soil erosion (cf. Bertine *et al.*, 1978), with high values reflecting large particle size material deposited during of periods of rapid soil erosion.

The dry weight, magnesium and calcium carbonate profiles for the Dayat-er-Roumi core (Fig. 7) show that these properties vary considerably throughout the core. In the core section between c. 70 and 12 cm, the dry weight is > 30% with a peak of > 40% at around 25 cm depth, where magnesium values are highest. The carbonate content is highest in the lower part of this section. In the top 12 cm section, dry weight declines to < 15% (although calcium carbonate shows a small increase), which suggests that the sediment particle size has decreased in the most recent sediment. The soil influx rate may also have decreased at this time. The average mole percent of magnesium in the carbonates throughout the core is 15.7 and as the mineralogy showed only calcite present, the carbonate mineral is high in magnesian calcite.

As in the previous core, the Dayat Affougah profiles are irregular, indicating unstable conditions throughout the period spanned by the core, particularly in the 70–30 cm section. The dry weight profile shows a pronounced peak around 66 cm depth, with a trend to lower values towards the core top. Both the mole percent magnesium and carbonate profiles exhibit major peaks at this depth, but higher in the core magnesium declines to low levels, especially between 50 and 30 cm. At around 66 cm the sediment is gritty and is composed almost entirely of dolomite (carbonate content is 88% and x = 0.45, where $Ca_{1-x}Mg_xCo3$ is the carbonate mineral) and indicates massive soil erosion in this period. In other sections, particularly between 50 and 30 cm depth, the carbonate mineral is low magnesian calcite (x = 0.066), all of which suggests that sources of eroded material have varied through time.

Profiles in the Lac Azigza core are much less variable than those in the other cores, with significant changes occurring only below 64 cm, where dry weight and carbonate values increase. The average mole percent magnesium in the core is 12.3, indicating that the carbonate mineral is high in magnesian calcite. Except fot the basal section of the core, the profiles indicate fairly stable soil erosion rates and hence considerable stability in the catchment over the recent past.

iv) Pollen

High ruderal pollen frequencies for *Liguliflorae*, *Gramineae*, *Cruciferae*, *Plantago*, *Rumex*, *Anthemis* and *Chenopodiaceae* occur throughout the Dayat-er-Roumi core (Fig. 8). These pollens are characteristic of the arable land, pastures, and olive plantations that now surround the site. They indicate that the catchment vegetation has been very disturbed by human activity for the entire period spanned by the core. Inspection of the tree and herb curves in the pollen summary diagram suggests that there has been no major vegetational change within the catchment, although, in the arboreal group, *Olea* has increased as *Quercus* has declined. The result of deliberate introductions of tree species is recorded in the profile by the *Olea*, *Pinus*, *Eucalyptus* & *Juglans* pollen. It is unlikely

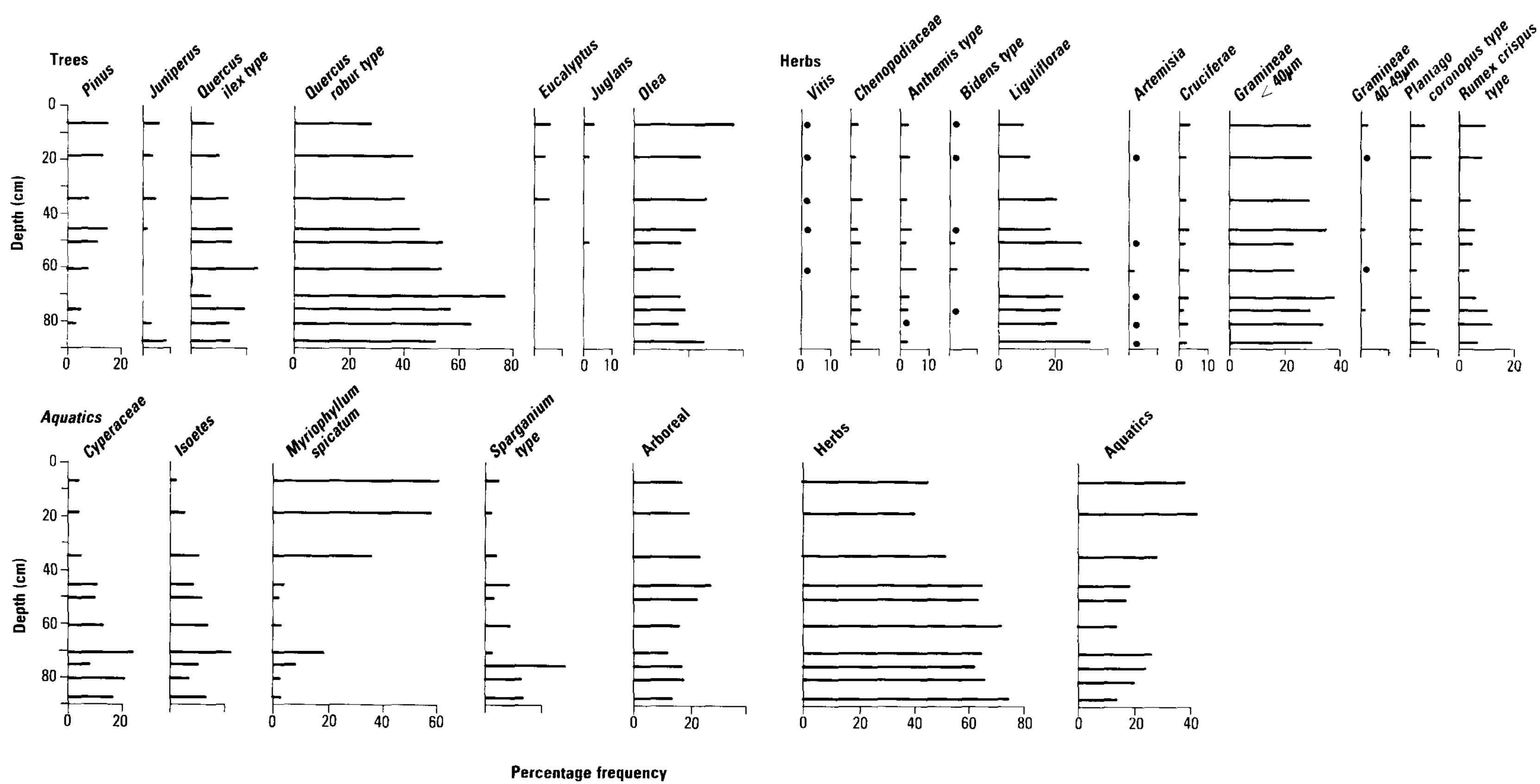

Fig. 8. Percentage frequency pollen diagrams for the Dayat-er-Roumi core with arboreal pollen (upper left), herb pollen (upper right), aquatic macrophyte pollen (lower left), and the summary diagram (lower right). Closed circles indicate < 2% frequency.

that fluctuations in ruderal pollen frequencies are indicative of vegetational change but, rather, that they reflect differences between soils eroded into the lake. Aquatic pollen values show a shift from *Isoetes/Sparganium* domination to *Myriophyllum spicatum* at 35–40 cm and may relate to siltation effects.

Clear evidence for human disturbance of catchment vegetation is also shown by the pollen diagram for the Dayat Affougah core (Fig. 9). This is most clearly demonstrated by the *Cedrus* and *Pinus* decline recorded at the core base and a concomitant increase in *Quercus ilex* type pollen and particularly in several anthropogenic disturbance indicators such as *Gramineae*, *Chenopodiaceae* and *Artemisia*. The peaks in these ruderal plants together with the higher values of *Olea* suggest an expansion of pastoral and arable farming and an extension of olive cultivation in the region. The recent expansion of pine recorded at the top of the diagram doutbless reflects recent planting. However, no olive or pine plantations occur within the catchment. The present dominance of the catchment forest by oak and juniper is reflected in the core but values of juniper pollen are low considering its present abundance. Pollen was scarce around 60 cm and virtually absent around 50 cm indicating rapid sediment accumulation of inwashed material with little pollen, subsoils being a likely source. Also, high values for *Sparganium* pollen at the latter depth could indicate expansion of the macrophyte fringe around the lake.

Stable catchment vegetation is indicated in the pollen diagram for much of the period spanned by the Lac Azigza core (Fig. 10), and high pollen values for *Cedrus* and *Quercus* reflect the current dominant catchment vegetation of *Cedrus atlantica* and *Quercus ilex*. Recent anthropogenic activity in the catchment and surrounding region is revealed at the core top where NAP (non-arboreal pollen) values rise, chiefly those of *Gramineae*, *Cruciferae* and *Rosaceae*, and AP values fall. The other more major change in the forest communities is recorded at the base of the core between 80 & 60 cm where *Cedrus* pollen declines from > 90 to c. 35% of total AP as the frequency of *Quercus ilex* type pollen sharply increases. This change possibly evidences replacement of *Cedrus* by the *Quercus* dominated woodland found today on northern slopes of the Azigza catchment (see Fig. 4). A *Cedrus* decline as sclerophyllous woodland (dominated by *Quercus ilex*) increases has been recorded elsewhere in Morocco and has been ascribed to both human disturbance and climatic change (Reille, 1976, 1977). At Lac Azigza the early *Cedrus* decline is probably anthropogenic as it is accompanied by significant increases in the major disturbance indicators: *Chenopodiaceae*, *Gramineae*, *Compositae* and *Plantago* as well as charcoal particles.

v) Diatoms

Both planktonic and benthic diatom taxa occur in all three sediment cores and tychoplanktonic forms, notably *Fragilaria* spp., are common at two sites. Planktonic diatoms are dominated by *Cyclotella* species and include a recently described taxon *C. 'azigzensis'* (F. Gasse pers. comm.). Most ecological information concerning diatoms in this study is taken from Hustedt (1937–39, 1957), Cholnoky (1968), Lowe (1974) and others. Diatom assemblages are expressed in several ways, as species percentage frequency diagrams (Figs. 11, 12 & 13), combined into habitat preference groups (viz. planktonic, tychoplanktonic, and benthic; Fig. 14), and as concentration curves (Fig. 15). Note in the latter figure that concentration scales are different and that maximum diatom abundance in the Dayat-er-Roumi core is about two orders of magnitude less than in the other two cores. This low relative diatom abundance is probably a consequence of soil inwash rather than low diatom productivity since, of the three sites, Dayat-er-Roumi is probably the most nutrient rich (Gayral, 1954).

The main features of the percentage frequency diagram for the Dayat-er-Roumi core (Fig. 11) are the increased abundance of *Fragilaria brevistriata* above 50 cm depth and the decline in frequencies of planktonic *Cyclotella meneghiniana* and, to a lesser extent, of *Cocconeis placentula* between the core base and 45 cm depth. Several

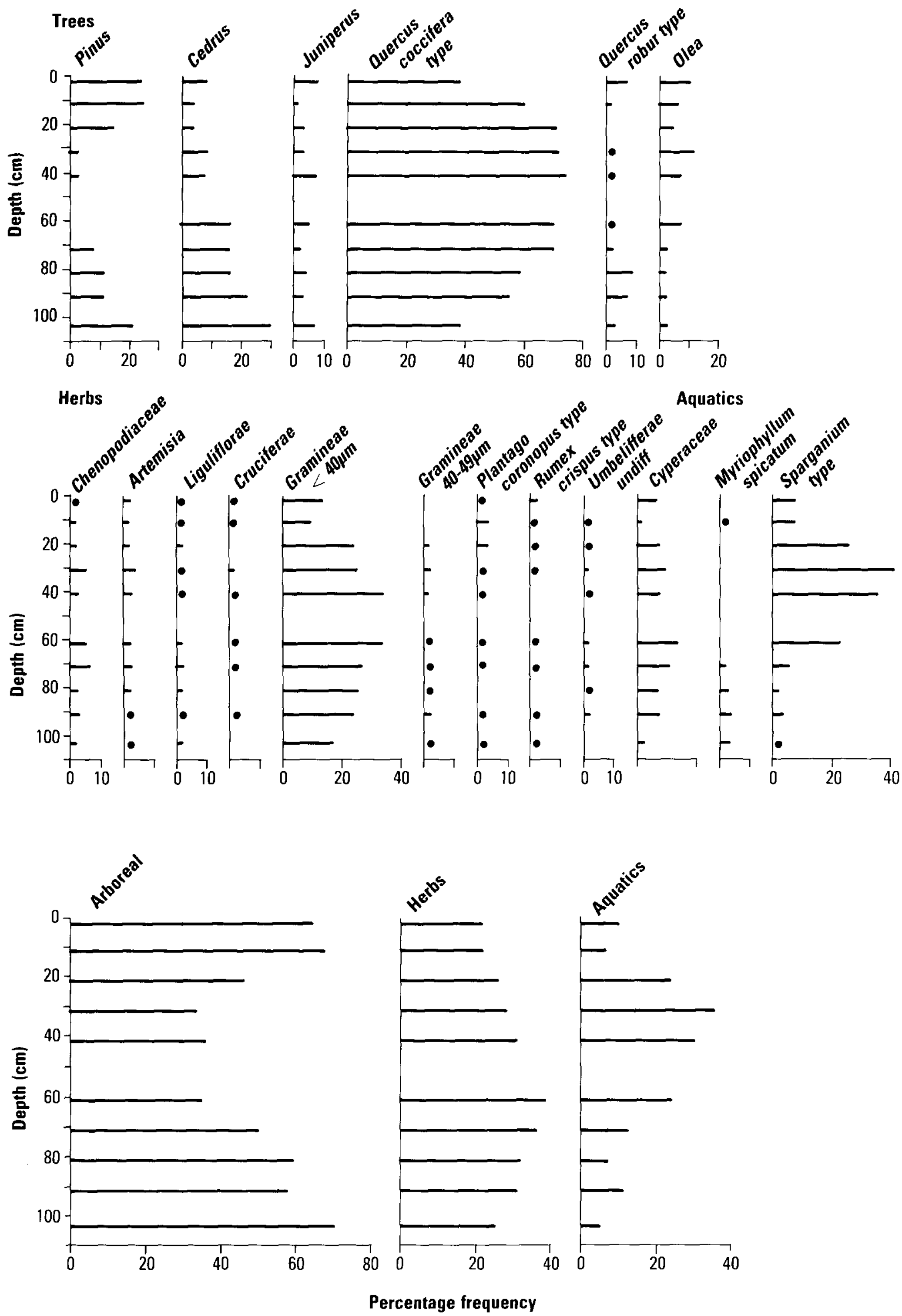

Fig. 9. Percentage frequency pollen diagrams for the Dayat Affougah core with arboreal pollen (upper), herb and aquatic macrophyte pollen (middle), and the summary diagram (lower). Closed circles indicate < 2% frequency. Note, pollen concentration at the 52 cm level was too low for routine counting.

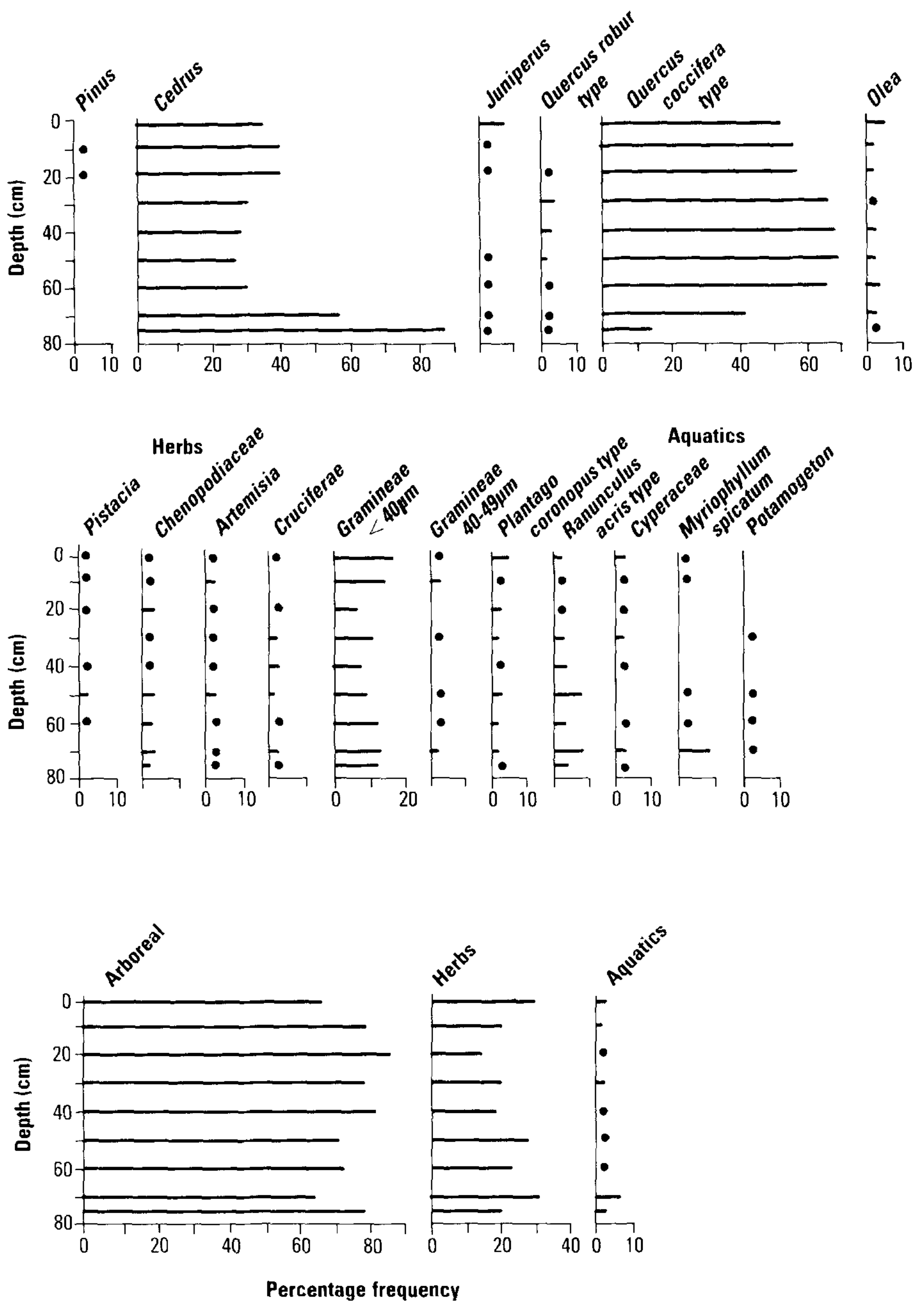

Fig. 10. Percentage frequency pollen diagrams for the Lac Azigza core with arboreal pollen (upper), herb and aquatic macrophyte pollen (middle), and the summarry diagram (lower). Closed circles indicate < 2% frequency.

species, *Amphora ovalis* var. *libyca*, *Anomoeoneis sphaerophora* and *Campylodiscus clypeus*, typical of epipelic habitats, achieve their highest frequencies between 45 and 60 cm. Similarly, aerophilic *Hantzschia amphioxys* and *Navicula neoventricosa* frequencies are only significant at 25 and 34 cm depth. In the top 10 cm several species, *C. pseudostelligera*, *F. virescens* v. *elliptica* and *Synedra ulna*, appear for the first time and probably indicate some enrichment, possibly from agricultural fertilizers. Interestingly, several attached species, e.g. *Achnanthes minutissima* and

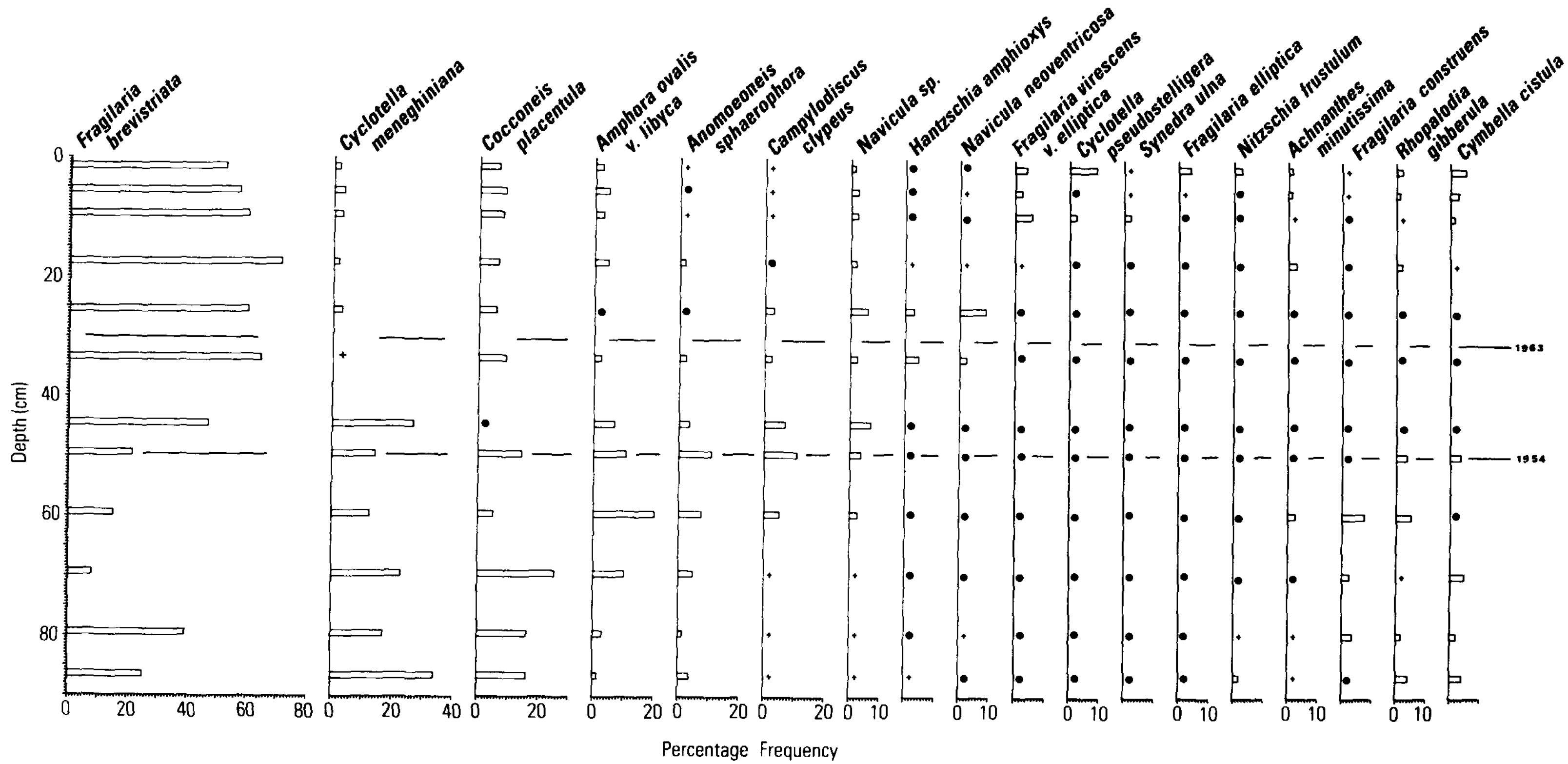

Fig. 11. Percentage frequency diatom diagram showing selected taxa in the Dayat-er-Roumi core. + indicates presence at < 2% frequency and closed circles indicate absence. Horizontal lines indicate selected levels dated by ^{137}Cs analysis (see Table 6).

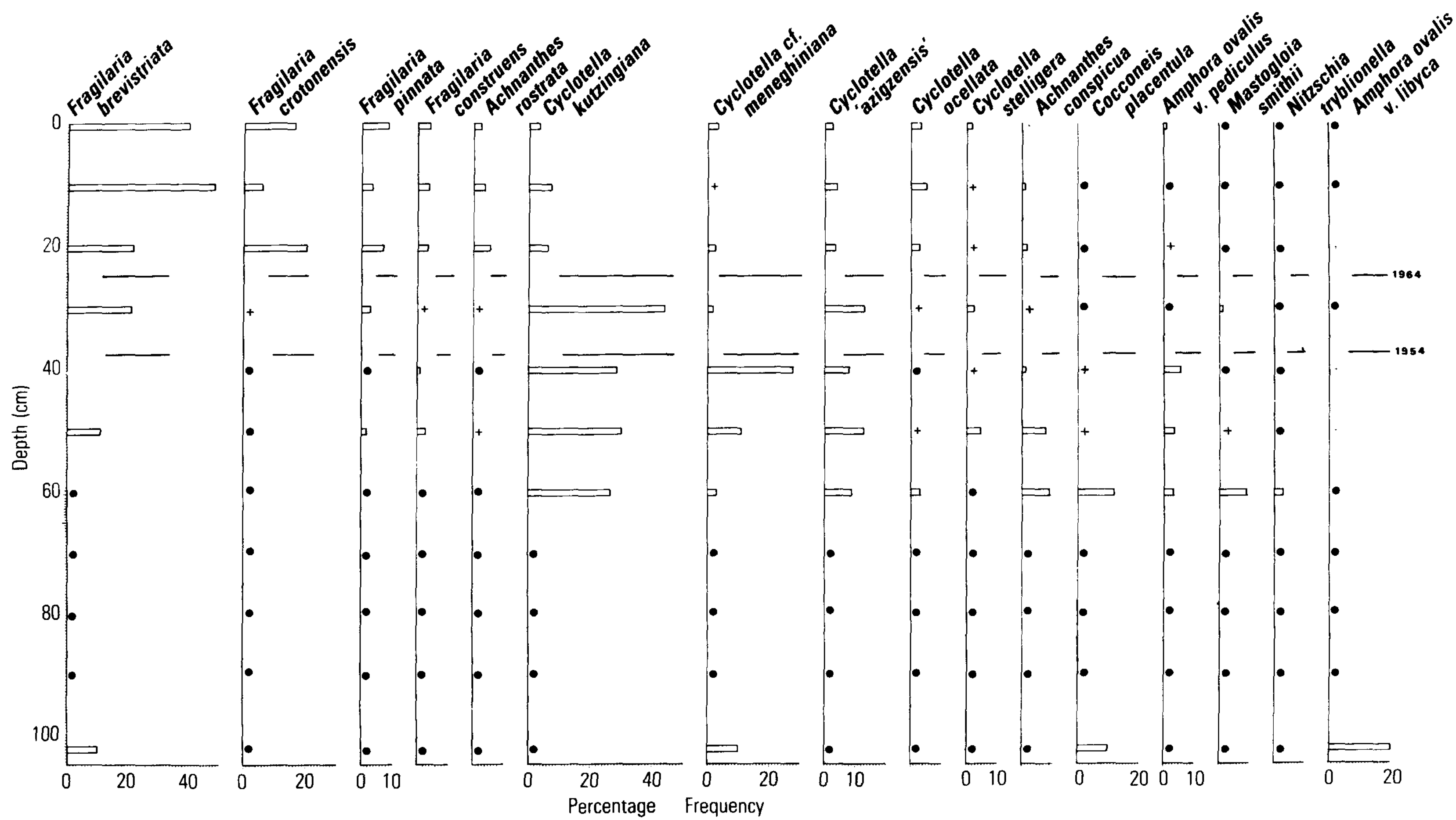

Fig. 12. Percentage frequency diatom diagram showing selected taxa in the Dayat Affougah core. + indicates at < 2% frequency and closed circles indicate absence. Note the total absence of diatoms between 60 and 100 cm depth. Horizontal lines indicate selected levels very tentatively dated by ^{137}Cs and ^{210}Pb analyses (see Table 7).

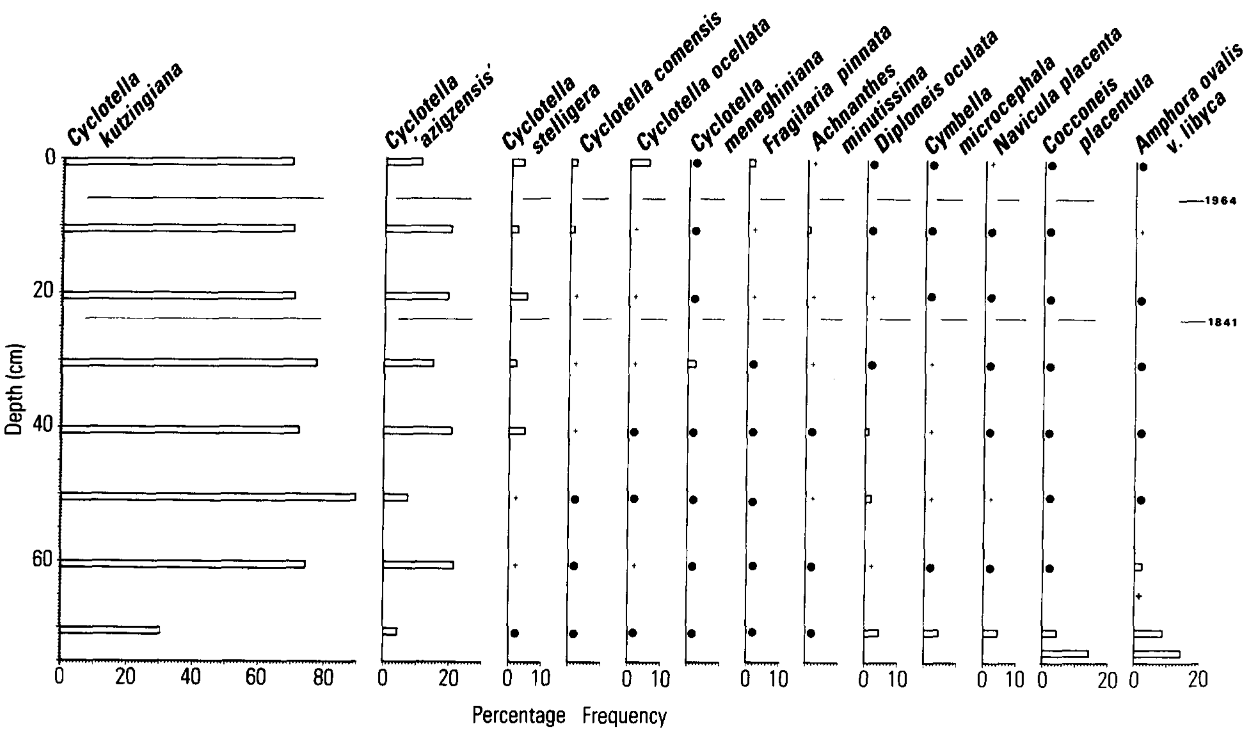

Fig. 13. Percentage frequency diatom diagram showing selected taxa in the Lac Azigza core. + indicates presence at < 2% frequency and closed circles indicate absence. Horizontal lines indicate selected levels dated by ^{210}Pb analysis (see Table 8).

Rhopalodia giberula, reappear in the surficial sediment following disappearance from the sedimentary assemblage between c. 60 and 17 cm depth.

The habitat preference diagram (Fig. 14) clearly demonstrates the virtual disappearance of the plankton component between the core base, where it exceeds 30% of the total assemblage, and c. 45 cm depth. Tychoplankton increases to dominance levels at and above 45 cm but towards the core top, plankton frequencies begin to recover. Benthic diatoms achieve dominance values of almost 70% between 70 and 45 cm, the depth range over which the total concentration of diatom cells in the sediment reach minimum values (Fig. 15). Diatom concentration declines rapidly from the core base to 60 cm depth but begins to increase again in the top 20 cm. Diatoms in the low concentration section (20–70 cm) are mainly periphytic forms and are usually present as broken valves. This section indicates massive inwash of material causing dilution of the diatom assemblage. A real increase in tychoplankton abundance, mainly *Fragilaria* spp., occurs at 45 cm and may indicate an extended littoral area following deposition of sediment from accelerated soil erosion, rather than any change in water quality. Increased turbidity possibly suppressed the plankton crops at this time. On the other hand, the change from *C. meneghiniana* to *F. brevistriata* could indicate a shift to less brackish conditions around this depth. However, despite possible changes in water chemistry, soil inwash effects appear to be the main factor affecting the diatom record in this core. The general conditions of high pH, moderate eutrophy and relatively high salinity have probably prevailed over the time period spanned by the core.

The major floristic change shown in the diatom frequency diagram for the Dayat Affougah core (Fig. 12) is an increasing abundance of *Fragilaria brevistriata* in the top 30 cm. This increase is accompanied by the appearance of *F. crotonensis* and by a sharp decline in *Cyclotella kutzingiana*

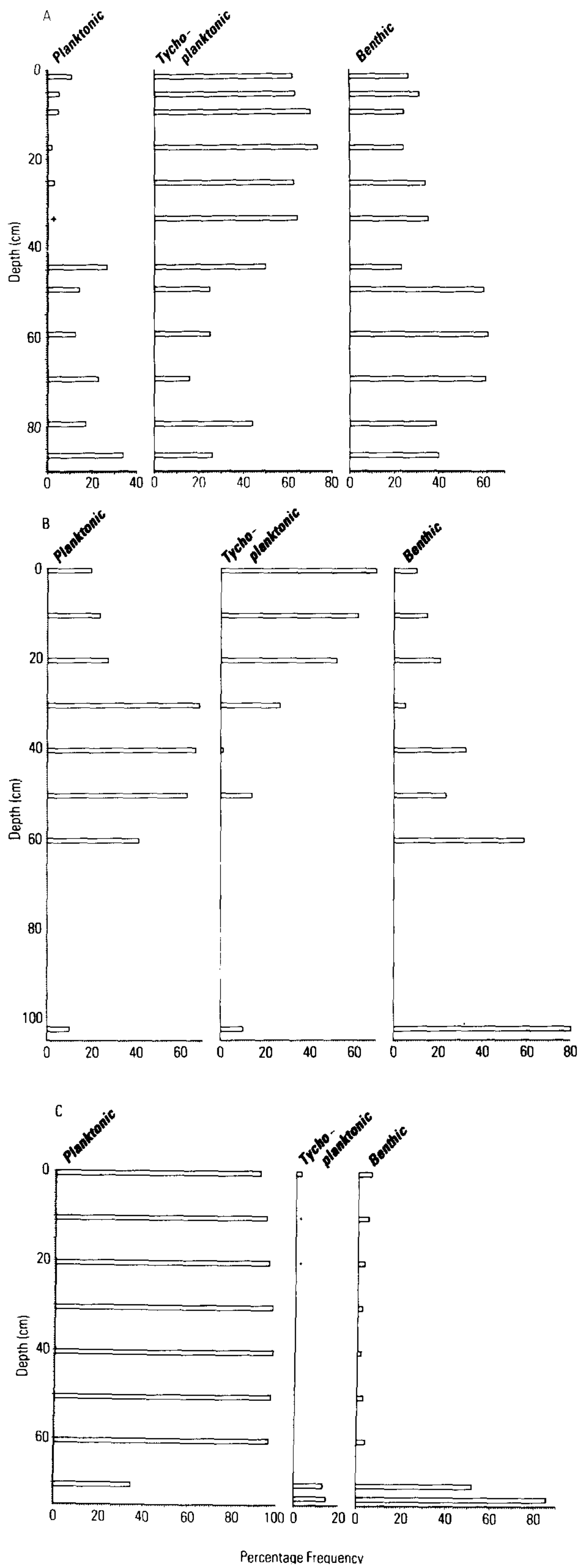

Fig. 14. Percentage frequency diatom diagrams showing taxa grouped according to habitat preference, Dayat-er-Roumi core (A), Dayat Affougah core (B), and the Lac Azigza core (C).

frequencies between 30 and 20 cm. cf. *C. meneghiniana* only occurs relatively infrequently (except at the 40 cm where it forms almost 30% of the total assemblage) and *C. kutzingiana* is the major planktonic species. Except for a few broken valves diatoms, are absent from the sediment between 60 and 100 cm. At the core base however a few species reappear e.g. *Amphora ovalis* v. *libyca*. At the point between 50 and 60 cm where the common diatom frequencies decline, several otherwise infrequent benthic species, *Achnanthes conspicua*, *Cocconeis placentula* and the halophilic *Mastogloia smithi*, achieve peak abundances.

The habitat preference diagram (Fig. 14) shows tychoplankton predominating above 30 cm depth, plankton between 30 and 50 cm, and benthic forms at 60 cm and at 103 cm. The diatom concentration curve (Fig. 15) shows that increasing tychoplankton parallels increasing total cell abundance. Below 30 cm diatom concentration is low and falls to zero or insignificant values below 60 cm. There is a slight concentration increase at the core base and unpublished diatom analysis of a longer core from this lake shows that diatoms, especially *Cyclotella* taxa, are abundant in sediment well below 1 m depth. The few diatoms in the lower portion of this core are mainly fractured and, as in Dayat-er-Roumi, dissolution does not appear to explain the absence of valves. These observations suggest a massive dilution of the diatoms by inwashed terrigenous material, an explanation supported by high frequencies of epipelic diatoms that bracket the maximum inwash horizon at 60 and 103 cm depth. Furthermore, diatom frequency changes of *Mastogloia smithi*, *Nitzschia tryblionella*, and *Achnanthes conspicua* indicate somewhat higher salinity in the 50–60 cm period as might be expected following dissolution of salts from disturbed pedocal soils. In addition, the increase of *Fragilaria crotonensis* at the top of the core is suggestive of some nutrient enrichment.

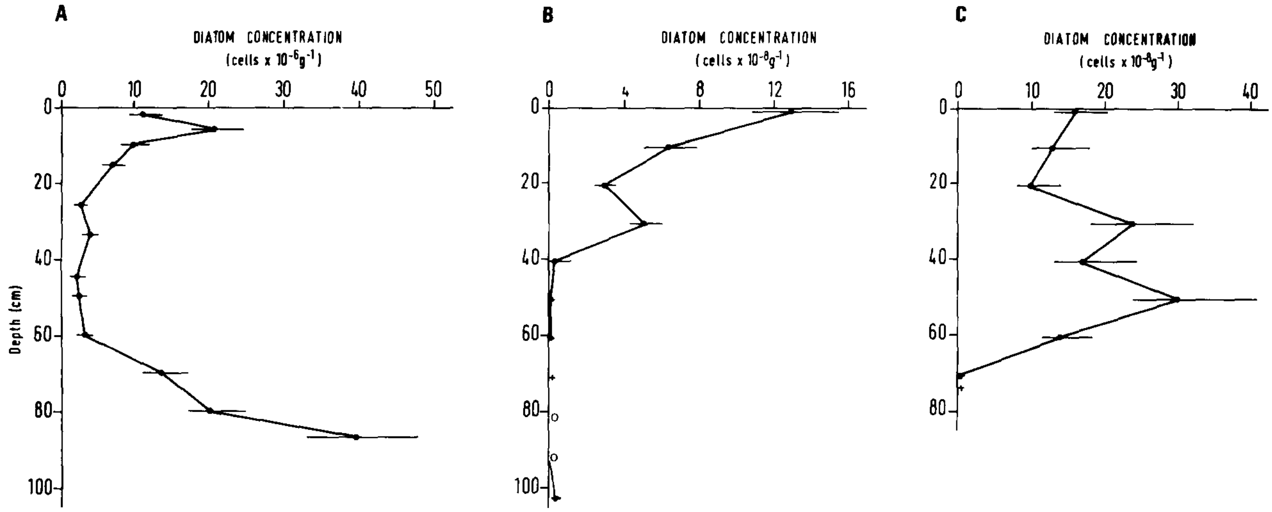

Fig. 15. Diatom concentration, as cells g^{-1} sediment dry weight, profiles for the Dayat-er-Roumi (A), Dayat Affougah (B) and Lac Azigza (C) cores. + indicates presence of occasional diatom valves, open circles indicates absence of diatoms. Error bars indicate the 95% confidence limits of the diatom concentrations.

More difficult to interpret is the shift from planktonic *Cyclotella* spp. to *Fragilaria brevistriata* observed around 30 cm. This occurred as total cell concentration was increasing and not as in Dayat-er-Roumi when total cell concentration was low. Moreover, there are no substantial areas of shallows in this lake (see Fig. 3) for increased colonization by *F. brevistriata*. Expansion of the reed beds surrounding Dayat Affougah might have provided greater area for diatom colonization but sampling of the macrophyte epiphyton (in 1979 & 1984) showed mainly *Gomphonema* spp. present. Speculative explanations of the *F. brevistriata* expansion include the possibility that the species is planktonic in habit and has competitively excluded *Cyclotella* taxa as water quality changed, or that increased redeposition of littoral sediment in the profundal has occurred.

The percentage frequency diagram for the Lac Azigza core (Fig. 13) shows that, except for levels below 65 cm depth, the diatom assemblage is dominated throughout by *Cyclotella kutzingiana* and *C. 'azigzensis'*. These two planktonic diatoms account for over 90% of the total valves present in the upper core section and indicate stable water quality over the period of deposition. The 70 and 73 cm levels are, however, markedly different in species composition with *Cyclotella* spp. diminished or absent and increased frequencies of *Cocconeis placentula* and *Amphora ovalis* v. *libyyca*. Elsewhere in the core, other diatoms are relatively unimportant, except for the small *Cyclotella* taxa, such as *C. stelligera* and *C. comensis*, which increase in frequency towards the core top.

The habitat preference groups (Fig. 14) reflect the dominance of the planktonic diatoms in this lake. Only at the core base do tychoplanktonic and particularly benthic forms increase in frequency. This is reflected by the diatom concentration curve (Fig. 15), cell concentration falls sharply below 60 cm as *Cyclotella* taxa decline. Hence, the large frequencies of benthic diatoms at the core base are somewhat misleading since they are caused by the absence of planktonic diatoms, rather than by any real quantitative increase in abundance. Here, as in the other cores, the diatom concentration decline appears to be caused not by cell dissolution but from dilution by inwashed clastic material. Furthermore, preliminary results from a longer core indicate that planktonic diatoms reappear in deeper sediment. The massive concentration change from > 10^9 cells to < 10^5 cells per g sediment between 50 and 70 cm therefore suggests a major disturbance in the lake catchment. Absence of *Achnanthes minutissima*, the most abundant periphytic diatom in the lake today (Flower, unpub.), at the core base and the substantial depth of this lake suggests that soil inwash rather than either slumping of littoral sediment or water level lowering is the likely cause of stratigraphic change below 50 cm depth.

Synthesis

Catchment disturbance combined with a seasonally dry climate will promote rapid soil erosion and consequently will accelerate lake sediment accumulation. Despite dating problems, high rates of sediment accumulation ($> 1.5\ \mathrm{cm\ yr^{-1}}$) have been demonstrated in the recent past for cores from two of the three Moroccan lakes and are linked with major, probably 20th century, land-use changes in the Dayat-er-Roumi and Dayat Affougah catchments. Although catchments and lake basin differences prevent direct comparisons between sites the recent sediment accumulation rate measured in the Lac Azigza core, where the catchment is predominantly under forest, is relatively low ($< 0.4\ \mathrm{cm\ yr^{-1}}$). This is only marginally higher than recent accumulation rates commonly measured in oligotrophic undisturbed temperate lakes (Davis *et al.*, 1984; Flower *et al.*, 1987). Where large-scale catchment disturbance has occurred, sediment core dating problems can arise if soil inwash has accelerated the sediment accumulation rate (e.g. Bertine *et al.*, 1978; Wasson *et al.*, 1987). In the Dayat-er-Roumi and Dayat Affougah cores soil inwash effects have produced discrepancies between ^{127}Cs and ^{210}Pb calculated dates and have prevented calculation of pre-1954 sediment chronologies. It is likely however that both these cores are composed entirely of sediment deposited within the 20th century.

Identification of the likely causes of accelerated sediment accumulation and sources of inwashed sediment necessitated systematic analysis of the cores using a combination of magnetic mineral, geochemical, and microfossil techniques. This combined approach was particularly important since the usefulness of each technique varied according to individual site characteristics. Hence, the Dayat-er-Roumi core contained a good though complex record of gully erosion reflecting disturbance of the well developed catchment soils rich in magnetic minerals. Alternatively, the surface erosion of thin highly calcareous soils in the Dayat Affougah and Lac Azigza catchments produced lake sediments with low concentrations of magnetic minerals and with a relatively poor magnetic record of catchment erosion. Where magnetic evidence is inadequate, geochemistry provided useful information and although discrimination between detrital and biogenically precipitated carbonate minerals is difficult, a consideration of calcium and magnesium ratios and particle weathering features indicates the occurrence of detrital carbonates in these cores. Sediment microfossils not only provided evidence of biological change but also, when expressed in concentration terms, of changes in catchment erosion (Battarbee & Flower, 1984). However, periods of microfossil assemblage dilution occur in all three cores and are so extreme as to limit the value of the microfossils as ecological indicators.

The recent environmental history of each site can be conveniently divided into periods using a combination of ^{137}Cs and ^{210}Pb sediment chronologies. The most recent period is represented by the core sections above the 1963 ^{137}Cs peak and clearly defined in the Dayat-er-Roumi and Lac Azigza cores though this is less so in Dayat Affougah. The second period corresponds to the core section between 1963 and the start of ^{137}Cs contamination in 1954. The third period precedes ^{137}Cs contamination and spans from 1953 to the time of deposition of the basal sediment in each core, for which dates are only available for the Azigza core.

The pre-1954 period: The ^{210}Pb chronology for the Lac Azigza core allows sediment dating back to c. 1840 AD whereas a consideration of accumulation rates in the other two cores, assuming an absence of hiatuses, suggests that all the sediment is post 19th century. Magnetic measurements in the Dayat-er-Roumi core indicate that the haematite rich material, probably representing old red soil, signals the start of a major acceleration in catchment soil erosion. Major magnetic fluctuations in the Dayat Affougah core, particularly for the HIRM/X_{LF} ratio, indicate large changes in soil erosion in this period. Additionally, the high values for sediment dry weight, where over 80% is weathered dolomite, and absence of diatoms offer strong evidence of major soil inwash. The declining diatom concentrations from the very base of both these cores are probably caused by dilution effects and suggest that accelerated soil erosion began before the period spanned by the cores. Ruderal pollen is at high abundance throughout this period in the Dayat-er-Roumi core whereas in Dayat Affougah over 70% of the pollen is arboreal and, although total pollen was low, indicates a shift from *Cedrus* to *Quercus* woodland. The increasing frequency of aquatic plant pollen in this core may indicate a real increase in the abundance of aquatic vegetation or merely reflect the absence of other pollen types. The Lac Azigza core demonstrates no major changes between 1840 AD and 1954; the high abundance of *Quercus* pollen and *Cyclotella* plankton indicate that stable conditions persisted since the 60 cm level which, by ^{210}Pb extrapolation, dates to c. 1630 AD. Below this depth however, the sediment dry weight increases and the magnetic signal declines as the carbonate content rises. These changes are linked with the loss of diatom plankton and a strong decline in total diatom abundance, all indicating major soil inwash. Furthermore, the tripling of the *Cedrus* pollen frequency below 60 cm depth in this core suggests that the inwashed material is top soil, low in magnetic minerals, possibly resulting from Cedar forest clearance.

The 1954–1963 period: There is considerable evidence that during this period soil inwash is the cause of the high rates of sediment accumulation in the Dayat-er-Roumi and Dayat Affougah cores. In the former, diatoms are at their lowest concentrations throughout the period; in the latter, diatom abundance is low at the beginning of the period but thereafter increases rapidly. Geochemistry is fairly constant in both cores, although carbonates form the bulk of the dry mass of sediment in the Dayat Affougah core and are probably detrital in origin. The magnetic signal for the period in Dayat Affougah is weak compared with the Dayat-er-Roumi core where peak values for magnetic parameters clearly indicate soil inwash. Furthermore, the high HIRM/X_{LF} ratio in the Dayat-er-Roumi core links the sediment source to paler pasture soils. There is considerable change in the pollen spectra at this time in the Dayat Affougah core, as the frequency of tree pollen increases and that from aquatic macrophytes sharply decreases. Although low pollen abundance makes interpretation difficult it is likely these changes evidence some forest regeneration in the catchment. In contrast, aquatic pollen at Dayat-er-Roumi increases in frequency over the period, possibly indicating colonization of newly created shallows by *Myriophyllum spicatum*. Diatom frequencies in the Dayat Affougah core show considerable change as *Fragilaria* taxa increase over planktonic *Cyclotella* taxa. The cause of this proliferation in tychoplankton and *F. crotonensis* is unclear but doubtless reflects a change in water quality, possibly mild nutrient enrichment from subsistence agriculture, rather than any water level change *per se* (cf. Flower & Nicholson, 1987). Compared with the earlier period, diatom changes are slight for this period in the Lac Azigza core but decreasing arboreal and increasing herb pollen frequencies evidence some woodland decline.

The post-1963 period: A declining sediment accumulation rate in both the Dayat-er-Roumi and Dayat Affougah cores indicates a reduction in the influx of eroded soil. The rates however remain relatively high at > 1 cm yr^{-1} and represent about 30 and 25 cm of sediment accumulation over this 21 year period, respectively. The Lac Azigza core contains only about 6 cm of post-1963 sediment and although this is a relatively low rate of accumulation it is higher than in previous periods. Magnetic measurements in the Dayat-er-Roumi core indicate that the greater proportion of the most recent sediment is derived from the paler top soil inwashed from the catchment. Furthermore, in this period sediment dry weight decreases as both diatom concentration and the proportion of pollen from aquatic plants increase. These observations all indicate that sediment supply from the catchment, particularly of top soil (cf. Flower *et al.*, 1984), is diminishing and that the biota of the lake is in a recovery phase. The continued absence of diatom plankton however suggests that suspended particulates are still abnormally high. As the sediment in both the Dayat Affougah and Lac Azigza cores is dominated by carbonate minerals (usually > 50% dry weight) the magnetic signal is relatively weak though there is evidence of a higher proportion of older red soil present in the former. A recovery phase is also indicated in Dayat Affougah since there is a marked increase in both diatom concentration and arboreal pollen types which evidence firstly, that supply of minerogenic material to the lake is decreasing and secondly, that catchment woodland is continuing to regenerate. It is noteworthy that despite a reduction in catchment erosion there is no woodland recovery in the intensively agricultural Dayat-er-Roumi catchment. The Lac Azigza core diatoms show no significant change in total abundance or species composition over this period compared with the preceeding period, indicating little change in either water quality or the supply of inwashed soil. There is however a continuing trend of increased herbaceous over arboreal pollen in this section which suggests further catchment deforestation.

In the foregoing, where magnetic evidence is inconclusive, sedimentary decreases in diatom abundance and increasing concentration of carbonate minerals have been used as indicators of soil inwash. Similarly, dilution of microfossil concentration and increase in sedimentary carbonate concentration have been used by Binford *et al.* (1987) to infer soil erosion episodes induced by human activity. Elsewhere, these sedimentary changes have been used to infer a variety of environmental perturbations such as low lake level and changes in lake productivity (Stoermer *et al.*, 1971; Bradbury & Winter, 1976; Battarbee, 1978; Hickman & Klarer, 1981). Only at the Affougah site in the pre-1963 period, where the sediment is high in aquatic pollen frequencies and carbonates and where unbroken diatom valves are virtually absent or indicate higher salinity, is there a plausible challenge to the inwash hypothesis. Alternative explanations that could possibly account for the observed stratigraphic changes are, an asymmetric distribution of recent sediment within the lake basin or a phase of lake level change. Information concerning sediment distribution awaits analysis of the full suite of cores collected from this lake (see Fig. 3) but the composition and appearance of dolomitic carbonates below 50 cm depth and reoccurrence of diatoms at the core base remain good, though not conclusive, evidence of soil inwash. A low water level phase is thought unlikely in this lake, there are no climatic data suggesting a sustained dry period earlier this century and since the lake is spring fed and relatively deep it should be buffered against transient periods of low precipitation. On the other hand, for Lac Azigza there are records of a water level lowering of over 5 m observed in the late 1940s (Gayral & Panousse, 1954) and again in the early 1980s (Flower & Foster, unpubl.). These fluctuations appear to be unrecorded in the sediment core, possibly because the littoral area is narrow and wave induced erosion is minimal (cf. Flower & Simola, 1989). They are not climatic but are probably caused by water escaping through a fault system in the floor of the lake (Gayral & Panousse, 1954).

Conclusions

The initial supposition that the sediment cores should record the perceived degree of catchment disturbance at each site is supported by the results of this study. Despite failure to date the beginning of inferred catchment disturbance at the three sites, sediment cores from Dayat-er-Roumi and Dayat Affougah provide clear evidence of recent and major erosion of catchment soils. The recent history of the Dayat-er-Roumi catchment is one of continuous agricultural disturbance upon which is superimposed the effects of a sequence of wetland drainage operations represented by peaks in the magnetic profiles (also see Flower *et al.*, 1984; Foster *et al.*, 1986). The cause of soil erosion at Dayat Affougah appears to be different and the pollen suggests catchment deforestation. Diatom communities have not yet stabilized at either of these sites but declining sediment accumulation rates and diminished soil inwash indicate partial recovery from past disturbance events. The recent history of Lac Azigza is quite different from the other two sites and reflects the relatively pristine nature of the remaining cedar forest and the low level of human activity in the catchment. Although this site experienced partial forest clearance, possibly in the 17th century, the overall picture since then is one of environmental stability. However, although the cedar forest around Lac Azigza receives official protection, the pollen record indicates that sheep grazing in the catchment has increased during the post-1963 period.

Without paleolimnological techniques the major changes in ecosystem structure and processes that have occurred in these three catchments would remain largely unknown. Despite problems of taphonomy and diagenesis and difficulties in interpretation there is no doubt that the overall results of this study are of considerable importance for catchment-lake management and are essential for defining habitat restoration objectives. Since long-term monitoring of lake-catchment ecosystems is difficult, expensive, and often inappropriate, paleolimnology offers the only feasible way to assess recent habitat degradation.

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