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^{14}C DATING, GEOCHEMICAL FEATURES, FAUNISTIC AND POLLEN ANALYSES OF THE UPPERMOST 10 M CORE FROM VALLE DI CASTIGLIONE (ROME, ITALY) (1)

A multidisciplinary study of the uppermost 10 m of the Pleistocene drilling of Valle di Castiglione is presented in this paper.

Castiglione crater, located in the northern sector of the Colli Albani volcanic complex, had an highly explosive activity due to the interaction between unsatured magma and regional acquifers, during 0.4-0.3 m.y. ago. The explosions that determined an almost perfect anular shape emplaced hydromagmatic products characterized by typical base surge sedimentary structures.

The lithostratigraphic sequence can be summarized in five main intervals, from bottom to top: from 10.60 to 7.80 m brownish black slighty calcareous muds, containing volcanic material; from 7.80 to 5.30 m massive brownish black tuffites, with some burrow casts in the upper part; from 5.30 to 3.03 m grey calcareous muds with fresh-water fauna, with a thin layer of tuffite between 4.15 and 4.00 m; from 3.03 m to the ground level peaty muds with molluscs and then interbeddings of peat and muds. The whole sequence is probably continuous and deposited in low-energy shallow water environment.

^{14}C ages along with the abundance of C, N, S, Fe, Mn, Cu and Zn for lacustrine organic matter-bearing sediments collected by core drilling in Valle di Castiglione, formerly a volcanic lake, are reported. The uppermost 15.60 m of the sedimentary suite yielded ages spanning from about 3500 to nearly 42,000 yr before present (BP) and thus pointing to an accumulation process lasted from Upper Pleistocene through Holocene, whereas deeper samples were too old to be dated with the conventional ^{14}C technique. Apart from a dating reversal the obtained ages exhibited a high positive correlation (r=0.97) with depth and the calculated overall sedimentation rate averaged 0.3 mm/yr.

Carbonate, Fe, Cu, Zn and Mn contents ranged from 0.1 to 79.3%, 0.64 to 4.85%, 30.6 to 122.5 ppm, 25.5 to 113.8 ppm and 207 to 800 ppm, respectively, and did not show any definite trend with depth. Fe, Cu and Zn displayed a good positive correlation with the detritic content (r=0.89, 0.84 and 0.88, respectively), while, on the contrary, Mn showed a fair positive correlation (r=0.78) with the carbonate fraction of the sediment. Such finding was further supported by the results of selective-dissolution trials.

Reduced sulfur, detected in all the samples at concentration levels ranging from 0.003 to up 1.69%, provided evidence that the accumulation of the whole sedimentary suite occurred under anoxic conditions, that is with organic input and sedimentation rate not compatible with the persistence of oxygen on the basin bottom.

Organic carbon and total nitrogen contents ranged between 0.62 and 17.45% and from 0.07 to 1.43%, respectively. Their sharp increase throughout the upper 3.40 m of the sediment column likely can be accounted for by enhanced organic input due to vegetation development in the catchment area because of climate amelioration.

A continuous function relating the drilling depth to the radiocarbon age of the samples is proposed and the trend of the sedimentation rate as a function of depth is derived.

The malacological analysis points out some significant variations in the faunal composition of the different layers of the sedimentary succession. Environmental changes as lacustrine or marshy biotope, recurrent phases of aridity or humidity related to a more or less cold or warm climate, are recognized on the basis of the composition of the land and fresh-water malacological associations. Also the presence of ostracods, fishes, amphibians, terrestrial vertebrates and characean remains is considered for the paleoenvironmental reconstruction. The malacological sequence suggests different climatic phases from the bottom to the top of the sequence: the last "würmian" cold phase, an arid phase of "Lateglacial" period and two Holocene phases are recognized.

The pollen analysis of Valle di Castiglione has provided two pollen diagrams (percentage and absolute) showing the history of vegetation from the full glacial to almost all the Holocene.

The main subdivision of the diagrams separates two very distinct vegetational phases: one dominated by steppic formations, indicating arid climate and assigned to the glacial period, the other showing gradual expansion of the forest, reaching the most vigorous development during the Holocene.

The steppe is mainly characterized by *Artemisia*, Gramineae and Chenopodiaceae with continuous but scarce presence of *Pinus* and sporadic deciduous trees *(Quercus, Betula)*. The forest shows greater floristic and vegetational complexity: dominant elements are oaks (both evergreen and deciduous), chiefly accompanied by *Corylus, Fagus, Ulmus, Carpinus, Tilia* and *Alnus* in variable frequences. The expansion of *Fagus* about 5000 years ago corresponds to the highest pollen concentration in the sediment and indicates an increase in humidity. Since about 3000 years BP evergreen oaks and human influence on vegetation increase.

The transition phases between the glacial and the Holocenic periods deserve much attention. They show general agreement with pollen diagrams from Spain and Greece: after the radiocarbon date 20,300 up to about 14,220 years BP a considerable expansion of pine and juniper occurred; later on, in correspondence with the main subdivision of the diagram, chronologically correlated with the beginning of the Lateglacial, several arboreal components of Quercetum Mixtum immigrate. They will spread definitively during Holocene.

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(1) Geology and vulcanology by D. De Rita. Lithostratigraphy by G. Dai Pra & B. Narcisi. Radiocarbon dating and geochemistry by M. Alessio, L. Allegri, F. Bella, G. Calderoni, C. Cortesi, S. Improta & V. Petrone. Correlation analysis between the drilling depth and radiocarbon age by S. Improta, M. Alessio & L. Allegri. Faunistic analysis by D. Esu. Pollen analysis by M. Follieri, D. Magri & L. Sadori. The boreholes S1 and S2 were financed by the "Progetto Geolazio" - Università "La Sapienza", Roma.

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Introduction

Valle di Castiglione is an ancient lake, dried out artificially, which occupied an explosion crater (diameter about 1 km) on the northern flank of the Colli Albani volcanic complex. It lies about 20 km East of Rome, 44 m a.s.l., 41° 53' 30" N, 12° 45' 35" E Greenw.

Mean annual rainfall on Pantano Borghese, a site very close to Castiglione, is represented in fig. 1 (MIN. LAV. PUBBL., 1951-55, 1955), annual mean values of minima and maxima of temperatures of Roma area are represented in fig. 2 (MIN. LAV. PUBBL., 1966).

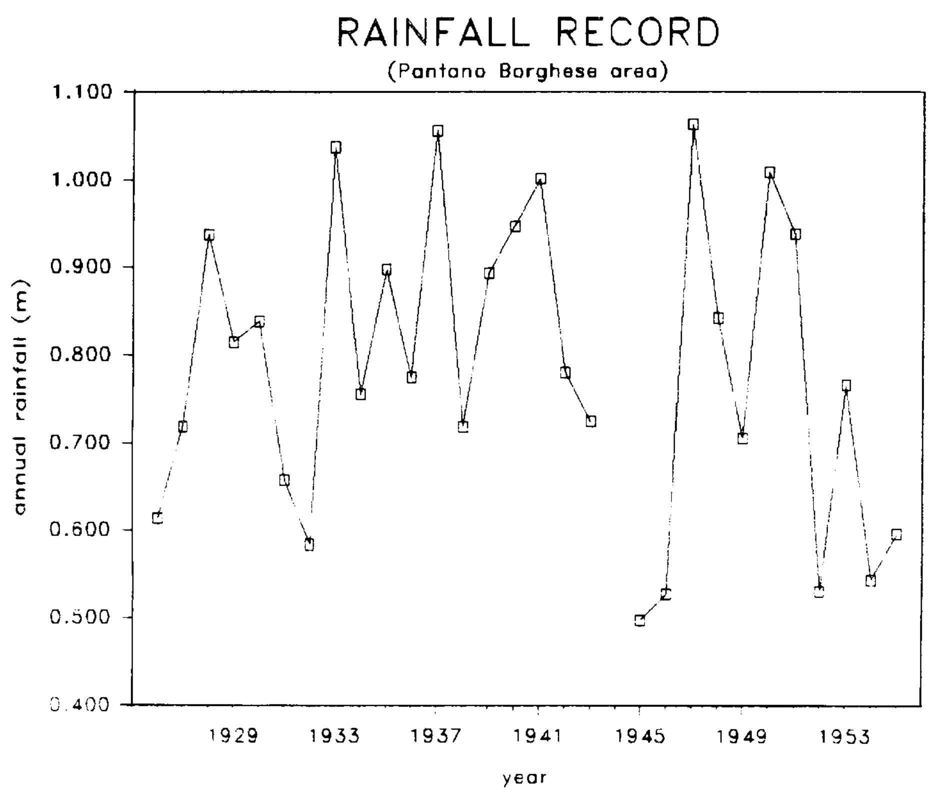


FIG. 1 — Annual rainfall since 1926 through 1955 measured at the station of Pantano Borghese (Rome) (53 m a.s.l.).

— Valori totali annui delle precipitazioni relativi alla stazione di Pantano Borghese (Roma) (53 m s.l.m.) per il periodo 1926-1955.

At present the human impact has completely modified the natural vegetation of the region, the potential vegetation is Mediterranean, of the Quercetea ilicis class (TOMASELLI, 1970).

The stratigraphical sequence of the uppermost 10 meters of the drilling is the subject of multidisciplinary studies synthetized in this work.

The main borehole (S1) was performed with a wire-line drill sampling, down to 88 m, undisturbed cores of sediment, 1.5 m in length and 10 cm in diameter. A second borehole (S2) was drilled 15 m far from the main one in the same way, to integrate some lack of sampling. All the analyses were made on these two cores.

In order to complete the pollen analysis and the stratigraphy, two new short cores down to 4 m were indispensable. A Hiller corer (3 cm diameter) was necessary for the stiffness of the sediment.

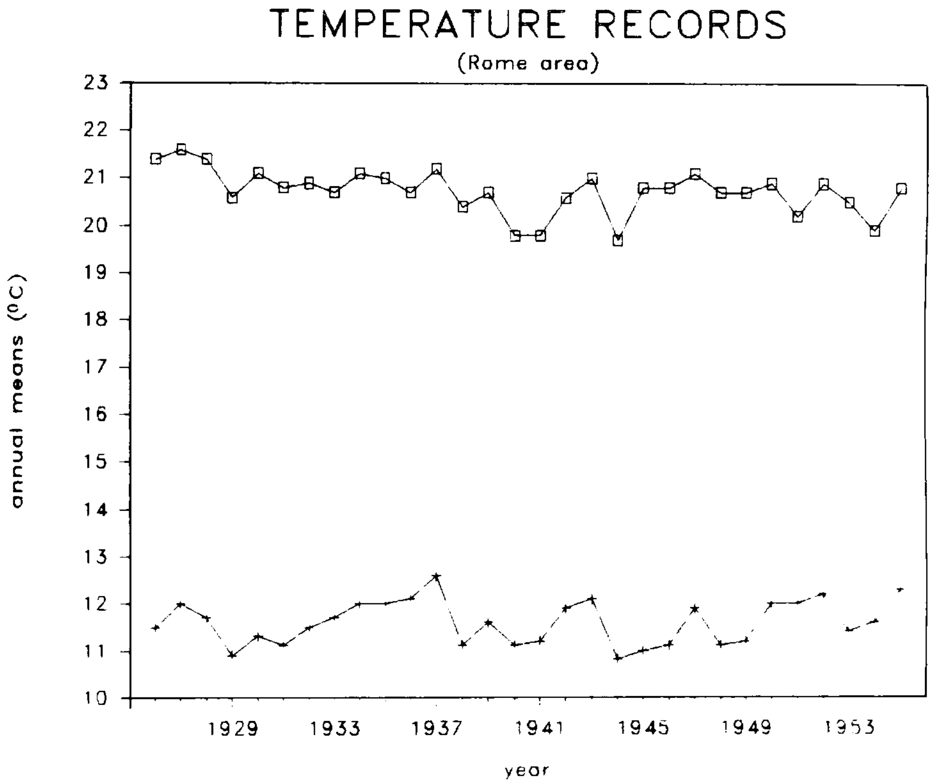
Geology and vulcanology

The Castiglione explosive center is located in the northern sector of the Alban hills volcanic complex. Its highly explosive activity was caused by interactions between the unsatured magma with shallow regional aquifers (CIVITELLI *et alii,* 1975; FUNICIELLO & PAROTTO, 1978). The crater formed in a subsided area between Rome and Tiburtini Mts (Fig. 3). In this sector, boundered to the North by the Pliocenic clays outcropping 100 m up the sea level, drilling for water supplies encountered the Pliocenic clays around 100 m below the sea level. This depression, with E-W direction, had to be present when the volcanism started in the area as it is actually almost completly filled up by the maximum thickness of the pyroclastic units of the Tuscolano-Artemisio central edifice (DE RITA *et alii,* in print).

The Castiglione crater developed at the southern margin of the subsided area, during the last stage of activity of the Tuscolano-Artemisio central edifice. Its products lie on the III Tuscolano-Artemisio pyroclasitc flow and are covered by the IV Tuscolano-Artemisio pyroclastic flow (0.36 m.y. RADICATI di BROZOLO *et alii,* 1978; BERNARDI *et alii,* 1982) and by final lava flows. Castiglione is the oldest hydromagmatic crater of the Alban Hills volcanic complex. Its activity is probably due to a single cycle that produced an almost perfect anular shape with 1 km diameter. The crater is formed by a 40 m thick sequence of cross and parallel bedded layers with impact sags and accretionary lapilli. Most layers

FIG. 2 — Annual mean values of minima (+) and maxima (□) temperatures for the 1926-1955 period at the station of Rome (51 m a.s.l.).

— Valori medi annui delle temperature minime (+) e massime (□) relative al periodo 1926-1955 rilevati nella stazione di Roma (51 m s.l.m.)



show inverse grading. These characteristics are typical of wet surge type activity (SHERIDAN & WOHLETZ, 1983) and Castiglione can be classified as a tuff cone (SHERIDAN & WOHLETZ, 1983) even if its morphology is not more evident as it has been covered by successive volcanic products of the final stage .

Lithostratigraphy

In order to define the lithostratigraphic sequence of the first ten meters, cores of drilling S1 from 10.60 to 4.00 m have been examined; from 4.00 m to the ground level the observations have been carried out on samples drilled by Hiller corer. Due to the thin diameter of the cores, the lithological description regarding this portion is lacking of more details.

Cores are examined in whole of their length in order to point out all possible variations in lithology, texture and colour and to check the presence of organic matter, mollusc shells and some other features.

The determination of the colour of the sediments has been performed using the Munsell Soil Colour Charts on moist sample.

The stratigraphic sequence is illustrated in Fig. 4. From the bottom to the top it can be summarized as follows:

10.60-7.80 m: medium to fine-grained brownish black muds (10YR 3/2), slightly calcareous and containing fine volcanic material. From 10.60 to 9.30 m Fe-hydroxide nodules scattered into the muds are present; their size varies from mm up to cm and they have probably a secondary origin. At 10.50 m and 8.00 m locally well preserved lacustrine mollusc shells occur. From 9.60 and 8.55 m some levels contain organic matter. From 9.40 to 9.10 m some piroxene and leucite crystals have been found. Between 8.60 and 8.40 m some bioturbation structures have been recognized.

7.80-5.30 m: massive consolidated fine-grained brownish black tuffites (10YR 2/2). From 7.70 to 7.00 m rare lacustrine mollusc shell fragments occur. Centimetric nodules similar to those observed in lower interval have been recognized at 7.30 m. In the upper part of this interval some thin burrow casts are present.

5.30-4.15 m: the sequence changes abruptly in grey calcareous muds (5Y 3/1). They are characterized by frequent bioturbation structures and by the presence of abundant mollusc shells.

4.15-4.00 m: a thin layer of dark tuffite (10 YR 2/1), containing rare continental shell mollusc fragments.

4.00-3.03 m: calcareous muds, changing in colour from grey (5 Y 4/1) to dark grey (2.5 Y 4/2) with rare mollusc fragments. The upper limit of this interval is sharp.

3.03-1.10 m: brownish black peaty muds (10 YR 3/2). The peat seems prevailing in the lower and in upper part of the interval and from 2.50 to 1.30 m the muds contain rare mollusc shell fragments. In the upper part of this interval Esu (see this paper) has described a large number of species of freshwater and land molluscs.

1.10-0.90 m: peaty bed.

0.90-0.70 m: dark grey fine-grained muds (2.5 Y 4/2) with bioturbation traces.

0.70-0.23 m: peat; thin interbeddings of calcareous muds at the base and the top and some fresh water shell molluscs occur.

0.23 m - ground level light grey calcareous muds (10 YR 7/2).

From the lithostratigraphic sequence of the first ten meters of the drilling some remarks can be drawn:

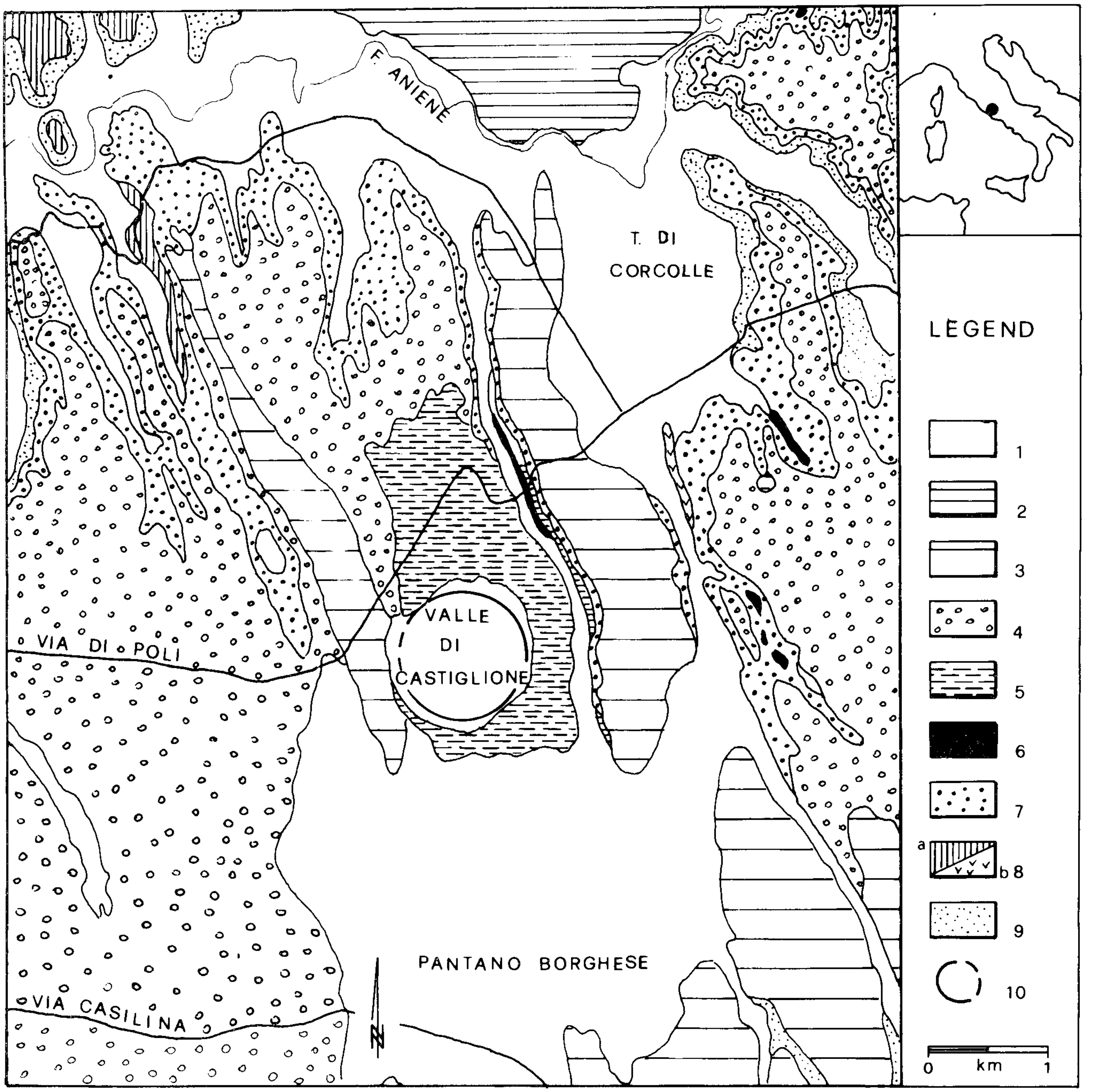


FIG. 3 — Geological sketch map of the Castiglione area. 1. Alluvia. 2. Travertine. 3. Leucititic lava flows of the Tuscolano-Artemisio final stage activity. 4. IV Tuscolano-Artemisio pyroclastic flow (0,36 m.y.; RADICATI DI BROZOLO *et alii* 1978; BERNARDI *et alii* 1982) ("Villa Senni" and "Pozzolanelle" *Auct.*). 5. Castiglione hydromagmatic unit. 6. Leucititic lava flows of the III cycle of the Tuscolano-Artemisio activity. 7. III Tuscolano-Artemisio pyroclastic flow ("Tufo lionato" e "Pozzolane medie" *Auct.*). 8. Pyroclastics (a) and lava flows (b) of the II cycle of the Tuscolano Artemisio activity. 9. II Tuscolano-Artemisio pyroclastic flow (0,54 m.y.; BERNARDI *et alii* 1982) ("Pozzolane rosse e nere" *Auct.*). 10. Castiglione crater rim.

— Schema geologico dell'area di Castiglione. 1. Alluvioni. 2. Travertini. 3. Lave leucititiche dell'attività finale dell'edificio Tuscolano artemisio. 4. IV colata piroclastica del Tuscolano-Artemisio (0,36 m.a.; RADICATI DI BROZOLO *et alii* 1978; BERNARDI *et alii* 1982) ("Villa Senni" e "Pozzolanelle" *Auct.*). 5. Unità idromagmatica di Castiglione. 6. Colate di lava leucititiche del III ciclo di attività tuscolano-artemisia. 7. III colata piroclastica di Tuscolano-Artemisio ("Tufo lionato" e "Pozzolane medie" *Auct.*). 8. Piroclastiti (a) e lave (b) del II ciclo di attività tuscolano-artemisia. 9. II colata piroclastica del Tuscolano Artemisio (0.54 m.a.; BERNARDI *et alii* 1982) ("Pozzolane rosse e nere" *Auct.*). 10. Orlo del cratere di Castiglione.

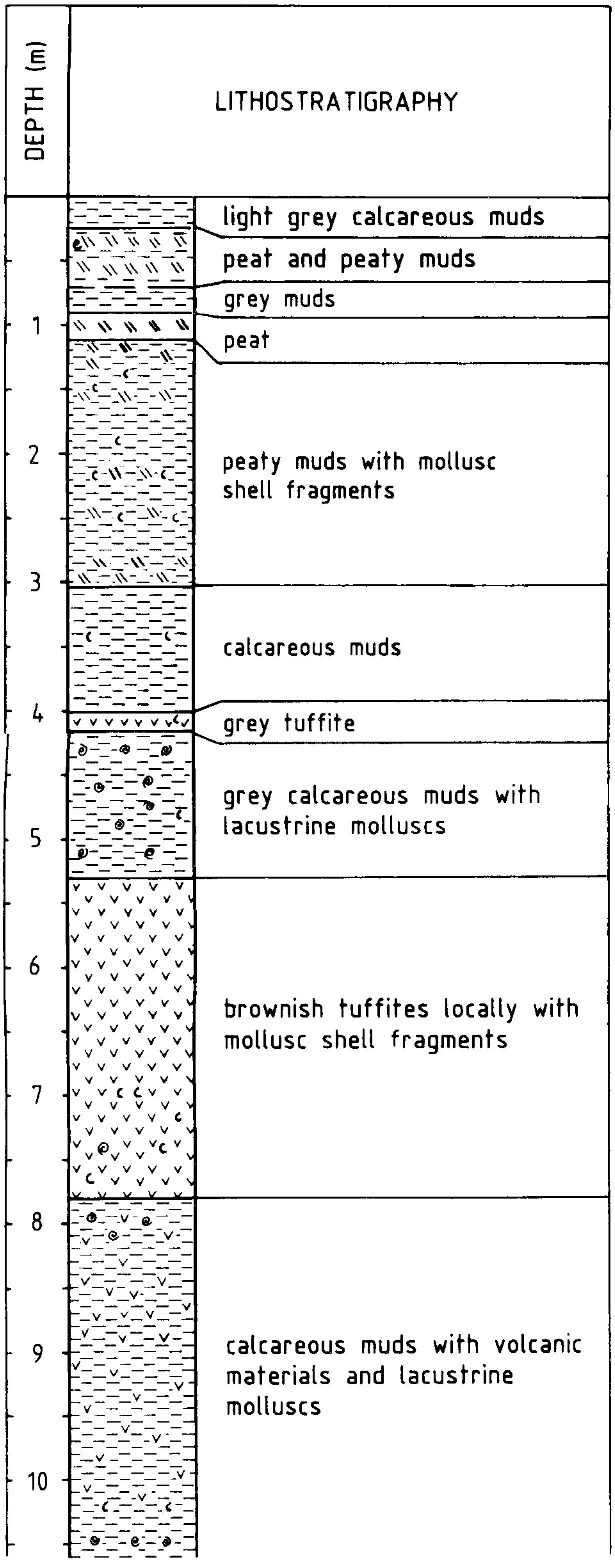


FIG. 4 — Lithostratigraphic sequence.
— Sequenza litostratigrafica.

a) the whole sequence seems to be deposited in subacqueous environment. This is inferred by the lithological features of the sediments, their textures, the occurrence of bioturbation structures and lacustrine molluscs in some parts of the sequence, even in the volcanic beds; from this it can be deduced that probably the sequence is continuous.

b) The grain size distribution along the sequence is very omogeneus and it is represented by fine-grained materials, probably deposited in low-energy shallow water environment. This is very likely for the part between 3.00 m and the ground level, where the occurrence of peat and peaty muds, consistent with higher contents of Nto and Cor in the samples analysed (Alessio *et alii,* see this paper), marks a decrease in water level and the development of a marshy environment.

c) Some portions of the sequence show the presence of calcareous component in the sediments. Actually sligthly calcareous muds occur in the lower interval between 10.60 and 7.80 m and calcareous muds in the levels between 5.30 and 3.03 m. The brownish tuffites between 7.80 and 5.30 m do not contain calcareous component. In the peaty sediments of the top of the sequence only thin interbeddings of calcareous muds have been recognized. This is in agreement with the distribution of carbonate content in the samples analysed (Alessio *et alii,* see this paper).

Radiocarbon dating and geochemistry

Lacustrine sediments represent an efficient sink for trapping organic and inorganic relics. While the former are partly autochthonous (aquatic biota) and partly allochthonous (terrestrial sources) in origin, the latter are almost totally recruited to sediment by water inflow from the drainage basin. Therefore the most straightforward approach to deal with the history of a lacustrine basin is based on the chronological reconstruction of the sediment accumulation coupled with the investigation of its fossil chemical record. Cares should be taken in interpreting dated metals- and organic matter-profiles in terms of chronological records, as diagenetic processes may give origin to a record unrepresentative of that provided by the parental materials. However, albeit limited changes of the primitive chemical record can be unnoticed, extensive diagenetic modifications are easily recognized due to the occurrence of peculiar distribution patterns for some sediment constituents.

This paper is aimed to outline the final 40,000 yr history of the ancient lake of Castiglione. In this view the upper part of the sediment suite was dated by means of ^{14}C technique and the chemical record analysed to determine the abundance of some selected elements and of one group of organic compounds (2).

(2) This research was financially supported by the Italian National Council of Researches (CNR) in the framework of the Progetto Strategico "Clima ed Ambiente dell'Area Mediterranea", Sottoprogetto "Climatologia Descrittiva". We wish to thank Prof. M. Follieri (Dipartimento di Biologia Vegetale, Università "La Sapienza", Roma) for making available the core samples; Mr. G. Morris (CBRI, Research Branch, Ottawa, Canada) for running C, N and S microanalyses; Mr. G. Aurisicchio (Centro di Studio per la Mineralogia e la Petrologia delle Formazioni Ignee, CNR, Roma) for his skilled assistance in AAS measurements and Mr. A. Occhigrossi (Dip.to di Fisica, Università "La Sapienza", Roma) for drawing the figures.

EXPERIMENTAL

All the core samples submitted to the analyses listed herein were previously dried at 110°C and finely powdered in an agate mortar.

^{14}C Chronology

Radiocarbon dating was performed on the organic matter carried by sediment samples, made rid of water - and acid - soluble constituents. These latter were removed, along with carbonate, by protracted boiling with 10% HCl. The obtained residues, after being washed and dried, were burnt in oxygen stream and the resulting carbon dioxide was used as filling gas for the proportional counters. Technique and equipment were previously reported by ALESSIO *et alii* (1970).

Humic acids

Humic acids were extracted according to the procedure recommended by the I.H.S.S. (e.g., see SCHNITZER & CALDERONI, 1985) and determined by redox titration with dichromate (KONONOVA, 1966).

Carbonate component

Analyses for carbonate were run by means of a Dietrich-Fruhling calcimeter and, for samples less than 10% in carbonate, by coulometric titration (ENGLEMANN *et alii*, 1985).

Stepwise selective dissolution of carbonate component

The method, after SPAN & GAILLARD (1986), allows the determination of carbonate-bound trace metals through a stepwise "titration" of carbonate in sediments with solutions of sodium acetate and acetic acid buffered at different pHs. These solutions are then analysed for trace metals and, to monitor carbonate dissolution, for Ca.

Metals

Fe, Mn, Cu and Zn measurements were run with a Perkin Elmer 460 AAS on solutions obtained by complete sample dissolution with a mixture of HF and $HClO_4$. The routinary techniques reported in the equipment handbook were adopted.

C, N, S

Organic carbon and total nitrogen analyses were carried out with a Carlo Erba C-N analyser on samples previously decarbonated with phosphoric acid. The method after ZHABINA & VOLKOV (1978) was chosen to analyse reduced sulfur.

RESULTS AND DISCUSSION

Radiocarbon dating

Table 1 lists conventional ^{14}C age (yr before present), $\delta^{13}C$ value and depth in core for the measured samples. Ages yielded by samples R-1314 S2/A through R-1320 S2/D, "calibrated" for temporal changes of ^{14}C in the atmosphere according to STUIVER & REIMER (1986) are also given. Data show that, close to 15.50 m in depth the sediment age approaches the older age which can be determined by the conventional ^{14}C technique.

The oldest age for the sediment suite, 41,700 ± 4700, was yielded by sample R-1554 S1/8, 15.40 to 15.60 m in depth; no ^{14}C activity was detected for six increasingly deeper core samples (R-1555 S1/9 through R-1317 S1/71a).

At first glance the measured ages, spanning from

TABLE 1
CONVENTIONAL ^{14}C AGES AND $\delta^{13}C$ VALUES FOR THE STUDIED SAMPLES

Sample (file)	Depth in core (m)	^{14}C age (yr BP)	Calibrated age (yr BP)	$\delta^{13}C$ (‰)
R-1314 S1/2A	1.15 - 1.25	3480 ± 50	3692 - 3835	- 30.0
R-1318 S2/A	1.90 - 2.00	7130 ± 75	7910 - 8031	- 34.3
R-1319 S2/C	2.09 - 2.19	4490 ± 65	4990 - 5293	- 25.1
R-1320 S2/C	2.19 - 2.25	5280 ± 65	5950 - 6181	- 22.8
R-1321 S2/D	3.31 - 3.40	9200 ± 200		- 22.4
R-1331 S2/E	4.30 - 4.50	14,220 ± 145		- 24.8
R-1332 S2/FS1	5.13 - 5.50	20,300 ± 700		- 24.4
R-1547 S2/1	7.17 - 7.30	24,900 ± 370		- 22.0
R-1548 S2/2	7.30 - 7.50	25,800 ± 600		- 22.0
R-1549 S1/3	9.85 - 10.00	31,300 ± 900		- 24.9
R-1550 S1/4	10.00 - 10.10	27,200 ± 1500		- 24.6
R-1551 S1/5	10.10 - 10.25	32,900 ± 1600		- 24.3
R-1552 S1/6	15.10 - 15.20	> 34,000		- 19.4
R-1553 S1/7	15.20 - 15.40	> 43,000		- 20.3
R-1554 S1/8	15.40 - 15.60	41,000 ± 4700		- 19.6
R-1555 S1/9	17.00 - 17.10	> 43,000		- 17.7
R-1556 S1/10	17.10 - 17.20	> 43,000		- 17.7
R-1557 S1/11	17.20 - 17.40	> 43,000		- 18.5
R-1315 S1/23	19.20 - 19.30	> 40,000		- 23.3
R-1316 S1/53	41.60 - 41.70	> 38,000		nd
R-1317 S1/71a	55.08 - 55.20	> 40,000		- 29.0

about 3500 to nearly 42,000 yr BP, provide evidence that the accumulation on the lake bottom of the final 15.60 m of the sedimentary suite lasted from upper Pleistocene through Holocene. The ^{14}C sequence established from the core samples is consistent with stratigraphy except for a trouble, just feebly hinted by the 31,300 ± 900 yr BP date (R-1549 S1/3) and a significant dating reversal which occurs at about 2.00 m in depth (R-1318 S1/A). Such a discrepancy of several thousand years can result from incorporation in sediment of either older organic material from terrestrial inwash or important amounts of aquatic biota which, instead of having metabolized atmospheric CO_2, took up that, ^{14}C-depleted, supplied to the lake water by sources other than atmosphere (hardwater effect). According to the geology of the studied area (see Fig. 3), both volcanic exhalation and travertine dissolution could have provided important amounts of ^{14}C-lacking CO_2. However it is biased results, chi-square test for crossplot of Figure 1 revealed that data points fit very poorly the least squares regression line, this implying significant changes in sedimentation rate. In fact, the mean sedimentation rate calculated for each dated interval ranged from 0.12 to 0.93 mm/yr.

Finally, it is recalled that ^{14}C dating of a sediment relies upon the assumption that the date of deposition should be strictly associated with its ^{14}C age. On the contrary, at Castiglione it is very likely that the lake bottom received both autochthonous and allochthonous organic matter inputs. These latter, albeit to a variable extent, could be resulted by preexisting materials already significantly old (e.g., humus-bearing leachates of topsoil) at the time of their trapping in sediment. Moreover, the lack of any reliable material for ^{14}C dating (e.g., wood or charcoal) in the core samples, ruled out the possibility to evaluate the validity of the results. Therefore

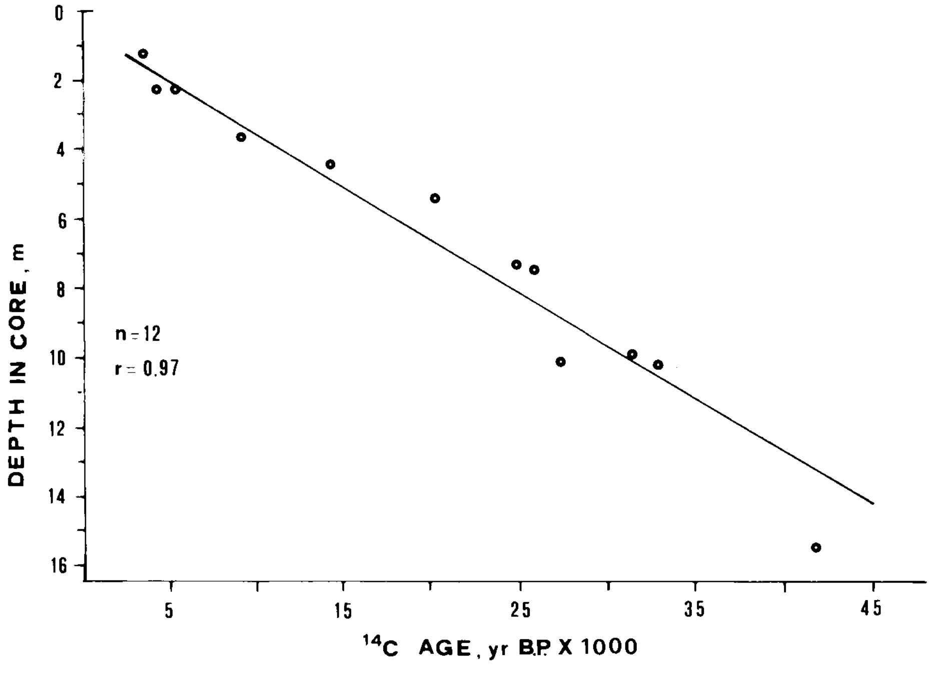


FIG. 5 — ^{14}C age vs. depth relationship for the dated samples. Least squares regression line is shown.

— Relazione età ^{14}C - profondità dei campioni. Si noti il notevole grado di correlazione tra le due variabili.

a difficult task to distinguish between the above sources of error and, in this respect, it is likely that further studies, including the carbon number distribution pattern for *n*-alkanes in sediment, would provide valuable information.

Fig. 5 points out the very good, almost proportional correlation (r=0.97) between ^{14}C age and depth; sample R-1318 S2/A was not included for its age quite inconsistent with stratigraphy. Due to the striking high extent of relationship between the two variables, it could seem reasonable to assume constant sedimentation rate throughout the oldest and younghest date of the core. According to this crude approximation the mean sedimentation rate over the about 39,000 yr time-span resulted close to 0.3 mm/yr. However, apart from any consideration on the importance of compactation, dehydration and changes of sediment composition in producing it is stressed that, as far as absolute chronology is concerned, the ages obtained should be cautiously interpreted and, in this respect, their most immediate and proper use is to serve for implementing a relative time-scale for the sedimentary column.

Hitherto, in the authors knowledge only one paper after BUDASSI & MORTARI (1986) dealt with the chronology of the sediments from Castiglione. In this work, on the basis of geotechnical investigations performed on samples from the same cores used in the present study, it is inferred the occurrence, close to 35 m in depth, of an erosion surface. According to the author the sediments overlying such 35 m deep uncomformity are younger then 25,000 yr. However, this tentative age evaluation conflicts with the ^{14}C chronostratigraphy, as this latter yields an age of 41,700 yr BP at a depth in core of only 14.40 m.

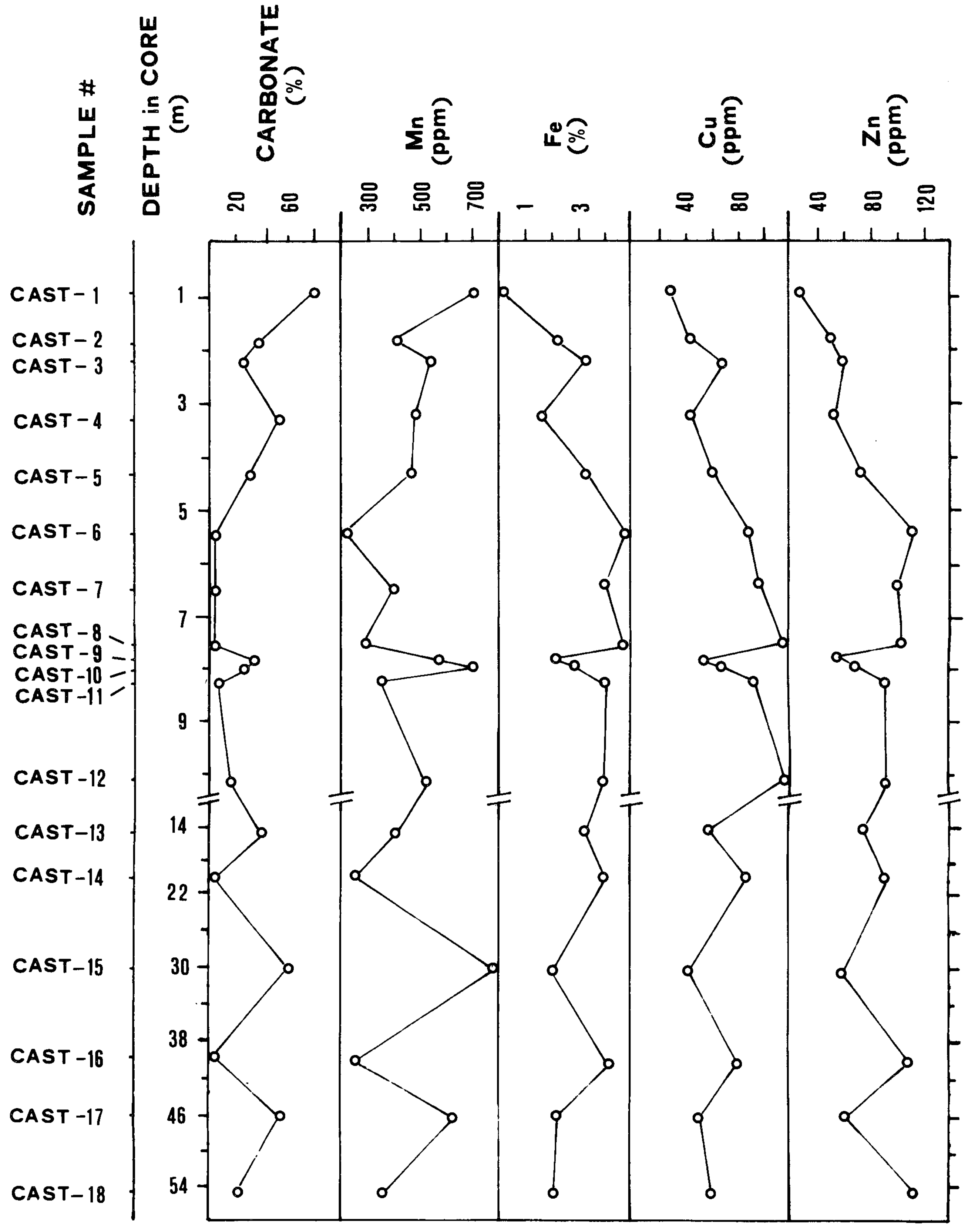


FIG. 6 — Profiles showing carbonate, Mn, Fe, Cu and Zn dependence to depth.

— Variazioni delle abbondanze della frazione carbonatica, Mn, Fe, Cu e Zn con la profondità.

Geochemistry of carbonate, Mn, Fe, Cu and Zn

Table 2 lists the samples analysed to investigate the chemical record of the sediment column. Profiles in Fig. 6 show that carbonate, Mn, Fe, Cu and Zn abundances range betwen 0.3 and 79.4%, 207 and 575 ppm, 0.64 and 4.85%, 30 and 122 ppm, 25 and 113 ppm, respectively, thus reflecting that the conditions governing the input to the lake bottom changed with time. At first glance the profiles point out that Fe, Cu and Zn display a reverse distribution pattern relative to carbonate and Mn and,

TABLE 2
DEPTHS IN CORE, HUMIC ACIDS (HA) CONTENTS AND Cor / Nto RATIOS FOR THE ANALYSED SAMPLES

Sample	Depth in core (m)	HA* (%)	C_{or}/N_{to}
CAST-1	1.00- 1.10	0.075	12.2
CAST-2	1.95- 1.98	0.060	15.0
CAST-3	2.09- 2.19	0.015	18.3
CAST-4	3.31- 3.40	0.030	14.5
CAST-5	4.40- 4.50	0.028	18.2
CAST-6	5.40- 5.50	0.072	22.6
CAST-7	6.50- 6.60	0.054	15.6
CAST-8	7.60- 7.70	0.035	11.1
CAST-9	7.80- 7.90	0.080	12.6
CAST-10	7.90- 8.00	0.060	12.0
CAST-11	8.20- 8.30	0.020	13.3
CAST-12	10.20-10.30	0.040	6.8
CAST-13	15.05-15.13	0.058	12.0
CAST-14	19.90-20.02	0.012	12.7
CAST-15	30.20-30.30	0.019	24.6
CAST-16	40.15-40.25	0.045	14.1
CAST-17	46.10-46.25	0.029	3.2
CAST-18	55.25-55.29	0.045	16.5

* on moisture - and carbonate - free basis.

in this respect, it is strongly suggested that different pathways of recruitement to the sediment were involved. Fig. 7 shows a fair good correlation between detrital content (3) and a) Fe (r=0.89), b) (r=0.84) and c) Zn (r=0.88). As the shown least squares regression lines yield low positive intercepts on the axes of metals concentration (Fe=0.25%, Cu = Zn = 20 ppm), it is argued that mineral detritus is far the main source for the three elements. In turn, only subordinate amounts of these latter, likely accounted for by solution transport and post-depositional remobilization from the bottom sediments, are held by carbonate and (or) organic matter.

Fig. 8 shows that Mn behaves antithetically with respect to Fe, Cu and Zn, because it exhibits a negative dependence to detritic content and a reasonable

(3) Clastic mineral content was calculated by subtracting the carbonate and organic matter (1.87 x organic carbon) contents from 100%. The factor to evaluate organic matter content relies upon the rough assumption that the whole organic matter is made up by kerogene and (or) proto-kerogene.

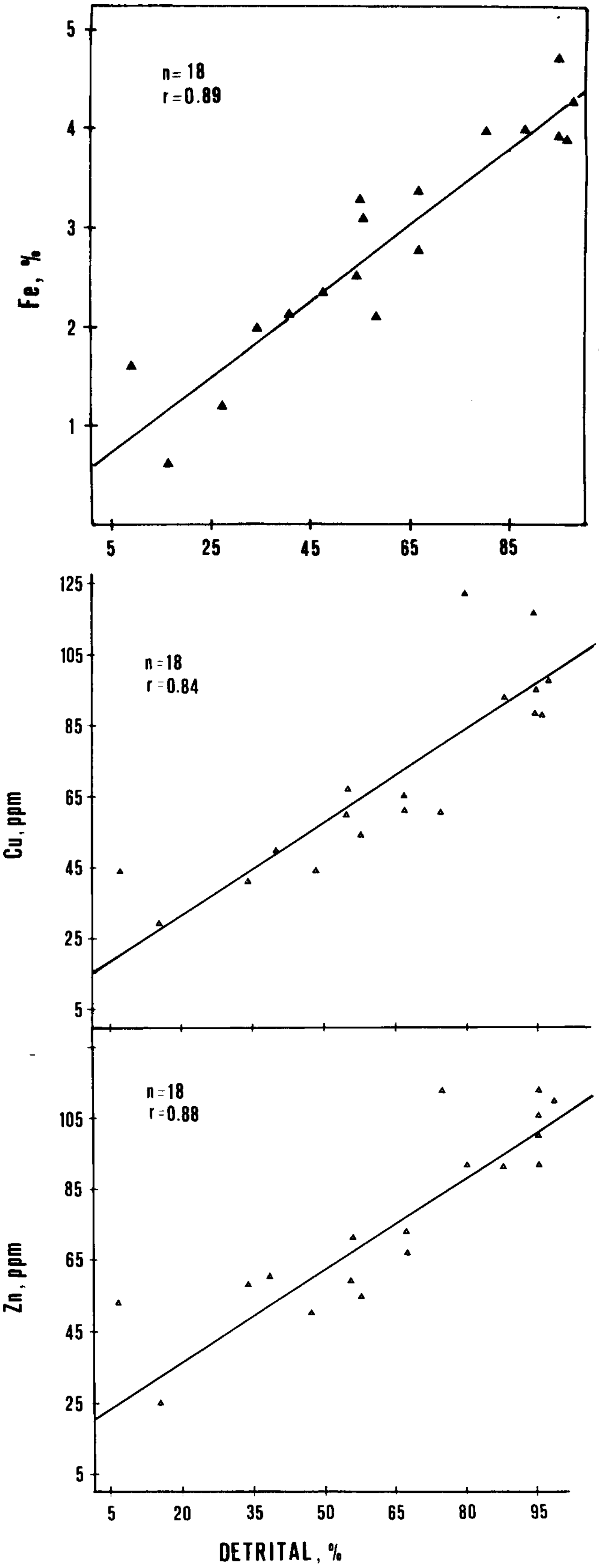


FIG. 7 — Relationship between detrital content and a) Fe, b) Cu and c) Zn for the studied samples. Least squares regression line is shown for each crossplot.

— Relazione tra il contenuto detritico dei sedimenti analizzati e a) Fe, b) Cu e c) Zn. I rispettivi coefficienti di correlazione sono riportati.

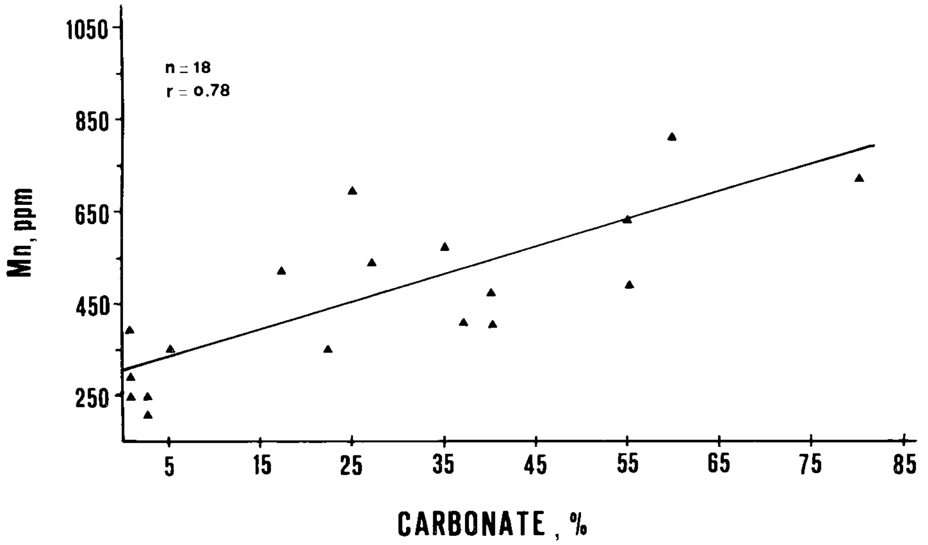


FIG. 8 — Carbonate *vs.* Mn crossplot. Least squares regression line is shown.

— Relazione tra le abbondanze del Mn e della frazione carbonatica per i campioni analizzati.

positive correlation (r=0.78) with carbonate. Such finding was further supported by the results of carbonate-selective leaching trials (SPAN & GAILLARD, 1986). Figure 5 shows, as an example, the results for sample CAST-9 and points out the close relationship between the amounts of Mn and Ca leached through each "titration" step, thus confirming the found Mn dependence to carbonate. Furthermore, carbonate-leaching trials revealed that the amounts of Mn carried by carbonate are always less than the bulk of the element, this being in fair agreement with the positive intercept on the Mn-axis yielded by the least squares regression line shown in Mn *vs.* carbonate plot (Fig. 9). However, while field evidence suggests that the detrital load supplied to the lake bottom through weathering of volcanites represented

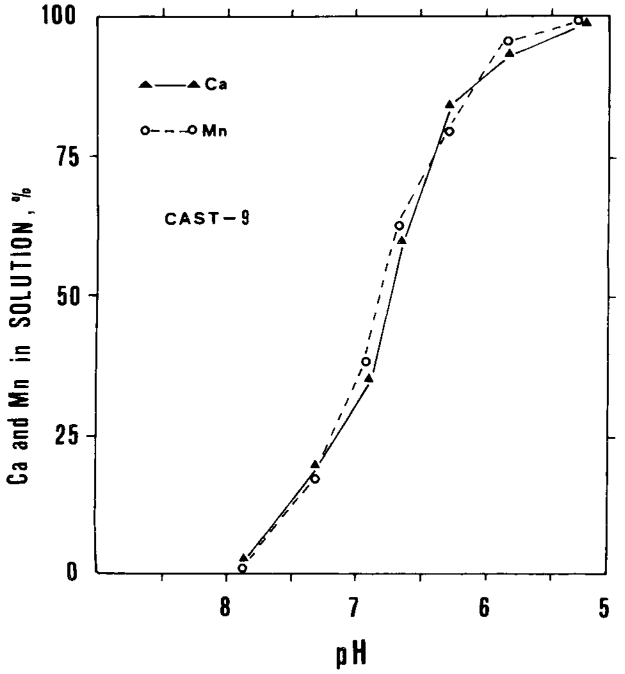


FIG. 9 — Ca and Mn contents measured during the carbonate-selective leaching for sample CAST-9. Ca and Mn are given as % of their respective amounts leached at pH 5.4.

— Risultati della dissoluzione selettiva della frazione carbonatica per il campione CAST-9. Si osservi l'incremento parallelo del Ca e del Mn in soluzione durante le varie fasi della "titolazione".

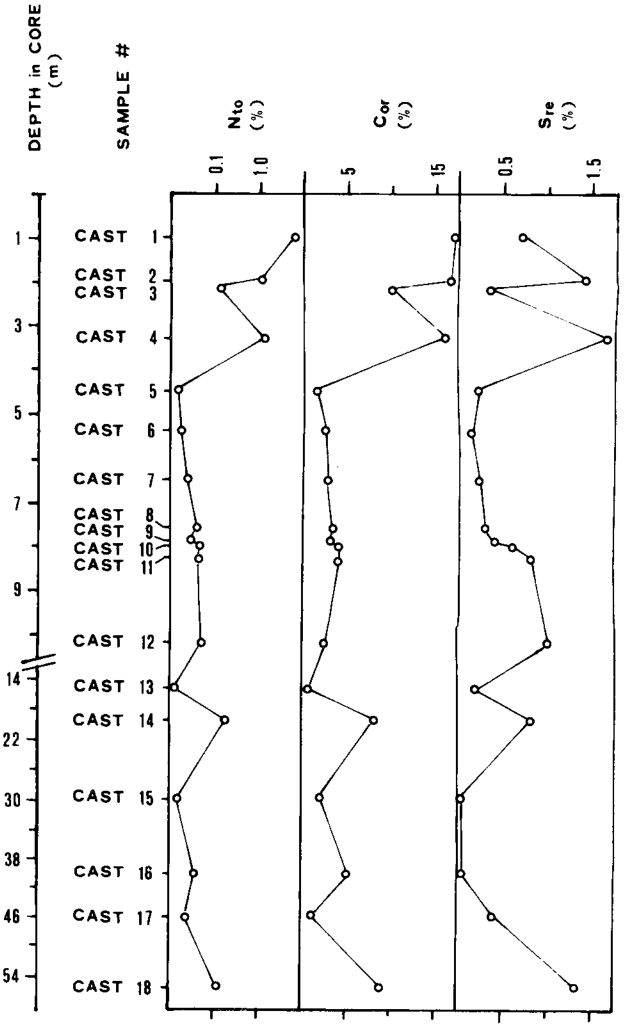


FIG. 10 — Profiles for total nitrogen (Nto), organic carbon (Cor) and reduced sulfur (Sre) throughout the sediment core.

— Abbondanze dell'azoto totale (Nto), carbonio organico (Cor) e zolfo ridotto (Sre) nei sedimenti carotati.

the most likely source of Mn, by contrast analytical data show that the element is mostly carried by carbonate. In this respect it could be inferred that post-depositional mobilization of Mn from detritus, by controlling the availability of Mn (II) in solution, played an important role in the origin of Mn-enriched carbonate. Such process, which is consistent with the findings after ROBBINS & CALLENDER (1975) and BERNER (1980) on the post-depositional leaching of Mn, it is mainly constrained by the narrow Eh-pH range required to a) bring Mn into solution and keep it as Mn (II) and, b) allow carbonate precipitation. As it is shown in the next section, at Castiglione sediments accumulated under anoxic conditions, this implying that, due to the impressive Eh drop subsequently to oxygen exhaustion *via* oxidative decay of organic matter, porewater in sediment could mobilize and hold Mn (II) (WILSON *et alii*, 1985). Interestingly, according to CARIGNAN & NRIAGU (1985), the re-mobilization of Mn is parallelled by such a pH and ΣCO_2 increase that precipitation of $CaCO_3$ and, subordinately $MnCO_3$, may occur.

Geochemistry of total N (Nto), Organic C (Cor), Reduced S (Sre) and Humic Acids (HA)

Profiles in Fig. 10 show that Nto, Cor and Sre contents range between 0.07 and 1.43%, 0.62 and 17.45%, 0.003 and 1.69%, respectively. Nto and Cor exhibit the higher contents within the upper 4 m of the sediment column (samples CAST-1 through CAST-4). It is very likely that this represents a primitive feature of the geochemical record which depended on increased organic matter input. In fact, the sharp fall in Cor and Nto contents from sample CAST-4 to CAST-5 can be hardly accounted for by diagenetic decay of the organic matter. Neither Cor nor Nto are depth-depending and, as diagenesis as a rule leads towards a continuous decrease of the two elements with time, inference is made that changes in the importance of the organic matter load overshadowed the effects of diagenetic decay.

Fig. 11 shows the excellent positive correlation between Cor and Nto (r=0.97). Such a feature strongly suggests that neither the nature nor the decaying pathways of the parental organic matter recruited to the sediment underwent dramatic changes with time.

Cor far exceeding Sre, as well as the lack of correlation between the two elements, are peculiar features for sediments from freshwater basins where sedimentation under anoxic conditions occurred.

Results for HA determination, ranging from 0.010 to 0.080% (see Table 2), are of some concern because markedly low for lacustrine, organic matter-enriched sediments from an anoxic (viz., well preserving) basin. Higher HA contents could be expected by considering that up to 40% of C in unhumified, fresh vegetal debris is extractable as compounds operationally defined HA (ERTEL & HEDGES, 1984). It is also noticed that the typical increase of HA with depth, produced by organic matter humification during diagenesis, is lacking and, Cor/Nto ratios (listed in Table 2), ranging between 3.2 (CAST-17) and 24.6 (CAST-15), were rather high. According to GREENLAND & FORD

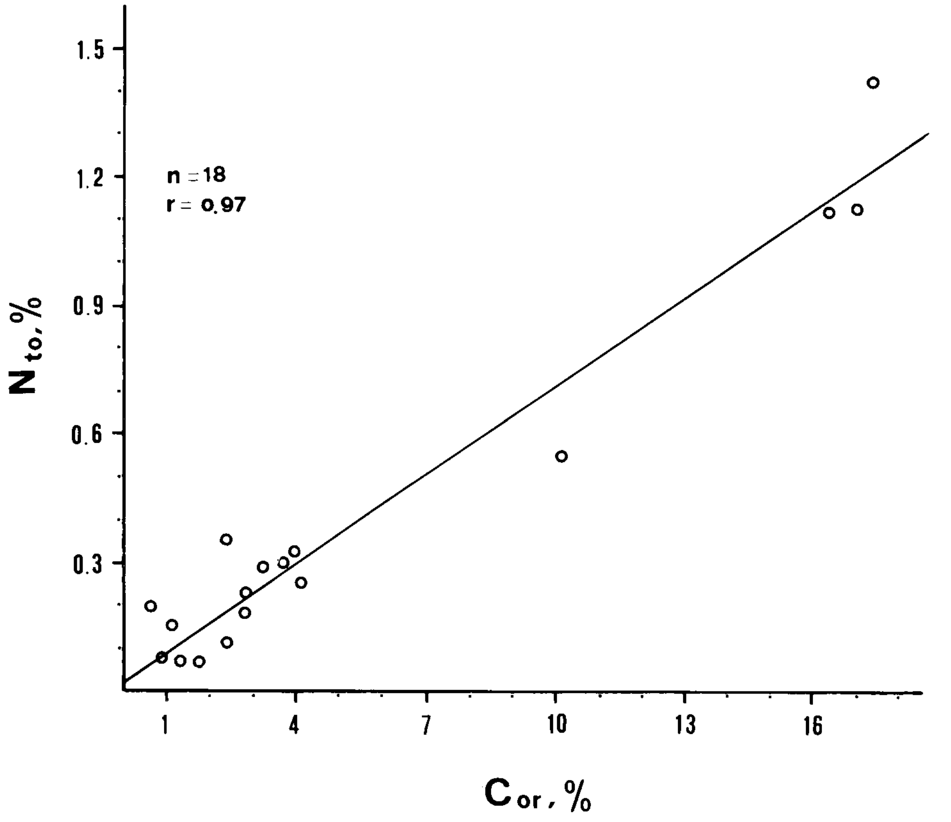


FIG. 11 — Cor *vs.* Nto relationship for the studied samples. A pronounced clustering is shown by samples > 3.40 m in depth.

— Diagramma Cor-Nto per il complesso delle sostanze organiche contenute nei campioni. Osservare come i campioni da profondità > 3.40 m si differenziano dai rimanenti.

(1964), high Cor contents and Cor/Nto ratios, coupled with low HA contents (not positively correlated with depth) are features that strongly point to the occurrence of well-preserved, scarcely or not at all decayed organic remnants in sediment. In addition, the low HA contents suggest that these compounds acted as reactive organic matter and underwent depletion to a significant extent, first in oxic and then in anoxic conditions, through oxidative decay.

Sre was detected in all the samples and shows (see Fig. 10) an erratic distribution with depth, likely because it is syngenetic with the sediment instead of being diagenetic in origin. In this respect its abundance could represent a primitive feature of the fossil chemical record. As Sre production implies sulphate reduction under anoxic conditions and in the presence of organic matter acting as electron donor, it is inferred that the lake bottom received a reactive Cor input far exceeding that required to exhaust the oxygen at the sediment-water interface.

Data after MULLER & MANGINI (1980) show that, regardless of organic input and sulphate concentration, Sre may only form at sedimentation rate $\geq 0.01 \div 0.04$ mm/yr, thus quite compatible with the occurrence of Sre in the analysed sediment column.

Fig. 12 shows a Cor *vs.* Sre crossplot divided into three sedimentation environments according to literature data. In addition to the lack of correlation between the two variables it is shown that data

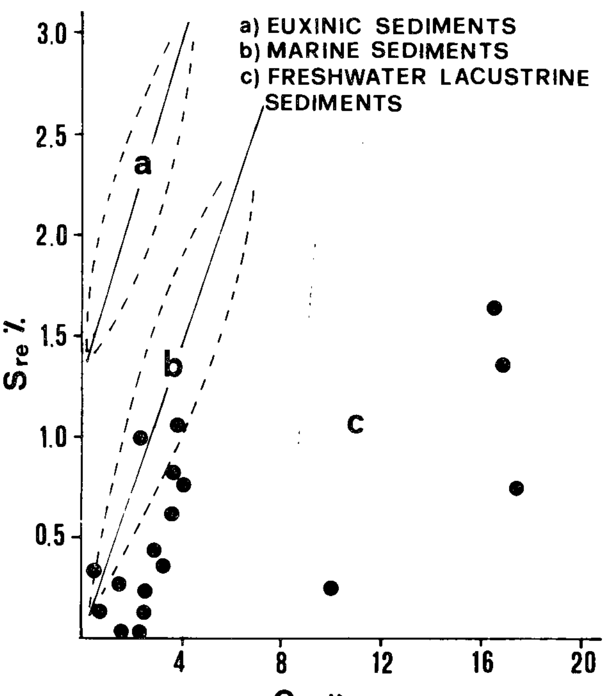


FIG. 12 — Cor *vs.* Sre crossplot. Envelops for a) euxinic, b) marine and c) freshwater lacustrine sediments are depicted (data after HIRST, 1974 and BERNER & RAISWELL, 1983).

— Diagramma Sre-Cor per i campioni studiati. La suddivisione nei tre ambienti di sedimentazione (euxinico, marino e lacustre dulcicolo) è stata ricavata dai dati di HIRST (1974) e di BERNER & RAISWELL (1983).

points for samples > 10% in Cor are markedly off relative to those samples < 4% in Cor, this leading to argue that the upper 3.40 m of the sediment suite experienced a dramatic increase of organic matter input. As this trend could not be matched by oxygen and sulphate contents at the water-sediment interface, only limited amounts of the organic matter load underwent oxidative decay.

Correlation analysis for the ^{14}C age *vs.* sample depth relationship

As ^{14}C shows a good, positive correlation (r =0.97) with sample depth it is stimulating to determine a continuous function to be used for a proper interpolation of the experimental data. In this view the accumulation rate of sediments in the Castiglione basin over the last 40,000 yr is modeled with the last squares method applied to a polynomial and by assuming the degree of the function according to the minimum X^2 criterion. According to such approach, it was found that for depths in core ranging from 1 to 16 m the best fit of the experimental data is expressed by a 4th order polynomial, its equation being as follows:

$$t = 3.0590 + 1.0799\,(d\text{-}d_0) + 1.2693\,(d\text{-}d_0)^2 - 0.1778\,(d\text{-}d_0)^3 + 0.006785\,(d\text{-}d_0)^4,$$

where t = ^{14}C age (Kyr BP), d = depth (m), d_0 depth (1.2 m) of the uppermost dated sample.

Fig. 13, showing the regression curve along with the experimental data, points out the fairly good fitting obtained. Therefore it appears that the curve represents a useful tool to relate samples of whatever depth in core with ^{14}C age.

The proposed ^{14}C age *vs.* depth function can also be applied for calculating the sedimentation rate (V = d/t) at any given depth in core, this allowing a theoretical reconstruction of its pattern. The sedimentation rate, V, is given by the following equation:

$$V = \frac{1}{1.0799+2.5386(d\text{-}d_0)-0.5334(d\text{-}d_0)^2+0.0271(d\text{-}d_0)^3}$$

which is represented in Fig. 14. The plot shows that V exhibits a sharp peak at about 31 Kyr BP, then is almost steady over a long time span and finally drops significantly starting from 5 up to 3 Kyr BP.

Faunistic analysis

METHODOLOGY

Out of the examined core, the continental sediments laying down to 10 metres of depth (from 0 m, land level, to –10 m) have undergone paleontological analysis to point out the slightest variations in the faunal component over the paleoenvironmental evolution of the basin. The analysis were carried out on decimetric samples, sometimes also at shorter intervals.

There are three intervals of discontinuity in the sedimentary material collected from drilling (from

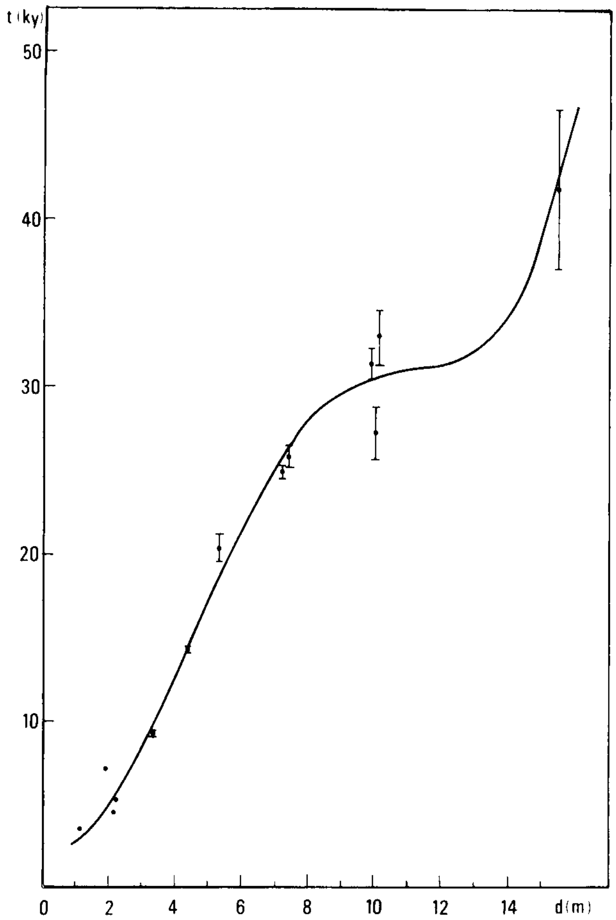


FIG. 13 — Radiocarbon age *vs.* drilling depth. The experimental errors are 1 standard deviation.

— Andamento della età radiocarbonio in funzione della profondità del sondaggio. I punti sperimentali sono corredati da un errore pari a 1 Σ.

2.30 to 2.60 m, from 2.67 to 3.31 m and from 8.75 to 9 m in depth) whose paleontological data are missing.

The examined samples come from either borings 1 (S 1) and 2 (S 2), which turned out to be equivalent in faunal assemblage.

The organic fauna remains, found at different fossiliferous layers, belong to the following taxa: Crustacea (Ostracoda), Mollusca (Gastropoda and Bivalvia), Pisces, Amphibia (Anura), Reptilia (Squamata) and Mammalia (Rodentia). In addition to these, gyrogonites of Characeae were found among fossil plant remains.

Species classification was effected on molluscs (land and fresh-water species) and on vertebrates (except for fishes) (4); the other fossil taxa are however reported for each level in the whole sedimentary sequence (Fig. 15). Twenty-five mollusc species were found out in the sequence examined:

Gastropoda-Prosobranchia: *Valvata (Cincinna) piscinalis* (MÜLLER), *Valvata (Valvata) cristata* (MÜLLER), *Bithynia leachi* (SHEPPARD) with opercula, *Pseudamnicola moussoni* (CALCARA); Pulmonata: *Carychium minimum* MÜLLER, *Physa fontinalis* (LINNAEUS), *Lymnaea (Stagnicola) palustris* (MÜLLER), *Lymnaea (Radix) peregra* (MÜLLER), *Lymnaea (Galba) truncatula* (MÜLLER), *Planorbis planorbis* (LINNAEUS), *Anisus spirorbis* (LINNAEUS), *Gyraulus laevis* (ALDER), *Armiger crista* (LINNAEUS), *Hippeutis complanatus* (LINNAEUS), *Acroloxus lacustris* (LINNAEUS), *Succinea (Succinella) oblonga* (DRAPARNAUD), *Oxyloma elegans* (RISSO), *Vertigo (Vertilla) angustior* JEFFREYS, *Vertigo (Vertigo) antivertigo* (DRAPARNAUD), *Vertigo (Vertigo) pygmaea* (DRAPARNAUD), *Vallonia enniensis* (GREDLER), *Vitrea botterii* (PFEIFFER), *Caecilioides acicula* (MÜLLER), *Perforatella* sp.

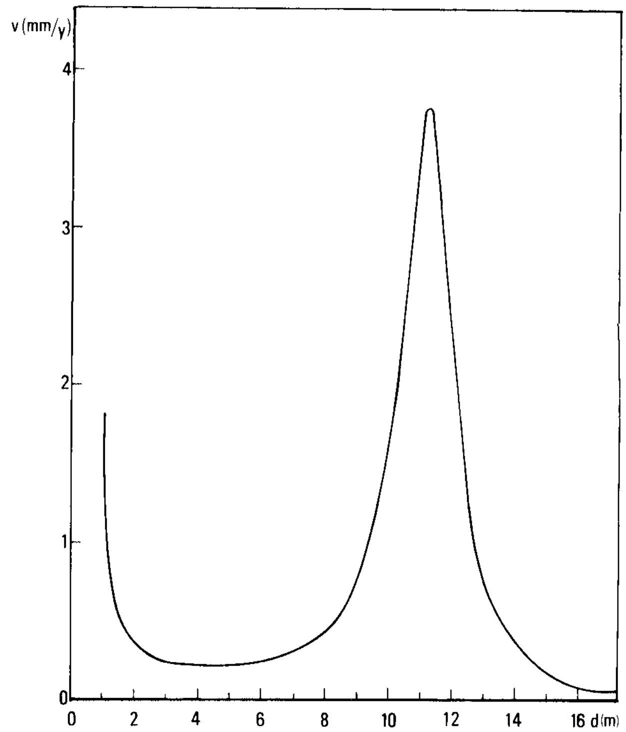


FIG. 14 — Sedimentation rate (mm/yr) *vs.* drilling depth.

— Andamento della velocità di sedimentazione (mm/anno) in funzione della profondità del sondaggio.

Bivalvia: *Pisidium* cfr. *nitidum* JENYNS.

Molluscan fauna, very abundant at some levels, is mostly well preserved. The frequency of the malacofauna at various levels is represented by a diagram in which the percentage of each species is considered in comparison with the sediment fraction of each sample, including in this also the other taxa above mentioned. The percentage of the other taxa is calculated in its turn compared with the residual sediment (Fig. 15).

On the basis of the homogeneity of the faunal association of subsequent levels it is possible to subdivide the extension of the drilling into a certain

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(4) Thanks are due to Dr. T. Kotsakis of Centro di Studio per la Geologia dell'Italia Centrale, C.N.R., Roma, for the identification of vertebrate remains.

FIG. 15 — Diagram of frequency of land and fresh-water molluscan species and other taxa. Percentages for molluscan fauna and the other taxa are not comparable. Further explanations in text. Marks line indicates percentages lower than 5%.

— Diagramma di frequenza delle specie di molluschi terrestri e di acqua dolce e degli altri taxa. La percentuale tra la fauna malacologica e gli altri taxa non è comparabile. Ulteriori spiegazioni nel testo. La linea tratteggiata indica percentuali inferiori al 5%.

number of intervals (A, B, C, D, E, F, G), each of them is different from the immediately upper and lower ones. Some intervals can in their turn be split into subintervals according to minor variations of the faunal differentiation.

THE FOSSILIFEROUS LAYERS

From the bottom to the top of the drilling several intervals are recognized:

A) From 10 to 6.80 m: molluscs are present within a very limited tract; more or less evenly spread ostracods and fishes remains (vertebrae, teeth and skeletal fragments), rare amphibians (anurans) and sporadic land vertebrates (fragments and vertebrae of rodents) are found.

In detail the faunal analysis reveals from 10 to 9.70 m a scarce presence of ostracods, fishes and unrecognizable remains of land vertebrates. From 9.70 to 9.10 m the sediment is enriched with ostracods (25%) and also fish-remains, after a short desappearance, become frequent (mostly from 9.30 to 9.20 m). From 9 to 8.75 m the drilled sediment is missing. From 8.50 to 7.70 m there is again a sporadic presence of ostracods (5%), at 8.20 m a minimum percentage of amphibians (anurans) is found (less than 5%), fishes are completely missing at some depth (from 8.40 to 8.20 m) and increase slightly with the occurrence of anurans and with the decrease of ostracods, then they are more or less evenly present up to the end of the interval A. From 7.70 to 6.80 m molluscs (lacustrine gastropods and bivalves) are found, ostracods and amphibians (anura) are mostly scanty (less than 5%), while fishes are more frequent (15-20%).

Specially molluscs are very rare, only three species are present: at 7.70 m a few specimens of *G. laevis* are found; a little over (at 7.50 m) it is sided by a small percentage of *L. peregra* and later by the small bivalve *P.* cfr. *nitidum* which, present in a small percentage, is confined within a very thin layer of sediments (from 7.25 to 7.15 m).

The few species of molluscs which have been collected reveal an environment of stagnant or scarcely running water.

From 7.15 to 6.80 m molluscs disappear and amphibians and fishes are still present eventhough sporadically. Towards the end of the interval, only a few remains of land vertebrates (reptiles, *Lacerta viridis* (LAURENTI), and rodents, *Pitymys* sp.) are found.

In the interval A it is possible to distinguish at least two subintervals, which from a paleoecological point of view can be framed as follows:

1) from 10 to 7.70 m, a fluctuating semi-arid phase is recognized; molluscs are absent (while they are present in lower layers, from 10.30 m to 11 m, here not considered) and mention should be made also of the tendency to decrease of the ostracods (which, at intervals, are completely missing) and of the overall scarcity of amphibians and of the small percentage of fishes;

2) from 7.70 to 6.80 m, the presence of the two species and, for a short time, of the three species of molluscs, eventhough scarcely represented, shows a climatic moist fluctuation in the generally dry interval A.

The whole interval seems to indicate a mostly cold and semi-arid climatic phase as suggested by the scarcity of lacustrine species.

B) From 6.80 to 5.30 m: completely sterile interval.

In comparison with the previous phase a climatic condition of heavy aridity is remarked.

C) From 5.30 to 4.10 m: conspicuous presence of specimens of fresh-water molluscs and ostracods. Amphibians (*Rana* sp., *Bufo* sp.), fishes, land vertebrates (reptiles and micromammals) and Characeae are rather rare.

In this interval 8 species of fresh-water gastropods are reported: *L. palustris, L. peregra, L. truncatula, P. planorbis, A. spirorbis, G. laevis, A. crista, A. lacustris.* In the whole interval there is abundance of gastropod specimens belonging to few species.

Mainly in the first part of this interval (up to –4,70 m) faunistic conditions of oligotypy are settled: the number of molluscan species discovered is rather low indeed. Mention should be made of the rare presence of *L. truncatula* at lower levels (from 5.30 to 5.20 m) in association with three more fully represented species (*L. peregra, G. laevis, A. crista*) and with one species scanty present too (*A. spirorbis*). In the immediately upper layers (from 5.20 to 4.85 m) the number of molluscs represented is restricted to three species, later they increase in number.

In the interval C the presence of aquatic molluscs certainly shows a less arid phase with slight variations in comparison with the previous ones in which they were absent at all. Nevertheless the malacological oligotypy testifies a still cold climatic phase, eventhough not so cold as the previous ones.

Moreover in the first part of the interval (from 4.85 to 4.80 m) concomitantly to the lower number of molluscan species and to the absence of amphibians and fishes, the presence of a rodent of alpine prairy, *Microtus nivalis* (MARTINS), is extremely meaningfull and emphasizes the cold climatic character of this phase.

The malacological association recorded suggests the presence of a lacustrine environment with a shallow water-body with slowly running or stagnant waters and with a rich aquatic vegetation. Two of the species found, *A. spirorbis* and *A. crista,* are often present in periodic waters so withstanding also alternate dry conditions (GIROD *et alii,* 1980).

D) From 4.10 to 3.60 m: malacofauna is absent; fishes, amphibians (anura, *Rana* sp.) and fragments of undetermined land microvertebrates (rodents) are found in a very small percentage.

The total disappearance of lacustrine molluscs and the scantiness of the other aquatic organisms suggest steppic conditions.

E) From 3.60 to 2.30 m: fresh-water molluscs are present again in a small percentage; ostracods (25%) and oogones of Characeae (less than 10%) are reported too.

Molluscs are represented here only by three species of gastropods living in very shallow and still waters (*L. peregra, G. laevis* and *A. crista*) and by a small bivalve (*P.* cfr. *nitidum*). The frequency of the specimens is very scarce also.

Within this interval, from 3.31 to 2.30 m, samples are missing except for a small part (7 cm from 2.67 to 2.60 m) where molluscs are not present, while ostracods (50%) predominate and a small percentage of amphibians (less than 10%) and a larger percentage of fishes (30%) are represented.

The first part of the interval introduces a more humid environment than in the previous ones, but the lack of more data does not allow to assume the evolution of faunal association in this interval.

F) From 2.30 to 1.20 m: a large number of species of fresh-water and land molluscs is present, while ostracods, aquatic and land vertebrates, fishes and Characeae are scanty or discontinuous.

In this interval several species of fresh-water gastropods are sided by land species, most of which appear for the first time in the examined part of the drilling, thus pointing out a clear sharp change in environment as compared to the previous intervals.

Fresh-water gastropods are represented by nine species: *V. cristata, B. leachi* with opercula, *P. moussoni, P. fontinalis, L. peregra, L. truncatula, A. spirorbis, G. laevis, A. crista;* land snails are represented by eight species: *C. minimum, S. oblonga, O. elegans, V. angustior, V. antivertigo, V. pygmaea, V. enniensis, Perforatella* sp. In the final levels of this interval also the small bivalve *P.* cfr. *nitidum* is found.

This malacological association suggests a marshy environment. The fresh-water species found are connected to shallow, stagnant waters, rich in vegetation, and the land species are typical of extremely humid environment, even permanently wet; only *V. pygmaea* is an occasional species in marshes being characteristic of calcareous grassy places (LOŽEK, 1964; PUISSÉGUR, 1976; KERNEY & CAMERON, 1979).

This interval, from a climatic point of view, can be ascribed to a warm and damp period.

G) From 1.20 to 0.10 m: several species of fresh-water and land molluscs are present, with a higher percentage of aquatic species; high percentage of ostracods and disappearance of other taxa (amphibians, fishes, land vertebrates and Characeae) are recognized.

Gastropods are here represented by few specimens but by many species; there are 10 fresh-water species: *V. piscinalis, V. cristata, B. leachi* with opercula, *P. moussoni, L. peregra, L. truncatula, A. spirorbis, G. albus, H. companatus, A. lacustris,* two of which are sporadically present only at the beginning of the interval and five are found for the first time in the ten meters of the examined deposit. At the top also the small bivalve *P.* cfr. *nitidum* is present. The aquatic species found are typical of stagnant or slowly running waters. Land gastropods are represented by 7 species: *C. minimum, O. elegans, V. pygmaea, V. enniensis, V. botterii, C. acicula, Perforatella* sp.; most of them live in wet places.

In this interval the more strictly hygrophilous molluscs, as *O. elegans, S. oblonga, V. angustior, V. antivertigo,* decrease in number of specimens or desappear, as compared with the previous interval, and aquatic vertebrates and Characeae are entirely absent. Moreover the appearance of some fresh-water gastropods as *V. piscinalis, A. lacustris, H. complanatus,* shows a decrease in vegetation in the hydric body (PUISSÉGUR, 1976).These factors testify the tendency to a more temperate and less humid climate as compared with the previous interval.

CONCLUDING REMARKS

The paleontological analysis carried out on the ten metres of drilling (S 1 and/or S 2) points out some meaningfull variations in the faunal composition of the different levels. These variations are due to environmental changes occurred over the sedimentary evolution of the basin.

From the bottom to the top, on the basis of the presence or absence of certain taxa, we can recognize recurrent phases of aridity and humidity, related to a more or less cold or warm climate.

The lower interval A (10 m – 6.80 m) is characterized by an overall cold-semiarid phase, where aridity is not excessively marked. Some aquatic taxa, indeed, are found all over the interval: eventhough ostracods, fishes and in a lower extent amphibians are discontinuously and scantly recurrent. The relevant scantiness of molluscs in this interval may testify a climatic cooling with a slight fluctuation toward less dry and cold conditions in coincidence with the occurrence of the only three molluscan species.

A more marked cold-arid climatic phase is represented by the interval B (6.80 m – 5.30 m) devoid of any faunal remains.

Intervals A and B are related to a cold "würmian" stadial phase in agreement with radiocarbon dating (Alessio *et alii,* this paper).

In the interval C (5.30 m – 4.10 m) several aquatic taxa appear again. The overall malacological oligotypy and the presence of a mountain grass-land rodent evidence a generally cold phase (ESU *et alii,* 1986), eventhough not so arid as the previous ones. This interval is supposed to represent the last "würmian" cold phase.

The interval D (4.10 m – 3.60 m) shows in its first part a marked aridity followed by the occurrence of scanty aquatic taxa. It can be related to an arid phase of Late Glacial period.

The analysis of the scarce organic remains of the interval E (3.60 m – 2.30 m) introduces a more humid phase than the previous ones, since the drilling material of most part of this interval is missing it is impossible to give more precise paleoenvironmental indications about it.

The following interval F (2.30 m – 1.20 m) is characterized by a clear sharp faunal variation showing the setting of a swampy environment and a warm-humid climatic phase. The interval F can be ascribed to a Holocene phase. The same indication is suggested by pollen analysis (see Follieri *et alii,* this paper). In the same period, also in France valleys we can observe the spreading of marshes malacological associations settled after those characterizing the cold-arid climatic phases of the last glaciation (PUISSÉGUR, 1976; 1980).

The interval G (1.20 m – 0.10 m), final part of the drilling, is characterized by the appearance of aquatic species living in less rich vegetated environments and by the disappearance of the more strictly hygrophilous species. The climate, similar to the present, comes out to be less humid than in the previous phase.

Pollen analysis

The palynological investigation carried out on the lacustrine sediments of Valle di Castiglione aims above all at the study of the palaeoenvironmental changes recorded in the uppermost 10 meters of the core (5).

Through identification and counting of pollen and spores, a floristic and vegetational reconstruction and accordingly a climatic interpretation are made possible.

The sampling interval is 10 cm down to 4.20 m, mostly 20 cm from 4.20 m to 10.60 m. The core gap from 2.30 m to 3.31 m has been integrated with a new core correlated to the main ones by means of pollen analysis. In all, 102 samples have been

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analyzed, 70 of them being reported in this work.

A more detailed work on a series of new cores, drilled with a hand-operated corer, will permit more frequent analysis and improvement of the zonation of the uppermost 4 meters of sediment.

The laboratory method utilized for most samples is schematically the following: a) 2cc sediment; b) chemical removal of: calcium carbonate (cold 37% HCl), silica (cold 40% HF for 12 hours) and humic acids (boiling in 10% NaOH); c) mounting in glycerine. Pollen concentration (grains/cc sediment) values have been obtained by adding *Lycopodium* tablets (STOCKMARR, 1971) to almost all samples.

Some samples with very scarce pollen content have been flotated on Thoulet solution (GIRARD & RENAULT-MISKOVSKY, 1969).

Quercus pollen has been identified according to criteria suggested by BENTHEM *et alii* (1984). Three groups have been distinguished: deciduous, ilex type and cerris type. The pollen of *Quercus suber* belongs to the morphological group of *Quercus cerris* type (SMIT, 1973).

The curve of Oleaceae includes both *Olea* and *Phillyrea*; *Viburnum* type includes *Viburnum* and *Sambucus*.

Since *Juniperus* and *Cupressus*, both living nowadays in Italy, cannot be distinguished on the basis of pollen morphology, the name "*Juniperus* type" is used in this work.

No pollen of *Pistacia*, present in other pollen diagrams of the Mediterranean region (e.g. PONS & REILLE, 1986; WIJMSTRA, 1969) has been found at Castiglione. Two species are living nowadays in Italy: *P. lentiscus* L. near the sea and *P. terebinthus* L. usually on calcareous slopes (TUTIN *et alii*, 1968). Valle di Castiglione lies about 40 km from the Tyrrhenian Sea in a volcanic region. The fairly small number of herbaceous taxa related to the number of arboreal taxa deserves to be noticed.

In the samples with prevailing AP (Arboreal Pollen) 300-800 pollen grains have been counted; at least two hundreds in those with dominant NAP (Non Arboreal Pollen).

The percentages are based on the pollen total sum, excluding limnophytes, telmatophytes, pteridophytes spores and indeterminable, whose percentages are calculated apart on the sum of the total of each group plus the pollen total sum (BERGLUND & RALSKA-JASIEWICZOWA, 1986).

The data obtained from pollen analysis are graphically represented in two diagrams: percentage diagram (Fig. 16) and concentration diagram (Fig. 17). Only some significant curves are shown in the concentration diagram. Lithology is drawn after Dai Pra and Narcisi, radiocarbon dates after Alessio *et alii*, estimated timescale after Improta *et alii* (see this paper).

The subdivision of pollen-stratigraphical data into local pollen zones has been made with the help of three numerical methods (CONSLINK, SPLITINF, SPLITLSQ) in the program ZONATION (GORDON & BIRKS, 1972), as also suggested in the project IGCP 158 (BERGLUND, 1986).

POLLEN ZONATION AND VEGETATIONAL HISTORY

The most general palynological subdivision of the two pollen diagrams distinguishes two thick sediment bodies: one (ZONE Y) between 10.60 m and 4.32 m dominated by steppic formations and the other (ZONE Z) between 4.32 m and 0.50 m, characterized by dominance of forest phases.

ZONE Y (10.60 m – 4.32 m)

Scarce presence of arboreal plants and high expansion of the herbs in percentage, but not in absolute values, are peculiar characteristics of this zone.

The steppic vegetation is alternatively dominated by *Artemisia*, Gramineae and Chenopodiaceae, accompanied by expansion phases of Ranunculaceae, Asteroideae and Caryophyllaceae. Among trees only *Pinus* is constantly present in low concentration. *Quercus*, *Betula* and *Salix* are the most frequent deciduous trees. This vegetational landscape indicates extremely arid climatic conditions where arboreal taxa can hardly survive. The continuous presence of *Ephedra* confirms the steppic arid character of the vegetation.

Subzone Y1 (10.60 m – 5.30 m)

Up to 8.40 m vegetation is represented by steppe with dominant *Artemisia* and Gramineae, accompanied above all by Chenopodiaceae, Ranunculaceae, Asteroideae, Caryophyllaceae and Umbelliferae. Among arboreal plants only *Pinus* presents a continuous curve reaching the highest percentage (22%) of the zone at 8.40 m; low culminations of *Juniperus* and *Ephedra* occur here and there. At 8.20 m the composition in percentage of steppic plants changes because of the increase of Chenopodiaceae (43%).

Then Artemisia is dominant again until the end of the zone, Gramineae show a temporary diminution both in percentage and in concentration. The decrease of *Pinus* percentage and its complete absence at 7.05 m (100% NAP) is interpreted as a climatic deterioration.

In the whole zone aquatic plants show high percentages and peaks in concentration.

Subzone Y2 (5.30 m – 4.32 m)

Pinus and *Juniperus* present the highest percentage culminations of the diagram; they suddenly decrease at the end of the zone in correspondence of a climatic amelioration and the consequent reappearance of trees more particular from the climatic and edaphic point of view.

The very low pollen concentration of the zone – such as to make the use of flotation on Thoulet solution necessary at 5.00 and 4.80 m – is related with the composition of the sediment which was found depleted in organic matter (see also Cor and Nto contents, Alessio *et alii* this paper).

ZONE Z (4.32 m – 0.50 m)

This zone is characterized by the progressive diffusion of arboreal plants, above all angiosperms, indicating the passage from the extreme conditions of the previous phase, through more or less warm and wet oscillations, to the Mediterranean climate which preludes the present one.

Times and ways of immigration and expansion of each taxon hold great importance in order to reconstruct the climatic trend occurring in this period.

Subzone Z1 (4.32 m – 3.65 m)

Pinus lowers gradually to small percentages while *Juniperus* decreases all of a sudden; *Corylus* immigrates at 4.19 m, *Quercus* (both deciduous and evergreen) begins to expand at 4.10 m; at the same depth *Betula, Tilia* and *Ulmus* appear; *Carpinus, Acer* and *Hedera* immigrate at 3.90 m, *Fagus* at 3.80 m.

This zone indicates an evident but short and not very pronounced climatic amelioration, preceded and followed by distinctly steppic conditions. At 3.70 m the increase both in percentage and in concentration of the herbs, expecially Gramineae, *Artemisia* and Chenopodiaceae is remarkable.

Subzone Z2 (3.65 m – 2.25 m)

Oaks and hazel progressively spread again, accompanied by all the arboreal taxa already present in the previous attempt of reafforestation. At the beginning of the zone Ericaceae, Oleaceae and *Alnus* join the forest formation in gradual evolution; *Quercus cerris* type is present from 3.40 m, *Buxus* from 3.30 m, *Fraxinus* and *Juglans* from 3.10 m.

From 2.90 m the concentration of trees and shrubs diminishes, while the concentration of herbs is increasing, with *Artemisia,* Caryophyllaceae, Chenopodiaceae and Gramineae expanding in sequence.

Subzone Z3 (2.25 m – 1.15 m)

With the decline of *Artemisia* and Chenopodiaceae, the forest is progressively increasing. It is characterized mainly by deciduous oaks, but also hazel plays an important role (30% at 1.60 m). The rise of *Fagus* (max 10,2%) indicates a wetter climate; the elm shows the same trend as the beech. In this phase *Ephedra* disappears.

The expansion of the forest is testified both by the percentages and the concentrations of trees, attaining respectively 67.1% and 108,000 grains/cc at 1.35 m; but the maximum value of total concentration of the whole diagram is found at the beginning of this zone at 2.10 m (186,500 grains/cc) where, though trees prevail over herbs, Gramineae show a considerable concentration growth.

On the whole the climate of this phase appears temperate-wet.

Subzone Z4 (1.15 m – 0.50 m)

In this zone the concentration lowers; at the beginning *Juniperus* and *Carpinus* present a low peak, at the same time *Fagus* and *Ulmus* decrease.

The vegetation that settles later on shows very peculiar characters: the considerable diffusion of *Quercus ilex* type (present since the very beginning of the reafforestation) indicates a Mediterranean climate, as confirmed also by the continuous curves of Ericaceae, Oleaceae and *Viburnum.* The expansion of *Alnus* in the uppermost samples is remarkable too. The diffusion of *Castanea* is likely to be referred to human influence, while *Juglans* does not show any evident expansion. No pollen of Cerealia has been found.

Chronology of vegetational phases

The agreement between the radiocarbon dates and the chronological sequence of vegetational phases of Valle di Castiglione is hard to discuss in detail because no other reliable dated diagram has been published in Italy yet. The dates at our disposal, compared with the several and well known dated diagrams of Europe, seem mostly acceptable.

According to the estimated time-scale, i.e. radiocarbon years interpolated from dated levels (see Improta *et alii* in this paper), the following chronological sequence of vegetational and climatic phases is proposed:

estimated age BP	*depth (m)*	*subzone*	
30,700	10.60	Y1	bottom of the diagram; Würmian arid phase characterized by steppic vegetation with scattered *Pinus* and rare deciduous trees.
18,500	5.30	Y2	expansion of *Pinus* and *Juniperus* concluding the glacial period.
14,000	4.32	Z1	Many trees and shrubs immigrate, indicating a temporary increase in precipitation and perhaps in temperature; the vegetational development of the forest ends abruptly with a new expansion of steppic plants. The climatic fluctuations of this period are contemporary with the Lateglacial.
10,800	3.65	Z2	Holocene begins with the progressive and definitive establishment of the forest, as a response to increasing moisture and perhaps also to rising temperature. Nevertheless more or less marked steppic oscillations still occur during the early Holocene.
5400	2.25	Z3	Lower boundary of the zone with the most vigorous forest development and the wettest climatic conditions of the diagram.
3200	1.15	Z4	Increase of Mediterranean vegetation, diffusion of chestnut, probable human impact; decreasing humidity, increasing temperature.

Discussion

A more detailed research about the stratigraphic sequence of Castiglione is in progress; however it is already possible to discuss some salient aspects.

The pollen diagram of Castiglione is in general agreement with the other diagrams of the Mediterranean region: during the glacial period the vegetation is mainly steppic with dominant *Artemisia*, Chenopodiaceae and Gramineae; the Holocene is characterized by development of the forest. The zones of transition (Y2 and Z1) between Würm and Holocene and the vegetational features of forest periods (Z2, Z3 and Z4) in Castiglione deserve particular attention.

After the longest steppic phase the first vegetational change (Y2) with marked increase of *Pinus* and *Juniperus* reaching together 50% of total pollen, occurs between the radiocarbon dates 20,300 and 14,220 BP. A similar situation with expansion of *Pinus* is found at Padul, Southern Spain (PONS & REILLE, 1986) in zone f (19,600-15,200 BP), and at Tenaghi Philippon, Northern Greece (WIJMSTRA, 1969) in zone X4, between the calculated ages of 20,000 and 16,000 BP. More problematic is the chronological comparison with Laghi di Monticchio, Southern Italy (WATTS, 1985), showing a clear phase with *Pinus* and *Juniperus*, but lacking reliable dates. The climatic interpretation of this phase, concluding the full glacial period, is still uncertain: "probably a slight increase in humidity" (ZEIST & BOTTEMA, 1982), "aucune rémission climatique nette" (PONS & REILLE, 1986); according to Esu (this work), at Castiglione in this period – interval C – "the overall malacological oligotypy and the presence of a mountain grass-land rodent evidence a generally cold phase, eventhough not so arid as the previous ones".

Afterwards at Castiglione a series of vegetational and climatic fluctuations preluded the Holocene. They took place after 14,220 ± 115 BP up to quite before 9200 ± 200 BP. The correlation with the Late glacial is very strict, both as to chronology and to the expansion of NAP that concludes this period.

"There is great regional variation in the intensity of response of vegetation to Lateglacial climatic events in Europe" (WATTS, 1980; see also WATTS 1986). Nevertheless the similarity of the expansion of oaks at Valle di Castiglione at the calculated age of 13,000 years BP, at Tenaghi Philippon after 14,600 BP and at Padul at 13,000 BP is remarkable. As the vegetational characters in these sites are more similar to the Holocene than to the glacial period – note that the main palynological subdivision of the diagrams of Castiglione lies under this zone – it would be better to speak of Proto-Holocene than of Late-glacial.

The vegetational features of the Holocene once again present some similarities with Padul, Tenaghi Philippon and Monticchio, above all in the considerable expansion of oaks that constitute the most important element of the forest in all these sites. But the trend of the curves of *Quercus* and the history of the other arboreal taxa are not directly comparable, since they are particular in each site. Even the pollen diagram of Monticchio, which is situated less than 300 km SE of Castiglione, but in a quite different landscape (530 m a.s.l.), shows important differences, for example *Quercus* decreases at Monticchio and increases at Castiglione in the course of the Holocene, and *Abies* is absent at Castiglione, while at Monticchio it attains 15%.

Two pollen diagrams directly comparable with Castiglione from a floristic point of view are those from Lago di Vico (FRANK, 1969) and from Lago di Monterosi (BONATTI, 1970) in the same region of Central Italy and on volcanic rocks. Unfortunately the first one lacks in details and in radiocarbon chronology, the second one presents a sequence in which "is difficult to detect the details of events owing to the slow sedimentation rate" (BONATTI, 1970).

The pollen analysis of Mezzaluna, Agropontino, South of Rome, is not comparable with Castiglione, because "pollen grains are assembled into groups of species on a sinecological basis" (EISNER *et alii*, 1986).

Comparisons with the Holocene records from other sites of the Mediterranean region are not made here. They would be necessarily vague owing to the scanty number of published diagrams in relation with the complexity of the vegetational situations. Such a complexity is testified also nowadays by the wide range of Mediterranean landscapes which are the result of the Holocene vegetational history.

General conclusions

The research herein presented has been carried out with a multi-disciplinary approach and, in this respect a comparative examination of the most significant results is of some concern. The framework required for this investigation was provided by either a comprehensive geologic setting of the study area and a somewhat detailed ^{14}C chronostratigraphy of the drilled sediment suite. The obtained palinological biostratigraphy resulted in fair agreement with the ^{14}C time-scale.

It is worthy of mention that the major changes in lithology and geochemical pattern which has been detected throughout the sediment core are matched by the implemented palinological and paleontological zonations. On this basis inference is made that the sediment suite represents a reliable record of the history of its own accumulation basin. As a result in many instances the inferred paleoenvironmental characteristics of the sedimentation basin (and those of its catchment area) are supported by data from distinct investigations. Let's show, as an example, the fully concordant information given by the experimental data set for the core sample 5.30 m deep (^{14}C age: 20,300 yr BP). At this depth in core the sharp lithological change from brownish tuffites to grey calcareous muds paralleled by a dramatic drop of organic matter and a low pollen concentration, as well as the occurrence of either oligotypic molluscan fauna and a rodent of Alpine praire, strongly suggest that the paleonvironment underwent notable modification. Accordingly, palynological data from 5.30 to 4.32 m depth in core revealed that in this pollen zone (Y2) of transition the first slight significant change of Würmian vegetation took place. Fauna remnants point to a cool climate, even though warmer than before.

Concerning Holocene, it has been found that sediments less than 3 m deep are by far the most C_{or} – and N_{to} – enriched. It is likely that this feature depends on the occurrence of scattered peat, which has been detected just within the final 3 m of the sediment core. The vegetation, subsequently to the manifest Holocenic beginning at 3.65 m in depth (extrapolated age: 10,800 yr BP), shows an increasing forestation trend that reaches its maximum in the pollen zone Z3. Here the oak mixed forest, including beech, expands. The corresponding faunal zone (F) exhibits a land molluscan fauna of very moist climatic regime.

Upward within the core the faunal and pollen zone G and Z4 have been recognized. Here the indications of oceanic climate are less evident than before, the pollen zone being characterized by the diffusion of Mediterranean taxa and by a gradual increase of the percentages of pollen reflecting the human impact, and the faunistic zone by the disappearance of the more strictly hygrophilous land species.

RIASSUNTO

In questo lavoro viene presentato uno studio pluridisciplinare riguardante i 10 metri superiori del sondaggio che attraversa i sedimenti pleistocenici di Valle di Castiglione.

Il cratere di Castiglione, localizzato nel settore settentrionale del complesso vulcanico albano, ha avuto un'attività altamente esplosiva dovuta all'interazione di magmi sottosaturi con gli acquiferi regionali, in un periodo di tempo compreso tra 0,4 e 0,3 m.a. L'esplosione che ha determinato la forma del cratere quasi perfettamente circolare ha portato alla deposizione di una serie di prodotti caratterizzati da strutture sedimentarie tipiche del base surge.

La successione litostratigrafica può essere sintetizzata in cinque intervalli principali, dal basso verso l'alto: da m 10,60 a m 7,80 limi brunastri leggermente calcarei con componente vulcanica; da m 7,80 a m 5,30 cinerite massiva color bruno scuro, con bioturbazioni nella parte superiore; da m 5,30 a m 3,03 limi calcarei grigi con fauna dulcicola, interrotti da m 4,15 a m 4,00 da un sottile livello di tufiti; da m 3,03 limi torbosi con molluschi e quindi alternanze di torbe e limi fino alla superficie. La successione può ritenersi continua e deposta in ambiente subacqueo a bassa energia.

Il presente lavoro riporta i risultati della cronologia a mezzo radiocarbonio effettuata utilizzando la sostanza organica contenuta nei sedimenti accumulatisi nel bacino costituito dall'antico lago di Castiglione. Vengono altresì presentati i valori delle abbondanze del C, N, S, Fe, Mn, Cu e Zn determinati, quando è stato possibile, sugli stessi campioni utilizzati per la datazione.

La cronostratigrafia con il ^{14}C ha permesso di stabilire che gli ultimi 15,60 m della serie sedimentaria si sono deposti a partire dal tardo Würm fino all'Olocene; le età misurate sono comprese tra 3480 anni BP (alla profondità di 1,15-1,25 m) e 41.700 anni BP (alla profondità di 15,40-15,60 m). L'età di campioni da profondità maggiori è risultata ripetutamente eccedente le possibilità di datazione del metodo.

I contenuti di carbonato (0,1-79,3%), Fe (0,64-4,85%), Cu (30,6-122,5 ppm), Zn (25,5-113,8 ppm) e Mn (207-800 ppm) nei sedimenti analizzati mostrano notevoli variazioni che tuttavia non sono relazionate alla profondità. È stato trovato che i contenuti di Fe, Cu e Zn sono correlati positivamente con la componente detritica dei sedimenti, mentre il Mn mostra una correlazione diretta con il contenuto in carbonato. Quest'ultima peculiarità geochimica è stata successivamente confermata dai risultati analitici ottenuti tramite dissoluzione selettiva della sola componente carbonatica dei sedimenti.

La presenza di tenori variabili di zolfo ridotto in tutti i campioni analizzati suggerisce che durante l'accumulo della serie sedimentaria il fondo del bacino è stato caratterizzato da condizioni di anossicità, verosimilmente determinatesi in risposta ai valori della velocità di sedimentazione nonché dell'apporto di sostanza organica.

Anche i contenuti di C organico e di N totale mostrano una ampia variabilità lungo il profilo dei sedimenti. In particolare il brusco aumento di questi due parametri (di un fattore di circa 4) negli ultimi 3,40 m del profilo riflette un corrispondente notevole incremento dell'apporto di sostanza organica sul fondo del lago, interpretabile in termini di aumento della vegetazione nel bacino di drenaggio come risposta a migliori condizioni climatiche.

Si propone una funzione continua che mette in relazione la profondità del sondaggio con l'età radiocarbonio dei sedimenti; tale funzione consente inoltre di ottenere l'andamento della velocità di sedimentazione in funzione della profondità.

L'analisi paleontologica mette in evidenza alcune significative variazioni nella composizione faunistica dei differenti livelli della successione sedimentaria esaminata. Mutamenti ambientali, come biotopi lacustri o stagnanti, ricorrenti fasi di aridità o di umidità relative a condizioni climatiche fredde o calde, vengono riconosciuti sulla base della composizione malacologica delle associazioni. Per la ricostruzione ambientale viene considerata anche la presenza di ostracodi, pesci, anfibi, vertebrati terrestri e oogoni di Characeae. La sequenza malacologica mette in evidenza differenti fasi climatiche. Dal basso verso l'alto si riconoscono l'ultima fase fredda "würmiana", una fase arida "tardolaciale" e due fasi oloceniche (la prima caldo-umida, la seconda temperata).

Le analisi polliniche di Valle di Castiglione hanno fornito due diagrammi pollinici (percentuale e assoluto) che descrivono la storia della vegetazione dall'ultimo glaciale a quasi tutto l'Olocene.

La suddivisione più generale dei diagrammi è quella che separa due fasi vegetazionali molto distinte: una caratterizzata prevalentemente da formazioni steppiche, indicanti clima arido e attribuita all'ultimo glaciale, l'altra con graduale sviluppo del bosco che, con successive oscillazioni, raggiunge il massimo rigoglio nell'Olocene. La steppa è costituita prevalentemente da *Artemisia*, Gramineae e Chenopodiaceae con continua ma scarsa presenza di *Pinus* e sporadiche piante caducifoglie (*Quercus*, *Betula*). Il bosco mostra invece ben maggiore complessità vegetazionale e ricchezza floristica: gli elementi dominanti sono le querce, sia sempreverdi che caducifoglie, accompagnate principalmente da *Corylus*, *Fagus*, *Ulmus*, *Carpinus*, *Tilia* e *Alnus* in proporzioni variabili; l'espansione del faggio intorno a circa 5.000 anni fa corrisponde alla maggiore concentrazione pollinica nel sedimento e indica un incremento di umidità. Da circa 3.200 anni dal presente aumentano le querce sempreverdi e l'influsso antropico sulla vegetazione.

Particolare attenzione meritano le fasi di transizione tra periodo glaciale ed Olocene, che trovano interessanti concordanze con diagrammi pollinici della Spagna e della Grecia: dopo la data ^{14}C di 20.300 fino a circa 14.220 anni si verifica una notevole espansione di pino e ginepro, in seguito, in corrispondenza della principale suddivisione del diagramma, cronologicamente correlata con l'inizio del tardoglaciale, immigrano numerose entità arboree del Querceto Misto che troveranno la definitiva diffusione durante l'Olocene.

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FIG. 16 — Total pollen concentration diagram and pollen percentage diagram.
— Diagramma pollinico della concentrazione totale e diagramma pollinico percentuale.

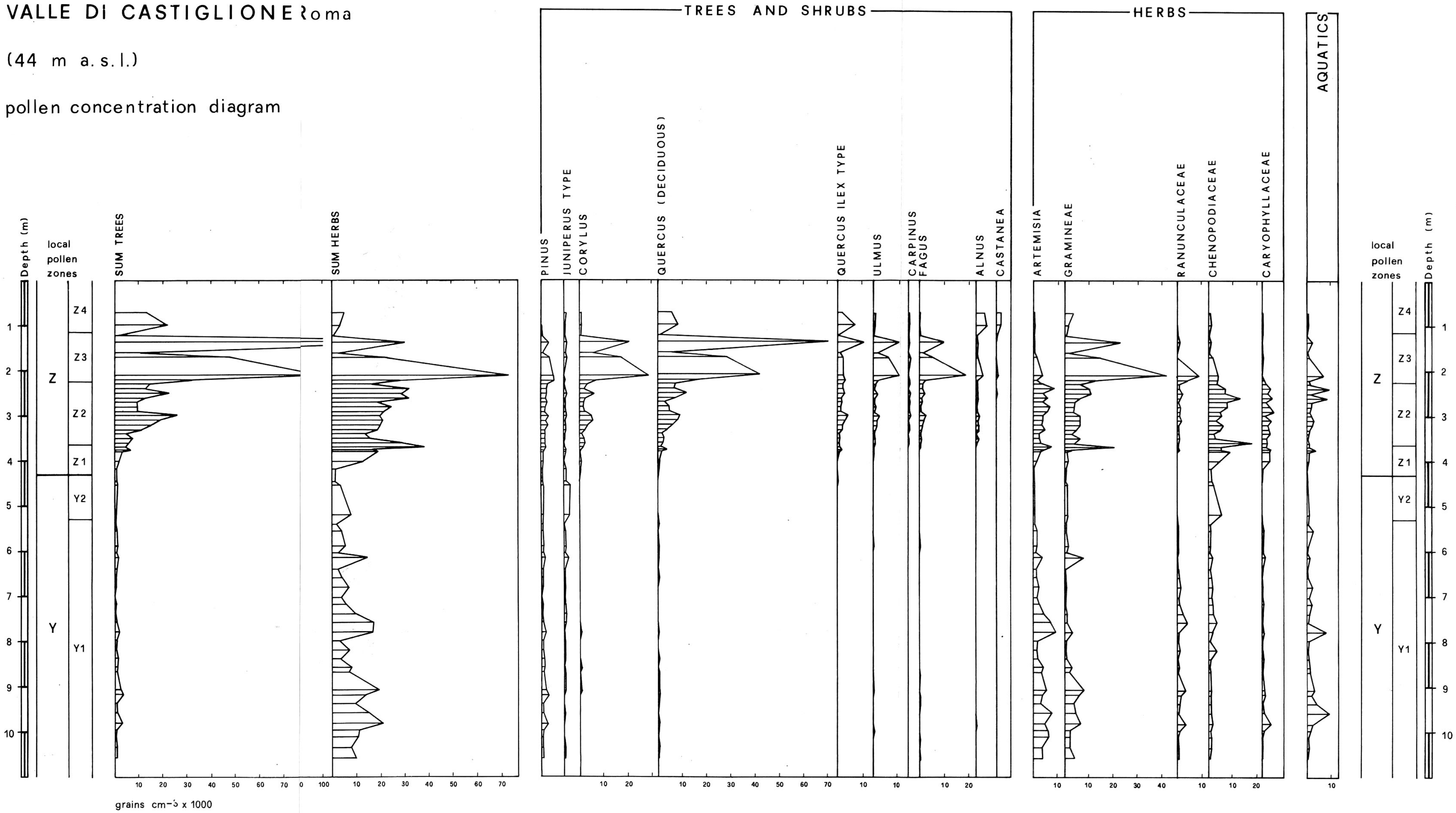

FIG. 17 — Pollen concentration diagram.

— Diagramma pollinico della concentrazione.