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SEDIMENTARY AND GEOCHEMICAL CHARACTERS OF LAKE COMO RECENT SEDIMENTS

RIASSUNTO. — I sedimenti, raccolti in quattro punti del Lago di Como in carote di circa 50 cm di lunghezza, sono stati analizzati ad intervalli di 1-2 cm relativamente ai seguenti parametri: granulometria, composizione mineralogica e chimica. Le quattro stazioni di prelievo (Olgiasca, Bellagio, Como e Lecco) sono state scelte in base alle differenze litologiche dei relativi bacini di drenaggio: corpi intrusivi, rocce metamorfiche, ofioliti, calcari, dolomie, etc. In tutte le stazioni i sedimenti sono classificati come «sandy-silt», tranne quelli di Bellagio che sono classificati come «mud». I principali minerali delle argille sono illite e clorite. Sono state determinate le concentrazioni di Ca, Fe, K, Mg, Mn, Na, Ti e di Co, Cr, Cu, Pb, Zn e sostanza organica. In generale si osserva un aumento della concentrazione di Cr, Cu, Pb e Zn nelle parti superficiali dei sedimenti ed una stretta correlazione fra questi elementi. Con il metodo del Cs-137 sono stati datati i sedimenti raccolti, che risultano essere stati depositati tra 50 e 150 anni con un coefficiente di sedimentazione pari a 0,2-0,3 g/cm²/anno. Sono stati infine calcolati i flussi medi degli elementi con i relativi livelli di accumulo naturali ed attuali; il flusso antropogenico di Cr, Cu, Pb e Zn è risultato essere anche tre volte superiore al flusso naturale degli stessi.

ABSTRACT. — Some sediment cores from prealpine Lake Como (Northern Italy) were sliced in 1-2 cm sections and analysed for grain-size, mineralogy and chemical composition. The sampling points (called Olgiasca, Bellagio, Como and Lecco) were chosen on account of lithologic differences in its drainage areas: intrusive bodies, metamorphic rocks, ophiolites, limestones, dolomites, etc. Sediments are «sandy-silt» in all cores except for one (Bellagio) which are «mud». Illite and chlorite are the main clay minerals. Contents of Ca, Fe, K, Mg, Mn, Na, Ti and Co, Cr, Cu, Ni, Pb, Zn and organic matter were determined. Generally a surface enrichment of Cr, Cu, Pb and Zn contents and a strong correlation among these elements can be observed. By Cs-137 method were dated the sediment cores, that were layed between 50 and 150 years with a sedimentation rate ranging from 0.2-0.3 g/cm²/yr. The fluxes of elements to the sediments together with natural and present-day loads were also computed; Cr, Cu, Pb and Zn anthropogenic fluxes are till 3-fold above its natural inputs.

Introduction

Lake Como recent sediments are almost unknown in their mineralogical and chemical composition. The first attempt to get a mineralogical analysis of bottom sediments was carried out in 1903 by ARTINI. The present work tries to deal entirely with the sedimentary problems, attending to deepest sediments too, with the aim to observe the development in the time of their chemical composition and the possible increase of heavy metal concentrations approaching the present time.

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This increase was already remarked in several European and North-American lacustrine and marine environments owing to industrialization of the last years (ERLENKEUSER et al., 1974; FORSTNER and MULLER, 1974; GOLDBERG et al., 1978; SKEI and PAUS, 1979; NRIAGU et al., 1979; WAHLEN and THOMPSON, 1980; KITANO et al., 1980).

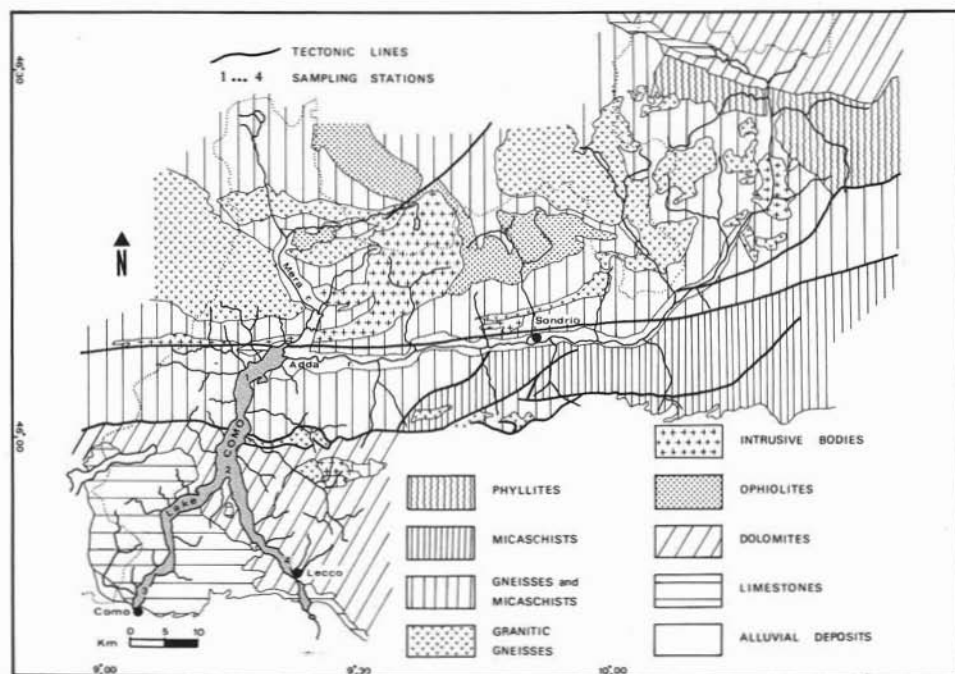


Fig. 1. — Geological sketch map of the drainage area of Lake Como (Northern Italy).

Lake Como occupies a deep and narrow glacial valley, marked by branching in the southern part (Como branch and Lecco branch); the length is about 50 km and the width is about 1-2 km (4 km in the branching point, Bellagio). Most freshwater input enters the north of the lake from Adda and Mera rivers (average 115 m³/sec.). From a geological point of view the drainage area reaches South-Alpine, Austroalpine and Pennine units and is interested by tectonic events of different time. This basin presents a wide range of lithotypes which are different in chemical composition too. These are metamorphic rocks (phyllites, micaschists, gneisses and granitic gneisses), intrusive bodies (granites, granodiorites, diorites and gabbros), ophiolites (serpentinites and amphibolites) in the northern part and Adda Valley (Valtellina); sedimentary rocks in the southern part: siliceous limestones in the Como branch, dolomites and siliceous limestones in the Lecco branch. A synthesis of geolithological situation of Lake Como drainage area is reported in fig. 1.

With this aim a series of core samples was collected in four points of the lake, which are different in geological characters: in the northern part, off Olgasca; in the central branching point, off Bellagio; in the end of the southern branches, off Como and off Lecco. Geographical and morphological data and sampling points are summarized in table 1.

In the collected sediments, Ca, Fe, K, Mg, Mn, Na, Ti among major elements and Co, Cr, Cu, Ni, Pb, Zn among trace elements were analysed. Grain-size analysis was carried out on all sediments and mineralogical analysis on the only clay fraction. The whole sediments were dated by Cs-137 method.

TABLE 1
Locations of cores and descriptive data

	STATION 1 Olgiasca	STATION 2 Bellagio	STATION 3 Como	STATION 4 Lecco
Sampling point	46°07' N 9°18' E	46°00' N 9°16' E	45°49' N 9°04' E	45°51' N 9°23' E
Sampling time	may 1979	may 1978	oct. 1978	dec. 1978
Depth of sampling (m)	200	270	60	80
Core length (cm)	30	27	58	73
Drainage area (km ²)	~3570	~400	~250	~150

Sampling and analytical methods

The sediment cores were collected with a gravity core barrel (10 cm in diameter), were sliced in 1-2 cm sections, afterward were dried at 60° C. 1.0 g of each section was homogenized in agate-mortar and dissolved by HF-HClO₄ digestion. Ca and Mg were determined by EDTA titration. Na and K were determined by flame photometer. Fe, Mn and Ti by photometric determination: with 1,10 phenanthroline (Fe), with Potassium periodate (Mn), with Hydrogen peroxide (Ti). All methods are described in JEFFERY (1970). Heavy metal concentrations were determined by atomic absorption spectrophotometry. On another portion of every section, grain-size composition by pipette method (FOLK, 1965) was detected. Clay minerals were determined by X-ray diffraction technique in the few centimeters only of the sediment cores. γ activity of Cs-137 was measured by Ge-Li detector on dried and homogenized sections. Loss on ignition, at 480° C, is assumed to represent the approximate content of organic matter.

Results

Chemistry

The analytical data relating to the concentrations of major and trace elements in the four Stations are shown in tables 2 and 3.

Particularly we can observe:

TABLE 2
Elemental concentrations, means, standard deviations and relative standard deviations in sediments of Lake Como (Stations 1 and 3)

cm	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Cr	Ni	Cu	Zn	Pb	Co	Org. matt.
	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	%
Station 1														
1	6.73	2.08	3.39	1.56	3.46	0.074	0.68	159	129	54	288	76	36	6.55
2	6.87	3.95	4.70	2.07	3.01	0.087	0.55	217	178	55	334	88	35	4.86
3	6.40	3.87	4.53	1.79	2.96	0.073	0.57	278	170	49	355	95	35	4.62
4	6.48	3.78	4.40	2.06	2.90	0.074	0.57	238	187	53	417	90	35	4.80
5	7.29	2.90	5.06	2.03	2.97	0.081	0.53	215	189	57	371	80	34	4.08
6	6.71	3.22	5.27	1.49	2.59	0.082	0.54	244	210	56	713	130	35	7.06
7	6.81	3.43	5.39	1.63	2.88	0.081	0.53	218	208	60	621	149	37	6.74
8	7.06	3.43	4.71	1.99	3.01	0.076	0.61	208	196	58	449	121	39	5.57
9	6.64	3.32	4.85	2.34	3.07	0.079	0.64	171	171	43	311	73	39	4.57
10	6.49	3.98	5.55	2.07	2.96	0.082	0.55	160	240	45	364	88	37	5.33
11/12	6.67	2.71	3.57	1.97	3.40	0.077	0.71	145	143	48	256	62	37	3.81
13/14	6.00	2.56	3.36	2.18	3.25	0.066	0.76	169	105	47	175	63	38	3.31
15/16	6.67	4.32	5.26	2.21	3.20	0.080	0.63	178	142	43	186	53	39	3.45
17/18	7.15	4.80	5.06	2.07	3.30	0.085	0.66	187	129	44	179	66	33	3.34
19/20	7.14	4.44	4.50	1.99	3.30	0.092	0.61	196	144	40	192	62	24	3.81
21/22	7.07	4.01	4.90	1.91	3.14	0.086	0.69	173	135	45	195	70	19	7.47
23/24	6.50	2.24	3.01	2.07	3.50	0.076	0.79	140	94	51	205	60	18	5.81
25/26	6.14	2.67	2.56	2.48	3.44	0.080	0.82	159	85	50	171	71	20	3.99
27/28	6.38	3.91	4.30	2.43	3.10	0.085	0.67	189	149	53	231	76	22	4.92
29/30	6.54	5.38	5.95	2.23	3.01	0.090	0.63	143	151	52	189	58	20	4.96
$\bar{x}$	6.69	3.55	4.52	2.03	3.12	0.080	0.64	189	158	50	310	81	32	4.92
σ	0.34	0.86	0.91	0.26	0.23	0.006	0.09	37	40	6	151	26	8	1.29
c	5.1	24.2	20.1	12.8	7.4	12.5	14.1	20	25	12	49	31	25	26.2
Station 3														
1	4.04	4.39	2.35	1.31	1.91	0.045	0.59	104	175	82	422	161	17	7.08
2	4.18	5.84	2.26	1.48	2.06	0.051	0.53	89	123	73	275	105	18	4.11
3	4.18	5.93	1.96	1.42	2.18	0.063	0.52	94	162	40	200	91	20	3.85
4	3.80	6.02	1.76	1.31	1.77	0.043	0.47	91	262	44	199	89	21	4.77
5	3.58	5.63	2.02	1.33	1.83	0.032	0.43	95	492	48	207	86	23	5.22
6	3.52	5.49	1.93	1.93	1.39	0.054	0.51	93	96	65	204	122	21	5.52
7	3.72	5.16	1.94	1.26	1.76	0.052	0.55	106	236	77	309	132	19	6.83
8	4.86	3.90	2.08	1.49	2.09	0.050	0.63	134	158	96	517	189	18	9.35
9	4.12	3.37	1.77	1.32	1.90	0.044	0.59	128	106	113	470	236	14	8.46
10	4.18	3.94	2.02	1.32	1.89	0.048	0.74	137	221	133	542	315	15	8.42
11/12	4.12	3.82	2.10	1.06	1.79	0.035	0.74	152	106	150	670	320	14	10.84
13/14	4.32	3.92	2.09	1.02	1.79	0.040	0.89	148	216	186	659	330	13	10.97
15/16	3.78	3.71	2.18	0.91	1.73	0.035	0.75	160	122	214	677	351	16	10.85
17/18	3.66	3.66	2.07	1.11	1.75	0.038	0.57	144	163	145	484	375	18	7.66
19/20	3.84	3.90	2.16	1.17	1.90	0.036	0.52	129	212	78	437	220	20	6.91
21/22	4.18	4.14	2.33	1.16	1.91	0.034	0.55	144	126	87	489	225	17	8.59
25/26	3.92	3.88	2.07	1.36	1.88	0.044	0.52	121	119	116	438	238	16	7.35
29/30	3.74	4.48	2.09	0.94	1.86	0.044	0.55	112	231	95	331	200	15	6.24
33/34	3.60	5.75	1.74	1.48	1.81	0.048	0.48	86	886	59	183	163	15	4.01
37/38	3.60	4.81	1.77	1.58	1.79	0.046	0.49	94	177	68	271	169	14	4.95
41/42	4.26	4.59	2.01	1.38	1.90	0.042	0.58	42	317	80	345	174	12	5.98
45/46	4.90	4.28	2.11	1.25	1.91	0.054	0.57	127	245	91	283	205	13	7.05
49/50	4.06	4.83	2.52	1.45	2.21	0.040	0.59	107	86	85	203	90	16	7.45
53/54	3.68	3.59	2.09	1.24	1.92	0.040	0.46	100	90	60	192	114	19	6.40
57/58	3.52	2.68	1.85	0.94	1.86	0.035	0.48	75	100	62	92	89	11	5.62
$\bar{x}$	3.97	4.47	2.05	1.29	1.87	0.044	0.57	112	208	94	363	191	16	6.98
σ	0.37	0.91	0.19	0.23	0.16	0.010	0.11	28	167	43	271	90	3	2.08
c	9.3	20.4	9.3	17.8	8.6	25.0	19.3	25	80	46	75	47	19	29.8

Station 1 (Olgiasca): average concentration of major elements in relative order of abundance is: Fe > Mg > Ca > K > Na > Ti > Mn. Ca and Mg contents are discontinuous along the core axis; Na, Mn and Ti are lightly floating; Fe and K are uniform. Average concentration of trace elements, in relative order of abundance, is: Zn > Cr > Ni > Pb > Cu > Co; all the elements show a remarkable increase towards the surface, similar trend is shown by organic matter content.

TABLE 3

Elemental concentrations, means, standard deviations and relative standard deviations in sediments of Lake Como (Stations 2 and 4)

cm	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Cr	Ni	Cu	Zn	Pb	Co	Org. matt.
	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	%
Station 2														
1	5.44	2.90	3.80	1.35	3.05	0.32	0.70	178	300	121	574	258	57	7.30
3	5.50	2.36	2.79	1.32	2.85	0.13	0.59	142	567	90	371	134	48	6.44
5	5.50	2.36	3.07	1.65	3.29	0.14	0.66	152	293	90	323	134	54	5.87
7	6.06	2.49	2.51	1.64	3.31	0.14	0.58	162	431	87	255	185	57	4.07
9	6.72	2.68	2.00	1.73	3.35	0.15	0.64	153	347	80	197	176	69	4.35
11	6.94	2.80	2.80	1.67	3.40	0.06	0.55	131	501	69	151	68	57	4.10
13	6.78	2.97	3.03	1.71	3.45	0.13	0.61	144	448	71	152	75	56	3.99
15	6.46	2.90	2.66	1.67	3.44	0.12	0.60	146	298	65	148	51	53	4.27
17	6.40	3.80	3.36	1.56	3.37	0.05	0.52	116	382	68	143	43	54	4.60
19	5.94	5.20	3.67	1.52	3.25	0.12	0.56	126	345	58	138	48	48	4.01
21	7.16	2.73	3.53	1.79	3.51	0.13	0.59	146	364	72	160	68	53	3.84
23	6.32	2.46	3.38	1.58	3.42	0.12	0.58	132	319	72	140	24	54	3.79
25	6.40	2.58	3.47	1.55	3.48	0.09	0.55	124	604	68	142	36	56	3.88
27	6.72	2.80	3.23	1.59	3.51	0.14	0.57	140	770	70	152	28	54	3.70
$\bar{x}$	6.31	2.93	3.09	1.59	3.33	0.13	0.59	142	426	77	217	94	55	4.59
σ	0.55	0.75	0.50	0.13	0.18	0.06	0.05	16	140	16	127	71	5	1.12
c	8.7	25.6	16.2	8.2	5.4	46.2	8.5	11	33	21	59	76	9	24.4
Station 4														
1	6.97	6.35	4.09	0.92	2.01	0.05	0.53	217	121	313	1484	348	16	15.14
3	7.45	7.81	5.45	1.00	2.34	0.05	0.53	58	131	418	2151	446	16	12.28
5	8.88	6.13	2.29	0.89	1.99	0.06	0.48	486	207	506	2996	729	16	15.43
7	5.43	5.63	3.24	1.75	2.07	0.05	0.40	219	102	183	1566	426	14	6.29
9	9.78	7.50	5.04	0.91	1.98	0.06	0.55	647	147	380	3214	705	17	10.66
11	10.61	7.01	5.20	1.01	1.90	0.09	0.73	625	146	320	2652	489	19	8.73
13	10.40	7.38	5.15	1.10	1.94	0.10	0.88	620	143	426	2267	422	25	8.30
15	10.72	8.12	5.22	0.96	1.72	0.12	0.99	684	137	380	1787	384	25	7.33
17	7.95	8.89	6.08	0.90	2.17	0.11	0.58	218	107	215	1448	380	19	7.45
19	5.90	11.09	6.98	1.03	2.19	0.09	0.53	119	72	165	1008	366	19	5.76
21	5.74	11.63	6.11	1.03	2.28	0.07	0.48	116	70	171	1000	430	20	4.87
25	5.91	11.91	7.01	0.91	2.05	0.08	0.51	129	81	367	1544	792	17	5.71
29	7.40	8.03	5.13	1.06	2.31	0.07	0.53	133	119	400	952	530	20	7.85
33	6.74	9.87	9.03	0.91	2.51	0.07	0.58	98	96	440	1060	452	22	6.25
37	6.57	11.06	5.92	1.09	2.12	0.07	0.47	87	62	480	1054	345	21	4.67
41	7.74	9.33	6.40	0.91	2.24	0.07	0.51	93	66	541	1236	259	17	8.65
45	8.83	8.44	6.22	0.91	2.08	0.08	0.47	85	62	444	1120	220	19	9.09
49	6.77	10.65	7.04	0.86	2.26	0.06	0.48	67	48	342	989	217	19	7.24
53	6.33	9.96	7.80	0.86	2.38	0.08	0.56	63	47	270	806	150	20	7.17
57	7.22	9.99	6.37	1.02	2.54	0.10	0.49	61	47	204	769	120	18	6.73
61	5.50	10.43	7.34	1.12	2.68	0.08	0.48	59	42	66	553	70	18	5.54
65	5.03	10.94	8.02	0.85	2.98	0.09	0.47	49	31	68	734	50	16	5.31
69	5.01	9.89	7.71	0.97	2.78	0.08	0.53	56	37	70	416	80	15	5.42
73	4.55	9.85	7.35	1.01	2.97	0.08	0.50	48	39	68	232	122	15	5.02
$\bar{x}$	7.23	9.08	6.09	1.00	2.27	0.08	0.55	210	90	301	1376	355	18	7.79
σ	1.83	1.81	1.55	0.18	0.33	0.02	0.13	219	46	149	785	207	3	2.97
c	25.3	19.9	25.5	18.0	14.5	25.0	23.6	104	51	50	57	58	17	38.1

Station 2 (Bellagio): average concentration of major elements is: Fe > K > Mg > Ca > Na > Ti > Mn. Fe, K, Na and Ti contents are fairly constant, while Ca, Mg and Mn show a strong fluctuation. Average concentration of trace elements is: Ni > Zn > Cr > Pb > Cu > Co. Cr, Cu, Pb and Zn levels increase considerably towards the top of the core like organic matter.

Station 3 (Como): average concentration of major elements is: Ca > Fe > Mg > K > Na > Ti > Mn. Fe, K and Mg amounts remain constant. Na is lightly floating, while Ca, Mn and Ti show a remarkable unconformity. Average concentration of trace elements is: Zn > Ni > Pb > Cr > Cu > Co. Cr, Cu, Pb

and Zn levels increase up to 10 cm and then decrease; organic matter follows the same behaviour.

Station 4 (Lecco): average concentration of major element is the same of the former Station. All the elements have a great variation along the vertical profile. Average concentration of trace elements is: $Zn > Pb > Cu > Cr > Ni > Co$. Cr, Cu, Pb and Zn amounts increase up to 9 cm and then decrease like organic matter. Zn content is remarkable ($\sim 0.1\%$).

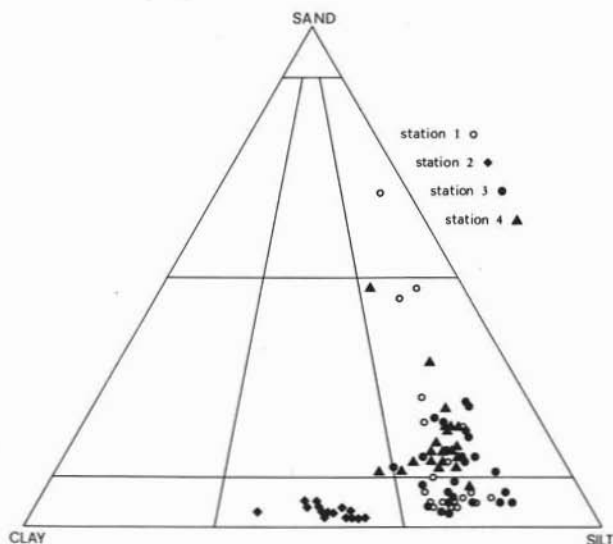


Fig. 2. — Sand-Silt-Clay ratios (sand < 2.0 mm, silt $< .0625$ mm, clay $< .0039$ mm; after FOLK, 1965).

Generally, the average contents of major elements vary in a wide range among the Stations, except for Ti; highest average amounts are observed in Station 4, lowest in Station 3. Along the vertical profile of the cores, a strong variation is generalized; the most discontinuous element is Calcium, followed by Mn and Mg, Fe and K are more uniform than others. In the Stations 3 and 4 the same relative order of abundance of major elements is shown, this is probably due to calcareous-dolomitic nature of both drainage basins.

Average concentrations of trace elements are very different, but there is a distinct increase upward, except for Co and Ni; this increase is more remarkable in the Stations 3 and 4 than in the other two. Organic matter even shows an enrichment towards the surface. This trend is remarked in some lake sediments of North America (NRIAGU et al., 1979; WAHLEN and THOMPSON, 1980) and Europe (FORSTNER and MULLER, 1974); in coastal marine sediments of North America (GOLDBERG et al., 1978), North Europe (ERLENKEUSER et al., 1974; SKEI and PAUS, 1979) and Japan (KITANO et al., 1980).

Grain-size analysis

Data concerning the four Stations are shown in table 4. The sand-silt-clay ratios are reported in fig. 2.

Particularly we can observe:

Station 1: a prevalence of silt fraction on clay and sand is shown; the average classification is «sandy silt» (Folk, 1965). We can remark: a very high standard deviation in sand percent with two layers characterized by values above average, where there is consequently, a clear decrease of silt content, while clay percentage remains constant.

TABLE 4

Grain-size and classification of sediments
of Lake Como

	SAND %	SILT %	CLAY %	Folk, 1965
Station 1				
$\bar{x}$ (20)	16.39	64.29	19.55	Sandy silt
σ	17.63	12.86	6.15	
$\bar{x}$ cm 1/5	7.59	71.08	22.40	Silt
" cm 6/10	6.84	67.92	25.17	Silt
" cm 11/14	35.83	49.51	14.58	Sandy silt
" cm 15/20	6.31	76.03	17.63	Silt
" cm 21/30	33.00	52.73	14.23	Sandy silt
Station 2				
$\bar{x}$ (14)	3.02	51.65	45.37	Mud
σ	1.06	5.15	4.78	
$\bar{x}$ cm 1/9	3.81	52.40	44.00	Mud
" cm 11/19	2.50	51.22	46.18	Mud
" cm 21/27	2.69	51.26	46.05	Mud
Station 3				
$\bar{x}$ (28)	11.01	69.15	19.40	Sandy silt
σ	6.73	5.90	5.42	
$\bar{x}$ cm 1/5	9.49	75.44	15.08	Silt
" cm 6/10	11.82	66.00	21.73	Sandy silt
" cm 11/20	8.03	66.64	24.67	Silt
" cm 21/30	8.08	74.45	17.48	Silt
" cm 31/50	19.25	65.88	14.43	Sandy silt
" cm 51/58	5.49	69.06	23.59	Silt
Station 4				
$\bar{x}$ (24)	16.91	63.31	19.72	Sandy silt
σ	8.41	7.17	46.56	
$\bar{x}$ cm 1/9	19.50	55.29	24.99	Sandy silt
" cm 11/20	15.88	64.67	19.35	Sandy silt
" cm 21/38	19.96	62.60	17.42	Sandy silt
" cm 41/58	16.12	66.69	17.26	Sandy silt
" cm 61/74	12.14	68.30	19.58	Sandy silt

Station 2: a light prevalence of silt percentage on clay is shown, whereas the percentage of sand is very low; the average classification is «mud». The sediment is homogeneous along the core sample. The differences with other Stations are due to the higher depth of sampling.

Station 3: silt fraction prevails over other components, with an increase of sand fraction in some layers, like Station 1, while clay remains constant. The average classification is «sandy silt».

Station 4: silt fraction prevails over clay and sand; along the core there are no remarkable differences among the components. The average classification is «sandy silt». In one of the cores, collected in this Station, at 28-30 cm two platy pebbles of a sedimentary rock (limestone) and one platy pebble of an

intrusive rock (diorite) 2.4 cm in diameter, and at 40 cm one platy pebble of a sedimentary rock (limestone) 5 cm in diameter were found.

X-ray analysis

The less than 2 μ size fraction, coming from the top, middle and bottom parts of each sediment core, shows the same mineralogical composition: illite and chlorite. However, in Station 3 with the former minerals, we observe

muscovite in higher part and a mixed layer illite-montmorillonite in the deeper part of sediment core. This mineralogical composition was also indicated in these European lakes: Léman (VERNET, 1972), Thuner (STURM and MATTER, 1972), Bieler (WEISS, 1979). In the core sample collected in Station 2, the complete mineralogical composition, at 27 cm, was determined: quartz, muscovite, illite, chlorite, plagioclase and dolomite.

TABLE 5

Two hypotheses about sedimentation rate and age by Cs-137 dating method

SEDIMENTATION RATE											
	z	$\bar{\rho}_B$	ϕ'	ϕ''	δ	ω_R	ω_A	ω_{L1}	ω_{L2}	ω_{L3}	ω_{L4}
STATION 1 Olgiassa	30	2.41	0.60	0.629	0.0377	0.270 0.270	1.801	3.792	1.652		
STATION 2 Bellagio	27	2.44	0.75	0.932	0.0041	0.338					
STATION 3 Como	58	2.38	0.50	0.891	0.0148	0.523 0.337	0.621	3.683	7.210	(1.682)	
STATION 4 Lecco	73	2.46	0.00	0.929	0.0039	0.187 0.198	2.480	0.422	2.024		0.668

Note - 1st hypothesis: differential sedimentation; 2nd hypothesis: alluvion.

z : maximum depth in sediment (cm); $\bar{\rho}_B$: density; ϕ' : porosity at final compaction; ϕ'' : porosity at sediment-water interface; δ : compaction coefficient; ω_R : "regular" sedimentation rate ($g/cm^2/yr$); ω_A : "anomalous" sedimentation rate; ω_{L1} - ω_{L4} : "alluvial" sedimentation rate.

DATING

Depth in core (cm)	10	20	30	40	50	60	70
STATION 1	1965 1966	1959 1960	1932 1934				
STATION 2		1972 1958					
STATION 3		1970 1973	1963 1963	1955 1948	1942 1964	1938 1923	
STATION 4		1968 1967	1954 1955	1944 1947	1924 1927	1894 1900	1862 1869
						1831 1840	

Dating of sediment

By measurements of Cs-137 γ activity, the sediment accumulation rate can be determined (RAVERA and PREMAZZI, 1972). This isotope was introduced in the atmosphere when started the nuclear weapons testing. By atmospheric fall-out, which began in 1954, the Cs-137 accumulates on the earth surface and in lake sediments too. The isotope concentration has a typical shape: it is remarkable in 1954 and shows a marked peak in 1963 (PENNINGTON et al., 1973).

From the profile of Cs-137 activity in the core samples, it is possible to identify therefore the centimeters of sediment corresponding to these two years. The determination of sedimentation rate was carried out with a method proposed by ROBBINS and EDGINGTON (1975); sedimentation rate is assumed uniform over the last several hundred years and the postdepositional mobility of radionuclide is very small. This method considers the sediment compaction, evaluated by the logarithmic decrease of sediment porosity with depth (ATHY, 1930). The sediment porosity was estimated from the density of the solid phases and from measured sediment water content. The Athy rule is valid in the core

TABLE 6

Comparison with sedimentation rates of other lacustrine and coastal marine sediments

	mg/cm ² /yr	cm / yr
LAKE COMO	198 - 339	0.70 - 1.40
Lake Superior ¹	2.5 - 78	0.01 - 0.20
Lake Huron ²	3.5 - 98	0.02 - 0.33
Lake Michigan ³	6.0 - 102	0.01 - 0.40
Lake Erie ⁴	18 - 164	0.04 - 0.67
Lake Ontario ⁵	8.5 - 122	0.03 - 0.12
Saguenay Fjord (CDN) ⁶	70 - 4000	0.10 - 7.00
Lake Sylvan (USA) ⁷	110	
Lake Canadaxago (USA) ⁷	520	
Lake Champlain (USA) ⁷	140	
Tokio Bay ⁸	130	
Saanich Inlet (CDN) ⁹	90 - 270	
Rana Fjord (N) ¹⁰		0.13
Western Baltic Sea (D) ¹¹		0.14
Chesapeake Bay (USA) ¹²		1.0 - 8.0
Walensee (CH) ¹³		1.0 - 9.0
Thunersee (CH) ¹⁴		0.2 - 0.8
Bodensee (CH) ¹⁵		0.15 - 0.30
Tegernsee (CH) ¹⁶		0.40

¹ Kemp et al. 1978 cf. Nriagu et al. 1979	Pb-210 method
² Robbins et al. 1978 cf. Nriagu et al. 1979	" "
³ Robbins and Edgington 1975	" "
⁴ Nriagu et al. 1979	" "
⁵ Kemp et al. 1978	" "
⁶ Smith and Walton 1980	" "
⁷ Wahlen and Thompson 1980	Cs-137 "
⁸ Kitano et al. 1980	Pb-210 "
⁹ Matsumoto and Wong 1977 cf. Wahlen 1980	" "
¹⁰ Skel and Paus 1979	" "
¹¹ Erlenkeuser et al. 1974	C-14 "
¹² Goldberg et al. 1978	Pb-210 "
¹³ Lambert 1978	" "
¹⁴ Sturm and Matter 1972	" "
¹⁵ Wagner 1972 cf. Förstner and Möller 1974	" "
¹⁶ Hamm 1971 cf. Förstner and Möller 1974	" "

sample collected in Station 2. On the contrary in the other cores we can observe two different parts: one following the former rule and other, layered in the first, not following this rule, with low porosity and high density relating to a sandy-silt composition. This discontinuous sedimentation is fit for two interpretations:

- 1) variations of terrigenous material input;
- 2) continuous turbidity currents due to very dense inflows, during the river flood stages (LAMBERT, 1978).

The first hypothesis can be named « differential sedimentation », the second one « alluvion ».

In the first case, once singled out two points concerning the years 1954 and 1963, an equation system is set up with data unknown the regular sedimentation rate ω_R , for the parts following the Athy rule and the anomalous rate ω_A , for the parts not following this rule. In the second case, for the parts following Athy's rule, the sedimentation rate is

ω_R . We can assume that the amount of sediment deposited by a single turbidity event is representative of all deposition in the year when the event is happened. Therefore, for each layer not following the Athy rule, we can consider a period of one year with a sedimentation rate ω_L . Hence every hypothesis gives two sedimentation rates and consequently two different ages of sediment cores (table 5). We estimate more valid the second hypothesis and we use it in the flux calculation.

In the four Stations we can observe an increase of the rate from North to South except for Station 4. This rate is high and similar to that observed in lakes with the same size and morphology. In comparison with great lacustrine basins, the rate is almost always very higher; this comparison is shown in table 6.

Discussion

Statistics

For all the elements analysed in each Station we computed the correlation coefficient « r » (tables 7 and 8).

TABLE 7

Correlation coefficients «r» among elemental concentrations (Stations 1 and 3)

														Station 1	
Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Cr	Ni	Cu	Zn	Pb	Co	Org. matt.		
	.27	.46*	-.36	-.13	.51*	-.46*	.20	.31	.06	.17	.16	.08	.17	Fe ₂ O ₃	
-.13		.74*	.20	-.34	.68*	-.41	.16	.26	-.31	-.14	-.10	-.15	-.17	CaO	
.34	-.14		-.19	-.74*	.52*	-.78*	.31	.72*	.03	.38	.32	.23	.18	MgO	
.01	.58*	-.18		.32	.13	.45*	-.43	-.39	-.37	-.65*	-.59*	-.33	-.61*	Na ₂ O	
.52*	.01	.42*	-.06		-.14	.82*	-.69*	-.83*	-.42	-.78*	-.70*	-.34	-.35	K ₂ O	
.31	.49*	.02	.58*	.15		-.28	-.08	.15	-.16	-.10	-.09	-.47*	.09	MnO	
.45*	-.39	.28	-.38	-.03	-.12		-.68*	-.90*	-.32	-.69*	-.59*	-.48*	-.21	TiO ₂	
.29	-.47*	.33	-.44*	-.07	-.26	.64		.53*	.35	.63*	.63*	.36	.12	Cr	
-.18	.45*	-.38	.13	-.11	.04	-.23	-.31		.35	.77*	.69*	.53*	.33	Ni	
.21	-.55*	.25	-.52*	-.20	-.33	.86*	.76*	-.26		.64*	.68*	.12	.47*	Cu	
.38	-.49*	.29	-.42*	-.10	-.30	.83*	.78*	-.26	.86*		.93*	.47*	.55*	Zn	
.20	-.56*	.12	-.47*	-.26	-.31	.74*	.78*	-.13	.90*	.87*		.39	.57*	Pb	
-.28	.54*	.06	.35	-.09	.12	-.43*	-.03	.04	-.39	-.21	-.36		-.16	Co	
.38	-.66*	.36	-.49*	-.08	-.42*	.83*	.82*	-.38	.86*	.89*	.77*	-.32		Org. matt.	

Station 3 * significance > 95%

TABLE 8

Correlation coefficients «r» among elemental concentrations (Stations 2 and 4)

														Station 2	
Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Cr	Ni	Cu	Zn	Pb	Co	Org. matt.		
	-.03	-.18	.76*	.80*	-.49	-.44	-.35	.24	-.63*	-.75*	-.53	.33	-.82*	Fe ₂ O ₃	
-.56*		.40	-.11	.00	-.14	-.33	-.42	-.19	-.42	-.26	-.27	-.34	-.21	CaO	
-.48*	.80*		-.37	.01	.22	-.08	-.20	-.02	.04	.13	-.25	-.56*	.08	MgO	
-.19	-.34	-.39		.81*	-.40	-.12	-.08	-.16	-.50	-.64*	-.30	.42	-.69*	Na ₂ O	
-.75*	.50*	.66*	-.11		-.45	-.37	-.35	.11	-.65*	-.78*	-.62*	.27	-.85*	K ₂ O	
.29	.25	.29	-.22	-.01		.85*	-.26	.83*	.82*	.75*	.17	.66*		MnO	
.70*	-.26	-.10	-.14	-.46*	.62*		.86*	-.44	.78*	.75*	.76*	.33	.65*	TiO ₂	
.84*	-.60*	-.57*	.03	-.69*	.26	.72*		-.29	.81*	.75*	.86*	.34	.60*	Cr	
.73*	-.76*	-.77*	.05	-.71*	-.12	.43*	.78*		-.21	-.21	-.32	-.12	-.24	Ni	
.63*	-.33	-.37	-.22	-.65*	-.23	.24	.34	.56*		.97*	.89*	.20	.89*	Cu	
.76*	-.65*	-.69*	-.01	-.72*	-.15	.36	.82*	.89*	.56*		.85*	.01	.96*	Zn	
.44*	-.35	-.54*	.04	-.67*	-.25	.16	.54*	.78*	.56*	.76*		.40	.78*	Pb	
.53*	.12	.13	-.17	-.41*	.54*	.73*	.38	.19	.37	.09	.09		-.09	Co	
.50*	-.72*	-.67*	-.22	-.46*	-.41*	.07	.39	.72*	.51*	.67*	.42*	-.19		Org. matt.	

Station 4 * significance > 95%

In the four Stations the correlations among Cr, Cu, Pb and Zn have the same high significance (99 %), as well as the correlations among these elements and organic matter; but in Stations 1 and 4 the correlations Cr-Cu and Cr-organic matter, though positive, have not significance. These correlations were also observed in two lakes of New York State (WAHLEN and THOMPSON, 1980).

Ti with Fe, Cr, Pb and Zn are positively correlated in Stations 2, 3, 4 and negatively in Station 1.

Hence each Station must be considered by itself for the very different lithology of drainage basin. The same cause should give the reason of the significant correlations observed in only two Stations or in only one and away from other

Stations (Ni with other trace elements in Station 1 and 4; Fe with trace elements in Station 4, Mn with trace elements in Station 2).

The most significant correlations among major elements and sediment components (table 9) are observed in Station 1, where are present sharp differences in grain-size composition along the core. Particularly K and Ti are positively correlated with sand fraction and negatively with silt fraction. Ca, Fe and Mg are positively correlated with silt fraction and negatively with sand fraction. Trace elements are positively correlated with clay fraction and negatively with sand fraction, as well as indicate in Lake Michigan (PEZZETTA and ISKANDAR, 1977) and in Lake Erie (NRIAGU et al., 1979).

TABLE 9
*Correlation coefficients «r» among sediment components
and elemental concentrations*

	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Cr	Ni	Cu	Zn	Pb	Co	Org. matt.
STATION 1														
silt	.67*	.61*	.79*	-.38	-.52*	.40	-.84*	.51*	.65*	-.06	.32	.23	.37	.07
sand	-.60*	-.57*	-.83*	.42	.64*	-.35	.91*	-.54*	-.77*	-.11	-.47*	-.39	-.46*	-.16
clay	.30	.37	.75*	-.44	-.80*	.12	-.89*	.56*	.89*	.44	.72*	.65*	.56*	.29
clay + org.matt.	.31	.33	.73*	-.51*	-.81*	.13	-.87*	.55*	.89*	.49*	.76*	.70*	.49*	
STATION 2														
silt	.46	-.59*	-.56*	.38	.29	.09	.17	.37	.18	.19	.01	.25	.68*	-.12
sand	-.78*	-.05	.23	-.54*	-.64*	.27	.35	.18	-.07	.51	.62*	.39	-.30	.73*
clay	-.37	.63*	.55*	-.35	-.24	-.16	-.27	-.45	-.16	-.30	-.11	-.34	-.72*	.02
clay + org.matt.	-.48	.59*	.56*	-.43	-.35	-.07	-.28	-.36	-.20	-.17	.02	-.24	-.72*	
STATION 3														
silt	.15	.28	.28	-.12	.42*	.07	-.03	-.15	-.03	-.20	-.02	-.22	.16	-.13
sand	-.25	.42*	-.34	.50*	-.33	.22	-.46*	-.34	.38	-.40	-.48*	-.28	.16	-.47*
clay	.12	-.78*	.08	-.47*	-.09	-.32	.57*	.55*	-.39	.70*	.57*	.58*	-.34	.72*
clay + org.matt.	.19	-.80*	.09	-.52*	-.15	-.35	.65*	.65*	-.39	.78*	.71*	.68*	-.34	
STATION 4														
silt	.07	.45*	.64*	-.80*	.42	.45*	.19	-.14	-.28	-.09	-.25	-.33	.26	-.13
sand	-.17	-.05	-.27	.79*	-.29	-.19	-.19	-.03	-.08	.01	-.01	.15	-.07	-.33
clay	.21	-.59*	-.48*	-.24	-.11	-.35	.06	.25	.56*	.13	.40	.24	-.26	.81*
clay + org.matt.	.33	-.67*	-.56*	-.25	-.24	-.38	.07	.32	.64*	.27	.52*	.31	-.24	

* significance > 95%

Element fluxes to the sediments

The elements are supplied to the Lake Como from both natural and anthropogenic sources; it is important to evaluate the contribution of each source to total elemental amount. Then we can calculate the fluxes of elements to the sediments, if we assume that diagenetic remobilization of elements after deposition is absent, that the elemental amounts in the deeper part of cores represent the natural loads and that sedimentation rate remains uniform for several years (GOLDBERG et al., 1978).

For each one of the four Stations the average contents of the elements in the sediments former to 1940 are considered the natural loads. The present-day average contents are related to surficial sediments (1-10 cm) and are meaning of the sum of the natural and anthropogenic inputs. Natural and present day fluxes

TABLE 10

Natural and present-day fluxes of elements to the sediments of Lake Como

NATURAL FLUXES		Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	TiO ₂	Cr	Ni	Cu	Zn	Pb	Co
Station 1														
$\bar{x}$ (2)		1.74	1.25	1.38	0.63	0.82	0.024	0.18	45	40	14	57	18	6
σ		0.03	0.28	0.32	0.04	0.02	0.001	0.01	9	.4	.2	8	3	.4
		years 1940-1934 (cm 27/28 - cm 29/30)												
Station 2														
$\bar{x}$ (5)		2.21	1.20	1.05	0.55	1.15	0.030	0.19	45	134	22	50	19	18
σ		0.13	0.34	0.14	0.03	0.03	0.010	0.01	4	27	2	2	5	1
		years 1972-1958 (cm 11 - cm 19)												
Station 3														
$\bar{x}$ (3)		1.49	1.49	0.75	0.46	0.68	0.015	0.20	31	72	29	93	53	5
σ		0.15	0.05	0.09	0.03	0.06	0.003	.003	15	40	2	24	20	1
		years 1944-1923 (cm 41/42 - cm 49/50)												
Station 4														
$\bar{x}$ (4)		1.28	2.03	1.41	0.19	0.49	0.010	0.10	12	9	44	154	28	4
σ		0.15	0.07	0.12	0.03	0.04	0.001	0.01	1	.5	23	35	12	.2
		years 1900-1869 (cm 49 - cm 61)												
PRESENT-DAY FLUXES														
Station 1														
$\bar{x}$ (7)		1.82	0.90	1.26	0.49	0.80	0.021	0.15	60	49	15	119	27	9
σ		0.08	0.18	0.18	0.07	0.07	0.001	0.01	10	7	1	43	7	.3
		years 1979-1965 (cm 1 - cm 7)												
Station 2														
$\bar{x}$ (5)		1.98	0.88	0.96	0.52	1.07	0.060	0.22	53	131	32	117	60	19
σ		0.19	0.08	0.23	0.06	0.07	0.030	0.02	5	38	5	49	17	3
		years 1980-1972 (cm 1 - cm 9)												
Station 3														
$\bar{x}$ (6)		1.34	1.29	0.71	0.37	0.61	0.013	0.24	49	58	51	195	107	5
σ		0.09	0.04	0.02	0.05	0.02	0.002	0.05	4	17	16	35	19	1
		years 1973-1963 (cm 10 - cm 19/20)												
Station 4														
$\bar{x}$ (5)		1.52	1.31	0.80	0.22	0.41	0.010	0.10	64	28	71	452	105	3
σ		0.34	0.20	0.26	0.07	0.03	0.001	0.01	47	8	24	158	34	.2
		years 1978-1967 (cm 1 - cm 9)												
Flux rates: oxides g 10 ⁻² /cm ² /yr														
heavy metals µg/cm ² /yr														

of elements calculated as product of sedimentation rates and elemental concentrations are shown in table 10; the anthropogenic fluxes were derived by subtracting the natural fluxes from the total fluxes of elements and point out the impact of industrialization.

Among major elements we note generally a weak decrease between natural and present-day fluxes; among trace elements we note a strong increase between the two fluxes for Cr, Cu, Pb and Zn while Co and Ni have no variations (GOLDBERG et al., 1978; SKEI and PAUS, 1979; NRIAGU et al., 1979; WAHLEN and THOMPSON, 1980). Particularly we can detail:

Station 1: major elements, except for Fe, show a decrease between natural and present-day fluxes. Trace elements show an increase, Zn anthropogenic flux is equal to the natural one.

TABLE 11

Anthropogenic fluxes of lead, zinc and copper to the sediments of Lake Como and to lacustrine and coastal marine sediments

	Pb		Zn		Cu	
	natural	anthrop.	natural	anthrop.	natural	anthrop.
LAKE COMO						
Station 1	18	9	57	62	14	1
Station 2	19	41	50	67	22	10
Station 3	53	54	93	102	29	22
Station 4	28	77	154	298	44	27
Santa Barbara Basin ¹	1.0	2.1	9.7	2.2	2.6	1.4
Naragansett Bay ²	2.6	124	14	230	3.1	193
Chesapeake Bay ³	4 - 5	2 - 8	15 - 19	4 - 34	4	.8 - 5
Rana Fjord ^{4*}	20	65	135	135	30	20
Lake Erie ⁵	.4 - 4	.2 - 12	.7 - 15	1 - 36	.5 - 8	.2 - 12
Lake Sylvan ⁶		16		24		38
Lake Champlain ⁶		16		20		4.9
Lake Michigan ⁷		2 - 48				
Saanich Inlet ⁸		4 - 11				6 - 14

¹ Bruland et al. 1974 cf. Goldberg et al. 1978

² Goldberg et al. 1977 cf. Goldberg et al. 1978

³ Goldberg et al. 1978

⁴ Skei and Paus 1979

⁵ Nriagu et al. 1979

⁶ Wahlen and Thompson 1980

⁷ Edgington and Robbins 1976 cf. Wahlen 1980

⁸ Matsumoto and Wong 1977 cf. Wahlen 1980

Flux rates in $\mu\text{g}/\text{cm}^2/\text{yr}$
* $\text{mg}/\text{m}^2/\text{yr}$

Station 2: major elements show a natural flux like the present-day one, except for Mn and Ti. Trace elements show an increase, except for Co and Ni; Pb anthropogenic flux is double and Zn one is equal to the natural flux.

Station 3: major elements, except for Ti, show a decrease between natural and present-day fluxes. Trace elements show an increase, except for Co and Ti; Pb and Zn anthropogenic fluxes are equal to the natural ones.

Station 4: major elements, except for Fe, Na and Ti, show a decrease between natural and present-day fluxes. Trace elements show an increase, except for Co; Cr anthropogenic flux is four times greater than the natural flux, while the Pb and Zn fluxes are double than its natural inputs.

In conclusion, we can infer that present-day major element input is mainly due to clastic erosion material, while for trace elements is mostly due to cultural pollution, except for Co and Ni. The rates of Cu, Pb and Zn accumulation in Lake Como sediments are very high both in natural and anthropogenic values. The ratio between the two fluxes are however lower than those observed in the lakes surrounded by heavily populated and industrialized regions, like Lake Erie (NRIAGU et al., 1979). Table 11 shows the fluxes of Cu, Pb and Zn to Lake Como sediments and to lacustrine and coastal marine sediments.

Conclusions

The great variations generally shown by concentrations of major elements among the core samples, would be attributed to different clastic material supplied to the sediments from natural runoff of areas with different lithology. The changes of contents along the cores, different for each element in the four Stations, suggest a change in clastic material input during the time. This variation is confirmed by grain-size composition profile for each core sample and by associated porosity differences, which influence on sedimentation rate.

In Station 1, directly affected on Adda and Mera river basins, based morely in crystalline and metamorphic rocks, the strong correlation among K, Ti and sand fraction suggests a detrital origin of these elements; this origin is excluded for Ca, Fe and Mg correlated to silt fraction. In Stations 1 and 3 trace elements are correlated to clay fraction and to organic matter. The cation exchange capacity of illite and chlorite is very low, consequently the precipitation as metallic coatings, incorporation in crystalline structure and in organic matter, would be the main trace elements enrichment processes in clays and organic matter.

Trace element contents show an increase towards the top of the cores, except for Co and Ni; really, if we consider the average amount of the deeper part of cores as representative of local natural load, we can observe, towards the surface, a concentration increase greater than 100 %.

Sedimentation rate is very high, but similar to rate of lakes with the same size and morphology. Anthropogenic fluxes of Cr, Cu, Pb and Zn to the sediments are till three times greater than the natural ones and show an enlarged availability of these elements due to cultural pollution. These fluxes are very higher in the southern Stations (Como and Lecco) where atmospheric pollutants and superficial runoff are present together with industrial and domestic sewage discharges, shipping operations and vehicle circulation.

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