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Mapping Sediment Accumulation Rate by using Volume magnetic Susceptibility Core Correlation in a contaminated Bay (Lake Geneva, Switzerland)

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Key words: ^{137}Cs dating, core correlation, lake sediment, sewage treatment plant, magnetic susceptibility 3-D.

ABSTRACT

The Bay of Vidy is the most contaminated area of Lake Geneva: contamination is caused by the effluent of the sewage treatment plant (STP) of the City of Lausanne. The implementation of a chemical stage in the treatment plant to remove phosphorus using $FeCl_3$ in 1971 is indirectly recorded in the lake sediments by a strong and sharp increase in the volume magnetic susceptibility (VMS) signal. A total of 43 sediment cores have been retrieved and measured for VMS. The synchronism of the VMS signal increase and its relation to the implementation of the P-removal stage in the STP has been shown in seven ^{137}Cs-dated sediment cores. The VMS signal has been used to date by stratigraphic correlation all of the 43 sediment cores and map the three-dimensional distribution of contaminated sediments. Over an area of 0.5 km^2, the sediment accumulation rates vary from 2.8 cm/y close to the effluent mouth, to 0.3 cm/y 1 km away. The total mass of contaminated sediments is estimated to 274,000 tons.

RESUME

La Baie de Vidy est la zone la plus contaminée du Léman, de part la présence des rejets des eaux de la station d'épuration de la ville de Lausanne et des communes environnantes. La mise en fonction en 1971 d'une étape de déphosphatation des eaux usées, utilisant du FeCl3, est indirectement enregistrée dans les sédiments de la baie par une rapide et forte augmentation du signal magnétique. Un ensemble de 43 carottes de sédiment a été prélevé dans la baie pour en mesurer la susceptibilité magnétique. Le synchronisme entre l'augmentation du signal magnétique et la mise en place de la phase de déphosphatation des eaux usées est vérifié par la datation (méthode du 137Cs) de 7 carottes. Le signal magnétique est utilisé pour corréler et ainsi dater les 43 carottes sédimentaires et établir une distribution tridimensionnelle des sédiments contaminés. Sur une étendue de 0.5 km2, le taux de sédimentation varie entre 2,8 cm/an, près de l'effluent de la station d'épuration, et 0,3 cm/an à environ 1 km de là. La masse totale de sédiments contaminés est estimée à 274'000 tonnes

1.- Introduction

Lake sediments are invaluable archives of the historical changes of a water body and its watershed. Deciphering the environmental signal stored in the sediment requires the establishment of an absolute time scale. In the absence of varves the dating of recent sediments is usually accomplished using ^{137}Cs or ^{210}Pb (e.g. Krishnaswami et al. 1971, Robbins & Edgington 1975, Dominik et al. 1981, Oldfield & Appleby 1984). However, these techniques are time consuming, and therefore only a restricted number of sediment cores can be dated. Thus mapping sediment accumulation rates (SAR) based on a dense set of cores is usually not feasible, unless another time marker, easily and rapidly measurable, is available. Volume magnetic susceptibility (VMS) has been used for core correlation and indirect dating (e.g. Thompson et al. 1975, Bloemendal et al. 1979, Appleby et al. 1985, Loizeau et al. 1997). In addition, Versteeg et al. (1995, 1996) have successfully used the VMS signal as a proxy for heavy metals and PAH contamination in Hamilton Harbour sediments.

In the present paper, we show that in the Bay of Vidy, the increase of the VMS signal is synchronous over the entire area and corresponds to 1971. Therefore, it can be used as a local isochron. The analysis of VMS in numerous sediment cores enable the preparation of a precise map of sediment accumulation rates. This map is also a representation of the

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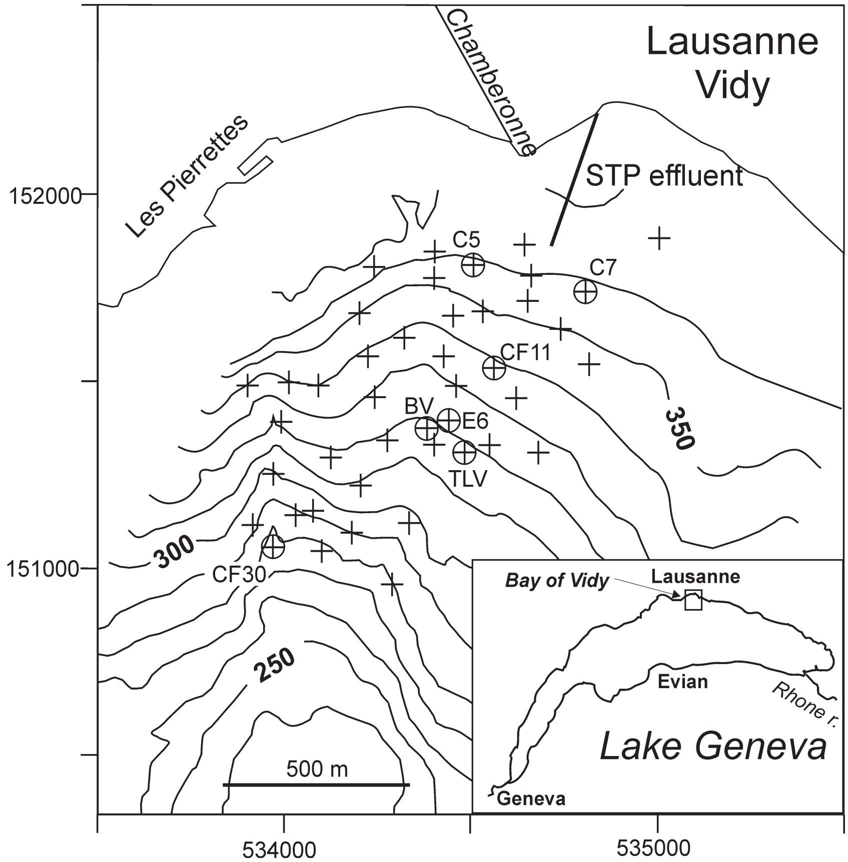

Figure 1. Topographic map of the Bay of Vidy, Lake Geneva. The mean lake level is 372 m asl. Crosses indicate site location of sediment cores. The 7 circled crosses indicate ^{137}Cs-dated cores with their name. Inset: Location of the Bay of Vidy in Lake Geneva.

three-dimensional distribution of sediments contaminated by the STP.

2.- Settings

Lake Geneva is the largest freshwater body in western Europe with a volume of 89 km^3. The Rhone river is its major tributary and provides about 70% of the affluent waters. In 1999, the permanent population in the lake watershed was 933,750 inhabitants and the tourist capacity was 624,240. The largest city on the lake shore is Lausanne, which releases its treated domestic and industrial wastewaters into the Bay of Vidy, on the northern shore of the lake (Fig. 1). The present capacity of the sewage treatment plant (STP) is 410,000 equiv. inhabitants. The STP of Lausanne started operation in 1964 with biological treatment, followed in 1971 by the implementation of phosphate elimination using $FeCl_3$ addition and subsequent precipitation in $Fe(OH)_3$. Most of the iron hydroxides are removed in the STP by sedimentation, but a fraction of it is released into the lake through the outlet. This results in higher Fe concentrations (factor 2 to 3) in the sediments of the Bay of Vidy compared to concentrations recorded before the implementation of the STP (Peytremann & Haller 1997). Gibbs-Eggar et al. (1999) have shown that the high values of VMS in the recent sediments of the Bay of Vidy are due to the presence of superparamagnetic magnetite grains. These type of grains can be formed either as secondary minerals in soil or as product of bacterial activity. In a recent study, Snoeyenbos-West et al. (submitted) show that these magnetite grains originate from the metabolic activity of *Geobacter*, a dissimilatory Fe(III) reducing bacterium. There is no other credible source of fine-grained detrital magnetite within the predominantly urban catchment. Studies elsewhere have shown that the magnetic properties of urban particulates are dominated by a mixture of MD magnetite and heamatite (Hunt et al. 1984, Hunt 1986).

The Bay of Vidy has long been recognised as the most contaminated part of the lake in term of nutrients (Williams et al. 1978), heavy metals (Mondain-Monval et al. 1984, Arbouille et al. 1989, Span et al. 1992), and organic pollutants (Pardos et al., submitted). Loizeau et al. (submitted) report sediment enrichment factors (compared to natural values) of 180, 71, 58, 18, and 18 for Hg, Cd, Zn, Pb, and Cu, respectively, in the most contaminated area, whereas these factors vary between only 1.1 and 2.6 for recent sediments from the centre of the lake.

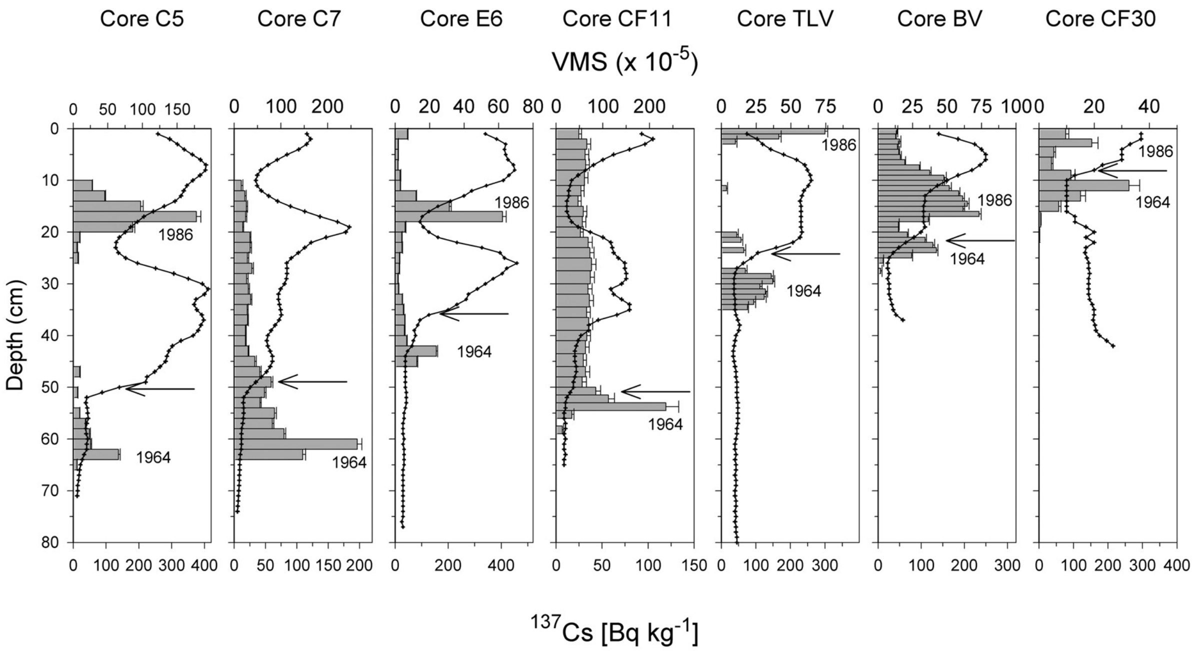

Figure 2. VMS and ^{137}Cs activity profiles of the seven dated cores. The arrows indicate the maximum gradient used to determine the date of the VMS increase (Tab. 1).

3.- Methods

The sampling was performed from "La Licorne", the 13m-long boat of the Institut F.-A Forel. The initial aim of this study was to draw an accurate topographic map of the Bay, as the only available map is 120 years old. Data were collected using a E-Sea Sound 206 echosounder (Marinatech) with a 200kHz transducer. The horizontal positioning was obtained by a Ashtec GPS (SCA-12) using a differential correction. The accuracy of the positioning was about 0.5 m. A total of 40 km of depth profiles were recorded over a 4 km^2 area, with a 50-m spacing between each profile.

Sediment cores were recovered from the boat with a Benthos gravity corer (figure 1) One core (named BV) was retrieved from the manned submersible F.-A. Forel, which allowed a visual selection of the sampling site and control of the coring operation.

VMS was determined in all cores using a MS2 susceptibility meter from Bartington with a type C probe. The susceptibility type C probe is 2 cm wide and the sediments within a few centimetres around the probe influence the measurement, which smoothes the profile. To identify with the same criteria the depth of a sharp transition, we selected in all cores the sediment section showing the maximum VMS gradient (Fig. 2).

Seven cores have been dated using ^{137}Cs activity. This artificial radionuclide has been introduced by atmospheric nuclear tests and by the Chernobyl accident. High ^{137}Cs activity in sediments can be used as stratigraphic markers by comparison with documented fallout pattern from the atmosphere. Maximum fallout from the tests occurred in 1963/1964, although the Chernobyl accident labelled sediments in 1986 (Ritchie & McHenry 1990). ^{137}Cs g-activity has been measured in bulk sediment samples with an HPGe spectrometer (Ortec EG&G).

Porosity was determined using the water content following Hakanson & Jansson (1983, eq. 4.2). Depth scale was converted to mass scale to compute sediment accumulation rate in [g cm^{-2} y^{-1}].

Sediment accumulation rates (SAR) have been obtained by the following equation:

$$SAR = m_{Cs} / t \text{ [g cm}^{-2}\text{ y}^{-1}] \quad (1)$$

With m_{Cs} the mass of sediment accumulated between the two ^{137}Cs peak horizons (Fig. 2), and t the time elapsed between these horizons (22 years). In the two cores where the ^{137}Cs peak of 1986 is absent, SARs have been calculated between 1964 and the sediment surface. Dating the VMS increase has been performed by using the equation:

$$\text{Date of VMS increase} = 1964 + m_{VMS} / SAR \quad (2)$$

With m_{VMS} the mass of sediment accumulated between the ^{137}Cs activity peak of 1964 and the maximum VMS gradient, and SAR the sediment accumulation rate determined by equation (1).

Finally SARs have been determined in all unopened cores by using equation (3):

$$SAR = d_{VMS} / t \; [cm/y] \quad (3)$$

With d_{VMS} the depth (in cm) of the maximum VMS gradient, and t the time elapsed between 1971 and date of core recovery (Table 1).

Organic matter content has been estimated by loss on ignition (LOI) (Hakanson & Jansson 1983).

Heavy metal (Fe, Pb, Cd, Cr, Cu, Zn, …) concentrations in sediments were obtained using an ICP-AES / ICP-MS (Poems1, TJA) after nitric acid (2M) digestion.

4.- Results and discussion

Topographic map

The topography of the bay (Fig. 1) is relatively simple, with the slope generally perpendicular to the coast line. However a sublacustrine canyon has been observed on the western side of the study area. It is 600 m long, 50 m wide and between 5 and 10 m deep. It ends at an altitude of 250 m (122 m water depth) with a deposition fan at 240 m (132 m water depth). This structure was observed during the previous topographic survey in 1892, but was represented with a less pronounced morphology, probably due to the discrete point measurement method used at that time.

Dated sediment cores

In the 7 dated cores (Tab 1, Fig. 2), the date of the VMS increase ranges between 1967 and 1972 with an average date for the 7 cores of 1970.4 ± 1.6 y, whereas the sediment accumulation rates vary between 0.14 and 0.89 [g cm^{-2} y^{-1}], that is by a factor 6 (Fig. 3). Taking into account the uncertainty of dating, there is not significant difference in the date of the VMS increase in all dated cores, and this corresponds exactly to the implementation of the chemical treatment using $FeCl_3$ to remove phosphorus from waste waters. Therefore, under the assumption of continuous sedimentation, the first maximum gradient in VMS profiles can be used as a time marker dated to 1971. Moreover, even if the sedimentation is discontinuous, the VMS signal can be used as a proxy for the contaminated sediment layers.

The assumption of continuous sedimentation is not always valid. The upper section of some cores (C5, C7,E6, CF 11) present a large trough in the VMS signal (Fig. 2). More-

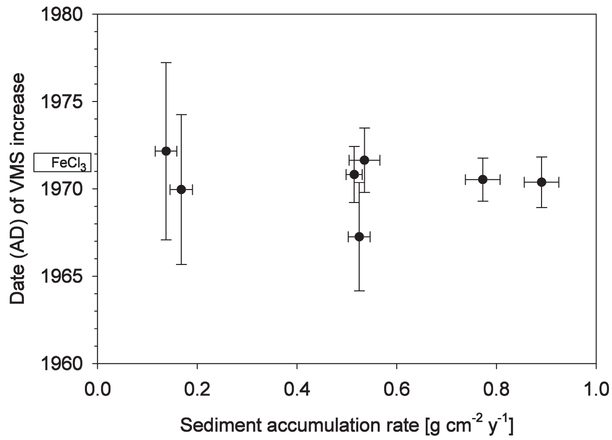

Figure 3. Dating of the VMS increase vs sediment accumulation rate. The 7 ^{137}Cs-dated cores give a date of the VMS increase not significantly different from 1971 (box labelled $FeCl_3$), in spite of sediment accumulation rates varying from 0.14 to 0.89 [g cm^{-2} y^{-1}] (Tab. 1). This date corresponds to the time of the implementation of a chemical stage in the STP using $FeCl_3$. Dates and sediment accumulation rate errors are given at 1 σ.

Core name	X coordinates [m]	Y coordinates [m]	Date of recovery	SAR [g cm^{-2} y^{-1}]	Date of VMS increase
C5	534516	151794	15/08/1995	0.89±0.03	May 1970±1.4y
C7	534784	151732	15/08/1995	0.77±0.03	July 1970±1.2y
E6	534440	151398	24/08/1995	0.54±0.03	August 1971±1.8y
CF11	534560	151540	01/06/1999	0.52±0.02	April 1967±3.1y
TLV	534500	151300	01/04/1988	0.51±0.02	October 1970±1.6y
BV	534442	151377	30/04/1997	0.17±0.02	January 1970±4.3y
CF30	533970	151060	01/06/1999	0.14±0.02	March 1972±5.1y
					Error-weighted average **June 1970±1.8y**

Table 1. Main data of the seven dated cores, ordered with decreasing sediment accumulation rates (SAR). Error are given at 1 σ.

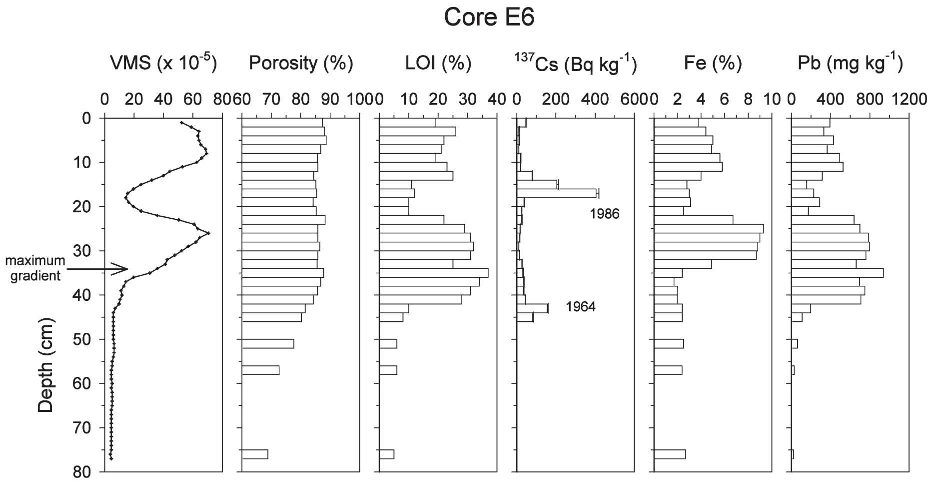

Figure 4. Sediment core E6. Profiles of VMS, porosity, LOI (organic matter), ^{137}Cs activity, and concentration of Fe and Pb. The two ^{137}Cs activity peaks correspond to the bomb test (1964) and Chernobyl accident (1986). The increase of VMS is defined as the layer presenting the maximum gradient. Pb concentration profile presents a sharp increase corresponding to the start of the sewage treatment plant of Lausanne (1964), whereas Fe increases simultaneously with VMS, both resulting from the implementation of a chemical stage in the STP using $FeCl_3$.

over, in cores C7 and CF11 the peak of ^{137}Cs of 1986 is absent, whereas it is extended in core BV (see also Monna et al., 1999). The sediments corresponding to the low VMS values are slightly finer grained than the under- and overlying sediment (Rozé 2001) and have lower concentration of heavy metals (Fig. 4 and Peytremann & Haller, 1997). These sections probably correspond to sediment originating from another source, from coastal areas, displaced as local slumps or by engineering work undertaken in 1986 to fasten down the effluent pipe on the lake floor (M. Maulaz, STP of Lausanne, oral communication). The dynamic transport of sediment may have eroded the sediments deposited in 1986 in some areas and accumulated ^{137}Cs-enriched sediment down current. However it seems that the eroded material did not represent an important fraction of the sedimentary record, because sediment accumulation rates derived from ^{137}Cs dating give all cores a similar date for the VMS increase.

As an example of the relation between the VMS and chemical parameters, profiles of VMS, porosity, organic matter, ^{137}Cs activity, and Fe and Pb concentrations from core E6 are shown on Fig. 4. In this core the two activity peaks of ^{137}Cs are attributed to fall-out from nuclear bomb tests (1964) and the Chernobyl accident (1986). From these dates we calculated an average sediment accumulation rate of 0.54 [g cm^{-2} y^{-1}] and determined August 1971 as the date corresponding to the first maximum gradient of VMS (from bottom to core top). There are notable differences in the profiles of Fe and Pb (Fig. 4). The contamination by Pb starts 8 centimetres below the Fe increase. Porosity, organic matter and other heavy metals (Cd, Cr, Cu, and Zn, not shown) behave the same as Pb. The Pb concentrations in the sediments significantly increase in 1964, which corresponds to the start of operation of the STP of Lausanne. From this date, the STP effluent played the role of a point-source of pollution, concentrating in one spot the contamination which was before dispersed from many outlets along the lake shore. On the other hand, the increase of the Fe concentration coincides with the VMS increase in 1971. This finding confirms the excellent quality of dating in this sediment core.

Mapping sediment accumulation rates

Using the VMS marker, sediment accumulation rates have been determined in all 43 cores sampled in the Bay of Vidy. The mean SAR from 1971 vary between 0.3 and 2.8 cm/y. A map of the SAR has been derived from these data (Fig. 5) which evidently shows the impact of the STP effluents on the SAR pattern. Maximum SARs are observed close to the end of the effluent pipe, with a preferential extension to the southwestern zone of the Bay. The SAR then decreases linearly with the distance from the pipe end. This pattern is similar to the distribution of contaminants (heavy metals) in the surface sediment in the Bay (Pardos et al. submitted). Using this map, we determine that the volume of contaminated sediments delineated by the VMS signal reaches 204,600 m^3. This represents a sediment mass of 274,160 tons, assuming a sediment density of 1.34 [g cm^{-3}], calculated from an average porosity of 85%, and a particle density of 2.25 [g cm^{-3}] (including 25% of organic matter), or 69,000 tons of dry sediments. The median concentrations of heavy metals in post-1964 sediments in the area vary, for example, between 632 and 3447 µg/g (mean value = 1170 µg/g) for Zn and between 165 and 528 µg/g (mean value = 280 µg/g) for Pb (Loizeau et al., submitted). Taking mean values, the mass of Zn and Pb stored in the sediments are 81 and 19 tons, respectively. This constitutes a potential hazard source for the lake biota when sediment resuspension occurs, as has been observed by the erosion of the sediment layer deposited in 1986.

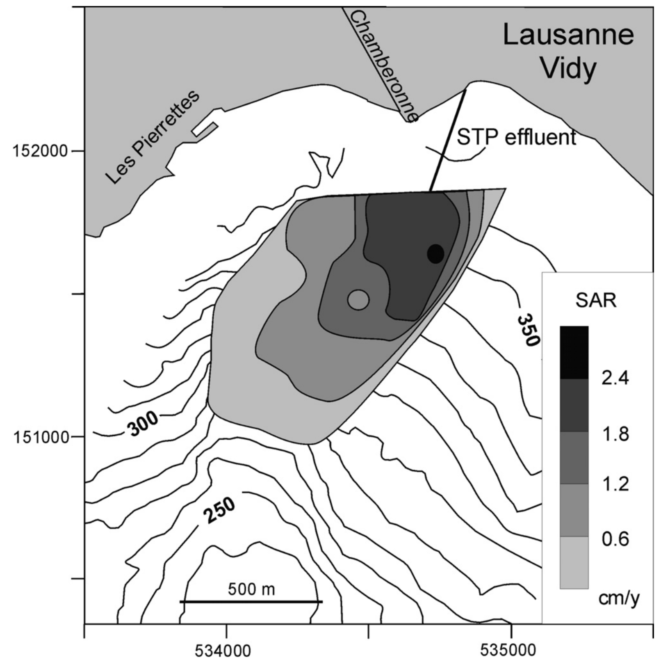

Figure 5. Map of the sediment accumulation rate (SAR) based on the VMS dating.

5.- Summary

The Bay of Vidy is influenced by a sewage treatment plant effluent outflow. The sediments record the start of the chemical stage in the STP by the presence of a strong magnetic signal. This signal results from the presence of magnetite grains originating from dissimilatory Fe(III) reducing bacteria. Dating of 7 cores indicates that the increase in the volume magnetic susceptibility (VMS) correlates over the entire bay, and can thus be used as an accurate time marker indicating 1971. From a total of 43 cores dated by the VMS signal, a high resolution map of sediment accumulation rates has been drawn. It shows the direct influence of the STP on the distribution of the sediments. It correlates also with the spatial distribution of contaminants such as heavy metals.

The method of detailed sedimentation rate mapping by using VMS signal, induced by Fe discharge from a STP, is probably also appropriate in other lakes receiving effluents from a similar source.

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REFERENCES

Appleby, P.G., Dearing, J.A., Oldfield, F. 1985: Magnetic studies of erosion in a Scottish lake-catchment. I Core chronology and correlation. Limnol. Oceanogr. 30, 1144-1153.

Arbouille, D., Howa, H., Span, D. & Vernet, J.-P. 1989: Etude générale de la pollution par les métaux et répartition des nutriments dans les sédiments du Léman. Rapp. Comm. int. Prot. Eaux Léman contre pollut., Campagne 1988, 139-172.

Bloemendal, J., Oldfield, F. & Thompson, R. 1979: Magnetic measurements used to assess sediment influx at Llyn Goddionduon. Nature 280-5717, 1097-1098.

Dominik, J., Mangini, A. & Muller, G. 1981: Determination of recent deposition rates in Lake Constance with radioisotopic methods. Sedimentology 28, 653-677.

Gibbs-Eggar, Z., Jude, B., Dominik, J., Loizeau, J.-L. & Oldfield, F. 1999 : Possible evidence for dissimilatory bacterial magnetite dominating the magnetic properties of recent lake sediments. Earth Planet. Sci. Let. 168, 1-6.

Hakanson, L. & Jansson, M. 1983: Principles of lake sedimentology. Springer-Verlag, Berlin, 316 p.

Hunt, A. 1986: The application of mineral magnetic methodes to atmospheric aerosol discrimination. Phys. Earth Planet. Inter. 42, 10-21.

Hunt, A., Jones, J. & Oldfield, F. 1984: Magnetic measurement and heavy metals in atmospheric particulates of anthropogenic origin. Sci. Tot. Environ. 33, 129-139.

Krishnaswamy, S., Lal, D., Martin, J.-M. & Meybeck, M. 1971: Geochronology of lake sediment. Earth Plant. Sci. Let. 11, 407-414.

Loizeau, J.-L., Dominik, J., Luzzi, T., Vernet, J.-P. 1997: Sediment core correlation and mapping of sediment accumulation rates in Lake Geneva (Switzerland, France) using volume magnetic susceptibility. J. Great Lakes Res. 23, 391-402.

Loizeau, J.-L., Pardos, M., Monna, F., Peytremann, C. & Dominik, J. (submitted): Impact of a sewage treatment plant effluent on sediment quality in a small bay in Lake Geneva (Switzerland). Part 2: Temporal heavy metals trends. Lakes & Reservoirs.

Mondain-Monval, J.-Y., Donard, O., Favarger, P.-Y. & Vernet, J.-P. 1984: Etude de la pollution des sédiments du Léman. Rapp. Comm. int. Prot. Eaux Léman contre pollut., Campagne 1988, 77-95.

Monna, F., Dominik, J., Loizeau, J.-L., Pardos, M. & Arpagaus, P. 1999: Origin and evolution of Pb in sediments of Lake Geneva (Switzerland - France). Establishing a stable Pb record. Environ. Sci. & Technol. 33, 2850-2857.

Oldfield, F. & Appleby, P:G. 1984: Empirical testing of 210Pb-dating models for lake sediments. In : Lakes sediments and environmental history (Ed. by HAWORTH, E.Y, & LUND, J.W.G). Univ. Minnesota Press, 93-124.

Pardos, M., Benninghof, C., De Alencastro, L.F. & Wildi, W. (submitted): Impact of a sewage treatment plant effluent on sediment quality in a small bay in Lake Geneva (Switzerland-France). Part 1: Spatial distribution of contaminants and potential for biological impact. Lakes & Reservoirs.

PEYTREMANN, C. & HALLER, L. 1997: Etude sédimentologique, géochimique et écotoxicologique des sédiments de la baie de Vidy. . Environmental sciences Diploma, No 10, University of Geneva, 121 p.

RITCHIE, J.C. & MCHENRY, J.R. 1990: Application of radioactive fallout cesium-137 measuring soil erosion and sediment accumulation rates and patterns: a review. J. Environ. Qual. 19, 215-233.

ROBBINS, J.A. & EDGINGTON, D.N. 1975: Determination of recent sedimentation rates in lake Michigan using Pb-210 and Cs-137. Geochim. Cosmochim. Ac. 39, 285-304.

ROZÉ, S. 2001: Evaluation des processus sédimentaires et du transport des sédiments contaminés dans la baie de Vidy. Environmental sciences Diploma, No 55, University of Geneva, 89 p.

SNOEYENBOS-WEST O., LOIZEAU, J.-L., DOMINIK, J. & LOVLEY, D.R. (submitted) : Evidence for the production of magnetite by Geobacter in Recent Lake Sediments. Earth Plant. Sci. Let.

SPAN, D., DOMINIK, J., LOIZEAU, J.-L., THOMAS, R.L. & VERNET, J.-P. 1992: Dynamic processes in relation to heavy metal distributions in surficial sediments: the example of Lake Geneva. In: Impact of heavy metals on the environment (Ed. by VERNET, J.-P.). ELSEVIER, 381-396.

THOMPSON, R., BATTARBEE, R.W., O'SULLIVAN, P.E. & OLDFIELD, F. 1975: Magnetic susceptibility of lake sediments. Limnol. Oceanogr. 20, 687-698.

VERSTEEG, J.K., MORRIS, W.A. & RUKAVINA, N.A. 1995: The utility of magnetic properties as a proxy for mapping contamination in Hamilton Harbour sediment. J. Great Lakes Res. 21, 71-83

VERSTEEG, J.K., MORRIS, W.A. & RUKAVINA, N.A. 1996: Mapping contaminated sediment in Hamilton Harbour, Ontario. Geosci. Can. 22, 145-151.

WILLIAMS, J.D.H., JAQUET, J.-M. & VERNET, J.-P. 1978 : Influence des rejets de deux stations d'épuration sur la teneur en phosphore des sédiments côtiers du Léman. Schweiz. Z. Hydrol. 40, 361-373

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