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Sediment distribution on a current-dominated lake delta (Versoix delta, Lake Geneva, Switzerland)

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Key words: Lake currents, delta sedimentation, wind drift, Lake Geneva

ABSTRACT

Lake delta morphology is determined by fluvial input, waves, lake currents, lake-level fluctuations and lake-basin topography. The current-dominated Versoix delta (*Petit-Lac* of Lake Geneva, Switzerland), has been studied in order to determine the role of wind-driven currents on transport and sedimentation of suspensions. Research included the study of sediment distribution in the lake basin, of currents due to wind forcing and modelling of lateral particle transport of suspended matter by lake currents.

Sediment input into the *Petit-Lac* mainly occurs by floods of the Versoix River. These floods are generally linked to precipitation under a regime of SW winds. Suspensions from river input are mainly deposited in an area SE and then S or even SW from the river mouth. Sediment transport is thus generally oriented in the opposite sense of the dominant wind direction during floods.

Sediments inside the lake basin originate from reworking on lake platforms, mainly during storms with NE winds.

Measurements of currents in the central part of the lake basin indicate wind-parallel lake currents at the surface and strong counter currents in the opposite direction in deep water. This particular current pattern, which is partly explained by the Ekman theory, may be linked to the general basin topography (channelled currents) and the unequal proportion of water masses on either side of the site (coastal set-up and set-down).

Modelling shows that, as a consequence of the strong deep currents, net fine sediment transport by deep counter currents occurs over several hundreds of meters to several kilometres. This result is consistent with the sediment distribution observed in the lake basin.

It can be postulated that changing wind or precipitation regimes may modify the depositional architecture. Further study of current systems, sediment architecture and sediment composition in lakes may, therefore, provide information about changes in these climatic factors since the last ice age.

RESUME

La morphologie des deltas lacustres est déterminée par l'apport fluviatile, par les vagues, les courants lacustres, les fluctuations du niveau et la topographie des fonds. Le Delta de la Versoix (Petit-Lac, Léman, Suisse) a fait l'objet d'une étude concernant l'influence des courants lacustres sur le transport et le dépôt des sédiments en suspension.

La Versoix constitue la source principale de sédiments. Les crues de la rivière sont généralement liées à des précipitations dans un régime de vents du SW. Le matériel en suspension apportées dans le lac lors de ces crues se déposent dans une zone située au SE, puis au S et même au SW de l'embouchure, dans une direction opposée à celle du vent dominant.

Au sein du lac, une partie du sédiment est remanié par des tempêtes de vent du NE (« bise »).

Des mesures de courants au sein du lac indiquent des courants parallèles au vent et au bassin en surface, et des contre-courants en profondeur. Cette courantologie, qui est partiellement expliquée par la théorie d'Ekman, peut être liée à la topographie particulière du bassin et la répartition inégale des masses d'eau de part et d'autre du site d'observation.

La modélisation du transport du matériel en suspension indique un déplacement et une sédimentation dans le sens des contre-courants à des distances de quelques centaines de mètres à quelques kilomètres de l'embouchure.

Sur la base de ces observations, il est postulé que des changements du régime des vents et des précipitations modifient l'architecture sédimentaire. L'étude des courants lacustres, de l'architecture et de la composition sédimentaire pourraient de ce fait fournir à l'avenir des informations sur les changements des régimes de vents et des précipitations depuis le dernier âge glaciaire.

1.- Introduction

1.1 Sediment distribution on lake deltas

Lake delta morphology is determined by fluvial input, waves, lake currents, lake-level fluctuations and lake-basin topography (Rust 1982, Coleman 1981). Based on these factors, Smith (1991) distinguished four lacustrine delta types: braid deltas,

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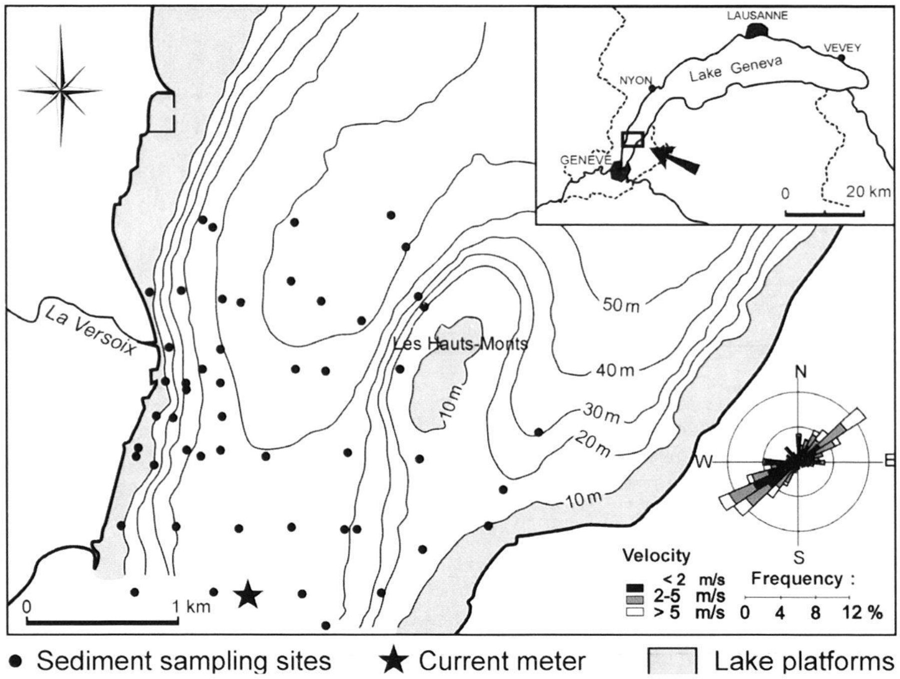

Figure 1. Location and bathymetric map of the Versoix - delta in the western part of Lake Geneva (Petit-Lac, Switzerland): sampling sites, position of the current meter and wind rose of dominant winds in the Geneva basin (Girardclos 2001).

stable-channel-mouth fan deltas, fan-forset deltas and wave deltas.

River water flowing into a stagnant lake water body has a certain inertia (Ekman 1905) and may form a jet. Depending on the relative densities, river water and sediment charge produce either overflow, interflow or underflow (Sturm & Matter 1978). Sedimentation subsequently occurs either by turbidity currents (underflow) or by pelagic deposition according to Stokes law (overflow and interflow). Spatial distribution of deltaic sediments on the lake bottom can be explained by these mechanisms, and also by lake currents and Coriolis deviation, which includes deviation of the river jet. Wind is generally considered to be the main force driving lake currents (Hutchison 1957, p.257).

For wind drift, currents are oriented by wind forcing in the upper part of the water column (Ekman 1905, Smith 1979). Due to the Coriolis force, current directions change from surface to deep currents following the Ekman spiral. For large lakes and oceans, Ekman (1905) has proposed an exponential decrease of the current velocity with depth.

1.2. The Versoix delta: test area for sediment distribution by lake currents

Recent studies involving sediment dynamics and distribution in lake basins during the Holocene (Baster 2002, Baster et al., this volume, Girardclos 2001, Girardclos et al., this volume), revealed the importance of wind drift. When comparing various lake deltas, the Versoix delta appears to be particularly well suited for studying wind drift and sediment distribution for the following reasons:

Delta morphology: The Versoix delta is located on the NW shore of the Petit-Lac of Lake Geneva (Fig. 1). A promontory on the shore indicates delta morphology. Lake-bottom topography shows this feature only as a smooth elevation. Therefore, it can be postulated that fluvial input by a jet stream and radial sediment distribution ahead of the delta front are not dominant, in opposition to the other deltas on Lake Geneva (Loizeau 1991).

Distinct sediment sources: The Versoix River is by far the dominant sediment source. The drainage basin includes the slopes of the Jura Mountains, containing fractured carbonate rocks, and part of the Swiss Plateau, containing detrital Molasse rocks and glacial (mainly till) sediments (Jayet 1964). The mean annual discharge is 3.2 m^3/sec and may be higher than 11 m^3/sec during floods, when the river provides a high input of gravel, sand and suspended matter to the lake. Sediment is produced and all kinds of sediments are reworked on the platforms along the shores and on the Hauts-Monts promontory (Fig. 1).

Lake currents: In the Versoix area, the lake basin of the Petit-Lac has a maximum depth of 65 m, which is much less than that of the upstream lake basin portion, the Grand Lac. The Versoix lake basin portion is narrowed by the presence of a subaquatic lake platform, the Haut-Monts, which forms a transverse promontory towards the E (Fig. 1). Therefore, water mass exchange will produce basin-parallel currents in this area, as indicated by local non-deposition zones (Gi-

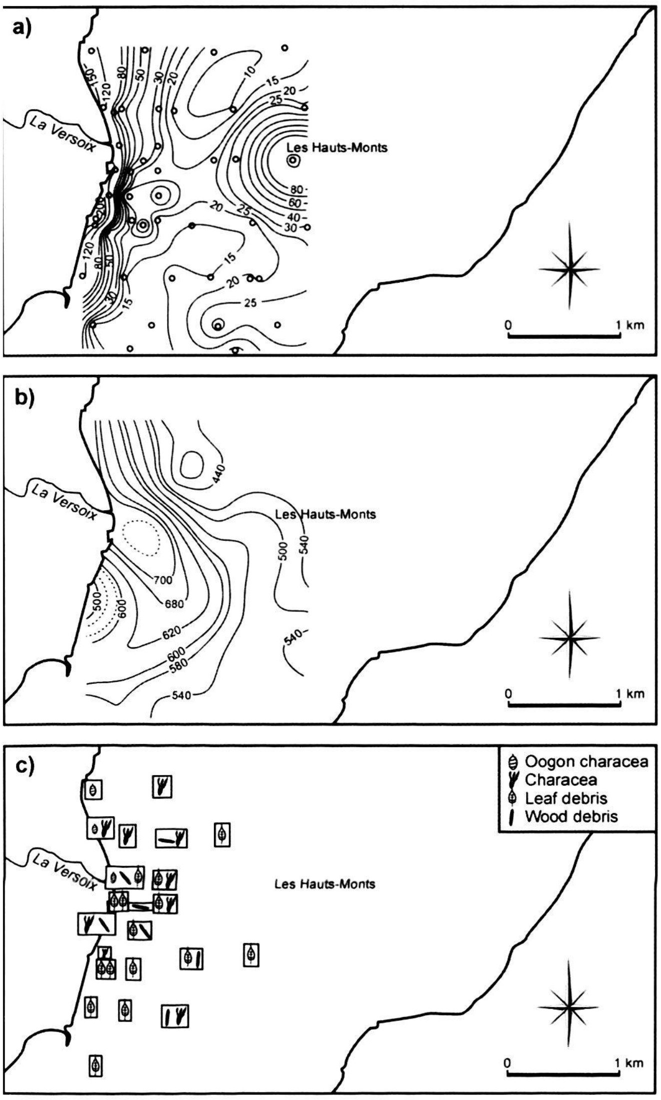

Figure 2. Sediment composition based on grab samples and short cores from the study sites:
a) Isolines of mean grain size (µm) of surface sediments.
b) Isolines (ppm) of inorganic non apatitic phosphorous of surface sediments.
c) Leaf, and wood debris and algal debris (Characeae) of surface sediments.

rardclos 2001).

Wind regime: The wind rose (Fig. 1 b) is dominated by SW and NE regimes, channelled by the Lake Geneva basin axis and the Jura mountain range.

1.3. Methods

The methods of investigation include three parts:

Analysis of surface sediment distribution in the lake basin from grab samples and short cores: grain size, phosphorous and macroscopic debris.

Measurement of lake currents by a 300 kHz Acoustic Doppler Current Profiler (ADCP from RD Instruments) during a 6 months period, from 2 October 1998 to 21 April 1999. The upward looking profiler was placed at a depth of 50 m in the centre of the lake section (Fig. 1). Currents were measured every 5 minutes with a pulse repetition frequency of 6 Hz, at 2-m intervals from 46 to 4 m water depth. Meteo Swiss provided data on wind directions and velocities at Geneva Airport, located 3 km from the study area.

Modelling trajectories of sediment particles from overflows and interflows, using measured current velocities and Stokes law.

2. - Sediment distribution

2.1. Grain size distribution

After sieving with a 1mm sieve to extract clasts, such as wood debris and tree leaves, grain size distribution was measured with a Laser Coulter LS 100 (Loizeau et al. 1994).

The distribution of mean grain size (Fig. 2a) indicates values higher than 80 µm in the high-energy wave zones of the lakeshore and on the Hauts-Monts platform. Grain size then decreases gradually with water depth. Areas with grain size less than 15 µm are located in the centre of the lake basin. A zone of larger mean diameters is located at the base of the slope SSE of the Versoix River mouth.

2.2. Phosphorous distribution in sediments

In lake sediments, phosphorous may be present in the following forms (Dominik et al. 1982):

- Organic phosphorous, linked to organic matter
- Inorganic apatitic phosphorous, mainly of detrital origin
- Inorganic non-apatitic phosphorous of human origin

All of these forms, including total phosphorous content, have been measured in grab samples and short cores. Fig. 2b presents the values of inorganic non-apatitic phosphorous. The Versoix River is the main source. Areas of equal concentration are oriented NW - SE near the river mouth, and a gradual reorientation to SW - NE occurs from the delta slope to the basin plain.

There is a clear correlation between high values of inorganic phosphorous concentration and the area of larger mean grain size at the base of the delta slope (Fig. 2 a).

2.3. Organic debris

Distribution of leaf and wood debris from land and Characea debris from shallow lake platforms is shown in Fig. 2c. The sampling sites with such debris are located mainly along the

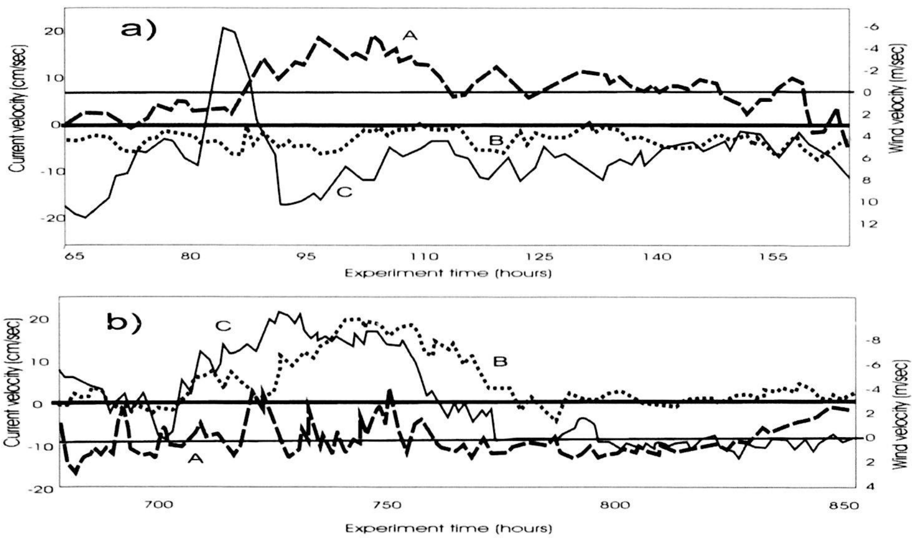

Figure 3. Records of wind-forced lake currents; projected onto SW – NE plane. Positive values correspond to SW-NE currents and winds; negative values correspond to NE-SW currents and winds. Lake current and wind velocity scales are inversed. Curve A: velocity at 4m depth; curve B: velocity at 48 m depth; curve C: wind velocity.
a: Record of wind-forced lake currents by «vent» (24 - 28 October 1998, experiment time 65 to 165 hours).
b: Record of win- forced lake currents by «bise» (18 - 25 November 1998, experiment time 679 to 850 hours).

western shore of the lake.

Two distinct zones are identified:

1. To the S and SE of the Versoix River mouth, leaves and wood debris dominate and Characea are rare.
2. To the N and NE of the Versoix River mouth, Characea dominate.

The main input to the southern zone derives clearly from the Versoix River, whereas the lake platform near Versoix provides the main input of algae.

3. - Wind and lake currents in the delta area

3.1. Winds

Statistical analysis of wind measurements confirms the dominance of NE – SW orientation during the period from 21 October 1998 to 21 April 1999. Two major regimes are recognised: Winds blowing NE – SW are known as «bise» and generally occur during dry weather and rather high atmospheric pressure conditions.

Winds blowing SW – NE are known as «vent» and typically are linked with wet weather and low pressure conditions.

Eighteen events of «vent», lasting from 8 hours to 9 days, were registered with mean wind velocities of 3.1 m/sec and a maximum of 8 m/sec. Thirteen recorded events of «bise», lasting from 14 hours to 9.5 days, showed mean wind velocity of 4.2 m/sec and a maximum speed of 12.3 m/sec. «Vent» regimes dominated, with 60% of the total time span.

3.2. Lake currents

Results of lake current measurements are shown in Fig. 3 and highlighted below. A 4-m water depth corresponds to «surface currents» and a 46-m water depth corresponds to «deep currents». Values for SW – NE-oriented currents are positive, and values for NE – SW-oriented lake currents are negative. In Fig. 3, scales for the wind and lake current velocities are in opposite directions.

During the recording period, maximum current velocities are 24.5 cm/sec measured near the surface and 19.5 cm/sec for deep currents; mean velocities are approximately 5 cm/sec near the surface and 2.4 cm/sec in deep water.

The following types of current events have been observed:

- Currents linked to wind events («vent» or «bise»). In the case, current directions at the surface correspond to wind directions and deep currents are reversed. The thickness of the upper layer is always less than that of the lower layer, ranging typically between 30 and 40% of the water depth.
- Currents due to internal waves or «seiches». In this case, surface and deep currents may be oriented in opposite directions but are not correlated with wind directions. The two layers are nearly of equal thickness and cyclic reversal of the current pattern occurs.
- Turbidity currents (underflows). These are of short duration and are only registered close to the lake bottom.

Although all of these events are important for the understanding of sediment distribution, only wind-forced currents, which are the dominant events in the water column, are analysed here.

« Vent »:

Figure 3a shows a characteristic record of wind-forced currents resulting from «vent» events.

After a period of changing wind directions, an extended «vent» regime developed at the airport meteorological station

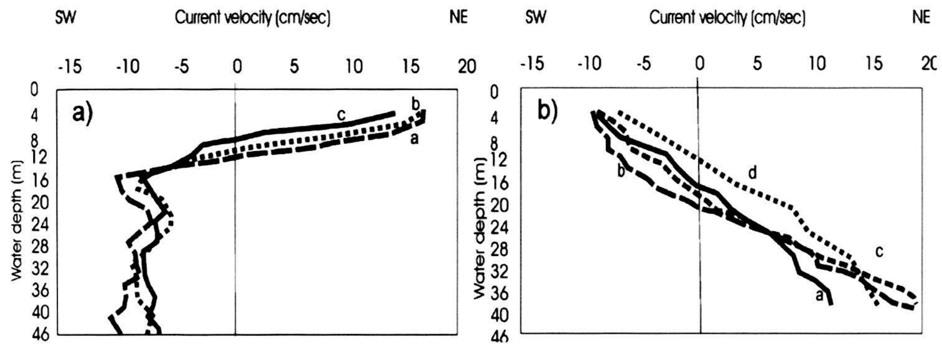

Figure 4. Depth distribution of current velocities during typical events:
a : SW – NE plane projection for «vent» (Figure 3a) at hours 95 (curve a) , 97 (curve b) and 99 (curve c) of the experiment time.
b: SW – NE plane projection for «bise» (Figure 3b), at hours 757 (curve a), 766 (curve b), 769 (curve c) and 777 (curve d) of the experimentation time.

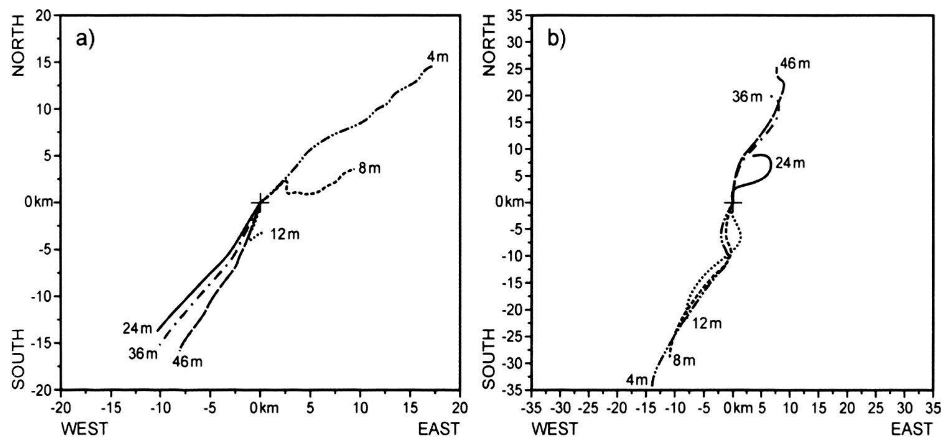

Figure 5. Cumulated current trajectories at different water depths between 4 m and 46 m.
a: Event of «vent» from 24 to 28 October 1998 (Fig. 3a).
b: Event of «bise» from 18 to 25 November 1998 (Fig. 3b)

at hour 89 after beginning of the experimentation (this was 25 October 7 h a.m.). Surface water currents in the lake already had changed to SW – NE currents at hour 87.5. A first wind speed peak of 17 m/sec was measured at hour 93.5. A major peak of 19 cm/sec in surface water velocities was observed at hour 98.5; counter currents in deep water at that time reached 5 cm/sec. This situation of wind-forced currents continued until hour 160, when wind-parallel surface currents broke down, despite continuation of a «vent» regime.

Depth distribution of currents during the same event at hours 95, 97 and 99 of the experiment is shown in Figure 4a. From the surface to about 12 m water depth, current velocities diminish rapidly from 15 to 17 cm/sec to 0 cm/s. Below that depth, currents flow in the opposite direction. The velocity first increases rapidly and the profile varies between 5 and 11cm/sec, without any clear trend, down to the depth of 46 m. During this event, trajectories of water displacement at different depths indicate that the transition from surface to deepwater current directions is continuous, in form of a right turning spiral (Fig. 5a).

« Bise »:

An example of «bise»-driven currents is shown for hours 679 to 850 in Figure 3b. During this event, wind speeds are slightly stronger and remain at a high level for longer time compared to the «vent» event. Wind and deep currents start almost simultaneously. In this case, deep counter-currents have higher maximum velocities than surface currents, the latter becoming very stable from hours 760 to 830. The velocity/depth profile (Fig. 4b) shows a regular gradient from surface to depth. The highest deep current velocities reaching 19 cm /sec are measured near the bottom. Compared to the «vent» event, the depth of the top layer has increased. A spiral of trajectories from the surface layer to depth is found (Fig. 5 b).

4. - Modelling of particle transport

Sediment particle trajectories were calculated at the location of the current meter in the following way:

- Applying Stokes law for sinking velocities of quartz and calcite particles in water with temperatures of 5 °C and 10 °C.
- Calculating lateral displacement along the NE – SW current axes for 2-m intervals between 4 m and 46 m water depth, using mean current velocities per event.

For a typical "vent" event (chapter 3), Fig. 6 shows calculated trajectories of quartz particles 13 and 30 microns in diameter, in 5 °C water temperature, which represents a homogenous water column in winter.

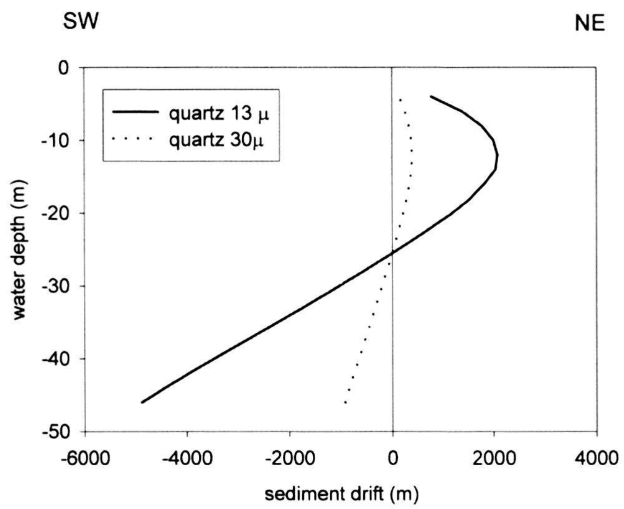

Figure 6. Particle trajectories along a NE-SW plane in a water column of 5 °C, calculated for the event of «vent» from 24 - 28 October 1998 (Fig. 3a). Trajectories have been calculated at the site of the current meter using Stokes law for quartz particles of 13 and 30 μm in diameter and homogenous mean current velocity for 2-m depth intervals.

The modelling results principally reveal the following:

1. Net transport of fine-grained fractions occurs in the direction of deep counter currents.
2. Typical transport distances calculated for the different sediment fractions are consistent with the distances measured for mean diameters of sediment grains between the Versoix River mouth and the lake basin.

5. - Discussion and conclusion

The Versoix River is the main sediment source in the study area. Grain-size distribution, inorganic phosphate in sediments and distribution of organic debris in the basin of the Petit-Lac indicate sediment transport from the river mouth towards the SE, in the direction of river flow. Suspended material is then deviated clockwise by an angle of 90°, flowing towards the SW, in the direction of the basin axes.

To the N of the delta area, algal debris in slope and basin sediments indicate a strong influence from the neighbouring coastal platform, where sediment is reworked during storms with NE winds ("bise").

Lake current measurements in the Petit-Lac in the winter of 1998/99 indicate wind-parallel surface currents and deep counter-currents in the opposite direction of surface currents.

Surface current directions are not in agreement with Ekman's (1905) model for deep water, which predicts an angle of 45 degrees between wind direction and surface water currents (see also Allen 1997, p. 309 - 315). Furthermore, measured surface current velocities are higher than expected. The observed differences with respect to the models may be mainly due to the channel effect of the local basin topography.

Postulated exponential velocity decrease with depth (Ekman 1905, Smith 1979) is not observed. Instead, deep current velocity profiles indicate either fluctuating values around a constant value («vent» regime), or even increasing velocity with depth («bise» regime). In addition, the near surface currents are pointing towards the open waters during «vent» - events while they point to and may be affected by the near-by end of the lake basin during «bise» - events. While we do find a right turning spiral between the top layer and the bottom layer, we do not see a spiral in the near surface layer as predicted by Ekman (1905). The details of these profiles are not yet completely understood. They may also be affected by the particular position of the current meter during our experimentation, to the general basin topography and to the unequal distribution of water masses on either side of the study area. A extended survey is now carried out in the study area, in order to provide the data set and the limiting conditions for lake-current modelling in this particular topographic situation, including processes such as coastal up-set and down-set.

The results of the of particle transport model indicate significant lateral displacement of the fine fraction by lake currents. Net displacement of several hundreds of meters to several kilometres can be calculated from the lake-current profiles of the Petit-Lac site.

In the Versoix area of the Petit-Lac of Lake Geneva, sediment analysis, lake-current measurements and modelling of particle transport show that:

- Suspensions derived from river input are transported within the lake basin, first by currents from the inertia of the river jet and then by wind drift.
- Coriolis forces and wind-driven lake currents deviate suspension transport directions clockwise from their initial trajectory.

In the particular study site, net fine sediment transport by deep counter currents occurs over several hundreds of meters to several kilometres before settling.

- Sediment input into the Petit-Lac mainly occurs by floods of the Versoix River. These floods are generally linked to precipitation under a regime of wind blowing from the SW. As a consequence, sediments are mainly deposited in an area SE and then S or even SW from the river mouth.
- Changing regimes of wind or precipitation, modify offshore depositional processes and architecture. Further study of the current system, sediment architecture and sediment composition in lakes may provide useful information about changes in these climatic factors since the last ice age.

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