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Bottom-current and wind-pattern changes as indicated by Late Glacial and Holocene sediments from western Lake Geneva (Switzerland)

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Key words: limnogeology, seismic stratigraphy, Lake Geneva, Late-Glacial, Holocene, isopachs, bottom currents
Mots-clés: limnogéologie, stratigraphie sismique, Lac Léman, Tardiglaciaire, Holocène, isopaques, courants profonds.

ABSTRACT

The Late-Glacial and Holocene sedimentary history of the Hauts-Monts area (western Lake Geneva, Switzerland) is reconstructed combining high resolution seismic stratigraphy and well-dated sedimentary cores. Six reflections and seismic units are defined and represented by individual isopach maps, which are further combined to obtain a three-dimensional age-depth model. Slumps, blank areas and various geometries are identified using these seismic data.

The sediment depositional areas have substantially changed throughout the lake during the end of the Late-Glacial and the Holocene. These changes are interpreted as the result of variations in the intensity of deep lake currents and the frequency of strong winds determining the distribution of sediment input from the Versoix River and from reworking of previously deposited sediments within the lacustrine basin.

The identified changes in sediment distribution allowed us to reconstruct the lake's deep-current history and the evolution of dominant strong wind regimes from the Preboreal to present times.

RESUME

L'histoire sédimentaire tardiglaciaire et holocène de la zone des Hauts-Monts (partie occidentale du Lac Léman, Suisse) est reconstruite grâce à la combinaison d'une stratigraphie sismique à haute résolution et de datations de carottes de sédiment. Six réflecteurs et unités sismiques sont définis et représentés sous forme de cartes isopaques individuelles, qui réunies, établissent un modèle âge-profondeur tridimensionnel. Des slumps, des zones 'sourdes' et la géométrie des réflecteurs sont identifiés à l'aide des données sismiques.

Les principales zones de dépôt sédimentaire ont considérablement changé durant la fin du Tardiglaciaire et l'Holocène. Ces changements, interprétés en terme d'intensité des courants lacustres profonds et de fréquence des forts vents, déterminent la distribution des apports sédimentaires de la Versoix et du remaniement des sédiments précédemment déposés au sein du bassin lacustre.

Ces modifications dans la distribution des sédiments ont permis de reconstruire l'histoire des courants lacustres profonds et l'évolution des régimes dominants des fort vents du Préboréal à nos jours.

1.- Introduction

Lake sediments are considered to be among the most sensitive archives of environmental and climate changes on the continents. The size and morphology of lakes and their associated features greatly determine the sediment record (Håkanson 1977, Pourriot & Meybeck 1995). In particular, large lakes register major events averaging long-term environmental changes. Their sediment infills, therefore, record regional climate changes allowing inter-site comparisons over distances of hundreds of kilometres (Eicher & Siegenthaler 1976, Kelts 1978, Lotter et al. 1992, Niessen et al. 1992), and eventually to the marine and ice core records. Depending on the part of the lacustrine basin –lake-bottom or delta/coastal areas- the sedimentary record is dominated by internal or external processes, respectively.

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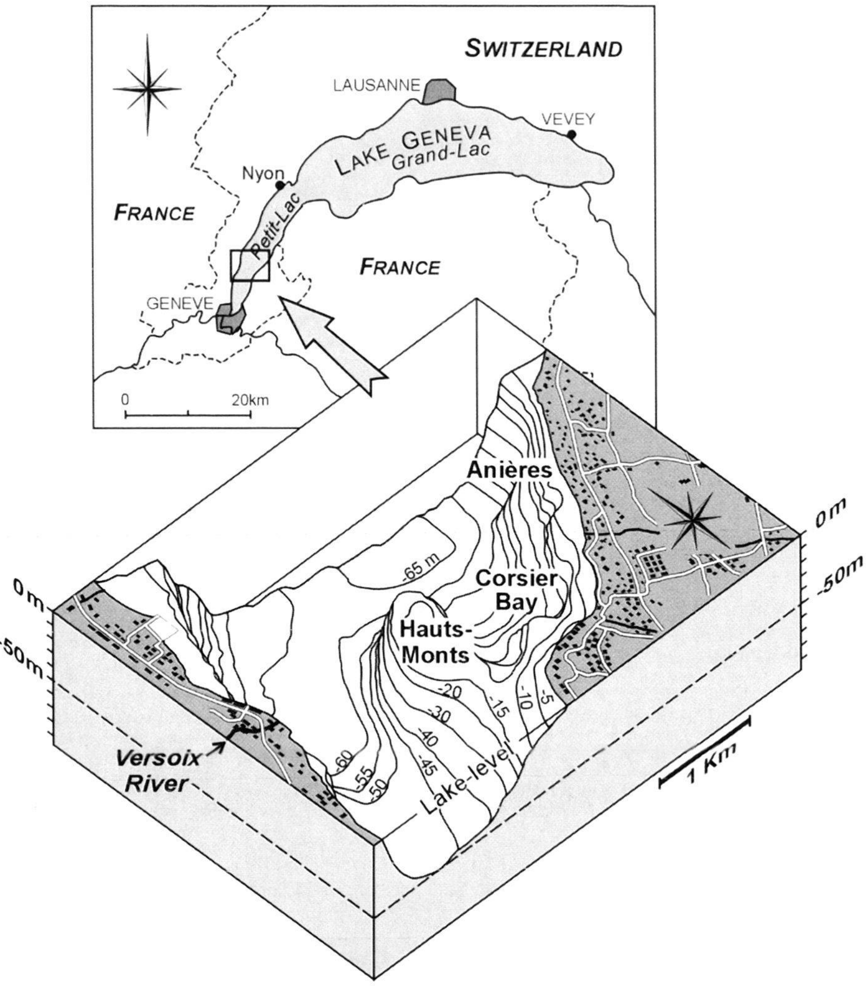

Fig. 1. Location map of Lake Geneva and 3D representation of the Hauts-Monts study area. Bathymetry is indicated in meters.

The sedimentary infill of numerous perialpine lakes has been studied during the last several years in Switzerland (Gaillard & Moulin 1989, Lister 1988, Lotter 1999, Niessen & Kelts 1989, Schwalb 1992, Sturm & Matter 1978, Wohlfarth & Schneider 1991), France (Chapron 1999, Magny 1992, Van Rensbergen et al. 1998) and Austria (Schmidt et al. 1998, Wessels 1998). However, the use of both high resolution seismic and sedimentary studies is still scarce. Lake Geneva, the largest freshwater basin in western Europe, is part of the Rhône River system and cuts across the Alpine foreland basin from the Alps to the Jura Mountains (Fig. 1, Wildi & Pugin 1998). Its bedrock morphology and Pleistocene glacial sediment infill have been previously described by Vernet & Horn (1971), Vernet et al. (1972), Wildi et al. (1997) and Moscariello et al. (1998). Detailed studies of the Holocene sediment record have also been published by Loizeau (1998), Moscariello (1996), Girardclos (2001), Baster (2002) and Baster et al. (this volume).

Lake Geneva is monomictic and mesotrophic, and its surface-water temperature varies yearly between 5°C and 20°C. The lake basin is traditionally and geographically divided into two components: the large, 300-m-deep "Grand-Lac" and the elongated, 50-70-m-deep "Petit-Lac".

The studied "Hauts-Monts" zone is located in the well-oxygenated and mixed waters of the Petit-Lac. The sedimentation in this area is influenced by the Versoix River mouth, which has an estimated median flow rate of 3 m^3/s (Département de l'Intérieur 1996), and by a large underwater promontory 9-14 m below the present lake level (alt. 372.05 m, Fig. 1). This subaquatic platform is a topographycally high piece of Molasse bedrock that resisted glacial erosion during the last ice ages.

This paper presents the Late-Glacial and Holocene paleoenvironmental evolution of a bottom-current dominated area in western Lake Geneva. Based on both seismic and sedimentological approaches we have reconstructed the changes in the geometry, lateral extent and thickness distribution of individual seismo-stratigraphic units throughout time and the associated paleoenvironmental history of the lacustrine basin.

2.- Methodology

2.1. Seismic data acquisition and processing

In 1997, 200 km of seismic profiles within a 4 x 3.5 km area have been acquired using a high resolution BATHY-1000 echosounder (Girardclos 2001), connected to a Differential Global Positioning System (DGPS) with an accuracy of ±2-10 m. The dominant wave frequency of this seismic system is 1.5-2 kHz. Following the Rayleigh's criterion, the calculated vertical resolution of the echosounder data is 0.25 m (Girardclos 2001). After standard seismic processing, the lines were digitally analysed with the PC software SEISVISION 4.0 of GEOGRAPHIX LTD. The seismo-statigraphic analyses was exported into ASCII files as x,y,z coordinates and converted from time values into depths. Each data set, representing a major seismic reflection, was then interpolated into digital grids (i.e. surfaces) with a radial basis function. These grids were plotted with either a 0.25- or a 0.5-m contour interval and then combined to calculate the thickness of each sedimentary sequence. Baster et al. (this volume) provide additional details on the seismic data acquisition and processing.

2.2. Dating of the seismic units

The correlation of the seismic reflections with 12 sedimentary cores, retrieved between 1997 and 1999, allowed the age determination of reflections n° 5, 6, 8 and 16 combining various methods: palynological analyses (Rachoud-Schneider 1999), ^{137}Cs activity measurements and one AMS-^{14}C date (ETH n° 20299). The other reflections' ages (reflections n° 9/10 and 14) were estimated compiling and correlating previous palynological analyses (Burrus 1980, Châteauneuf & Fauconnier 1977, Lüdi 1939, Moscariello 1996, Reynaud 1981). The time scale displayed in Fig. 2 is based on chrono- and biozones defined for the Swiss Plateau (Ammann et al. 1996, Lotter 1999).

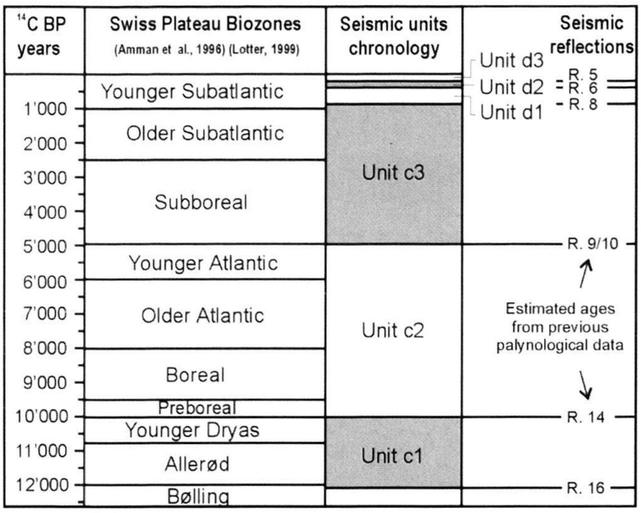

Fig. 2. Late-Glacial and Holocene ages of the Hauts-Monts area seismic reflections and units inferred from palynological analyses of 12 sediment cores and estimated from previous palynological data in western Lake Geneva (Burrus 1980, Châteauneuf & Fauconnier 1977, Lüdi 1939, Moscariello 1996, Reynaud 1981).

Unit c1* represents the end of the Late-Glacial, from the end of the Bølling to the beginning of the Preboreal (Fig. 2). Unit c2 spans the first half of the Holocene, from the Preboreal to the end of the Younger Atlantic. Unit c3 encompasses the entire Subboreal, the Older Subatlantic and the very beginning of the Younger Subatlantic. All the remaining units d1, d2 and d3 represent the Younger Subatlantic. The high resolution of the Younger Subatlantic palynological data (Girardclos 2001) enabled us to estimate that unit d1 corresponds to the late Middle Ages, unit d2 to Modern Times (16^{th} - 18^{th} century) and the uppermost unit d3 to the contemporary epoch (19^{th} century to present).

3.- Seismic stratigraphy

3.1. Reference echosounder profile

A close-up of the eb1 echosounder profile (Fig. 3) summarises the seismo-stratigraphic units identified in the Hauts-Monts area. This seismic line is oriented NW-SE and located in the 60-65-m-deep centre of the Petit-Lac basin, about 1 km from the Versoix River mouth. The semi-continuous to continuous reflections have medium to high amplitudes with moderate frequencies. Unit (c1) is bounded by the reflections n° 16 (bottom) and n° 14 (top) and is characterised by a parallel layering. Reflection n° 14 is truncated in the SE part of the profile. The upper sequences (seismic units c2 to d3) are discordant with unit c1 and form lakeward dipping foresets that downlap and onlap onto unit c1.

The generally semi-continuous to continuous reflections and the well-defined stratification of the seismic sequences indicate a lacustrine origin for these units. The truncation of reflection n° 14 in the SE part of the profile reveals a past erosional event. The observed downlap and onlap prograding sequences from NW to SE (above unit c1) are usually interpreted as prograding delta or fan geometry (Badley 1985). Various directions of the progradation can be observed and indicate that another process is shaping this geometry (see Section 4).

3.2. Thickness maps

The thickness of the different seismic units c1 to d3 were estimated from the 200 km of echosounder profiles and isopachs are shown for each sediment sequence separately (Fig. 4). Additional features (slumps, seismic blank areas, reflections

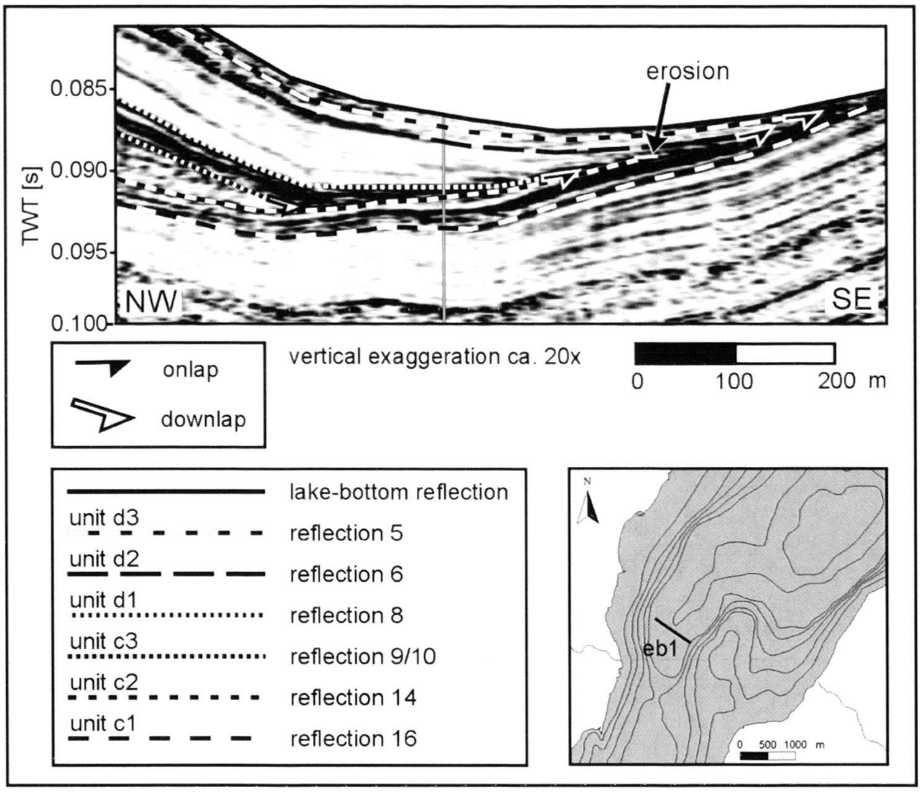

Fig. 3. Close-up of the interpreted echosounder profile eb1. Seismic units c1 to d3 are separated by reflections (n° 5-16) that are traced with different line patterns. On this profile, units c2 to d3 are prograding SE with downlap and onlap geometry. The truncated seismic reflection n°14 indicates a past erosional event.

geometry), analysed from 2D echosounder data and the inferred main sediment supply are also shown on the maps.

Gas blanking

A wide blank area in the eastern part of the basin can be distinguished in all the thickness maps (Fig. 4 a-f). This area follows the lake slope and extends lakewards away the Versoix River mouth.

Unit c1, end of Bølling → beginning of Preboreal (Fig. 4 a):

This map shows the sediment distribution pattern at the end of unit c1. The layer thickness varies from 0 to 2.5 m. 2D seismic profiles indicate that sediment slumping started from two places in the NW part of the basin during this interval. The volume of the northern slump represents more than 4 x 10^6 m^3 of sediment. The thickest stratified sediments are localised along the NW-SE area facing of the northern slump. An extensive non-deposition area of 838'000 m^2 appears at the top of unit c1. Along its northern side, the top of unit c1 is bounded by the downlap geometry of reflection n° 14, which becomes truncated along its southern side.

Unit c2, Preboreal → end of Younger Atlantic (Fig. 4 b):

Unit c2 thickness varies from 0 to 4 m with maximum values located in the deepest part of the basin (NE) and close to the Versoix River mouth (W and SW). The thinnest sediments are found near the 675'000 m^2 of non-deposition area. As unit c1, this unit is bounded to the north by downlap and onlap geometry of its upper reflection (n° 9/10), which becomes truncated towards the south. The non-deposition area of unit c2 determines irregular lobes and its centre is shifted ca. 300 m SSE from the centre of the unit c1 non-deposition area.

Unit c3, Subboreal → beginning of Younger Subatlantic (Fig. 4 c):

Unit c3 thickness ranges from 0 to 4.5 m, thickenning in the NE part of the basin, on the northern slope of the Hauts-Monts promontory and SE of the Versoix River mouth. In contrast to units c1 and c2, unit c3 is bounded by downlap and onlap geometries along the entire perimeter of the non-deposition area. The non-depositional area has the same centre as unit c2 but is about half the size (394'000 m^2).

Unit d1, late Middle Ages (Fig. 4 d):

The unit d1 isopachs indicate substantial sedimentary changes

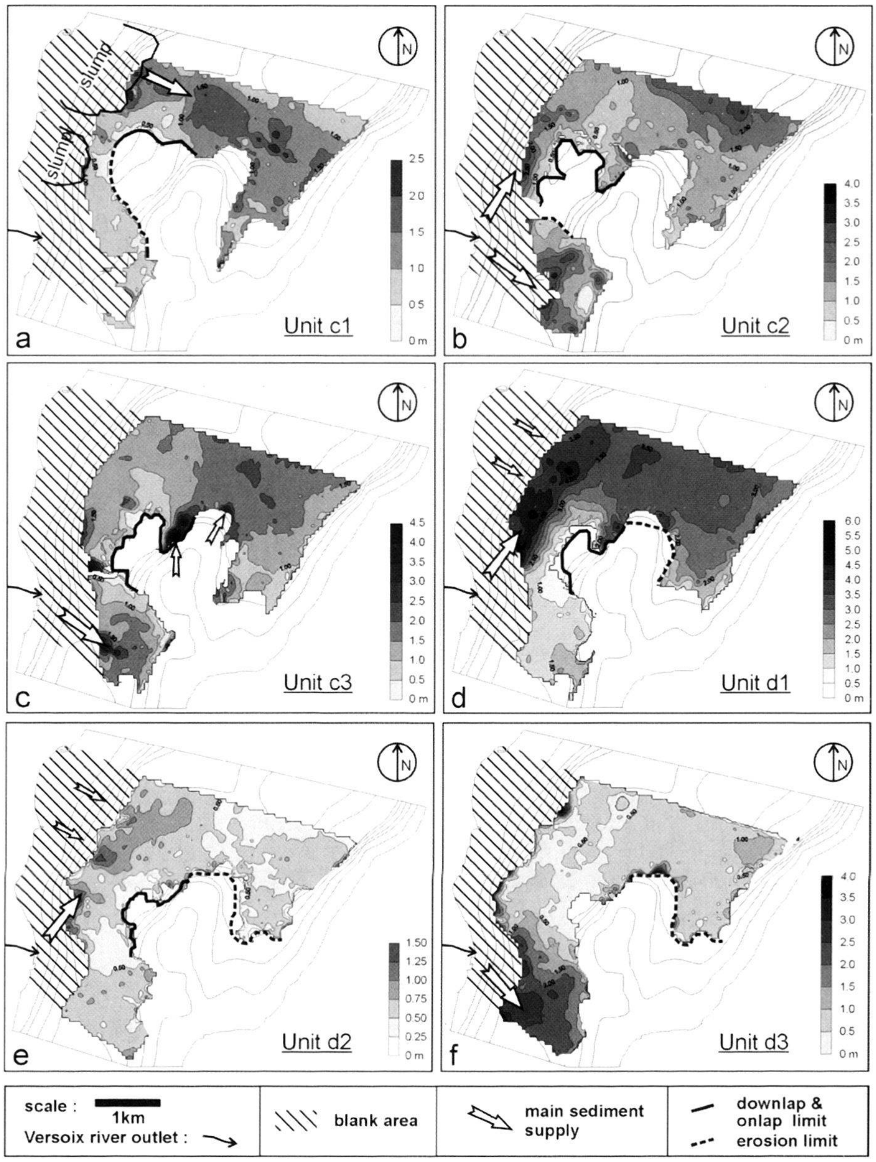

Fig. 4. Thickness maps of the Hauts-Monts area sequences showing changes in the sedimentary depositional patterns. The underlying thin lines are the approximate present bathymetry contours of the lake basin. a) Unit c1 end of Bølling ® beginning of Preboreal, b) Unit c2, Preboreal ® end of Younger Atlantic, c) Unit c3, Subboreal ® beginning of Younger Subatlantic, d) Unit d1, late Middle Ages, e) Unit d2, Modern Times (16th-18th century), f) Unit d3, contemporary epoch (19th century - present).

at the beginning of the Subatlantic biozone. The sediments are comparatively thicker in the northern part of the basin forming a sediment tongue NE of the Versoix River mouth. The non-depositional area is further reduced in comparison to the previous units comprising an area of only 195’000 m^2. It is bounded by the downlap and onlap geometry of unit d1. A long truncation of the top reflection (n°6) surrounds the northern side of the promontory at 35 to 45 m depth below present lake level.

Unit d2, Modern Times (16^{th}-18^{th} century) (Fig. 4 e):

The most recent situation (unit d2) is similar to that of the late Middle Ages (unit d1), but the difference in thickness between the northern and the southern part of the basin is less pronounced. The non-depositional area of unit d2 is again smaller (147’000 m^2) than that of unit d1 and it is delimitated with the downlap and onlap geometries of unit d2. An extensive truncation of the top reflection (n°5) encircles the NE side of the promontory at depths of 40-55 m like unit d1.

Unit d3, contemporary epoch (19th century - present) (Fig. 4 f):

Unit d3 is 0 to 4 m thick and the sediment distribution is completely different from the previous one. The sediment supply of the Versoix River is oriented once again SE, 90° from the main lake flow. Because of the limited vertical resolution of our seismic data, the unit d3 non-deposition area could not be accurately determined. However, previous work (Girardclos 2001, Fig. 5.22 and 5.23) shows that the thick SW sedimentary sequences contain two truncated sub-units, suggesting a probable non-deposition area as large as that of unit c2.

4.- The Late Glacial and Holocene sediment distribution: Discussion

4.1. Limnological processes

Sediment distribution in lacustrine basins is determined by both input and internal dispersion processes. The main external sediment source of the study area is the Versoix River (Ulmann 2000, Ulmann et al., this volume). Increasing input can be further linked to flood events from rain and melting snow. The lake's autochthonous sedimentation, biologically induced by coastal organisms, mainly occurs on shallow lake flat areas, where strong winds rework the deposited sediments. These platforms, are up to 10 m deep and are particularly well developed along the NW lake shore and on the Hauts-Monts promontory due to Molasse bedrock and ice age deposits that resisted past glacial erosions (Service Cantonal de Géologie 1974) (Fig. 1). Sediment distribution from the river mouth into the lake basin starts at the river plume, either through overflow, interflow or underflow, depending on the density difference between river and lake water (Giovanoli 1990, Sturm & Matter 1978). For overflow and interflow, further sediment transport occurs by internal lake currents. Reworked sediments from lake platforms are also transported toward the deepest part of the lake basin and deposited near the Hauts-Monts platform by the same way. These processes are attested by terrestrial and shelly layers in Younger Subatlantic sediments cores (Girardclos 2001).

Today's measurements in the central part of the Hauts-Monts basin indicate the development of wind-parallel lake currents at the surface and counter-currents in deep water. During the Versoix flooding events, the main sediment transport is generally oriented opposite to the dominant wind direction and can be explained by strong deep currents in this particular area (Ulmann et al., this volume). Therefore, the origin of such deep water currents are certainly due to strong winds. At this location (-65 m depth), other types of water movements (seiches, horizontal or vertical mixing, etc.) cannot explain such geographical and temporal extent of the erosion, non-deposition and transport of sediments. Indeed Lake Geneva surface seiches –as stationary waves- generate only small water displacements and velocities, whereas stronger internal seiches at the thermocline level have their highest amplitudes and velocities near the coast (Lemmin 1998). Vertical and horizontal mixing, which are small scale water movements, occur during a particular thermal stratification state of the lake but are ultimately due to the turbulence effect of the large scale water displacements like currents (Lemmin 1998).

Presently, heavy rain and resulting river floods are generally linked to barometric depressions and winds blowing from the SW, whereas strong NE winds are associated with maximum fetch and sediment reworking on the platform. It has been, therefore, postulated that the recent sedimentation SW and N-NE of the Versoix River mouth is linked to SW and NE winds, respectively (Ulmann et al., this volume). The

Time Period	Seismic units	Main sediment input	Intensity of deep lake currents	Frequency of strong winds	Dominant strong wind regime
Beginning of Preboreal	C1	Mainly slumping	Very strong	Very high	?
Preboreal → end of Younger Atlantic	C2	Versoix River input, to the NE and SE	Strong	High	Equally NE and SW
Subboreal → beg. of Younger Subatlantic	C3	Versoix River input to the SE and slumping from Hauts-Monts	Medium	Medium	SW
Late Middle Ages	D1	Versoix River to the NE and/or Lake Platform reworking	Low	Low	NE
Modern Times (16th-18th century)	D2	Versoix River to the NE and/or Lake Platform reworking	Very low	Very low	NE
Contemporary epoch (19th century - present)	D3	Versoix River input to the SE	Strong	High	SW

Table 1. Summary of the primary sedimentological features and evolution through time of the main parameters regulating sediment distribution in the Hauts-Monts area.

chemical composition of the sediments and the distribution of terrestrial plant debris, algae and molluscs support this interpretation (Ulmann et al., this volume).

Deep lake currents associated with dominant wind regimes, therefore, seem to be the main cause of sediment distribution in the study area, and leads us to the following interpretations.

4.2. Interpretation of the sediment distribution

Based on these preliminary considerations, the following causes regulating sediment distribution and its seismic expression are proposed:

Gas blanking:

The blank area is attributed to the presence of methane (Badley 1985, Fader 1997), most probably produced by the degradation of the organic matter from the Versoix River (Ulmann et al. 2002, this volume). The presence of gas in the study area is also attested by gas bubbles traces in sediment cores (Girardclos, 2001). Since gas can migrate upwards through the sediment layers, it is not possible to assign an age to this layer.

Unit c1, end of Bølling → beginning of Preboreal: (Fig. 4 a):

The high sediment thickness NE of the study area is obviously linked to a major slump on the northern lake slope that may have triggered a gravity flow that crossed the lake basin and later settled onto the lake bottom to form a homogenite (Chapron et al. 1999). Storms or earthquakes can trigger such instabilities (Mulder & Cochonat 1996; Postma 1984). The non-deposition area NW of the Hauts-Monts platform is the geographical representation of the stratigraphic geometry already discussed for the *eb1* echosounder profile (Fig. 2). It is most probably the result of strong bottom currents that prevent sediment deposition.

Unit c2, Preboreal → end of Younger Atlantic (Fig. 4 b):

The isopachs indicate increased sediment supply by the Versoix River. The sediments are distributed at the bottom of the slope NE and SE from the river mouth. The decrease in the non-deposition area at the foot of the Hauts-Monts platform and its 300 m shift to the SSE indicate a decrease in the bottom currents and a probable change in lake circulation patterns.

Unit c3, Subboreal → beginning of Younger Subatlantic (Fig. 4 c):

Unit c3 is characterised by the ongoing sediment input from the Versoix River in the SW part of the study area and by the sediment input from slumping of the Hauts-Monts slopes in the NE lake basin. The sharp decrease of the non-deposition area indicates a decrease in the bottom-current action.

Unit d1, late Middle Ages (Fig. 4 d):

The dominant sedimentation area follows the lake slope along the platform NE of the Versoix River mouth, indicating either deviation of the river plume or intense reworking on the lake platform NW of the basin. In any case, the sediment load is oriented in a direction that is opposite to the main lake flow. Only wind-induced currents that have modified in turn the lake circulation can explain this sediment distribution. The increased thickness of unit d1 (0-6 m) during this short time interval points towards a sharp rise in sedimentation rate, which is most probably related to the heavy deforestation of the catchment area that increased both runoff and denudation processes during the late Middle Ages (Le Roy Ladurie 1983).

Unit d2, Modern Times (16th-18th century) (Fig. 4 e):

The unit d2 sediment distribution is similar to that of unit d1. Sedimentation rates appear to be lower than those of unit d1 (0 to 1.5 m thick). This indicates a new decrease in the bottom-current action in the centre of the basin, and a reduction of the Versoix delta sediment supply. The opposite orientation of the Versoix River sediment load to the surface lake flow suggests that wind-induced currents dominated the lake circulation in this part of the basin.

Unit d3, contemporary epoch (19th century - present) (Fig. 4 f):

The sediment supply from the Versoix River is located SW of the river mouth. This observation is consistent with studies of the recent Versoix River sediment distribution and can be explained by deep counter currents originating from SW winds (Ulmann et al. 2002, this volume). In Corsier Bay (Girardclos 2001), the similarity of the truncated geometry between unit d3 and units d1 and d2, indicates that heavy erosion probably occurred during the contemporary epoch. Its 35-55 m depth suggests that this erosion resulted from deep erosive currents along the Corsier Bay slope.

4.3. Chronological synthesis of the currents action on the sediments

The main interpreted sedimentological features (cf. previous paragraph) are presented chronologically in Table 1 (col. 1 to 3). Using the erosion patterns and the variation in the non-deposition area, the intensity of past deep lake currents was reconstructed for the Holocene (Table 1, col. 4).

As previously explained, the present distribution of the sediment in the Hauts-Monts area is due to the strong wind regimes and their resulting meteorological conditions (rain, etc.). Based on the model for the present situation, it is possible to define the relative frequency of strong winds (Table 1, col. 5) and to reconstruct dominant past wind regimes (Table 1, col. 6) for the western Swiss Plateau.

5.- Conclusions

Our results show that lake currents have influenced the sediment distribution of the Hauts-Monts area since the very beginning of the Preboreal (end of unit c1). In addition, the identified current action may have been initiated during the lowering of the lake level by at least 20 m between the Oldest Dryas and the Preboreal (Gallay & Kaenel 1981), as well as with changes in weather pattern most probably associated with the early Holocene major climate warming.

The particular topography of the Hauts-Monts platform which narrows the lake basin, certainly accelerates the existing bottom currents and thus enhances their effect on the sediments. This could explain the infrequency (or even uniqueness ?) of the observed sedimentological features in Lake Geneva at depths greater than -60 m. This hypothesis is supported by similar bottom morphologies (topographic constrictions, narrow passages and confining slopes) observed in the central Mediterranean Sea that control bottom-current activity (Marani et al. 1993).

The imprint of the variable influence of currents in the sediments is shown as three distinctive types of sedimentological features:

1.- a non-deposition area in the centre of the basin (60-65 m depth),

2.- erosion of sedimentary sequences in the centre of the basin (60-65 m depth) and in Corsier Bay (35-55 m depth), and

3.- a repeated shift of sediment supply and sediment distribution.

To our knowledge, such a 'current stratigraphy' has not been previously established for another lake or a comparable basin, as climate change is usually expressed in terms of temperature and moisture changes (e.g. Pfister 1999). Lacustrine and marine contourites in Lake Malawi (Johnson & Ng'ang'a 1990, Scholz & Finney 1994, Scholz & Rosendahl 1990) and the Mediterranean Sea (Marani et al. 1993) are similar to Lake Geneva's in their geometry, morphological types and topographical locations. These authors attribute the Mediterranean and Malawi contourites to subrecent –or even presently active- bottom-current action. But as they occur in much bigger and deeper basins, their bathymetry and dimension are comparatively much greater than in western Lake Geneva. Marani et al. (1993) pointed out the importance of local sea-bottom morphology accelerating local deep circulation patterns and speculate whether the generation of the central Mediterranean contourites could also be regionally controlled by cyclic glacio-eustatic fluctuations of sea level. Because the Lake Malawi and Mediterranean contourites have not been dated yet, they cannot be used as possible proxies of climate change. It is, therefore, difficult to compare our observations and interpretations with previously published climate or bottom-current related records. Thus, our model showing changes in frequency and magnitude of strong wind regimes represents the first attempt to define wind pattern evolution during the Holocene not only in the western Swiss Plateau but also in other areas of the globe.

Several questions remain open and need further investigation to constrain our conclusions. One option to test them would be to quantify and model the 3D current velocity distribution within the modern lake basin. The latter combined with a precise determination of the different sediment source areas will allow a more accurate reconstruction of the mechanisms behind past sediment distribution and their triggering forces. This may provide a unique reconstruction of former wind directions and the associated atmospheric circulation patterns over the Swiss Plateau.

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