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A 600-year sedimentary record of flood events from two sub-alpine lakes (Schwendiseen, Northeastern Switzerland)

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Key words: Lake sediments, flood events, environmental change, siderite, vivianite, late Holocene, Schwendiseen, Toggenburg.

ABSTRACT

Short sediment cores from two small interconnected sub-alpine lakes (Vorderer and Hinterer Schwendisee) in northeastern Switzerland contain a continuous record of environmental changes, which occurred during the last 600 years. Several light-colored layers within predominantly organic carbon-rich sediments display elevated density values and a high amount of detrital material. This composition points towards an allochthonous origin, which we interpret as material brought into the lake by unusually strong rainfall events. Based on this interpretation, four event horizons were identified in the sedimentary record. These horizons were dated combining a ^{137}Cs and ^{210}Pb-based chronology with meteorological and historical data. They occurred mostly within the 19th and at the beginning of the 20th century, whereas only one event occurred prior to 1800. The well-documented strong rainfall event that occurred on June 14, 1910 is observed in the sedimentary record as the thickest detrital horizon. These short-lived climatic events archived in the sediments of both lakes are superimposed on a longer-term environmental trend characterized by fluctuating conditions in organic productivity. The formation and preservation of authigenic minerals, such as siderite and vivianite, are most likely related to intervals of different primary productivity in the water column.

ZUSAMMENFASSUNG

Sedimentkerne aus zwei kleinen, miteinander verbundenen sub-alpinen Seen in der Nordostschweiz enthalten Informationen über die vergangenen Umweltbedingungen der letzten 600 Jahre. Mehrere helle Lagen in einem durchwegs organisch reichem Hintergrundsediment zeigen erhöhte Dichtewerte und einen grossen Anteil an detritischem Material. Diese Zusammensetzung der Lagen weist deutlich auf einen allochthonen Ursprung und den Eintrag durch Starkniederschlagsereignisse hin. Vier solche starke Niederschlagsereignisse konnten in den Kernen identifiziert werden. Diese wurden mittels der kombinierten Analyse der ^{137}Cs und ^{210}Pb Aktivitäten und dem Vergleich mit meteorologischen und historischen Daten datiert. Die Lagen konzentrieren sich dabei auf das 19. und den Beginn des 20. Jahrhundert, nur ein Ereignis fand vor 1800 statt. Als dickste Ereignislage in den Kernen ist der gut dokumentierte Starkniederschlag vom 14. Juni 1910 vorhanden. Die kurzen klimatischen Extremereignisse werden überlagert von langfristigen Umweltveränderungen, die einen starken Einfluss auf die Primärproduktion der Seen hatten. Die Bildung und Erhaltung von authigenen Mineralien, wie Siderite und Vivianite, scheinen mit Perioden von unterschiedlicher Primärproduktion in der Wassersäule verbunden zu sein.

1.- Introduction

One major concern in the recent discussion on global climate change is the prospective frequency and severity in the very near future of extreme events such as heavy rainfall, storms, avalanches, heat waves and drought (Easterling et al. 2000). The impact of such extreme events on civil infrastructure, human society and natural ecosystems is assumed to be larger than that of the steadier, but slower changes in climate (Beniston 2000). Rebetez et al. (1997) analysed the precipitation record of several meteorological stations across Switzerland and documented a slight increase in the occurrence of extreme rainfall events during the 20th century. A recently published study (Frei & Schär 2001) showed that the statistical significance for an increase of such rare and extreme rainfall events is weak due to the limited time period covered by the instrumental meteorological data. One possibility to expand the record of past extreme events is the analysis of lake deposits that have the potential to archive such strong rainfalls through changes in sediment composition (Siegenthaler & Sturm 1991; Thorndycraft et al. 1998). Previous studies confirmed that small alpine lakes are ideal high-resolution archives to analyse

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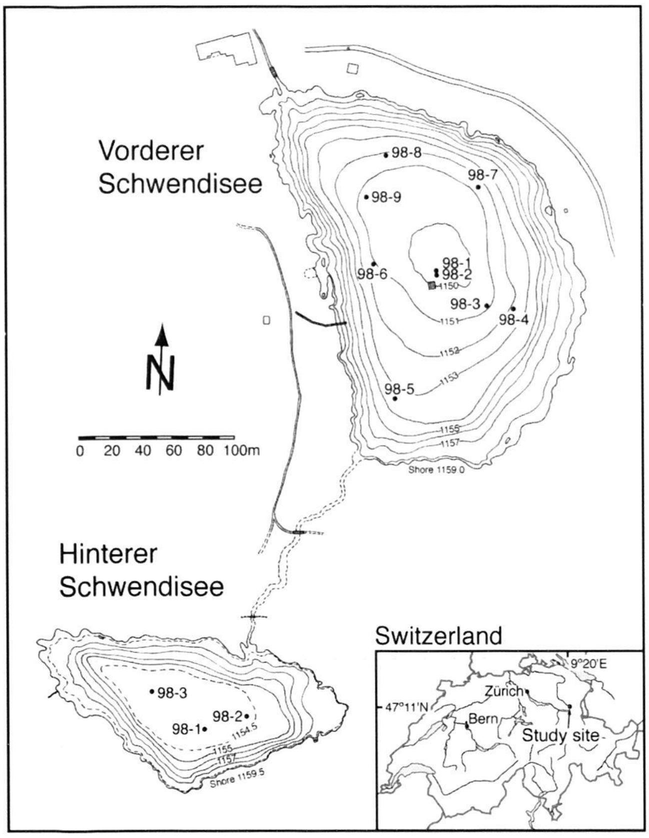

Figure 1. Bathymetrical map of the Vorderer and Hinterer Schwendisee. The labeled dots represent the coring locations. The bathymetry is from Alois Heigl, Rudolf Steiner Schule, Kreuzlingen, Switzerland.

past climatic and environmental conditions on various timescales (e.g. Blass et al. this volume, Lanci et al. 1999, Steiner et al. 2000). In this study, we report how strong rainfall events are preserved in two interconnected lakes located in a mountainous area. Their unique setting and variable sensitivity to detrital sedimentation have produced two distinctive records with different resolutions and thresholds to past rainfall events.

2.- Study site

The Vorderer and Hinterer Schwendisee ("Lower and Upper Lake Schwendi") are two small sub-alpine lakes located on the northern slope of the Churfirsten range in the Toggenburg area (northeastern Swiss Alps) at an altitude of 1.159 m.a.s.l. (Fig. 1). The two lakes, 0.033 and 0.012 km^2 in size (Schwab 1992), respectively, lie in a morphological depression eroded by glaciers and sealed by till-deposits (Fig. 2). They are partly surrounded by moraines from different glacial stages (Keller 1988). The theoretical hydrological catchment covers approximately 5 km^2 (Müller et al. 1998, Schwab 1992). Over 75% of the drainage area consists of Cretaceous limestone (i.e. Schrattenkalk and Sewerkalk) with a high potential for carstification (Attinger 1988), which strongly diminishes the real catchment area. Tracer experiments confirmed subterraneous drainage of this area towards the southwest (Rieg 1994). The effective catchment area is partly used for agriculture as mountain pasture; the other part is forested. The Hinterer Schwendisee, though smaller, drains a larger part of the effective catchment area and is, therefore, more affected by the detrital input. The water from the Hinterer Schwendisee flows through a small creek into the Vorderer Schwendisee, from where the water leaves the system through a small river called Seebach. The maximum water depth of the Vorderer and Hinterer Schwendisee is 9.7 m and 5.3 m (Schwab 1992), respectively. The first scientific investigations of the two lakes took place already at the end of the 19th century, when Asper & Heuscher (1887/88) published the first bathymetrical maps of the two lakes together with temperature measurements and faunal investigations. In more recent times several biological studies about past vegetation changes were performed in the peat zone around the lakes (for summary of palynological analyses see Burga (1991) and Bürgisser (1973). Schwab (1992) studied the hydrology, thermal behaviour and water chemistry of the two lakes during one annual cycle and documented a dimictic mixing behaviour with an overturning water body in spring and fall and a stratified column in summer and winter. During the summer stagnation, oxygen is absent in the profondal zone of both lakes. Additionally, the input of oxygen into the deeper layers by the overturning water body in spring and fall is low due to the long-lasting snow and ice cover. Results from Schwab (1992) indicate that the two lakes are an independent hydrological system decoupled from the underlying karst water complex.

Figure 2. Photograph of the Hinterer (on the left) and the Vorderer Schwendisee taken from the south.

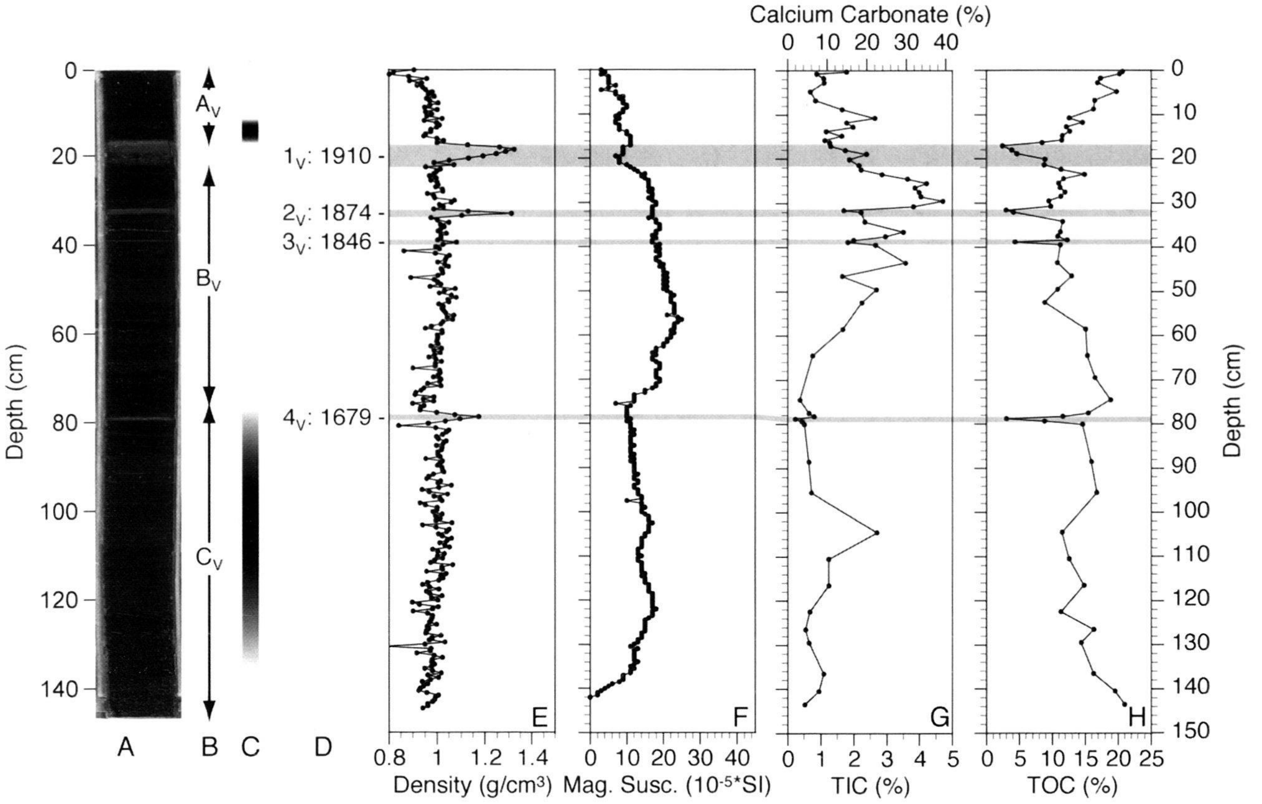

Figure 3: Sedimentology, petrophysical properties and geochemical data for core VSCH 98-1, the reference core of the Vorderer Schwendisee. A) core photograph; B) sedimentological units; C) the occurrence of vivianite patches or layers; D) light-colored detrital layers and year of deposition; E) density (g*cm-3); F) magnetic susceptibility (10-5*SI); G) total inorganic carbon in dry weight percent (in % TIC and % calcium carbonate); and H) total organic carbon in dry weight (%TOC). The detrital layers (grey bars) interpreted as flood events are characterized by high densities and reduced values of TIC and TOC.

Today, the two lakes and the surrounding wetlands are a protected area but frequently visited in summer by swimmers. In 1965, a water intake pipe was installed in the Vorderer Schwendisee. This provided for the essential water supply of the nearby villages for some years, but today it is only rarely used.

3.- Field and laboratory methods

A seismic survey with a 3.5 kHz pinger source was undertaken to image the sedimentary architecture of the Vorderer Schwendisee. The penetration of the seismic signal was very shallow so that no subsurface information could be retrieved (Gilli 1999). This is most likely associated with high gas content in the sediments originated from decomposing organic matter. Many rising air bubbles during coring operation confirm in fact the high gas content within the sedimentary package. Such gas-masking was earlier described in many other Swiss lakes of different settings such as Lake Zurich (Giovanoli et al. 1984), Lake Lugano (Niessen 1987), and Lake Champfer (Leemann 1993).

Several short gravity cores were recovered along different transects in the two lakes (Fig. 1). All cores were scanned every 5 mm for their physical properties (p-wave velocity, gamma-ray-density and magnetic susceptibility) using a GEOTEK™ multi-sensor core logger. The cores were subsequently opened, photographed and described. In both lakes a reference core from the central part of the basin (VSCH 98-1 and HSCH 98-1) was chosen for detailed sedimentological, geochemical and mineralogical analysis and for establishing a sediment chronology. Although a uniform 5 cm sampling interval was used for sediment analyses throughout the core, a closer interval was used in sections with visual changes in the lithology. Total carbon (TC) and total inorganic carbon (TIC) was coulometrically measured with an UIC, Inc.™ system. For the TC-measurement, the samples were combusted by 950ºC to turn any forms of carbon into CO_2, which was measured in the coulometer. The samples for the TIC analysis were treated with 2N $HClO_3$ to release the CO_2 from any carbonate miner-

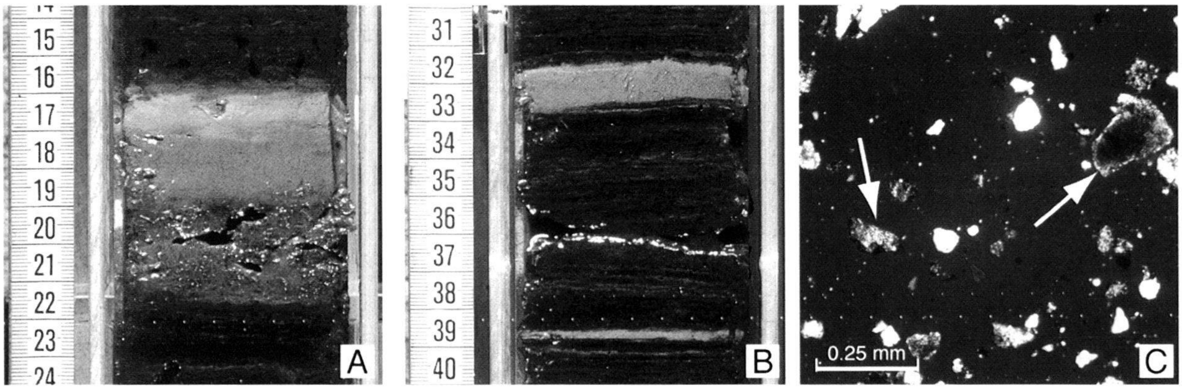

Figure 4. Detail photographs of the detrital layers in core VSCH 98-1 (i.e. detail A and B with cm scale on the left side) and a smear slide of the sandy layer in the event horizon 1H in core HSCH 98-1. A) event horizon 1V consists of an organic carbon-rich base overlain by a silty clay, with a dominant light-colored clay cap; B) event horizon 2V (31.5-32.4 cm) with a 2 -3 mm thick clay cap and the thinner event horizon 3V (38.7-38.9cm). Shiny spots in a depth of ~36 cm are water-rich areas with a high light reflectance; and C) smear slide of the sandy layer in event horizon 1H (core depth: 28.8 cm) of core HSCH 98-1. This sand layer mainly comprises of quartz and glauconite grains (arrows), which are clearly of detrital origin. The grains have an angular shape with rounded edges.

als. Due to the slow dissolution reaction, the samples were heated during the treatment. Total organic carbon content (TOC) was calculated as difference between TC and TIC. Smear slides, thin sections and X-ray diffraction analysis were used to characterize the mineralogical content of the sediments. ^{137}Cs and ^{210}Pb activities were measured in the uppermost 16.6 cm and 15.5 cm of cores VSCH 98-1 and HSCH 98-1, respectively. The combination of both methods provided a coherent and robust chronology.

4.- Results

4.1. Vorderer Schwendisee

The reference core from the Vorderer Schwendisee, VSCH 98-1, comprises mainly dark brownish to blackish organic carbon-rich material with intervals containing very fine and sometimes faint clay-silt/calcareous laminae. The water content is very high with values around 90 weight-%. No lamination is present in the first 3 cm and below 140 cm where organic matter dominates the sediment composition. Four major light-colored clay to silt-rich layers can be visually recognized in the core VSCH 98-1 (Fig. 3) at a depth of 16.6-21.8 cm (Layer 1_V), 31.5-32.4 cm (2_V), 38.7-38.9 cm (3_V) and 78.5-79.6 cm (4_V). Layer 1_V is the thickest horizon with a ~ 2.6 cm thick organic-rich base containing fragments of aquatic mosses overlain by light-colored silty clay, followed by a dominant clay cap at the top (Fig. 4A). The layers 2_V, 3_V, 4_V are thinner, whereas layer 2_V (Fig. 4B) and 4_V are divided into a dark-grey silty base and a light-grey clay top. The horizon 3_V consists only of a 2-mm thick light-grey clay layer (Fig. 4B). In the physical property profiles, these four distinct layers are recognized as positive peaks in the otherwise fairly uniform density distribution with a mean value of 1 g/cm^3 (Fig. 3). The chemical analysis of these layers reveals a relatively low content in TOC and TIC compared with the background sediments. These light-colored horizons can be traced in the cores according to their petrophysical signature and core description throughout the whole basin (Fig. 5). The youngest three horizons (1_V, 2_V, 3_V) are restricted to the deeper part of the basin, whereas layer 4_V is also present in the more shallow lake area. Core VSCH 98-1 shows intervals with a distinctive chemical and petrophysical pattern (Fig. 3). Interval A_V (0 - 16.6 cm) above the youngest event horizon is faintly laminated with the exception of the uppermost 3 cm, revealing constantly increasing TOC values towards the top. The TIC initially shows a similar trend, but then drops down to a value of around 1% in the topmost 10 cm. Some patches of vivianite (hydrated iron phosphate) are visible recognized by their blue oxidized colour in the few lowermost cm of interval A_V (Fig. 3C). Interval B_V (22 cm - 72 cm) is fine laminated and is characterized by elevated magnetic susceptibility values and a fourfold upcore increase of TIC with a rapid decrease at the top. According to the X-ray diffraction analysis, the carbonate fraction consists mainly of calcite ($CaCO_3$) and a minor amount of siderite ($FeCO_3$). The interval C_V (72 – 146.5 cm) consists in the upper part above 123 cm of fine, but only faintly laminated sediments grading subsequently into a very organic carbon-rich section at the base of the core with decomposed plant fragments. Patches and layers of vivianite are present in interval C_V except for the lowest part (Fig. 3C). The presence of vivianite was confirmed by X-ray diffraction analysis.

^{137}Cs activity shows one major peak in the depth interval between 7.0 and 7.5 cm (Fig. 6). The activity above this peak has moderate values, where as below 10 cm depth it ap-

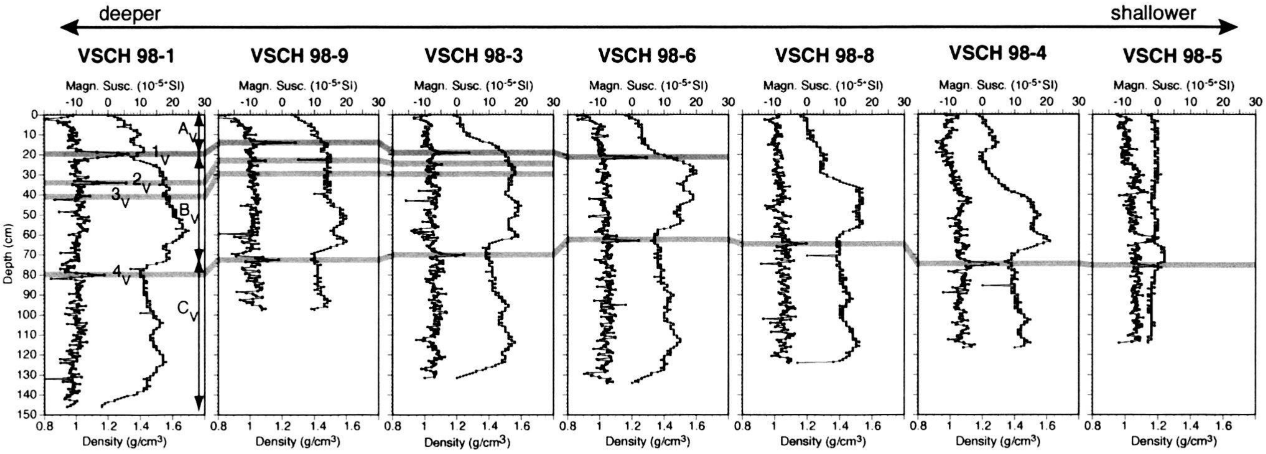

Figure 5. Transect of seven cores in the Vorderer Schwendisee arranged according to water depth. For each core, the density (black squares) and the magnetic susceptibility (grey dots) are displayed. The four event horizons can be traced throughout the basin, but three of the four horizons are restricted to the deeper basin. This distribution pattern points towards the existence of underflow as the dominant depositional process during extreme rainfall events.

proaches zero. No second peak can be recognized. Visual inspection of the topmost section of the core confirmed the contamination with PVC splinters as an artefact of the core opening procedure and would explain the lack of a peak in this interval. The ^{210}Pb activity profile (Fig. 6) shows a consistent linear downcore decrease in a logarithmic diagram revealing a sedimentation rate of 0.22 cm/year. The topmost seven data points in the uppermost 3.5 cm show lower values than expected, probably due to the same disturbance factors as in the ^{137}Cs profile and/or due to remobilisation processes under anoxic conditions (Erten et al. 1985). Therefore, these data points were not considered for the regression. Combining the ^{137}Cs and the ^{210}Pb data, the single peak at 7.0 - 7.5 cm can be assigned with high confidence to the end of the superficial atomic bomb tests in 1963 (Fig. 6) resulting in average sedimentation rate of 0.21 cm/year. The 1987-Cs peak (i.e. the nuclear reactor accident in Tschernobyl) is probably missing due to the discussed core disturbances.

4.2. *Hinterer Schwendisee*

The sediments recovered in the cores from the Hinterer Schwendisee are overall similar to those from the Vorderer Schwendisee. The core HSCH 98-1 consists of organic carbon-rich sediments intercalated with light-colored silty to clayey laminae (Fig. 7), which are thicker than in core VSCH 98-1. The water content ranges from 60 to 90%. A distinctive interval between 13.9 and 34.6 cm (layer 1_H) contains two different lithologies. The lowermost part (28.8 – 34.6 cm) consists of an accumulation of aquatic mosses covered by a 14.9 cm thick package (13.9 – 28.8 cm) with a fining upward grading from sand to clay-size-fraction. Smear slides examinations of the sand fraction revealed that the composition of the grains is mainly quartz with some subordinated glauconite (Fig. 4C). The grains have an angular shape although edges are smoothed. The top of this graded interval consists of a dominant light-grey clay cap. This graded unit has low magnetic susceptibility, TIC and TOC values. Additionally, this interval shows high, but upcore decreasing density values, coinciding with the described gradation in grain size. Beside this major interruption of the ordinary lake's organic carbon-rich background sedimentation, two additional major layers are found at depths of 41.6 – 42.8 cm (2_H) and 53 – 55 cm (3_H). They are both characterized by a dark-grey, silty clay base and a light-colored clay top. The background sediment can be divided into two intervals above and below layer 1_H (Fig. 7). Interval A_H (0.0 – 13.9 cm) is, in the lower part, faintly laminated, whereas the topmost 3.5 cm is homogeneous and organic carbon-rich with a fluffy appearance. A general trend upcore towards increasing TOC- and TIC-values can be observed within interval A_H. Interval B_H (34.6 – 68.2 cm) consists of thin bright detrital layers, which are responsible for the highly fluctuating TIC curve (Fig. 7).

As observed for core VSCH 98-1, the ^{137}Cs and ^{210}Pb profiles for core HSCH 98-1 point towards coring disturbances in the topmost 4 cm. The ^{137}Cs profile shows a small peak at 6.25 cm. Towards the top, the ^{137}Cs activity increases in the first 4 cm, which suggests a similar contamination as in core VSCH 98-1. As a precaution, the first 4 cm were also neglected in the regression of the ^{210}Pb analysis, resulting in a sedimentation rate of 0.16 cm/year. This matches approximately the sedimentation rate from the Cs data (0.18 cm/year), where the 6.25 cm peak is interpreted as the 1963 event.

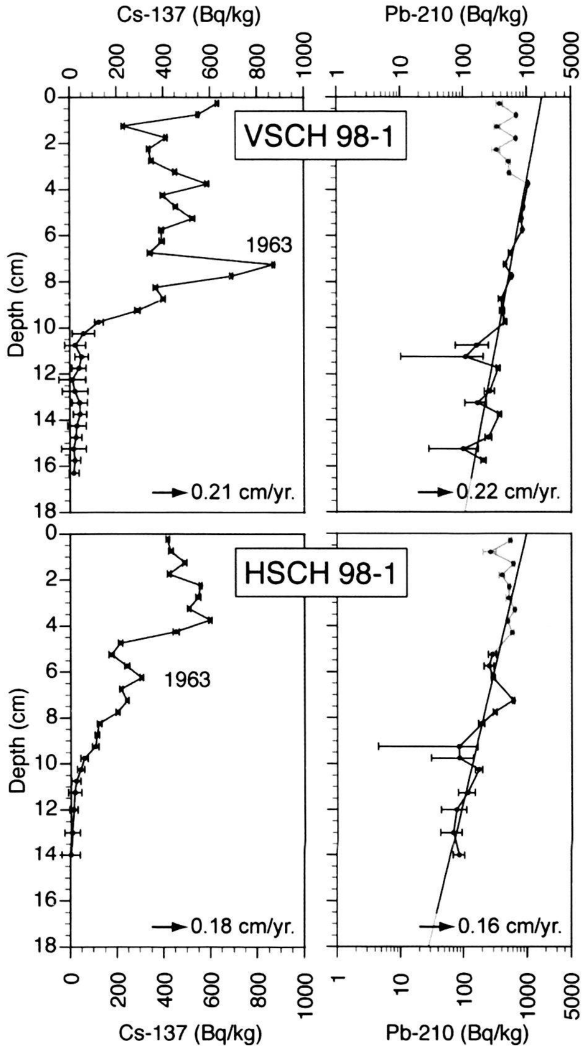

Figure 6. The activity profiles of Cs-137 and Pb-210 for the two cores VSCH 98-1 and HSCH 98-1. A good consistency can be observed between the two dating methods in each lake revealing a slightly higher sedimentation rate for the Vorderer Schwendisee. For detail discussions of the activity profiles see text.

5.- Discussion

5.1. Extreme rainfall events

The described light-colored layers in both sediment records are characterized by high density, low TIC- and TOC-values, which strongly indicates a depositional mechanism of individual major flood events supplying a high detrital load into the lake system. In particular, the glauconite grains at the base of the youngest event in core HSCH 98-1 must have been brought in from the catchment area, where the glauconite bearing mid-Cretaceous Garschella Formation outcrops (Föllmi & Ouwehand 1987). These event horizons are thicker in the Hinterer Schwendisee than in the Vorderer Schwendisee. In addition, the overall higher density values and lower water content in core HSCH 98-1 indicates a comparatively higher detrital influence in the Hinterer Schwendisee. Although the detrital input is higher in the Hinterer Schwendisee than in the Vorderer Schwendisee, sedimentation rates in the former are lower (0.16 - 0.18 cm/year vs. 0.21 – 0.22 cm/year). The comparison of the two sedimentary records shows an almost fourfold higher TOC content in core VSCH 98-1 than in core HSCH 98-1. The higher TOC content in core VSCH 98-1 may indicate an enhanced primary productivity in the Vorderer Schwendisee, as supported by today's slightly higher water temperature than in the Hinterer Schwendisee (Schwab 1992). Nevertheless, the comparable lower TOC values in core HSCH 98-1 are probably the result of the dilution due to the higher detrital input, which, in turn, reduces the primary production due to the generally higher water turbidity. The relatively higher sedimentation rate in core VSCH 98-1 than in core HSCH 98-1 indicates, however, that primary productivity in the Vorderer Schwendisee can compensate and even overcome the lack of detrital input to yield a higher sedimentation rate.

The calculated sedimentation rate based on the activity of the ^{137}Cs and ^{210}Pb radionuclides (Fig. 6) allows the dating of the described flood horizons. According to these different sedimentation rates, the youngest and strongest flood event occurred around 1919-1923 (1_V) and 1911-1920 (1_H) in the Vorderer and Hinterer Schwendisee, respectively, suggesting that these two layers are the result of the same event (Figs. 3 and 7). A flood event causing a deposition of over 20 cm in the Hinterer Schwendisee should have been recorded in the meteorological stations in the area. The records from the nearby station in Wildhaus, as well as the meteorological station in Starkenbach which is located 6 km downstream of the studied lakes, have been analysed for the occurrence of strong rainfall events for the time period 1880 - 1970 (Zeller et al. 1977). The highest one-day rainfall amount during this period occurred on June 14, 1910. This day registered 190 mm of rainfall, which is more than a tenth of the mean annual rainfall of 1.803 mm/year (Spreafico et al. 1992). Such a high rainfall intensity and the temporal proximity within reasonable errors to the calculated ages of the horizons makes it very likely that the youngest horizons deposited in both basins were formed by this extreme flood in the summer of 1910. Additionally, this rainfall event produces by far, the thickest event horizon in both records and, therefore, fits very well with this extraordinary historical event. The newspaper "Neue Zürcher Zeitung" (NZZ; June 15, 1910) reported on the severity of this 1910 flood: *"Seit 24 Stunden regnet es ununterbrochen. Fast alle Bergbäche treten über die Ufer und reissen alles mit, aufgeschichtetes Holz und Stege nicht verschonend..."* (Translation by the authors: *"For 24 hours it rained continuously. Almost all mountain creeks spelled over their banks ripping out*

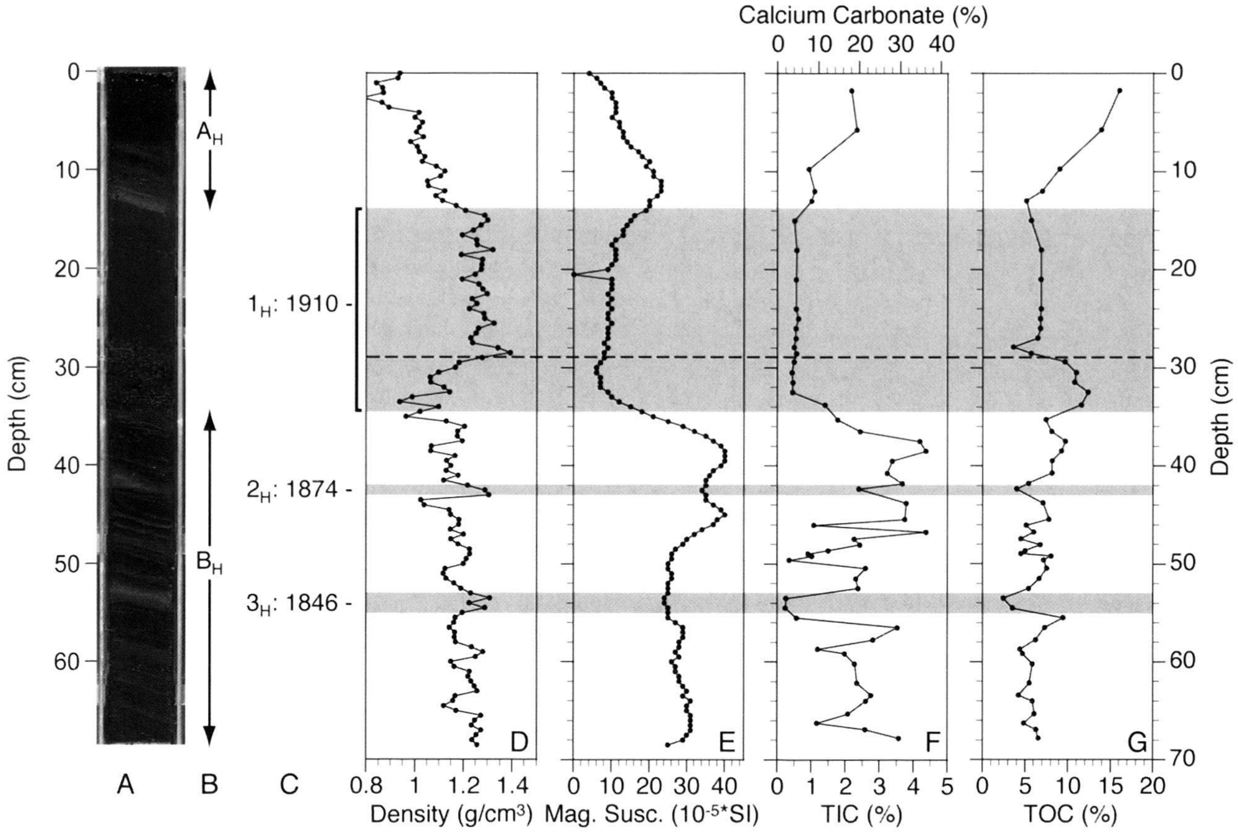

Figure 7. Sedimentology, petrophysical properties and geochemical data for core HSCH 98-1, the reference core of the Hinterer Schwendisee. A) core photograph; B) sedimentological units; C) light-colored detrital layers and year of deposition; D) density (g*cm-3); E) magnetic susceptibility (10-5*SI); F) total inorganic carbon in dry weight percent (in % TIC and % calcium carbonate); and G) total organic carbon in dry weight (%TOC). The detrital layers (grey bars) interpreted as flood events are characterized by high densities and reduced values of TIC and TOC

everything in their path not sparsing trees and footbridges…"). One year after our coring campaign, a heavy rainfall event occurred in the period May 19-21, 1999 resulting in a one-day rainfall amount of 201.5 mm at the station Wildhaus (Aschwanden & Bürgi, 2000). The analyses of several cores taken in winter 2000 revealed no light-colored event horizon neither in the record of the Vorderer nor in the record of the Hinterer Schwendisee. The reasons for the missing flood horizons are speculative, but the cultivated alpine pasture may have increased the water retention and decreased the potential for sediment erosion. Looking at the flood events before the 20th century and assuming a constant sedimentation rate, the second youngest flood would have occurred between 1864 – 1866 (2_V) and 1866 – 1871 (2_H) in the Vorderer and Hinterer Schwendisee, respectively (Figs. 3 and 7). For this time interval, the meteorological records of the Toggenburg area are incomplete (Zeller et al. 1977). However, a study by Gees (1997) compiled all of the evidence from meteorological records and historical notes of past flood events of the Sitter River, which is in a drainage area that lies approximately 8 km to the north of the two studied lakes. According to this study, a catastrophic flood event occurred on July 30h, 1874, most likely causing the second youngest event horizon in the sedimentary records of the two lakes. The small discrepancy between the calculated age and the age based on the historical records can be reconciled by assuming slightly enhanced carbonate sedimentation at the end of the 19th century (Fig. 3G). Extrapolating the sedimentation rate downcore, the next older flood horizon is found in core VSCH 98-1 at a depth of 38.7 –38.9 cm and was most likely deposited in the years 1846 –1847 (3_V), which correspond exactly with a catastrophic event documented for August 23, 1846 in the historical flood chronicle of Gees (1997). By applying a constant sedimentation rate to core HSCH 98-1, the flood horizon event occurring at a depth of 53 – 55 cm (3_H) would have been deposited around 1815, but the higher abundance of thin bright layers increased the sedimentation rate dramatically in the overlaying interval, so that this horizon also likely represents the 1846 event. Only core VSCH

98-1 records an even older flood event horizon at a depth of 78.5-79.6 cm (4_V), which has a possible date around 1660. Comparing this age with the historical record, it is most likely that it was caused by a flood event reported for July 14th, 1679 (Gees 1997). As with the overlaying horizons, the calculated age is too old, indicating that sedimentation rates during the 17th to 19th centuries were slightly higher than in the 20th century. Under the assumption of a constant sedimentation rate of 0.22 cm/year for the lowermost interval C_V the oldest sediments of core VSCH 98-1 would be deposited around ~1375.

The occurrence of flood horizons is focused during the 19th and the beginning of the 20th centuries. Core HSCH 98-1 shows a remarkable higher frequency of detrital layers in the interval B_H in the 19th century than in the 20th century (i.e. interval A_H). Surprisingly, no detrital horizon was deposited in the lowest part of the core VSCH 98-1 covering the time interval between the end of the 14th century and 1679. The absence of strong rainfall events since 1910 is in good agreement with the historical analysis of the level of Rhine River, which shows rare extreme flash floods in the period 1882 – 1994 coinciding with generally warm and dry summers (Pfister 1999). This natural trend of rainfall events was superimposed by the pervasive deforestation during the 18th and 19th centuries that has decreased the soil's water retention capacity. In addition, rivers were regulated and straightened leading to a faster runoff. A newspaper reporter from the "St. Galler Zeitung" (August 3, 1874) called already attention to the problem of deforestation and its implication for increased surface runoff: *"Ein Blick auf die schwindenden Waldbestände unserer Bergabhänge und Thalschaften: auf die nackt und nackter werdenden Höhen zeigen die Ursache dieser Erscheinung. Holzt mehr ab, holzt alles ab wenn ihr in Zukunft Jahr für Jahr solche Kalamitäten haben wollt!"* (Translation by the authors: *A look to the vanishing forest on our hillslopes and valleys; on to the bare and progressively barer highs shows the reason for this phenomenon. Cut more, cut everything down if in the future you would like to have, year for year, such calamities!*) Already in these early years people began to realize the connection and feedbacks between deforestation and increasing runoff. With this recognition in mind, the Swiss government enacted a protection law in 1876 to insure the sustainable management of the forests in the Alpine areas. This law was expanded to apply nation-wide in 1902 (Kasper 1988).

The lateral distribution of the flood horizons in the Vorderer Schwendisee (Fig. 5) reveals insight into the depositional mechanism of these events. Three of the four horizons are concentrated in the deepest part of the basin and only layer 4_V can be detected in the shallower area. This depositional pattern was earlier described in Lake Brienz (Sturm & Matter 1978) and Lake of Walenstadt (Hsü & Kelts 1985) and is associated with density currents produced by floods carrying a large amount of suspended detritus. Even if the basin of the Vorderer Schwendisee is significantly smaller than the previously mentioned pre-alpine Swiss lakes, similar underflow could have deposited the detrital layers.

5.2. Long-term environmental changes

As previously mentioned, several intervals of the two studied cores show distinct sedimentological, geochemical and petrophysical signatures expressing long-term changes – naturally and/or human-induced – in the environment. The interval 1910 – 1998 (A_V and A_H) appears in both studied cores as an increase in TOC and TIC, except for the TIC values in core VSCH 98-1 for the second half of the 20th century (Fig. 3). The trend of increasing TOC and TIC values are possibly related to anthropogenic eutrophication. Furthermore, the impact of swimmers by phosphorous and nitrogen input on small lake systems is not negligible and in the case of the two studied lakes may play a role (Schulz 1981). The drop in TIC is seen only in core VSCH 98-1 and the timing of the decrease correlates well with the construction of the water intake pipe (1965). The reduction of anoxic conditions in the bottom waters of the lake affected the carbon chemistry preventing the formation of authigenic carbonate minerals, such as siderite. The interval (B_V) between ~1710 and 1910 shows a fourfold increase in carbonate content and high magnetic susceptibility values. X-ray diffraction analysis of selected samples within this interval shows the presence of siderite. Whether siderite is solely responsible for the increase in carbonate content or whether the calcite detrital flux is also enhanced during that interval remains unsolved. In contrast, the interval C_V, covering the time interval prior to ~1710, shows low TIC and magnetic susceptibility values. Vivianite is present as patches, sometimes concentrated within certain layers (Fig. 3C). The formation of vivianite and siderite both need anoxic conditions together with low sulfide and calcium concentration (Kelts & Hsü 1978). Furthermore, Postma (1981) showed that, although pH and phosphate concentration are the major controlling factors for the formation of both minerals, comparatively lower pH and high phosphate concentrations favour the formation of vivianite relative to siderite. Thus, the presence of vivianite in the sedimentary record of the Vorderer Schwendisee may indicate higher organic matter decomposition due to a higher primary productivity. This would imply that, before ~1710 and after 1910 (i.e. intervals C_V and A_V), the lake was characterized by high primary productivity levels. Conversely, the time interval between these two ages contains the culmination of the Little Ice Age and shows comparatively lower productivity levels that are most likely due to a drop in lake's water temperatures that would in turn limit or even prevent certain algal blooms.

6.- Summary and Conclusions

The analysis of the sedimentary records of the two lakes revealed several light-colored horizons probably associated with extreme flood events. ^{137}Cs and ^{210}Pb radionuclide analyses combined with meteorological and historical data, resulted in a coherent chronostratigraphy. The ^{137}Cs and ^{210}Pb dating revealed a sedimentation rate for the Vorderer and Hinterer Schwendisee of 0.21 – 0.22 cm/year and 0.16 - 0.18 cm/year, respectively. The extreme rainfall event, which occurred on June 14, 1910, is recorded as the thickest event horizon in both lakes. Three additional event horizons correlate well with historical floods in the years 1874, 1846 and 1679. The higher occurrence of extreme floods in the second half of the 19th and the beginning of the 20th century corresponds with a time interval of higher rainfall (Pfister 1999). In addition, pervasive deforestation during this time period decreased the water retention capacity of the soils leading into a higher surface runoff and erosion rates. Long-term changes in the sediment composition were observed in both cores documenting long-term environmental changes in the watershed and of the water body of the lake. The occurrence of siderite or vivianite can be interpreted as productivity indicators showing a higher primary productivity of the lake before ~ 1710 and at the beginning of the 20th century. The intervening time span of the Little Ice Age is thus recorded in the sediments of the Vorderer Schwendisee as a period of low primary productivity. In addition, man-made perturbations are recognized in the youngest part of the sedimentary archive. The construction of a water intake in 1965 changed the water chemistry, and the increase in TIC and TOC in the 20th century maybe attributed to higher degree of utilisation of the two lakes and their surroundings as a recreational area.

The sedimentary archives of the two lakes provide valuable information about past environmental conditions on different temporal and geographical scales. They allow us to assess the timing of heavy flood events in the past and show the potential of these lacustrine sediments to extent the record of such strong climatic events into pre-historical times.

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