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Autor: Blass, Alex / Anselmetti, Flavio S. / Ariztegui, Daniel

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60 years of glaciolacustrine sedimentation in Steinsee (Sustenpass, Switzerland) compared with historic events and instrumental meteorological data

ALEX BLASS [1,2], FLAVIO S. ANSELMETTI [1] & DANIEL ARIZTEGUI [1,3]

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ABSTRACT

The high-alpine Steinsee (1.930 m a.s.l.) is a proglacial lake located in front of an oscillating icefront since 1924. The existing well-documented glacial and climatic history of the area can be compared with the last 60 years of continuous sedimentation. This lake provides thus a unique opportunity to quantify erosional and depositional processes in proglacial lacustrine settings.

High-resolution seismic profiles (3.5 kHz) pictured the architecture of the glaciolacustrine deposits in a quasi 3-D mode indicating that about 5 m of sediments have been accumulated in the central part of the basin in only 60 years of the lake's existence. A set of vibrocores allowed further quantification and description of the glaciolacustrine sediments. Partially layered deposits of sand and gravel at the bottom of the cores are interpreted as a mixture of allo-moraines and lacustrine sediments that are overlain by a about 0.5 m thick graded unit deposited during a catastrophic lake outburst. The uppermost halves of the cores are characterized by very fine laminae of sand to silty clay. Cs-137 dating of these deposits confirmed the annual character of the laminae that are, therefore, true glacial varves. However, these varves are not simply light-coloured coarse, and dark-coloured fine couplets, as known from other proglacial lakes. They are rather finely-laminated deposits with variable grain size and thickness that can be bundled in an annual package capped by a silty clay layer, deposited during the winter months below the ice.

High sedimentation rates occurred when the glacier tongue directly entered the lake whereas they are comparatively lower when the glacier tongue retreated behind the delta. Strong summer rainfalls deliver large quantities of sediment suspension in the meltwater discharge triggering the formation of density currents in the lake along the delta front. The instrumental data combined with an accurate age model indicate that not every strong precipitation event has triggered the formation of a turbidite. Thus, other additional factors such as sediment availability are playing a critical role in causing turbidite deposits.

ZUSAMMENFASSUNG

Seit 1924 befindet sich der hochalpine proglaziale Steinsee (1.930 m.ü.M.) unmittelbar vor der Zunge des Steingletschers. Die gut dokumentierte klimatische und glaziale Geschichte der Region kann mit 60 Jahren kontinuierlicher Sedimentation im See verglichen werden. Somit ermöglicht diese Untersuchung die Quantifizierung der Erosions- und Sedimentationsprozesse in einem proglazialen, lakustrinen System.

Ein Netz von hochauflösenden seismischen Profilen (3.5 kHz) bildet die glaziolakustrine Sedimentarchitektur in quasi drei Dimensionen ab. Diese Daten weisen darauf hin, dass sich in den 60 Jahren seit der Seeentstehung ca. 5 m Sediment im zentralen Bereich abgelagert haben, die durch eine Serie von Vibrokernen im Detail erfasst werden können. An der Basis der Kerne befinden sich teilweise geschichtete Sedimente mit Sand und Geröll, die als eine Mischung von Allomoränen und lakustrinen Ablagerungen interpretiert werden. Diese werden von einer 0.5 m mächtigen gradierten Schicht überlagert, die während einem katastrophalen Seeausbruch abgelagert wurde. Die jüngsten Einheiten weisen eine feine Lamination auf, die mittels Cs-137 Datierungen als glaziale Varven, also Jahreslagen interpretiert werden können. Jede dieser Jahreslagen besteht aus mehreren dünnen Laminationen mit variabler Korngrösse und Dicke, die von einer dünnen, siltigen Tonlage überdeckt werden, welche im Winter unter dem Eis abgelagert wurde.

In Phasen, während denen der Gletscher direkt in den See mündete, ergibt sich eine hohe Sedimentationsrate. Diese Raten sind tiefer, wenn sich der Gletscher hinter dem Delta befand. Starke Sommerniederschläge liefern grosse Mengen von detritischem Sediment in das Schmelzwasser, was zu Trübeströmungen an der Deltafront führt. Die Kombination von instrumentellen meteorologischen Daten mit einem genauen Altersmodell weist darauf hin, dass nicht jeder Starkniederschlag auch einen Trübestrom verursacht. Demzufolge spielen für die Bildung der Turbidite auch andere Faktoren wie Sedimentverfügbarkeit eine wichtige Rolle.

1.- Introduction

Long- and short-term responses of glaciers to presumed globally concurrent climatic changes can be inferred by using glacial varves (annually-laminated sediments) from proglacial lakes. As early as 1912, Gerard De Geer first described in Sweden glaciolacustrine laminated sediments deposited

[1] Geological Institute ETH Zürich, Sonneggstrasse 5, 8092 Zürich, Switzerland
[2] Present address: Sonnenbergstrasse 45, 8032 Zürich, Switzerland
[3] Present address: Institute F. A. Forel & Dept. of Geology and Paleontology, University of Geneva, Switzerland, 10, route de Suisse, 1290 Versoix
Corresponding author: alexblass@bluewin.ch

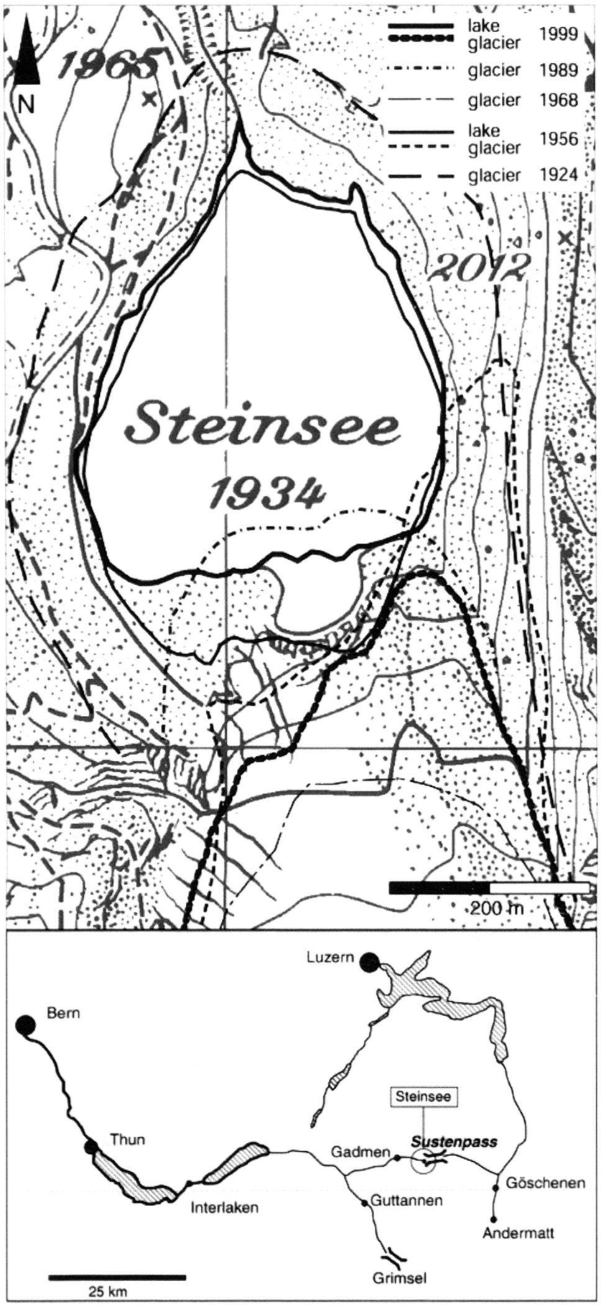

Fig. 1. Topographic map of Steinsee (from LK 1:25'000). The outlines of the lakeand the glacier at five different stages are indicated. The inserted map shows an overview of Central Switzerland with the location of the study area.

seasonally and coined the term varves that comes from the Swedish word varv which means a circle (De Geer 1912). He identified two components in a one year cycle and called each couple varves setting up one of the most accurate methods to both reconstruct and date glacier variations. This concept was further applied world-wide to other sequences providing unique paleoenvironmental archives in the same fashion as ice core records. More recently, however, several studies have shown that proglacial laminated sediments can have a different structure and more variable patterns than the ones originally described in Swedish glaciolacustrine sequences (e.g. Sturm 1979, Lambert & Hsü 1979, Karlén 1981, Leemann & Niessen 1994a and 1994b, Ohlendorf et al. 1997). This called for caution in the interpretation of old varved sequences and pointed towards the urgent need to develop more actualistic models of glaciolacustrine sedimentation. Modern lakes provide us with natural laboratories where to study the different processes leading to the formation of varved sediments (e.g. Hsü & Kelts 1985, Hsü & McKenzie 1985). Combined with the often well-documented history of Swiss glacier variations and modern instrumental data, proglacial lake sediments in the Swiss Alps offer a unique opportunity to achieve this task. Here we present the results of our study of Steinsee, a small proglacial lake in the central Alps of Switzerland. We have combined a limnogeological approach including novel geophysical, coring and analytical technologies with an exceptional historical and meteorological data set. This approach allowed us to (1) reconstruct and quantify proglacial deposition, (2) model the pattern of varves formation in the lake, and (3) compare this sedimentological model with both instrumental temperature and precipitation data for the last 60 years.

Steinsee is located in the Sustenpass area in the Central Alps of Switzerland at an altitude of 1.930 m a.s.l. (Fig. 1). The lake is located in the polymetamorphic "Erstfelder"-gneiss-zone of the internal alpine massifs (Aar-massif) consisting mainly of biotite-plagioklase-gneiss (Labhart 1977). The basin is almost circular in shape with a diameter of about 500 m, a surface area of 0.109 km2, and a maximum depth of 20 m. The catchment area amounts to 8.5 km2 and reaches an altitude of up to 3.600 m a.s.l. About 70 % of it is currently covered by glacier ice (Fig. 2a).

2.- History of the lake

The proximity to a main alpine road (Sustenpass) and some touristic infrastructure (Hotel Steingletscher) provided a well-documented history of the lake. The position of the glacier-tongue has been measured since 1894. The first photography of the glacier dates from 1870 (King 1974) and a series of subsequent photographs document the evolution of the Stein Glacier throughout the last 130 years (Fig. 2).

Around 1920 the Stein Glacier completely covered the present position of the lake (Fig. 2b). In 1924 the glacier began to retreat. Subsequently the glacier's surface strongly decreased until the terminal moraine started to dam the meltwater masses (Fig. 2c). The eastern debris-covered part of the ice tongue melted much slower than the western part and,

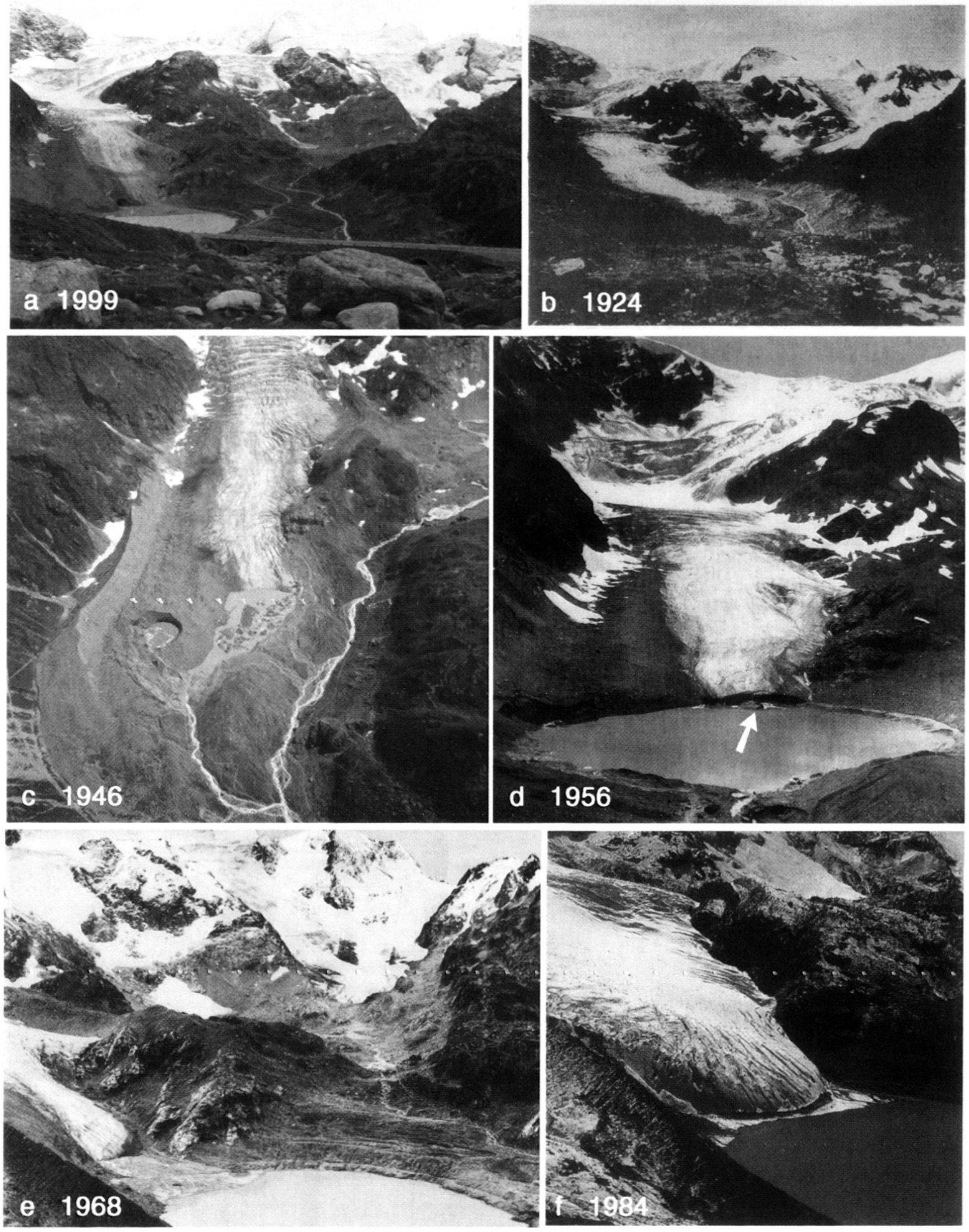

Fig. 2. Photographs of Steinsee and Stein Glacier documenting the evolution as a function of time: a) and b) are both taken from an identical viewpoint. a) 1999; b) 1924 - The glacier still occupies the future Steinsee basin; c) 1946 - Aerial view showing the initial state of the Steinsee with the glacier prevailing in the eastern part and the new and old drainage systems; d) 1956 - Photo of the lake taken shortly after the lake outburst, which lowered the lake level by 5.5 m and which exposed the deposits of the delta (indicated by arrow); e) 1968 - The glacier receded to its shortest length since 1924; f) 1984 - The glacier advanced again and covered the entire delta plain.

therefore, the initial lake was located in the western part of today's basin and drained towards the north-west. This drainage pattern formed erosional channels that are still visible today. The consolidation of the northern morainic rampart resulted in the change of the lake's drainage from the north-western shore to the north between 1941 – 1945 (King 1974). This change caused a gradual lake-level drop from 1.942 m a.s.l in 1940 to 1.939 m a.s.l. in 1950. However the water-depth increased simultaneously by 1.5 m per year, due to subaquatic ablation of the ice underlying the young lake floor. During this period the width of the lake was increased by a remarkable rate of 15-25 m per year to the east, whereas the length (north-south axis) increased much slower (Haefeli & Müller 1957). This initial phase of the lake was accompanied by a continuous recession of the glacier. In 1955 the calving ice margin ended still in the lake just on the very southern part of the tongue-basin. The subaerial ice front stepped back faster than the subaquatic and thus protected part of the glacier. The main stream of the glacial meltwater entered the lake about 4 m below the lake-surface. Accumulation of sediment load underwater formed a subaquatic delta with sediments overlying the ice-masses (Haefeli & Müller 1957). In the night of July 29 1956, a catastrophic lake-outburst happened. The late thaw combined with heavy thunderstorms and constructional work at the lake-outlet, led to the collapse of the terminal moraine at the outflow. Within a few hours the lake level dropped by 5.5 m (Haefeli 1962) so that the subaquatic delta became subaerially exposed as indicated by the arrow in Fig. 2d. The higher flow regime of the now subaerial glacier-stream flushed part of the deltaic sediments into the lake (Haefeli & Müller 1957) so that the water ran directly over the ice. At the outflow the freshly eroded incision revealed dead ice lenses. After this incident the Power Company "Kraftwerke Oberhasli" (KWO) launched a survey-program. The survey report of Haefeli (1961) recommended some structural measures at the lake outlet to prevent another potential collapse of the dam and further damages in the valley. There is no doubt that there was still stagnant ice underlying the lake bottom during that time, at least in the delta-proximal eastern part of the basin (Haefeli & Müller 1957).

The Stein Glacier kept retreating until it reached its minimal length in 1968 (Fig. 2e). Since the catastrophic outburst, the shape of the lake continued to change. In about 40 years since 1956 the delta, however, prograded about 75 m northward while the width did nearly not change (Fig. 1). This progradation was mainly due to the short advancing period of the glacier from 1969 to 1989 (Fig. 2f).

After heavy thunderstorms on the 23 of August 1998, a second lake outburst took place. This event lowered the lake-level by additional 2 m (Wegmann, pers. comm.). Today the lake level is positioned at 1.930 m a.s.l. and the tongue of the glacier lies approximately 100 m behind the delta shore.

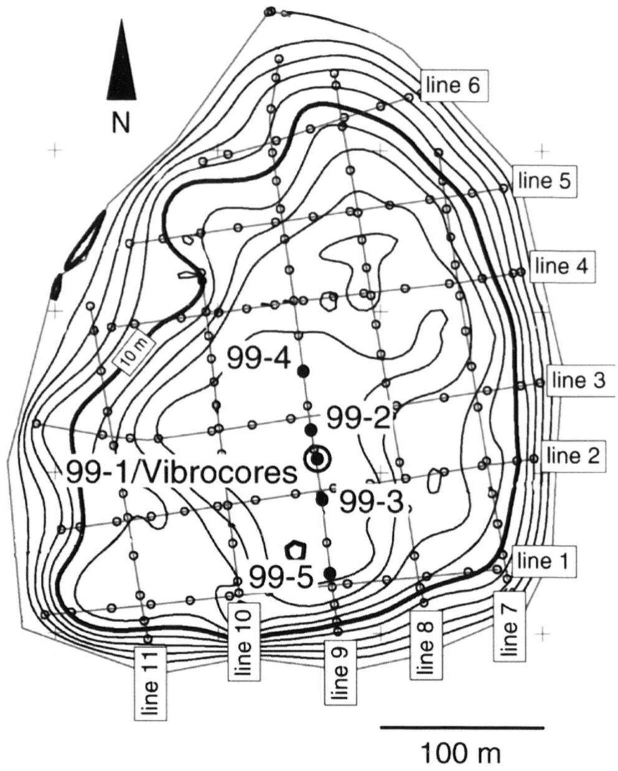

Fig. 3. Bathymetrical map showing the seismic transects (every 100th shotpoint marked by open circles) and coring locations of short core transect (solid small circles) and vibrocores (open large circle). Contour interval is 2 m.

3.- Methods

A high-resolution, single channel seismic survey with a 3.5 kHz pinger system was undertaken in July 1999 from an inflatable boat. A dense grid of eleven seismic lines allows to compile a quasi-3D architecture of the sedimentary basin-fill. Precise positioning of the boat was achieved with a laser-based survey system using a reflector located on the boat that was tracked from a base station on shore. Shot interval was 250 milliseconds (ms). Seismic data were digitally recorded in SEG-Y format, then processed and interpreted in the Limnogeology Laboratory of the ETH by the SPW and Kingdom-Suite software, respectively. Constant shallow noise, caused by the own vibrations of the pinger, were digitally subtracted from the signal. A bandpass filter (1400-6500 Hz) and an automatic gain control with window length of 50 ms were applied. Based on the seismic data five gravity cores were first taken along an inflow-to-outflow-transect. Sediment composition and strong consolidation prevented recovering of sufficiently long cores so that the maximum core length obtained was only about 40 cm. To retrieve a longer, complete sedimentary section a pneumatic vibrocoring system was flown by helicopter onto the frozen lake surface in April 2000. Three cores with a maximum length of 2.8 m were obtained from a location within the central part of the lake basin. Prior to splitting the cores were petrophysically scanned using a Multi Sensor Core Logger (MSCL; Geotek Ltd.) to measure p-wave-velocity, density and magnetic susceptibility at a sample interval of 0.5 cm. Split cores were photographed, sedimentologically described, and sampled for further analyses. Thin sections and smear slides were prepared using standard procedures. Cesium (Cs) 137 analysis (e.g. Erten et al. 1985) of core Stein004 were performed at a resolution of 4 cm at the EAWAG in Dübendorf.

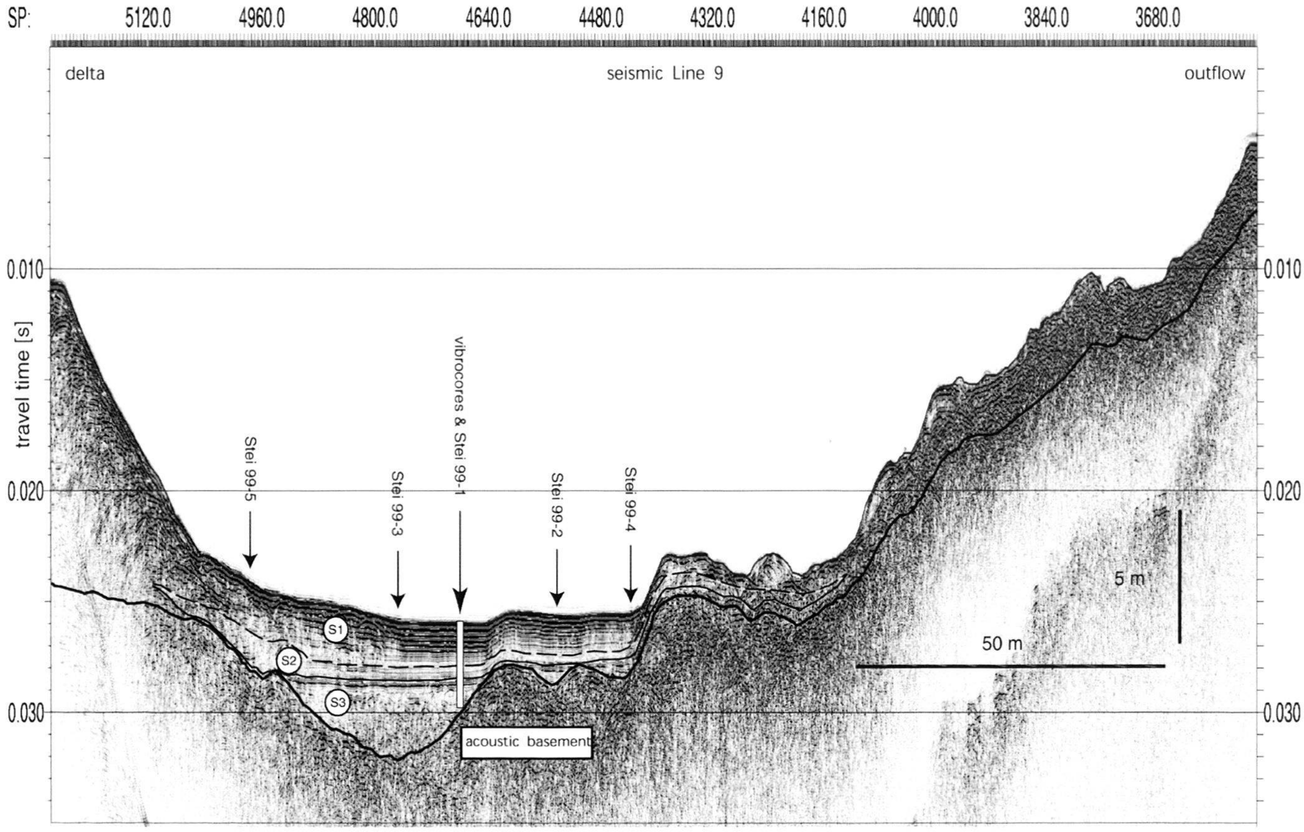

Fig. 4. 3,5 kHz seismic line 9 imaging the subsurface on an inflow (left) to outflow (right) transect. Three seismic units can be discerned, based on their seismic facies and their geometric pattern (S1, S2 and S3). Core locations are indicated by vertical arrows. Note vertical exaggeration.

Grain size spectra from 1.2 µm to 600 µm were measured with a Malvern Mastersizer at the EMPA in Dübendorf.

4.- Results and Discussion of seismic data and core analysis

Seismic Stratigraphy

The high-resolution seismic data were used to image the sedimentary basin fill, to establish a seismic stratigraphy, and further to quantify the sediment volumes of each seismic unit. In addition the data were also used to determine the best coring localities and to map the current bathymetry (Fig. 3). P-wave velocities obtained from the cores vary between 1500 and 1700 m/s, so that one millisecond (ms) two-way travel time (twt) represents approximately 0.75-0.85 m in the sandy to silty material. The seismic signal easily penetrated the regularly bedded lacustrine sediments but became scattered and absorbed at the acoustic basement, most likely ancient supraglacial debris or lodgment till, indicating a maximum thickness of lacustrine sediments of more than 5 m. Three seismic units (S1-S3) can be distinguished that overlie the acoustic basement as shown in Fig. 4. The topography of the acoustic basement is characterised by an undulated morphology with the deepest basin in the south and with steep edges on the lake sides (Fig. 5a).

The lowermost seismic unit S3 is seismically partially transparent, in particular in the upper half, while it becomes more massive to chaotic in the lower part. This lowermost imaged unit is up to 5 ms twt thick, which equals approximately 4 m. S3 infills the deepest depressions of the acoustic basement. A high-amplitude reflection occurs between S2 and S3 (Fig. 4).

The overlying unit S2 appears seismically almost transparent indicating low or gradual lithological variability (Fig. 4). Unlike unit S3, S2 is characterized by a draping geometry and is deposited also in lake marginal areas. The maximum thickness of this unit is approximately 1 ms twt or 0.8 m. In the lake-marginal areas, S2 overlies directly the acoustic basement, whereas is deposited on top of S3 towards

Tab. 1. Total volumes of seismic sequences and water fill with error estimates. The volumes were calculated by interpolations between seismic sections and by converting seismic two way travel times to meters using MSCL velocities.

Lake data		Confidence
lake level in august 1999	1930.5 m a.s.l.	+/- 0.3 m
lake surface area	109 000 m^2	+/- 1%
water volume	1 255 000 m^3	+/- 1%
Sediment volumes		
total sediment volume (S1+S2+S3)	200 000 m^3	+/- 10%
seismic unit S1	23 000 m^3	+/- 20%
seismic unit S2	8 000 m^3	+/- 20%
seismic unit S3	169 000 m^3	+/- 20%

the center of the lake.

The youngest and uppermost seismic unit S1 is laterally rather continuous. The almost horizontal reflections indicate a well bedded lithology. S1 is focused mostly over the central area of the basin, where it reaches a maximum thickness of approx. 2 ms twt or 1.5 m. Reflections within S1 mostly mimic the underlying topography and drape thus any relief created by the previously deposited sequences. S1 also comprises the steeply dipping foresets of the delta, which are hardly penetrated by the acoustic signal.

Volume Calculations

The dense grid of the seismic survey allows an interpolation of the seismic horizons in between the lines and an extrapolation to the lake margin. All horizons and related seismic units are picked over the entire extent of the lake, with higher confidence in the central areas. The marginal areas have a rather chaotic structure caused by higher slope inclinations (non-vertical paths of the recorded signal), the shallower water depth, and strong impedance contrasts, so that some uncertainties exist for calculations of sediment volumes. In particular the prograding, steeply dipping delta formation, part of S1, could only be considered as far as it could be imaged from the boat during the survey. All volumes have been calculated through a 2 by 2 m grid and by converting twt into meters using the mean p-wave velocities of the appropriate sections identified in the MSCL data. Table 1 displays parameters and resulting volumes, as well as approximate error margins. The present water volume is 1'255'000 m^3. The volumes of seismic unit S1, S2 and S3 are 23'000, 8'000 and 169'000 m^3, respectively. The distribution of the total sediment thickness (S1, S2 and S3) is shown in Fig. 5b, which documents the thickest sedimentary succession in the southern basin on top of the basement depression, as indicated on Fig. 5a. This pattern is mostly caused by seismic unit 3, which is characterized by sediment focusing into the deepest part of the lake, whereas units 1 and 2 are more uniformly distributed.

Sedimentology of the cores

A lithological composite section has been assembled using different cores in order to describe the sedimentological evolution (Fig. 6). The correlation between individual cores has been established based on petrophysical and lithological features. All depth indications hereafter refer to the composite depth as shown in Fig. 6 and not to the depth of the individual cores. The first 24 cm of the composite section are taken from short-core Stei99-1, that shows much less disturbance than the upper sections of the vibrocores. From 24 cm to 158 cm, sections 1 and 2 of core Stei00-1 provide the best sedimentary record. From 158 cm to the base of the composite section at 227 cm, section 3 of core Stei00-4 was used. All cores were taken close to the deepest, flat area of the lake (Fig. 3 and Fig. 4). The sedimentary record has been divided into three characteristic lithologic units named I-III.

Lithologic unit I, the youngest deposits, (0-114 cm) consists of a complex alternation of very fine horizontal laminae, which have an average thickness of 0.1 mm, and cm-thick

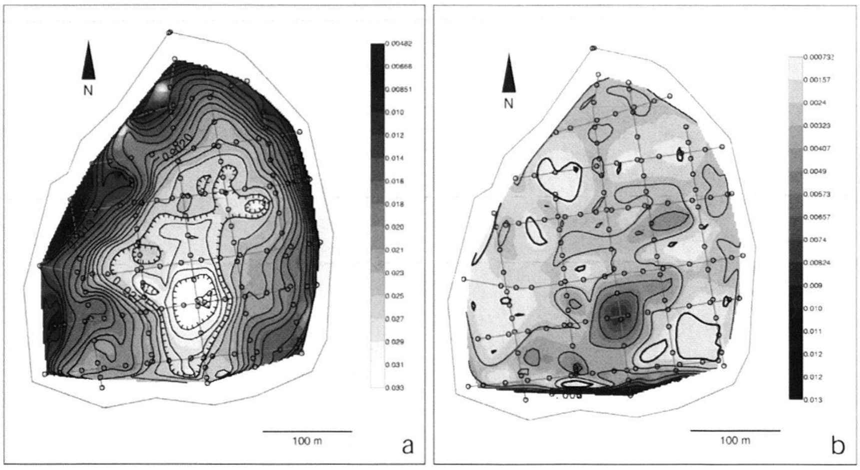

Fig. 5. a) Morphologic map of the acoustic basement in two-way travel time [s], indicating the depression just in front of the modern delta; b) Total thickness of lacustrine sediments in two-way travel time [s].

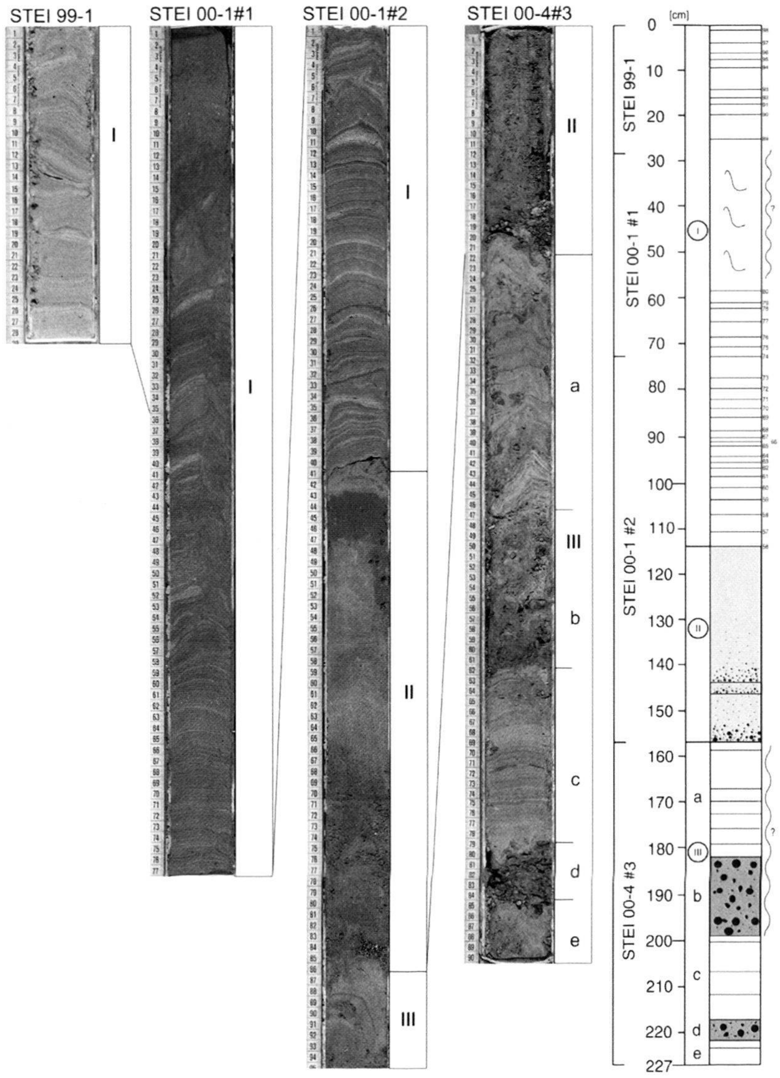

Fig. 6. Left: Composite section of the Steinsee sedimentary record from three different cores retrieved from the central area of the lake. Note the partially high disturbance of the sedimentary layering by the vibrocorer. The top corresponds to short core Stei99-1 whereas the lower sections assemblage parts of two vibrocores Stei00-1 and 00-4. The three lithologic units and subunits within unit III are indicated at the right side of the core photographs (depth specified in core depth in cm); right: Schematic composite section with lithologic units and subunits (depth specified in composite depth in cm). The age model of the varved section is indicated by the two-digit numbers (= years) at right side

graded layers (Fig 6, Fig 7). These graded layers typically consist of very fine sand at the bottom gradually changing into clayey silt at the top. Results from grain size analysis show that for a typical graded layer grain size ranges from 100 µm, sometimes 200 µm, to about 1 µm with a median of approximately 10 µm. However, some layers show no gradation. The layers with the finest grain size (median 2-5 µm) stand out prominently by their dark, olive green color. These clay-sized lithologies are usually 0.1-2 mm thick and easily identified in the thin sections (Fig. 7), but are more difficult to be recognised on the slabbed core surface. The boundary to the overlying coarser layer is always sharp. The spacing between these individual dark olive layers ranges between 1 and 5 cm.

Lithologic unit II (114 – 158 cm) is composed of three fining upward cycles. The uppermost one is with 34 cm the thickest cycle. Grain-sizes of this cycle range from coarse-sand at the bottom to silty clay at the top. The lower 10 cm of unit II comprise two cycles that are thinner and coarser-grained. The central cycle is characterised by a grain-size from coarse sand to silt. The lowermost cycle contains gravel-rich coarse sand at the bottom which gradually changes to silt at the top.

Lithologic unit III, the oldest recovered sediments, consists of fine sandy to silty layers alternating with very poorly sorted coarse-grained deposits. It can be subdivided into five subunits a) to e), which can be distinguished by their grain size distribution. Subunit IIIa (158 - 182 cm) consists of thin laminae of very fine sand to silty clay fraction. These laminae range in thickness from 0.2 to 3 mm, are often graded and sometimes intercalated with coarse-sand to gravel-sized grains embedded in a distinctly finer-grained matrix. The finest-grained laminae have grain sizes from silt to clay. Subunit IIIb

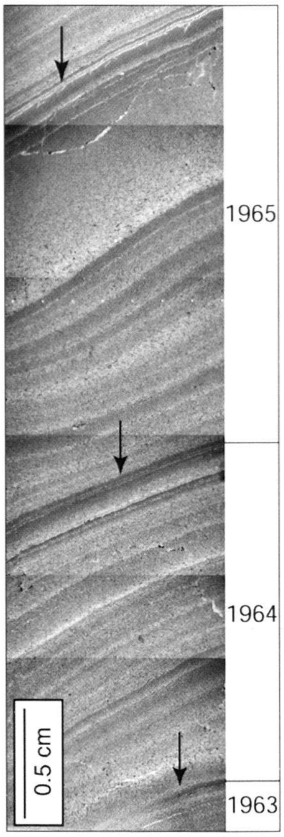

Fig. 7. Composite thin-section of a part of lithologic unit I covering the period from late 1963 to early 1966. Arrows mark the distinctive olive-greenish coloured fine grained layers, which are interpreted as winter layers. A series of graded thin laminae are bundled into one annual layer (varve).

(182 - 199 cm) consists of poorly sorted material with a grain-size spectra consisting of 15% gravel (up to 2 cm), 35% coarse sand and 50% silt and clay. Poor layering is sporadically visible. Subunits IIIc (199 - 217 cm) and IIIe (222 - 227 cm) are similar to subunit IIIa but are better sorted (no gravel), less disturbed, and slightly coarser grained. Subunit IIId (217 - 222 cm) has an unsorted, unstratified and matrix-poor texture with 35% gravel (up to 2 cm), 40% coarse sand, 20 % medium to fine sand, and 5% silt and clay. There is a fine grained drape on top of this subunit.

Petrophysical data and seismic-to-core correlation

The multisensor core logger (MSCL) data of the two major vibrocores Stei00-4 and Stei00-1 correlate nicely with the lithologic units discussed above (Fig. 8). The finely stratified lithologic unit I coincides in the MSCL data with high-frequency and medium amplitude changes in density and p-wave velocity. The graded intervals representing unit II can be recognized in the MSCL data by a distinct pattern with gradually upward decreasing density and p-wave velocity values without high-frequency changes dominated by the thickest upper cycle (Fig. 8). The highly heterogeneous lithology of unit III is recognized in the density and velocity curves by a scattering signal with high-amplitude changes. This excellent match between lithologic units and petrophysical signature suggests clearly that the three seismic units S1, S2 and S3 (Fig. 4) can be correlated to the three lithologic units I - III (Fig. 6, Fig. 8) using the physical property data. Lithologic unit I is characterized on the density log by cm-scaled high amplitude variations, which are too thin to be resolved by the 3.5 kHz signal. The series of distinctly subparallel reflections of S1 are thus caused by interference from the finely laminated, laterally continuous layering of lithologic unit I. The gradual change of acoustic properties and thus the lack of small scale impedance contrast of the deposits in lithologic unit II, related to the thick upper coarsening upward cycle, produce the transparent seismic facies in S2. The coarse base of lithologic unit II displays clearly the highest Vp and density values (Fig. 8) and in fact coincides with the high-amplitude reflection at the S2-S3 boundary. Finally, the complex petrophysical signature originating from the very heterogeneous deposits in lithologic unit III corresponds to the rather chaotic seismic facies of S3.

5.- Dating and age model

The ^{137}Cs method was used to determine the sedimentation rates and to validate the annual character of the laminations in lithological unit I. Global ^{137}Cs emission to the atmosphere was first intensified in 1963 as a consequence of nuclear testing programs (Eidg. Kommission zur Überwachung der Radioaktivität 1982) and 20 years later in Europe as an effect of the nuclear power plant accident in Tschernobyl on April 26th, 1986. According to several studies in Swiss alpine and perialpine lakes (such as Erten et al. 1985), these two major peaks in ^{137}Cs can be expected in Steinsee as well. ^{137}Cs is mainly transferred by rain into the lakes and is preferentially adsorbed by micaceous components of the sediments (De Preter 1990, Desloges 1994). The mica-poor, relatively coarse sediments of Steinsee have, consequently, a very low affinity to adsorbe Cesium. The ^{137}Cs profile from the longest core (core Stei00-4) shows only one main peak with a maximum of 89 Bq kg-1 at a depth of 0.94 m (Fig. 9). Considering the sedimentation rate this peak can only represent the 1963 maximum and not the 1986 event. The missing 1986 peak is likely located in a poorly preserved section of the measured core, where vibrocoring probably mobilized part of the sediment.

Each winter, the surface of the lake is totally frozen so generally no sediment enters from the glacier stream and the

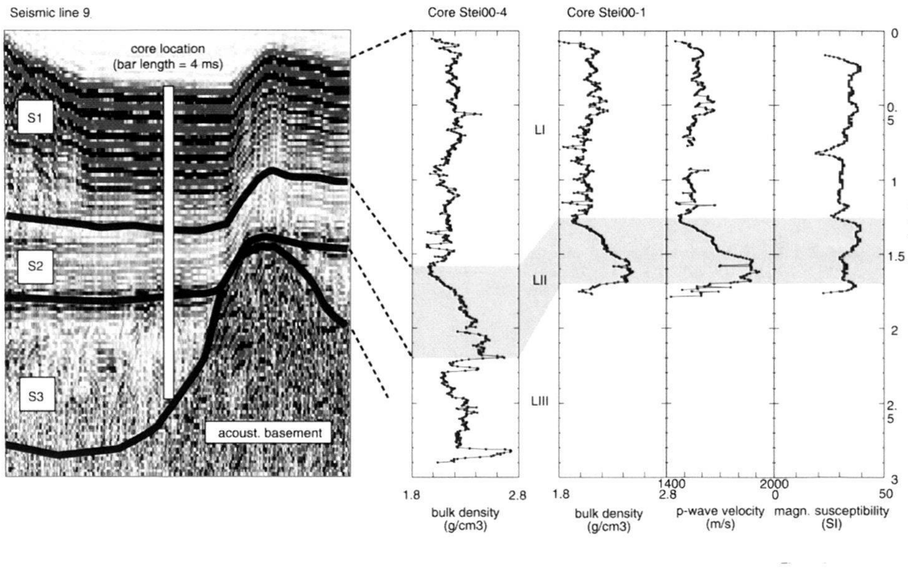

Fig. 8. Correlation of the seismic record with petrophysical data and lithologic units of cores Stei00-4 and Stei00-1. Bulk density, p-wave velocity and magnetic susceptibility data for core Steil00-1 are shown at right. Core Stei00-4 (center) was cored in an aluminum liner, so that no magnetic and Vp data could be logged. The lithologic units I to III are indicated in grey shading overlying the petrophysical data. The dashed lines are the correlation to the seismic Line 9, on which the cores are positioned (left). Assuming a velocity of 1600 m/s, the core mark on the seismic section of 4 ms length equivalents 3.2 m, or roughly the penetrated depth of core Stei00-4. Seismic units S1 – S3 coincide well with lithological units I - III. A characteristic seismic facies reflects the density pattern of each unit.

existing suspension of the water column is settling down during the first winter months. By interpreting the clayey distinctive dark olive-greenish coloured laminae as winter-deposits (Fig. 7), an annual sedimentation pattern can be identified and varves can be counted. Having identified the year 1963 the Cesium data (Fig. 9), and using the modern lake floor as marker for 1999, an annual age model can be established (Fig. 6). The uppermost part of core Stei00-1 section 1 is, however, strongly deformed so that the interval between 25 and 58 cm (Fig. 6) could not be interpreted on an annual scale corresponding to the time interval between 1982-1989.

Historical data further confirm this age model. According to Haefeli & Müller (1957) the catastrophic outburst in July 1956 resulted in a 5.5 m sudden drop of lake level and caused a massive sediment influx into the lake originating mostly from the delta area. Combining the 137 Cs data with varve counting, the graded and coarse lithologic unit II is placed in the year 1956 and is in fact the sedimentary result of this catastrophic lake level drop. There is no lithologic evidence, however, recording the smaller outburst in 1998.

Lithological unit III was deposited prior to 1956 and the record of the composite section probably dates back to 1948 (Fig. 2c). Unfortunately the sediments in subunits IIIa and IIIb are quite disturbed because the large content of sandy material became easily liquefied during vibrocoring. A precise counting of the varves was thus not possible for this lower part of the section.

6.- Comparing the sedimentary record with instrumental meteorological data and glacial activity

Five meteorological stations have been used to calibrate the sedimentary record with instrumental meteorological data and glacial activity (Fig. 1). The varve thickness representing the years 1957 through 1997 (without the uninterpreted years 1982-89) were compared with climatological data from the Grimsel, Guttannen, Andermatt, Göschenen and Gadmen stations (SMA 1956-1998a, Fig. 10). Assuming that the winter-month-precipitation (mostly snowfall) is not of further interest, the climatological parameters used in this study are mean annual precipitation and mean air-temperature from May until October and the number of strong rainfall events exceeding a certain threshold value (yearly return-period). Precipitation-data includes rainfall and the water equivalent of snowfall as determined by the Swiss Meteorological Institute (SMA 1956-1998b).

Varve thickness (Fig. 10a) exhibits a moderate correlation with annual summer precipitation measured on Grimsel (Fig. 10b), with an r^2=0.35, and Guttannen (r^2=0.35). Data from Andermatt, Göschenen and Gadmen (Fig. 1) indicate less of a correlation with r^2 values of 0.11, 0.07, and 0.2, respectively. Least square regressions of varve thickness to the number of strong rainfalls events of Andermatt, Göschenen, Guttannen, Gadmen and Grimsel yield r^2 values of 0.001, 0.05, 0.06, 0.13 and 0.26. The Grimsel record (distance to Steinsee = 22 km) shows, however, the best correlation, probably because of its equal elevation (Fig. 10). Microclimatic influences and small scale variations, e.g. local thunderstorms are a common feature in this extreme topographic area and are thus inevitably not considered. In addition, the daily sum of a long lasting moderate rainfall (without special significance to the sediment supply of the lake) could be higher than a heavy thunderstorm lasting few minutes with a resulting high sediment input. Prob-

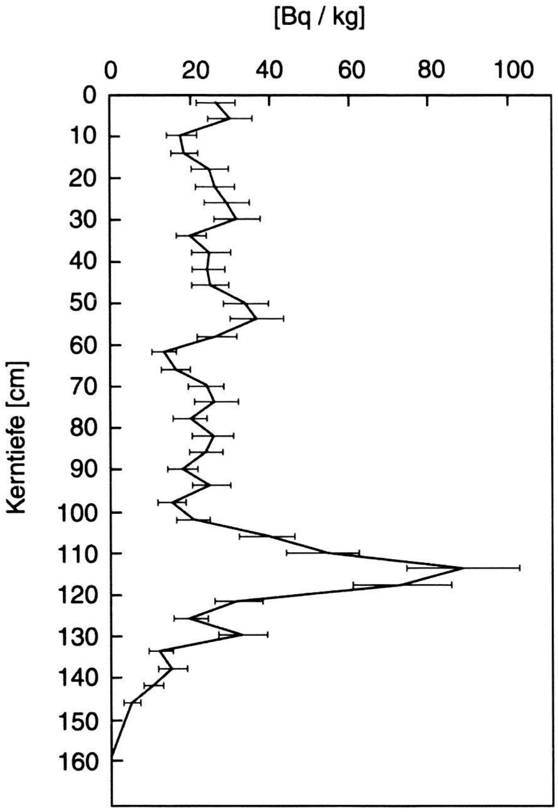

Fig. 9. Cesium 137 analysis for Core Stei00-4: Only one major peak is evident instead of expected two maxima. In consideration of the sedimentation rate and the presence of winter layers with finest grain size, this peak can only represent the 1963-maximum due to enhanced Global 137 Cs emission to the atmosphere in 1963. The samples are measured at a resolution of 4 cm, the depth is indicated in core depth of Stei00-4 and the radiation in Bq/kg.

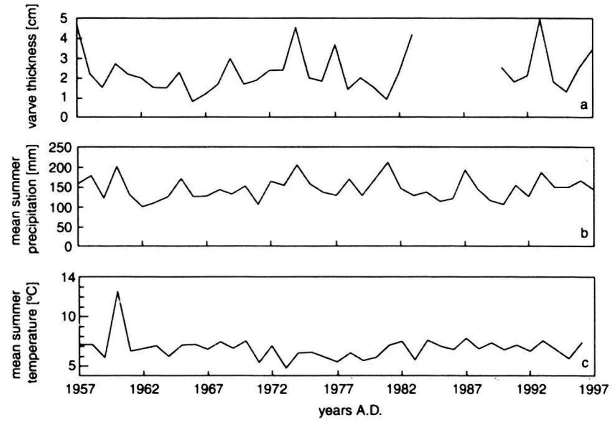

Fig. 10. Correlation of varve thickness (a), mean summer precipitation (b) and mean summer temperatures (c) in the interval from 1957 until 1997. The climatic record was measured at the Grimsel meteorological station. Note the moderate correlation between varve thickness and precipitation (r2=0.35), and the lack of correlation between varve thickness and mean temperature (r2=0.05).

ably therefore, the varve thickness record shows no correlation with the yearly number of strong rainfall events at the closest station in Gadmen.

These results show that the annual sediment accumulation rate is partially controlled by the amount of rainfall during summertime. In fact it has been several times observed by the first author and mentioned in Schlüchter (1989) that precipitation enhanced suspension load in the Stein Glacier stream are causing steady turbidity currents (Fig. 11). About 70 % of the prominent coarser graded layers between 1956 and 1973 may be related to strong rainfall events (Fig.12). However, not every strong rainfall corresponds to a sandy layer, even if several stations recorded exceptional rain fall (i.e. not only a local phenomenon). Some of them might be precipitate as snowfall events such as Oct. 8th, 1964 and May 6th, 1968.
The moderate correlation of rainfall data and varve thickness (Fig. 10) may also be explained by the fact that the relationship of precipitation, resulting runoff and thus enhanced sediment load of the stream is rather complex. E.g. sediment influx can suddenly increase with no apparent variation in discharge of the glacier stream (Østrem 1975, Gurnell & Warburton 1990). Such pulses are interpreted as instabilities in the subglacial and proglacial drainage network, injecting large quantities of suspended sediment into the meltwater. Varve-thickness thus can not simply be compared with the number of strong rainfall events because the climatic signal is superimposed on the effect of sediment availability.

Not all proglacial lake systems are controlled by rainfall. Østrem (1975) showed that the glacial runoff from a Norwegian glacier is not a function of rainfall but of summer air temperature controlling ablation rate of the ice. Analogously, varve thickness of Lake Oeschinen and Lake Silvaplana in Switzerland is rather driven by mean summer air temperature as shown by Leemann (1993) and Ohlendorf et al. (1997), respectively. Examples above are from much larger lakes than Steinsee and, therefore, not dominated by delta-proximal deposits (i.e. turbidites). The varves in those comparatively larger lakes are different and formed by simple light/coarse and dark/fine couplets. In contrast, varve thickness versus mean summer air temperatures regression on Steinsee data (Fig. 10c) determined at the Grimsel station between 1957 to 1997 displays hardly any correlation (r^2=0.05).

Varve thickness exhibits a positive correlation with the position of the glacier from 1957 until 1967 (r^2=0.7) when the glacier has been receding rapidly (Fig. 13). In 1956 the ice masses were still entering the lake and, therefore, the system was characterised by a very proximal sediment source. During the retreat of the glacier, the sediment supply decreased ac-

Fig. 11. View from the glacier tongue over the delta plain to the lake during a strong summer rainfall in the year 2000. Note the enhanced steady turbidity current that enters the lake as light-coloured turbid water, before it descends into the deepest lake area by underflow.

cordingly. In the years after 1968 no correlation was found between ice extent or the yearly length change and the varve thickness. Due to the lack of age control in the period between 1982 and 1989, the 1989-advance period could not be considered for this correlation, but average sedimentation rate over this period indicates that there was no significant increase in theedimentation rate. Similar observations have been reported by Desloges (1994) and Leonard (1986). High sedimentation rates in a time interval of one to a few decades occur either during and immediately following periods of moraine deposition (i.e. maximum ice-stands) or during periods of rapid ice recession.

7.- Summary and Conclusions

The high-resolution seismic survey of Steinsee combined with targeted sediment cores allowed a 3-D analysis of the entire basin infill. Three distinctive lithological units match reciprocal seismic sequences and represent individual stages of the lake.

Lithological unit III was deposited very close to the glacier front probably after 1947 but before 1956. The intercalation of coarse and very poorly sorted sediments (subunits IIIb, IIId) with comparatively fine-grained and very well sorted intervals (subunits III a, c, e) is very unlikely to be a subglacial sediment. Therefore, we interpret the poorly-sorted, gravel-rich deposits found in the lowermost part of the core as originated from unstable masses of debris (i.e. supraglacial debris and subaquatic meltout till) at the ice margin (Figs. 2c and 2d) transported under water by gravitational processes to the central area of the lake. Thus, these sediments would correspond to a till facies of glaciogenic subaquatic flow (Dreimanis 1979, Gravenor et al. 1984, Schlüchter 1989). The sediment source might have been located either on the eastern ice body that was still present at this time, or on the southern ice margin (Fig. 1). The sections in which coarse-grained material is embedded in a distinctive fine-grained matrix as well as the intervals in which a weak layering is visible (subunit IIIb) would indicate a decreasing influx of gravel material associated with an increasing distance from the ice front (i.e. sediment source). The drastic 5.5 m lake-level drop in July 1956 exposed the previously deposited subaquatic delta that was overlying the frontal ice masses of the glacier. The resulting change in the flow regime eroded and flushed the 1 to 3 m thick sand bar into the basin so that the watermasses of the glacial stream flowed directly over the ice (Haefeli 1962). During that event ca. 8'000 m^3 of sediment were flushed in three pulses from the delta and the slopes into the deepest part of the lake basin depositing the multi graded lithological unit II.

The varved sediments of Steinsee within lithological unit I are finely-laminated with variable grain size and thickness that can be bundled into annual packages, each capped by a clayey winter layer. Thus, they are not simply light/coarse and dark/fine couplets as known from other proglacial lakes. The central part of the lake is still in a relatively proximal position to the delta and affected, therefore, by turbidity currents that cause an annual sequence of mostly graded and very thin laminae. The very fine layers are deposited during the winter months when no further sediment is brought to the lake and the clay fractions in suspension settle down below the ice cover. Glacier ablation is also prevented during these months and precipitation changes from rain- to snowfall. According to Stokes' law, the winter sedimentation probably ends already by Febru-

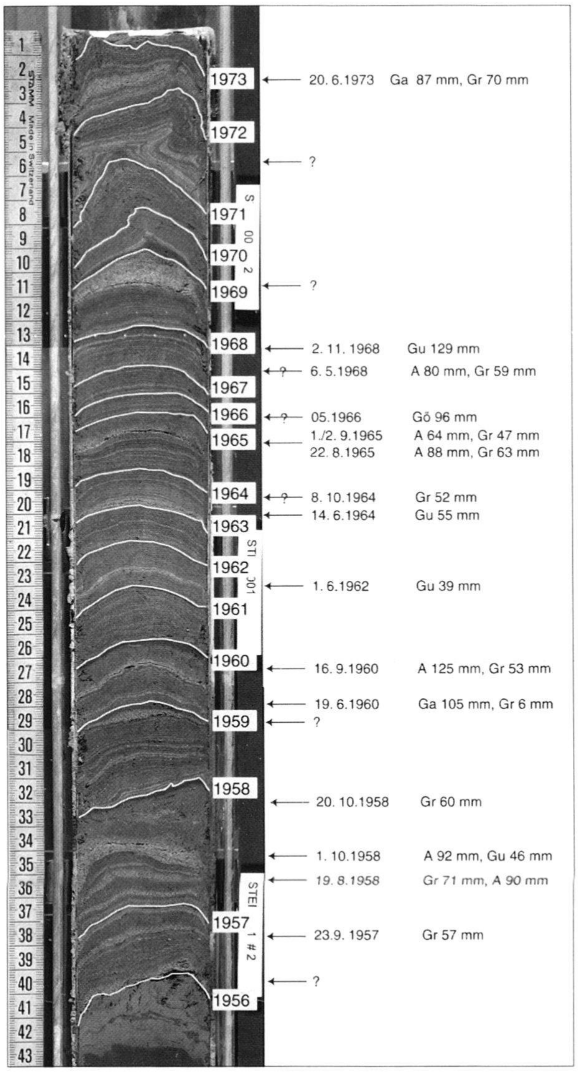

Fig. 12. Tentative correlation of exceptional heavy rainfall events with coarser grained graded layers of the sedimentary record from 1956 until 1973 using the established age model. The daily sum of rainfall is specified in mm at the meteorological stations of Andermatt (A), Guttannen (Gu), Grimsel (Gr), Göschenen (Gö) and Gadmen (Ga). About 70 % of the rainfall events may coincide with the graded layers. This correlation has to be viewed cautiously, since stations are not directly located on the lake and local variability during summer rainstorms is high.

ary and the lake remains frozen for two more months. The thickness of the winterlayer varies from year to year, possibly reflecting the amount of suspended matter that has been transported into the lake during summer and fall.

Our sedimentary results combined with historical and instrumental data indicate that in the case of Steinsee varve thickness is not a function of summer air temperature as previously described for other lakes by several authors (e.g. Leemann 1993, Desloges 1994), but partially controlled by mean

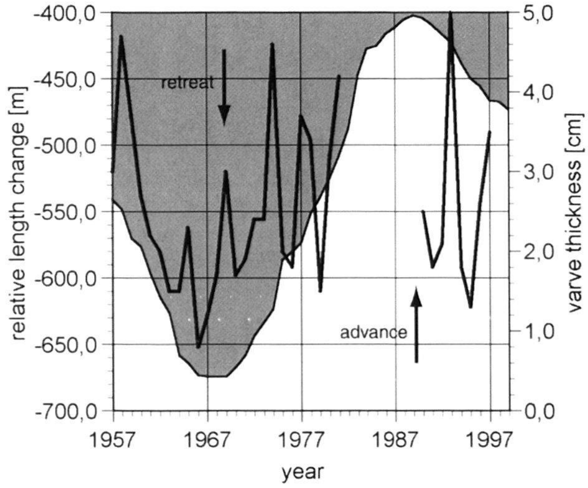

Fig. 13. Correlation between relative length change of the Stein Glacier (left axis, grey-white area) and varve thickness (right axis, thick black line) plotted against the time interval from 1956 until 1999. The glacier-length data are taken from "les variations des glaciers suisses" (1957-2000). The varve thickness is decreasing due to the retreat of the glacier until 1968. Data between 1980 and 1989 are missing due to heavy core disturbance (vibrocoring).

annual summer precipitation instead. It seems, however, that sediment availability combined with increasing instability of the subglacial and proglacial drainage network may play a critical role regulating sediment fluxes to the lake basin and, therefore, varve thickness' and structure. It appears that the last 60 years climatic signal archived in Steinsee sediments is partially masked by sediment availability in the catchment area that is in turn controlled by the position of the ice margin. Hence, the relative distance between the glacier front and the lake basin plays a crucial role leading both structure and pattern of varved sequences in this proglacial lacustrine setting.

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