Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 98 (2005)

Heft: 3

Artikel: The last 1300 years of environmental history recorded in the sediments of Lake Sils (Engadine, Switzerland)

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DOI: https://doi.org/10.5169/seals-169180

0012-9402/05/030319-14
DOI 10.1007/s00015-005-1166-5
Birkhäuser Verlag, Basel, 2005

Eclogae geol. Helv. 98 (2005) 319–332

The last 1300 years of environmental history recorded in the sediments of Lake Sils (Engadine, Switzerland)

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Key words: Proglacial lake, limnogeology, geochemistry, Alps, mega turbidite, eutrophication, 'Little Ice Age' (LIA), climate change, Holocene

ABSTRACT

Proglacial Lake Sils is located in the Upper Engadine (south-eastern Swiss Alps) at 1800 m a.s.l. and is the uppermost of four lakes in the valley. A high-resolution seismic survey combined with geophysical and chemical data of 22 short sediment cores, and ^{137}Cs, ^{210}Pb, and ^{14}C AMS dating provide insight into the sedimentological development of the lake during the last 1300 years. The deposits consist of diffusely laminated clayey silts. In contrast to nearby Lake Silvaplana, no varves could be detected. Sedimentation rates are on average 1.1 mm per year (40 mg cm^{-2}a^{-1}) which is much lower than in the adjacent Engadine lakes. The most prominent sediment feature is a turbidite that was deposited around cal AD 700, has a thickness of up to more than 6 metres and a total estimated volume of 6.5*10^6 m^3, which is more than the total cumulated sediment mass deposited since that time (4.5 * 10^6 m^3).

The sediments deposited after around AD 1880 show higher contents of organic carbon (C_{org}) and biogenic silica (bSi), which suggests enhanced primary production due to increasing tourism in the area and subsequent higher nutrient supply to the lake. Sediments with distinctly lower C_{org} and bSi concentrations, but with larger grain-size medians and higher mica concentrations were accumulated between AD 1500 and 1880. These features are related to a late period of the 'Little Ice Age' when major regional glacier advances occurred.

ZUSAMMENFASSUNG

Der von Gletscherwasser gespiesene Silsersee liegt im Oberengadin in den Schweizer Südost-Alpen auf 1800 m ü. M. und ist der Oberste in der Engadiner Seen-Kette. Aufgrund von hoch auflösenden, seismischen Daten und ungefähr zwei Dutzend Sedimentkernen, datiert anhand von ^{137}Cs, ^{210}Pb und AMS ^{14}C, mit anschliessenden geophysikalischen und geochemischen Analysen, kann hier eine breite Datenbasis präsentiert und die sedimentologische Entwicklung des Sees in den letzten 1300 Jahren aufgezeigt werden. Die Ablagerungen sind diffus laminiert und bestehen hauptsächlich aus tonigem Silt. Varven, wie im benachbarten Silvaplanersee, wurden keine erkannt. Die Sedimentationsrate liegt mit 1.1 mm pro Jahr (40 mg cm^{-2}a^{-1}) ungefähr eine Grössenordnung tiefer als in den anderen Engadiner Seen. Ein bis zu 6 Meter mächtiger Turbidit wurde um AD 700 abgelagert. Das geschätzte Volumen von 6.5*10^6 m^3 liegt wesentlich über dem seither abgelagerten Volumen von 4.5 * 10^6 m^3.

Seit ungefähr AD 1880 wurde in den Sedimenten markant höhere Werte an organischem Kohlenstoff (C_{org}) und biogenem Silizium (bSi) gemessen. Dies wird auf die seit anfangs des letzten Jahrhunderts stark angestiegenen Touristenzahlen zurückgeführt, was ein erhöhtes Angebot an Nährstoffen im See verursacht hat. In der Periode von ca. AD 1500 – 1880 wurden einerseits deutlich tiefere Konzentrationen an bSi und C_{org}, andererseits besser sortierte und gröbere Sedimente festgestellt und zudem erhöhte Glimmer Werte gemessen. Diese Veränderungen werden mit einer späten Phase der 'kleinen Eiszeit' in Verbindung gebracht, wo alle Alpengletscher stark an Grösse zugenommen haben.

Introduction

High mountain lakes have been extensively used as archives for past environmental changes. The Upper Engadine (ca. 1800 m a.s.l.) in the eastern Swiss Alps (Fig. 1) is characterized by a succession of four lakes (Lake Sils, Lake Silvaplana, Lake Champfèr and Lake St. Moritz) that are exposed to the same climatic conditions but exhibit very different sediments (Ariztegui et al. 1996; Leemann & Niessen 1994; Ohlendorf 1998) and, therefore, provide a unique experimental setting for limnogeological, paleoenvironmental and paleoclimatic studies. Lake Sils is the uppermost lake in the valley and thus believed to be least influenced by human activity. Lake Sils is located upstream of Lake Silvaplana, a very important paleoclimatic archive that is varved over large periods of the Holocene (Gobet et al. 2003; Leemann & Niessen 1994; Ohlendorf et al.

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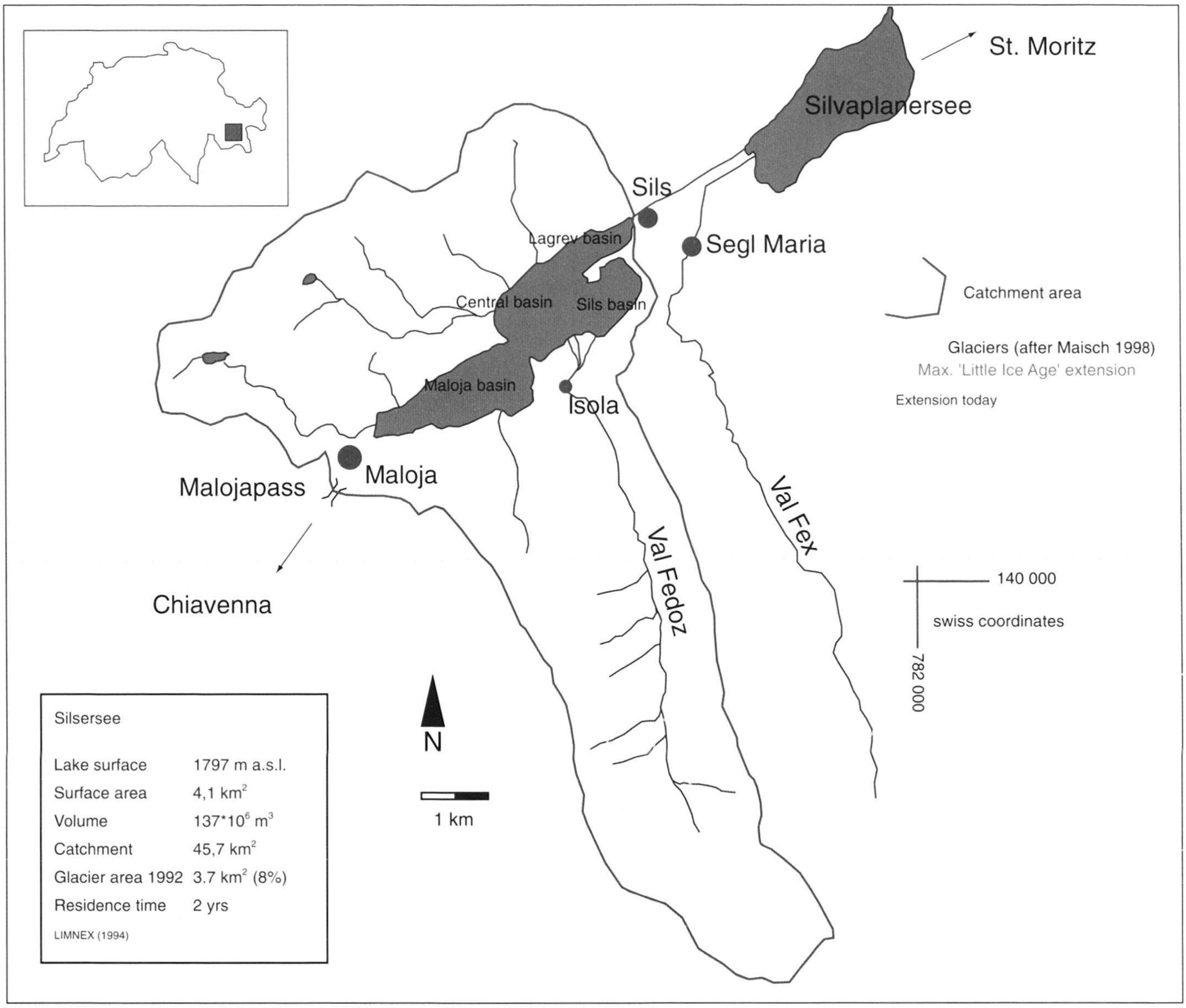


Fig. 1. Overview map of Lake Sils with its catchment area and glacier extensions (1992). Note the indicated names of the different lake basins. The Isola delta and a crag ridge near Sils divide the lake into its different parts.

1997). Furthermore, studies in Lake Silvaplana, Champfèr and St. Moritz pointed out that human activities had a strong impact on the sediments since around AD 1910 (Bigler unpubl. data, Ohlendorf 1998; Bigler unpubl. data, Züllig 1982).

In contrast to these lakes, little is known about Lake Sils. Sediment cores were retrieved in the 1990s (Leemann & Niessen 1994; Ohlendorf 1998), but no detailed analyses were performed. Thus, the goal of our study was to test a) whether the sediments of Lake Sils are annually laminated (varved) as those in adjacent Lake Silvaplana (Leemann & Niessen 1994), b) whether anthropogenic activities of the 20th century are detectible, and c) whether the 'Little Ice Age' (LIA), a period of cool climate with major regional glacier advances from around AD 1280 to 1860 (Holzhauser & Zumbühl 1999), is recorded in the sediments. This latter question is of major interest and an active debate as the LIA could be detected in Lake Silvaplana and in different records from pro- and periglacial lakes located in the Canadian Rockies, Norway and the French Alps (Chapron et al. 2002; Leemann & Niessen 1994; Leonard 1997; Luckman 2000; Moore et al. 2001; Nesje et al. 2001). This is quite surprising for lakes in the Alps, as recent high-resolution monthly multi-proxy temperature reconstructions for the Alpine Arc and Europe, in general, suggest that the temperature anomalies during the LIA were largely a phenomenon of cold winter temperatures while summer temperatures did not experience major departures

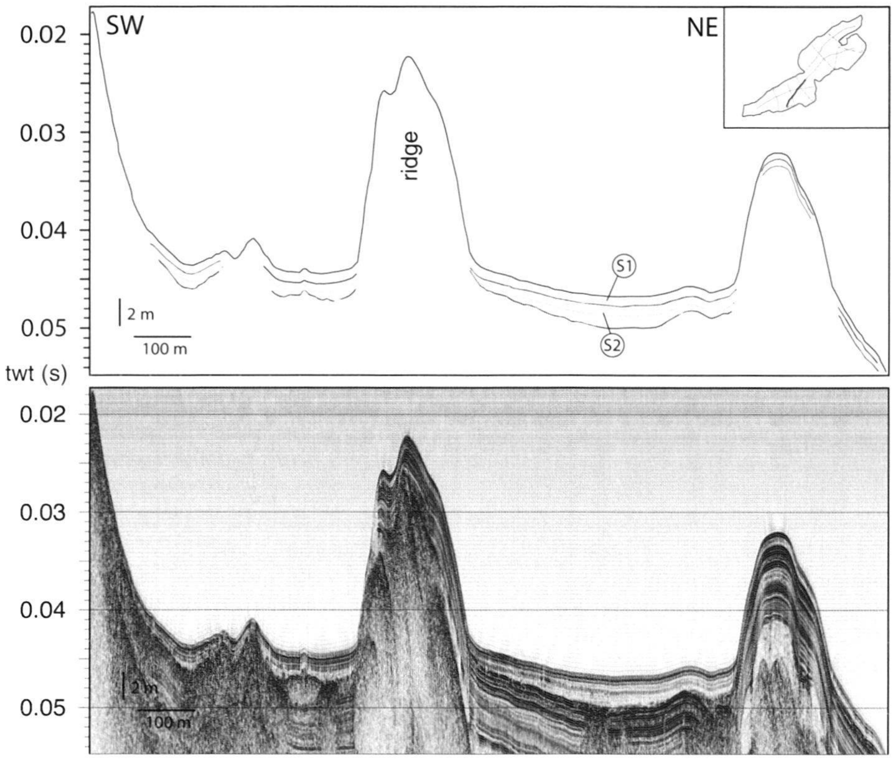


Fig. 2. Part of seismic line 3a in the Maloja basin and its interpretation. The position of the line is shown in the small overview map. Seismic unit S2 is characterized by an almost transparent facies which is typical for uniform sediments or gradual lithological changes such as turbidites. Unit S1 has typically continuous high-amplitude reflections indicating more vertically heterogeneous sediments.

(Casty et al. in press; Luterbacher et al. 2004). At least in Lake Silvaplana and Sils, sediment supply diminishes during late autumn and ice covers the lakes during winter, implying that the sediments 'see' largely the summer season, when temperatures were found to be more stable through the last 500 years. So it remained unclear if and how the 'Little Ice Age' is recorded in the sediments of Lake Sils.

In order to amend the studies of Lake Silvaplana, Champfèr, and St. Moritz and to establish a base for a more detailed future research, a broad range of data will be shown in this study. In the following, we present reflection seismic data, which allowed us to image the sedimentation distribution pattern. The sediment cores, together with the seismic data, allow to obtain accumulation rates throughout the lake. Two reference cores were dated and analysed in detail, in order to get a better understanding of the sedimentary and limnogeologic evolution and the environmental history of the lake and its catchment.

Study area

Lake Sils is located in the Engadine area of the south-eastern Swiss Alps at an altitude of about 1800 m a.s.l. (Fig. 1). It is the uppermost of four lakes in the main valley. Clastic sedimentation is dominant in the upper lakes (Lake Sils, Silvaplana and Champfèr) while chemical and biological processes govern the sedimentation in Lake St. Moritz (Ariztegui et al. 1996). The Fedoz River, the main contributor to Lake Sils, has formed the prominent Isola delta. The outflow discharges into Lake Silvaplana. Lake Sils consists of four different basins (Fig. 1) and is a dimictic lake, which turns usually over in May shortly after the ice break up and in late autumn (LIMNEX 1994). Lake Sils is an oligotrophic system with about 5 to 7 mg l^{-1} O_2 and about 10 µg l^{-1} P_{tot} in the bottom water during the summer stagnation phase. Temperatures of the bottom waters range between 3.5 and 5.5 °C while surface water temperatures range between 0 and 15 °C. Conductivity ranges from 80 to 105 µS cm^{-1} and the water hardness is 3.2 – 3.9 °fr. H. (Bosli-Pavoni 1971). Maximum water depth is 71 meters and the mean residence time is about 2 years (LIMNEX 1994).

The Engadine has a rather continental climate compared with the Swiss Plateau with typically larger diurnal and annual temperature amplitudes and drier conditions. The lowest mean temperatures occur in January (-7.8°C) while the maximum mean temperatures are measured in July (10.8°C). On average, maximum precipitation occurs in August (121 mm) whereas a minimum is observed in February (42 mm). Total precipitation amounts to 978 mm per year (SMA 2002). Most of the moist air comes from the south. Typically, a strong, local valley wind (Maloja wind) from southwest develops on sunny days when airflow at synoptic scales is weak.

The Engadine valley follows a major geologic fault system, the Engadine line. This discontinuity dissects a pile of east dipping Pennine and Austro-Alpine nappes three of which crop

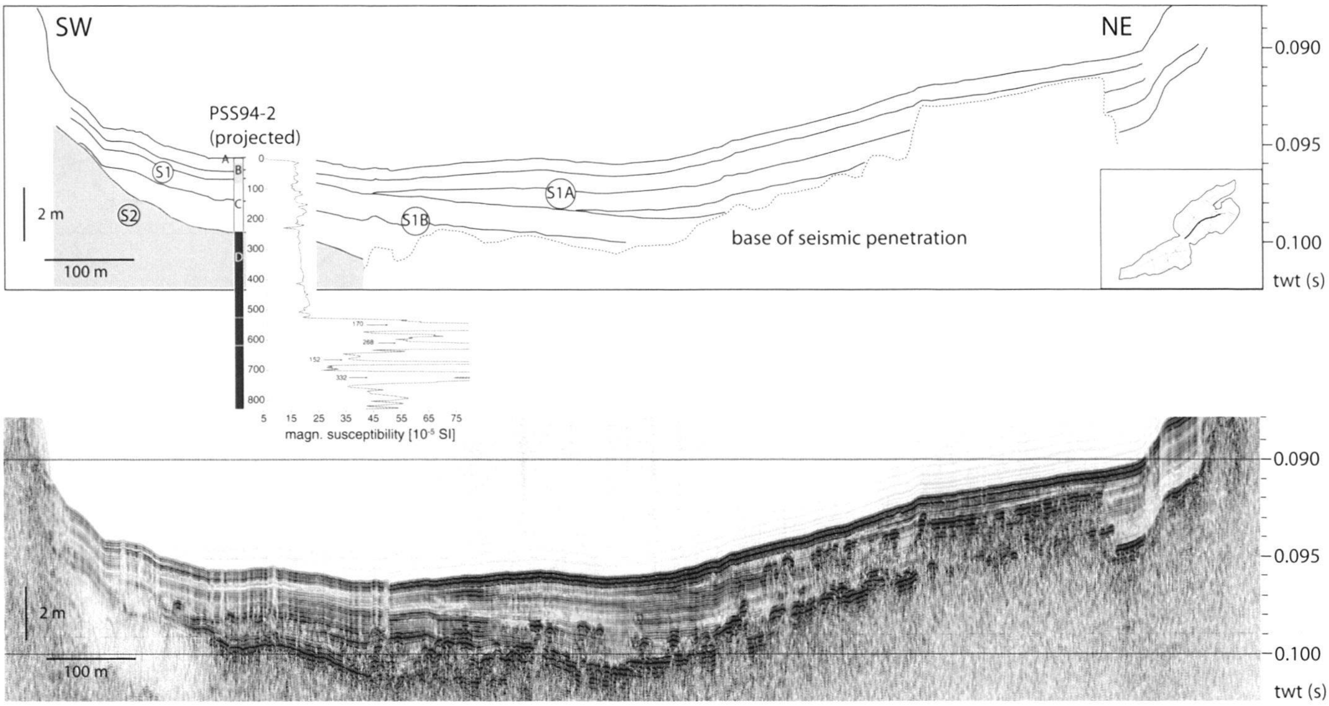


Fig. 3. Part of seismic line 3a in the Central basin and its interpretation with the projected piston core PSS94-2 and magnetic susceptibility data. The transparent seismic facies S2 correlates nicely with unit D (mega turbidite) of the long piston core PSS94-2 whereas the continuous high-amplitude reflections of S1 are represented by unit A–C. Note that the lower strata S1B are inclined to the northeast while the overlying packages (S1A) dip to the southwest, partially downlapping on the lower strata.

out in the catchment. The Pennine Margna-Sella nappe that covers most of the catchment lies south and west of the lake and the Pennine Platta nappe borders to the northeast. The Austro-Alpine Err-Bernina nappe is located northeast of the area (Staub 1946). Rock types include mostly gabbros, amphibolites, gneisses, green-schists and carbonates (Spillmann 1993).

The catchment is characterized by steep slopes to the north and by rather smooth slopes rising up to the Fedoz valley in the south. In 1992, 8 % of the catchment area was glaciated, mostly in the Fedoz valley. Genetically, the lakes developed in depressions where large dead-ice bodies melted in Late Glacial times (Suter 1981). The lakes are separated from each other by Holocene alluvial fans. The largest Holocene glacier advance in the Fedoz valley happened during the 'Little Ice Age' around AD 1850 and ended far behind the Late Glacial ice extensions (Maisch et al. 1999; NFP 31 1998; Vogel 1995).

Fieldwork and Methods

A high-resolution, single-channel seismic survey was carried out on Lake Sils using a 3.5 kHz pinger system with a shot interval of 250 milliseconds. In total, 14 km of seismic profiles were recorded. Precise positioning of the boat was achieved with a GPS. Data were processed and interpreted at the Limnogeology Laboratory of ETH. Constant shallow noise, caused by the own vibration of the pinger were digitally subtracted from the signal. A band-pass filter (1400-6500 Hz) and an automatic gain control with a window length of 50 ms were applied.

22 short cores of up to 1.3 meters in length were retrieved from Lake Sils in June 2003 using a gravity corer and transparent PVC liners with a diameter of 63 mm. In addition, two long piston cores (PSS94-2 and PSS94-5), taken but not opened by Ohlendorf et al. in 1994, have been used to amend and calibrate the seismic data. Whole cores were scanned by a multi-sensor core logger (MSCL; Geotek Ltd.) for density, p-wave velocity and magnetic susceptibility. Afterwards, the cores were opened, described and photographed before and after oxidation. Two reference cores (Sis03-8 and Sis03-23) from different basins were sampled for detailed analysis. The uppermost 10 cm were sampled every 0.5 cm, whereas the rest of the core was sampled at 1 cm intervals.

Three terrestrial plant macrofossil samples were AMS ^{14}C dated at Poznan, Poland, and calibrated (Bronk Ramsey 2001; Stuiver et al. 1998). ^{137}Cs and ^{210}Pb gamma radiation was measured for both reference cores at EAWAG, Dübendorf. Unsupported ^{210}Pb activities were obtained by level by level subtraction of ^{226}Ra activities from total activities. A constant rate of ^{210}Pb supply model (CRS) was used (Appleby & Oldfield 1992) to calculate sedimentation rates and model ages which were verified with the ^{137}Cs fall-out peaks of 1963 and 1986.

Total carbon, nitrogen and sulphur concentrations were measured with a gas chromatograph (HEKAtech, Euro AE Elemental Analyser). A CO_2-coulometer (Coulometric Inc.) was used to quantify carbonate content (TIC) of the sediment. As TIC concentrations in the sediments are two orders of magnitude smaller than the total carbon (0.01 – 0.05 weight %), total carbon is assumed as equivalent to organic carbon content. To determine the biogenic silica content, a leaching method modified after Mortlock & Froelich (1989) was used (Ohlendorf & Sturm subm.). The results were corrected for inorganic silica, derived from clay minerals (Demaster 1981) using the Al concentration in the leachate (Al:Si ratio of 2:1). Grain-sizes were measured with laser diffraction (Malvern Mastersizer Hydro 2000S) using a 0.02 – 300 µm size window. Samples were pretreated with 1M NaOH and 15 % H_2O_2 to remove biogenic silica (mostly diatoms) and organic matter, respectively. The major mineralogical composition of the sediments was determined with x-ray diffraction (Scintag XDS 2000 diffractometer at 45 kV and 40 mA with Cu K-α, 4 and 70° [2°Θ]).

Results

Seismic data

High-resolution seismic profiles (Figs. 2 and 3) provide information about the seismic stratigraphy, the 3-D sedimentary basin fill and the volume of each unit. The seismic signal penetrated in the Maloja basin over 35 milliseconds (ms) two-way travel time (twt), which is approximately 25 metres. Here, the analyses are confined to the uppermost seismic strata where core data were available, and the strata are continuous in the whole lake. In contrast to the Maloja basin, penetration depth was only about 6 ms twt in the Central basin and the Sils basin, most likely due to trapped gas in the sediments. Penetration was poorest in the Lagrev basin with almost structureless to chaotic reflections. The seismic signal became scattered and absorbed most likely at inter-bedded gravel and blocks (Stoker et al. 1997).

Accordingly, two seismic units, S1 and S2, can be distinguished. The lower unit S2 is seismically transparent or only shows weak, low-amplitude reflections due to a very low acoustic impedance contrast (Fig. 2). This is typical for a uniform lithology or low, gradual changes. Its thickness varies between 0.5 – 2 ms twt (ca. 0.35 – 1.4 m) in the Maloja basin whereas its bottom is not acoustically imaged in the Central basin. A low-amplitude reflection that is only visible in the Maloja basin, divides S2 in two parts. The lower part of S2 fills in the depressions of the underlying strata and is laterally onlapping, whereas the upper part of S2 shows a more uniform thickness. The high-amplitude top reflection of S2 is partially disturbed by acoustic blanking likely due to shallow gas in the central basin (Fader 1997). Unit S2 is not visible in the Sils and

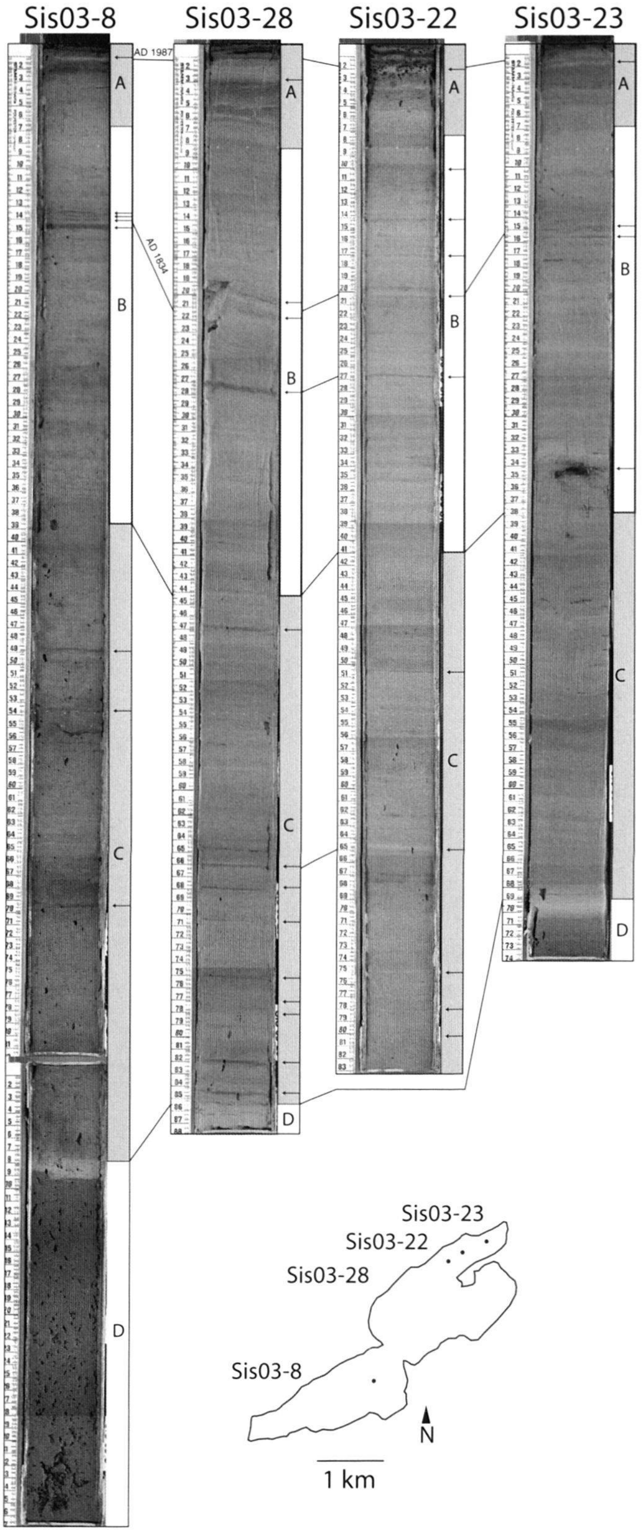


Fig. 4. Composite core pictures of Sis03-8, 22, 23 and 28 with indicated sedimentary units. Thin turbidite layers are marked with small arrows that are related to extreme rainfall events (AD 1834 and 1987). Unit D of the cores represents the recovered part of the mega turbidite. Note the decreasing number of turbidites from core Sis03-28 to 23.

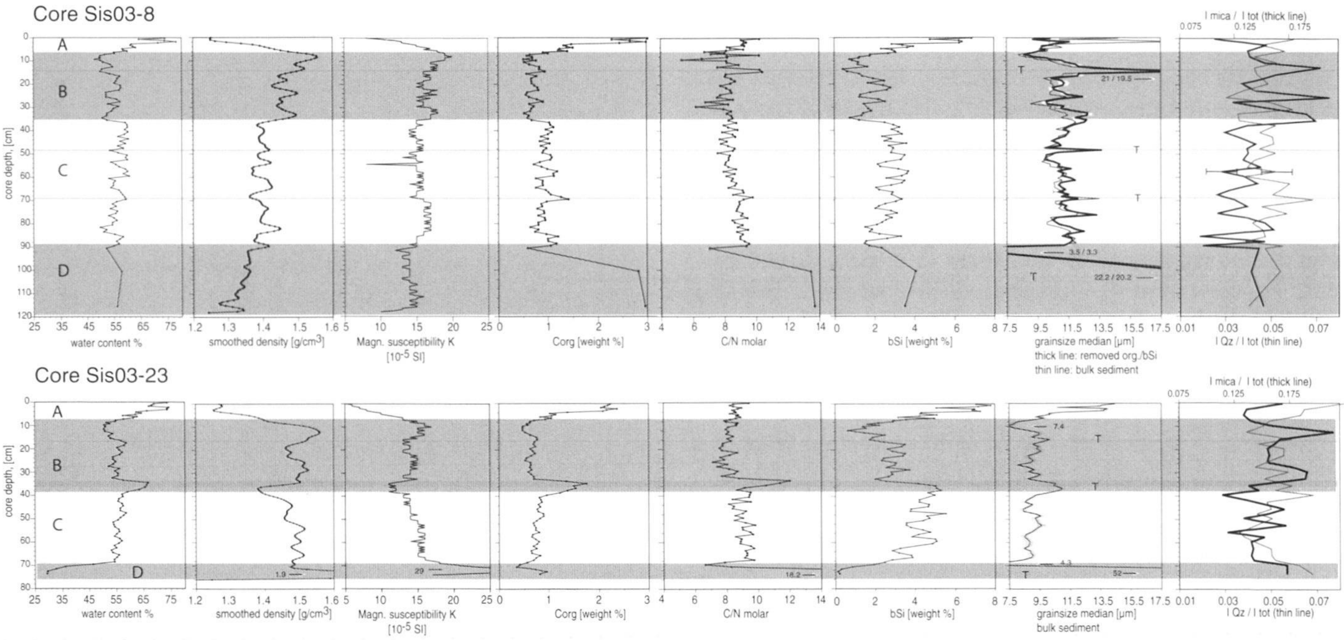


Fig. 5. Geophysical and chemical analyses of both reference cores Sis03-8 (Maloja basin) and 23 (Lagrev basin) with indicated units A to D. Thin turbidite layers are highlighted and marked with a 'T'. Note the strong changes in the very recent sediments (unit A) and the distinct shifts at the B / C boundary. Biogenic silica and C/N ratios show a slight trend in unit C.

Lagrev basin due to the low penetration depth of the seismic signal.

In the Maloja basin and the more delta-distal part of the Central basin the upper seismic unit S1 is characterized by continuous high-amplitude reflections (Fig. 2). The thickness is highly dependent on the location: 0.5 ms twt (ca. 0.4 m) are measured on top of a ridge while the thickness increases up to 4 ms twt (ca. 2.8 m) in the flat parts of the basin. Unit S1 has a different seismic facies in the delta-proximal part of the Central basin with two sub-sequences that are separated by an unconformity: a younger, partially downlapping sequence dips mainly southeast from the Sils basin towards the Central basin (S1A) whereas underlying reflections are inclined to the northeast (S1B; Fig. 3). However, based on the delta-proximity, one would expect stronger prograding delta sequences to the northwest that are actually very weakly developed.

Sedimentology

Four different lithological units were distinguished according to colour, petrophysical and geochemical properties of the cores. In general, lithology of unit A to C is relatively homogenous.

Unit A

This uppermost unit is about 5 to 15 cm thick, depending on the core location, and is characterized by a silty, light-grey lithology that is finely but rather diffusely laminated (Fig. 4). The uppermost 3 to 15 mm show a light to dark brown colour (Fe-oxides). Frequently black layers (FeS) were observed, but disappeared a few hours after the core had been exposed to the air. Only in some parts, very thin (0.5 – 1 mm), rhythmic laminae can be recognized. Distinct coarser layers consist of silt to sandy silt at the bottom and change gradually into clay at the top. These are interpreted as turbidites. Unit A is characterized by C_{org} values between 2 and 3 % of the total sediment mass.

Unit B

Unit B is about 15 to 85 cm thick and has similar lithological characteristics as unit A, but distinct black layers are rare, thin black laminae sporadic, and the C_{org} content is lower than 1 % (Fig. 5). There are no brown Fe-oxide layers.

Unit C

Unit C has a thickness between 18 and 150 cm and developed overall a slightly darker colour than unit B. C_{org} values are around 1 % (Fig. 5).

Unit D

The recovered thickness of unit D varies between 2.5 and 29 cm in the short cores (Fig. 4), and, where retrieved, forms the lowermost core unit. In the piston core, recovered by Ohlendorf et al. in 1994 in the Central basin, unit D is over 6 m thick without penetrating to its bottom (Fig. 3). Only half of the 22

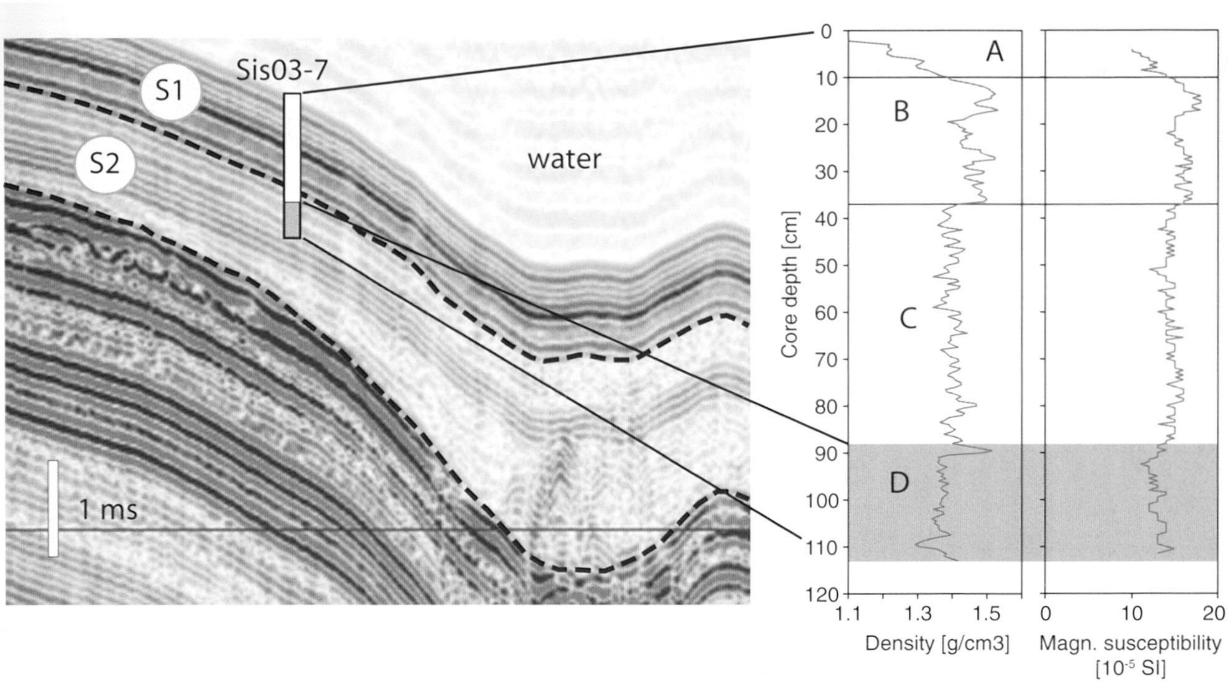


Fig. 6. Correlation of seismic line 4b and petrophysical data of core Sis03-7. The high-amplitude reflections of S1 represent the relatively strong lithological changes of unit A – C while the low-amplitude and mostly transparent facies of S2 corresponds to the top of unit D (mega turbidite). The core length in the seismic profile is transformed using an average p-wave velocity of 1500 m s^{-1}.

short cores reached the top of unit D that lies in a sediment depth of 35 to 91 cm in the short cores and in 245 cm in the piston core PSS94-2, respectively. Unit D comprises two subunits D1 and D2.

Subunit D1 represents the clayey top of unit D. The colour of the bottom part of D1 is light-beige turning upward into a light green. The thickness is uniform (ca. 1 cm) over the entire lake basin. The underlying subunit D2 is a very inhomogeneous complex sediment pack with extremely varying thickness (1.5 to more than 575 cm), with several different sequences and very diverse organic content. In the Maloja basin the organic content of D2 is generally very high with large terrestrial plant debris (reeds, fragments of trunks, roots and twigs). Clastic fraction consists mostly of coarse to very fine sand at the bottom fining upward to silt. A distinct decrease in size and amount of organic debris material is observed from Maloja towards the Central basin and the siliciclastic fraction at the bottom of the unit gets better sorted and overall finer. In the Central and the Lagrev basin unit D2 consists of different graded sequences with grain-sizes from coarse sand to silt and a relatively low organic content. Single sections show laminations with different degrees of disturbance.

The entire unit D is interpreted to be a mega turbidite in combination with slump deposits, since it exhibits the typical structures as described e.g. in Sturm & Matter (1972) and Schnellmann et al. (2002).

Petrophysical data and seismic-to-core correlation

The multi-sensor core logs correlate nicely with the lithological units discussed above (Fig. 5 and 6). The units A, B and C show high frequency and medium-amplitude changes in density and magnetic susceptibility in agreement with the series of high-amplitude reflections of seismic unit S1. In the Maloja basin the mega turbidite (unit D) that shows mostly low gradual lithologic changes, correlates to the transparent seismic unit S2 (Fig. 6 and Fig. 2). In the Central basin the seismic profiles have been calibrated with the PSS94-2 core using a travel velocity of 1500 ms^{-1}.

Chronology

^{137}Cs activities in core Sis03-8 show two peaks at a depth of 0.75 cm and 2.25 cm (Fig. 7), which are interpreted as the radioactive fallout maximum of Tschernobyl in 1986 and atmospheric nuclear weapon testing in 1963 (Appleby 2001). ^{210}Pb activities were measured from the cores Sis03-8 and 23. A mean sedimentation rate of 0.6 mm yr^{-1} or 22 mg cm^{-2} yr^{-1} is calculated from linear regression from both cores. The ^{210}Pb activities deviate from the theoretical exponential distribution of the unsupported ^{210}Pb, most notably in the topmost layers, although both cores were not disturbed during coring. No major hydrological changes happened in the last 150 years that could have changed sediment distribution and would require the application of the CIC model (Constant

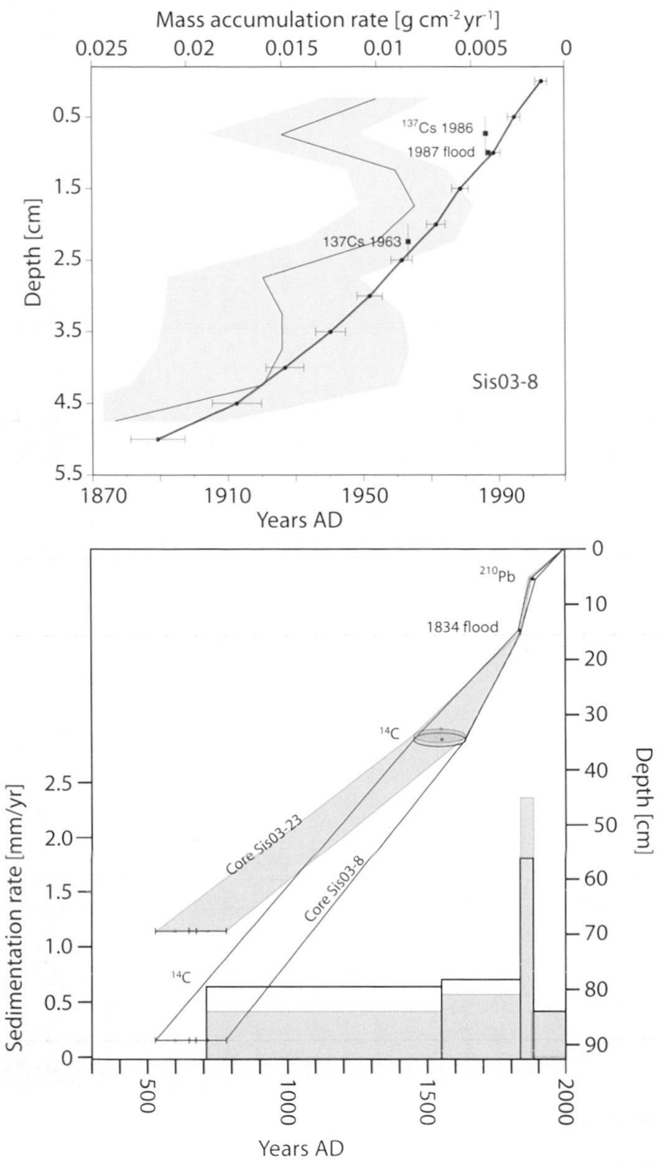


Fig. 7. Above: CRS age-depth model of Sis03-8 (thick line) with error bars (95 %) in comparison with maximum ^{137}Cs peaks and the 1987-flood. The thin line indicates calculated mass accumulation rates with a shaded 95 % error range.
Below: Combined age-depth model for Sis03-8 and 23 with 95 % confidence interval for ^{14}C and ^{210}Pb dates. The 1834-flood was caused by one of the most severe rainfall events in the documented history. It triggered also a turbidite layer in Lake Silvaplana. The sedimentation rates show an increase after about AD 1500, and are especially high around 1850. Note the different sedimentation rates of the reference cores before around AD 1500.

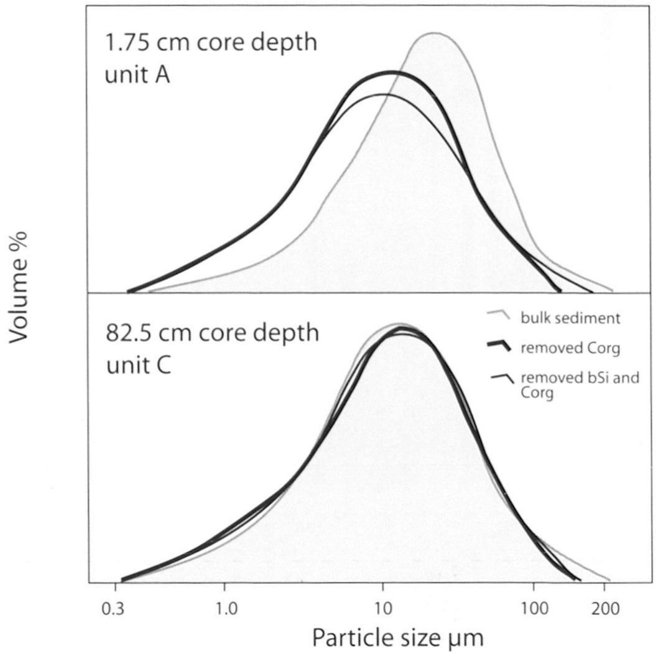


Fig. 8. Grain-size distributions of two sediment samples for bulk analysis (shaded), with removed organic matter (thin line) and with both removed organic matter and biogenic silica (thick line). In the uppermost layers (unit A, anthropogenic eutrophication) differences are relatively high, particularly in fraction above 10µm. In the lower core unit C, only removal of the organic fraction biases the distribution.

Initial Concentration). Either, the sedimentation rate has not been constant, or vertical migration of ^{210}Pb occurred in the top sediment layers (Abril 2003). Appleby & Oldfield (1992) showed that the CRS model (Constant Rate of ^{210}Pb Supply model) is often not sensitive to vertical mixing in the uppermost layers. Here, we used the CRS model, calculated sedimentation rates at a given depth (Binford 1990) and tested the results with the ^{137}Cs data (Fig. 7). The CRS age-depth profiles are in good agreement with the 1986 and 1963 ^{137}Cs peaks. The CRS model results are further supported by a distinct turbidite layer at 1.0 and 1.7 cm core depth of Sis03-8 and Sis03-23, respectively, which has been interpreted as the result of the flooding in 1987 (Röthlisberger 1991). This 1987-turbidite has also been detected in Lake Silvaplana (Ohlendorf 1998).

The bottom of unit B is dated between cal AD 1450 and 1640 (95 % probability, Table 1). Two dates exist for the top of the mega turbidite (unit D), cal AD 650 to 780 and cal AD 530 to 670 (Table 1). Since material remobilisation is inherent to turbidites, we use the younger date as a maximum age for the timing of the event.

The summary age-depth model (Fig. 7) matches well with a prominent turbidite layer at 14.5 cm (Sis03-8) and 15.5 cm (Sis03-23) core depth which we relate to the catastrophic flood in summer 1834 (Pfister 2004; Schwarz-Zanetti & Schwarz-Zanetti 1988). The 1834-flood is also recorded in Lake Silvaplana (Ohlendorf 1998).

Geochemistry and petrophysical data

The topmost parts (unit A) of the two reference cores show a steep increase in organic carbon (by ca. 1 to 3 %), biogenic sil-

Tab. 1. AMS ^{14}C dates determined from macro fossils of the cores Sis03-2 and 23.

Core	Core depth [cm]	Material	Lab. ID	^{14}C yr BP	Cal AD (95 % probability)
Sis03-23	32.5 – 35.5 cm	Bark, small twig (one year)	Poz-5422	355 ± 35	1450 – 1640
Sis03-23	69 – 72 cm	3 small twigs (1 – 2 years)	Poz-5423	1300 ± 35	650 – 780
Sis03-2	85 cm	Leave fragments, small twigs (1 year)	Poz-5424	1465 ± 40	530 – 670

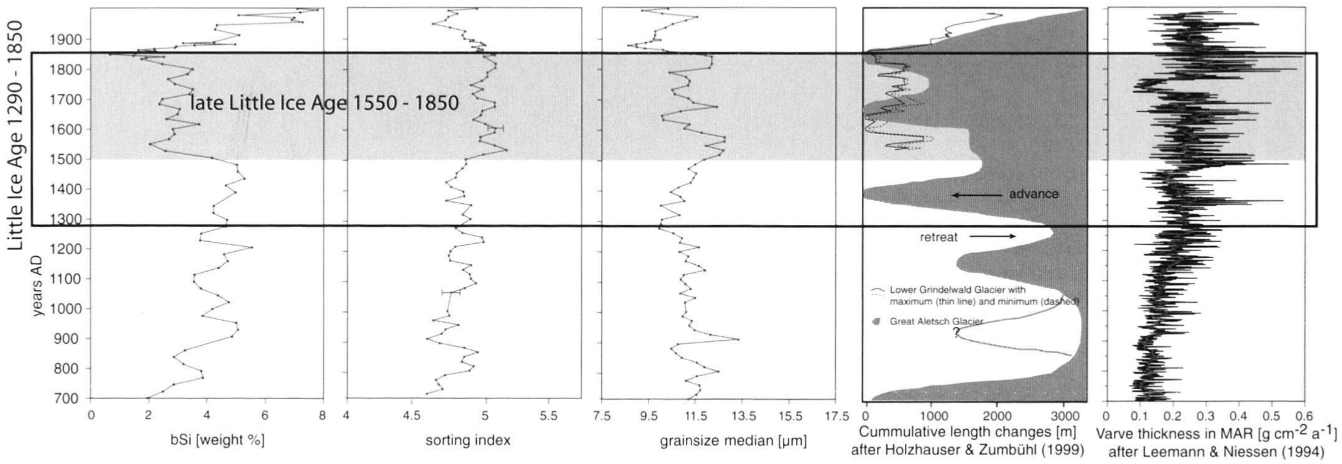


Fig. 9. Comparison of biogenic silica (of Sis03-23), grain-size sorting and median (of Sis03-8) with glacier length reconstructions of the Aletsch Glacier (shaded area) and the Lower Grindelwald Glacier (thin line) after Holzhauser & Zumbühl (1999), and varve thicknesses of Lake Silvaplana (Leemann & Niessen 1994). The late period of the 'Little Ice Age' is highlighted. It includes the major glacier advances in the 17th and 19th century.

ica (by about 3 to 8 %) and the C/N ratio. The data show a two-step, up core process with a stronger increase in the most recent sediments (Fig. 5). Water contents are generally very high but decreasing with depth (57 – 78 %). In turn, density and magnetic susceptibility correlate inversely with the water content and increase with depth from 1.2 to 1.4 g cm^{-3} and 5 to 15 * 10^{-5} SI units, respectively.

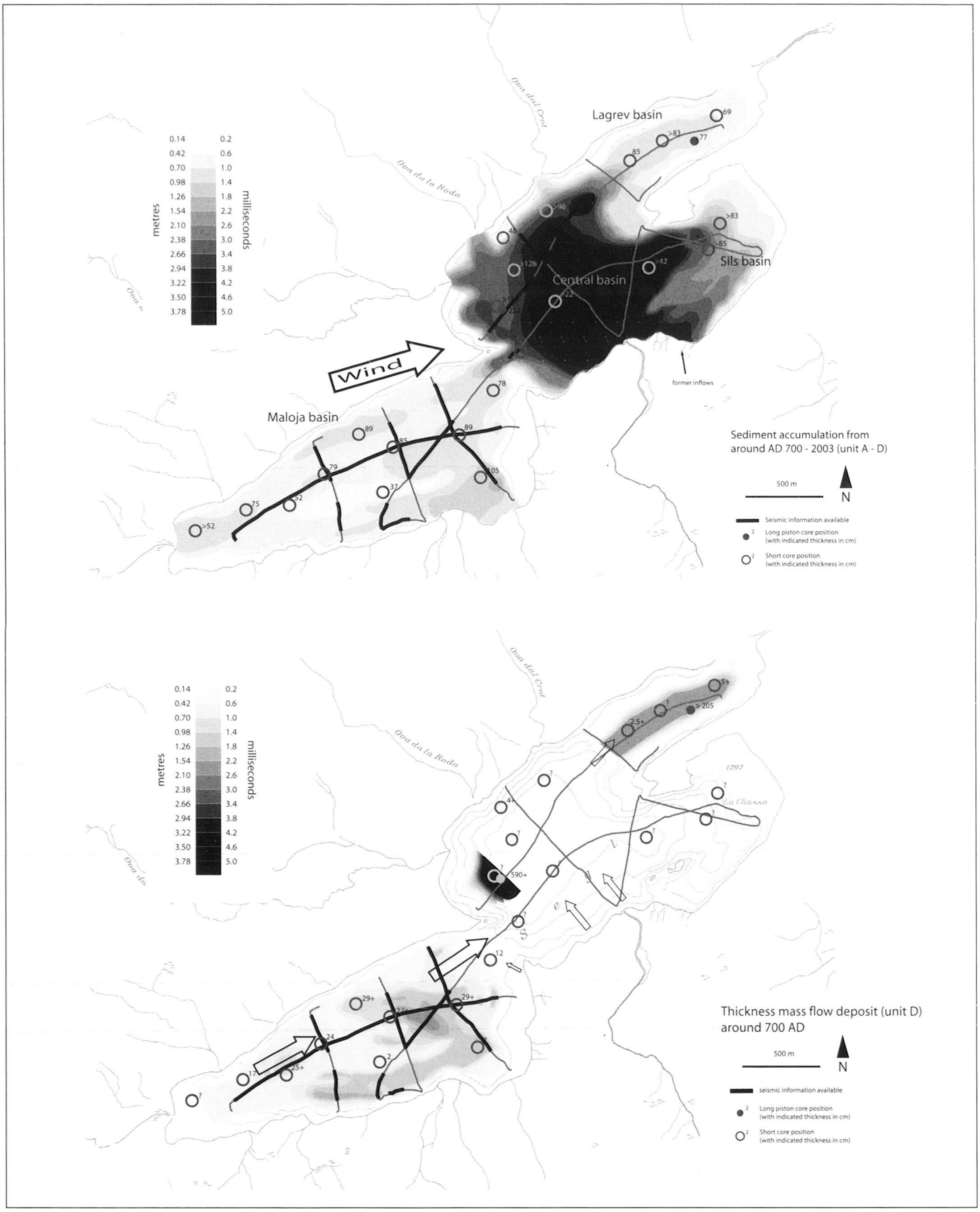
Unit B has, compared to the rest of the core, a distinctly lower C_{org} (< 1 %) and bSi (< 3 %) content. Particularly, bSi exhibits three major minima. C/N ratios show peak values where turbidites occur. Compared with unit A, water content (48 – 57 %) is lower, density (1.4 – 1.6 g cm^{-3}) and magnetic susceptibility (up to 20 SI units) generally higher.

In unit C, C_{org} and bSi is, in general, higher than in unit B. In Sis03-23, both bSi and C_{org} show a weak decreasing trend with depth, while C/N ratio is slightly increasing. Consistently, water contents are higher than in unit B (49 – 61 %) whereas density (1.35 – 1.45 g cm^{-3}) and magnetic susceptibility (13 – 17 * 10^{-5} SI units) is lower.

In unit D (turbidite), bSi and C_{org} concentrations are highly variable. Water contents of D1 are between 45 – 57 % while densities are around 1.5 g cm^{-3} and magnetic susceptibility range between 14 and 17 * 10^{-5} SI units. Water contents of subunit D2 are relatively high in the upper organic-rich parts, but lower than 30 % in the well-sorted, organic-poor sands. In accordance to the water contents, densities range from 1.2 g cm^{-3} in the upper organic-rich part to 1.9 g cm^{-3} in the sandy parts of subunit D2. Magnetic susceptibility increases with depth and reaches values above 25 * 10^{-5} SI units.

Grain-size and mineralogy

In core 8, grain-size was measured before and after removing bSi (mostly diatoms) and organic matter. Parallel measurements revealed that diatom frustules may have a considerable influence on grain-size data. The differences in both median and the distribution pattern are particularly large in the uppermost part of the cores (unit A, Fig. 9) where bSi is high and diatoms abundant (Fig. 5). In the lower parts (unit B and C), the results for the treated and non-treated samples are almost similar except for the coarse-grained tail end of the distribution curve (> 100 µm) which is influenced by organic material (Fig. 8). However, Fig. 5 shows that the direction and the amplitude of the shift with removal of bSi is sample-specific and changes with the size of the diatoms and organic matter relative to the size of the silici-clastic fraction.


Lagrev basin
Central basin
Sils basin
Maloja basin
Wind
former inflows
Ova dal Crot
Ova da la Roda
metres
milliseconds
Sediment accumulation from around AD 700 - 2003 (unit A - D)
500 m
N
Seismic information available
Long piston core position (with indicated thickness in cm)
Short core position (with indicated thickness in cm)
Thickness mass flow deposit (unit D) around 700 AD
La Chassa
1797

Grain-size medians vary considerably with depth and show maximum values in turbidite deposits (Fig. 5). Apart from the turbidites, there are long-term variations and trends. Rather high-frequency median variations persist in the lower two-thirds of unit C followed by a long-term increase that has three major peaks in unit B (Fig. 5). The sorting index which is defined as the maximum peak height of the distribution shows about the same trends (Fig. 9).

X-ray diffraction analysis indicates that quartz, chlorite and muscovite are the most abundant minerals in the sediments of Lake Sils. Amphiboles and feldspars constitute the comparatively minor contributors. Mica minerals (chlorite, muscovite) have significantly higher concentrations in unit B (Fig. 5).

Sediment volumes

The dense grid of the seismic survey allows us to interpolate thickness contours of seismic horizons and thus, to estimate volumes of sediment strata (Fig. 10). The area of the steep delta deposits were not considered, because the seismic information is not adequate in this part of the basin. In order to get a denser coverage, seismic data were amended with core information from locations not positioned on seismic lines. Core depths were converted in two-way travel times by using a pw-velocity of 1500 m s^{-1} (Fig. 6) and calibrated. The thickness contours of the mega turbidite (unit D) and the post-turbidite sediment thickness (units A-C) were calculated. They are most reliable in the Maloja basin; while the data in particular for the turbidite is sparse in the rest of the lake (Fig. 10) due to the limited sonic penetration and lack of long cores.

The mega turbidite extends over the entire lake and shows large thickness variations (Fig. 10). In the Maloja basin thicknesses amount up to 1.55 m and more than 6 m were detected in the Central basin at the front of the delta; which is confirmed by the sediments of the long piston core PSS94-2 (Fig. 3). In the Lagrev basin, close to the outflow, turbidite thickness amount to more than 2 m as confirmed by piston core PSS94-5 (Ohlendorf unpubl. data). By using mean thickness values of five characteristic areas, total volume of this mega turbidite is calculated at $6.5 * 10^6$ m^3 of sediments.

The sediment distribution of S1 (units A to C) shows the dominant influence of the Fedoz River with respect to sediment yield (Fig. 10). About 3.5 m are measured in the Central basin compared to about 0.7 m in the Maloja and the Lagrev basins (Fig. 10). In total $4.5 * 10^6$ m^3 sediments were accumulated since the mega event around AD 700 which is less than what was deposited during that short-lived event 1300 years ago.

Discussion

Limnogeological development of Lake Sils

The sedimentation history of Lake Sils during the last 1300 years is the complex result of various factors such as the regional climate, its impact on the catchment environment, and, last but not least, human activity. The first sharp increase in bSi and organic carbon at the beginning of unit A is interpreted as human-induced start of eutrophication after around AD 1880 (Fig. 5). Tourism began in the Engadine around 1860 (Züllig 1982). Two hotels and some large buildings were constructed by a Dutch Earl in Maloja in the late 19th century (Boppart 1982) while the first Hotel in Sils was opened in 1865 (Zuan 1984). Rising waste water production led to a significant increase in the nutrient supply to the lake which in turn enhanced the primary production. The second and even stronger increase of the biogenic silica and C_{org} concentration took place around 1960 as a result of fast growing tourist numbers. Overnight stays in Sils increased from 1940 to 1970 by 5000 stays every year. After 1970, the growth rate doubled (Gemeinde Sils 1994). During the same time, bottom water oxygen concentrations of Lake Sils decreased from 9 mg l^{-1} in 1965 to 5 mg l^{-1} in 1992, although a sewage plant was built around 1960 (LIMNEX 1994). Today, the sediment-water interface is still oxic as evidenced by the sediments, only single layers in the sediment are anoxic.

In light of the last 1300 years, the sediments between around AD 1500 and 1880 (unit B) are quite different with distinctly lower C_{org} and bSi contents, relatively high mica concentrations (Fig. 5) and better sorted, coarser siliciclastics. We consider two explanations. Reduced primary production and, thus, lower C_{org} and bSi flux due to the lack of nutrients or harsher climate, or dilution of C_{org} and bSi due to higher clastic sedimentation rates (e.g. Leonard 1986a). We favour the later explanation. First, the C/N ratio would have changed significantly with a lake biomass collapse of almost 50 %. Secondly, the age-depth model does suggest an increase in average sedimentation rates after AD 1500. Thirdly, the mineralogy shows a clear signal of enhanced mica supply to the lake (Fig. 5) and, finally, grain-size data demonstrate a shift towards better sorted and coarser clastic particles. Enhanced sediment supply and turbidity would consequently also have a negative impact on productivity through limited light availability for photosynthesis (Battarbee et al. 2001).

This period of modified sedimentation is temporally coinciding with the more traditional chronological definition of the 'Little Ice Age' from 1550 to 1850 (Jones & Bradley 1992) with major glacier advances in the Alps (Fig. 9). Preliminary results

Fig. 10. Above: Sediment accumulation since about AD 700 (units A – C). Seismic lines (highlighted where information is available) and core locations with thicknesses are drawn. The dominant proportion of the sediments is deposited in the Central basin. Sedimentation is also relatively high in the Sils basin due to former inflows from the Isola delta and Coriolis effects.
Below: Thickness contour of the AD-700-turbidite (S2, unit D). In the Central basin, total thickness is unknown, but exceeding 6 m. Arrows display possible flow direction of the event. By far the largest proportion was deposited in the Central basin in front of the Isola delta.
(Background map: Vector 25 © 2003 Swisstopo)

from high-resolution sediment trap data in Lake Silvaplana suggest that sediments, suspended in glacial runoff, are by far the most important sources for sediment flux in the centre of the lake (Sturm unpubl. data). For example, during the exceptionally hot, but dry Summer of 2003 (SMA 2004), record sediment yields were measured from June to September. We suggest that glacial activity (abrasion and melt-water transport) is the most important agent to govern sediment flux. The geochemical and physical properties of the sediments agree with findings from other lakes (Ariztegui et al. 1997; Desloges 1994; Leemann & Niessen 1994; Leonard 1986b; Leonard 1997; Moore et al. 2001; Nesje et al. 2001; Vanderaveroet et al. 1999). However, there are documented glacier advances in the 12^{th} and 14^{th} century (Holzhauser & Zumbühl 1999) that have not affected the sediments of Lake Sils. Thus, we consider a change in the climatic regime after AD 1500 as a possible explanation (Bard et al. 2000; Büntgen et al. in press).

The gradual increase of bSi and C_{org}, and the constant decrease of C/N ratios in the centuries before AD 1500 suggest rising paleoproductivity of the lake as a consequence of more favourable paleoclimatic conditions or land use changes in the catchment. Evidence for regional deforestation was found in pollen and charcoal data from sediments of Lake St. Moritz between AD 700 to about 1700 (Gobet et al. 2003). A relationship between deforestation, intensification of land use and cattle grazing, as well as subsequent enhanced nutrient supply has been found also in other Alpine and Scandinavian lakes (Anderson et al. 1995; Hausmann et al. 2002; Schmidt et al. 2002). An alternative explanation might be the indirect influence of regional climatic changes (Bard et al. 2000; Büntgen et al. in press) on primary production with effects on runoff and nutrient supply to the lake.

Sediment distribution patterns

Combined seismic and core data allow the sedimentological characterisation of the different basins and the sediment distribution within the lake. A comparison of the sediment volume, accumulated in different parts of the lake since around AD 700, clearly shows the dominant role of the Fedoz River regarding sediment influx: about 3.5 m of sediments, i.e. 2.7 mm/yr, were accumulated in the Central basin compared to 0.9 m, i.e. 0.7 mm/yr, in the Maloja and the Lagrev basins (Fig. 10). Surprisingly high values are observed in the Sils basin, which could be due to Coriolis effects (Sturm & Matter 1972) and wind-driven transportation by the Maloja wind as observed by the authors in the field. Furthermore, wind-driven sediment redistribution from the Sils basin towards the southwest is likely, since the Maloja wind potentially induces subaquatic currents. This would agree with the thinning and partially downlapping seismic strata (Fig. 3). The variable characterisation of these units is thought to reflect migrating river inflow in the delta plain or variations of the sediment input. Grain-size data further confirm that the Fedoz River never drained into the Maloja basin since about AD 700. The sediments of the Lagrev basin are influenced by snow avalanche and debris flows reaching the lake as evidenced by the structure-less to chaotic seismic facies and the rough topography. This interpretation is confirmed by drop-stones and debris flow deposits in the cores. Turbidites are most abundant in the Central basin in front of the Isola delta with decreasing frequency and thickness towards the outlet (Fig. 4). The Maloja basin with its relatively small river inflows has a calm sedimentation regime with about half the turbidite frequency of the Lagrev basin.

The sediment distribution pattern changed after about AD 1500. The geochemical and mineralogical data of the short cores suggest that the Lagrev basin benefited to a greater extent from increasing sediment input. Before that time, sedimentation rates were lower in the Lagrev basin compared to the Maloja basin, but about the same afterwards. In addition, bSi dilution by silici-clastic input is stronger in the Lagrev core (Sis03-23, Fig. 5). It seems that the AD 1500 boundary is represented by the seismic unconformity between S1A and S1B (Fig. 3) which would imply a coincidental shift of the embankment with increasing sedimentation.

The AD 700 mega turbidite, which covers the entire lake, was very likely not generated by an extreme rainfall event as the clayey top is very thin compared to the rest of the deposit. Furthermore, an extreme rainfall event is very unlikely to transport such huge amount of sediment (Sturm & Matter 1978; Sturm et al. 1995). The sedimentary record (grain-size, sorting, and terrestrial organic matter) rather suggests a collapse of the Isola delta that caused the enormous slump and turbidite deposits. This points to the possibility that the delta collapse induced seiche waves which caused shore erosion at least in the Maloja area (cf. Schnellmann et al. 2002; cf. Siegenthaler et al. 1987). Such mechanisms would explain most of the sedimentary features, such as the multi-graded units and the relatively low organic content along the delta front compared to the large terrestrial macrofossils found in the Maloja basin.

Comparison with the other Engadine lakes

All Engadine lakes experience the same climatic conditions, but their sediments are very diverse ranging from pro- to periglacial sediments (Ariztegui et al. 1996). Within this set of lakes, Lake Sils has the lowest accumulation rate. The difference in the sedimentation rate compared to Lake Silvaplana can be explained by (a) its larger surface area (factor 1.5), (b) by its smaller catchment area (factor 0.35) and (c) by its smaller glaciated area (factor 0.6 in 1992). A significant particle export to Lake Silvaplana is very unlikely since the outflow of the Inn River is 2 km apart from the main inflow and bathymetry and geometry of the lake favour sedimentation within the Central basin. The lower sedimentation rates, respectively lower input of suspended sediments from the rivers, may also explain the absence of varves in Lake Sils. Due to oxic conditions in the sediment, bioturbation cannot be fully excluded.

The recent changes in C_{org} and bSi are also reported from Lake Silvaplana and Lake St. Moritz further down the valley. Anthropogenic eutrophication is much stronger in Lake Silvaplana where bSi increases from about 1 to 11 % and C_{org} from 0.5 to 2 % (Ohlendorf 1998). Lake St. Moritz shows the strongest eutrophication effect with C_{org} rising from 2 to 5 % (Ariztegui et al. 1996). Although Lake Sils is believed to be least influenced by human activity, the onset of blackish sediments occurred much earlier in Lake Sils (around AD 1880) than in Lake Silvaplana (AD 1960, Ohlendorf et al. 1997). Eutrophication started in Lake St. Moritz around 1910 (Züllig 1982).

The period of enhanced sediment supply around AD 1500 – 1850 (late 'Little Ice Age') was also found in Lake Silvaplana (Leemann 1993) confirming the non-local character of the signal (Fig. 9). It seems that proglacial Alpine lakes can record such climatic changes (Leemann & Niessen 1994; Leonard 1997; Nesje et al. 2001), although the 'Little Ice Age' seems to have been more a phenomenon of the winter season (Casty et al. in press; Luterbacher et al. 2004). We think that the memory effect of the glaciers in the catchment may play a major role.

Conclusion

A high-resolution seismic survey combined with 22 short cores reveals a comprehensive picture of the basin fill and its sedimentary features over the last 1300 years for Lake Sils. Four lithological units have been distinguished and could be matched to the seismic units.

The lowermost sedimentary unit (unit D) shows multi-graded, coarse grained and partially organic-rich sequences with a thickness of up to 6 m and is interpreted as a mega turbidite. It covers the entire lake bottom. Unit D is dated between AD 650 and 780. The overlaying, mostly light-grey, clayey silts (units A-C) are finely, but rather diffusely laminated, but no varves could be recognised. Unit B exhibits lower organic carbon and biogenic silica contents, but higher mica concentrations, grain-size medians and overall higher sedimentation rates. Unit B is dated to between around AD 1500 and 1880. This period is thought to reflect the sedimentary response to late 'Little Ice Age' (AD 1500 – 1860) that brought about major glacier advances in the Alps. The most recent unit A (since AD 1880) consists of more frequent black layers and shows a steep, two-step increase in organic carbon and biogenic silica which has been interpreted as beeing a result of anthropogenic eutrophication starting around AD 1880. At that time, the Engadine became increasingly attractive to tourists and construction (Züllig 1982). The onset of the eutrophication in Lake Sils occurred earlier than in Lake St. Moritz (Ariztegui et al. 1996) and Silvaplana (Ohlendorf 1998).

Since seismic profiles show typical features of water current activity, sediment redistribution within Lake Sils, due to the Coriolis effect and wind shear induced drifts, is likely. The average sedimentation rate in the distal parts of the lake is about 0.7 mm per year (25 mg $cm^{-2}a^{-1}$), which is an order of one magnitude lower than in the other Engadine lakes (Züllig 1982; Leemann & Niessen 1994). Combined seismic and core information indicate that most of the sediments (~ 70 %) are deposited at the front of the Isola delta in the Central basin. The volume of the AD 700 mega turbidite with about 6.5 * 10^6 m^3 is even greater than the volume deposited during the last 1300 years (4.5 * 10^6 m^3).

Acknowledgements

The help of Brian Sinnet and Alois Zwyssig was essential during the field work and laboratory phases of the project. Brian kindly improved the English of the manuscript. We would like to thank Christian Ohlendorf for providing important information and for valuable hints. We are also grateful to Thomas Kulbe for his guidance in the x-ray analysis and for various discussions. Thanks are also due to Emmanuel Chapron for his support with the grain-size analysis and Gwen Bessire for composing the core pictures. Michael Schnellmann helped to conduct the seismic survey and Erwin Grieder provided the Cs and Pb analysis. We thank Christian Kamenik for helping with the statistics and Chrigu Bigler for his support concerning the diatoms. Financial support was granted by the NCCR Climate (Swiss National Science Foundation SNF) and the ENLARGE project (SNF No. 200021-103892/1).

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Manuscript received November 2, 2004
Revision accepted July 1, 2005