Major sedimentation pattern changes in the Rhone Delta (Lake Geneva, Switzerland-France) around 1300 and 1600 AD revealed by seismic and sedimentary records

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Abstract

The seismic record of recent sediments of the Rhone delta in Lake Geneva (Switzerland, France) presents a discontinuity over a large area of the delta. Previous studies hypothesized that sediments inducing this discontinuity could originate from a giant rock fall (named Tauredunum*) that occurred in the Lake Geneva watershed in 583 AD. To verify this hypothesis, two long cores have been retrieved from the lake sediments in the region where the sediment pile thickness is reduced. The sediment sequence presented three major units, with an upper, fine grained and laminated sediments (Unit A), and intermediate unit consisting of alternating coarse and fine grained sediments (Unit B), and a lower unit (Unit C) with sediment characteristics comparable to Unit (A). Unit B was interpreted as sediments inducing the seismic discontinuity. Two organic remains were sampled in Unit B and Unit A, and dated by AMS ^{14}C to 1390-1440 cal. AD and 1680-1780 cal. AD, respectively. The base of Unit B was dated by extrapolation to 1310 cal. AD that is more than six centuries after the* Tauredunum *rock fall. Moreover, the structure of the intermediate unit was interpreted as a succession of turbidite deposits and hemipelagic sedimentation. The mode of deposition of the sediments and, mainly, the AMS ^{14}C dating of organic remains invalidate the hypothesis of an origin of the intermediate unit in relation to the* Tauredunum *rock fall. Possible processes are larger inputs (as compared to present time) of detrital material during the "Little Ice Age" and a shift in the sand lobes at the end of sub-lacustrine canyons.*

Keywords: *radiocarbon dating, Léman, Tauredunum, seismic reflection, lake sediment*

Introduction

Lake sediments are extensively used as continental archives of environmental changes. Various proxies are usually used to reconstruct these changes, including geochemical tracers and biological constituents. Sediment structure and texture can also provide some information about modifications that occurred in the watershed and lake basin itself. The history of Lake Geneva has been studied since Forel (1892) and his renowned monograph "Le Léman". Since that time, many authors studied the sedimentary filling of the lake by seismic exploration (e.g. Vernet et al. 1974; Winnock 1965) and sediment coring (Vernet et al. 1984; Loizeau et al. 1997). Investigations of Zingg et al. (2003) confirmed the recognition in the Rhone delta (Eastern part of Lake Geneva) of a discontinuity between two seismic sequences of different internal geometry and facies, and linked it to the 'M reflector' first described by Loizeau (1991). Based on extrapolation of sedimentation rates of the second half of 20th century measured in the distal part of the delta, this

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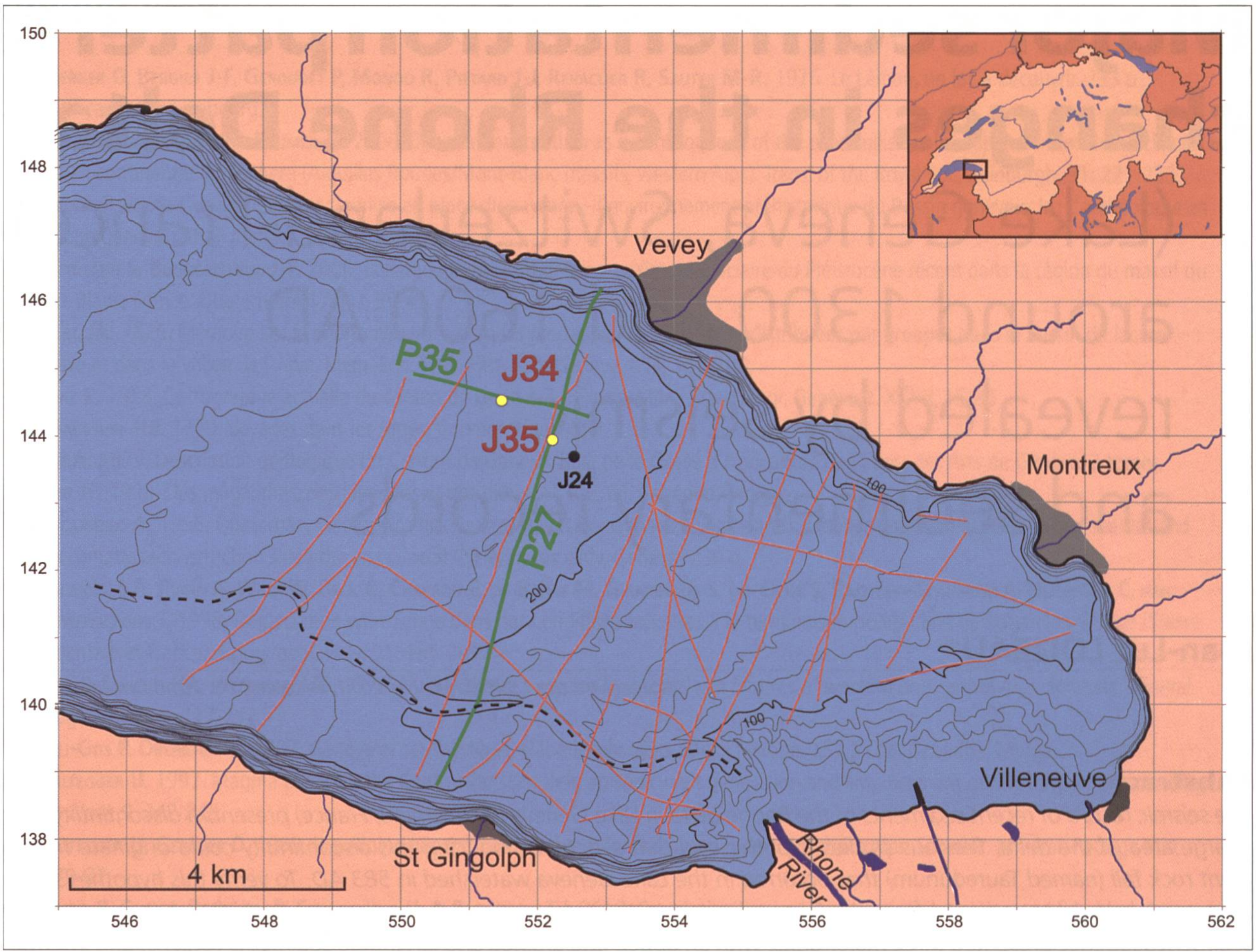

Fig. 1. Location of the study sites in Lake Geneva. Red lines represent traces of the 3.5 kHz seismic profiles. Cores J34 and J35 (yellow points) have been recovered on the tracks of seismic profiles P35 and P27 (green lines), respectively. Extracts of the two seismic profiles are shown of Fig. 2. Black dot corresponds to the location of an adjacent 137Cs and Hg- dated core (J24, Loizeau et al. 1997; Dominik et al. 1991, 1992). The black dashed line marks the current active canyon.

author proposed to relate the presence of this discontinuity to a catastrophic event that occurred in the watershed in the year 583 AD, known as the *Tauredunum* rock fall. This event induced a tsunami on Lake Geneva which destroyed buildings along the lakeshore. Several authors have retained the same theory to explain this discontinuity and facies change in seismic data (Dupuy 2006; Schoeneich et al. 2007; Zingg et al. 2003).

In this paper, unpublished seismic and sedimentary data, as well as two radiocarbon dates, allow to reinterpret the seismic record in the Rhône delta in Lake Geneva, and give new insight in the sedimentation history of this delta.

Setting

Lake Geneva covers a total surface area of 580.1 km², holds a volume of 89 km³ of freshwater, and the maximum depth reaches 309.7 m at its centre. The Rhone River (Fig. 1) is the main tributary with an annual mean discharge of 182 m³/s for the 1935-2008 period (OFEV 2009) that corresponds to 75 per cent of the total water input discharge. It also contributes to 80 per cent of the sediment load to the lake, with several million tons of particles brought to the lake every year (Loizeau and Dominik 2000). This large amount of matter accumulated since the last glaciation and formed a lacustrine delta in the eastern part of the lake. The delta comprises one major and several adjacent canyons discovered by Forel (1888) and precisely defined by the new bathymetric map of Sastre et al. (2010). A total thickness of more than 350 meters of sediments was deposited in this part of the lake (Dupuy 2006; Vernet et al. 1974). The recent lake sediments in the delta are usually fine to medium silts, decreasing in size with increasing distance from the river mouth. Recent sandy deposits are observed in the bottom of the canyon and in sand lobes at the extremity of the main canyon (Giovanoli 1990; Loizeau 1998). The main canyon has been created and is maintained by density currents originating from the Rhone River, either as water loaded with a high suspended particle content or avalanches triggered in the proximal part of the delta (Forel 1888; Lambert and Giovanoli, 1988).

During the second half of the 20th century, numerous dams have stopped the normal flow of tributaries of the Rhone River. In 1990, the total capacity of the reservoirs accounted for 1.22 km^3, representing 20 per cent of the mean annual water discharge to Lake Geneva (Loizeau and Dominik 2000). Associated reduction of the sediment load has been evaluated in the delta by comparing sediment accumulation rates corresponding to periods before and after the construction of the dams. Loizeau et al. (1997) have shown that a two-fold reduction in the eastern part of the lake had occurred.

Methods

Seismic reflection profiles were obtained in June 1986 with a mud penetrator of the BRGM (Bureau de recherches géologiques et minières, France) with a 3.5 kHz frequency, installed on the research vessel of the Institut F.-A. Forel "La Licorne". A total of 110 km of seismic profiles (Fig. 1) was recorded on paper only. Therefore no post-treatment processing was applied. At the time of data collection, GPS was not available and positioning was performed using radar (JFS 932) images, with an accuracy of about 100 m. Major results of this survey will not be discussed here in detailed but are found in Loizeau (1991).

Six Kullenberg-type cores were retrieved in 1990 from the lake sediment using the ETH/EAWAG corer (Kelts et al. 1986) with the collaboration of Dr. M. Sturm from EAWAG. However, only two of them (J34 and J35) were long enough (791 and 697 cm, respectively) to go through the entire upper sediment sequence. These two cores were retrieved in the distal part of the lake delta, at 7.1 and 6.3 km distance from the Rhone River mouth, respectively (Fig. 1).

Volume magnetic susceptibility (VMS) was measured prior opening using a Bartington susceptibility meter (MS1 with a probe C, 80 mm opening). The cores were opened longitudinally, photographed and sub-sampled (64 and 59 samples in J34 and J35, respectively) for sedimentological analyses. Sediments were dried at 40°C to constant weight to calculate water content. Grain size was determined by laser diffraction using a Coulter LS-100, following the procedure described by Loizeau et al. (1994). Two samples of organic matter remains (lignin) had been recovered from core J34 (at 284 and 568 cm depths) to be ^{14}C-dated by AMS technique. These samples were prepared at the Radiocarbon laboratory, Department of Geography of the University of Zurich (GIUZ) and measured at the AMS Radiocarbon Dating laboratory of the ETHZ in 1996 (Bonani et al. 1987). Deviation of radiocarbon dating due to the large time lag between sampling and measurement should be minimal because the samples were dried a few days after core retrieval and kept under dry conditions (Wohlfarth et al. 1998). The measured conventional radiocarbon dates were calibrated by applying the Calib v5.2 software (Stuiver and Reimer 1993) in combination with the IntCal04 calibration data set (Reimer et al. 2004).

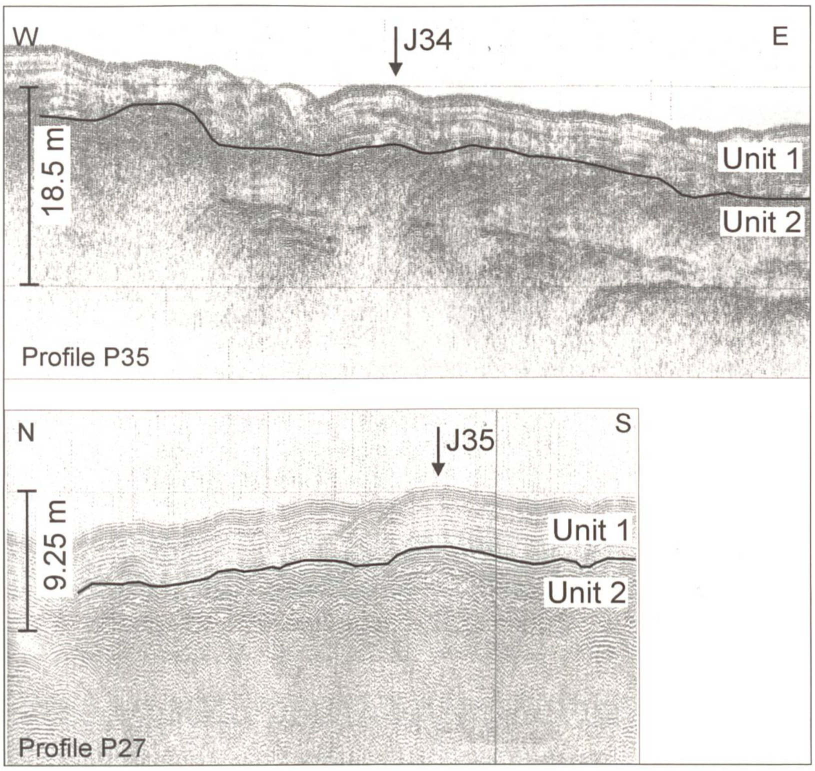

Fig. 2. Extracts of the 3.5 kHz seismic profiles of Lake Geneva sediments. Location of the profiles is presented on Figure 1. A) P35 along which core J34 was recovered. B) P27 along which core J35 was recovered. Sediment thickness is calculated assuming a sound velocity in the sediment of 1480 m/s. The black line underlines the limit between seismic Unit 1 and Unit 2.

Results

Seismic reflection survey

Seismic reflection data revealed a marked discontinuity in the sismostratigraphic column, mainly observed on the northern part of the lacustrine delta. This discontinuity

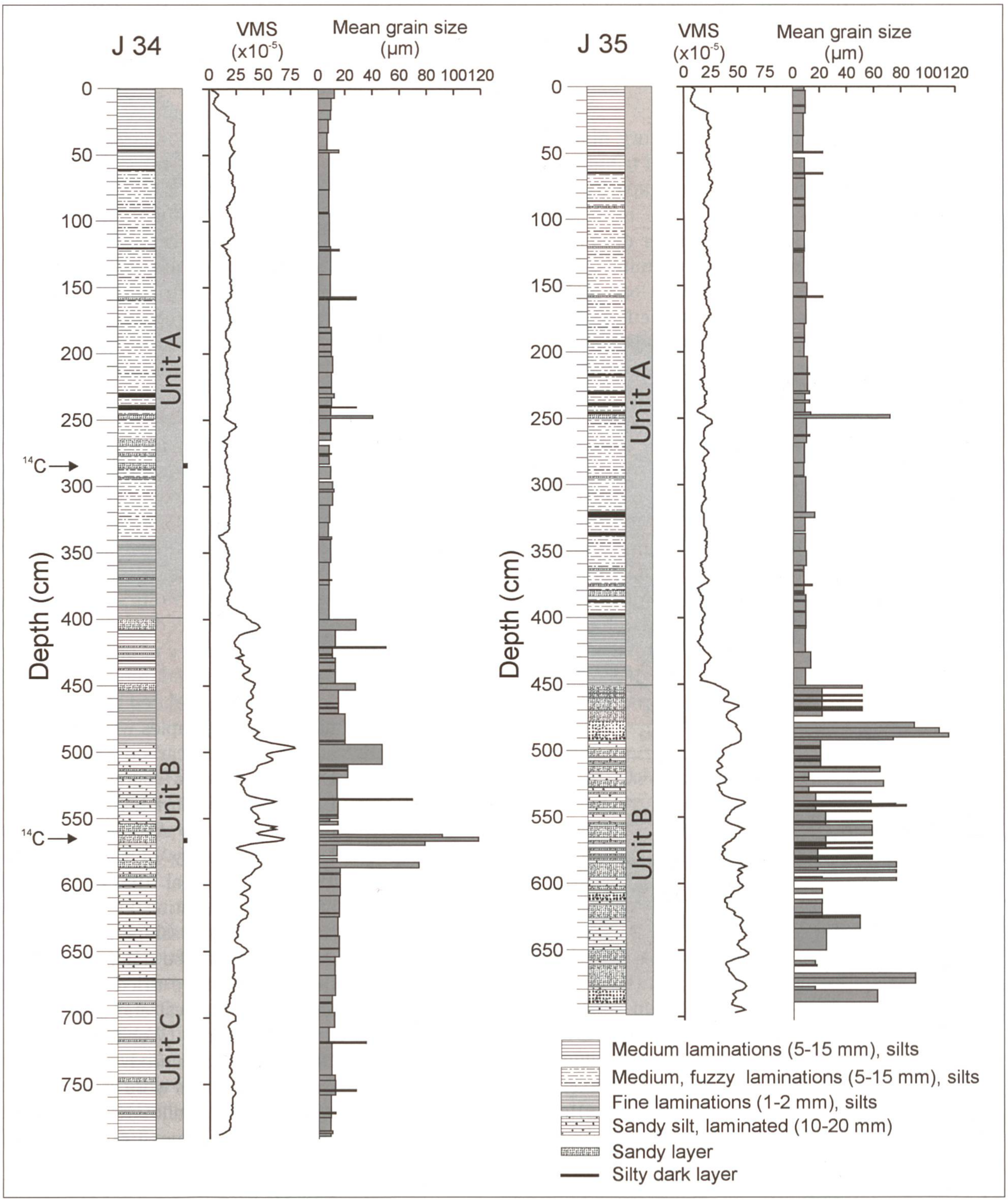

Fig. 3. Lithology, volume magnetic susceptibility (VMS), and mean sediment grain-size of cores J34 and J35. Levels of AMS 14C dating are shown on core J34.

consisted in a facies change with a sharp boundary that allowed defining two seismic units (Units 1 and 2). The seismic facies of Unit 1 consisted of medium to strong amplitude, undulating parallel and continuous reflections with rare hyperbolas, which were probably due to a 3D effect of bumpy delta structure. The seismic facies of Unit 2 consisted of strong to very strong amplitude chaotic reflections with very frequent hyperbola structures. A clear thickness decrease from the region close to the river mouth towards the deepest basin eastwards was observed, which certainly reflects the direct influence of the Rhône River sediment load. Assuming a sound velocity in the recent sediment of 1480 m/s (Girardclos et al. 2007), Unit 1 was more than 20 m thick at 2.5 km from the mouth, whereas it was less than 5 m thick 7 km away.

Unit 1, described as the 'upper sequence' in Zingg et al. (2003) and Dupuy (2006) with a lower boundary called 'M'reflector, was also present in this lower resolution seismic data and displayed similar seismic facies and thickness distribution. The seismic data processing also showed that frequent hyperbolas of Unit 2 on unmigrated lines could be interpreted as internal discontinuities due to coarse sediment (Zingg et al. 2003).

The sedimentary record

The sediment record showed two contrasted facies, represented on one hand by Units A and C, and on the other hand Unit B (Fig. 3). Unit A, present from 0 to 400 cm core depth in J34 and down to 450 cm core depth in J35, as well as Unit C (from 650 to 790 cm core depth in J34), consisted of alternating sequences of very fine (1 mm) to thick (5-15 mm) lamina of fine silts, rarely interrupted by fine sandy deposits or dark layers. Unit B was marked by a sharp increase in mean sediment grain size and consisted in alternating layers of silty and sandy sediments. Its lower boundary was defined at 670 cm core depth in J34 but could not be reached in core J35. Thus Unit B had a minimum thickness of 260 cm. The VMS profile showed, from top to bottom core, values around $25 \cdot 10^{-5}$ in Unit A, increasing to $\sim 50\text{-}75 \cdot 10^{-5}$ in Unit B, and decreasing to $25 \cdot 10^{-5}$ in Unit C, which correlated with variations in sediment grain size.

Seismic-to-core correlation, based on calculated depth, allowed attributing the seismic discontinuity from Unit 1 to Unit 2 to the sedimentary change from Unit A to Unit B. The high reflectivity of Unit 2, which reduced the seismic penetration, combined to the gradual sedimentary change from Unit C to B, prevented detecting the sedimentary facies change of Unit C on the seismic record.

Radiocarbon dating and age-depth model of the sedimentary record

Two lignin samples were selected for radiocarbon dating in core J34 at 268cm- and 564 cm-core depth (Table 1). The calibrated age of the deepest sample (568 cm, Unit B) ranged from 1320 to 1440 AD (rounded to the nearest 10 yr), with a higher probability (71 per cent) between 1390 and 1440 AD. The sample in Unit A (284 cm) gave an uncalibrated date of 135 ± 55 y BP. The calibrated age ranged between 1680 and 1952 AD. The highest probabilities were a date between 1720 and 1760 AD (25 per cent) and between 1830 and 1890 AD (30 per cent), respectively. Evidences from an adjacent ^{137}Cs- and Hg-dated short sediment core (J24; Loizeau et al. 1997; Dominik et al. 1991, 1992) and correlation with core J34 with VMS signal (data not shown) allowed to reduce the possible age range of this Unit A sample. The beginning of industrial Hg contamination is observed in the sedimentary record around 1880-1900, therefore the end of the 19th century was positioned at about 40 cm sediment depth in J34. This excludes AMS ^{14}C dates younger than 1880. Moreover, it is unlikely that 240 cm of fine grained sediments were deposited in about 50 years without drastic changes in sediment structure and texture in Unit A. These observations restricted the possible date range of the Unit A sample (284 cm) to 1680-1760 AD, with the highest probability between 1720-1760 AD (Table 1). An age model was drawn from the median points in range of possible dates (Fig. 4), thus giving a mean sedimentation rate of 0.93 cm y^{-1} from the 15th to the mid-18th century. When SARs were expressed as a sediment thickness deposited per year (cm y^{-1}), differences between contemporaneous and historical ranged between 0.7 and 1.1 cm y^{-1}. However, this method of computing the sediment rate didn't take into account variations of sediment compaction, revealed by porosity changes. Surface sediments were less compact than deeper sediments, with mean water contents of 70 and 40 per cent, respectively (data not shown). Using these values and a mean particle density of 2.6 g cm^{-3}, mass-based SAR were estimated to 0.25 g cm^{-2} y^{-1} during the last century and to 0.88 - 1.07 g cm^{-2} y^{-1} between the 15th and 19th centuries, that is a four-fold reduction during the last century (Fig. 4).

Table 1. Radiocarbon dating of core J34, age ranges as calculated by the software Calib 5.2 (Stuiver and Reimer 1993, at site http://www.calib.org/calib).

Sample (core/depth)	^{14}C yr BP	Cal AD age range	Probability* (1 sigma)
J34/284 cm	135 ± 55	1680- 1707	0.152
		1719- 1764	0.247
		1774- 1775	0.005
		1800- 1826	0.138
		1832- 1886	0.300
		1913- 1939	0.149
		1951- 1952	0.009
J34/568 cm	530 ± 55	1323- 1347	0.288
		1392- 1438	0.712

*relative area under probability distribution, after the Reimer et al. (2004) dataset.

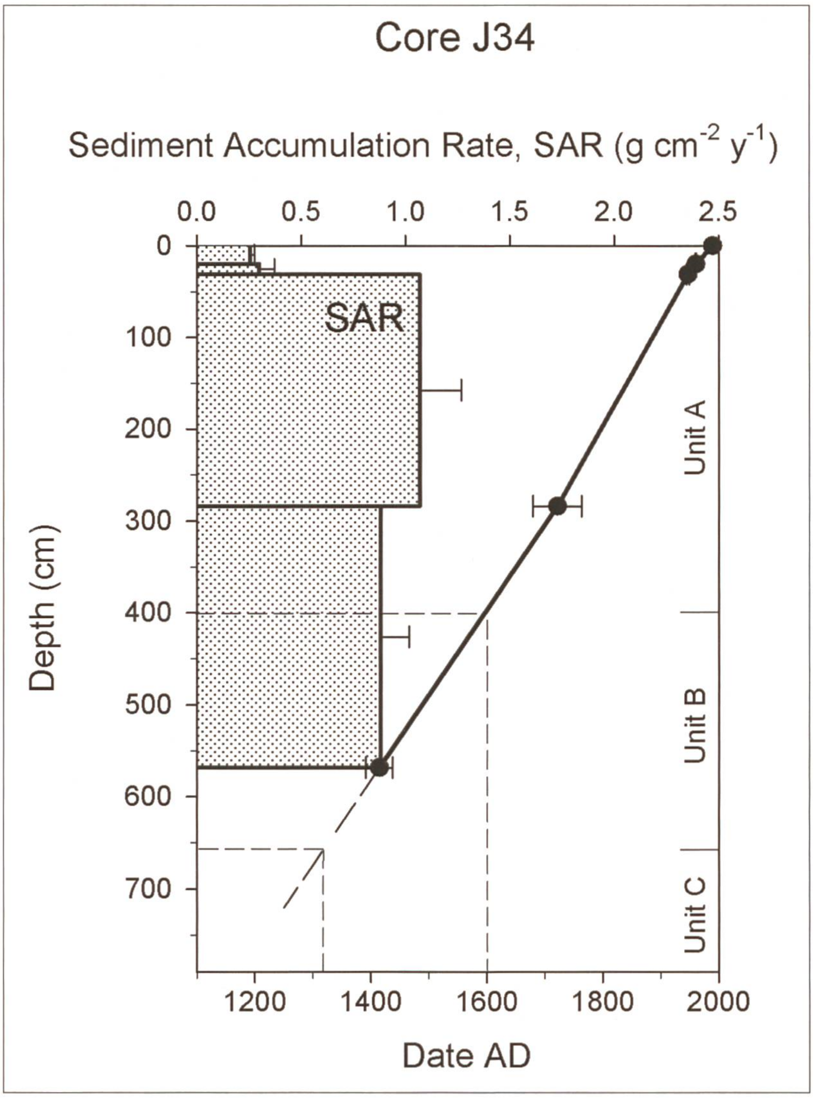

Fig. 4. Age-depth model and sediment accumulation rate (SAR; g cm-2 y-1) estimated in core J34. Dating is based on correlation of 137Cs and Hg profile on an adjacent core (Loizeau et al 1997), and the two AMS 14C dates. SAR is determined using a particle density of 2.6 g cm-3, and a water content of 70 and 40% for the 20th, and 15th-19th centuries, respectively. Uncertainty bars correspond to age ranges (cf. Table 1) and SAR ranges based on maximum age ranges.

Discussion

Various authors (Loizeau 1991; Zingg et al. 2003; Dupuy 2006) recognized the presence of the seismic Unit 1 over a large part of the delta. In the region where the two Kullenberg-type cores were collected, the transition between seismic Unit 1and Unit 2 was observed at a sediment depth lower than 5 m. As mentioned previously, it is thus likely that this transition corresponds to the change from sedimentary Unit A to Unit B.

The coarse grain size of Unit B, with layers of mean grain size in the coarse silt - sand range, implies a high-energy mode of sediment transport. The coarse grained layers could be due to turbidity currents initiated by hyperpicnal flows (e.g. Mulder et al. 2003; Chapron et al. 2005) resulting from large Rhone river floods or by the distal deposit of mass movements (e.g. Schnellmann et al. 2005; Girardclos et al. 2007). These coarser layers in Unit B are slotted with finer, silty sediment layers similar to those observed in Unit A, and can be interpreted as a 'hemipelagic' type of sediment interspersed with turbiditic deposits. From these observations we conclude that sedimentary Unit B (i.e. seismic Unit 2) was not deposited as a single sedimentological event, as it was previously proposed (Loizeau 1991; Zingg et al. 2003; Dupuy 2006) but rather reflects a period of time with increased coarse sediment input.

Based on extrapolation of sediment accumulation rates for the second half of the 20th century, Loizeau (1991) estimated the age of the transition between Unit 1 and Unit 2 ('M reflector') greater than 1000 years, and proposed that this discontinuity in the delta sediment record was linked to a catastrophic rock fall, the *Tauredunum*, which occurred October 3rd, 564 AD (Gisler et al. 2007). The present study, with new sedimentary and dating evidence, gave a much younger age for the discontinuity (~1600 AD), and point to an alternation of hemipelagic and turbidite deposits for Unit B, clearly indicating that this sediment sequence cannot be not due to a single catastrophic event. Therefore, the trace of the *Tauredunum* event should be found deeper in the sedimentary record. Moreover, extrapolation toward older sediment shows that the base of Unit B corresponds to about 1300 AD, and older sediment (Unit C) were very similar to those deposited as present Unit A. These modifications in particles size could be related to a shift in the active sub-lacustrine canyons and delta depocenters. The 20th century activity centre is located on the southern side of the delta, with the main canyon running along the southern side of the lake, and the presence of sand lobes at the end of this canyon (Loizeau 1998). A recent detailed map of the Rhone delta morphology (Sastre et al. 2010) shows the presence of several canyons in the northern part of the delta, which were certainly active in the past. Such a shift could be triggered by internal (e.g. canyon avulsion) or external drivers (major floods, earthquake). For instance, a good candidate is a major earthquake (Mw 6.4) that occurred in March 1584, with an epicentre around the town of Aigle, 12 km upstream the Rhone mouth (ECOS 2002). It produced a tsunami in the lake that destroyed two villages on the lakeshore. Such an event may deeply change the delta architecture and sediment routing on the lake floor.

A second observation is the 4-fold reduction of the SAR during the 20th century. Loizeau et al. (1997) have already shown a reduction factor of 1.2 to 2.4 in the sedimentation rate of the lacustrine Rhone River delta after the construction of hydropower dams in the mid-20th century, probably due to sediment trapping in reservoirs.

A complementary explanation for higher SAR in the 16th and 18th centuries compared to the first half of the 20th century could be related to a change in particle source. Many authors (e.g. Blass et al. 2005; Leemann 1993; Leonard 1997) have shown that higher sediment yields are recorded during glacier advance. Therefore the glacier recession following the Little Ice Age (1550-1850 AD) observed in the Alps (Collins 2008) may explain the decrease of sediment inputs in the 20th century.

Conclusion

New evidence from sedimentary structures and AMS ^{14}C dating revealed an episode of coarser sediments (Unit B) deposited between 1300 and 1600 AD in the distal part of the Rhone Delta in Lake Geneva. The transition from the upper sequence (Unit A) and the coarser Unit B was recognized in the seismic record as a change in reflection characteristics. Previous studies attributed this change to deposits related to the catastrophic *Tauredunum* rock fall in 583 AD. The present results demonstrate that sediment of Unit B deposited seven centuries after the rock fall, hence this hypothesis is incorrect and traces of the giant *Tauredunum* rock fall have to be searched deeper in the sediments, or further downstream in the lake. The sediment accumulation rates between the 15th and 19th century were at least four times higher than those observed during the last century. Further studies on the whole watershed are needed to evaluate the respective role of the various processes involved in sediment particle yield in the significant SAR decrease, such and glacier recession, reforestation and land use change.

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