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Research paper

The role of mass-transport deposits and turbidites in shaping modern lacustrine deepwater channels

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ABSTRACT

Subaquatic canyons are an important pathway for sediment transport into oceanic and lacustrine basins. Understanding the mechanisms governing their geomorphological evolution is a key to predict the sediment distribution patterns through these sediment conduits as well as to implement geo-hazard assessments. Submerged channels developed in large lacustrine basins offer a small-scale natural laboratory to understand the sedimentological processes operating in submarine channels. For this reason, a multidisciplinary research initiative -including time-lapse, high-resolution bathymetric surveys, innovative coring using submersibles, *in situ* geotechnical tests, and geophysical and sedimentological analyses- was applied to unravel the factors controlling the geomorphological evolution of the Rhone delta channels in Lake Geneva during the last decades. The morphology of the lacustrine Rhone Delta consists of a freshwater delta system deeply incised by nine canyons (C1–C9). Geotechnical measurements in proximal areas and sediment cores retrieved in the distal fans at the end of each canyon revealed complex sediment dynamics. No turbidity current events have occurred in the easternmost canyons (C1–C4) during the last decades while the western canyons sediment record (C5–C9) indicated repeated flushing events during the 20th century. The main “active” canyon C8 has been dominated by turbidite activity on the canyon floor with frequent overspill events along the levees. A large $6.2 \times 10^6 \text{ m}^3$ Mass-Transport Deposit (MTD) that resembles a debris in its upper section was found in the distal area of the active channel. The MTD was dated at 1998–2000 CE and most likely originated from proximal delta areas affected by frequent slope failures of the steep channel walls. *In situ* geotechnical tests on the modern proximal channel floor showed an unconsolidated soft top-layer that might have served as a low-friction surface favouring the MTD long run-out distance to the distal part of the channel. The MTD has had a major effect morphological evolution of the distal channel by filling the existing conduit, indirectly promoting the formation of a new channel. The role of MTD emplacement in subaquatic channels has important implications for hydrocarbon exploration as they control channel avulsion processes and the location of sand-prone deposits. This study gives a detailed insight on poorly investigated short-term sedimentological dynamics that affect the long-term evolution of turbidite systems and channel migration processes. This detailed model of a river-dominated deep-lacustrine depositional system can be used as an analog for similar modern and ancient deep-water systems.

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1. Introduction

Modern subaquatic channels located on continental margins and in deep lakes are important features that funnel large amounts of sediment from land to the deep ocean and lake basins.

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Understanding their geomorphological evolution and related depositional patterns have significant economic consequences as they provide insight on processes which controlled ancient deep water hydrocarbon-bearing channels (Abreu et al., 2003; Mayall et al., 2006; Posamentier and Kolla, 2003). The interplay of erosion and sedimentation by low-density hyperpycnal currents constantly reshapes underwater channel-levee complexes (Posamentier and Kolla, 2003; Puig et al., 2014). Mass-Transport Deposits (MTDs) are also conspicuous components in the stratigraphic record that deeply modify the shape of subaquatic channels and contribute to their sediment infill, while possibly even acting as stratigraphic seals for hydrocarbon reservoirs (Alves et al., 2014; Cardona et al., 2016; Moscardelli et al., 2006). MTDs are also linked to some of the most important near-seafloor geohazards such as submerged slope failures with large tsunamigenic potential (e.g. Kremer et al., 2012). Thus, determining their triggers, emplacement, morphology and extent is crucial for deep-water hydrocarbon exploration as well as for geohazard assessments.

Recent studies using outcrops and 3D seismic imaging have thoroughly explored the role of MTD emplaced in channels (Bernhardt et al., 2012; Ortiz-Karpf et al., 2015), which control the distribution, morphology and evolution of avulsion lobe complexes in ancient records. Nevertheless, the response of turbidity currents to channel floor morphology inherited from prior MTDs is poorly understood (Bernhardt et al., 2012). Similarly, little is known in regards to short-term geomorphological changes affecting unconsolidated MTDs which might not be preserved in the sedimentary record. High-resolution time-lapse bathymetric datasets in modern subaquatic channels in lacustrine basins provide an excellent tool to investigate these processes. In particular, the availability of high-resolution bathymetric datasets (Girardclos et al., 2012; Kremer et al., 2015b; Sastre et al., 2010) and the well-known boundary conditions of the Rhone subaquatic channels in Lake Geneva (Switzerland/France) make this site a prime research location to investigate the depositional patterns of MTD and turbidites operating in deep-water channels.

In recent years, multidisciplinary research efforts in the Rhone Delta in Lake Geneva have been undertaken to explore the active Rhone subaquatic canyons (Corella et al., 2014; Girardclos et al., 2012; Kremer et al., 2015a, 2015b; Lambert and Giovanoli, 1988; Loizeau, 1991; Loizeau et al., 1997; Sastre et al., 2010; Stark et al., 2013). Overall we synthesize the resulting time-lapse bathymetric dataset incorporating new sedimentological and geotechnical analyses using innovative sampling techniques via manned submersibles and research vessels. This study has a twofold aim: i) proposing a depositional model for river-dominated sub-lacustrine channels; ii) investigating the role of MTDs and turbidites in the evolution and maintenance of the Rhone sub-aquatic channels in Lake Geneva as well as their geohazard and economic consequences.

2. Study site

Lake Geneva (372 m a.s.l, 309 m depth) is a large deep-water basin in central Europe and one of the largest freshwater lakes in the continent (Fig. 1A). It covers a surface area of 580 km² and has a catchment area of 7420 km². The lake basin lies between the Jura Mountains and the Prealps. It was carved by glacial erosion into the Molasse bedrock during the Pleistocene (Wildi and Pugin, 1998). Lake Geneva is monomictic and it is mainly fed by the Rhone River (82% of the total water inflow to the lake (OFEV, 2009)). Several small tributaries also discharge in the Rhone Delta, such as the Eau Froide, Grand Canal, and the Stockalper Canal (Fig. 1B). The Rhone River watershed (5240 km²) is entirely located in the Alps and shows a high altitudinal gradient (mean altitude of 2130 m,

maximum of 4634 m; OFEV, 2009). The watershed lies in igneous, carbonate and metamorphic rocks such as granites, ophiolites, gneiss and micaschists from the Alpine geological nappes (Kremer et al., 2015a). The Rhone river contributes an average water inflow of 182 m³/s to the lake and generates frequent sediment-laden underflows. A prior study in the Rhone Delta documented more than 30 underflow events over a period of 78 days in the summer season, most of them being related to hydrological events recorded upstream in the Rhone River (Lambert and Giovanoli, 1988).

Morphologically, the Rhone Delta in Lake Geneva represents a complex freshwater delta system deeply incised by nine channels (C1–C9), of which only one (C8) remains active nowadays (Corella et al., 2014; Kremer et al., 2015b; Sastre et al., 2010, Fig. 1B). The two easternmost canyons C1 (1.02 km-long) and C2 (1.20 km-long) are the shortest canyons in the Rhone Delta. C1 is connected to a small river inlet (Eau Froide River, Fig. 1B). Both canyons have smooth morphologies and their sinuosity index (SI; calculated as the ratio of the distance along the channel axis to the straight-line valley length) is ~1, classifying them as “straight” channels according to Clark et al. (1992). The canyons C3 (5.87 km-long, SI-1.08) and C4 (5.42 km-long, SI-1.14) show complex canyon heads and share a common distal canyon at ~140 m water depth (Sastre et al., 2010). The westernmost canyons are longer, more incised and display steeper slopes. C5 (9.41 km-long, SI-1.27) is the second canyon in terms of length and sinuosity. In its proximal and middle sections, C5 is deeply incised in the remnants of a wider paleochannel. This canyon was probably connected to the Vieux-Rhone, a former mouth of the Rhone River that was blocked at the end of the 19th century (Sastre et al., 2010). Canyons C6 (2.82 km-long, SI-1.22) and C7 (3.81 km-long, SI-1.3) are the narrowest canyons with headwaters located at the northern proximal levee of the main canyon C8 (Fig. 1) while the southernmost canyon C9 (5.14 km-long, SI-1.1) shows a canyon head close to the Stockalper Canal (Sastre et al., 2010).

The active channel C8 is 13.87 km-long, with a low sinuosity (SI = 1.12) connected to the Rhone River mouth and extending distally to the deep lake basin, reaching a water depth of 309 m (Fig. 2) (Loizeau et al., 1997). The northern levee is significantly higher and displays steeper slopes than the southern counterpart (Girardclos et al., 2012; Sastre et al., 2010). The proximal channel-levee complex extends along the first 6 km down to 225 m water depth (Fig. 2). This area is characterized by widespread undulating bedforms on the thalweg and multiple recent, crescent-shaped slide scars on the sidewalls of the channel (Girardclos et al., 2012). The slope along the thalweg is 2.1° on average. Sidewalls of the channel display inclinations up to 45–50° (Fig. 2). The adjacent downstream part of the channel floor between 225 and 250 m depth – i.e. 6–10 km from the river mouth – lacks detectable bedforms in the bathymetric data and is characterized by a significant reduction of the slope along the thalweg (0.4° on average) (Fig. 2). The distal channel shows large areas covered with sand waves (Girardclos et al., 2012) and a slight steepening of the slope (0.8° on average) (Fig. 2).

3. Methods

3.1. Sediment coring

Several sediment cores were retrieved in August 2011 in the distal areas of the nine channels (CAN01 to CAN09, Figs. 1 and 3) using standard UWITEC gravity coring tools from a surface vessel. In order to complement the dataset, additional sediment cores were retrieved in the proximal (LP, 103 m depth), middle (LM, 160 m depth) and distal (LD, 220 m depth) areas of the northern levee of the active canyon C8 (Fig. 2B) (Corella et al., 2014), in proximal,

Fig. 1. Inset with (A) Lake Geneva bathymetry and location in western Switzerland, (B) Multibeam bathymetric map recorded in 2008 CE (modified from [Sastre et al., 2010](#)) with sediment coring and geotechnical testing (numbers 1 to 7) sites in the nine Rhone Delta subaquatic channel thalwegs (C1 to C9).

middle and distal areas of the canyon floor (Can08-4, Can08-3 and Can08-2; 130, 188 and 236 m depth respectively) ([Fig. 2C](#)) and on the southern proximal (S-LP, 110 m depth), middle (S-LM, 175 m depth) and distal (S-LD, 226 m depth) southern levee ([Fig. 2B](#)). Underwater manned vehicles were used to obtain complementary sediment cores where the topography or sediment properties impede standard gravity coring methods. Thus, in February 2002, the robotic arms from the F.A. Forel submersible collected a sediment core in a peculiar structure with strongly compacted sands in the distal active canyon C8 (VS 18, 269 m depth; ≈ 10 km from the river mouth, [Fig. 2A](#)). In June 2011 another two cores were retrieved, one at the same location (M16d) and the other one in the newly-developed distal channel (M7d) using the MIR submersibles operated by the Russian Academy of Sciences.

3.2. Bathymetric surveys and visual observations in the active canyon

Geomorphological changes in the distal area of Lake Geneva's active canyon were investigated in detail using four bathymetry datasets recorded between 1986 and 2012. Single beam echosounders were used in 1986 (Krupp Atlas Echograph 450) ([Loizeau, 1991](#)) and in June 2000 (Marimatech E-Sea Sound 206C) ([Sastre, 2003](#)) ([Fig. S1](#)). Later, complementary datasets were

recorded with multibeam echosounders: a SeaBeam 1050 with 3° beam width in 2008 (5 m cell-size) ([Sastre et al., 2010](#)) and a Kongsberg EM 2040 with 1° beam width in 2012 (2 m cell-size) ([Girardclos et al., 2012](#)). Volumetric calculations were performed using the GIS 3D analysis "surface-volume" tool after surface homogenization by implementation of a triangular irregular network over discrete bathymetric points and inverse distance weighing.

3.3. In-situ geotechnical testing

In situ geotechnical surveys using the portable free-fall penetrometer NIMROD were performed along the proximal canyon floor in the subaquatic canyons C3, C5 and C8 ([Table 1](#), location [Figs. 1 and 2](#)) to provide complementary information on the geotechnical characteristics of the superficial sediment. NIMROD measurements were carried out from a small research vessel. This penetrometer yields the sediment strength along a vertical profile and the layering of shallow sediments ([Stark et al., 2013](#)). The approach described in [Stark et al. \(2009\)](#) was used to estimate an equivalent of quasi-static bearing capacity (QSBC) that accounts for changes in penetration velocity, which result in non-linear coupling effects between the penetration velocity and the estimated sediment strength. The obtained quasi-static bearing capacity (QSBC) is thus a measure of the sediment strength (or resistance to insertion)

Fig. 2. Multibeam bathymetric map from active canyon C8 recorded in 2012 CE (Girardclos et al., 2012) and down-channel slope gradient profile of the canyon floor. The bathymetry map shows the location of sediment cores and geotechnical tests sites. (A) Sediment cores M16d, M7d and VS18 retrieved in the 1998–2000 MTD deposit. MS16d and VS18 were retrieved in 2011 CE and 2002, respectively. Logs from left to right: core depth (cm); sediment-core images, interpreted lithology, density, magnetic susceptibility, water content, grain-size (sand/silt ratios; thin blue line indicates the mean grain-size); Vane shear strength profile is also shown for core M7D. (B) Sediment cores from the northern canyon levee (LD, LM, LP; Corella et al., 2014) (top) and southern levee (S-LD; S-LM; and S-LP) (bottom). (C) Sediment cores retrieved in the proximal (CAN08-4; Corella et al., 2014), middle (CAN08-3) and distal canyon floor (CAN08-2 and CAN08-1). Core depth (cm), sediment core images and lithology are shown for all the cores. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

after correcting for the effects of changes in the penetration rate and penetration surface area.

3.4. Laboratory analyses

Physical properties (magnetic susceptibility, density) of the entire cores were measured every 5 mm with a Geotek multi-sensor core logger (MSCL). Cores were split lengthwise in two halves afterwards and photographed using a digital camera under controlled-light conditions. Sediment lithology was visually described including colour and textures. Grain-size distributions of the sediment were measured in the sediment cores with sample-spacing ranging from 1 to 4 cm using a Coulter LS100 particle-size analyzer. Discrete samples were freeze-dried to estimate sediment water content. Shear-vane tests were carried out on core M7d to measure the sediment shear strength with a 5 cm spacing using a HM-504A pocket shear-vane device, with a rotation speed of $\sim 30\text{--}40^\circ/\text{min}$ until the peak shear strength was exceeded.

4. Results

4.1. Sedimentary facies distribution in the Rhone Delta subaquatic channels in Lake Geneva

The sediment record of the distal part of the four easternmost canyons (C1 to C4, Figs. 1 and 3) displayed typical hemipelagic sediments consisting of couplets of brownish organic-rich silty layers and sub-mm thick calcite-rich white laminae. Calcite layers probably originate from endogenic calcite precipitation linked to spring-summer algal blooms (Wunderlin et al., 2014). The couplets are punctuated by mm-to cm-thick dark-grey silty detrital layers (Fig. 3) that reflect the allochthonous input into the lake, mostly transported within the Rhone river plume and dispersed northward during interflow events, due to predominant current patterns in the eastern region of the lake (Giovannoli, 1990).

Sediment cores in the distal part of western canyons C5, C6, C7 and C9 were composed of hemipelagic sediments alternating with 1–7 cm-thick sandy turbidites. These turbidites showed a fining-upward pattern topped by a layer of fine sediments (Fig. 3). On the proximal active C8 canyon floor (Fig. 3; cores Can08-4 and Can08-3) amalgamated, dm-thick coarse sand turbidites were found. Sedimentation in the middle by-pass area of the C8 channel consisted of alternating hemipelagic sediments and thin turbidites (core Can08-2). In the distal C8 canyon part, dm-thick, coarse sand turbidites were observed that were interpreted as the onset of a distal depositional area (core Can08-1). Sediment cores from the levees of canyon C8 displayed alternating hemipelagic sediment layers and cm-thick turbidite layers that decrease in thickness towards distal areas of both the southern and northern levees and likely originate from overspill events (Corella et al., 2014) that decreased in thickness towards distal areas on both the southern and northern levees (cores LP, LM, LD, S-LP, S-LM and S-LD; Fig. 2B).

4.2. Geotechnical testing in the proximal channels

In the canyon floor of the active (C8), intermittently active (C5) and inactive (C3) submerged channels QSBC profiles (Table 1) indicated a thin and soft top layer that could represent either stirred-up sediment in the process of sediment remobilization and/or sediment recently deposited with a lower state of consolidation (Stark et al., 2013).

In the active C8 canyon, the penetration depth was limited to 6–7 cm and QSBC equivalents ranged from 17.5 to 24 kPa. On the thalweg of the proximal C8 canyon (18–145 m water depth), the soft top layer thickness progressively increases from East (2 cm; site

1) to West (5 cm; site 3) (Fig. 4). In the proximal part of intermittently active canyon C5 (37 and 85 m water depth) and inactive canyon C3 (18 and 63 m water depth) the penetration depth was much higher and ranged from 20 cm to 65 cm with QSBC equivalents from 2.1 to 10 kPa. In both canyons the top layer thickness does not show significant fluctuations with water depth (Table 1). Geotechnical testing at the proximal part of the inactive canyon C3 showed thicker soft top layers (17 and 18 cm) than in C5 and C8 in both shallow (site 6; 18 m water depth; 17 cm top layer thickness) and deeper sites (site 7; 63 m water depth; 18 cm top layer thickness).

4.3. Recent Mass-Transport Deposits (MTD) in the active C8 canyon

4.3.1. MTD geomorphological and volumetric characterization

A large MTD situated in the distal depositional area of the channel C8 (dashed red box in Fig. 2) was first discovered in 2000 CE by comparing two bathymetric datasets recorded in 1986 CE and 2000 CE (Loizeau, 1991; Sastre, 2003). This comparison indicated an underwater relief inversion with a 10 m-thick mound-like structure replacing the former channel pathway mapped in 1986 CE (Fig. 5). High-resolution multibeam bathymetry datasets acquired in the same area in 2008 CE and 2012 (Girardclos et al., 2012; Sastre et al., 2010) showed a relief consistent with the one initially mapped at lower resolution in 2000 CE (Fig. 2). Furthermore, the 2012 CE bathymetry revealed a lobate lake floor morphology covering the mound structure over a $\sim 1.3 \times 0.6 \text{ km}^2$ area, and was interpreted as the original MTD surface morphology which has been overprinted by ongoing sedimentation (Fig. 2). Volumetric calculations between the 1986 CE and 2000 bathymetric datasets indicate that the deposit involved $\sim 6.2 \times 10^6 \text{ m}^3$ of sediment. The 2012 CE bathymetry map highlights the formation of a new 2.5 km long and 50 m wide elongated channel (Fig. 6). Volumetric calculations between 2000 CE and 2012 bathymetric surveys (Fig. 6) indicates that a total of $5.1 \times 10^4 \text{ m}^3$ of sediment has been removed by the incision forming the new channel representing a mean erosion rate of $4.2 \times 10^3 \text{ m}^3/\text{yr}$ for this feature.

4.3.2. MTD lithology

Sediment cores VS18, M7d and M16d were retrieved via manned submersibles on top of the MTD (Fig. 2A), allowing the lithological characterization of the MTD upper section. The lack of grading, the high density ($1.9\text{--}2.0 \text{ g/cm}^3$) and high shear strength (10–10.5 kPa), the very poorly sorted texture ($O_1 = 1.96\text{--}2.94$) and the high mud content (silt content: 15–20%), as well as the sharp grain-size drop at the top of the bed (Fig. 2A) are indicative of a debrite resulting from *en masse* deposition (Talling et al., 2007). Assuming that the observed density of 1.9 g/cm^3 for the upper sediment interval is applicable to the entire bed volume, this deposit is equivalent to a mass of $11.78 \times 10^6 \text{ t}$. A thin turbidite with a fining-upward pattern and a discrete coarse basal sublayer is overlying the debrite. The MTD deposit in M16d core, retrieved in 2011, is draped by 7.5 cm of hemipelagic sediments.

5. Discussion

5.1. Turbidite activity in the Rhone Delta channels in Lake Geneva

The Rhone Delta system in Lake Geneva is dominated by a complex interplay between turbidites funnelled through its sub-aquatic channels and hemipelagic background sedimentation. Fine-grained hemipelagic sediments record dilute suspension and fall-out clay sedimentation in the eastern channels and inter-channel areas (Loizeau, 1991) and within eastern canyon fan systems. On the other hand, turbidites in the Rhone delta area

Fig. 3. Sediment core data of inactive (top) and intermittently active canyons (bottom) in the distal part of the subaquatic channels in the Rhone Delta with core images, interpreted lithology, magnetic susceptibility profiles and grain size analyses (clay-silt-sand % and mean value as blue line) (coring sites located in Fig. 1, for grain-size legend see Fig. 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

represent gravity flow events channelized through the Rhone canyons with frequent overspill events in the levees (Corella et al., 2014). The Rhone turbidites in Lake Geneva greatly contribute to the sediment infilling of the deep lake basin (Kremer et al., 2015a).

The lack of turbidites in C1 to C4 sedimentary sequences indicates that these canyons have remained inactive during the last decades. Radiometric-dated cores in C1 and C2 (Wunderlin et al., 2014) lacked indicators of flushing events reaching the distal fans for the last 90 years suggesting a disconnection of the feeding river mouth (i.e. Eau Froide River) and its subaquatic counterpart C1 during the last century. The smooth morphologies of the eastern

inactive canyons shown in multibeam bathymetric imaging suggest that the occurrence of recent slope failures in the canyon walls is rather unlikely. This fact and the lack of turbidites recorded in C3 and C4 channel fans indicate that these canyons have remained inactive over the last decades. The low estimates of QSBC and a thick soft top layer identified at sites 6 and 7 in C3 (Table 1) suggested a more intense sedimentation and/or lack of remobilization of poorly consolidated sediment deposits (Stark et al., 2011), pointing to the likely absence of erosive underflows in the proximal C3 canyon floor.

The turbidites disrupting the hemipelagic sedimentation in the

Table 1Geotechnical results from *in situ* NIMROD measurements on the thalwegs from the proximal canyons C3, C5 and C8 shown in Fig. 1.

Canyon	Site nr./depth	Penetration depth (cm)	Impact velocity (m/s)	QSBC (kPa)	Top layer thickness (cm)	Hydrostatic pressure (kPa)	Excess pore pressure (kPa)
C8	1 (18 m)	6	3	24 ± 0.6	2	130	28
	2 (129 m)	6	2	24 ± 4	3	1233	43
	3 (145 m)	7	2	17.5 ± 2.5	5	1394	33
C5	4 (37 m)	65	4	2.1 ± 0.4	6	222	9
	5 (84 m)	28	3.1	2.8 ± 0.5	6	850	11.5
C3	6 (18 m)	25	2	3 ± 0.5	17	120	11
	7 (63 m)	20	2	10 ± 2	18	585	50

western canyons C5, C6, C7, and C9 indicated intermittent activity with occasional gravity flows flushing through the canyon during extreme flood events and/or subaquatic slope failures. The location of C6 and C7 headwaters at the northern proximal levee of the main canyon C8 suggest that turbiditic flows are most likely related to extreme hydrological events (i.e. underflows) funnelled through the main canyon that reactivated these secondary channels. Besides C8, canyons C5 and C9 apparently show the largest hydro-sedimentary activity as 6 turbidite events were recorded in their distal fans during the last decades. Geotechnical testing in the proximal canyon floor of C5 revealed that the soft top layer thickness at sites 4 and 5 (6 cm, Table 1) was thinner than soft top layer thickness recorded on the levees (10 cm, site 1 in Stark et al., 2013). This difference can be explained by a lower sediment accumulation in the proximal channel, likely resulting from erosive, ongoing underflow currents in the proximal area. Such intermittent inferred flushing events in canyon C5 might be linked to either i) an increase in the hydrological activity of the Grand Canal that feeds the Rhone Delta close to C5 headwaters (Fig. 1) and/or ii) slope failures related to the high sediment load from the river mouth. These alternate pathways of the river seemed to operate frequently in the emerged Rhone Delta before the 19th century Rhone canalisation. Indeed, Kremer et al. (2015b) recently discussed the reactivation of the Rhone Delta eastern canyons by channel switching, in relation to modifications in the subaerial sediment routing during a large historical flood of the 15th century (i.e. the 1469 CE centennial flood in the Swiss Rhone Valley).

5.1.1. Turbidites in the active canyon C8

Frequent underflows detected in the active canyon (Giovannoli, 1990) suggest that turbidity currents are a key factor controlling the morphology of the active canyon. Multiple coring across the active channel-levee system (Fig. 2B and C) revealed that processes operating throughout the channel certainly involve erosive, bypassing and depositional areas. Turbidite amalgamation in cores Can08-3 and Can08-4 as well as geotechnical testing at sites 1, 2 and 3 (Table 1) revealed stiffer sediments in the C8 thalweg than in other canyons, possibly pointing to ongoing erosion through underflow events in the proximal canyon floor that frequently remove loose top-layer sediments and prohibit a more significant accumulation of sediment. The strong inferred sediment dynamics and erosive processes indicate an active connection between the underwater canyon and the subaerial Rhone River mouth. The presence of hemipelagic sediments in the by-pass area pointed to a modification of the flow conditions most likely related to the change in slope gradient shown in Fig. 2. Thus, turbiditic flows would efficiently bypass the middle canyon leaving only reduced turbidite traces on the canyon floor (core Can08-2) and distal levees (S-LD and N-LD). In these flows most of the sediment would remain in suspension and be advected through the channel with little sediment re-entrainment. This possible process may also explain the observed absence of bedforms on the C8 canyon floor in this area (Girardclos et al., 2012). Thicker turbidites described in core Can08-1 suggest the deceleration of the flow and are attributed to the onset of the depositional area consistent with the position along the canyon where *in situ* observations during the MIR dives in 2011 CE showed an upward migration and dissipation of hyperpycnal currents (Corella et al., 2014).

5.2. MTDs in the Rhone Delta C8 active canyon

The time-lapse bathymetry campaigns and coring via manned submersibles enabled the investigation of the recently discovered MTD that is obstructing the main canyon (Figs. 2, 5 and 6). The available dataset provides a unique opportunity to elucidate its possible triggers, depositional processes and short-term geomorphological evolution.

5.2.1. MTD dating and triggers

Sediment core M16d retrieved in 2011 CE (Fig. 2A) is characterized by 7.5 cm of hemipelagic sediments deposited over the MTD. A mean sedimentation rate of 0.7–0.8 cm/yr was estimated for the last decade by correlating sediment cores VS18 and M16d, retrieved in 2002 CE and 2011, respectively. This sedimentation rate is consistent with the sediment accumulation rates ranging between 0.5 and 1 g cm⁻² yr⁻¹ (SR = ~0.4–0.8 cm/yr) calculated for the area by Loizeau et al. (2012). According to this sedimentation rate and to the time when the relief inversion was first discovered (May 2000 CE) (Sastre, 2003), and assuming that no sediment loss occurred during the coring operations, the MTD would have been

Fig. 4. Estimated QSBC (Quasi-Static Bearing Capacity) and deceleration-depth profiles from NIMROD testing in the proximal C8 channel from site 3 to 1 (for location refer to Fig. 1). Thin and thick grey lines indicate maximum and minimum QSBC values, respectively. The grey band indicates the thickness of the soft top-layer defined by the QSBC profiles. Further information is shown in Table 1.

Fig. 5. 3D Shaded relief of bathymetry map recorded in 2000 displaying a mound-like structure in the distal part of the Rhone Delta active channel. Colored points indicated the depth difference between 2000 CE and 1986 -modified from Loizeau (1991) and Sastre (2003) - (Fig. S1). Purple dotted line indicates the extent of the mound-like structure. For geographical location of Fig. 5 refer to the red outline rectangle in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deposited between 1998 CE and May 2000.

From the seismological, meteorological and hydrological catalogues (Fäh, 2011; OFEV, 2009), no instantaneous triggers such as earthquake shaking, strong winds, seiche wave, major flood, and/or rapid lake level change could be identified between 1998 and 2000 AD. Therefore, a spontaneous failure, likely due to sediment overloading, provides the best explanation for the slope failure related to the MTD, as already observed in other river-delta settings (Girardclos et al., 2007). In the proximal channel levees, the high sedimentation rate (>2.6 cm/yr) combined with elevated gas-related pore pressure (Corella et al., 2014; Sollberger et al., 2014), as well as the multiple recent, crescent-shaped slide scars on the sidewalls of the channel (Girardclos et al., 2012), allow the assumption of an initial failure in the proximal levees where slopes can reach up to 50° inclination (Fig. 2).

5.2.2. MTD transport mechanism

Previous studies that investigated cohesive debris flows leading to the formation of debrites similar to the one found in the Rhone Delta suggested *en-masse* deposition in relatively thin and laminar dense flows. In contrast to the turbiditic flows described in previous sections, debris flows seem to experience little mixing with the ambient sea/lake water and their occurrence is usually restricted to a relatively proximal setting, close to the initial slope failure. However, here the debrite was identified in distal areas of the channel (Figs. 2, 4 and 6). We hypothesize that the soft top-layer covering the proximal channel floor (Fig. 4) opposed less friction against the moving debris flow, enabling a longer transport path from proximal to distal areas in a manner similar to the shear wetting mechanism induced by a basal slurry layer proposed by Illstad et al. (2004) from laboratory experiments, and observed in large outdoor debris flow flume facilities (Iverson et al., 2011). We

assume that the low-strength soft top-layer of mud is frequently reworked by regular underflows, and thus was also present when the MTD was emplaced. The measured increase of downslope thickness of the soft top-layer (Fig. 4) may have promoted an increasing debris flow velocity down-canyon in the proximal area. This hypothesis corroborates large-scale laboratory experiments which have also shown that such a top fluidizing layer does not only accelerate the flow but also favours the entrainment of additional material from the canyon (Iverson et al., 2011). Furthermore, this soft top layer may have enhanced the mixing of the debris flow with the surrounding lake water and eventually led to the formation of an associated low-volume dilute turbidity current (Talling, 2013), possibly explaining the turbidite topping the debrite in cores VS18 and M7D (Fig. 2A). The abrupt decrease in the slope from 2.1° in proximal areas to 0.4° at the onset of the bypass area (Fig. 2) most likely slowed down the debris flow, bringing the MTD to a halt at the onset of the depositional area, i.e. ~ 9 km away from the river mouth.

5.2.3. Implications for geohazard assessments

Mass movements that drive MTDs occurrence have significant hazardous implications as they are capable of damaging costly sea floor installations and sub-sea communication cables (Bruschi et al., 2006; Carter et al., 2014) and/or generate large tsunami waves threatening coastal communities. As an example, the Nice airport scarp failure in 1979 evolved into a hybrid flow that mobilized 8×10^6 m³ - similar to the volume displaced by the 1998–2000 CE MTD event - and triggered a tsunami wave 2–3 m height (Mulder et al., 1997). A simplified tsunami wave numerical model of Lake Geneva (Kremer et al., 2015c) has recently shown that mass movements involving sediment volumes of 10^6 – 10^7 m³ could lead to 1–3 m high waves, reaching the adjacent lakeshore in

Fig. 6. (Top) 2012 CE multibeam map of the distal area of the channel showing geomorphological features (Data: Girardclos et al. (2012)). (Bottom) Bathymetry difference map between 2012 CE and 2000 multibeam datasets revealing strong erosion and the development of a new narrow distal channel. Negative (red) values indicate erosion, positive (blue) values point to deposition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

only a few minutes. In the present case, no significant sudden lake level change was recorded in Lake Geneva limnological stations between 1998 CE–2000, *a priori* indicating that the 1998–2000 CE event did not trigger a tsunami wave. However, we cannot exclude that a small tsunami wave happened unnoticed by limnological instruments due to the long sampling intervals (every 15 min) and/or to the typical spline filtering that is applied to raw lake-level values to remove wind waves artefacts (OFEV, 2009). The lack of and associated tsunami can also be explained by a difference in sedimentary processes. Indeed, the tsunami numerical model of Lake Geneva was proposed for large initial mass failures when, in this case, the moving mass may likely have initially started with a small volume and probably increased in size during MTD evolution through erosion and re-entrainment processes.

5.2.4. The Mass-Transport Deposits control on sediment dispersal patterns and geomorphology of deep-water channels

The various types of MTDs that were described in the sedimentary record of the distal basin of Lake Geneva significantly contributed to the sediment budget of the deep lake basin with volumes ranging from 22×10^6 to 250×10^6 m³ (Kremer et al., 2015c). The mobilized volumes are in the same order of magnitude than similar events in the marine realm (Hampton et al., 1996;

Talling, 2014).

Recent MTDs emplaced within the channels likely play an important role in the sediment distribution and evolution of the active Rhone delta channel system. The 1998–2000 CE event involved an estimated 11.78 million tons of sediment, almost six times more than the annual Rhone River sediment load (OFEV, 2009). The resulting deposit that is still filling the former channel has modified the sediment pathways and dynamics in the distal channel area. We propose that the turbidity currents slow down and deposit a portion of their sandy, high-density loads just upstream of the MTD morphological high (Fig. 6, core Can08-1). This process might also explain the up to 5 m channel floor aggradation mapped between 2008 CE and 2012 in that area (Girardclos et al., 2012). This example highlights the potential for stratigraphically trapped sandstone accumulations in ponded MTDs mini-basins which are difficult to predict using seismic-reflection and/or well-logs datasets (Stright et al., 2013). The MTD control on turbiditic flows (slow-down and partial deposition) most likely also led to the formation of a new narrow and elongated channel as seen on the 2012 CE bathymetry map (Fig. 6) and to the observed re-formation of the buried channel segment through retrogressive breaching processes (Mastbergen and Van Den Berg, 2003). Although the tail of the former channel, initially mapped by Loizeau (1991), is still

visible in the recent bathymetry (Fig. 6), it was morphologically separated from the rest of the channel and is at present no longer active. The newly forming small distal channel is now 2.5 km long and 50 m wide and almost connecting with the broader upstream channel thalweg (Fig. 6). Between 2000 CE and 2012 almost ~1% of MTD total volume has been removed by incision to form the new channel (Fig. 6). The lack of a hemipelagic draping layer in the new-forming channel (see core M7d retrieved by MIR in 2011, Fig. 2A) indicated the existence of recent and most certainly ongoing flows that are flushing away fine sediment on a regular basis at a mean rate higher than $4 \times 10^3 \text{ m}^3/\text{yr}$. Thus, we can postulate that the presently forming channel will likely connect the new downstream channel to the main thalweg within the next few years, restoring a single main sediment conduit from the river mouth to the basin plain. It follows that the typical evolution of meandering channels with continuous channel amalgamation can be altered by abrupt morphological changes following MTD deposition, favouring channel switching processes. In the case of the Rhone Canyon in Lake Geneva, the presence of numerous abandoned channel relicts in the distal area close to the 1998–2000 CE MTD location (Fig. 6) suggests that this process is frequently changing the channel morphology. Hence, the impact of MTDs on deep-water channels evolution, currently largely underestimated, could explain some unsolved cases in alluvial fans and distal channels with rapidly evolving sediment dynamics and morphologies. Although this study showed that these types of beds are likely short-lived and may leave reduced traces in the sedimentary record, they also favor the migration of the distal channel course, ultimately controlling the location and extent of the distal fans where the largest deep-water sandy turbidites are emplaced.

6. Summary

The analyses of a multi-source dataset from the Rhone Delta in Lake Geneva allowed detailed investigations of the main sedimentological processes operating in this present sublacustrine channel. The depositional model proposed in this study may serve as an analog for other modern systems and also ancient submarine canyons. Hemipelagic sedimentation dominates in the easternmost inactive canyons, revealing a disconnection from subaerial river hydrological activity. The westernmost canyons record intermittent flushing events in the distal fans and ongoing erosive underflows in the proximal sections. The active canyon shows a complex sediment dynamics, with turbidite flows and overspill events on the levees, suggesting an active connection between the canyon and the subaerial Rhone River mouth. Time-lapse bathymetries, *in situ* observations and sediment coring via manned submersibles revealed a MTD blocking the distal active canyon. This MTD, dated at 1998–2000 CE, involved 11.78×10^6 tons of sediment. It was most likely initiated by a slope failure in the proximal levees due to preconditioning rapid sediment accumulation and high gas-related excess pore pressures. The identification of a thin soft top layer on the present proximal canyon floor points to shear-wetting processes allowing the debris flow to travel a presumed ~9 km run-out distance over low gradient slopes in the bypass area. The MTD seems to indirectly control the sediment pathways and geomorphological evolution in the distal channel. This evidence on how channel floor morphology, inherited from prior MTDs, is affecting the pathways of turbidity currents shows how turbidites may accumulate in sand-rich mini-basins created by MTDs. Down-canyon, a new channel has been forming rapidly during the last decade, most likely due to retrogressive breaching processes affecting the 1998–2000 CE MTD and sediment routing to the distal basin. Overall, this study exemplifies the short-lived nature of MTD emplaced in deep-water channels and highlights their significant

but currently underestimated role in the morphological evolution of underwater channels. This opens new perspectives for the interpretation of similar deposits in the geological records, which are difficult to predict with conventional well-log and seismic reflection datasets.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.marpetgeo.2016.07.004>.

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