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Morphology and recent history of the Rhone River Delta in Lake Geneva (Switzerland)

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Abstract The current topographic maps of the Rhone Delta—and of Lake Geneva in general—are mainly based on hydrographic data that were acquired during the time of F.-A. Forel at the end of the nineteenth century. In this paper we present results of a new bathymetric survey, based on single- and multi-beam echosounder data. The new data, presented as a digital terrain model, show a well-structured lake bottom morphology, reflecting depositional and erosional processes that shape the lake floor. As a major geomorphologic element, the sub-aquatic Rhone Delta extends from the coastal platform to the depositional fans of the central plain of the lake at 310 m depth. 9 canyons cut the platform edge of the delta. These are sinuous ("meandering") channels formed by erosional and depositional processes, as indicated by the steep erosional canyon walls and the depositional levees on the canyon shoulders. Ripples or dune-like morphologies wrinkle the canyon bottoms and some slope areas. Subaquatic mass movements are apparently missing on the delta and are of minor importance on the lateral lake slopes. Morphologies of the underlying bedrock and small local river deltas are located along the lateral slopes of Lake Geneva. Based on historical maps, the recent history of the Rhone River connection to the sub-aquatic delta and the canyons is reconstructed. The transition from three to two river branches dates to 1830–1840, when the river branch to the Le Bouveret lake bay was cut. The transition from two to one river branch corresponds to the achievement of the correction and dam construction work on the modern Rhone River channel between 1870 and 1880.

Keywords Bathymetry · Multi-beam · Delta topography · Lake Geneva · Rhone River Delta · Sub-aquatic canyons

Résumé Les cartes topographiques actuelles du delta lémanique du Rhône—et du Léman en général—sont largement basées sur des données hydrographiques anciennes, notamment de l'époque du chercheur F.-A. Forel, à la fin du 19ème siècle. Cette publication présente une nouvelle bathymétrie, basée sur des levés effectués à l'aide de sonars mono- et multifaisceaux. La carte montre une morphologie lacustre finement structurée. Le delta lacustre du Rhône s'étend de la large plate-forme côtière jusqu'à la plaine centrale du Léman à 310 m de profondeur. La bordure de la plate-forme est entaillée par les têtes de 9 canyons qui descendent le versant du delta en lacets («méandres»). Ces ravins correspondent à la fois à des phénomènes d'érosion, comme en témoignent les talus sub-verticaux, et à des structures de dépôt, comme l'indiquent les levées sur les épaules des canyons. Le fond des ravins, comme certaines surfaces de pentes en dehors des canyons,

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comportent des rides ou dunes de courants d'origine sédimentaire. Les structures de glissement sont pratiquement absentes sur le delta et n'ont qu'une faible importance sur les versants latéraux. Quelques morphologies rocheuses et de petits deltas de rivière sont collés contre les versants latéraux d'origine glaciaire du bassin lacustre. L'histoire de la connexion entre le Rhône et les différents canyons est reconstruite à l'aide de cartes historiques. La transition d'un Rhône à trois chenaux à une embouchure à deux chenaux s'est faite entre 1830 et 1840, avec la coupure du chenal menant à la baie du Bouveret. La réduction à un seul chenal date de 1870-1880, avec la coupure du Vieux-Rhône dans le cadre des travaux de correction du Rhône.

Mots clés Bathymétrie · sonar multifaisceaux · topographie deltaïque · Léman · Rhône · ravins sous-lacustres

Introduction

Deltas are highly sensitive interfaces between rivers and lacustrine or marine ecosystems. In particular, climate parameters that influence river runoff and soil erosion, but also tectonic and other geological processes as well as human activity may considerably change delta processes such as deposition and erosion, and therefore affect the morphology of the aerial and sub-aquatic parts of the deltas (e.g. Adams et al. 2001; Coleman 1981; Rust 1982). Deltas of perialpine lakes generally formed during the Late Glacial and the Holocene (Baster et al. 2003; Hinderer 2004; Jäckli 1958) when the proglacial lakes became gradually filled by the river loads. Proxies, such as pollen records, stable isotopes, authigenic carbonates contained in delta sediments, sedimentation centre migration and others, registered since then climate and environmental history, as well as the environmental impact of human activity (Girardclos et al. 2005).

Lake Geneva formed during the Pleistocene by glacial erosion (Wildi et al. 1999). The Rhone Delta of Lake Geneva (Fig. 1) is mainly the product of Late and Post-Glacial deposition of soil and rock erosion products due to glacial and river erosion. The surface of the drainage area is 5,220 km^2 with a mean elevation of 2,130 m, and the mean annual discharge of the Rhone for the years 1935–2004 is 182 m^3/s (maximum 227 m^3/s, minimum 127 m^3/s, OFEV 2006). The mean annual sediment load of the Rhone River at the monitoring station of "Porte-du-Scex" is 3,317 $\times$ 10^3 t (http://www.bafu.admin.ch/hydrologie). Runoff and sediment transport are strongly influenced by hydroelectric power production (Loizeau and Dominik 2000). The development of the sub-aquatic part of the Rhone Delta has been mainly investigated by high-resolution seismics and sediment core analysis (Loizeau 1991, 1998; Zingg et al. 2003), without any modern bathymetric data.

The topography of the lacustrine delta is represented on the official topographic Swiss maps at scales of 1:25,000 and 1:50,000 by isohypses of an equidistance of 10 or 20 m. The bathymetric data used for the establishment of these maps are however ancient. The first manual depth measurements have been performed on Lake Geneva by De Saussure (1779), De La Bèche (1819), Martins (1866) and Pictet-Mallet (1875). Forel (1892) published the hydrographic depth measurements established by Ph. Gosset and J. Hörnlimann, as part of the measurements for the «Siegfried Atlas» of Switzerland 1:25,000, and data of A. Delebecque for the French part of the lake. These maps

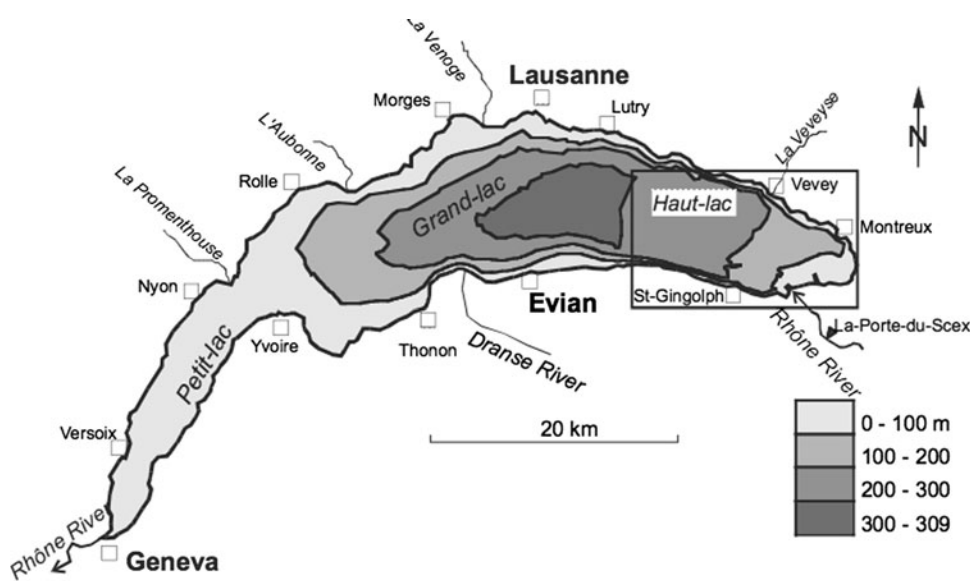

Fig. 1 Study area of the Rhone Delta on Lake Geneva

have only been modified locally for specific purposes during the last century.

The main topographic features discovered by Forel (1885, 1888, 1892) are the sub-aquatic canyons. The author described in particular the modern canyon of the Rhone with a length of 10 km, a width of 500–800 m and a maximum depth of 50 m. He also discovered secondary canyons to the East of the main canyon. Forel (1892) discussed in detail the three possible origins of the modern canyon that are: erosion, sedimentation and heritage from a former fluvial valley. The author argued that the river water entering the lake is generally colder (and thus denser) than the lake, and that this water is therefore flowing down the delta slope as a density current. The author concluded that the modern canyon is due to sediment erosion by this current and to deposition of sediments on the canyon shoulders. These density currents, with velocities of up to 1 m/s, have been measured in situ by Lambert and Giovanoli (1988) at a water depth of 150 m, almost a century after the work of Forel. These authors also put forward the role of sediment suspensions in turbidity currents, due either to the river input or to the detachment of unstable sediment deposits on the canyon walls. Sastre (2003) described the deposits of such mass movements of several tens of millions of tons of sediments in the distal part of the sub-aquatic fan of the Rhone delta.

With the support of Canton du Valais and contributions of the city of Montreux and the Canton de Vaud, we established a new single-beam bathymetric survey on the sub-aquatic Rhone Delta in 2004 and 2005. The results of this survey provided the motivation for a mandate by the Federal Office of Topography (Swisstopo) for a multi-beam pilot survey on the “Haut-Lac” of Lake Geneva. This survey was conducted in collaboration between the Institute Forel and the Renard Centre of Marine Geology. This paper presents the results of the surveys and a historical review on the link between delta morphology and the recent history of the Rhone River.

Bathymetric acquisition, data processing and mapping

Equipment and measurement methods

GPS positioning

A *Garmin-178* GPS instrument was used for navigation. A mobile *H-Tech* GPS recorded the precise position of the boat during single-channel acquisition. These positions were then corrected during post-processing with respect to the data of a fixed *H-Tech* GPS station installed at the Institute Forel (Versoix). A *Leica GX 1230* GPS system of Swisstopo with instant DGPS correction by GPRS transmission was used for the multi-beam survey. Despite the fact that this DGPS-correction was not always available, accuracy of positioning was within ±2 m for most boat positions.

Water temperature survey

As the sound velocity is a direct function of water density, and thus water temperature, temperature profiles were run daily, either with a *Züllig HPT Multi parameter sensor* (single-beam survey) or with a «*Sea and sun*» CTD sensor for the multi-beam survey. A CTD *Valport* sensor continuously measured the sound velocity near the transducers. Depth dependent water temperature data were used to compute water depth.

Sonars

A «*Marimatech* 206» sonar with frequencies of 33 and 200 kHz was used for the single-beam survey. Only data from less than 20 m water depth were used for the production of the bathymetric map (Fig. 3). One to six depth data per second, depending on water depth, were recorded on a lap-top computer. The multi-beam survey was carried out with a *Seabeam 1050* sonar from *ELAC Nautik*, with a frequency of 50 kHz. This system combines 108 beams on two transducers that covered a total angle of 120° and individual beam angles of 3° (Fig. 2). The multi-beam pings as fast as possible depending on the water depth. The 1 s GPS data are filtered (interpolated) via a *Kalman* filter and the motion sensor data (100 Hz update; heave, roll, pitch and heading) are online taken into account for beam forming, transmission and reception. The ping frequency was roughly between 300 ms and 2 s. Minimum water

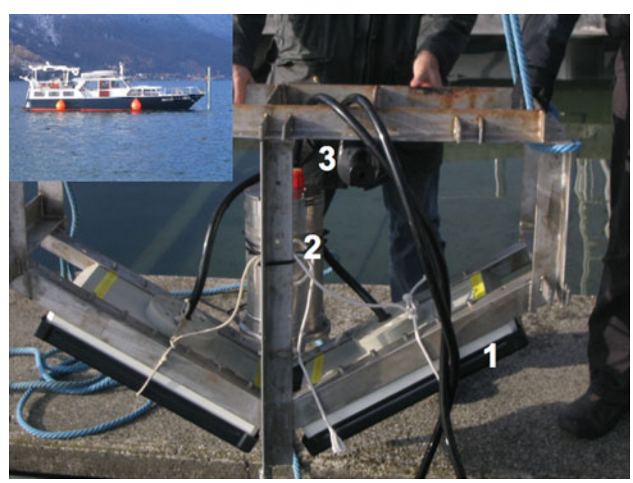

Fig. 2 Multi-beam antenna and working mode during data acquisition with the antenna fixed in front of the research vessel “La Licorne”. *1* Transducers, *2* Motion sensor, *3* CTD-sensor

depth for this application was about 20 m. The boat movement was corrected by a motion sensor *iXsea–octans 3000*. The multi-beam transducers were fixed on the bow of the boat.

Depth data from sonar measurements and pressure based sensor depth of the lake bottom was within a range of 1%. However, such comparisons are of limited significance, as the GPS position is only valid for the boat, but not for the sensor on the lake bottom.

Navigation

The single- and multi-beam surveys were mainly carried out with the 17 t research vessel "La Licorne" of Institute Forel. For shallow water depths along the coast, an open boat with a flat bottom was used.

Bathymetric survey

The single-beam survey was carried out in 2004 and 2005, during several short missions. Multi-beam data were acquired from 27 January to 9 February 2008, in almost homogenous lake temperature conditions (no thermocline). Navigation was performed along pre-defined routes. For the single-beam survey, in less than 20 m water depth, data were registered along shore parallel routes, with a horizontal distance of approximately 50 m between the profiles. For the multi-beam survey, results were registered and viewed on the board computer on-line. Navigation was carried out in a way to have a minimum overlap between the covered areas. Navigation velocity was between 4 and 6 km/h. Data were post-processed in the laboratory.

Post processing and mapping

Post-processing of single-beam data was carried out in the laboratory as follows:

- Correction of the survey GPS-position by data from the fixed GPS on shore. The files were correlated with the help of registered GPS-time. After correction, the accuracy of the positioning is ±1 m.
- Correction of depth values by:
    - Elimination of erroneous depth data (signals due to fish, plants, cables, etc.).
    - Calculation of water depth using data from the temperature profile.
    - Correction of lake level fluctuations according to data from the limnological station of St Prex (http://www.hydrodaten.admin.ch for).
    - Time correlation of depth and position data to establish a georeferenced data set.

Post-processing of multi-beam data was performed as follows:

- Cleaning of depth and position data with Nautik «*HDP Edit*» software: Elimination of erroneous GPS positions, of "noise" due to fish, plants, cables, etc.
- Establishment of final X, Y, Z data files with *Nautik HDP* post software, taking into account all relevant parameters, such as the sound velocity profile, heave role and pitch, GPS antenna offsets and lake level fluctuations. Final editing was done within the *Fledermaus* software package of *IVS 3D* (version 6.4).

For the establishment of the map and digital terrain model (Fig. 3), the coastline was digitized from the 1/25,000 topographic map and defined as 0 m water depth line. For the depth range from 0 to 20 m, single-beam x, y, z data were interpolated (by *kriging*) into a 5 m grid using *Surfer 8* (Golden Software). For water depths deeper than 20 m, multi-beam data were interpolated into a 5 m grid with GMT 4.2 (*Generic Mapping Tool*, Wessel and Smith 1998).

For further cleaning of depth data from erroneous signals and for map presentation we used *Fledermaus* (*IVS 3D* software). In order to visualize ripple structures and other eventual sedimentary figures, we renounced on smoothing residual irregularities of the lake bottom in areas based on multi-beam data (Fig. 3). Therefore small differences between grid-points may be seen on the map. In contrast to this, map areas based on single-beam data have been smoothed, to "hide" the survey routes.

Lake bottom morphology

The «Haut-Lac» of Lake Geneva is occupied by the proximal and distal part of the Rhone Delta and delimited by the lateral slopes of the lake basin, formed by glacial erosion during the last ice age (Fig. 3).

The mouths of the Grand-Canal, Vieux-Rhône and Rhone River constitute promontories of the coast line on the Rhone Delta between Villeneuve and Le Bouveret. The shallow lake plateau along the coast is the widest just to the west of Villeneuve, between Grand-Canal and the Rhone River mouth. This plateau is inclined towards the lake, and in general, forms a transition to the steeper slopes at a water depth of ~10 m. Two major gravel pits in the distal part of this plateau (Figs. 3, 5) are located in water depths of 20 m (G2) and 30 m (G1).

The canyons C1 to C9 (Fig. 3) are the most spectacular morphologies of the delta slopes. In their upper part, these erosive and depositional features may be formed by one or more separate channels. At the starting point of the canyons, the lake platform edge is deeply cut. The canyon beds are sinuous ("meandering"). After a straight channel axis

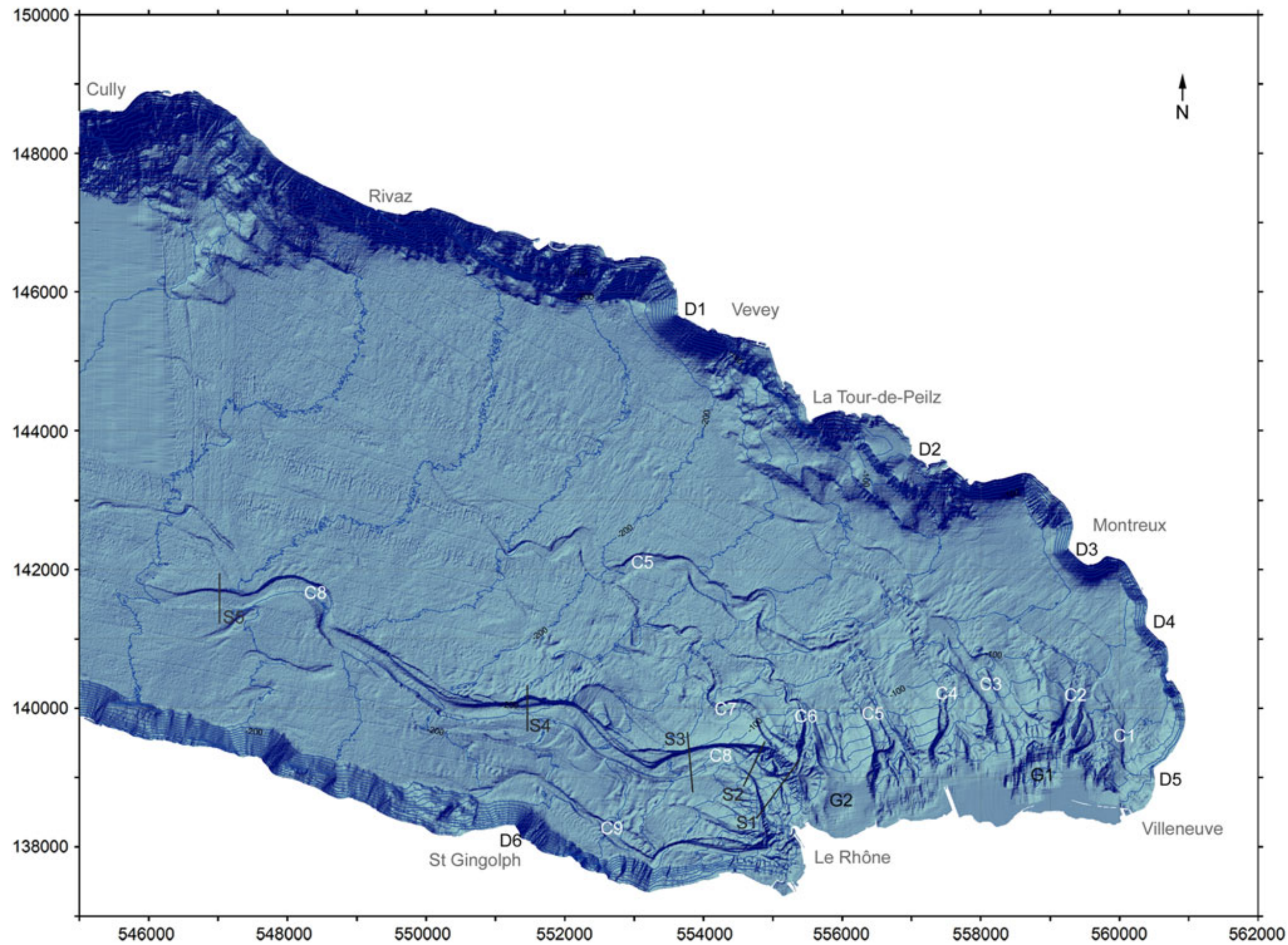

Fig. 3 Bathymetric map and digital terrain model of the Haut-Lac of Lake Geneva (light from NW). Equidistance of equal depth lines: 20 m. Swiss coordinates; lake level elevation: 372 m a.s.l. *C1–C9* Canyons of the sub-aquatic Rhone Delta, *D1* Veyveyse Delta, *D2* Baie de Clarens Delta, *D3* Baye de Montreux Delta, *D4* Veraye Delta, *D5* Tinière Delta, *D6* Morge Delta, *G1*, *G2* Main gravel pits, *S1–S5* transects in Fig. 6

in the approximate direction of the steepest slope, from the platform margin down to a water depth of 100–150 m, all the canyons first describe a left-turn, before turning back to the right. The sinuous channels may then be followed all the way down to the depositional fans. The canyon walls at the northern side of the channels are usually steeper than those on the southern side and have an erosive imprint. More or less explicit levee structures are frequently observed on both sides of the canyons. The delta surfaces between the channels are often occupied by current ripple morphologies. The different canyons are also characterized by the following particularities:

- C1 and C9 correspond to the depressions that delimit the delta with respect to the Rhone valley slopes. C1 corresponds to the sub-aquatic continuations of the Eau Froide River and a local affluent north of Villeneuve.
- C2 corresponds to a smooth canyon morphology, without any link to a modern river.
- C3 has a double, and in the upper slope, a triple channel (Fig. 4). Between 30 and 120 m depth, the eastern walls of the canyons are very steep. The lower and distal part of the canyon, form about 140–190 m water depth, is common to C3 and C4.
- C4 is expressed, down to 100 m water depth, by a complex canyon head. In the lower part, the canyon is linked to C3, with a long section occupied by current ripples or dunes (Fig. 4).
- C5 corresponds to the canyon of the «Vieux- Rhone» river channel (before it's correction) and is the second most important of all canyons in terms of length and width. In it's central part, a narrow channel cuts the wider and shallower, probably older main channel. The distal depositional fan is mainly located between 220 and 250 m water depth.
- C6 and C7 are well expressed, narrow channels. As their starting points are close to the present Rhone

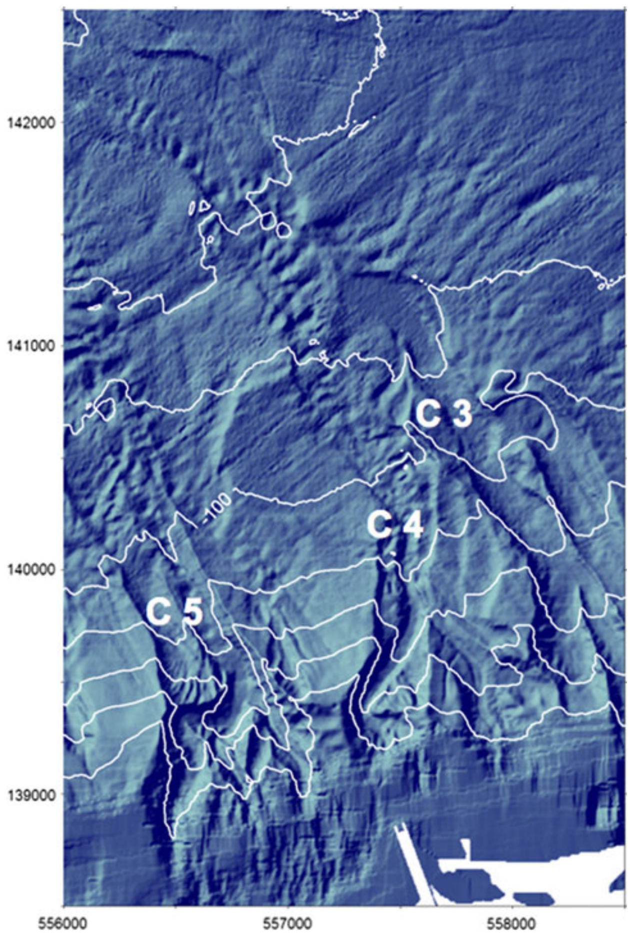

Fig. 4 Canyons *C3*, *C4* and *C5*; the canyon bottoms and the delta surfaces outside the canyons are occupied by current ripples and dunes. Equidistance of isobaths: 20 m

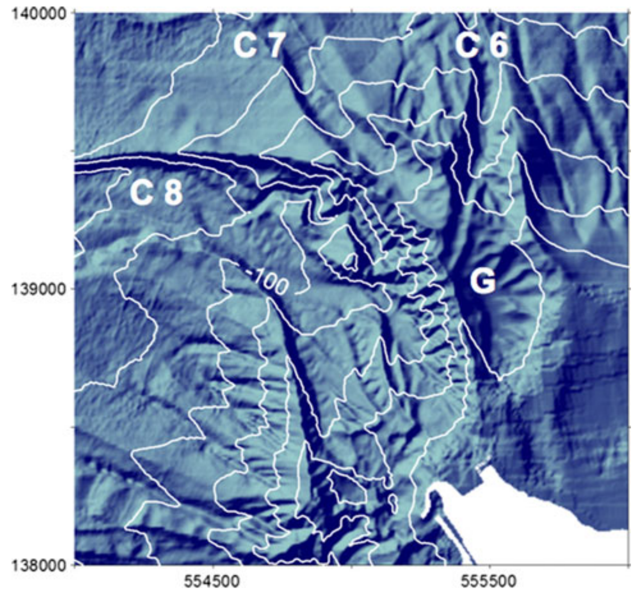

Fig. 5 Canyon head *C8*, corresponding to the modern canyon of Rhone River in Lake Geneva. The depression in the shallow part of the area corresponds to a gravel pit (*G*). Equidistance of isobaths: 20 m

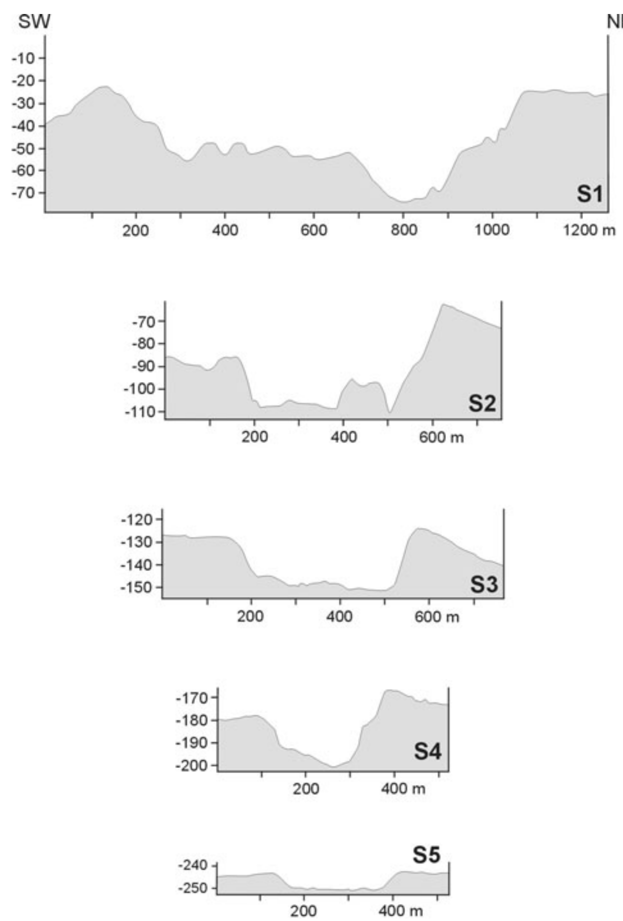

Fig. 6 Sections of the modern Rhone River Canyon *C8*, at water depths (canyon bottom) of 50 m (*S1*), 100, 150, 200 and 250 m (*S5*)

River mouth (Fig. 5), these canyons are likely still active during river floods, due to overflow of C8.

- C8 is the active modern canyon of the Rhone River described by different authors since Forel (1885). A complex sediment ridge occupies the centre of the channel in the uppermost part. In this section, the channel wall to the East of the canyon shows a multitude of erosional features, with small niches (Fig. 5).

  Close to it's head, the canyon has a depth of 50 m and a width of 1,000 m (Fig. 6). From 50 m to 200 m water depth, the north-eastern levee is higher than the south-western levee, most probably due to Coriolis deviation of the flow over the canyon levee. Depositional overflow structures are observed on the external slope of the south-western levee.

  Former, probably not any more active meander morphologies are preserved between 160 and about 180 m water depth on both sides of the main channel of the

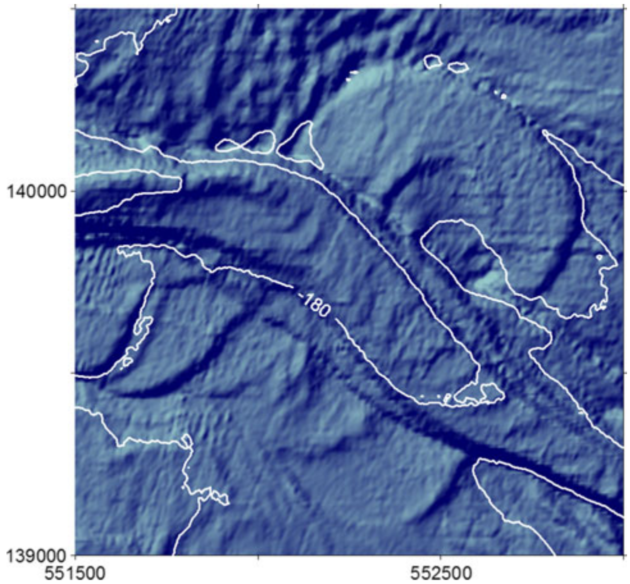

Fig. 7 Former canyon meander of canyon C8 and sand dunes on the modern canyon bottom and outside the canyon. Equidistance of isobaths: 20 m

canyon (Fig. 7). The depositional fan extends down to the deepest lake basin (Fig. 3). In the distal part of the fan, abandoned canyon sections are visible on both sides of the current canyon termination.

- C9 is linked to a former Rhone River tributary, which emptied into the "Le Bouveret" bay (see chapter 4). It corresponds presently partly to the canyon of the Stockalper Canal; it is separated from the Rhone River bed by a dam and by a natural levee.

The comparison of the current canyon morphology with data obtained in ancient campaigns is difficult, due to very different resolution of ancient and modern data.

On the lateral slopes, the deltas of the Veyveyse, Baye de Clarens, Baye de Montreux, Veraye, Tinière and Morge rivers (D1–D6 on Fig. 3) form minor promontories along the coastline. These deltas have no sub-aquatic canyons, but only small incisions or smooth valley structures running from the coast to the deep basin. Some slope deposits form minor cones along the coast between Villeneuve and Montreux (Château de Chillon), and on the opposite side of the lake, between Le Bouveret and St Gingolph.

Sub-aquatic ridges of NW–SE orientation, in the vicinity of Rivaz, between la Tour-de-Peilz and Cully, and between Vevey and Montreux are due to sub-aquatic outcrops of conglomerate of the Subalpine Molasse (Figs. 3, 8). In the absence of delta deposits, lake sediments on top of the conglomerate bars are only thin.

In a few places, deposits due to slope instability may be observed in the lower part of the slopes (Fig. 3).

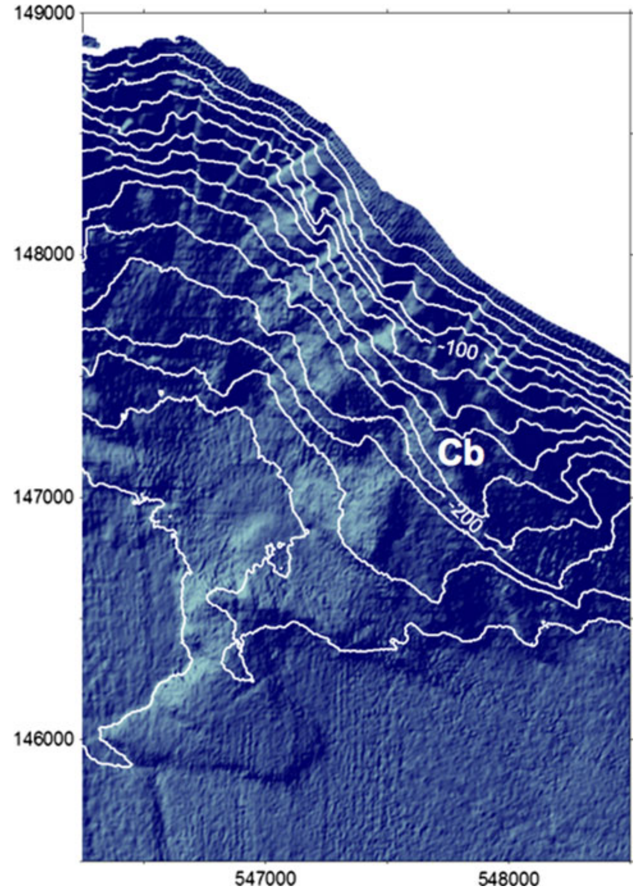

Fig. 8 Sub-aquatic detail morphology of inclined conglomerate bars, belonging to the Subalpine Molasse between Riva and Cully. *Cb* Conglomerate bars. Equidistance of isobaths: 20 m

History of the connection of the Rhone River to the subaquatic Rhone Delta

Most of the data on the recent geological history of the Rhone River valley upstream Lake Geneva stem from geotechnical investigations for highway construction and other geotechnical purposes. According to Freymond (1971), surface sediments on the aerial Rhone Delta are mostly fine sand and silt overlaying about 10 m of fluvial gravel. Lacustrine sandy silt is found deeper down.

The geological map presented by the same author, and geo-electrical investigations by Meyer de Stadelhofen (1964) also indicate gravel deposits from older Rhone River beds at the surface. One of these former river beds has been recognized to the North of Chessel Noville villages (Fig. 9), and is linked to the lake bay of Villeveuve. Although these data indicate important changes of the Rhone River channel during the past few centuries, the distribution of gravel indicates that the river mostly passed south of the hills of Chessel-Noville.

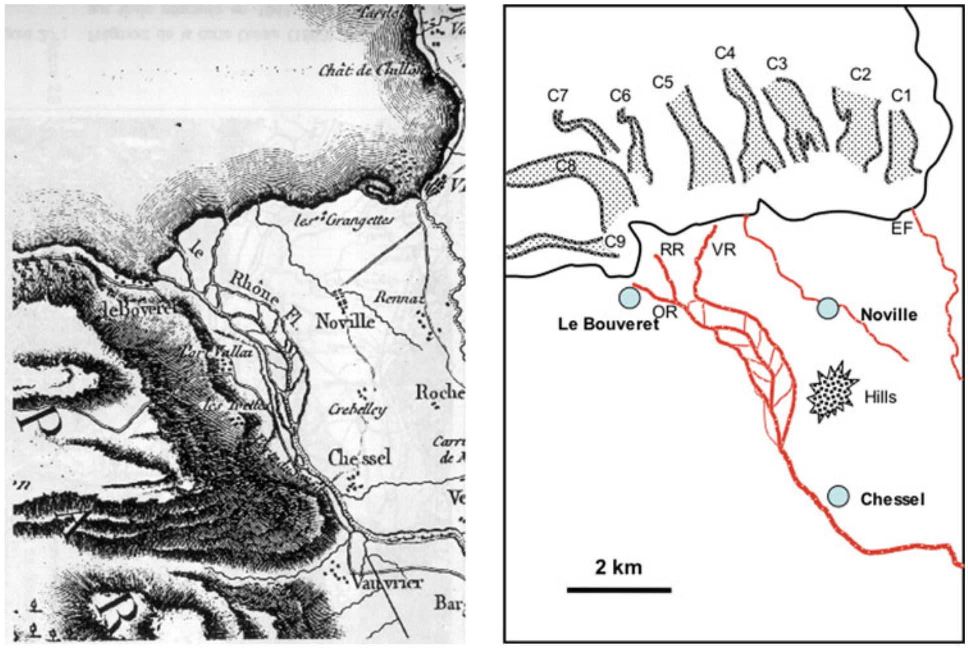

Fig. 9 Map of the lower Rhone valley and the terrestrial part of the Rhone Delta by Mallet (1781), compared with modern coastline and canyons. *EF* Eau Froide, *FR* former bed of Rhone River flowing into the bay of Le Bouveret, *RR* main Rhone River Bed, *VR* Vieux Rhone

Old maps and sketches by Schoepf (1577–1578), Du Villard (1581), Goulart (1606), Plep (1638) and D'Abbeville (1663), located a single mouth of the Rhone River close to Le Bouveret. Other maps show different positions of the river mouth, up to the locality of Monthey (Münster 1541) located 16 km upstream the present Rhone River mouth. These observations may be tribute to the period of observation, corresponding to either high (flood) or low water levels. Already, Forel (1892, vol. I, p. 267) wrote about these maps[1]: "… the presentation of the lake on these maps is so eccentric, that it is impossible to give any credibility to details".

The first realistic map has been established by Chopy (1730), using results from triangulation work (see Saiz-Lozano 2005). This map presents three distinct river beds and river mouths along a straight coastline. The three river beds are shown with equal width. However, the map is probably not sufficiently precise to conclude on the dynamics of the different river channels.

The map of Mallet (1781) still shows three river beds (Fig. 9) and is probably more accurate with respect to the coastal morphology than the work of Chopy. The mouths of the Vieux-Rhône and the modern channel of the Rhone River are clearly identified. The third arm of the river goes into the lake bay of Le Bouveret. The Vieux-Rhone has its prolongation in canyon C5; the modern Rhone and the third mentioned channel are linked respectively to canyons C8 and C9 (Fig. 3).

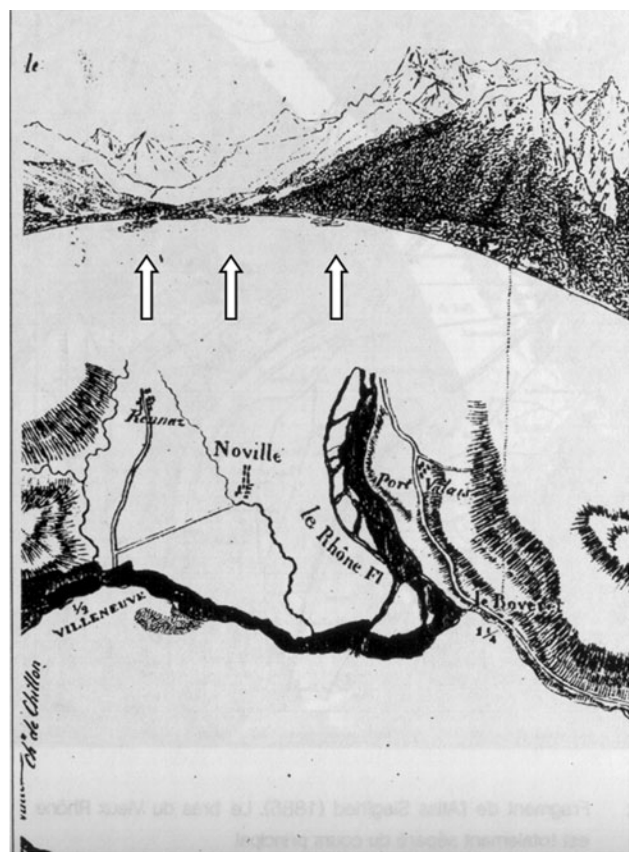

Fig. 10 Sketch from a passenger boat (*above*) and map of the coast line and Rhone Delta (*below*) by Dubois (1824). *Arrows* River plumes indicate the position of three river mouths

The military engineers of the emperor Napoleon established a new map of the western part of the Rhone Delta in 1802, with the modern channel of the Rhone River as the

[1] "… dans ces cartes le dessin du lac est tellement fantaisiste qu'il est impossible d'attribuer la moindre autorité aux détails qui y sont figurés."

most important one, and a minor channel in the bay of Le Bouveret. The river bed of the Vieux-Rhone is not indicated, probably due to the limited extension of the map that had been established for the project of a new road from Geneva to Milan.

Dubois (1824) established the landscape view of the Rhone Delta (Fig. 10) from the bridge of the «Guillaume Tell», the first steamer navigating on Lake Geneva from 1823. His map and sketch again show the three river beds, as stated by Mallet (1781), and three plumes entering the lake.

The first official Swiss maps, known as "Dufour maps", have been established for the area of the Rhone Delta in 1844, and published in 1860. Two channels of the Rhone River are represented: the modern Rhone River channel and the Vieux-Rhone. Therefore, the channel entering the lake in the bay of Le Bouveret disappeared between 1824 and 1844.

Long lasting efforts of the local population and authorities to limit the risks of flooding were intensified by the Federal decisions of 1863 and 1870 for the co-financing of such measures. Important river correction and embankment construction work started on the southern bank (Canton Valais) in 1864, and on the northern bank (Canton Vaud) in 1870 (De Kalbermatten 1964). During this work, the channel of the Vieux-Rhone was definitively cut and the Rhone River dammed as shown by the Siegfried Atlas map sheet 496 in 1886. Therefore, the river channel and the sub-aquatic canyon of the Vieux-Rhône are not active any more since 1870–1880.

The dammed Rhone River was planned to avoid sedimentation and erosion in the river bed. Therefore, since the correction of the Rhone River, no sediment is deposited in the lower Rhone Valley upstream Lake Geneva and on the subaerial part of the delta. The sediment load reaches the river mouth, where subaerial levees prograde 300 m into the lake. A sand bar in the continuation of the Rhone River formed after dam construction, corresponding to a "friction dominated effluent" type deposit ("middle ground bar", Wright 1977) in the area of interaction between the sediment loaded river flume and the lake bottom. This sand bar separated the effluent into two branches, both feeding canyon C8. It was destroyed in 1957, in order to avoid rapid coastal sedimentation (Lachavanne et al. 1975).

Gravel extraction on the last 1.5 km of the Rhone River up-stream the river mouth and on the lake plateau of the sub-aquatic delta were authorized in 1929. A further diminution of sediment input into Lake Geneva occurred all along the twentieth century by the retention of sediments in hydroelectric reservoirs in numerous alpine valleys in the Rhone River catchment. These installations and their exploitation also changed the hydraulic regime of the Rhone River, and certainly the flow characteristics in the main canyon C8 (Loizeau and Dominik 2000).

Conclusions

The new bathymetric map of the "Haut-Lac" of Lake Geneva presents a well-structured lake bottom morphology. The main features recognized are the following:

- The sub-aquatic Rhone Delta, extending from the wide coastal platform to the depositional fans of the central plain of the Lake.
- The platform edge of the delta is cut by 9 canyons. These are sinuous ("meandering") channels and show erosional and depositional features, as indicated by the steep erosional canyon walls and the depositional levees on the canyon shoulders.
- Deposits due to slope instability are observed in some canyons.
- The canyon bottoms and some slope areas are wrinkled by ripples or dune-like morphologies.
- Some bedrock structures and small local river deltas are located along the lateral slopes of Lake Geneva and form the main morphological features on these slopes.

Following the above enumerated facts, the recent history of the Rhone River connection to the sub-aquatic delta and the canyons may be resumed as follows:

- In historic times, the easternmost canyon C1 has a connection with the local Eau Froide River.
- The canyons C2 and C3 may be relics of the time, when the Rhone River (or a branch of this river) was flowing on the southern side of the hills of Chessel-Noville, as indicated by the presence of fluvial sand and gravel (Freymont 1971). Also, no historical document confirms this hypothesis.
- Canyons C4–C9 correspond to the input and overflow structures of the three river branches of the Rhone River testified on maps since about 250 years: the Vieux-Rhone, the modern Rhone River channel and the river branch entering the lake bay of Le Bouveret.
- The transition from three to two river branches dates from 1830 to 1840, when the river branch to the Le Bouveret lake bay was cut. The transition from two to one river branch in 1870–1880 corresponds to correction and dam construction on the modern Rhone River channel. Therefore, since about 130–140 years, canyon C8 remains the only permanently active canyon on the sub-aquatic Rhone Delta, whereas C7 is active during flood situations.

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