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Autor: Girardclos, Stéphanie / Hilbe, Michael / Corella, Juan Pablo

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Searching the Rhone delta channel in Lake Geneva since François Alphonse FOREL

Stéphanie GIRARDCLOS[1,2*], Michael HILBE[3], Juan Pablo CORELLA[1,2,4], Jean-Luc LOIZEAU[1,2], Katrina KREMER[1,2], Tonya DELSONTRO[3,5], Angel ARANTEGUI[6], Andrea MOSCARIELLO[1], Frédéric ARLAUD[1], Yosef AKHTMAN[7], Flavio S. ANSELMETTI[3,8] and Ulrich LEMMIN[7]

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Abstract

In the late 19th century, F.A. FOREL led investigations of the Rhone River delta area of Lake Geneva that resulted in the discovery of a textbook example of a river-fed delta system containing impressive subaquatic channels. Well ahead of the marine counterparts, scientific observations and interpretations of water currents shaping the delta edifice for the first time documented how underflow currents carry cold, suspension-laden waters from the river mouth all the way to the deep basin. These early investigations of the Rhone delta laid the basis for follow-up studies in the 20th and 21th centuries. Sediment coring, water-column measurements, manned submersible diving, seismic reflection profiling and bathymetric surveying eventually provided a rich database to unravel the key erosional and depositional processes, further documenting the impact of human-induced changes in the catchment.

With the merging of old and new scientific knowledge, today a comprehensive understanding prevails of how a delta changes through time, how its channels are formed, and what potential natural hazards may be related to its evolution. New and efficient bathymetric techniques, paired with novel coring operations, provided a time-series of morphologic evolution showing and quantifying the high dynamics of the delta/channel evolution in an unprecedented temporal and spatial resolution.

Future investigations will continue to further quantify these dynamic processes and to link the evolution of the subaquatic domain with changes and processes in the catchment and with natural hazards. Its size, easy access, and large variety of states and processes will continue to make the Rhone delta area a perfect 'laboratory' in which general processes can be studied that could be upscaled or downscaled to other marine and lacustrine deltas.

Keywords: *Lake Geneva, Léman, Rhone delta, submersible, channel, canyon, multibeam bathymetry, underflow*

Introduction

Submarine and sublacustrine deltas are prominent geomorphic and depositional features typically forming at the mouth of rivers when they enter a water basin. Deltas represent geographically, environmentally, and ecologically important connections between the land and aquatic environment and thus are often key locations for the development of living communities spanning from specific flora and fauna to human populations (e.g., deltas of the Nile, Mississippi, Ganges, Rhine, Rhone, Po rivers). Deltaic sedimentary sequences accumulated in the geological past also can contain large amounts of hydrocarbon accumulations, which make them amongst the most important deposits for exploration and develop-

1 *Section of Earth and Environmental Sciences, University of Geneva, Rue des Maraîchers 13, CH-1205 Geneva (Switzerland).*
2 *Institut des Sciences de l'Environnement (ISE), University of Geneva, Route de Drize 7, CH-1227 Carouge (Switzerland).*
3 *Eawag, Swiss Federal Institute of Aquatic Science & Technology, Überlandstrasse 133, CH-8600 Dübendorf (Switzerland).*
4 Present address: *Museo Nacional de Ciencias Naturales (MNCN–CSIC), Serrano 115bis, 28006 Madrid (Spain).*
5 *Department of Environmental Systems Science, ETH Zürich, Universitätsstrasse 16, CH-8092 Zürich (Switzerland).*
6 *Department of Earth Sciences, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza (Spain).*
7 *Ecole Polytechnique Fédérale de Lausanne (EPFL), ENAC-IIE-ECOL, Station 2, CH-1015 Lausanne (Switzerland).*
8 Present address: *Institute of Geological Sciences, Univ. of Bern, Baltzerstrasse 1-3, CH-3012 Bern (Switzerland).*
* Corresponding author: E-mail: stephanie.girardclos@unige.ch

ment of this primary natural resource. Therefore, understanding deltaic genetic processes, including the geomorphological evolution (Ericson et al. 2006; Syvitski et al. 2009) and mechanisms controlling their outbuilding processes or erosion (e.g. river floods frequency, sediment supply, sea level changes; Syvitski and Kettner 2011) is not only of priority for the larger scientific community (geoscientists, biologists, anthropologists etc.), but as also for governmental and international land and energy regulatory organizations.

The Rhone delta in Lake Geneva (Switzerland and France) is one of the very first deltas described with a rigorous scientific approach (Forel 1885). F.A. FOREL, the founder of limnology, noted the presence of a prominent and deeply incised channel, which is relatively uncommon for lacustrine deltas with the exception of the Rhine delta in Lake Constance (Wessels et al. 2010). However, deep delta channels are very frequent features of large fluvial-dominated deltas in the ocean (Amazon, Mississippi, Ganges, Niger, Nile; amongst others: Normark et al. 2002). The Rhone delta channel in Lake Geneva is in fact a classic example of an underwater, river-dominated delta system, characterized by a delta top, with its prograding foreset, channel, fan and pro-delta regions (Wright and Coleman 1973; Galloway 1975). As such, it represents a classic, self-contained miniature replica of much larger systems developed around the world.

The well-developed channel system in the Rhone delta makes it a very interesting case to be compared with large marine deltas. Deltaic subaqueous channels are in fact highly sensitive geomorphic features that can be altered dramatically with slight modifications in their controlling environmental and geological conditions, both naturally (e.g., changes in water and sediment supply), and human-induced (e.g., dams, engineering work, etc). In fact, several large delta structures around the world may potentially collapse within the 21th century due to anthropogenic disturbances (Syvitski et al. 2009).

The long and well documented history of human-induced alteration in the Rhone delta allows us to understand the deltaic evolution as a possible consequence of this human impact, and to capture important processes, which can be applied to other deltas around the world. Such human-induced impacts include the river channelization since 1863 for flood regulation (Vischer 2003), the lake hydraulic management with a level kept at ~372 m altitude a.s.l since 1886, and the construction of numerous hydroelectric dams in the upstream Alpine catchment (Loizeau and Dominik 2000; Sastre et al. 2010). As such, the continuous research effort of numerous limnologists and limnogeologists during the last 130 years have greatly contributed to develop integrated management strategies for the preservation of the Rhone river, Rhone delta and Lake Geneva environmental quality (Vernet et al. 1980; Santiago et al. 1994; Wildi et al. 2006; Thevenon et al. 2011a, 2011b).

In this paper, which represents a tribute to the pioneer work of F.A. FOREL, we i) summarize the limnogeological research conducted in the Rhone delta since the 19th century; and ii) present new results of recent multi-approach research conducted using multibeam bathymetry surveys, manned submersible observations, and sediment coring. From these scientific findings we suggest new perspectives for the near-future research in the Rhone delta. Ultimately, we show that the Rhone delta channel in Lake Geneva is a world-relevant example of a lacustrine deltaic environment, as well as a remarkable natural laboratory that serves as an analog for deep-water channels in the marine environment.

120 years of research (1885-2005)

The Rhone channel discovery (1885)

The channel of the Rhone delta in Lake Geneva was discovered by the pioneering bathymetric surveys carried out in the 19th century that aimed to describe the basin topography. The first detailed and complete bathymetric map (Fig. 1) of Lake Geneva was published in 1895 by F.A. FOREL (Fig. 2) via manual depth measurements carried out in 1885 by Ph. Gosset and J. Hörnlimann for the "Siegfried Atlas" of Switzerland at 1:25'000 scale, and by A. Delebecque for the French sector of the lake (Delebecque 1898). The present official bathymetric map of Lake Geneva (Swiss Federal Office of Topography at 1:25'000 scale) is still based on this 19th century dataset.
After initial publications in 1885 and 1888, F.A. FOREL summarized the knowledge of that time concerning the Lake Geneva sub-lacustrine channels ("*ravins sous-lacustres*" in French) in the 'Le Léman' book (Forel 1895). He described the 500 to 800 m wide and up to 50 m deep underwater channel that still remained 10 m deep at 230 m water depth offshore of Saint-Gingolph (Fig. 1). At that time, the channel-valley structure could be followed over 9.5 km down to a water depth of 255 m, for a total sinuous length of 10.25 km. In his book, F.A. FOREL discussed the formation processes of this large channel and excluded a pure influence of erosion processes or a morphologic heritage from a former fluvial valley. Regarding the sedimentation processes, he observed a longitudinal variation in the cross-

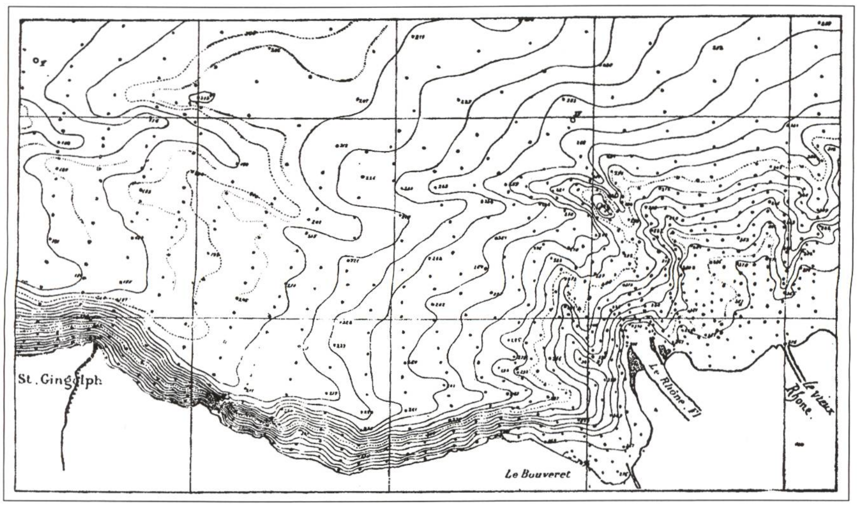

Fig. 1. Rhone channel bathymetry in Lake Geneva with 10 m contour line as drawn by J. Hörnlimann from manual soundings in 1885, and reproduced by F.A FOREL in his book Le Léman (p. 64, 1895).

Fig. 2. Picture of F.A. FOREL, 46 years-old, in Lausanne (Photo Francis de Jongh 1887, © Musée historique de Lausanne).

section of the main channel in which the channel was deeper near the proximal Rhone delta and shallower in the distal area. He concluded that this could not have been caused solely by sediment deposition as, if this was the case, the channel would have been more filled closer to the river mouth. Based on the description of a similar sub-lacustrine channel in Lake Constance by von Salis in 1883 (von Salis 1884), and on the observation that both channels were directly connected to major river mouths, he ruled out a local geological cause and instead proposed a common explanation. F.A. FOREL postulated that these channels were formed by the large inflowing rivers flowing and sinking like 'underwater cascades' into the lake water. In fact, at the 'Bataillière' site where the Rhone plunges into the lake, he observed the river suddenly disappearing. Such a phenomenon was later observed in Lake Brienz (Anselmetti et al. 2007; Girardclos et al. 2007) and in Lake Constance, where the Aare and Rhine (respectively) plunge to depth and vanish from the surface. He also correlated these observations with temperature measurements in Lake Geneva, which revealed contrasting values for inflowing river and lake-surface waters. F.A. FOREL used this data to infer a water-density contrast which could further support his model of a plunging river. He concluded that large underwater channels were caused by high-density river-induced water currents and sediment transport. All these concepts and ideas were later validated and proven during the 20th century (see next chapter).

In order to explain the formation of the Rhone channel, F.A. FOREL proposed a sedimentological model implying a slow differential aggradation between the central water flow pathway, where sediments are transported and washed away, and the sides of the water flow, where current velocities slow down inducing turbulence and sediment deposition. He believed these differentiated transport and sedimentation mechanisms could form valley and levee-like topography leading ultimately to the complex channel structure. At that time, F.A. FOREL thought that river inflow could not erode fine-grained sediments such as mud (vol 1 p. 385 in: Forel 1895) as was proven by Hjulstrom's experience 23 years after F.A. FOREL's death (Hjulstrom 1935).

Studying the Rhone delta in the 20th century

During the 1930's, following the pioneer work of F.A. FOREL, researchers from the University of Geneva undertook an extensive study of Lake Geneva in order to understand its sediment record. At the beginning of the 20th century, Romieux (1930) identified the role of sand particles in the Rhone river input, while Paréjas (1929) attempted to quantify sedimentation rates by counting individual layers though to be annual, using the 'varve' concept of Gerard De Geer, chief pioneer and populariser of varve research. Forty years later, however, radioisotope dating demonstrated that the 'varves' Paréjas observed were merely irregular clastic sediment laminations.

After World War II, modern concepts and methods of sedimentology, originally developed for oceanography and oil-industry research, were successfully applied to lake basins and initiated a new research interest in Lake Geneva (Vernet et al. 1971). In 1966,

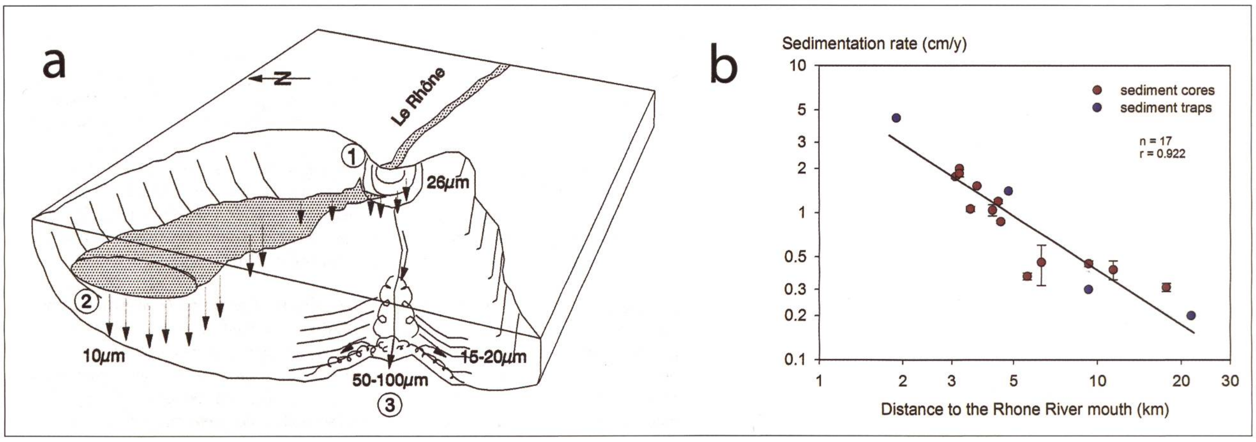

Fig. 3. (a): The Rhone delta model with three types of sedimentation : 1 The proximal sedimentation of coarse particles builds a delta foreset; 2 the interflow fine sediment transport is deflected to the North and 3 the erosion, transport and deposition by underflow currents form channels and distal fan. (b): Inverse correlation between the logarithmic value of the Eastern Lake Geneva sedimentation rate and the distance to the Rhone river mouth. From Giovanoli (1990) and Loizeau (1991).

Dussart presented a new Rhone channel map, interpreting it as a structure created by turbidity currents with the levee dissymmetry caused by the water current deviation. Houbolt and Jonker (1968) combined seismostratigraphy profiles and the study of sediment cores to map the extent of the Rhone channel and fan. At the same time, the study of tritium concentrations in water by Meybeck (1970) proved that the Lake Geneva turbidity currents originate from the Rhone River and that the mixing with lake water increases with distance to the river mouth.

Krishnaswamy et al. (1971) did the first dating of lake sediments based on ^{210}Pb and ^{137}Cs activity using sediment from Lake Geneva. This achievement initiated extensive sediment dating and method-related research (Favarger and Vernet 1979; Vernet et al. 1975, Vernet et al. 1984), which led to important knowledge on the distribution of sedimentation rate and to a much better understanding of limnogeological processes. In 1980, the 'Institut F.-A. Forel', an interdisciplinary institute in lake research, was funded at the University of Geneva (Dominik and Loizeau 2012), fostering a wide spectrum of research themes in lacustrine sedimentology. Between 1970 and 2005, a variety of Lake Geneva research was conducted including studies on the Holocene sediment record (Châteauneuf and Fauconnier 1977; Creer et al. 1975; Baster et al. 2003; Girardclos et al. 2005), the origin of Lake Geneva sediments (Jaquet et al. 1980; Jaquet et al. 1983), evolution of currents (Lemmin 1998; Girardclos et al. 2003), and river plume dynamics and slope failures in the Rhone delta area (Dominik et al. 1983; Giovanoli 1990; Lambert and Giovanoli 1988; Loizeau 1991). These studies revealed that the Rhone delta dynamics are mainly controlled by three sedimentation processes, which mainly depend on the river discharge and water density (Fig. 3a). When river discharge is low, suspended particles deposit near the river mouth forming a delta foreset structure. If the incoming river flow density is comprised between the one of the epilimnion and the one of the hypolimnion, then it propagates along the thermocline. This displacement, which happens virtually without any friction, is influenced by the Coriolis force, thus deviating the flow and bringing fine silt particles preferentially to the northern part of the delta. In contrast, if river inflow is denser than the hypolimnion (i.e. cold or with high suspension load), underflow currents build up a distal delta morphology with valleys, tributary channels and fans, thus transporting coarse silt- and fine sand-sized sediment up to 15 km to the west. Giovanoli (1990) and Loizeau (1991) also quantified and mapped the sedimentation rate in the Rhone delta area, showing that its logarithmic value is inversely proportional to distance from the river mouth (Fig. 3b). For detailed review on Lake Geneva sedimentation rates, please refer to Loizeau et al. (2012).

In 2000, Loizeau and Dominik estimated the evolution of the Rhone river sediment load during the 20^{th} century from discharge data and showed that the sediment input decreased by at least a factor 2. This calculated decrease, interpreted as a consequence of numerous upstream hydropower dams, might have also induced a lower probability of underflow turbidity currents in the Rhone channel. A preliminary study on the frequency of coarse sediment deposits at the end of the Rhone river sublacustrine channel (Sastre 2003), however, contradicts this interpretation, as the occurrence of turbidite layers didn't seem to decrease for this time interval. This suggests that slope failure and strong floods still played a major role in shaping the recent Rhone channel and fan structure in the past 50 years.

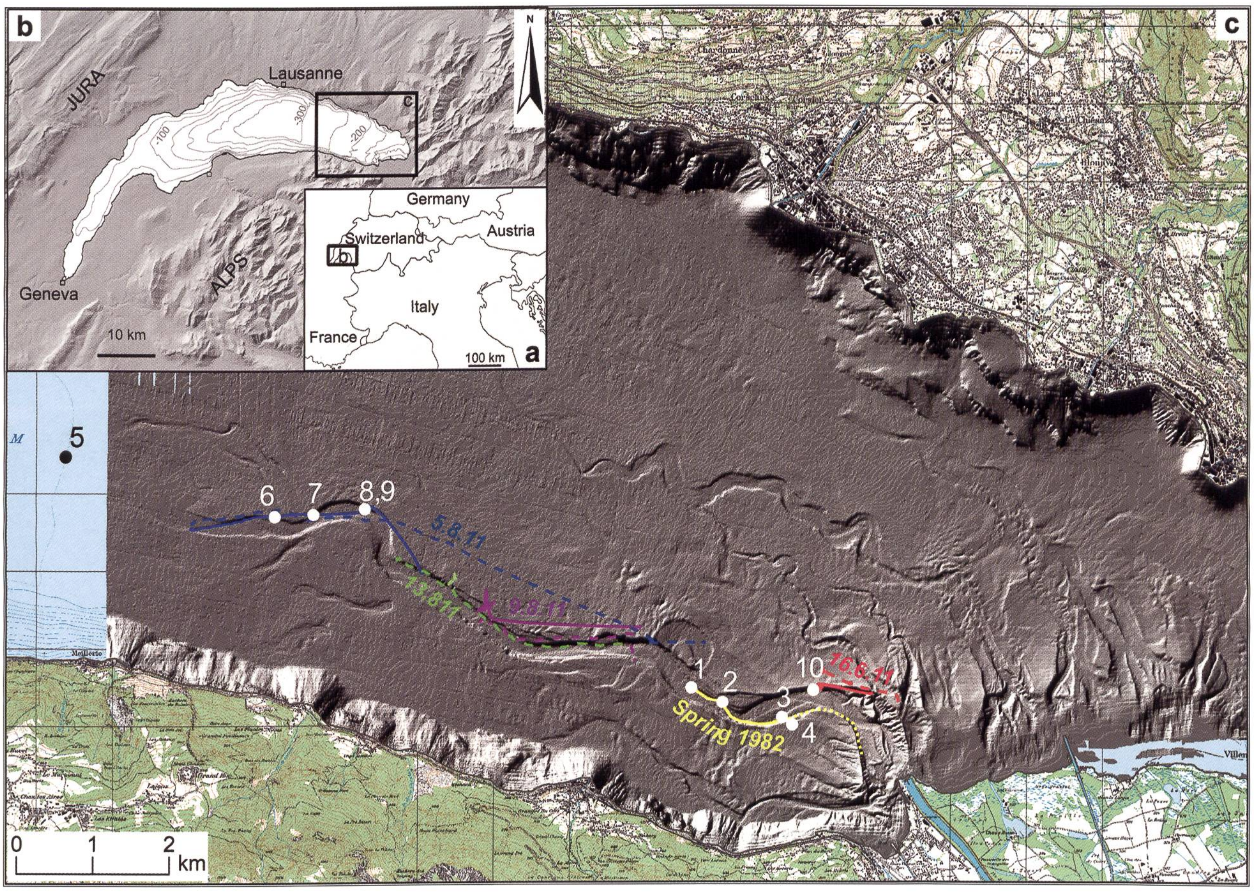

Fig. 4. Location maps of the Rhone delta channels in Lake Geneva (a, b), with c) the manned submersible routes and observation stations (black and white points) from 1982 to 2011. The FA Forel *route in spring 1982 (yellow line) and observation stations 1-4 (1982) and 5 (February 2002).* MIR 1 *(plain lines) and* MIR 2 *(dotted lines) routes on June 16th (red), August 5th (blue), August 9th (magenta) and August 13th (green) 2011 with video observations (stations 6-9) and sediment-wall coring (station 10). Shaded bathymetry data from Sastre et al (2010) and Swisstopo map figure as background.*

Exploring the Rhone channel with manned submersible (1982-2005)

Since the Lake Geneva region was also home to Auguste Piccard (1884-1962) and his son Jacques Piccard (1922-2008), inventors of several submersibles since 1945, local researchers took advantage of this geographical proximity to explore the deep basin of Lake Geneva with manned submersibles. Jean-Pierre Vernet, limnogeologist at the University of Geneva, dove in Lake Geneva in April 1965 with the mesoscaphe '*Auguste Piccard*', a tourist submersible built between 1962 and 1964 for the Exposition Nationale Suisse of 1964 (Swiss National Exposition). During his three dives, lasting 8 to 12 hours each, he observed lake bottom sediments while colleagues took water samples (Vernet 1966). However, they did not reach the Rhone channel area.

To our knowledge, the first dive in the Rhone channel took place with the *FA Forel* (also named 'PX-28'), a manned submersible, which was launched in 1978 and designed by Jacques Piccard for one pilot and two passengers. Jean-Pierre Vernet and Jacques Piccard dove in the Rhone channel on March 22nd, May 21st and May 26st 1982 from 175 to 35 m water depth, with the goal of observing the morphology of the channel bottom and evaluating the potential of using the submersible for future scientific research. From his short unpublished report (Vernet 1982), we could summarize Vernet's visual observations and reconstruct the likely *FA Forel* underwater route (Fig. 4: route spring 1982, yellow line):

- Station 1. At 180 m depth, a dense network of fish traces, apparently made by Lota lota, appears on the channel-floor sediment. A pile of broken tree branches and wood pieces lie on the channel floor, forming a volume of 10-m-length by a few-m-width and about 1-m-height. Some branches still have leaves or needles attached, which is interpreted by Vernet to indicate recent deposition (Fig. 4, station 1).
- Station 2. In the Northern and Northeastern sides of the sub-vertical channel walls, sediment layers alternate between light-colored fine-grained and darker coarse-

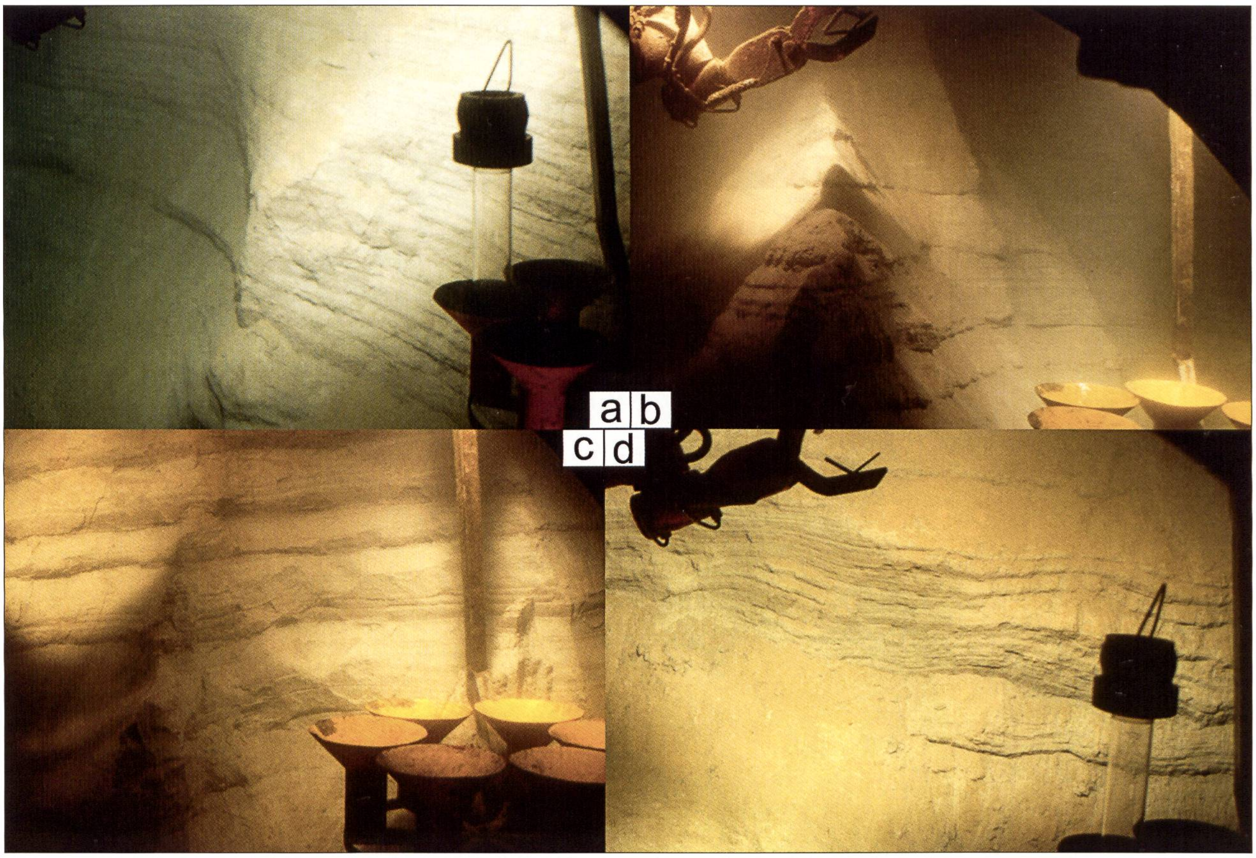

Fig. 5. The Rhone channel walls were photographed onboard the FA Forel *submersible by Jean-Pierre Vernet in 1982. Slide images show sub-horizontal sediment layering of varying silt- to sand-sized granulometry with wall steepness up to 45-50° degrees. Picture courtesy from the Musée du Léman (Nyon, Switzerland) from ML Piccard archive folder SBS II-VI 82, IV 83. Slides nos. 4 25, 1 7A, 1B 30A and 4 8. For location, refer to Fig. 4, station 2.*

grained layers (Fig. 4, station 2). Color images (Figs. 5a to d) reveal steep channel walls, with slope angles up to 45-50° degrees (Fig. 5c) and a sub-horizontal sediment stratification, showing frequent silt- to sand-sized granulometric variations.

- Station 3. In the Southern side of the channel, at 120 m depth (Fig. 4, station 3), a very steep wall reveals alternating fine layers of vegetation debris and branches sticking out of the sediment layers.
- Station 4. The flat area on the top of the walls is covered by monotonous ripple marks. At certain places, the channel edge shows a clean 'cut' morphology, which possibly indicates the scar of recent channel wall slope failures (Fig. 4, station 4).

Two decades later, on February 18th 2002, Jean-Luc Loizeau and Vincent Sastre dove in the Rhone channel with *FA Forel* to explore its distal part, after a sediment-core study revealed that the area was surprisingly rich in coarse sand (Sastre 2003). They discovered a large area, at least 500x300 m, covered by coarse and compacted sand, including partly buried tree logs and wood branches at 270-280 m depth (Fig. 6). In the same area, comparative bathymetric surveys performed in 1986 and in 2001 revealed that this part of the channel was completely filled by more than 75 mio m^3 of sediment (Sastre 2003), pointing to a large mass-transport deposit, which most certainly resulted from a sub-lacustrine mass movement or a large flood event in the Rhone channel.

The *FA Forel* archives, called 'Fonds Jacques Piccard', were only recently deposited at the Musée du Léman in Nyon (Switzerland) by the 'Fondation pour l'étude et la protection de la mer et des lacs'. Since they have not yet been published or indexed, a detailed future analysis may reveal additional scientific contributions of the past manned submersible activity to the Rhone channel research and exploration.

Research since 2005

Mapping the channel morphology from multibeam bathymetry

The recent advances in multibeam echosounding technology allow the production of digital lake bathymetry maps at high resolution, similar to high-

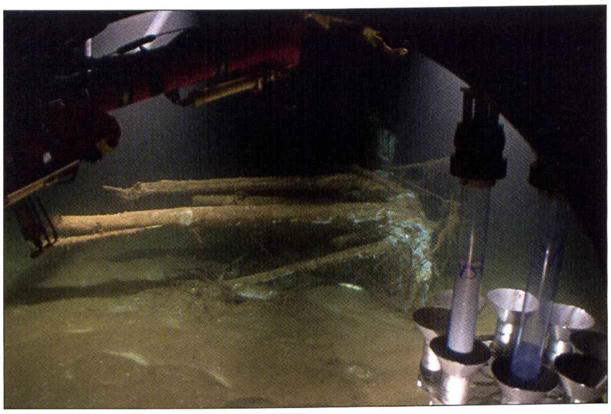

Fig. 6. Image of several tree logs and wood branches sticking out of the sediment floor in the very distal part of the Rhone channel at 270-280 m water depth. Photograph taken by Vincent Sastre aboard the FA Forel *on 18th February 2002 (from Sastre, 2003). For location, refer to Fig. 4, station 5.*

quality digital elevation models (DEMs) on land (Hilbe et al. 2011; Ledoux et al. 2010; Wessels et al. 2010). These data permit a detailed inspection of the lake floor morphology and the detection of features with sizes down to a few meters and depth changes of a few decimeters and complement high-resolution seismic reflection data (Dupuy 2006; Debret et al. 2010; Fiore et al. 2011; Wirth et al. 2011; Lauterbach et al. 2012).

In January and February 2008, a mapping survey of the Rhone delta area was conducted using a SeaBeam 1050 multibeam echosounder. The resulting raster dataset with a cell size of 5 m served as the basis of a high-resolution bathymetric map published by the Institute F.-A. Forel in 2010 (Figs. 7a; from Sastre et al. 2010). This new map not only updated the previously available bathymetry data in this area, but also defined the exact morphology of the main Rhone delta channel (C8; Figs. 7a) and of numerous smaller channels on the delta slope, both proximally (C3-7 and C9) and distally (at the end of the main channel C8, Fig. 7a). These meandering channels show erosional and depositional features, as indicated by the steep eroded channel walls and the depositional levees on the channel shoulders. The small side channels C1-7 and C9 are interpreted as ancient channels, which were active when the Rhone river mouth was still branching and/or moving according to the natural delta evolution, prior to its channelization in 1863-

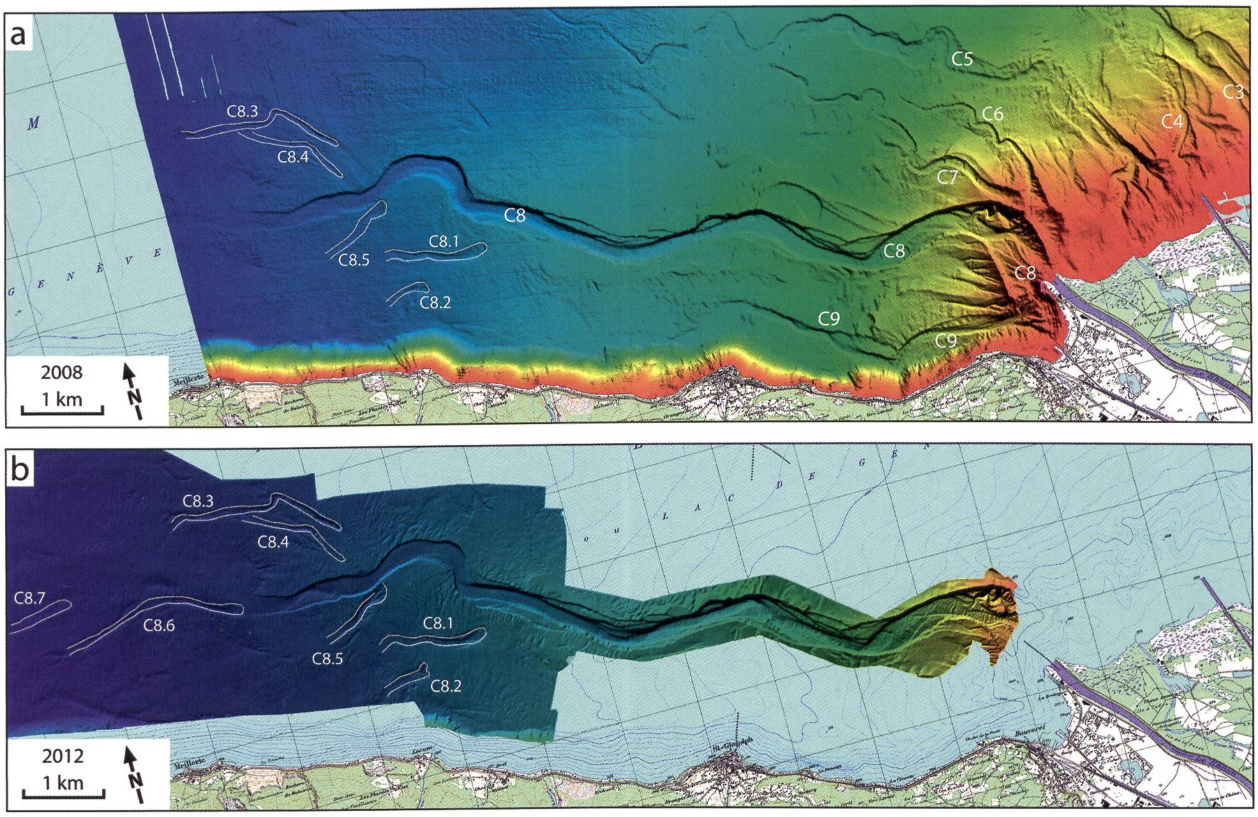

Fig. 7. Multibeam bathymetry maps of the Rhone main delta channel from February 2008 (a) and March 2012 (b), with labeled main (C8) and side (C3-7, C9) channels as well as distal branches of the main channel (C8.1-8.7). (a) Bathymetry data from 2008 has a cell size of 5 m (redrawn from Sastre et al. 2010) and (b) bathymetry data from 2012 a cell size of 2 m (this study). The 2012 bathymetry map reveal a newly formed channel (C8.6) at the end of C8, as well as large areas covered with sand wave bedforms.

64 (Sastre et al, 2010). Other features, like slide scars and bedforms, previously known from manned submersible observations, could be confirmed and exactly located (Fig. 7a). On the whole, this map truly unveiled a hidden world to both researchers and the general public.

On the 28th and 29th of March 2012, new bathymetry data were acquired with a Kongsberg EM 2040 multibeam echosounder, producing a bathymetry dataset with better resolution (2 m cell size) covering the main Rhone channel (C8; Fig. 7b). The new dataset confirmed the previous map, showing a stable general morphology of the channel. A close comparison of the two datasets, however, reveals important erosional and depositional changes that reflect the dynamic sedimentation in this environment.

The central part of the main channel, from around 100 m to 225 m water depth (Figs. 8a-d), is characterized by widespread undulating bedforms on the channel floor, with typical heights of 0.5-2 m and wavelengths of 30-100 m (Figs. 8b, 8d and 9a). In this part of the channel, the floor was eroded by up to 8 m between 2008 and 2012 (Figs. 8b and 8d). Along the newly incised sections, a number of new small slide scars can be identified on the sidewalls of the channel (Fig. 8d). Their headwalls are crescent-shaped, with individual widths of 20 to 70 m, and often occur next to each other along sections of several hundred meters length. While some of these features can be identified on both datasets from 2008 and 2012, a number of them have formed between 2008 and 2012, most probably caused by the incision of the channel floor and over steepening of its lateral slopes (Fig. 8d).

In contrast to the central part, the adjacent downstream part of the channel floor between 225 m and 260 m water depth (Figs. 7b, 8e-f) has a conspicuously smooth appearance, without widespread bedforms visible in the bathymetry maps. A comparison of the two datasets shows that the channel floor in this section has been an important depositional area, with up to 5 m aggradation in the same 4 years interval. While distinctive features on the channel floor are rare in this part, large areas outside the channel are pervasively covered with undulating bedforms. These are typically smaller than the ones observed in the upstream part of the channel, with heights of 0.2-1 m and wavelengths of 15-50 m (Figs. 8f, 9b and 9c). They have sinuous crests that are generally oriented parallel to the isobaths, while the local slope gradient is often pointing away from the channel rims. This pattern suggests that hyperpycnal flows in the channel may flow over its levees and transport sediment over the lower delta slope, as previously proposed by Giovanoli (1990) and Loizeau (1991; Fig. 3a). However, as erosional or depositional changes in lake floor elevation are much smaller and lie within the measurement error in this area, these processes cannot be quantified.

Near the end of the main channel C8, a new, 2.5 km long, 20 to 50 m wide and up to 6 m deep channel meander can be detected in the 2012 dataset (Figs. 8e and 8f). This channel C8.6 (Figs. 7b, 9) is absent in the 2008 multibeam data, thus it must have formed during the intervening 4 years. In this case, the present morphology of the C8.6 channel is only the transient expression of the erosive action by underflow currents originating from the Rhone river inflow, and we can assume that it will ultimately form a wider and deeper channel, to finally reach a size similar to the former channel observed in 1986 (Loizeau 1991).

The described morphologies and changes prove that active erosion and deposition are still currently shaping the Rhone channel that was discovered more than 120 years ago. The observed bedforms with wavelengths of 15-100 m can be classified as sand waves and indicate current velocities on the order of 0.5-1 m/s (Stow et al., 2009), which is in agreement with the underflow velocities measured in the main Rhone channel C8 by Lambert and Giovanoli (1988). The detected changes of lake-floor elevation are large enough to be detected by repeated bathymetric surveys in intervals of a few years. Our data show that erosion and deposition vary strongly in space and can change in a short time period (4 years). They point to possible varying evolution in time, depending on long-term hydrological and climatic changes. They also indicate the occurrence of catastrophic events, such as floods and sublacustrine mass-movements in the delta realm (Girardclos et al. 2007; Kremer et al. 2012; Mulder et al. 1997).

Future research on this topic, including repeated high-resolution bathymetric monitoring of the most active areas, will contribute to the understanding of the Rhone channel evolution as well as to fundamental knowledge on the hydrological and environmental factors controlling delta dynamics and morphology.

Small-scale sedimentary structures from MIR submersible observations

In summer 2011, a new research program with manned submersibles was started in Lake Geneva using the Russian MIR 1 and MIR 2 submarines from the Shirshow Oceanographical Institute in Moscow. This 'Elemo' research program, financed by a private sponsor, was coordinated by the Ecole polytechnique fédérale de Lausanne (EPFL) and included the par-

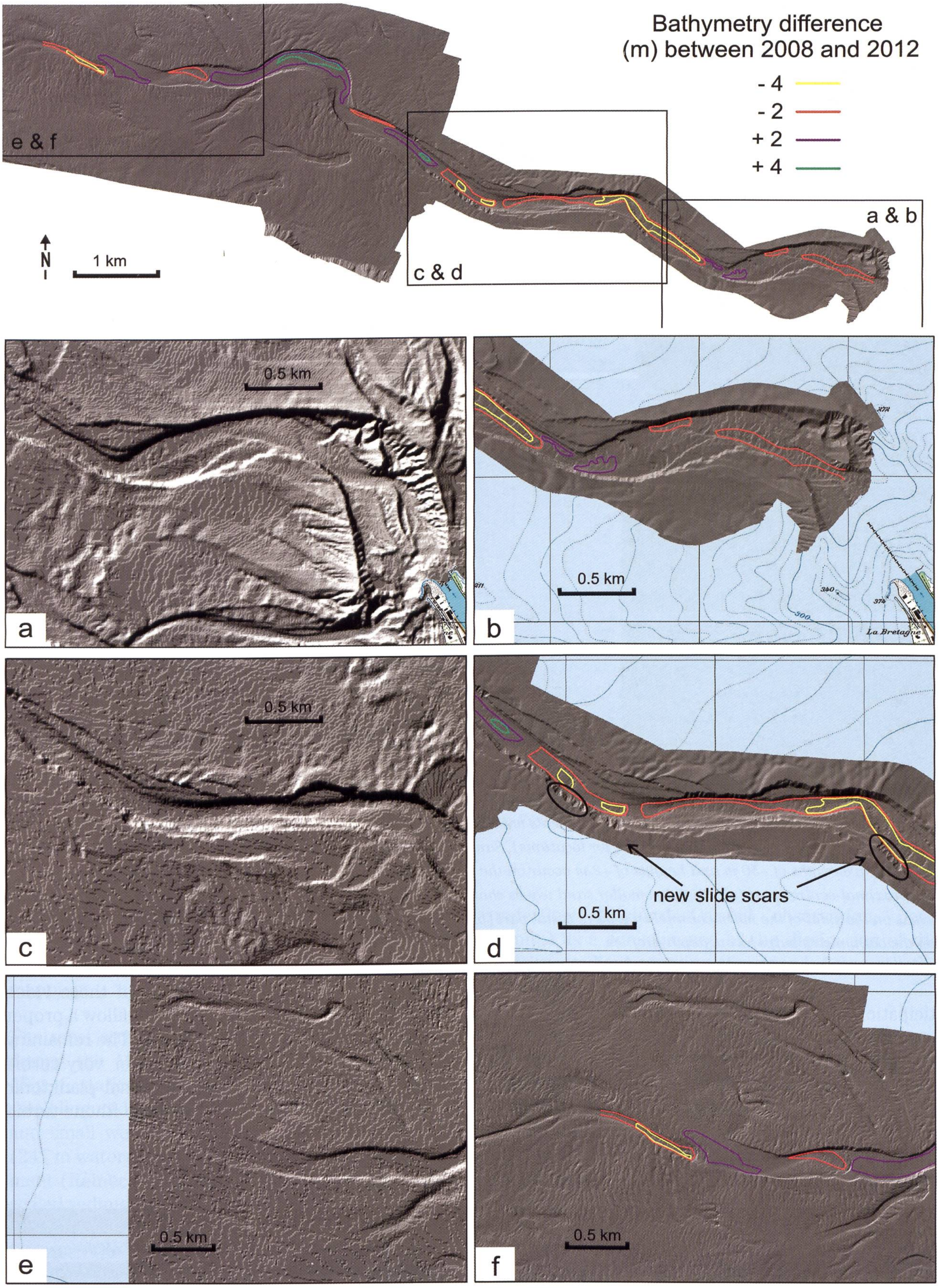

Fig. 8. Detailed shaded multibeam bathymetry maps of the Rhone main channel, with panels of the February 2008 (a, c and e; from Sastre et al. 2010) and March 2012 (b, d and f; this study) channel morphology. Colored isolines indicate erosion (-) and deposition (+) in meters. New slide scars appear close to areas of strong bottom erosion (d). Refer to upper panel for channel overview, panel location and contour lines color scale.

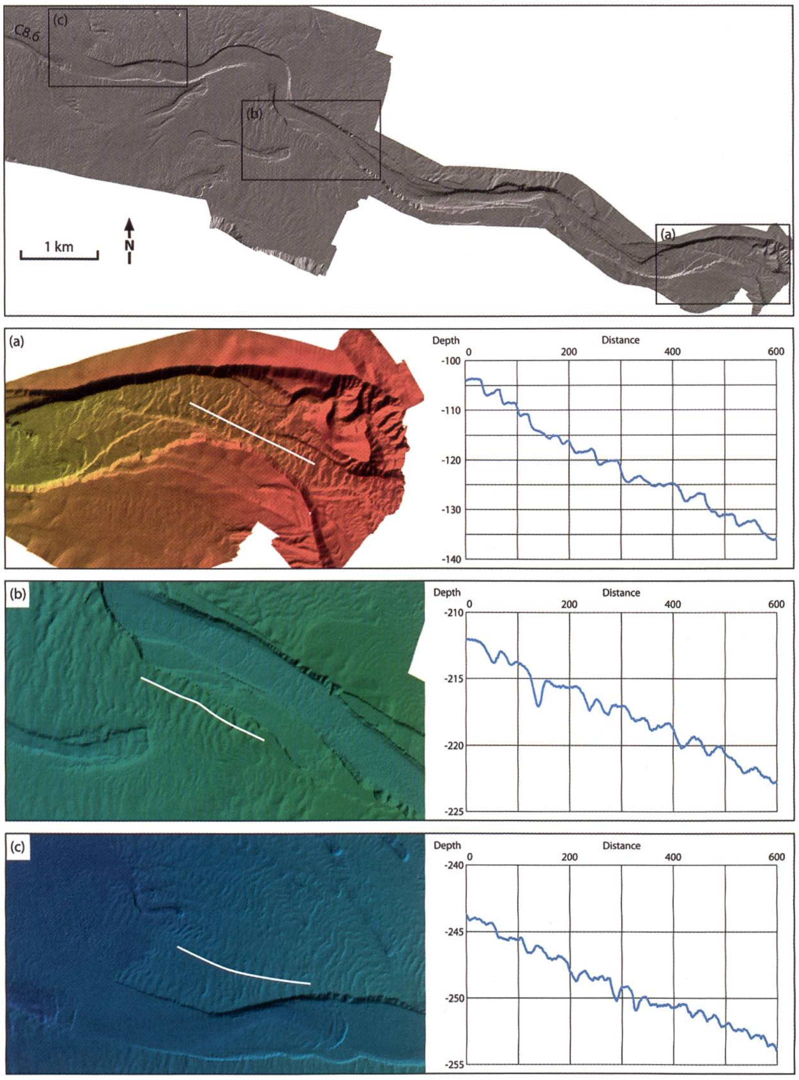

Fig. 9 Depth-distance profiles (m) across bedform fields within and near the main Rhone delta channel (see upper panel for locations). Sand waves with typical wavelengths of ~50 m and heights of ~2 m occur on the channel floor in the proximal-central part (a). Slightly smaller sand waves characterize the areas on the sides of the main channel in a more distal part (b, c). White lines on the bathymetry maps locate depth profiles.

ticipation of researchers from various Swiss and foreign institutions (www.elemo.ch). The program was composed of three main research packages, with one focusing on the Rhone delta in respect to formation, sedimentation and stability, methane ebullition, organic burial efficiency, and intrusion from the mixed boundary layer. Since most of this research is still in progress, we will only present some preliminary results.

The Elemo research in the area of the main Rhone channel included a total of 33 dive hours (Fig. 4) each lasting from 3 to 5.5 hours, depending on the research program and weather conditions. The MIRs dove on June 16th 2011 in the proximal Rhone channel, on August 9th and August 13th in the middle part, and on August 5th in the distal part of the channel (Fig. 4). The underwater trajectories of the submersibles were calculated by combining the GPS-based position of the main floating platform and the triangulation of the submersibles using a number of submerged acoustic beacons. Unfortunately, the resultant raw position was in many cases unreliable and comprised many obvious outliers. Correspondingly, the navigation data describing the 3D trajectories of the MIR submersibles have been comprehensively analyzed and consolidated by suppressing instantaneous outliers, as well as by applying a non-linear interpolation to the missing GNSS data using a Kalman filter (Akhtman et al. 2012).

In the active channel, a total of ~6 km on the channel bottom (i.e. 2.5 hours) and ~8 km on the levee (i.e. 1.5 hour) were video recorded (Tab.1). Two hours of these video data are of sufficiently good quality to allow a proper interpretation of bottom morphology. The remaining Rhone channel dives took place under very turbid conditions, due to the normal seasonal planktonic bloom (Tadonléké et al. 2009) and the Rhone turbid

Table 1. List of videos recorded in the Rhone channel area in 2011 with the MIR submersibles

Dive date	Sub. name	Video duration	Video file link
16-06-2011	MIR 1	0:30:42	*http://www.youtube.com/watch?v=IB7xWqhl4mw*
05-08-2011	MIR 1	1:39:16	*http://www.youtube.com/watch?v=4R46ZP2X9cM*
05-08-2011	MIR 2	0:10:56	*http://www.youtube.com/watch?v=1HWYx26JxQQ*
09-08-2011	MIR 1	0:56:21	*http://www.youtube.com/watch?v=lgqCbxX75U0*
09-08-2011	MIR 2	0:18:46	*http://www.youtube.com/watch?v=tsdglUxJi0g*
13-08-2011	MIR 1	0:16:59	*http://www.youtube.com/watch?v=jOKgBzboTk4*

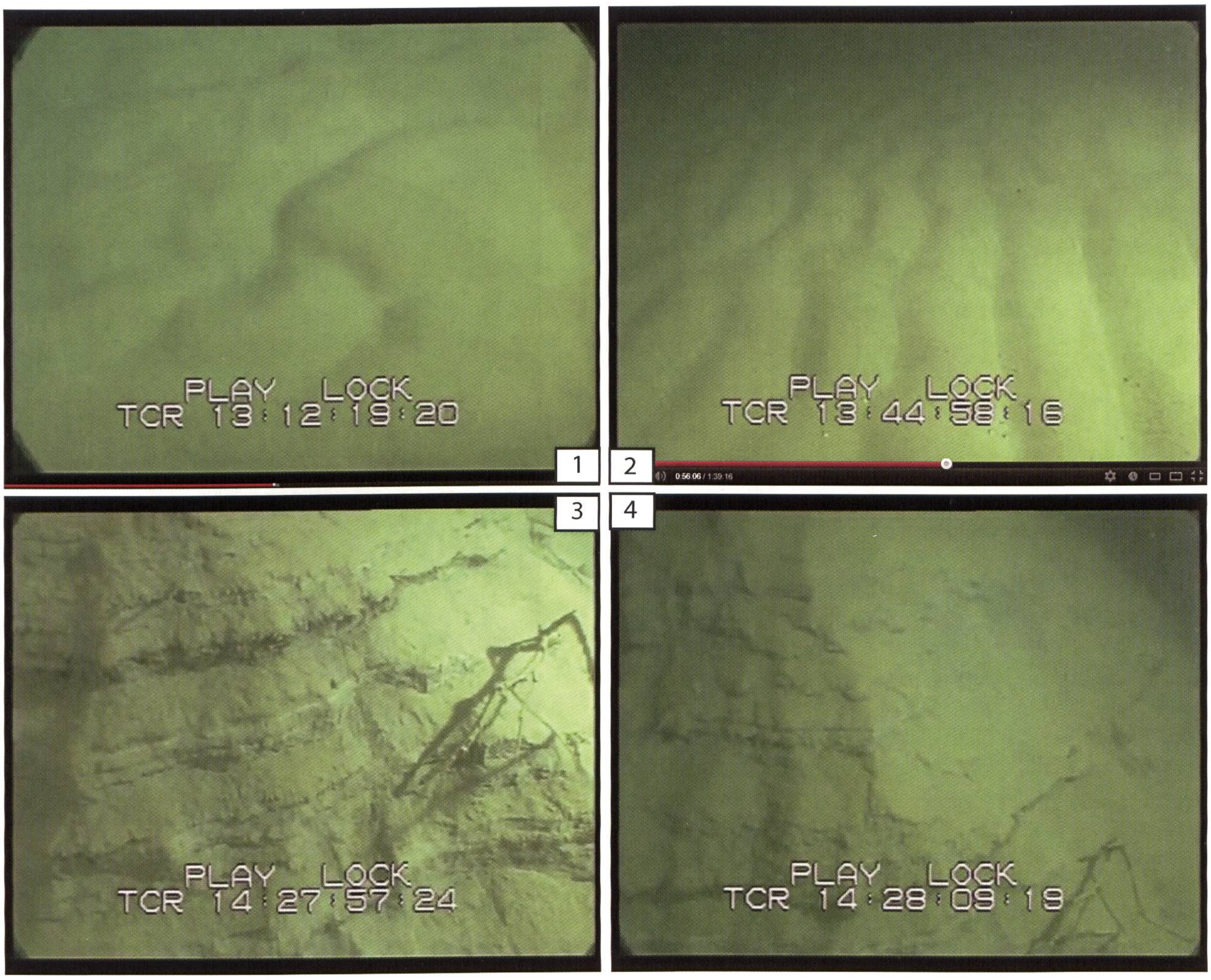

Fig. 10. Video images from records of the channel bottom morphology with linguoid small ripples (1) and weak undulatory asymmetrical small current ripples (2). Ripples have few cm to dm length. A wood branch entrapped in delta sediments sticks out of the channel wall due to differential flow erosion (3, 4). Refer to Fig. 4 for image locations (stations 6 to 9) and to Table 1 for video details.

inflow (Burrus et al. 1989; Giovanoli 1990; Santiago et al. 1992), resulting in low water transparency. This prevented adequate channel observation and mapping.

The most striking morphological features observed during the MIR dives in the distal channel floor (Fig. 4, stations 6 to 9) are large areas covered by small linguoid ripples (250 m water depth, Fig. 10.1) and small weakly undulating asymmetrical ripples (247 m water depth, Fig. 10.2) in fine silt-sized sediment (Reineck and Singh 1986a). These cm- to dm-scaled sedimentary structures are typical for current ripples and point to genetic flow velocities of ~25 to 50 cm/s. The transition from undulatory (proximal) to linguoid (distal) ripples reflects a decrease of stream power (Reineck and Singh 1986b), which is most probably due to a decrease of current velocity at this water depth. The slowing of the current is possibly caused by an upward migration of the underflow (Richard Carmili observation, pers. comm.) as a consequence of the dissipation of the density gradient merging the river inflow with the lake water.

Five-hundred meters upstream, in a pronounced channel meander (Fig. 4, stations 6-9), the northern side wall is steep with sub-horizontal sediment layering (Fig. 10 insets 3 and 4), similar to structures observed proximally by Vernet in 1982 (Fig. 5, location Fig. 4 station 2). We also observed a wood branch sticking out of the sub-horizontal sediment layers (Figs. 10.3 and 10.4), as was already mentioned by Vernet (1982). This structure is certainly due to the differential erosion of wood entrapped in deltaic deposits, which remains in place while the surrounding sediment is washed away. This observation confirms sediment erosion of the channel wall as it was measured by multibeam bathymetric data (see previous chapter).

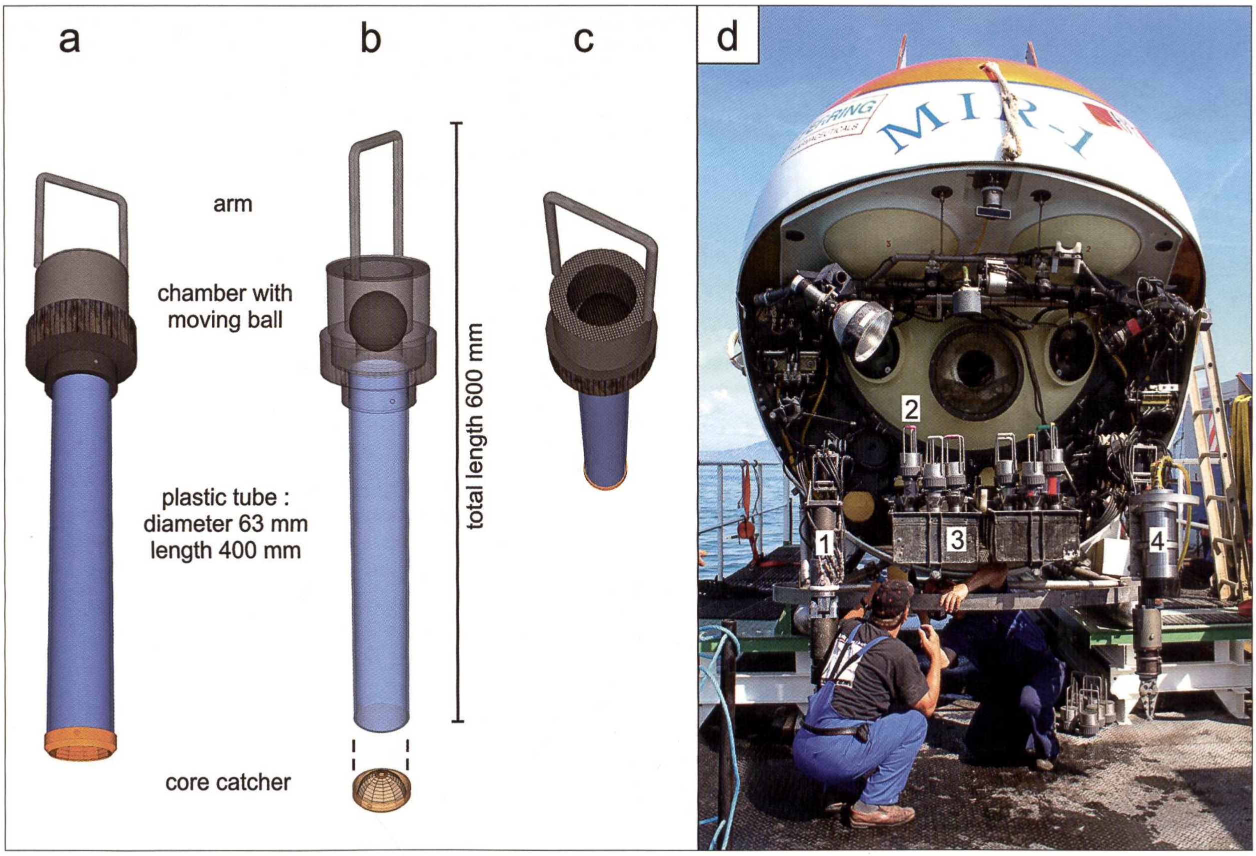

Fig. 11. New sediment coring device called 'elemo corer' *used underwater with MIR submersibles (design by U. Lemmin and F. Arlaud). Oblique view from side (a), transparent side view (b) and view from above (c). The internal moving ball closes the plastic tube after coring and holds the sediment sample by a slight vacuum. When sand is sampled, an additional core catcher is used. (d) Picture of the MIR 1 submersible front with Russian crew. The starboard robotic arm (1) was used for deployment and recovery of the coring device (2), stored into metallic holders in drawers (3). The video camera is attached to the portside robotic arm (4).*

The ripple structures on the channel bottom, the marks of erosion on channel walls (Fig. 10), as well as the varying erosional and depositional patterns on the channel floor (Fig. 8) indicate that the distal channel morphology is shaped by the complex interplay of both erosive and transporting action of currents. These current features are certainly due to the Rhone river inflow currents (Mulder et al. 1998; Mulder et al. 2003), as shown by the detailed study of Lambert and Giovanoli (1988). They reported 19 events with bottom-current speeds between 10 and 50 cm/s from June 14th to August 28th 1985. During this 84-day period, water temperature and Rhone river discharge were also monitored, allowing the interpretation of five down-channel events with maximum speeds >50 cm/s as riverborne turbidity currents, and one event with a velocity above 90 cm/s during a mass movement-induced turbidity current. As such, the non-negligible role of mass movements (Mulder and Cochonat 1996), and mass movement-triggered turbidity currents (Kremer et al. 2012), must be taken into account to understand the Rhone channel morphology.

In conclusion, the visual observations recorded by the video cameras on the MIR submersibles in summer 2011 correspond well to those made by Vernet in spring 1982 in the proximal part of the Rhone channel (Vernet 1982), thus leading to the conclusion that similar sedimentological processes can control the channel course from its mouth to the end. The morphological and dimensional features of these subaqueous bedforms, which can be seen at large scale on multibeam bathymetry (Figs. 8 and 9), and at small scale from *in-situ* observations (Fig. 10), certainly respond to several factors such as flow depths, grain-size or rapid changes in the mean underflow velocities (Flemming 2000; Mazumder 2003). At a smaller scale, the sedimentary structures resemble flow-transverse bedforms documented in modern large deep-sea channels (Arzola et al. 2008; Mountjoy et al. 2009; Normark et al. 2002; Smith et al. 2007), although some specific features such as the tree logs and wood branches in channel bottom (Fig. 6) might be related to the site-specific peri-alpine setting of the Rhone channel. Ongoing research carried out by several researchers from Institute F.-A. Forel and the

EPFL intends to characterize and quantify these sediment structures and evaluate their migration patterns related to variability in river inflow during the last decades.

Coring and dating channel walls

During the MIR dives of Summer 2011 (Fig. 4), a new gravity-coring device (Fig. 11), the 'elemo' corer, designed by Ulrich Lemmin based on a former *FA Forel* coring system, and built at the EPFL, was used to sample sediment *in-situ* from the channel floor and walls. Attached to a metallic handle, a plastic chamber contains a plastic ball, which can move up freely during sediment coring to let water escape (Figs. 11b and c). When the coring device is pulled out of the sediment surface, the plastic ball moves down again and closes the sampling plastic tube, creating a slight vacuum, which holds the sampled sediment in place. When the *elemo* coring device was used for sandy deposits, a core catcher (designed by Frédéric Arlaud based on an original ETH Zurich model) was placed at the end of the corer to help maintain the sand in the tube after sampling (Fig. 11b). Up to twelve sediment corers (Fig. 11d) were deployed onboard the MIR, using the starboard robotic arm for retrieval of sediment cores, while the portside arm was monitoring the operation with a video camera. After coring, the device and the cored sediment were placed into a metallic holder with rubber plugs that sealed the plastic tubes from the bottom until the end of the dives. Sediment could be retrieved and subsampled once the MIRs were out of the water.

A sediment core (M6b) taken almost at horizontal angle from the steep northern side of the Rhone channel wall was sampled at 112 m water depth with the MIR 1 submersible on June 16th 2011 (Fig. 4, station 10). The top of the wall at this location is at 103 m, i.e. 9 m above the cored location. Radiocarbon dating (ETH-44253) on charcoal and plant remains from core M6b gave an age of 315 ± 45 ^{14}C BP, yielding a calibrated age of 1585 ± 65 AD for the 1-sigma probability (68.2%; Reimer et al. 2004; Stuiver et al. 2005). As the core level corresponds to a sediment depth of 9 m, the inferred mean sedimentation rate is 1.8-2.5 cm/y for this part of the delta. Referring to the ~1.5 km distance to the Rhône river mouth, this sedimentation-rate value is significantly lower than the model proposed by Giovanoli (1990) and Loizeau (1991; Fig. 3b) for recent Rhône delta sedimentation rates (i.e. 3-4 cm/y). However, the model is based on contemporary sedimentation rate, not taking into account sediment compaction. Assuming a probable slight sediment compaction, with a water content decrease from 60% at the surface to 40% at 9 m depth, the sedimentation rates aren't significantly different. More detailed sampling and analyses are thus necessary to evaluate the sedimentation trend in the proximal delta during the last 360-500 years.

The use of manned submersibles for coring operations have allowed a unique opportunity to retrieve sub-horizontal sediment cores in specific location, such as steep channel walls, where standard gravity coring is not possible. Future analyses on the collected sediment cores will enable a further comprehension on the sediment dynamics and limnogeological processes in the Rhone delta.

Conclusions

F.A. FOREL's first observations and conclusions on the Rhone delta and its channel system represent the very first scientific accounts of deep-water channel systems predating the research in marine deep-water systems and related processes by several decades. In particular, F.A. FOREL's conclusions on the importance of contrasting density of water-flow current anticipated some of the important 20th and 21st century research topics of marine geology, such as hypo- and hyperpycnal flows and their control on generation of turbidity currents and associated sedimentary and depositional processes. However, F.A. FOREL himself did not yet understand the key role of erosion in the channel formation.

Limnogeological research in the 20th century showed that the Rhone channel morphology matches, at small scales, the structure of large-scale submarine deltas, and demonstrated that similar sedimentological processes, such as underflow and turbidity currents, govern its formation. The geographical proximity with the Piccard family allowed fruitful research collaboration, leading to pioneering *in-situ* observations of the underwater channel structures onboard the *FA Forel* submersible.

Recent scientific work in the Rhone delta channel, including multibeam bathymetric surveys conducted in February 2008 and in March 2012, as well as *in-situ* video observations and sediment coring onboard the MIR submersibles in summer 2011, reveal new insights on the channel morphology and its formation processes. Small linguoid and weak undulatory asymmetrical ripples, as well as exposed wood branches in channel walls, point to transporting and erosive currents in the distal channel part. Bathymetric data indicate considerable changes in channel-floor morphology in the 4 years interval, with up to 8-m-deep erosion and 5-m-high deposition. Adjacent to the eroded channel-floor sections, new slide scars indicate that channel walls were certainly destabilized by this erosion, leading to triggering of small mass movements. The detailed bathymetric survey from March 2012 also revealed that large areas in the proximal channel floor and on the distal levee slopes are covered by sand waves of varying 0.2-2 m heights and 15-100 m length, which suggest current velocities on the order of 0.5-1 m/s. Sediment dating from channel walls suggests a mean sedimentation rate of 1.8-2.5 cm/yr for the past 350 to 500 years at ~1.5 km distance from the river mouth. The most striking feature is a new small channel forming at the end of the main channel valley, in an area where the channel was filled in 2008. Altogether, this dataset points to currently active channel formation with erosional processes playing a key role.

During all these pioneering and challenging endeavours in Lake Geneva, the Rhone delta area provided the laboratory for various scientists to achieve unprecedented knowledge using novel tools well ahead of their time. In this perspective, the observations and lessons learned from investigating Lake Geneva's Rhone delta and its channel system represent historical landmarks for the progress of geosciences, not only with a local, but most certainly also with a worldwide impact.

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