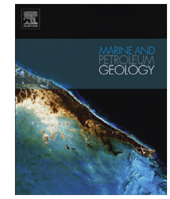
Marine and Petroleum Geology 77 (2016) 515–525

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo



Research paper

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

J.P. Corella [a, *], J.-L. Loizeau [b], K. Kremer [a, 1], M. Hilbe [c], J. Gerard [d], N. le Dantec [e, 2], N. Stark [f], M. González-Quijano [d], S. Girardclos [a]

[a] Department of Earth Sciences and Institute for Environmental Sciences, University of Geneva, Switzerland
[b] Institut F.-A- Forel and Institute for Environmental Sciences, University of Geneva, Switzerland
[c] Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[d] Repsol Exploracion S.A., Madrid, Spain
[e] Ecological Engineering Laboratory, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland
[f] Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, United States

ARTICLE INFO

Article history:
Received 24 January 2016
Received in revised form
10 June 2016
Accepted 5 July 2016
Available online 8 July 2016

Keywords:
Subaquatic channels
Mass-transport deposits MTD
Turbidites
Cohesive flows
Geomorphology

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 6.2×10^6 m^3 Mass-Transport Deposit (MTD) that resembles a debrite 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.

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.

* Corresponding author. Present address: Department of Atmospheric Chemistry and Climate, Institute of Physical Chemistry Rocasolano, CSIC, Madrid, Spain.
[1] Present address: Swiss Seismological Service, ETH Zurich.
[2] Present address: CEREMA, UMR CNRS-UBO 6538, Technopôle Brest Iroise, France.

http://dx.doi.org/10.1016/j.marpetgeo.2016.07.004
0264-8172/

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 synthetize 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 km^2 and has a catchment area of 7420 km^2. 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 km^2) 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 m^3/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,