Geomorphology 241 (2015) 1–18

Contents lists available at ScienceDirect

Geomorphology

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

Submarine canyons and channels in the Lower St. Lawrence Estuary (Eastern Canada): Morphology, classification and recent sediment dynamics

Alexandre Normandeau [a,*], Patrick Lajeunesse [a], Guillaume St-Onge [b]

[a] Centre d'études nordiques, GEOTOP & Département de géographie, Université Laval, Québec, QC G1V 0A6, Canada
[b] Canada Research Chair in Marine Geology, GEOTOP & Institut des sciences de la mer de Rimouski, Université du Québec à Rimouski, Rimouski, Québec, Canada

ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form 27 March 2015
Accepted 28 March 2015
Available online 8 April 2015

Keywords:
Submarine canyons
Gravity flows
St. Lawrence Estuary
Seabed morphology
Sedimentary processes

ABSTRACT

Series of submarine canyons and channels observed in the Lower St. Lawrence Estuary (LSLE) provide an opportunity to analyze in great detail the morphology, spatial distribution and modern activity of such systems in a relatively shallow (≤300 m) semi-enclosed basin. Based on their geomorphology and physical settings, the canyons and channels were classified into four categories according to their feeding sources (ancient or recent): glacially-fed, river-fed, longshore drift-fed and sediment-starved systems. Their activity was interpreted based on geomorphological characteristics such as the presence of bedforms related to gravity flows, backscatter intensity, axial incision and the presence of rapidly deposited layers in surficial sediments. River-fed deltas were interpreted as inactive, mainly because suspended sediment concentrations at river mouths are low, preventing the generation of hyperpycnal currents or delta-lip failures related to high sediment supply. Longshore drift-fed canyons, present where the coastal shelf narrows, were found to be episodically active probably due to earthquakes or extreme storm events. Unlike other longshore drift-fed canyons observed elsewhere in the world, they are active infrequently because of the modern low rates of sediment supply to their heads. The most active canyons are the sediment-starved type and were observed near Pointe-des-Monts. Their activity is probably due to slope failures and to the presence of strong hydrodynamic processes. Therefore, sediment supply is not the main mechanism responsible for modern canyon and channel activity in the LSLE. However, sediment supply has been an important factor during the formation of the submarine channels and canyons. Their quasi-exclusive occurrence on the Québec North Shore is attributed to its larger watershed and important sedimentary delivery during deglaciation. The Québec North Shore watershed is 20 times greater than the Québec South Shore watershed, which favored the transport of greater volumes of sediment during the early-Holocene. Moreover, the slope proximity to the shore led to the formation of longshore-drift fed systems on the North Shore when sediment supplied to rivers were transferred on a narrow shelf.

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1. Introduction

Submarine canyons and channels incise most of the world's continental shelves and act as preferential routes for the transport of continental sediments to the deep-sea. In some cases, canyons incise the continental shelf up to a depth of <100 m and transfer coastal sediments to depths of more than 1000 m, mainly by gravity flows (e.g., Gaudin et al., 2006; Mulder et al., 2012). The activity of submarine canyons and channels depends largely on the rate of sediment supply at their head and on oceanographic processes able to remobilize these sediments (Puig et al., 2014). Many submarine canyons of the world are currently active in the present sea-level highstand (Boyd et al., 2008; Khripounoff et al., 2009; Xu et al., 2010; Biscara et al., 2011; Mulder et al., 2012; Paull et al., 2013). However, recent studies have demonstrated that canyon activity does not necessarily depend on relative sea-level (RSL) positions (Boyd et al., 2008; Ducassou et al., 2009), as previously suggested by sequence stratigraphic models (Vail et al., 1977). Tectonic and climatic factors, as well as the type and volume of sediments, play a major role in canyon activity (Stow et al., 1983; Bouma, 2004). For example, tectonic processes influence the width and slope of the continental shelf and the rock susceptibility to erosion and are known to have an important role in canyon activity in California (Covault et al., 2007) and the Mediterranean Sea (Migeon et al., 2006, 2012). The type and volume of sediment include the capacity of a material to be eroded and transported, while climate largely influences precipitations, which in turn influences river floods and sediment delivery to the coast. All these processes can have more impact than RSL positions on canyon activity (e.g., Ducassou et al., 2009).

Deep-water submarine fans have been largely studied for their hydrocarbon potential (Mayall et al., 2006), whereas shallow submarine fans within continental shelves have been the focus of fewer studies (e.g., Conway et al., 2012; Normandeau et al., 2013, 2014; Warrick et al., 2013). Recent studies on shallow submarine canyons using

* Corresponding author. Tel.: +1 418 656 2131x4508.
E-mail address: alexandre.normandeau.1@ulaval.ca (A. Normandeau).

http://dx.doi.org/10.1016/j.geomorph.2015.03.023
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high-resolution multibeam echosounders have allowed imaging in great detail the recent and frequent sedimentary processes acting within them (Hill et al., 2008; Conway et al., 2012; Hughes Clarke et al., 2014). Such shallow submarine canyons or channels are often observed at the head of fjords up to a depth of 400 m, at the mouth of rivers supplying considerable amounts of sediments (e.g., Conway et al., 2012). More recently, submarine fans were also discovered in very shallow sectors of continental shelves at depths of less than 60 m (Normandeau et al., 2013; Warrick et al., 2013). More attention is now being drawn to these small-scale systems in shallow environments because they can be mapped at a higher resolution using higher frequency multibeam echosounders and can provide high-resolution visualization of gravity-driven processes. Similar shallow-water systems have been reported in the Lower St. Lawrence Estuary (LSLE) (Duchesne et al., 2003; Gagné et al., 2009; Pinet et al., 2011; Normandeau et al., 2014), one of the largest and deepest estuary in the world with depths reaching ~350 m.

Submarine canyons are also known to transfer eroded coastal sediments to deeper marine basins (e.g., Romans et al., 2009; Budillon et al., 2011). Yoshikawa and Nemoto (2010) demonstrated that submarine canyons can profoundly affect coastal sediment dynamics because they often constitute the end of a littoral cell. In the LSLE, coastal erosion affects a large part of the coastline (Bernatchez and Dubois, 2004). It was first hypothesized that the numerous submarine canyons and channels present along the margin of the LSLE were still active and could contribute significantly to coastal erosion by transferring coastal sediments to the Laurentian Channel (Gagné et al., 2009; Pinet et al., 2011; St-Onge et al., 2011). However, evidence for this hypothesis at the LSLE scale is still lacking. Based on a high-resolution geomorphological mapping and surface sediment analysis (box cores) approach, this study aims to: 1) provide a classification of submarine canyons and channels present in the LSLE, where they were formed in a similar environment and in similar climatic and tectonic conditions, but with distinct morphologies; 2) define the factors controlling the distribution of canyons and channels in a semi-enclosed basin; and 3) assess the sedimentary processes currently shaping these systems. This paper highlights the heterogeneity of types of incisions in an otherwise relatively similar bathymetric environment.

2. Physical setting

The LSLE is one of the largest estuaries in the world, reaching 200 km in length, 50 km in width and ≤350 m in depth (Fig. 1). It is located between the Grenville (north) and Appalachian (south) geological provinces, in eastern Canada. The Grenville geological province is mainly composed of hard igneous and metamorphic rocks (Franconi et al., 1975). The littoral is composed of many deltas, which are at the origin of the sand-size sediment found throughout the LSLE shoreline (Lessard and Dubois, 1984; Sala and Long, 1989; Dionne and Occhietti, 1996; Bernatchez, 2003; Jaegle, 2014). The base-level of the canyons and channels, which is the lowest point a particle can attain in the marine realm, is the Laurentian Channel, at ≤350 m (Loring and Nota, 1973). The Appalachian region bordering the LSLE is formed by the sedimentary rocks of the Gaspé Peninsula and is Paleozoic in age.

The LSLE basin contains in some sectors ~400 m thick of sediments that recorded glaciation, deglaciation and the establishment of postglacial conditions (Cauchon-Voyer et al., 2008; St-Onge et al., 2008; Duchesne et al., 2010). Eight seismic units were identified in the LSLE, ranging from ice-contact sediments, to deglacial (ice-proximal and ice-distal) and recent sediment deposition. More local units are related to submarine mass movements and Holocene fans, located punctually on the Québec North and South shores. A surficial deposit map of the LSLE was realized by Pinet et al. (2011) and illustrates the silt-sand nature of the margins of the Laurentian Channel and the finer silts of the trough, where most sediments originate from the North Shore (Jeagle, 2014).

3. Methodology

3.1. Data and methods

Multiple multibeam echosounder datasets were merged in order to produce the high-resolution bathymetric maps of the LSLE. Depths greater than 30 m were mapped by the Canadian Hydrographic Service (CHS) on board the CCGS Frederick G. Creed using a Kongsberg Simrad EM-1000 (95 kHz; ~10-m grid resolution; before 2005) and an EM-1002 (95 kHz; ~10-m grid resolution; since 2005) and on board the Guillemot using a Simrad EM-3000 (before 2005) and an EM-3002 (since 2005). New surveys were undertaken over submarine canyons in 2012 on board R/V Coriolis II, using a Kongsberg EM-2040 (300 kHz; 1-m grid resolution) to improve the horizontal resolution of the images. This system also allowed extracting backscatter intensities to produce reflectivity maps of the seafloor. Shallower areas of the LSLE were mapped by the Centre interdisciplinaire de développement en cartographie des océans (CIDCO) on board the R/V Bec-Scie and R/V Gabrielle C using a SEA SwathPlus-M (234 kHz; 2-m grid resolution) in 2009–2011 and our group on board the R/V Louis-Edmond-Hamelin in 2012 using a Reson Seabat 8101 (240 kHz; 3-m grid resolution). Seismic data were acquired using an Edgetech X-Star 2.1 Chirp (2–12 kHz; cm-scale vertical resolution) subbottom profiler and an Applied Acoustics Squid 2000 sparker (2.4 kJ; m-scale vertical resolution). In total, more than 500 km of seismic lines were acquired during the 2012 expedition on board R/V Coriolis II.

Box cores were collected during the 2012 Coriolis II cruise in different sectors of the LSLE and in 2006 in the Les Escoumins area (Gagné et al., 2009). The box cores were first opened, visually described and photographed. The cores were then analyzed through a *Siemens somatom volume sensation* CT-Scan that allowed a non-destructive visualization of longitudinal and transverse sections of cores using X-ray attenuation. Gray levels vary mainly according to density (Fortin et al., 2013) and allow identifying sedimentary structures and establishing a high resolution stratigraphy (e.g., St-Onge and Long, 2009). Grain-size analysis was performed using a *Horiba laser sizer.* Sediments were diluted into a calgon solution for ≥3 h, shaken and then submitted to an ultra-sound bath in order to disaggregate the particles. At least three runs were averaged. Statistical parameters were obtained using the Gradistat software (Blott and Pye, 2001). The approximate age of the surficial sediments was determined by counting the activity of the radiogenic isotope ^{210}Pb (half-life = 22.3 yrs) via gamma emission at the Centre d'études nordiques. Dating encompasses approximately a century.

3.2. Terminology

Because the submarine canyons and channels studied in the LSLE are located in an inner-shelf shallow-water environment, the terminology used here differs slightly from the one used in deep-water settings. For example, Talling (2014) used the term *canyon* for deep incisions (>100 m) formed primarily by erosion and *gully* was used for smaller incisions (<100 m). If we used this terminology, all the incisions in the LSLE would be considered as gullies. We thus use a different terminology that is adapted to the bathymetric setting of the LSLE: (a) *Canyon* is used here for incisions (generally 10s of meters) formed primarily by erosion that reach the base-level, which is the bottom of the Laurentian Channel. Canyons are generally, but not exclusively, V-shaped. (b) *Gullies* are small-scale incisions (<10 m deep), that generally do not reach base-level. (c) *Channels* are defined as conduits that are formed primarily by depositional flows (Talling, 2014) and that reach the shelf edge or the base-level. They are generally U-shaped and have wide and relatively flat floors.

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