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Late-Quaternary glacial to postglacial sedimentation in three adjacent fjord-lakes of the Québec North Shore (eastern Canadian Shield)

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ABSTRACT

High-resolution swath bathymetry imagery allowed mapping in great detail the sublacustrine geomorphology of lakes Pentecôte, Walker and Pasteur, three deep adjacent fjord-lakes of the Québec North Shore (eastern Canada). These sedimentary basins have been glacio-isostatically uplifted to form deep steep-sided elongated lakes. Their key geographical position and limnogeological characteristics typical of fjords suggest exceptional potential for long-term high-resolution paleoenvironmental reconstitutions. Acoustic subbottom profiles acquired using a bi-frequency Chirp echosounder (3.5 & 12 kHz), together with cm- and m-long sediment core data, reveal the presence of four acoustic stratigraphic units. The acoustic basement (Unit 1) represents the structural bedrock and/or the ice-contact sediments of the Laurentide Ice Sheet and reveals V-shaped bedrock valleys at the bottom of the lakes occupied by ice-loaded sediments in a basin-fill geometry (Unit 2). Moraines observed at the bottom of lakes and in their structural valleys indicate a deglaciation punctuated by short-term ice margin stabilizations. Following ice retreat and their isolation, the fjord-lakes were filled by a thick draping sequence of rhythmically laminated silts and clays (Unit 3) deposited during glaciomarine and/or glaciolacustrine settings. These sediments were episodically disturbed by mass-movements during deglaciation due to glacial-isostatic rebound. AMS ^{14}C dating reveal that the transition between deglaciation of the lakes Pentecôte and Walker watersheds and the development of para- and post-glacial conditions occurred around 8000 cal BP. The development of the lake-head river delta plain during the Holocene provided a constant source of fluvial sediment supply to the lakes and the formation of turbidity current bedforms on the sublacustrine delta slopes. The upper sediment succession (i.e., ~4–~6.5 m) consists of a continuous para-to post-glacial sediment drape (Unit 4) that contains laminated and massive sediment and series of Rapidly Deposited Layers. These results allow establishing a conceptual model of how a glaciated coastal fjord evolves during and after deglaciation in a context of rapid glacio-isostatically induced forced regression.

1. Introduction

During Quaternary glaciations, fjords acted as preferential pathways for the flow of glacial ice originating from continental ice sheets, leading to the transfer of large volumes of ice and sediments to the marine environment (Syvitski and Praeg, 1987, 1989; Hambrey, 1994; Syvitski and Shaw, 1995; Howe et al., 2010). Fjords can provide a long-term sedimentary record to reconstruct past ice sheet dynamics such as ice-flow and rates of ice retreat or advance (Evans et al., 2002; Howe et al., 2010; Schumann et al., 2012; Dowdeswell and Vásquez, 2013; Dowdeswell et al., 2014). Thick sedimentary in fills in fjords and bedforms preserved at their bottom provide a record of marine and terrestrial glacial processes and depositional environment successions that occurred during glacial, deglacial, paraglacial and postglacial times (Boyd et al., 2008; Baeten et al., 2010; Cowan et al., 2010; Forwick and Vorren, 2010; Bertrand et al., 2012; St-Onge et al., 2012; Breuer et al.,

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2013; Dowdeswell and Vásquez, 2013; Hjelstuen et al., 2013; Kempf et al., 2013; Hodgson et al., 2014; Flink et al., 2015). Fjords have generally been described in coastal and estuarine environments, but they also occur in lacustrine settings when freshwaters are enclosed in preglacial and glacial overdeepened valleys (Nasmith, 1962).

Following deglaciation of coastal regions, some fjord basins were isolated from the sea to form fjord-lakes due to glacio-isostatic rebound (Batterson et al., 1993; Batterson and Catto, 2001; Lajeunesse, 2014; Dietrich et al., 2017b). Sharing similar limnogeological characteristics with coastal fjords, fjord-lakes have shown their potential for reconstructing past ice sheet dynamics, deglaciation, paleoenvironmental changes and natural hazards in studies using marine hydroacoustic, geophysical and sediment sampling analysis techniques, as demonstrated in Europe (Van Rensbergen et al., 1999; Beck et al., 2001; Fanetti et al., 2008; Hilbe et al., 2011; Heirman et al., 2012; Turner et al., 2012; Pinson et al., 2013; Vogel et al., 2013), British Columbia (Eyles et al., 1990, 1991; Desloges and Gilbert, 1995, 1998; Gilbert and Butler, 2004; Gilbert and Desloges, 2005, 2012; Gilbert et al., 2006a; Gilbert et al., 2006b; Tunnicliffe et al., 2012), New York State (Mullins and Hinchey, 1989; Mullins and Eyles, 1996; Mullins, 1998; Mullins and Halfman, 2001), Montana (Mullins et al., 1991), eastern Canada (Lajeunesse, 2016) and Patagonia (Kastner et al., 2010; Waldmann et al., 2010; Van Daele et al., 2016).

In eastern Canada, deep fjord-lakes occur in many locations along the formerly glaciated Québec North Shore and the east coast of Newfoundland and Labrador. However, their morphology and stratigraphy as well as their sedimentary processes associated with the transitions from glacial to postglacial environmental conditions during glacial-isostatic rebound remain undocumented. Here we describe the geomorphology, stratigraphy and sedimentology of three fjord-lakes of eastern Canada: lakes Pentecôte, Walker and Pasteur in order to 1) reconstruct their Late Quaternary morphological and sedimentary evolution in response to deglaciation and glacio-isostatic rebound and 2) establish a deglaciation and sedimentation conceptual model for fjord-lakes under glacio-isotatic rebound. This paper provides the geomorphological context and history for a continuous sedimentary record of paleoenvironmental changes in three Québec North Shore watersheds, from deglaciation to the establishment of modern (i.e., postglacial) conditions. The proposed conceptual model serves as an example of how a glaciated coastal fjord develops upon deglaciation, at the interplay of marine and terrestrial settings influenced by a rapid glacio-isostatically induced forced regression.

2. Regional setting

Lakes Pentecôte, Walker and Pasteur are located in the central sector of the Québec North Shore (northwestern Gulf of St. Lawrence, eastern Canada), at elevations of 84 m, 115 m and 86 m, respectively (Fig. 1). They are situated at the downstream end of long (>60 km) north-south-oriented glacial valleys that are deeply incised into the Precambrian Grenville geological province of the Canadian Shield. The lakes are located in the transition zone between the coastal lowlands and the highlands of the Canadian Shield (i.e., Laurentian Highlands) that reach >300 m above sea level (asl) in the study area. The lakes generally form elongated basins with steep sidewalls with morphologies typical of fjords (e.g., potholes and p-forms on their sidewalls; Holtedahl, 1967). The length of lakes Pentecôte, Walker and Pasteur reach ~15, ~30 and ~18 km, respectively. Lake Walker has the largest watershed covering an area of 1896 km^2 compared to 1227 km^2 for Lake Pentecôte and 739 km^2 for Lake Pasteur. Lakes Walker and Pasteur lie on homogeneous granitic gneiss complexes. Lake Pentecôte lies on different geological suites and complexes composed principally of anorthosite, granite and paragneiss separated by faults (Moukhsil et al., 2011) that probably control structurally the bifurcation of the lake in its center. These fjord-lakes are mainly fed by their head deltas formed by large rivers that discharge into their northern extremities (Normandeau et al., 2016a). The lakes flow into the Pentecôte, aux-Rochers and Pasteur Rivers, respectively, at their southern end towards the Gulf of St. Lawrence (Fig. 1C).

During deglaciation, the marine-based Laurentide Ice Sheet (LIS) margin stabilized slightly offshore along the Québec North Shore to deposit apron-shaped grounding-zone wedges (GZW) (Fig. 1C) (Lajeunesse, 2016). The youngest GZW is probably correlated to the eastward extent of the early Younger Dryas Saint-Narcisse Morainic System deposited between 12.8 and 12.2 ka cal BP in southern Québec (Occhietti, 2007). As ice retreated ~30–50 km farther north onto the Laurentian Highlands, the LIS margin re-stabilized and deposited the Québec North Shore Moraine (Dubois and Dionne, 1985), a major morainic system correlated with the late Younger Dryas Mars-Batiscan Moraine deposited between 12.2 and 11.5 ka cal BP (Occhietti et al., 2011). Between 11.5 and 10.8 ka cal BP, the LIS margin stabilized near the outlet of lakes Pentecôte, Walker and Pasteur valleys and deposited thick glaciomarine ice-contact outwash fans. The glacio-isostatically flexured lowlands and valleys were submerged by the Goldthwait Sea transgression at a maximum elevation of 130 m asl (i.e., marine limit) (Dredge, 1983; Hein et al., 1993), reaching the studied lakes between ~11.1 and 10.6 ka cal BP (9.5 ^{14}C ka BP; Dubois and Dionne, 1985; King, 1985). Under rapid glacio-isostatic rebound prevailing during the early stage of deglaciation (i.e., ~3.2 cm a^{-1} during the first millennia; Dionne, 2001), coastal structural valleys were isolated from the sea allowing the formation of fjord-lakes (Lajeunesse, 2014, Dietrich et al., 2017b). Between 8.2 and 7.5 ka cal BP, the LIS margin had retreated over the Canadian Shield until it stabilized north of the Manicouagan Reservoir, ~100 km north of the study area (Occhietti et al., 2011; Ullman et al., 2016). During this period, most major watersheds of the Québec North Shore were undergoing their final stage of deglaciation (Dietrich et al., 2017b).

The investigated lakes are located north of the Lower St. Lawrence Seismic Zone (LSLSZ), where low magnitude (M=<5.1) historical earthquakes have been recorded (Lamontagne et al., 2003; Lamontagne, 1987). Acoustic stratigraphy surveys previously undertaken by Ouellet (1997) in lakes Pentecôte, Walker and Pasteur led to the observation of only a limited number of subaqueous mass-movements deposits near the upper boundary of deglacial sediments; they have not been observed in Holocene sediments.

3. Methods

3.1. Hydroacoustic and geophysical data

High-resolution bathymetric data were collected in 2011 in Lake Walker and 2014 in Lake Pentecôte, on the 8 m-long R/V Louis-Edmond-Hamelin using a Reson Seabat 8101 multibeam echosounder (240 kHz), the Hypack® software, an Ixsea Octans III gyrocompass motion sensor and a Geneq Sx Blue II DGPS (~60 cm precision). A survey was carried out in 2014 in Lake Pasteur on a 4.5 m inflatable boat using a GeoAcoustics GeoSwath Plus compact (250 kHz) bathymetric interferometric sonar, the GS + software, a SMC motion sensor and a Hemisphere V101 111 DGPS (~60 cm precision). A repeated survey of the Lake Walker Gravel River delta was carried out in 2016 using a Kongsberg EM 2040C multibeam echosounder (200–400 kHz) coupled with positioning sensor Kongsberg Seapath 330 with GNSS antennas. Sound velocity profiles were obtained with an Odom DigiBAR Pro probe to correct for sound velocity changes in the water column. These mapping