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Reprint of Evolution of an anthropic source to sink system: Wabush lake☆

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ABSTRACT

Wabush Lake is one of the few very well-constrained source-to-sink sedimentary systems in the world that exhibits near-continuous turbidity currents. In this system, approximately 20 million tons of mine tailings are delivered each year to a 40 km^2 lake. Multibeam bathymetric surveys of this lake were carried out between 1999 and 2011. In addition, a program of extensive sampling and seismic surveys, an airborne LiDAR survey and a photogrammetric survey were carried out during this period. The objective of this study was to determine the evolution through time of this anthropic source-to-sink system, from the point where sediments exit the slurry pipelines at the head of the system to the distal end and bottom of the Lake. The total volume of the Lake is around 1×10^9 m^3.
Analysis of subaerial and subaqueous datasets allows the evaluation of disposal strategies on the delta topset and on tailings accumulation. Disposal strategies influence the dynamics of the channels on the topset, thus in turn affecting the accumulation of tailings throughout the lake, as well as the shoreline advancement rate. Subaqueous erosional channels present on the bed of the Lake influence the depositional pattern of tailings as well as their granulometric distribution. These erosional channels are created by the shoreward migration of knickpoints. In some places, this migration can be documented over multiple surveys.
Finally, sequential analysis of the 1999, 2004, 2006, 2008 and 2011 surveys has allowed detailed documentation of the infilling of the Lake, including the migration of sediment depocenters, the mechanism of emplacement and the progressive infilling of a series of minibasins.

1. Introduction

Sedimentary source-to-sink systems often extend thousands of square kilometers, from high-elevation mountains to abyssal plains. It is usually difficult to obtain a comprehensive overview of all the processes occurring in these systems. Furthermore, the time scale over which the relevant processes take place often means that any direct observations of processes are often little more than snapshots. A better understanding of source-to-sink dispersal systems is important in order to better monitor and model the fate of sediment and pollutants in such systems. This may also help to interpret stratigraphic records, and also to interpret otherwise similar systems that are not evolving as fast as the Wabush Lake system.

Iron Ore Company of Canada (IOC) has been discharging iron tailings into Wabush Lake since 1964. In order to reduce environmental impacts on the lake, many studies have been carried out in order to understand the various physical processes occurring in Wabush Lake. As part of their monitoring efforts, IOC tracks sediment discharge. This helps optimize their operations as well as reduce their environmental impact. The case of Wabush Lake provides a rare opportunity to evaluate a near-complete source-to-sink sedimentary system, for which the governing parameters are well-constrained and the basin is closed. The system has its source at several tailings slurry pipeline outfalls, the locations of which are moved from time to time. The rate of sediment output is accurately documented according to the necessities of mine operation. The size distribution of the tailings, which includes sand and silt, is also well-documented. Sediment from the outfalls creates a highly dynamic, actively prograding subaerial fan-delta, where most of the sand-sized particles are emplaced. The flow passing the delta foreset is hyperpycnal in the sense that the sediment-laden water is denser than the water in the lake. Thus, the flow plunges to create near-continuous turbidity currents (Turmel et al., 2015). It has been observed that turbidity currents are volumetrically the dominant sediment transport process on our planet (Talling et al., 2015), thus underlining the relevance of their study. At Wabush Lake, these currents disperse the finer sediment throughout most of the subaqueous part of the system. They also create erosive channels, leveed channels, sediment waves and shoreward-migrating knickpoints, as commonly seen

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in natural submarine settings. The distal boundary of the Lake Wabush system is a subaqueous sill, which is sufficiently high that very little sediment escapes beyond it. Thus, the complete source-to-sink system, with a length of only ~9 km, lies between the slurry pipe outfalls and the sill. The whole lake is 15 km long. The subaqueous part of this system is an excellent analog to a submarine minibasin that is unconnected to the bathymetry farther downdip. In addition, the lake has several connected sub-minibasins.

From the very beginning of our involvement in this project in 2003, it was clear that the first step toward the study of tailings transport and accumulation was the acquisition of a high-resolution multibeam bathymetric map of the lake floor. This was done for the first time in 2004 (Locat, 2005). Since then, substantially more information on Wabush Lake has been acquired, such as subsequent multibeam surveys in 2006, 2008 and 2011, an aerial LiDAR survey of the subaerial portion of the delta in 2008, a photogrammetric survey of the subaerial portion of the delta in 2011 and seabed sampling in 2006, 2008 and 2011. In this chapter, we focus on the evolution between 2008 and 2011, but we also make references to and comparisons with the evolution between 1998 and 2008. More information on the evolution between 1999 and 2008 may be found in Turmel et al. (2010, 2014, 2015). The main objectives of this paper are to illustrate the effect of the turbid underflows on the evolution of the subaqueous portion of the delta, and to give some insight on the formation of submarine channels and canyons.

2. IOC operations and Wabush Lake setting

Wabush Lake is located in the western part of Labrador (Canada), near the Quebec-Labrador border. This lake is surrounded by gently rolling low relief hills of Proterozoic rocks (Klein, 1966). The lake has an overall N-S orientation, is 15 km long and 3.5 km wide. South of the Lake, the Iron Ore Company of Canada subaerially discharges tailings derived from the nearby mine. This discharge has created a delta that continues to prograde into Wabush Lake. This progradation has been going on since 1964, and tailings discharge has had a mean historical rate of approximately 20×10^9 kg per year. This value increased to 25×10^9 kg between 2008 and 2011.

From south to north (Fig. 1), i.e., from the delta to its northern end, the lake is characterized by a 7-km-long trench that has an average slope of 3°. Fig. 2 shows a cross-section of the lake as well as its evolution between 1999 and 2011. This trench is bounded at its northern end by a natural sill. The deepest point of the southern portion of the lake is just south of the sill, at a depth of 72 m in 2011 (Fig. 2). The sill was, at the time of the last survey, ~10 m above the basin floor. North of this natural sill, the lake deepens to a maximum depth of ~90 m.

Two different systems are used by the mine to discharge their tailings, one for the coarser material and another for the finer material. The grain-size distributions for both systems are shown on Fig. 3. The coarser tailings are mostly in the sand size (75%), whereas the finer tailings are about 50% sand and 50% silt. The coarser tailings consist of about 95% of the total mass, and their solid concentration by weight in the slurry pipelines that deliver the material to the delta topset is between 15 and 22%. The remaining 5% is carried through the finer system, with a solid concentration of about 5% in the slurry pipeline. The water used in the process is fresh water from the lake. This water has about the same temperature before and after mixing with the tailings. Figs. 1 and 4 show the location, in 2011, of the two pipeline outlets. As mentioned above, this location is not constant in time, since it evolves as the delta progrades. Between 2008 and 2011 the pipes carrying the coarser tailings were moved farther north, i.e., downstream, approximately 200 m and raised by ~3 m. The pipes carrying the fine tailings were not moved, but an engineered channel was created to channelize the flow farther out on the topset. When the sediment-laden water reaches the shoreline, the concentration of sediment is still high enough to be manifested by a sediment plume (Fig. 4).

3. Hyperpycnal deltas

Delta formation has been intensively studied, by analyzing outcrops (e.g., Ori and Roveri, 1987), by performing physical or numerical modeling (e.g. Ritchie et al., 2004) or via observation of actual deltas (e.g., Smith and Jol, 1997). The delta created in Wabush Lake is a hyperpycnal delta, i.e., one built by river water that is denser than the lake water, so that the river plume plunges to form a turbidity current (e.g., Mulder and Syvitski, 1995). The exact sediment concentration of the plunging flow is not known at Wabush Lake. This delta provides a simple and thus easily interpretable example for which there is no influence from any allogenic forcing such as tectonics. It is also characterized by an advancing point of flow sediment discharge. This advancing sediment source has created an elongated delta, as noted by Kim et al. (2009).

The subaerial topset beds of the deposit are found between the sediment source and the subaqueous section of the delta. In Wabush Lake, this morphology is that of a fan delta: the flow coming from the pipes enters a zone of reduced stream power, resulting in topset emplacement. It is this section of the delta where the coarsest fraction of sediments is likely found (Bull, 1977). Fan-delta evolution without allogenic forcing shows autogenic cycles of sheet and channelized flow (Parker et al., 1998a,b; Van Dijk et al., 2008, Van Dijk et al., 2009, Clarke et al., 2010). Recent experiments done by Fernandez et al. (2011) to simulate Wabush Lake conditions, i.e., with an advancing feed point, have shown that the flow along the topset is also characterized by a successive alternation between avulsing channel and sheet flows. Field observations at Wabush Lake are in agreement with these observations (Turmel et al., 2015).

When the flow on the topset reaches the shoreline, it still has a sediment concentration such that the entering fluid is denser than the ambient lake water, corresponding to hyperpycnal conditions (e.g., Mulder and Syvitski, 1995; Normark and Piper, 1991). Under these conditions, the river flow plunges near the shoreline into deeper water. When the density difference is sufficient, the plunging flow reaches the bottom and forms a turbidity current that is sustained as long as hyperpycnal inflow conditions persist. A delta mostly influenced by hyperpycnal flows will be different from the well-known Gilbert-type delta. Gilbert-type deltas are more influenced by avalanching of grains, leading to steep-sloped foreset deposits controlled by the angle of repose. The main difference in the geometry of the delta is in the foreset, with hyperpycnal deltas having a lower foreset slope angle than that of a Gilbert-type delta, due to the overriding turbidity current (Kostic et al., 2002).

The mode of deposition on the foreset in hyperpycnal deltas is a function of the turbidity current flow characteristics. Experiments done by Gerber et al. (2008) show that both grain size and sediment discharge modify the slope angle. The foreset slope is also influenced by the sediment concentration in the turbidity current (Fernandez et al., 2011). When the slope angle is in equilibrium with the flow overriding the foreset, Gerber et al. (2008) showed that there is sediment bypassing on the foreset, which in turn leads to the creation of lobes that backstep onto the foreset due to the sharp reduction of the slope angle at the foreset toe. On the other hand, when the turbidity current is not in equilibrium, sediment storage is initiated on the upper portion of the foreset, until a new bypass slope is reached (Gerber et al., 2008; Lai and Capart, 2007).

4. Methodology

4.1. Multibeam

Bathymetric multibeam surveys were conducted in 2004, 2006, 2008 and 2011, in addition to a single-beam bathymetric survey conducted in 1999. Bathymetric data in 1999 were acquired using a single-beam ODOM Echotrac DF3200 Mark II digital echosounder. At