Lake bottom imagery: a simple, fast and inexpensive method for surveying shallow freshwater ecosystems of permafrost regions

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Widespread and diverse in permafrost landscapes, freshwater ecosystems play a crucial role in maintaining the traditional lifestyle of northern communities as habitats for aquatic plants and wildlife, and many are also biogeochemical hotspots that strongly emit greenhouse gases. Limnological and paleolimnological studies are of great importance for understanding the past, present and future dynamics of such aquatic systems. This paper presents a novel, highly integrated lake-bottom imagery strategy for surveying lake-bottom water and sediments prior to sampling. It is user-friendly and easily portable, can be implemented rapidly in the field with directly accessible data, and is much less expensive than regular lake basin surveying techniques. The method integrates GPS-assisted sonar technology, underwater HD photo-video camera, and water depth and temperature sensors. Examples from Canadian High Arctic permafrost landscapes, where the method has been recently applied, are reported and discussed.

RÉSUMÉ
Abondants et diversifiés en zone de pergélisol, les écosystèmes aquatiques d'eau douce jouent un rôle crucial dans le maintient du mode de vie traditionnel des communautés nordiques et représentent des sources significatives de gaz à effet de serre. Les études limnologiques et paléolimnologiques permettent de mieux comprendre la dynamique passée, présente et future de ces écosystèmes. Cet article présente une stratégie novatrice et intégrée d'imagerie du fond des mares et lacs qui peut être utilisée dans l'échantillonnage de la colonne d'eau et des sédiments lacustres. Cette méthode peut être réalisée en quelques heures sur le terrain et fait appel à des instruments simples d'utilisation, facilement transportables et sensiblement moins chers que les outils standard d'étude des bassins sédimentaires. La méthode intègre un système sonar-GPS portable, une caméra HD submersible et des capteurs de température et de pression. Des exemples d'utilisation de la méthode en zone de pergélisol dans le Haut Arctique canadien sont présentés et discutés.

1 INTRODUCTION

Freshwater ecosystems are an abundant feature of permafrost landscapes and show a great diversity of shapes, sizes, and limnological properties (Pienitz et al. 2008; Breton et al. 2009; Rautio et al. 2011; Vincent et al. 2013; Grosse et al. 2013). They also play a key role in maintaining the traditional lifestyle of northern communities (e.g., fishing and hunting) and are hotspots for biogeochemical exchanges between terrestrial, aquatic and atmospheric environments (Laurion et al. 2010). Moreover, they will impact permafrost biogeosystem dynamics in the future, as climate-induced permafrost thawing and degradation will result in an increase of their spatial coverage and depth by thermokarst processes (USARC 2003).

Paleolimnology, which studies the history of freshwater ecosystems (especially ponds and lakes) and their drainage basins based on lacustrine sediment archive analysis, has gone through several methodological and conceptual developments during the last decades. This multidisciplinary field greatly benefited from technological advances in many disciplines such as electronic microscopy, image analysis or radiometric dating (e.g., Last and Smol 2001; Francus 2004). Yet, the first fundamental task of paleolimnologists has remained the same over the years: collecting high quality lake sediment cores at sites representative of lake internal and external conditions, generally at the deepest portion of the lake basin. However, these sites are rarely at the center of the lakes and are inaccessible to direct visual observations, which complicates the selection of optimal sampling sites. Seismic or acoustic technologies can be of great help in characterizing lake basin morphology (Scholz 2001), but they are generally expensive and time-consuming, difficult to conduct in remote regions and poorly adapted to shallow aquatic ecosystems such as thermokarst ponds and lakes.

The purpose of this paper is to present a novel strategy of sampling lake sediments, which integrates modern and readily available lake bottom imagery tools. We show field examples from lakes in permafrost landscapes in Arctic Canada (Figure 1), and discuss the benefits and limitations of the approach.

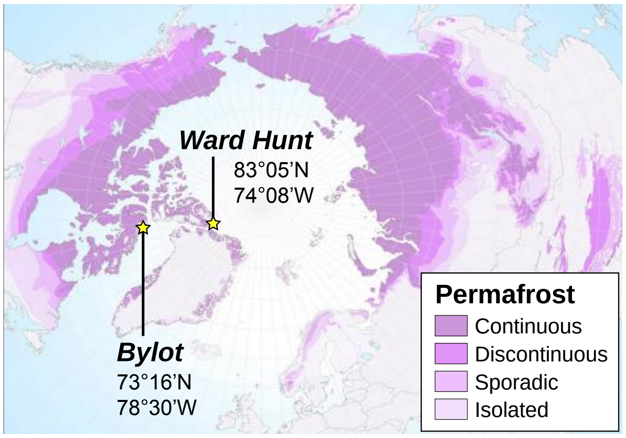

Figure 1. Location of the study sites (Bylot Island and Ward Hunt Island, Nunavut) within the circumpolar continuous permafrost zone (modified from Brown et al. 1998).

2 INTEGRATED LAKE BOTTOM IMAGERY AND SURVEYING

2.1 Lake bathymetry

We use a 'recreational fisherman' sonar system equipped with an internal GPS (Humminbird model 859XD). It is light, compact, affordable and user friendly, and can be quickly mounted on a small zodiac with a 12V battery (Figure 2). Lake-depth signals are continuously recorded along regularly spaced navigation lines (from ~ 5 to 25 m, depending on pond/lake size) and transferred on a SD memory card (Figure 3). Using the compatible AutoChart software installed on a laptop, depth data are interpolated between navigation lines to produce geo-referenced 3D bathymetric maps that can be visualized immediately on-site (Figure 5b; see below). This equipment allows rapid bathymetric surveys (2-3 hours) of small lakes (< 1 ha).

Figure 2. Photographs of the integrated portable GPS-sonar system installed on a small zodiac. The antenna (circled) is fixed outside the zodiac to float at the water surface.

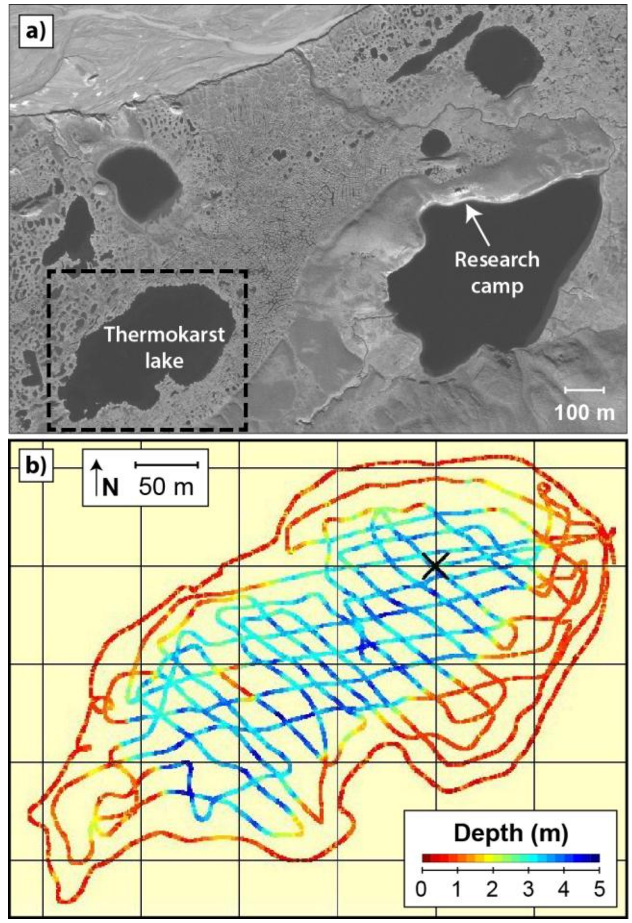

Figure 3. Thermokarst lake bathymetry survey in the Canadian Arctic using a portable sonar. (a) Satellite image (GeoEye-1, 18 July 2010) showing the mapped thermokarst lake within a glacial valley (Bylot Island, Nunavut; Figure 1). (b) Recorded depth signals along navigation lines (~ 25-m spacing) in the thermokarst lake.

2.2 Lake bottom imagery

Coupled with the GPS-sonar system, we use a waterproof HD photo-video wide-angle camera (GoPro model Hero3+ Black edition). It is one of many inexpensive models with standard housings that are rated to 60 m depth. The camera is installed on a light-weight pole, a falling weight or even on a separate instrument measuring limnological properties (water temperature, dissolved oxygen, etc.), and controlled from a boat or the lake shore. It is equipped with diffused LED lights to allow the capture of still images or videos of the ice, water column and lake bottom even under restricted light conditions (Figure 4a). It can also be connected (via coaxial wi-fi cable) to a cellular phone or tablet for real time observations. Such a system allows direct visual observations of the lake water column and bottom conditions including surface sediments, which can be used in conjunction with bathymetric maps to locate the best coring sites. It can also be used to confirm unequivocally the thermokarstic origin of permafrost lakes, as submerged and degraded ice-wedge polygons and frost crack troughs can be observed directly at the bottom (Figure 4b).

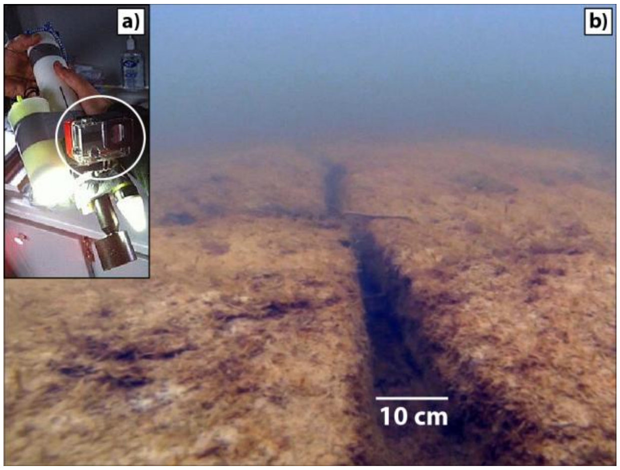

Figure 4. Lake bottom imagery using a waterproof HD camera. (a) Installation of the camera (circled) on a RBR conductivity-temperature-depth profiler, with lights fixed on the sides. (b) Photograph of the bottom of a thermokarst lake (Bylot Island, Nunavut; Figure 1), showing submerged ice-wedge polygons (~ 1 m depth) and degraded frost crack troughs.

3 APPLICATION TO FRESHWATER ECOSYSTEMS IN PERMAFROST LANDSCAPES: EXAMPLES FROM THE CANADIAN HIGH ARCTIC

3.1 Finding the best locations for lake sediment coring and installation of sediment traps

Bylot Island (Nunavut) is located in the Eastern Canadian Arctic (lat. 74°N; Figure 1). Numerous glacial valleys spread from the center of the Island and are dynamic biogeosystems rich in permafrost ground ice, peat, and aquatic environments (Allard 1996; Fortier and Allard 2004). Ponds and lakes are widespread and can release high amounts of carbon formerly trapped in permafrost through greenhouse gas emissions (Laurion et al. 2010; Negandhi et al. 2013). Characterizing their age and evolution through time is thus relevant for determining climate-permafrost feedbacks across the Arctic.

Bathymetric mapping was conducted in a few lakes in July 2014. Goals were to characterize the bottom morphology of lakes and to locate the best coring sites for paleolimnological studies. The example shown here is a small (~ 1 ha) glacial (kettle) lake (Figure 5). Navigation lines were surveyed at 5-10 m grid spacing, which took about 2-3 hours. The generated bathymetric map showed a deep section (> 10 m), not in the lake center but rather near to southwest shore. A 37-cm long sediment core was collected from its deepest part (Figure 5c). A sediment trap was also installed at the bottom to collect settling material during the following years. The depth of this lake (much deeper than thermokarst lake) and the nature of the material retrieved (sand and gravel) confirmed the glacial origin of the lake.

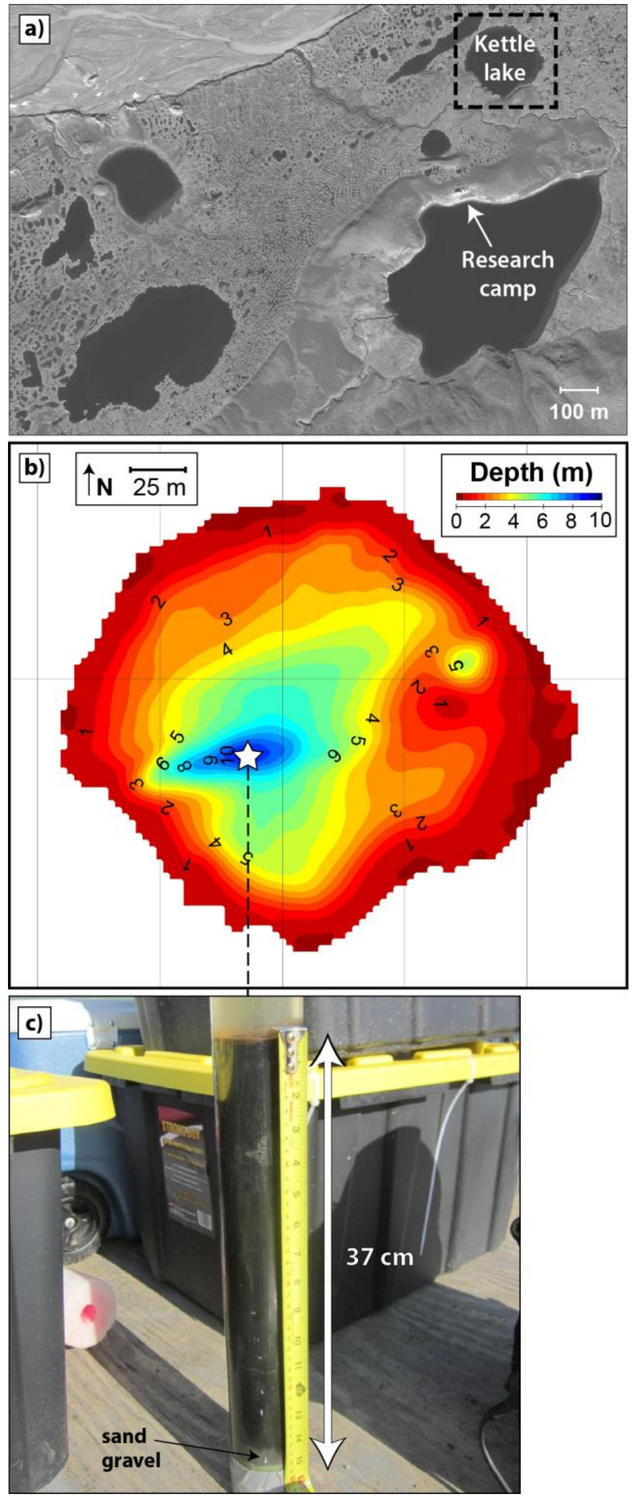

Figure 5. Paleolimnological sampling in a kettle lake of the Canadian Arctic. (a) Satellite image (GeoEye-1, 18 July 2010) showing the sampled kettle lake within a glacial valley (Bylot Island, Nunavut; Figure 1). (b) Bathymetric map generated using the above-mentioned GPS-sonar system. (c) Photo of a 37-cm long sediment core collected from the deepest part of the lake (white star on the map).

3.2 Imaging lake bottom conditions of a High Arctic lake with a multiyear lake-ice cover

Ward Hunt Island (Nunavut) is located at the northern tip of Canada, north of Ellesmere Island (lat. 83°N; Figure 1). Ward Hunt Lake (WHL) occupies a central depression on the Island and is generally covered at its center by perennial ice up to 4 m thick (Vincent et al. 2011). Lake bottom conditions are thus difficult to assess directly, and bathymetric surveys over the entire lake area are not feasible. However, the ice cover on WHL recently experienced a substantial reduction in extent and thickness, even showing ice-free conditions at some years (Paquette et al. 2015), potentially driving important limnological changes.

In August 2014, a waterproof camera with two submersible flashlights were fixed on a RBR instrument (Figure 3a) and lowered to the bottom of WHL through multiple holes drilled through the ice cover. The RBR device allows for continuous recording of water temperature, electrical conductivity and depth as it moves down the water column. While previous work suggested that the microbial mats observed in the shallow littoral waters were not likely to extend under the multiyear thick ice cover (Antoniades et al. 2007), our video images at the deepest site revealed a continuous and luxuriant bottom community dominated by cyanobacterial mats and bryophytes (Figure 6).

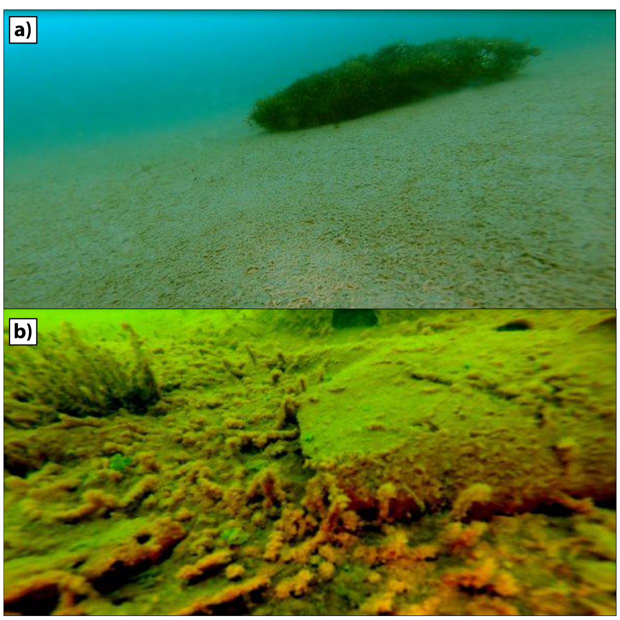

Figure 6. Lake bottom imagery under a multiannual ice cover using a HD video camera installed in a waterproof housing (Ward Hunt Island, Nunavut; Figure 1). (a) Shallow zone (~ 5 m deep) with bryophyte patches and cylindrical sedimentary features. (b) Lake bottom (~ 10 m deep) with continuous microbial mats and cyanobacteria-coated bryophytes.

Other sites surveyed showed different appearances, which allowed the documentation of the spatial variability of WHL benthic communities. These observations are now being followed up with detailed sampling and analysis to investigate their exact composition and implications for lake water biogeochemistry. Such observations, coupled with recently available bathymetric map made using interpolations from several ground penetrating radar survey lines over the lake ice cover (Paquette et al. 2015), will help localize the best limnological sampling and paleolimnological coring sites for subsequent fieldwork campaigns.

4 BENEFITS, OTHER APPLICATIONS AND LIMITATIONS OF THE METHOD

Our lake survey ‘tool-kit’ includes a small packable zodiac, a portable sonar equipped with a GPS and an HD video camera installed in a waterproof housing. The whole ensemble can be transported and deployed in the field by a single person, which is a notable advantage compared to more traditional seismic/acoustic lake-basin analysis technologies. This optimized observation system allows new insights into limnological aspects (e.g., ice characteristics, water column turbidity, extent of light penetration, bottom morphology and benthic communities) of remote shallow aquatic systems, including High Arctic ponds and lakes. It is efficient for rapidly localizing the best sites for sampling the benthos, and the best coring sites for paleolimnological reconstructions. It is affordable (< 3 k$ US in 2014 for the sonar, software, and camera), easy to deploy, and provides real-time data in the field that can then be used to guide sampling.

Taken separately, the above-mentioned tools have already been used to study lake bottom conditions, for example assessing freshwater fish populations using underwater video (Wilson et al. 2015) or characterizing thaw lake basin morphology using GPS-sonar (West and Plug 2008). To our knowledge however, we provide a first integration of all these technologies for surveying shallow permafrost aquatic systems. Such a method could be helpful in small systems with complex sedimentological dynamics (Bouchard et al. 2011; 2014a).

This lake bottom imagery system can also be applied to other types of limnological surveys, such as water column sampling in a morphologically complex lake, precise sampling of benthic flora/fauna, or optimal positioning of greenhouse gas bubble traps to quantify ebullition flux (Bouchard et al. 2014b; in review) (Figure 7). The video imaging also allows the deployment of sediment corers to be closely monitored and evaluated during its positioning and later during the sampling.

Moreover, our portable video camera system can be used to study lake-ice properties such as composition, thickness and bottom geometry, as well as gas accumulation within the ice cover. Lowering the camera down a hole drilled through the ice cover allows for determining the relative proportion of snow-derived (white) and congelation (black, columnar) ice, and characterizing the gas bubbles trapped in the ice. Once below the ice cover, the camera can look up at an angle to characterize the bottom topography of the ice cover and accumulation of gas under the ice cover.

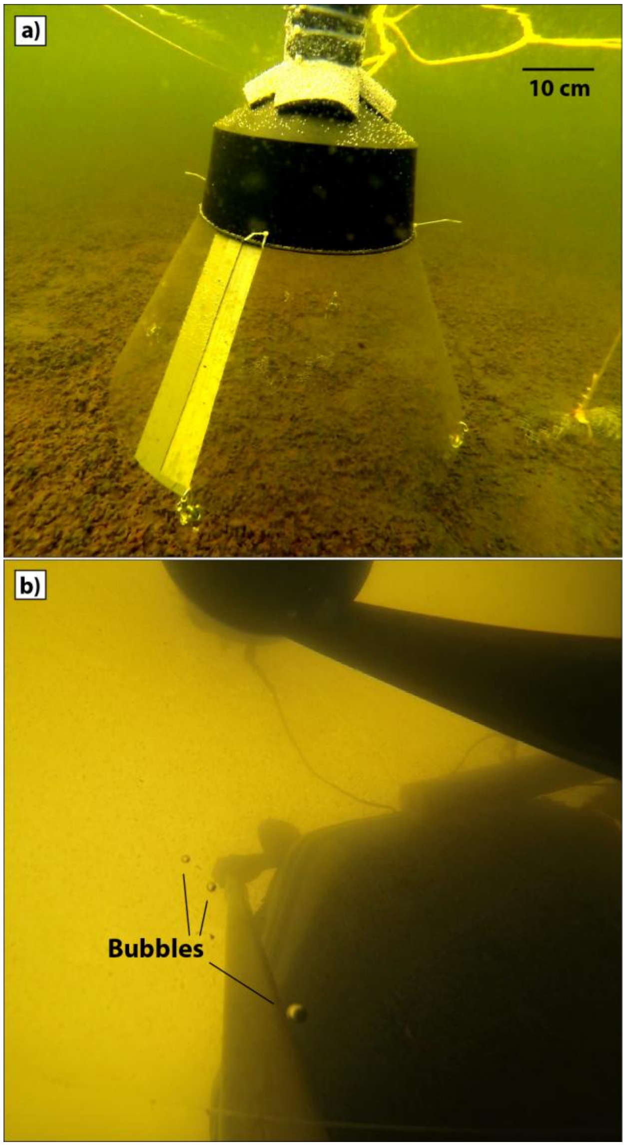

Figure 7. Sampling gas bubbles produced within pond and lake sediments using submerged funnels (Bylot Island, Nunavut; Figure 1). (a) Bubble-trapping funnel installed at the bottom of a shallow polygonal pond. The above-mentioned waterproof HD photo-video camera allowed to confirm that funnel installation did not disturbed the bacterial mat at the bottom. (b) A view from underneath a similar funnel installed over the center of a thermokarst lake (Figure 3). Bubbles could be filmed while rising towards the upper part of the funnel.

There are, however, some minor limitations in using such techniques and tools. User must be careful when manipulating instruments, as some parts are not heavy-duty (especially cables). The GPS-sonar spatial resolution does not appear to be adequate for very small and shallow ponds (few meters in diameter, often less than one meter in depth). The sonar battery (12V) has a limited operation time (2-3 hours), even when fully charged, which can be challenging for remote and cold sites. The waterproof rating of the HD camera casing may not be sufficient in lakes deeper than a few tens of meters, and the cellular phone/tablet option (via coaxial wi-fi cable) is limited by signal strength of transmission to about 15-20 m. Another system using AV cables instead of wi-fi signal could solve this issue.

Lake-bottom imagery using modern technology is a simple, fast and inexpensive way to explore and sample ice cover and bottom conditions of shallow freshwater ecosystems in remote permafrost regions. Furthermore, it is non-destructive and allows preservation of lake-bottom sediments for further exploration and sampling. Both limnological and paleolimnological investigations can greatly benefit from this approach.

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